The Higgs physics case

Summary of Snowmass and Priorities

Laura Reina (FSU)

Cool Copper Collider Workshop – February 6-7, 2023

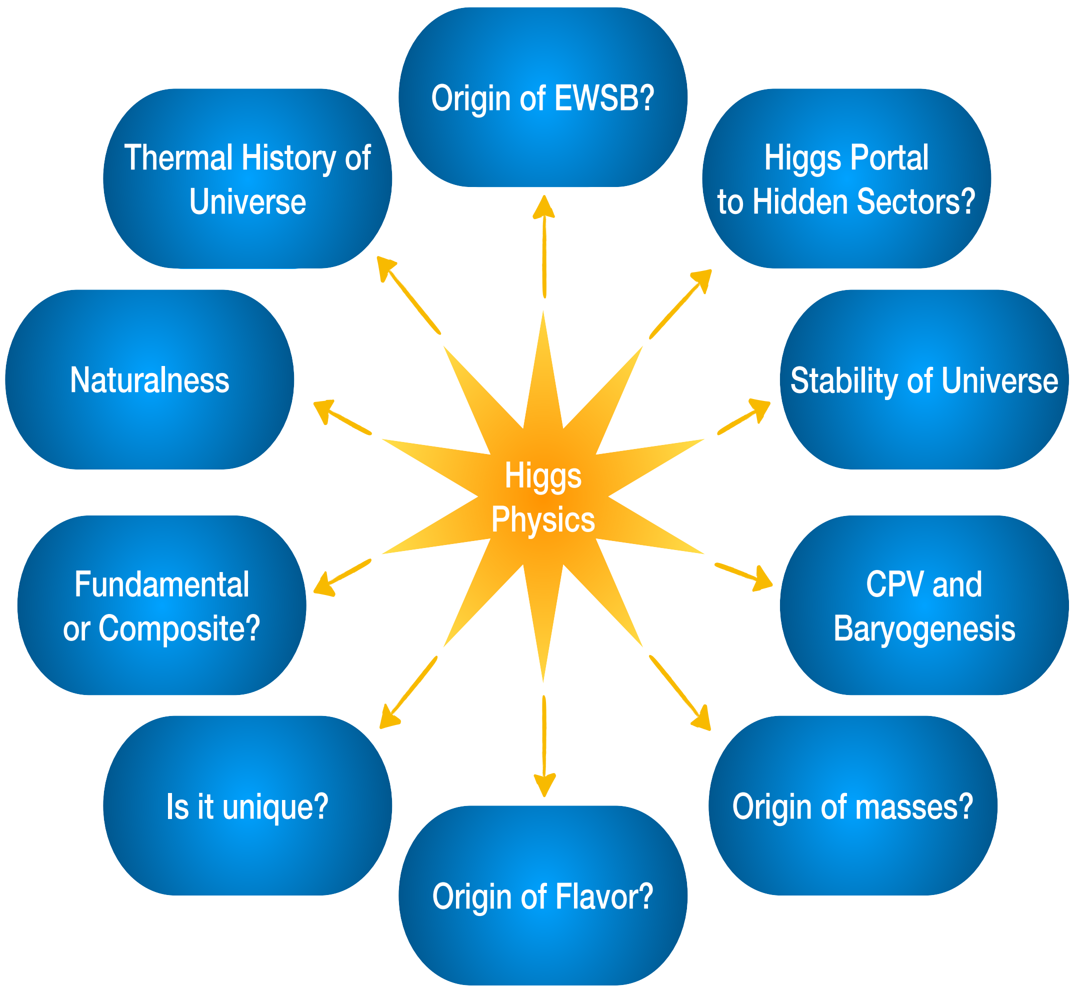
From the work of the Snowmass 2021-22 Energy Frontier

Conveners: Meenakshi Narain, Laura Reina, Alessandro Tricoli

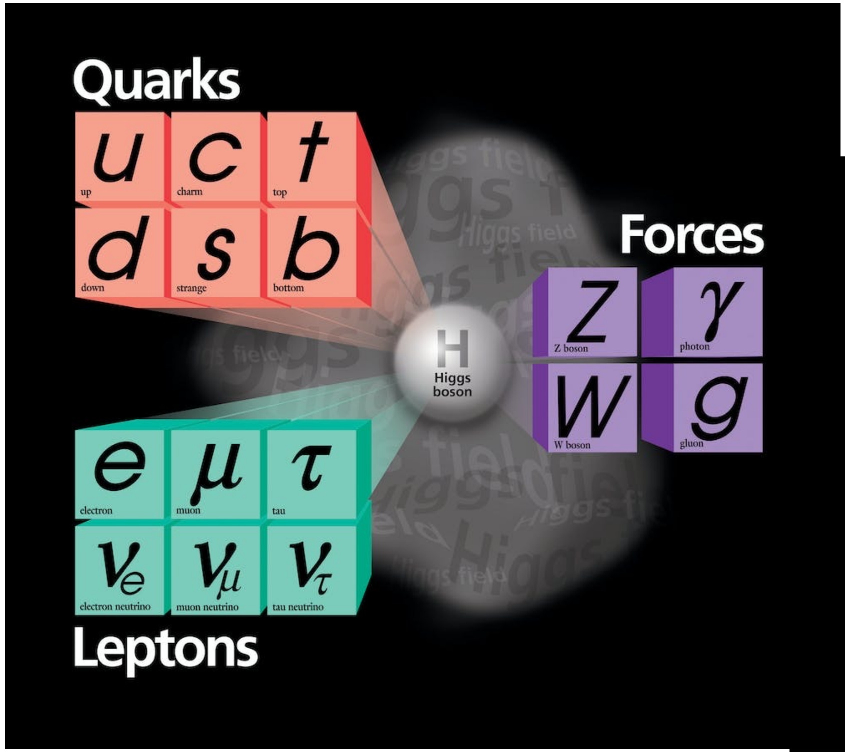
Higgs Topical Group Conveners: Sally Dawson, Patrick Meade, Isobel Ojalvo, Caterina Vernieri

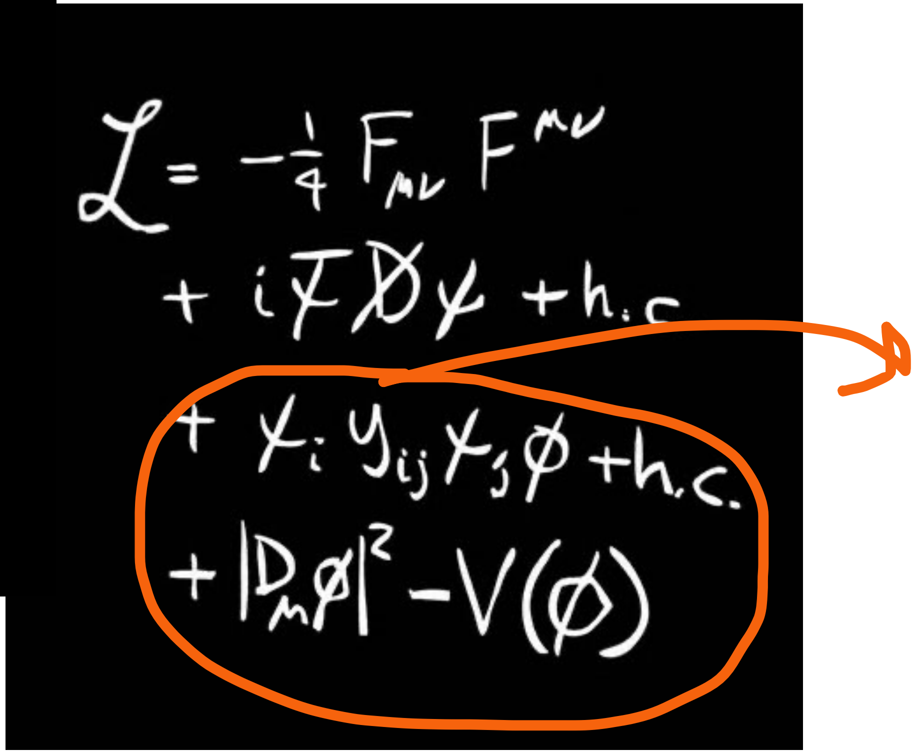
Higgs physics identified as central to the Energy Frontier physics program

Unique link to BSM physics



Higgs central to the Standard Model of particle physics





... half of it is about Higgs!

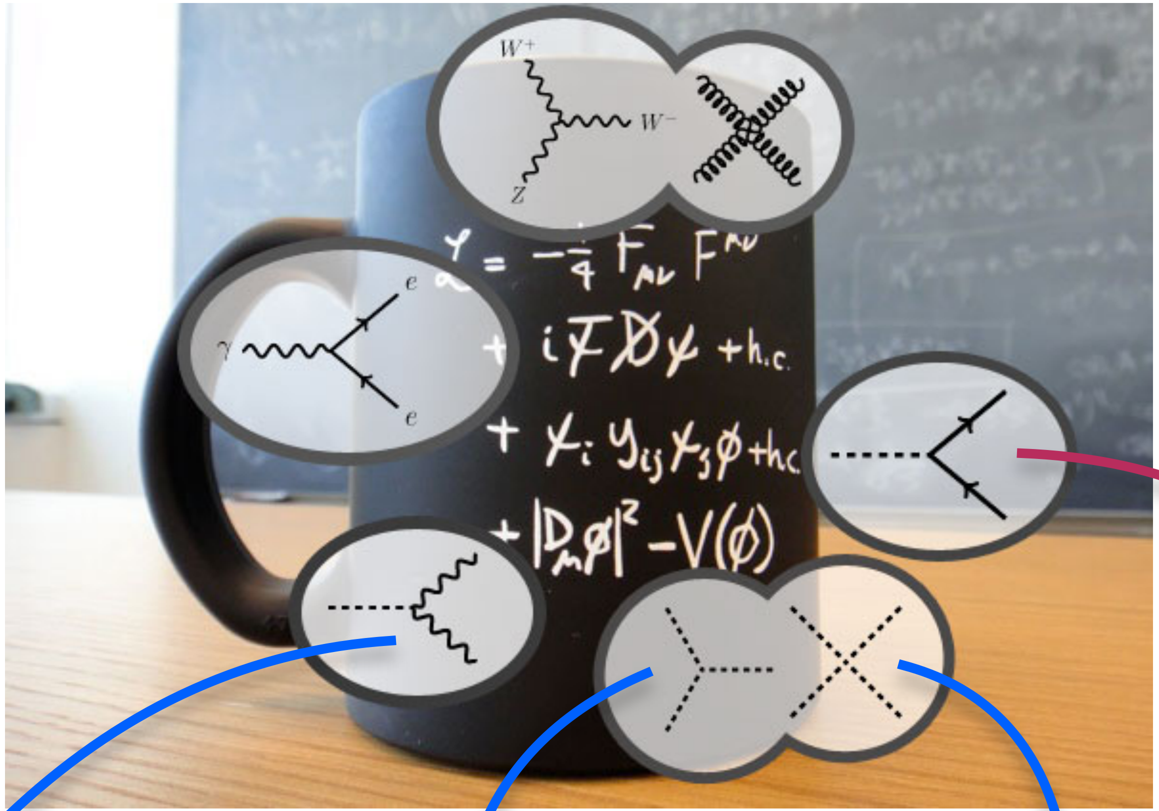
In confirming its successful description of electroweak interactions,

the SM has given us the first evidence of new physics: the Higgs boson

Future explorations at the EF will have to make the most out of it!

SM: unique pattern of Higgs couplings and particle masses

Very constrained
Very predictive
yet
Very unsatisfactory



$$-2i\frac{M_V^2}{v}g^{\mu\nu}$$

$$-3i\frac{M_H^2}{v}=-6iv\lambda$$

$$-3i\frac{M_H^2}{v^2}=-6i\lambda$$

$$-i\frac{m_f}{v}=iy_f$$

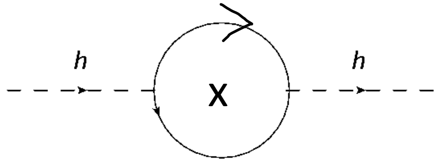
The true origin of such pattern escapes the SM

The origin of SSB and ultimately of the EW scale is unexplained by the SM

- Why the Higgs potential? Why $\mu^2<0$?
  - Dynamical origin? What induces it?
  - Cubic and quartic couplings, same λ?

$$V(\phi) = \mu^2 \phi^\dagger \phi + \lambda (\phi^\dagger \phi)^2$$

- Why M_H=125 GeV? → Hierarchy problem – Naturalness
  - Mass of scalar not protected by symmetry, receives large quantum corrections



$$\Delta M_H^2 \propto \pm \frac{\lambda_X}{16\pi^2} M_X^2$$

Yukawa interactions depends on arbitrary parameters, unexplained by the SM

- Why the hierarchy of Yukawa couplings ↔ fermion masses?
- Why flavor diagonal scalar couplings? Why only one scalar?
- Other sources of flavor mixing and CP violation?
- A new force all together?

$$L_{Yukawa} = y_{ij} \bar{\psi}_L^i \phi \psi_R^j + h.c.$$

fermion masses

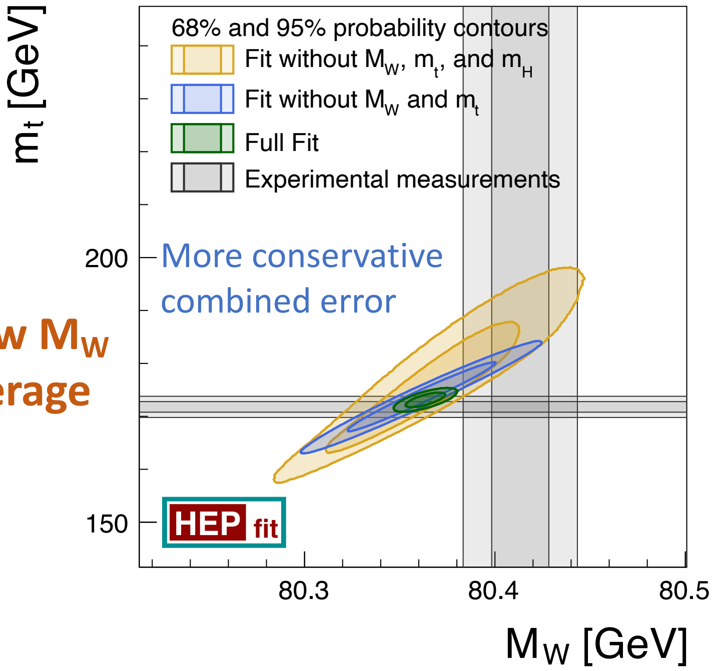
$$y_{ij} \to \frac{m_f}{v} \delta_{ij}$$

$$\phi \to H + v$$

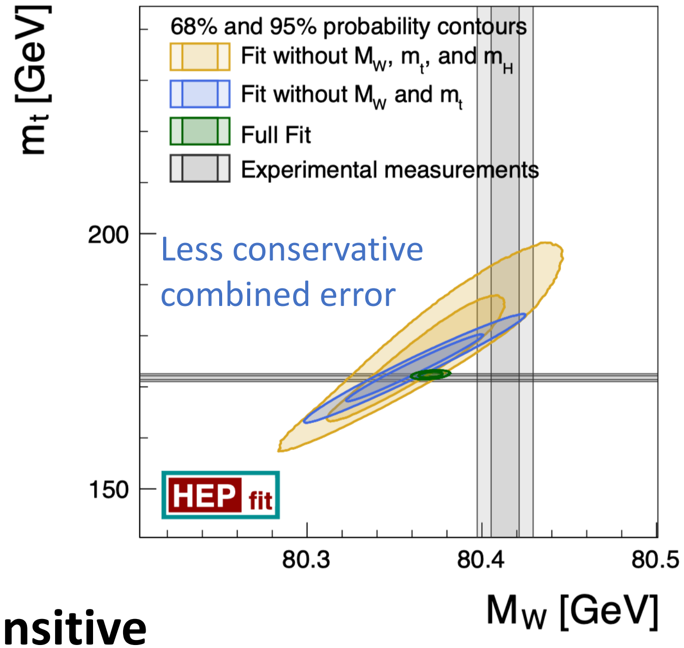
Yukawa couplings

From SM global fits to the EW phase transition, highly sensitive to new physics

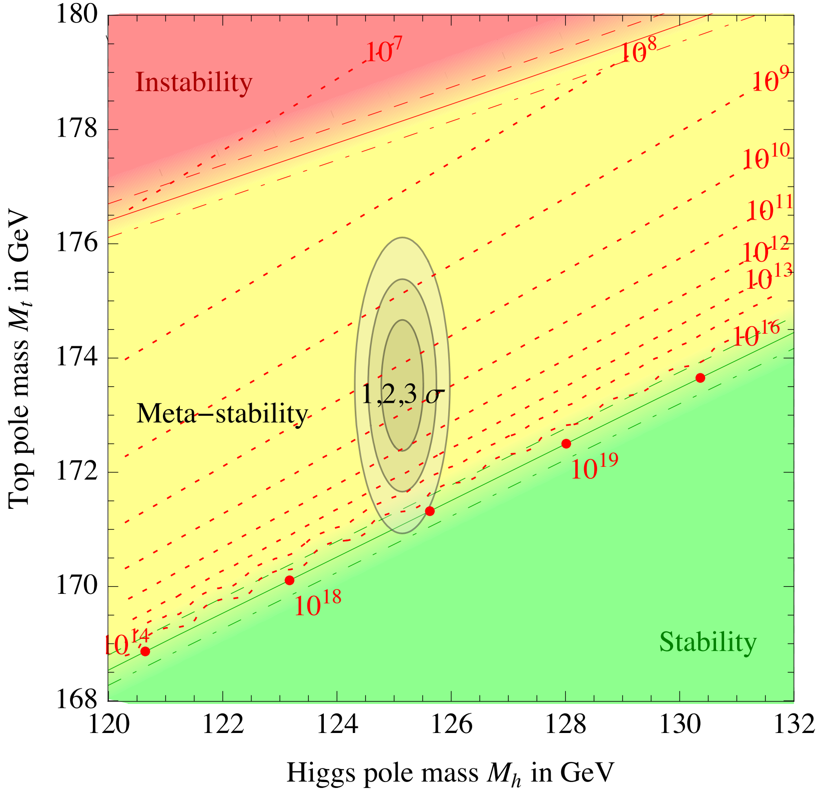
New M_W average



De Blas et al. [arXiv: 2204.04204]



Strongly constrained and very sensitive to stress testing of SM parameters

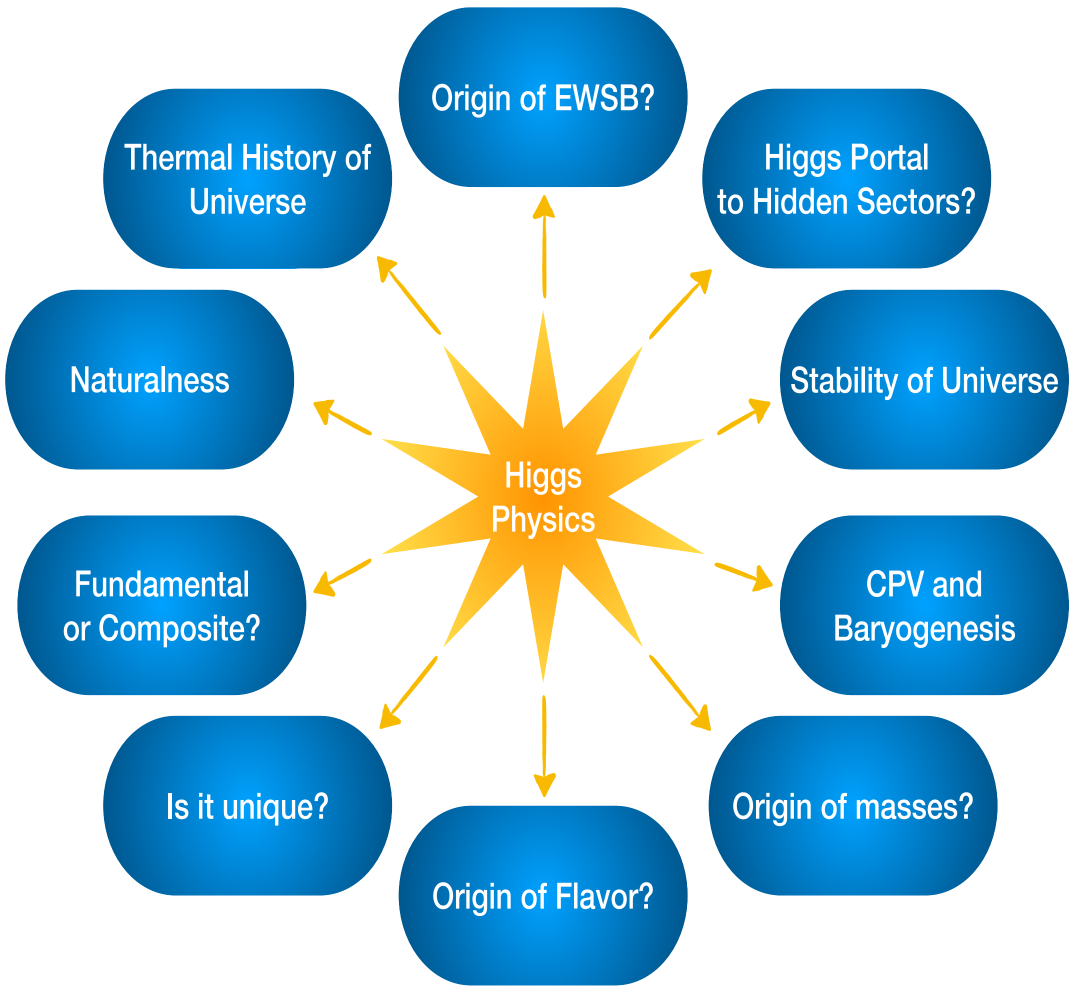


Criticality (**$\lambda \to 0$**) condition reached for $\Lambda \approx 10^{10}$–10^{12} GeV.
Is this a signal of NP below the Planck scale?

Buttazzo et al. [arXiv:1307.3536]

Higgs physics identified as central to the Energy Frontier physics program

Unique link to BSM physics

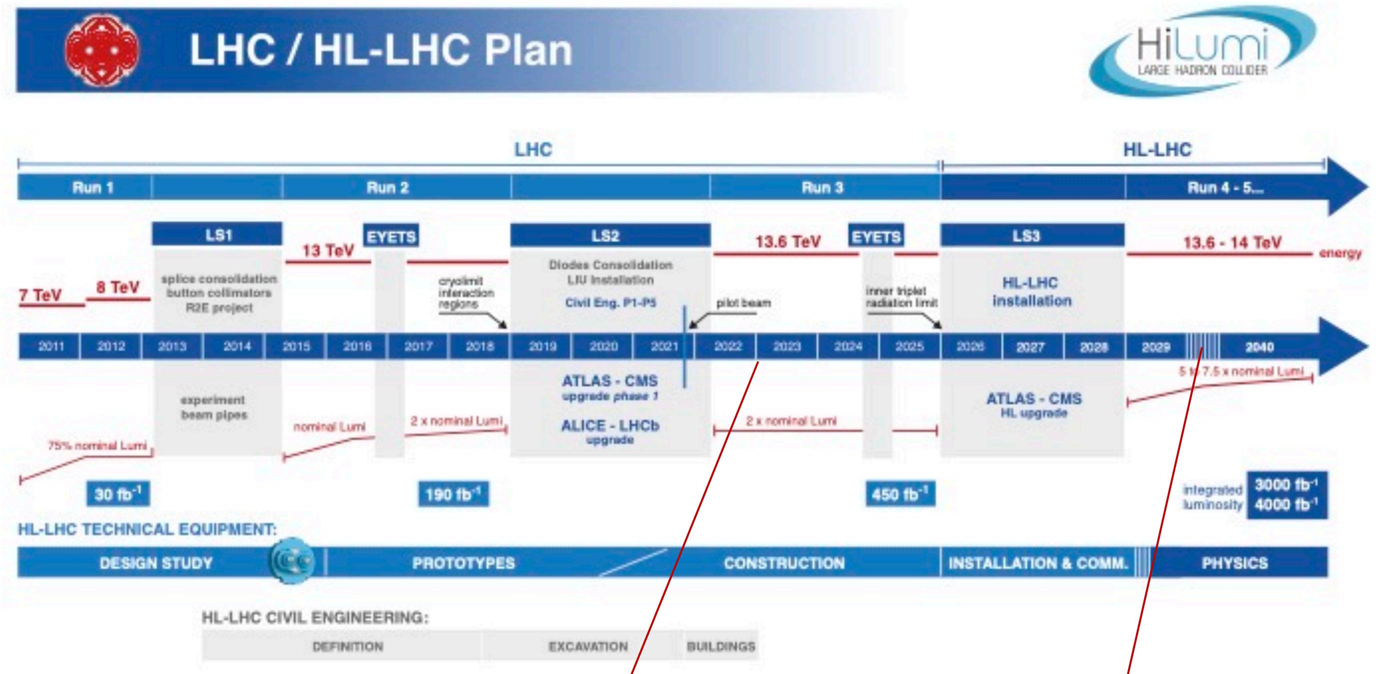


Didn’t we know all this already?

Previous P5 gave us a “Higgs driver”

Lots has happened in ten years

Ten years of LHC physics and looking ahead



We are only here

Many years of HL running ahead of us

Higgs physics has been at the core of the LHC physics program

Snowmass 2013/Previous P5

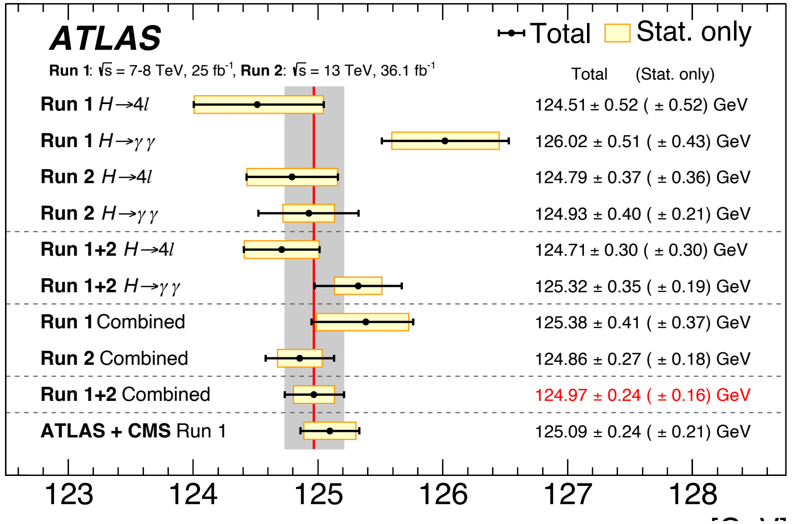
- **Run 1**: **Higgs discovery**
- **Run 2**: **Higgs couplings**
  - outperformed expectations
- **Run 3 to HL-LHC**
  - **Higgs precision program**

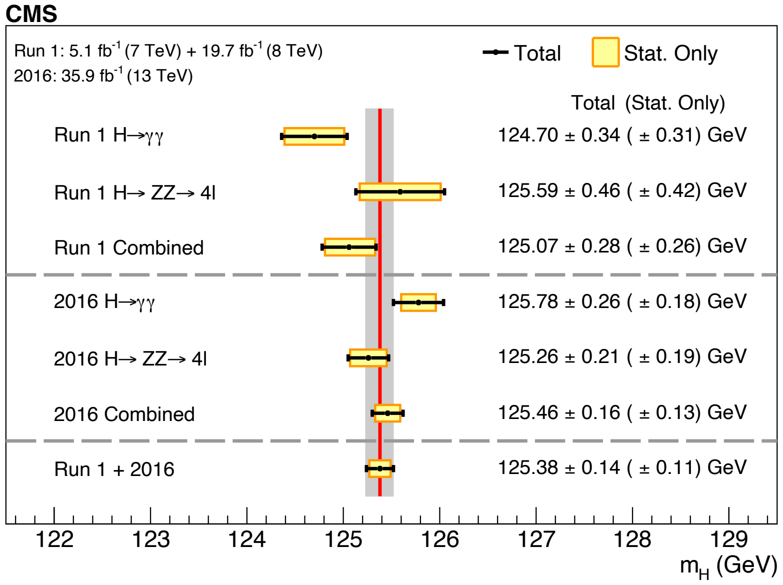
Snowmass 2021/Current P5

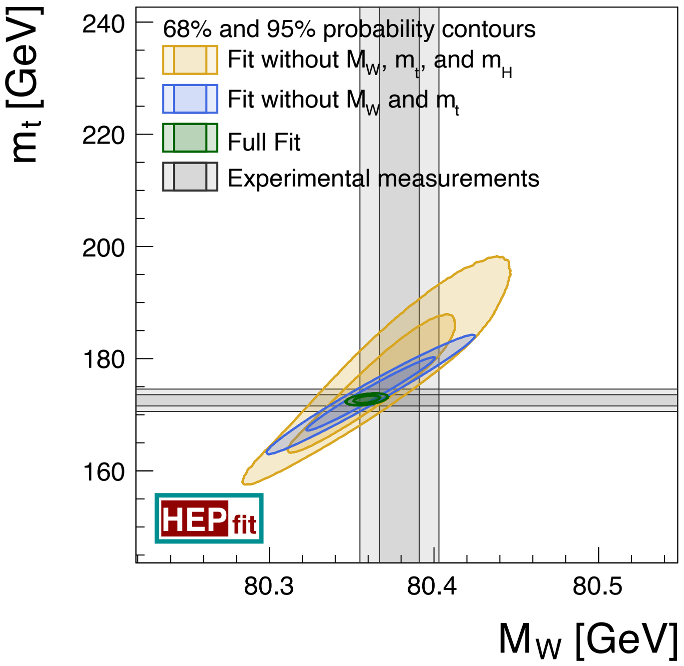
- → 2-fold increase in statistics by the end of Run 3
- → 20-fold increase in statistics by the end of HL-LHC!

Run 1+2

From discovery to precision physics

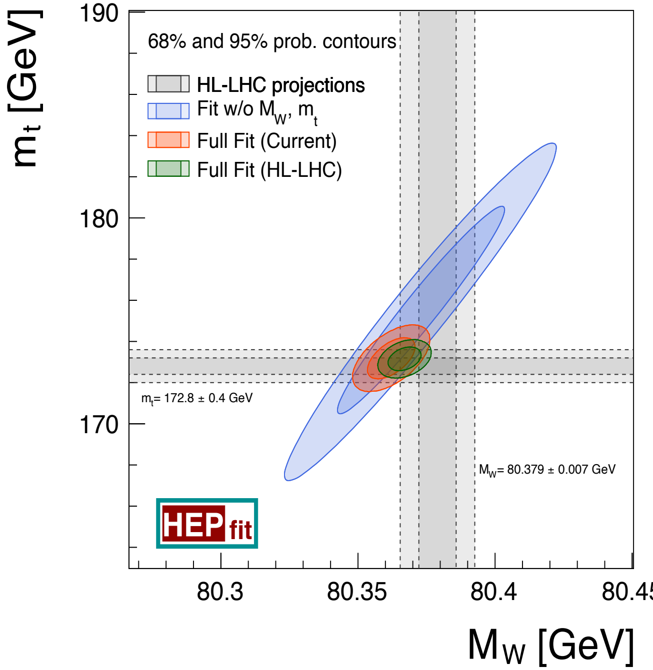






De Blas et al. [2204.04204]

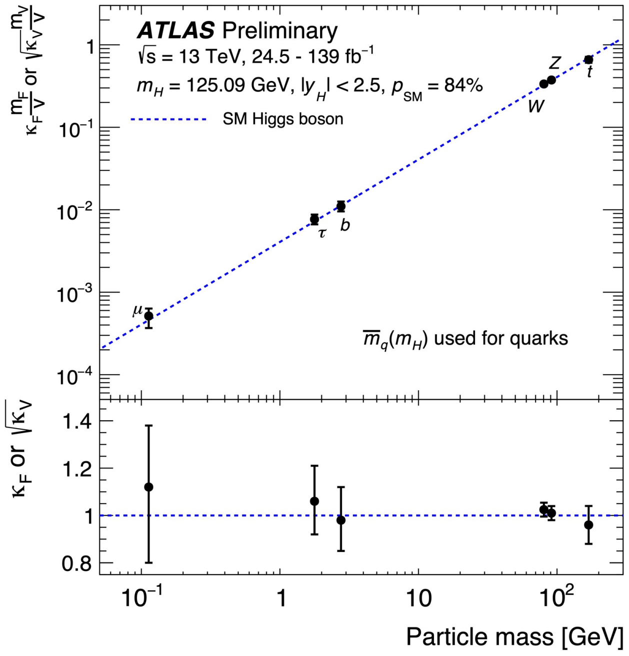
De Blas et al. HL/HE-LHC Report [1902.04070]



M_H promoted to EW precision observable

Run 2 Zooming in on couplings to probe the TeV scale

CMS, arXiv:2207.00043

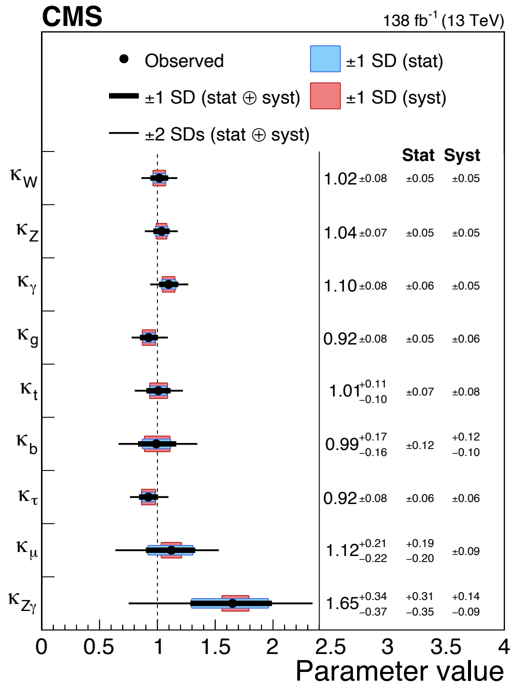


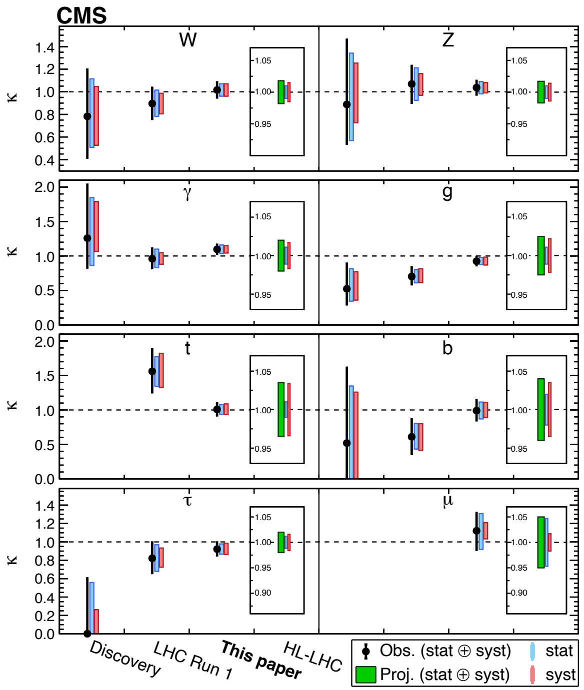
$$\kappa = g_X/g_X^{SM} = 1 + \Delta\kappa$$

$$\Delta\kappa \propto v^2/\Lambda_{BSM}^2$$

Precision on $\Delta\kappa$

reach for Λ_{BSM}





- ➢ Couplings to **W/Z at 5-10 %**
- ➢ Couplings to **3rd generation to 10-20%**
- ➢ **First measurements of 2nd generation** couplings

- ➢ **HL-LHC projections** from **partial Run 2** data (YR):
  - ➢ **2-5 % on most couplings**
  - ➢ **< 50% on Higgs self-coupling.**
- ➢ **Full Run2** results **drastically improve partial Run 2 results:** better projections expected

Run 2 and beyond

Beyond SM-coupling rescaling

Model new physics by extending the SM Lagrangian by effective interactions (ex. SM EFT)

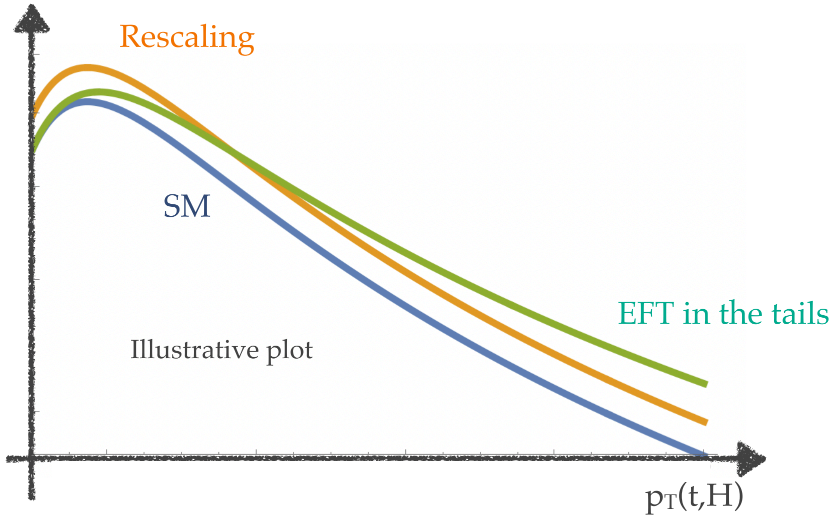
$$\mathcal{L}_{\rm SM}^{\rm eff} = \mathcal{L}_{\rm SM} + \sum_{d>4} \frac{1}{\Lambda^{d-4}} \mathcal{L}_d = \mathcal{L}_{\rm SM} + \frac{1}{\Lambda}\mathcal{L}_5 + \frac{1}{\Lambda^2}\mathcal{L}_6 + \cdots$$

$$\mathcal{L}_d = \sum_i C_i^{(d)} \mathcal{O}_i^{(d)}, \quad \left[\mathcal{O}_i^{(d)}\right] = d$$

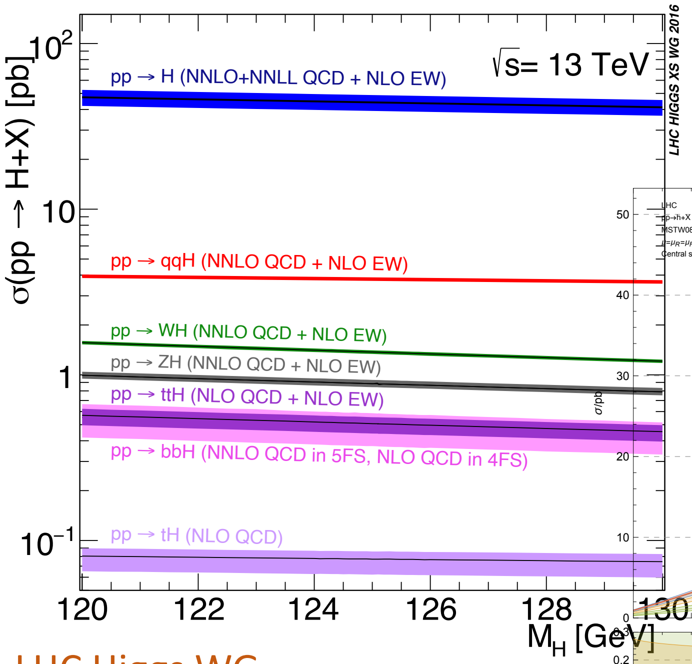
Under the assumption that new physics leaves at scales $\Lambda > \sqrt{s}$

Expansion in $(v, E)/\Lambda$: **affects all SM observables** at both low and high energy

- **SM masses and couplings** → **rescaling**
- **Shapes of distributions** → more visible in **tails of distributions**

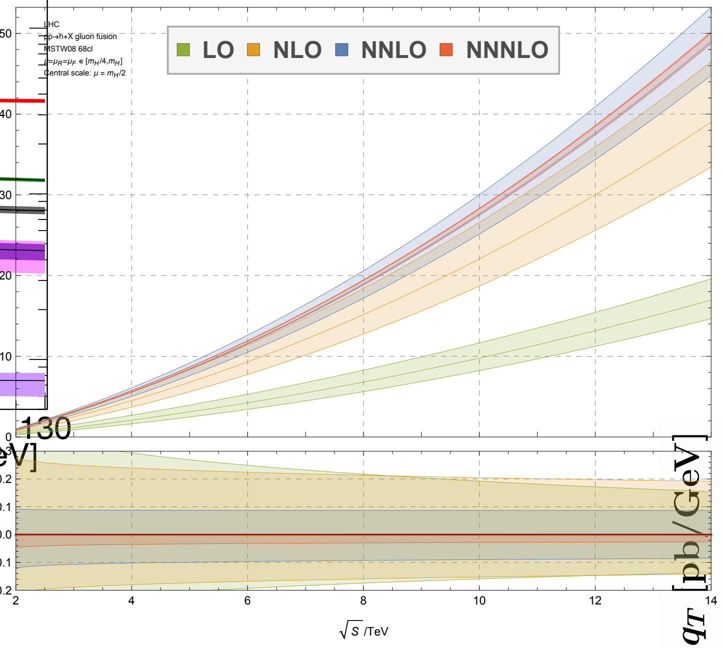


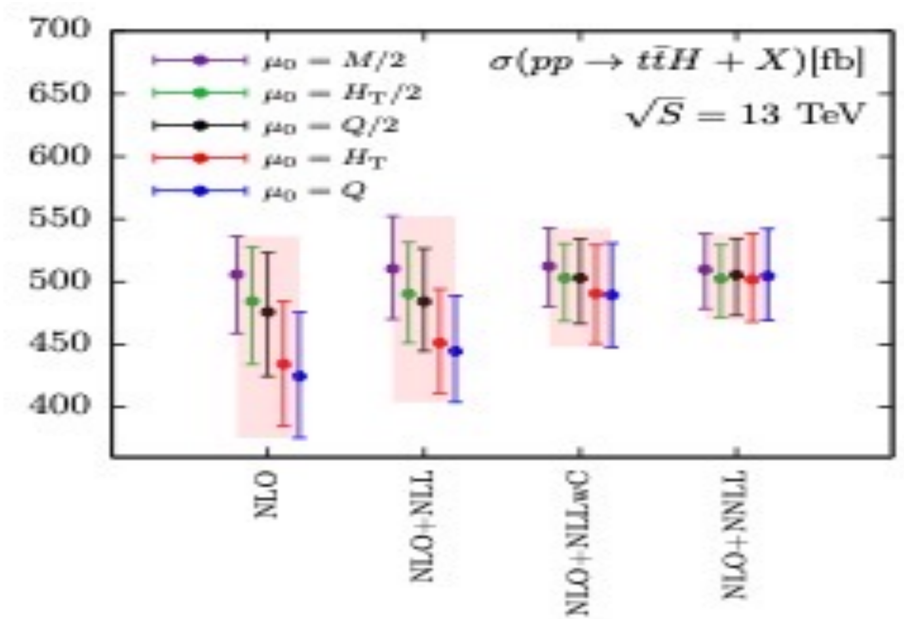
Theory has come a long way



LHC Higgs WG

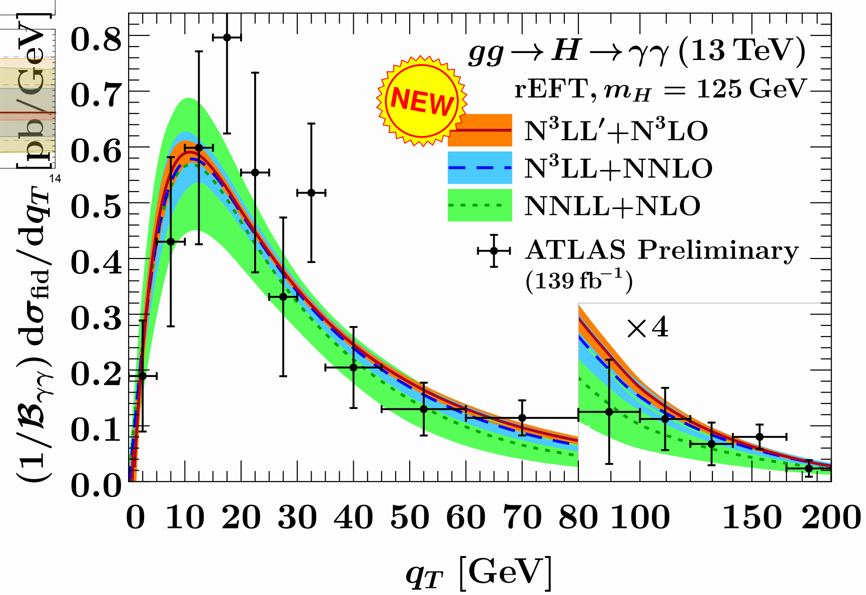
Anastasiou et al. [1502.06056]





Kulesza et al. [1812.08622]

Bliss et al. [2102.08039]

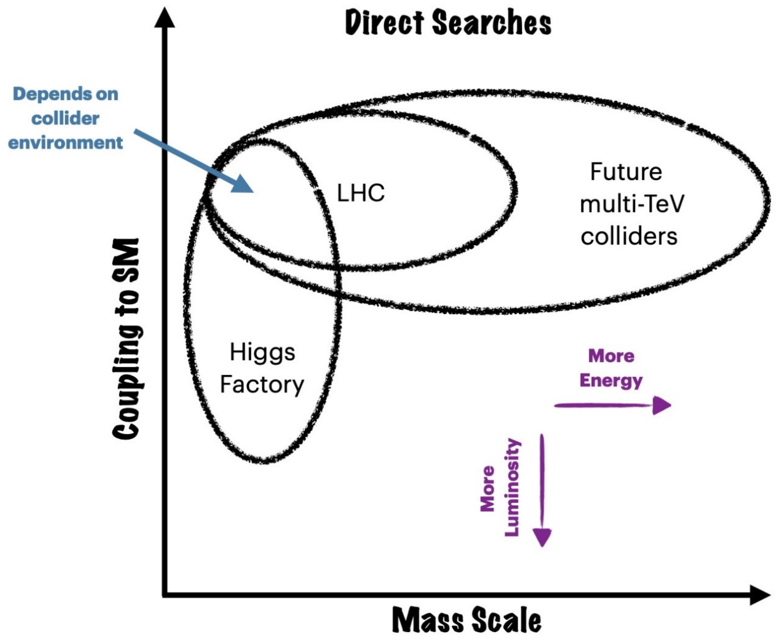


Several backgrounds also know at NLO QCD+EW or improved NLO (+NNLL) (e.g. W/Z+j, ttbb, ttW, ttZ, ttγ, …)

What to look for after HL-LHC

Beyond the HL-LHC: Precision and Energy

New physics can be at low as at high mass scales,
Naturalness would **prefer scales close to the EW scale**, but the LHC has already placed **strong bounds around 1-2 TeV.**

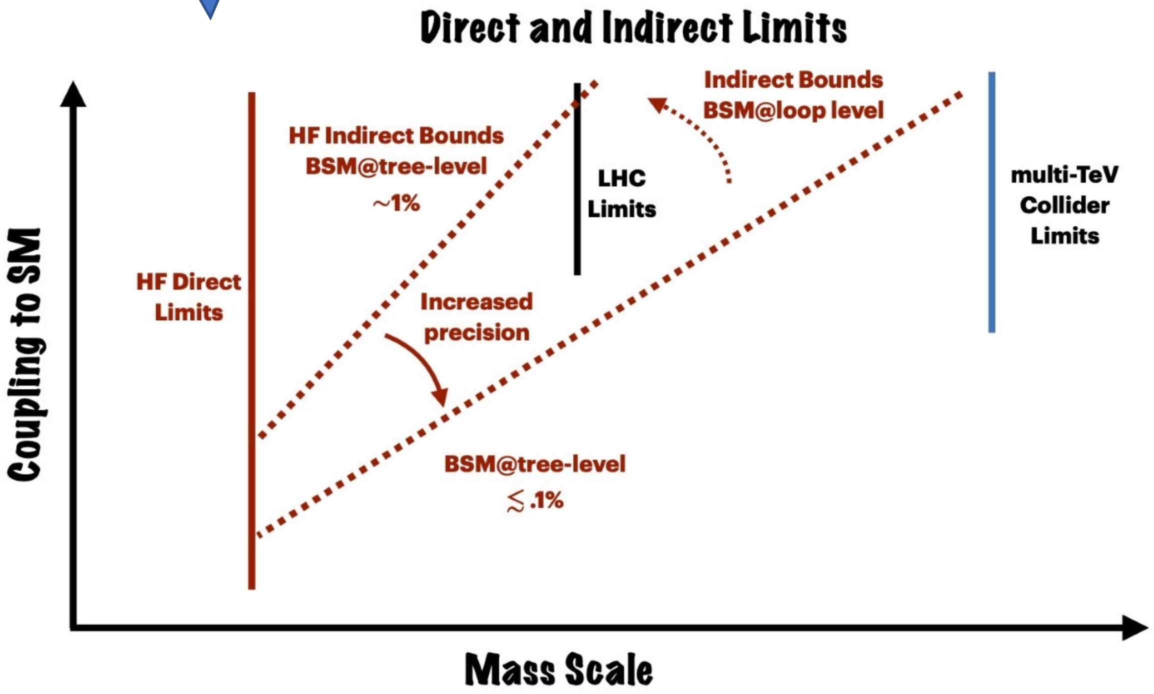


Higgs coupling measurements and direct searches will complement each other in exploring the 1-10 TeV scale and beyond.

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**:
$\delta\eta_{SM} \sim 1/16\pi^2 \times g^2_{BSM} E^2/M^2$



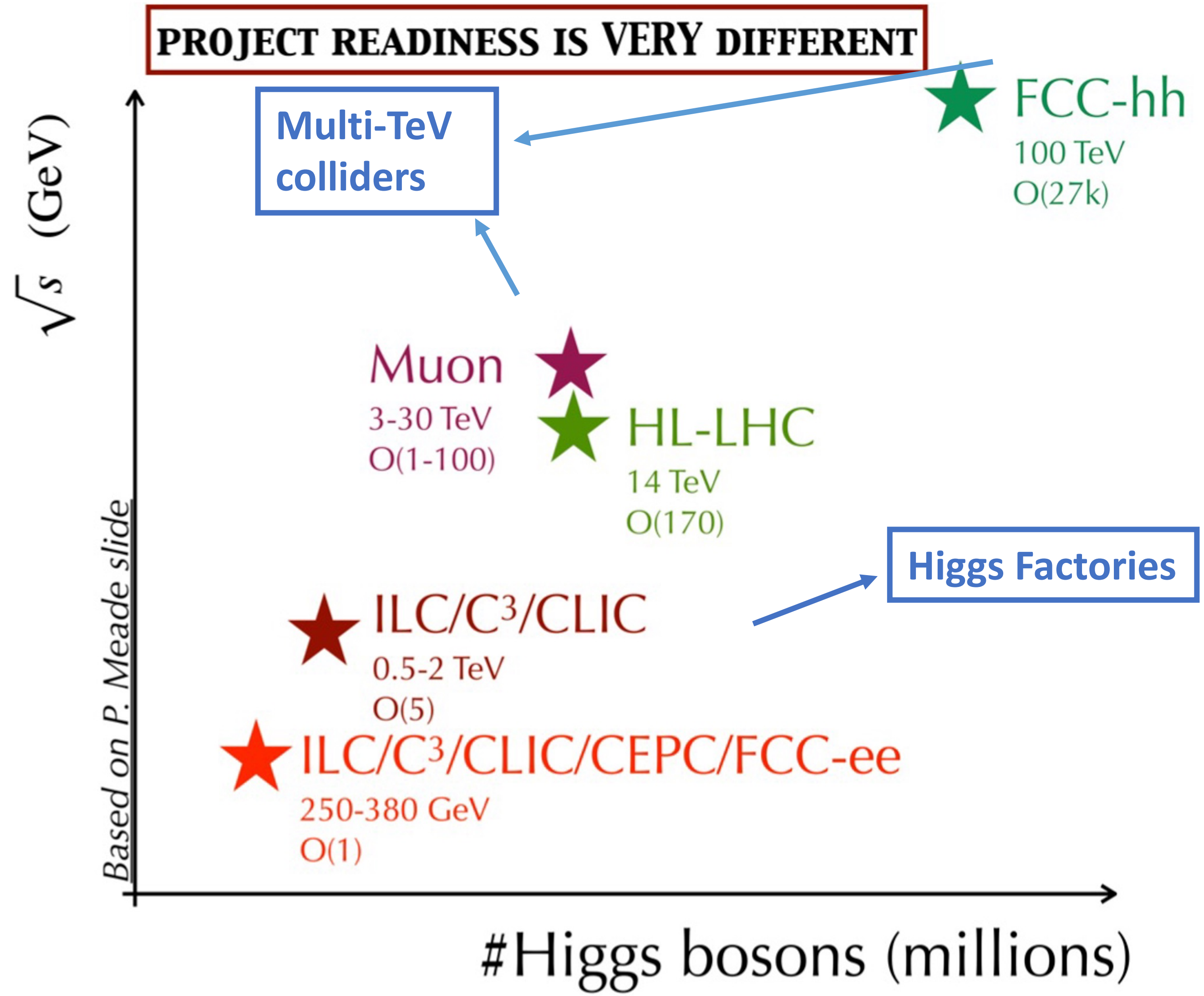
Beyond the HL-LHC: proposed future colliders

LEPTON COLLIDERS

- **Circular e+e-** (CEPC, FCC-ee)
  - **90-350 GeV**
  - *strongly limited by synchrotron radiation above 350– 400 GeV*
- **Linear e+e-** (ILC, CLIC, C^3)
  - **250 GeV — > 1 TeV**
  - *Reach higher energies, and can use polarized beams*
- **μ+μ-**
  - **3-30 TeV**

HADRON COLLIDERS

- **75-200 TeV** (FCC-hh)



Snowmass 21:
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		

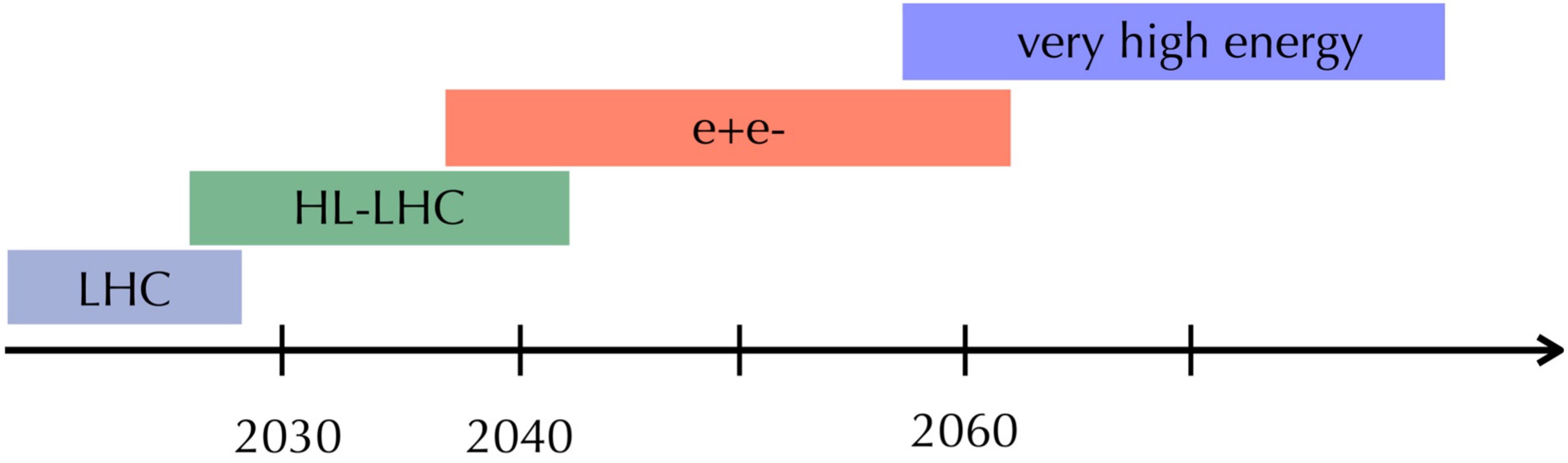
Snowmass EF wiki: https://snowmass21.org/energy/start

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 Collider ITF report (arXiv: 2208.06030)

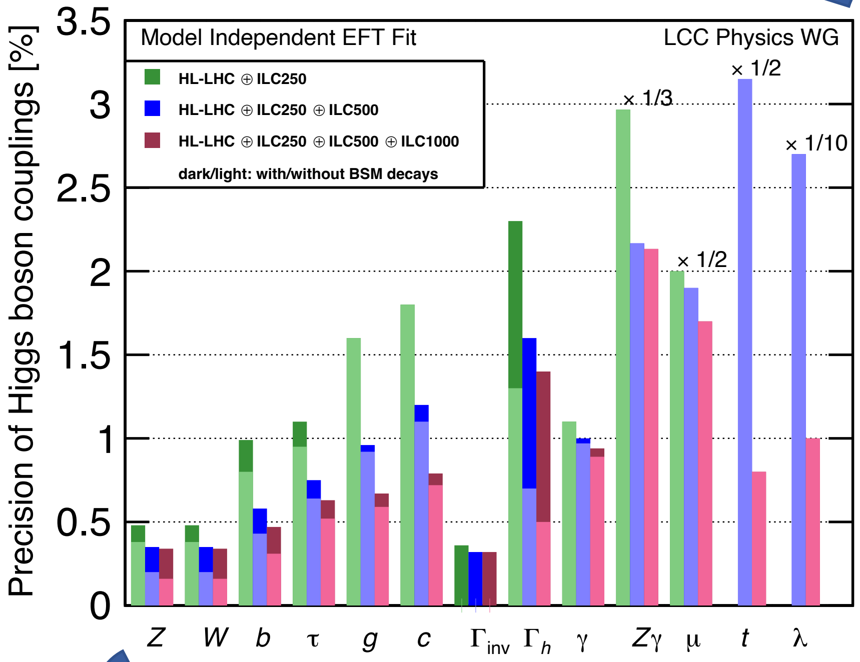
Beyond the HL-LHC: projections for Higgs couplings

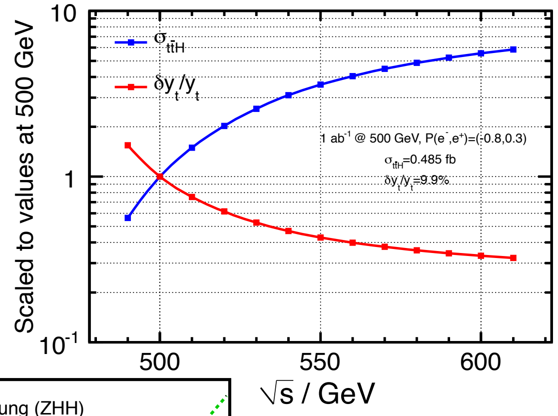


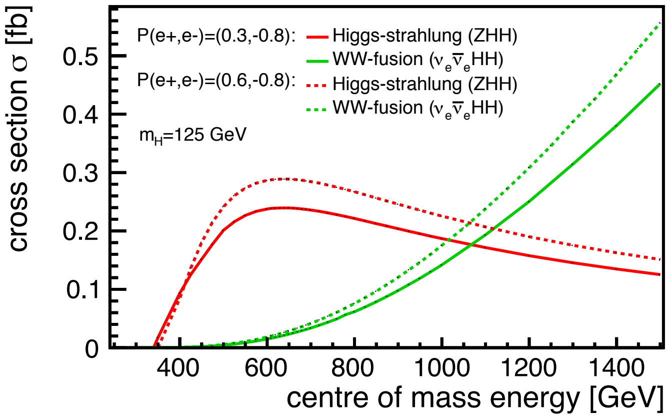
H couplings to:	**O(5-15)%**	**O(0.1-1)%**	**O(1)‰**
H self-coupling to	**<O(50)%**	**O(20)%**	**O(1)%**

From C. Vernieri – Snowmass 21 EF Workshop - Brown U. - March 2022

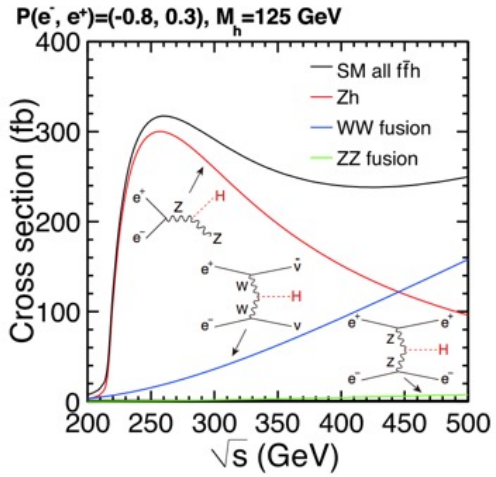
The case of e^+e^- Higgs factories



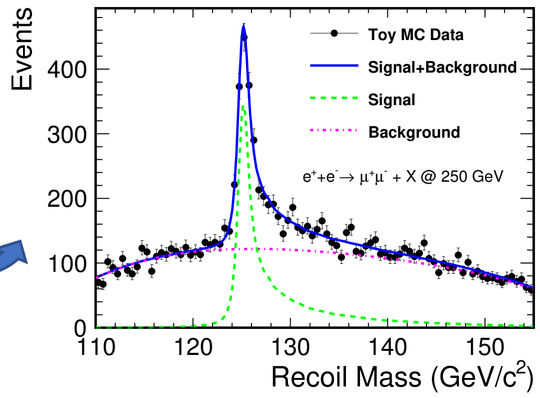


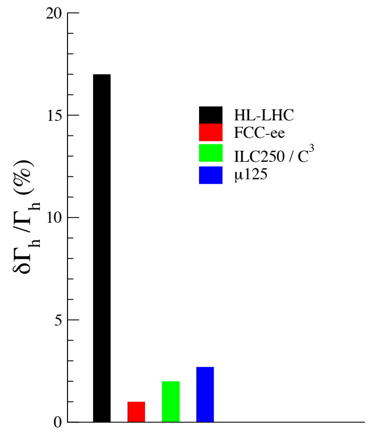


Energy matters
top-Yukawa, HH, extended Higgs sectors need >500 GeV

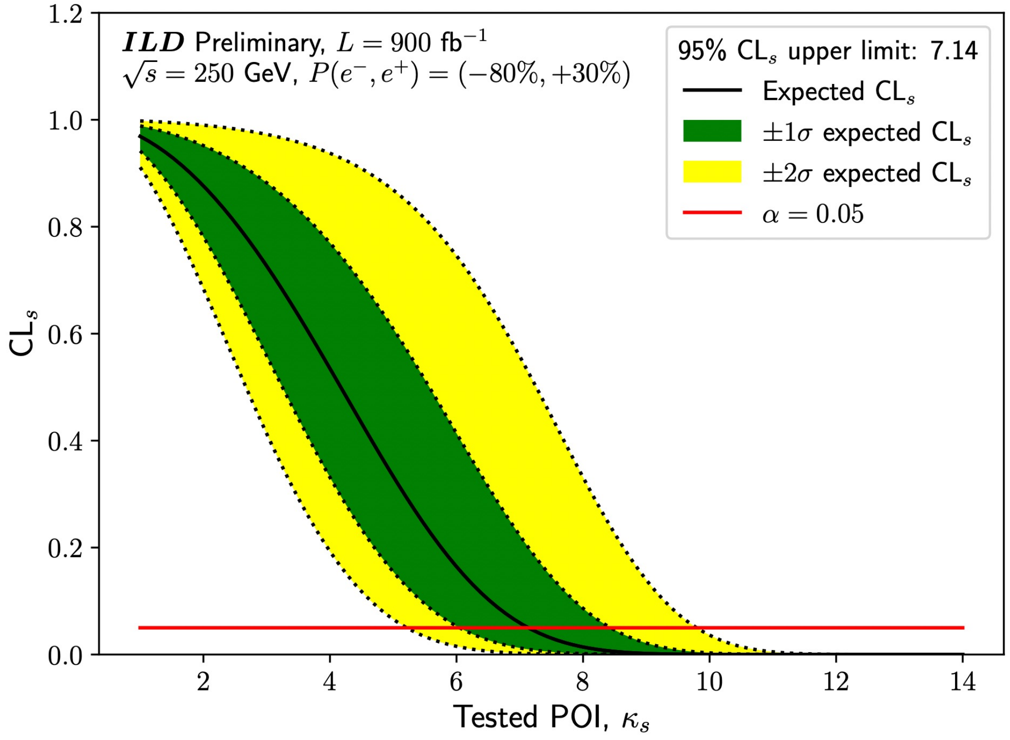


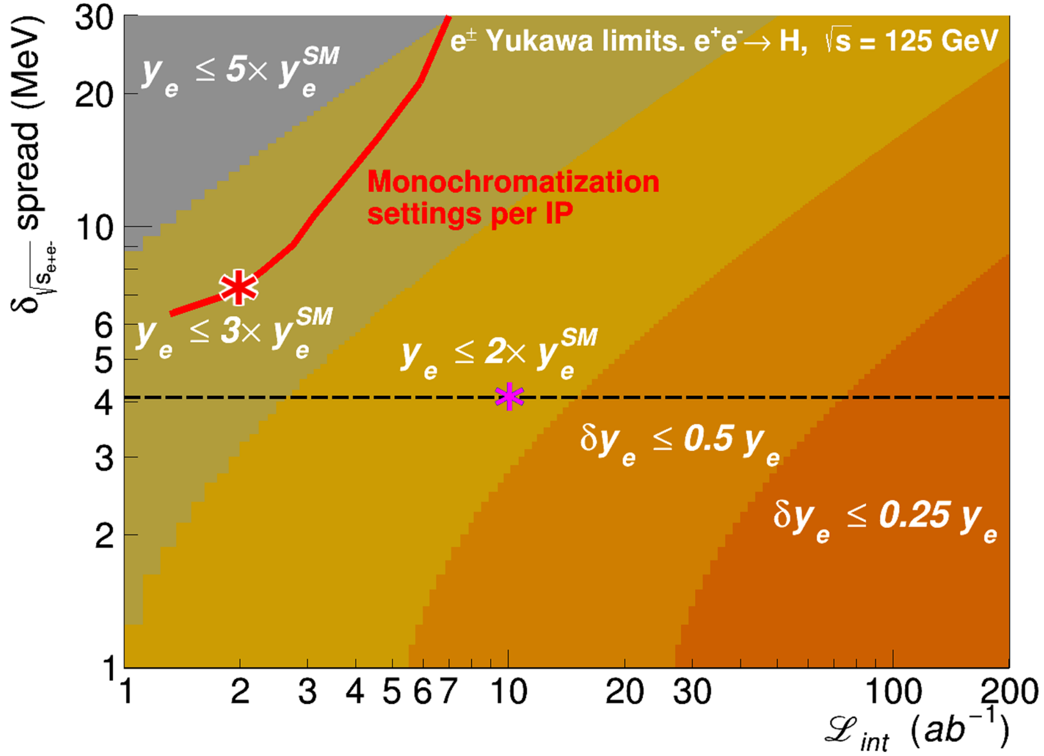
Model-independent Γ_H measurment





Reach for light fermion Yukawa couplings: highlights





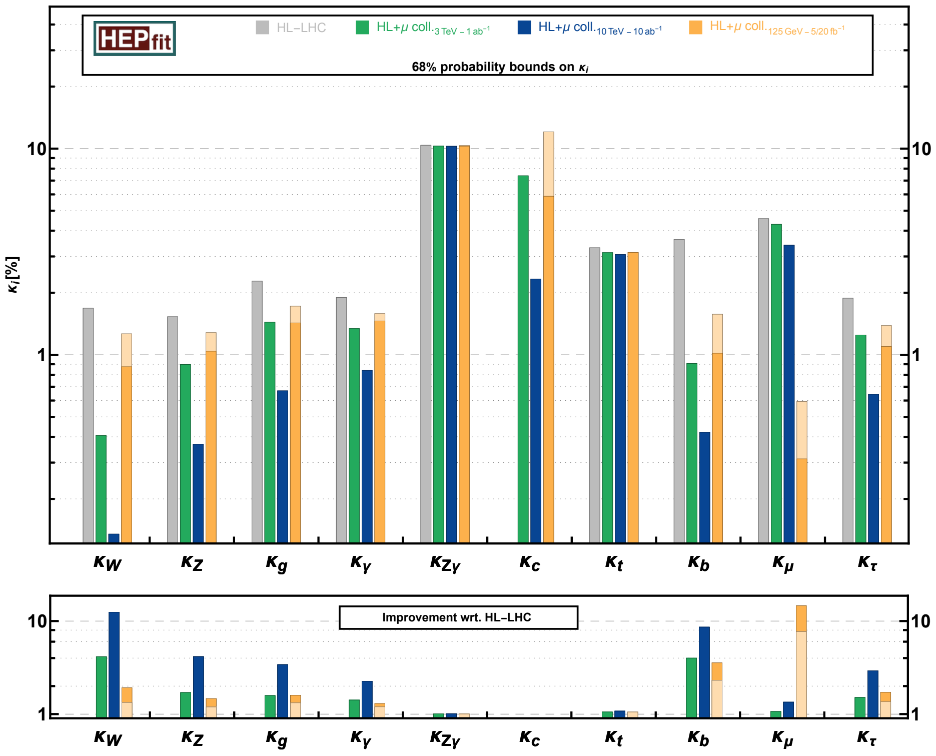
- Studying ZH with Z going to leptons and neutrinos
- κ_s< 7.14 at 95% c.l.

arXiv:2203.07535

- Electron Yukawa at FCC-ee (s-channel H)
- κ_e< 1.6 at 95% c.l.

arXiv:2107.02686

The case of a Muon Collider

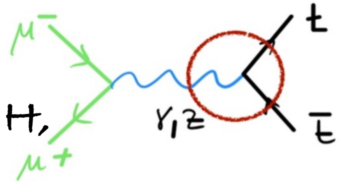


- **Many stages/upgrades:**
  - 125 GeV on-Higgs resonace
  - 3 TeV
  - 10 TeV
  - >10 TeV (14, 30, … TeV)
- **Lepton collider**
  - Cleaner environment → **precision**
- **… but high energy**
  - Pushing the EF → **discovery**
- **Competitive/complementary to ~100 TeV hadron collider**
- **Contained size**
  - M_μ~ 200 m_e → reduced synchrotron radiation (x 1.6 x10^{-9})
- **New physics regimes**
  - E > Λ_{EW}
  - EW radiation

See I.Ojalvo's talk

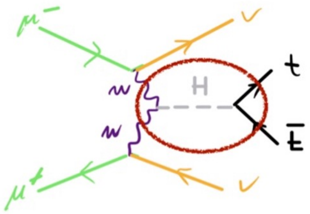
Snowmass 21 EF Higgs TG Report (arXiv:2209.07510) & MuC Forum Report (arXiv:2209.01318)

$\sqrt{s} \lesssim$ 1-5 TeV



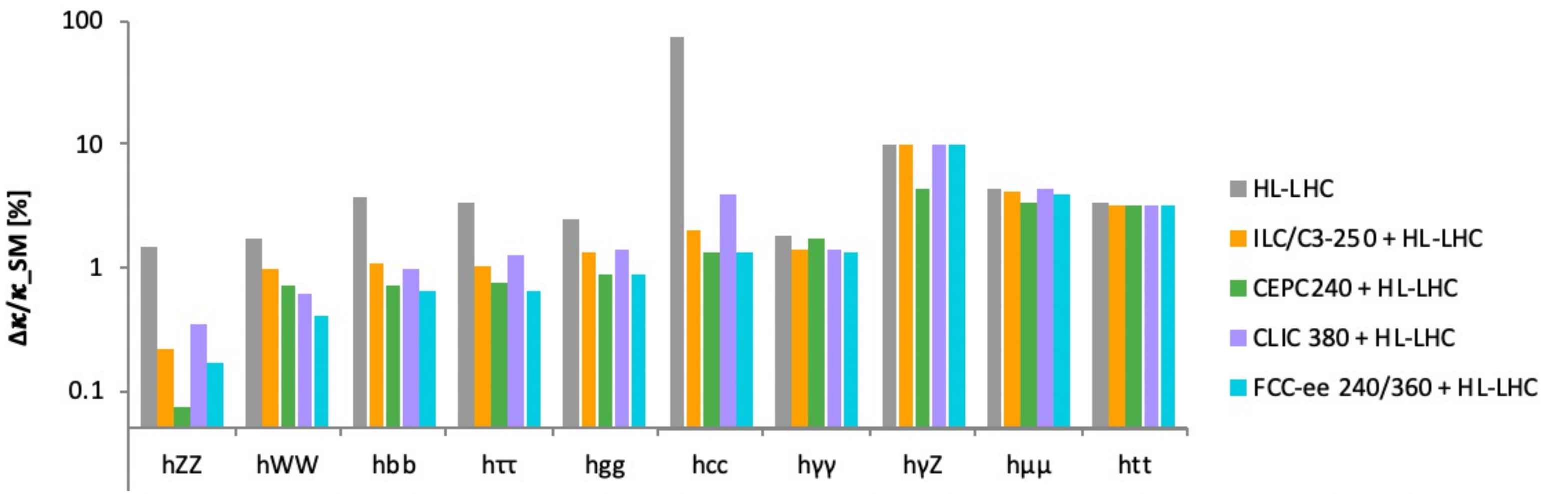
$$\sigma_s \sim \frac{1}{s} \quad \longleftrightarrow \quad \sigma_s \sim \frac{1}{M^2} \log^n \frac{s}{M}$$

$\sqrt{s} \gtrsim$ 1-5 TeV



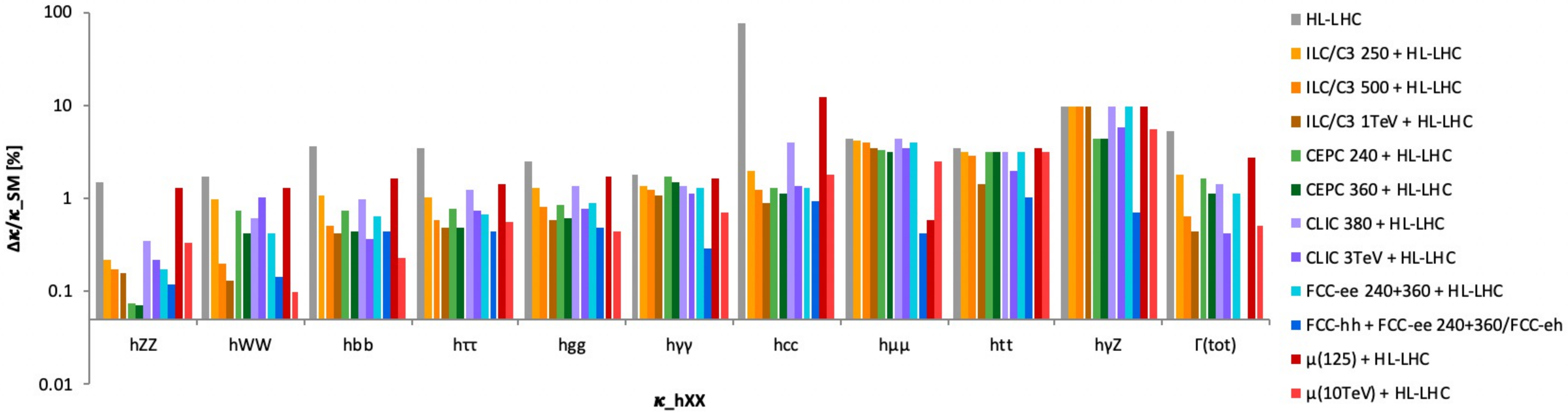
Reach of future colliders for Higgs couplings: a closer look

Based on full Run 2 dataset analyses



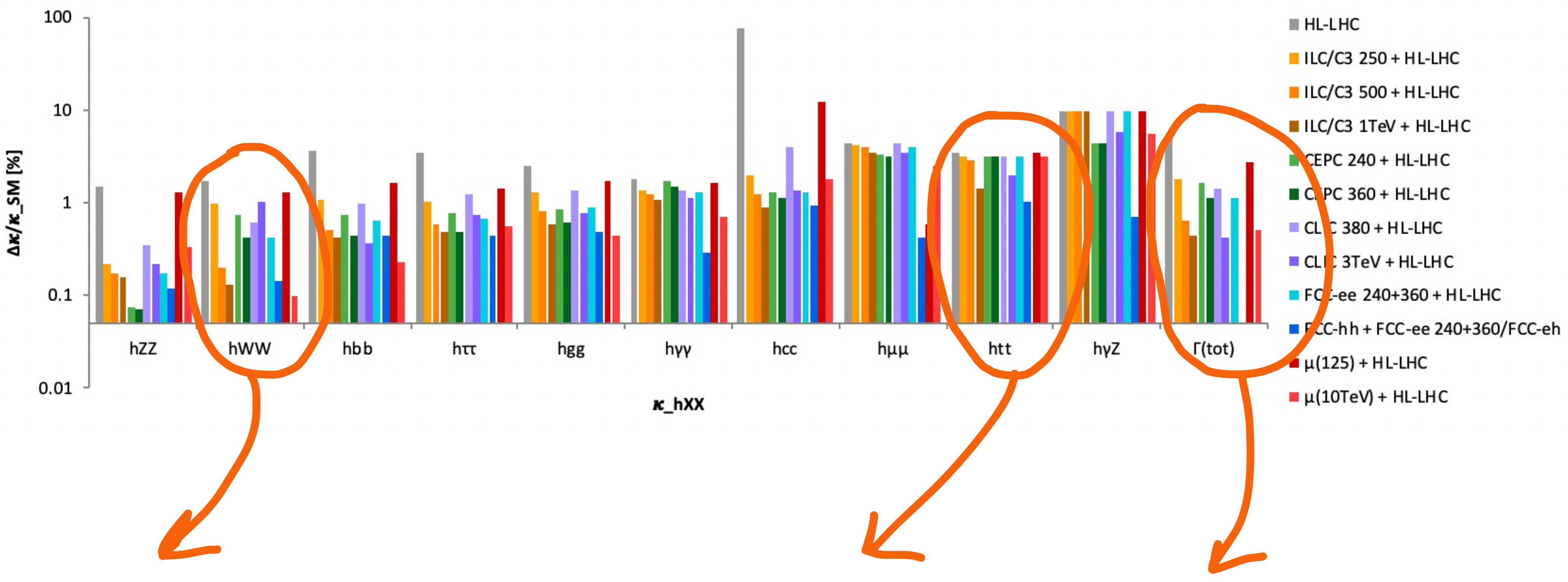
Initial stages of future e^+e^- machines

From Snowmass 2021 EF Higgs Topical Group Report arXiv:2209.07510



Final reach of all considered future colliders

Focusing on final reach of e^+e^- machines



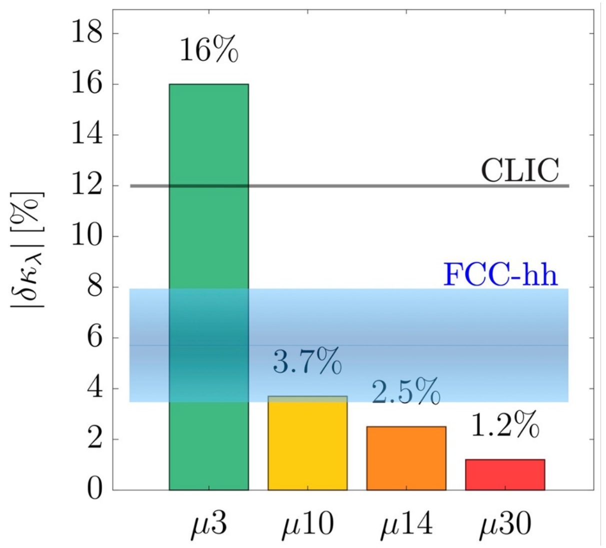
ILC/C^3 reach beyond 500 GeV and upgrade to 1 TeV allows drastic improvements in measuring couplings to W and top as well as more precision in a model independent measurement of the total width.

What about Higgs self-coupling?

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%
μ(3 TeV)	-	15-30%	15-30%
μ(10 TeV)	-	4%	4%

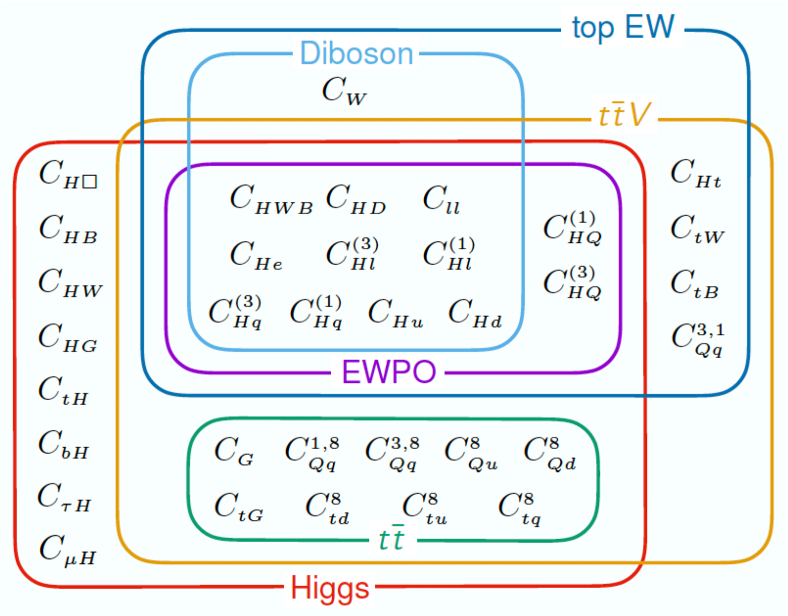
- ATLAS and CMS HL-LHC updated
- FCC-hh updated arXiv:2004.03505
- Added MuC reach:



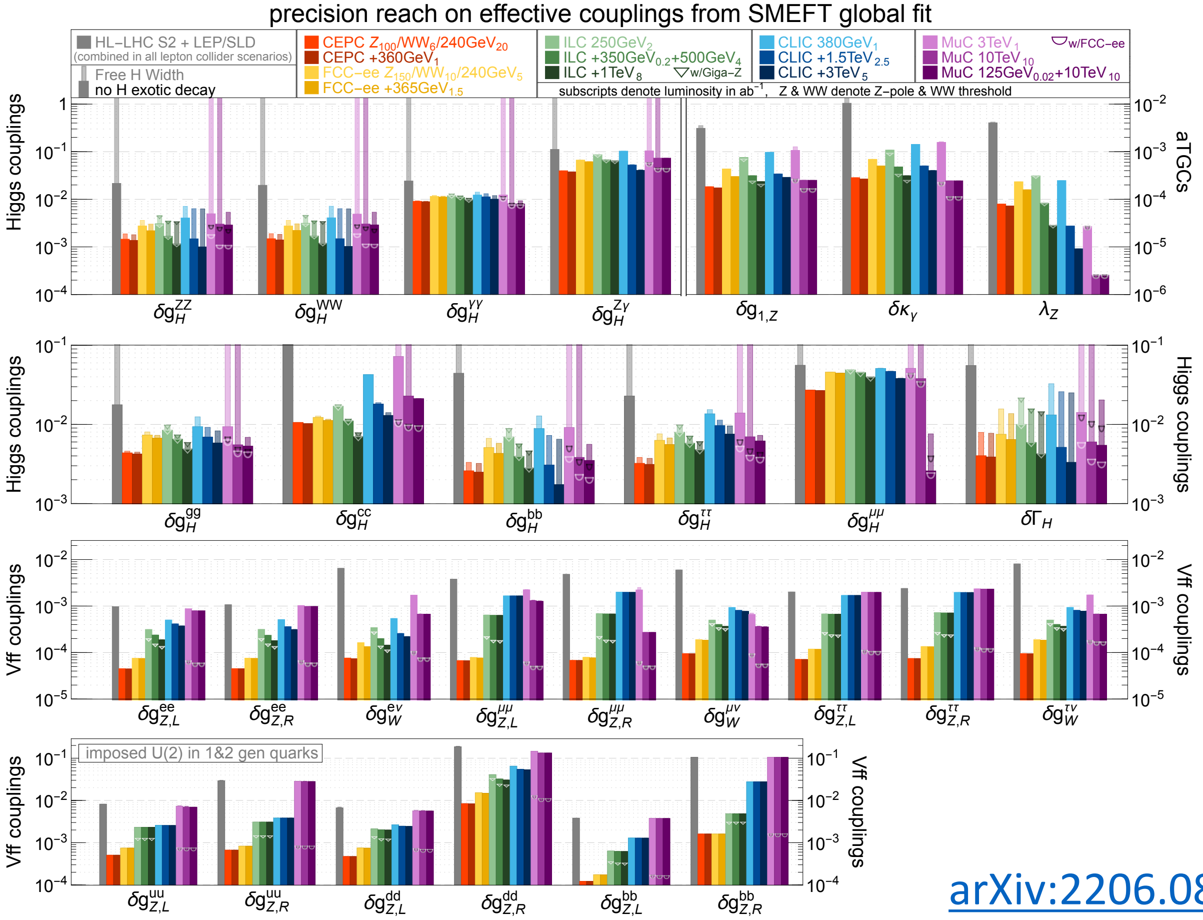
arXiv:2203.07256

Constraining BSM via global EFT fits

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} + \left(\frac{1}{\Lambda^2}\sum_i C_i O_i + {\rm h.c.}\right) + O(\Lambda^{-4})$$



EW + Higgs



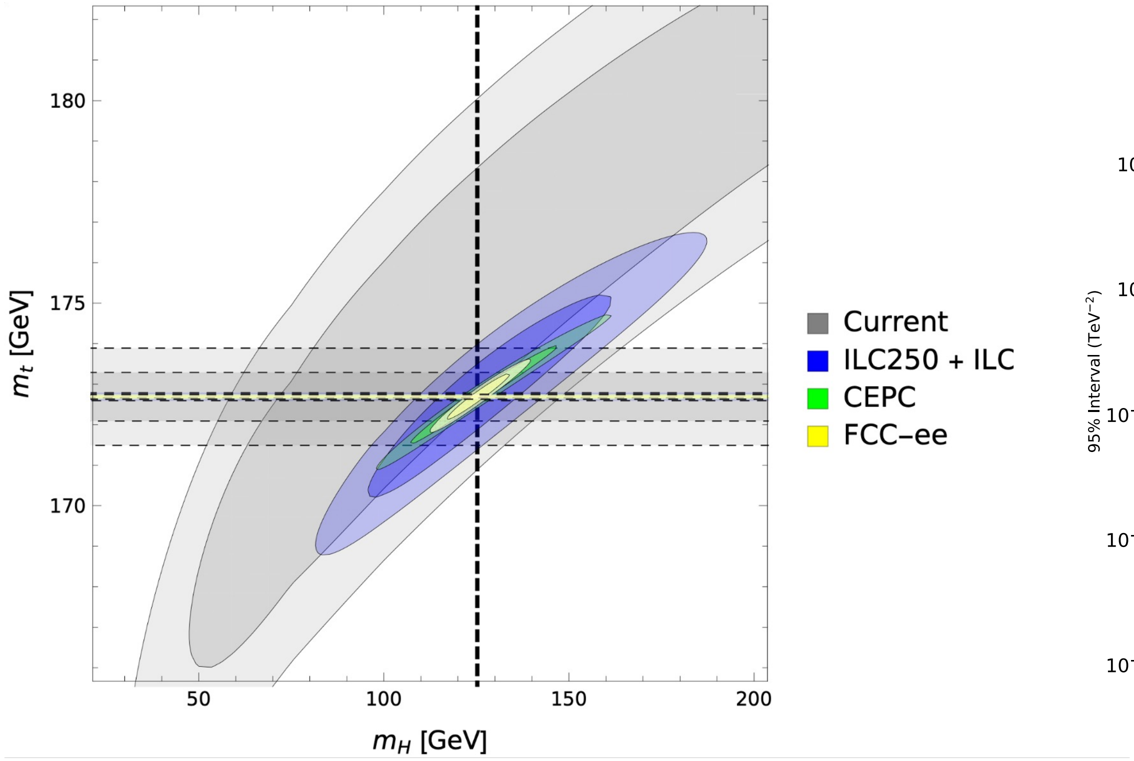
arXiv:2206.08326

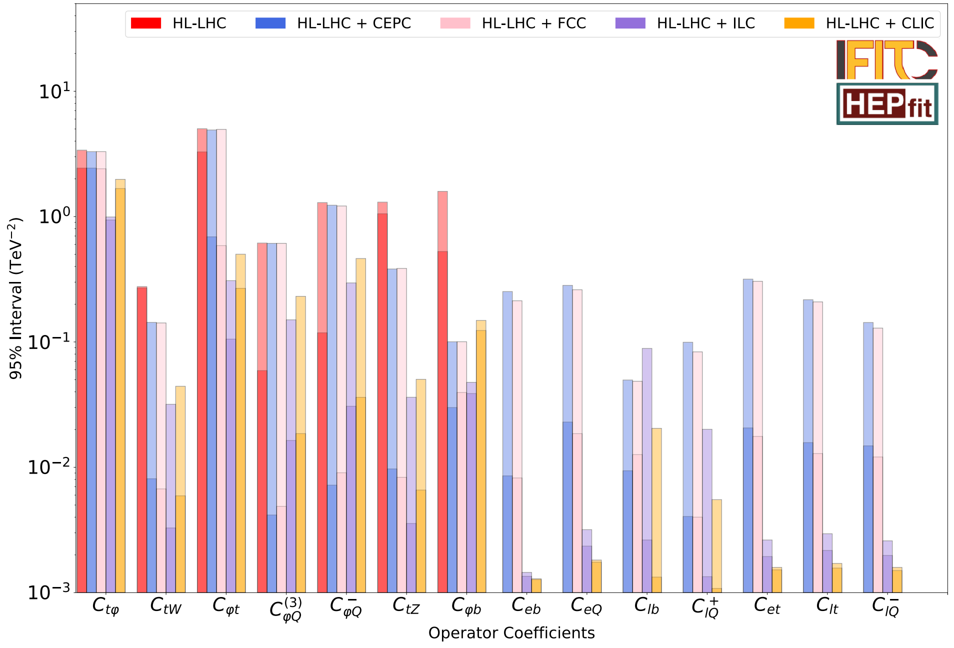
EFT connects different processes with large correlations: pattern of coefficients give insights on underlying BSM model

Interplay with top-quark precision measurements

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

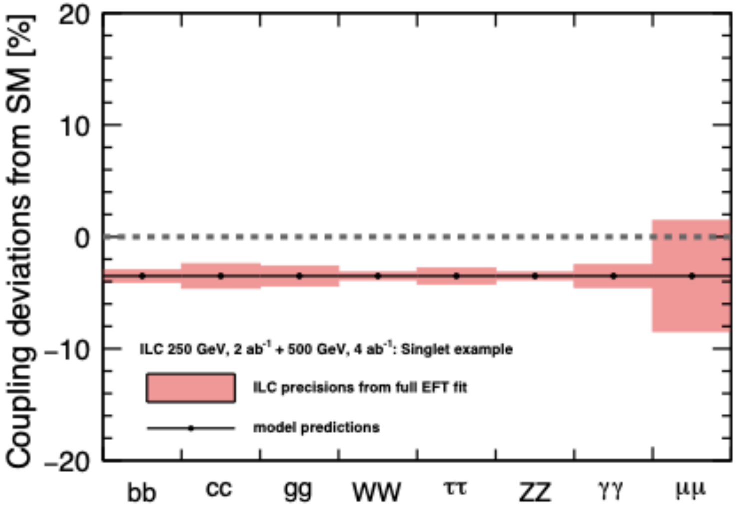




From Snowmass 2021 EF HF and EW TG's Reports arXiv:2209.11267, arXiv:2209.08078

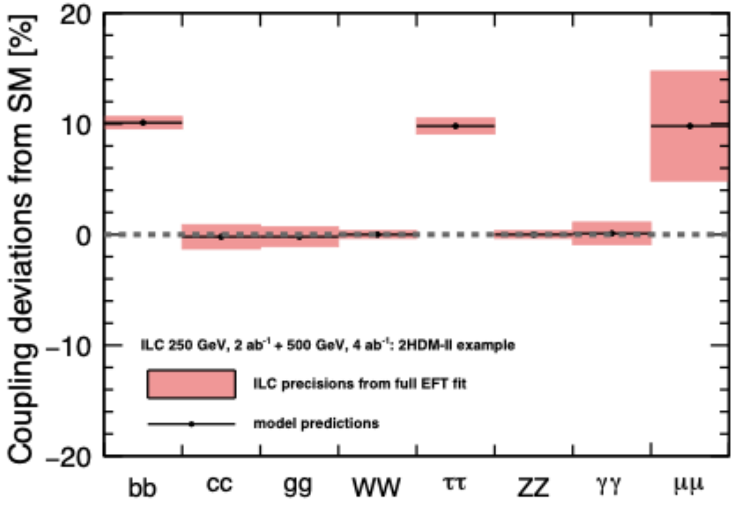
Disentangling models from EFT patterns

The “inverse Higgs” problem



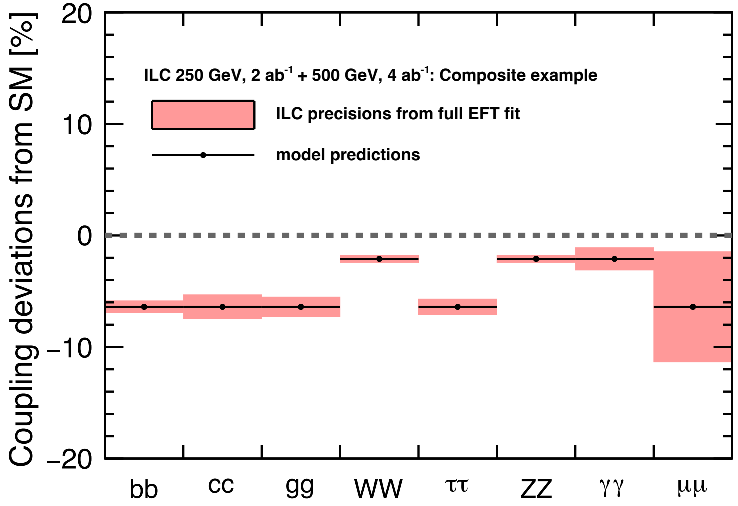
additional scalar singlet

(m_S=2.8 TeV, max mixing)



2HDM-II

(MH=600 GeV, tanβ=7)



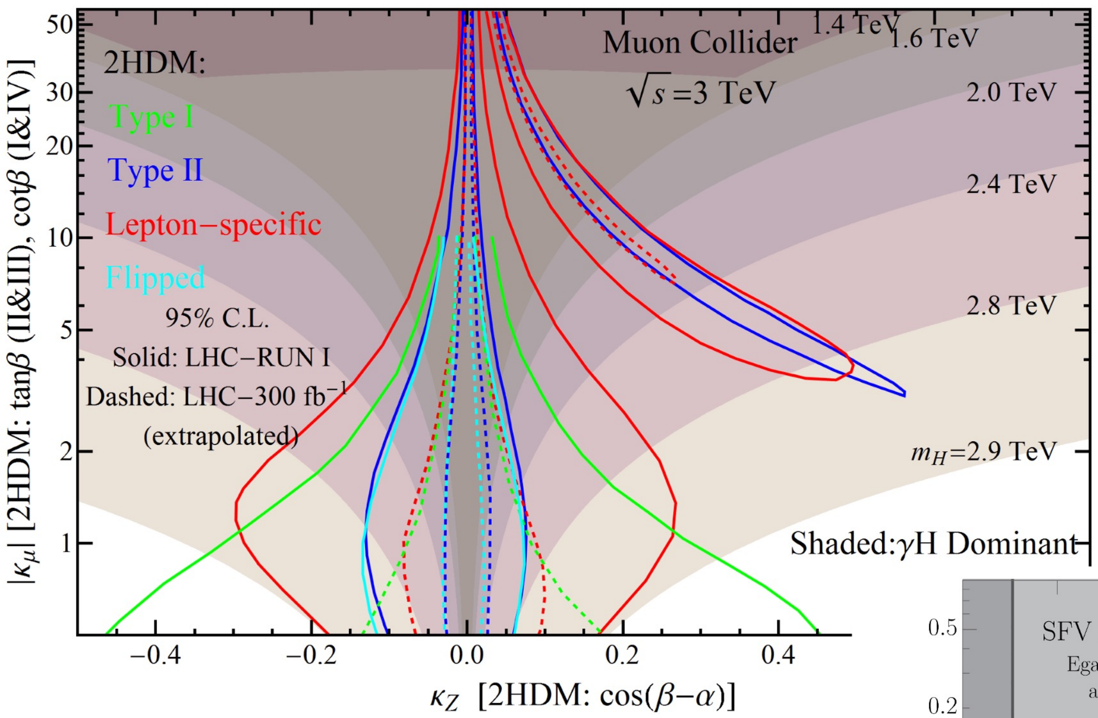
Composite Higgs

(f=1.2 TeV)

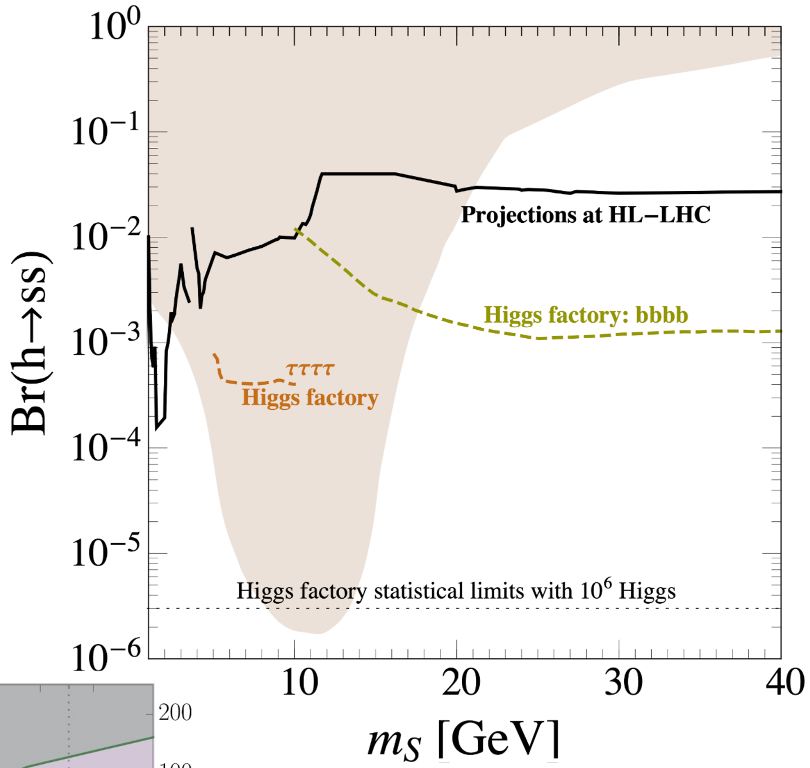
Snowmass 2021: ILC white paper (arXiv: 2203.07622)

Examples to illustrate the **different patterns of Higgs coupling deviations** from **different BSM models**

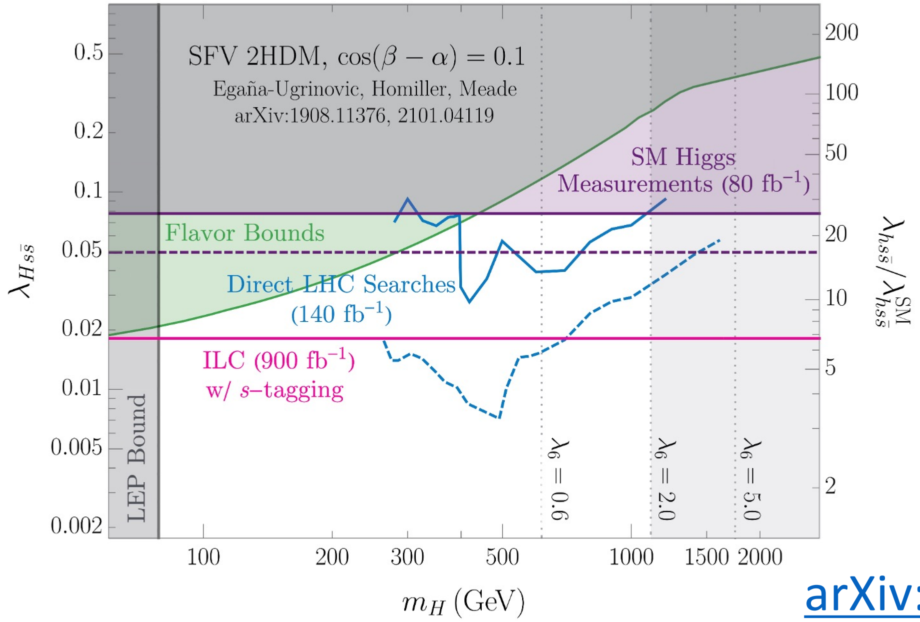
Extended Higgs sectors - direct BSM portal



arXiv:2203.07261



arXiv:2203:08206



arXiv:2203:07535

Extended Higgs sectors: 2HDM, extra singlets, …

Higgs and flavor: probing anomalous Hss coupling

Setting priorities

EF has prioritized the case of a Higgs Factory

From the **Snowmass 2021 Executive Summary of EF report**:

The EF supports **continued strong US participation in the success of the LHC, and the HL-LHC** construction, operations, computing and software, and most importantly in the physics research programs, including auxiliary experiments.

The EF supports a **fast start for construction of an e+e− Higgs factory** (linear or circular), **and a significant R&D program for multi-TeV colliders** (hadron and muon). **The realization of a Higgs factory will require an immediate, vigorous, and targeted detector R&D program**, while the study towards multi-TeV colliders will need significant and long-term investments in a broad spectrum of R&D programs for accelerators and detectors.

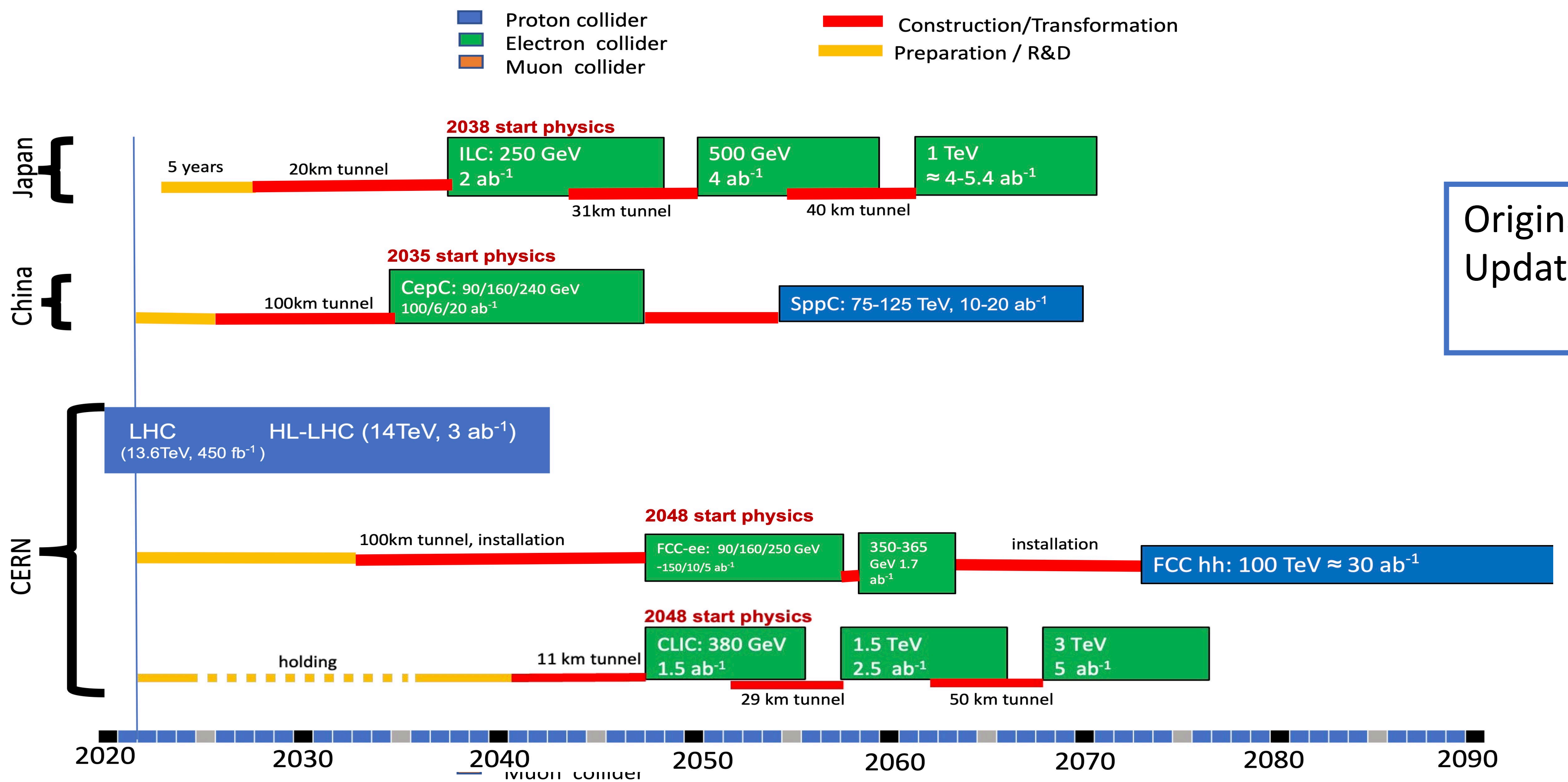
The US EF community has also expressed **renewed interest and ambition to bring back energy-frontier collider physics to the US soil** while maintaining its international collaborative partnerships and obligations.

[EF report: arXiv: 2211.11084]

Summary

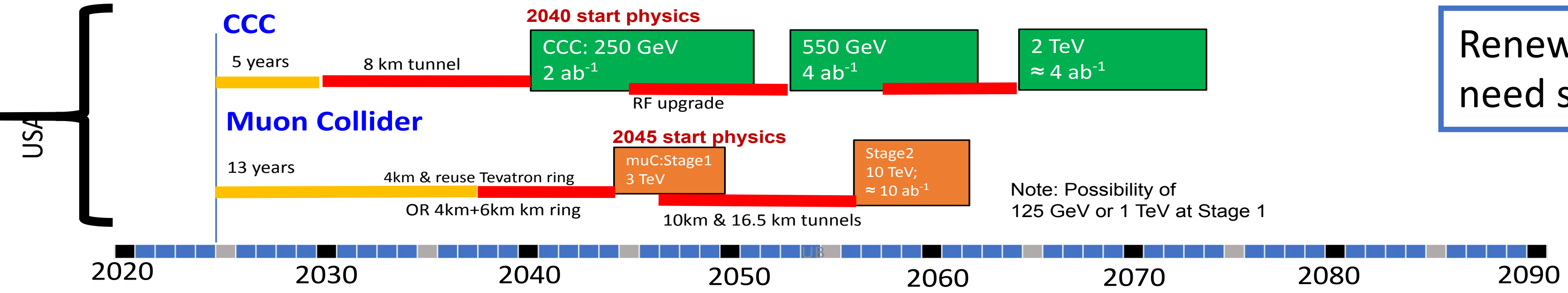
- **The Higgs discovery has been fundamental in opening new avenues to explore physics beyond the SM** and the Higgs-physics program ahead of us promises to start answering some of the remaining fundamental questions in particle physics.
- **Collider physics** remains as a **unique and necessary test of any BSM hypothesis**.
- **Many new directions have been explored during the Snowmass 2021 exercise**, **building on previous studies (ESG)**, and have indicated the need to explore the TeV scale beyond LHC reach by pushing both **precision (Higgs factories) and energy (multi-TeV colliders)**.
- **Increasing the accuracy on SM observables** (Higgs, top, EW) could allow to **test higher scales**: a factor of 10 in precision could allow to test scale in the 10 TeV range and betyond.
- The **possibility of reaching c.o.m. energies above 500 GeV in e+e- collisions is crucial** to improve the full spectrum of HL-LHC measurements, including **top-Higgs** and **Higgs self-coupling**, as well as **probing extended Higgs sectors and new physics that can eluded the LHC.**

Additional material



Original timeline from ESG
Updated during Snowmass 2021
(see EF Report)

Proposals emerging from Snowmass 2021 for a US based collider



Renewed interest in lepton colliders:
need supporting R&D in near future

Higgs precision reach of Future Colliders: a summary