Should China Build the Great Collider?

by Stephen Hawking and Gordon Kane*

Foreword

Stephen Hawking was perhaps the most well-known theoretical physicist of our time.

He is mainly known for his contributions to gravitational physics. His career started with the cosmological singularity theorems and his subsequent work on their refinement with Roger Penrose. In the next phase of his career, he found the black hole area theorem and discovered thermal radiation from black holes, and, perhaps most tantalizingly, the black hole information paradox. From a successful application of quantum mechanics to black holes, he moved on to apply these ideas to the whole Universe. He realised that quantum fluctuations during an inflationary epoch in the early Universe could give rise to the now-observed irregularities in the cosmic microwave background and to some of the large-scale structure observed in the Universe today. These ideas also lead to speculations about the origin of the Universe, perhaps as part of a multiverse.

To the public, his popular books have been a huge success and have inspired many to think about and study theoretical physics. His professional career reached its climax with him becoming the Lucasian Professor of mathematics at the University of Cambridge, a worthy successor to two previous holders of this chair, Isaac Newton and Paul Dirac. Such brilliance was recognized early with his election to a Fellowship of Royal Society at the extremely young age of 32. Although best known for his mathematical approach to physics, he appreciated the role of experiment. In the late 1960s, he was involved in an early, but ultimately abortive, attempt to search for gravitational waves.

Tragically, in 1963, he was diagnosed with motor neuron disease which progressively robbed him of many of the abilities we take for granted. He became confined to a wheelchair, could only communicate through his computer and was almost completely paralyzed. These afflictions never sapped his enthusiasm either for life or for science. One of the last things he did was to sign the letter below. He passed away peacefully on March 14, 2018. He would have pointed out, in his typically mischievous fashion, that it was an appropriate day as it was Einstein's 139th birthday.

— Malcolm Perry

Throughout the history of human civilization, and especially for the past four centuries, understanding our physical universe has been a goal of many people. It is the focus of physics. By the end of the 20th century, we had arrived at a successful, but incomplete, description of our world: the Standard Models of particle physics and of cosmology. This description is valid to the highest energies and to the edges of the universe. It achieves the traditional goals of physics.

These Standard Models are descriptions, and we do not yet know why they are correct. In addition, the Standard Models do not include gravity, particularly a quantum theory of gravity. And they do not include an explanation of the dark matter of the universe, or why there were equal amounts of matter and antimatter at the big bang but today the amount of antimatter in the universe is only one billionth of the amount of matter, and much more. The boundaries of physics

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have changed over the past few decades. Physicists have become more ambitious. Beginning in the 1970s, efforts were made to unify the forces into one underlying force rather than the several we apparently observe. Around the same time, the idea of supersymmetry was found to be a powerful ingredient in our potential understanding of such unification. That was reinforced in the 1980s with the discoveries of inflation and string theory. Back in the 1920s Ernest Rutherford said "Don't let me catch anyone talking about the universe in my department." Today it is different, as Steven Weinberg put it, "Scientists of the past were not just like scientists of today who didn't know as much as we do. They had completely different ideas of what there was to know or how you go about learning it."

Progress in physics can come from new concepts or new tools, such as new particle colliders or new detectors. Without the CERN Laboratory Large Hadron Collider (LHC) we would not know about the existence of the Higgs boson, which changes and sharpens in fundamental ways our understanding of the universe. For many people it is a source of awe and comfort to see that humans can understand our universe.

A historical guide as to how not to proceed comes from the U.S. cancellation of the Superconducting Super Collider (SSC) in 1993. That has led to the U.S. no longer being the world leader in basic particle physics, and created an opening for China to move toward that position. It is well documented that the SSC failed for several complicated reasons, political and accidental ones, mismanagement, demanding international participation, and more, with cost overruns not being a dominant one.

The discovery of the Higgs boson at CERN in 2012 was a wonderful and major step forward in understanding the universe. It taught us that the Standard Model of particle physics along with broken symmetries that allow mass lead to a successful description of our world. The role of the Higgs interaction is remarkable—if electrons could not get mass via interacting with the Higgs field then atoms would be the size of the universe and our world could not exist. Further, when electrons do get mass via the interaction with the Higgs field, quantum corrections make them so massive they turn into black holes unless some new physics yet to be discovered allows them to be stabilized at their actual mass. The proposed collider will search for clues to that new physics.

The proposed Chinese collider would have two phases. The first would be a Circular Electron Positron Collider (CEPC), and the second a Super Proton Proton Collider (SPPC). Both would be in a long tunnel, hopefully about 100 km around. The first phase would focus on learning what the Higgs physics is telling us about a deeper underlying theory. For example, the LHC data on Higgs boson (h) decays suggests that the observed Higgs is like a Standard Model Higgs, even though we know from quantum corrections that the Higgs cannot actually be a Standard Model one. The several Higgs boson decay branching ratios are all consistent with being equal to the Standard Model predictions, even though they could have been very different. But the LHC data still actually allows quite different outcomes. The most important decay is $h \to Z + Z$, where Z's are the bosons that mediate the weak neutral interactions. The ratio of its LHC value to the prediction is about 1.3 ± 0.3. The LHC can only improve that uncertainty a little with further running, while CEPC could provide an order of magnitude better precision, and really tell us if the Higgs boson was Standard Model-like or not. The situation is similar for several other decays. Also, our present best understanding of the Higgs boson implies that it should be accompanied by partners. Finding them will require a higher energy new collider, and searching for them would be a major goal of a future collider. Better data about Higgs boson properties that could come from a new collider could lead to truly deeper understanding of the remarkable role of Higgs physics.

There is an International Linear Collider program in Japan (ILC) whose goals overlap those of CEPC. There are also studies at CERN about future colliders. One, CLIC, is a linear electron-positron collider whose goals would overlap CEPC. In the past there have often been accelerators or colliders in different countries or regions with overlapping goals. Scientifically that can be valuable, and it is surely valuable for all the countries or regions that construct them, as we discuss below.

One great advantage of CEPC over other proposals, such as the ILC and CLIC, is that it can have a second phase, called SPPC, to collide protons at higher energies. The CEPC tunnel will be available for SPPC, for free. There are strong motivations for extending the total energy to at least two or three times the LHC energy, and perhaps ultimately about six or seven times the LHC energy could be feasible. That would require development of higher field superconducting magnets. With proton-proton collisions one can plan for the high luminosity needed to observe signals, and for a research program lasting decades. One major result to aim for at a higher energy collider is the data needed to understand how the Higgs boson itself gets its mass. The second main goal is to search at significantly higher energies to see what might be discovered.

While no one can be sure what might be discovered eventually at CEPC or SPPC beyond the guaranteed Higgs physics, one interesting possibility is the fundamental symmetry called supersymmetry. It might lead to observable partners of the Standard Model particles, just as the charge conjugation symmetry led to an antiparticle for every particle. If so, we know their properties are such that they might be observable at the higher energy SPPC.

Some people have said that the absence of superpartners or other phenomena at LHC so far makes discovery of superpartners unlikely. But history suggests otherwise. Once the b quark was found, in 1979, people argued that "naturally" the top quark would only be a few times heavier. In fact the top quark did exist, but was forty-one times heavier than the b quark, and was only found nearly twenty years later. If superpartners were forty-one times heavier than Z bosons they would be too heavy to detect at LHC and its upgrades, but could be detected at SPPC. In addition, a supersymmetric theory has the remarkable property that it can relate physics at our scale, where colliders take data, with the Planck scale, the natural scale for a fundamental physics theory, which may help in the efforts to find a deeper underlying theory. CERN is also studying building a higher energy proton-proton collider (FCC), with total energy eventually about six times that of LHC, perhaps initially only two-three times LHC. Most likely only one very high energy extension will be built since it will be fairly costly.

It would be of tremendous benefit to China to build CEPC and its future upgrades. An essential point to grasp is that when one is at the frontier of knowledge and understanding, progress requires new techniques and developments and insights. Otherwise discoveries would have already been made. Existing techniques and facilities cannot go further. This has shown up in the past from the LHC in a number of well documented areas, including inventing the World Wide Web with its huge impact on economies world-wide and then grid computing. Someone said imagine that CERN (where the World Wide Web was invented for particle physics) had one penny for each use, then particle physics would have all the funding it could use. More industries include magnet technology and superconducting wire technology, a multi-billion dollar accelerator industry, a multi-billion dollar imaging industry that owes its existence to the development of particle physics detectors, other billion dollar industries, and many tangible benefits. Such technologies generate revenues far exceeding the investment for collider construction.

Arguably the third industrial revolution was triggered by the invention of the World Wide Web at CERN. The requirements for data acquisition and storage and access, and the materials and technologies needed for CEPC and SPPC could help lead to the fourth industrial revolution. For the first decades of the third industrial revolution High Energy Physics led, and only in recent years industry has overtaken HEP. History may repeat itself for the fourth.

About half of all PhD's earned at CERN go to people who move into industries and areas outside of particle physics, and enrich those areas. That would happen with CEPC too. A major effect comes because innovations can lead to start-up companies, but startups can be risky. With LHC to provide an initial market for the products of the start-ups, they have been far more likely to succeed. That would be true for a Chinese collider too. New technologies emerge because particle physics necessarily is at the frontiers, and new approaches and techniques are needed to interrogate nature more deeply. China can accelerate the expansion of its economy by investing in a major collider.

Possibly the largest benefit would be attracting a large number of bright young Chinese to science and its goals. Those young people would get excited about many areas of science along the way, and decide to work in those areas, greatly strengthening the entire scientific enterprise in China. The Chinese educational system could handle the challenge of educating many more scientists and benefit greatly from it.

CEPC may make fundamental new discoveries. Even so, a proton-proton collider will be needed to discover more or explore properties of new particles, via a long circular ring with thousands of high field magnets. Again history provides a guide. The bosons (W and Z and gluons) that mediate the forces of the Standard Model were discovered at lower energy facilities. Then CERN built and ran the LEP electron-positron collider for two decades, studying the Standard Model and alternatives, and establishing the Standard Model. Then using the same tunnel, LHC colliding protons at higher energies was built, and discovered the Higgs boson.

Could there be any alternatives to a higher energy facility to discover or exclude new particles? People have invented clever methods to accelerate protons and/or electrons to higher energies, but unfortunately all approaches have led to luminosities far too small to discover new physics. At best they lead to a few events per decade, rather than the tens or hundreds of events a year needed. Seeing the Higgs boson signal at LHC above backgrounds that could fake it took over 200,000 events per detector. In the SSC era of the 1980s opponents of the SSC claimed that new magnet technologies would emerge that would replace the well-established superconducting magnets, but four decades later such new magnet technologies have still not arrived, and are unlikely to exist. A description of the scientific and cultural case for such a collider has been presented in *From the Great Wall to the Great Collider: China and the Quest to Uncover the Inner Workings of the Universe*, by Steve Nadis and

Shing-Tung Yau, published by the International Press of Boston in 2015.

China has several medium size scientific projects, such as the China Spallation Neutron Source that has just successfully turned on, operated by the Institute of High Energy Physics and the Institute of Physics, one of four such facilities in the world. CERN is unique in high energy physics, the world leader, and a world center for high energy physics with thousands of physicists from around the world working at CERN, and large numbers of visitors converging on CERN to see the laboratory and the detectors. If China built CEPC and then SPPC as a large science project it could become the international center of high energy physics, supplanting the role of CERN. CERN is also studying building such colliders, but only after a decade or more of upgrading and running the Large Hadron Collider.

The Chinese have so far taken a wise approach to financing a number of large science facilities, but mostly not at the leading position in the world, in terms of science, technology, investment scale, and cultural impact. It is important for China move ahead to take the leading role, at least in a few selected areas. The CEPC is a good choice for its scientific importance and technology impact, drawing on thirty years' experience with the BEPC. Nearly all the costs will be spent in China. Once China is proceeding, other countries will join in, stimulating great international collaboration centered around grand human ambitions, in a spirit of a peace and harmony.

Today collider construction is a mature technology. Cost and time estimates will be examined by experts, and are likely to be basically accurate. China's GDP per capita is not yet as high as that of wealthy nations. But that should not be a reason to back away from the collider. On the contrary, the collider will provide work and stimulate economic benefits for many more people. China's total GDP is now among the largest in the world, and can afford a future collider. It has been pointed out by Yifang Wang that the cost of CEPC (and even SPPC) as a fraction of GDP would not exceed that of the existing and scientifically very successful low energy Chinese collider, the Beijing Electron Positron Collider (BEPC) when it was built. Such investments stimulate the technological advances that raise developing nations to economic leaders. It is important for China to continue to show wisdom about supporting scientific research. Funds for a collider should not compete with nor adversely affect other science funding. Each area should have its funding at a level that is healthy for its development.

The Chinese particle physics community has matured. It mastered the low energy collider technology with the Beijing collider, BEPC. Many Chinese physicists have worked at collider laboratories such as CERN and Fermilab. If frontier activities are underway in China, foreign physicists will come to where the action is, and help make any effort maximally successful. When discoveries come, recognition is broadly spread. There is some tradition in particle physics for group leaders and for those whose efforts made the collider possible, to get Nobel Prizes. For the CERN collider the accelerator physicist Simon van der Meer and Carlo Rubbia were recipients, and for the earlier discovery of the charmed quark it was Samuel Ting and Burton Richter. We can expect Chinese Nobel Prizes.

Could new theoretical concepts or tools emerge that would move science forward without new collider facilities? Of course new ideas might lead to new insights. But no matter how elegant a theory might be, without data we will not know if it really describes or explains aspects of nature. Without the discovery of the Higgs boson, there would still be many doubters about the existence of the Higgs field describing our vacuum state. Results from astrophysics and cosmology and the cosmic microwave background provide information about important questions, but no amount of results from these areas could have told us about the top quark existence or mass, or about the Higgs physics, or the unification of forces and more. Data will be crucial to select theories about major issues such as what is the dark matter, or can we unify and simplify the theory of the forces and relate the forces to the Higgs mechanism that allows mass, or what causes the rapid inflation at the beginning of our universe, and more.

It is remarkable that human cultures could reach the level that provided data and ideas that have allowed us to take our understanding of our physical universe to the beginnings of time and to the edges of the universe. China could take us to the next deeper level via knowledge obtained from future collider data. The country that makes the greatest advances in discovering the workings of nature itself, via the sciences of particle physics and cosmology, will be permanently remembered in history for glorious achievements.