Energy Frontier - Vision

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

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.**

The Energy Frontier vision in a nutshell

It is essential to

- **Complete the HL-LHC program,**
- **Start now a targeted program for detector R&D for Higgs Factories**
- **Support construction of a Higgs factory**
- **Ensure the long-term viability of the field by developing a multi-TeV energy frontier facility such as a *muon collider* or a *hadron collider*.**

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 extends the direct search for *new elementary particles*
  - It measures the *Higgs-boson couplings* to reach sensitivity to BSM physics in the TeV range
  - It puts bounds on the *Higgs-boson self coupling* and give first indications on the Higgs potential
  - It measures the EW couplings of the top quark at a level that is sensitive to corrections from BSM physics
  - It extends our understanding of *QCD and strong interactions* by improving the precision of its measurements
- **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, including the construction of auxiliary experiments that extend the reach of HL-LHC in kinematic regions uncovered by the detector upgrades
- In addition, the time scales for realizing what comes next requires also an effort to **advance preparations for the next collider of the intermediate future during this time frame**.

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*
  - Search for *exotic Higgs decays* and explore the Higgs portal to hidden sectors
  - Measure the EW couplings of the top quark at a level that can clearly reveal corrections from BSM physics
  - *Stress test the consistency of the SM* with substantial improvement in precision
  - Perform precision measurements of *QCD to deepen our understanding 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.
- In addition, investment in a long term robust program of **detector and collider R&D focused on both Higgs factory and multi-TeV colliders** (hadron collider, muon colliders) is necessary for solving the many outstanding challenges, and the long term viability of collider physics.

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, Muon Coll.)

- **The physics case is outstanding** and rests on the potential to:
  - Greatly extend the reach for BSM scenarios motivated by *naturalness*
  - *Understand the origin of EW symmetry breaking* by *testing the Higgs potential*
  - Probe the *origin of flavor* by producing particles with flavor-dependent couplings to quarks and leptons
  - Conclusively *search for* thermal *dark-matter candidates* in a broad class of models at high masses
  - Explore a *broad range of BSM phenomena at the highest foreseeable energy scale*
- A 10-TeV **muon collider** (MuC) and 100-TeV **proton-proton collider** (FCC-hh, SppC) directly probe the order 10 TeV energy scale with different strengths that are unparalleled in terms of mass reach, precision, and sensitivity.
- 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 a **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 community has to continue to work with the international community on detector designs and develop extensive R&D programs.
    - To realize this, the funding agencies (DOE and NSF) should fund a **R&D program** focused on participation of the US community in future collider efforts as partners (as currently US is severely lagging behind).
- **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.
    - The international community also realizes that a vibrant and concurrent program in the US in energy frontier collider physics is **beneficial for the whole field, as it was when Tevatron was operated simultaneously as LEP.**

EF Colliders: Opportunities for the US

- **Planning to proceed in multiple parallel prongs may allow us to better adapt to international contingencies** and eventually build the next collider sooner. Such a strategy will also help develop a robust long term plan for the global HEP community, with U.S. leadership in EF colliders.
- **Attractive opportunities** to be considered are:
    - **A US-sited linear e^+e^- collider (ILC/C^3)**
    - **Hosting a 10-TeV range Muon Collider**
    - **Exploring other e^+e^- collider options to fully utilize the Fermilab site**
- Bold “new” projects offer the next generation some challenges to rise to and inspire more young people from the US to join HEP and in the long term help with strengthening the vibrancy of the field.

↳ **More than 40 contribute papers on Muon Coll. studies during Snowmass 21**

↳ **New C^3 proposal gained momentum during Snowmass 21**

EF Resources and Timelines

➢ Five year period starting in 2025

- Prioritize *HL-LHC physics program,* including auxiliary experiments
- 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 Muon Coll.* 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 Muon Coll.*

➢ After 2035

- Support 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 Muon Coll.*
- Ramp up funding support for *detector R&D for EF multi-TeV colliders*

EF Resources

- The EF community recognizes that our success crucially depends on the vision and resources obtained by the **Acceleration Frontier (AF)** and strongly support the AF in its resource needs and requests to
    - Establish and e+e- Higgs Factory program
    - Start R&D for EF multi-TeV colliders and ramp up funding support for these endeavors.
- The visibility and strong interdependence between EF and **Theory Frontier (TF)** is key to the success of both frontiers. The opportunity for continued collaborations has been at the core of the progress of the EF until now and will continue to be so. The EF supports a strong and well-funded theory program.