Energy Frontier - Vision

Snowmass Community Summer Study (CSS)

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

P5 now and then

Among **existing P5 physics drivers**, the following are **directly related to EF proposed vision**

- Use the **Higgs boson as a new tool for discovery**
- **Explore the unknown**: new particles, interactions, and physical principles
- Identify the new physics if **dark matter**

Compared to last P5 the **EF is now at turning point** for which **the exploration of the 1-10 TeV scale becomes crucial to shed light on physics beyond the Standard Mode**l

➢ **The HL-LHC is the approved short-term project** with the potential to shed light on BSM physics directly through searches and indirectly via precision measurements of the Higgs boson and all SM parameters.

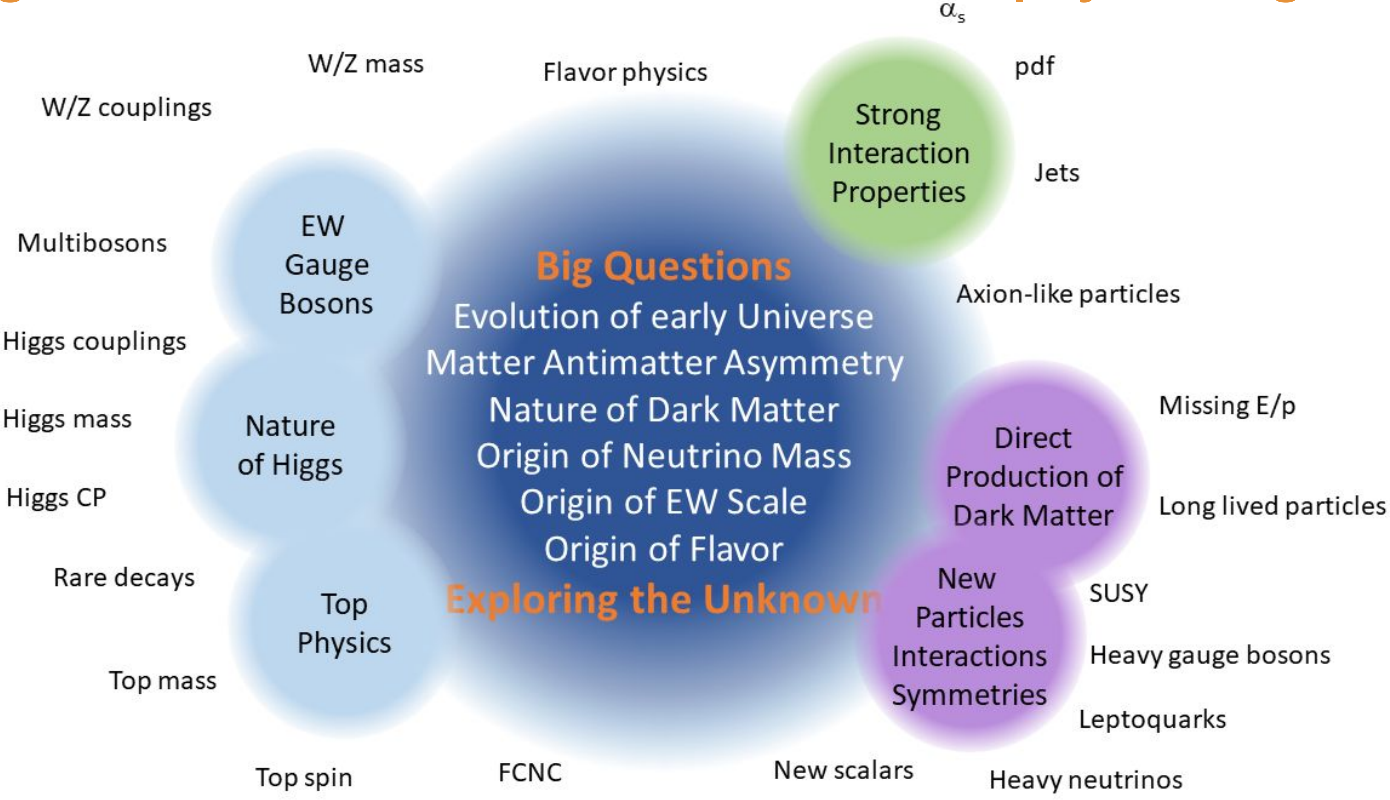
➢ During this **Snowmass** the focus of the discussion is to **identify projects and machines that will extend the reach of the HL-LHC** is terms of precision and direct searches.

➢ **Preparations for the next collider** experiments beyond the HL-LHC **have to start now** to maintain and strengthen the vitality and motivation of the community.

P5 should also consider new drivers to enhance the science: **advancement of a diverse and inclusive workforce** (diverse backgrounds, diverse expertise, different career levels)

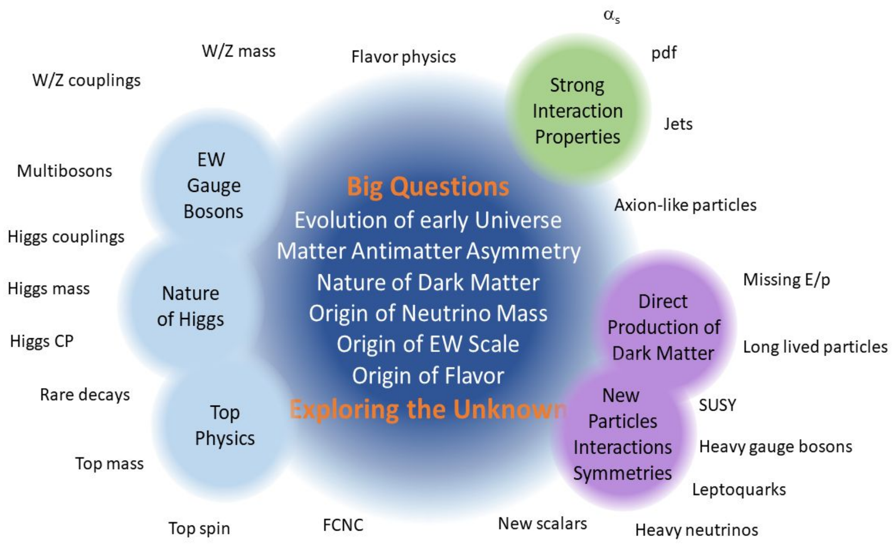
Energy Frontier: explore the TeV energy scale and beyond

Through the breadth and multitude of collider physics signatures



Addressing the “**Big Questions**” and “**Exploring the unknown**” are the main scientific goals of the EF

to be pursued following



Two main avenues

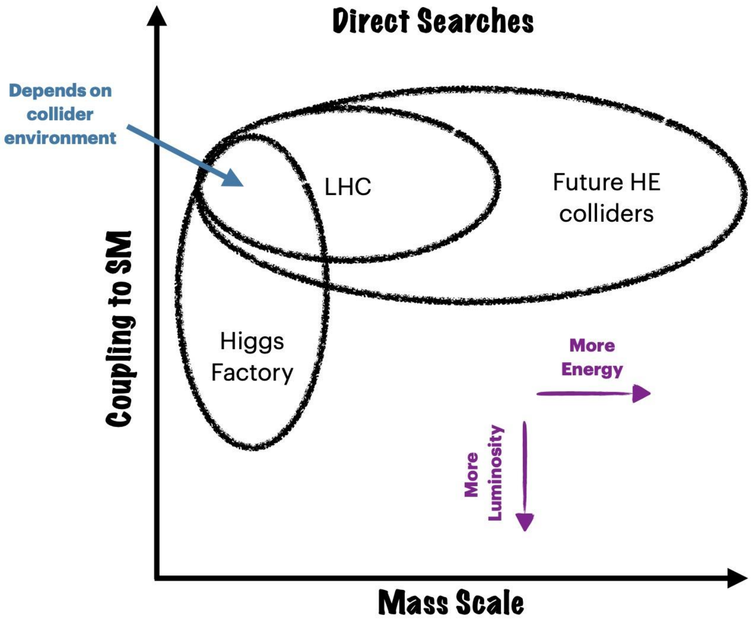
- ➢ **Study known phenomena at high energies looking for indirect evidence of BSM physics**
  - ○ Need **factories of Higgs bosons** (and other SM particles) to probe the TeV scale via precision measurements
- ➢ **Search for direct evidence of BSM physics at the energy frontier**
  - ○ Need to directly reach the **multi-TeV scale**

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 to push beyond the 1 TeV scale



Snowmass 2021: EF Benchmark Scenarios

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

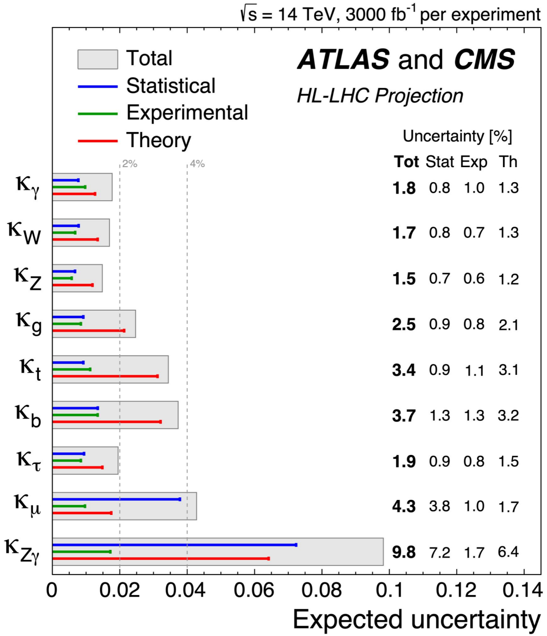
Collider	Type	$\sqrt{s}$	$\mathcal{P}[\%]$ e^-/e^+	$\mathcal{L}_{\rm int}$ ab^{-1}/IP	Start Date Const.	Start Date Physics
HL-LHC	pp	14 TeV		3		2027
ILC & C^3	ee	250 GeV	$\pm 80/\pm 30$	2	2028	2038
		350 GeV	$\pm 80/\pm 30$	0.2		
		500 GeV	$\pm 80/\pm 30$	4		
		1 TeV	$\pm 80/\pm 20$	8		
CLIC	ee	380 GeV	$\pm 80/0$	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		

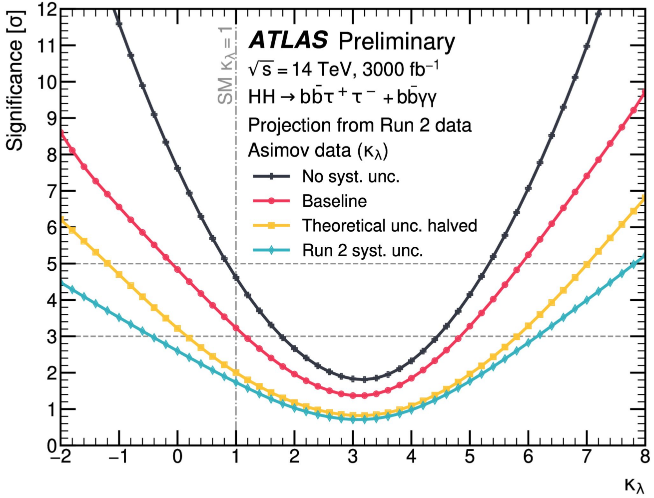
Timelines are taken from the ITF report (AF)

The physics case of the HL-LHC is very strong

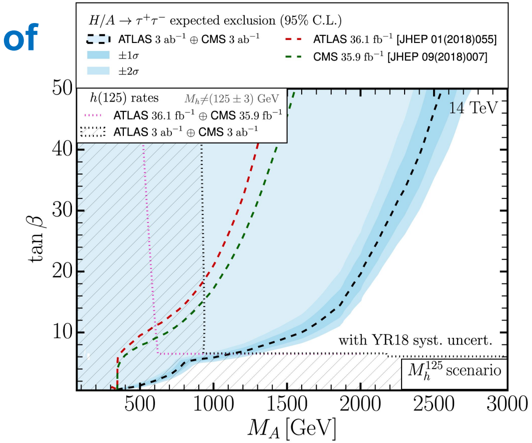


Sensitive to BSM physics in measure of Higgs couplings

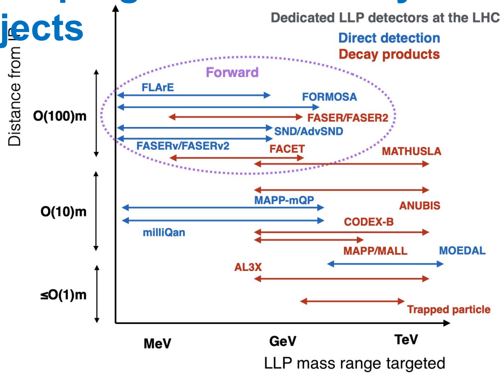
First bounds on Higgs self-coupling



Extended reach of BSM searches

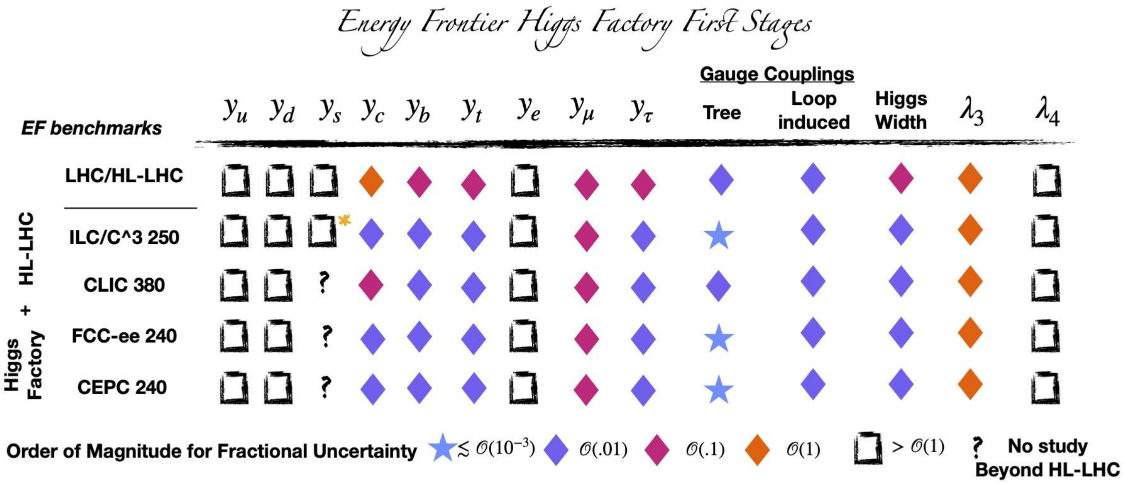


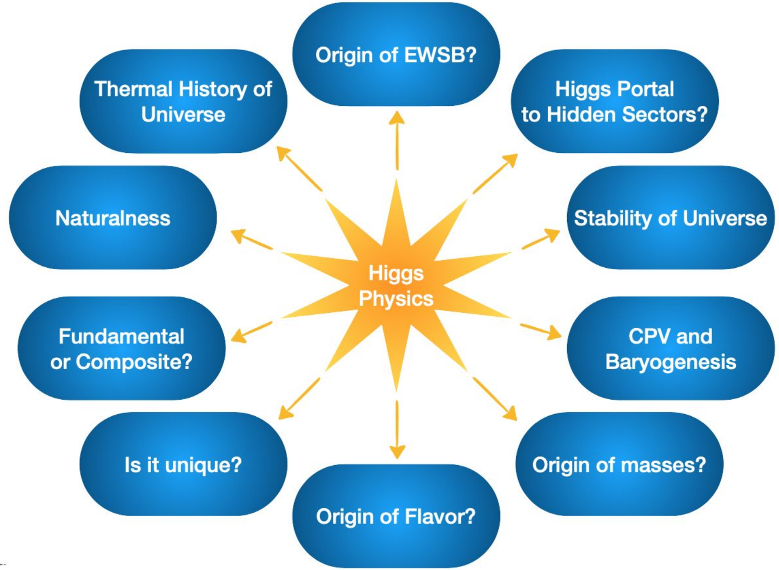
Broad program of auxiliary projects



Pushing the Higgs-boson precision program is crucial

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

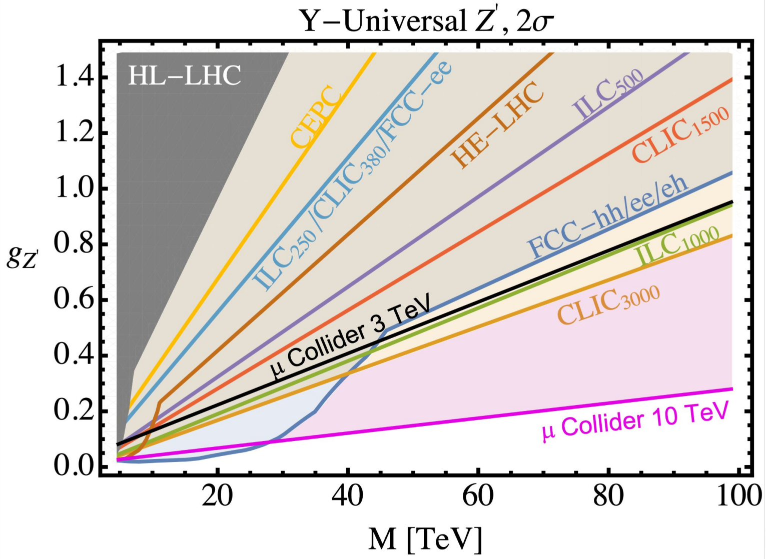




Higgs Factories

- Higgs couplings at sub-percent level
- Search for exotic Higgs decays
- Explore Higgs portal to hidden sector
- Stress-test consistency of the SM
- Direct access to low-mass/weak-coupling BSM

Multi-TeV colliders: the ultimate exploration

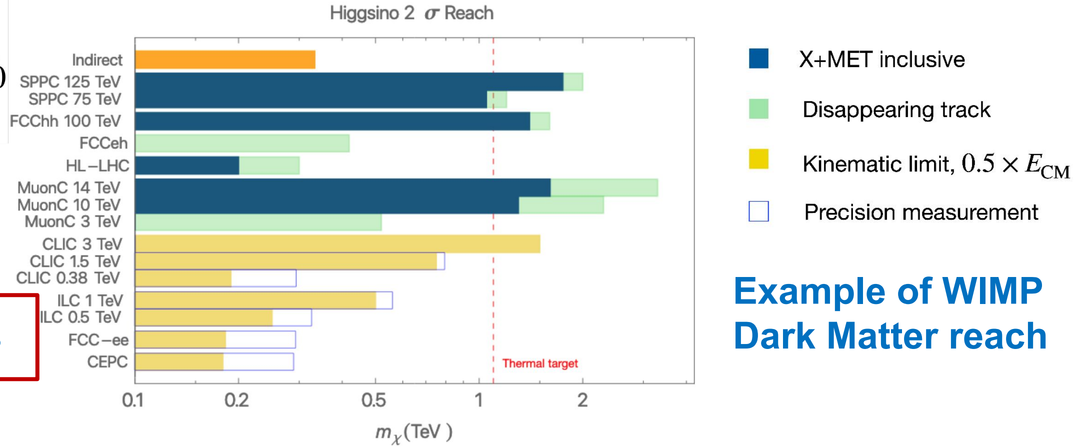


Example: Heavy Boson (Z') models

Greatly extend the reach of BSM scenarios

Higgs self-coupling at few %

collider	Indirect-h	hh	combined
HL-LHC	100-200%	50%	50%
ILC_{250}/C^3-250	49%	–	49%
ILC_{500}/C^3-550	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%



Example of WIMP Dark Matter reach

EF Vision

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.**
- **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
- **For the next decade and beyond**
  - **2025-2030**: Prioritize HL-LHC physics program, including auxiliary experiments
  - **2030-2035**: Continue strong support for HL-LHC physics program
  - **After 2035**: Support continuing the HL-LHC physics program to the conclusion of archival measurements

The intermediate future is an e^+e^- Higgs factory

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 various proposed facilities have a strong core of common physics goals**: it is important to **realize at least one somewhere in the world.**
- **A fast start towards construction is important**. There is **strong US support** for initiatives that could be realized on a time scale relevant for early career physicists.
- **For the next decade and beyond**
    - **2025-2030**: Establish a targeted e^+e^- Higgs Factory detector R&D for US participation in a global collider
    - **2030-2035**: Support and advance construction of an e^+e^- Higgs Factory
    - **After 2035**: Begin and support the physics program of an e^+e^- Higgs Factory

The long-term future is a multi-TeV collider

- 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.**

- **For the next decade and beyond**
  - **2025-2030**:
    - Develop an initial design for a first stage TeV-scale Muon Collider in the US (pre-CDR)
    - Support critical detector R&D towards EF multi-TeV colliders

  - **2030-2035**: Demonstrate principal risk mitigation and deliver CDR for a first-stage TeV-scale Muon Collider

  - **After 2035**:
    - 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 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.

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

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

The Energy Frontier vision in a nutshell

It is essential to

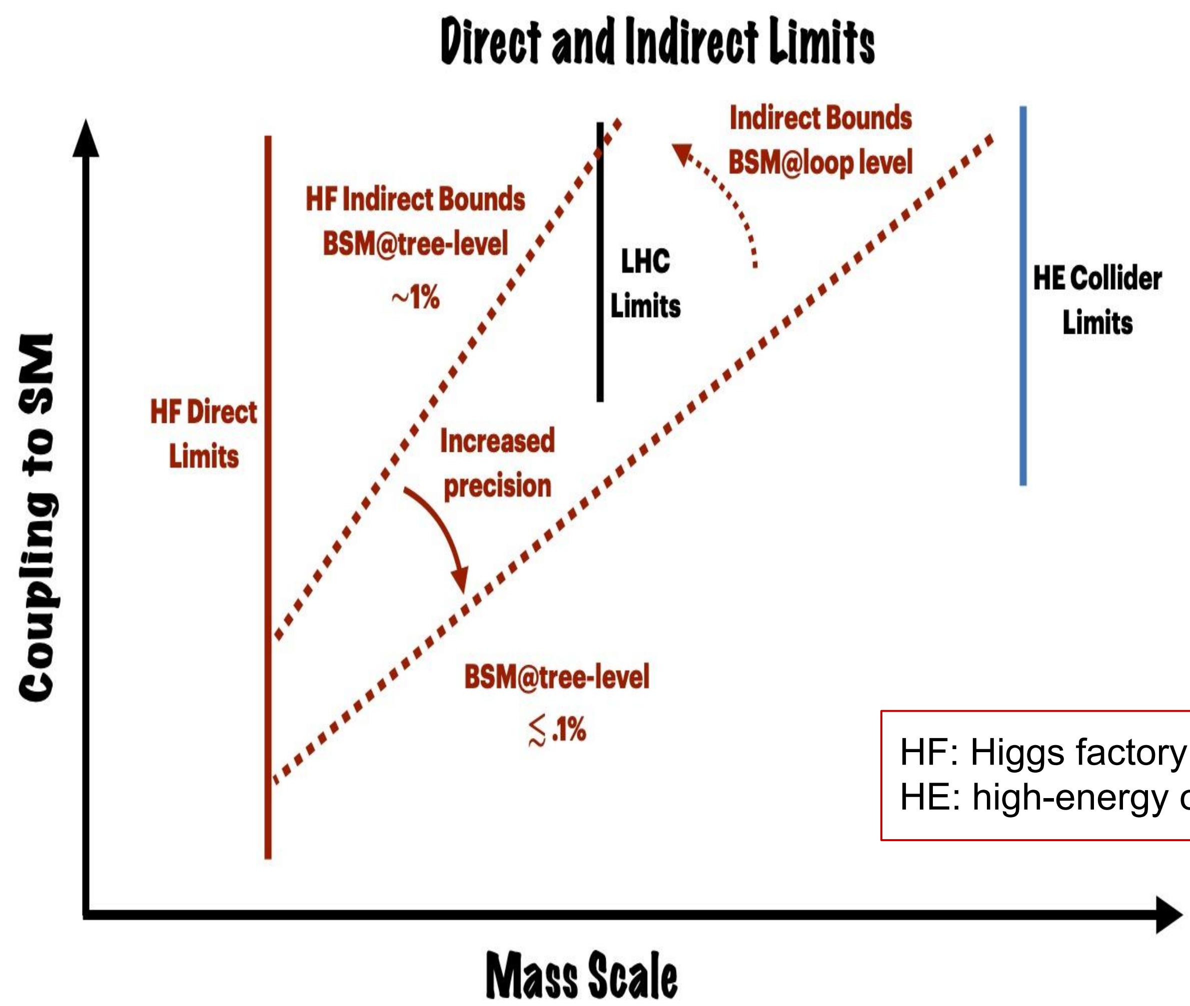
- **Complete the HL-LHC program,**
- **Start now a targeted program for detector R&D for Higgs Factories**
- **Support a fast start of the construction of a Higgs factory**
- **Ensure the long-term viability of the field by developing a multi-TeV energy frontier facility such as a *muon collider* or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

Support to AF, CEF, CompF, IF, and TF is crucial to the realization of the EF vision

Backup

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 and advance *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*



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

Reach of Higgs factories (integrated staging)