Working together on the Next Big Collider

By XIN Ling (Staff Reporter)

High energy physicists in China are completing the conceptual design of a collider, almost four times as big as the Large Hadron Collider in Europe, which will be used to study the details of the Higgs particle and physics beyond the Standard Model.

"Things are moving forward rapidly," WANG Yifang, director general of the CAS Institute of High Energy Physics, said at the International Workshop on Circular Electron-Positron Collider (CEPC) in November 2017. "We will seek government support sometime between 2020 and 2025."

A Higgs Factory (and beyond)

According to the Conceptual Design Report revealed during the workshop, the ring-shaped tunnel for CEPC will be 100 km in circumference, twice the size scientists were originally thinking.

Calling 100 km "the right level of ambition to have", Brian Foster from Oxford University said it would be difficult to justify making it smaller because it won't be much cheaper. "You gain a lot by being at 100 kilometers. The tunnel is a resource you can use for many, many years towards the end of the century."

When electrons and positrons are accelerated to very high speeds and clash into each other, they annihilate and release particles such as Higgs bosons and Z bosons. While the Large Hadron Collider (LHC) can also produce Higgs, it simultaneously produces many other particles which makes the scene "fuzzy and messy", said project director LOU Xinchou. In comparison, CEPC can create a "clean" picture and is ideal for the study of the Higgs.

The Higgs boson was the last piece scientists were missing in the Standard Model puzzle. First suspected to exist in the 1960s, it had never been detected by experiment until 2012. It is indeed a strange elementary particle. Scientists know now it has only mass but no spin or charge, which makes its existence theoretically paradoxical.

One thing CEPC may help to see is the particle's structure, said Nima Arkani-Hamed from the Institute for Advanced Study at Princeton. With 30 times better resolution than that of LHC, CEPC may tell whether Higgs is point-like or has some sub-structure, which makes a huge difference for what it means for the future of physics.

If CEPC ever gets built, it can be upgraded later to a more powerful proton-proton collider ("SppC") with unprecedented 100 TeV collision energy, to become a discovery machine for New Physics beyond the Standard Model.

In China, the Beijing Electron-Positron Collider is going to complete its mission around the year 2025. Right after the detection of the Higgs boson, Chinese scientists set their eyes high on a future-oriented machine, which they would like to build with their expertise from BEPC. With the support of the Ministry of Science and Technology, the National Natural Science Foundation of China and the Chinese Academy of Sciences, the pre-study of CEPC has made quick and remarkable progress. The 403-page *CEPC-SppC Conceptual Design Report*: Volume I: *Physics and Detector*, which took 480 authors from 19 countries to compile, and the 328-page *Volume II: Accelerators*, which took 300 authors from 13 countries, will be finalized in 2018.

According to WANG, they plan to seek official support sometime between 2020 and 2025, within the recently released framework of "China-initiated large international science projects". Several local governments have already shown interest in hosting the machine, including the coastal city of Qinhuangdao 300 km east of Beijing. If everything goes as scheduled, CEPC will start taking data in 2030 at the earliest.

Industrial Consortium

The Report said that the technical readiness of CEPC is high, but substantial challenges remain. For instance, the efficiency of klystrons needs to be improved to reduce the electricity and operation costs. Domestic industry needs to develop key devices such as superconducting-radio-frequency cavities and high power cryogenic refrigerators. And the technology to build SppC's superconductivity magnets is still non-existent, and is going to require many years of complicated and advanced research and development.

Since these cutting-edge technologies are not only important for building CEPC-SppC, but also applicable to many industries such as microwave, superconducting, cryogenics, and electronics, it has attracted more than 50 corporations to join the R&D efforts, making a perfect case for technology transfer. At the workshop, a ceremony was held to launch the CEPC Industrial Promotion Consortium, or CIPC, with representatives from state-owned enterprises, the private sector, and investment companies.

"CIPC is the first of its kind in China," said WANG. "It has huge practical meaning, as we are relying not just on government investment but also on the industrial sector. We are mobilizing social support to make CEPC-SppC happen," he added.

Statistics show that the input versus output ratio for big accelerator projects is about 1:3. It means with every dollar you invest in an accelerator, you end up making 3 dollars out of it.

"The technology advances you gain pay for the project itself," said Daniela Bortoletto from Oxford University.

International Collaboration

Efforts to build the next big collider have also been going on in Japan and Europe.

Michel Davier from LAL-Orsay in France was involved in the conceptual design of the International Linear Collider in Japan for many years. But the project is moving slowly and still waiting for government approval. While in Europe, LHC has other research priorities besides Higgs physics and the plan to build a successor is not on the top of its agenda.

"There's a big opportunity here in China if the Chinese government supports the project," Davier said.

But China probably won't be able to do it alone. The collider comes with an extremely high price tag, with an estimated overall cost of five billion dollars. About 20-30% can come from European, American and Japanese partners in the form of in-kind contribution.

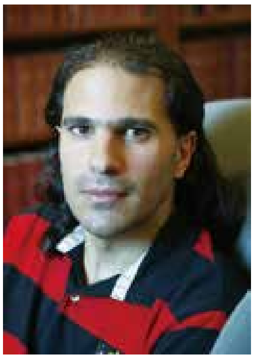
Also, there are not enough accelerator physicists in China right now. "One of the greatest challenges of CEPC would be to have sufficient technical experts," Foster said. "China would need help from the outside world. That's good, because the rest of the world would want to contribute, and CEPC should be an international project. I'm sure China would want it to be an international project."

Davier called for the project to "be more international" and more ready to take "ideas from outside CAS and China". He was echoed by Bortoletto, who suggested the institute to "develop a framework for international collaboration and enhance openness". She saw collaboration as the key to the success of CERN, where everybody works together "in a seamless fashion".

With China's economic muscle, ambition and expertise, the next big collider is looming on the horizon. "Let's work together to define the real future of particle physics," WANG said.

The Importance of Higgs Physics and CEPC

Beyond the 20th Century Physics



Professor Nima ArKani-Hamed.

What happened in the early part of the 20th century is that the very language and structure of physics was changed. We had two big revolutions of relativity and quantum mechanics, and they changed what physics was about. Most of the time, in the development of any science, there is a well established general framework. There are lots of mysteries and puzzles we'd like to understand, but we don't have to question the foundations to address these problems. For example, after the big revolution of Newton's laws, people had a good hundred years where they didn't have to upend the principles. They just kept extending them further and further, and into more and more areas. Only every now and then is there a period where we extend our understanding to the limits, and we find some questions that just don't fit. There is no good explanation for them in the standard picture, and it's at those moments that something much more radical has got to happen.

Our generation happens to be in such a special period. We have very profound indications that there's something wrong with the principles we have today. For instance, on very general grounds, we expect that the idea of space-time has got to break down when we go to sufficiently small distances. That's startling, because physics has always been about describing how things move in space as they evolve in time. It's hard to imagine what the loss of space-time could possibly mean. However, it's very likely that there is no space-time in the next description of physics. It probably just doesn't make an appearance in the equations. Another example is, since the fundamental laws seem to operate on very small distances, it's mysterious that the universe is so big. It's hard to understand how incredibly violent quantum fluctuations at incredibly short distances allow the large, smooth universe we see out there.

These are the two major puzzles in our understanding of the world today, and they go to the very heart of the foundations of the field. At the same time, the existing principles seem to work very well. If there's something so terribly wrong, why does it seem to work so well? That shows how deep the next ideas have to be. That's the huge challenge of physics. As I said, most epochs are not about addressing challenges like that. They are about fully exploring the ramifications of the principles you have already. But we are not in a period like that. We are in a period where we need to figure out some way to go beyond the principles that we inherited from the 20th century.

Point-like or Structured: Higgs Study for the Future

I'm a theoretical physicist, so I've given a description of the problems from the perspective of a theoretical physicist. But if you ask what is the best thing we can do experimentally in order to get more clues about these questions, then the Higgs particle is probably the most important character in the game.

It's in some sense the simplest elementary particle we have ever seen. Almost all other particles, like the electron, have charge or/and spin. The Higgs has no charge or spin. It just has mass. It has no other properties than that whatsoever. We predicted it half a century ago, and it was detected for the first time at the Large Hadron Collider (LHC) in 2012.

This one particle played a crucial role in completing the 20th century picture of physics. It’s the closing of a door of 20th century physics. But on the other hand, it kicks open the door of 21st century physics. The very simplicity of the Higgs particle, and the fact that it has only mass but no spin or charge, makes its existence very paradoxical theoretically — because if it doesn’t have any other properties other than mass, it doesn’t have properties that can be controlled in a powerful way by the symmetry of space and time we know about.

We had many ideas for what could solve that paradox, and we made predictions for new particles at the LHC. However, none of those predictions have come true. This was a very difficult theoretical paradox, and it stimulated 30 years of work. And those 30 years seem to have been going down the wrong paths. It’s more important than ever to just study the Higgs particle experimentally.

So we can build accelerators, produce lots and lots of Higgses, and study its properties in 20 or 30 different ways. And the most important question is whether the Higgs looks like a point or it has some structure to it. If it had some structure, all of our theoretical paradoxes would evaporate. It would be perfectly compatible with everything because it would have some internal properties that can be determined by the symmetry of space and time. Everything would be fine; a theorist would be totally happy. If it continues to look point-like — we theorists are in trouble! This would represent the most important “null result” in physics in over a century, going back to the experimental search for the lumineferous aether in the late 1800’s.

And the LHC won’t give us a clear enough picture of the Higgs to draw a conclusion on these issues. It only gives a very fuzzy picture of what the Higgs looks like. If we build the Circular Electron-Positron Collider (CEPC), we will get 30 times better resolution, and we can tell if it’s really a point or at least it’s far more point-like than anything we’ve seen before. It makes a huge difference for what it means for the future of physics.

CEPC, the Most Important Experiment We Can Do Now

So we are at this moment of a profound questioning of the basic principles, and there are not many experiments we can do in this direction. I think the CEPC is by a fair margin the most powerful thing we can do. Whatever answer we will get with it, we are going to get a decisive answer to some very clear questions.

Inauguration of the Center for Future High Energy Physics on December 17, 2013. From left: Nima Arkani-Hamed, CHEN Hesheng, David Gross, and WANG Yifang.

Some people complain that we can't be guaranteed that the CEPC or SppC will produce new elementary particles. Some think doing this is only worth it if you see new particles. That’s a big confusion. It is not the case! We don’t really care about the particles. We care about fundamental laws. The Higgs is already a new particle, and it's already “New Physics”. It’s new in the sense that we've never seen anything like it before. So anything we discover by putting it under a microscope and looking at it carefully is going to teach us something fundamental.

We are at a moment where we don’t know what the theoretical future of the subject is. We need help from experiments and what we can say with certainty is *anything* the machine sees is going to tell us “don’t do this, do that!” So it will definitely get results.

CEPC will have a big, rich experimental program with lots of measurements. The machine will be looking at the Higgs with many different kinds of “light”, using photons and many other kinds of particles as probes. The results will force physics down one direction or another to grapple with some of those really huge problems, and be just as important in a thousand years as it is now.

We don't know what the CEPC will see, but the issues at stake are so profound that any experimental answer is going to settle some big issues one way or the other.

In One More Generation, China Can Lead the Field

China's progress in high energy physics is very remarkable. China entered the scene in 1984, and went from BEPC to the early 2010s with a spectacular success of Daya Bay (neutrino experiment). That shows what can be done in one generation. In one generation you go from just becoming one of many players to doing the incisive measurement on a fundamental question.

I think Yifang's vision is that in one more generation, you can be the world leader of the entire subject. That's very possible. My feeling about this whole endeavor, and part of the reason for my enthusiasm for China, is that there are not that many things in life I find are what you want to do for purely idealistic reasons, and what other people also want to do for reasons of self interest aligned perfectly with each other. The CEPC is really a case like that. Purely selfishly, as far as physics is concerned, it would be fantastic to get China involved in fundamental physics in a big way, just for the ocean of talent and resources it has! And you already see in the last ten years the noticeable increase in the number of really brilliant young Chinese graduate students and postdocs in theoretical physics. It's possible to start really leading the field. It would be really great for science if we actually had this machine, because we are not going to have it in the US, and we may have it in Europe but it's not so obvious.

I cannot imagine another area of science, which with the investment of money — a significant amount of money but still a fixed amount of money — you become instantly the world leader in the subject. That's more or less unique for a field like particle physics. We don't have a million machines. If you have *the* big machine, that will de facto become the center of the world.

I used to tell my friends that if I went to sleep and woke up in 30 years and someone told me there is a big collider in the world, where is it? I would say it's in China. It feels like it has a certain sense of inevitability to it, like "of course it should happen here" — for the idealistic reasons. But we will see. I mean, its scientific importance cannot be overstated. And its potential benefits for China are not just for science, but for the self-perception of its people — great people who do great, bold, risky, ambitious things. It's very important for a great nation to have great ambitions. Nothing would make me happier than if my own country had such ambitions. But given that that's not in the cards, someone on planet earth should be doing it.

This article is based on a conversation between Professor Nima Arkani-Hamed and BCAS reporter XIN Ling in November 2017 at the Institute of High Energy Physics, Chinese Academy of Sciences in Beijing.

Arkani-Hamed is a theorist with wide-ranging interests in fundamental physics, from quantum field theory and string theory to cosmology and collider physics. He was educated at Toronto and Berkeley and was a professor at Berkeley and Harvard before joining the Institute for Advanced Study at Princeton University in 2008. He is a member of the US National Academy of Sciences and was an inaugural winner of the Breakthrough Prize in Fundamental Physics. He is also head of the Center for Future High Energy Physics in Beijing, China.

CEPC: The "Right Ambition" to Have for China

The Circular Electron-Positron Colloder (CEPC) is a very exciting project, and I've been particularly struck by the progress over the past year. Last November at the international advisory committee meeting of CEPC, we advised Yifang to increase the radius of the machine to a hundred kilometers. It's about twice the size they were originally thinking, but it seemed to us that a hundred kilometers was the right level of ambition to have. Only one year later, in the past couple of days, we did a review of the accelerator design, and it's really now remarkably advanced. There is a design for all the parts of the machine which looks like it would work, and the costing is starting to look good. There are still some technological challenges, but there are clear ways to meet those challenges.

Professor Brian Foster.

Technical Readiness

CEPC-SppC is a very large project, and you have to find the most cost-effective way to do it. For the electron machine (CEPC), technologically, some magnets have to have a very low field. You would have thought it's difficult to make extremely strong magnets, but actually it's also quite difficult to make very weak magnets. That's a technical challenge for CEPC, and it requires some proper engineering work to be done.

The proton machine (SppC), the one that might follow CEPC in 20 or 30 years, requires superconducting magnets. That's something really difficult and we don't know how to build them now. It will require many, many years of very complicated and advanced research and development.

There are some very exciting ideas about how to make the machine cheaper with new sources of acceleration — something we call "plasma wake field acceleration". Instead of using big cavities and accelerating objects, you will use very tiny cells filled with gas. You ionize the gas to push the electrons and nuclei away from each other, and then accelerate particles very rapidly in a very short distance and time. That's still very experimental and we don't know how to do it in a way that is necessary for a particle-physics collider. It's not in the core design of the machine, but if it could be shown to work, it would make it cheaper and much easier to work with.

Chinese Leadership

In the field of particle physics, China has done a lot of useful and important work with BEPC. But the BEPC is quite a small-scale project. The discovery at Daya Bay made China clearly one of the world leaders in particle physics. That was a big moment, when everyone suddenly took notice that China was now a big player in particle physics. The CEPC-SppC project has also significantly raised China's standing and profile.

I was struck by the number and capability of the young people here. This weekend when we were having our review, half of the presentations were given by young scientists, those aged maybe between 30 and 35. That isn't the case in many other laboratories in the world. It was very impressive to see these extremely talented, bright, young people taking leads in major technological aspects of this project.

What's critical in a project like this is guaranteed funding. My impression of China is that once it starts to do a big project, it carries on. What makes it difficult in the United States to build big projects is that every year the Congress decides whether or not it still likes the idea. But in China, once the government decides to build something, that's it. It just goes on. For a project of this size, that's the most important thing. It's going to be stable and reliable, and will attract people from outside. If they believe there's stability in the project, they will come and spend time and work on it.

There's no reason to believe the project would not be delivered on time and within budget. I'm not being optimistic; we have a track record in particle physics of succeeding without major cost overruns, even for a project as big as the Large Hadron Collider (LHC) in Europe.

Rival Plans

There are several similar ideas to CEPC-SppC in other parts of the world.

In Europe, the main purpose is to find a successor to the LHC. Although there is a design for an electron-positron machine, the emphasis is much more on a proton machine. It's different from China's plan to build a Higgs factory first and then eventually replace it with a proton machine. CERN's proton machine will be ten times more energetic than LHC to produce and study new heavy particles.

In Japan, the first stage of the proposed International Linear Collider (ILC) is also going to be a Higgs factory, exactly like here. But the ILC is an expensive project because its accelerating modules will be made of niobium, which is a very expensive material (it's all superconducting). The ILC and CEPC are very different machines. They are complimentary in many ways, and there wouldn't be any reason why you couldn't have both at the same time. While the ILC can easily be increased in energy by extending the machine, CEPC cannot go much higher in energy without becoming extremely expensive to run.

Challenges vs. Ambitions

One of the greatest challenges for China would be to have sufficient technical experts. There are not yet

The 2017 meeting of the International Advisory Committee of CEPC, held at the Institute of High Energy Physics, Chinese Academy of Sciences in November 2017.

enough accelerator physicists here in China. You would need help from the outside world. That's good, because the rest of the world would want to contribute, and CEPC should be an international project. I'm sure China would want it to be an international project.

If the project gets approved, scientists will come to China like they go to Geneva now. However, for foreign scientists it'll be important that their spouses can be employed here. There's a whole list of things you need to do to attract an international work force to a big laboratory. I've worked in Japan, which has very similar challenges in many respects to those that China will face. The government must be enthusiastic about attracting foreigners.

Finally, you need to look at CEPC-SppC as a long-term investment. It is a combination of a Higgs machine and a proton machine, and once you have that big tunnel you can do successively different things. Of course the initial cost is large, but if you divide that by 50 or 60 years, the cost per year is actually not so great. And it will be a world-leading facility — there's no doubt about it.

If you look at how much is being spent in particle physics over the past 50 years, it actually hasn't increased. So we're not talking about increasing the amount. We're talking about more or less maintaining it. Now, of course, if China did this project, the balance would change.

There's a very strong upward trajectory in China's particle physics, and Yifang has been a very remarkable leader in that regard. He is extremely well respected internationally, as he is very energetic and he has a big influence on people. No subject is driven by a single individual, but remarkable and talented individuals can make a difference in how things are perceived. With Yifang I can sense that ambition.

This article is based on a conversation between Professor Brian Foster from the Department of Physics, University of Oxford and BCAS reporter XIN Ling in November 2017 at the Institute of High Energy Physics, Chinese Academy of Sciences in Beijing.

Brian Foster graduated from London University in 1975 and obtained a doctorate from Oxford in 1978. Foster led the particle physics group at Bristol University until 2003, subsequently becoming Perkins Professor at Oxford University and Fellow of Balliol College. In 2010 Foster was awarded an Alexander von Humboldt Professorship at the University of Hamburg. He is a Fellow of the Royal Society and its Vice-President-Elect.