# Energy Frontier Report Overview, EW, and BSM

## Energy Frontier Community Meeting

### Reports Reading and Discussion

June 24, 2022


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

# Energy Frontier: explore the TeV energy scale and beyond

## to answer still open Big Questions and Explore the Unknown

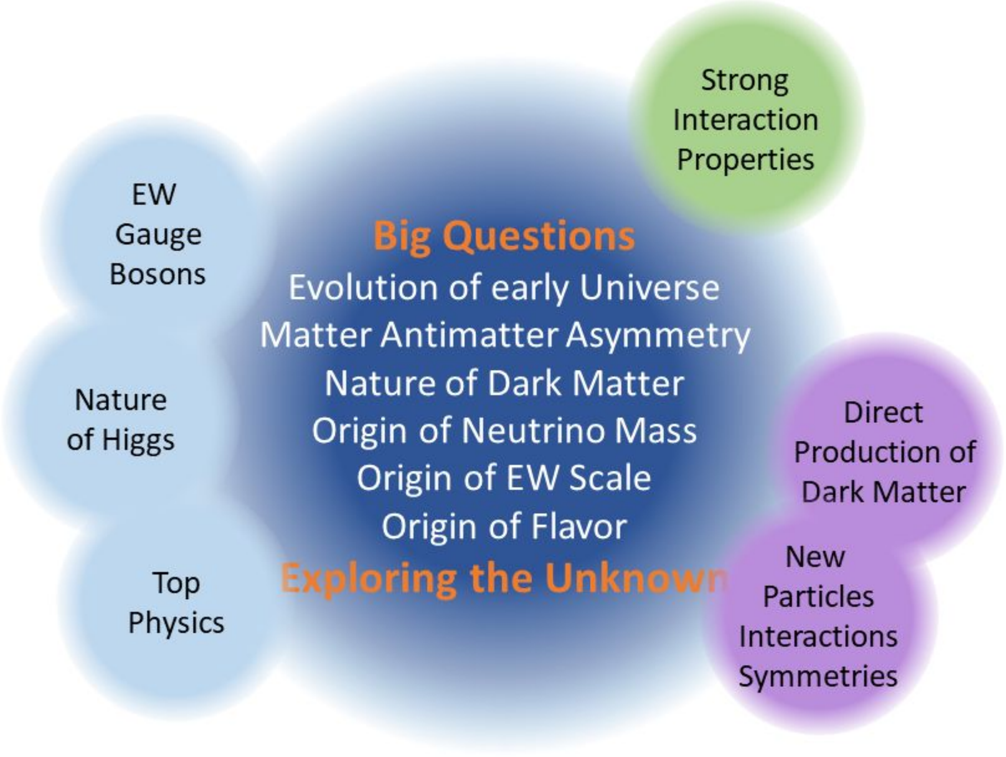
**Big Questions**

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**

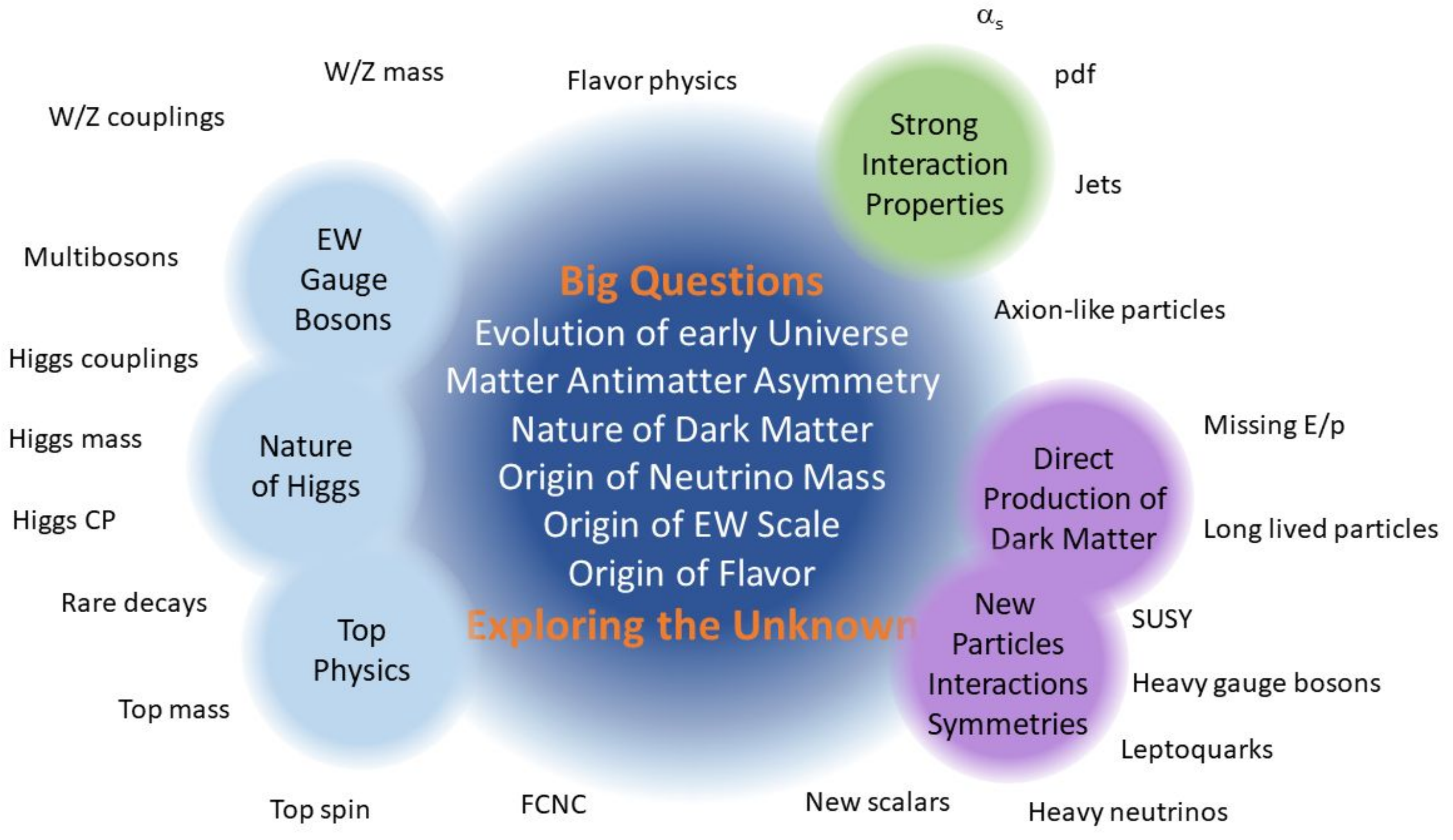
# Energy Frontier: explore the TeV energy scale and beyond

## 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



# Setting the stage - Future scenarios

# 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**

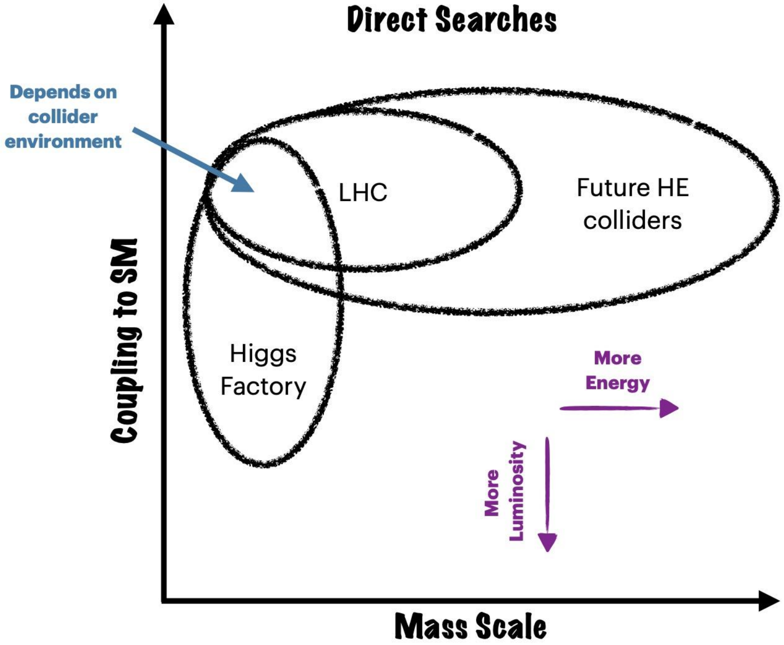
- **Search for direct evidence of BSM physics at the energy frontier**
  - Need to explore the multi-TeV scale → **Need energy**
  - Need to explore what LHC/HL-LHC may have difficulty exploring → **Need luminosity**

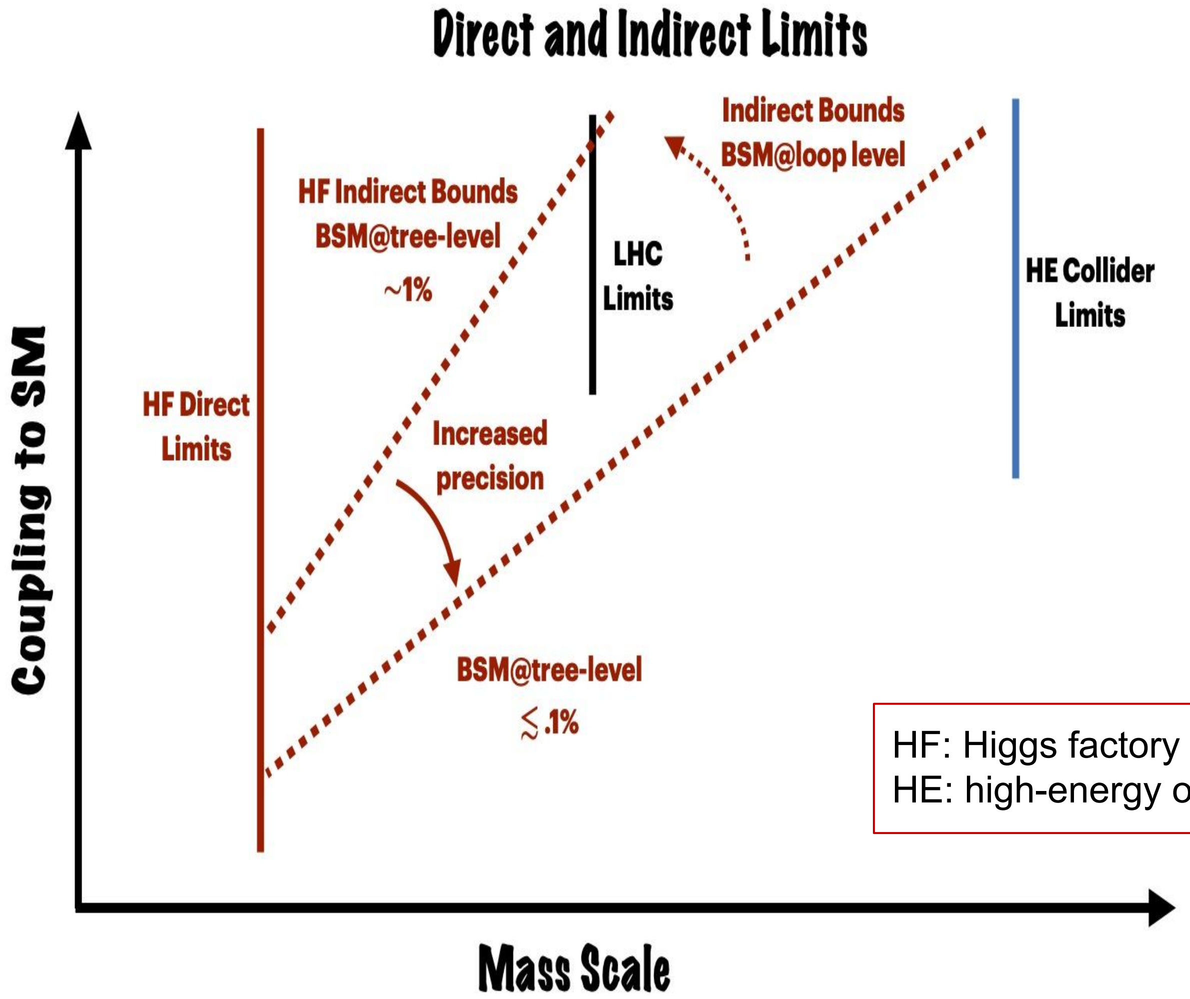
# Energy Frontier Machines: energy and precision

**New physics can be at low as 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

# Snowmass 2021: EF Benchmark Scenarios

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

| Collider | Type | $\sqrt{s}$ | $\mathcal{P}[\%]$ $e^-/e^+$ | $\mathcal{L}_{int}$ $ab^{-1}$ |
|---|---|---|---|---|
| HL-LHC | pp | 14 TeV | | 6 |
| ILC and $C^3$ c.o.m almost similar | ee | 250 GeV | $\pm80/\pm30$ | 2 |
| | | 350 GeV | $\pm80/\pm30$ | 0.2 |
| | | 500 GeV | $\pm80/\pm30$ | 4 |
| | | 1 TeV | $\pm80/\pm20$ | 8 |
| CLIC | ee | 380 GeV | $\pm80/0$ | 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 |
| | | $2\ M_{top}$ | | 1.5 |
| muon-collider (higgs) | $\mu\mu$ | 125 GeV | | 0.02 |

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

| Collider | Type | $\sqrt{s}$ | $\mathcal{P}[\%]$ . $e^-/e^+$ | $\mathcal{L}_{int}$ $ab^{-1}$ |
|---|---|---|---|---|
| HE-LHC | pp | 27 TeV | | 15 |
| FCC-hh | pp | 100 TeV | | 30 |
| LHeC | ep | 1.3 TeV | | 1 |
| FCC-eh | | 3.5 TeV | | 2 |
| CLIC | ee | 1.5 TeV | $\pm80/0$ | 2.5 |
| | | 3.0 TeV | $\pm80/0$ | 5 |
| High energy muon-collider | $\mu\mu$ | 3 TeV | | 1 |
| | | 10 TeV | | 10 |

Timelines will be taken from the ITF report from AF.

# Physics Highlights from Snowmass 21
# Energy Frontier - EW physics

EF01 - Higgs boson properties and couplings
EF02 - Higgs boson as a portal to new physics
EF03 - Heavy flavor and top-quark physics
EF04 - EW precision physics and constraining new physics

# Key physics questions of the EF program

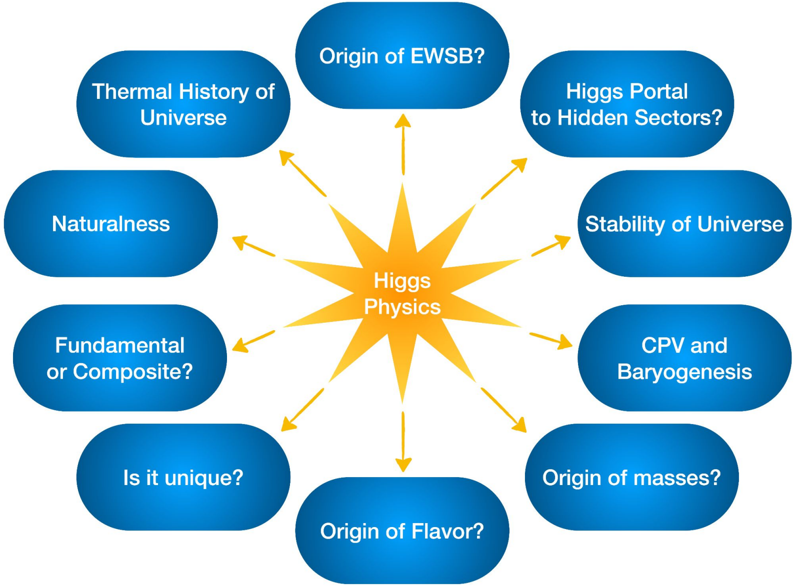
## What is the origin of the electroweak scale?

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 UV physics from **precision Higgs measurements** (mass, width, couplings)? How does this improve the constraining power of global EW fits?
- Can we measure the shape of the **Higgs potential**?
- Can the Higgs give us insight into **flavor** and vice versa?
- What are the implications for **Naturalness**?
- Can constraints come from phenomena not yet considered or accessible at colliders?

➢ **Focus points for EW and BSM Topical Groups**

# Higgs and BSM physics

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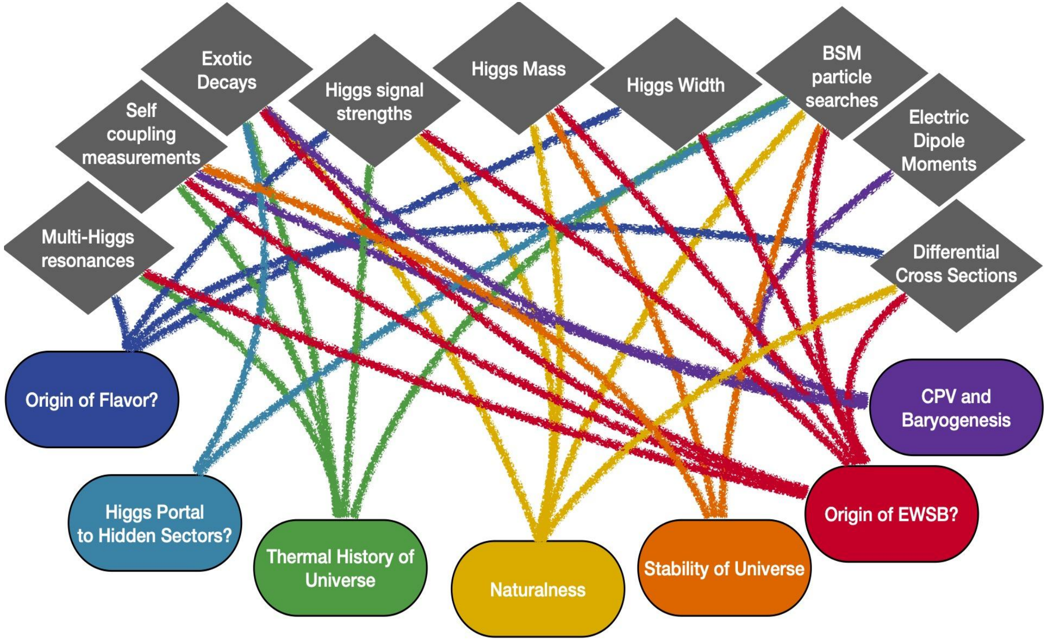
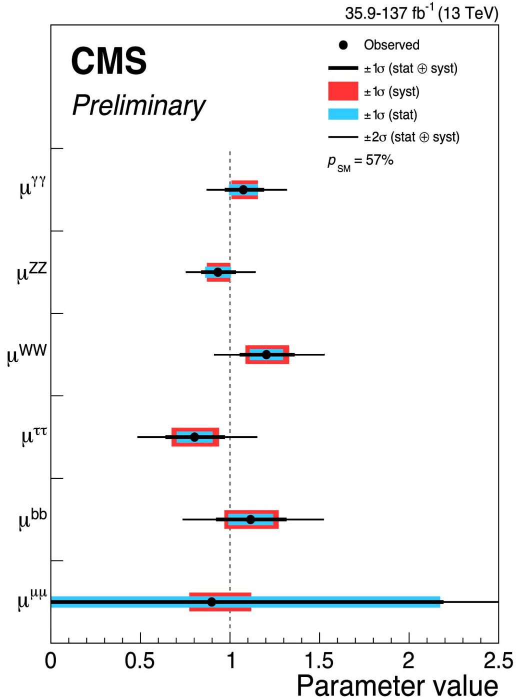
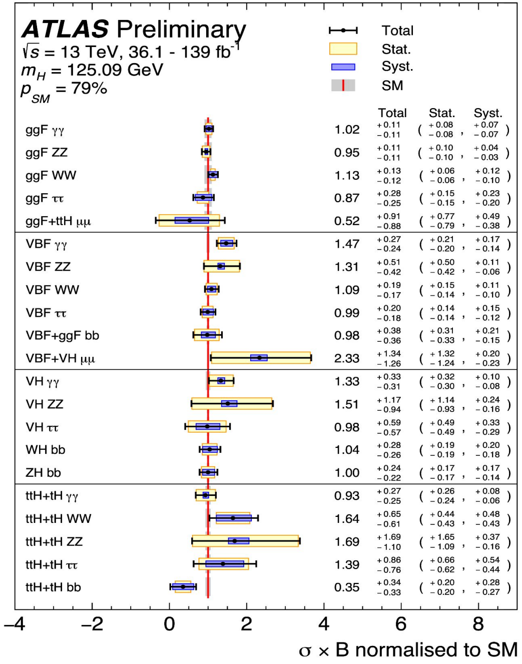
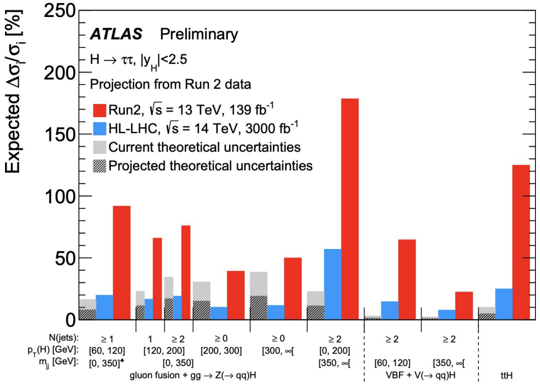


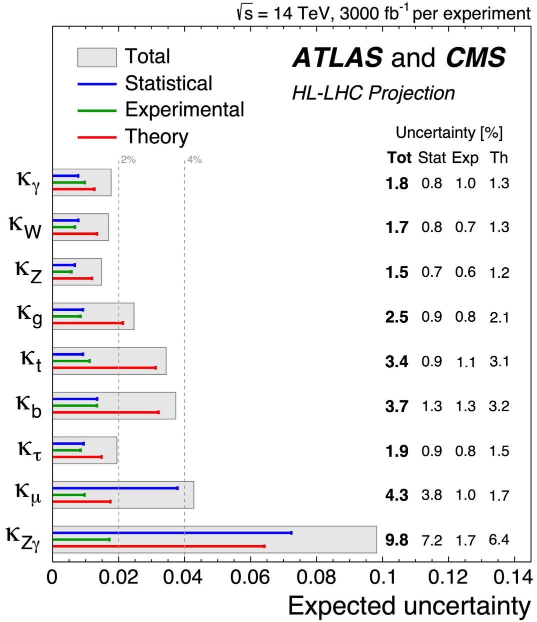

A **probe** that can answer **big questions** through a multitude of **signatures**

# Higgs: from LHC to HL-LHC



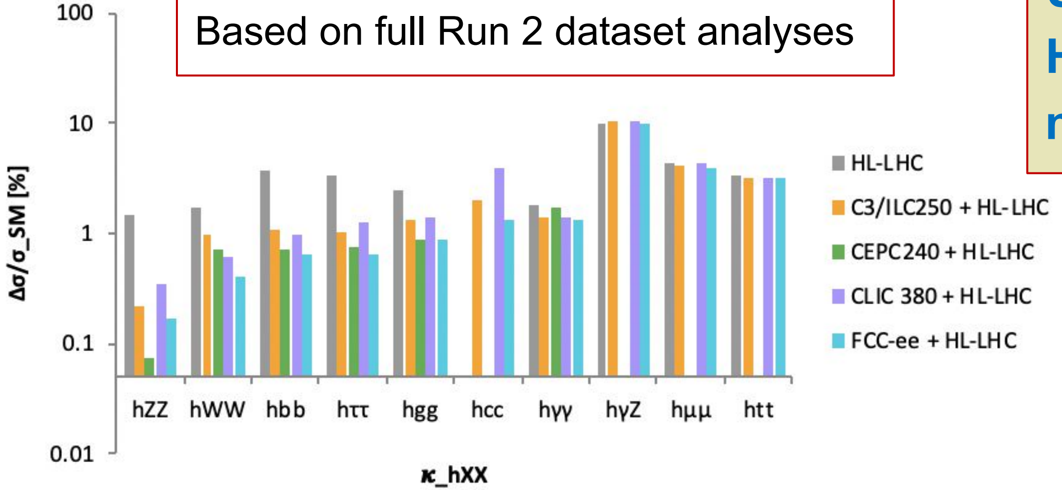

The reach of the HL-LHC is the foundation for planning the future. LHC is exceeding our expectations and HL-LHC projections will improve accordingly.

# Higgs couplings at future colliders

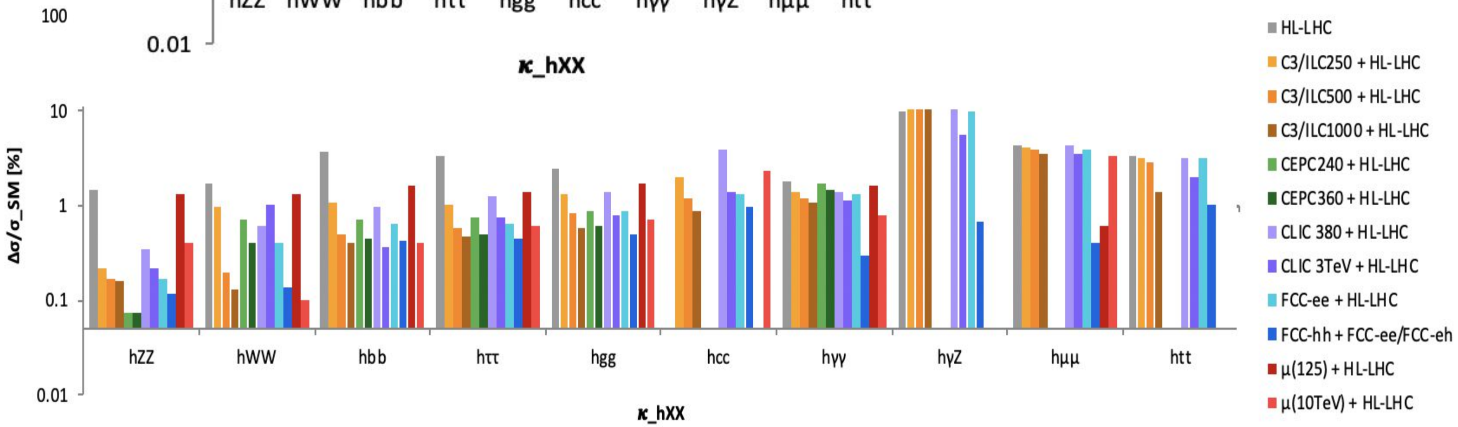
From Snowmass 2021 EF Higgs TGs Report

Based on full Run 2 dataset analyses

**Updated reach for Higgs-boson coupling measurements**

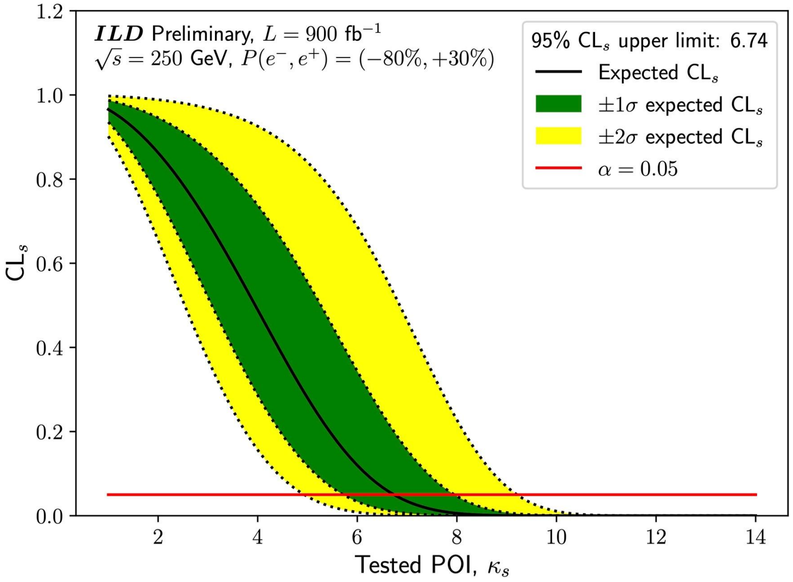


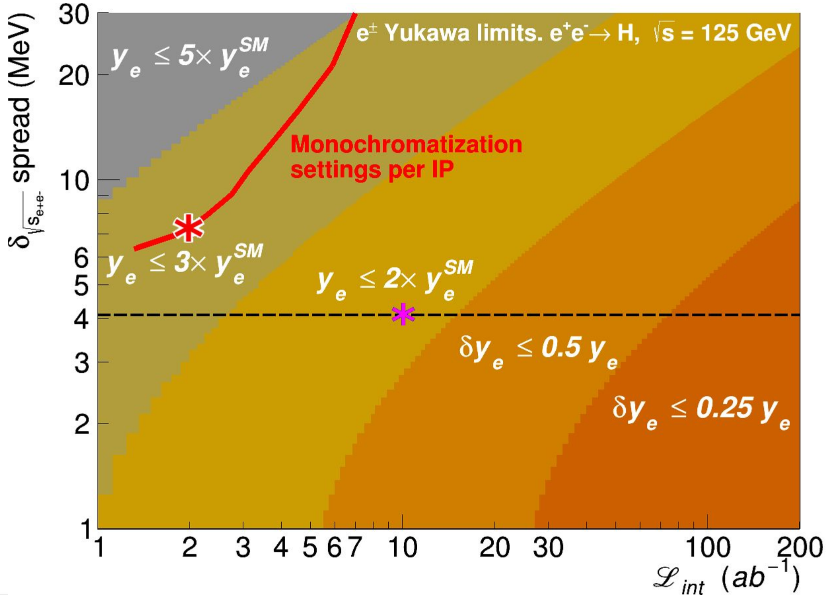

Initial stages of future e+e- machines




Final reach of all considered future colliders

# Reach for light-fermion Yukawa couplings




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

- Electron Yukawa at FCC-ee
- $\kappa_e$< 1.6 at 95% c.l.

arXiv:2203.07535

arXiv:2107.02686

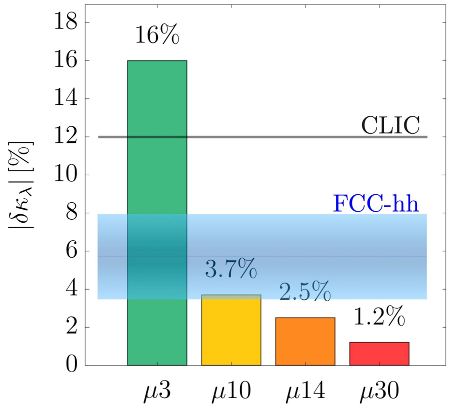
# Updated reach for Higgs-self coupling

| 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% |
| $\mu$(3 TeV) | - | 15-30% | 15-30% |
| $\mu$(10 TeV) | - | 4% | 4% |

ATLAS and CMS HL-LHC updated

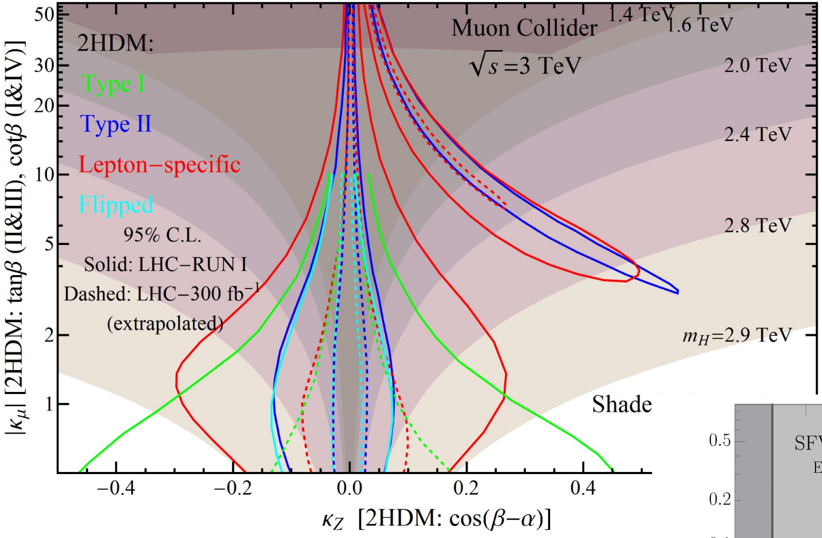
FCC-hh updated arXiv:2004.03505

Muon Collider reach:



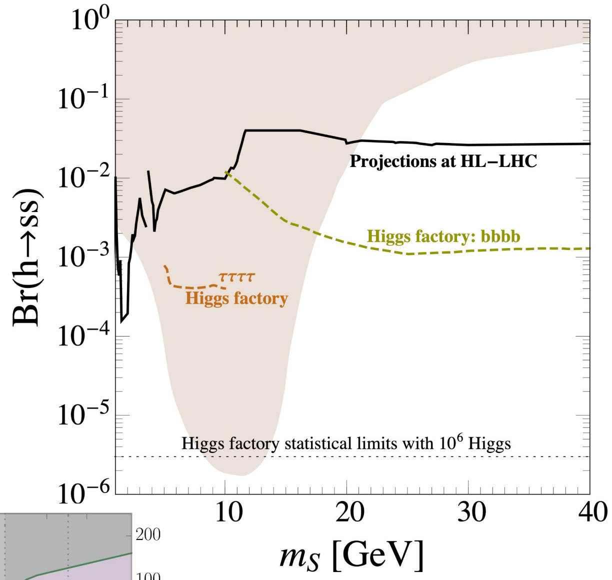

arXiv:2203.07256

# Higgs as a portal to BSM physics

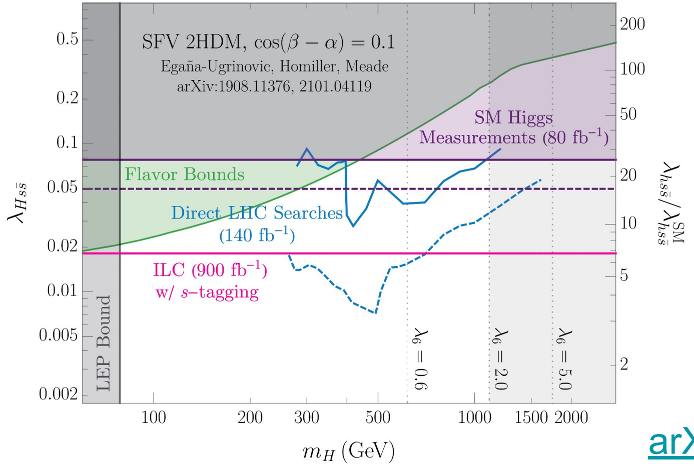



arXiv:2203.07261

**Extended Higgs sectors**:
2HDM, extra singlets, …




arXiv:2203:08206



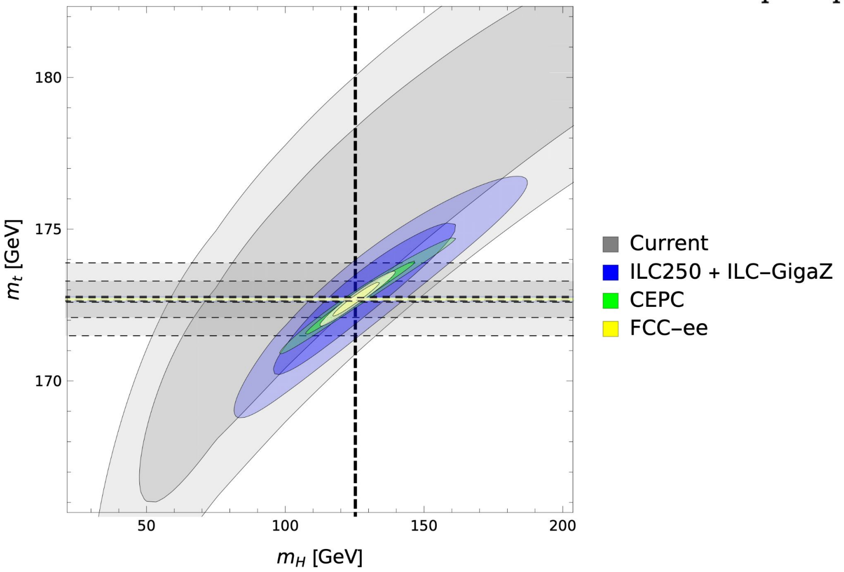

**Higgs and flavor:**
probing anomalous Hss coupling

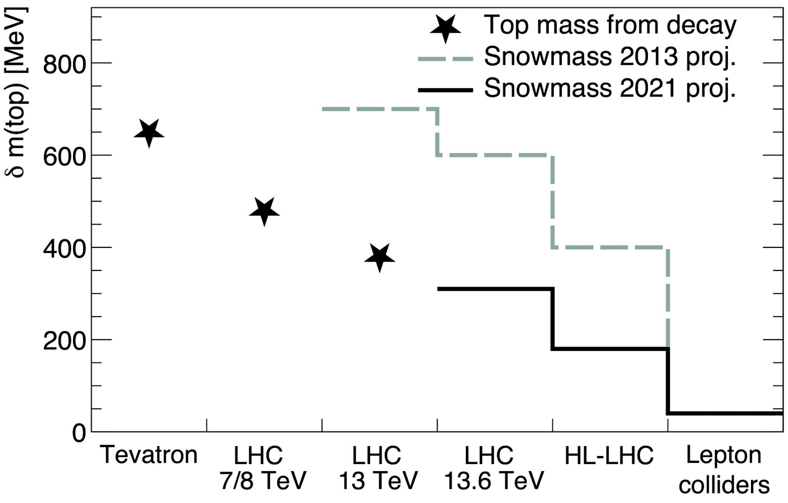
arXiv:2203:07535

# Top-quark physics

Stress testing the SM and exploring anomalous couplings

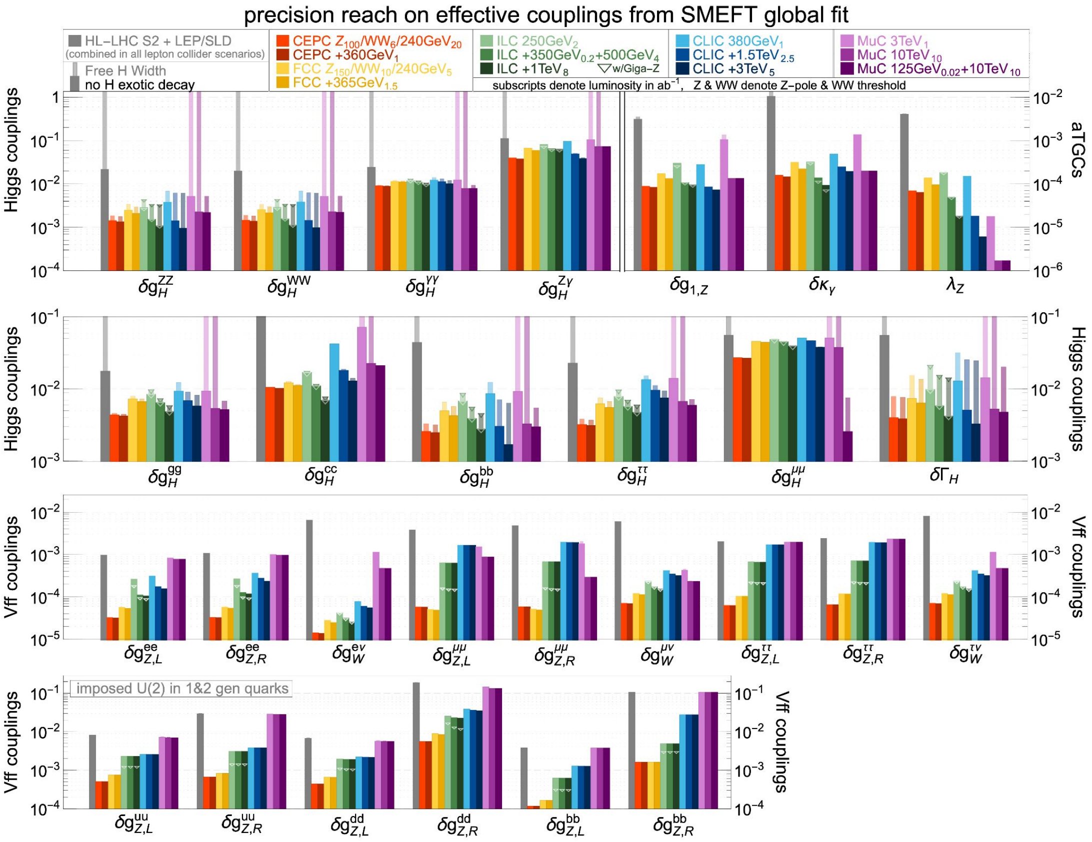
| Parameter | HL-LHC | ILC 500 | FCC-ee | FCC-hh |
|---|---|---|---|---|
| $\sqrt{s}$ [TeV] | 14 | 0.5 | 0.36 | 100 |
| Yukawa coupling $y_t$ (%) | 3.4 | 2.8 | 3.1 | 1.0 |
| Top mass $m_t$ (%) | 0.10 | 0.031 | 0.025 | – |
| Left-handed top-$W$ coupling $C^3_{\phi Q}$ (TeV$^{-2}$) | 0.08 | 0.02 | 0.006 | – |
| Right-handed top-$W$ coupling $C_{tW}$ (TeV$^{-2}$) | 0.3 | 0.003 | 0.007 | – |
| Right-handed top-$Z$ coupling $C_{tZ}$ (TeV$^{-2}$) | 1 | 0.004 | 0.008 | – |
| Top-Higgs coupling $C_{\phi t}$ (TeV$^{-2}$) | 3 | 0.1 | 0.6 | |
| Four-top coupling $c_{tt}$ (TeV$^{-2}$) | 0.6 | 0.06 | – | 0.024 |



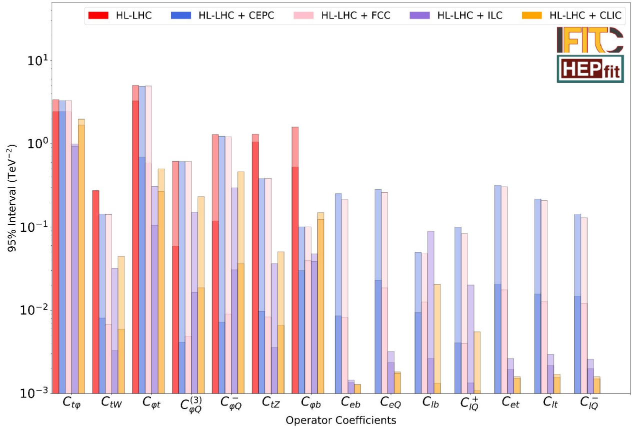




From Snowmass 2021 EF HF and EW TGs Reports

# Constraining BSM via global fits of Higgs+EW+top data




## Including top-quark observables




[arXiv:2206.08326](arXiv:2206.08326)

**Improved fits wrt ESG results**
(more scenarios, top observables, extended set of EFT couplings)

**Focus on interpretation**:
benchmark models, Higgs inverse problem, EFT validity

# Physics Highlights from Snowmass 21 Energy Frontier - BSM physics

EF08 - Model specific explorations
EF09 - More general exploration
EF10 - Dark Matter at colliders

# Building a comprehensive program of BSM searches

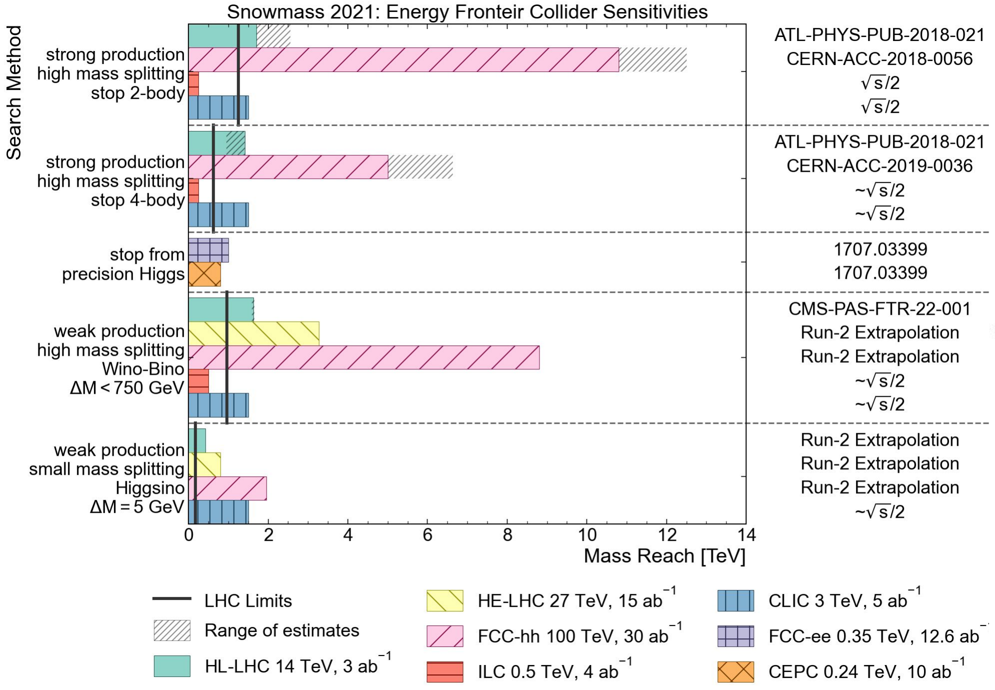
## How to build a complete program of BSM searches via both model-specific and model independent explorations?

- 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. But ...
  - **Which models to consider? How to compare model spaces in a consistent way?**
- Study alternative paradigms with respect to traditional BSM searches (ex: long-lived and feebly-interacting particles).
  - **Can future detectors and accelerators probe such particles?** (Including DM searches)
- How do we conduct searches in a more model-independent/agnostic way ?
- How do we compare the results of different experiments in a more model-independent way to ensure complementarity and avoid big gaps in coverage?

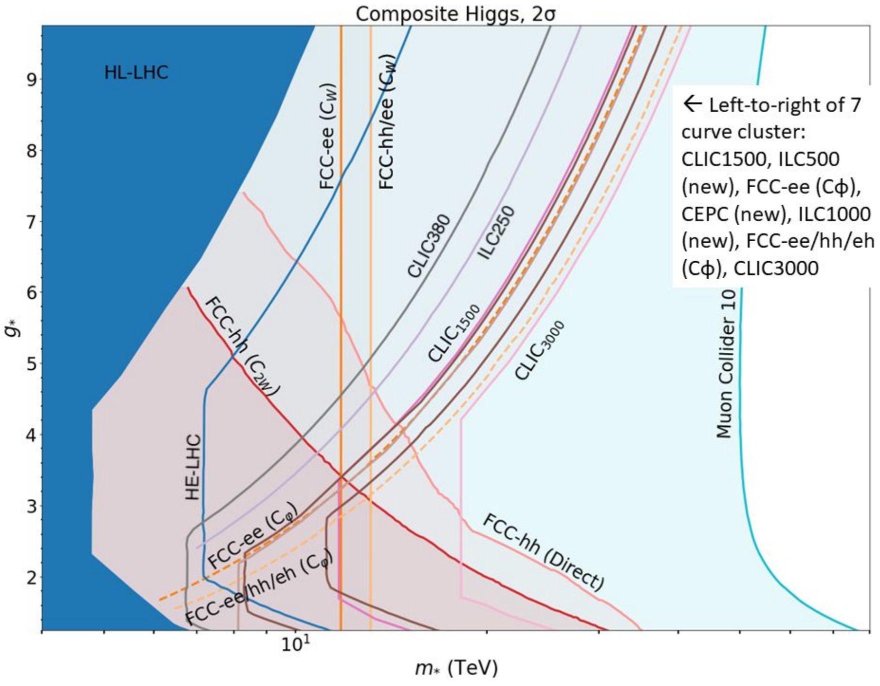
➢ **Focus points for BSM Topical Groups**

# Examples of BSM model-specific explorations

## SUSY models




## Composite Higgs models




**From Snowmass 2021 EF BSM Topical Group Report**

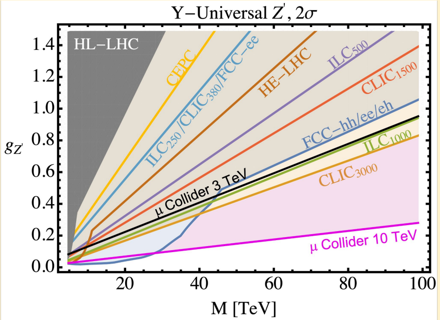
# Examples of BSM general explorations

Identify important benchmarks, explore new collider options, focus on the physics messages

## Heavy Bosons

Identified simplified models:

- Dilepton
- Dijets
- Diboson (VV, Vh, etc)
- Decays including Heavy Neutrinos



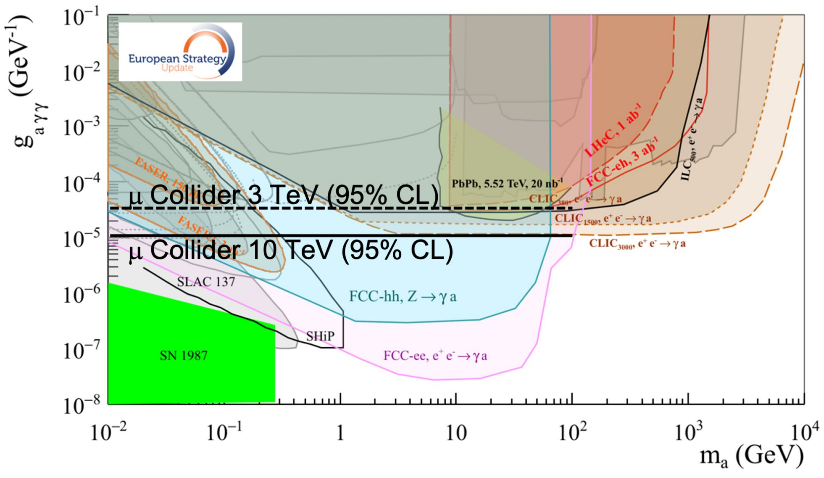

Layout the basic reach of future collider programs **comprehensively** in these simplified modes.

Resonance search and EFT searches are both needed.

arXiv:1910.11775
arXiv:2203.07256

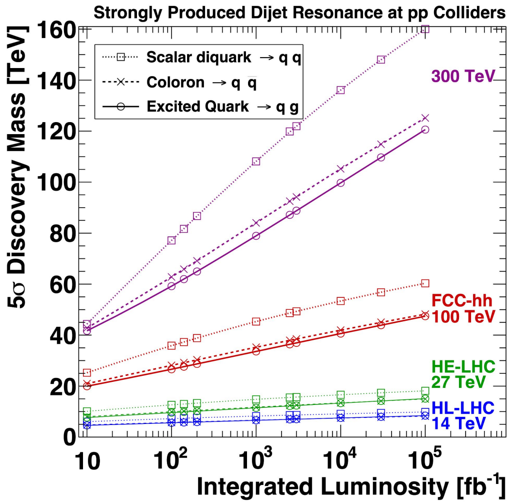
| Machine | Type | √s (TeV) | ∫L dt ($ab^{-1}$) | Source | Z′ Model | 5σ (TeV) | 95% CL (TeV) |
|---|---|---|---|---|---|---|---|
| HL-LHC | p p | 14 | 3 | R.H. | $Z'_{SSM} \to$ dijet | 4.2 | 5.2 |
| | | | | ATLAS | $Z'_{SSM} \to l^+ l^-$ | 6.4 | 6.5 |
| | | | | CMS | $Z'_{SSM} \to l^+ l^-$ | -- | 6.8 |
| | | | | EPPSU* | $Z'_{Univ}(g_Z'=0.2)$ | -- | 6 |
| ILC250/ CLIC380/ FCC-ee | $e^+ e^-$ | 0.25 | 2 | ILC | $Z'_{SSM} \to f^+ f^-$ | 4.9 | 7.7 |
| | | | | EPPSU* | $Z'_{Univ}(g_Z'=0.2)$ | -- | 7 |
| HE-LHC/ FNAL-SF | p p | 27 | 15 | EPPSU* | $Z'_{Univ}(g_Z'=0.2)$ | -- | 11 |
| | | | | ATLAS | $Z'_{SSM} \to e^+ e^-$ | 12.8 | 12.8 |
| ILC | $e^+ e^-$ | 0.5 | 4 | ILC | $Z'_{SSM} \to f^+ f^-$ | 8.3 | 13 |
| | | | | EPPSU* | $Z'_{Univ}(g_Z'=0.2)$ | -- | 13 |
| CLIC | $e^+ e^-$ | 1.5 | 2.5 | EPPSU* | $Z'_{Univ}(g_Z'=0.2)$ | -- | 19 |
| Muon Collider | $\mu^+ \mu^-$ | 3 | 1 | IMCC | $Z'_{Univ}(g_Z'=0.2)$ | 10 | 20 |
| ILC | $e^+ e^-$ | 1 | 8 | ILC | $Z'_{SSM} \to f^+ f^-$ | 14 | 22 |
| | | | | EPPSU* | $Z'_{Univ}(g_Z'=0.2)$ | -- | 21 |
| CLIC | $e^+ e^-$ | 3 | 5 | EPPSU* | $Z'_{Univ}(g_Z'=0.2)$ | -- | 24 |
| FCC-hh | p p | 100 | 30 | R.H. | $Z'_{SSM} \to$ dijet | 25 | 32 |
| | | | | EPPSU* | $Z'_{Univ}(g_Z'=0.2)$ | -- | 35 |
| | | | | EPPSU | $Z'_{SSM} \to l^+ l^-$ | 43 | 43 |
| Muon Collider | $\mu^+ \mu^-$ | 10 | 10 | IMCC | $Z'_{Univ}(g_Z'=0.2)$ | 42 | 70 |
| VLHC | p p | 300 | 100 | R.H. | $Z'_{SSM} \to$ dijet | 67 | 87 |
| Coll. In the Sea | p p | 500 | 100 | R.H. | $Z'_{SSM} \to$ dijet | 96 | 130 |

Increasing Z′ Sensitivity



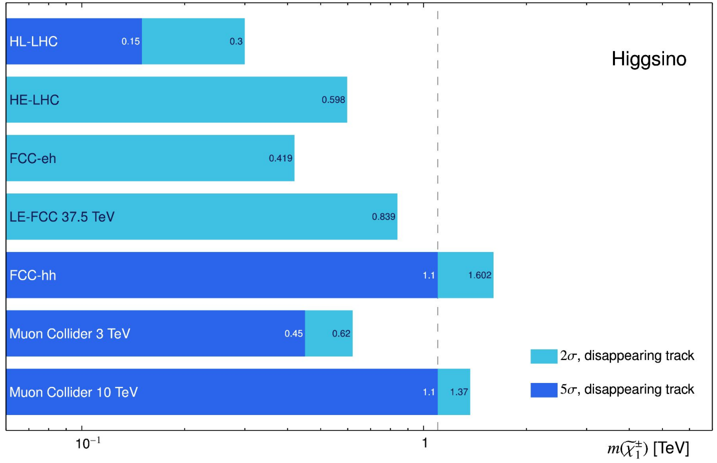

## Axion searches

arXiv:1910.11775
arXiv:2203.06520
arXiv:2203.07261

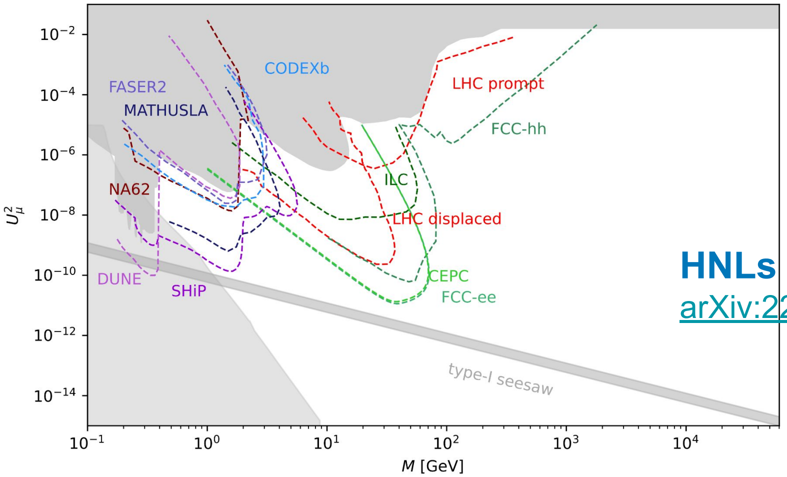



## Di-jet resonances

arXiv:2202.03389




## LLP, arXiv:2102.11292



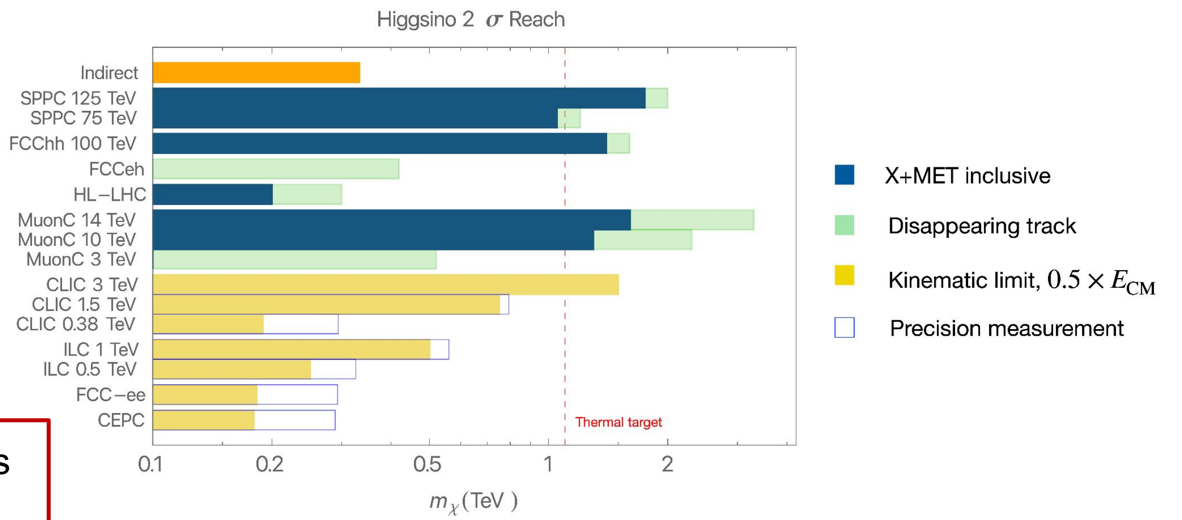

## HNLs

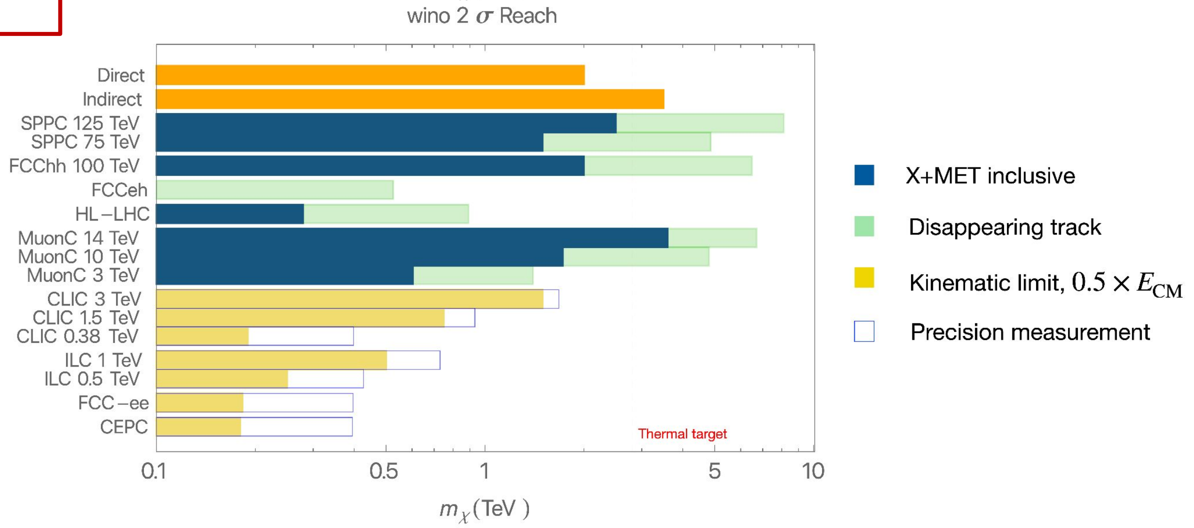
arXiv:2203.05502

# Dark matter at colliders

Complementing observation in astrophysics experiments

Probing interaction of DM with SM particles
Discriminating between different models

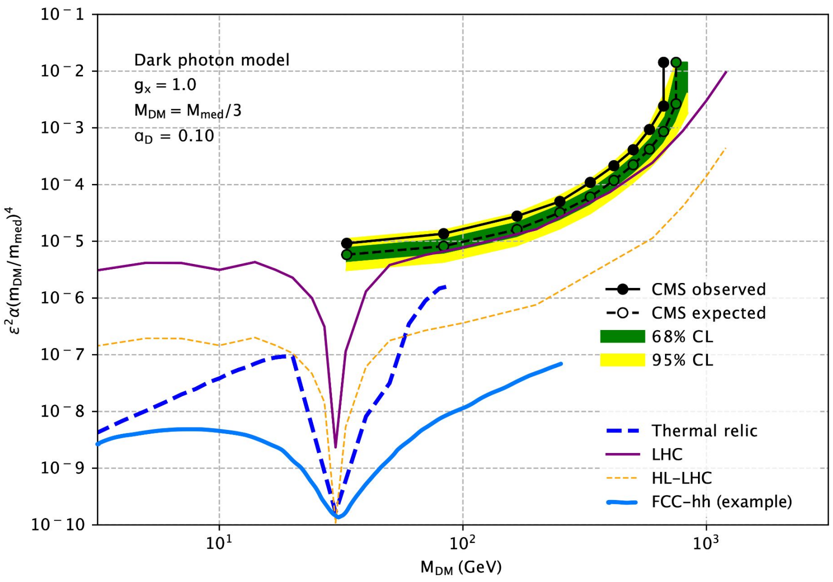


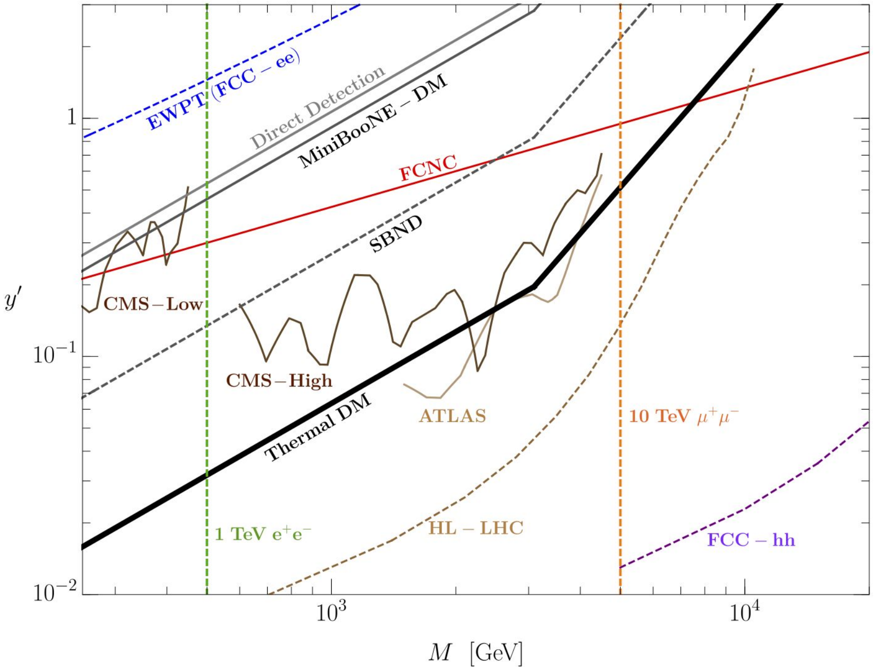




**Example of WIMP DM reach**
arXiv:1910.11775
(update in progress)

# Beyond the WIMP paradigm

DM from models with extra scalar mediators
arXiv:1812.05103, arXiv:2107.08059




Reinterpretation of invisible particles searches in terms of dark photon parameters
**From EF10 report**

Topical Group Reports will be presented in the afternoon session

# Back-up slides

# Energy Frontier Topical Groups

Ten Topical Groups focused on **Electroweak**, **QCD**, **BSM physics**

| 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) |

# Liaisons, task forces, cross-frontier fora

| Other Frontier | Liaisons |
| --- | --- |
| Neutrino Physics Frontier | André de Gouvêa (Northwestern) |
| Rare Processes and Precision | Manuel Franco Sevilla (Maryland) |
| Cosmic Frontier | Caterina Doglioni (Lund), Antonio Boveia (Ohio State) |
| Theory Frontier | Laura Reina (FSU) |
| Accelerator Frontier | Dmitri Denisov (BNL), Meenakshi Narain (Brown) |
| Computational Frontier | Peter Onyisi (U.Texas) |
| Instrumentation Frontier | Caterina Vernieri (SLAC), Maksym Titov (CEA Saclay) |
| Community Engagement Frontier | Daniel Whiteson (UCI), Sergei Gleyzer (Alabama) |

## Early Career Representative

- **Grace Cumming** (U.Virginia)
- **Matt Le Blanc** (U.Arizona)

## Muon Collider Forum Coordinators

**EF: Kevin Black** (U. Wisconsin-Madison), **Sergo Jindariani** (Fermilab)
**AF: Derun Li** (LBNL), **Diktys Stratakis** (Fermilab)
**TF: Patrick Meade** (Stony Brook U.), **Fabio Maltoni** (Louvain U., Bologna)

## e+e- Collider Forum Coordinators

**EF: Maria Chamizo Llatas** (BNL), **Sridhara Dasu** (Wisconsin)
**AF: Emilio Nanni** (SLAC), **John Power** (ANL)
**IF: Ulrich Heintz** (Brown), **Steve Wagner** (Colorado)

## Monte Carlo task force and production team

Coordinated by **John Stupak** (U. Oklahoma)
1) Assess the MC needs ⇒ **"Task force"**
2) Produce MC samples ⇒ **"Production Team"**

# Energy Frontier Meetings

**2020**

- Energy Frontier **Kick-off Meeting**, May 21, 2020, see agenda
- **Energy Frontier Workshop "Open Questions and New Ideas"**, July 20-22, 2020,
- **Snowmass CPM Meeting: EF Report** (Oct. 2020): focus points and key questions.

**2021**

- **EF slowed down activities in 2021 until June**
  - Community continued to work collaboratively
  - Monte Carlo production activities continued to support the needs of EF
  - Occasional and informal Topical Group 'conversations' to assure scientific continuity and support of ongoing activities
- **EF restart workshop** - August 30-Sep 3, 2021

**2022 - Building towards the CSS and the final Report**

- **EF Workshop, Brown University. March 28 - April 1 2022**
  - Planning towards EF reports (frontier and Topical Group)
  - Building EF vision
- **EF Topical Group Convener Meeting - FNAL - June 6-7 2022**
  - Formulating the EF report
- **EF Meeting with Representative of Future Project Proponents - Stony Brook U., June 13-15 2022**
  - Discussing EF vision
- **EF community meeting pre-CSS - June 24 2022 (virtual)**
  - Presenting draft of EF reports (frontier and Topical Group)

# 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:

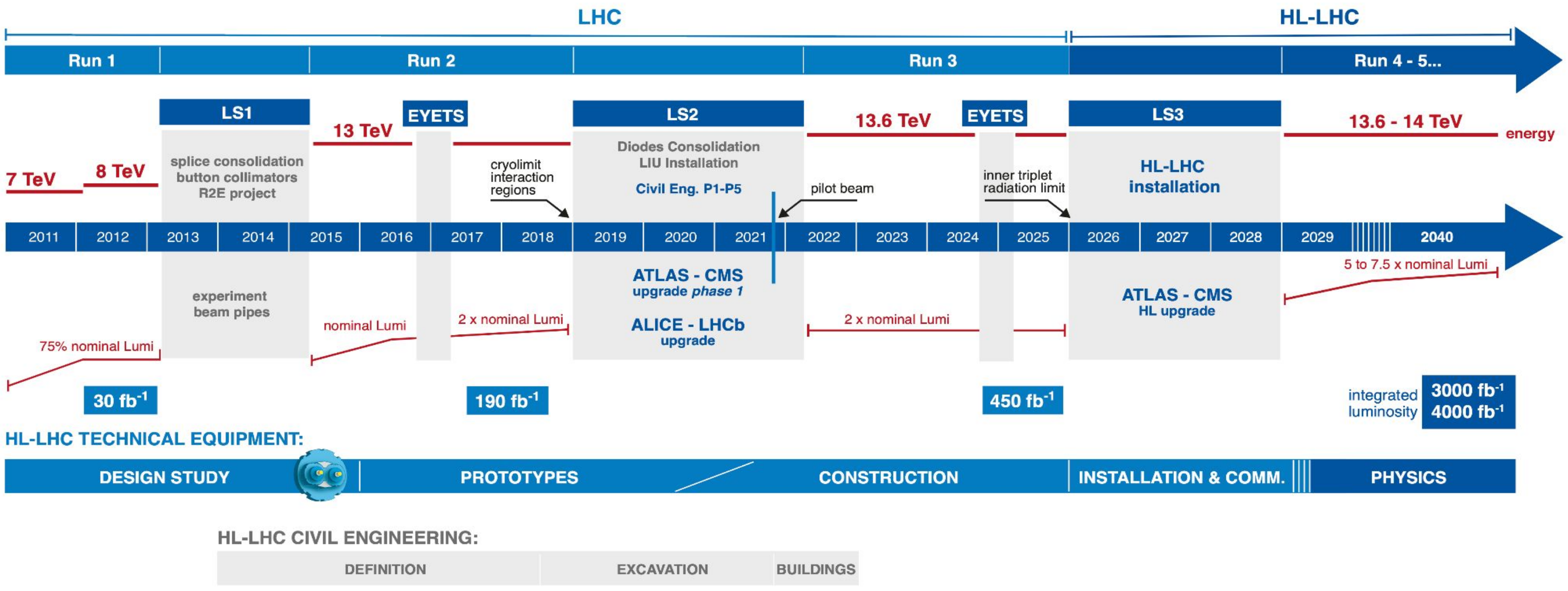
- e+e- linear colliders (Dec. 15, 2021): https://indico.fnal.gov/event/52161/
- e+e- circular colliders (Jan. 19, 2022) https://indico.fnal.gov/event/52534/
- μ+μ- colliders (Feb. 16, 2022): https://indico.fnal.gov/event/53010/
- circular pp and ep colliders (Mar 16, 2022): https://indico.fnal.gov/event/53473/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

**Converged to dedicated discussion at the EF Workshop (March 28-April 1).**

# LHC / HL-LHC Plan



# ESG: Future Collider Scenarios & Timelines