The Physics case for
Energy Frontier Discovery Machines

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Seattle, July 23rd 2022
Colliders at the Energy Frontier have been instrumental in understanding the building blocks of the Standard Model (SM) of Particle Physics.
Building the Standard Model

Colliders at the Energy Frontier have been instrumental in understanding the building blocks of the Standard Model (SM) of Particle Physics.
Keys to success

Theory ↔ Experiment ↔ Direct ↔ Indirect
Keys to success

Theory ↔ Experiment

Direct ↔ Indirect

LEP EWK Working Group, 1996 - 2012

1996

2005

March 2012
Keys to success

Theory ↔ Experiment

Direct ↔ Indirect

LEP EWK Working Group, 1996 - 2012

PLB 716 (2012) 1, PLB 716 (2012) 30

July 2012

ATLAS

Data

Sig+Bkg Fit \( m_H = 126.5 \text{ GeV} \)

Bkg (4th order polynomial)

H \rightarrow \gamma \gamma

Events / 3 GeV

Events - Bkg

PLB 716 (2012) 1, PLB 716 (2012) 30

CMS

Data

\( \sqrt{s} = 7 \text{ TeV}, L = 5.1 \text{ fb}^{-1} \)

\( \sqrt{s} = 8 \text{ TeV}, L = 5.3 \text{ fb}^{-1} \)

Events / 3 GeV

K_{\phi} > 0.5

m_{\phi} (GeV)

m_{4\ell} (GeV)
The (current) Standard Model is not enough!

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
The (current) Standard Model is not enough!

Plenty of extensions of the Standard Model have the potential of addressing these questions, including the ones we haven’t thought of yet.

Most pointing to higher energy scales where new particles will manifest.

arXiv:1311.0299
Probes and Signatures of new physics at colliders

With such an exciting and vast landscape of possibilities, the **breadth of the experimental program** is of paramount importance.

Colliders offer the unique ability to probe, with a single experimental setup, all sectors of the SM and its extensions.
The Large Hadron Collider

Run 3 has started!

First Stable Beams at 6.8 TeV of Run3!

Credit: CERN
Beyond LHC

Direct Searches

- LHC
- Future HE colliders

- Higgs Factory

Coupling to SM vs. Mass Scale

- More Energy
- More Luminosity

Depends on collider environment
Beyond LHC
Operation: 2029 to ~2040

Only a fraction of the p-p center-of-mass energy is transferred through the hard-scattering interaction

=> Large integrated luminosity allows access to higher energy scales as well

And more: new auxiliary experiments at HL-LHC can further boost its discovery potential!
How to reach even higher center-of-mass energy?

\[ \text{pp} \quad \text{e}^+\text{e}^- \quad \mu^+\mu^- \]

multi-TeV lepton-hadron colliders also considered, not discussed here
How to reach higher center-of-mass energy?

- Large collider ring, stronger magnets
  - re-use FCC-ee/SpeC tunnel

\[ p \propto q B \rho \]

- Need large statistics (luminosity) to sample highest energy scales

<table>
<thead>
<tr>
<th></th>
<th>FCC-hh</th>
<th>SppC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Center-of-mass [TeV]</td>
<td>100</td>
<td>75 (125-150)</td>
</tr>
<tr>
<td>Circumference [km]</td>
<td>91</td>
<td>100</td>
</tr>
<tr>
<td>Luminosity [/ab/yr] / IP</td>
<td>3</td>
<td>~1</td>
</tr>
</tbody>
</table>
How to reach higher center-of-mass energy?

- Large synchrotron radiation implies linear accelerator
  \[ P_{\text{loss}} \propto q^2 \gamma^4 \]
- Need large acceleration gradients
- Low physics backgrounds, easier event reconstruction
- \( \gamma \gamma \) technically preferred, but physics less studied

<table>
<thead>
<tr>
<th>ILC/CLIC/CCC</th>
<th>Wakefield Accelerators</th>
</tr>
</thead>
<tbody>
<tr>
<td>Center-of-mass [TeV]</td>
<td>3</td>
</tr>
<tr>
<td>Length [km]</td>
<td>27-59</td>
</tr>
<tr>
<td>Luminosity [/ab/yr]</td>
<td>0.6</td>
</tr>
</tbody>
</table>
How to reach higher center-of-mass energy?

- Large community interest during Snowmass
  - ~40 EF contributed papers
  - > 60 early-career authors in forum report
- Expect large beam-induced background ($\tau_0 \mu \sim 2\mu$s)
- Low physics backgrounds
- In principle scalable to even higher energies

<table>
<thead>
<tr>
<th></th>
<th>MuC-3</th>
<th>MuC-10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Center-of-mass [TeV]</td>
<td>3</td>
<td>10 (14)</td>
</tr>
<tr>
<td>Circumference [km]</td>
<td>4.5</td>
<td>10</td>
</tr>
<tr>
<td>Luminosity [/ab/yr]</td>
<td>0.2</td>
<td>2</td>
</tr>
</tbody>
</table>
Lepton vs Hadron colliders: expected signals

**Protons:** involve scattering of constituents (partons)
**Leptons:** full center-of-mass energy available in collisions

Practically, a lot of details that depend on the specific process, hence the need for a broad set of studies

Adapted from arXiv:2103.14043
Not a “simple” jump in Energy

Moving to ~10 TeV parton/lepton energy scale has qualitative new features

Just 1/100s examples: **new dominant production mechanisms**

\[ \sigma \sim 1/\hat{s} \]

\[ \sigma \sim \log \hat{s} \]
Not a “simple” jump in Energy

Moving to ~10 TeV parton/lepton energy scale has qualitative new features

Just 2/100s examples: detectors

New technology to develop detectors able to extract the full physics potential

**Radiation Hardness**

![Radiation Hardness Diagram]


More than x10 than HL-LHC at FCC-hh
- requires robust R&D

**Event Reconstruction**

Unprecedented complexity:
- innovative algorithms / detectors’ layouts
- O(10)ps timing information

![Event Reconstruction Diagram]

NEW Proved feasibility of full event reconstruction in a muon collider detector with detailed simulations
## How (When) do we get there?

<table>
<thead>
<tr>
<th>Proposal Name</th>
<th>CM energy nom. (range) [TeV]</th>
<th>Lum./IP @ nom. CME $[10^{34} \text{ cm}^{-2}\text{s}^{-1}]$</th>
<th>Years of pre-project R&amp;D</th>
<th>Years to first physics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Muon Collider</td>
<td>10 (1.5-14)</td>
<td>20</td>
<td>&gt;10</td>
<td>&gt;25</td>
</tr>
<tr>
<td>LWFA - LC - $\gamma\gamma$</td>
<td>15 (1-15)</td>
<td>50</td>
<td>&gt;10</td>
<td>&gt;25</td>
</tr>
<tr>
<td>(Laser-driven)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PWFA - LC - $\gamma\gamma$</td>
<td>15 (1-15)</td>
<td>50</td>
<td>&gt;10</td>
<td>&gt;25</td>
</tr>
<tr>
<td>(Beam-driven)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Structure WFA - LC - $\gamma\gamma$</td>
<td>15 (1-15)</td>
<td>50</td>
<td>&gt;10</td>
<td>&gt;25</td>
</tr>
<tr>
<td>(Beam-driven)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FCC-hh</td>
<td>100 (1-15)</td>
<td>30</td>
<td>&gt;10</td>
<td>&gt;25</td>
</tr>
<tr>
<td>SPPS</td>
<td>125 (75-125)</td>
<td>13</td>
<td>&gt;10</td>
<td>&gt;25</td>
</tr>
</tbody>
</table>

from Snowmass AF Implementation Taskforce

- None of these colliders is happening tomorrow
- Critical to address as quickly as possible the key R&D challenges
These colliders have enormous potential to answer fundamental questions!

Group our guide to physics beyond the SM in three categories

1. Observed phenomena lacking a fundamental explanation
   - Dark Matter
   - Matter-Antimatter asymmetry in the Universe
   - Origin of neutrinos masses
   - …

2. Guiding theoretical principles
   - Natural energy scale “cut-offs”
   - Flavor structure of the SM
   - …

3. Unexpected new phenomena
   - Historically have opened roads to revolutionary discoveries
Dark Matter at Colliders

Aim to create Dark Matter in laboratory and study its properties in detail
- very complementary to searches in the cosmic frontier!
- WIMP, Mediator searches, Beyond-WIMP

Example: WIMP in minimal models
- Non-baryonic matter, no EM interactions observed (dark), ~84% of matter
- Evolution of dark matter density regulated by production/annihilation processes

In a minimal weakly-interactive model, DM is part of a EWK multiplet
- Fixing its structure allows to compute rates
- Comparing with observed density can derive a target DM particle mass

Typical EWK cross-section from unrelated quantities

\[ \Omega \chi h^2 \simeq \text{const.} \cdot \frac{T_0^3}{M_{Pl}^3 \langle \sigma v \rangle} \simeq \frac{0.1 \text{ pb} \cdot c}{\langle \sigma v \rangle} \]
A statement on the WIMP paradigm at colliders
A statement on the WIMP paradigm at colliders
A statement on the WIMP paradigm at colliders

![Graph showing indirect detection limits at various collider energies. The graph includes bars for indirect detection, SPPC at 125 TeV and 75 TeV, FCChh at 100 TeV, FCChe, HL-LHC, MuonC at 14 TeV, 10 TeV, and 3 TeV, CLIC at 3 TeV, 1.5 TeV, and 0.38 TeV, ILC at 1 TeV, 0.5 TeV, and FCC-ee, and CEPC. The x-axis represents the Higgsino mass (m_\chi) in TeV, and the y-axis represents the reach at 2σ. The graph also shows the thermal target and kinematic limit (0.5 x E_{CM}).]
A statement on the WIMP paradigm at colliders

Need multi-TeV colliders to arrive to this natural target
I have] A dream… and the importance of flexibility!

Discovery of a Dark Matter signal in direct-detection

Adapted from arXiv:2207.03764

FAKE SIGNAL: for illustration only
[I have] A dream… and the importance of flexibility!

Discovery of a Dark Matter signal in direct-detection

Its properties studied at HL-LHC

Adapted from arXiv:2207.03764

Adapted from arXiv:2205.06013
[I have] A dream... and the importance of flexibility!

Discovery of a Dark Matter signal in direct-detection

Its properties studied at HL-LHC

High-Energy collider explores a whole spectrum of particles around it

Adapted from arXiv:2205.06013

Increasing mass

Adapted from arXiv:2207.03764

FAKE SIGNAL: for illustration only
Exploring the unknown: new forces

Probe mediator of new forces to the tens of TeV range!
High Energy <-> High Luminosity <-> High Precision

HE machines, with appropriate detector, are also precision measurement devices!

<table>
<thead>
<tr>
<th></th>
<th>H factories</th>
<th>$l^+ l^- @ 3$ TeV</th>
<th>$l^+ l^- @ 10$ TeV</th>
<th>pp @ 100 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td># Higgs bosons</td>
<td>~$10^6$</td>
<td>~$5 \cdot 10^6$</td>
<td>$10^7$</td>
<td>~$10^{10}$</td>
</tr>
</tbody>
</table>

Obviously an over-simplification, control of systematics and physics background play very important roles!

Extremely rare process: only multi-TeV colliders can probe it accurately.

<table>
<thead>
<tr>
<th>collider</th>
<th>Indirect-$h_{SM}$</th>
<th>$h_{SM}h_{SM}$</th>
<th>combined</th>
</tr>
</thead>
<tbody>
<tr>
<td>HL-LHC [27]</td>
<td>100-200%</td>
<td>50%</td>
<td>50%</td>
</tr>
<tr>
<td>ILC$_{250}/C^3$-250 [20, 17]</td>
<td>49%</td>
<td>-</td>
<td>49%</td>
</tr>
<tr>
<td>ILC$_{500}/C^3$-550 [20, 17]</td>
<td>38%</td>
<td>20%</td>
<td>20%</td>
</tr>
<tr>
<td>ILC$_{100}/C^3$-1000 [20, 17]</td>
<td>36%</td>
<td>10%</td>
<td>10%</td>
</tr>
<tr>
<td>CLIC$_{380}$ [22]</td>
<td>50%</td>
<td>-</td>
<td>50%</td>
</tr>
<tr>
<td>CLIC$_{1500}$ [22]</td>
<td>49%</td>
<td>36%</td>
<td>29%</td>
</tr>
<tr>
<td>CLIC$_{3000}$ [22]</td>
<td>49%</td>
<td>9%</td>
<td>9%</td>
</tr>
<tr>
<td>FCC-ee [23]</td>
<td>33%</td>
<td>-</td>
<td>33%</td>
</tr>
<tr>
<td>FCC-ee (4 IPs) [23]</td>
<td>24%</td>
<td>-</td>
<td>24%</td>
</tr>
<tr>
<td>FCC-hh [28]</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$\mu$ (3 TeV) [26]</td>
<td>-</td>
<td>15-30%</td>
<td>15-30%</td>
</tr>
<tr>
<td>$\mu$ (10 TeV) [26]</td>
<td>-</td>
<td>4%</td>
<td>4%</td>
</tr>
</tbody>
</table>

3-5%
Solutions to the hierarchy problem

The unique scalar nature of the Higgs boson suggests new physics. Testing the $\lesssim 10$ TeV regime provides very strong tests of this arguments (other options are also possible).

Compositness

New “symmetries”

$$M_H^2 = M_{\text{tree}}^2 + \left( \frac{H}{H} \right) + \left( \frac{H}{t} \right) + \left( \frac{t}{t} \right) + \left( \frac{H}{H} \right)$$
Higgs compositness

New constituents and inevitable a new “strong force” to bind them together
- Visible effects from direct searches as well as precision measurements
- Evaluated through sensitivity of effective Wilson coefficients

Unitarity limit \( \sim 4\pi \)

Expect a strong coupling
Supersymmetry

Long-sought for very good reasons
- alleviate hierarchy problem
- can provide a natural Dark Matter candidate
- fundamental in extensions that unify all forces (including gravity)

Large model-parameters space and vast phenomenology

Simplified classes of signatures  Full models with additional assumptions
Supersymmetry

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- alleviate hierarchy problem
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Large model-parameters space and vast phenomenology

Simplified classes of signatures

Full models with additional assumptions (in backup)

Multi-TeV colliders extend the reach to the ~10 TeV scale!
Heavy Neutrinos

... and much MUCH more!

Vast program addressing the fundamental questions outlined and much more!

Axion-like Particles

... and ability to react to signals found in low-energy experiments

Credit: LHCb, CERN Courier

Credit: muon g-2 collab.
Concluding…
The night sky

The SM particles

- Gluino
- Higgsino
- Neutralino
- Stop
- Heavy neutrino 1
- Heavy neutrino 2
- Extra-dimension: KK towers
- Extra-dimension: Vector-like quark
- Extra-dimension: Vector-like lepton
- Extra-dimension: Z'
- Dark photon
- Dark Higgs
- Dark pion
- Dark eta

Something unexpected...

Credits: NASA, ESA, and J. Lotz, M. Mountain, A. Koekemoer, and the HFF Team (STScI)
When the morning (end of Snowmass) comes, it is important we find the resources to develop the tools that get us to those “stars” in the most effective way.

The Energy Frontier advocates for wide-range and strong R&D activities in Accelerator, Computing, Instrumentation, Theory and their intersections to ensure a robust program that will **enable multi-TeV colliders to become a reality**, and that is flexible enough to adapt to what we will (or will not) find along the way.
Keys to success: Theory <-> Experiments

Experimental breakthroughs and Theoretical advancements have both contributed to this success

**Prediction of charm quark**

Predicted to explain suppression of FCNC: 
\[ \text{BR}(K^0 \rightarrow \mu\mu) \sim 10^{-8} \]

Then discovered through direct production of J/Ψ

**Discovery of bottom quark**

No obvious reason for a 3rd generation, still..

Bottom quark discovery through production of Upsilon meson

PRL 33, 1406 PRL 33, 1404 (1974)

Keys to success: Precision measurements <-> Direct searches

Precision measurements can stress-test the Standard Model and ultimately point towards the energy scale we need for a discovery

Electroweak precision observables

Precision measurements of electroweak observables can over-constrain Standard Model parameters
- electroweak unification parameters link different observables
- sensitivity to virtual corrections if accuracy is high enough

e.g. sensitivity of W mass corrections to top and Higgs masses

Lepton-Hadron colliders

Proposals for electron-hadron (and muon-hadron) colliders as well!

<table>
<thead>
<tr>
<th>Collider</th>
<th>Type</th>
<th>$\sqrt{s}$</th>
<th>$\mathcal{P} [%]$</th>
<th>$\mathcal{L}_{int}$ ab$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>LHeC</td>
<td>ep</td>
<td>1.3 TeV</td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>FCC-eh</td>
<td></td>
<td>3.5 TeV</td>
<td></td>
<td>2</td>
</tr>
</tbody>
</table>

- And synergy with the Electron-Ion collider (EIC) at BNL
- Improved measurements of proton parton distribution function
  - fundamental for precision measurements at hadron colliders!
- Direct discovery potential as well!
Guiding theoretical principles: the Hierarchy problem

Example: Naturalness

- The Higgs boson is the only fundamental scalar we found so far
- Intrinsic “unstable” mass corrections from virtual contributions

\[ M_H^2 = M_{\text{tree}}^2 + (H_H) + (H_t) + \ldots \]

\[ \Delta M_H \sim \Lambda^2 \]

\( \Lambda \rightarrow \) scale where new physics enters

- Connected to: “Why the EWK scale is so much lower than e.g. Planck scale?”
- Additional contribution that (partially) cancel the divergency is needed

\[ \sim 0.1 - 10 \text{ TeV} \]

- The better the cancellation, the higher the need for additional energy scale is pushed on, it is therefore “natural” to expect some contribution near the EWK scale
- **Multi-TeV colliders** are needed to elucidate the hierarchy between EWK and Planck scales observed
Supersymmetry

Long-sought for very good reasons
- alleviate hierarchy problem
- can provide a natural Dark Matter candidate
- fundamental in extensions that unify all forces (including gravity)

Large model-parameters space and vast phenomenology

Simplified classes of signatures

Full models with additional assumptions (in backup)

Multi-TeV colliders extend the reach to the ~10 TeV scale!
Supersymmetry

Long-sought for very good reasons
- alleviate hierarchy problem
- can provide a natural Dark Matter candidate
- fundamental in extensions that unify all forces (including gravity)
- …

Large model-parameters space and vast phenomenology

Full models with additional assumptions:

pMSSM -> Minimal Supersymmetric model +
external constraints + simplifying assumptions

Hypothetical scenario:
- Colored points: allowed parameter space after future precision measurements of H-bb (@1%) coupling.
- Solid lines: direct searches of an heavy Higgs

Multi-TeV colliders needed to extend reach beyond HL-LHC!
Probing LLPs with LHC Auxiliary Detectors

LHC coverage
(ATLAS, CMS, LHCb)

Forward
(FASER, LHCb, NA62, ...)

Transverse
(CODEX-b, MATHUSLA, ...)

SCHEMATIC

Dedicated LLP detectors at the LHC
Direct detection
Decay products

Distance from IP

Forward
FORMOSA
FASER/FASER2
SND/AdvSND
FASERw/FASERw2
FACET
MATHUSLA

0(100)m

0(10)m

0(1)m

MeV
GeV
TeV

LLP mass range targeted

\[ \sqrt{s} \]

lighter
cc, bb, \( \tau \tau \)
\( h, t \)
heavier

B. Batell
HL-LHC auxiliary experiments: Heavy Neutral Leptons

Just one example out of many – strong synergy with Rare-Processes Frontier
HL-LHC auxiliary experiments: Higgs Portal

\[ \text{Br}[S \to \mu\mu] = 1 \]

\[ \text{Br}[S \to \text{hadrons}] = 1 \]

\[ m_S = 0.5 \text{ GeV} \]

\[ m_S = 10 \text{ GeV} \]
Resource needs and plan for the five year period starting 2025:

1. Prioritize HL-LHC physics program, including far-forward experiments,
2. Establish a targeted $e^+e^-$ Higgs Factory detector R&D program for US participation in a global collider,
3. Develop an initial design for a first stage TeV-scale Muon Collider in the US, with pre-CDR document at the end of this period,

Resource needs and plan for the five year period starting 2030:

1. Continue strong support for the HL-LHC physics program,
2. Support construction of a $e^+e^-$ Higgs Factory,
3. Demonstrate principal risk mitigation and deliver CDR for a first stage TeV-scale muon collider.

Resource needs and plan after 2035:

1. Evaluate continuing HL-LHC physics program to the conclusion of archival measurements,
2. Begin and support the physics program of the Higgs Factories,
3. Demonstrate readiness to construct and deliver TDR for a first-stage TeV-scale muon collider,
4. Ramp up funding support for detector R&D for EF multi-TeV Colliders.