Snowmass Energy Frontier Overview

Laura Reina (FSU)

P5 Town Hall – BNL – April 12, 2023

Snowmass 2021

Representing the work of the Snowmass 2021-22 Energy Frontier

Conveners: Meenakshi Narain, Laura Reina, Alessandro Tricoli

Energy Frontier:
Exploring the TeV Scale and beyond

Through the breadth and multitude of collider physics signatures

Big Questions

Evolution of early Universe

Matter Antimatter Asymmetry

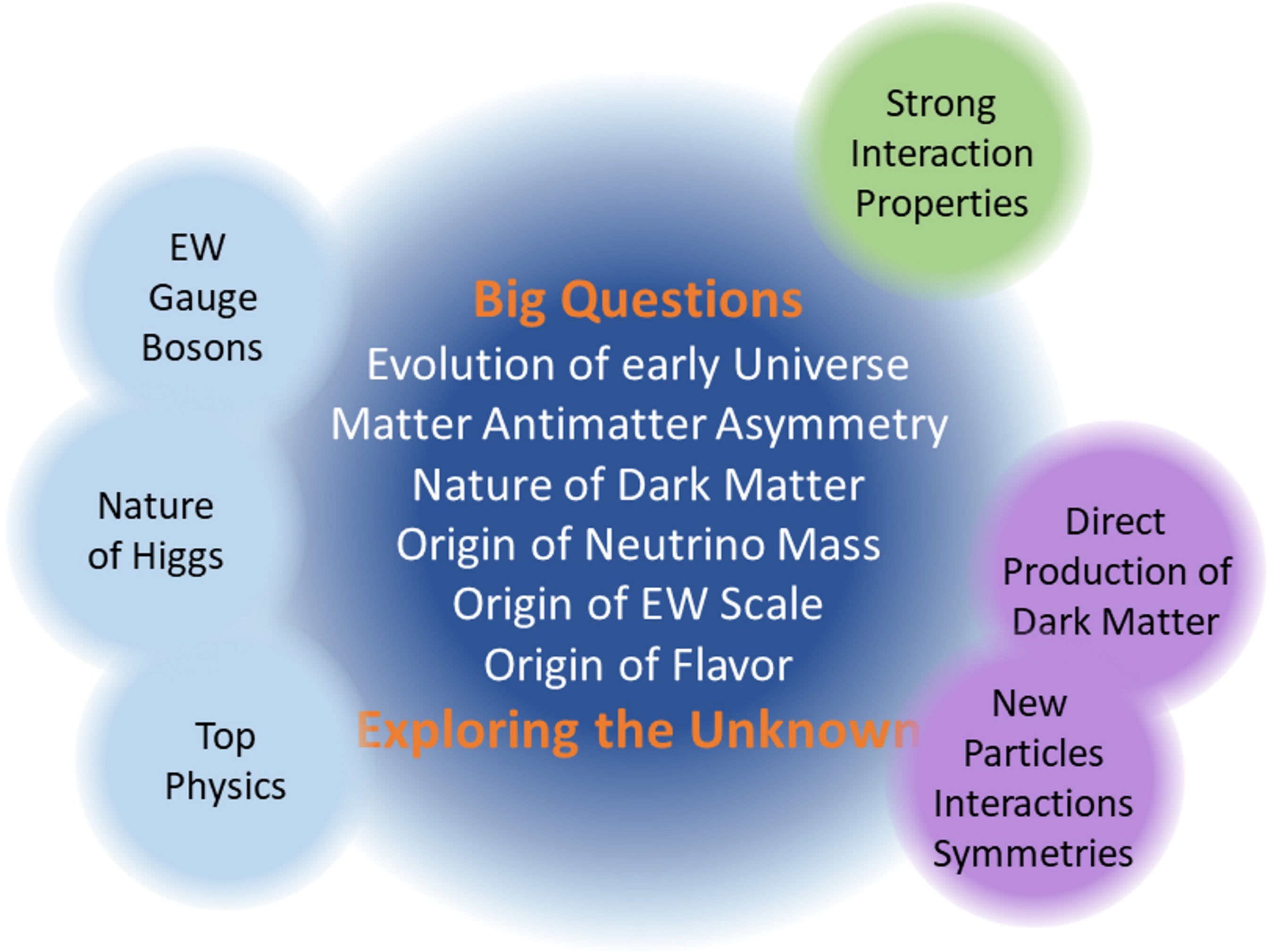
Nature of Dark Matter

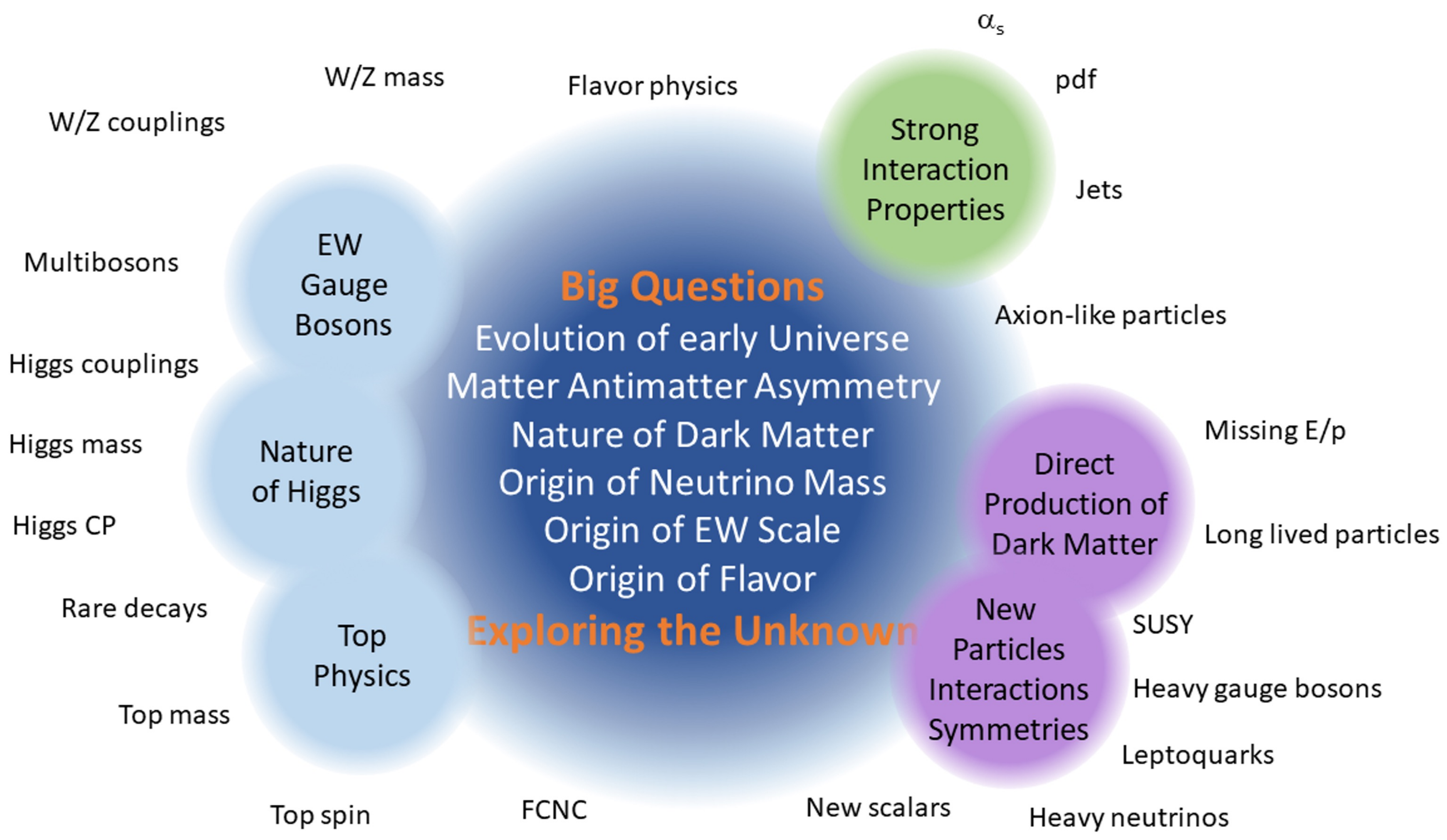
Origin of Neutrino Mass

Origin of EW Scale

Origin of Flavor

Exploring the Unknown


Strong Interaction Properties
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
Nature of Higgs
Direct Production of Dark Matter
New Particles Interactions Symmetries
Top Physics



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
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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

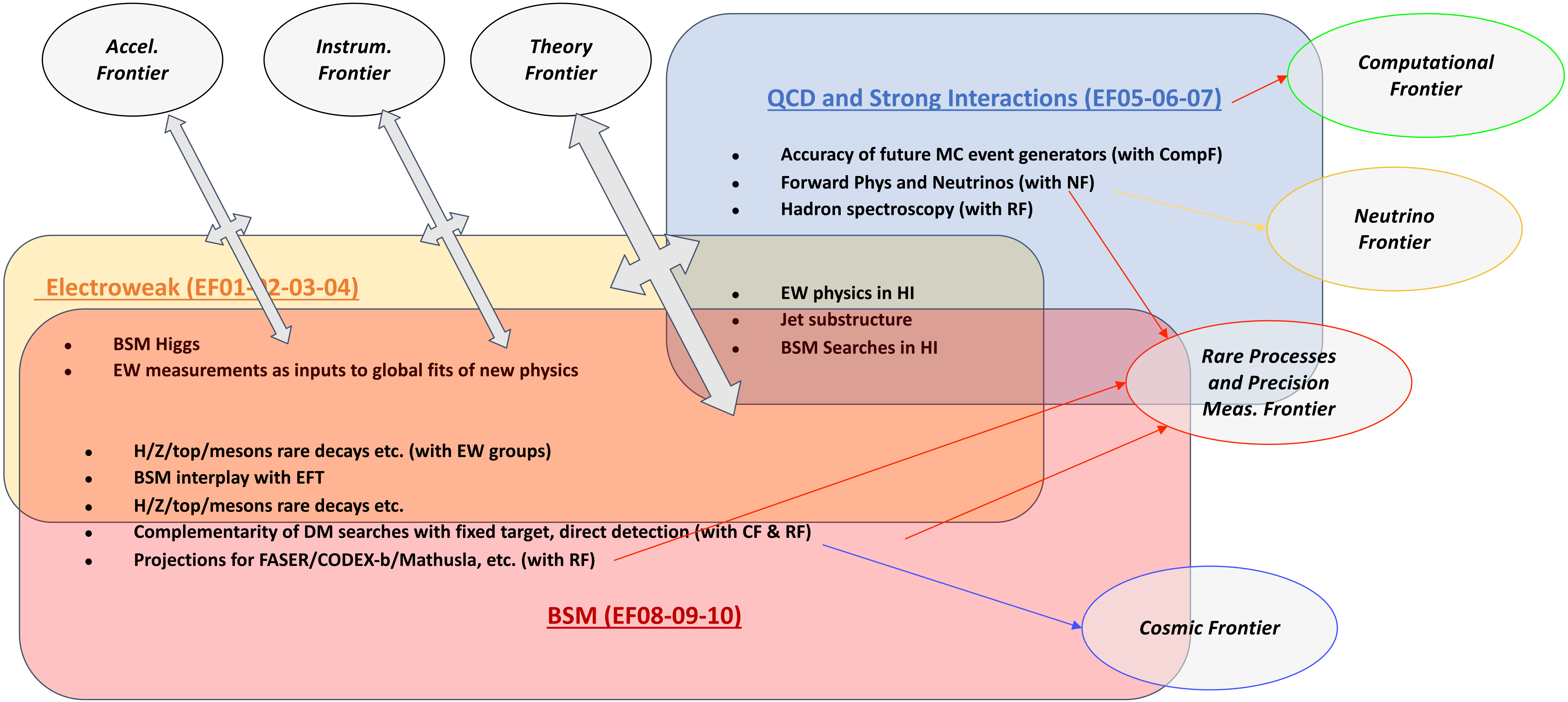
Energy Frontier:
Topical Groups, Liaisons, Task Forces, Contributed Papers, Reports

A tribute to all the people who contributed

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

	Topical Group	Co-Conveners		
Higgs, EW, top	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)
QCD and S.I.	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)	
BSM	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)

Synergies among EF TGs and with Other Frontiers



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)

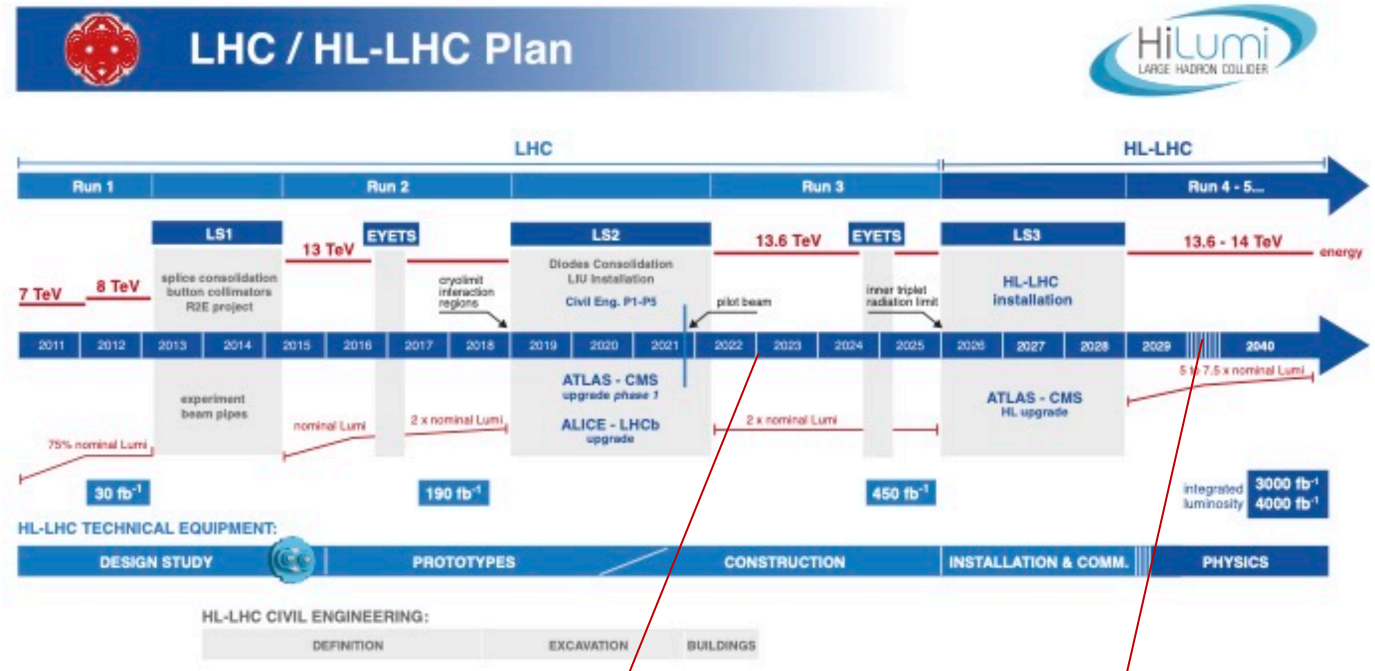
Monte Carlo task force and production team

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

Snowmass Book: Energy Frontier (All reports and >160 contributed papers)
Snowmass EF wiki page (Full summary of activities during Snowmass 21-22)
Snowmass EF Indico page (Links to all Snowmass EF meetings)

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

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

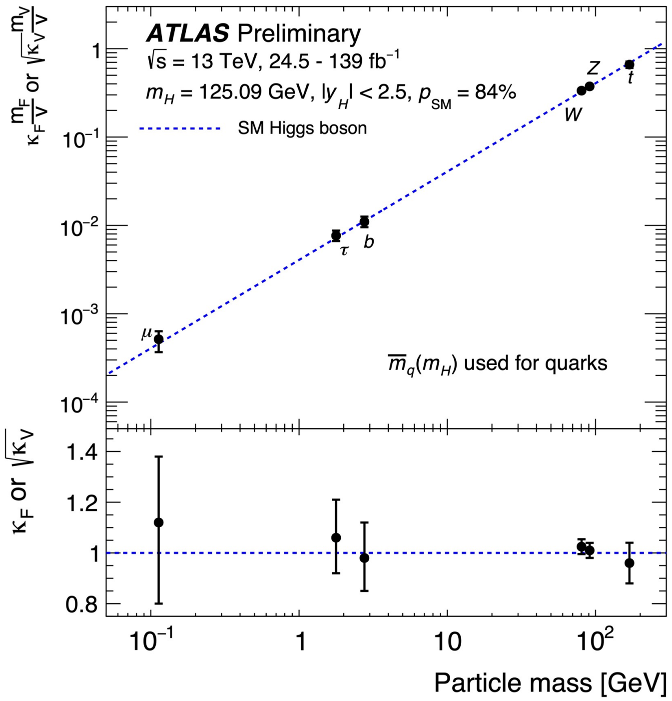
Snowmass 2013/Previous P5

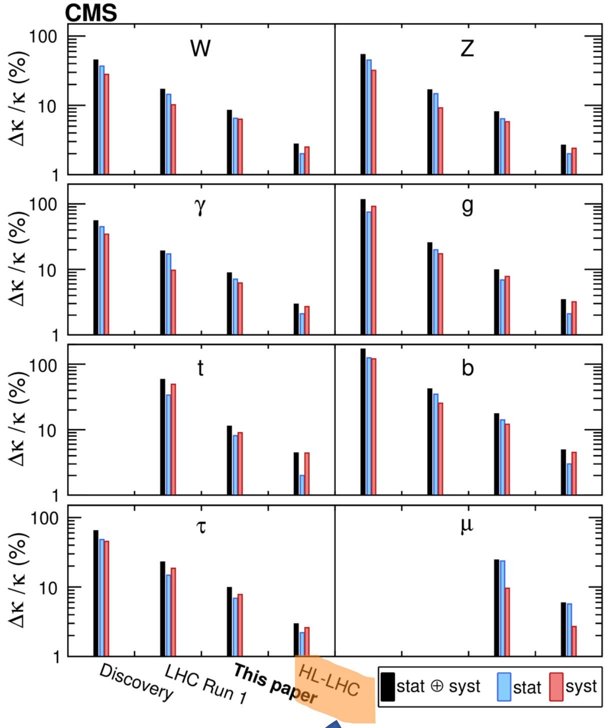
- **Run 1**: **Higgs discovery**
- **Run 2**: **Higgs couplings**
  - outperformed expectations
- **Run 3 to HL-LHC**
  - **Higgs precision program**

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!

(HL)LHC : Zooming in on couplings to probe the TeV scale





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

$\Delta\kappa \sim O(v^2/\Lambda^2)$

For new physics at 1 TeV expect deviations of O(6%)

Higher accuracy probes higher scales

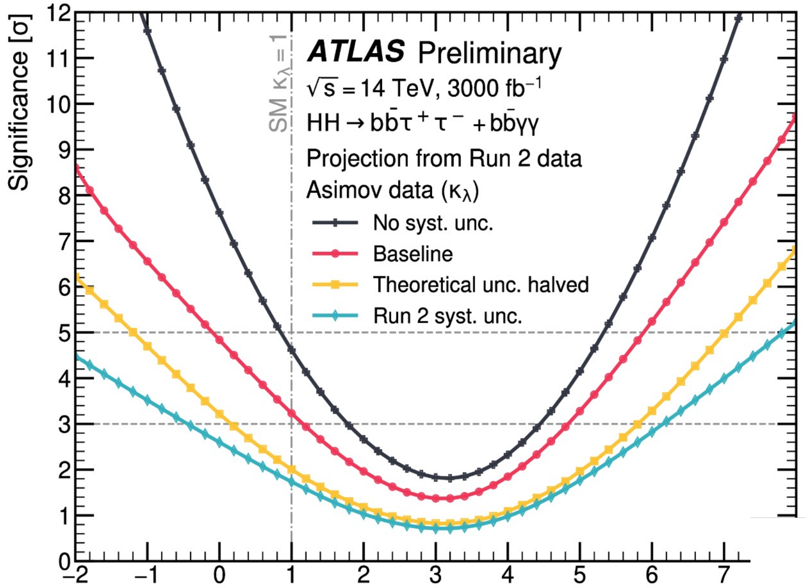
➢ LHC Run 2

- ➢ 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:

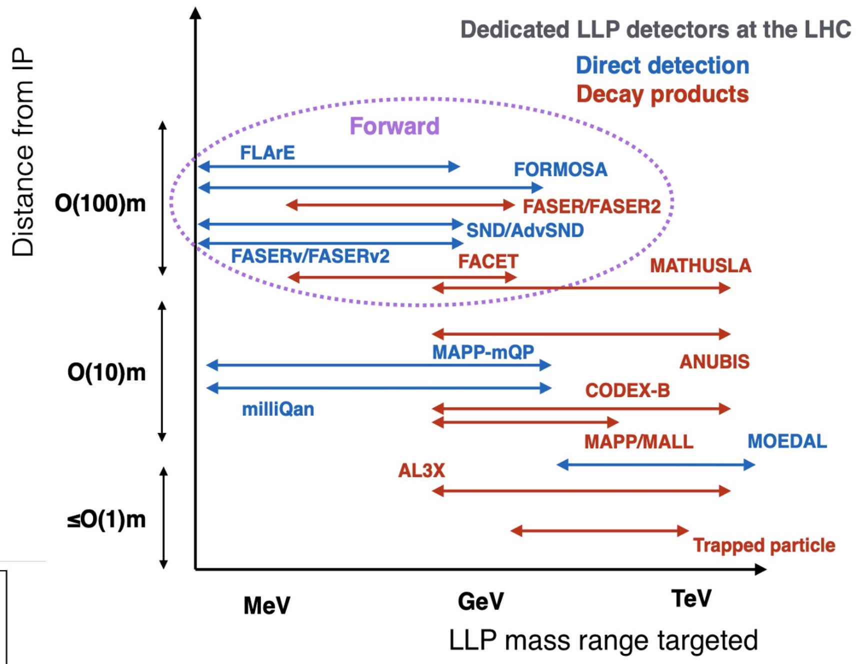
- ➢ **2-5 % on most couplings**
- ➢ **< 50% on Higgs self-coupling.**

HL-LHC: the physics case is overall very strong



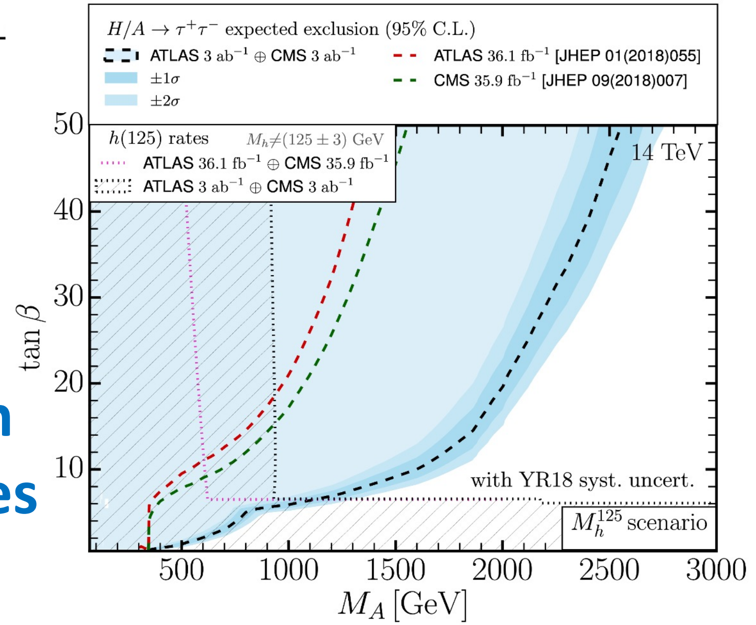
First bounds on Higgs self-coupling

See G. Brooijmans's and A. Canepa's talks



Broad program of auxiliary projects

See H. Lubatti's J. Feng's, and S. Gori's taks



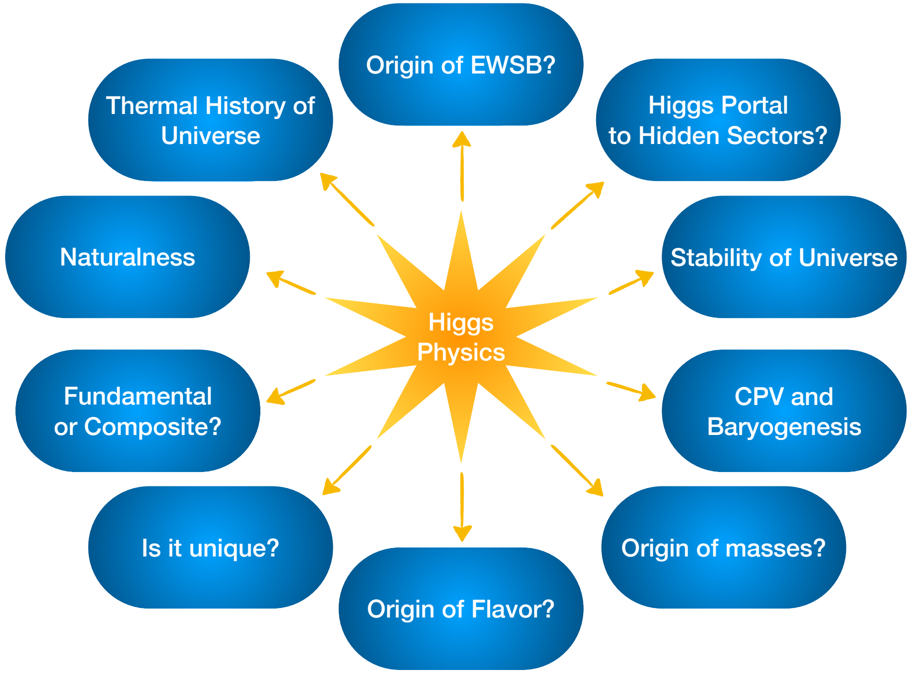
Extended reach of BSM searches

Beyond the HL-LHC

Higgs physics to answer key questions

What is the origin of the EW scale?

The discovery of the Higgs boson has sharpened the big open questions and given us a unique handle on BSM physics.

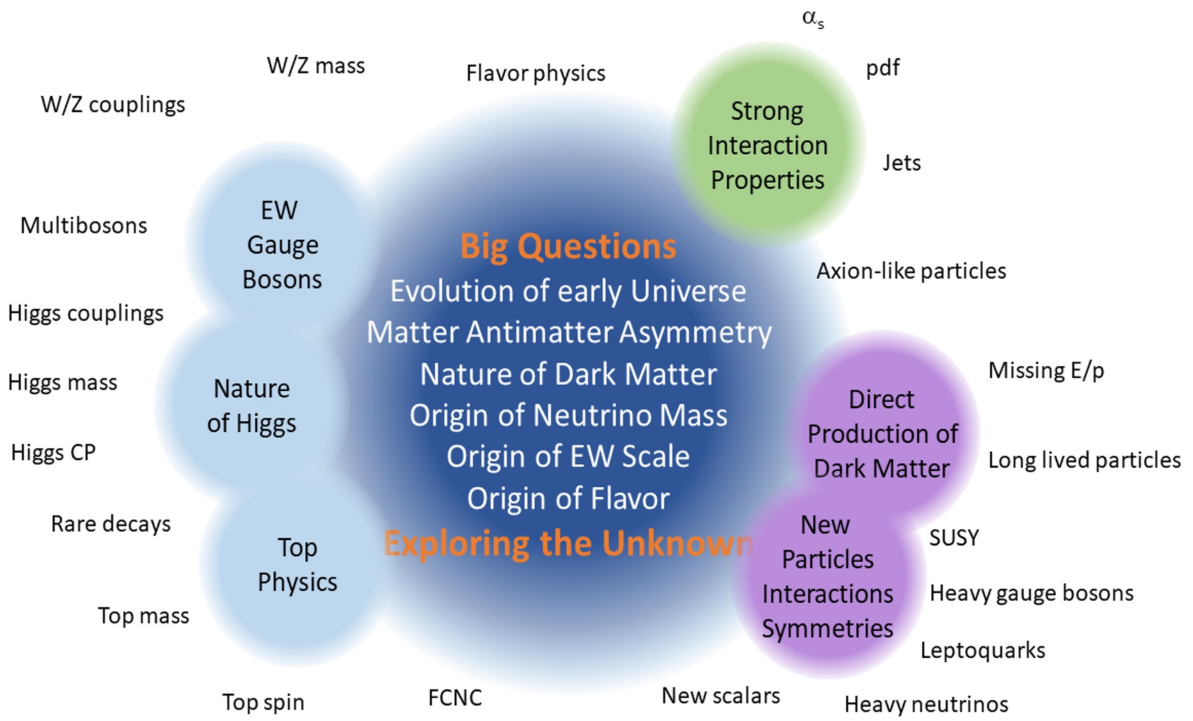


- Why the $M_H \ll M_{planck}$ **hierarchy problem**?
- What are the implications for **Naturalness**?
  - No fine-tuning: Is the scale of new physics close by? crucial to **explore 1-10 TeV region**!
- Higgs: **Elementary vs composit**? **One Higgs**? **More**?
- Why the shape of the **Higgs potential** ⟶ **Higgs self coupling(s)**
- Can Higgs properties give us **insights on flavor** and vice versa?
  - SM Higgs pattern very constraining: more scalars induce scalar FCNC
  - Fermion mass hierarchy: Yukawa interactions: new force all together ??

The origin of the SM Higgs pattern escapes the SM itself

Addressing the "**Big Questions**" and "**Exploring the unknown**"

should then be pursued following

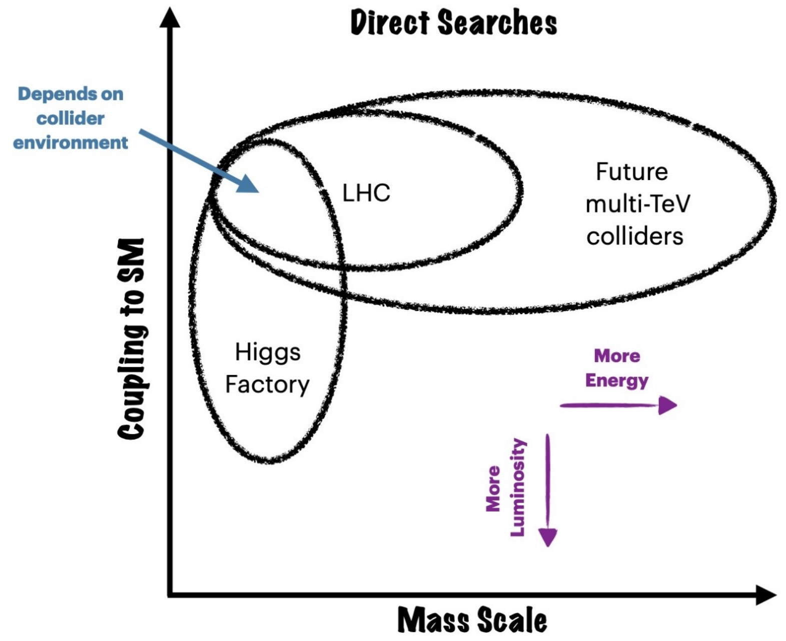


Two main avenues

- **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.**

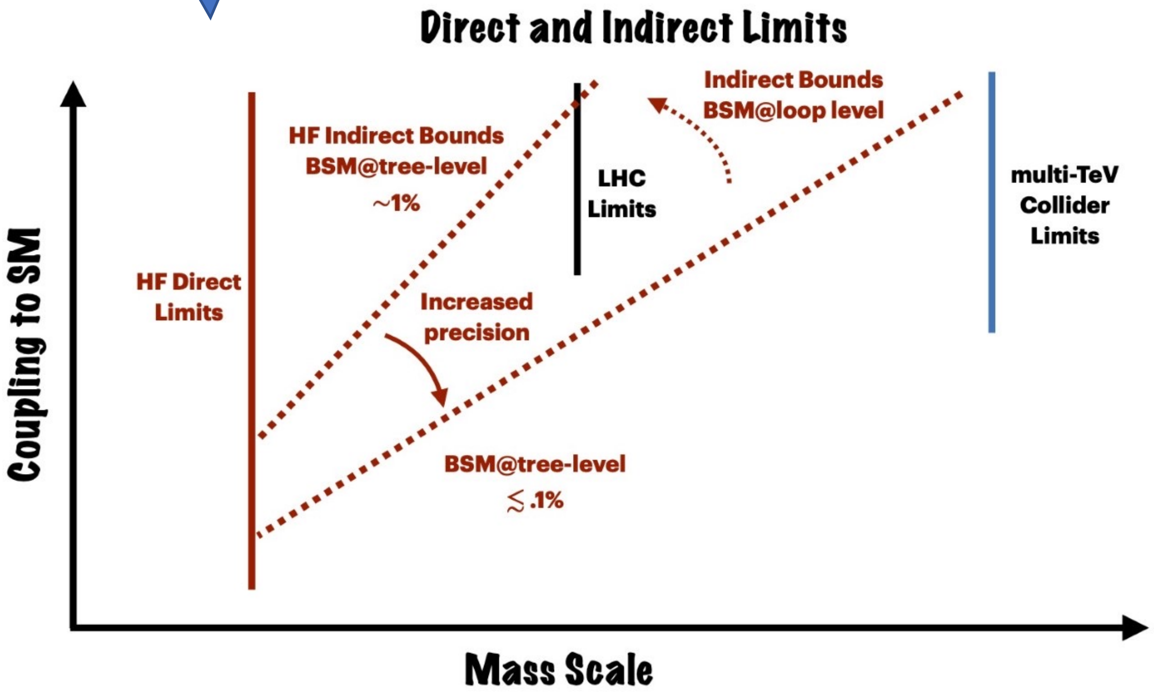


Higgs coupling measurements and direct searches will complement each other in exploring the 1-10 TeV scale and beyond.

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



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		

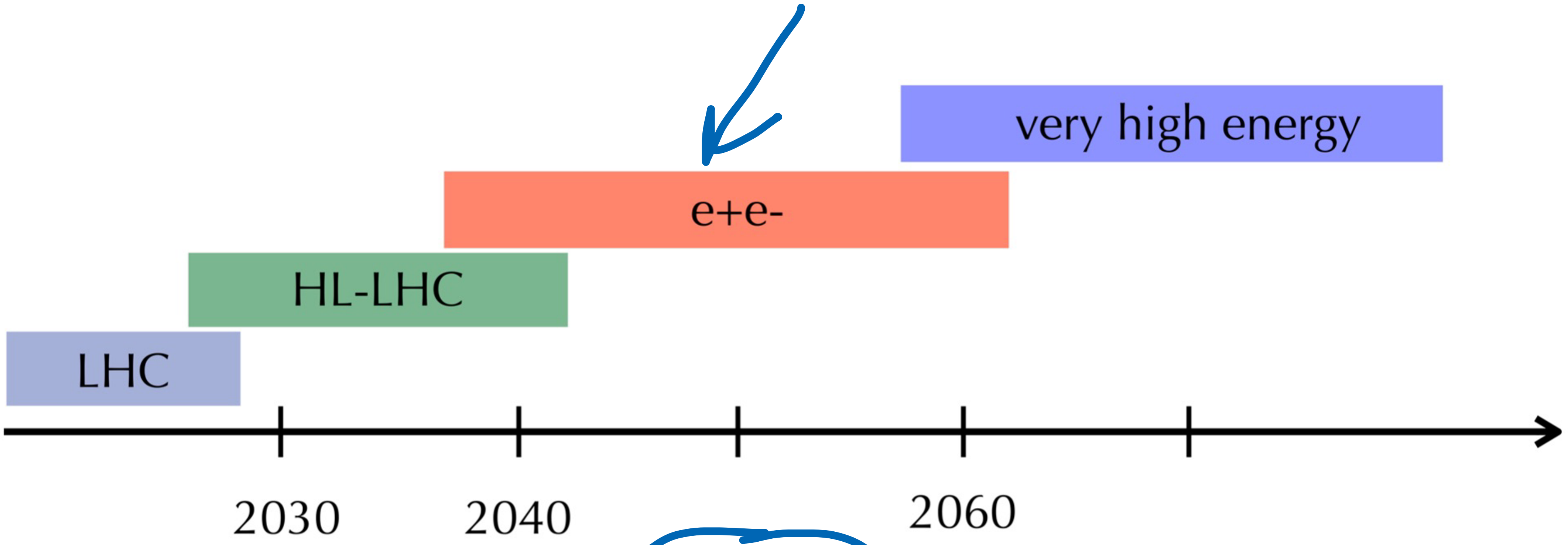
Multi-TeV colliders (> 1 TeV c.o.m. energy)

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)

Higgs Factories

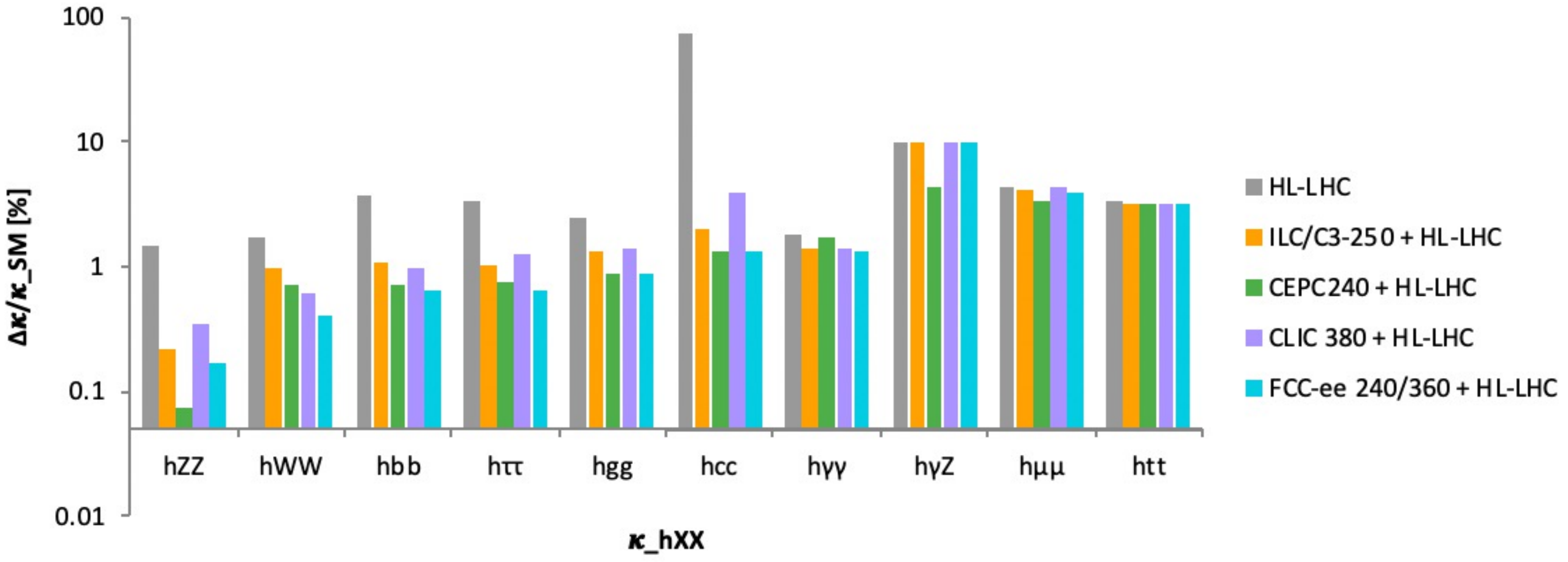
Beyond the HL-LHC: projections for Higgs couplings



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

Higgs factories: precision

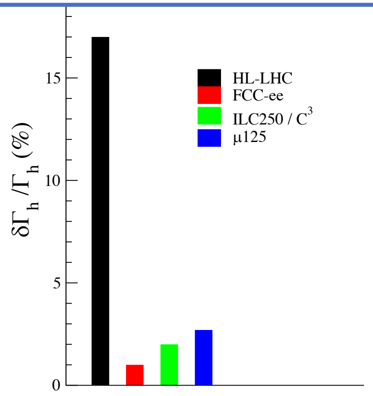


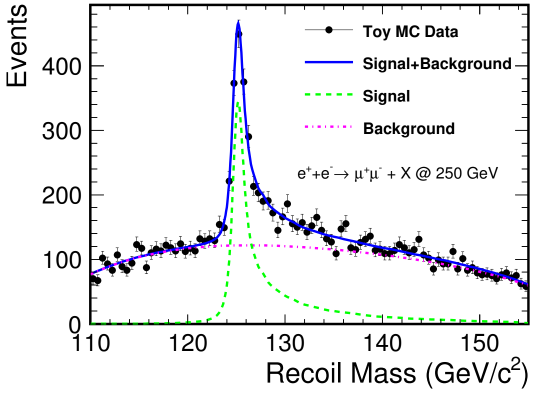
From Snowmass 2021 EF Higgs Topical Group Report arXiv:2209.07510

Initial stages of future e^+e^- machines

A clear improvement over HL-LHC reach

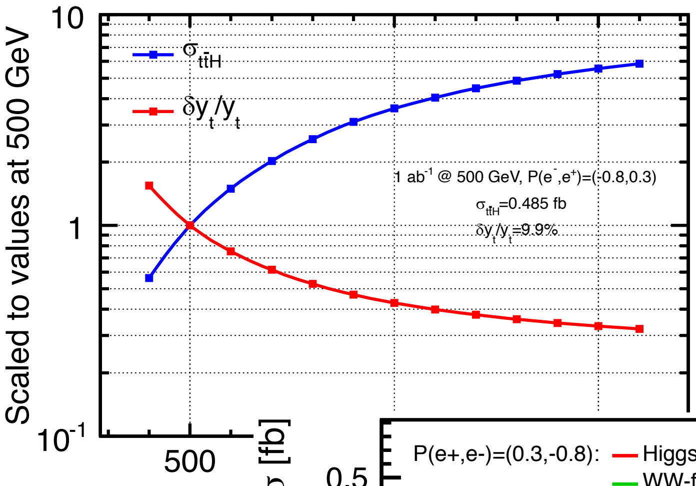
Plus a model-independent Γ_H measurement

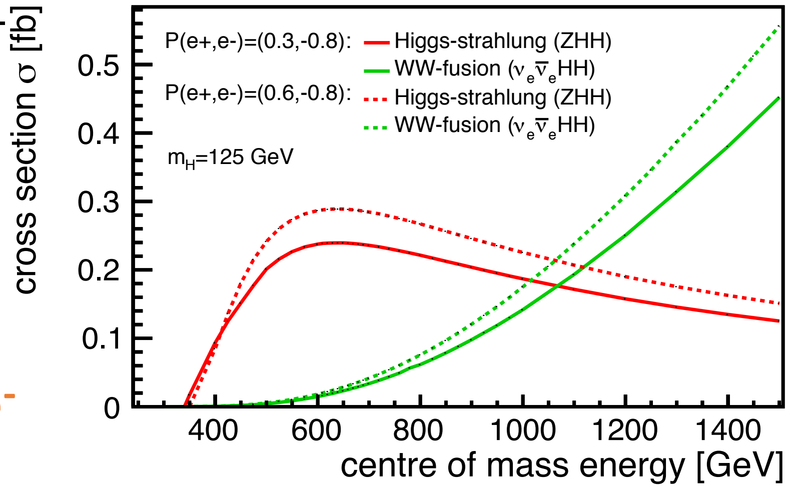




Plus the possibility of polarized beams (linear e+e-)

Higgs factories: precision and energy





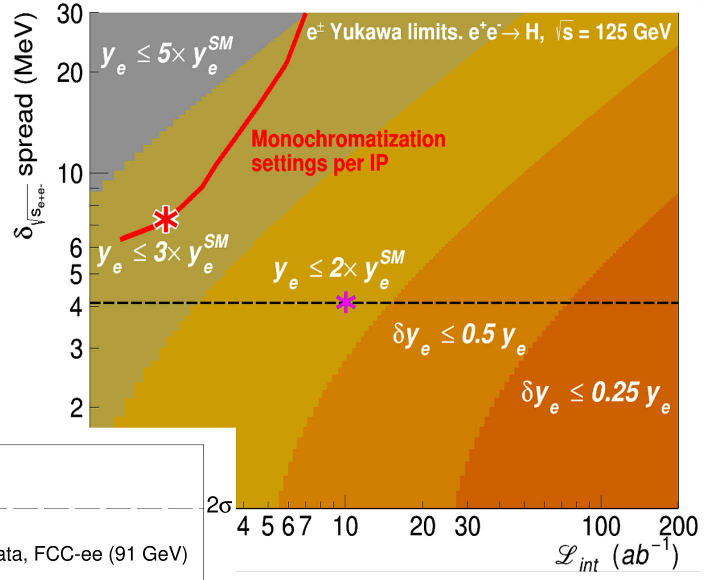
linear e$^+$e$^-$

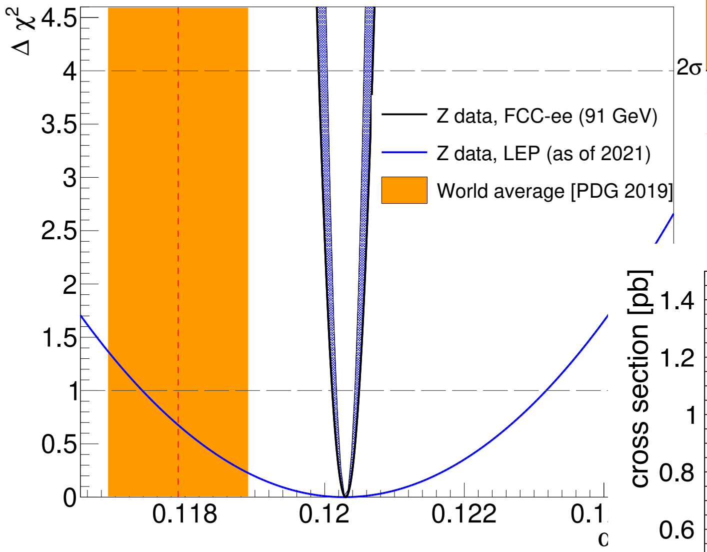
Energy matters:
top-Yukawa, HH, extended
Higgs sectors need >500 GeV

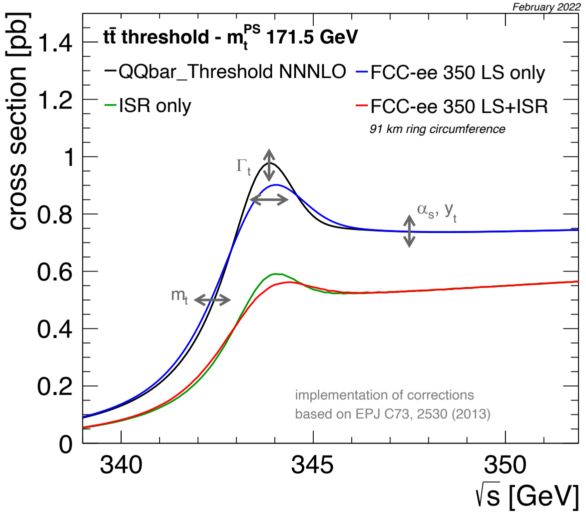
Luminosity matters:
Light Yukawas, α_s,
m_t, Γ_t

circular e$^+$e$^-$

κ_e< 1.6 at 95% c.l.
arXiv:2107.02686



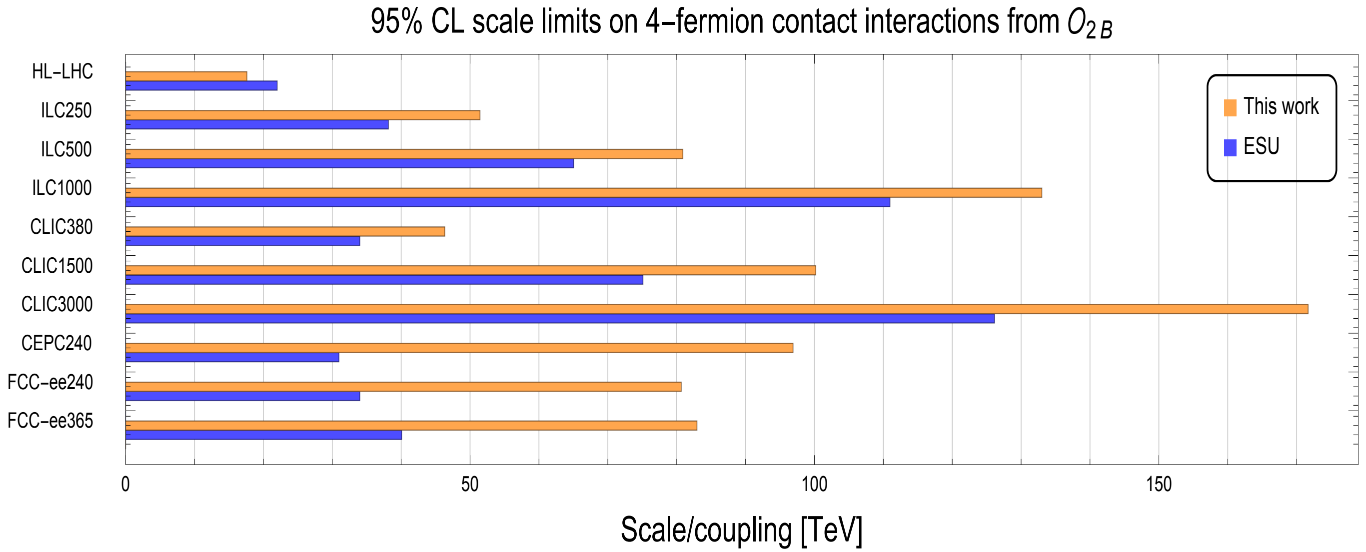


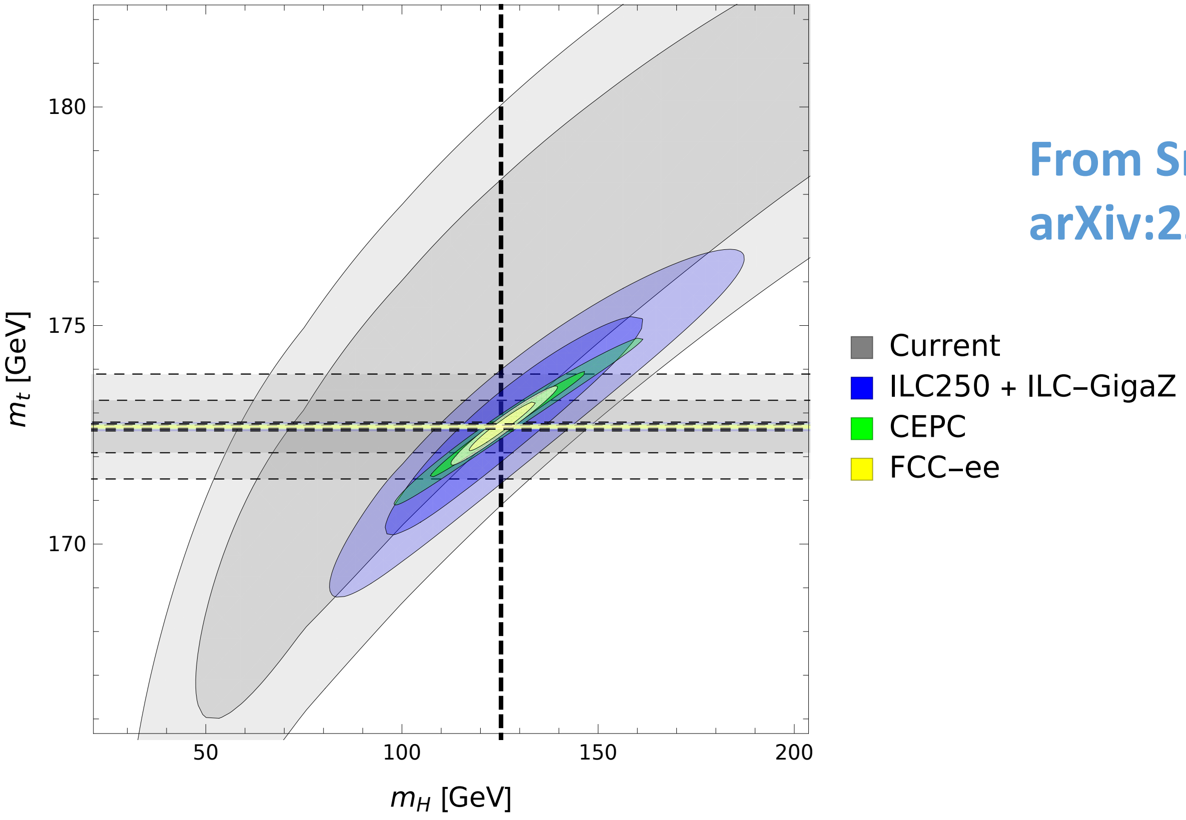


More in L. Wang's, A. White's, and
S. Rajagopalan's talks

Higgs factories beyond Higgs

Stress testing the SM and exploring anomalous couplings



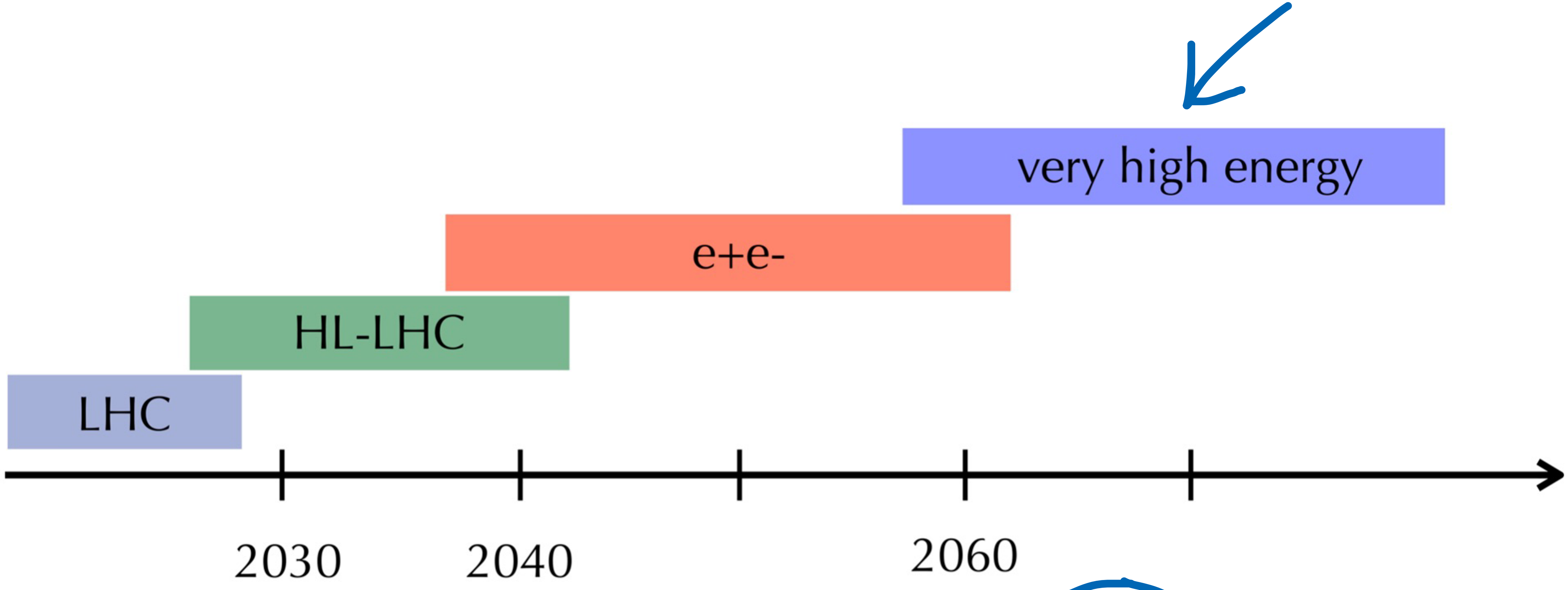


From Snowmass 2021 EF HF and EW TG's Reports
arXiv:2209.11267, arXiv:2209.08078

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

Multi-Tev Colliders

Beyond the HL-LHC: projections for Higgs couplings

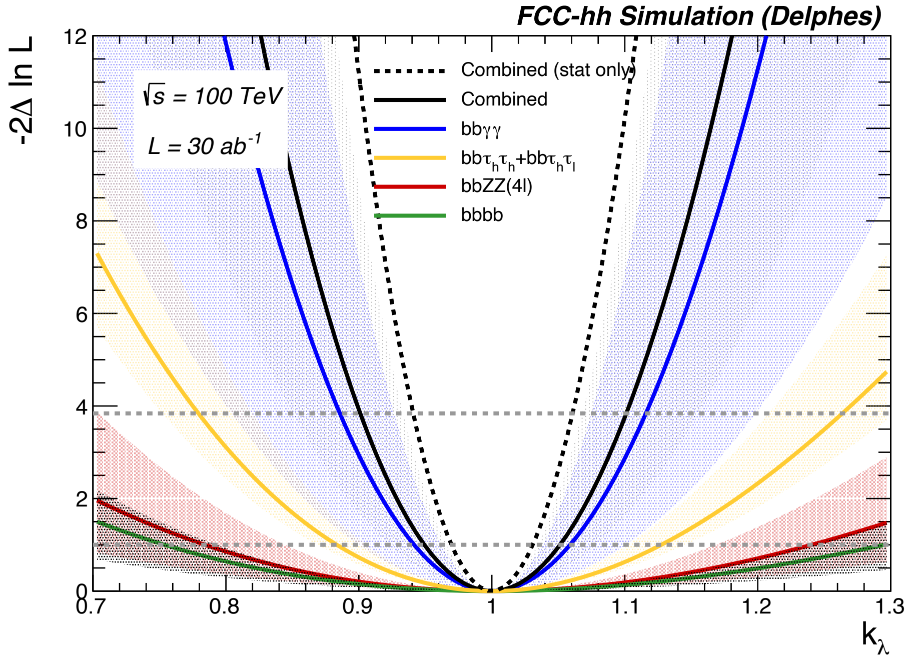


H couplings to:	**O(5-15)%**	**O(0.1-1)%**	**O(1)‰**
H self-coupling to	**<O(50)%**	**O(20)%**	**O(1)%**

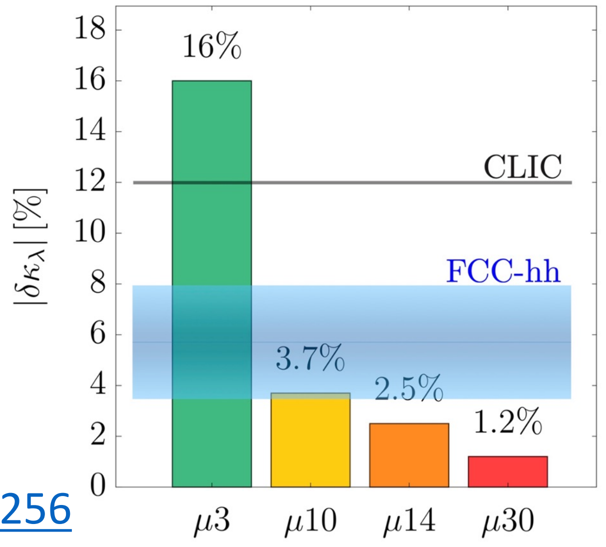
From C. Vernieri – Snowmass 21 EF Workshop - Brown U. - March 2022

Multi-TeV colliders: measuring the 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%

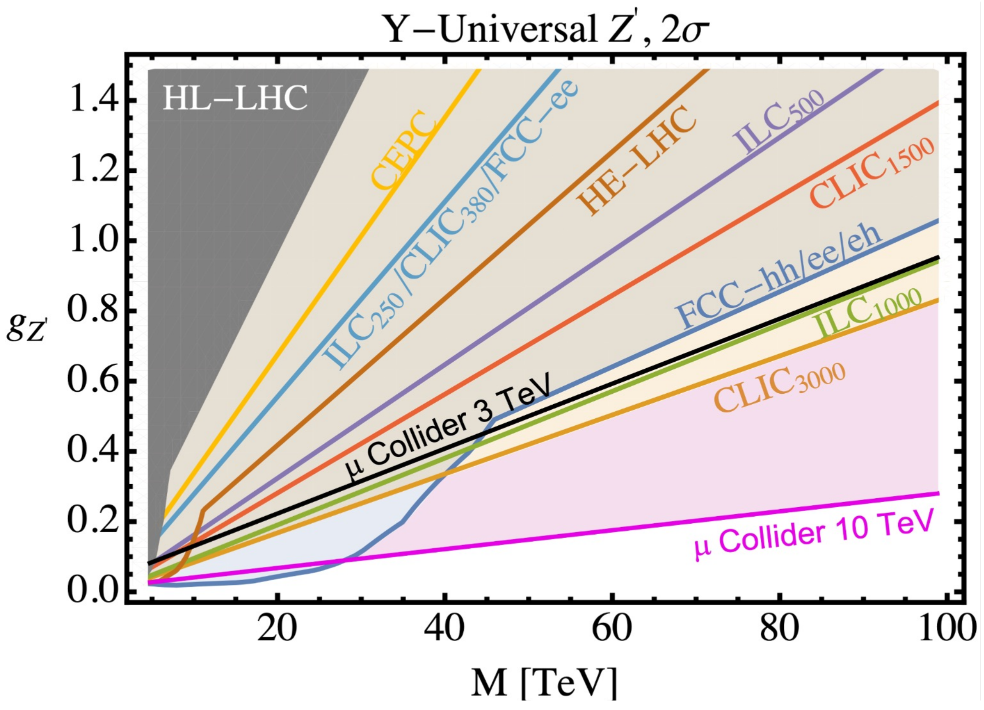


arXiv:2004.03505



arXiv:2203.07256

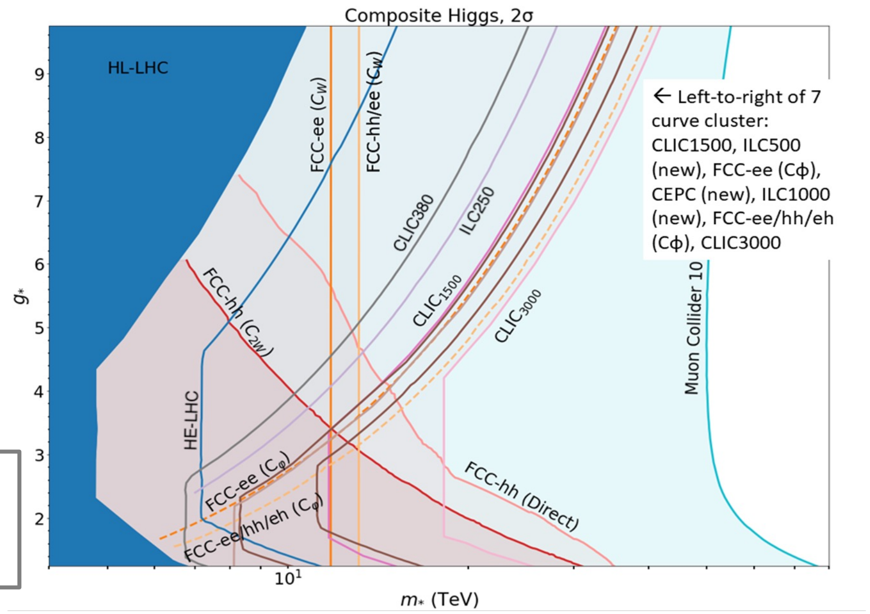
Multi-TeV colliders: the ultimate exploration



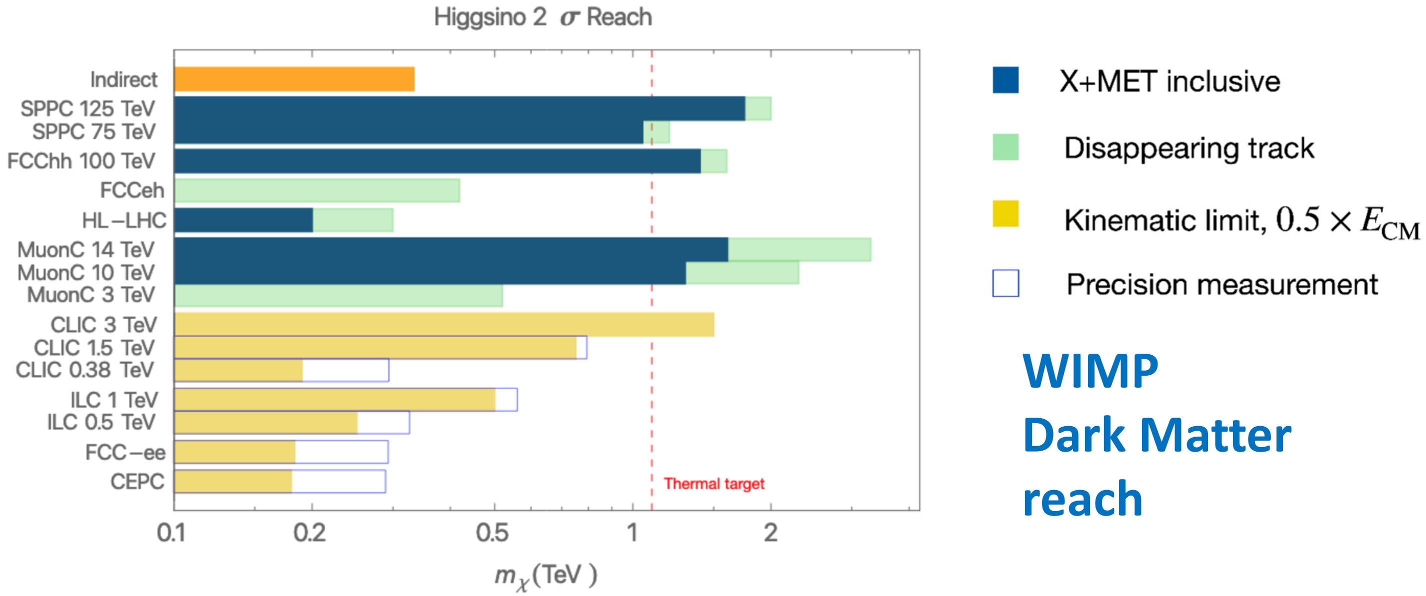
Heavy Boson (Z') models

Greatly extend the reach of BSM scenarios

Higgs composite models



More in P. Meade's, S. Eno's, And S. Jindariani's talks



WIMP Dark Matter reach

EF vision

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.

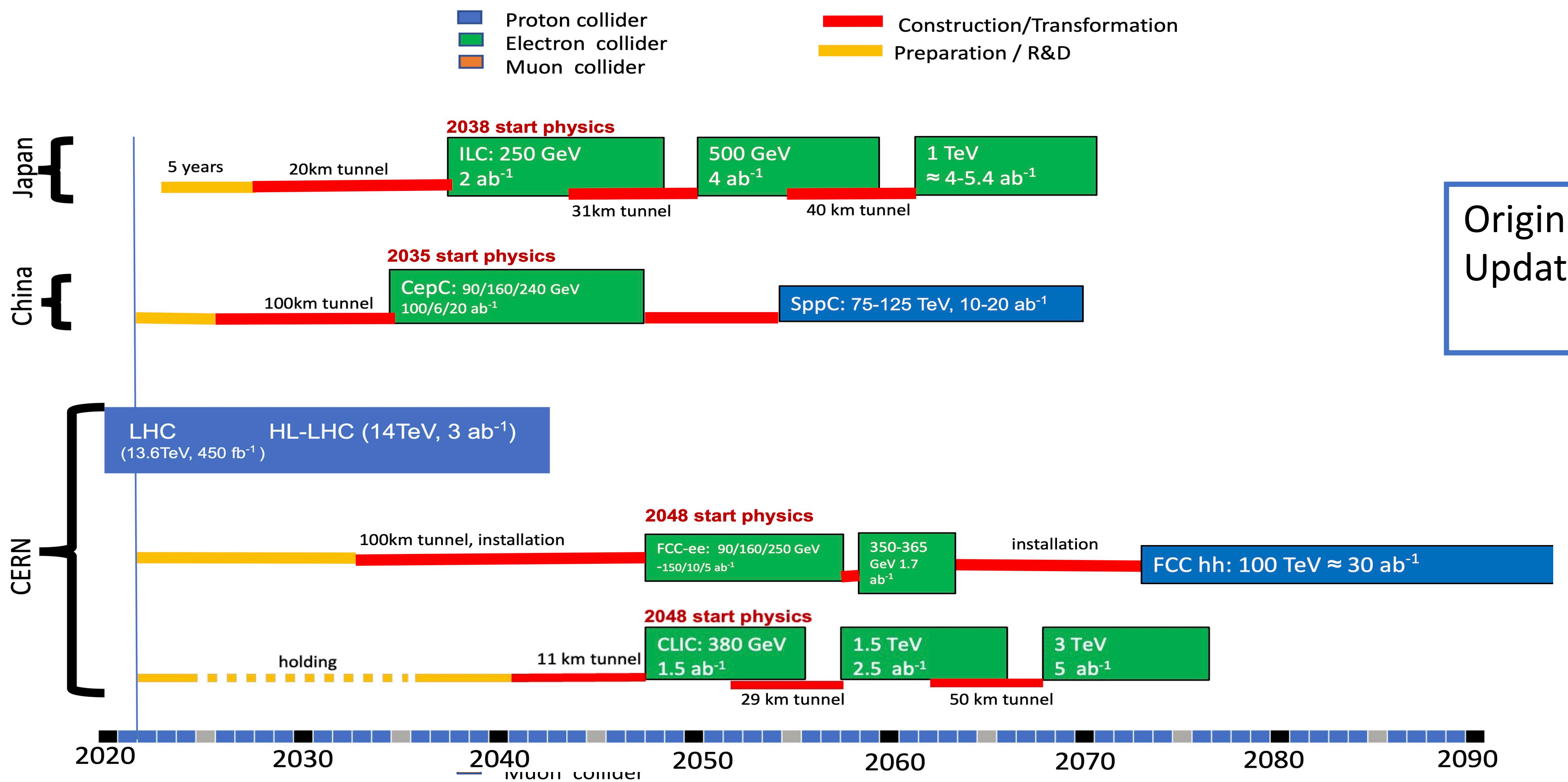
The EF supports a **fast start for construction of an e+e− Higgs factory** (linear or circular), **and a significant R&D program for multi-TeV colliders** (hadron and muon). The realization of a Higgs factory will require an immediate, vigorous, and targeted detector R&D program, while the study towards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

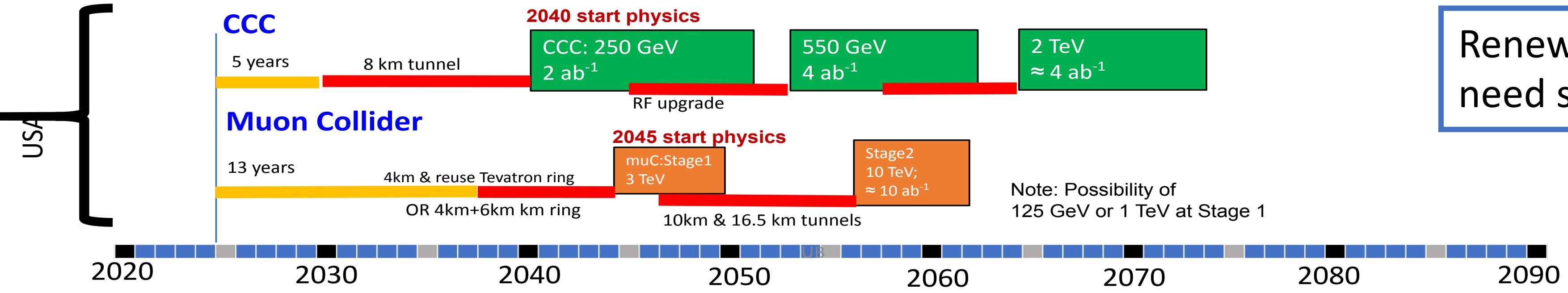
EF Resources and Timelines

- **Five year period starting in 2025**
  - Prioritize *HL-LHC physics program,* including auxiliary experiments
  - Establish a targeted *e^+e^- Higgs Factory detector R&D* for US participation in a global collider
  - Develop an *initial design for a first stage TeV-scale Muon Coll.* in the US (pre-CDR)
  - Support critical *detector R&D towards EF multi-TeV colliders*
- **Five year period starting in 2030**
  - Continue strong support for *HL-LHC program*
  - Support and advance *construction of an e+e- Higgs Factory*
  - Demonstrate principal risk mitigation and deliver *CDR for a first-stage TeV-scale Muon Coll.*
- **After 2035**
  - Support continuing *HL-LHC physics program* to the conclusion of archival measurements
  - Begin and support the *physics program of the Higgs Factories*
  - Demonstrate readiness to construct and deliver *TDR for a first-stage TeV-scale Muon Coll.*
  - Ramp up funding support for *detector R&D for EF multi-TeV colliders*



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

The Energy Frontier vision in a nutshell

It is essential to

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

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

Additional material

EF Vision - Expanded

The immediate future is the HL-LHC

- During the next decade it is essential to complete the **highest priority recommendation of the last P5** and to fully realize the scientific potential of the **HL-LHC collecting at least 3 ab^{-1} of data**.

- **Continued strong US participation is critical** to the success of the HL-LHC physics program, in particular for the Phase-2 detector upgrades, the HL-LHC data taking operations and physics analyses based on HL-LHC data sets, including the construction of auxiliary experiments that extend the reach of HL-LHC in kinematic regions uncovered by the detector upgrades

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

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

The intermediate future is an e^+e^- Higgs factory, either based on a linear (ILC, C^3, CLIC) or circular collider (FCC-ee, CepC).

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

The long-term future is a multi-TeV collider

- A 10-TeV **muon collider** (MuC) and 100-TeV **proton-proton collider** (FCC-hh, SppC) directly probe the order 10 TeV energy scale with different strengths that are unparalleled in terms of mass reach, precision, and sensitivity.

- The main limitation is technology readiness. **A vigorous R&D program** into accelerator and detector technologies **will be crucial.**

- **For the next decade and beyond**
  - **2025-2030**:
    - Develop an initial design for a first stage TeV-scale Muon Collider in the US (pre-CDR)
    - Support critical detector R&D towards EF multi-TeV colliders
  - **2030-2035**: Demonstrate principal risk mitigation and deliver CDR for a first-stage TeV-scale Muon Collider
  - **After 2035**:
    - Demonstrate readiness to construct and deliver TDR for a first-stage TeV-scale Muon Collider
    - Ramp up funding support for detector R&D for EF multi-TeV colliders

EF Colliders: Opportunities for the US

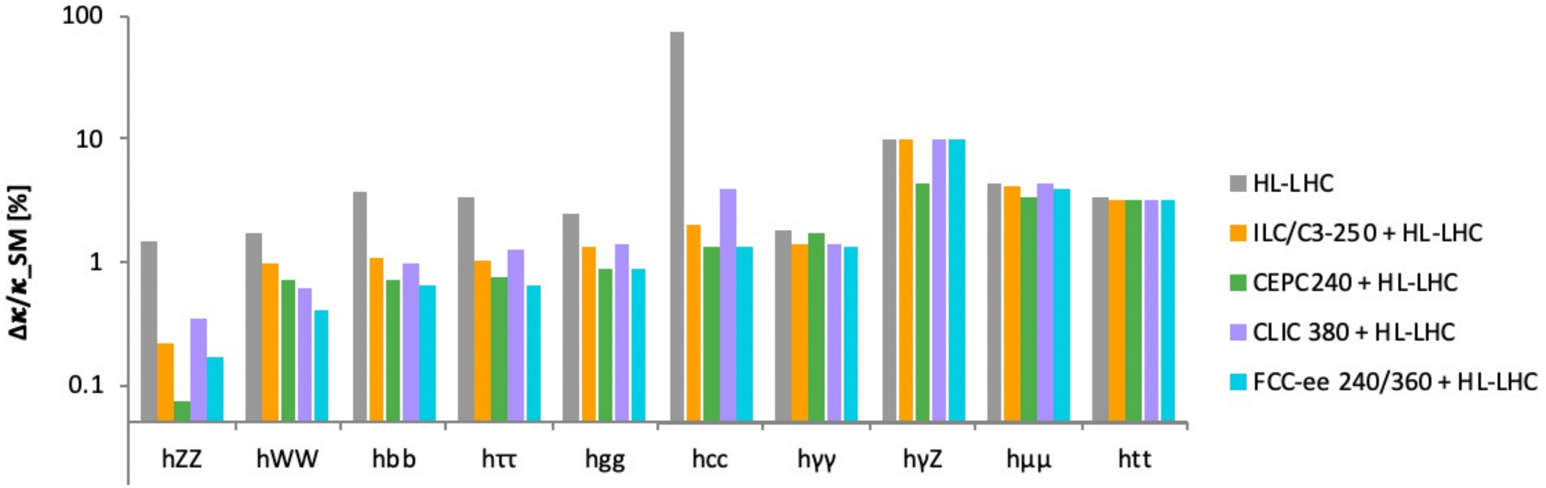
- Our vision for EF can only be realized as a **worldwide program** and we need to envision that **future colliders will have to be sited all over the world** to support and empower an international vibrant, inclusive, and diverse scientific community.
- The US community has to continue to work with the international community on detector designs and develop extensive R&D programs. To realize this, the funding agencies (DOE and NSF) should fund a **R&D program** focused on participation of the US community in future collider efforts as partners (as currently US is severely lagging behind).
- **The US EF community has expressed renewed interest and ambition to bring back energy-frontier collider physics to the US soil** while maintaining its international collaborative partnerships and obligations, for example with CERN.
- The international community also realizes that a vibrant and concurrent program in the US in energy frontier collider physics is **beneficial for the whole field, as it was when Tevatron was operated simultaneously as LEP.**
- **Planning to proceed in multiple parallel prongs may allow us to better adapt to international contingencies** and eventually build the next collider sooner.
- **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.

Physics Highlights from EF reports

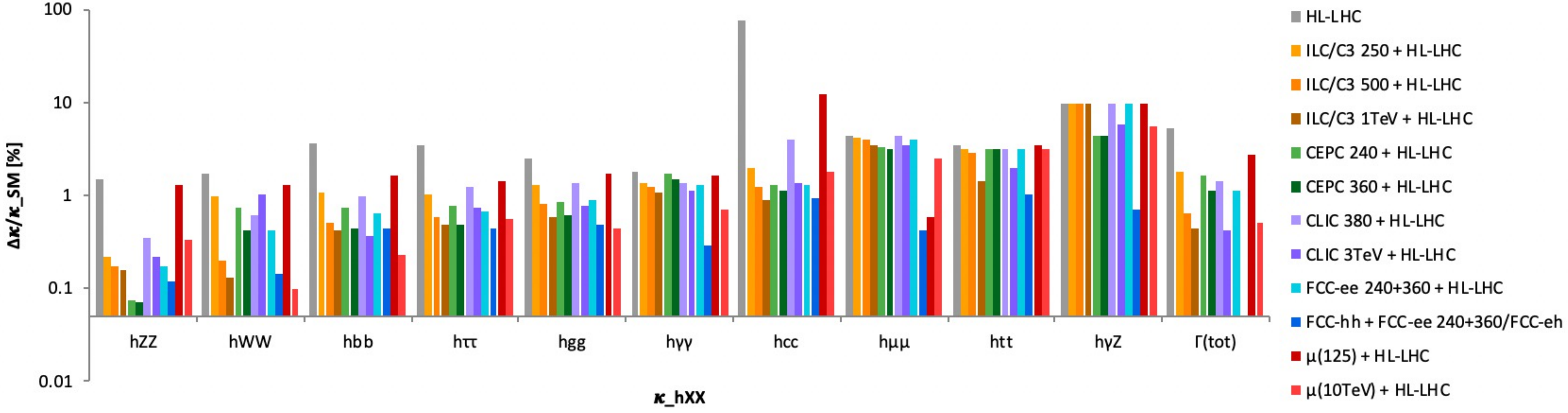
Reach of future colliders for Higgs couplings: a closer look

Based on full Run 2 dataset analyses

From Snowmass 2021 EF Higgs Topical Group Report arXiv:2209.07510



Initial stages of future e^+e^- machines



Final reach of all considered future colliders

Beyond SM-coupling rescaling

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

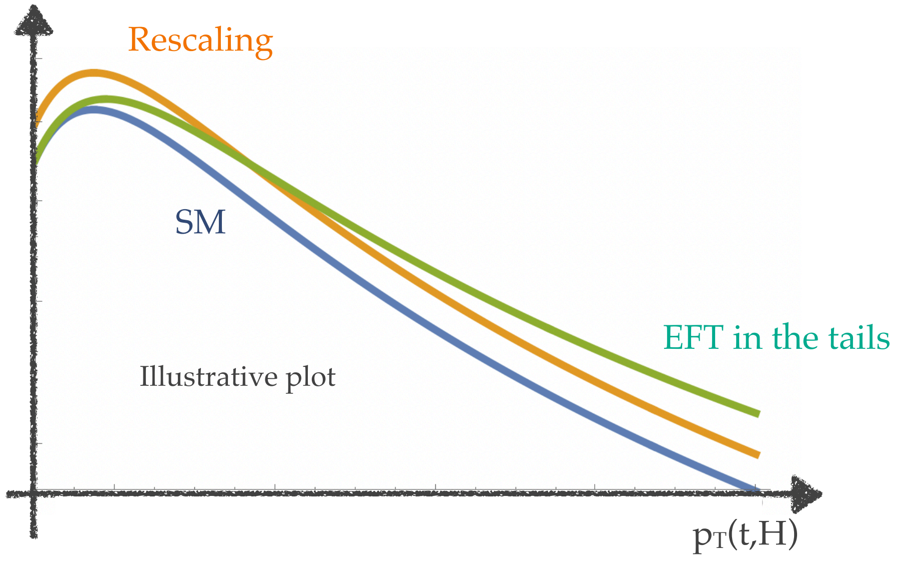
$$\mathcal{L}_{\rm SM}^{\rm eff} = \mathcal{L}_{\rm SM} + \sum_{d>4} \frac{1}{\Lambda^{d-4}} \mathcal{L}_d = \mathcal{L}_{\rm SM} + \frac{1}{\Lambda}\mathcal{L}_5 + \frac{1}{\Lambda^2}\mathcal{L}_6 + \cdots$$

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

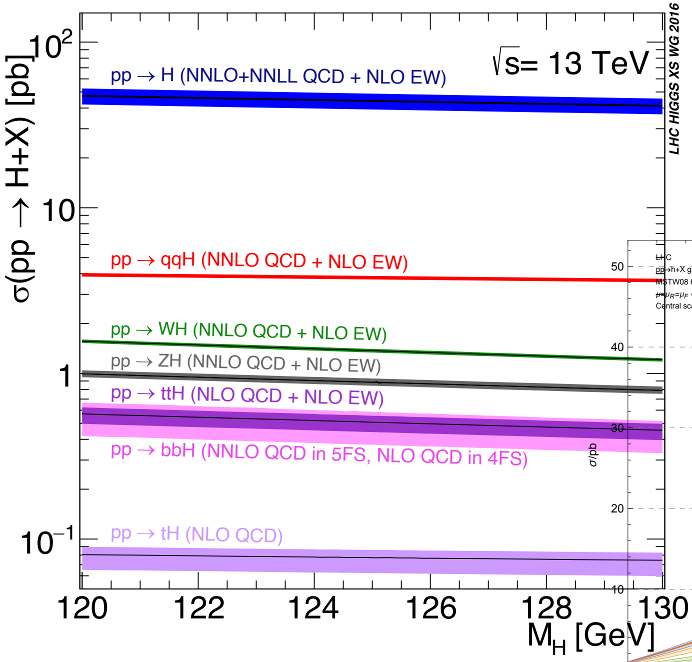
Under the assumption that new physics lives at scales $\Lambda > \sqrt{s}$

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**

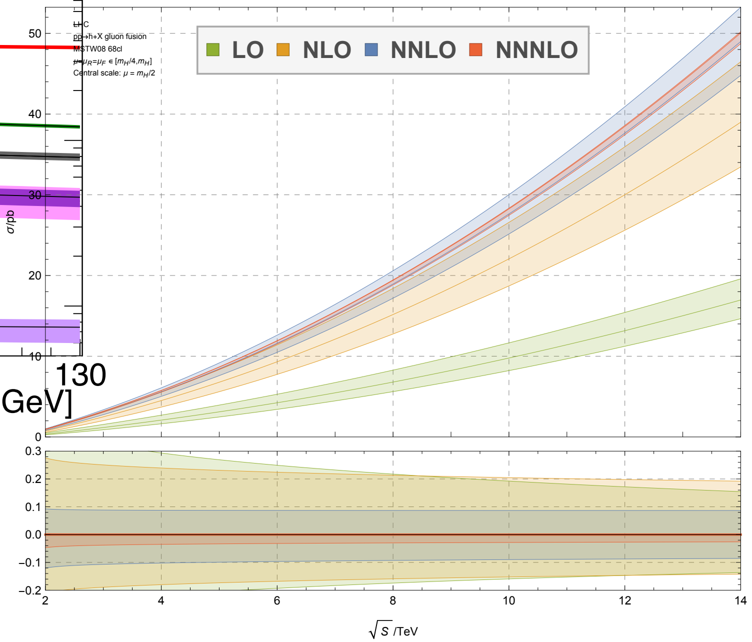


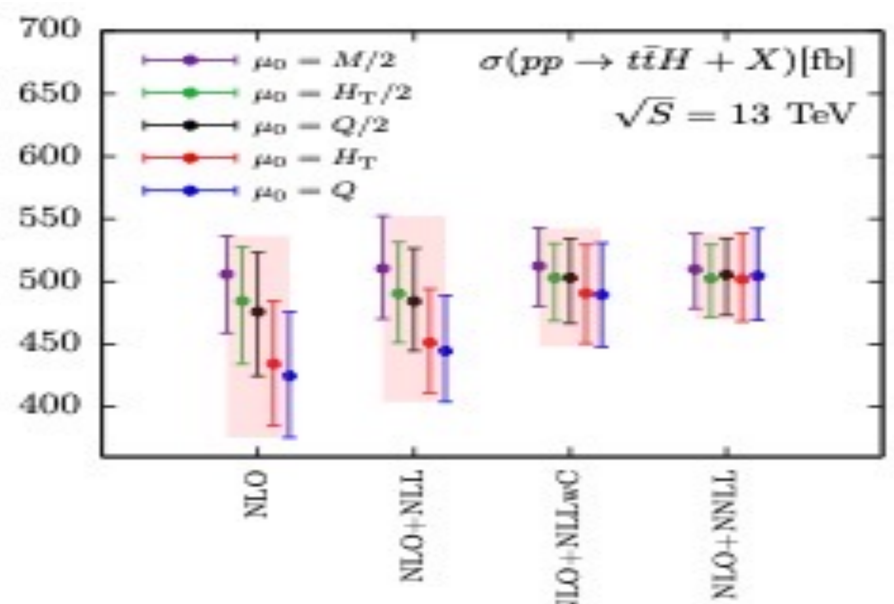
Theory has come a long way



LHC Higgs WG

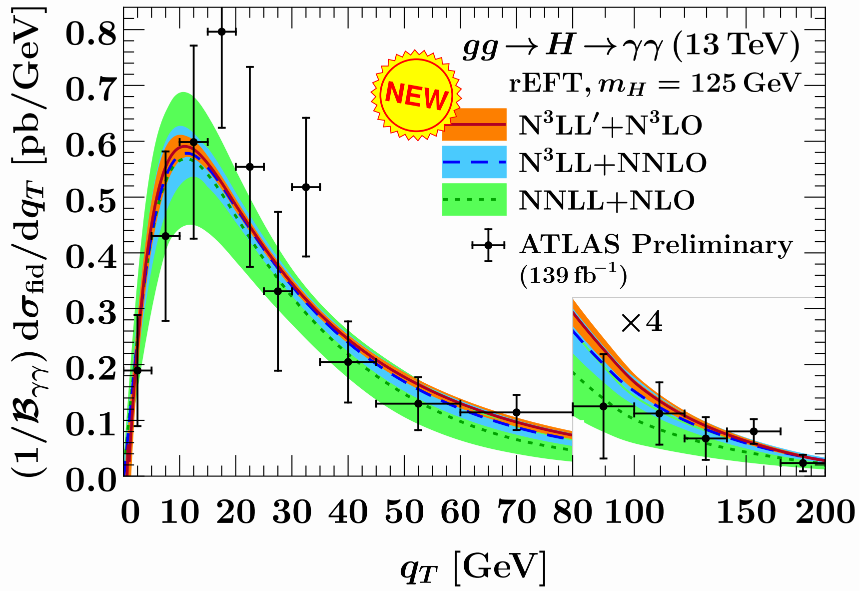
Anastasiou et al. [1502.06056]





Kulesza et al. [1812.08622]

Bliss et al. [2102.08039]

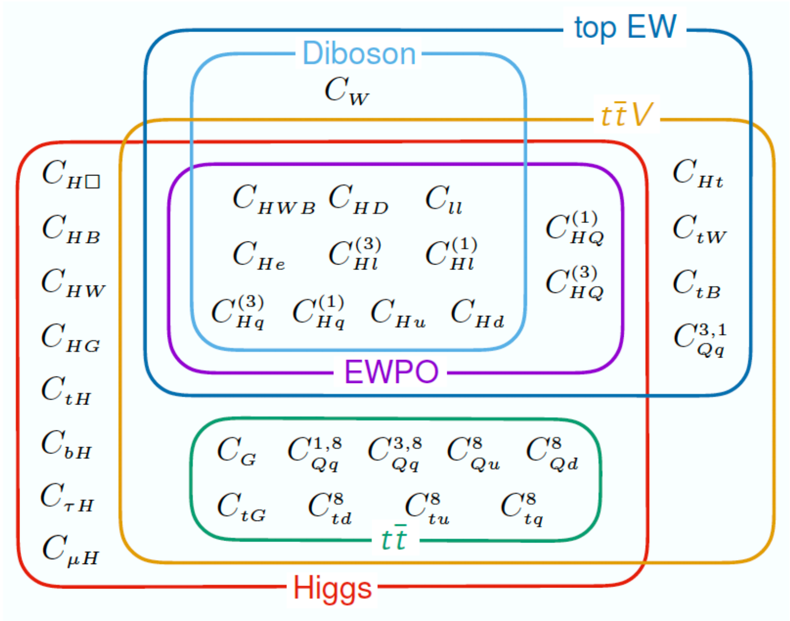


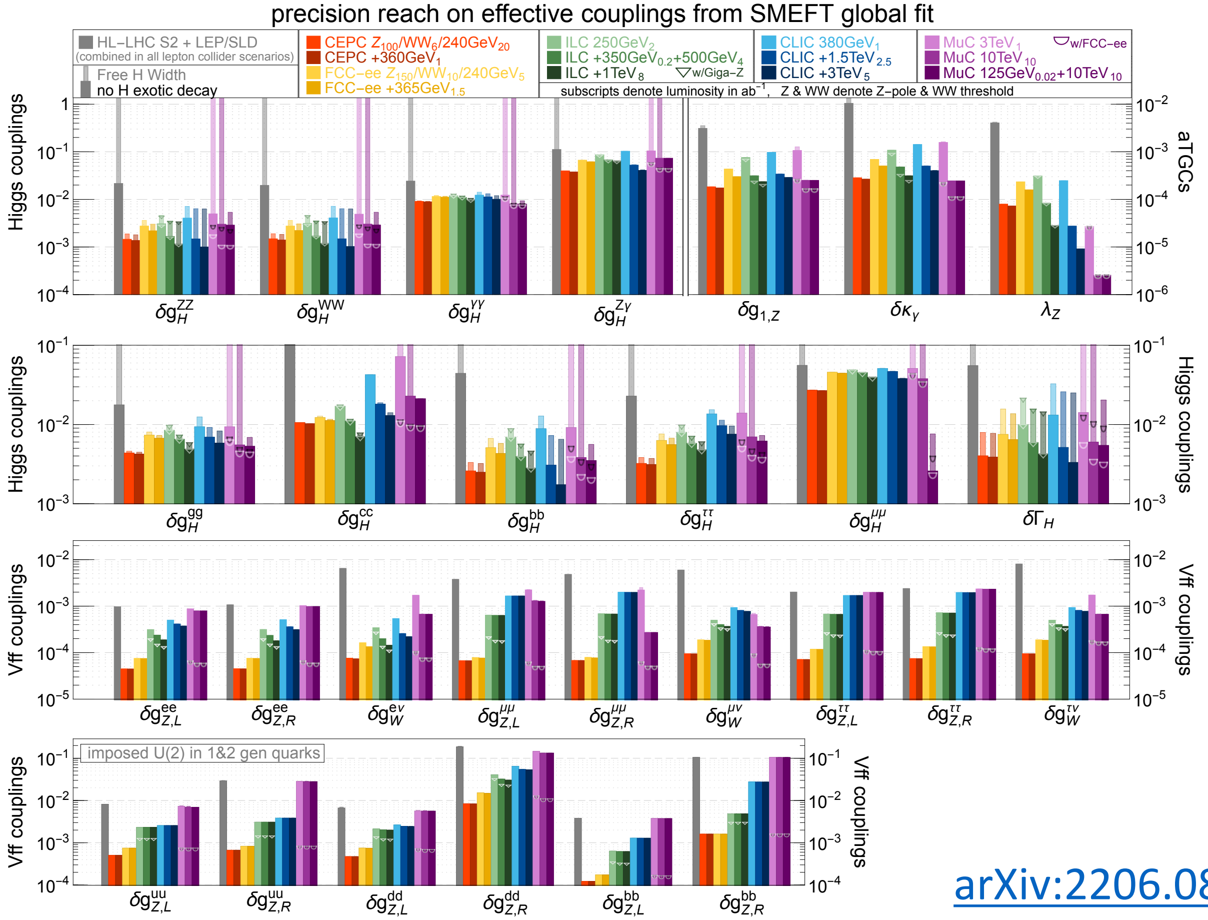
Several backgrounds also know at
NLO QCD+EW or improved NLO (+NNLL)
(e.g. W/Z+j, ttbb, ttW, ttZ, ttγ, …)

Constraining BSM via global EFT fits

EW + Higgs

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





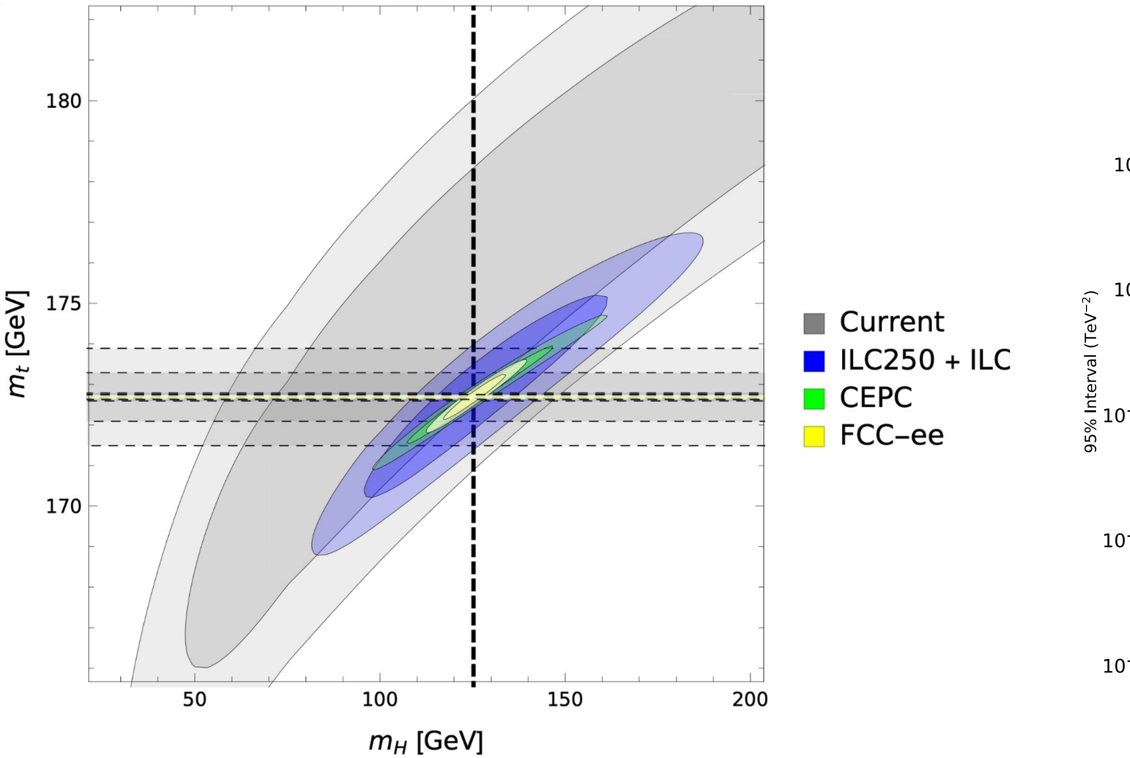
arXiv:2206.08326

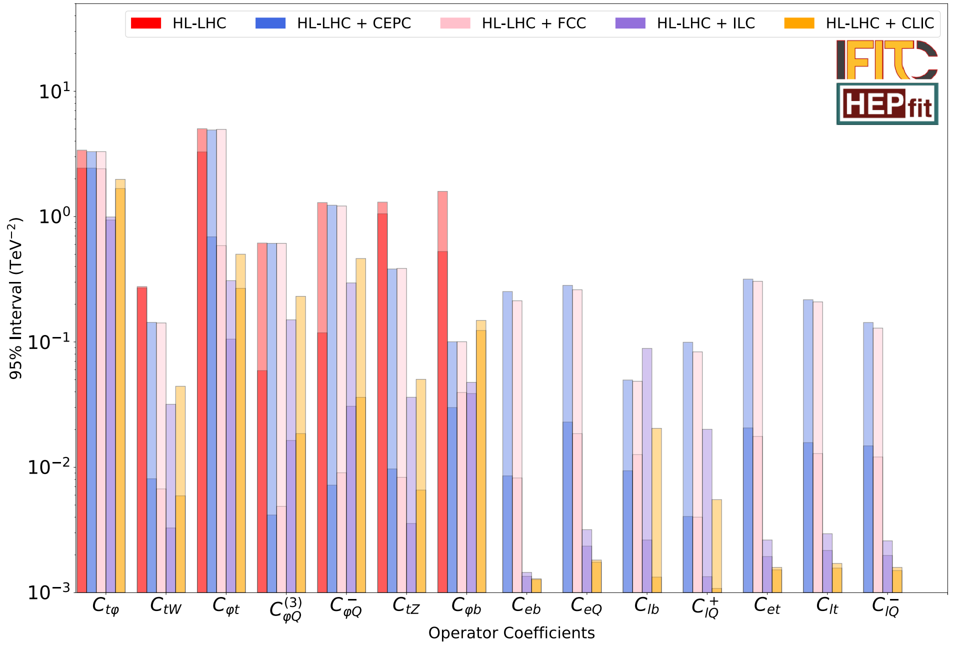
EFT connects different processes with large correlations: pattern of coefficients give insights on underlying BSM model

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

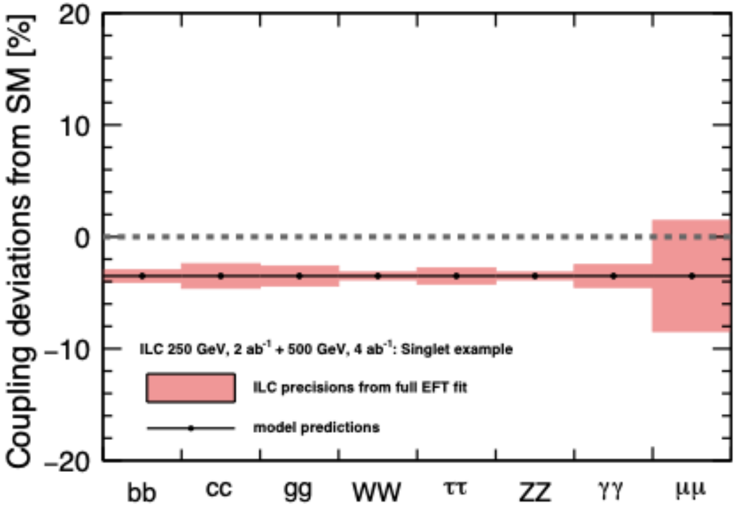




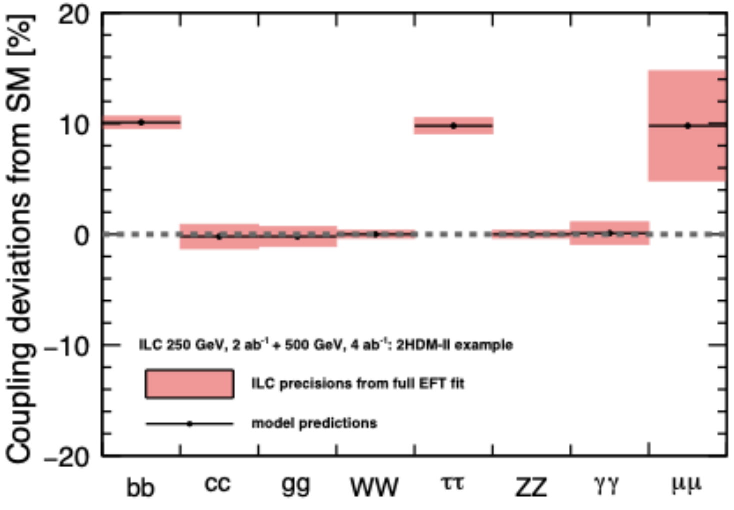
From Snowmass 2021 EF HF and EW TG's Reports
arXiv:2209.11267, arXiv:2209.08078

Disentangling models from EFT patterns

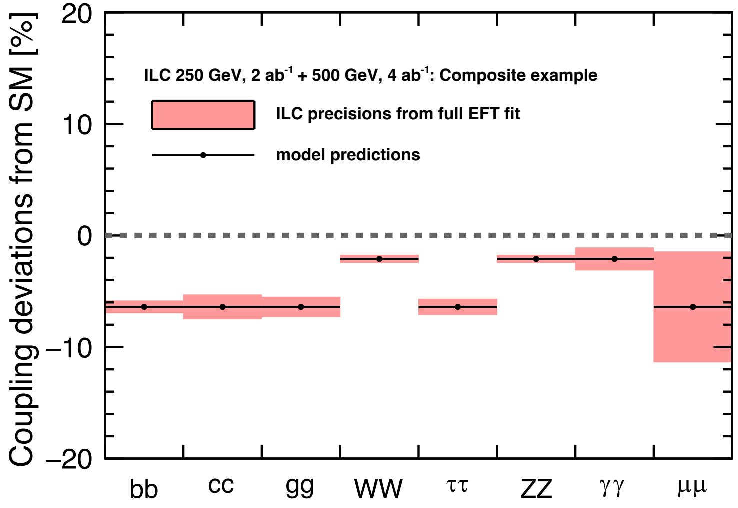
The “inverse Higgs” problem



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**

Future of Perturbative QCD calculations

Les Houches wish-list

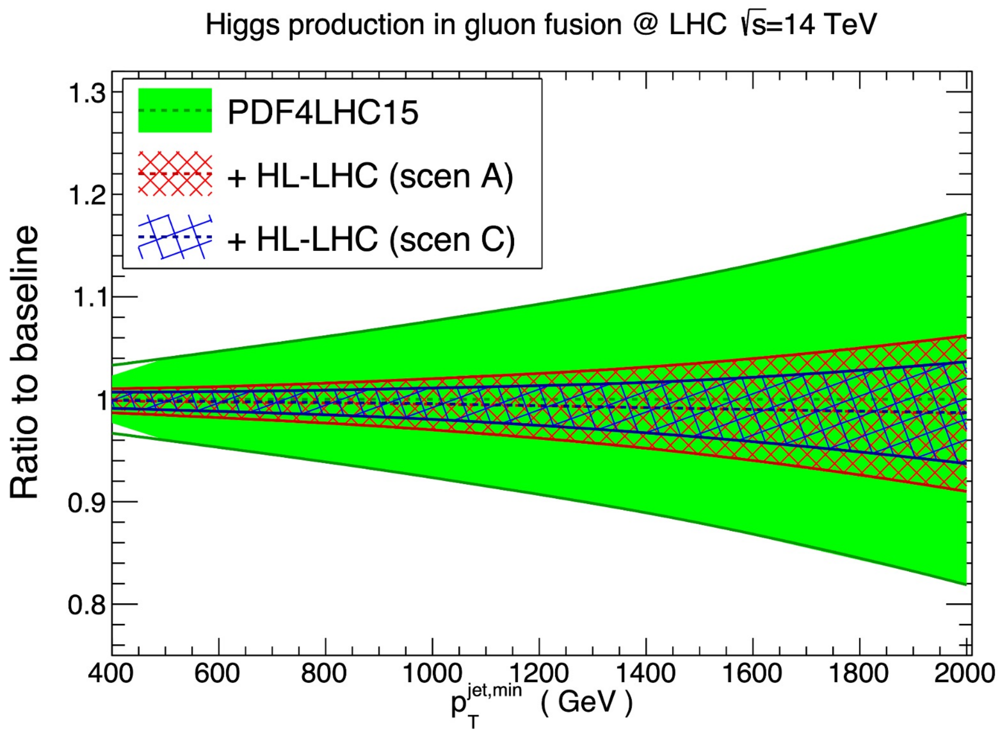
process	known	desired
$pp \to H$	$\mathrm{N^3LO_{HTL}}$, $\mathrm{N^2LO^{(t)}_{QCD}}$, $\mathrm{N^{(1,1)}LO^{(HTL)}_{QCD\otimes EW}}$	$\mathrm{N^4LO_{HTL}}$ (incl.), $\mathrm{N^2LO^{(b,c)}_{QCD}}$
$pp \to H+j$	$\mathrm{N^2LO_{HTL}}$, $\mathrm{NLO_{QCD}}$, $\mathrm{N^{(1,1)}LO_{QCD\otimes EW}}$	$\mathrm{N^2LO_{HTL}}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

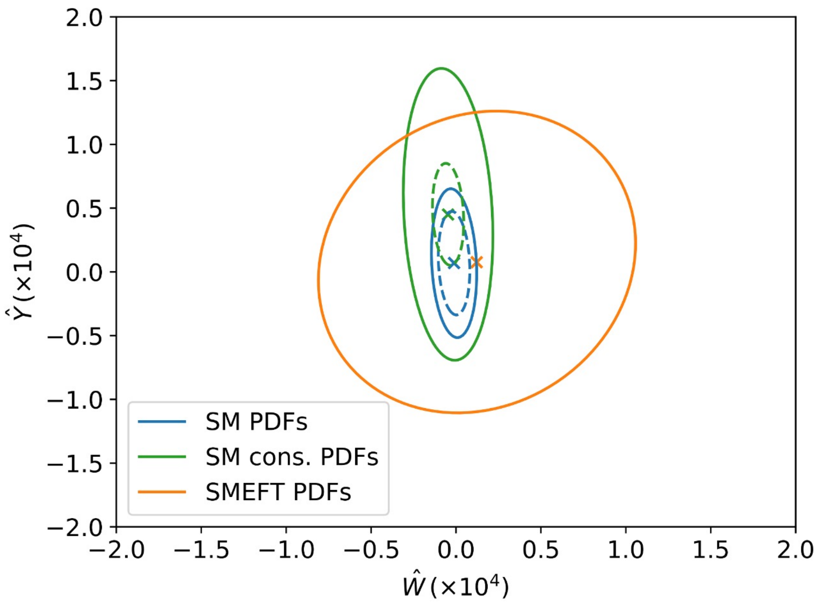
- **α_s uncertainty is a limiting factor in many measurements, e.g. Higgs couplings, at the HL-LHC**

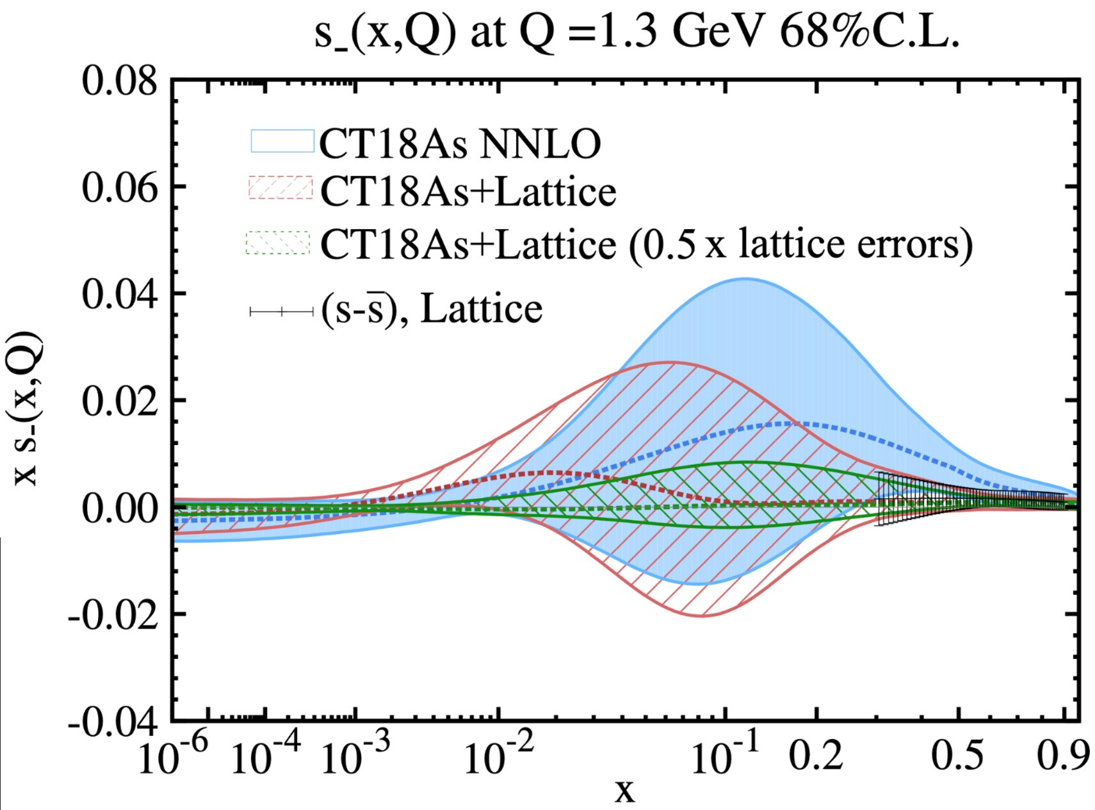
	Relative $\alpha_s(m_Z)$ uncertainty	
Method	Current	Near (long-term) future
(1) Lattice	0.7%	$\approx$ 0.3% (0.1%)
(2) τ decays	1.6%	$<$ 1.%
(3) $Q\overline{Q}$ bound states	3.3%	$\approx$ 1.5%
(4) DIS & PDF fits	1.7%	$\approx$ 1% (0.2%)
(5) e^+e^- jets & evt shapes	2.6%	$\approx$ 1.5% ($<$ 1%)
(6)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

- **FCC-ee:** 3×10^{12} $Z\to qq$ at the Z pole, and $\sqrt{s}$ 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 $l^+l^- \to H[\to gg]Z[\to ll]$
  - Identification of weak-strahlung emission, and g→tt in jets
  - Track functions in jet substructure

Future of PDF determination

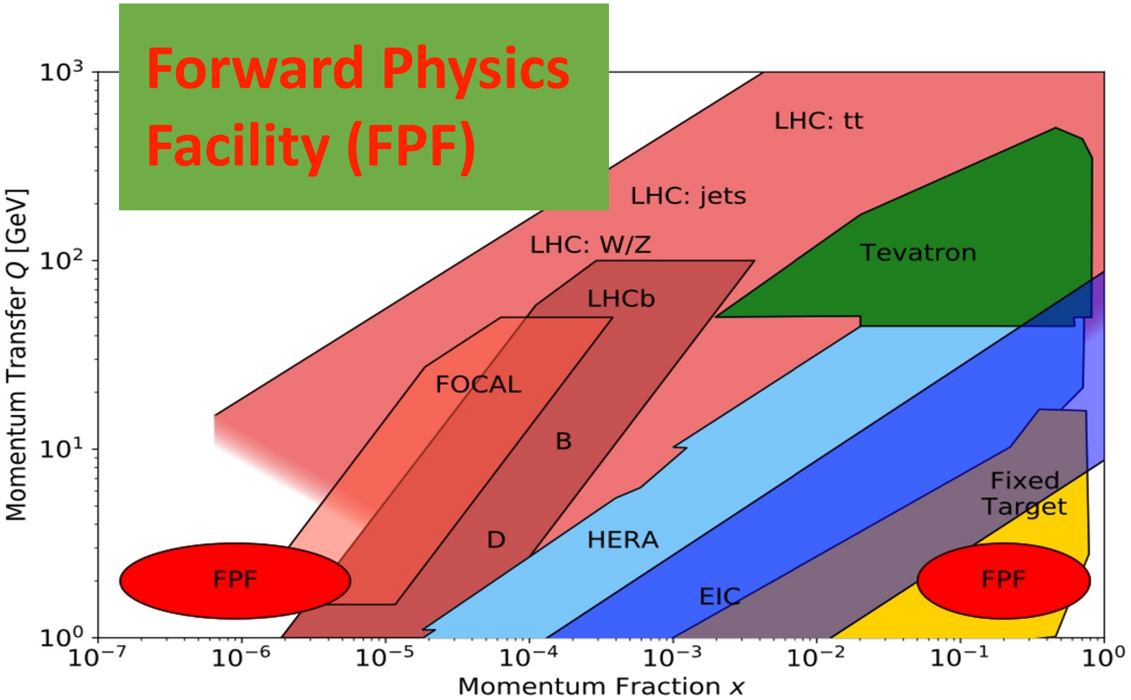


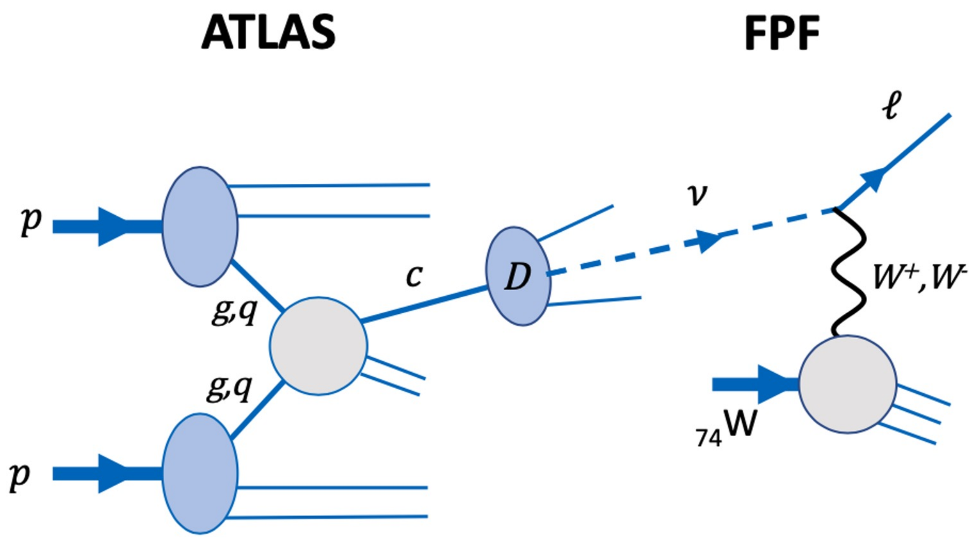




arXiv:2204.07944

Forward Physics

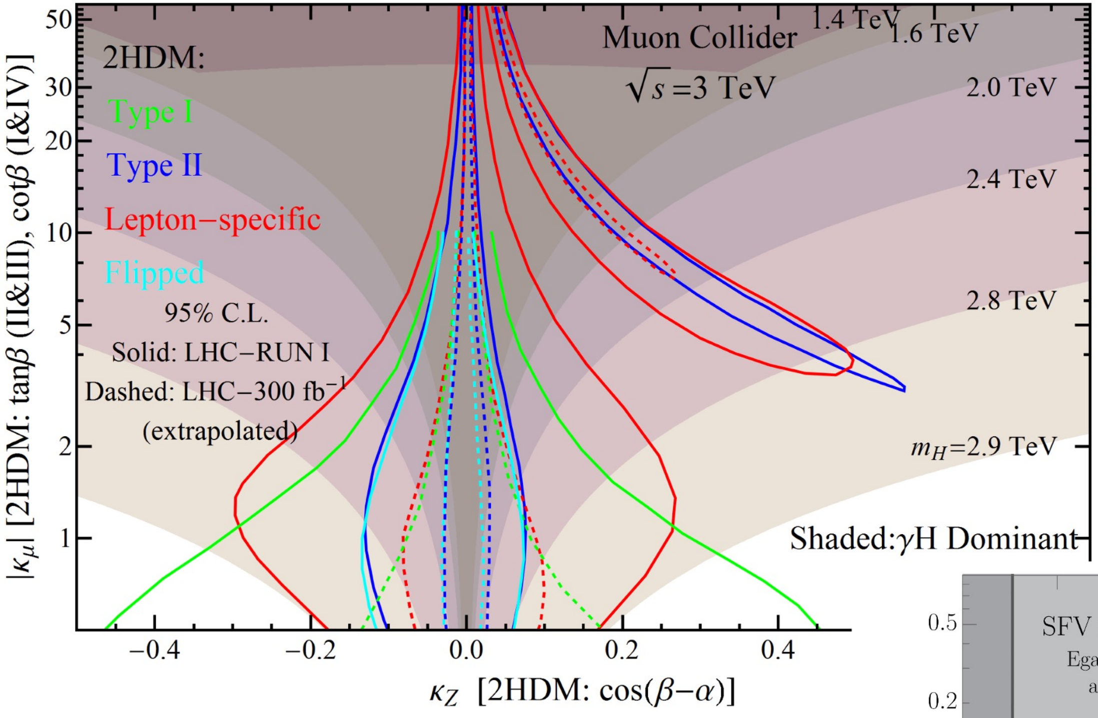




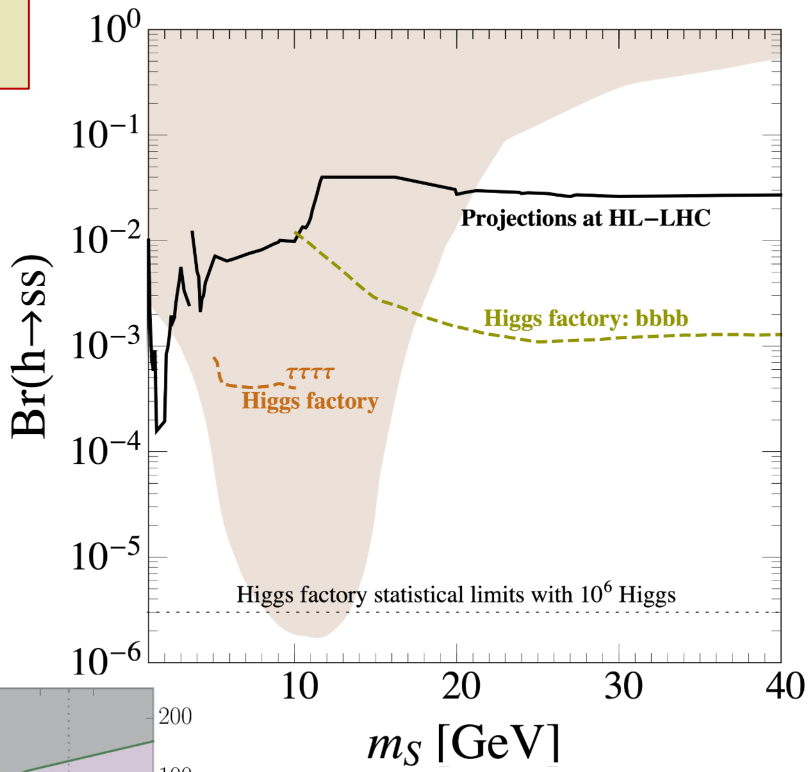
- FPF will detect **far-forward neutrinos** from charm meson decays by DIS on a tungsten target
  - Improved predictions for key astroparticle physics processes, such as ultra-high energy neutrino-nucleus and cosmic ray interaction cross-sections
- **Neutrino–induced CC DIS** structure functions provide access to different quark flavor combinations compared to charged-lepton DIS
  - FPF will complement EIC
- PDF information, e.g. **high-x intrinsic charm**

- **Diffraction:**
  - Interesting to understand QCD dynamics, probing Odderon and Pomeron models, exploration of EW and BSM physics
  - Requires the combination of experimental measurements, e.g. EIC and FPF, and theoretical work
  - The FPF also allows exploration of BFKL evolution and gluon saturation

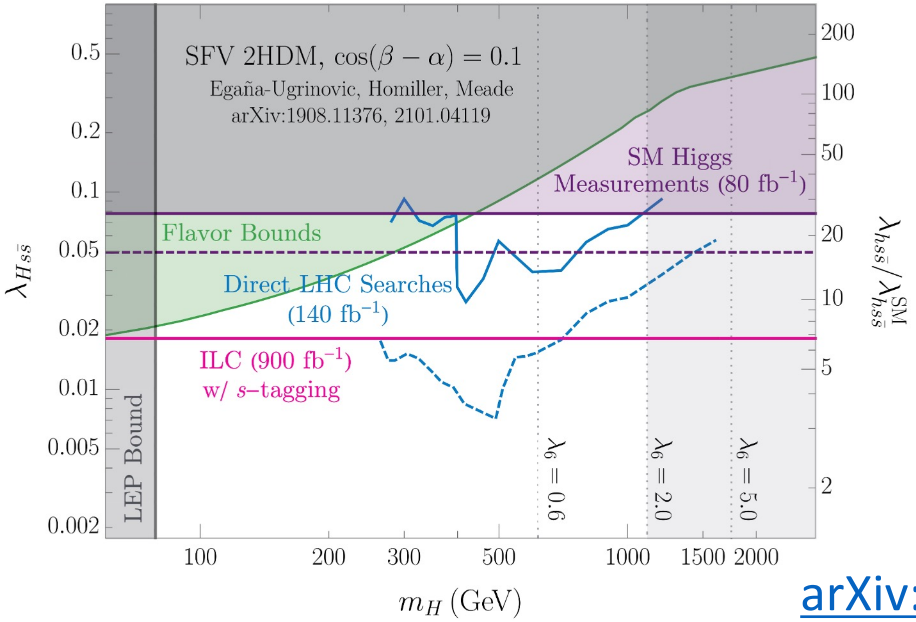
BSM explorations: extended Higgs sectors



[arXiv:2203.07261](https://arxiv.org/abs/2203.07261)



[arXiv:2203:08206](https://arxiv.org/abs/2203.08206)



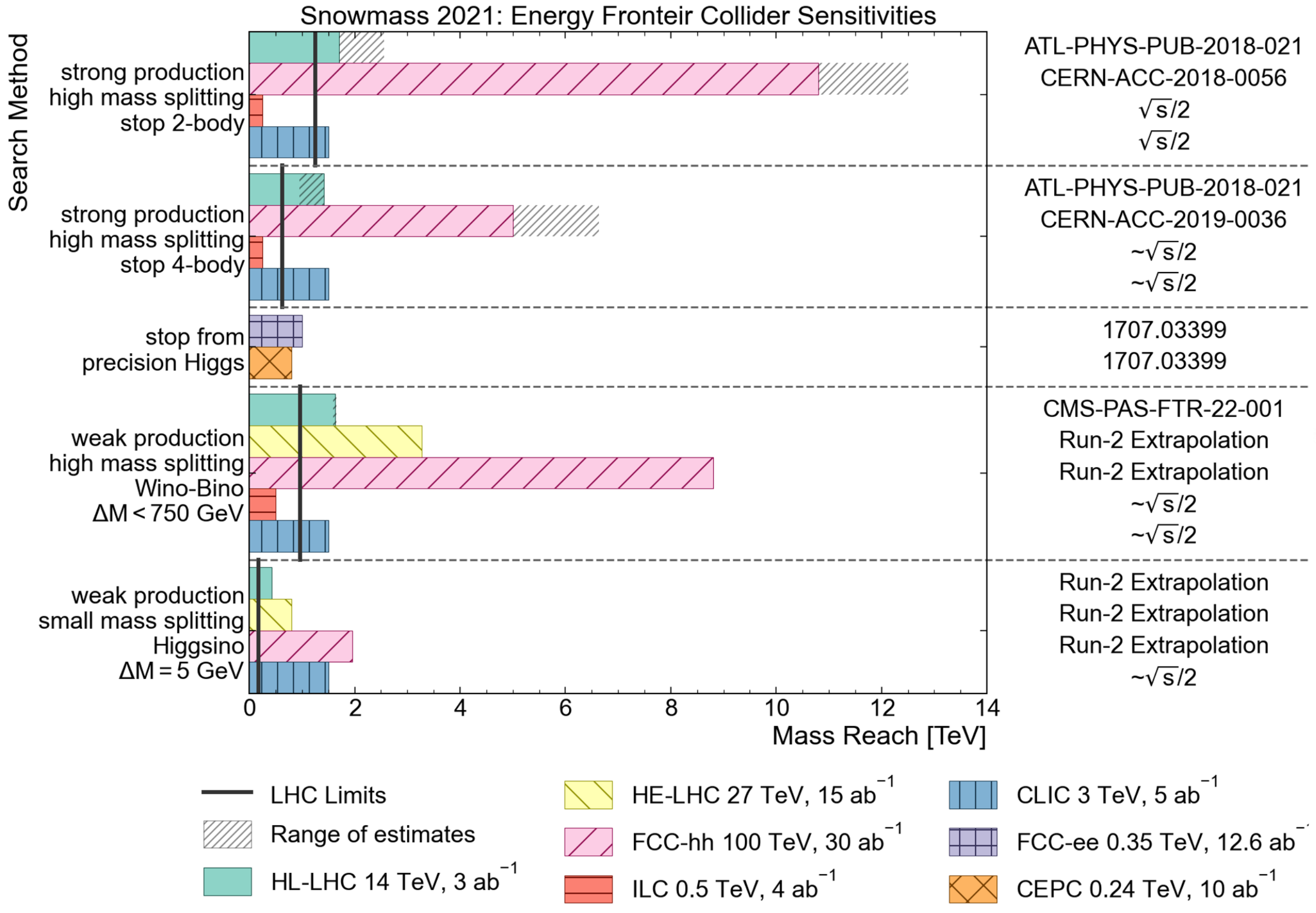
Extended Higgs sectors:
2HDM, extra singlets, …

Higgs and flavor:
probing anomalous
Hss coupling

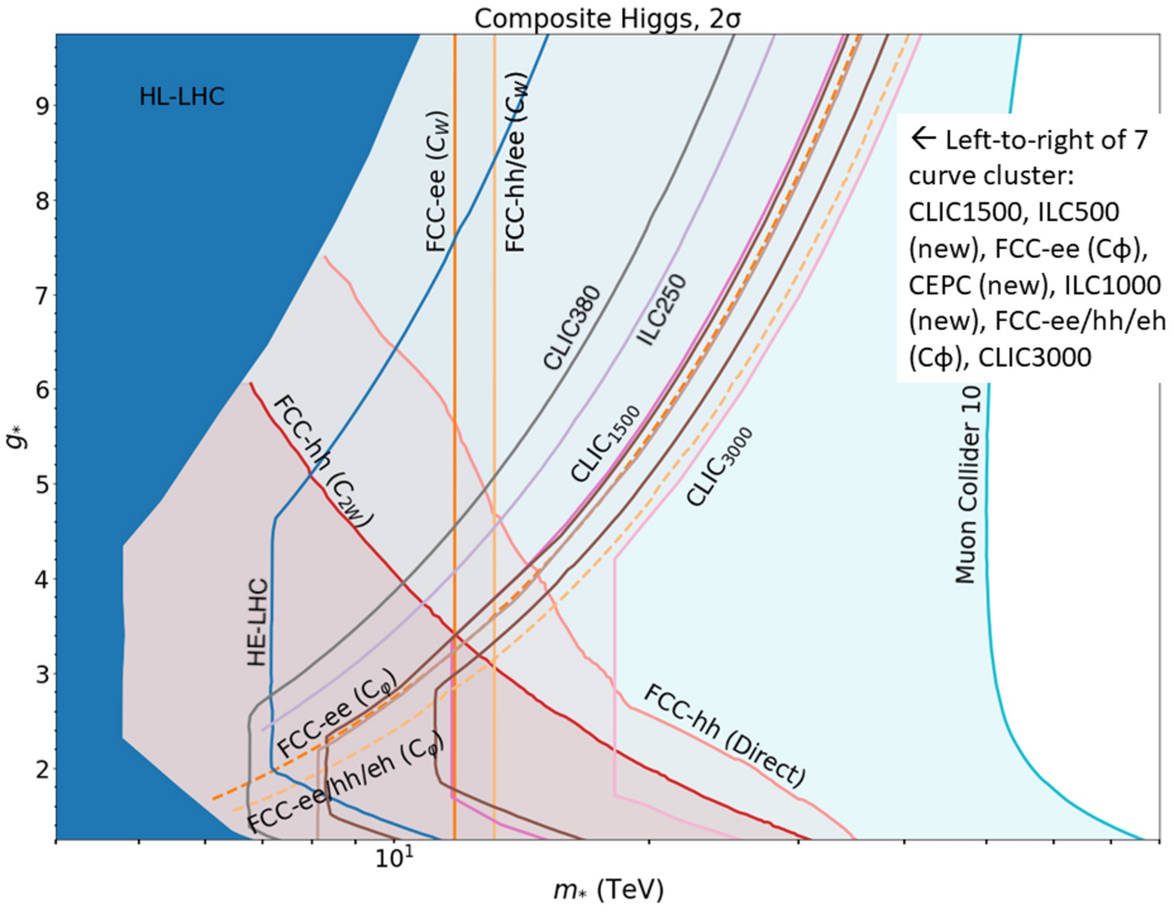
[arXiv:2203:07535](https://arxiv.org/abs/2203.07535)

Examples of BSM model specific explorations

SUSY models



Composite Higgs models



From Snowmass 21 EF BSM Topical Group Report

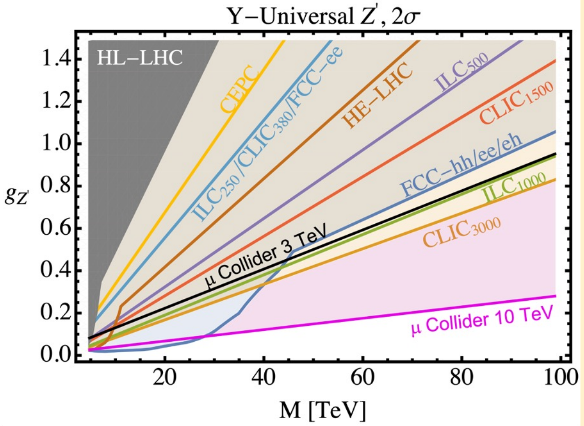
Examples of BSM general explorations

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

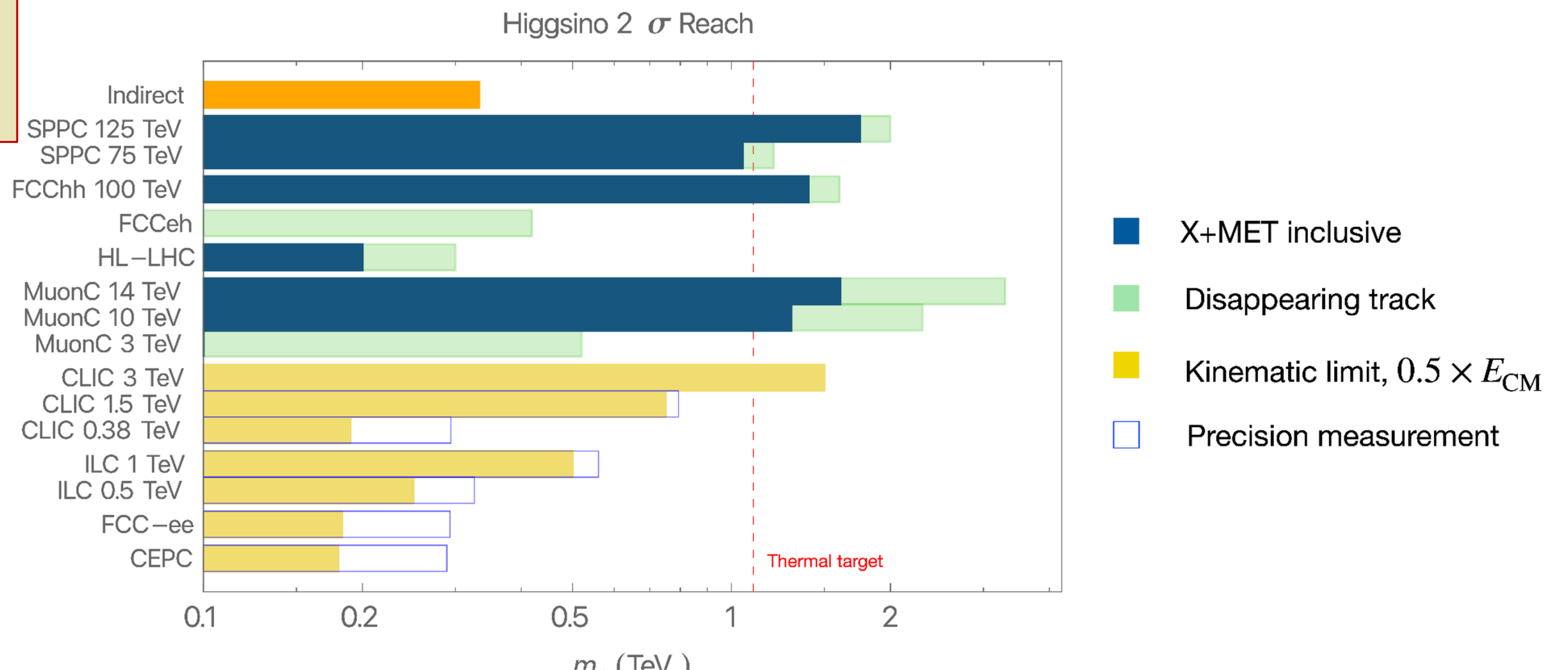
Machine	Type	√s (TeV)	∫L dt (ab^{-1})	Source	Z' Model	5σ (TeV)	95% CL (TeV)
HL-LHC	p p	14	3	R.H.	$Z'_{SSM} \to$ dijet	4.2	5.2
				ATLAS	$Z'_{SSM} \to l^+ l^-$	6.4	6.5
				CMS	$Z'_{SSM} \to l^+ l^-$	--	6.8
				EPPSU*	$Z'_{Univ}(g_Z'=0.2)$	--	6
ILC250/ CLIC380/ FCC-ee	$e^+ e^-$	0.25	2	ILC	$Z'_{SSM} \to f^+ f^-$	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

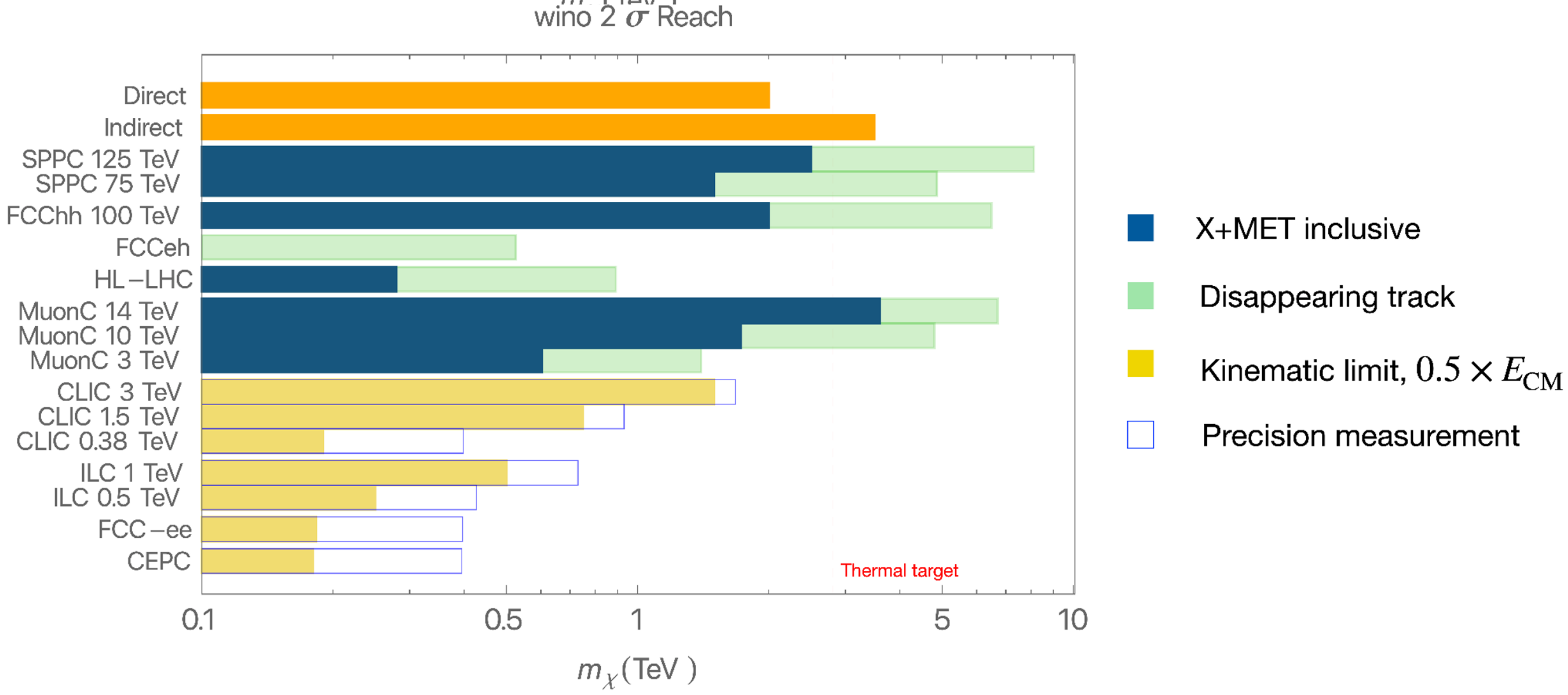
Increasing Z' Sensitivity

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