EF Report: 2.7 Enabling EF Research & 2.8 EF Viison

EF Meeting - Reports Reading and Discussion

June 24, 2022

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Snowmass EF wiki: https://snowmass21.org/energy/start

2.7 Enabling Energy Frontier Research

Goals and Context

- Goals
    - Addressing the “Big Questions” outlined earlier is the main scientific goal of the EF.
    - It is essential that the two complementary directions are pursued: 1) Study known phenomena, and 2) Search for direct evidence of BSM physics.
    - Discoveries at the EF are linked to new accelerators, detector instrumentation, advances in theory, and innovative analysis technologies and frameworks and require substantial R&D in several scientific sectors
- Context
    - The EF is at a turning point, in which experimental guidance is needed to shed light on new physics beyond the SM. Several projects have been proposed to provide such guidance:
        - The HL-LHC is the most awaited and the approved short-term project
        - Other projects identified as the next step in terms of precision measurements and direct searches, include Higgs factories and multi-TeV colliders.
        - A clear path towards the identifying the next collider project is needed.

Collaboration

- Interdependence between Frontiers and between US and international communities
  - The Energy Frontier community in the US is fully integrated in and interdependent with the broad international community of particle physicists, which includes experimentalists, theorists, accelerator and detector physicists in the various domains that pertain to HEP as well as nuclear physics.
- Cross-fertilization between Energy Frontier and other domains of physics
  - The cross-fertilisation between different domains of particle physics is a strength of the Energy Frontier and has to be nurtured and supported for continued future opportunities
    - e.g. The consideration of EIC, within the Energy Frontier topical groups for this Snowmass study, has been instrumental in fostering opportunities for cross-fertilization between the two fields of HEP and Nuclear Physics. The two (international) communities are well integrated, beyond the artificial and too-often restricting boundaries set by funding agencies.

Building and investing in a Community

- Building a diverse Energy Frontier community
  - A vibrant, inclusive, diverse and capable scientific community are necessary for any success of the US scientific community in the Energy Frontier. These can be achieved by
    1. innovation as well as empowerment and
    2. training of the next generation of leaders in the Energy Frontier.
  - Opportunity to engage early career scientists with challenging problems on physics prospects for colliders, detector design, software, analysis and computational techniques.
- Investments essential to the progress of the Energy Frontier
  - Energy Frontier scientific program depends on transformative advances in several critical areas e.g. innovation in collider and detector technologies, cutting-edge computational techniques as well as novel theoretical ideas and accurate calculations.
  - These research area need significant immediate investment in order to accomplish the programmatic goals and sustain a competitive scientific community in the next decade.
  - The resources to be allocated will have to be commensurate to the vast range and amount of scientific output that is expected by those experiments.

2.8 The Energy Frontier Vision

The Energy Frontier vision

- **The discovery of the Higgs boson at the LHC**, of which we are celebrating the 10th anniversary in 2022, has added one crucial piece of the puzzle to the SM.
- It **has completed the SM and** at the same time **provided a unique portal to explore physics beyond the Standard Model** thanks to its intimate connections to the still open big questions of particle physics.
- **Discovery new physics will also involve the unknown and we need to explore it going beyond existing frameworks.**
- **Collider physics allows to explore a uniquely broad range of phenomena** and pursue both indirect and direct validations of BSM physics.
- **The EF envisions a physics program articulated into immediate-future, intermediate-future, and long-term-future colliders.**

EF Vision - The immediate future

The immediate future is the HL-LHC.

- During the next decade it is essential to complete the **highest priority recommendation of the last P5** and to fully realize the scientific potential of the HL-LHC collecting at least 3 ab^{-1} of data.
- **The physics case is very strong**:
  - It can extend the direct search for new elementary particles
  - It can measure the Higgs-boson couplings to reach sensitivity to BSM physics in the TeV range
  - It can puts bounds on the Higgs-boson self coupling and give first indications on the Higgs potential
  - It can provide the best measurements of top-quark couplings beyond the reach of the first generation of future colliders
- **Continued strong US participation is critical** to the success of the HL-LHC physics program, in particular for the Phase-2 detector upgrades, the HL-LHC data taking operations and physics analyses based on HL-LHC data sets.

EF Vision - The intermediate future

The intermediate future is an e^+e^- Higgs factory, either based on a linear (ILC, C^3, CLIC) or circular collider (FCC-ee, CepC).

- **The physics case is compelling** and rest on the ability to
  - Measure the Higgs-boson couplings to sub-percent level and discern the pattern of BSM physics behind possible deviations from SM predictions
  - Search for exotic Higgs decays and explore the Higgs portal to hidden sectors
  - Measure the SM (W,Z,t,H) to very high precision and stress test its consistency
  - Perform precision measurements of QCD as testing ground of QFT in both perturbative and non-perturbative regimes.
- **The various proposed facilities have a strong core of common physics goals**: it is important to realize at least one somewhere in the world.
- **A timely implementation is important**. There is **strong US support** for initiatives that could be realized on a time scale relevant for early career physicists.

EF vision - The long-term future

In the long term EF envision a collider that probes the multi-TeV scale, up or above 10 TeV parton center-of-mass energy (FCC-hh, SppC, MuC)

- **The physics case is outstanding** and rest on the potential to:
  - Significantly constrain scenarios motivated by naturalness
  - Produce the fundamental particles that generate the mechanism of EW symmetry breaking
  - Produce particle with flavor-dependent couplings to quarks and leptons
  - Search for dark-matter particles in the strong-coupling region of dark sectors
  - Explore the unknown at the highest possible energy scale
- A 100-TeV proton-proton collider (FCC-hh, SppC) provides an effective energy reach of a 10-TeV muon collider (MuC). A pp-collider has easier access to colored states and compositeness studies, a MuC can take advantage of VV-fusion and benefit from excellent signal to background,
- The main limitation is technology readiness. **A vigorous R&D program** into accelerator and detector technologies **will be crucial.**

EF Colliders: Opportunities for the US

- Our vision for EF can only be realized as **worldwide program** and we need to envision that **future colliders will have to be sited all over the world** to support and empower an international vibrant, inclusive, and diverse scientific community.

- **The US EF community has expressed renewed interest and ambition to bring back energy-frontier collider physics to the US soil** while maintaining its international collaborative partnerships and obligations, for example with CERN.

↳ **More than 40 contribute papers on MuC studies during Snowmass 21**

↳ **New CCC proposal gained momentum during Snowmass 21**

- **Attractive opportunities** to be considered are:
    - **A US-sited linear e^+e^- collider (ILC/CCC)**
    - **Hosting a 10-TeV range Muon Collider**
    - **Exploring other e^+e^- collider options to fully utilize the Fermilab site**

EF Resources and Timelines

- **Five year period starting in 2025**
  - Prioritize HL-LHC physics program
  - Establish a targeted e+e- Higgs Factory detector R&D for US participation in a global collider
  - Develop an initial design for a first stage TeV-scale MuC in the US (pre-CDR)
  - Support critical detector R&D towards EF multi-TeV colliders
- **Five year period starting in 2030**
  - Continue strong support for HL-LHC program
  - Support construction of an e+e- Higgs Factory
  - Demonstrate principal risk mitigation and deliver CDR for a first-stage TeV-scale MuC
- **After 2035**
  - Evaluate continuing HL-LHC physics program to the conclusion of archival measurements
  - Begin and support the physics program of the Higgs Factories
  - Demonstrate readiness to construct and deliver TDR for a first-stage TeV-scale MuC
  - Ramp up funding support for detector R&D for EF multi-TeV colliders

Your input is valuable for us

- **Please give us your input on the**
  - Energy Frontier reports
  - Topical Group reports
- **We also welcome your individual input on the vision for EF in this document.**

Back-up slides

EF - towards the CSS - UW Seattle

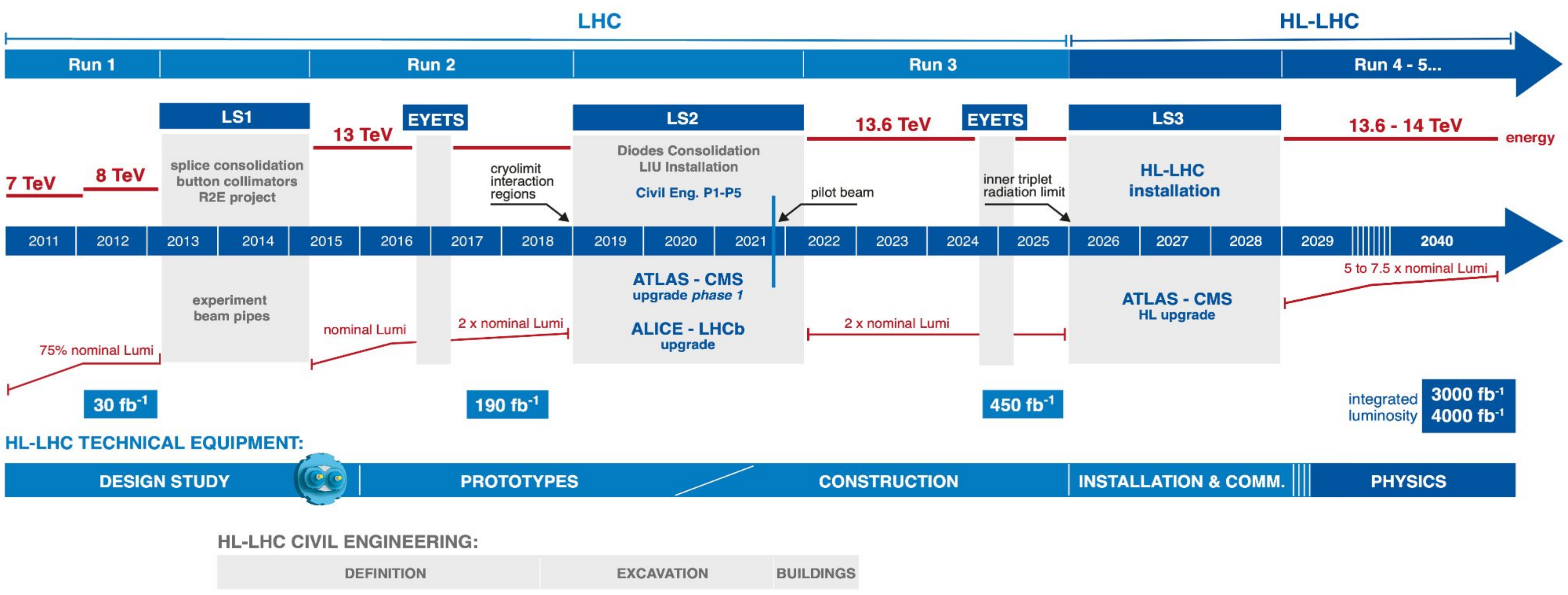
EF community meeting pre-CSS - June 24 2022 (virtual)

- Presenting draft of EF reports (frontier and Topical Groups)
- Presenting EF vision
- Panel Discussion on question proposed by the TGs
- Report from e+e- forum
- Report from m+m- forum

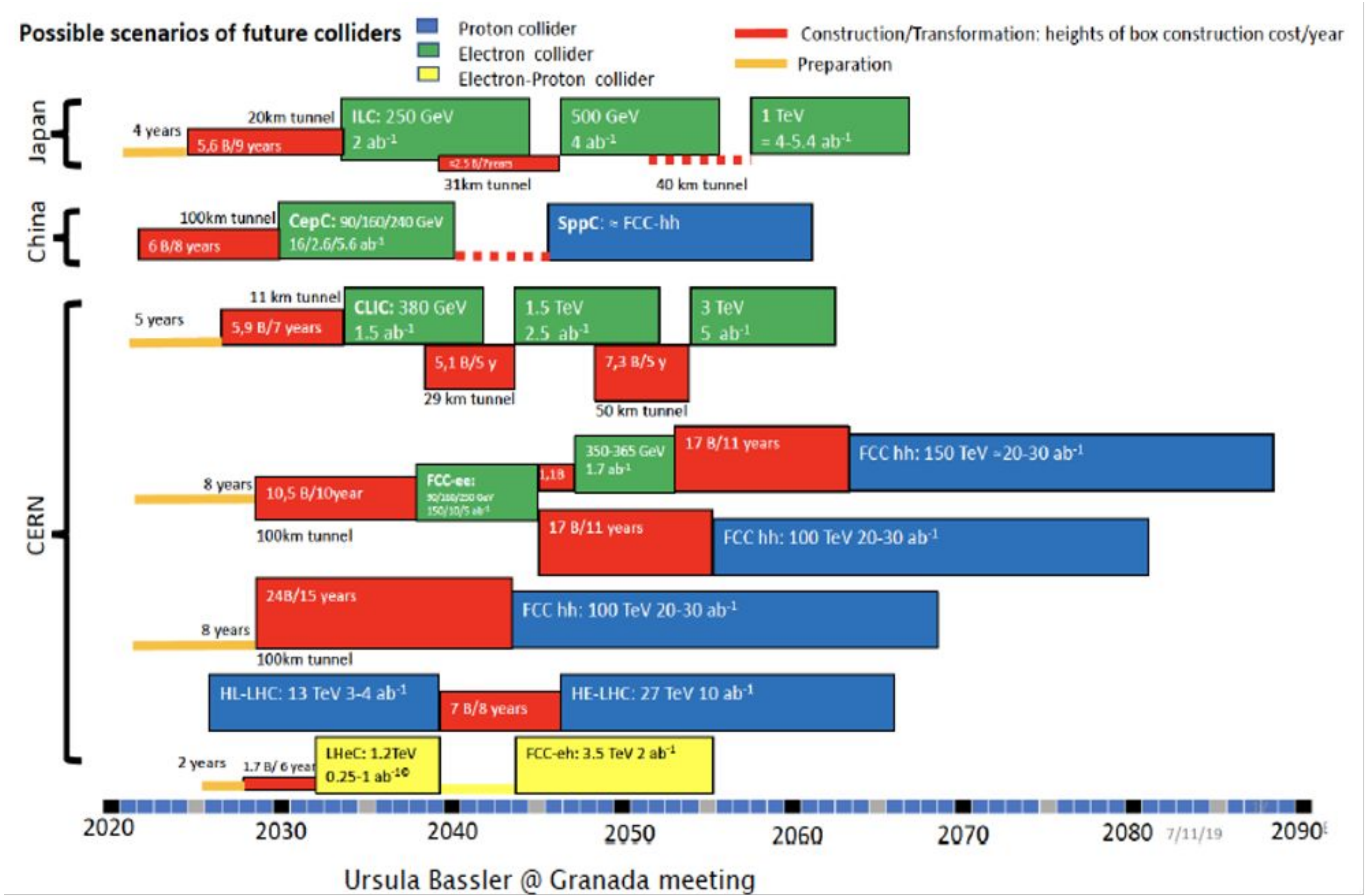
With ample built-in time for discussion.

- X-Frontier sessions at CSS - crucial to build a common vision

LHC / HL-LHC Plan



ESG: Future Collider Scenarios & Timelines



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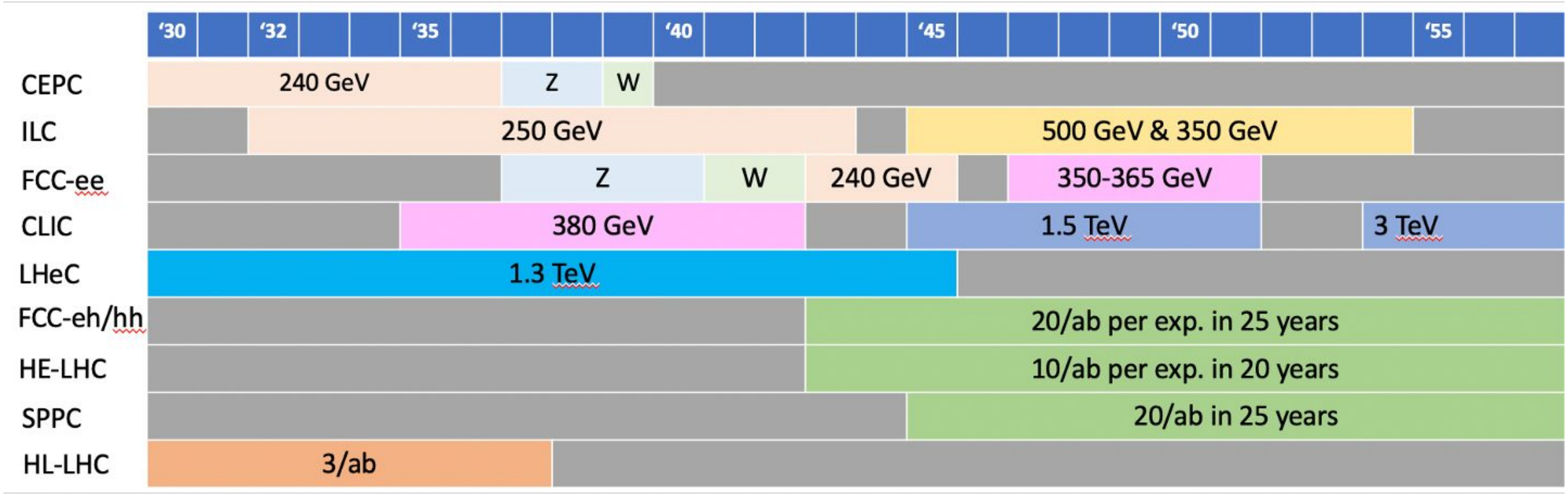

https://arxiv.org/pdf/1905.03764.pdf

ESG: Future Collider Scenarios & Timelines

	T_0				+5					+10					+15					+20			...	+26
ILC	0.5/ab 250 GeV						1.5/ab 250 GeV						1.0/ab 500 GeV				0.2/ab $2m_{top}$	3/ab 500 GeV						
CEPC	5.6/ab 240 GeV							16/ab M_Z		2.6 /ab $2M_W$										SppC =>				
CLIC	1.0/ab 380 GeV										2.5/ab 1.5 TeV									5.0/ab => until +28 3.0 TeV				
FCC	150/ab ee, M_Z				10/ab ee, $2M_W$		5/ab ee, 240 GeV				1.7/ab ee, $2m_{top}$												hh,eh =>	
LHeC	0.06/ab						0.2/ab					0.72/ab												
HE-LHC	10/ab per experiment in 20y																							
FCC eh/hh	20/ab per experiment in 25y																							

https://arxiv.org/pdf/1905.03764.pdf