A case for a very large circular electron-positron collider

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We explore the physics case for building a facility for high energy physics based around a very large circular tunnel which, in the first instance, would house a high-luminosity electron-positron collider with 300 GeV CM energy. This facility would be able to make a detailed study of the weak sector, in particular the measurement of the properties of light Higgs bosons in and beyond the standard model. At a later date, one could imagine upgrading the energy to study the top threshold and possibly the Higgs self coupling or installing an $\mathcal{O}(100)$ TeV pp collider in the same ring, giving access to possible physics beyond the standard model at a very high energy scale.

1. Introduction

The LHC was built to study the physics at high energy and answer the question which large scale is the relevant one. Most discussions in the theoretical literature have focused on a scale of $\mathcal{O}(1)$ TeV. The precise scale is somewhat unclear. What is sure is that the electroweak scale of $v \sim 250$ GeV plays a role in the weak interactions. The importance of this scale has been confirmed by the discovery of a Higgs signal near 125 GeV. Other searches indicate that the scale of new physics beyond the standard model could be significantly higher than $\mathcal{O}(1)$ TeV. Arguments based on naturalness suggest that new physics in the flavour sector with $\mathcal{O}(1)$ couplings could emerge at a scale of $\mathcal{O}(10)$ TeV. Though it is still too early to tell, since new physics might yet be just around the corner, the recent LHC data does give some indication on how to proceed after the LHC. On the one hand the presence of a light Higgs shows the need to build a Higgs-factory, which would be a lepton-collider with only a moderate energy. On the other hand the absence of new states near the 1 TeV scale asks for a machine that can go beyond LHC energies in a major way. A future facility should preferably be able to combine the two requirements.

There have been a number of widely discussed ideas on how to proceed; for instance a muon-collider, a linear collider anywhere in the range from 300 GeV to 3 TeV CM energy or an upgrade of the LHC to a higher luminosity or possibly a larger energy. What is lacking in the discussion so far is the possibility of building a circular electron-positron collider larger than LEP. Whether this neglect is justified is not clear to us and that is why we would like to raise some questions on this possibility in this contribution.

As the CM energy rises, a linear collider will become a cheaper option for colliding leptons than a circular ring. Therefore it has often been said that LEP was the largest possible circular electron-positron collider. Estimates of where a linear collider becomes cheaper are in the range 300-400 GeV. In the past most discussions about a linear collider have focused on a CM energy of 500 GeV and upwards, and for such discussion there is little doubt that a linear collider is the best option. However, if, as seems likely, there is a physics case for building a lepton collider at lower energies, it is less clear what is the best option and a more detailed comparison seems justified. Moreover a high luminosity linear collider has some irreducible drawbacks, leading to the presence of beamstrahlung that has a deteriorating effect on the precision with which energies and momenta in collisions are known. If therefore the discovery of new physics would depend heavily on the precision reachable in the experiment a large circular collider might be better, as there one is only limited by bremsstrahlung.

Given these considerations, we give below some arguments why a large circular lepton collider should be considered as a serious option for the future of accelerator physics. It should be mentioned that having a large circular collider has the significant advantage that at a later stage one can convert the collider into a large hadron collider as was done in going from LEP to the LHC. Indeed, such a proton-proton collider could achieve energies of $\mathcal{O}(100)$ TeV, enabling a thorough study of physics at very high scales.

2. A Higgs factory

The idea of a Higgs factory is to study the properties of the Higgs boson with as high a precision as possible. This includes, for instance, branching ratios and self-couplings, of which there are many studies in the literature. High precision and luminosity is also needed for invisible decay of the Higgs, in particular if the decay takes place from an off-shell Higgs. However to truly establish the standard model in its simplest form it would be necessary to measure the Higgs width, or more precisely the Higgs lineshape. As the standard model Higgs width is about 4 MeV, this is the ultimate precision one should aim for. There are basically three options, none of them without problems, that should be considered in detail.

2.1. A muon collider

In a muon collider, the Higgs can be produced directly and one can make an energy scan to probe the resonance region of the Higgs signal as in LEP with the Z-boson. The question with a muon collider is whether one can actually build it. Particularly important is the luminosity as the production cross section is small. One should be sensitive to the presence of Higgs bosons similar to the standard model, but with reduced couplings. There is some evidence for a 10% Higgs peak in the LEP data. To study such a reduced peak one would need ten times more luminosity than for a pure standard model Higgs boson.

2.2. A linear collider

The second possibility would be a 250-300 GeV linear collider. The problem here is that the Higgs boson is not produced directly. This implies that one needs a very high precision in the measurement of the momenta of incoming and outgoing particles, as the spectrum has to be determined from the recoil in the process $e^+e^- \to ZH$. There is a detector and a collider aspect. As one needs to measure a Higgs peak with a precision of $\mathcal{O}(MeV)$ the outcoming decay products of the Z boson, muons and electrons, must be measured with a momentum precison of $\Delta p/p \approx 10^{-5}$. One needs detailed detector studies to determine if this is possible. A complicating factor is the presence of beamstrahlung. The presence of beamstrahlung gives rise to an uncertainty in the interaction-energy of the electrons and positrons. As we need a precison of $\mathcal{O}(MeV)$, beamstrahlung may reduce the resolution to an unacceptable level. However this should be studied in more detail. Most studies for a linear collider are focused on 500 GeV. It would be useful to study an optimal design for Higgs physics with a focus on measuring the lineshape.

2.3. A circular colider

The problem of beamstrahlung can be largely avoided by going to a very large circular collider with a CM energy of 250-300 GeV. Instead of beamstrahlung one has synchrotron radiation. Synchrotron radiation can be reduced by enlarging the radius of the ring to $\mathcal{O}(100)$ km.[1] Unlike the linear collider, where the accelerating gradient dictates the length of the collider, the accelerating cavities would be 'warm' and could be similar to those used at LEP. It should be studied in detail how synchrotron radiation limits the precision with which the Higgs lineshape can be measured. This is important in order to determine the size of the ring. It is not so much the energy loss that is important here, but its effect on the precision of the collider-energy. In common with the linear collider, one has the problem of measuring the outgoing leptons with a precision of $\Delta p/p \approx 10^{-5}$. At a later stage one could consider upgrading the machine to 400 GeV in order to study the top threshold precisely and to study double Higgs production.

3. Organizational aspects

Although the civil engineering cost of such a large tunnel will be high, from the accelerator point of view a circular electron-positron collider is the easiest to build and could be achieved with current technology. In the longer term, a facility of this size would make a very natural stepping stone to study proton-proton collisions at very high energies, far beyond any LHC upgrade. A facility of this type would provide an exciting physics program for O(40) years and would require cooperation at an unprecedented level on the global scale. Given the long time scales involved, it would be interesting to explore the physics case for a $\sqrt{s} \sim 250 - 400$ GeV electron positron collider to fully explore the Higgs signal seen at the LHC, followed with a $\mathcal{O}(100)$ TeV proton-proton collider to probe the high energy frontier.

There are no very serious estimates of the cost of building such a machine. There are mostly scaling laws. Scaling up the LEP costs and assuming a 100 km ring one could cost in the region of 20 GCHF over a period of 40 years. However one should study the costs much more carefully.

Nonetheless, given the fact that the expected cost of the proposed machine is significantly larger than the cost of the LHC, one has to consider new ways to finance the construction. It appears that the construction will surpass the means of single regions. One is therefore truly speaking about a world machine. It is therefore necessary to give some thought on how to organize the financing, building and running of the machine. The structure of CERN, based on financial contributions of member states poportional to

[1] The largest collider proposed hitherto had a 230 km circumference.

GDP, has been very succesful. It has led beyond the obvious successes in science to profound changes in the way european nations collaborate with each other [1]. The obvious proposal would therefore be to essentially copy this structure, however at the global level, creating an Earth Centre for High Energy Physics (ECHEP).

Single regions would be expected to contribute proportional to their GDP. Given the changes taking place in the world economy it appears to us that the creation of such a structure is timely. What exactly is a region, one should of course define more precisely, but already in the planning for the ILC the first outlines of similar structures have appeared. Given the strong position of CERN Europe should probably take the lead in creating such a structure. Given the new challenges in high energy physics a purely european strategy, however successful in the past, may not anymore be appropriate, but should be part of a global strategy.

REFERENCES

[1] H. Schopper, LEP-The Lord of the Collider Rings at CERN 1980-2000.