String Derived Z' Model at an Upgraded Superconducting Super Collider

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Abstract

The future of collider physics is under investigation. With the High Luminosity LHC program lasting until the late 2030s, the next machine in the energy frontier is envisioned to appear in 30–40 years, which may be too far into the future to sustain the field. In this paper we explore the physics potential of an Upgraded Superconducting Super Collider (USSC). The Original Superconducting Super Collider (OSSC) was planned to operate at 20TeV beam energy, and with improved magnet technology and/or longer tunnel, one may envision that it can be extended to 25–30TeV beam energy. Given that the decision on the OSSC construction took place in Autumn 1988 and it was planned to start operation in the 1996-1999 period, an USSC can be constructed 10–15 years from construction and fill the gap between the end of HL–LHC and the future envisioned machines. While the main mission of the USSC will be to test the Standard Model and its electroweak and strongly interacting sectors, as a specific example we illustrate the invariant mass distribution at NNLO in QCD for a 5 TeV Z' in the string derived Z' model.

Keywords: symmetry, Hadron, Collider, LaTeX, sample
DOI: 10.31526/ACP.BSM-2023.4

1. INTRODUCTION

Fundamental particle physics is at a crossroad. On the one hand the basic understanding of the constituent matter and interactions crystallised in the Standard Particle Model that correctly accounts for all experimental observations to date. The latest victory on this triumphant march, culminating over one hundred years of experimental research and discovery, has been the experimental discovery of the Higgs boson at 125.11GeV. The Standard Model utilises the theoretical framework of point Quantum Field Theories and is also used in the Standard Cosmological Model that correctly predicts some of the observed features such as the primordial abundance of light elements. It is further noted that given our current understanding of the fundamental matter and interactions, it is plausible that the Standard Model remains unperturbed up energy scales much above the energy scales being probed in contemporary experiments, *i.e.* the Grand Unified Theory (GUT) scale, at which the three gauge interactions of the Standard Model are merged into one, or the Gravitational Unified Theory (GUT) at the Planck scale, at which the gravitational interaction is synthesised with the gauge interactions. On the other hand, the Standard Model leaves much to be desired. Our basic understanding of the content and composition of the matter in the universe is lacking. Most of this matter is hidden from us, and we do not understand why that which is not hidden exists at all. Furthermore, most of the energy stored in the universe is not in the form of matter at all. Most importantly, however, is the nature of the Higgs boson and the electroweak symmetry breaking mechanism. We do not understand how the Standard Model can remain viable up to much higher energy scales, while maintaining the stability and perturbativity of its scalar sector. That is the most urgent contemporary question that requires further experimental elucidation.

Much of this celebrated success was made possible by the development of collider technology. It is clear that collider tools will cease to provide a viable experimental probe once the required energy regimes will enter the Grand Desert Scenario envisioned in GUTs. Nevertheless, the nature of the Higgs boson and the mystery of electroweak symmetry breaking can only be unravelled effectively by utilising colliding machines. The pivotal question that occupies the community at present is which collider facility is best at present to advance the objectives of the field. In this note we propose that the best option in terms of feasibility and timeline is an Upgrade of the Super Conducting Super Collider (USSC) that was designed and partially constructed in the early 1990s. We give some superficial arguments in favour of this possibility that to our knowledge has not been discussed seriously so far among the options that are being debated. To examplify the potential utility of the USSC we analyse the physics of a superstring derived Z' model in the energy scales that will be probed in the USSC. Additionally, we discuss briefly other research aspects of the experiment

The lightness of the Standard Model scalar sector as compared to the large scales envisioned in GUTs is best accommodated in its supersymmetric extensions, which mandate the existence of at least two electroweak Higgs doublets in vector–like representations. This introduces a new version of the hierarchy problem which is known as the μ–problem. This problem is particularly acute in string–derived models that reproduce the phenomenological features of the Minimal Supersymmetric Standard Models. Namely, what prevents the μ–parameter from being of the order of the Planck scale, rather than of the order of the TeV or weak scales. We proposed that a solution to this problem can be found if the Higgs multiplets are chiral under an additional $U(1)$ symmetry that remains unbroken down to low scales. In this case, the μ–parameter is only generated by the Vacuum Expectation Value that breaks the additional $U(1)$ symmetry.

In this paper, we show the invariant mass distribution for a 5 TeV string derived Z', produced in the Drell-Yan (DY) process at the USSC with $\sqrt{S} = 50$ TeV of center of mass energy and compare this distribution to that at obtained at the LHC with $\sqrt{S} = 13$ TeV.

The study of gauge kinetic-mixing interactions $\chi F^{\mu\nu} F'_{\mu\nu}$ in the lagrangian [1] will be shown in a separate work. The effect of such a renormalizable operator is important in this context because it may be produced by physics at energy scales above the Z' breaking scale, with no suppression by the large-mass scale [2, 3] and can affect the couplings of Z's at the TeV scale [4]. The interplay between the gauge kinetic–mixing parameter and gauge coupling of the Z', as well as other Z' properties, can be probed by using forward–backward asymmetry (A_{FB}) distributions in Drell–Yang scattering, where this observable can have an advantage in extra–resonance searches and as a model discriminator tool [5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16].

2. FEASIBILITY AND TIMELINESS

At the outset we should attest that we are not accelerator physicists. The remarks made here are not based on expert knowledge in accelerator physics. Nevertheless, they follow pure logic and familiarity of historical development of collider based research over the past 35+ years. The future of particle accelerators has undergone detailed studies by the American and European communities over the past few year that are published and are accessible online [17, 18, 19, 20]. A leading experimental facility at the Energy Frontier (EF), the High–Luminosity Large Hadron Collider (HL–LHC) will operate at CERN until the mid– to late–2030s. The experimental program beyond HL–LHC at CERN is currently under study and will entail a well laid out program of Future Circular Collider (FCC) program with e^+e^- and hh phases. There isn't enough praise in the world that can be bestowed on CERN and its experimental program since its establishment in the 1950s. CERN stands as the model for international collaboration and cooporation at the forefront of human curiosity and exploration. CERN has its experimental program on the Energy Frontier well laid out beyond 2050. The physics case and the experimental instruments to explore it are planned and justified. There is not much to add. The other contemporary global players with potential capacity in the Energy Frontier are China and the United States. Detailed community studies are on–going that can be found in the published summaries, with the most relevant being the Accelerator Frontier [19] and the Energy Frontier [18].

These reports contain many excellent proposals that can be divided into two main categories. Precision lepton colliders that will provide instruments to perform detailed studies of the Higgs particle and its properties, as well as precision studies at the $t\bar{t}$ threshold. The initial phase of this program will be an initial run at 250GeV Centre of Mass (CoM) energy with increasing energy up to 1TeV and the few TeV CoM regime. The colliders in this category include the International Linear Collider (ILC) that has been in discussion since the early 90s, the Compact Linear Collider (CLIC); the Circular Electron Positron Collider (CEPC); the Cool Copper Collider (C^3); and High-Energy-LEptoN (HELEN) collider. Another class in this category is the Muon Collider that will provide a precision machine with reach into the multi–TeV energy scale. The second category are the hadron–hadron colliders that include the FCC–hh with 100TeV CoM energy, a hadron–hadron phase in the Future Circular Collider (FCC) at CERN that will have an initial e^+e^- program, similar to the LEP/LHC program, and the Super Proton-Proton Collider (SPPC) with a planned 100TeV CoM energy to operate in China after the CEPC and using the same tunnel complex and infra–structure in a multi–staged approach, similar to that planned for the CERN FCC. Another category of proposed colliders are the electron-proton colliders, *e.g.* the LHeC, and the electron–ion collider *e.g.* the EIC, that provide more limited scope in terms of Higgs precision studies and/or discovery potential.

In terms of the timeline of the current proposals, the HL–LHC will run until the mid–to–late 2030s. It is then envisioned that within a 10 year period the FCC program can be set in motion and start operation toward the mid to late 2040s, with an initial e^+e^- phase, followed by hadron–hadron phase. A similar timeline is envisioned for the CEPC to be followed by the SPPC. The ILC program may be operational by mid–to–late 2030s. The initial phases of the lepton colliders will run at 0.25TeV and will be limited to precision Higgs studies. It is noted that e^+e^- machines require relatively short accelerator R&D, whereas the envisioned hadron machines at 100TeV require substantial accelerator R&D. The Muon Collider requires substantial accelerator R&D before it can be considered as a physics exploratory machine. The programs for the hadron machines envisions discovery machines at 100TeV at timeline reaching beyond the 2050s.

An alternative route for an hadron–hadron machine is to consider an Upgrade of the Super Conductor Super Collider (USSC) that was being built in the early 1990s and was terminated by the US congress in October 1993. In terms of magnet technology the SSC magnets were supposed to operate at 6T with an initial aperture of 4cm bore that was increased to 5cm bore, with increased cost of the total project from 6B to 11B USD. It was designed at 20TeV per beam with 40TeV CoM energy and $10^{33}/(\mathrm{cm}^2\cdot\mathrm{s})$ total luminosity. We can consider that with modern magnet technology an increase of the magnetic field to 8-10T will enable the construction of a machine with 25–30TeV beam energy with 50–60 CoM energy. The main advantage of this option is that the required accelerator R&D is substantially shortened. The project will utilise the blueprint of the SSC design, albeit with some modification for the upgrade. The Original SSC (OSSC) site was chosen in October 1988 and it was initially planned to start operations in 1996, which was delayed to 1999. Given this timelines, the timeline for the USSC is 10–15 years from the decision point, *i.e.* mid–to–late 2030s.

In terms of the physics reach, it is clear that the main focus of experimental particle physics should be the study of the properties of the Higgs boson and its many couplings. Particularly vital is to elucidate the electroweak symmetry breaking mechanism are the self–couplings in the Higgs potential. The optimal machines for this purpose are the lepton machines. In that respect, however, the e^+e^- machines at the lower energy scale are limited scope machines and their prospects as discovery machines are limited. Hadronic machines offer a less clean environment to study the Higgs parameters, but offer a more extensive energy reach and discovery potential. We should comment, however, that there is an erroneous cultural perception among some researchers that an accelerator project is successful only if some new physical phenomena is discovered by it. We advocate that an accelerator project at the energy frontier should be deemed successful if it delivers on the specified properties on which it was designed, *e.g.* in terms of energy and luminosity. It should then be considered as substantially contributing to general knowledge if it is able to reduce the error bars on the Standard Model parameterisation of the experimental observables.

In terms of location, the USSC could be built in the US, China and/or Europe. The technical know–how exist in Europe and the US and will need to be acquired in China. All three have the industrial capacity to carry out the project. It is the prevailing culture in this field that projects of this scale are global projects with active collaborations from all over the globe and from different societal regimes. However, all three are conducting community studies that are well underway. Borrowing the cost estimates from the Snowmass studies [19], we may estimate the cost of the project between 10B-20B USD. The question then is which entities possess the financial resources to fund the project. Given that the required accelerator technology is off the shelf technology Saudi Arabia (SA) can also fund the construction of the USSC as a Middle East (ME) project, at a cost equivalent to the establishment of a few football teams. Given that SA will need to buy the technical know–how and to build the industrial capacity, we can multiply the projected cost by a factor of five, *i.e.* 50B–100B USD. As a ME project the USSC can build on the experience gained in the SESAME ME project and subject to geological studies base the USSC at the SESAME site. The construction of the USSC and successful delivery on the specified design parameters would be by itself an enormous success. Following the CERN experience of providing a platform for cooperation, the USSC can serve as a Project for Peace, promoting curiosity driven collaboration.

3. THE PHYSICS CASE

In this section we will briefly discuss in general the physics case for the USSC. A more detailed analysis will be presented in a forthcoming publication, including a detailed technical proposal and elaboration of the physics case. We comment that the physics case of a project of this financial commitment must be based on improving the measurement of the parameters of the prevailing theory, *i.e.* measurement of the Standard Model parameters. The discovery of new physics can only be regarded as an added bonus. On the other hand, there is a non–zero chance that the USSC will stumble on the new physics threshold that is anticipated to exist in connection with the electroweak symmetry breaking mechanism. While this cannot be guaranteed, there is potentially a big prize to be won. As an example, we analyse the invariant mass distribution an NNLO in QCD for a 5 TeV Z' produced at in pp collisions at $\sqrt{S} = 13$ and $\sqrt{50}$ TeV. It is clear that more elaborate study is required for the general physics case. We note, however, that proposals for projects with intermediate energy scales between the current LHC energy scale at 14TeV and the projected FCC–hh energy scale at 100 TeV are being discussed at the order of double the LHC energy, *i.e.* 28 TeV CoM energy. The USSC on the other hand will operate at 50-60 TeV CoM energy. The USSC therefore targets the mid–energy range between the LHC and the planned FCC–hh. It is clear that the physics case has to be based on improving the measurements of the Standard Model parameters and at present the primary interest is the measurements of the couplings of the Higgs field, *i.e.* the coupling of the Higgs field to the Standard Model fermions and vector fields, and most importantly the Higgs self–couplings that will elucidate the nature of the Higgs potential and the electroweak symmetry breaking mechanism. It is further evident that the optimal machine to preform these measurements is a lepton accelerator. However, the scope of a e^+e^- accelerator at 0.25–0.5 TeV will be limited to Higgs studies. On the other hand the USSC will have by far greater chance of stumbling on the much anticipated layer of new physics which is associated with the electroweak symmetry breaking mechanism. While this is not guaranteed, the mere construction of the ME USSC will be regarded as a transformative contribution for regional development.

Details of the string derived Z' model can be found in the literature [21, 22, 23, 16]. String inspired Z' models have been of interest since the mid–eighties (see *e.g.* [24, 7, 25, 26]) due to the appearance of Grand Unified Theoretical (GUT) structures in heterotic–string compactifications. However, the construction of string derived models that allow for an extra $U(1)$ symmetry to remain unbroken down to low scales proved to be challenging. The reason is that the symmetry breaking pattern $E_6 \to SO(10) \times U(1)_A$ in string constructions results in an anomalous $U(1)_A$ that cannot remain unbroken down to lower energy scales [27]. Viability of a low scale Z' vector boson mandates the construction of string models with anomaly free $U(1)_A$. This can be achieved by enhancing $U(1)_A$ to a non–Abelian symmetry as in ref. [28], or by utilising self–duality under the Spinor–Vector Duality (SVD) [29, 30, 31], as in ref. [21]. We further note that the string derived Z' models [21] has an extended Pati–Salam symmetry at the string scale. The heavy Higgs states in the string model that are available to break the extended Pati–Salam symmetry imply that the breaking scale of this linear combination coincides with the breaking scale of the Pati–Salam symmetry. In the string–derived Z' model the observable and hidden sector gauge symmetries are given by:

$$\begin{aligned} \text{observable} &: \quad SO(6) \times SO(4) \times U(1)_1 \times U(1)_2 \times U(1)_3 \\ \text{hidden} &: \quad SO(4)^2 \times SO(8) \end{aligned}$$

The string spectrum contains the required massless states to break the GUT symmetry to the Standard Model. The two $U(1)$ symmetries $U(1)_1$ and $U(1)_2$ are anomalous in the string model

$$\text{Tr}U(1)_1 = 36 \qquad \text{and} \qquad \text{Tr}U(1)_3 = -36. \tag{1}$$

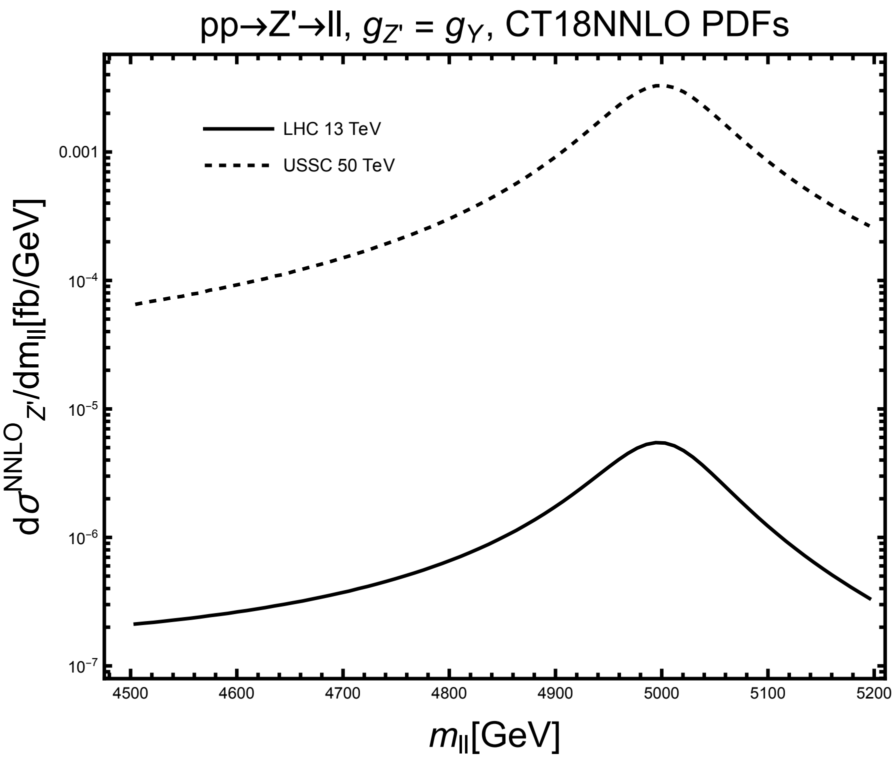

FIGURE 1: Invariant mass distribution at NNLO in QCD for a 5 TeV Z' produced in pp collisions at $\sqrt{S} = 13$ TeV and $\sqrt{S} = 50$ TeV.

and the E_6 combination,

$$U(1)_\zeta \;=\; U(1)_1 + U(1)_2 + U(1)_3\,, \tag{2}$$

is anomaly free and can be part of an unbroken $U(1)_{Z'}$ symmetry at low scales. The Pati–Salam gauge symmetry is reduced by the VEVs of the heavy Higgs states $\mathcal{H}$ and $\overline{\mathcal{H}}$, with charges under the Standard Model gauge group given by:

$$\begin{aligned}
\overline{\mathcal{H}}(\bar{\mathbf{4}},\mathbf{1},\mathbf{2}) \quad &\rightarrow \; u^c_H\left(\bar{\mathbf{3}},\mathbf{1},\; \tfrac{2}{3}\right) + d^c_H\left(\bar{\mathbf{3}},\mathbf{1},-\tfrac{1}{3}\right) + \overline{\mathcal{N}}\,(\mathbf{1},\mathbf{1},0) + e^c_H\,(\mathbf{1},\mathbf{1},-1) \\
\mathcal{H}\,(\mathbf{4},\mathbf{1},\mathbf{2}) \quad &\rightarrow u_H\left(\mathbf{3},\mathbf{1},-\tfrac{2}{3}\right) + d_H\left(\mathbf{3},\mathbf{1},\; \tfrac{1}{3}\right) + \mathcal{N}\,(\mathbf{1},\mathbf{1},0) + e_H\,(\mathbf{1},\mathbf{1},\; 1)
\end{aligned}$$

The VEVs along the $\mathcal{N}$ and $\overline{\mathcal{N}}$ flat directions leave $N = 1$ spacetime supersymmetry and the $U(1)$ combination

$$U(1)_{Z'} \;=\; \frac{1}{5}(U(1)_C - U(1)_L) - U(1)_\zeta \;\notin\; SO(10), \tag{3}$$

unbroken below the string scale. This $U(1)_{Z'}$ symmetry is anomaly free provided that $U(1)_\zeta$ is anomaly free.

Anomaly cancellation down to low scale mandates the existence of additional chiral states in the spectrum that are vector–like under the Standard Model gauge group. The spectrum below the Pati–Salam symmetry breaking scale is summarised in table 1. We note therefore that these extra electroweak Higgs doublets can only receive mass when the $U(1)_{Z'}$ symmetry is broken, and relates the electroweak symmetry breaking scale to the $U(1)_{Z'}$ breaking scale. An additional $SU(2)_L$ doublet pair is added to facilitate gauge coupling unification at the string scale. However, one can envision that the question of gauge coupling unification can be addressed in other ways and that the chirality of the electroweak Higgs doublets under $U(1)_{Z'}$ is the origin of the electroweak symmetry breaking scale. We then anticipate a rich new sector to appear in association with the $U(1)_{Z'}$ symmetry breaking scale.

A detailed analysis of precision studies of this string derived Z' model recently appeared [16] and we refer the reader to this paper for the details of the methodology. In Fig. 1, we illustrate the central theory predictions at NNLO in QCD for the invariant mass distribution of a 5 TeV Z' produced in pp collisions at $\sqrt{S} = 13$ TeV and $\sqrt{S} = 50$ TeV respectively, obtained with the `MCFM-10.2.2` computer program [32] with CT18NNLO parton distribution functions (PDFs) of the proton [33]. We note that the invariant mass distribution scales up by approximately 3 orders of magnitude as the center of mass energy goes from 13 TeV to 50 TeV, making the USSC a machine with novel and superior discovery potential.

4. CONCLUSIONS

In this article we proposed the USSC as a feasible and timely collider experiment to explore the physics of the electroweak symmetry breaking mechanism. While the optimal machine to measure the Higgs parameters and properties most precisely is an e^+e^-

collider, the USSC is more likely to stumble on the new physics that is anticipated to exist in connection with electroweak symmetry breaking mechanism. Different excellent proposals are being studied for the future collider physics program and each will have its advantages and disandvantages. A key advantage of the USSC proposal is that it does not require substantial accelerator R&D and proposes to use established accelerator technology, albeit with upgraded magnets and beam energy as compared to the OSSC. We further analysed the production of the string derived Z' at the USSC as compared to the LHC. From our analysis we note the invariant mass distribution scales up by approximately 3 orders of magnitude when proton beams collide at 50 TeV as compared to the LHC. This increases the discovery potential of the USSC.

ACKNOWLEDGEMENTS

The work of MG and AM is supported by the National Science Foundation under Grant no. 2112025. AEF would like to thank the CERN theory group for hospitality and discussions and acknowledges the support of a CERN Associateship. MG would like to thank the Erwin Schrödinger International Institute for Mathematics and Physics (ESI) in Vienna, for hospitality and discussions, and partial support.

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Field	$SU(3)_C$	$\times SU(2)_L$	$U(1)_Y$	$U(1)_{Z'}$
$\hat{Q}_L^i$	3	2	$+\frac{1}{6}$	$-\frac{2}{5}$
$\hat{u}_L^i$	$\bar{3}$	1	$-\frac{2}{3}$	$-\frac{2}{5}$
$\hat{d}_L^i$	$\bar{3}$	1	$+\frac{1}{3}$	$-\frac{4}{5}$
$\hat{e}_L^i$	1	1	$+1$	$-\frac{2}{5}$
$\hat{L}_L^i$	1	2	$-\frac{1}{2}$	$-\frac{4}{5}$
$\hat{D}^i$	3	1	$-\frac{1}{3}$	$+\frac{4}{5}$
$\hat{\bar{D}}^i$	$\bar{3}$	1	$+\frac{1}{3}$	$+\frac{6}{5}$
$\hat{H}_{\text{vl}}^i$	1	2	$-\frac{1}{2}$	$+\frac{6}{5}$
$\hat{\bar{H}}_{\text{vl}}^i$	1	2	$+\frac{1}{2}$	$+\frac{4}{5}$
$\hat{S}^i$	1	1	0	-2
$\hat{H}_1$	1	2	$-\frac{1}{2}$	$-\frac{4}{5}$
$\hat{H}_2$	1	2	$+\frac{1}{2}$	$+\frac{4}{5}$
$\hat{\phi}$	1	1	0	-1
$\hat{\bar{\phi}}$	1	1	0	$+1$
$\hat{\zeta}^i$	1	1	0	0

TABLE 1:

Supermultiplet spectrum and quantum numbers, with i=1,2,3 for the three light generations. The charges are displayed in the normalisation used in free fermionic heterotic–string models.