Building the case for future explorations at the Energy Frontier

Laura Reina (FSU)

The University of Oklahoma

October 26, 2023

From the work of the Snowmass 2021-22 Energy Frontier

Conveners: Meenakshi Narain, Laura Reina, Alessandro Tricoli

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

Higgs, EW, top

QCD and S.I.

BSM

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, contributed papers

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)

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

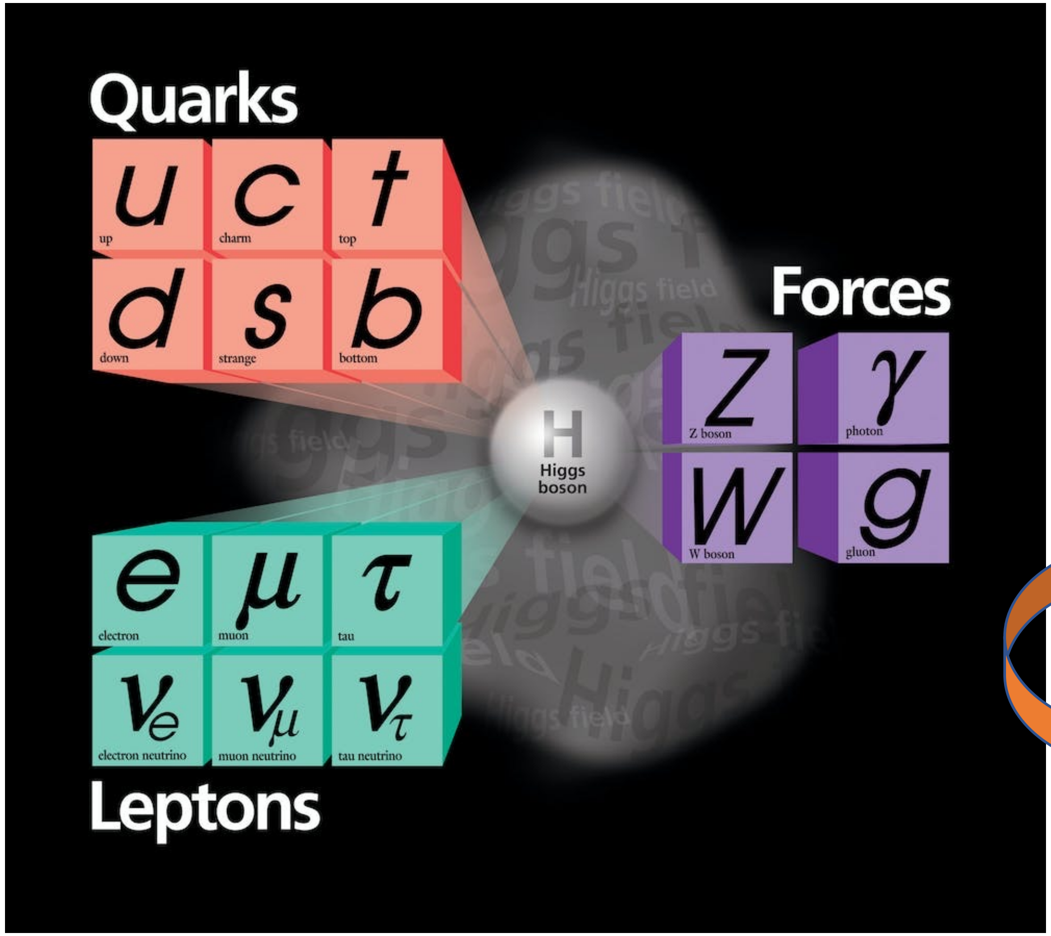
Coordinated by **John Stupak** (U. Oklahoma)
1) Assess the MC needs ⇒ **"Task force"**
2) Produce MC samples ⇒ **"Production Team"**

>160 Contributed Papers, TG and general frontier meetings, and fora's activities served as basis to the EF main reports.

Energy Frontier:
Exploring the TeV Scale and beyond

Through the breadth and multitude of collider physics signatures

Exploring beyond the Standard Model of particle physics



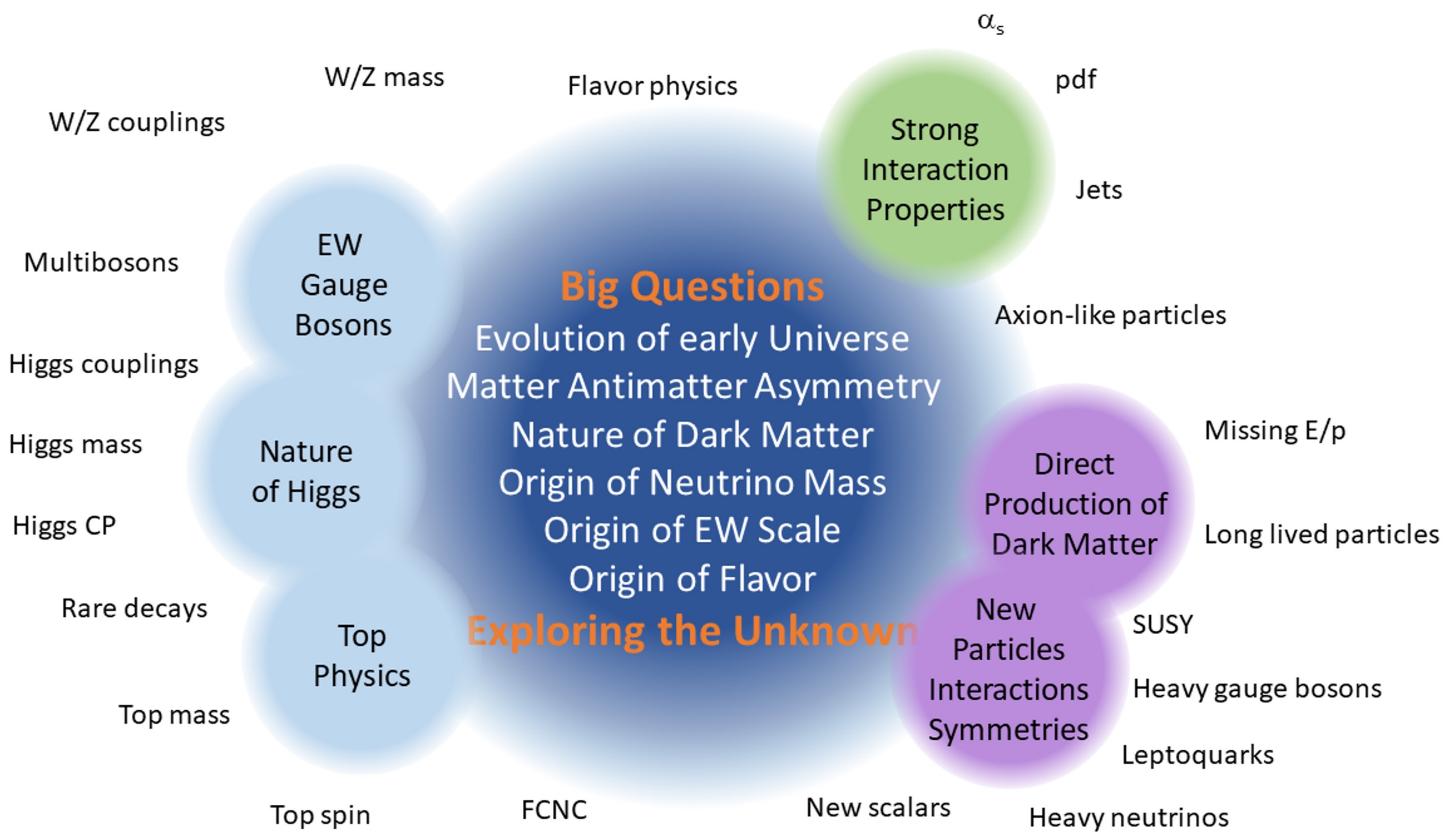
A very minimal quantum field theory describing strong, weak, and electromagnetic interactions, based on a local (gauge) symmetry

$$SU(3)_C \times SU(2)_L \times U(1)_Y \rightarrow SU(3)_C \times U(1)_Q$$

Strong interactions: gluons → $m_g = 0$
Electromagnetic interactions: photon → $m_\gamma = 0$
Weak interactions: $W^\pm$ and Z → $M_W, M_Z \neq 0$

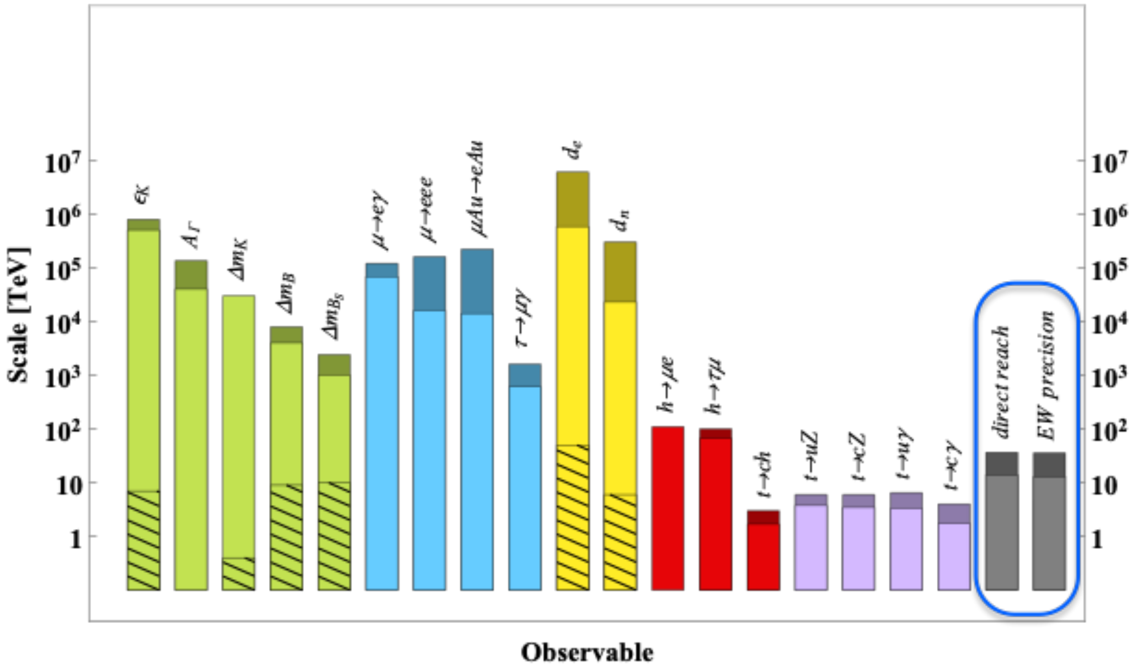
Due to the presence of a **scalar field** whose potential spontaneously breaks the gauge symmetry of electroweak interactions and gives origin to massive gauge bosons (W,Z)

The Higgs boson (H) is the physical particle associated with such field



α_s
W/Z mass
Flavor physics
pdf
W/Z couplings
Strong Interaction Properties
Jets
Multibosons
EW Gauge Bosons
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
Axion-like particles
Higgs couplings
Higgs mass
Nature of Higgs
Missing E/p
Direct Production of Dark Matter
Higgs CP
Long lived particles
Rare decays
Top Physics
New Particles Interactions Symmetries
SUSY
Heavy gauge bosons
Top mass
Leptoquarks
Top spin
FCNC
New scalars
Heavy neutrinos

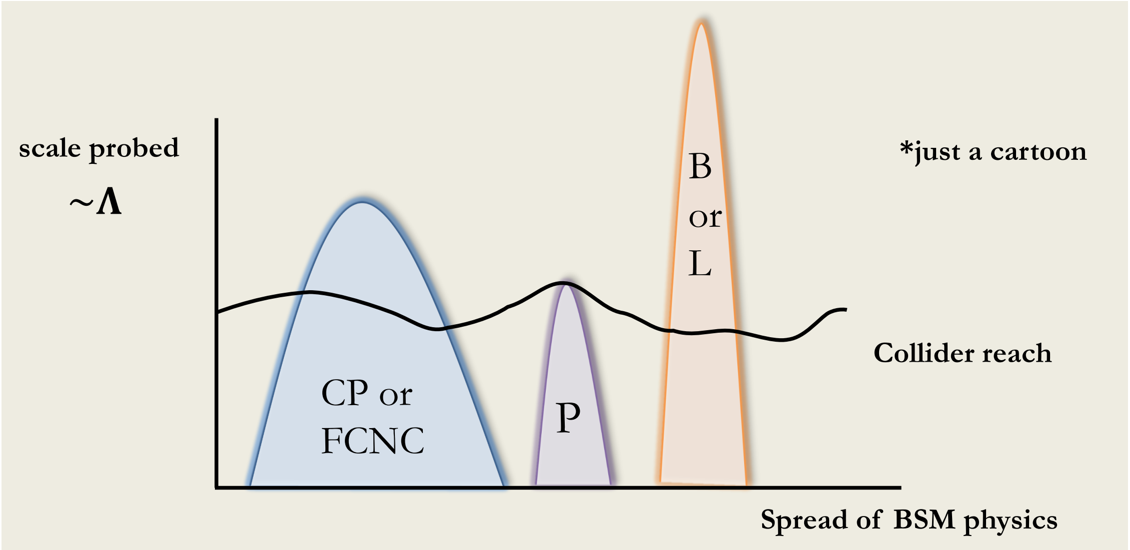
Emphasizing the breadth of collider physics



[European Strategy, arXiv:1910.11775]

Colliders may not be able to indirectly probe scales as high as e.g. flavor physics, but they provide a huge spectrum of measurements

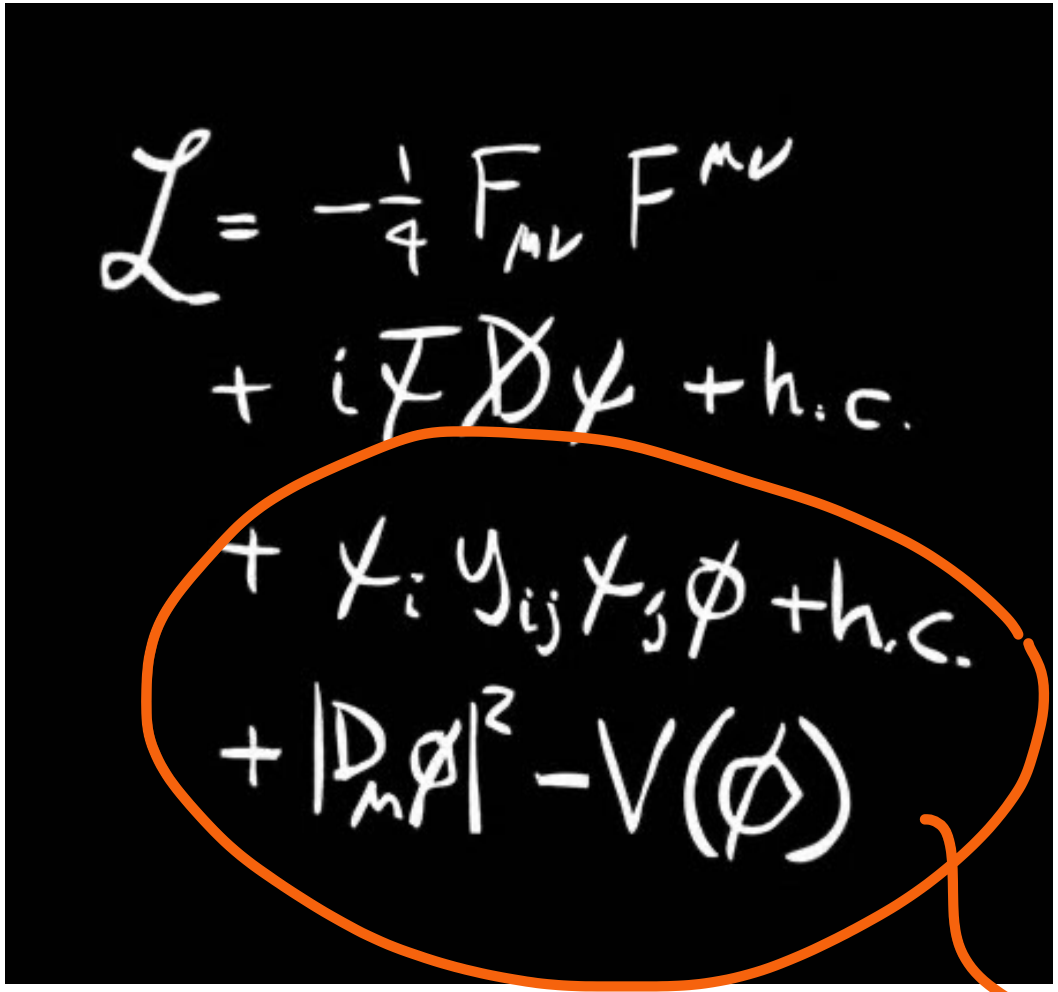
complementarity

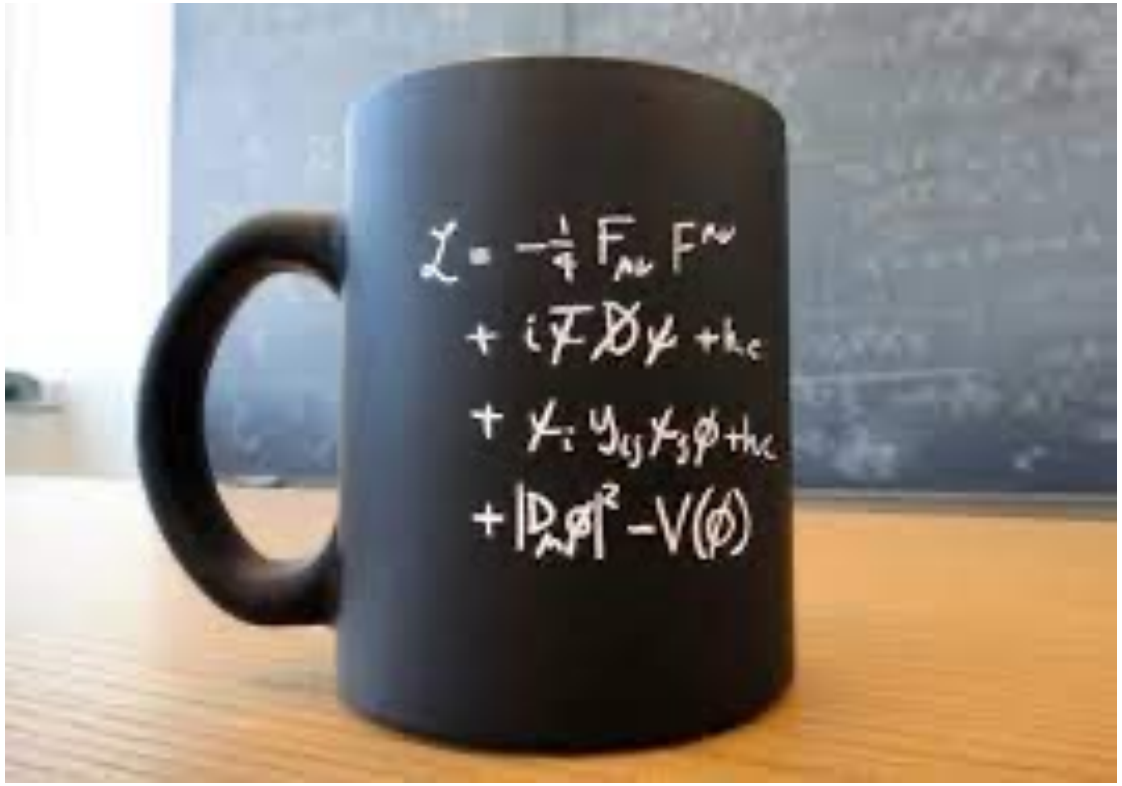


Any new physics hypothesis will have to stand the test of colliders

[J. de Vries, talk at Snowmass 21 CPM]

The Standard Model: so simple that it can fit on a mug!

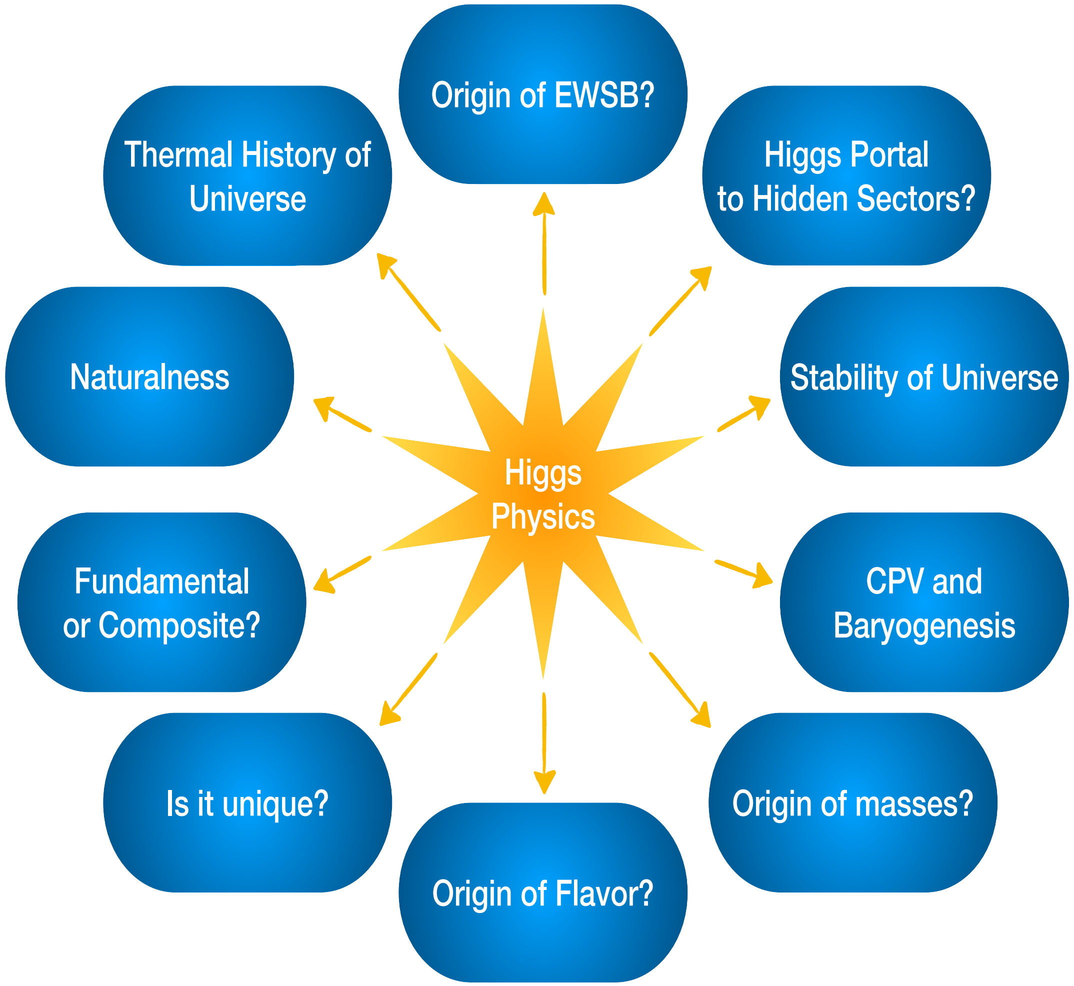




… and half of it is about Higgs!

Higgs physics identified as central to the Energy Frontier physics program

Unique link to BSM physics



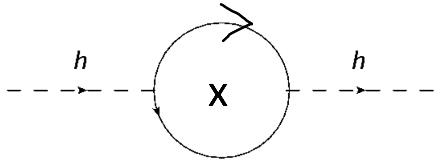
The origin of the SM Higgs pattern escapes the SM itself

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?

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

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

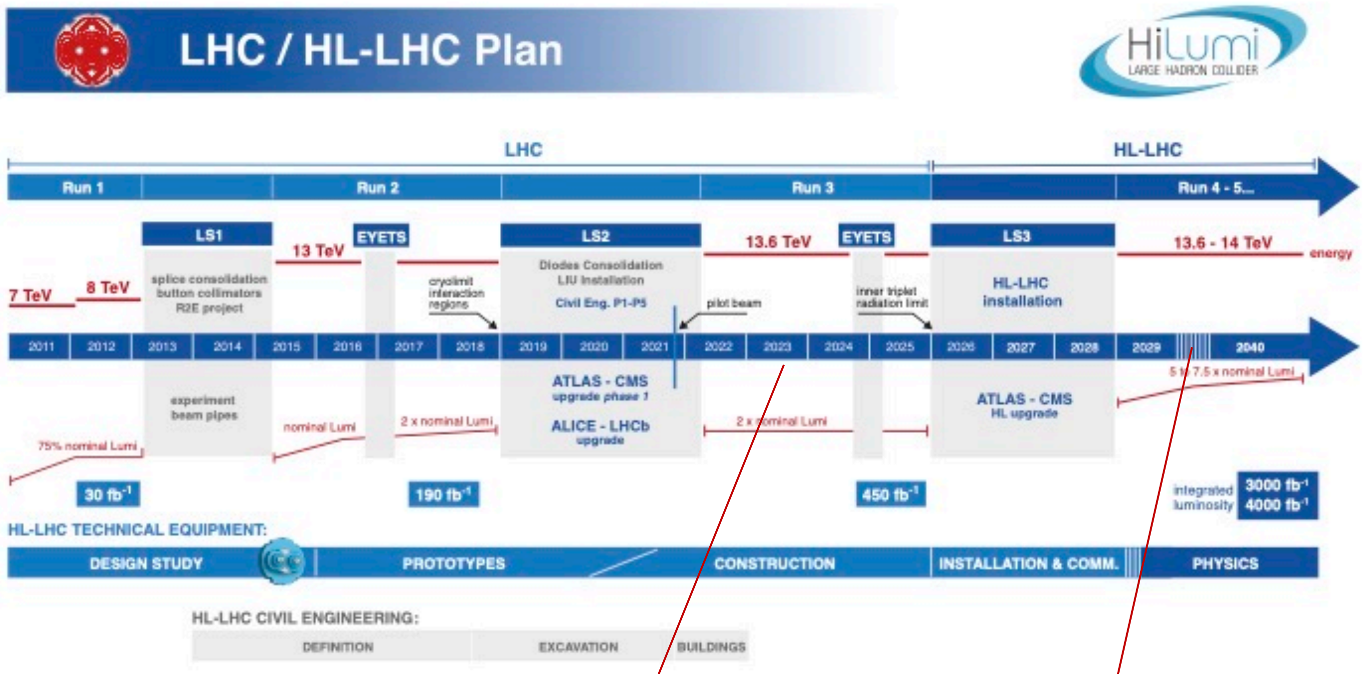
$$\phi \rightarrow H + v$$

fermion masses

Yukawa couplings

The LHC and its legacy

Ten years of LHC physics and looking ahead



We are only here

Many years of HL running ahead of us

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

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

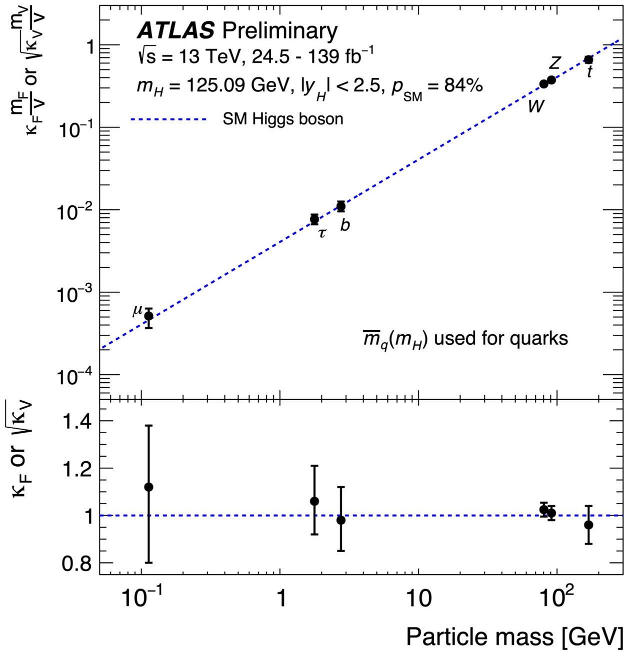
Snowmass 2013/Previous P5

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

Snowmass 2021/Current P5

Run 2 Zooming in on couplings to probe the TeV scale

CMS, arXiv:2207.00043

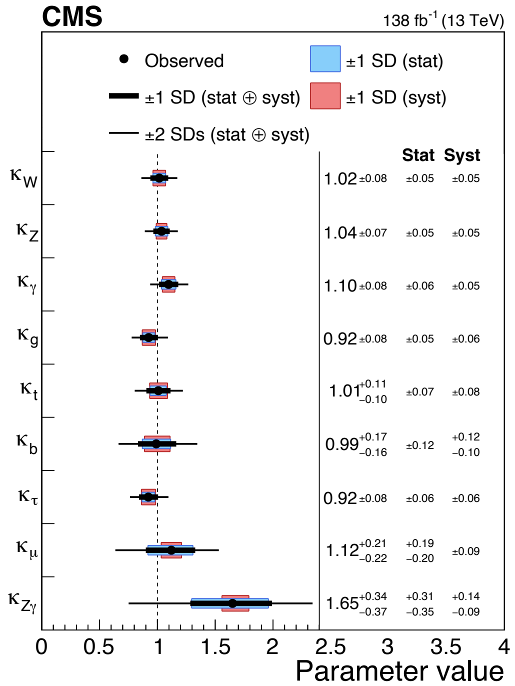


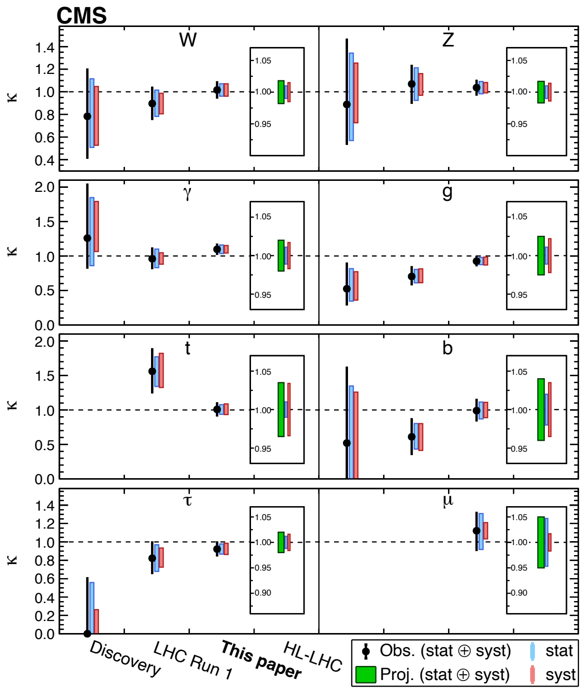
$$\kappa = g_X / g_X^{SM} = 1 + \Delta\kappa$$

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

Precision on $\Delta\kappa$

reach for Λ_{BSM}

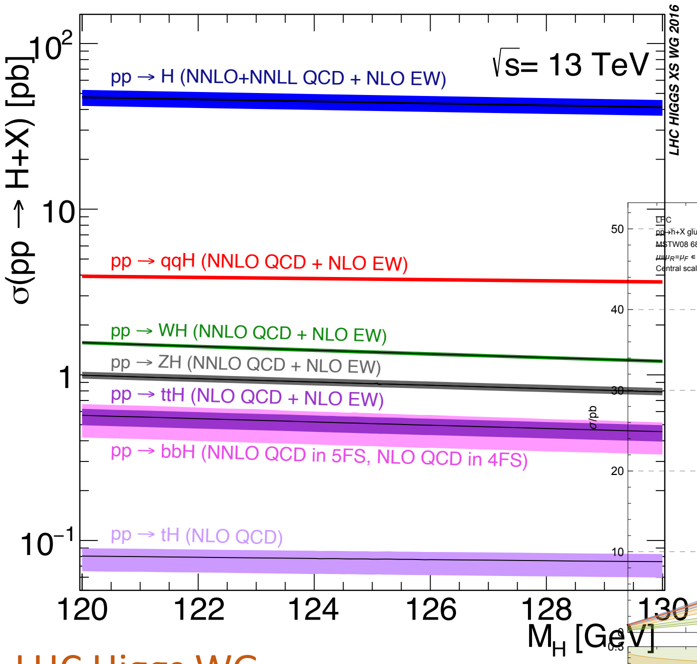




- Couplings to **W/Z at 5-10 %**
- Couplings to **3rd generation to 10-20%**
- **First measurements of 2nd generation** couplings

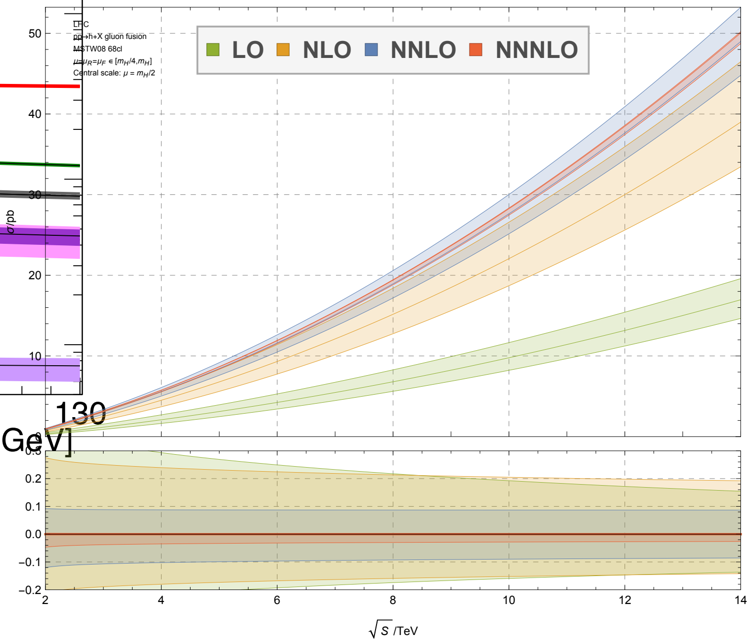
- **HL-LHC projections** from **partial Run 2** data (YR):
  - **2-5 % on most couplings**
  - **< 50% on Higgs self-coupling.**
- **Full Run2** results **drastically improve partial Run 2 results:** better projections expected

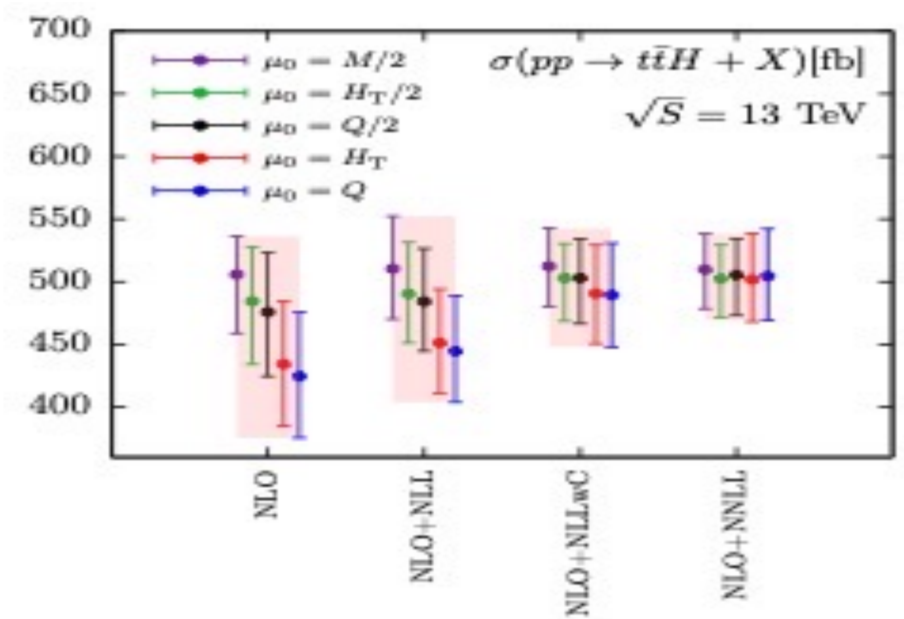
Theory has also come a long way



LHC Higgs WG

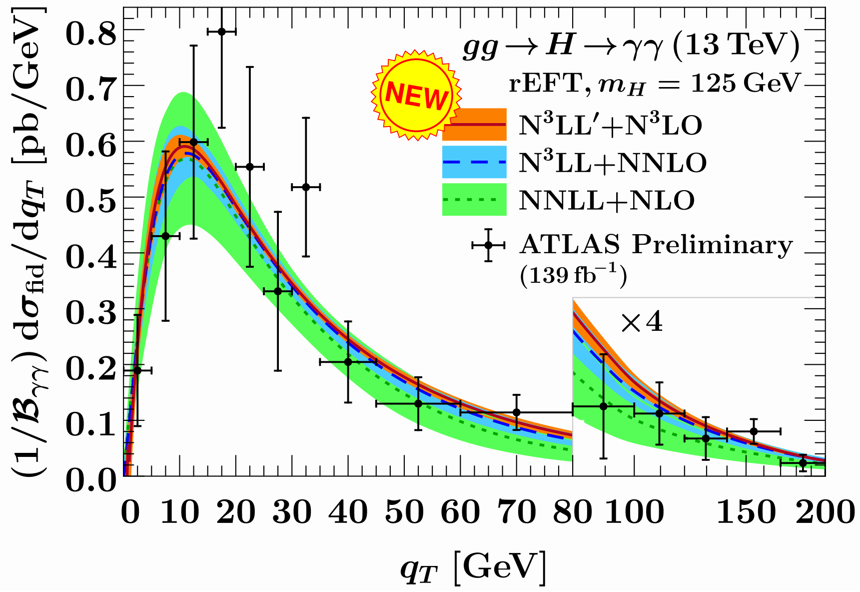
Anastasiou et al. [1502.06056]





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, …)

Beyond SM-coupling rescaling

Run 2 and beyond

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

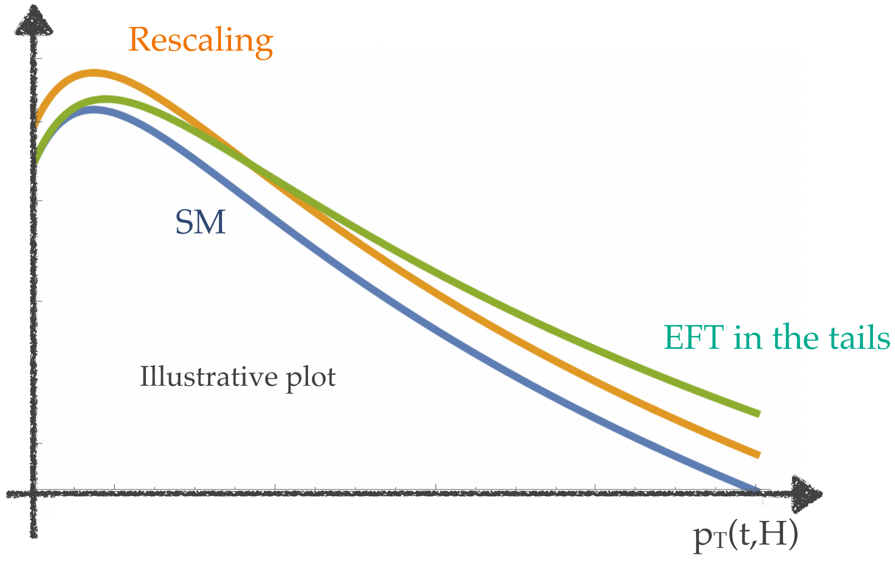
$$\mathcal{L}_{\rm SM}^{\rm eff} = \mathcal{L}_{\rm SM} + \sum_{d>4} \frac{1}{\Lambda^{d-4}} \mathcal{L}_d = \mathcal{L}_{\rm SM} + \frac{1}{\Lambda}\mathcal{L}_5 + \frac{1}{\Lambda^2}\mathcal{L}_6 + \cdots$$

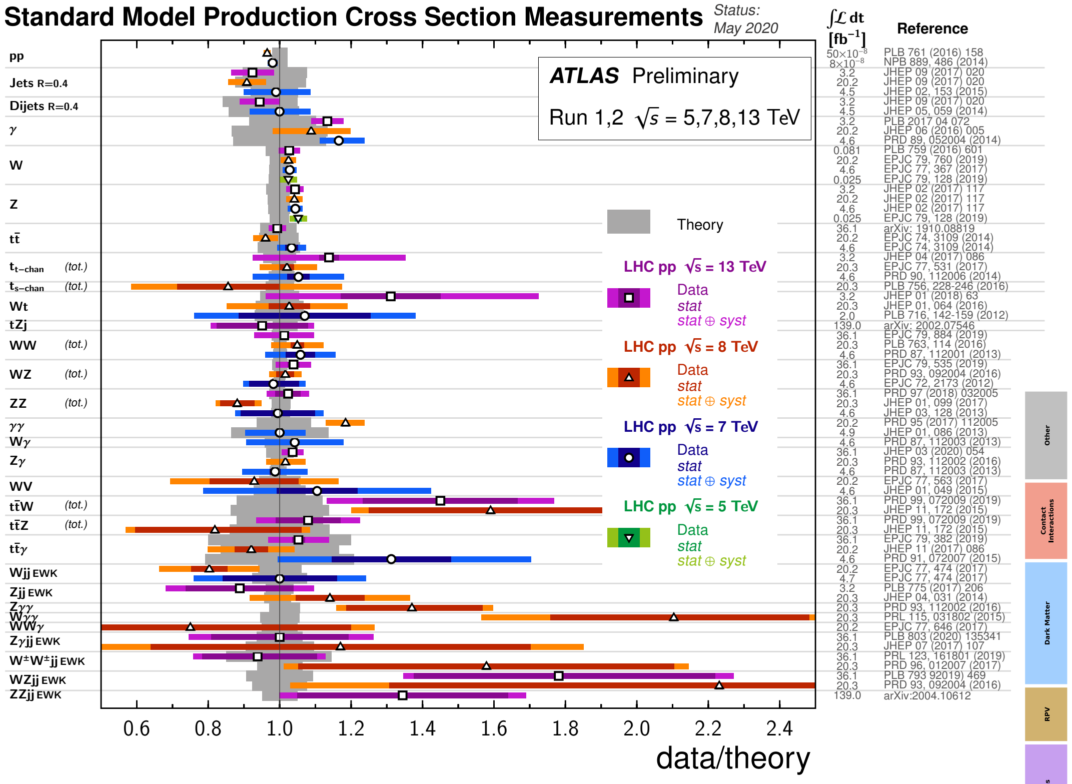
$$\mathcal{L}_d = \sum_i C_i^{(d)} \mathcal{O}_i^{(d)}, \quad \left[\mathcal{O}_i^{(d)}\right] = d$$

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

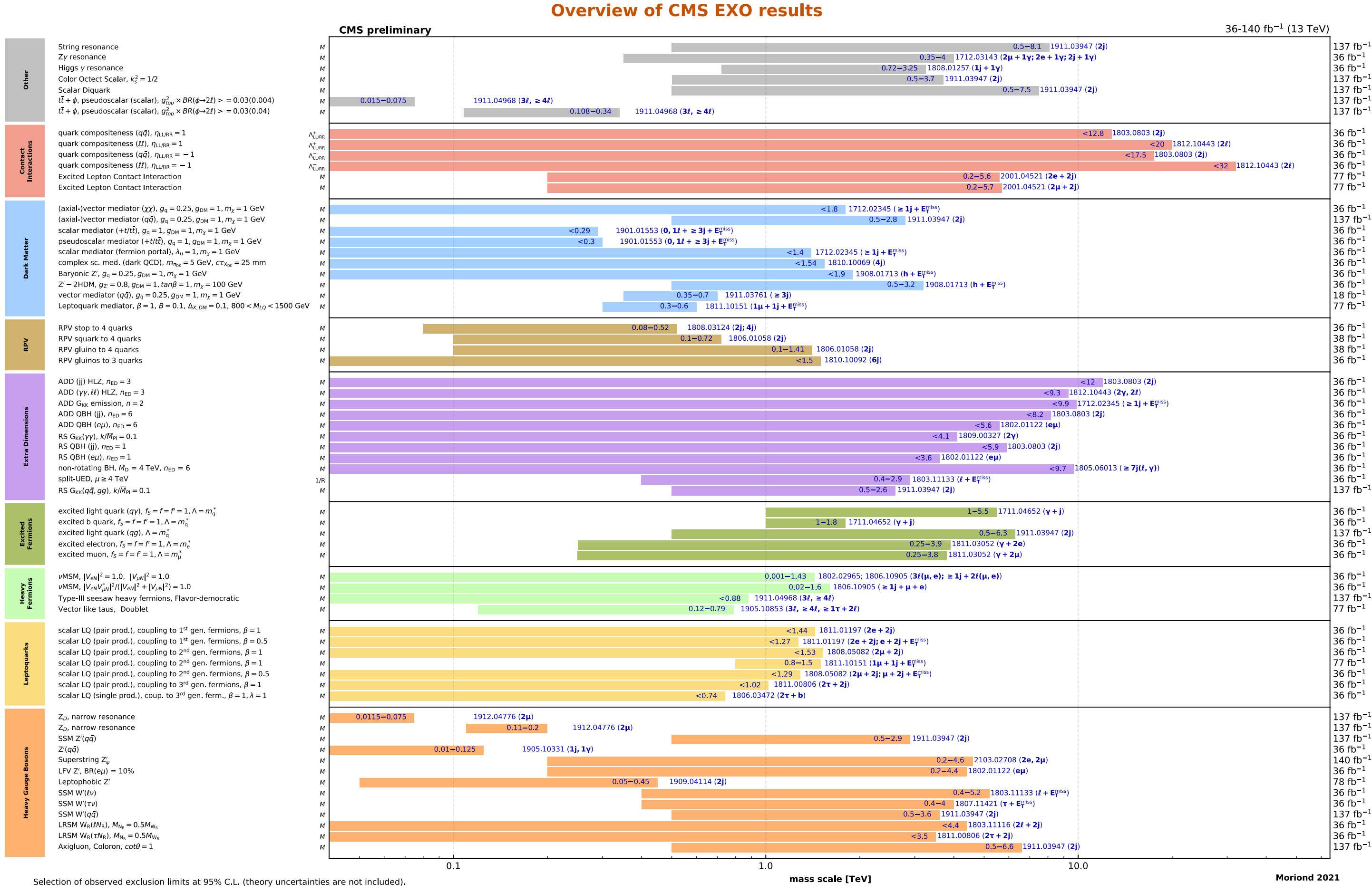
Expansion in $(v, E)/\Lambda$: **affects all SM observables** at both low and high energy

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





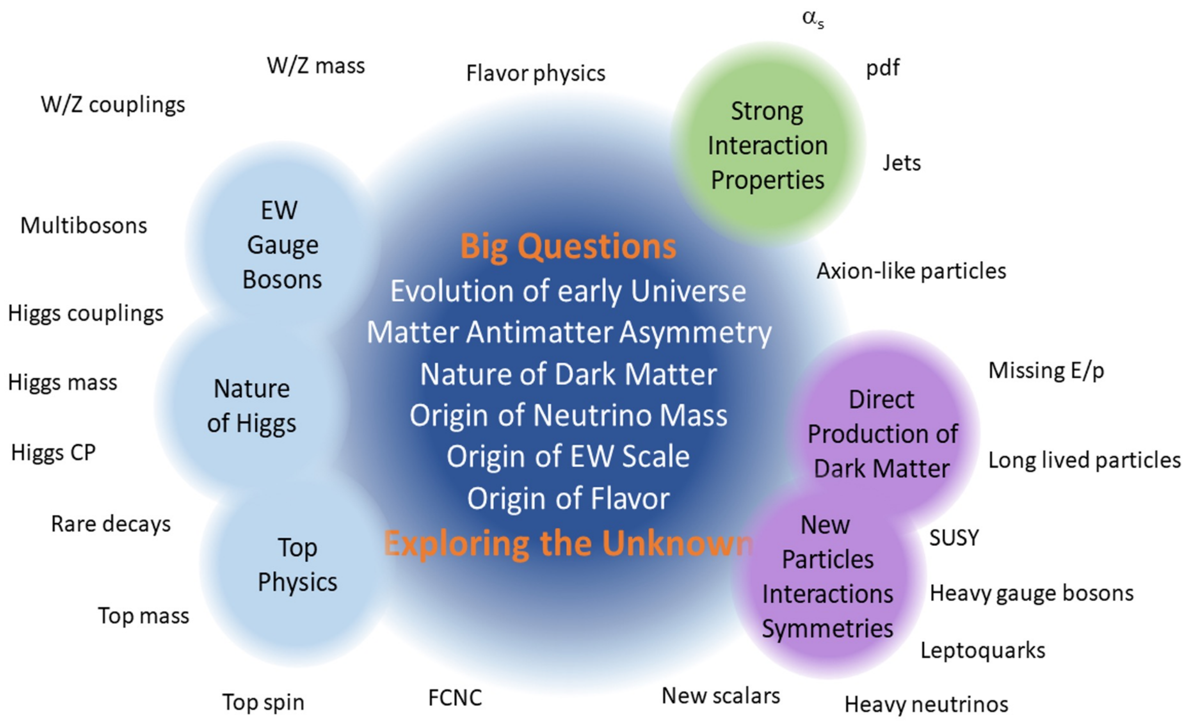
... to which we should add a unique spectrum of SM measurements and BSM direct searches!



What is the path forward beyond the HL-LHC?

Beyond the HL-LHC

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



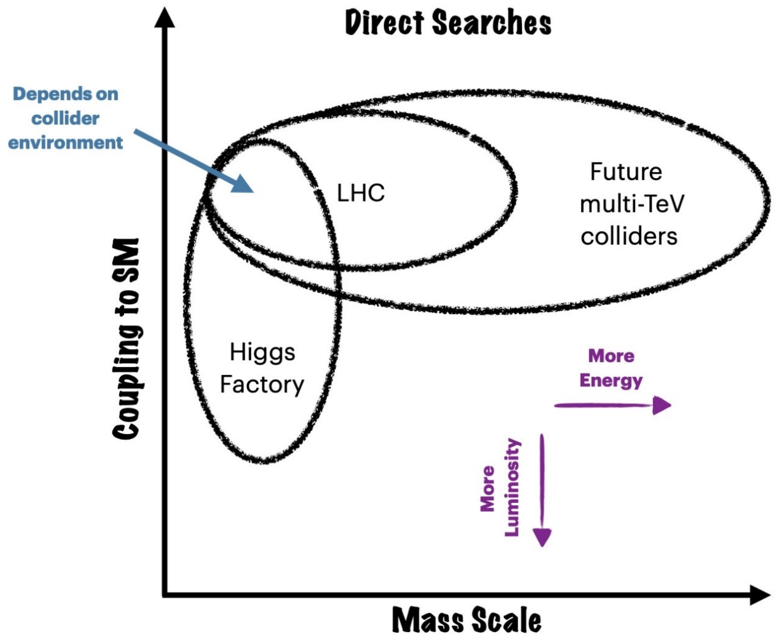
Should be pursued following

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 **multi-TeV colliders**

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.**

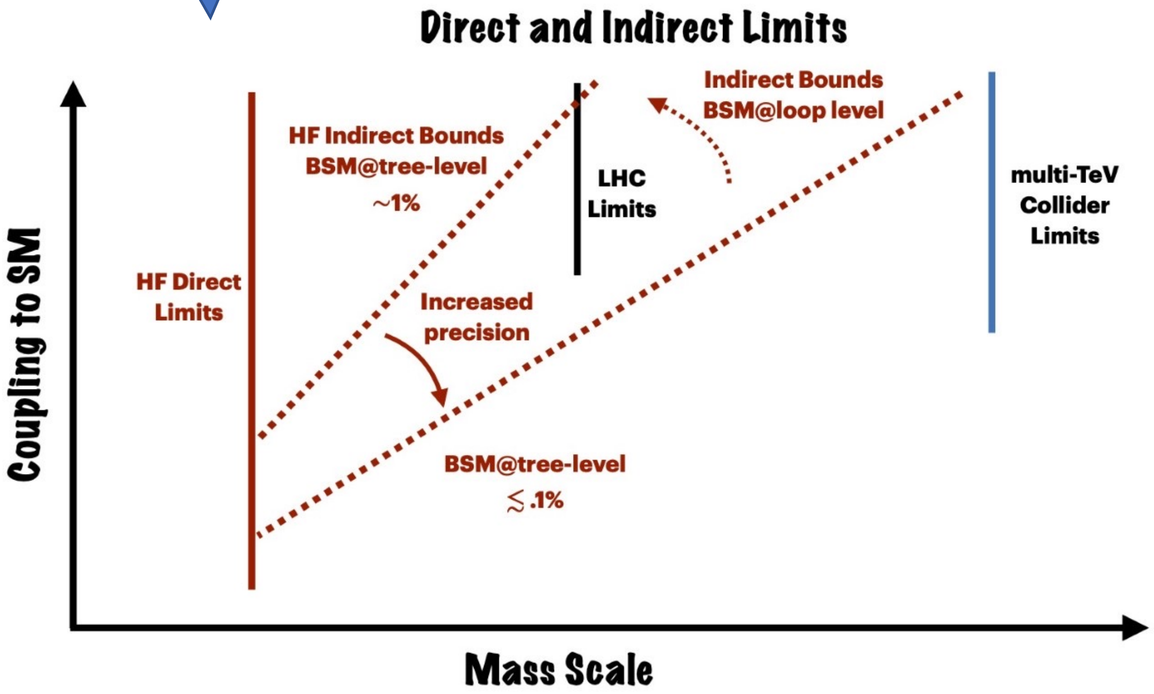


Higgs coupling measurements and direct searches will complement each other in exploring the 1-10 TeV scale and beyond.

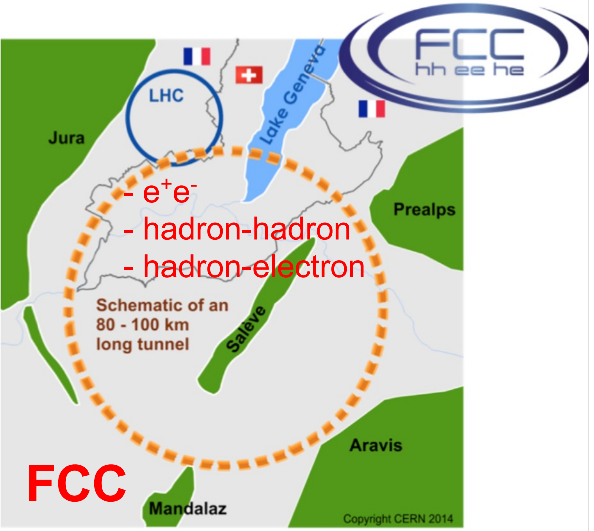
In a simplified picture:

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

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



EF future colliders



Hadrons

- large mass reach ⇒ exploration?
- S/B ~ 10^{-10} (w/o trigger)
- S/B ~ 0.1 (w/ trigger)
- requires multiple detectors (w/ optimized design)
- only pdf access to $\sqrt{\hat{s}}$
- ⇒ couplings to quarks and gluons

Leptons

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

Circular

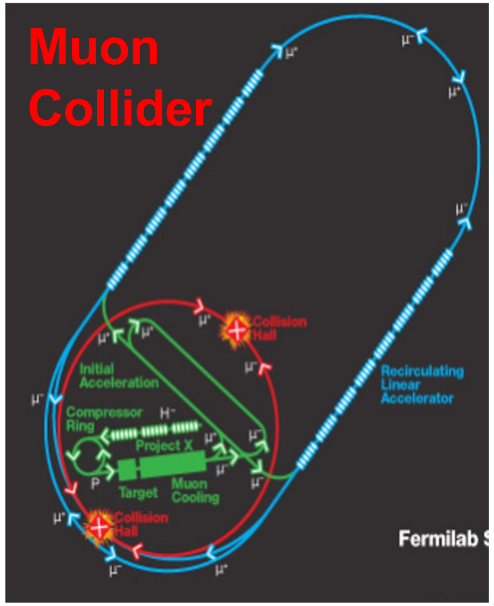
- higher luminosity
- several interaction points
- precise E-beam measurement (O(0.1MeV) via resonant depolarization)
- $\sqrt{s}$ limited by synchroton radiation

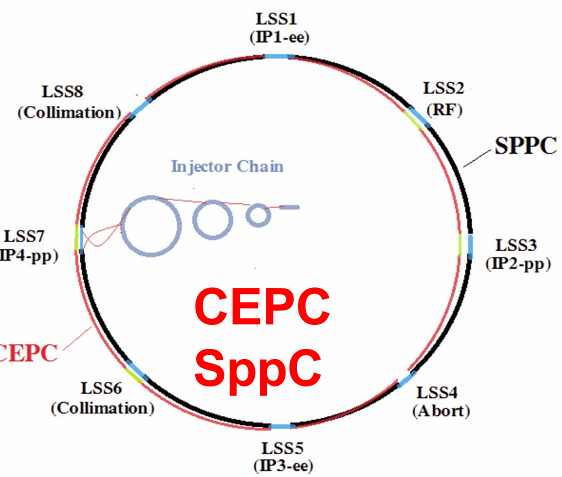
Linear

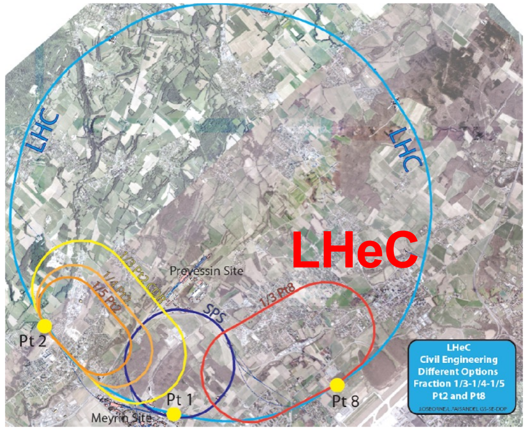
- easier to upgrade in energy
- easier to polarize beams
- "greener": less power consumption*
- large beamsthralung
- one IP only

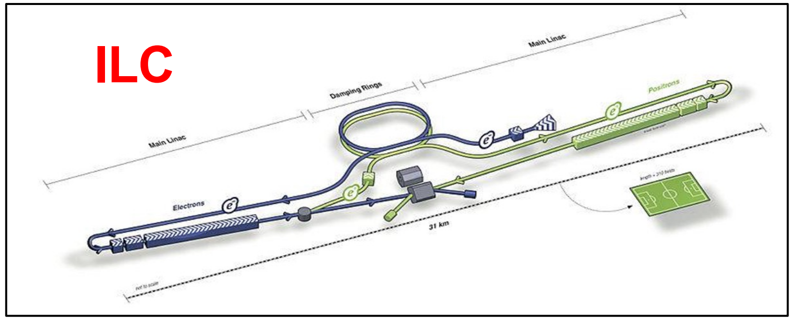
*energy consumption per integrated luminosity is lower at circular colliders but the energy consumption per GeV is lower at linear colliders

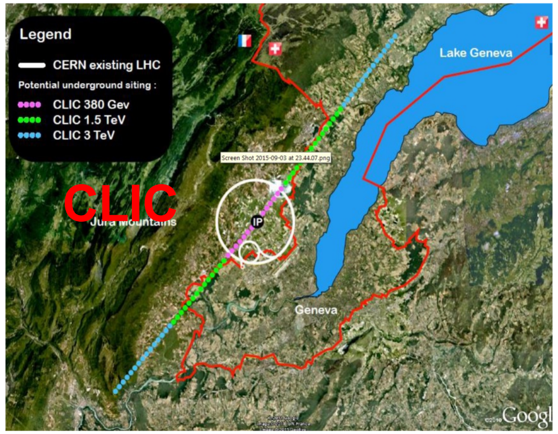
hristophe Grojean Future Measurements 9 Inst. Pascal, Dec. 4, 2019











SM21 added CCC (C^3)

Snowmass 21: EF Benchmark Scenarios

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

Collider	Type	$\sqrt{s}$	$\mathcal{P}[\%]$ e^-/e^+	$\mathcal{L}_{\text{int}}$ ab^{-1}/IP	Start Date Const.	Start Date Physics
HL-LHC	pp	14 TeV		3		2027
ILC & C^3	ee	250 GeV	$\pm80/\pm30$	2	2028	2038
		350 GeV	$\pm80/\pm30$	0.2		
		500 GeV	$\pm80/\pm30$	4		
		1 TeV	$\pm80/\pm20$	8		
CLIC	ee	380 GeV	$\pm80/0$	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^+	$\mathcal{L}_{\text{int}}$ 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	$\pm80/0$	2.5	2052	2058
		3.0 TeV	$\pm80/0$	5		
μ-collider	$\mu\mu$	3 TeV		1	2038	2045
		10 TeV		10		

Timelines are taken from the Collider ITF report (arXiv: 2208.06030)

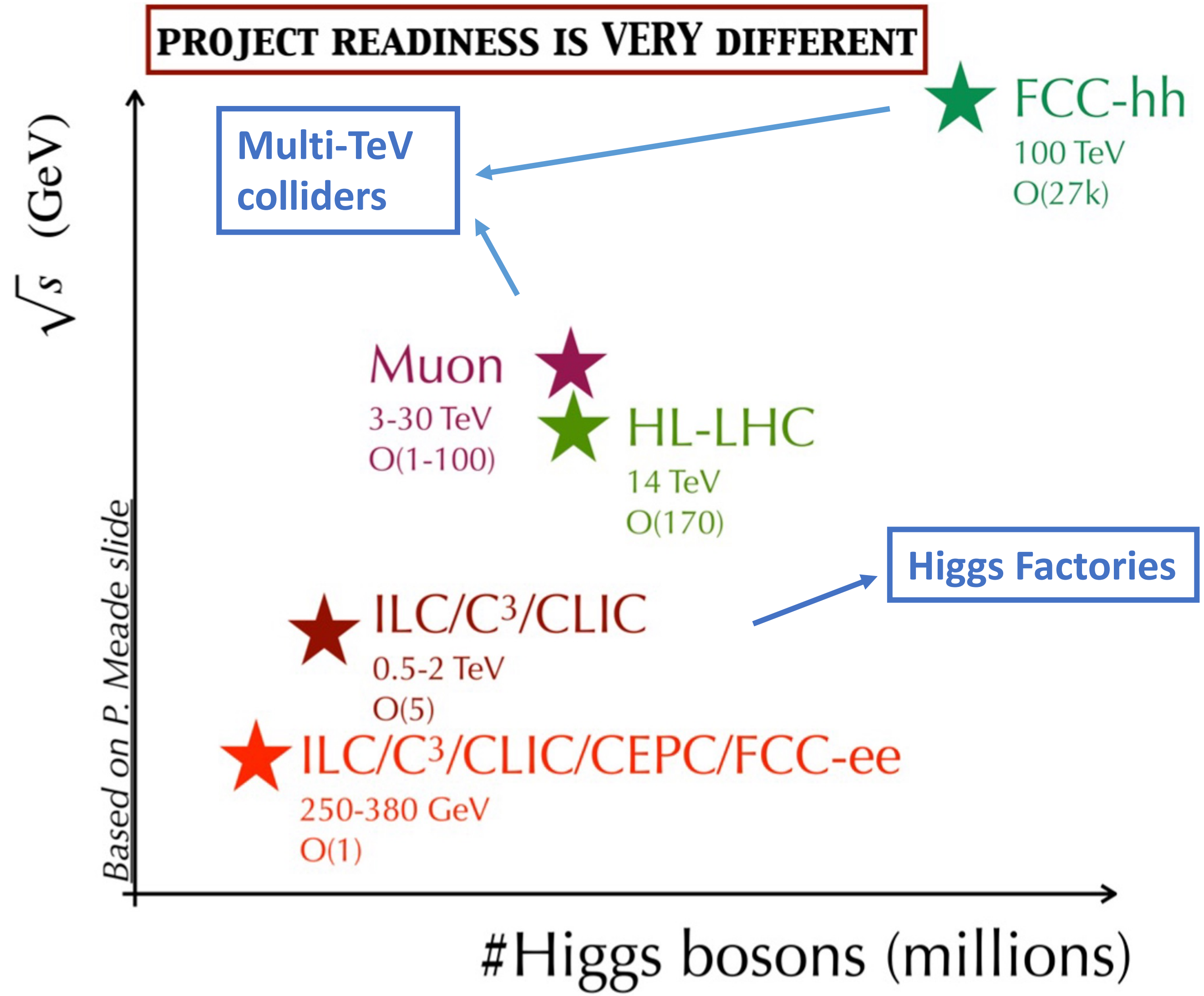
Beyond the HL-LHC: proposed future colliders

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**

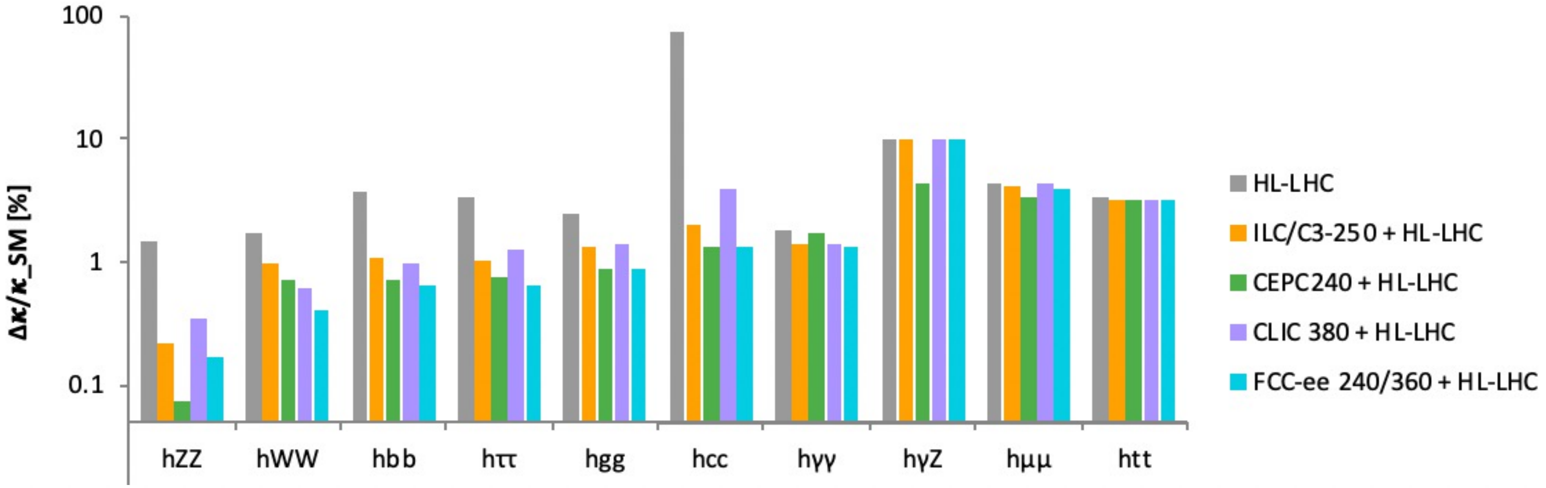
HADRON COLLIDERS

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



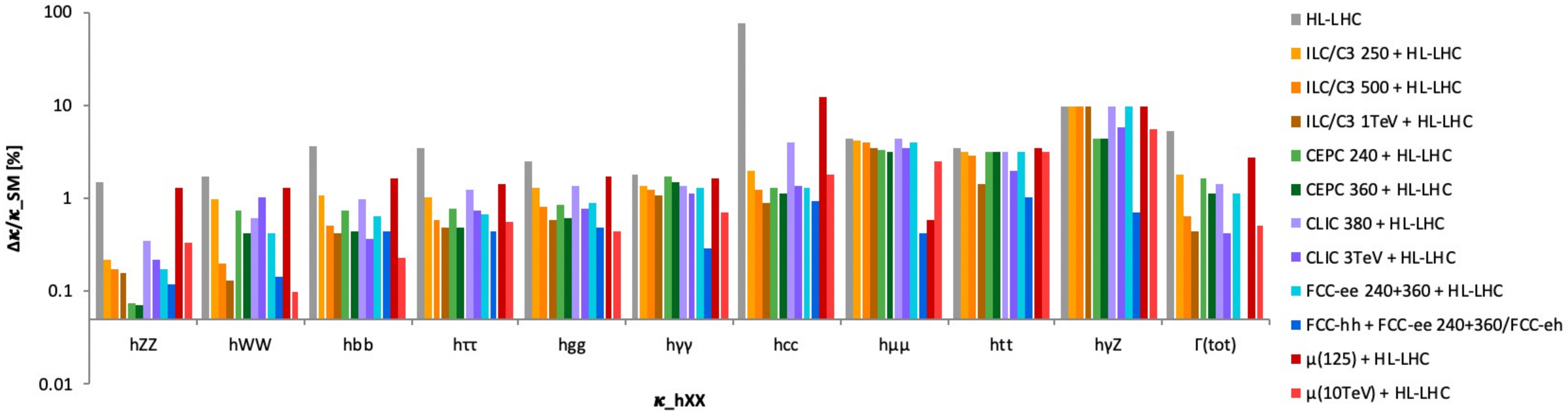
Reach of future colliders for Higgs couplings: a closer look

Based on full Run 2 dataset analyses



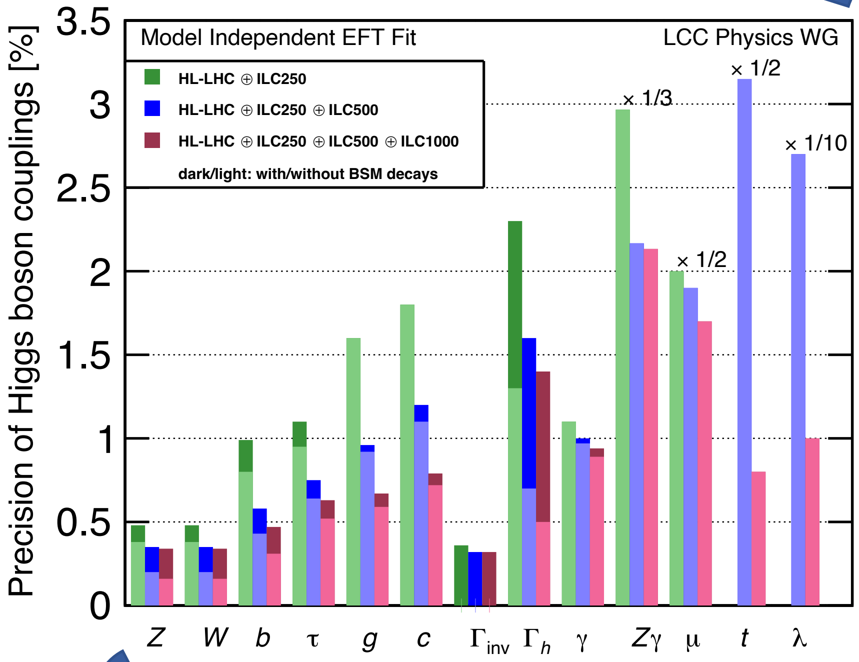
Initial stages of future e^+e^- machines

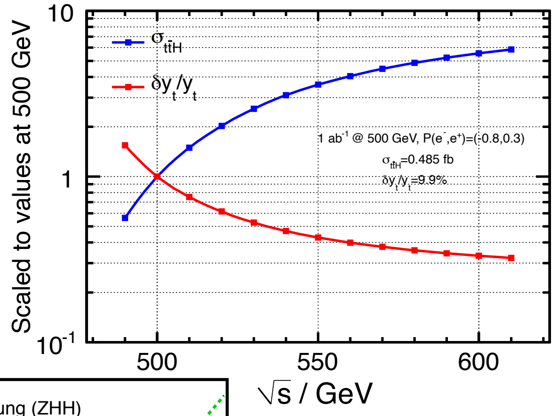
From Snowmass 2021 EF Higgs Topical Group Report arXiv:2209.07510

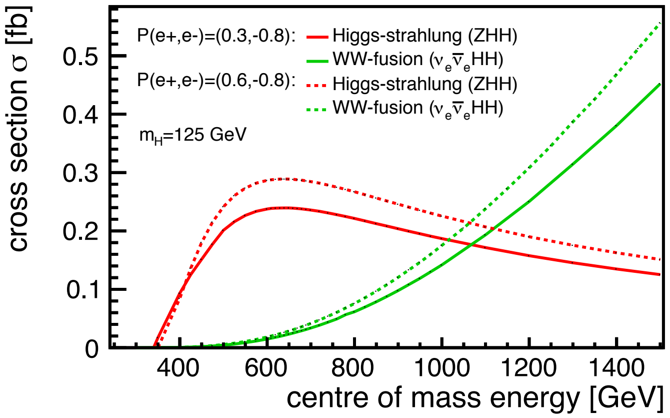


Final reach of all considered future colliders

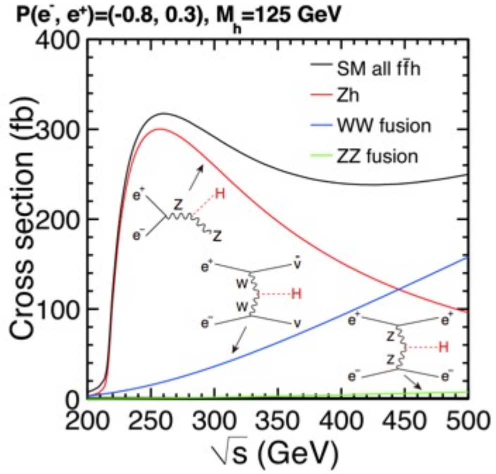
The case of e⁺e⁻ Higgs factories



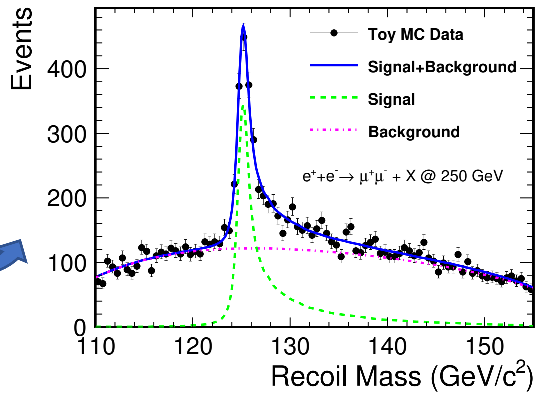


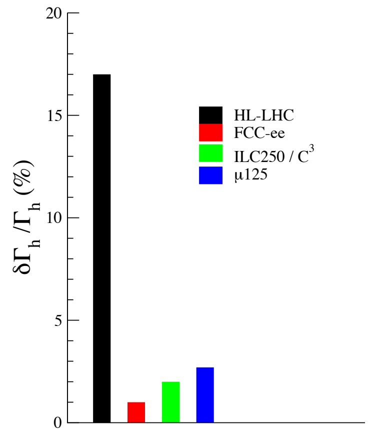


Energy matters
top-Yukawa, HH, extended Higgs sectors need >500 GeV

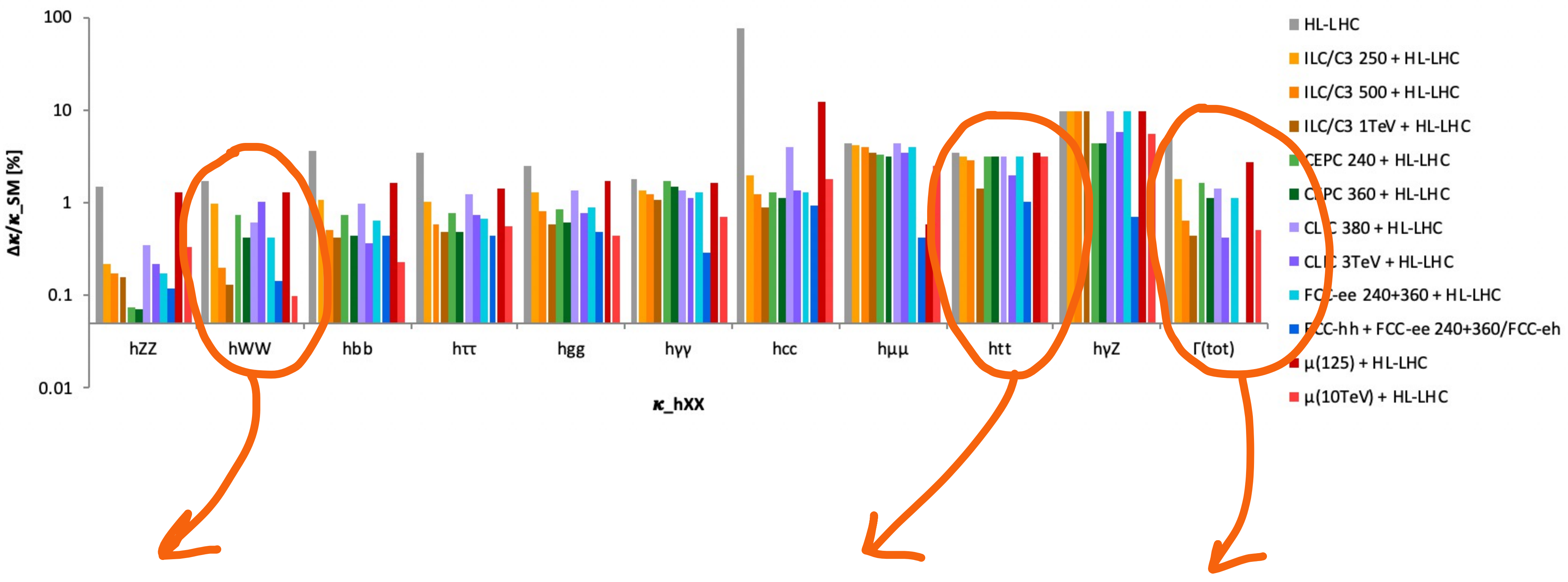


Model-independent Γ_H measurment





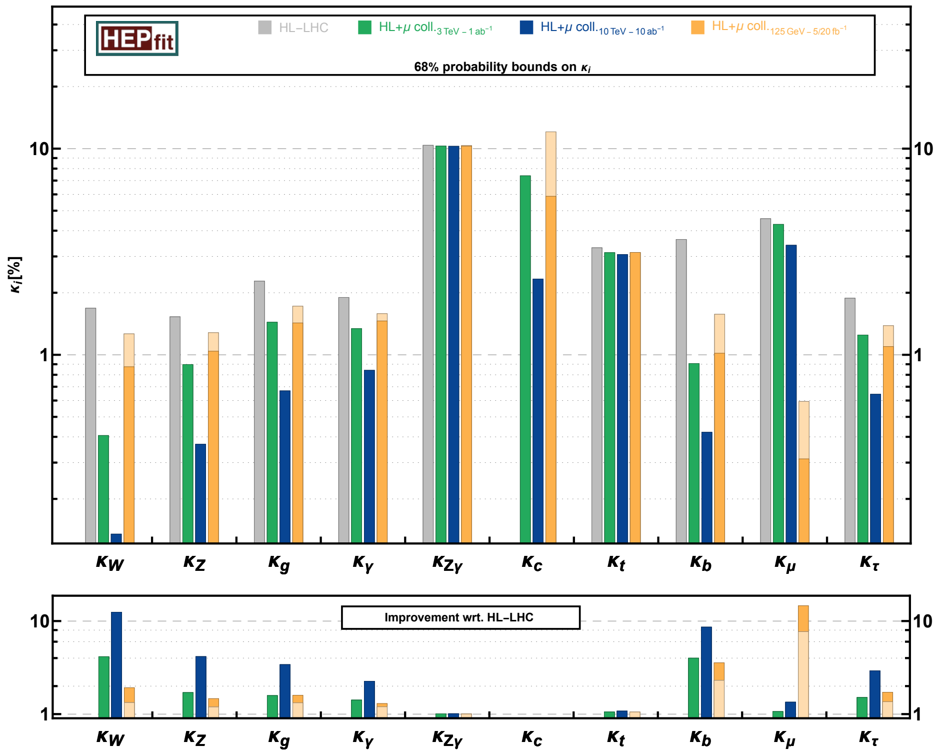
Focusing on final reach of e^+e^- machines



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?

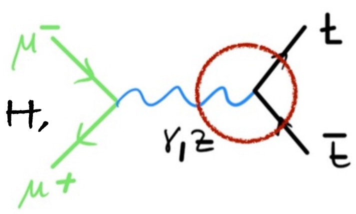
The case of a Muon Collider



- **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

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

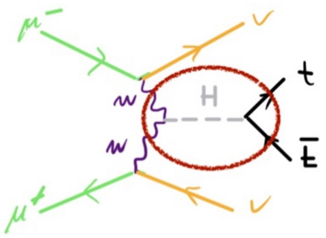
$\sqrt{s} \lesssim$ 1-5 TeV



$$\sigma_s \sim \frac{1}{s}$$

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

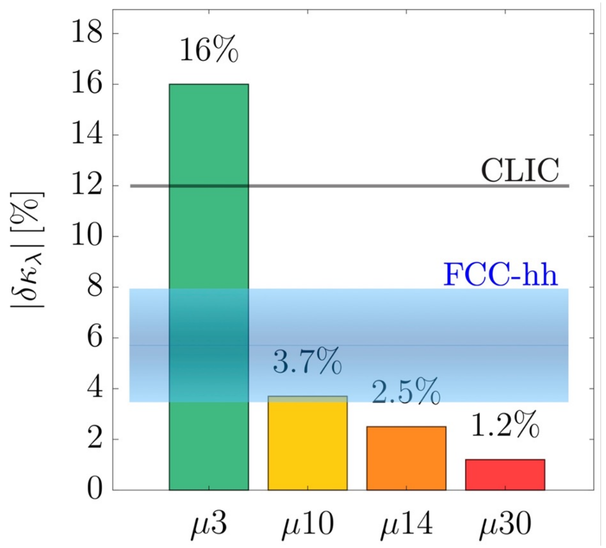
$\sqrt{s} \gtrsim$ 1-5 TeV



Reach for Higgs self-coupling

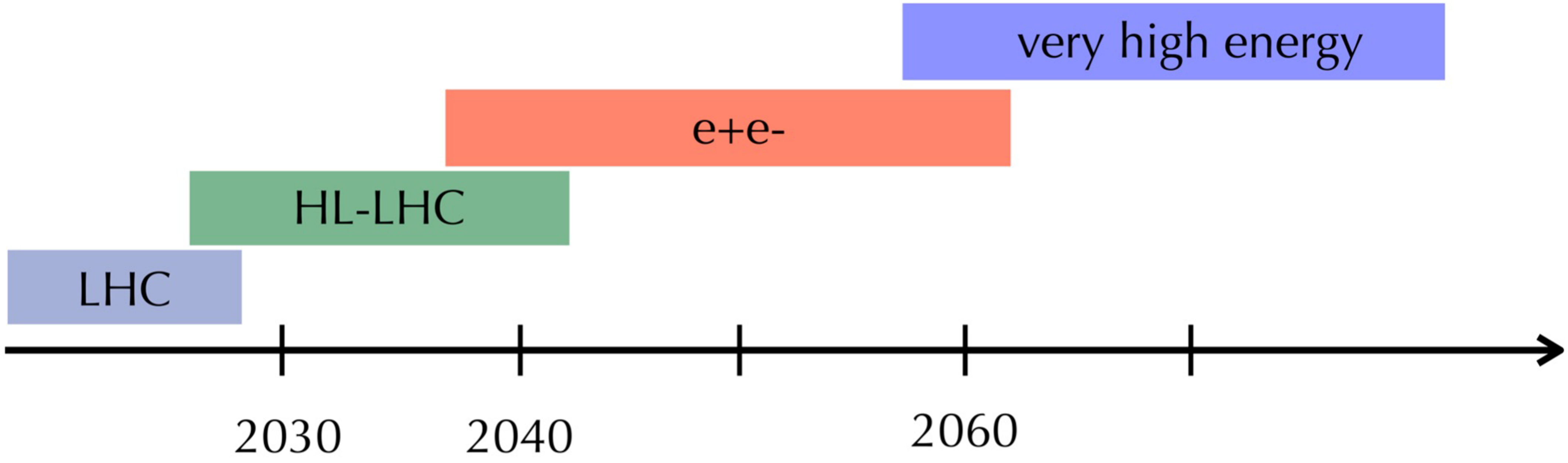
collider	Indirect-h	hh	combined
HL-LHC	100-200%	50%	50%
ILC_{250}/C^3-250	49%	–	49%
ILC_{500}/C^3-550	38%	20%	20%
$CLIC_{380}$	50%	–	50%
$CLIC_{1500}$	49%	36%	29%
$CLIC_{3000}$	49%	9%	9%
FCC-ee	33%	–	33%
FCC-ee (4 IPs)	24%	–	24%
FCC-hh	-	2.9-5.5%	2.9-5.5%
μ(3 TeV)	-	15-30%	15-30%
μ(10 TeV)	-	4%	4%

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



arXiv:2203.07256

Beyond the HL-LHC: projections for Higgs couplings

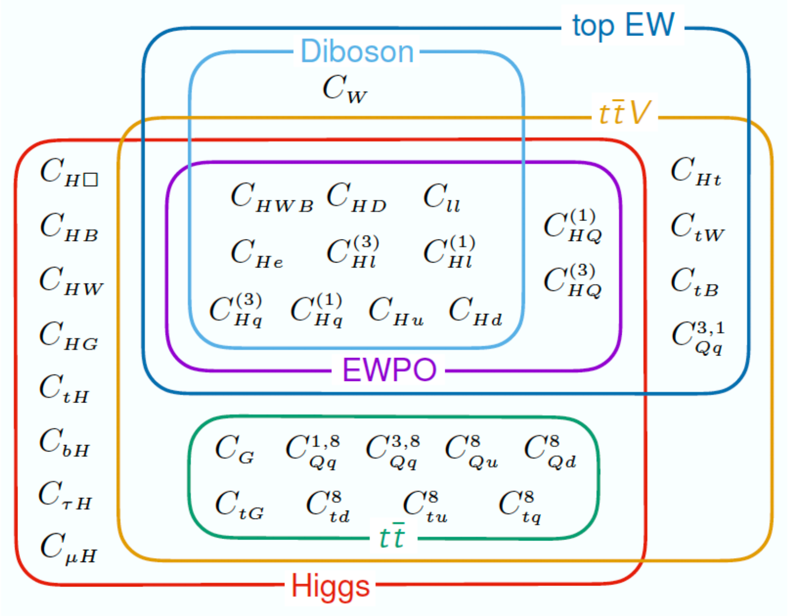


H couplings to:	**O(5-15)%**	**O(0.1-1)%**	**O(1)‰**
H self-coupling to	**<O(50)%**	**O(20)%**	**O(1)%**

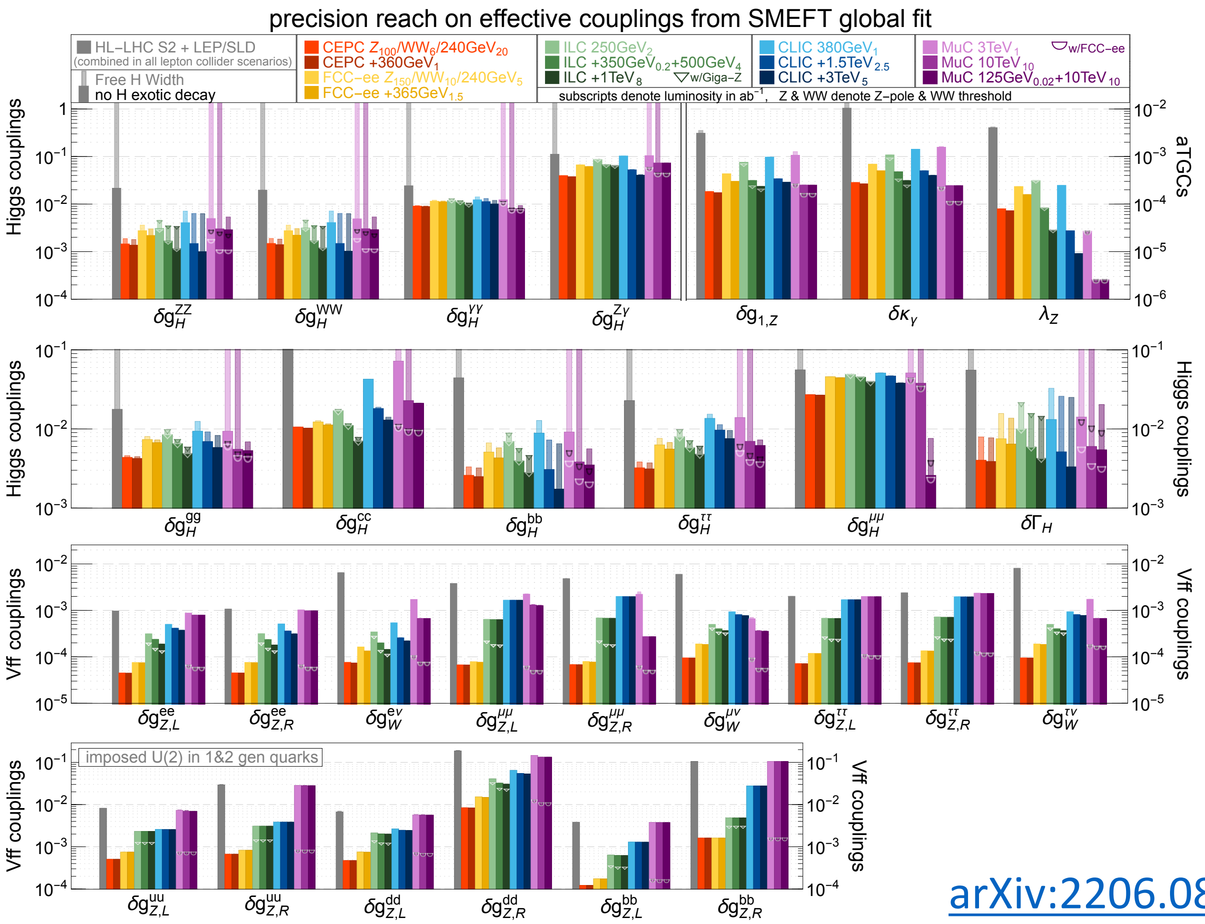
From C. Vernieri – Snowmass 21 EF Workshop - Brown U. - March 2022

Constraining BSM via global EFT fits

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



EW + Higgs



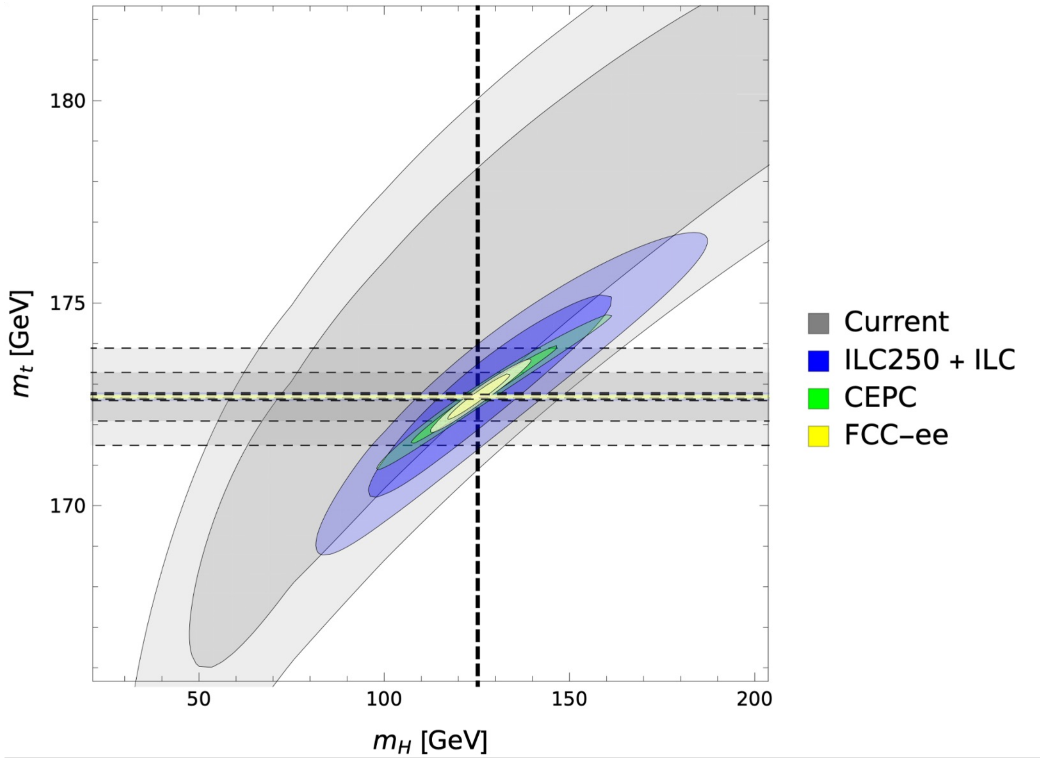
arXiv:2206.08326

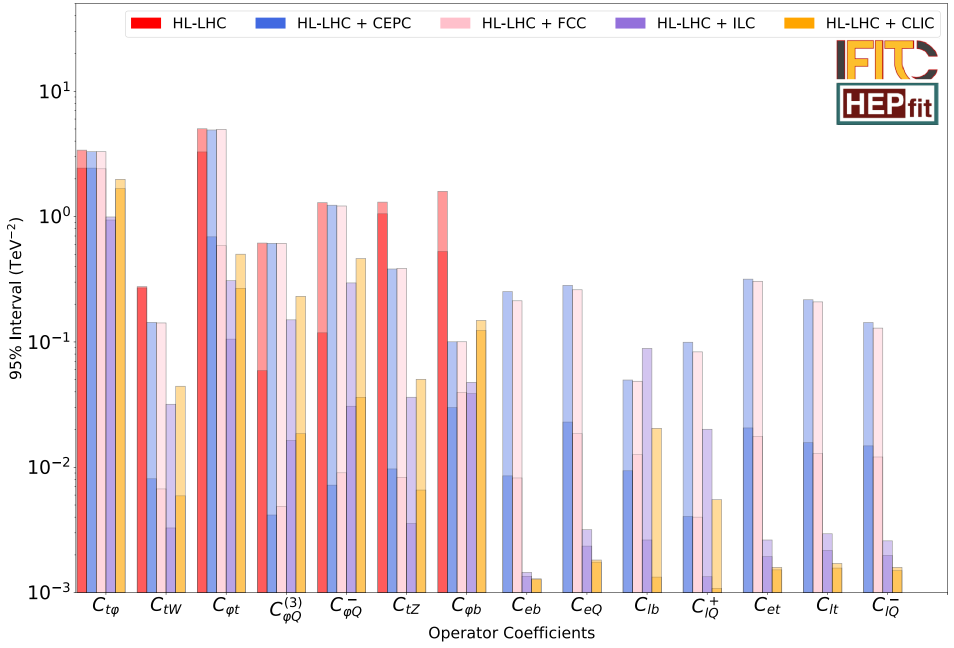
EFT connects different processes with large correlations: pattern of coefficients give insights on underlying BSM model

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

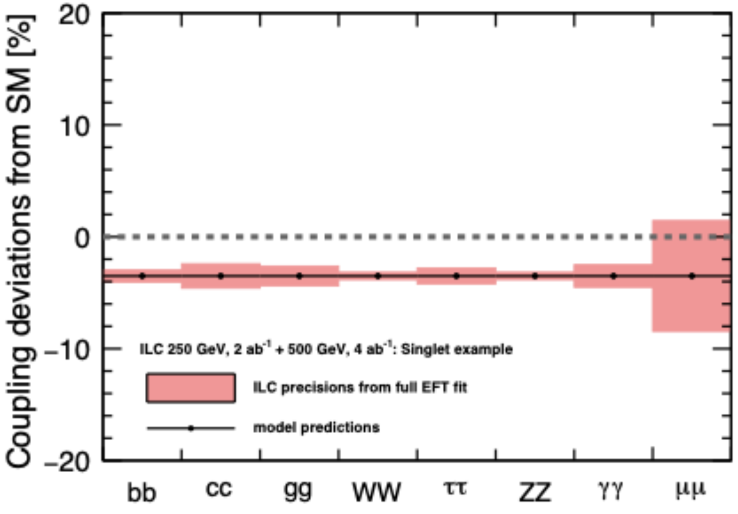




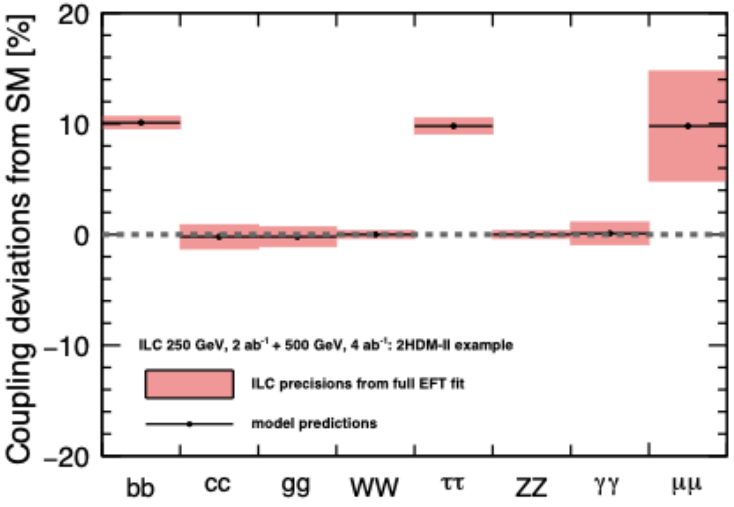
From Snowmass 2021 EF HF and EW TG's Reports arXiv:2209.11267, arXiv:2209.08078

Disentangling models from EFT patterns

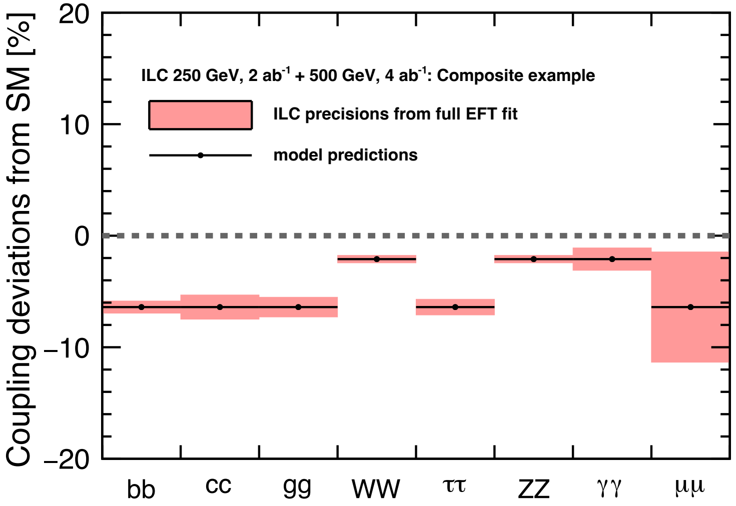
The “inverse Higgs” problem



additional scalar singlet
(m_S=2.8 TeV, max mixing)



2HDM-II
(MH=600 GeV, tanβ=7)

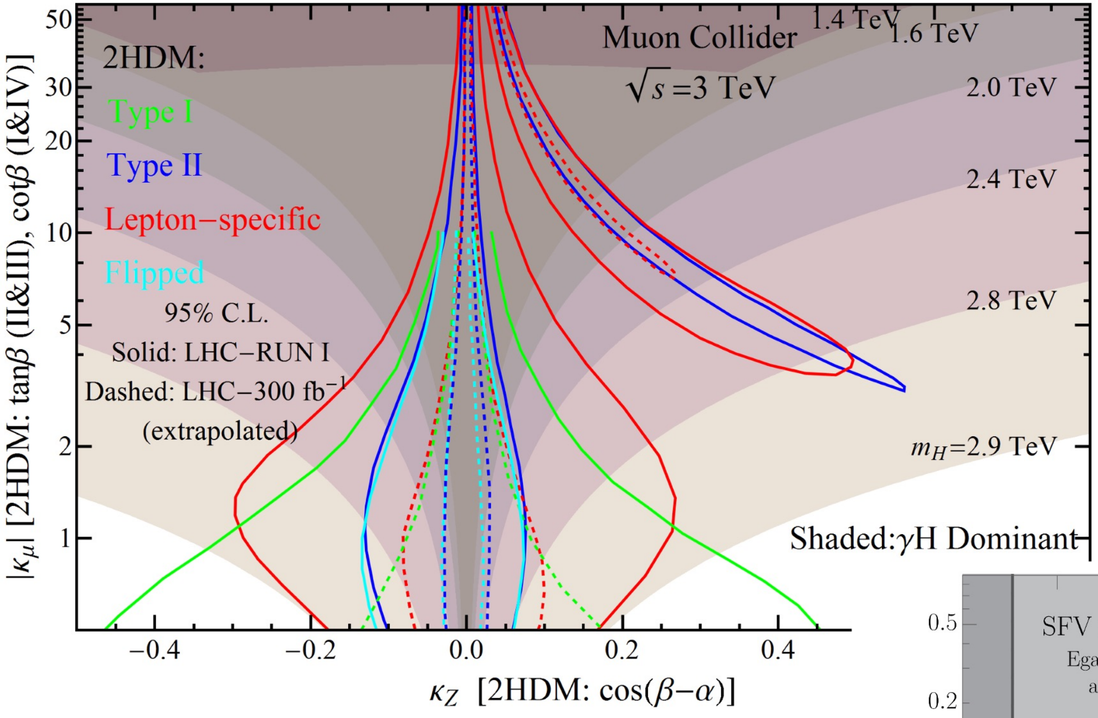


Composite Higgs
(f=1.2 TeV)

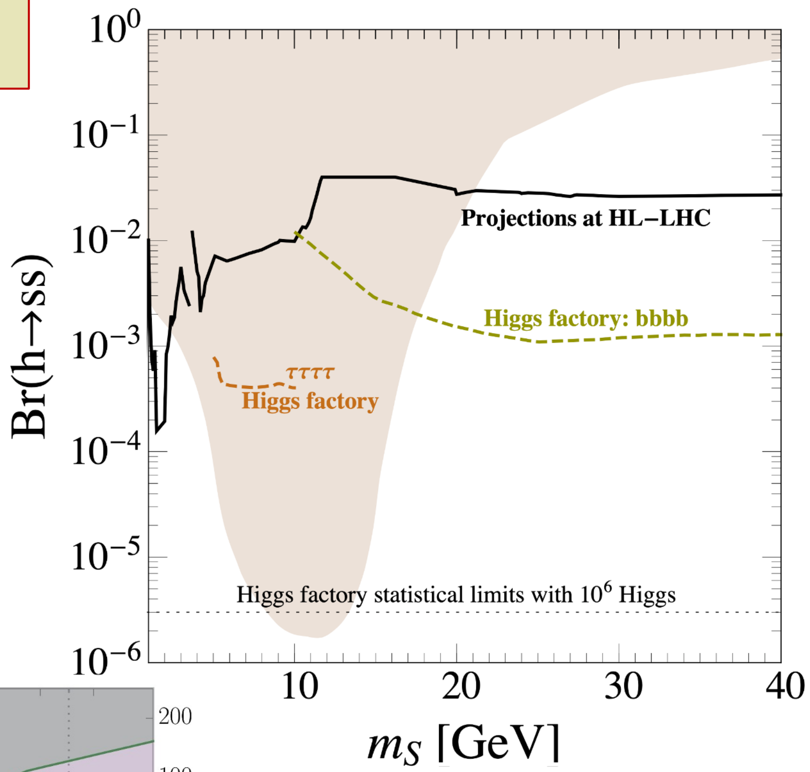
Snowmass 2021: ILC white paper (arXiv: 2203.07622)

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

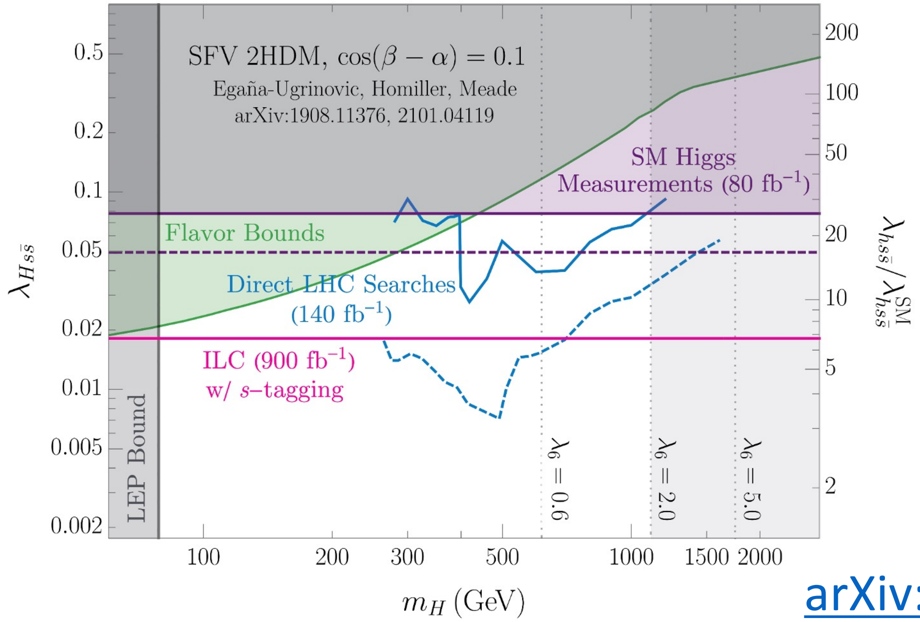
BSM explorations: extended Higgs sectors



arXiv:2203.07261



arXiv:2203:08206



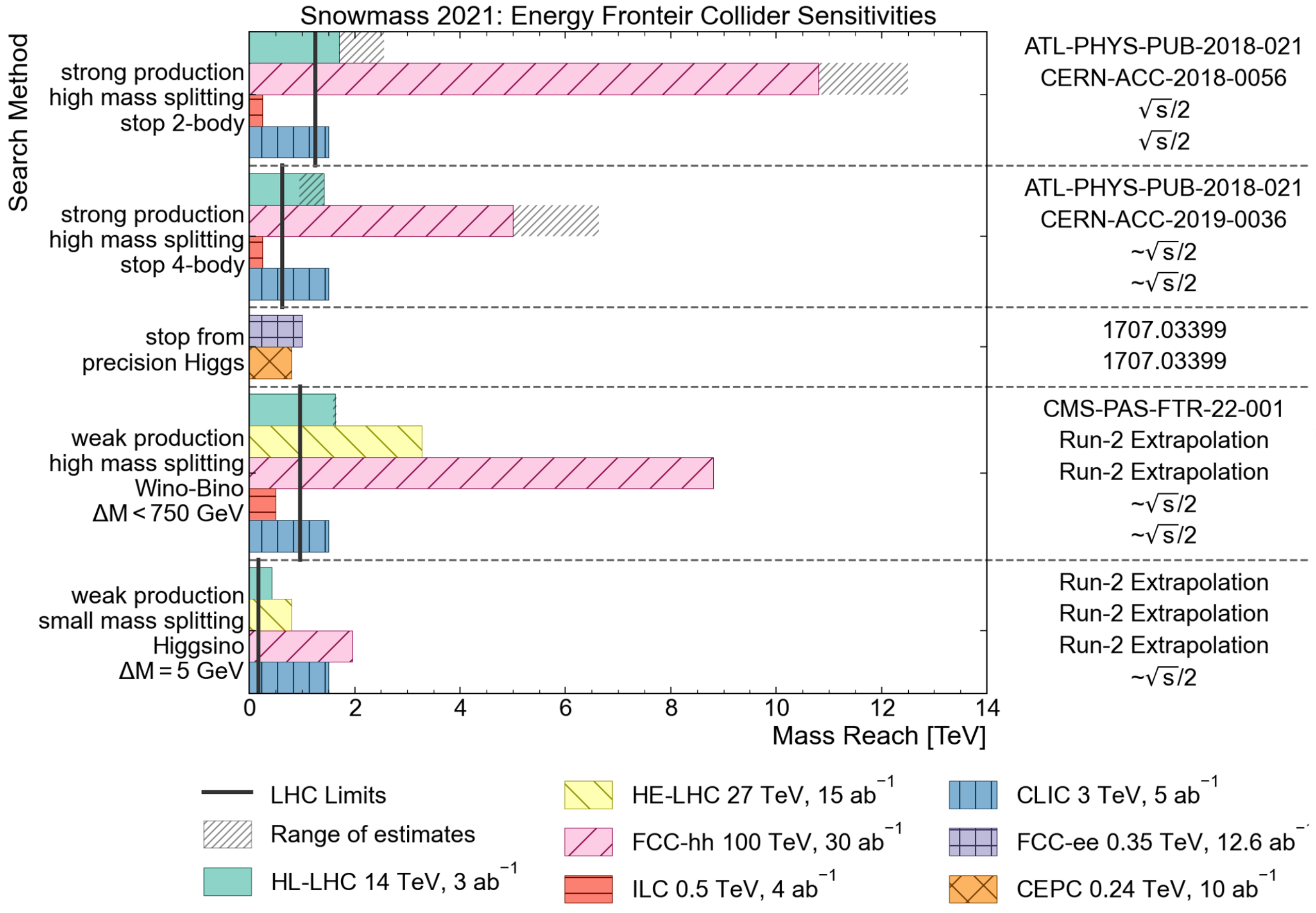
arXiv:2203:07535

Extended Higgs sectors:
2HDM, extra singlets, …

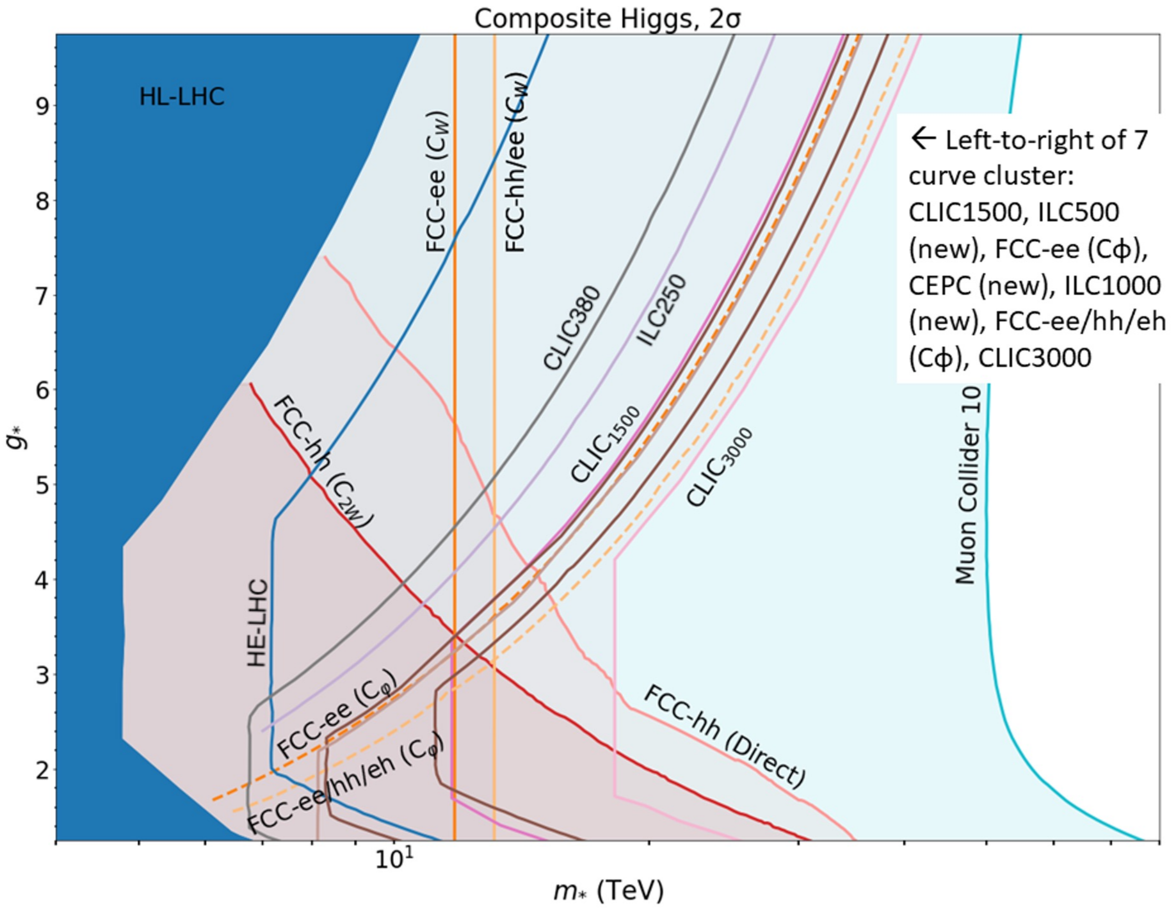
Higgs and flavor:
probing anomalous
Hss coupling

Examples of BSM model specific explorations

SUSY models



Composite Higgs models



From Snowmass 21 EF BSM Topical Group Report

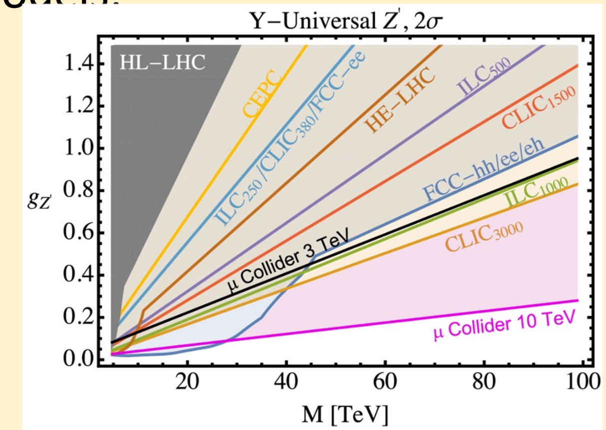
Examples of BSM general explorations

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

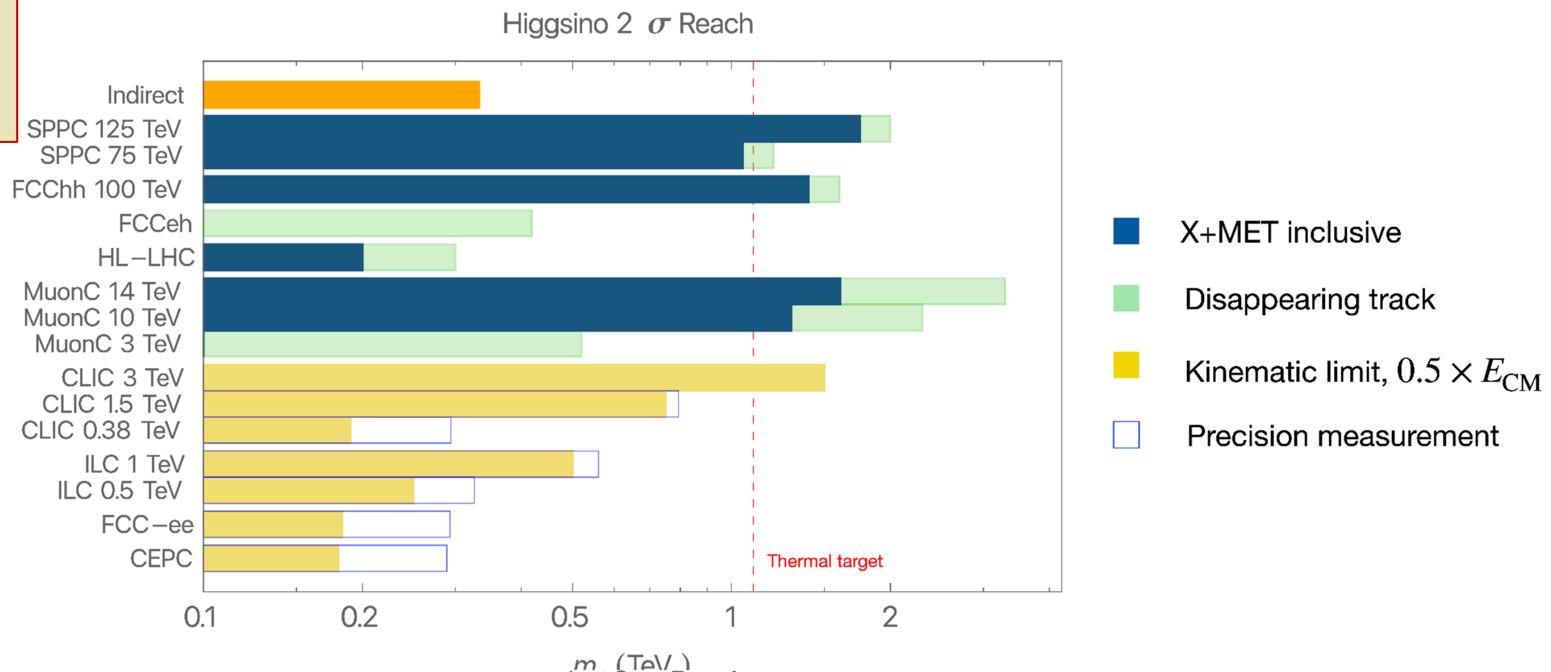
Increasing Z' Sensitivity

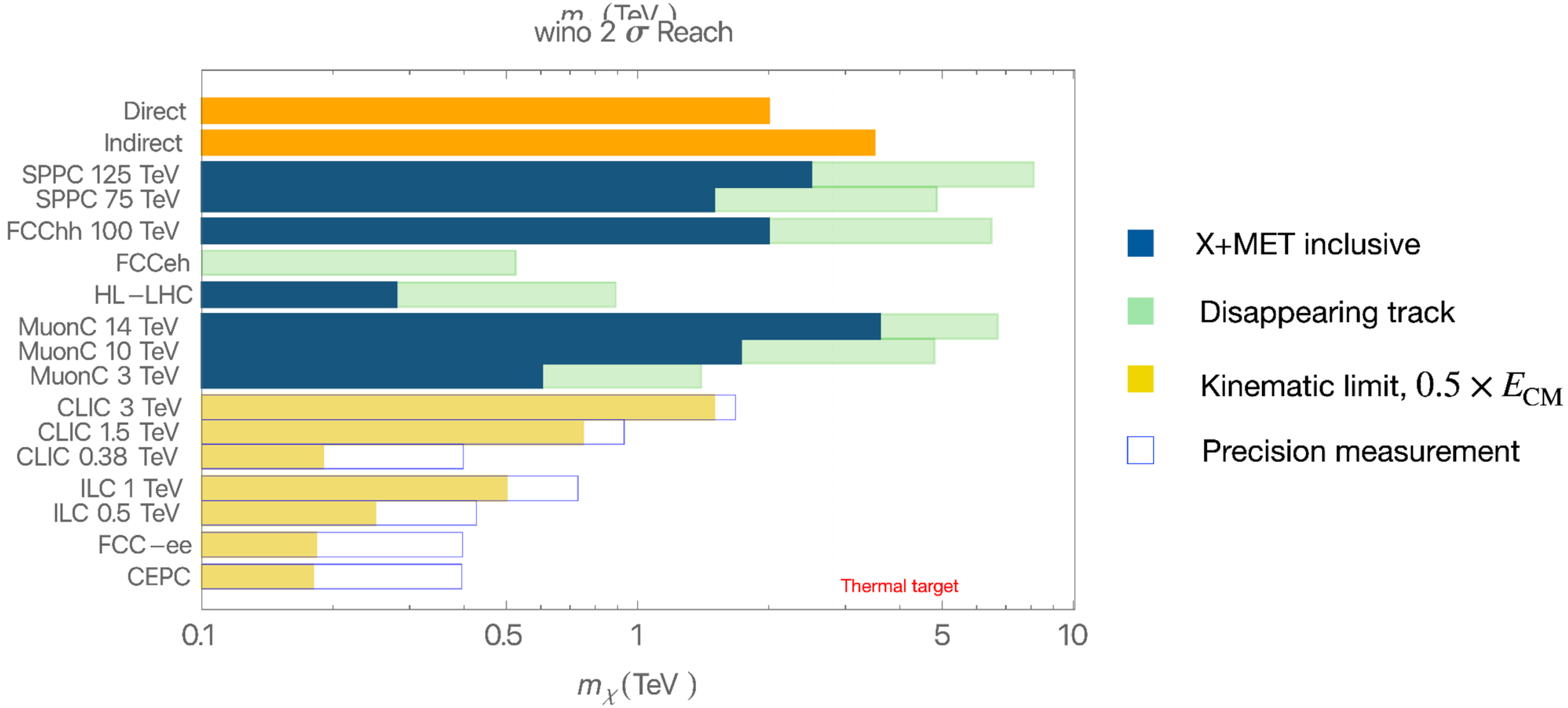
Dark matter at colliders

Complementing observation in astrophysics experiments

Probing interaction of DM with SM particles
Discriminating between different models

Example of WIMP DM reach
[arXiv:2210.01770](https://arxiv.org/abs/2210.01770)





Future of Perturbative QCD calculations

Les Houches wish-list

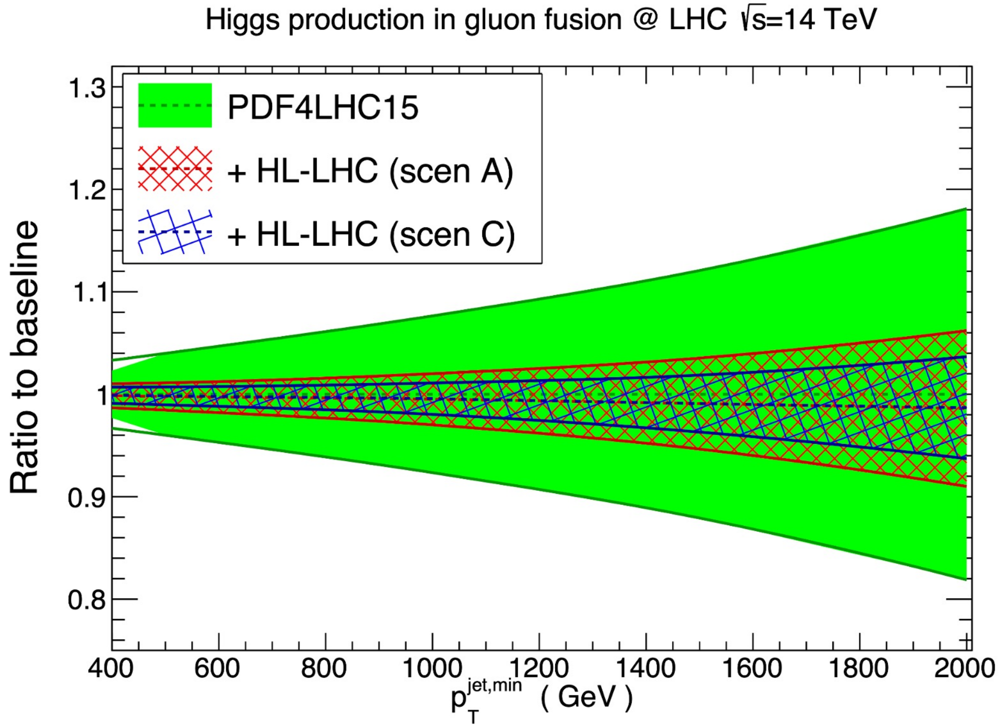
process	known	desired
$pp \to H$	$\mathrm{N^3LO_{HTL}}$, $\mathrm{N^2LO^{(t)}_{QCD}}$, $\mathrm{N^{(1,1)}LO^{(HTL)}_{QCD\otimes EW}}$	$\mathrm{N^4LO_{HTL}}$ (incl.), $\mathrm{N^2LO^{(b,c)}_{QCD}}$
$pp \to H+j$	$\mathrm{N^2LO_{HTL}}$, $\mathrm{NLO_{QCD}}$, $\mathrm{N^{(1,1)}LO_{QCD\otimes EW}}$	$\mathrm{N^2LO_{HTL} \otimes NLO_{QCD} + NLO_{EW}}$
$pp \to H+2j$	$\mathrm{NLO_{HTL} \otimes LO_{QCD}}$ $\mathrm{N^3LO^{(VBF^*)}_{QCD}}$ (incl.), $\mathrm{N^2LO^{(VBF^*)}_{QCD}}$, $\mathrm{NLO^{(VBF)}_{EW}}$	$\mathrm{N^2LO_{HTL} \otimes NLO_{QCD} + NLO_{EW}}$, $\mathrm{N^2LO^{(VBF)}_{QCD}}$
$pp \to H+3j$	$\mathrm{NLO_{HTL}}$, $\mathrm{NLO^{(VBF)}_{QCD}}$	$\mathrm{NLO_{QCD} + NLO_{EW}}$
$pp \to VH$	$\mathrm{N^2LO_{QCD} + NLO_{EW}}$, $\mathrm{NLO^{(t,b)}_{gg \to HZ}}$	
$pp \to VH+j$	$\mathrm{N^2LO_{QCD}}$	$\mathrm{N^2LO_{QCD} + NLO_{EW}}$
$pp \to HH$	$\mathrm{N^3LO_{HTL} \otimes NLO_{QCD}}$	$\mathrm{NLO_{EW}}$
$pp \to H+t\bar{t}$	$\mathrm{NLO_{QCD} + NLO_{EW}}$, $\mathrm{N^2LO_{QCD}}$ (off-diag.)	$\mathrm{N^2LO_{QCD}}$
$pp \to H+t/\bar{t}$	$\mathrm{NLO_{QCD}}$	$\mathrm{N^2LO_{QCD}}$, $\mathrm{NLO_{QCD} + NLO_{EW}}$
$pp \to V$	$\mathrm{N^3LO_{QCD}}$, $\mathrm{N^{(1,1)}LO_{QCD\otimes EW}}$, $\mathrm{NLO_{EW}}$	$\mathrm{N^3LO_{QCD} + N^{(1,1)}LO_{QCD\otimes EW}}$, $\mathrm{N^2LO_{EW}}$
$pp \to VV'$	$\mathrm{N^2LO_{QCD} + NLO_{EW}}$, $+\mathrm{NLO_{QCD}}$ (gg)	$\mathrm{NLO_{QCD}}$ (gg,massive loops)
$pp \to V+j$	$\mathrm{N^2LO_{QCD} + NLO_{EW}}$	hadronic decays
$pp \to V+2j$	$\mathrm{NLO_{QCD} + NLO_{EW}}$, $\mathrm{NLO_{EW}}$	$\mathrm{N^2LO_{QCD}}$
$pp \to V+b\bar{b}$	$\mathrm{NLO_{QCD}}$	$\mathrm{N^2LO_{QCD} + NLO_{EW}}$
$pp \to VV'+1j$	$\mathrm{NLO_{QCD} + NLO_{EW}}$	$\mathrm{N^2LO_{QCD}}$
$pp \to VV'+2j$	$\mathrm{NLO_{QCD}}$ (QCD), $\mathrm{NLO_{QCD} + NLO_{EW}}$ (EW)	Full $\mathrm{NLO_{QCD} + NLO_{EW}}$
$pp \to W^+W^+ + 2j$	Full $\mathrm{NLO_{QCD} + NLO_{EW}}$	
$pp \to W^+W^- + 2j$	$\mathrm{NLO_{QCD} + NLO_{EW}}$ (EW component)	
$pp \to W^+Z + 2j$	$\mathrm{NLO_{QCD} + NLO_{EW}}$ (EW component)	
$pp \to ZZ + 2j$	Full $\mathrm{NLO_{QCD} + NLO_{EW}}$	
$pp \to VV'V''$	$\mathrm{NLO_{QCD}}$, $\mathrm{NLO_{EW}}$ (w/o decays)	$\mathrm{NLO_{QCD} + NLO_{EW}}$
$pp \to W^\pm W^+ W^-$	$\mathrm{NLO_{QCD} + NLO_{EW}}$	
$pp \to \gamma\gamma$	$\mathrm{N^2LO_{QCD} + NLO_{EW}}$	$\mathrm{N^3LO_{QCD}}$
$pp \to \gamma + j$	$\mathrm{N^2LO_{QCD} + NLO_{EW}}$	$\mathrm{N^3LO_{QCD}}$
$pp \to \gamma\gamma + j$	$\mathrm{N^2LO_{QCD} + NLO_{EW}}$, $+\mathrm{NLO_{QCD}}$ (gg channel)	
$pp \to \gamma\gamma\gamma$	$\mathrm{N^2LO_{QCD}}$	$\mathrm{N^2LO_{QCD} + NLO_{EW}}$
$pp \to 2\,\mathrm{jets}$	$\mathrm{N^2LO_{QCD}}$, $\mathrm{NLO_{QCD} + NLO_{EW}}$	$\mathrm{N^3LO_{QCD} + NLO_{EW}}$
$pp \to 3\,\mathrm{jets}$	$\mathrm{N^2LO_{QCD} + NLO_{EW}}$	
$pp \to t\bar{t}$	$\mathrm{N^2LO_{QCD}}$ (w/ decays)+ $\mathrm{NLO_{EW}}$ (w/o decays) $\mathrm{NLO_{QCD} + NLO_{EW}}$ (w/ decays, off-shell effects) $\mathrm{N^2LO_{QCD}}$	$\mathrm{N^3LO_{QCD}}$
$pp \to t\bar{t}+j$	$\mathrm{NLO_{QCD}}$ (w/ decays, off-shell effects) $\mathrm{NLO_{EW}}$ (w/o decays)	$\mathrm{N^2LO_{QCD} + NLO_{EW}}$ (w/ decays)
$pp \to t\bar{t}+2j$	$\mathrm{NLO_{QCD}}$ (w/o decays)	$\mathrm{NLO_{QCD} + NLO_{EW}}$ (w/ decays)
$pp \to t\bar{t}+Z$	$\mathrm{NLO_{QCD} + NLO_{EW}}$ (w/o decays) $\mathrm{NLO_{QCD}}$ (w/ decays, off-shell effects)	$\mathrm{N^2LO_{QCD} + NLO_{EW}}$ (w/ decays)
$pp \to t\bar{t}+W$	$\mathrm{NLO_{QCD} + NLO_{EW}}$ (w/ decays, off-shell effects)	$\mathrm{N^2LO_{QCD} + NLO_{EW}}$ (w/ decays)
$pp \to t/\bar{t}$	$\mathrm{N^2LO_{QCD}}$*(w/ decays) $\mathrm{NLO_{EW}}$ (w/o decays)	$\mathrm{N^2LO_{QCD} + NLO_{EW}}$ (w/ decays)
$pp \to tZj$	$\mathrm{NLO_{QCD} + NLO_{EW}}$ (w/ decays)	$\mathrm{N^2LO_{QCD} + NLO_{EW}}$ (w/o decays)

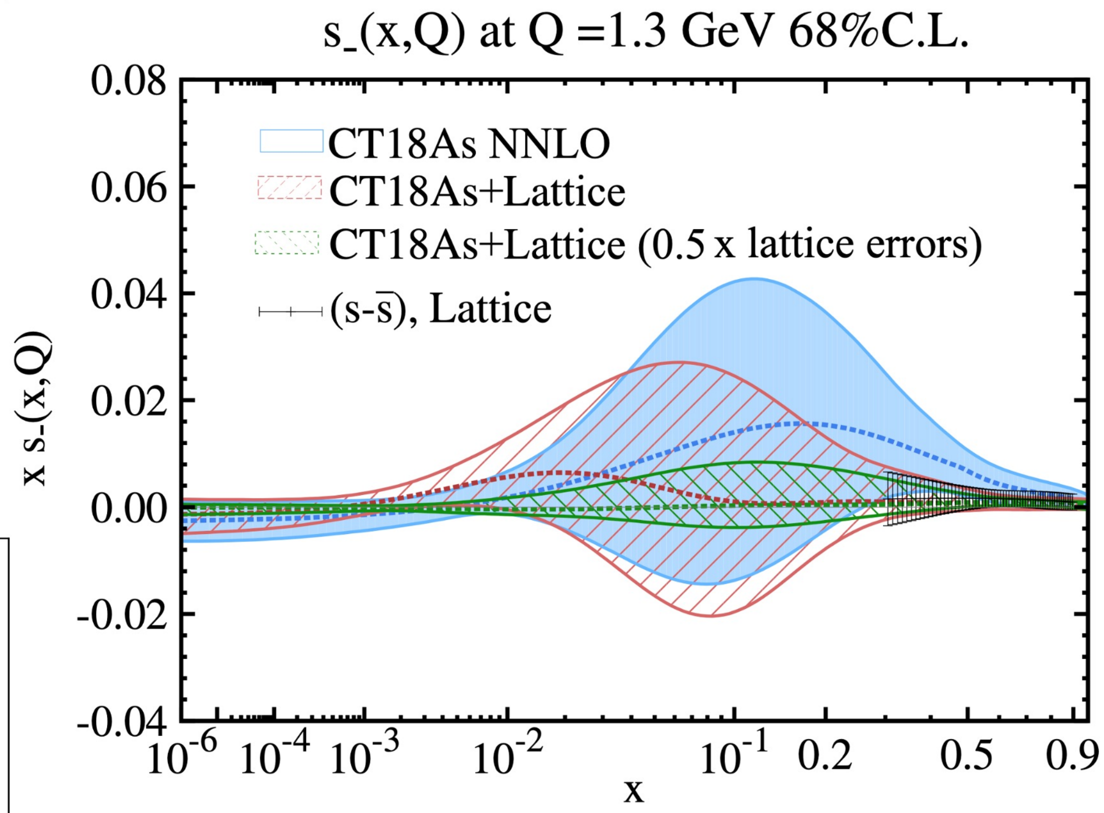
- **α_s uncertainty is a limiting factor in many measurements, e.g. Higgs couplings, at the HL-LHC**

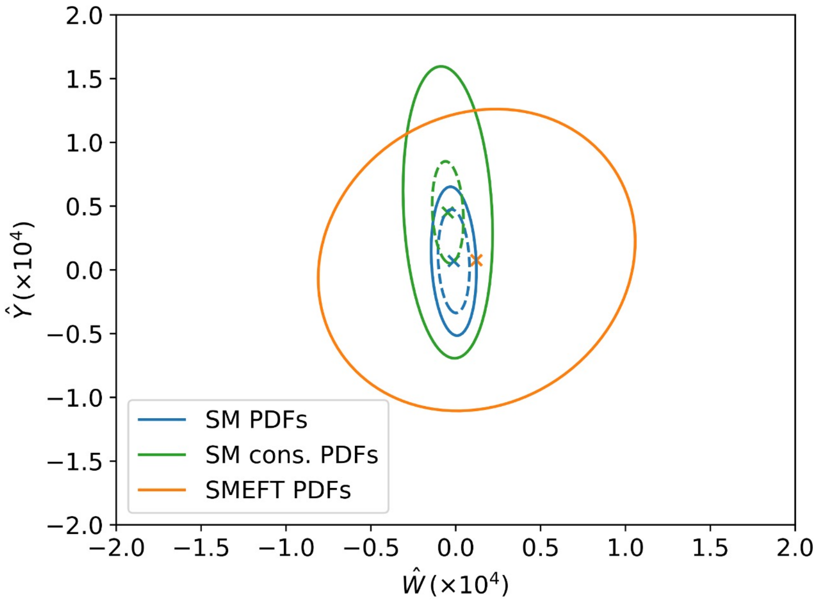
	Relative $\alpha_s(m_Z)$ uncertainty	
Method	Current	Near (long-term) future
(1) Lattice	0.7%	$\approx$ 0.3% (0.1%)
(2) τ decays	1.6%	$<$ 1.%
(3) $Q\bar{Q}$ bound states	3.3%	$\approx$ 1.5%
(4) DIS & PDF fits	1.7%	$\approx$ 1% (0.2%)
(5) e^+e^- jets & evt shapes	2.6%	$\approx$ 1.5% ($<$ 1%)
(6) Electroweak fits	2.3%	($\approx$ 0.1%)
World average	0.8%	$\approx$ 0.4% (0.1%)

- **FCC-ee:** 3×10^{12} Z→qq at the Z pole, and √s calibration 10's keV provides unparalleled α_s precision → searches for small deviations from SM predictions that could signal BSM
- **Jet substructure techniques:**
  - Identification of q/g-initiated jets in l^+l^- → H[→ gg]Z[→ ll]
  - Identification of weak-strahlung emission, and g→tt in jets
  - Track functions in jet substructure

Future of PDF determination







[arXiv:2204.07944](https://arxiv.org/abs/2204.07944)

Setting priorities

In conclusion

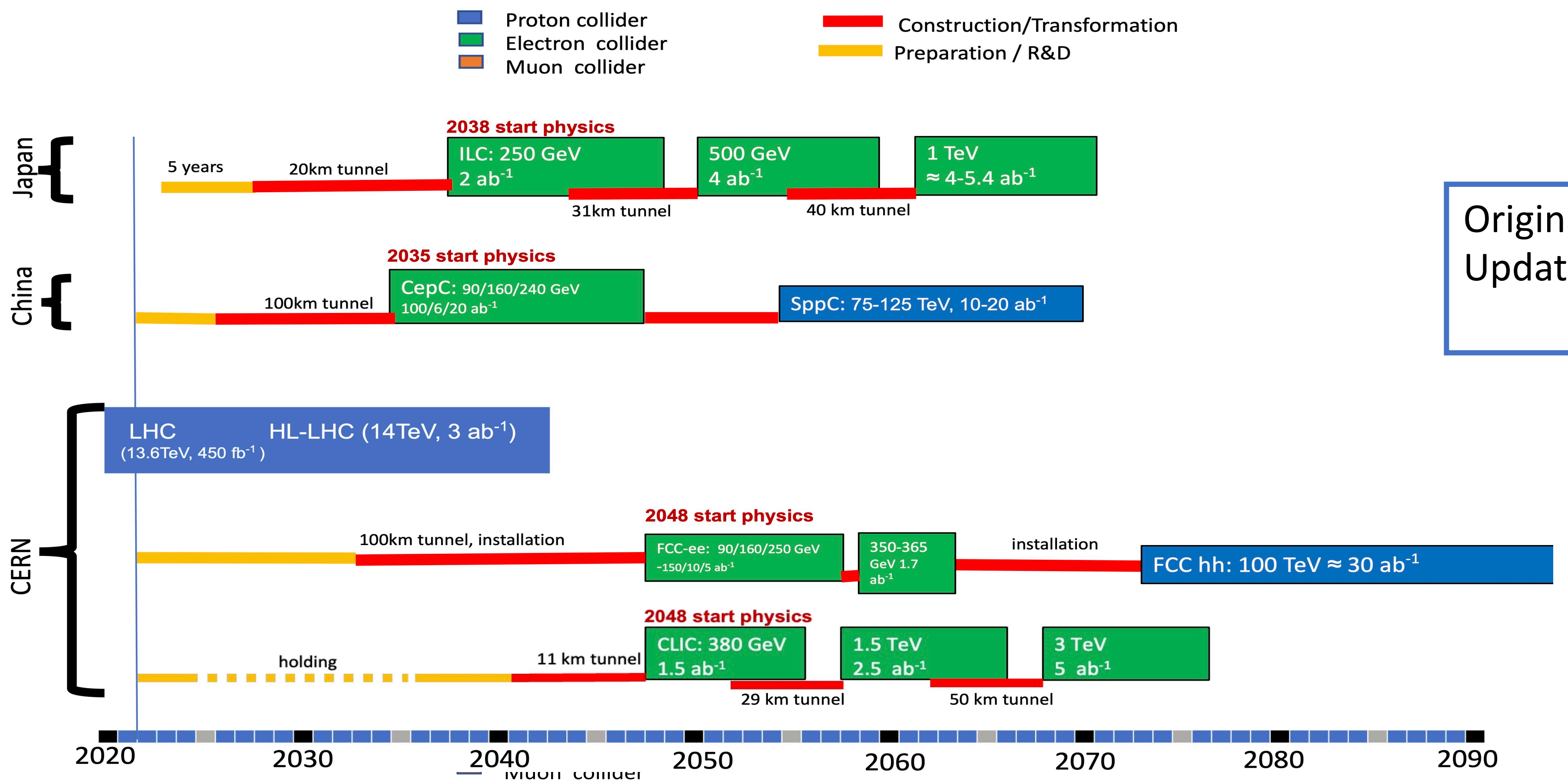
- **The Higgs discovery has been fundamental in opening new avenues to explore physics beyond the SM** and the Higgs-physics program ahead of us promises to start answering some of the remaining fundamental questions in particle physics.
- **Collider physics** remains as a **unique and necessary test 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 elude the LHC.**

The Energy Frontier vision in a nutshell

It is essential to

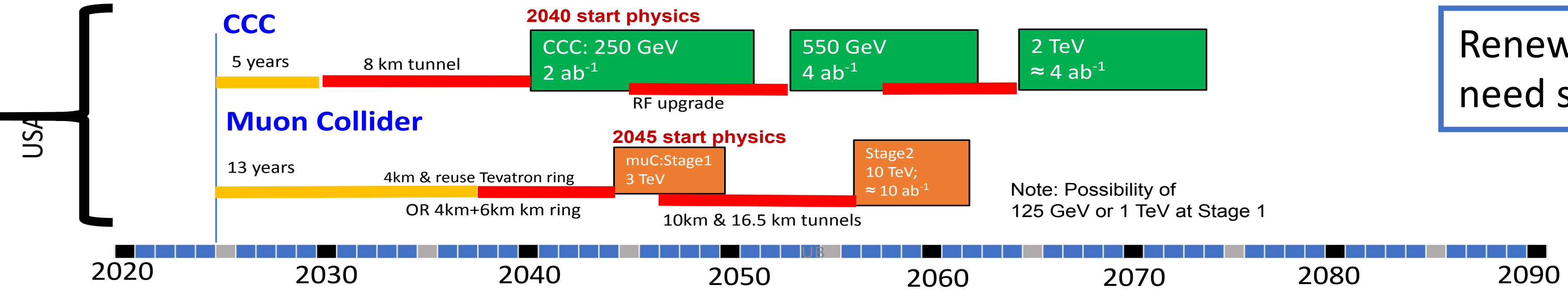
- **Complete the HL-LHC program,**
- **Start now a targeted program for detector R&D for Higgs Factories**
- **Support a fast start of the construction of a Higgs factory**
- **Ensure the long-term viability of the field by developing a multi-TeV energy frontier facility such as a *muon collider* or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

Timelines



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