

Energy Frontier Vision

[Cool Copper Collider Session]

Snowmass Community Summer Study (CSS)

Seattle, July 17-26, 2022

Laura Reina (FSU), [Meenakshi Narain \(Brown U.\)](#), Alessandro Tricoli (BNL)

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

Energy Frontier: explore the TeV energy scale and beyond

Aims at advancing the investigation of still open fundamental questions
and exploring the unknown.

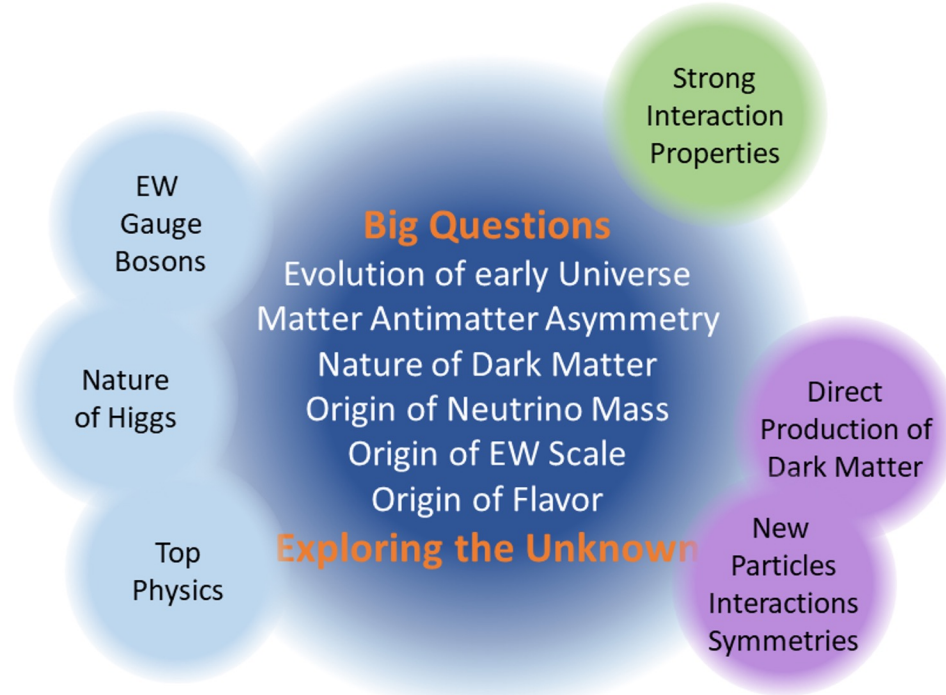
Big Questions

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

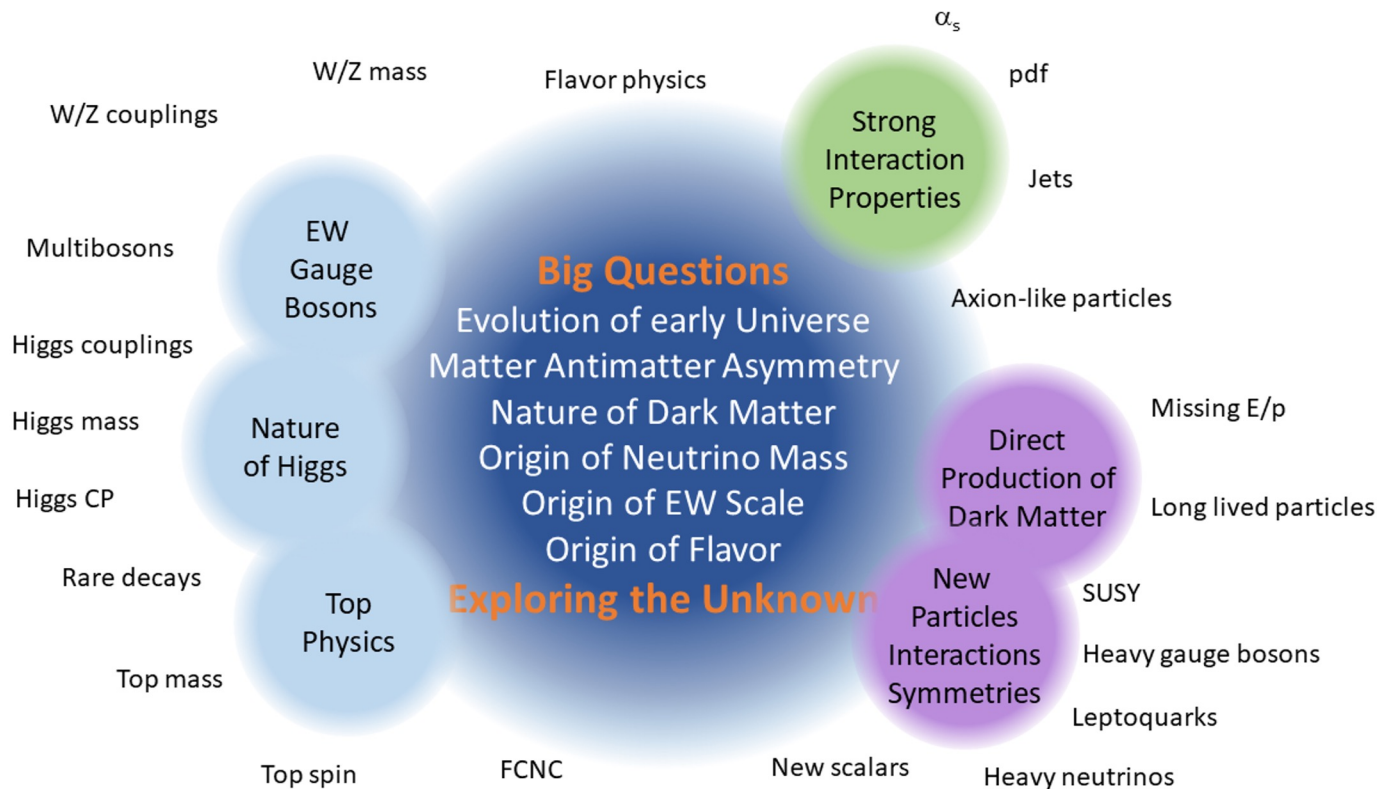
Energy Frontier: explore the TeV energy scale and beyond

Each question manifests as a variety of processes, that can be used as probes to discover and characterize the nature of the new physics



Energy Frontier: explore the TeV energy scale and beyond

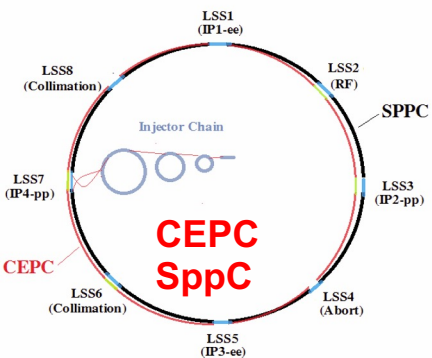
Through the breadth and multitude of collider physics signatures



Energy Frontier: explore the TeV energy scale and beyond

- Addressing the “Big Questions” need EF explorations to proceed along two main complementary directions:
 - **Study known phenomena at high energies for indirect evidence of BSM physics**
 - **Search for direct evidence of BSM physics at the energy frontier**
- The Energy Frontier is at a turning point, in which experimental guidance is needed to shed light on new physics beyond the SM.
 - The HL-LHC is the approved short-term project with a potential to shed light on BSM physics directly through searches and indirectly via precision measurements of the Higgs boson and all SM parameters.
 - During this Snowmass, the focus of the discussion is to identify projects and machines which extend the reach of the HL-LHC in terms of precision measurements and direct searches.
 - Preparations for the next collider experiments beyond the HL-LHC have to start now to maintain and to strengthen the vitality and motivation of the community.

Which machines?



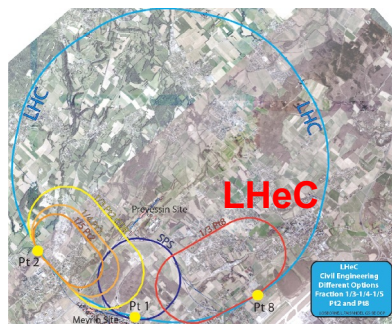
Hadrons

- 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)
- ▶ only pdf access to \sqrt{s}
- \Rightarrow couplings to quarks and gluons

Circular

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

Christophe Grojean



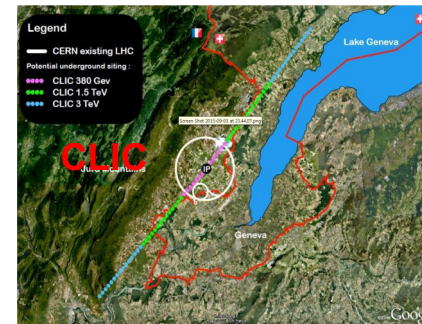
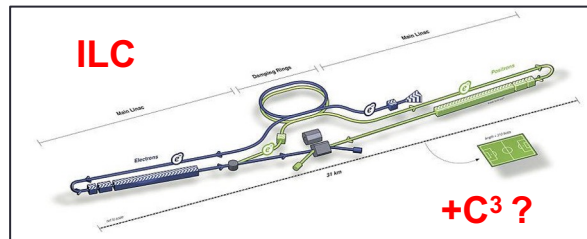
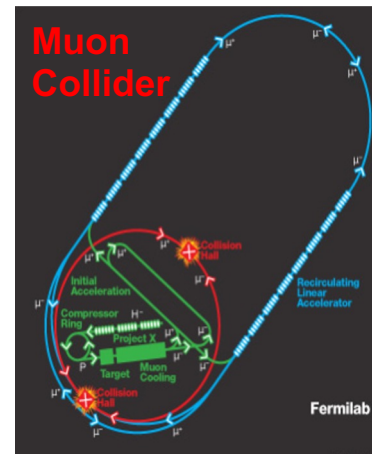
*energy consumption per integrated luminosity is lower at circular colliders but the energy consumption per GeV is lower at linear colliders
Future Measurements 9 Inst. Pascal, Dec. 4, 2019

Leptons

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

Linear

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



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

Collider	Type	\sqrt{s}	$\mathcal{P}[\%]$ e^-/e^+	\mathcal{L}_{int} ab^{-1}
HL-LHC	pp	14 TeV		6
ILC and C ³ c.o.m almost similar	ee	250 GeV	$\pm 80 / \pm 30$	2
		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
CEPC	ee	M_Z		60
		$2M_W$		3.6
		240 GeV		20
		360 GeV		1
FCC-ee	ee	M_Z		150
		$2M_W$		10
		240 GeV		5
		$2 M_{\text{top}}$		1.5
muon-collider (higgs)	$\mu\mu$	125 GeV		0.02

Snowmass 2021: EF Benchmark Scenarios

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

Collider	Type	\sqrt{s}	$\mathcal{P}[\%]$ e^-/e^+	\mathcal{L}_{int} ab^{-1}
HE-LHC	pp	27 TeV		15
FCC-hh/SppC	pp	100 TeV		30
LHeC FCC-eh	ep	1.3 TeV		1
		3.5 TeV		2
CLIC	ee	1.5 TeV	$\pm 80 / 0$	2.5
		3.0 TeV	$\pm 80 / 0$	5
High energy muon-collider	$\mu\mu$	3 TeV		1
		10 TeV		10

The Energy Frontier vision

- **Collider physics allows to explore a uniquely broad range of phenomena**
- **To cover the diversity of the program, we need to provide opportunities to go beyond existing frameworks**
- The Energy Frontier aims to facilitate US leadership in an innovative, comprehensive, and international program of collider physics.
- The timescales to fully realize the Energy Frontier vision extend to the end of this century, and the ultimate goals can only be realized if our actions foster a vibrant, diverse, and intellectually rich US Energy Frontier community.
 - Building such a community is only possible if our plans reflect the aspirations of and provide a rich and continuous string of opportunities for Early Career physicists.
- **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 its scientific potential by collecting at least 3 ab^{-1} of data.
- **The physics case is very strong:**
 - It extend the direct search for new elementary particles
 - It measure 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 provide the best measurements of top-quark couplings beyond the reach of the first generation of future colliders
 - 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 the completion of the detector upgrades, operations of the detectors, data taking and analysis, 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 rests 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 SM (W,Z,t,H) to very high precision and stress test its consistency
 - Perform precision measurements of QCD as tests of QFT in both perturbative and non-perturbative regimes.
- **The e^+e^- colliders** are the vehicle that will enable the above program, and can be essentially realized with current technology.
- It is important to realize at least one **e^+e^- Higgs factory** 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 envisions 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 rests 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 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.
- The US EF community proposes to some options which are considered as **attractive opportunities** for building a domestic EF collider program
 - **A US-sited linear e^+e^- collider (ILC/CCC)**
 - **New CCC proposal gained momentum during Snowmass 21 (~25% authors EC)**
 - **Hosting a 10-TeV range Muon Collider**
 - **More than 40 contribute papers on MuC studies during Snowmass 21 (~50% of authors are early career physicists (61 people))**
 - **Exploring other e^+e^- collider options to fully utilize the Fermilab site**
- Bold “new” project such as a linear e^+e^- Cool Copper Collider, and a muon collider will offer the next generation some challenges to rise to.
 - It will inspire more young people from the US to join HEP and in the long term help with strengthening the vibrancy of the field.

EF Colliders: The CCC proposal

- The proposals and R&D efforts to address the innovative detector developments for Higgs factories are well underway globally and many challenges are resolved.
- The CCC proposal offers
 - Cost reduction options to the ILC
 - Facilitates the energy upgrade, and extends the energy reach to 2 TeV
- Targeted accelerator R&D for CCC, is very important in the near term.
- Since this is Snowmass CSS, as a community it is important for us to discuss:
 1. What is the plan of the ILC community to incorporate and support the R&D for CCC [while waiting a decision from Japan to host the ILC
 1. Lowering costs of proposed projects should be the continual goal
 2. Plans for siting an ILC+CCC option in the US – location, costs [R&D and construction]
 3. Develop plans for ILC/CCC at CERN

[my personal point of view: points 2 and 3 above are alternate strategies which should be encouraged as no e⁺e⁻ Higgs factory option has been decided, and we have to be ready for any contingencies.]

Energy Frontier Resource needs 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 Collider in the US, with pre-CDR document 2760 at the end of this period,
 - Support critical detector R&D towards EF multi-TeV colliders
- **Five year period starting in 2030**
 - Continue strong support for HL-LHC physics program
 - Support construction of an e+e- Higgs Factory
 - Demonstrate principal risk mitigation and deliver CDR for a first-stage TeV-scale Muon Collider
- **Beyond 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 Muon Collider
 - 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.**
- **Strong collaboration with the Theory Frontier is key to the success of both frontiers.**

Backup

Energy Frontier Machines

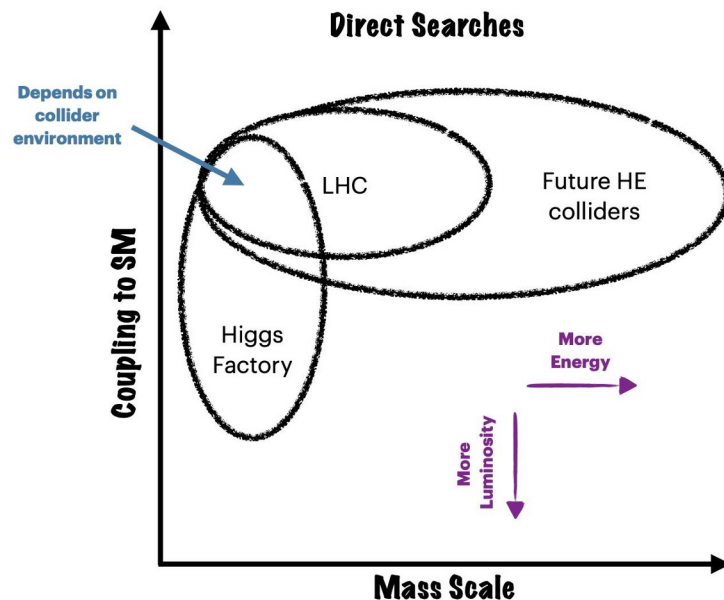
- Discoveries at the Energy Frontier are intricately linked to new accelerators, detector instrumentation, advances in theory (including calculation tools), and innovative analysis technologies and frameworks.
- Goals of the next Energy Frontier Machines:
 - **Look for indirect evidence of BSM physics**
 - 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**
- A clear path towards the identification of the next collider project has to be well supported by the US and international community as a whole.

Energy Frontier Machines: energy and precision

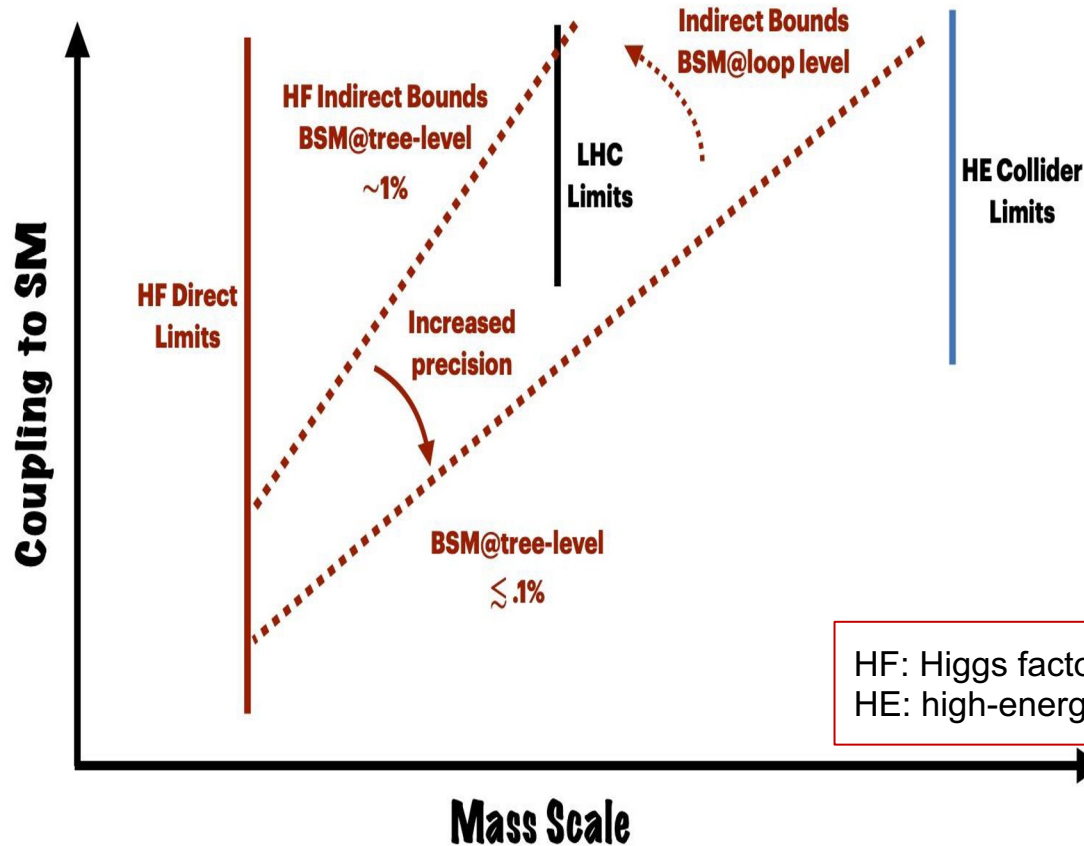
New physics can be at low and at high mass scales: Naturalness would prefer mass scale close to the EW scale, but direct searches of specific models have placed stronger bounds around 1-2 TeV.

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.



Direct and Indirect Limits



In a simplified picture:

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

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

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

Big Picture Questions set at the beginning of Snowmass

Snowmass Day, Sept 24, 2021

- Why is physics at the energy frontier important?
- How should the US be involved in near future and far future energy-frontier machines after HL-LHC?
- What could be the energy-frontier machines that follow the HL-LHC?
- How can the US continue to play a leadership role in energy-frontier experiments?
- How can the Snowmass process help develop a plan for the energy-frontier research and convince the community about our priorities?
- Should we start entertaining the idea of a future collider in the US again? If so, what are our goals, the benefits for the US and the international community, and how can we get there?
- etc...