Overview of the Energy Frontier

Public PAC Meeting

Fermilab, June 22, 2022

Meenakshi Narain (Brown U.)
Laura Reina (FSU)
Alessandro Tricoli (BNL)

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

Energy Frontier: explore the TeV energy scale and beyond

to answer still open Big Questions and Explore the Unknown

Big Questions

Evolution of early Universe

Matter Antimatter Asymmetry

Nature of Dark Matter

Origin of Neutrino Mass

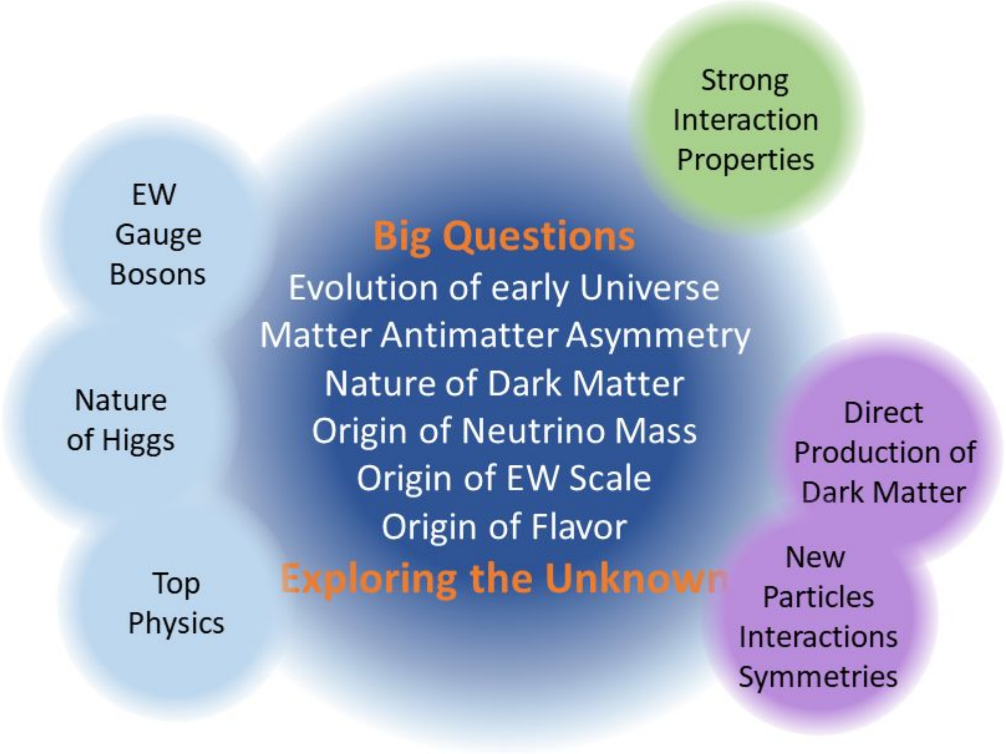
Origin of EW Scale

Origin of Flavor

Exploring the Unknown

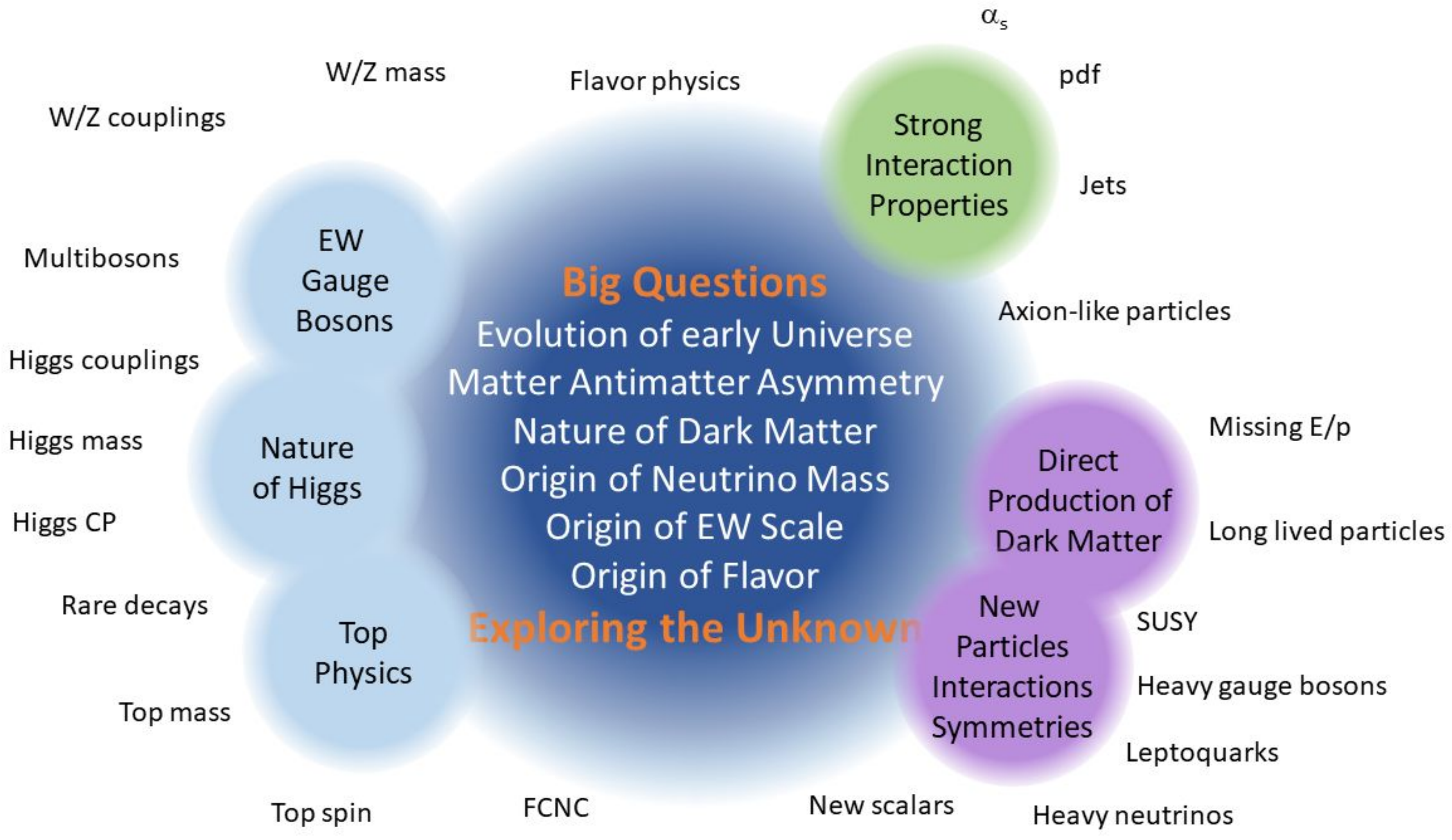
Energy Frontier: explore the TeV energy scale and beyond

Using Standard Model and Beyond Standard Model probes



Energy Frontier: explore the TeV energy scale and beyond

Through the breadth and multitude of collider physics signatures



Energy Frontier Topical Groups

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

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

Liaisons, task forces, cross-frontier fora

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

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)

Early Career Representative

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

Monte Carlo task force and production team

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

Energy Frontier Meetings

2020

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

2021

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

2022 - Building towards the CSS and the final Report

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

Setting the stage - Future scenarios

Energy Frontier Machines

Discoveries at the Energy Frontier are enabled by the development of new accelerators and detector instrumentation.

EF explorations should proceed along **two main complementary directions:**

- **Study known phenomena at high energies looking for indirect evidence of BSM physics**
  - Need factories of Higgs bosons (and other SM particles)
  - Need high precision to probe the TeV scale and beyond
  - **Need both luminosity and energy**

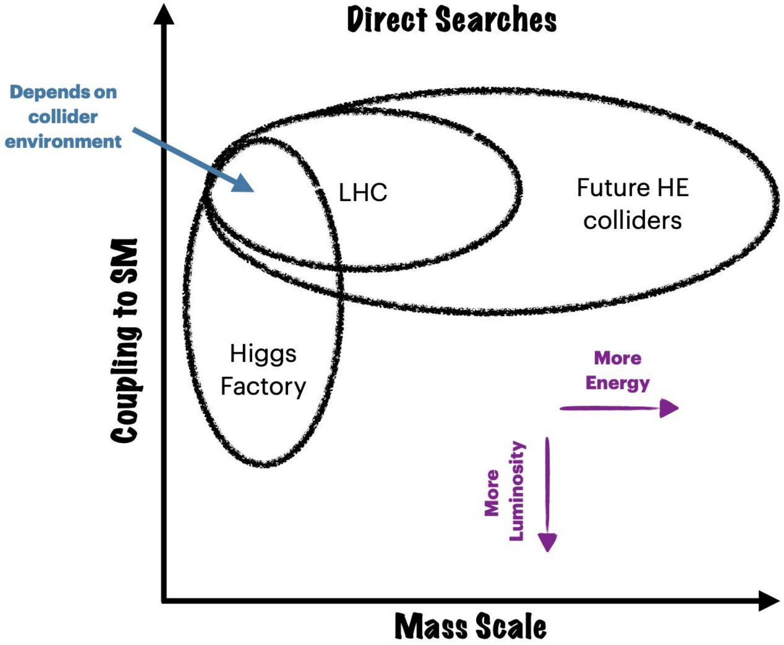
- **Search for direct evidence of BSM physics at the energy frontier**
  - Need to explore the multi-TeV scale → **Need energy**
  - Need to explore what LHC/HL-LHC may have difficulty exploring → **Need luminosity**

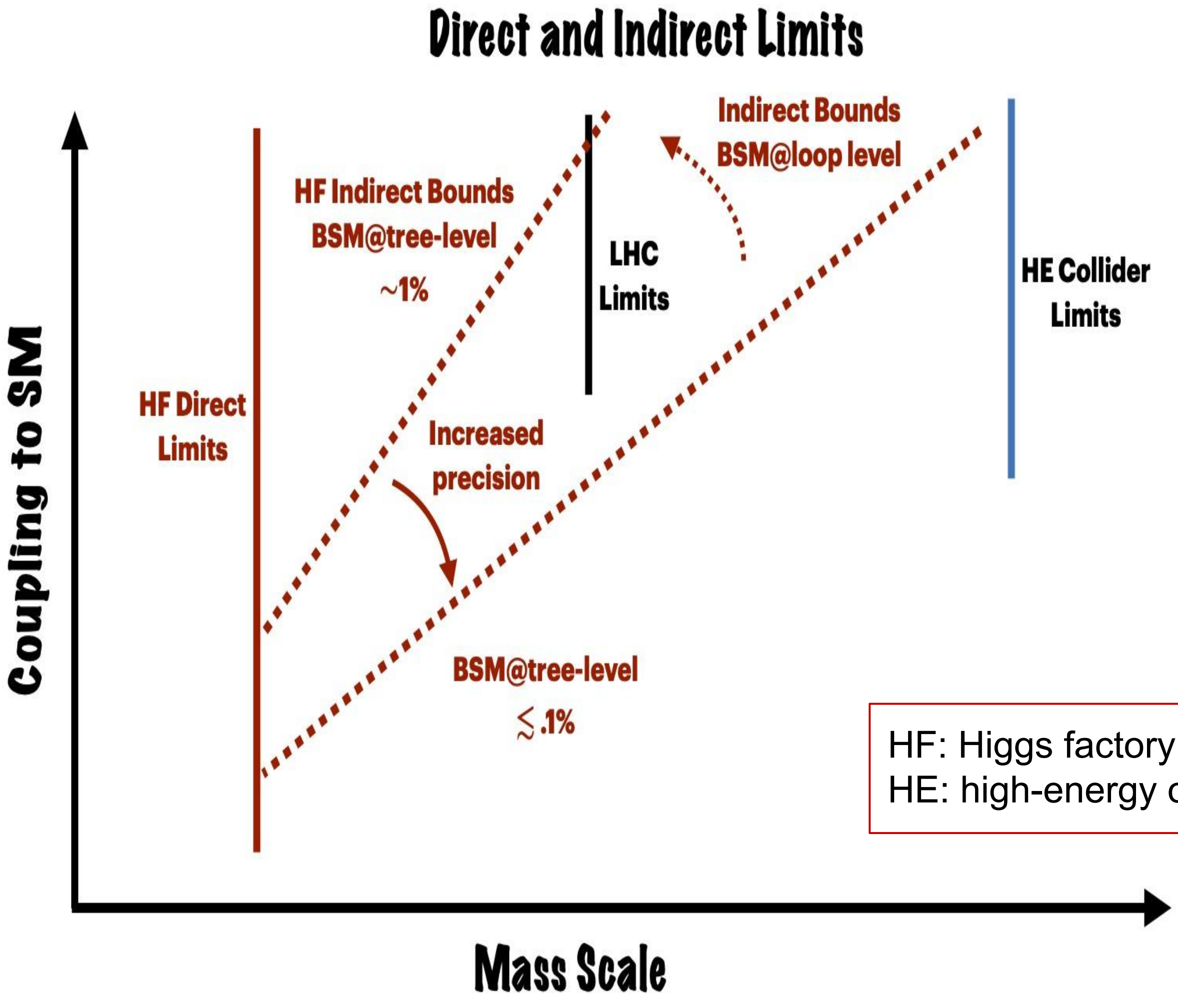
Energy Frontier Machines: energy and precision

New physics can be at low as at high mass scales: Naturalness would prefer mass scale close to the EW scale, but direct searches of specific models have placed stronger bounds around 1-2 TeV.

Depending on the mass scale of new physics and the type of collider, the primary method for discovery new physics can vary.

We need to use both energy and precision.



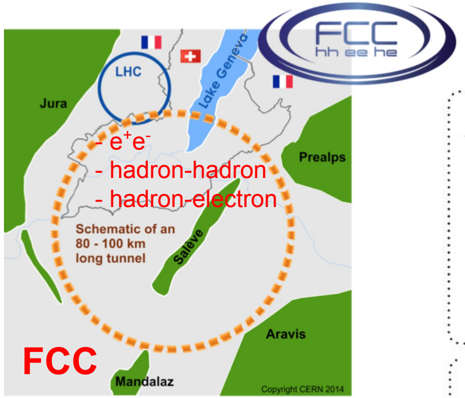


In a simplified picture:

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

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

HF: Higgs factory
HE: high-energy or multi-TeV collider



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

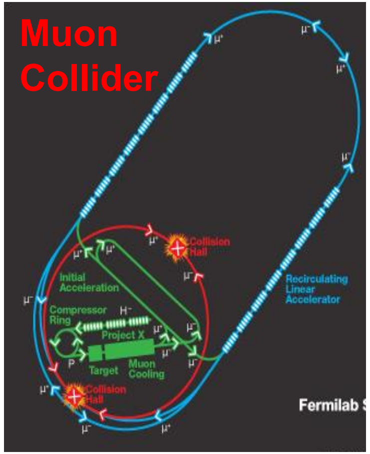
- higher luminosity
- several interaction points
- precise E-beam measurement (O(0.1MeV) via resonant depolarization)
- $\sqrt{s}$ limited by synchroton radiation

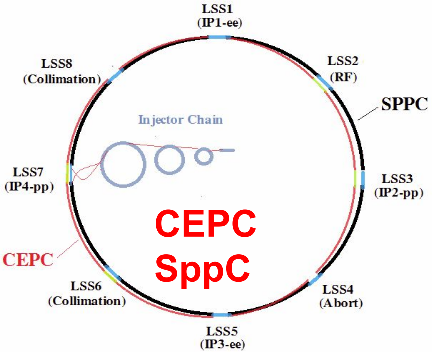
Linear

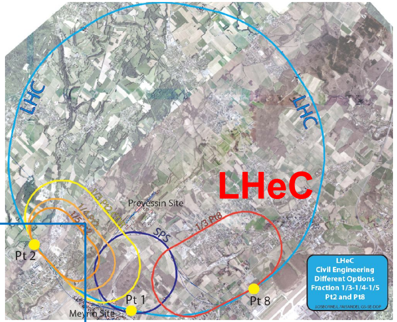
- easier to upgrade in energy
- easier to polarize beams
- "greener": less power consumption*
- large beamsthralung
- one IP only

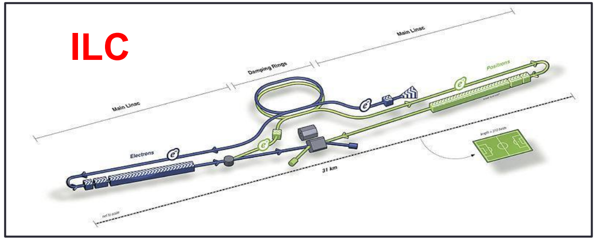
*energy consumption per integrated luminosity is lower at circular colliders but the energy consumption per GeV is lower at linear colliders

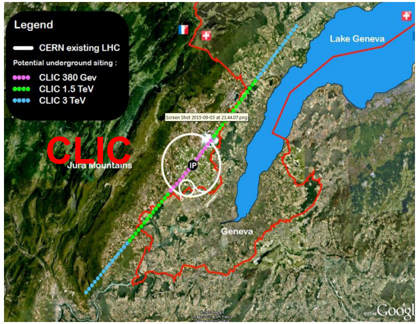
hristophe Grojean Future Measurements 9 Inst. Pascal, Dec. 4, 2019











- **Added C^3**
- **Gamma-gamma?**
- **Advanced colliders?**

Snowmass 2021: EF Benchmark Scenarios

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

Collider	Type	$\sqrt{s}$	$\mathcal{P}[\%]$ e^-/e^+	$\mathcal{L}_{\text{int}}$ ab^{-1} /IP
HL-LHC	pp	14 TeV		3
ILC & C^3	ee	250 GeV	$\pm80/\pm30$	2
		350 GeV	$\pm80/\pm30$	0.2
		500 GeV	$\pm80/\pm30$	4
		1 TeV	$\pm80/\pm20$	8
CLIC	ee	380 GeV	$\pm80/0$	1
CEPC	ee	M_Z		50
		$2M_W$		3
		240 GeV		10
		360 GeV		0.5
FCC-ee	ee	M_Z		75
		$2M_W$		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
HE-LHC	pp	27 TeV		15
FCC-hh	pp	100 TeV		30
SPPC	pp	75-125 TeV		10-20
LHeC	ep	1.3 TeV		1
FCC-eh		3.5 TeV		2
CLIC	ee	1.5 TeV	$\pm80/0$	2.5
		3.0 TeV	$\pm80/0$	5
μ-collider	$\mu\mu$	3 TeV		1
		10 TeV		10

Timelines will be taken from the ITF report from AF.

Snowmass Agora on Future Colliders

Series of events jointly organized by AF and EF, hosted by the Future Colliders initiative at Fermilab, to discuss both near and far future collider proposals, in different stages of development, synergistically grouped into five categories:

- e+e- linear colliders (Dec. 15, 2021): https://indico.fnal.gov/event/52161/
- e+e- circular colliders (Jan. 19, 2022) https://indico.fnal.gov/event/52534/
- μ+μ- colliders (Feb. 16, 2022): https://indico.fnal.gov/event/53010/
- circular pp and ep colliders (Mar 16, 2022): https://indico.fnal.gov/event/53473/
- advanced colliders (April 13, 2022): https://indico.fnal.gov/event/53848/

Critical discussions of physics reach, challenges and RD required, synergies with global context and local resources, timeframe, cost projection.

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

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

A taste of Physics Highlights from Snowmass 21 - Energy Frontier

Key physics questions of the EF program

What is the origin of the electroweak scale?

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

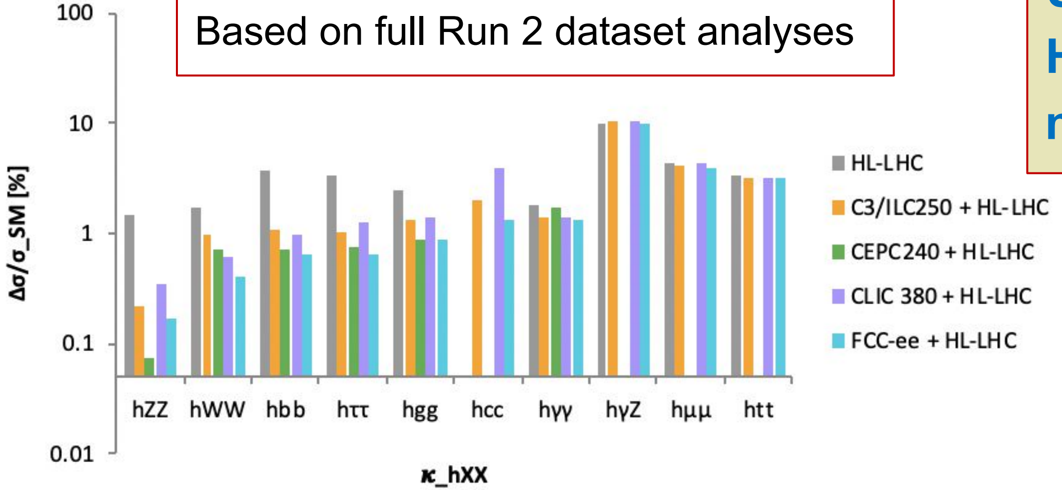
- Can we uncover the nature of UV physics from **precision Higgs measurements** (mass, width, couplings)? How does this improve the constraining power of global EW fits?
- Can we measure the shape of the **Higgs potential**?
- Can the Higgs give us insight into **flavor** and vice versa?
- What are the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

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

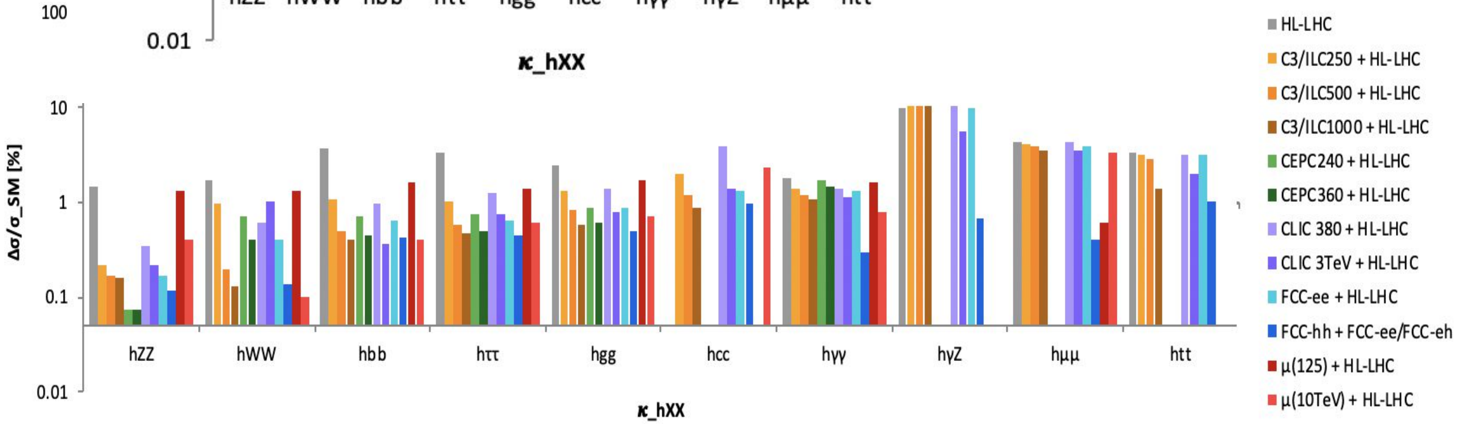
Physics highlights - Higgs, top, EW

Based on full Run 2 dataset analyses

Updated reach for Higgs-boson coupling measurements

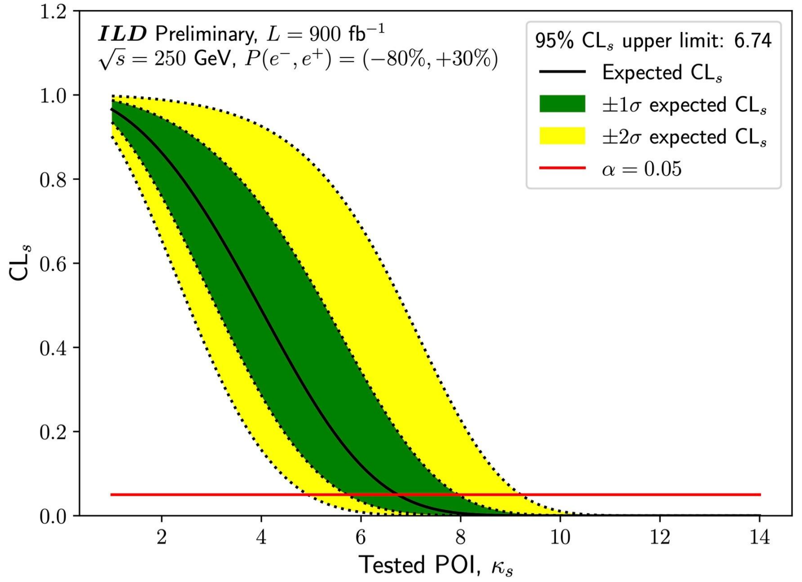


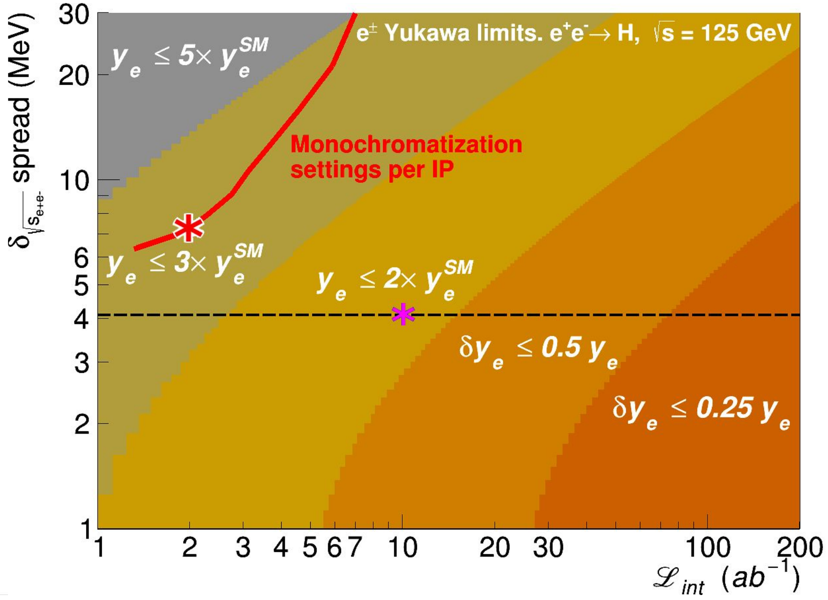
Initial stages of future e+e- machines



Final reach of all considered future colliders

Reach for light-fermion Yukawa couplings





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

arXiv:2203.07535

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

arXiv:2107.02686

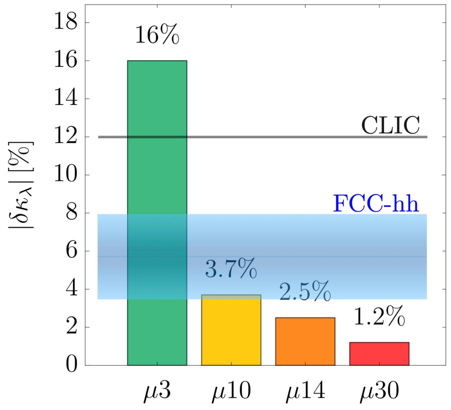
Updated reach for Higgs-self coupling

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

ATLAS and CMS HL-LHC updated

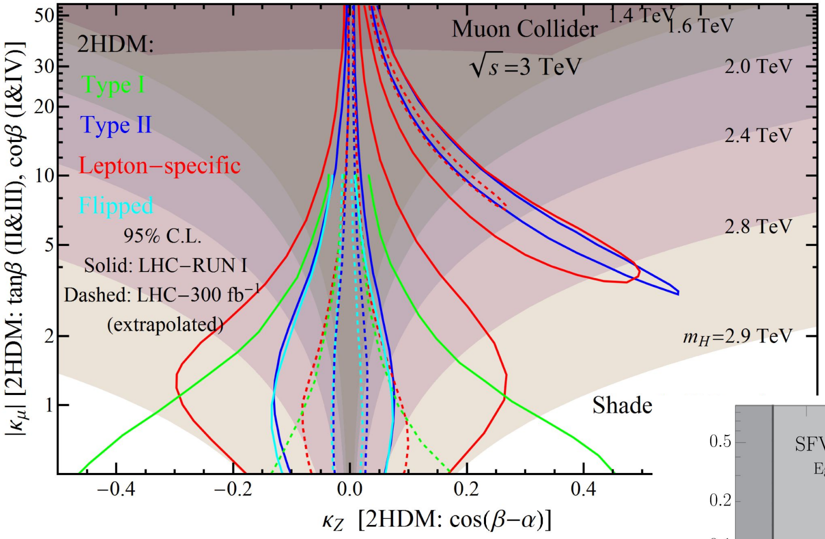
FCC-hh updated arXiv:2004.03505

Muon Collider reach:



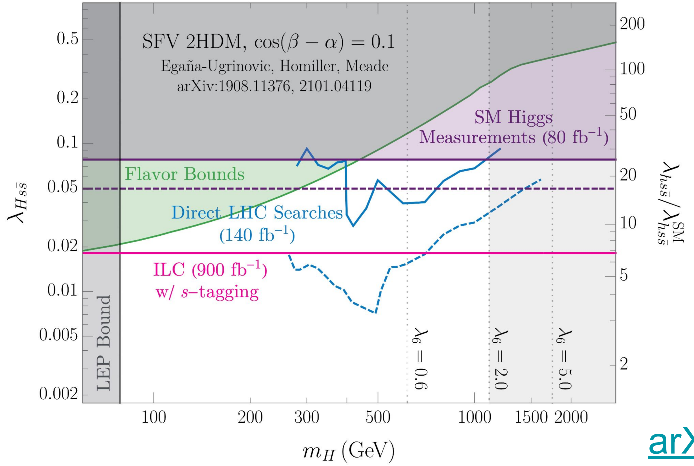
arXiv:2203.07256

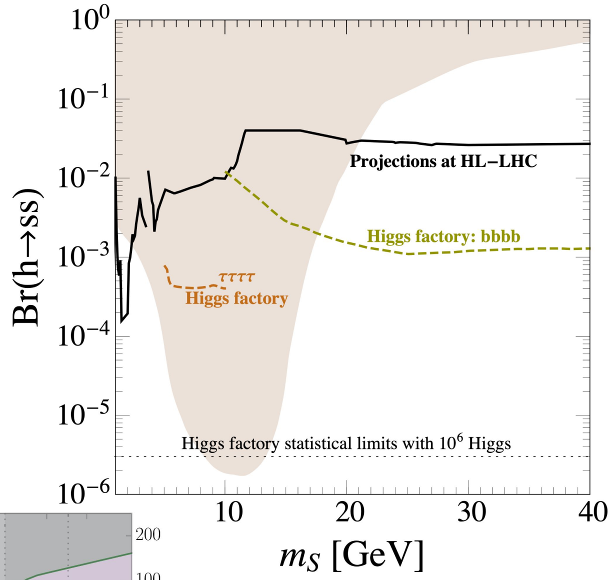
Higgs as a portal to BSM physics



arXiv:2203.07261

Extended Higgs sectors: 2HDM, extra singlets, …





arXiv:2203:08206

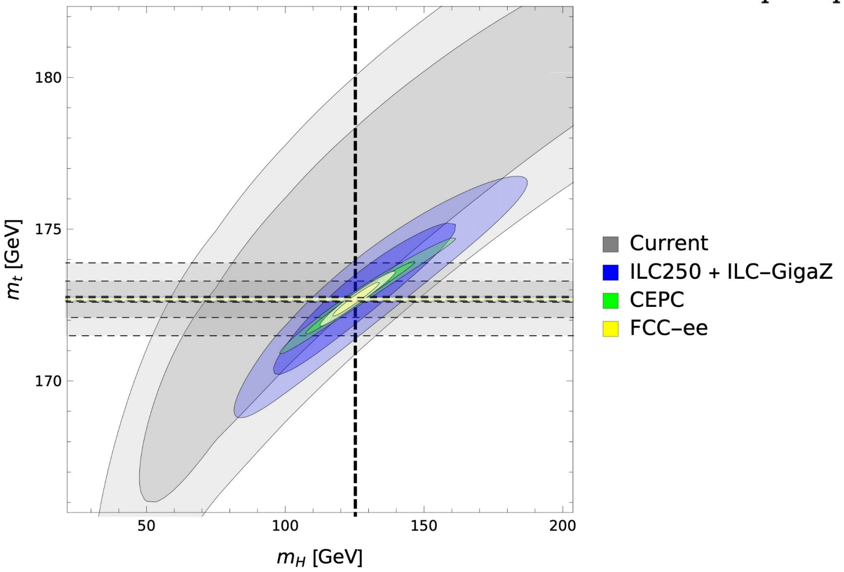
Higgs and flavor: probing anomalous Hss coupling

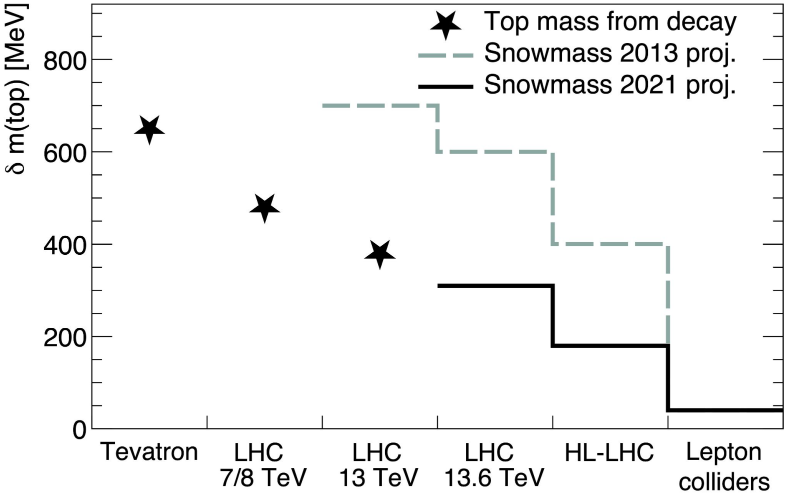
arXiv:2203:07535

Interplay with top-quark precision measurements

Stress testing the SM and exploring anomalous couplings

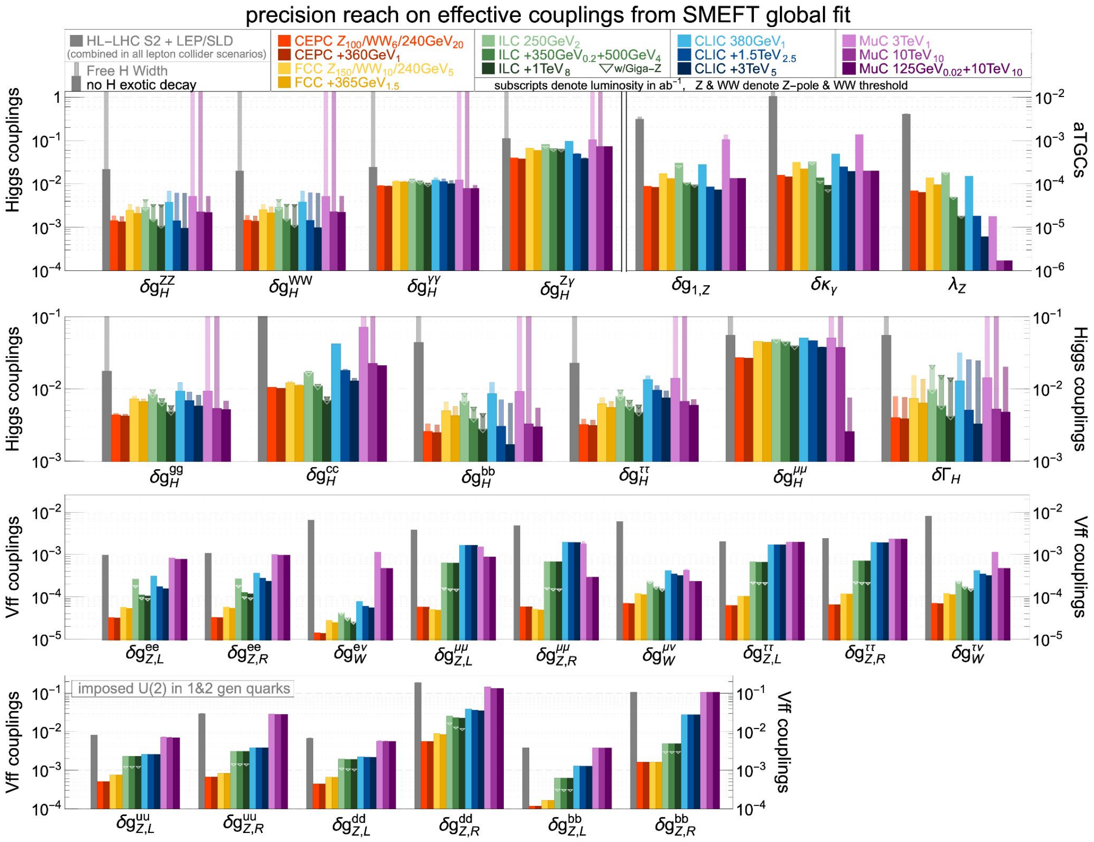
Parameter	HL-LHC	ILC 500	FCC-ee	FCC-hh
$\sqrt{s}$ [TeV]	14	0.5	0.36	100
Yukawa coupling y_t (%)	3.4	2.8	3.1	1.0
Top mass m_t (%)	0.10	0.031	0.025	–
Left-handed top-W coupling $C^3_{\phi Q}$ (TeV^{-2})	0.08	0.02	0.006	–
Right-handed top-W coupling C_{tW} (TeV^{-2})	0.3	0.003	0.007	–
Right-handed top-Z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



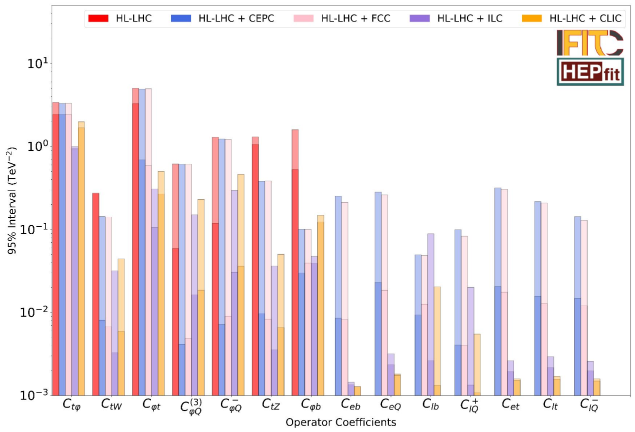


From Snowmass 2021 EF HF and EW TGs Reports

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



Including top-quark observables



[arXiv:2206.08326](https://arxiv.org/abs/2206.08326)

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

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

Key physics questions of the EF program

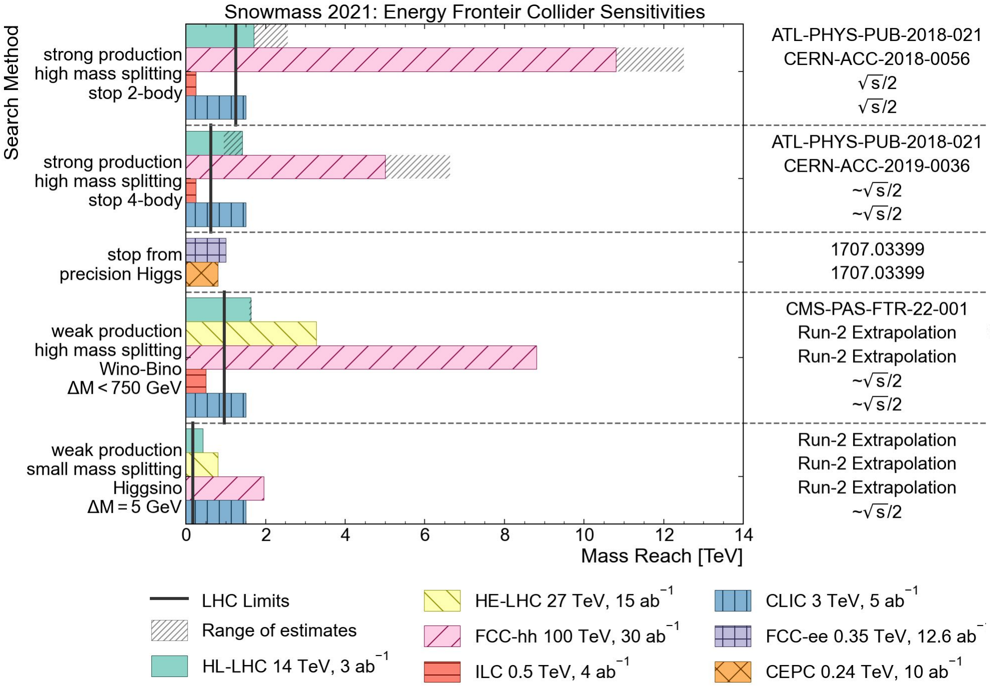
How to build a complete program of BSM searches via both model-specific and model independent explorations?

- Models connect the high-level unanswered questions in particle physics (dark matter, electroweak naturalness, CP violation, etc) to specific phenomena in a self-consistent way.
  - Allow the comparison of experimental reach between various approaches, e.g. direct searches vs precision. But ...
  - **Which models to consider? How to compare model spaces in a consistent way?**
- Study alternative paradigms with respect to traditional BSM searches (ex: long-lived and feebly-interacting particles).
  - **Can future detectors and accelerators probe such particles?** (Including DM searches)
- How do we conduct searches in a more model-independent/agnostic way ?
- How do we compare the results of different experiments in a more model-independent way to ensure complementarity and avoid big gaps in coverage?

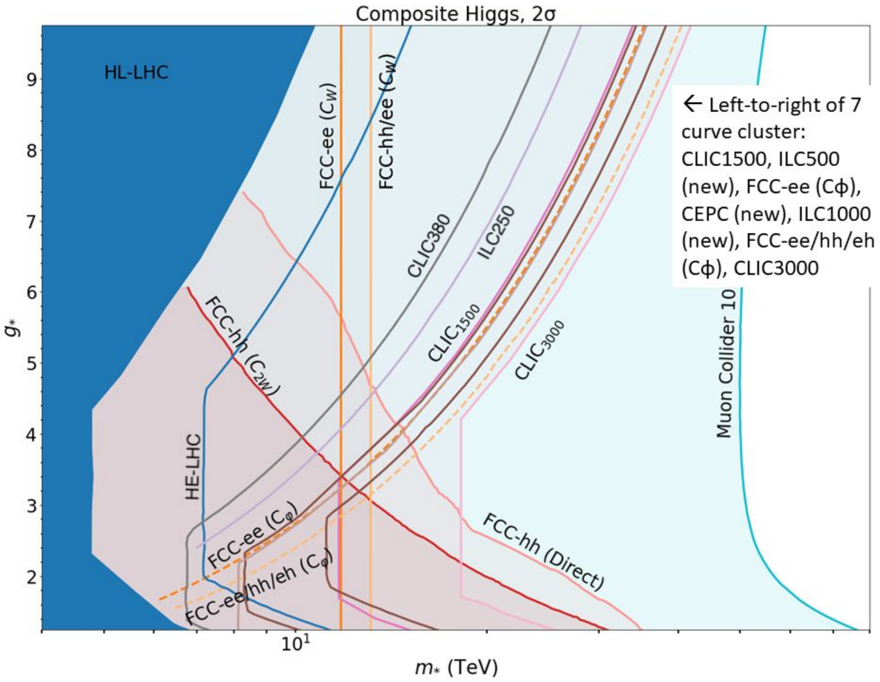
➢ **Focus points for BSM Topical Groups**

Examples of BSM model specific explorations

SUSY models



Composite Higgs models



From Snowmass 21 EF BSM Topical Group Report

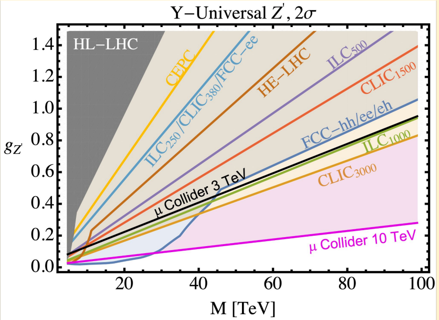
Examples of BSM general explorations

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



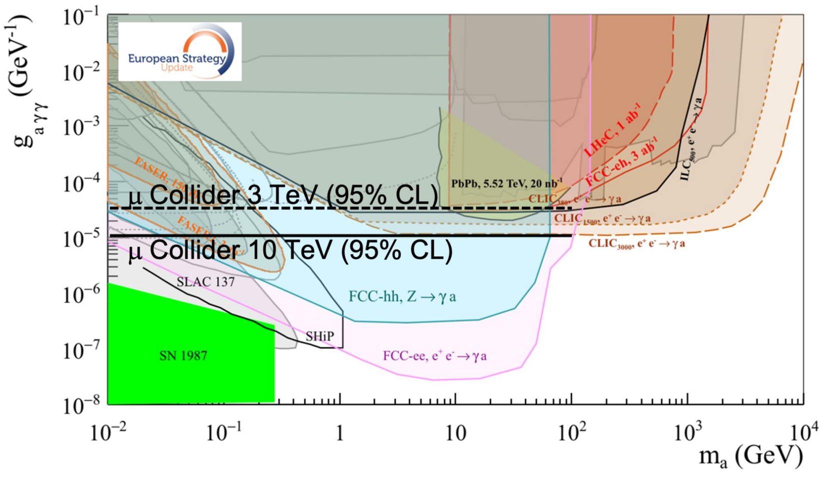
Layout the basic reach of future collider programs **comprehensively** in these simplified modes.

Resonance search and EFT searches are both needed.

arXiv:1910.11775
arXiv:2203.07256

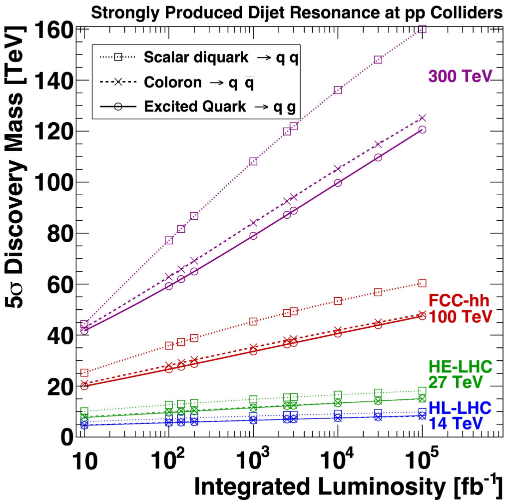
Machine	Type	√s (TeV)	∫L dt (ab^{-1})	Source	Z' Model	5σ (TeV)	95% CL (TeV)
HL-LHC	p p	14	3	R.H.	$Z'_{SSM} \to$ dijet	4.2	5.2
				ATLAS	$Z'_{SSM} \to l^+ l^-$	6.4	6.5
				CMS	$Z'_{SSM} \to l^+ l^-$	--	6.8
				EPPSU*	$Z'_{Univ}(g_Z'=0.2)$	--	6
ILC250/ CLIC380/ FCC-ee	$e^+ e^-$	0.25	2	ILC	$Z'_{SSM} \to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



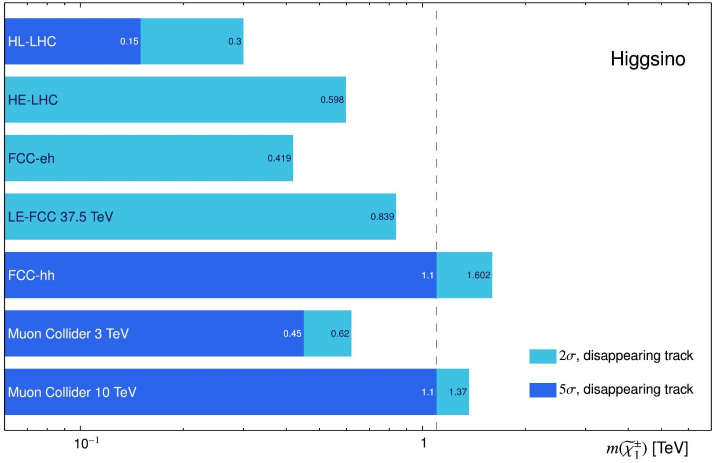
Axion searches

arXiv:1910.11775
arXiv:2203.06520
arXiv:2203.07261

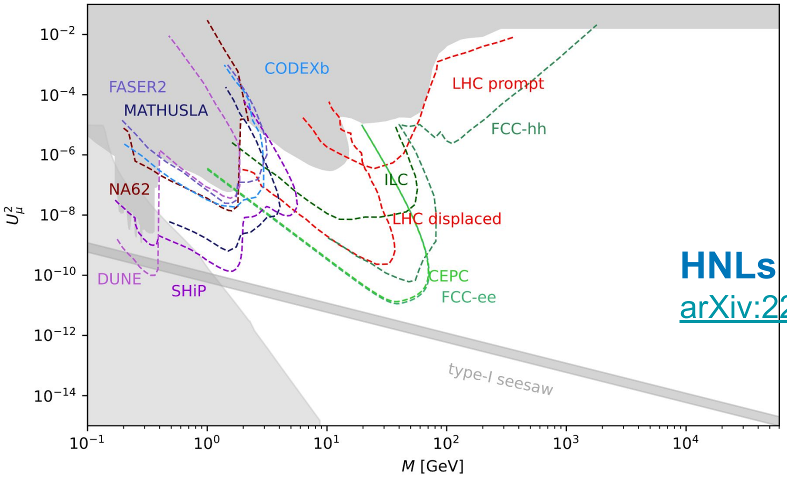


Di-jet resonances

arXiv:2202.03389



LLP, arXiv:2102.11292



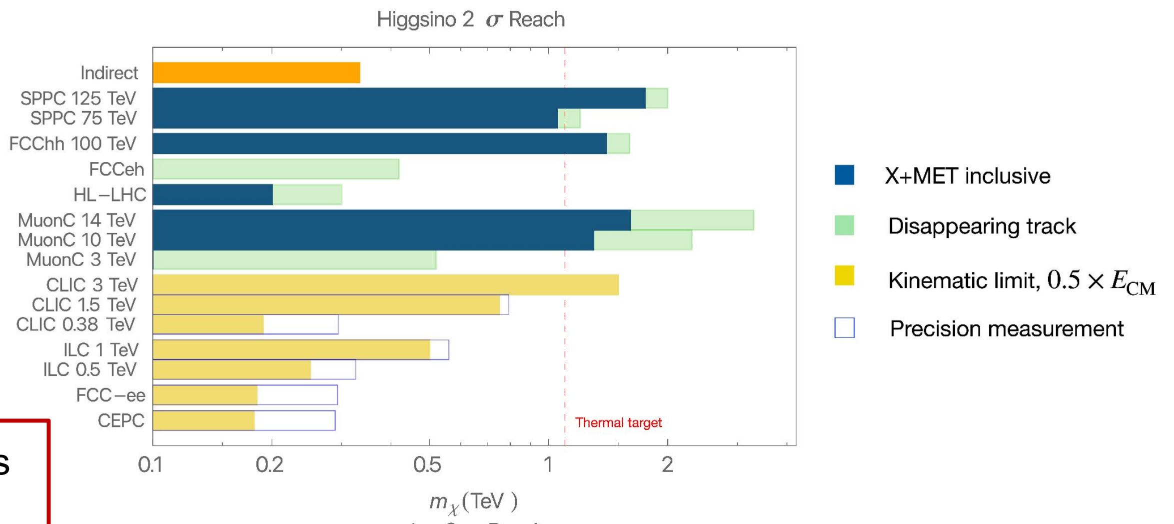
HNLs

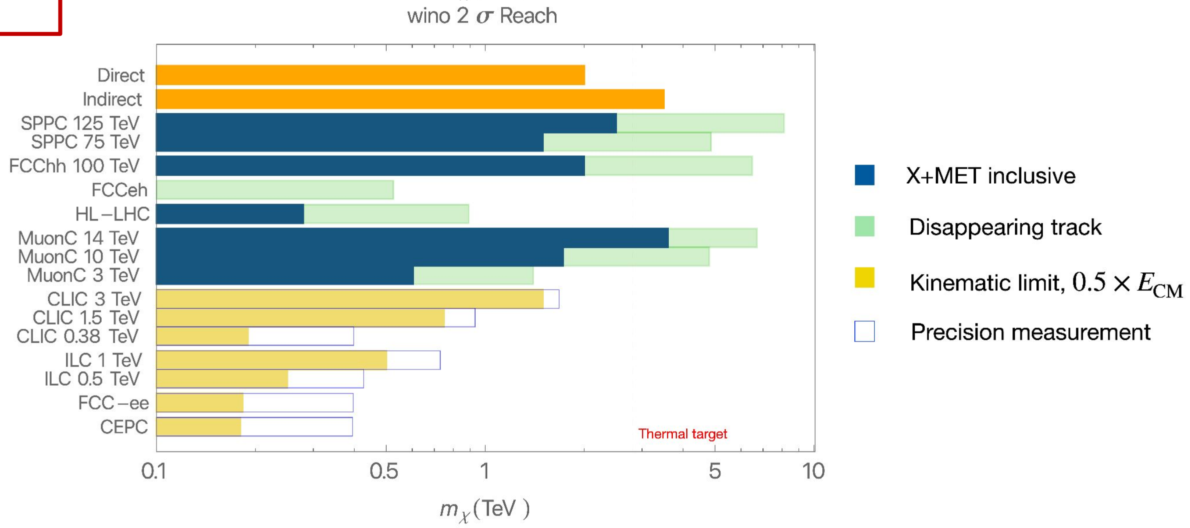
arXiv:2203.05502

Dark matter at colliders

Complementing observation in astrophysics experiments

Probing interaction of DM with SM particles
Discriminating between different models

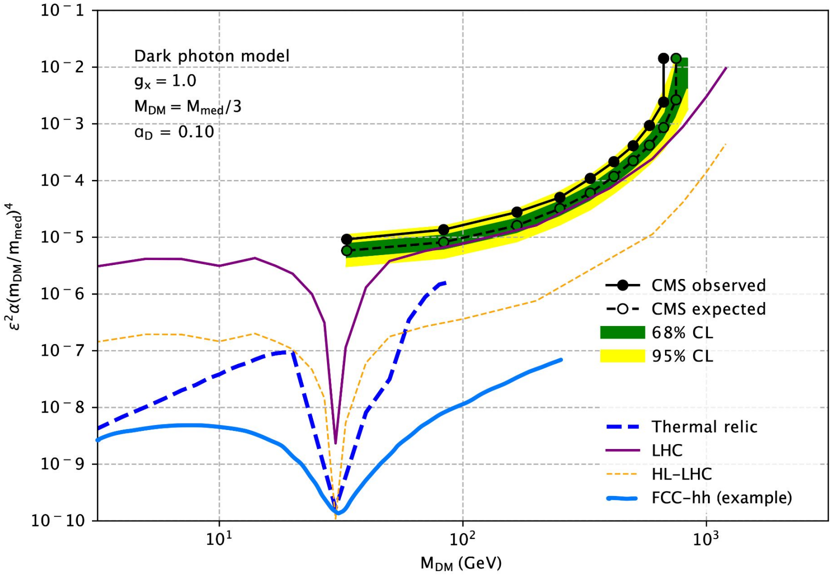


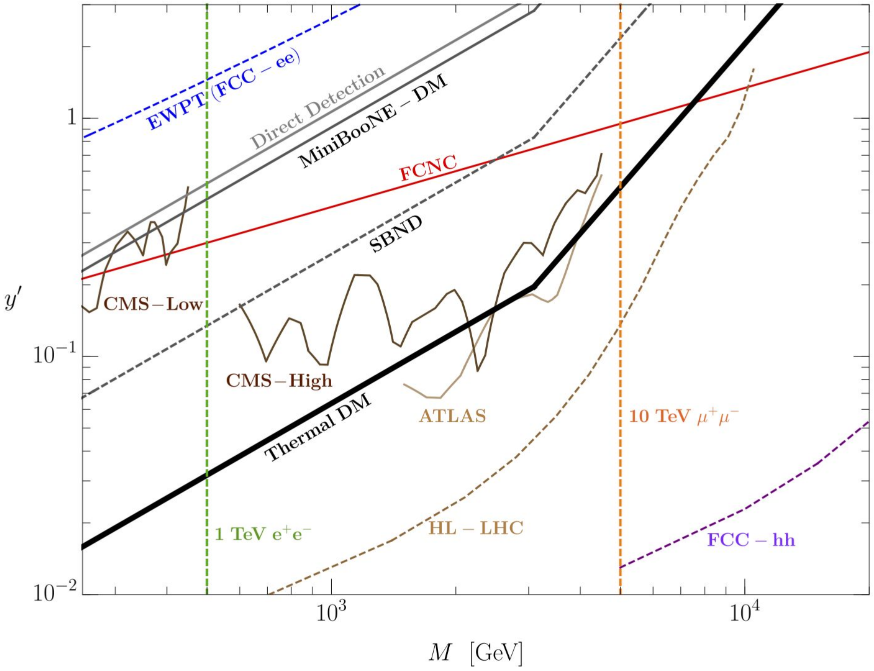


Example of WIMP DM reach
arXiv:1910.11775
(update in progress)

Beyond the WIMP paradigm

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





Reinterpretation of invisible particles searches in terms of dark photon parameters

From EF10 report

Key physics questions of the EF program

What can we learn of the nature of strong interactions in different regimes?

Fundamental (theory + phenomenology):

- What precision in α_S can be reached by each future machine/experiment?
- Define the direction of **future high-precision QCD calculations**
- What is the **evolution of jets as a function of energy** at the EIC and at hadron colliders?
- **Are jets universal?** If not, how do we deal with non-universality in our hadronization models?
- **PDFs coming from lattice calculations** – how to benchmark them using conventional PDFs?

Data and Computing:

- Strengths and weaknesses of existing MC event generators – define what is needed for the future.
- Find a better way to analyze and study **multiple-parton interactions and the underlying event.**
- What can we learn about **non-perturbative physics** using minimum-bias events at the LHC?

➢ **Focus points for QCD Topical Groups**

Future of Perturbative QCD calculations

Les Houches wish-list

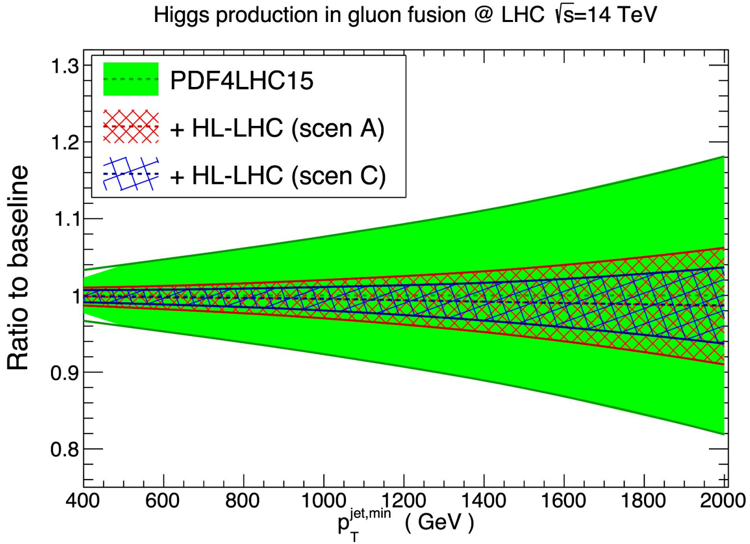
process	known	desired
$pp \to H$	N^3LO_{HTL}, $N^2LO^{(t)}_{QCD}$, $N^{(1,1)}LO^{(HTL)}_{QCD\otimes EW}$	N^4LO_{HTL} (incl.), $N^2LO^{(b,c)}_{QCD}$
$pp \to H + j$	N^2LO_{HTL}, NLO_{QCD}, $N^{(1,1)}LO_{QCD\otimes EW}$	$N^2LO_{HTL} \otimes NLO_{QCD} + NLO_{EW}$
$pp \to H + 2j$	$NLO_{HTL} \otimes LO_{QCD}$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

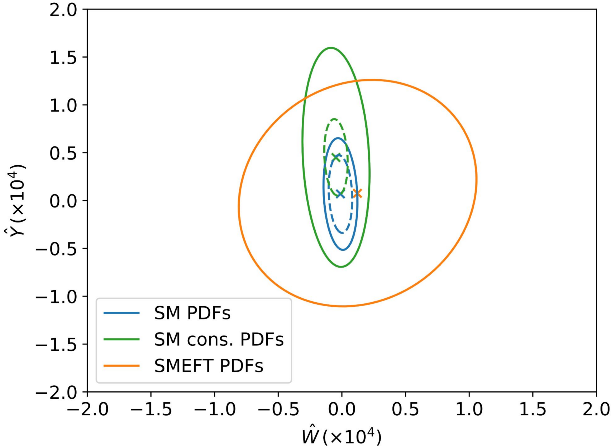
- **α_s uncertainty is a limiting factor in many measurements, e.g. Higgs couplings, at the HL-LHC**

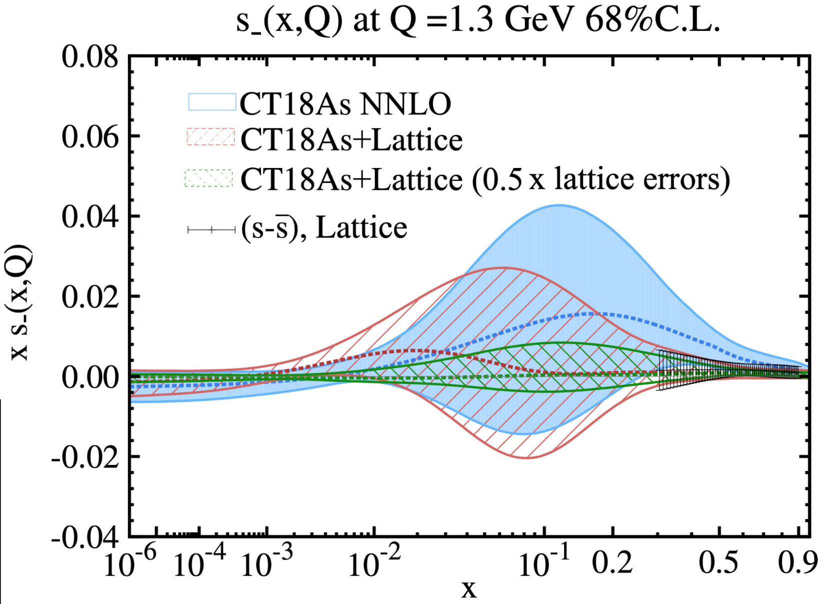
	Relative $\alpha_s(m_Z)$ uncertainty	
Method	Current	Near (long-term) future
(1) Lattice	0.7%	$\approx$ 0.3% (0.1%)
(2) τ decays	1.6%	$<$ 1.%
(3) $Q\overline{Q}$ bound states	3.3%	$\approx$ 1.5%
(4) DIS & PDF fits	1.7%	$\approx$ 1% (0.2%)
(5) e^+e^- jets & evt shapes	2.6%	$\approx$ 1.5% ($<$ 1%)
(6) 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 $g\to tt$ in jets
  - Track functions in jet substructure

Future of PDF determination

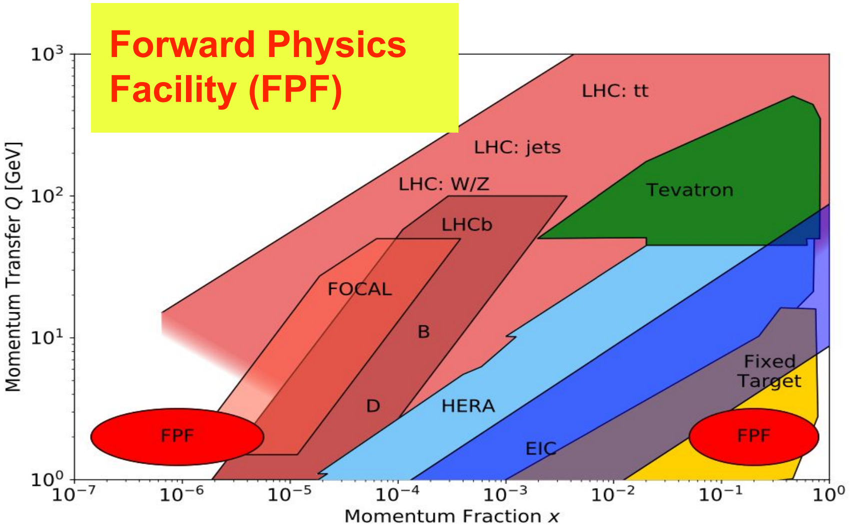


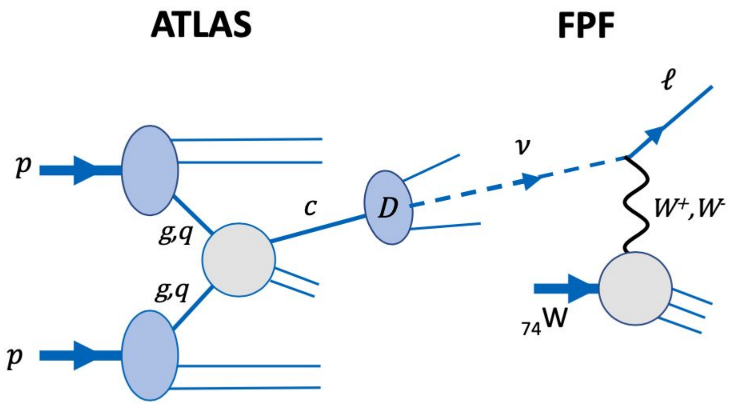




arXiv:2204.07944

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

Snowmass 21 - EF vision

The Energy Frontier vision

- **The discovery of the Higgs boson at the LHC**, of which we are celebrating the 10^{th} anniversary in 2022, has added one crucial piece of the puzzle to the SM.
- It **has completed the SM and** at the same time **provided a unique portal to explore physics beyond the Standard Model** thanks to its intimate connections to the still open big questions of particle physics.
- **Discovery new physics will also involve the unknown and we need to explore it going beyond existing frameworks.**
- **Collider physics allows to explore a uniquely broad range of phenomena** and pursue both indirect and direct validations of BSM physics.
- **The EF envisions a physics program articulated into immediate-future, intermediate-future, and long-term-future colliders.**

EF Vision - The immediate future

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.
- **The physics case is very strong**:
  - It can extend the direct search for new elementary particles
  - It can measure the Higgs-boson couplings to reach sensitivity to BSM physics in the TeV range
  - It can puts bounds on the Higgs-boson self coupling and give first indications on the Higgs potential
  - It can provide the best measurements of top-quark couplings beyond the reach of the first generation of future colliders
- **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.

EF Vision - The intermediate future

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 physics case is compelling** and rest on the ability to
  - Measure the Higgs-boson couplings to sub-percent level and discern the pattern of BSM physics behind possible deviations from SM predictions
  - Search for exotic Higgs decays and explore the Higgs portal to hidden sectors
  - Measure the SM (W,Z,t,H) to very high precision and stress test its consistency
  - Perform precision measurements of QCD as testing ground of QFT in both perturbative and non-perturbative regimes.

- **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 timely implementation is important**. There is **strong US support** for initiatives that could be realized on a time scale relevant for early career physicists.

EF vision - The long-term future

In the long term EF envision a collider that probes the multi-TeV scale, up or above 10 TeV parton center-of-mass energy (FCC-hh, SppC, MuC)

- **The physics case is outstanding** and rest on the potential to:
  - Significantly constrain scenarios motivated by naturalness
  - Produce the fundamental particles that generate the mechanism of EW symmetry breaking
  - Produce particle with flavor-dependent couplings to quarks and leptons
  - Search for dark-matter particles in the strong-coupling region of dark sectors
  - Explore the unknown at the highest possible energy scale
- A 100-TeV proton-proton collider (FCC-hh, SppC) provides an effective energy reach of a 10-TeV muon collider (MuC). A pp-collider has easier access to colored states and compositeness studies, a MuC can take advantage of VV-fusion and benefit from excellent signal to background,
- The main limitation is technology readiness. **A vigorous R&D program** into accelerator and detector technologies **will be crucial.**

EF Colliders: Opportunities for the US

- Our vision for EF can only be realized as **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 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.

↳ **More than 40 contribute papers on MuC studies during Snowmass 21**

↳ **New CCC proposal gained momentum during Snowmass 21**

- **Attractive opportunities** to be considered are:
  - **A US-sited linear e^+e^- collider (ILC/CCC)**
  - **Hosting a 10-TeV range Muon Collider**
  - **Exploring other e^+e^- collider options to fully utilize the Fermilab site**

EF Resources and Timelines

- **Five year period starting in 2025**
  - Prioritize HL-LHC physics program
  - 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 MuC 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 construction of an e+e- Higgs Factory
  - Demonstrate principal risk mitigation and deliver CDR for a first-stage TeV-scale MuC
- **After 2035**
  - Evaluate 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 MuC
  - Ramp up funding support for detector R&D for EF multi-TeV colliders

EF - towards the CSS - UW Seattle

EF community meeting pre-CSS - June 24 2022 (virtual)

- Presenting draft of EF reports (frontier and Topical Groups)
- Presenting EF vision
- Panel Discussion on question proposed by the TGs
- Report from e+e- forum
- Report from m+m- forum

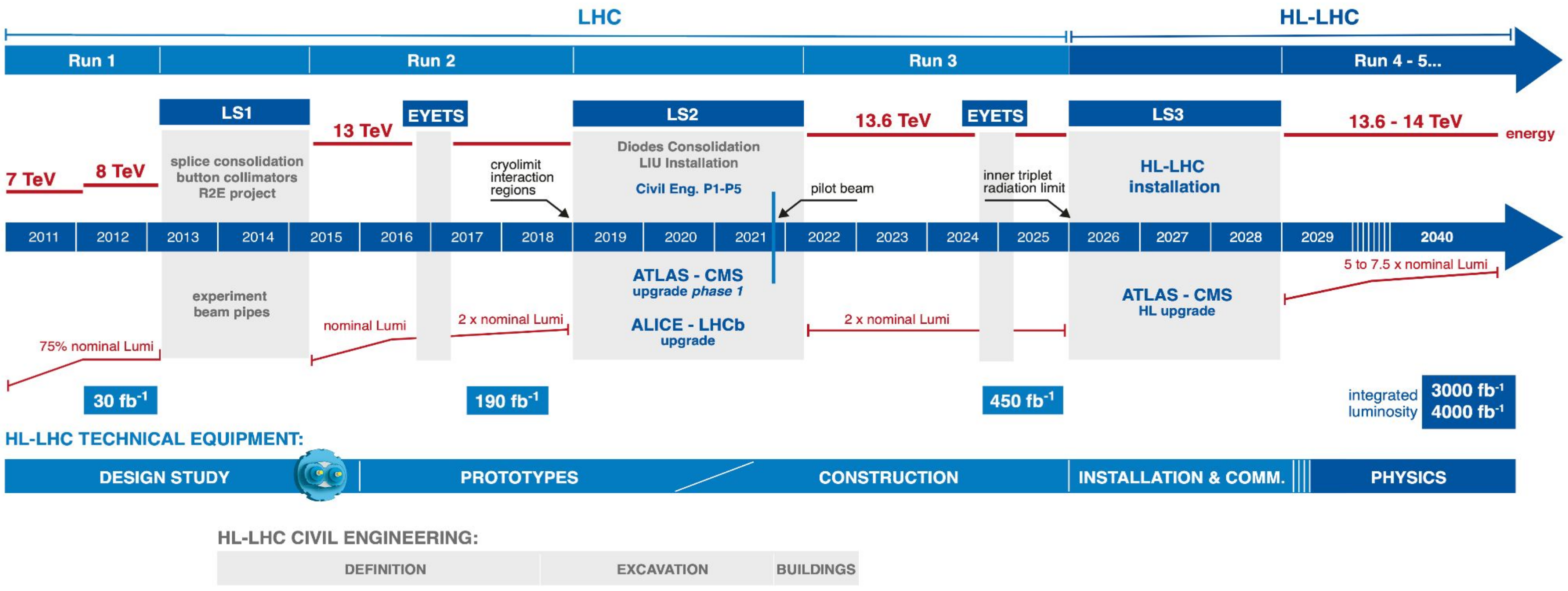
With ample built-in time for discussion.

Give us input on your vision for EF in this document.

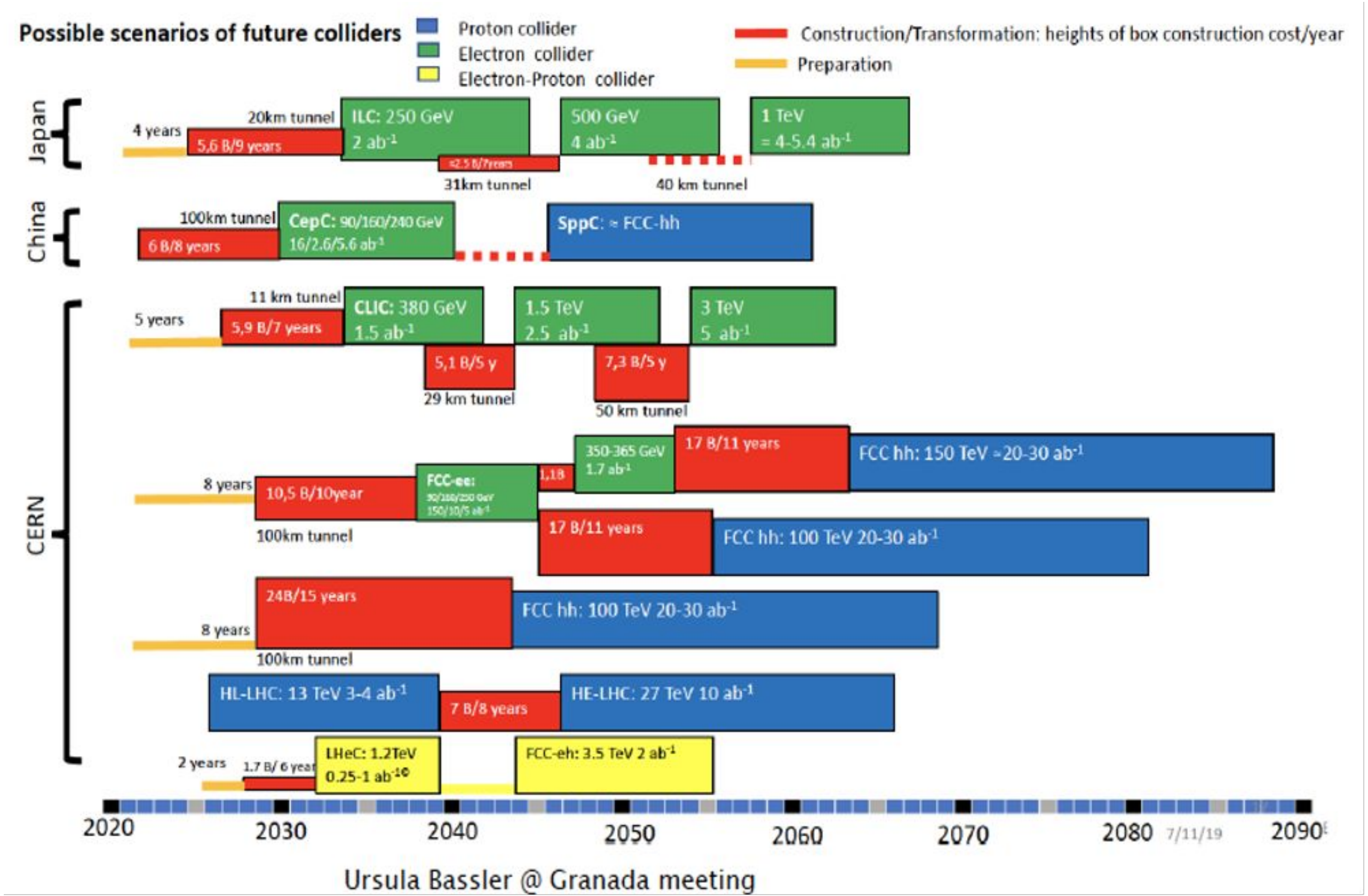
X-Frontier sessions at CSS - crucial to build a common vision

Back-up slides

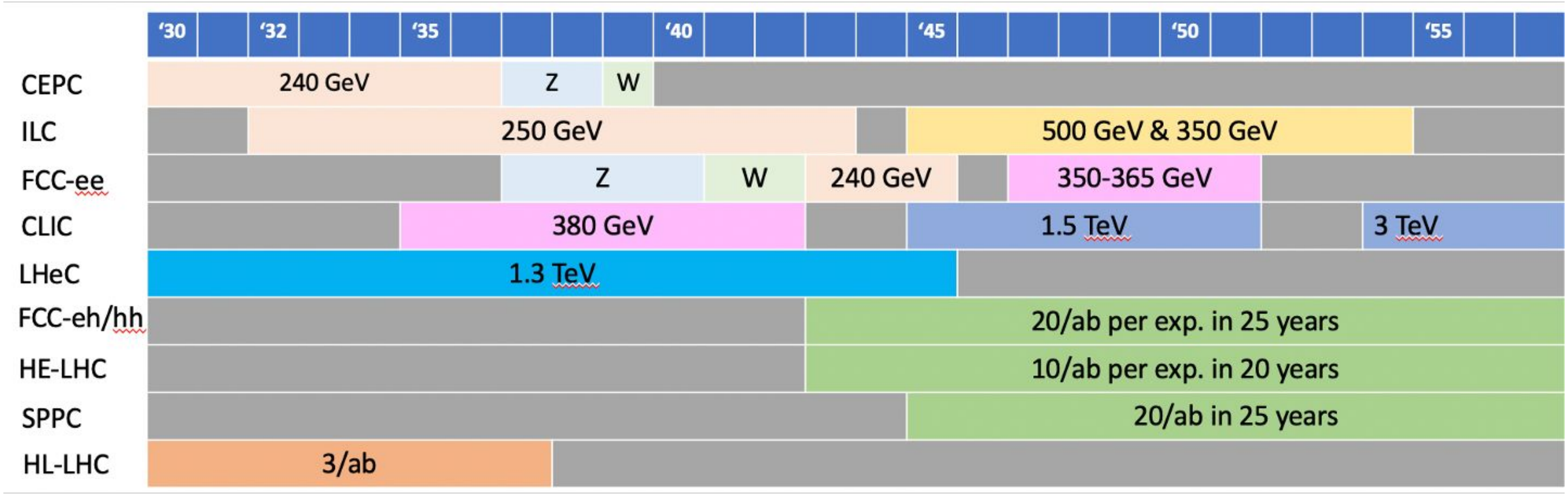
LHC / HL-LHC Plan



ESG: Future Collider Scenarios & Timelines



ESG: Future Collider Scenarios & Timelines



https://arxiv.org/pdf/1905.03764.pdf

ESG: Future Collider Scenarios & Timelines

	T_0				+5					+10					+15					+20			...	+26
ILC	0.5/ab 250 GeV						1.5/ab 250 GeV						1.0/ab 500 GeV				0.2/ab $2m_{top}$	3/ab 500 GeV						
CEPC	5.6/ab 240 GeV							16/ab M_Z		2.6 /ab $2M_W$										SppC =>				
CLIC	1.0/ab 380 GeV										2.5/ab 1.5 TeV									5.0/ab => until +28 3.0 TeV				
FCC	150/ab ee, M_Z				10/ab ee, $2M_W$		5/ab ee, 240 GeV				1.7/ab ee, $2m_{top}$												hh,eh =>	
LHeC	0.06/ab						0.2/ab					0.72/ab												
HE-LHC	10/ab per experiment in 20y																							
FCC eh/hh	20/ab per experiment in 25y																							

https://arxiv.org/pdf/1905.03764.pdf