The Energy Frontier Vision

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Meenakshi Narain (Brown U.)
Laura Reina (FSU)
Alessandro Tricoli (BNL)

EF Reports: https://snowmass21.org/energy/start#final_reports
Energy Frontier: explore the TeV energy scale and beyond to answer still open Big Questions and Explore the Unknown

Big Questions
Evolution of early Universe
Matter Antimatter Asymmetry
Nature of Dark Matter
Origin of Neutrino Mass
Origin of EW Scale
Origin of Flavor
Exploring the Unknown
Energy Frontier: explore the TeV energy scale and beyond
Using Standard Model and Beyond Standard Model probes

Big Questions
Evolution of early Universe
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Nature of Dark Matter
Origin of Neutrino Mass
Origin of EW Scale
Origin of Flavor

Exploring the Unknown

EW Gauge Bosons
Nature of Higgs
Top Physics

Strong Interaction Properties
Direct Production of Dark Matter
New Particles Interactions Symmetries
Energy Frontier: explore the TeV energy scale and beyond
Through the breadth and multitude of collider physics signatures

Big Questions
Evolution of early Universe
Matter Antimatter Asymmetry
Nature of Dark Matter
Origin of Neutrino Mass
Origin of EW Scale
Origin of Flavor
Exploring the Unknown

- W/Z mass
- Flavor physics
- Strong Interaction Properties
- jet
- PDF
- Axion-like particles
- Missing E/p
- Long lived particles
- SUSY
- Heavy gauge bosons
- Leptoquarks
- Heavy neutrinos

- EW Gauge Bosons
- Multibosons
- Higgs couplings
- Higgs mass
- Higgs CP
- Rare decays
- Nature of Higgs
- Top Physics
- Top mass
- Top spin
- FCNC
- New scalars
Discoveries at the Energy Frontier are enabled by the development of new accelerators and detector instrumentation.

EF explorations should proceed along two main complementary directions:

- **Study known phenomena at high energies looking for indirect evidence of BSM physics**
  - Need factories of Higgs bosons (and other SM particles)
  - Need high precision to probe the TeV scale and beyond
  - → Need both luminosity and energy

- **Search for direct evidence of BSM physics at the energy frontier**
  - Need to explore the multi-TeV scale → Need energy
  - Need to explore what LHC/HL-LHC may have difficulty exploring → Need luminosity
Energy Frontier Machines: energy and precision

New physics can be at low and at high mass scales: Naturalness would prefer mass scale close to the EW scale, but direct searches of specific models have placed stronger bounds around 1-2 TeV.

Depending on the mass scale of new physics and the type of collider, the primary method for discovery new physics can vary.

We need to use both energy and precision.
In a simplified picture:

New physics at tree level:
$$\delta \eta_{SM} \sim g_{BSM}^2 \frac{E^2}{M^2}$$

New physics at loop level:
$$\delta \eta_{SM} \sim \frac{1}{16\pi^2} \times g_{BSM}^2 \frac{E^2}{M^2}$$

HF: Higgs factory
HE: high-energy or multi-TeV collider
What Machine?

**Hadrons**
- large mass reach $\Rightarrow$ exploration?
  - $S/B \sim 10^{-10}$ (w/o trigger)
  - $S/B \sim 0.1$ (w/ trigger)
- requires multiple detectors
  - (w/ optimized design)
- $\gamma$ limited by synchrotron radiation
- $\Rightarrow$ couplings to quarks and gluons

**Leptons**
- $S/B \sim 1 \Rightarrow$ measurement?
- polarized beams
  - (handle to choose the dominant process)
- limited (direct) mass reach
- identifiable final states
- $\Rightarrow$ EW couplings

**Circular**
- higher luminosity
- several interaction points
- precise E-beam measurement
  - ($\gamma(0.1\text{MeV})$ via resonant dipolarization)
- $\gamma$ limited by synchrotron radiation

**Linear**
- easier to upgrade in energy
- easier to polarize beams
- $\gamma$ "greener": less power consumption*
  - large beamstrahlung
- one IP only

*energy consumption per integrated luminosity is lower at circular colliders but the energy consumption per GeV is lower at these colliders

**Additions**
- Added $C^3$
- Gamma-gamma?
- Advanced colliders?

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**Future Measurements**

*Inst. Pascal, Dec. 4, 2019
# Snowmass 2021: EF Benchmark Scenarios

Higgs-boson factories  
(up to 1 TeV c.o.m. energy)

<table>
<thead>
<tr>
<th>Collider</th>
<th>Type</th>
<th>$\sqrt{s}$</th>
<th>$\mathcal{P}[$% $]_{e^{-}/e^{+}}$</th>
<th>$L_{\text{int}}$ ab$^{-1}$/IP</th>
<th>Start Date</th>
<th>Physics</th>
</tr>
</thead>
<tbody>
<tr>
<td>HL-LHC</td>
<td>pp</td>
<td>14 TeV</td>
<td>3</td>
<td>2027</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ILC &amp; C$^3$</td>
<td>ee</td>
<td>250 GeV</td>
<td>±80/±30</td>
<td>2</td>
<td>2028</td>
<td>2038</td>
</tr>
<tr>
<td></td>
<td></td>
<td>350 GeV</td>
<td>±80/±30</td>
<td>0.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>500 GeV</td>
<td>±80/±30</td>
<td>4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CLIC</td>
<td>ee</td>
<td>380 GeV</td>
<td>±80/0</td>
<td>1</td>
<td>2041</td>
<td>2048</td>
</tr>
<tr>
<td>CEPC</td>
<td>ee</td>
<td>$M_Z$</td>
<td>50</td>
<td>2026</td>
<td>2035</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>$2M_W$</td>
<td>3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>240 GeV</td>
<td>10</td>
<td></td>
<td></td>
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</tr>
<tr>
<td></td>
<td></td>
<td>360 GeV</td>
<td>0.5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FCC-ee</td>
<td>ee</td>
<td>$M_Z$</td>
<td>75</td>
<td>2033</td>
<td>2048</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>$2M_W$</td>
<td>5</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>240 GeV</td>
<td>2.5</td>
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<tr>
<td></td>
<td></td>
<td>$2M_{top}$</td>
<td>0.8</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\mu$-collider</td>
<td>$\mu\mu$</td>
<td>125 GeV</td>
<td>0.02</td>
<td></td>
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<td></td>
</tr>
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</table>

### Multi-TeV colliders  
(> 1 TeV c.o.m. energy)

<table>
<thead>
<tr>
<th>Collider</th>
<th>Type</th>
<th>$\sqrt{s}$</th>
<th>$\mathcal{P}[$% $]_{e^{-}/e^{+}}$</th>
<th>$L_{\text{int}}$ ab$^{-1}$/IP</th>
<th>Start Date</th>
<th>Physics</th>
</tr>
</thead>
<tbody>
<tr>
<td>HE-LHC</td>
<td>pp</td>
<td>27 TeV</td>
<td>15</td>
<td>2063</td>
<td>2074</td>
<td></td>
</tr>
<tr>
<td>FCC-hh</td>
<td>pp</td>
<td>100 TeV</td>
<td>30</td>
<td>2055</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SpEC</td>
<td>pp</td>
<td>75-125 TeV</td>
<td>10-20</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LHeC</td>
<td>ep</td>
<td>1.3 TeV</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FCC-eh</td>
<td>ep</td>
<td>3.5 TeV</td>
<td>2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CLIC</td>
<td>ee</td>
<td>1.5 TeV</td>
<td>$\pm80/0$</td>
<td>5</td>
<td>2052</td>
<td>2058</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3.0 TeV</td>
<td>$\pm80/0$</td>
<td>5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\mu$-collider</td>
<td>$\mu\mu$</td>
<td>3 TeV</td>
<td>1</td>
<td>2038</td>
<td>2045</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>10 TeV</td>
<td>10</td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

Timelines are taken from the ITF report (AF)
Snowmass Agora on Future Colliders

Series of events jointly organized by AF and EF, hosted by the Future Colliders initiative at Fermilab, to discuss both near and far future collider proposals, in different stages of development, synergistically grouped into five categories:

- e+e- circular colliders (Jan. 19, 2022) [https://indico.fnal.gov/event/52534/](https://indico.fnal.gov/event/52534/)
- μ+µ- colliders (Feb. 16, 2022): [https://indico.fnal.gov/event/53010/](https://indico.fnal.gov/event/53010/)
- circular pp and ep colliders (Mar 16, 2022): [https://indico.fnal.gov/event/53473/](https://indico.fnal.gov/event/53473/)
- advanced colliders (April 13, 2022): [https://indico.fnal.gov/event/53848/](https://indico.fnal.gov/event/53848/)

Critical discussions of physics reach, challenges and RD required, synergies with global context and local resources, timeframe, cost projection.

Other specific dedicated meetings can be found on EF/AF Snowmass websites.
Key physics questions and studies of the EF program
Key physics questions of the EF program

Origin of the electroweak scale?

The Higgs discovery has given us a unique handle on BSM physics and any future plan needs to make the most out of it.

- Can we uncover the nature of high-energy (UV) physics from precision Higgs measurements (mass, width, couplings)?
- Can we measure the shape of the Higgs potential?
- Can the Higgs give us insight into flavor and vice versa?
- How can we stress test the SM with top quark?
- What are the implications for Naturalness?
- Can constraints come from phenomena not yet considered or accessible at colliders?

See EW, Top and BSM Topical Group Reports
## Higgs-self coupling reach

<table>
<thead>
<tr>
<th>collider</th>
<th>Indirect-$h$</th>
<th>$hh$</th>
<th>combined</th>
</tr>
</thead>
<tbody>
<tr>
<td>HL-LHC</td>
<td>100-200%</td>
<td>50%</td>
<td>50%</td>
</tr>
<tr>
<td>ILC$_{250}/C^3$-250</td>
<td>49%</td>
<td>—</td>
<td>49%</td>
</tr>
<tr>
<td>ILC$_{500}/C^3$-550</td>
<td>38%</td>
<td>20%</td>
<td>20%</td>
</tr>
<tr>
<td>CLIC$_{380}$</td>
<td>50%</td>
<td>—</td>
<td>50%</td>
</tr>
<tr>
<td>CLIC$_{1500}$</td>
<td>49%</td>
<td>36%</td>
<td>29%</td>
</tr>
<tr>
<td>CLIC$_{3000}$</td>
<td>49%</td>
<td>9%</td>
<td>9%</td>
</tr>
<tr>
<td>FCC-ee</td>
<td>33%</td>
<td>—</td>
<td>33%</td>
</tr>
<tr>
<td>FCC-ee (4 IPs)</td>
<td>24%</td>
<td>—</td>
<td>24%</td>
</tr>
<tr>
<td>FCC-hh</td>
<td>—</td>
<td>2.9-5.5%</td>
<td>2.9-5.5%</td>
</tr>
<tr>
<td>$\mu$ (3 TeV)</td>
<td>—</td>
<td>15-30%</td>
<td>15-30%</td>
</tr>
<tr>
<td>$\mu$ (10 TeV)</td>
<td>—</td>
<td>4%</td>
<td>4%</td>
</tr>
</tbody>
</table>

## Stress Test of the SM

![Graph showing Higgs mass distribution and coupling reach](image)

- **Current**
- **ILC250 + ILC-GigaZ**
- **CEPC**
- **FCC-ee**
Key physics studies of the EF program

Aim to build a complete program of BSM searches via both model-specific and model independent explorations

- Models connect the high-level unanswered questions in particle physics (dark matter, electroweak naturalness, CP violation, etc) to specific phenomena in a self-consistent way.
  - Allow the comparison of experimental reach between various approaches, e.g. direct searches vs precision.

- Study alternative paradigms with respect to traditional BSM searches (ex: long-lived and feebly-interacting particles).

- We also aim to conduct searches in a more model-independent/agnostic way

- Complementarity between collider searches, cosmic probes (e.g. Dark Matter), neutrino experiments, rare process experiments etc.

See BSM Topical Group Reports
Examples of BSM explorations at colliders

Heavy Boson (Z') model

Composite Higgs models
**Complementarity of collider physics**

**Example of WIMP Dark Matter reach**

Collider physics complementing observations in astrophysics

**Heavy Neutral Leptons**

High energy reach of EF collider experiments compared to other experiments
Key physics topics of the EF program

What can we learn of the nature of strong interactions in different regimes?

Fundamental (theory + phenomenology):

- High precision in strong coupling $\alpha_s$ can be reached by each future machine/experiment
- New directions of future high-precision QCD calculations
- Evolution of jets as a function of energy at the EIC and at hadron colliders
- Are jets universal? If not, how do we deal with non-universality in our hadronization models?
- PDFs coming from lattice calculations

➢ See QCD Topical Group Report

<table>
<thead>
<tr>
<th>Method</th>
<th>Relative $\alpha_s(m_Z)$ uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) Lattice</td>
<td>Current: 0.7%</td>
</tr>
<tr>
<td></td>
<td>Near (long-term) future: $\approx$ 0.3% (0.1%)</td>
</tr>
<tr>
<td>(2) $\tau$ decays</td>
<td>1.6%</td>
</tr>
<tr>
<td>(3) $Q\bar{Q}$ bound states</td>
<td>3.3%</td>
</tr>
<tr>
<td>(4) DIS &amp; PDF fits</td>
<td>1.7%</td>
</tr>
<tr>
<td>(5) $e^+e^-$ jets &amp; evt shapes</td>
<td>2.6%</td>
</tr>
<tr>
<td>(6) Electroweak fits</td>
<td>2.3%</td>
</tr>
<tr>
<td>World average</td>
<td>0.8%</td>
</tr>
</tbody>
</table>

TeraZ statistics allows unprecedented precision in $\alpha_s$ and can provide evidence of BSM.
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.
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 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 the 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 beyond the SM
  - Stress test the consistency of the SM with substantially 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 mechanism of EW symmetry breaking and measure the Higgs potential
  - Shed light on the origin of flavor
  - Conclusively search for dark-matter candidates in a broad category of 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 $\text{e}^+\text{e}^-$ collider (ILC/C$^3$)
  - Hosting a 10-TeV range Muon Collider
  - Exploring other $\text{e}^+\text{e}^-$ 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 recognizes the need for strong support to the Accelerator Frontier for the above requests.