The Energy Frontier Vision

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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

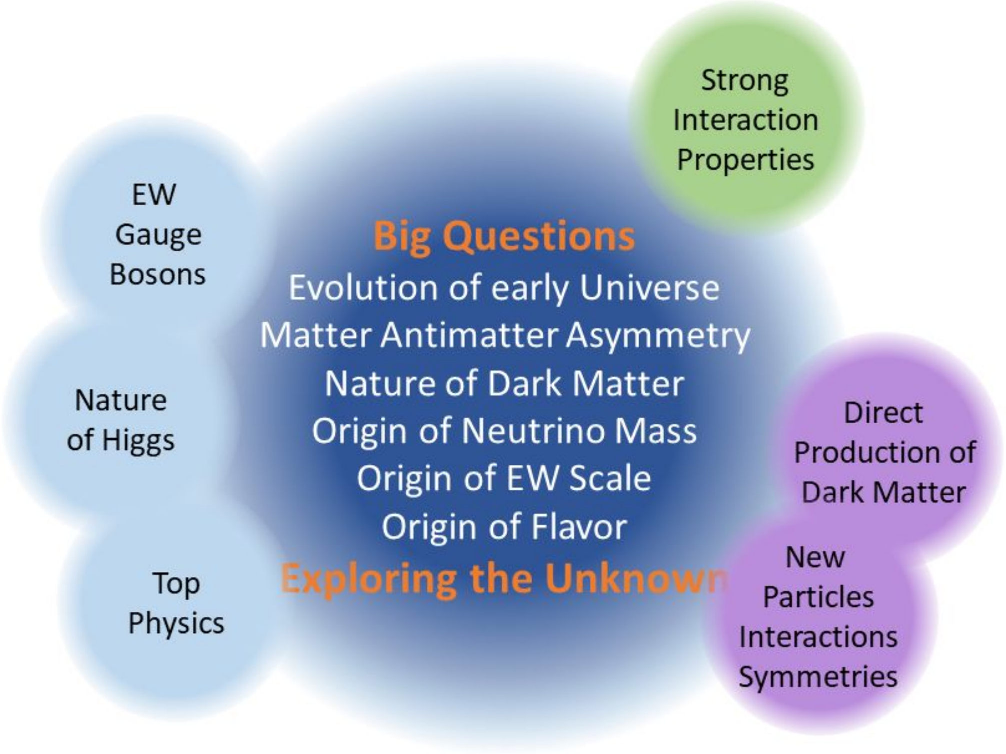
Origin of EW Scale

Origin of Flavor

Exploring the Unknown

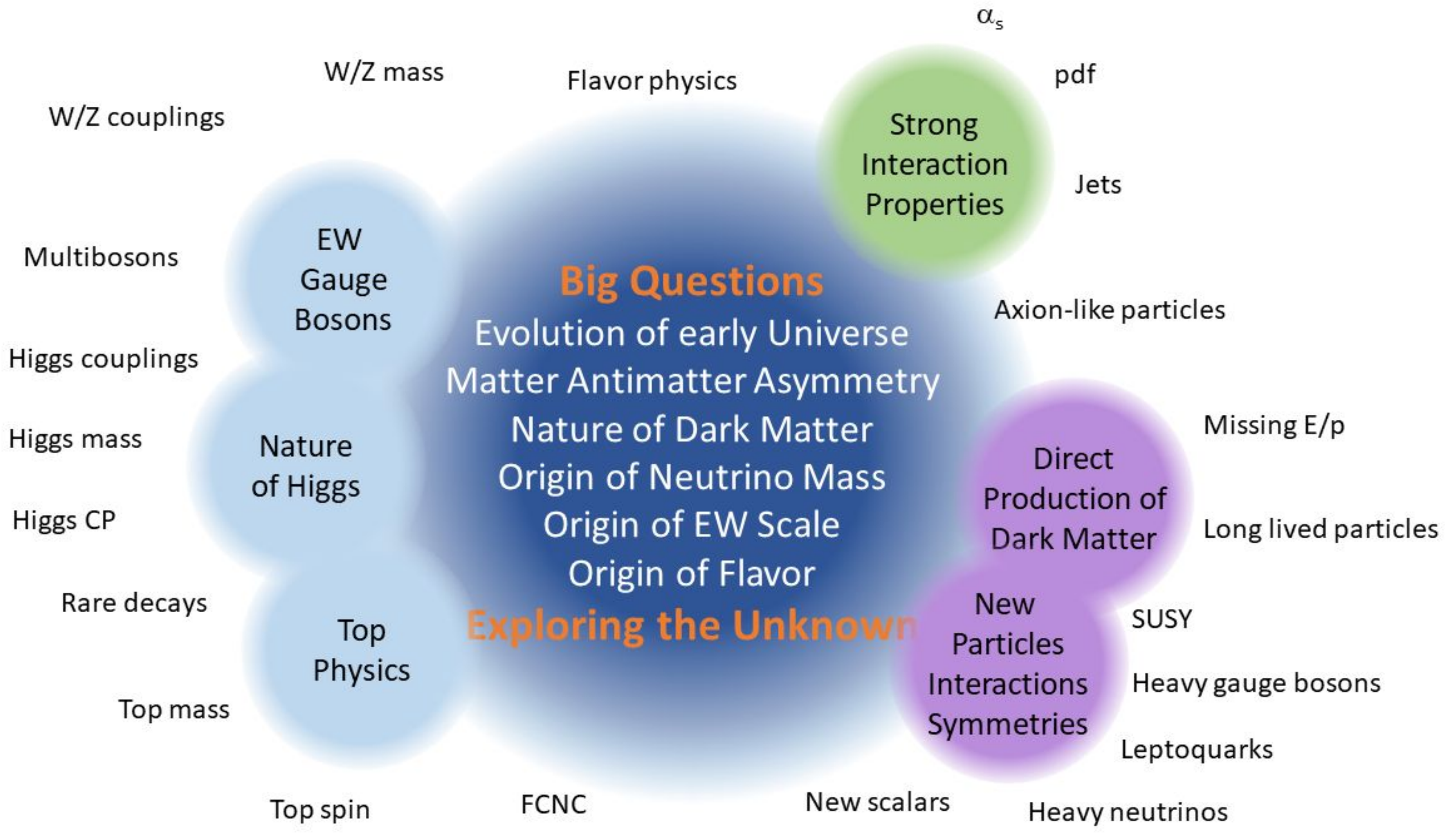
Energy Frontier: explore the TeV energy scale and beyond

Using Standard Model and Beyond Standard Model probes



Energy Frontier: explore the TeV energy scale and beyond

Through the breadth and multitude of collider physics signatures



Energy Frontier Machines

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:**

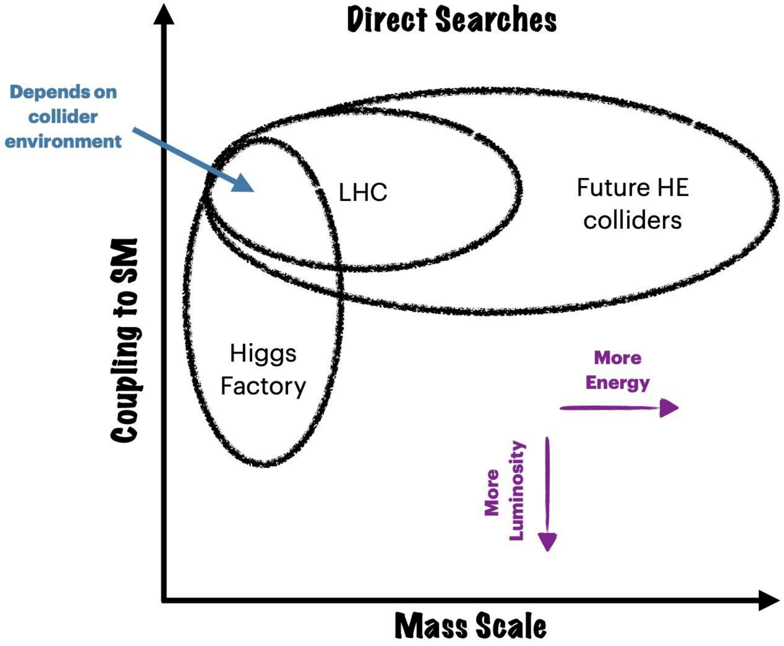
- ➢ **Study known phenomena at high energies looking for indirect evidence of BSM physics**
  - Need factories of Higgs bosons (and other SM particles)
  - Need high precision to probe the TeV scale and beyond
  - →**Need both luminosity and energy**
- ➢ **Search for direct evidence of BSM physics at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

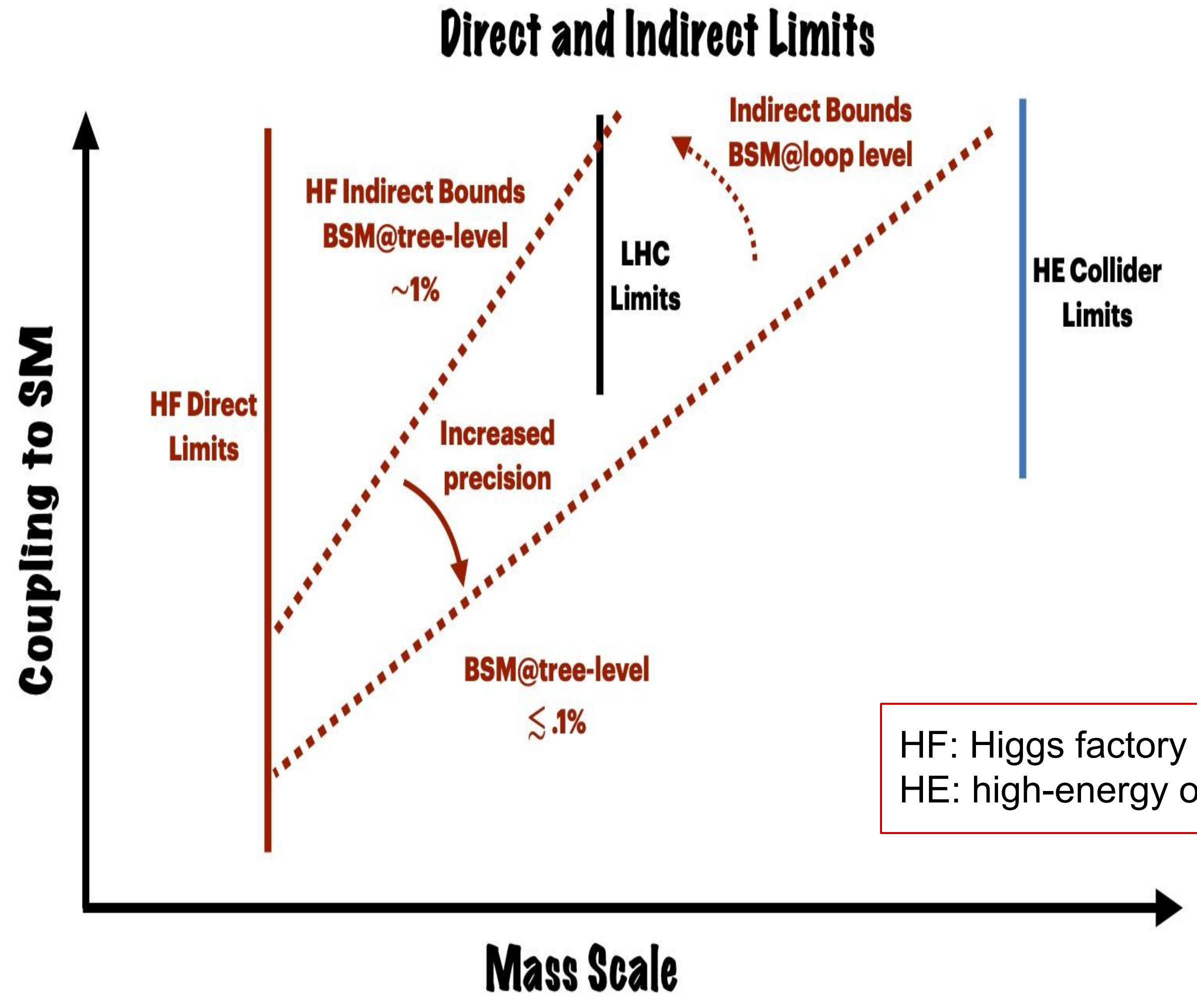
Energy Frontier Machines: energy and precision

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.





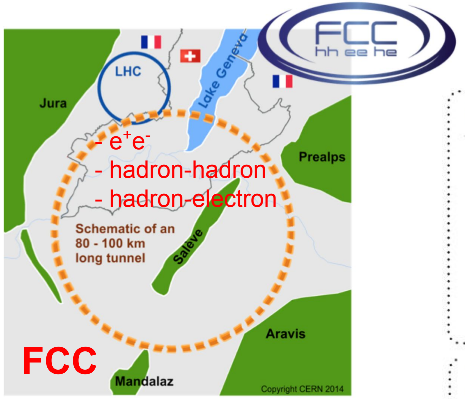
In a simplified picture:

New physics at tree level:
$\delta\eta_{SM} \sim g^2_{BSM}\, E^2/M^2$

New physics at loop level:
$\delta\eta_{SM} \sim 1/16\pi^2 \times g^2_{BSM}\, E^2/M^2$

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

What Machine?



Hadrons

- large mass reach ⇒ exploration?
- S/B ~ 10^{-10} (w/o trigger)
- S/B ~ 0.1 (w/ trigger)
- requires multiple detectors (w/ optimized design)
- only pdf access to $\sqrt{\hat{s}}$
- ⇒ couplings to quarks and gluons

Leptons

- S/B ~ 1 ⇒ measurement?
- polarized beams (handle to chose the dominant process)
- limited (direct) mass reach
- identifiable final states
- ⇒ EW couplings

Circular

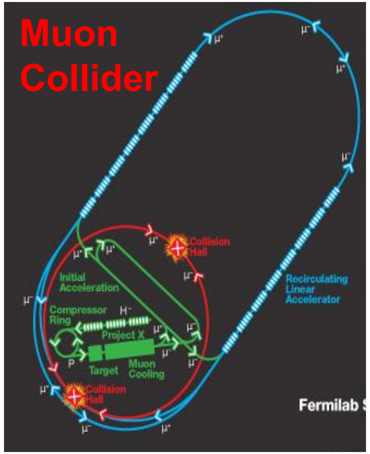
- higher luminosity
- several interaction points
- precise E-beam measurement (O(0.1MeV) via resonant depolarization)
- $\sqrt{s}$ limited by synchrotron radiation

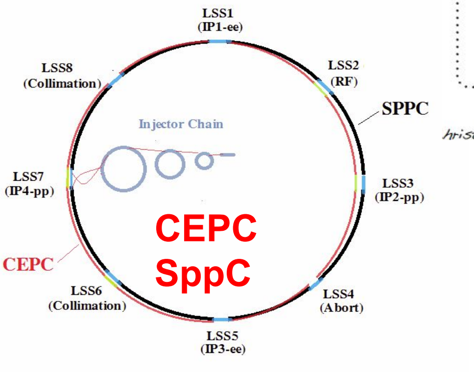
Linear

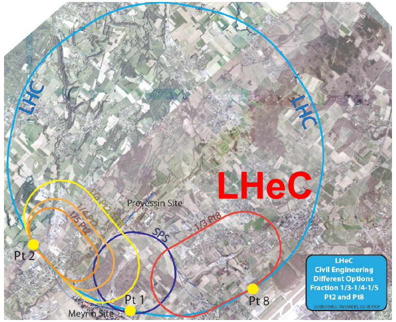
- easier to upgrade in energy
- easier to polarize beams
- "greener": less power consumption*
- large beamsthralung
- one IP only

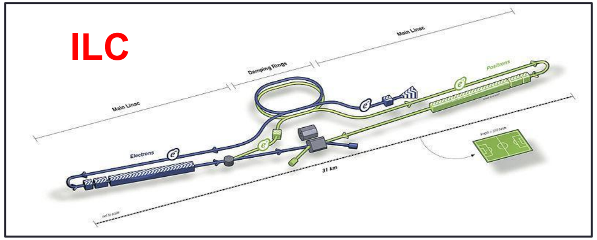
*energy consumption per integrated luminosity is lower at circular colliders but the energy consumption per GeV is lower at linear colliders

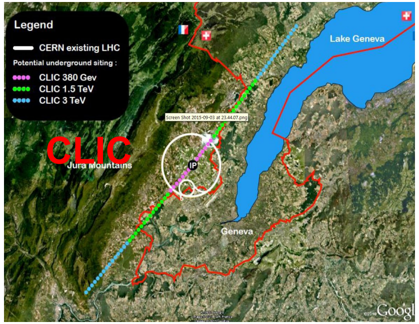
hristophe Grojean   Future Measurements   9   Inst. Pascal, Dec. 4, 2019











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

Snowmass 2021: EF Benchmark Scenarios

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

Collider	Type	$\sqrt{s}$	$\mathcal{P}[\%]$ e^-/e^+	$\mathcal{L}_{\rm int}$ ab^{-1}/IP	Start Date Const.	Start Date Physics
HL-LHC	pp	14 TeV		3		2027
ILC & C^3	ee	250 GeV	$\pm 80/\pm 30$	2	2028	2038
		350 GeV	$\pm 80/\pm 30$	0.2		
		500 GeV	$\pm 80/\pm 30$	4		
		1 TeV	$\pm 80/\pm 20$	8		
CLIC	ee	380 GeV	$\pm 80/0$	1	2041	2048
CEPC	ee	M_Z		50	2026	2035
		$2M_W$		3		
		240 GeV		10		
		360 GeV		0.5		
FCC-ee	ee	M_Z		75	2033	2048
		$2M_W$		5		
		240 GeV		2.5		
		$2\ M_{top}$		0.8		
μ-collider	$\mu\mu$	125 GeV		0.02		

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

Collider	Type	$\sqrt{s}$	$\mathcal{P}[\%]$. e^-/e^+	$\mathcal{L}_{\rm int}$ ab^{-1}/IP	Start Date Const.	Start Date Physics
HE-LHC	pp	27 TeV		15		
FCC-hh	pp	100 TeV		30	2063	2074
SppC	pp	75-125 TeV		10-20		2055
LHeC	ep	1.3 TeV		1		
FCC-eh		3.5 TeV		2		
CLIC	ee	1.5 TeV	$\pm 80/0$	2.5	2052	2058
		3.0 TeV	$\pm 80/0$	5		
μ-collider	$\mu\mu$	3 TeV		1	2038	2045
		10 TeV		10		

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:

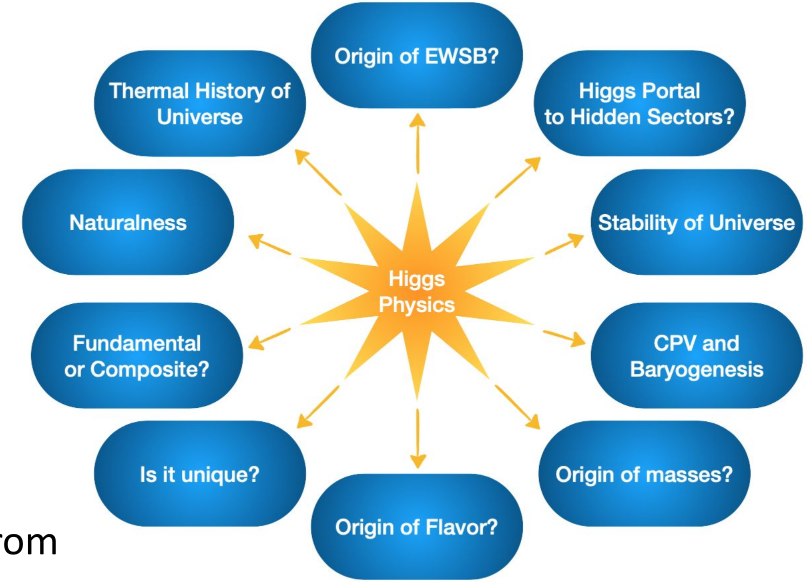
- e+e- linear colliders (Dec. 15, 2021): https://indico.fnal.gov/event/52161/
- e+e- circular colliders (Jan. 19, 2022) https://indico.fnal.gov/event/52534/
- μ+μ- colliders (Feb. 16, 2022): https://indico.fnal.gov/event/53010/
- circular pp and ep colliders (Mar 16, 2022): https://indico.fnal.gov/event/53473/
- advanced colliders (April 13, 2022): 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.

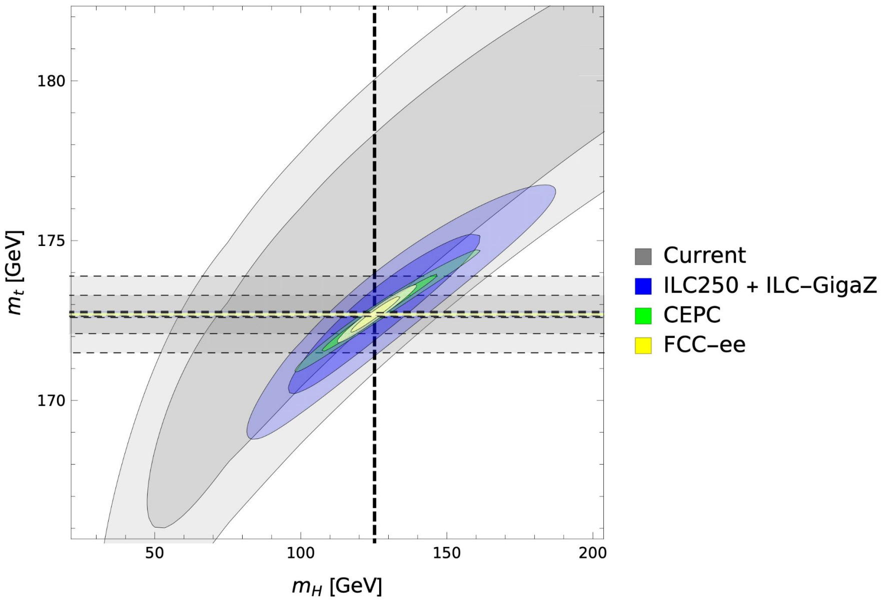
- Can we uncover the nature of high-energy (UV) physics from **precision Higgs measurements** (mass, width, couplings)?
- Can we measure the shape of the **Higgs potential**?
- Can the Higgs give us insight into **flavor** and vice versa?
- How can we stress test the SM with **top quark**?
- What are 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

collider	Indirect-h	hh	combined
HL-LHC	100-200%	50%	50%
$\text{ILC}_{250}/\text{C}^3\text{-}250$	49%	–	49%
$\text{ILC}_{500}/\text{C}^3\text{-}550$	38%	20%	20%
CLIC_{380}	50%	–	50%
CLIC_{1500}	49%	36%	29%
CLIC_{3000}	49%	9%	9%
FCC-ee	33%	–	33%
FCC-ee (4 IPs)	24%	–	24%
FCC-hh	-	2.9-5.5%	2.9-5.5%
μ(3 TeV)	-	15-30%	15-30%
μ(10 TeV)	-	4%	4%

Stress Test of the SM



Key physics studies of the EF program

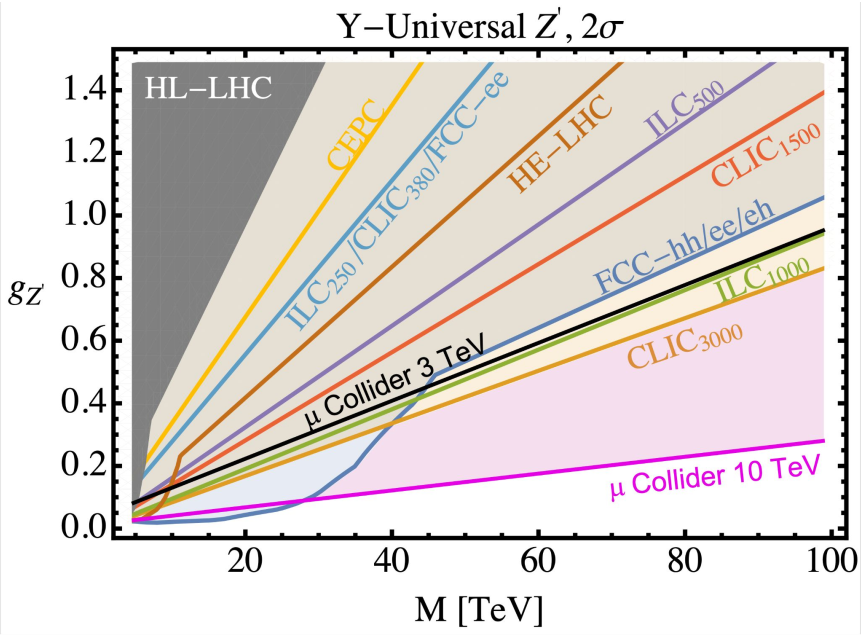
Aim to build a complete program of BSM searches via both model-specific and model independent explorations

- 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.

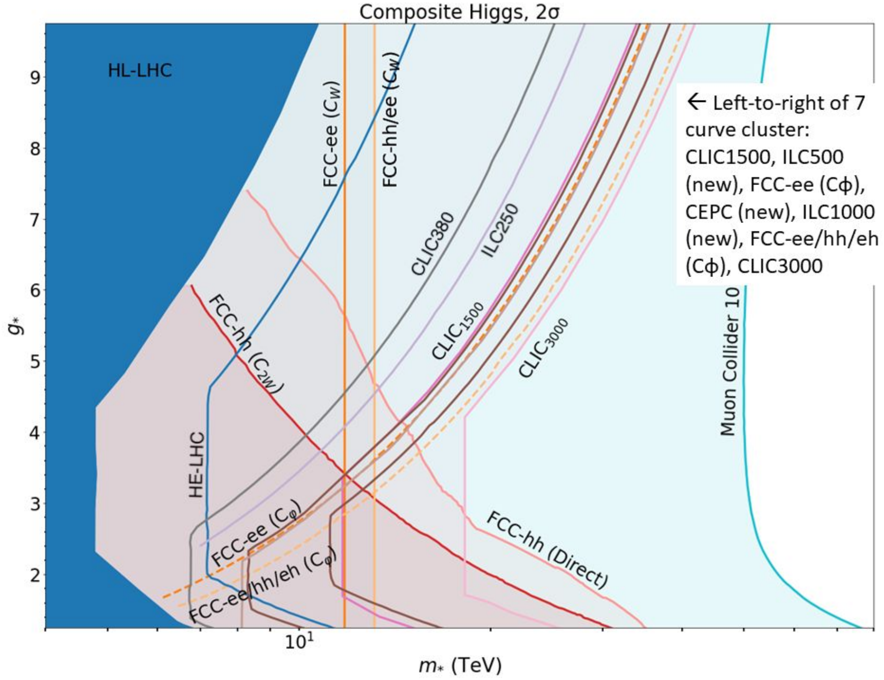
➢ **See BSM Topical Group Reports**

Examples of BSM explorations at colliders

Heavy Boson (Z') model

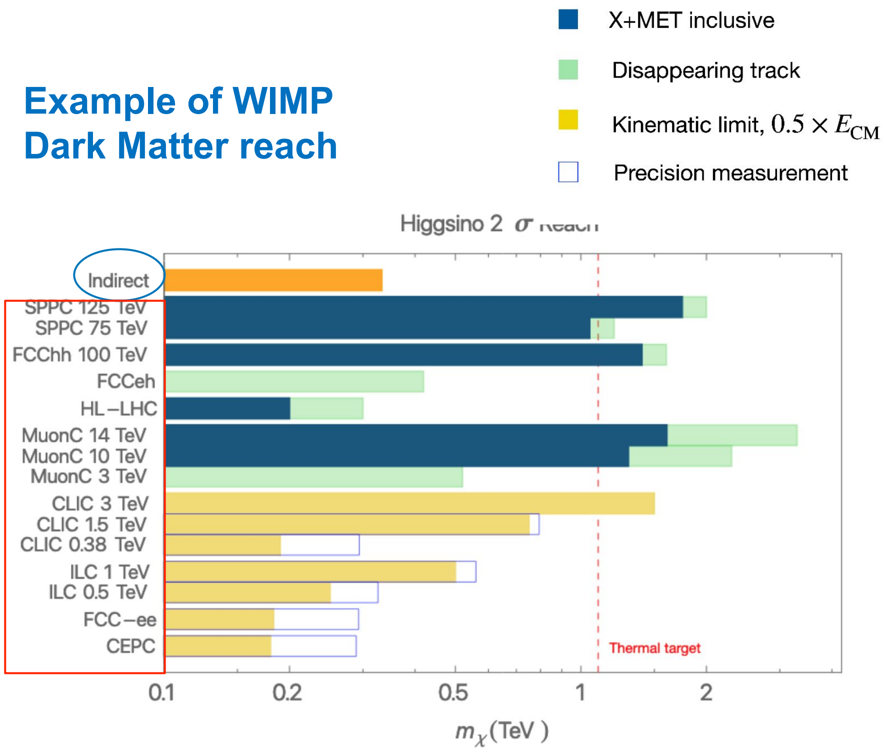


Composite Higgs models



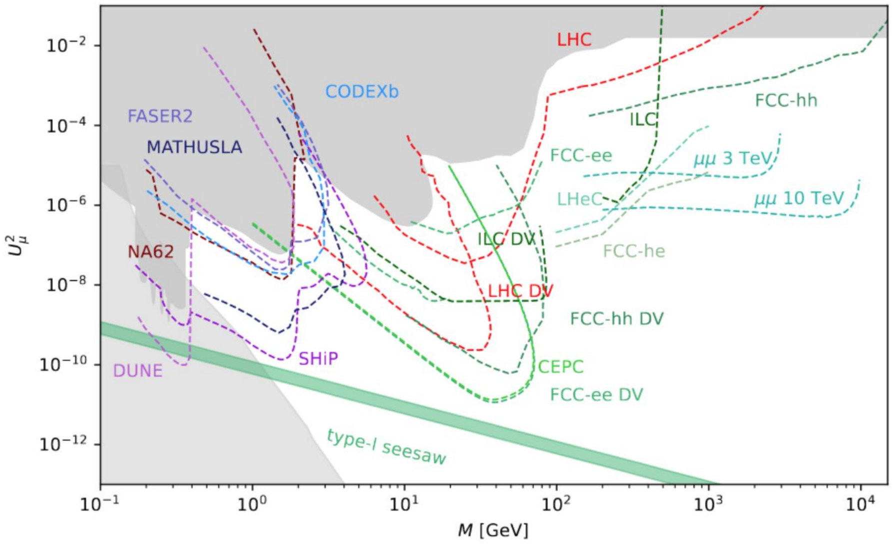
Complementarity of collider physics

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 α_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**

TeraZ statistics allows unprecedented precision in α_s and can provide evidence of BSM

	Relative $\alpha_s(m_Z)$ uncertainty	
Method	Current	Near (long-term) future
(1) Lattice	0.7%	$\approx$ 0.3% (0.1%)
(2) τ decays	1.6%	$<$ 1.%
(3) $Q\overline{Q}$ bound states	3.3%	$\approx$ 1.5%
(4) DIS & PDF fits	1.7%	$\approx$ 1% (0.2%)
(5) e^+e^- jets & evt shapes	2.6%	$\approx$ 1.5% ($<$ 1%)
(6) Electroweak fits	2.3%	($\approx$ 0.1%)
World average	0.8%	$\approx$ 0.4% (0.1%)

➢ **See QCD Topical Group Report**

The Energy Frontier vision in a nutshell

It is essential to

- **Complete the <u>HL-LHC program</u>,**
- **Start now a targeted program for <u>detector R&D for Higgs Factories</u>**
- **Support <u>construction of a Higgs factory</u>**
- **Ensure the long-term viability of the field by <u>developing a multi-TeV energy frontier facility</u> 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 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 recognizes the need for strong support to the Accelerator Frontier for the above requests.**