Energy Frontier - Vision

Higgs Hunting 2022

Sep 12-14, 2022

Meenakshi Narain (Brown U.)

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

DPF Community Planning Exercise - aka Snowmass

- The charge of the Snowmass Process:
  "define the most important questions in the field of particle physics and identify promising opportunities to address them."
- Timescale:
  Planning for 2025-2035 with a view toward 2050
- Sponsored by Division of Particles and Fields of the American Physical Society

The Range of Snowmass Discussion

There are **ten** Snowmass Frontiers spanning **scientific areas** of particle physics addressing fundamental questions about the universe, and **technical areas** which enable scientific work

Accelerator Frontier

Energy Frontier

Rare Processes and Precision

Instrumentation Frontier

Undergrounds Facitities

Cosmic Frontier

Neutrino Frontier

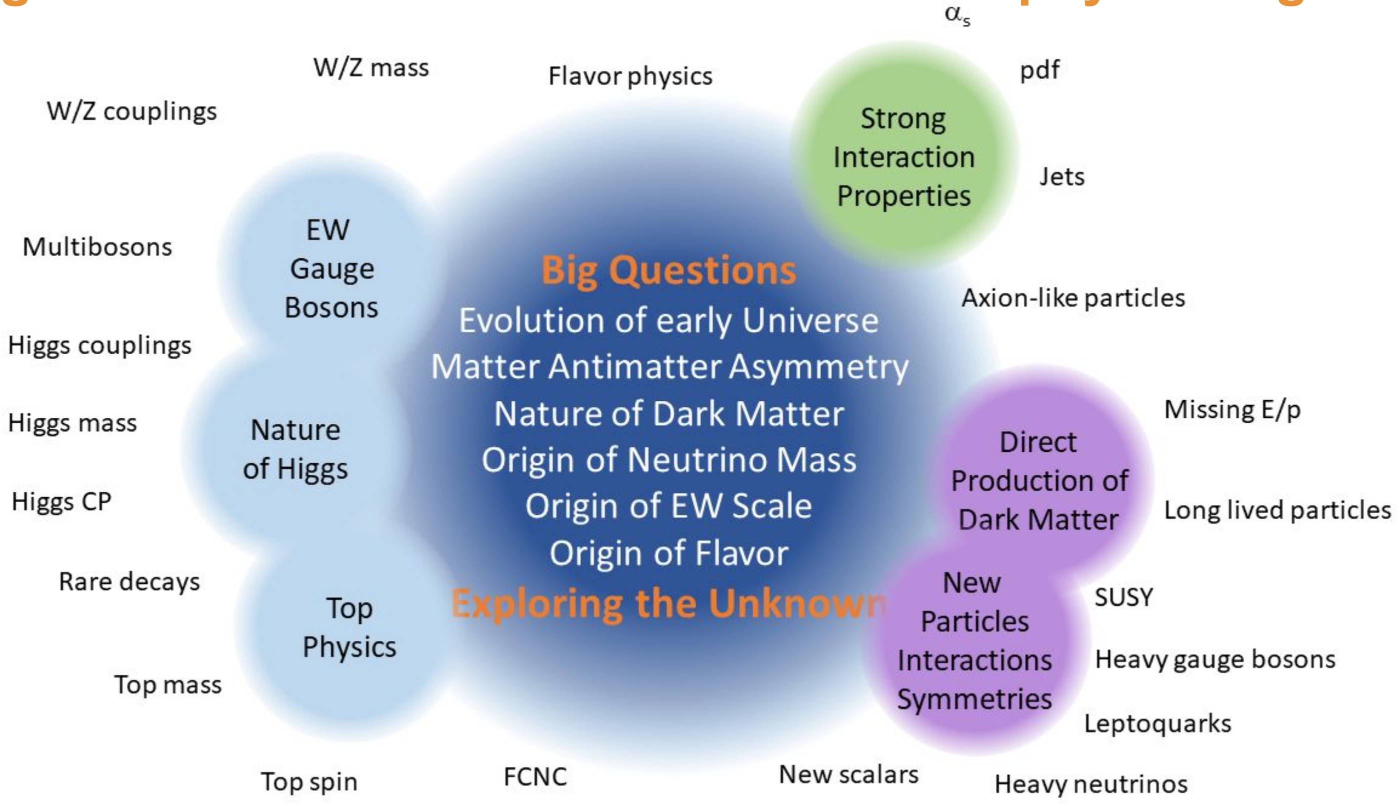
Computational Frontier

Theory Frontier

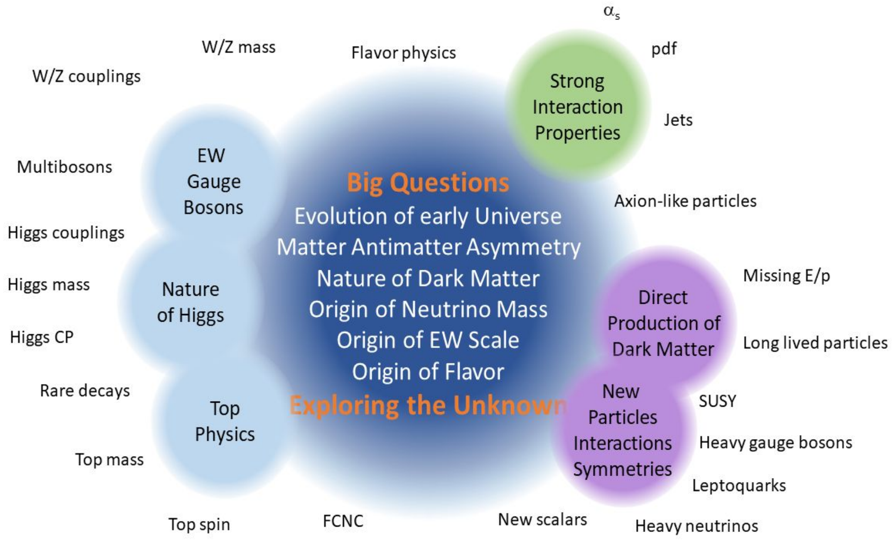
Community Engagement Frontier

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 Topical Groups

Ten Topical Groups focused on **Electroweak**, **QCD**, **BSM physics** **established in May 2020**

Topical Group	Co-Conveners		
EF01: EW Physics: Higgs Boson properties and couplings	Sally Dawson (BNL)	Caterina Vernieri (SLAC)	
EF02: EW Physics: Higgs Boson as a portal to new physics	Patrick Meade (Stony Brook)	Isobel Ojalvo (Princeton)	
EF03: EW Physics: Heavy flavor and top quark physics	Reinhard Schwienhorst (MSU)	Doreen Wackeroth (Buffalo)	
EF04: EW Physics: EW Precision Physics and constraining new physics	Alberto Belloni (Maryland)	Ayres Freitas (Pittsburgh)	Junping Tian (Tokyo)
EF05: QCD and strong interactions: Precision QCD	Michael Begel (BNL)	Stefan Hoeche (FNAL)	Michael Schmitt (Northwestern)
EF06: QCD and strong interactions: Hadronic structure and forward QCD	Huey-Wen Lin (MSU)	Pavel Nadolsky (SMU)	Christophe Royon (Kansas)
EF07: QCD and strong interactions: Heavy Ions	Yen-Jie Lee (MIT)	Swagato Mukherjee (BNL)	
EF08: BSM: Model specific explorations	Jim Hirschauer (FNAL)	Elliot Lipeles (UPenn)	Nausheen Shah (Wayne State)
EF09: BSM: More general explorations	Tulika Bose (U Wisconsin-Madison)	Zhen Liu (Maryland)	Simone Griso (LBL)
EF10: BSM: Dark Matter at colliders	Caterina Doglioni (Lund)	LianTao Wang (Chicago)	Antonio Boveia (Ohio State)

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.

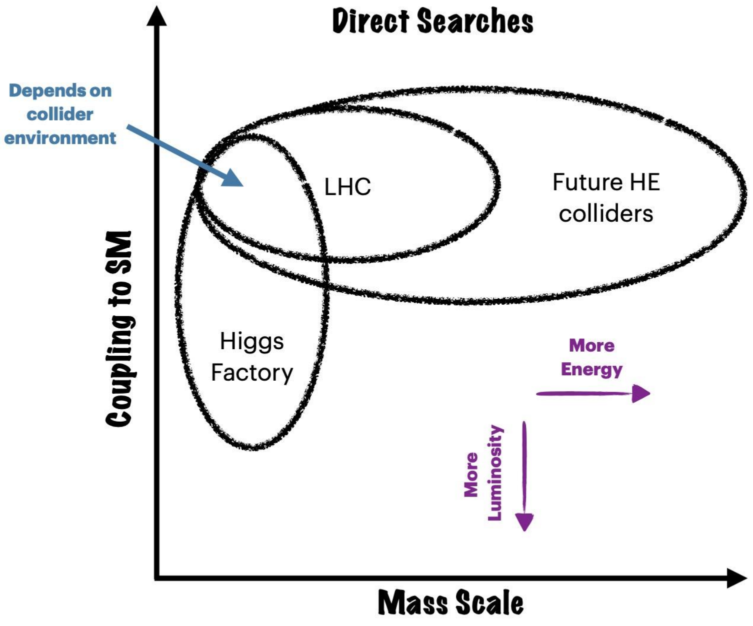
Other specific dedicated meetings can be found on EF/AF Snowmass websites.

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.

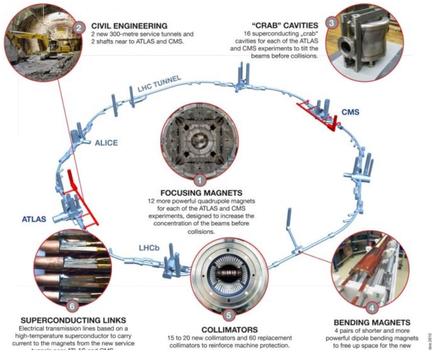
We need to use both energy and precision to push beyond the 1 TeV scale

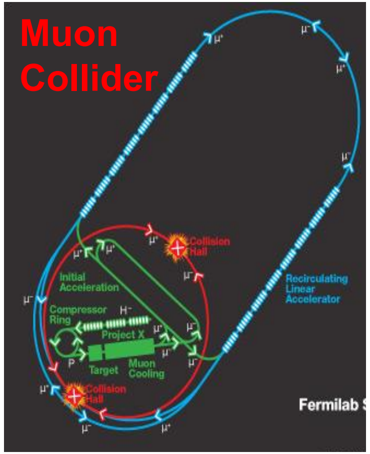


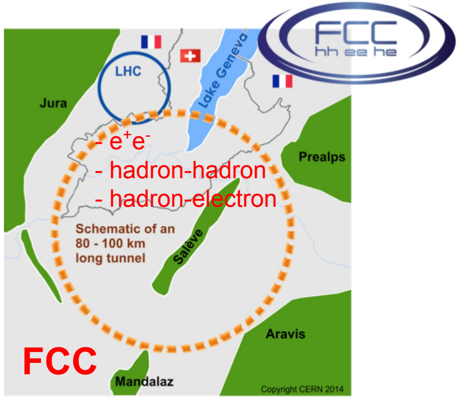
Which machines?

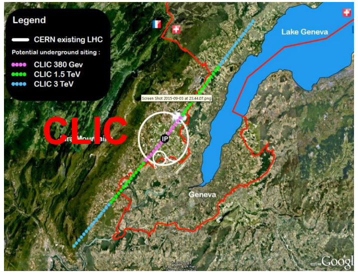
- **Looking for indirect evidence of BSM physics**
  - Need **factories of Higgs bosons** (and other SM particles) to probe the TeV scale via precision measurements
- **Search for direct evidence of BSM physics at the energy frontier**
  - Need to directly reach the **multi-TeV scale**

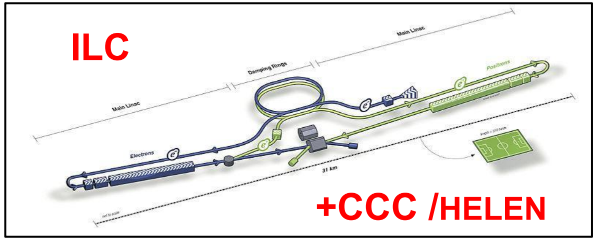
HL-LHC

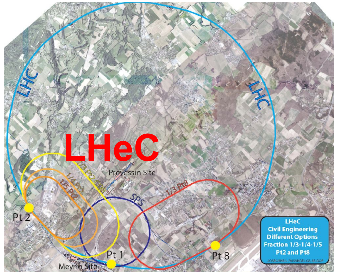


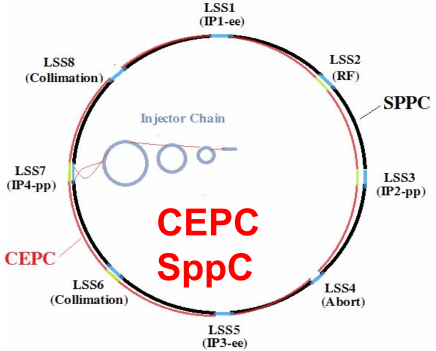








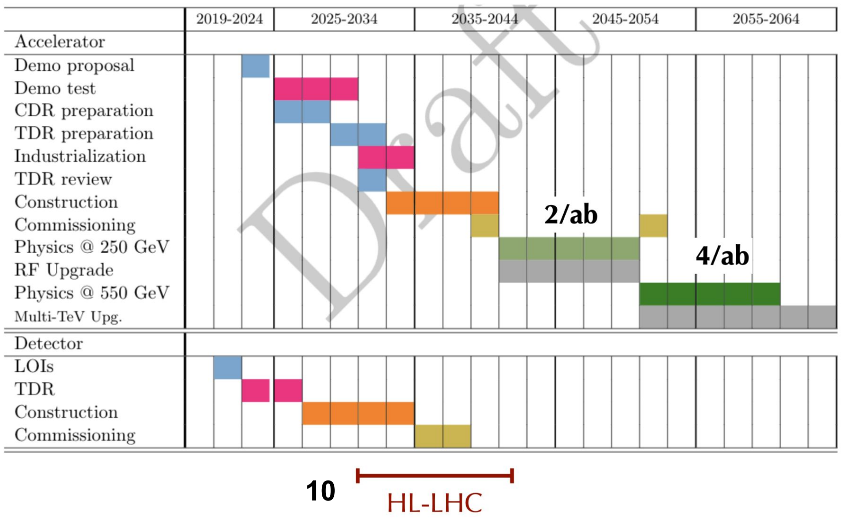




C3 - Cool Copper Collider

- Based on a new SLAC technology
- Two Key Technical Advances:
  - Distributed Coupling & Cryo-Copper RF
- Operation at cryogenic temperatures
  - (LN2 ~80K)
- Robust operations at high gradient:
  - 120~MeV/m

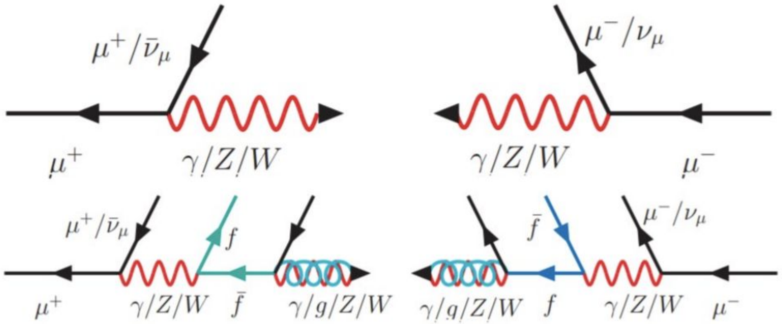
C³ timeline

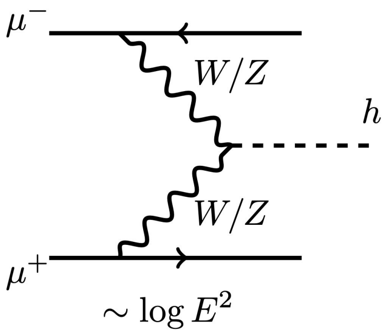


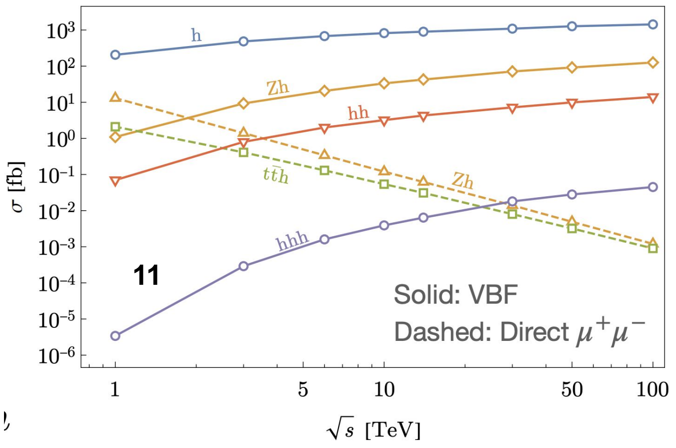
- Scalable to multi-TeV operation
- Operate at 250 and 550 GeV with possible commissioning at the Z pole

Muon Colliders

- First proposed more than 50 years ago, renewed interest in Muon Collider facilities in recent years, due to recent advances in technology!
- Muons do not suffer from energy loss due to Bremsstrahlung that makes e+e- circular machines difficult! But they do have a very short lifetime.
- Muon Colliders are actually EWK colliders with a mix of initial states







Snowmass 2021: EF Benchmark Scenarios

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

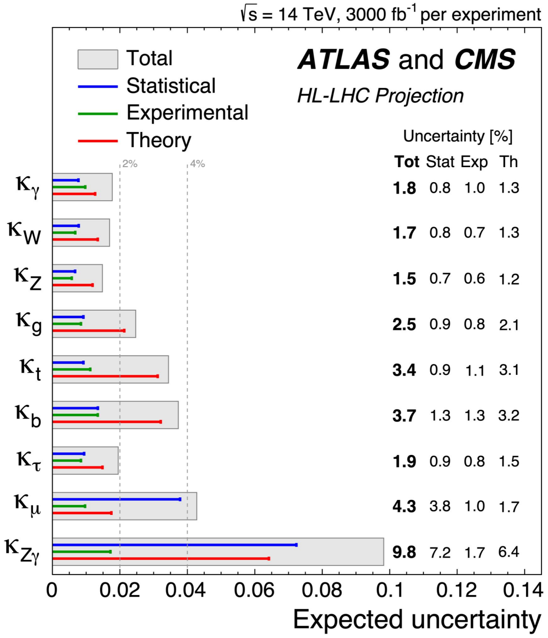
Collider	Type	$\sqrt{s}$	$\mathcal{P}[\%]$ e^-/e^+	$\mathcal{L}_{\text{int}}$ ab^{-1}/IP	Start Date Const.	Start Date Physics
HL-LHC	pp	14 TeV		3		2027
ILC & C^3	ee	250 GeV	$\pm 80/\pm 30$	2	2028	2038
		350 GeV	$\pm 80/\pm 30$	0.2		
		500 GeV	$\pm 80/\pm 30$	4		
		1 TeV	$\pm 80/\pm 20$	8		
CLIC	ee	380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

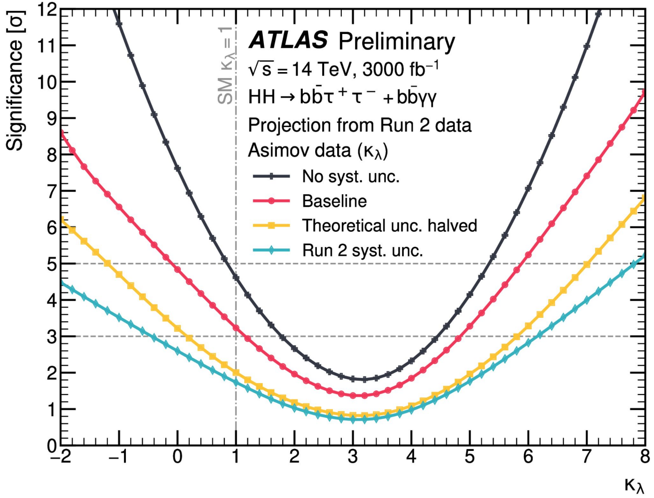
Timelines are taken from the ITF report (AF)

The physics case of the HL-LHC is very strong

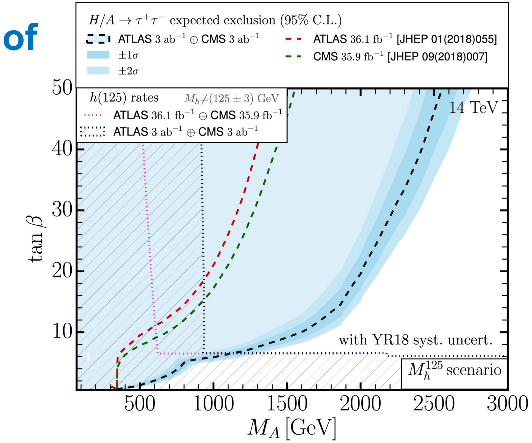


Sensitive to BSM physics in measure of Higgs couplings

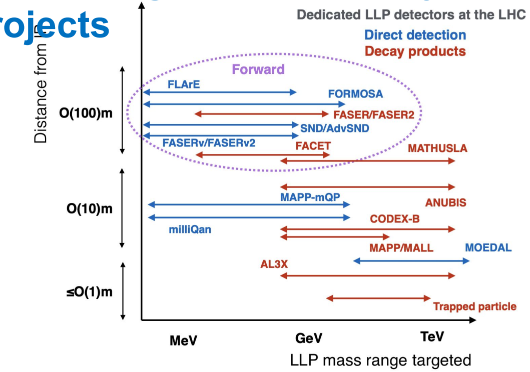
First bounds on Higgs self-coupling



Extended reach of BSM searches



Broad program of auxiliary projects

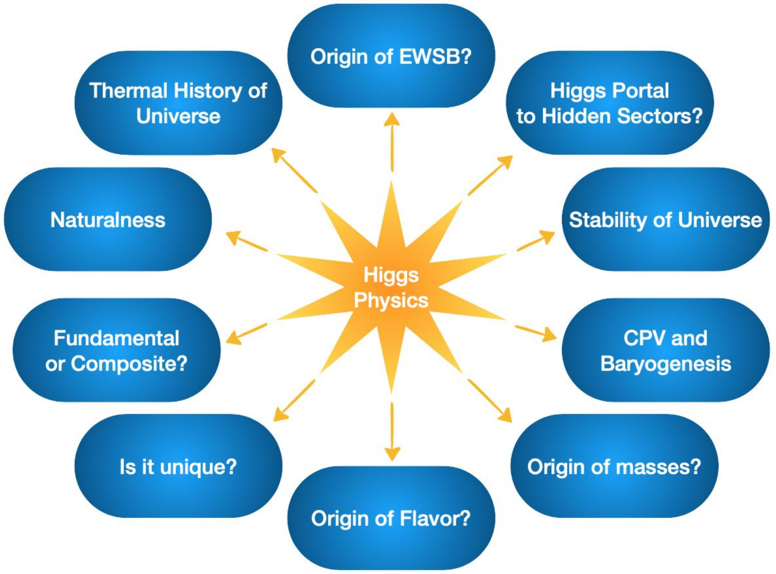


Pushing the Higgs-boson precision program is crucial

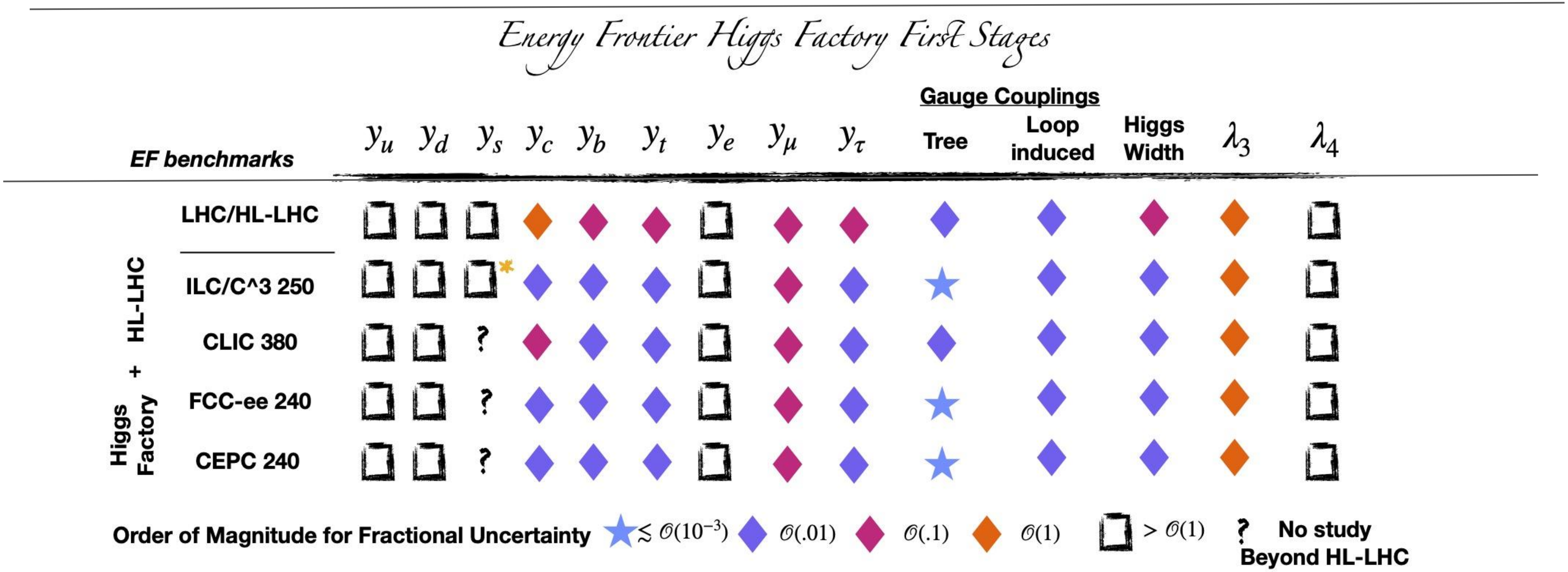
The Higgs discovery has given us a unique handle on BSM physics and any future plan needs to make the most out of it.

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**

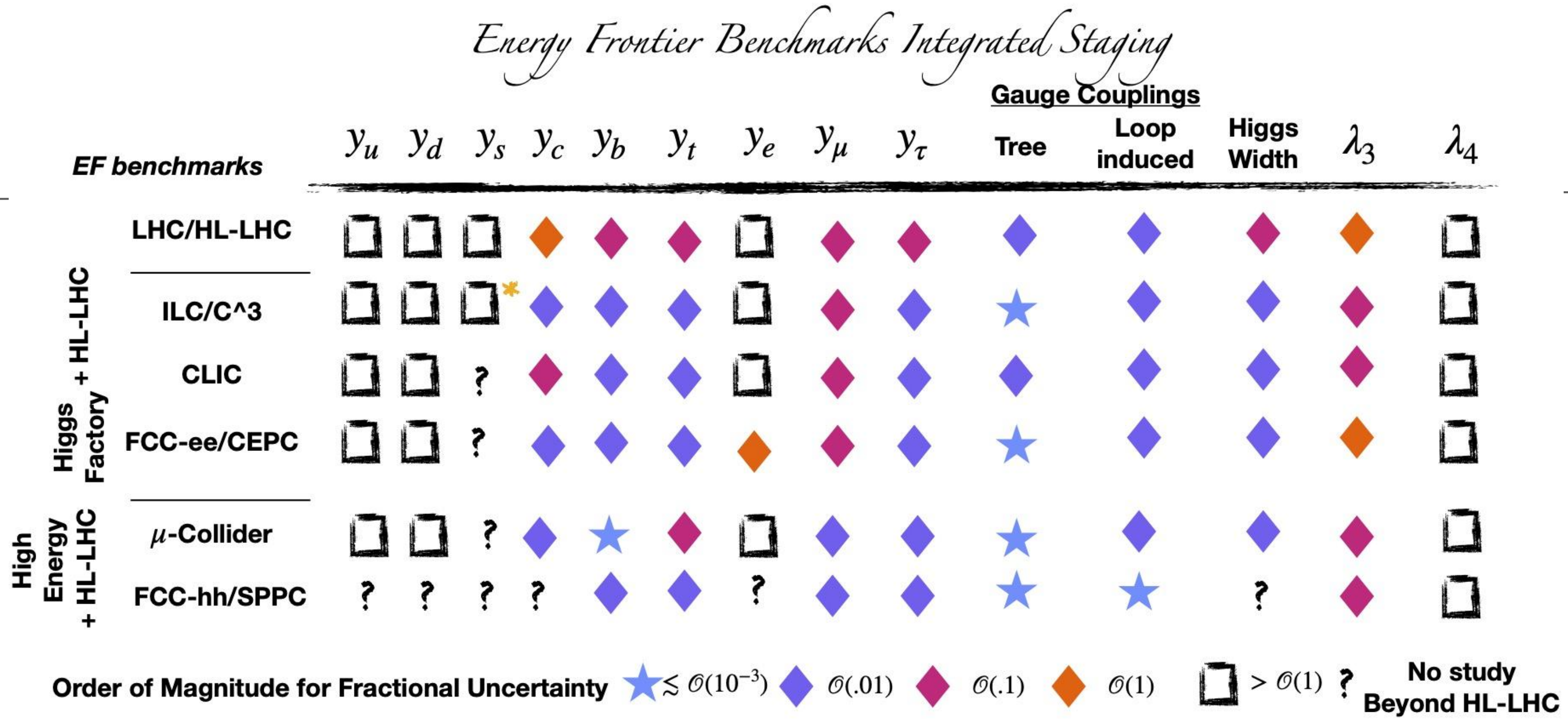


Reach of Higgs factories (first stages)



All first stage Higgs factories are very similar.

Reach of Higgs factories (first stages)

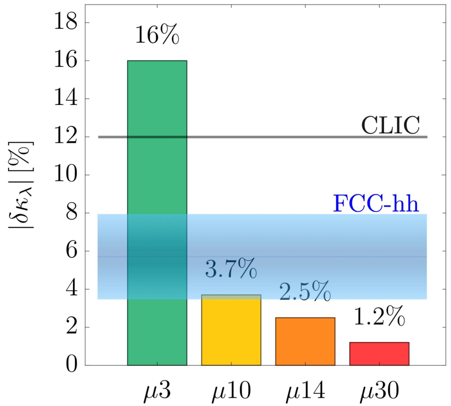


Linear colliders begining to demonstrate advantages especially in the Higgs self coupling compared to circular e+e− colliders, whereas the circular colliders can potentially measure the electron Yukawa.

Updated reach for Higgs-self coupling

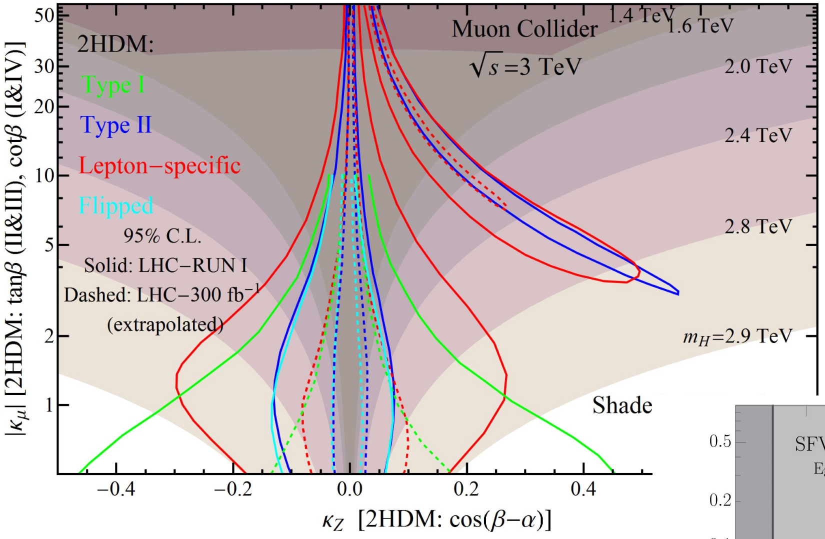
collider	Indirect-h_{SM}	$h_{SM}h_{SM}$	combined
HL-LHC [24]	100-200%	50%	50%
ILC_{250}/C^3-250 [14, 17]	49%	–	49%
ILC_{500}/C^3-550 [14, 17]	38%	20%	20%
ILC_{100}/C^3-1000 [14, 17]	36%	10%	10%
$CLIC_{380}$ [19]	50%	–	50%
$CLIC_{1500}$ [19]	49%	36%	29%
$CLIC_{3000}$ [19]	49%	9%	9%
FCC-ee [20]	33%	–	33%
FCC-ee (4 IPs) [20]	24%	–	24%
FCC-hh [25]	-	3.4-7.8%	3.4-7.8%
μ(3 TeV) [23]	-	15-30%	15-30%
μ(10 TeV) [23]	-	4%	4%

- ATLAS and CMS HL-LHC updated
- FCC-hh updated arXiv:2004.03505
- Muon Collider reach:



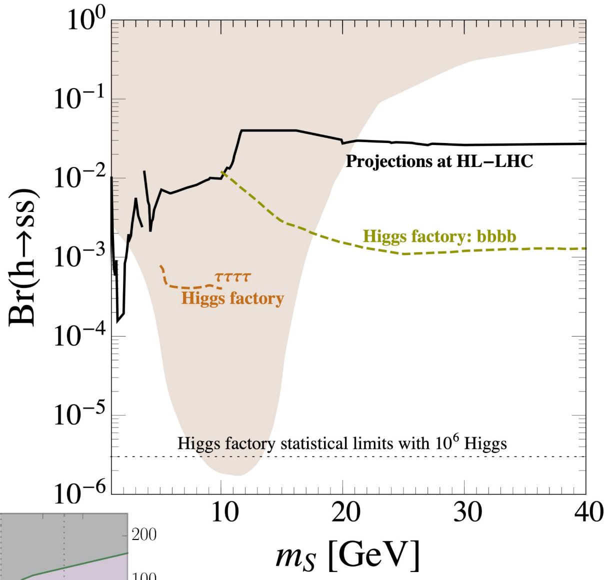
arXiv:2203.07256

Higgs as a portal to BSM physics

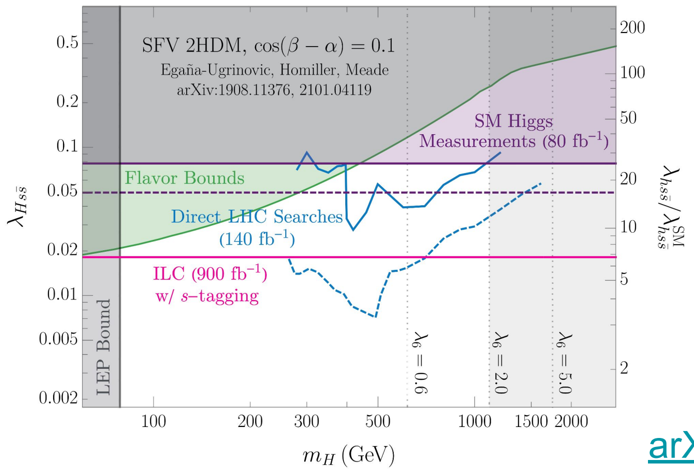


arXiv:2203.07261

Extended Higgs sectors:
2HDM, extra singlets, …

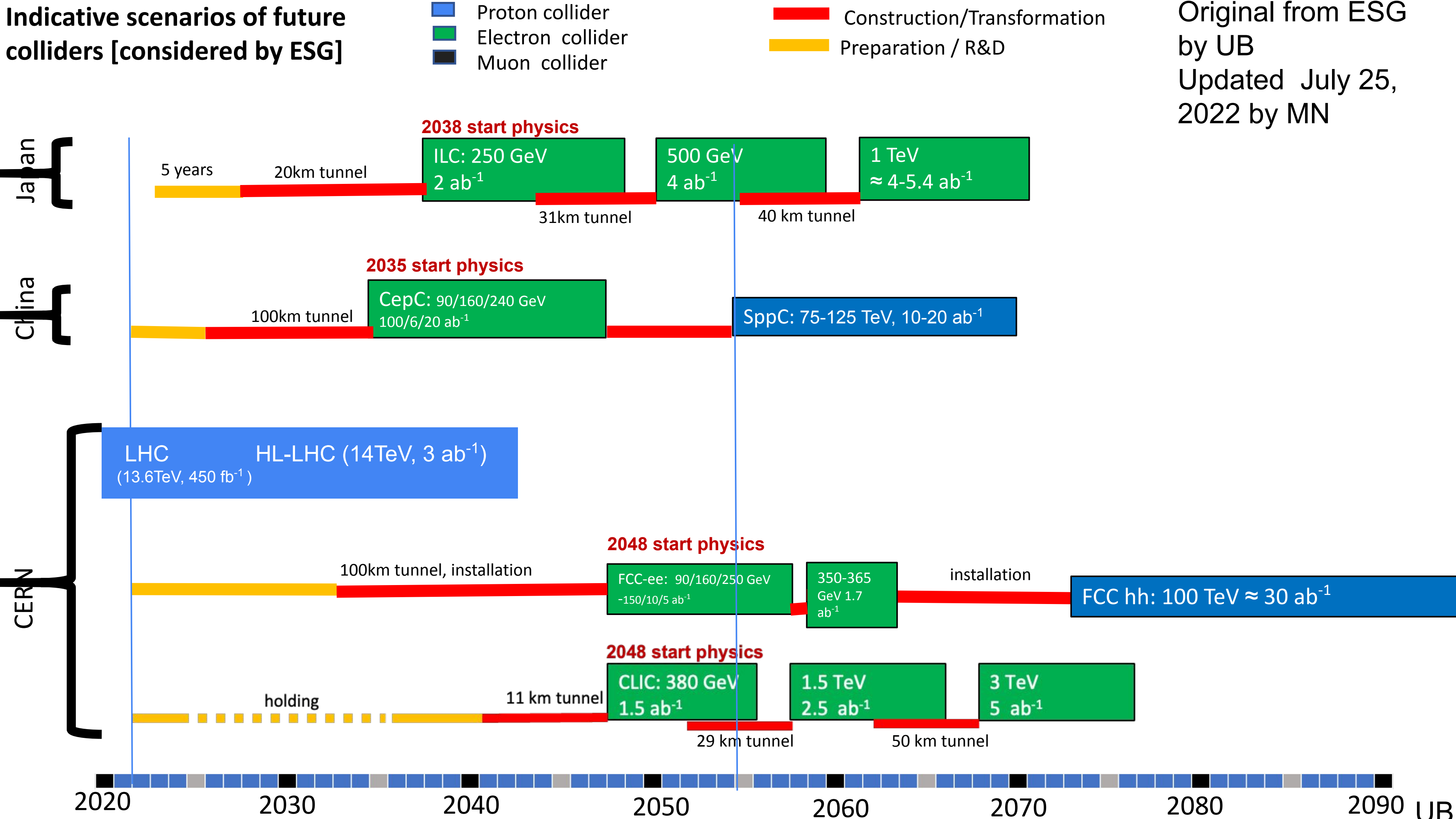


arXiv:2203:08206



Higgs and flavor:
probing anomalous
Hss coupling

arXiv:2203:07535



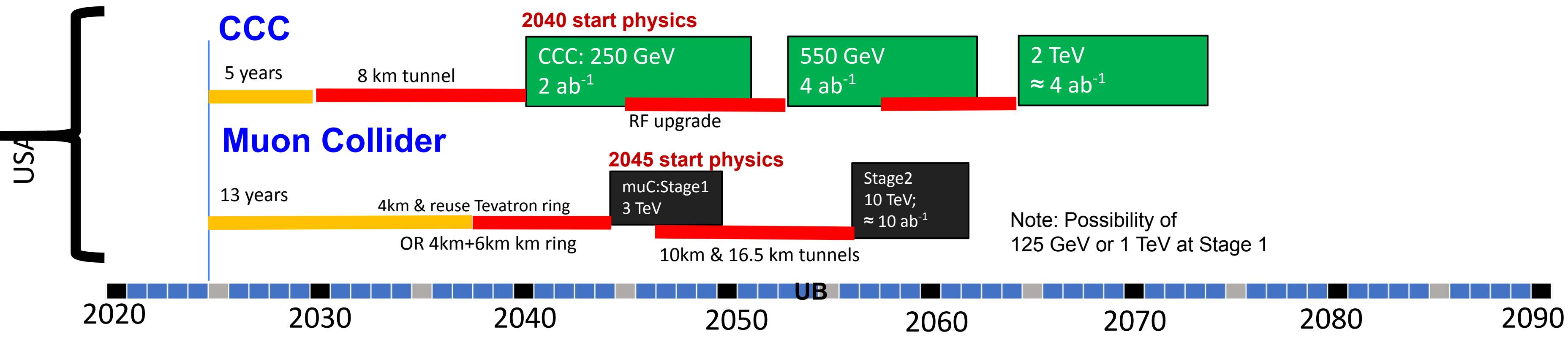
Indicative scenarios of future colliders [considered by ESG]
Proton collider
Electron collider
Muon collider
Construction/Transformation
Preparation / R&D
Original from ESG by UB
Updated July 25, 2022 by MN
Japan
2038 start physics
5 years
20km tunnel
ILC: 250 GeV
2 ab-1
31km tunnel
500 GeV
4 ab-1
40 km tunnel
1 TeV
≈ 4-5.4 ab-1
China
2035 start physics
100km tunnel
CepC: 90/160/240 GeV
100/6/20 ab-1
SppC: 75-125 TeV, 10-20 ab-1
CERN
LHC
(13.6TeV, 450 fb-1)
HL-LHC (14TeV, 3 ab-1)
2048 start physics
100km tunnel, installation
FCC-ee: 90/160/250 GeV
-150/10/5 ab-1
350-365 GeV 1.7 ab-1
installation
FCC hh: 100 TeV ≈ 30 ab-1
2048 start physics
holding
11 km tunnel
CLIC: 380 GeV
1.5 ab-1
29 km tunnel
1.5 TeV
2.5 ab-1
50 km tunnel
3 TeV
5 ab-1
2020
2030
2040
2050
2060
2070
2080
2090
UB

Possible scenarios of future colliders

- Proton collider
- Electron collider
- Muon collider
- Construction/Transformation
- Preparation / R&D

Original from ESG by UB
Updated July 25, 2022 by MN

Proposals emerging from this Snowmass for a US based collider



- **Timelines technologically limited**
- Uncertainties to be sorted out
  - Find a contact lab(s)
  - Successful R&D and feasibility demonstration for CCC and Muon Collider
  - Evaluate CCC progress in the international context, and consider proposing an ILC/CCC [ie CCC used as an upgrade of ILC] or a CCC only option in the US.
  - International Cost Sharing

- Consider proposing hosting ILC in the US.

Accelerator & Detector R&D Needs

Higgs Factories Multi-TeV Machines

Viability of Facilities and Challenges (from AF)

Support a fast-start for construction of an e+e- Higgs Factory

- ILC:
  - Ready to go, polarization
  - Long, e+ source,
- FCCee & CEPC :
  - Ongoing feasibility study
  - Longest, $$, power consumption
- CLIC:
  - Lowest power needs, shortest
  - 2-beams (or klystrons?), tolerances
- Cool Copper Collider or HELEN:
  - **new proposals from Snowmass**
  - lower cost option to ILC/CLIC
  - CCC capability up to 120-155 MV/m

Support for R&D for EF multi-TeV colliders

- CLIC-3 TeV :
  - Established CDR, demo facilities
  - Long, $$$, huge power consumption
- FCChh-100 TeV:
  - Re-use FCCee tunnel, high-L, LHC exp.
  - 20(?) yrs for 16 T magnets, $$$, power
- SPPC-125 TeV:
  - Re-use CepC tunnel, ep 0.12+62.5 TeV
  - (N) yrs for 20 T magnets, $$$, power
- Muon Collider-10(14) TeV:
  - Potentially lowest cost, best Lumi/TWh
  - 6D cooling R & D on many subsystems

Detector R&D Needs

Preparation of a Technical Design for a Detector needs an R&D program

- Highly segmented detectors with good resolution were simulated to make the case for physics studies for Higgs Factories & Multi-TeV Colliders.
- **We do need complex/cutting-edge detectors to meet the ambitious physics goals!** The needs extend beyond generic R&D.
  - Address the specific detector challenges for e^+e^- colliders.
- **Such a program needs to start now in the U.S.:**
  - to explore the technology to build a full-scale e^+e^- collider detector
  - It takes about 10 years from CD0 to end of construction of a collider detector.
  - **Thus investment in targeted detector R&D for a Higgs Factory has to start soon**!

Detector R&D Needs for Higgs Factory

Main features identified together with Instrumentation Frontier:

- Pixel tracker with lowest possible mass and possible radius
- Low-mass outer tracker for excellent momentum resolution to high energies
- A highly segmented calorimeter for particle flow
- A large superconducting solenoid enclosing calorimeter and tracker
- Muon chambers
- Triggerless readout
- Timing detectors
- Particle ID K/π/p separation
- Sophisticated electronics to handle large data volume

- Understanding the Machine Detector Interface
- Need engineering to go from prototypes to detector

Costs

Large Projects

Project	Construction Start date (yr)	Construction End date (yr)	Construction Cost B$
Higgs Factories			
CepC	2026	2035	12-18
CCC (higgs Fac)	2030	2040	7-12
ILC (higgs Fac)	2028	2038	7-12
CLIC	2041	2048	7-12
FCC-ee	2033	2048	12-18
Multi-TeV Colliders			
Muon Collider (3 TeV)	2038	2045	7-12
Muon Collider (10 TeV)	2042	2052	12-18
SppC	2043	2055	30-80
HE CCC	2055	2065	12-18
HE CLIC (3 TeV)	2062	2068	18-30
FCC-hh	2063	2074	30-50

Cost estimates from the ITF report by AF. Please refer to the document for explanations now they were estimated and associated caveats

Link to the report on AF wiki

Medium Project Scale R&D requests

Project	R&D Start date (yr)	R&D End Date (yr)	R&D cost M$
Higgs Factory detector R&D	now	2035	~100-150
CCC higgs factory	2024	2028	~100
CCC High Energy	2045	2050	~200
Muon Collider (1-3 TeV)	now	2040	~300
Muon Collider (10 TeV)	2040	2047	~200

Estimated US Contributions
In the spirit of Snowmass
numbers are very
preliminary. They give an
approximate scale.

Need to be vetted further.

Energy Frontier 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 for a first-stage TeV-scale Muon Collider
  - **After 2035**:
    - Demonstrate readiness to construct 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**

Next Steps

- The reports from the Frontiers and Topical Groups are being finalized
  - They will be appearing on arXiv during the next month.
- The next Particle Physics Project Prioritization Panel (P5) is being formed.
- P5 will consider the long-term strategic roadmap for the U.S. particle physics program under realistic budget scenarios.
- Prof. Hitoshi Murayama (UC Berkeley) will serve as chair of the next P5.
  - Expect the full panel to be formed and active in the next couple of months
- There will be further opportunities for community input to P5
- Expect P5 deliberations and report in 2023.

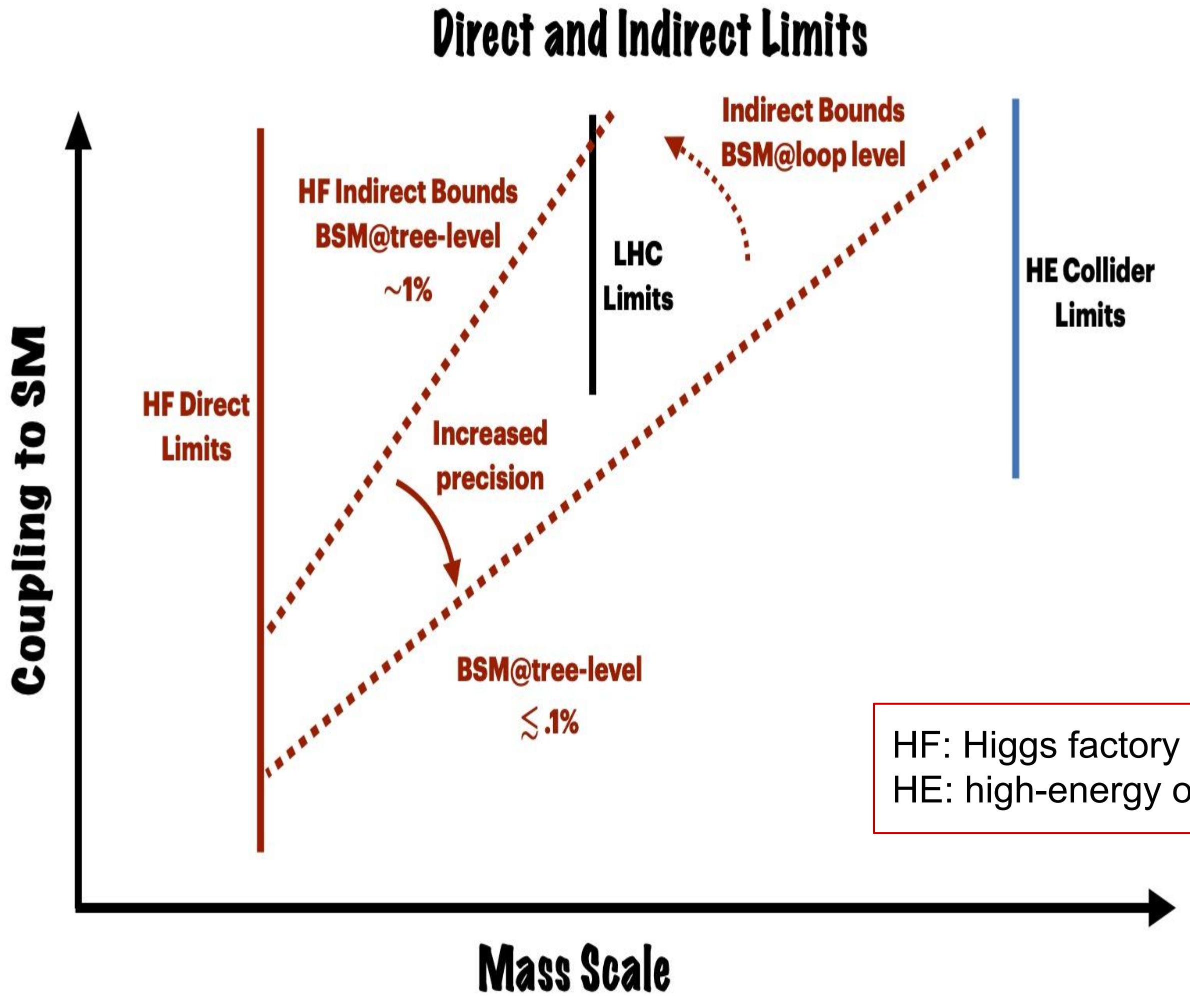
Summary

- An opportunity for US to take leadership in colliders

- US EF community strongly supports

1. A fast start of construction of an e+e- Higgs Factory (FCC-ee, ILC, C^3, CLIC)
2. Request for targeted detector R&D for Higgs Factory
3. Request for investment in R&D towards lowering of costs for Higgs Factory
    a. interest in new technologies from early career scientists
4. Request for investment in R&D towards multi-TeV colliders
    a. significant interest for adding muon collider R&D.

Backup



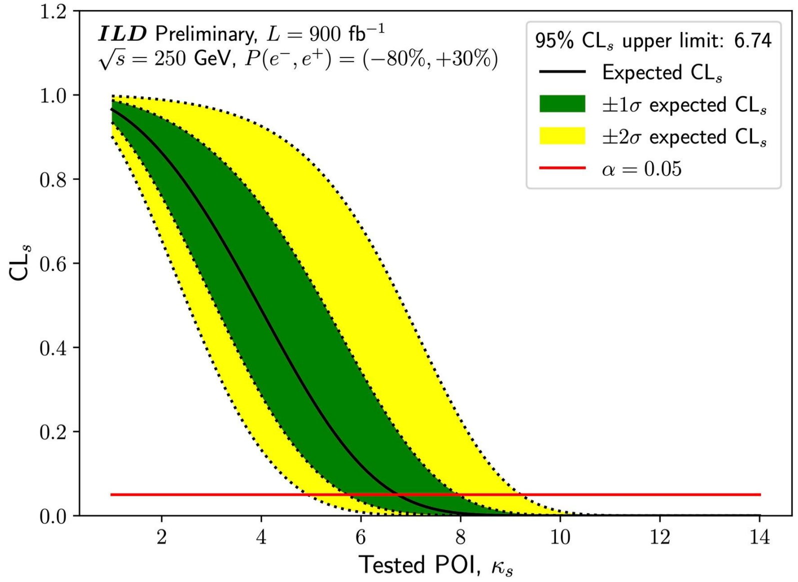
In a simplified picture:

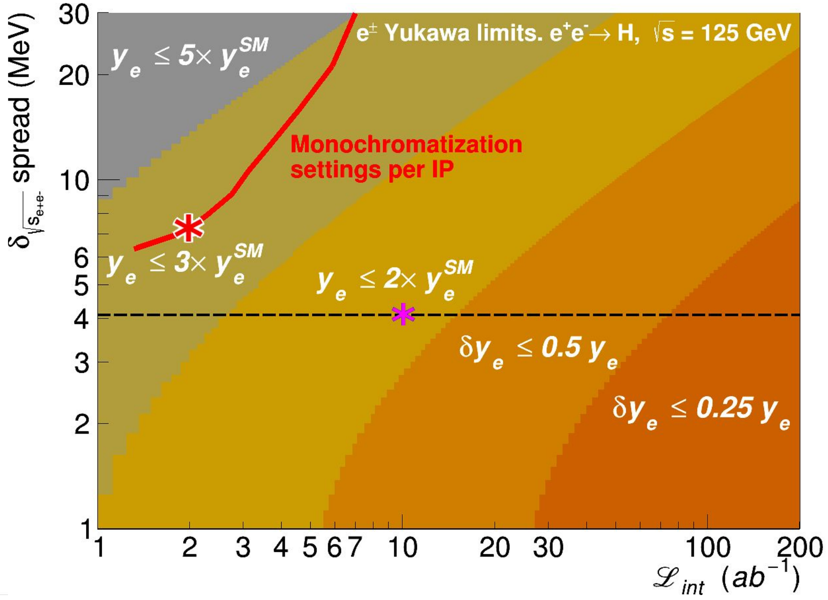
New physics at tree level:
$\delta\eta_{SM} \sim g^2_{BSM}\, E^2/M^2$

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 for light-fermion Yukawa couplings





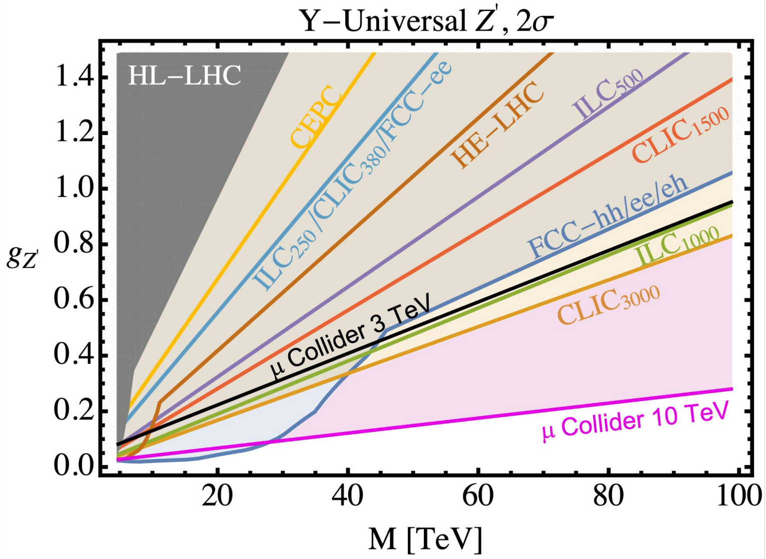
- Studying ZH with Z going to leptons and neutrinos
- κ_s<6.74 at 95% c.l.

arXiv:2203.07535

- Electron Yukawa at FCC-ee
- κ_e< 1.6 at 95% c.l.

arXiv:2107.02686

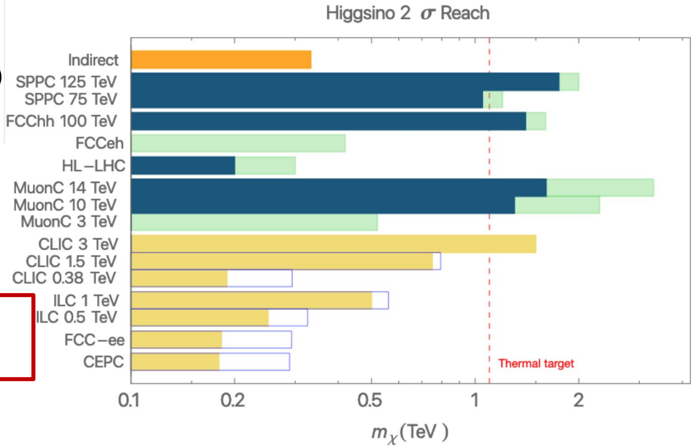
Multi-TeV colliders: the ultimate exploration



Example: Heavy Boson (Z') models

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%



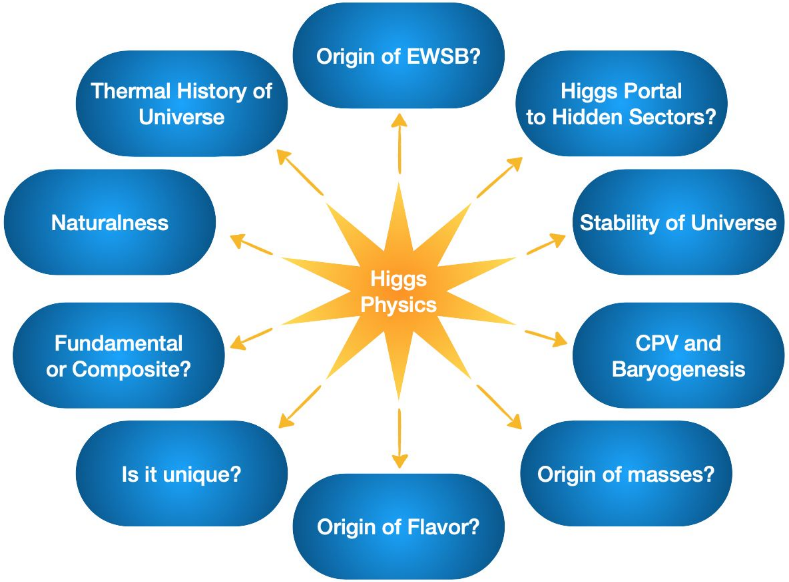
Example of WIMP Dark Matter reach

Greatly extend the reach of BSM scenarios

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%
ILC_{250}/C^3-250	49%	–	49%
ILC_{500}/C^3-550	38%	20%	20%
$CLIC_{380}$	50%	–	50%
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FCC-ee	33%	–	33%
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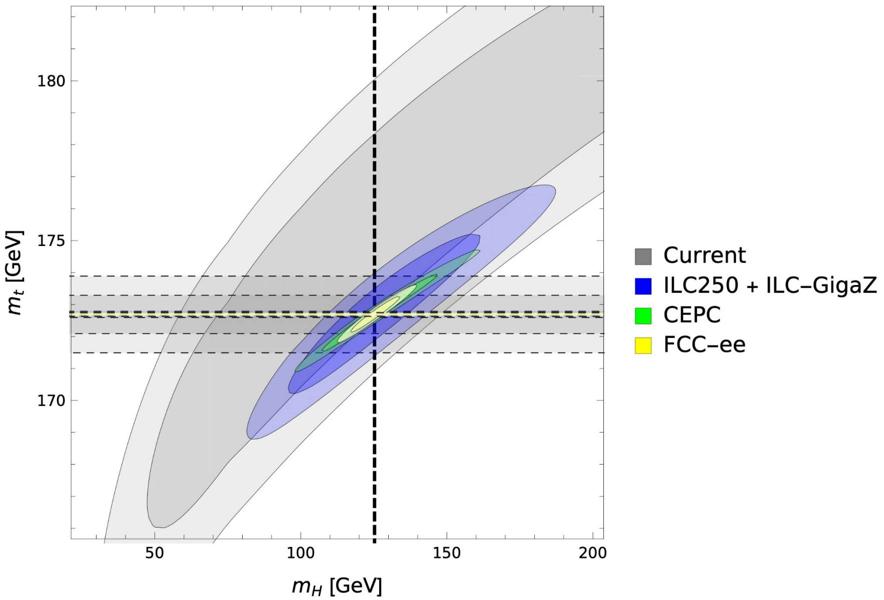
FCC-hh	-	2.9-5.5%	2.9-5.5%
μ(3 TeV)	-	15-30%	15-30%
μ(10 TeV)	-	4%	4%

Stress Test of the SM



Key physics studies of the EF program

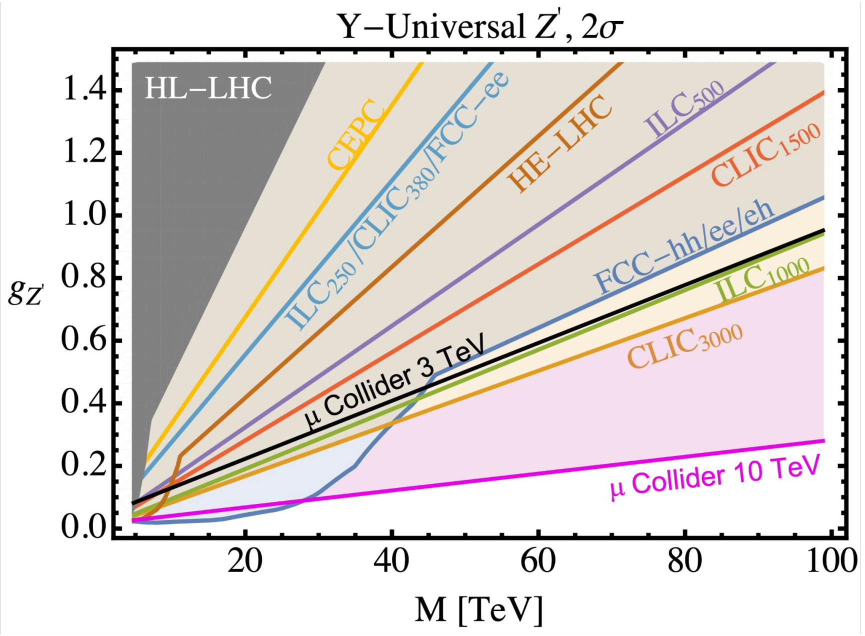
Aim to build a complete program of BSM searches via both model-specific and model independent explorations

- 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.

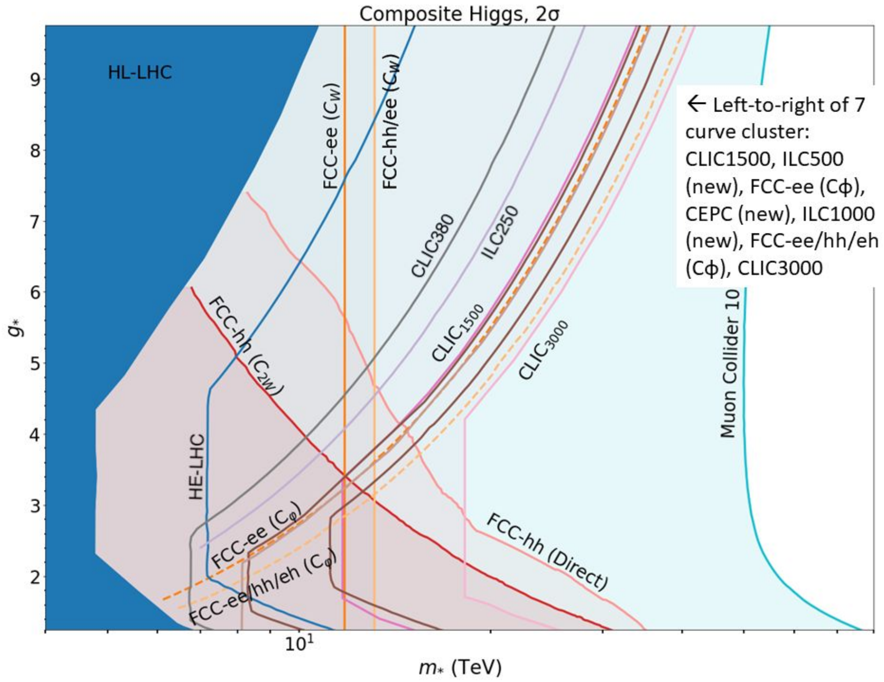
➢ **See BSM Topical Group Reports**

Examples of BSM explorations at colliders

Heavy Boson (Z') model

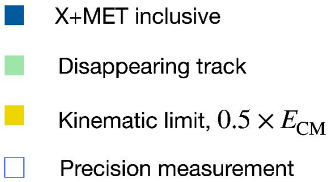


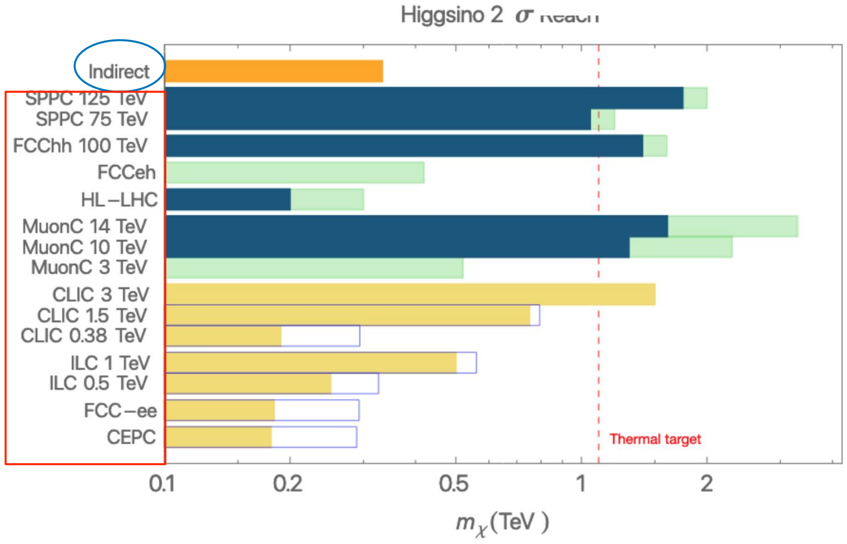
Composite Higgs models



Complementarity of collider physics

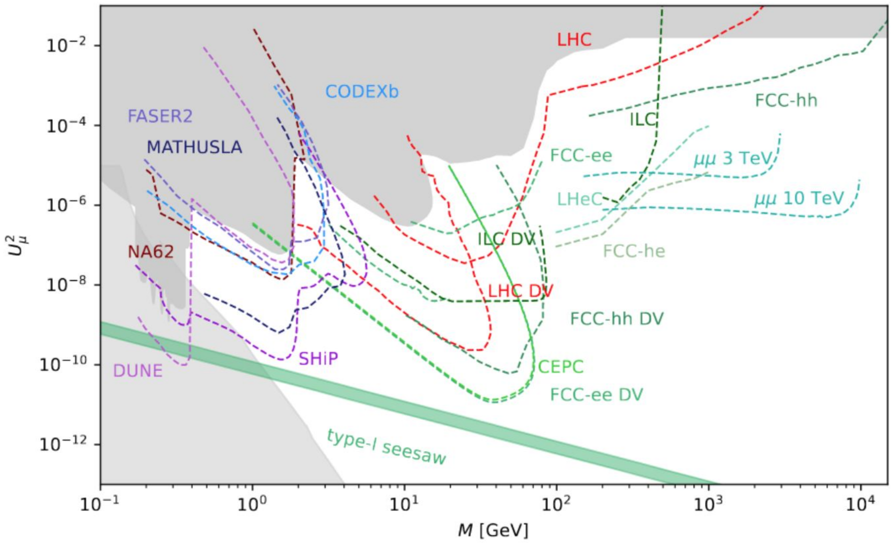
Example of WIMP Dark Matter reach





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**

➢ **See QCD Topical Group Report**

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

Method	Relative $\alpha_s(m_Z)$ uncertainty 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%)