

**Written evidence submitted by Dr Martin Bauer, Institute for Particle Physics
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Dear Committee members,

Personal background

my name is Martin Bauer, I'm an associate professor at the UK's national centre for particle phenomenology, the Institute for Particle Phenomenology (IPPP) in Durham. I work on theoretical particle physics in a broad sense: my research is relevant for experiments ranging from the large hadron collider (LHC) at CERN to quantum-sensor experiments in the UK. Since 2019 I'm a member of Science Board, the principal scientific advisory committee for the Science and Technology Facilities Council's (STFC) for which I advise on the UK national strategy, infrastructure prioritisation, the national particle physics, astronomy, nuclear physics and astrophysics and the funding of individual projects.

I'm writing to provide evidence on the scientific motivation as well as on the international strategic context of the planned, future collider at CERN.

Scientific rationale

Motivated by some of the detailed questions asked during the oral evidence session I would like to outline the scientific motivation for the future CERN project in more detail and illustrate the kind of questions it would answer. I'll focus on the case for fundamental physics here.

There is a significant difference between a proton-proton collider like the Large Hadron Collider (LHC) and an electron-positron collider like the planned Future Circular Collider FCC-ee. At a hadron collider the initial state and its energy in every collision can only be inferred from the particles produced in the process and since protons are composite particles made from quarks and gluons there are several fundamental particles that can take part in the collisions at once, it's a messy environment. In contrast, for electron-positron colliders the initial state and its energy are precisely known, they provide a very clean environment. In fact the energy at electron-positron colliders can be set precisely by the experimentalists. In this sense –even though both are colliders– they're very different experiments: hadron colliders provide broad, multi-process exploration capabilities, whereas lepton colliders enable focused, high-precision investigations.

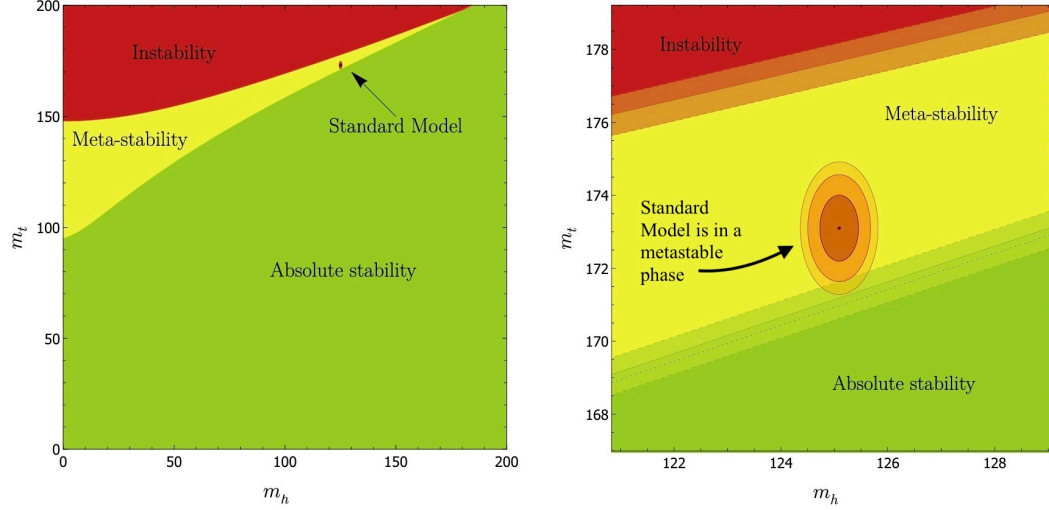


Figure 1: The phase diagram of the standard model where regions of unstable (red), metastable (yellow) and stable (green) phases are shown as a function of the Higgs mass and the top quark mass. Our current best measurements put us in the yellow region, but the uncertainty (the orange contours) is so large that the real value could still fall in the stable region (or close enough for the transition not to happen during the age of the Universe). Figure taken from Andreassen et. al, Phys. Rev. D 97 (2018) no.5, 056006 .

The Standard Model of Particle physics is a quantum field theory and therefore any interaction is influenced by quantum effects induced by 'all' other particles in nature. There is really no good analogy for this outside the quantum realm, but it is similar to the way the orbit of planets are changed by the presence of other planets in the solar system. Precision measurements of Uranus' orbit lead to the discovery of Neptune and in the same way measurements of precision observables in the Standard Model can probe other Standard Model particles and other undiscovered particles. In contrast to planetary orbits, the heavier a particle, the smaller these indirect effects, so that high precision machines can indirectly probe the presence of heavier particles. This insight has led to the indirect discovery of the top quark and the Higgs boson at electron-positron colliders before they were directly produced later.

A future circular collider like the FCC-ee would measure electroweak observables with 20 to 50-fold improved precision and achieve a 10-fold improved determination of Higgs couplings. The precision in Higgs physics is particularly important, as it allows to test whether the scalar discovered at the LHC is in fact the Standard Model Higgs boson. It would also clarify whether the Higgs boson decays into particles not yet discovered. Here

–instead of a futile attempt to present a list of observables– I will focus on a single specific example where precision measurements at the FCC-ee would have profound implications for fundamental physics.

One of the important scientific questions that was raised by the discoveries at the LHC is whether our Universe is in a stable phase. A good example for an inherently unstable phase is supercooled liquid, which exists in the liquid state even though it is below its freezing temperature. It is unstable, because any slight perturbation leads to solidification.

The mass of the Higgs boson measured at the LHC puts the Universe in a potentially unstable (a metastable) phase. If the Higgs boson was only 3% heavier or the top quark 1-2% lighter, the Universe would be stable, so precision is key to understand the implications of what we observe. Figure 1 shows that the currently best measurements of the Higgs mass, top mass and strong coupling constant do point to a metastable phase.

When super-cooled liquids undergo a phase transitions they locally form ice crystals that expand until the whole liquid solidifies. If the Universe underwent a phase transition, it could lead to local changes in physical constants, such as the electron mass, which would have significant and far-reaching effects. It's an open question whether a phase transition could happen in the future, did occur in the early Universe, or whether a so far undiscovered mechanism keeps the Universe in it's current phase.

A precise measurement of the Higgs interaction with itself, with the top quark, and of the strong coupling constant at a future collider would settle this question.

Quantum sensors are also precision experiments, but they aren't alternative ways of obtaining the same information. Their strengths is in complementary precision measurements. For example the best measurement of the electromagnetic coupling constant has been achieved with a Caesium atomic clock, whereas the future electron-positron collider would deliver the world-leading measurement of the strong coupling constant.

International strategic environment

The experimental strategy of the UK and Europe is not formulated in isolation. In December 2023, the high-energy physics advisory panel to the US Department of Energy and National Science Foundation released their 10-year strategic plan for US particle physics (<https://www.usparticlephysics.org/2023-p5-report/>). US priorities include strong support for the FCC-ee:

"A Higgs factory is the next step toward fully revealing the secrets of the Higgs boson within the quantum realm. We advocate substantial US participation in the design and construction of accelerators and detectors for an off-shore facility, and we advocate investment of effort to support development of the Future Circular Collider-electron (e^-) positron (e^+) (FCC-ee) and the International linear Collider

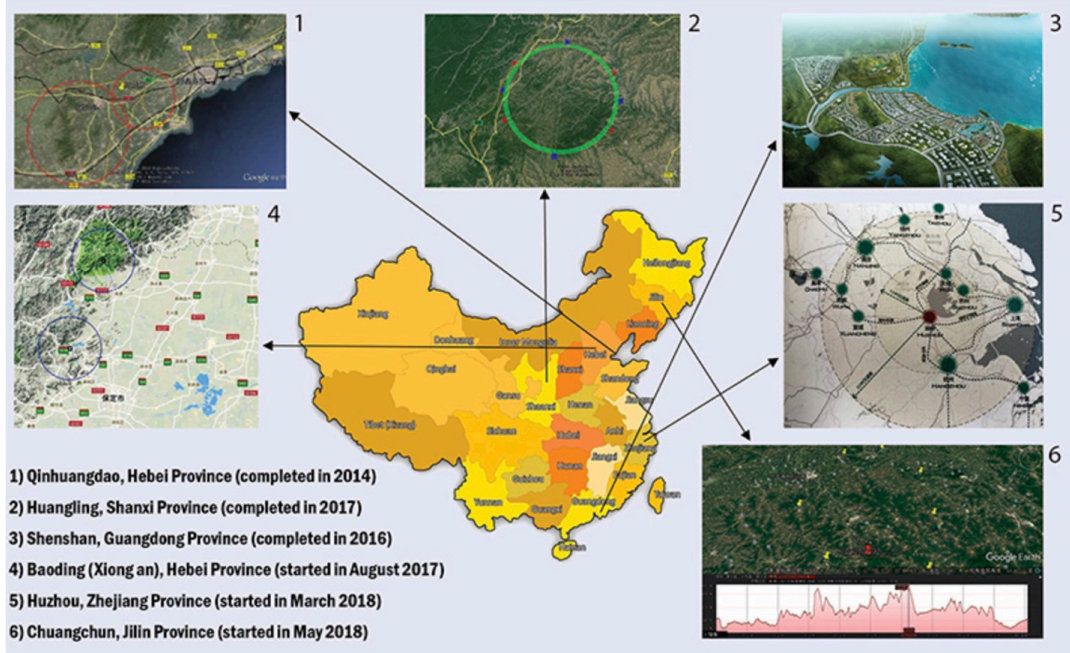


Figure 2: Candidate sites for the future Chinese CEPC. Figure taken from <http://cepc.ihep.ac.cn>.

(ILC), along with a parallel and increasingly intensive program of R&D pursuing revolutionary accelerator and detector technologies. These are crucial for a leadership role in the design and construction of the Higgs factory and for our aspiration to lead and potentially host a next high-energy collider facility beyond the Higgs factory."

Meanwhile, also in December 2023, China has published the technical design report for the planned Circular Electron-Positron Collider (CEPC), a project almost identical to the FCC-ee with the ambition to outcompete the UK, Europe and US supported project (<http://cepc.ihep.ac.cn/>). The FCC-ee would be build in a 90km tunnel with up to 350 GeV centre-of-mass energy, CEPC plans with a 100km tunnel and 240 GeV centre-of-mass energy. The site selection for CEPC is in progress and expected to be completed soon, see Figure 2. The technical design report explicitly states

"Extensive research and development efforts have been completed for the technical systems of the CEPC, with all hardware prototypes meeting or exceeding design requirements. These accomplishments demonstrate the readiness of the CEPC for the

construction phase, expected to begin around 2027-2028 during China's 15th Five-Year Plan, pending government approval."

It is almost certain that only one of these experiments will eventually be realised. The decision for the UK to support the future CERN collider therefore has an important political dimension beyond the scientific questions with long-term implications for retaining expertise and leadership in the field as well as access to spin-off technology.

I hope my letter clarifies some of the questions raised during the evidence session and please don't hesitate to get in contact if I can contribute any further.

11 March 2024