TDR
Introduction Chapter

Tuesday CEPC TDR Meeting
March 18, 2025

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Introduction Chapter Goals

Short 10-pages chapter

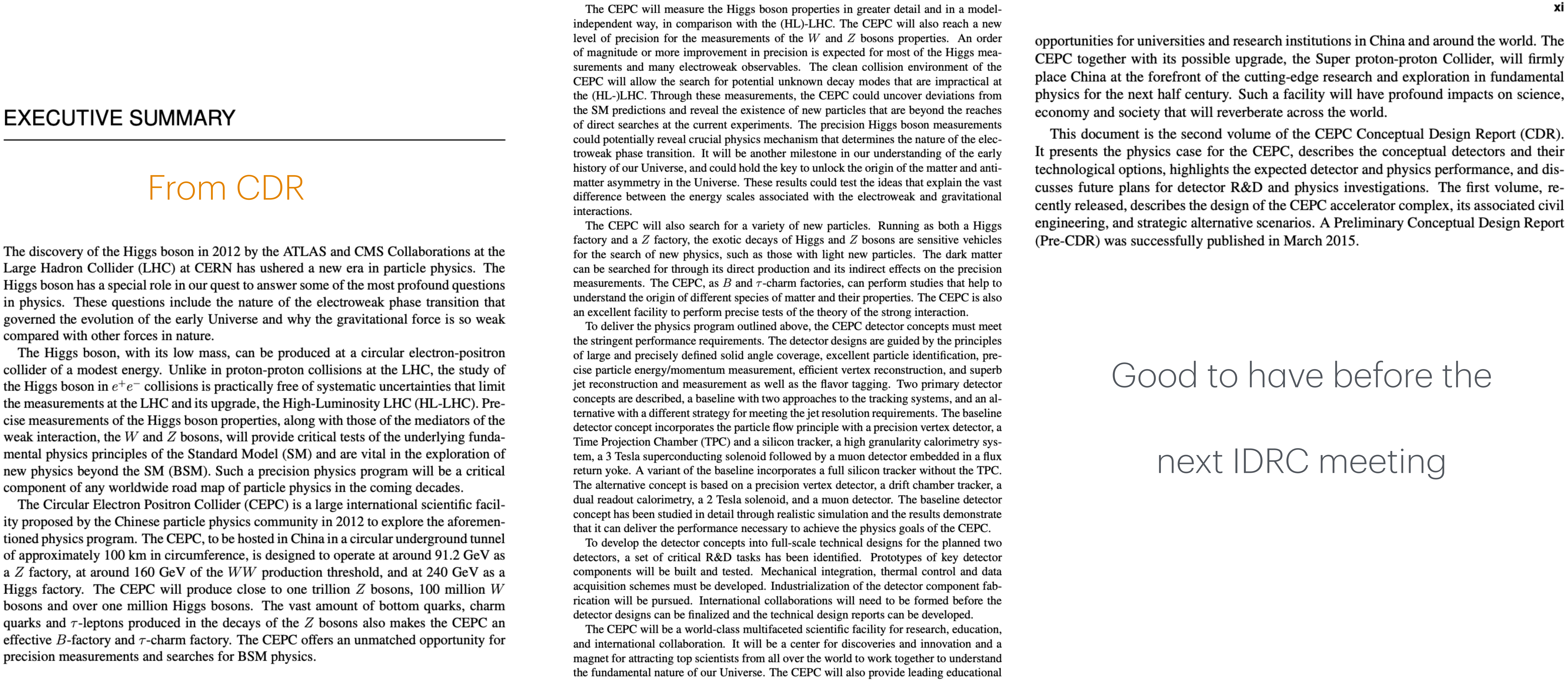
- Overview of the full TDR document
- Overview of the current context for the CEPC
- Brief Physics Case → mostly references to the White Papers
- Collider and Experimental Environment
- Brief introduction of the detector concept and explanation about the R&D stages and extensions
- Brief summary of performance and physics benchmarks
- Future plans and outlook (2 paragraphs)

Suggest to change name of chapter from “Physics Goal and Requirements” to simply “Introduction”

In addition, we need a brief Executive Summary

Executive Summary

Maximum 2-pages: Give a very simple overview of all document



EXECUTIVE SUMMARY

From CDR

The discovery of the Higgs boson in 2012 by the ATLAS and CMS Collaborations at the Large Hadron Collider (LHC) at CERN has ushered a new era in particle physics. The Higgs boson has a special role in our quest to answer some of the most profound questions in physics. These questions include the nature of the electroweak phase transition that governed the evolution of the early Universe and why the gravitational force is so weak compared with other forces in nature.

The Higgs boson, with its low mass, can be produced at a circular electron-positron collider of a modest energy. Unlike in proton-proton collisions at the LHC, the study of the Higgs boson in e^+e^- collisions is practically free of systematic uncertainties that limit the measurements at the LHC and its upgrade, the High-Luminosity LHC (HL-LHC). Precise measurements of the Higgs boson properties, along with those of the mediators of the weak interaction, the W and Z bosons, will provide critical tests of the underlying fundamental physics principles of the Standard Model (SM) and are vital in the exploration of new physics beyond the SM (BSM). Such a precision physics program will be a critical component of any worldwide road map of particle physics in the coming decades.

The Circular Electron Positron Collider (CEPC) is a large international scientific facility proposed by the Chinese particle physics community in 2012 to explore the aforementioned physics program. The CEPC, to be hosted in China in a circular underground tunnel of approximately 100 km in circumference, is designed to operate at around 91.2 GeV as a Z factory, at around 160 GeV of the WW production threshold, and at 240 GeV as a Higgs factory. The CEPC will produce close to one trillion Z bosons, 100 million W bosons and over one million Higgs bosons. The vast amount of bottom quarks, charm quarks and τ-leptons produced in the decays of the Z bosons also makes the CEPC an effective B-factory and τ-charm factory. The CEPC offers an unmatched opportunity for precision measurements and searches for BSM physics.

The CEPC will measure the Higgs boson properties in greater detail and in a model-independent way, in comparison with the (HL)-LHC. The CEPC will also reach a new level of precision for the measurements of the W and Z bosons properties. An order of magnitude or more improvement in precision is expected for most of the Higgs measurements and many electroweak observables. The clean collision environment of the CEPC will allow the search for potential unknown decay modes that are impractical at the (HL-)LHC. Through these measurements, the CEPC could uncover deviations from the SM predictions and reveal the existence of new particles that are beyond the reaches of direct searches at the current experiments. The precision Higgs boson measurements could potentially reveal crucial physics mechanism that determines the nature of the electroweak phase transition. It will be another milestone in our understanding of the early history of our Universe, and could hold the key to unlock the origin of the matter and antimatter asymmetry in the Universe. These results could test the ideas that explain the vast difference between the energy scales associated with the electroweak and gravitational interactions.

The CEPC will also search for a variety of new particles. Running as both a Higgs factory and a Z factory, the exotic decays of Higgs and Z bosons are sensitive vehicles for the search of new physics, such as those with light new particles. The dark matter can be searched for through its direct production and its indirect effects on the precision measurements. The CEPC, as B and τ-charm factories, can perform studies that help to understand the origin of different species of matter and their properties. The CEPC is also an excellent facility to perform precise tests of the theory of the strong interaction.

To deliver the physics program outlined above, the CEPC detector concepts must meet the stringent performance requirements. The detector designs are guided by the principles of large and precisely defined solid angle coverage, excellent particle identification, precise particle energy/momentum measurement, efficient vertex reconstruction, and superb jet reconstruction and measurement as well as the flavor tagging. Two primary detector concepts are described, a baseline with two approaches to the tracking systems, and an alternative with a different strategy for meeting the jet resolution requirements. The baseline detector concept incorporates the particle flow principle with a precision vertex detector, a Time Projection Chamber (TPC) and a silicon tracker, a high granularity calorimetry system, a 3 Tesla superconducting solenoid followed by a muon detector embedded in a flux return yoke. A variant of the baseline incorporates a full silicon tracker without the TPC. The alternative concept is based on a precision vertex detector, a drift chamber tracker, a dual readout calorimetry, a 2 Tesla solenoid, and a muon detector. The baseline detector concept has been studied in detail through realistic simulation and the results demonstrate that it can deliver the performance necessary to achieve the physics goals of the CEPC.

To develop the detector concepts into full-scale technical designs for the planned two detectors, a set of critical R&D tasks has been identified. Prototypes of key detector components will be built and tested. Mechanical integration, thermal control and data acquisition schemes must be developed. Industrialization of the detector component fabrication will be pursued. International collaborations will need to be formed before the detector designs can be finalized and the technical design reports can be developed.

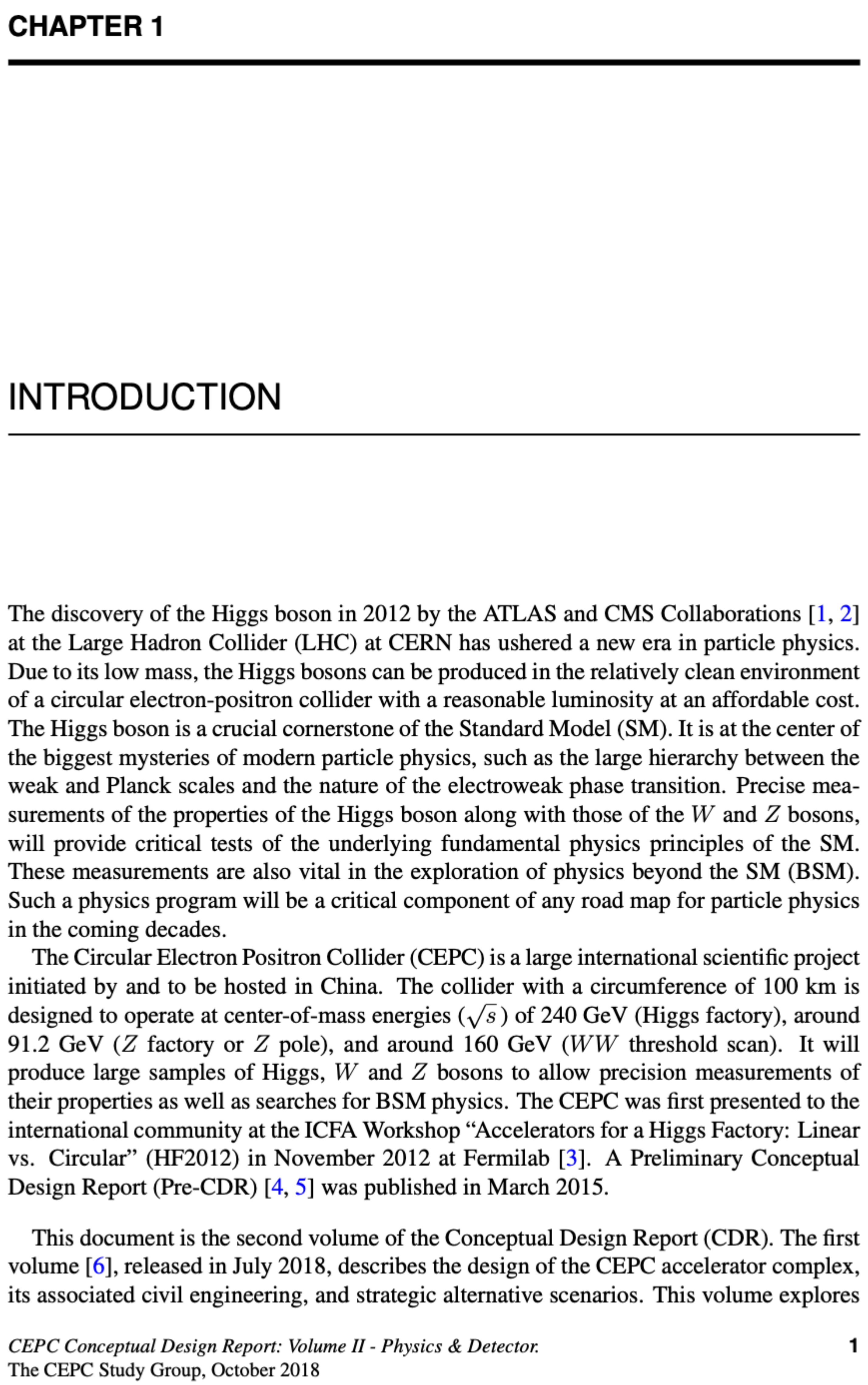
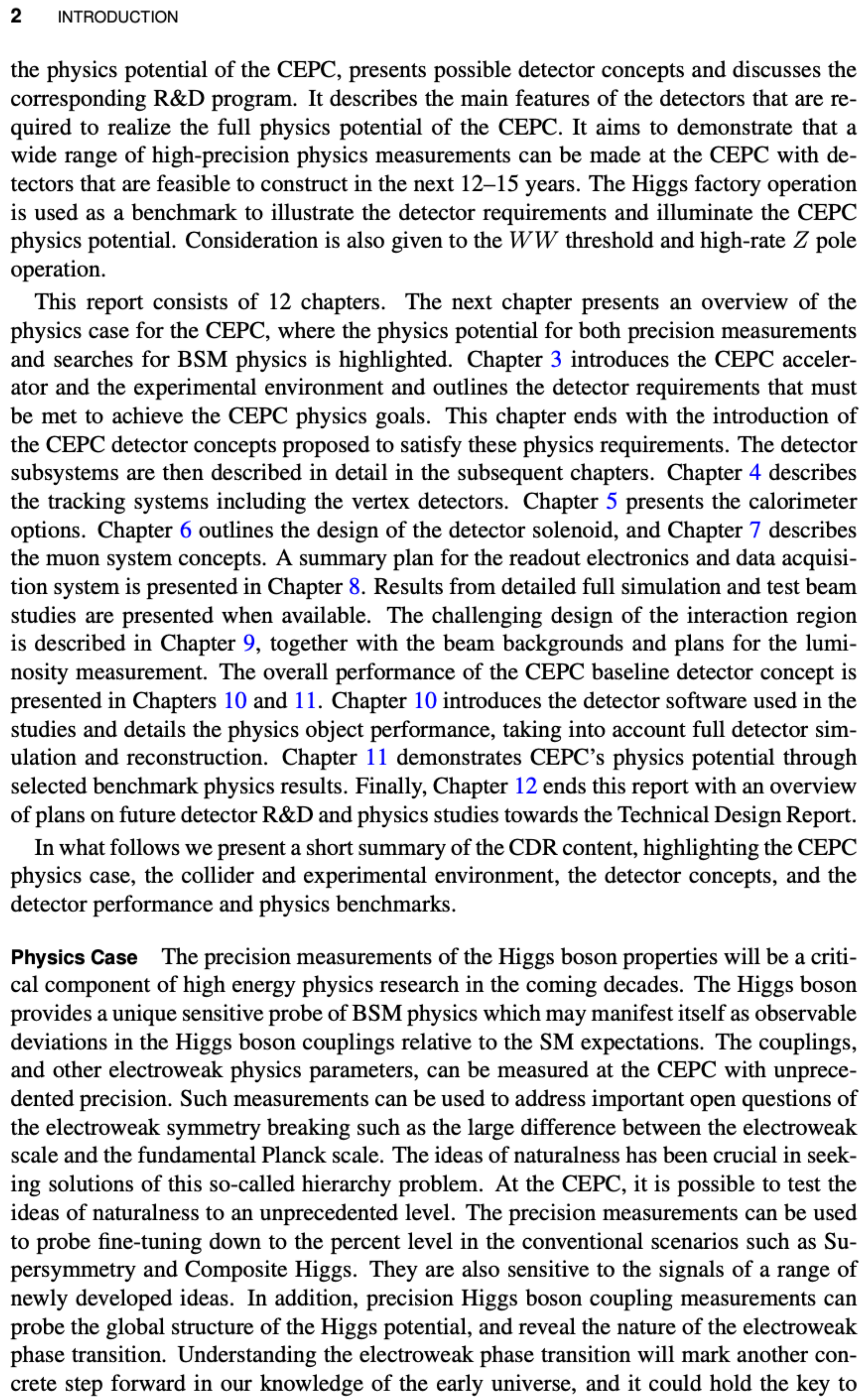
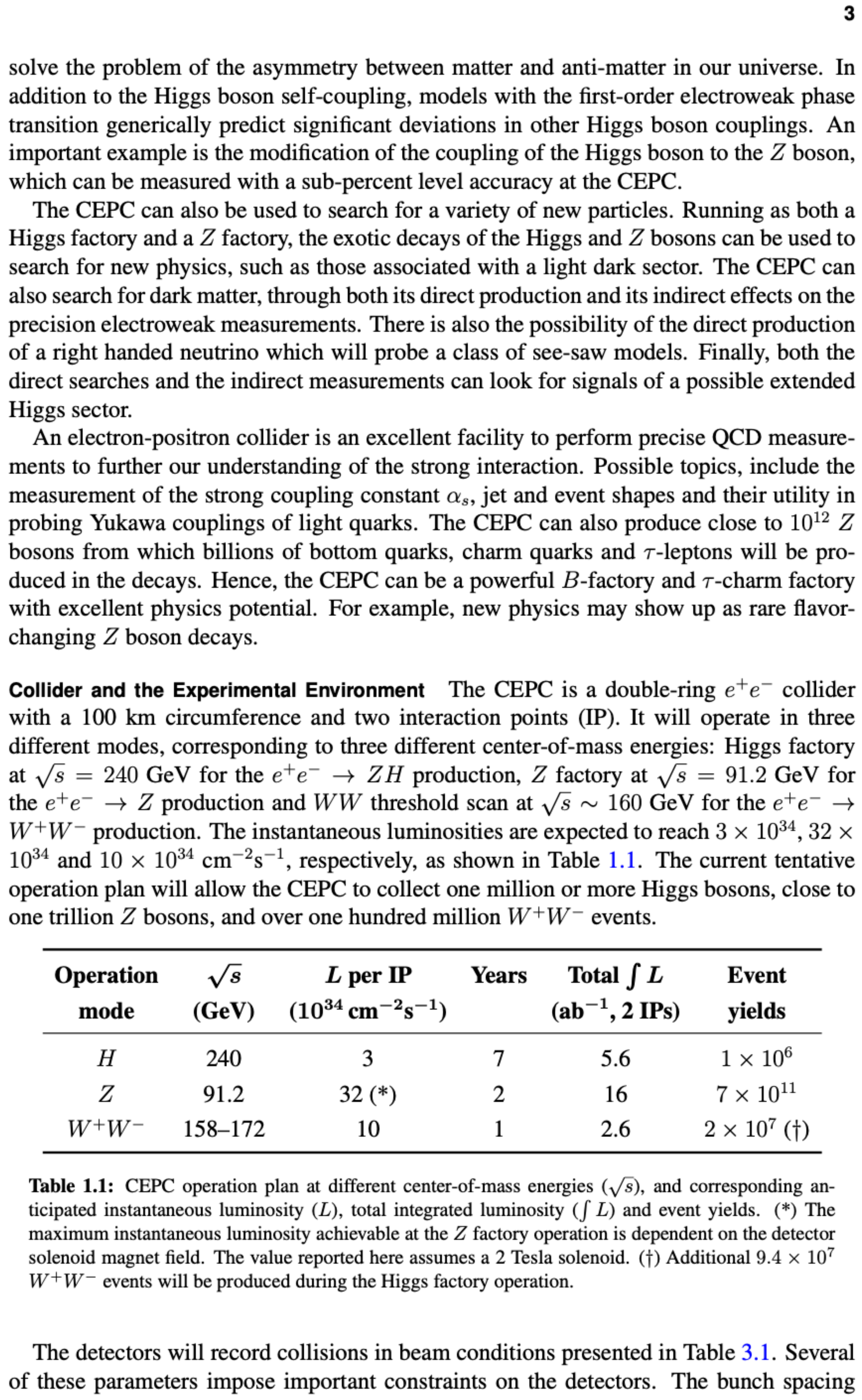
The CEPC will be a world-class multifaceted scientific facility for research, education, and international collaboration. It will be a center for discoveries and innovation and a magnet for attracting top scientists from all over the world to work together to understand the fundamental nature of our Universe. The CEPC will also provide leading educational opportunities for universities and research institutions in China and around the world. The CEPC together with its possible upgrade, the Super proton-proton Collider, will firmly place China at the forefront of the cutting-edge research and exploration in fundamental physics for the next half century. Such a facility will have profound impacts on science, economy and society that will reverberate across the world.

This document is the second volume of the CEPC Conceptual Design Report (CDR). It presents the physics case for the CEPC, describes the conceptual detectors and their technological options, highlights the expected detector and physics performance, and discusses future plans for detector R&D and physics investigations. The first volume, recently released, describes the design of the CEPC accelerator complex, its associated civil engineering, and strategic alternative scenarios. A Preliminary Conceptual Design Report (Pre-CDR) was successfully published in March 2015.

Good to have before the

next IDRC meeting

Introduction Chapter from CDR

CHAPTER 1

INTRODUCTION

The discovery of the Higgs boson in 2012 by the ATLAS and CMS Collaborations [1, 2] at the Large Hadron Collider (LHC) at CERN has ushered a new era in particle physics. Due to its low mass, the Higgs bosons can be produced in the relatively clean environment of a circular electron-positron collider with a reasonable luminosity at an affordable cost. The Higgs boson is a crucial cornerstone of the Standard Model (SM). It is at the center of the biggest mysteries of modern particle physics, such as the large hierarchy between the weak and Planck scales and the nature of the electroweak phase transition. Precise measurements of the properties of the Higgs boson along with those of the W and Z bosons, will provide critical tests of the underlying fundamental physics principles of the SM. These measurements are also vital in the exploration of physics beyond the SM (BSM). Such a physics program will be a critical component of any road map for particle physics in the coming decades.

The Circular Electron Positron Collider (CEPC) is a large international scientific project initiated by and to be hosted in China. The collider with a circumference of 100 km is designed to operate at center-of-mass energies ($\sqrt{s}$) of 240 GeV (Higgs factory), around 91.2 GeV (Z factory or Z pole), and around 160 GeV (WW threshold scan). It will produce large samples of Higgs, W and Z bosons to allow precision measurements of their properties as well as searches for BSM physics. The CEPC was first presented to the international community at the ICFA Workshop "Accelerators for a Higgs Factory: Linear vs. Circular" (HF2012) in November 2012 at Fermilab [3]. A Preliminary Conceptual Design Report (Pre-CDR) [4, 5] was published in March 2015.

This document is the second volume of the Conceptual Design Report (CDR). The first volume [6], released in July 2018, describes the design of the CEPC accelerator complex, its associated civil engineering, and strategic alternative scenarios. This volume explores the physics potential of the CEPC, presents possible detector concepts and discusses the corresponding R&D program. It describes the main features of the detectors that are required to realize the full physics potential of the CEPC. It aims to demonstrate that a wide range of high-precision physics measurements can be made at the CEPC with detectors that are feasible to construct in the next 12–15 years. The Higgs factory operation is used as a benchmark to illustrate the detector requirements and illuminate the CEPC physics potential. Consideration is also given to the WW threshold and high-rate Z pole operation.

This report consists of 12 chapters. The next chapter presents an overview of the physics case for the CEPC, where the physics potential for both precision measurements and searches for BSM physics is highlighted. Chapter 3 introduces the CEPC accelerator and the experimental environment and outlines the detector requirements that must be met to achieve the CEPC physics goals. This chapter ends with the introduction of the CEPC detector concepts proposed to satisfy these physics requirements. The detector subsystems are then described in detail in the subsequent chapters. Chapter 4 describes the tracking systems including the vertex detectors. Chapter 5 presents the calorimeter options. Chapter 6 outlines the design of the detector solenoid, and Chapter 7 describes the muon system concepts. A summary plan for the readout electronics and data acquisition system is presented in Chapter 8. Results from detailed full simulation and test beam studies are presented when available. The challenging design of the interaction region is described in Chapter 9, together with the beam backgrounds and plans for the luminosity measurement. The overall performance of the CEPC baseline detector concept is presented in Chapters 10 and 11. Chapter 10 introduces the detector software used in the studies and details the physics object performance, taking into account full detector simulation and reconstruction. Chapter 11 demonstrates CEPC's physics potential through selected benchmark physics results. Finally, Chapter 12 ends this report with an overview of plans for future detector R&D and physics studies towards the Technical Design Report.

In what follows we present a short summary of the CDR content, highlighting the CEPC physics case, the collider and experimental environment, the detector concepts, and the detector performance and physics benchmarks.

Physics Case The precision measurements of the Higgs boson properties will be a critical component of high energy physics research in the coming decades. The Higgs boson provides a unique sensitive probe of BSM physics which may manifest itself as observable deviations in the Higgs boson couplings relative to the SM expectations. The couplings, and other electroweak physics parameters, can be measured at the CEPC with unprecedented precision. Such measurements can be used to address important open questions of the electroweak symmetry breaking such as the large difference between the electroweak scale and the fundamental Planck scale. The ideas of naturalness has been crucial in seeking solutions of this so-called hierarchy problem. At the CEPC, it is possible to test the ideas of naturalness to an unprecedented level. The precision measurements can be used to probe fine-tuning down to the percent level in the conventional scenarios such as Supersymmetry and Composite Higgs. They are also sensitive to the signals of a range of newly developed ideas. In addition, precision Higgs boson coupling measurements can probe the global structure of the Higgs potential, and reveal the nature of the electroweak phase transition. Understanding the electroweak phase transition will mark another concrete step forward in our knowledge of the early universe, and it could hold the key to solve the problem of the asymmetry between matter and anti-matter in our universe. In addition to the Higgs boson self-coupling, models with the first-order electroweak phase transition generically predict significant deviations in other Higgs boson couplings. An important example is the modification of the coupling of the Higgs boson to the Z boson, which can be measured with a sub-percent level accuracy at the CEPC.

The CEPC can also be used to search for a variety of new particles. Running as both a Higgs factory and a Z factory, the exotic decays of the Higgs and Z bosons can be used to search for new physics, such as those associated with a light dark sector. The CEPC can also search for dark matter, through both its direct production and its indirect effects on the precision electroweak measurements. There is also the possibility of the direct production of a right handed neutrino which will probe a class of see-saw models. Finally, both the direct searches and the indirect measurements can look for signals of a possible extended Higgs sector.

An electron-positron collider is an excellent facility to perform precise QCD measurements to further our understanding of the strong interaction. Possible topics, include the measurement of the strong coupling constant α_s, jet and event shapes and their utility in probing Yukawa couplings of light quarks. The CEPC can also produce close to 10^{12} Z bosons from which billions of bottom quarks, charm quarks and τ-leptons will be produced in the decays. Hence, the CEPC can be a powerful B-factory and τ-charm factory with excellent physics potential. For example, new physics may show up as rare flavor-changing Z boson decays.

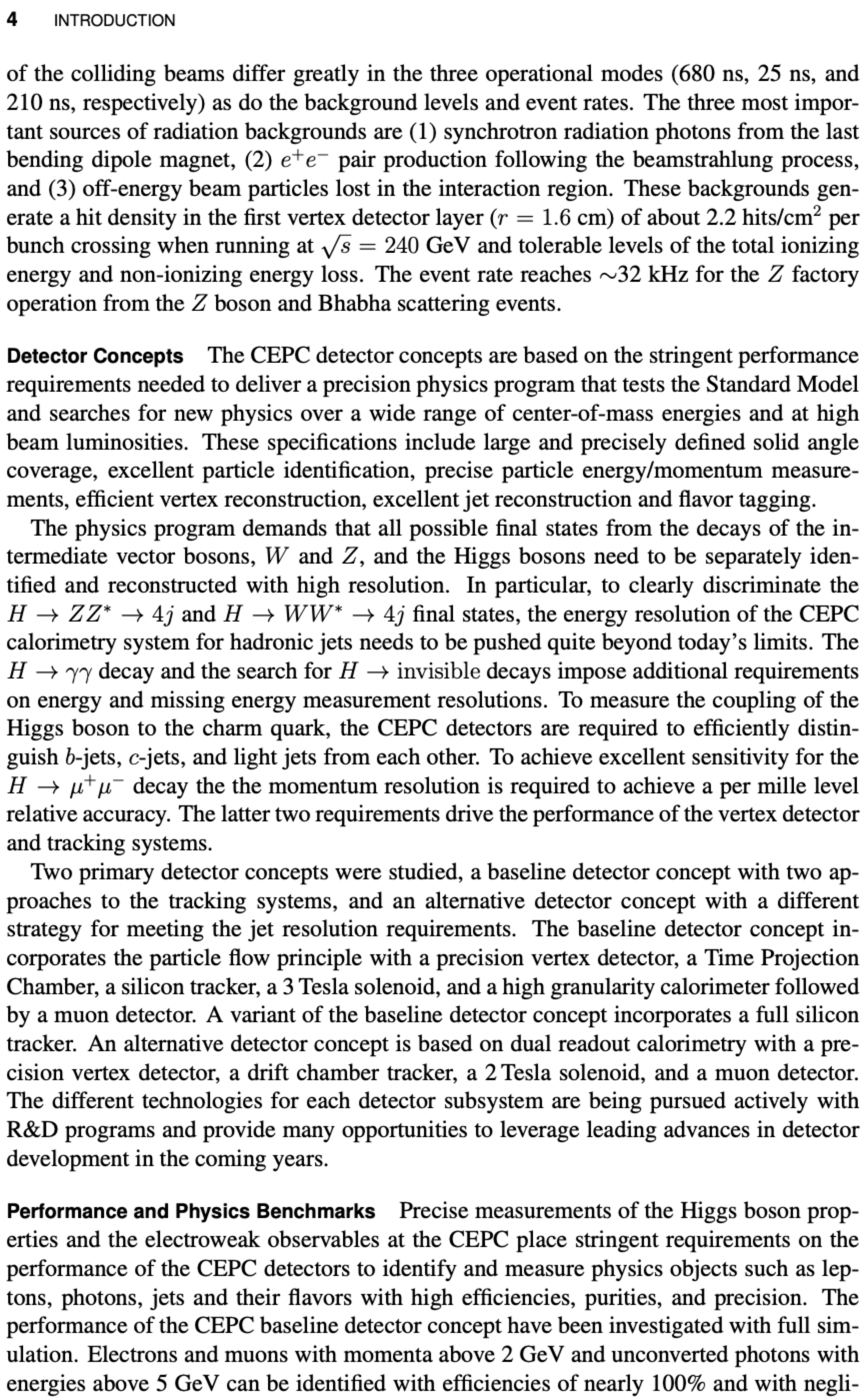
Collider and the Experimental Environment The CEPC is a double-ring e^+e^- collider with a 100 km circumference and two interaction points (IP). It will operate in three different modes, corresponding to three different center-of-mass energies: Higgs factory at $\sqrt{s} = 240$ GeV for the $e^+e^- \to ZH$ production, Z factory at $\sqrt{s} = 91.2$ GeV for the $e^+e^- \to Z$ production and WW threshold scan at $\sqrt{s} \sim 160$ GeV for the $e^+e^- \to W^+W^-$ production. The instantaneous luminosities are expected to reach 3×10^{34}, 32×10^{34} and 10×10^{34} $\mathrm{cm^{-2}s^{-1}}$, respectively, as shown in Table 1.1. The current tentative operation plan will allow the CEPC to collect one million or more Higgs bosons, close to one trillion Z bosons, and over one hundred million W^+W^- events.

Operation mode	$\sqrt{s}$ (GeV)	L per IP ($10^{34}\ \mathrm{cm^{-2}s^{-1}}$)	Years	Total $\int L$ ($\mathrm{ab^{-1}}$, 2 IPs)	Event yields
H	240	3	7	5.6	1×10^6
Z	91.2	32 (*)	2	16	7×10^{11}
W^+W^-	158–172	10	1	2.6	2×10^7 (†)

Table 1.1: CEPC operation plan at different center-of-mass energies ($\sqrt{s}$), and corresponding anticipated instantaneous luminosity (L), total integrated luminosity ($\int L$) and event yields. (*) The maximum instantaneous luminosity achievable at the Z factory operation is dependent on the detector solenoid magnet field. The value reported here assumes a 2 Tesla solenoid. (†) Additional 9.4×10^7 W^+W^- events will be produced during the Higgs factory operation.

The detectors will record collisions in beam conditions presented in Table 3.1. Several of these parameters impose important constraints on the detectors. The bunch spacing

Introduction Chapter from CDR



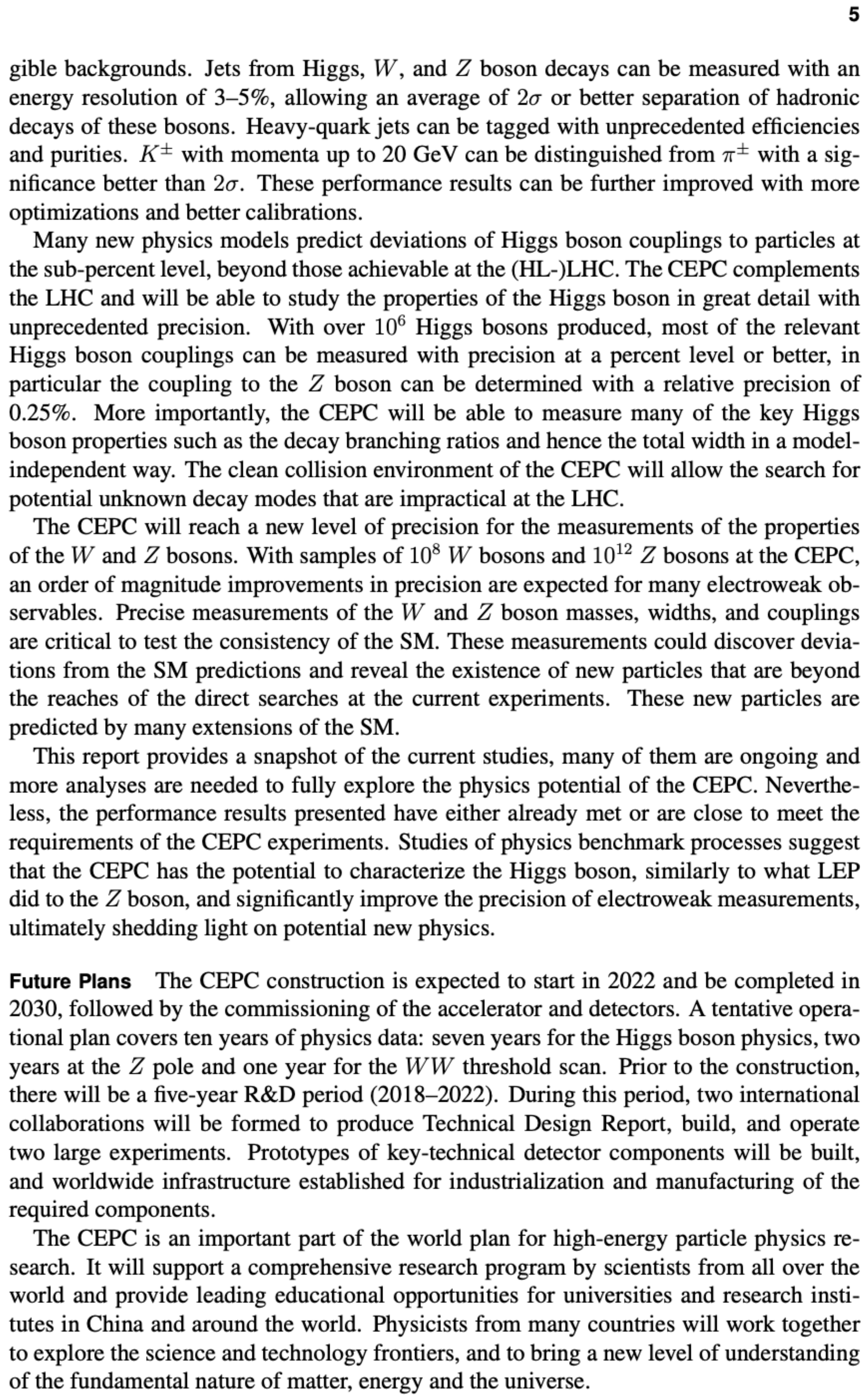
of the colliding beams differ greatly in the three operational modes (680 ns, 25 ns, and 210 ns, respectively) as do the background levels and event rates. The three most important sources of radiation backgrounds are (1) synchrotron radiation photons from the last bending dipole magnet, (2) e^+e^- pair production following the beamstrahlung process, and (3) off-energy beam particles lost in the interaction region. These backgrounds generate a hit density in the first vertex detector layer ($r = 1.6$ cm) of about 2.2 hits/cm^2 per bunch crossing when running at $\sqrt{s} = 240$ GeV and tolerable levels of the total ionizing energy and non-ionizing energy loss. The event rate reaches $\sim$32 kHz for the Z factory operation from the Z boson and Bhabha scattering events.

Detector Concepts The CEPC detector concepts are based on the stringent performance requirements needed to deliver a precision physics program that tests the Standard Model and searches for new physics over a wide range of center-of-mass energies and at high beam luminosities. These specifications include large and precisely defined solid angle coverage, excellent particle identification, precise particle energy/momentum measurements, efficient vertex reconstruction, excellent jet reconstruction and flavor tagging.

The physics program demands that all possible final states from the decays of the intermediate vector bosons, W and Z, and the Higgs bosons need to be separately identified and reconstructed with high resolution. In particular, to clearly discriminate the $H \to ZZ^* \to 4j$ and $H \to WW^* \to 4j$ final states, the energy resolution of the CEPC calorimetry system for hadronic jets needs to be pushed quite beyond today's limits. The $H \to \gamma\gamma$ decay and the search for $H \to$ invisible decays impose additional requirements on energy and missing energy measurement resolutions. To measure the coupling of the Higgs boson to the charm quark, the CEPC detectors are required to efficiently distinguish b-jets, c-jets, and light jets from each other. To achieve excellent sensitivity for the $H \to \mu^+\mu^-$ decay the the momentum resolution is required to achieve a per mille level relative accuracy. The latter two requirements drive the performance of the vertex detector and tracking systems.

Two primary detector concepts were studied, a baseline detector concept with two approaches to the tracking systems, and an alternative detector concept with a different strategy for meeting the jet resolution requirements. The baseline detector concept incorporates the particle flow principle with a precision vertex detector, a Time Projection Chamber, a silicon tracker, a 3 Tesla solenoid, and a high granularity calorimeter followed by a muon detector. A variant of the baseline detector concept incorporates a full silicon tracker. An alternative detector concept is based on dual readout calorimetry with a precision vertex detector, a drift chamber tracker, a 2 Tesla solenoid, and a muon detector. The different technologies for each detector subsystem are being pursued actively with R&D programs and provide many opportunities to leverage leading advances in detector development in the coming years.

Performance and Physics Benchmarks Precise measurements of the Higgs boson properties and the electroweak observables at the CEPC place stringent requirements on the performance of the CEPC detectors to identify and measure physics objects such as leptons, photons, jets and their flavors with high efficiencies, purities, and precision. The performance of the CEPC baseline detector concept have been investigated with full simulation. Electrons and muons with momenta above 2 GeV and unconverted photons with energies above 5 GeV can be identified with efficiencies of nearly 100% and with negligible backgrounds. Jets from Higgs, W, and Z boson decays can be measured with an energy resolution of 3–5%, allowing an average of 2σ or better separation of hadronic decays of these bosons. Heavy-quark jets can be tagged with unprecedented efficiencies and purities. $K^\pm$ with momenta up to 20 GeV can be distinguished from $\pi^\pm$ with a significance better than 2σ. These performance results can be further improved with more optimizations and better calibrations.



Many new physics models predict deviations of Higgs boson couplings to particles at the sub-percent level, beyond those achievable at the (HL-)LHC. The CEPC complements the LHC and will be able to study the properties of the Higgs boson in great detail with unprecedented precision. With over 10^6 Higgs bosons produced, most of the relevant Higgs boson couplings can be measured with precision at a percent level or better, in particular the coupling to the Z boson can be determined with a relative precision of 0.25%. More importantly, the CEPC will be able to measure many of the key Higgs boson properties such as the decay branching ratios and hence the total width in a model-independent way. The clean collision environment of the CEPC will allow the search for potential unknown decay modes that are impractical at the LHC.

The CEPC will reach a new level of precision for the measurements of the properties of the W and Z bosons. With samples of 10^8 W bosons and 10^{12} Z bosons at the CEPC, an order of magnitude improvements in precision are expected for many electroweak observables. Precise measurements of the W and Z boson masses, widths, and couplings are critical to test the consistency of the SM. These measurements could discover deviations from the SM predictions and reveal the existence of new particles that are beyond the reaches of the direct searches at the current experiments. These new particles are predicted by many extensions of the SM.

This report provides a snapshot of the current studies, many of them are ongoing and more analyses are needed to fully explore the physics potential of the CEPC. Nevertheless, the performance results presented have either already met or are close to meet the requirements of the CEPC experiments. Studies of physics benchmark processes suggest that the CEPC has the potential to characterize the Higgs boson, similarly to what LEP did to the Z boson, and significantly improve the precision of electroweak measurements, ultimately shedding light on potential new physics.

Future Plans The CEPC construction is expected to start in 2022 and be completed in 2030, followed by the commissioning of the accelerator and detectors. A tentative operational plan covers ten years of physics data: seven years for the Higgs boson physics, two years at the Z pole and one year for the WW threshold scan. Prior to the construction, there will be a five-year R&D period (2018–2022). During this period, two international collaborations will be formed to produce Technical Design Report, build, and operate two large experiments. Prototypes of key-technical detector components will be built, and worldwide infrastructure established for industrialization and manufacturing of the required components.

The CEPC is an important part of the world plan for high-energy particle physics research. It will support a comprehensive research program by scientists from all over the world and provide leading educational opportunities for universities and research institutes in China and around the world. Physicists from many countries will work together to explore the science and technology frontiers, and to bring a new level of understanding of the fundamental nature of matter, energy and the universe.

References

[1] ATLAS Collaboration, *Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC*, Phys. Lett. B **716** (2012) 1–29, `arXiv:1207.7214 [hep-ex]`.

[2] CMS Collaboration, *Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC*, Phys. Lett. **B716** (2012) 30–61, `arXiv:1207.7235 [hep-ex]`.

[3] Q. Qin, *A Circular Higgs Factory*, . `https://indico.fnal.gov/event/5775`. Accelerators for a Higgs Factory: Linear vs Circular (HF2012).

[4] The CEPC-SPPC Study Group, *CEPC-SPPC Preliminary Conceptual Design Report, Volume I - Physics and Detector*, . `http://cepc.ihep.ac.cn/preCDR/volume.html`. IHEP-CEPC-DR-2015-01, IHEP-TH-2015-01, IHEP-EP-2015-01.

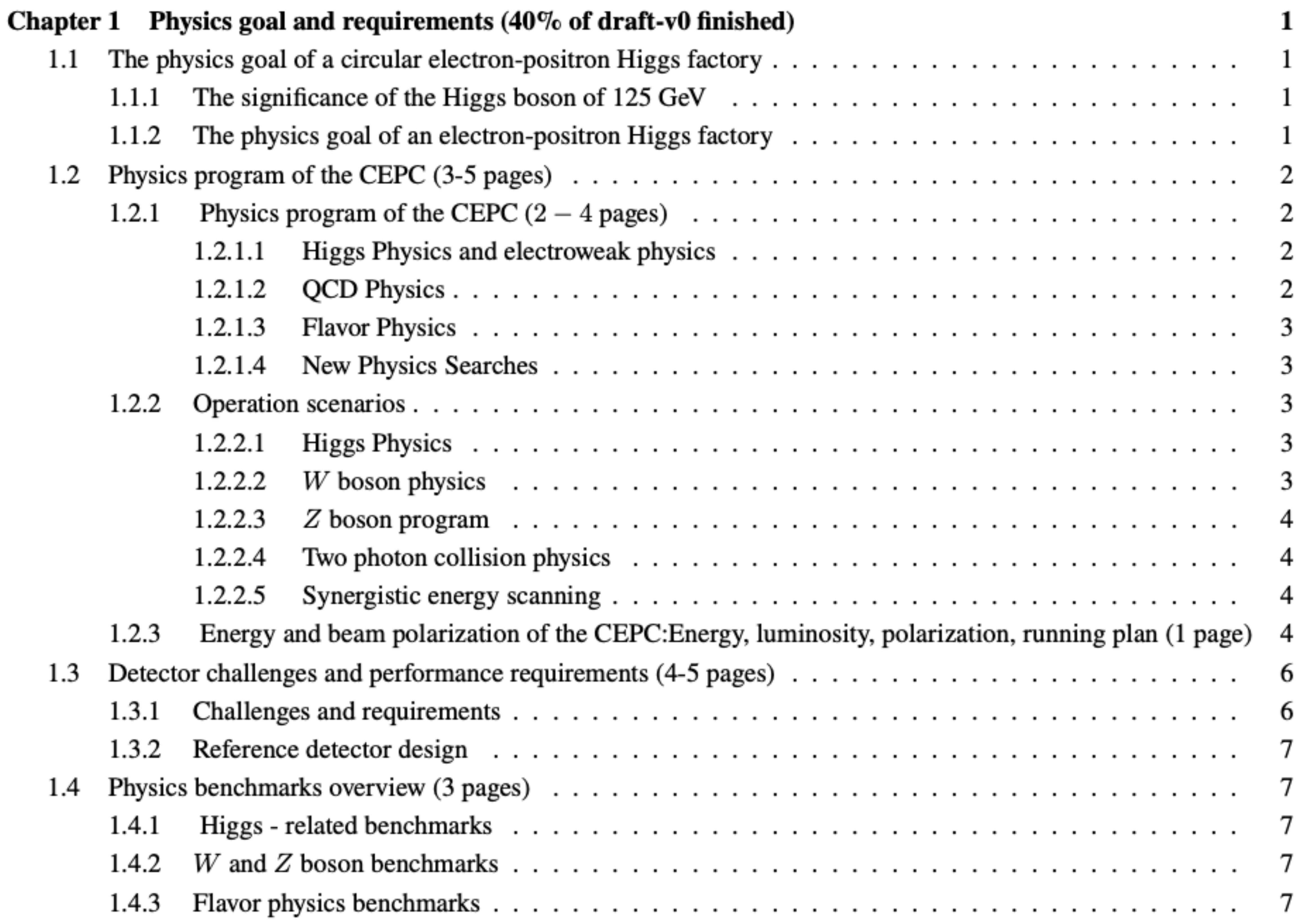
[5] The CEPC-SPPC Study Group, *CEPC-SPPC Preliminary Conceptual Design Report, Volume II - Accelerator*, 2015. `http://cepc.ihep.ac.cn/preCDR/volume.html`. IHEP-CEPC-DR-2015-01, IHEP-AC-2015-01.

[6] The CEPC Study Group, *CEPC Conceptual Design Report, Volume I - Accelerator*, `arXiv:1809.00285 [physics.acc-ph]`.

Introduction Chapter

Short 10-pages chapter

- Current outline, thanks to Gang Li
  - Assumes a more extensive content than what we had in the CDR
- **Key items needed:**
  - 3-4 pages: References to physics white papers
    - 1-2 plots with physics summary (Higgs couplings, exotics Higgs, or Z-pole physics)
  - Table with physics benchmarks summary
  - Table with accelerator operations modes



Introduction Chapter Outline

Short 10-pages chapter → reference all other chapters

- Overview of the context for the CEPC, link to the accelerator TDR, and overview of full TDR document
- Chapter 1.1: Physics Case
  - Higgs, electroweak, QCD physics, flavor physics, new physics searches, outlook for top physics at upgraded
- Chapter 1.2: Collider and Experimental Environment
  - Operation modes (do we talk about upgrades?)
- Chapter 1.3: Detector concept and TDR organization
  - Detector challenges
- Chapter 1.4: Performance and physics benchmarks
  - Summary table of physics benchmarks, reference chapter
- Chapter 1.5: Future plans and outlook (2 paragraphs)