Compact Colliders Of Tomorrow:
The Cool Copper Collider & The Muon Collider

Precision Electroweak to Discoveries at the Energy Frontier

based on US Snowmass 2021-22 discussions

Report of the Snowmass 2021 e^+e^--Collider Forum

Maria Chamizo Llatas, Sridhara Dasu, Ulrich Heintz,
Emilio Nanni, John Power, Stephen Wagner

Muon Collider Forum Report

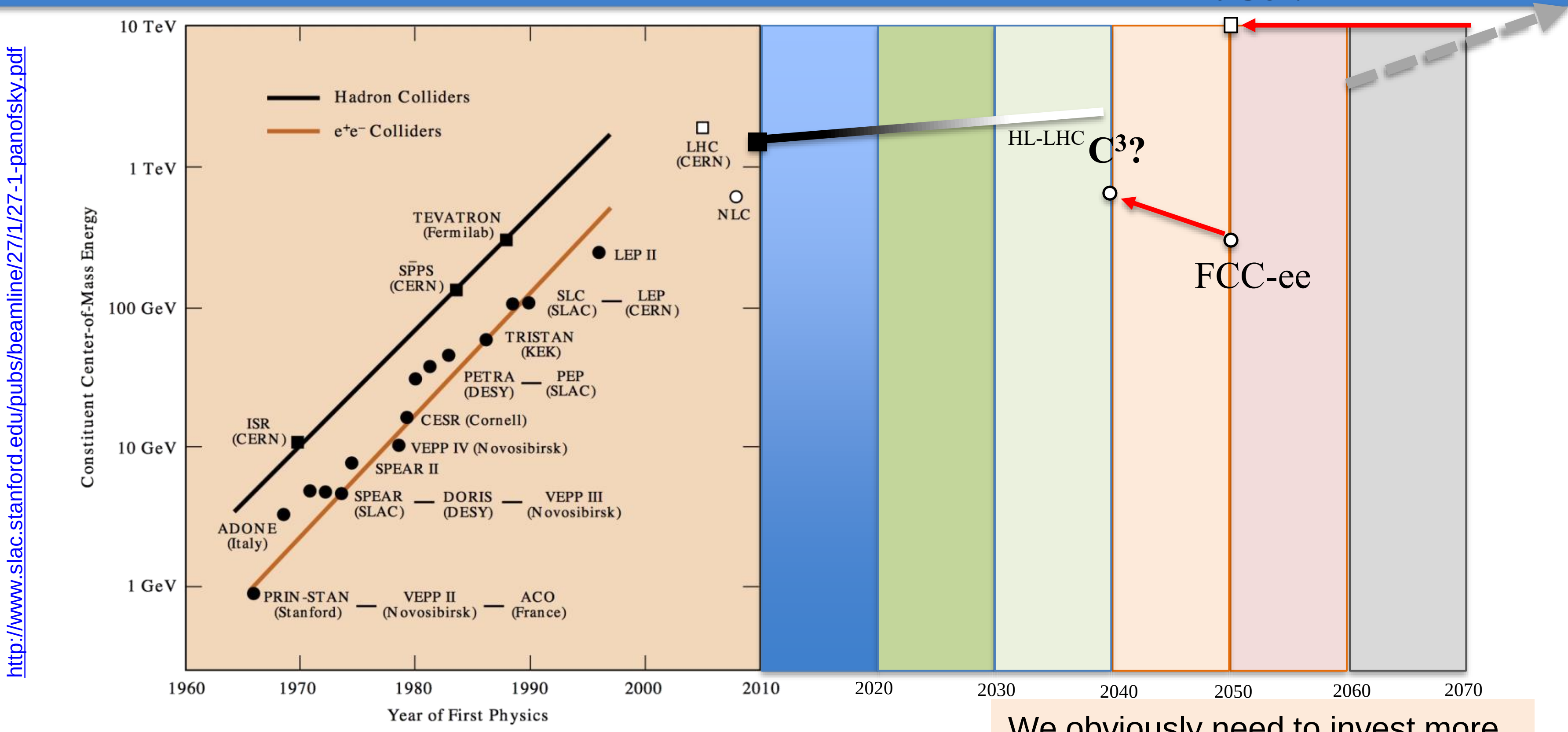
Forum Conveners: K.M. Black[1], S. Jindariani[2], D. Li[3], F. Maltoni[4,5], P. Meade[6], and D. Stratakis[2],

https://www.muoncollider.us/
https://muoncollider.web.cern.ch/

Report of the Snowmass'21
Collider Implementation Task Force

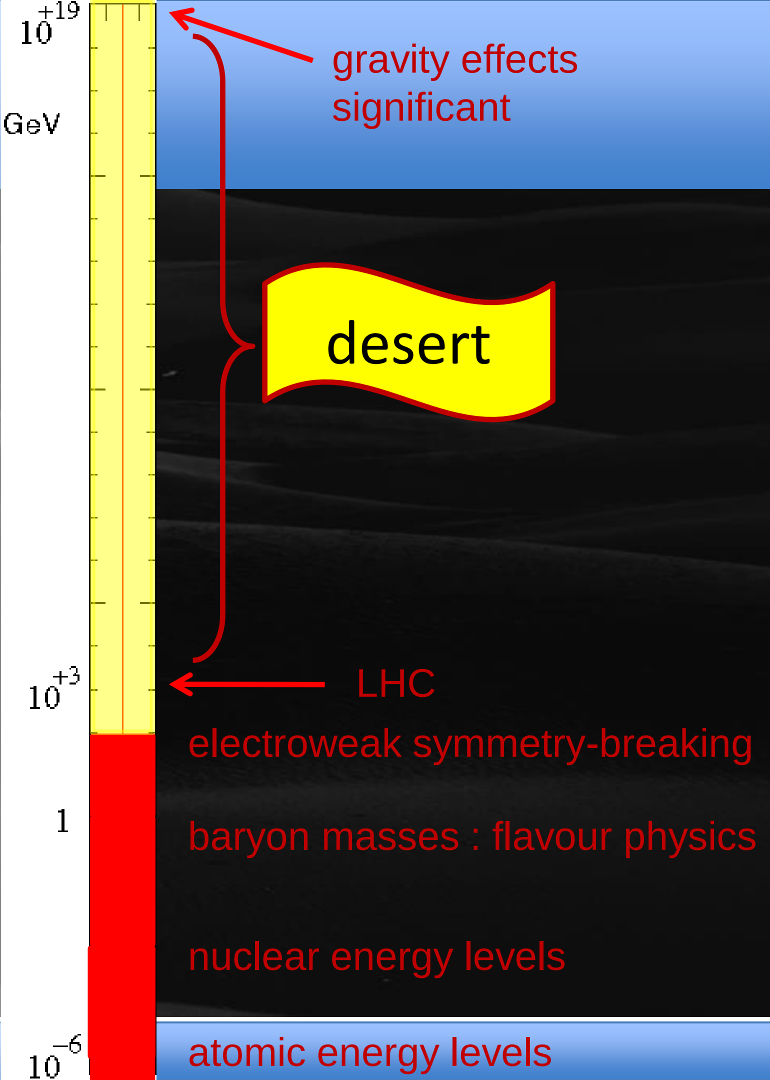
Thomas Roser (chair)[1], Reinhard Brinkmann[2], Sarah Cousineau[3], Dmitri Denisov[1], Spencer Gessner[4], Steve Gourlay[5], Philippe Lebrun[6], Meenakshi Narain[7], Katsunobu Oide[8], Tor Raubenheimer[4], John Seeman[4], Vladimir Shiltsev[9], Jim Strait[9], Marlene Turner[5], and Lian-Tao Wang[10]

Colliders @ the Energy Frontier!



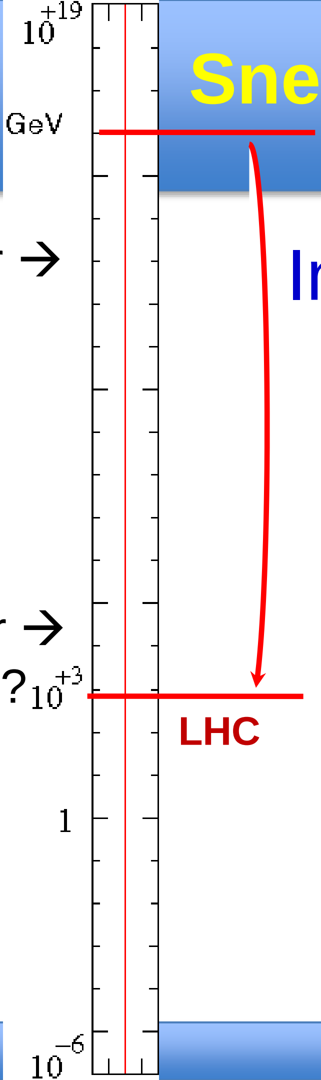
We obviously need to invest more in machine R&D; more people

Energy Scales ...



Adapted from
Sreerup Raychaudhuri, TIFR

Sneak Peek into the Desert



Flavor sector → new physics

Higgs sector → new physics?

In the language of quantum field theory...

$$m \rightarrow m + \delta m(Q^2)$$
$$g \rightarrow g + \delta g(Q^2)$$

...our window into the desert

Newly Discovered Higgs sector → most promising

Physics Case for the Energy Frontier

From $\sqrt{s} = M_Z \rightarrow M_{WW} \rightarrow M_{Z+H} \rightarrow M_{tt} \rightarrow 500\ GeV \rightarrow 550\ GeV \rightarrow 15\ \text{TeV}$

Higgs Factory

Shovel Ready

The Science Drivers

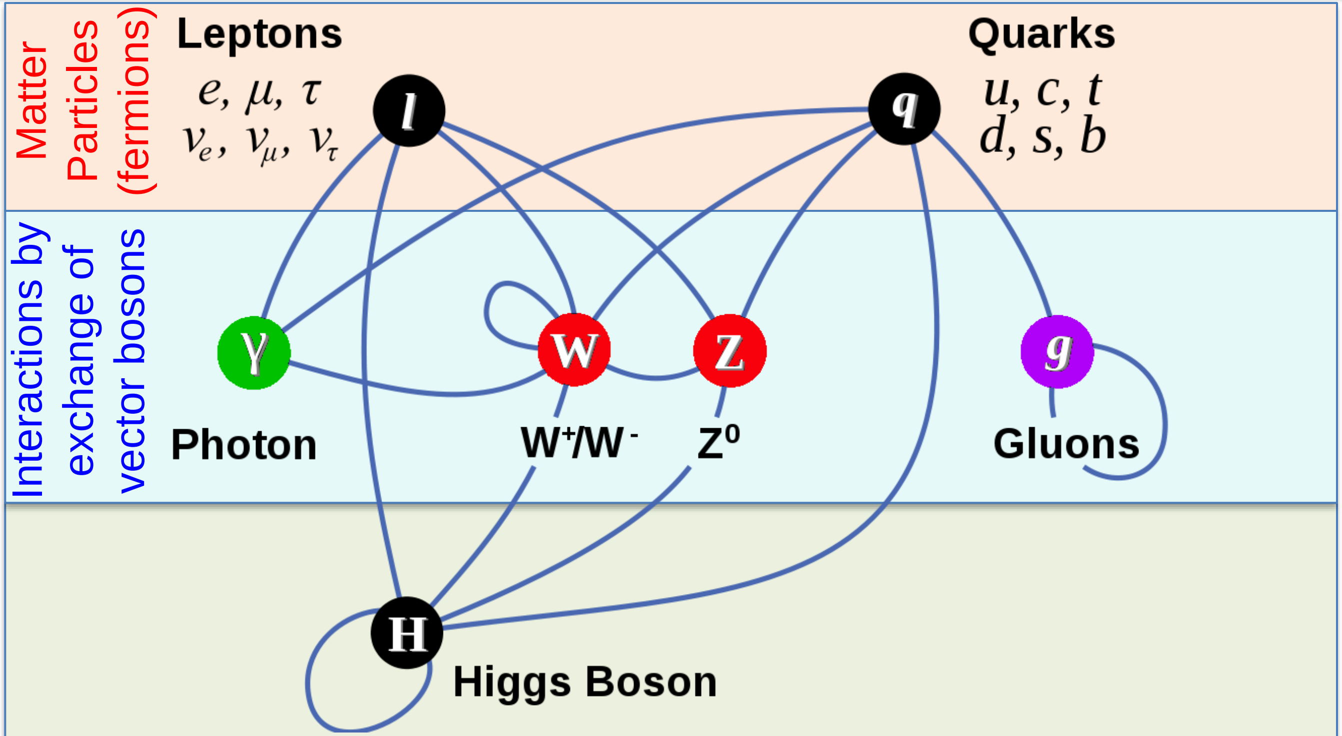
The U.S. community is implementing its vision for the future based on five intertwined science drivers. These compelling lines of inquiry show great promise for discovery.

- *Use the Higgs boson as a new tool for discovery*
- *Pursue the physics associated with neutrino mass*
- *Identify the new physics of dark matter*
- *Understand cosmic acceleration: dark energy and inflation*
- *Explore the unknown: new particles, interactions, and physical principles*

O(10) TeV

Further Research

Particles & Interactions of The Standard Model



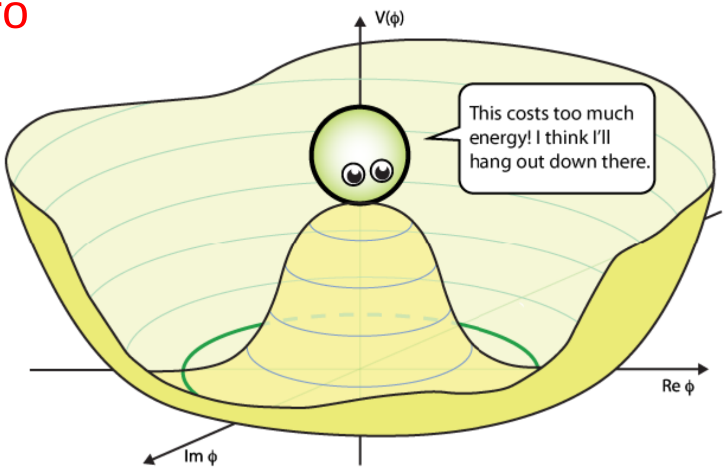
The edifice on which SM is built: The complex scalar doublet, with non-zero VEV, results in masses for W^+/W^- and the Z & massive Higgs. Fermions also get mass interacting with H.

Higgs Field is Special

Electro-Weak Symmetry Breaking

50 years ago, gauge theory unified electro-weak interactions, but could not accommodate non-zero masses for $W^{\pm}$ & Z

Introduction of a doublet of complex scalar fields with **peculiar** potential provided masses for $W^{\pm}$ & Z and left γ massless!



$$\phi = \begin{pmatrix} \phi_1 + i\phi_2 \\ \phi_3 + i\phi_4 \end{pmatrix}$$

The remnant fourth field degree of freedom is the Higgs Boson discovered in 2012

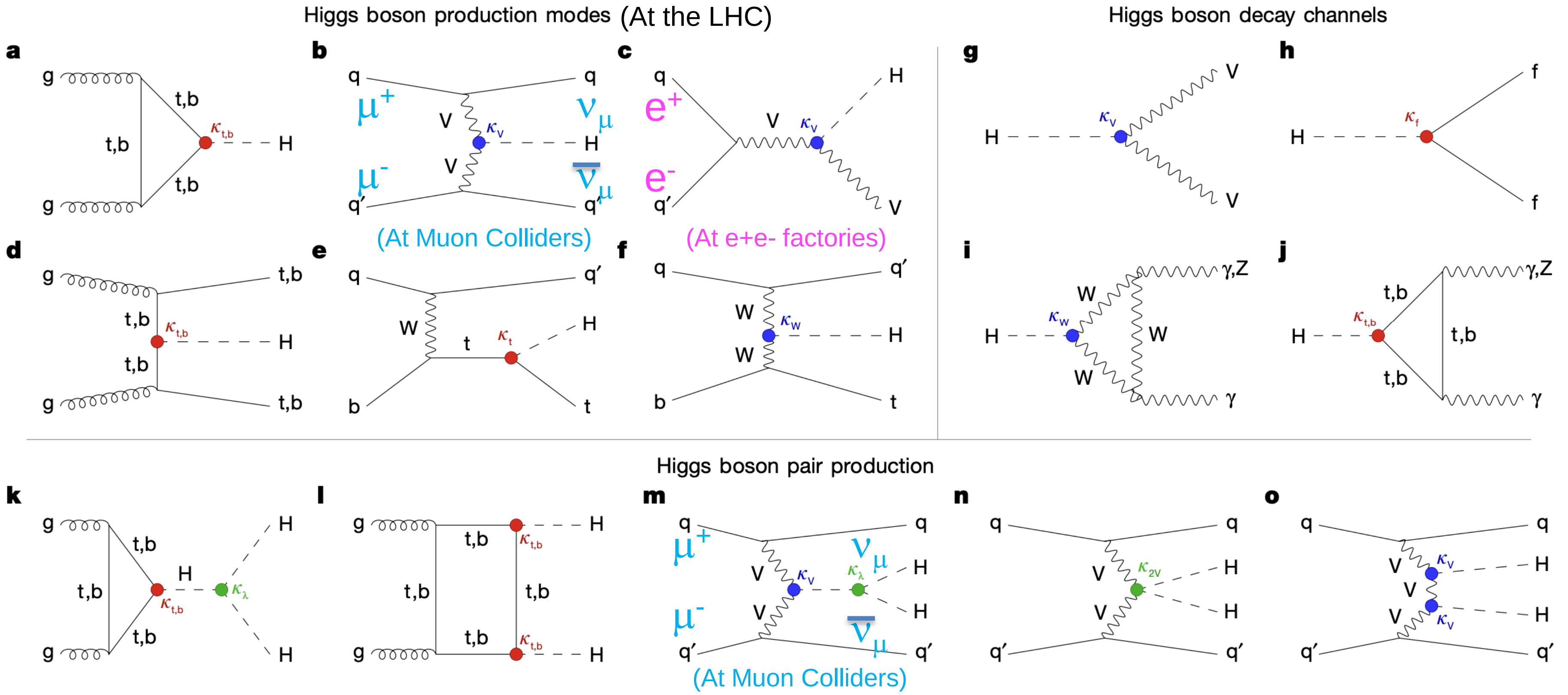
Coupling to Higgs field provides masses to matter particles!!

$$\mathcal{L} = |D_\mu \Phi|^2 - \mu^2\Phi^2 - \lambda\Phi^4$$

For $\mu^2 < 0$, minimum $v = \sqrt{-\frac{\mu^2}{2\lambda}}$

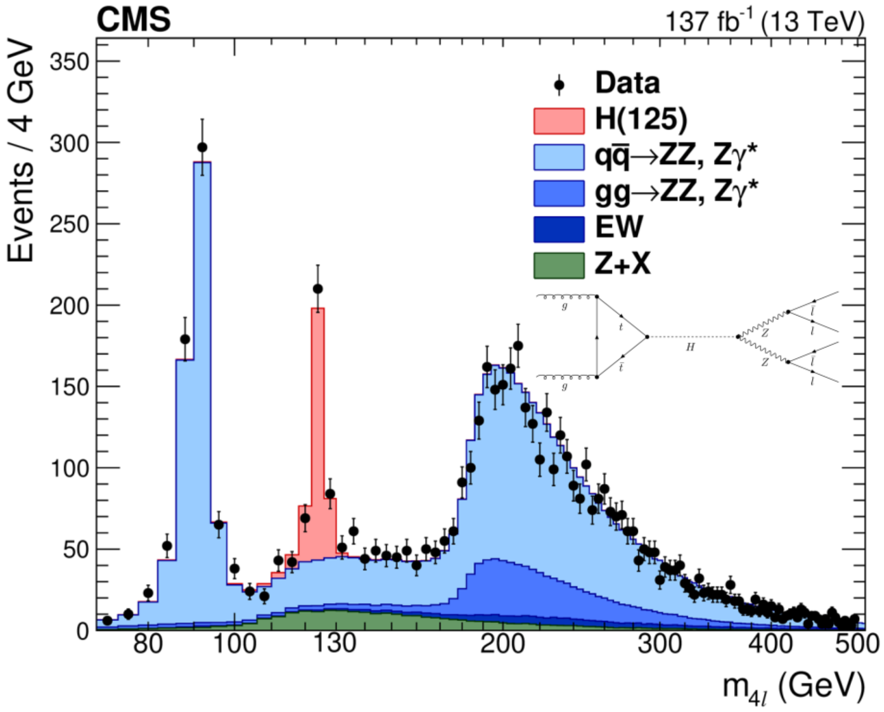
Asserting the form of the potential requires measuring di-higgs production

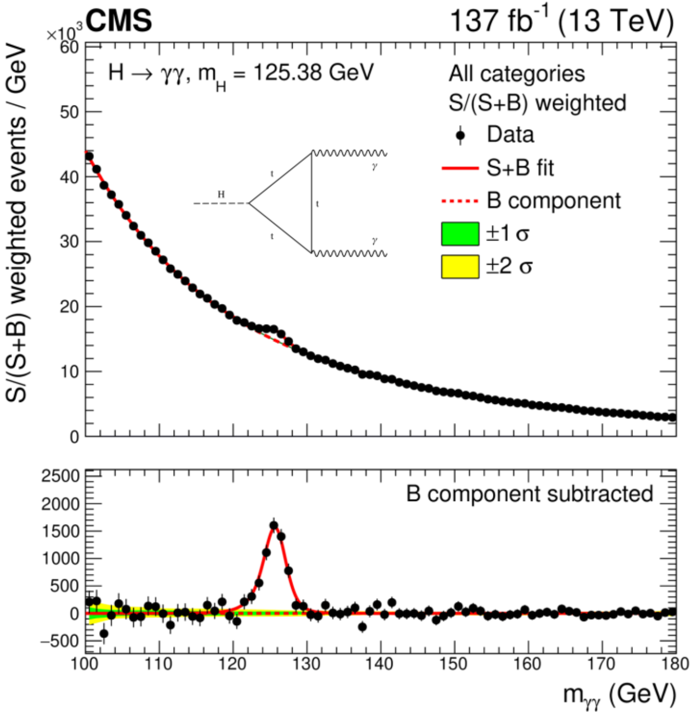
Higgs Boson Couplings, Production and Decays



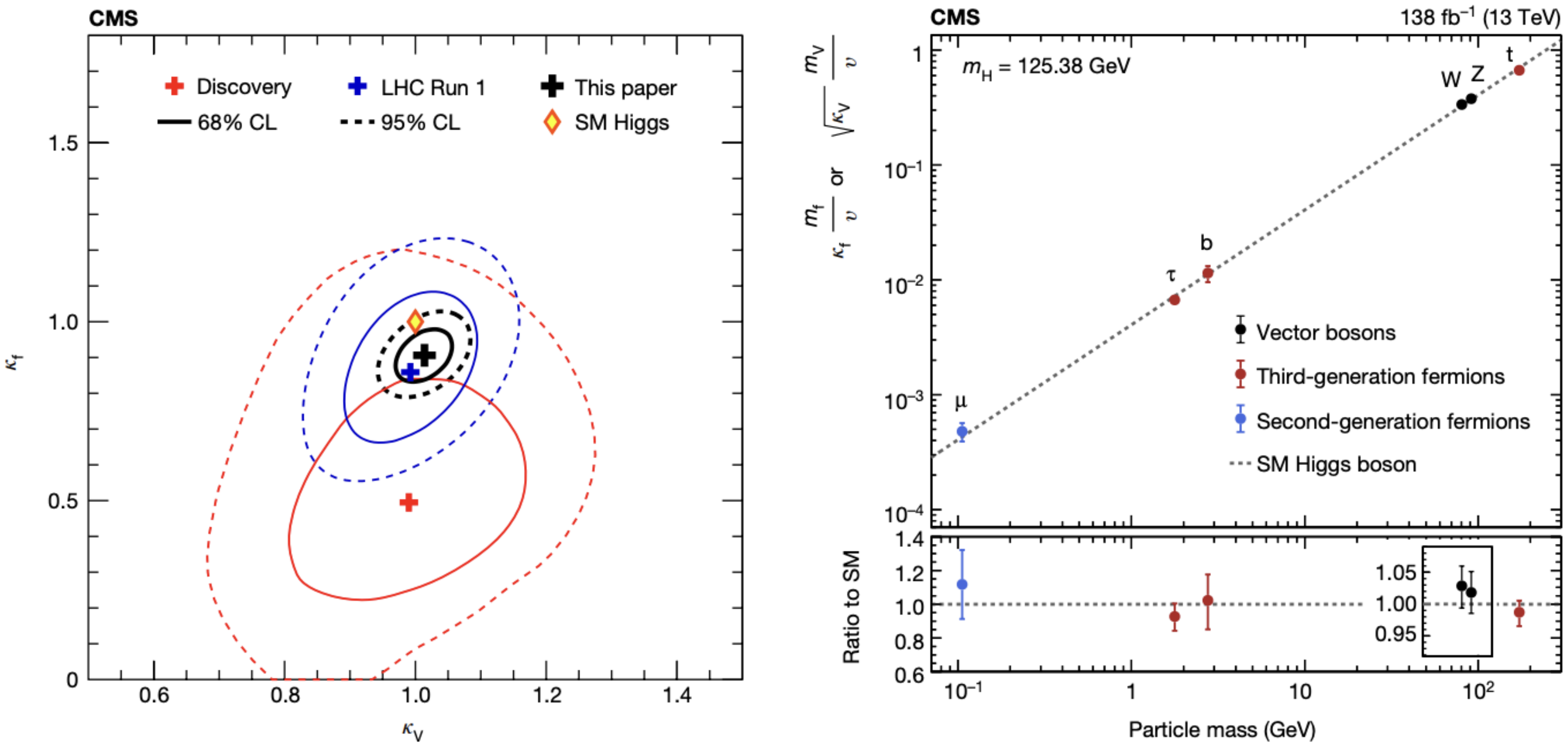
Current Status of Golden Channels @ LHC

Our Higgs boson data sets are enabling detailed studies of the SM





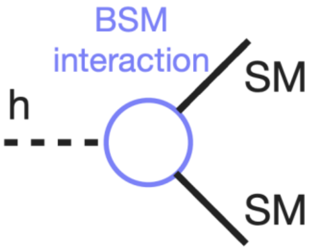
Current Status of Higgs Couplings



Discrepancies at this level if any would imply <1 TeV scale new physics – we did not see either

What's Next?
Sub-percent Level Higgs Couplings → 10 TeV BSM

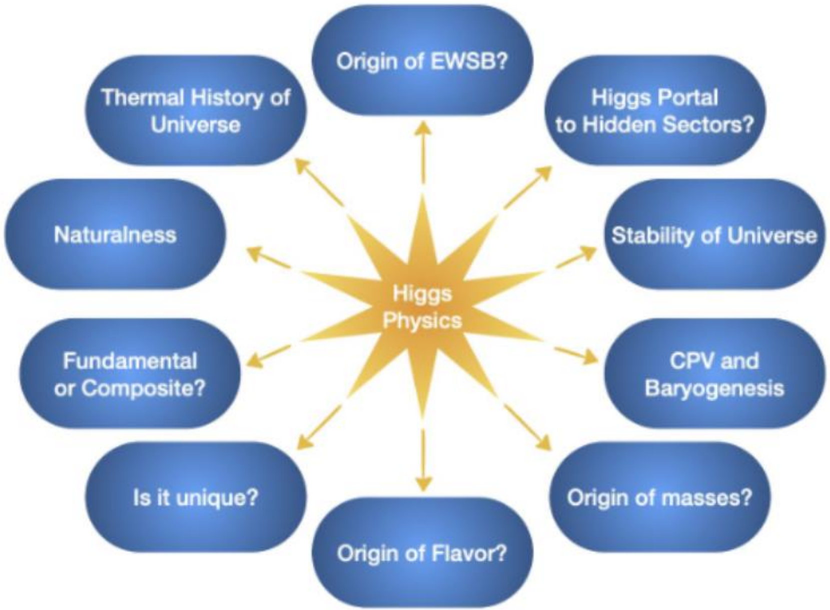
Can we use precision measurements to indirectly probe new physics at higher energies?
Are higgs couplings to SM particles modified?



		HL-LHC few%	Higgs Factory 0.1%
Tree-level	$\sim \frac{v^2}{M^2}$	~1 TeV	~few TeV
Loop-level	$\sim \frac{1}{4\pi^2}\frac{v^2}{M^2}$	~100 GeV	~1 TeV

Couplings Deviations found at C^3 e^+e^- Higgs Factory
→
BSM @ 10 TeV Muon Collider

Higgs Central to Many Fundamental Topics



Percent level Higgs couplings deviations from SM values ➔ BSM physics at 10 TeV

$e^+ e^-$ Higgs Factory ➔ Energy Frontier (10 TeV) Muon Collider

Colliders Of Tomorrow

Many Opportunities at the Energy Frontier

FCC-pp, SPPS	100 km	100 TeV ~ E_{qq} ~15 TeV	500 - 3000 $fb^{-1}sy^{-1}$
FCC-ee, CEPC	100 km	240, 365 GeV	850, 155 $fb^{-1}sy^{-1}$
CLIC-ee	50 km	0.38,1.5, 3 TeV	150, 370, 590 $fb^{-1}sy^{-1}$
ILC-ee	31 km	250, 500 GeV	75, 180 $fb^{-1}sy^{-1}$
C^3-ee	7 km	250, 550 GeV	100, 200 $fb^{-1}sy^{-1}$
HL-LHC	**27 km**	**14 TeV ~ E_{qq}~ 2 TeV**	**200 - 500 $fb^{-1}y^{-1}$**
μCol	~27 km	10, 15 TeV	1000 - 2000 $fb^{-1}sy^{-1}$
μCol	6 km	3, 6, 10 TeV	200, 500 $fb^{-1}sy^{-1}$

snowmass year = 10^7s

Higgs Factories

With 5 y R&D could get physics rolling by 2040 for ~$10B

Proposal Name	CM energy nom. (range) [TeV]	Lum./IP @ nom. CME [10^{34} cm^{-2}s^{-1}]	Years of pre-project R&D	Years to first physics	Construction cost range [2021 B$]	Est. operating electric power [MW]
FCC-ee[1,2]	0.24 (0.09-0.37)	7.7 (28.9)	0-2	13-18	12-18	290
CEPC[1,2]	0.24 (0.09-0.37)	8.3 (16.6)	0-2	13-18	12-18	340
ILC[3] - Higgs factory	0.25 (0.09-1)	2.7	0-2	<12	7-12	140
CLIC[3] - Higgs factory	0.38 (0.09-1)	2.3	0-2	13-18	7-12	110
CCC[3] (Cool Copper Collider)	0.25 (0.25-0.55)	1.3	3-5	13-18	7-12	150
CERC[3] (Circular ERL Collider)	0.24 (0.09-0.6)	78	5-10	19-24	12-30	90
ReLiC[1,3] (Recycling Linear Collider)	0.24 (0.25-1)	165 (330)	5-10	>25	7-18	315
ERLC[3] (ERL linear collider)	0.24 (0.25-0.5)	90	5-10	>25	12-18	250
XCC (FEL-based $\gamma\gamma$ collider)	0.125 (0.125-0.14)	0.1	5-10	19-24	4-7	90
Muon Collider Higgs Factory[3]	0.13	0.01	>10	19-24	4-7	200

Energy Frontier Machines

With 10 y R&D could get physics rolling by 2050 for ~$18B

Proposal Name	CM energy nom. (range) [TeV]	Lum./IP @ nom. CME [10^{34} cm^{-2}s^{-1}]	Years of pre-project R&D	Years to first physics	Construction cost range [2021 B$]	Est. operating electric power [MW]
Muon Collider	10 (1.5-14)	20 (40)	>10	>25	12-18	~300
LWFA - LC (Laser-driven)	15 (1-15)	50	>10	>25	18-80	~1030
PWFA - LC (Beam-driven)	15 (1-15)	50	>10	>25	18-50	~620
Structure WFA (Beam-driven)	15 (1-15)	50	>10	>25	18-50	~450
FCC-hh	100	30 (60)	>10	>25	30-50	~560
SPPS	125 (75-125)	13 (26)	>10	>25	30-80	~400

Higgs Factory Physics Timeline vis-à-vis Integrated Luminosity

Caveat – run plans are adjustable; start of physics times are different

- Technically feasible times: ILC < 12y, FCC-ee, CLIC, CEPC, C3 : 13-18y
  - ILC “shovel ready” + C3 Short R&D –potential for earliest start
  - FCC-ee, CLIC – post HL-LHC
- Circular colliders have shorter runs, higher luminosity
- Linear collider runs have access to polarization and higher energy
- Both provide good precision on Higgs Couplings & EWK

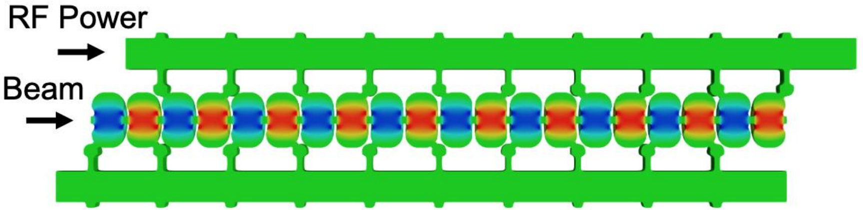
time	T0	T+5	T+10	T+15	T+20	T+25	T+30
FCC-ee	150/ab Mz	10/ab 2Mw; 5/ab 240 GeV	1.7/ab 2mtop	mH			
CEPC	100/ab Mz; 6/ab 2Mw; 10/ab 240GeV		1/ab-1 2mtop				
ILC (and C3)	2/ab 240 GeV		0.1/ab MZ; 0.1/ab 2mtop	4/ab 500 GeV		8/ab 1 TeV	
CLIC	1.1/ab 380 GeV		3.5/ab 1.5 TeV		5.6/ab 3 TeV		

C3 – Cool Copper Collider – New Option

Breakthrough in the Performance of RF Accelerators

SLAC

- RF power coupled to each cell – no on-axis coupling
- Full system design requires modern virtual prototyping

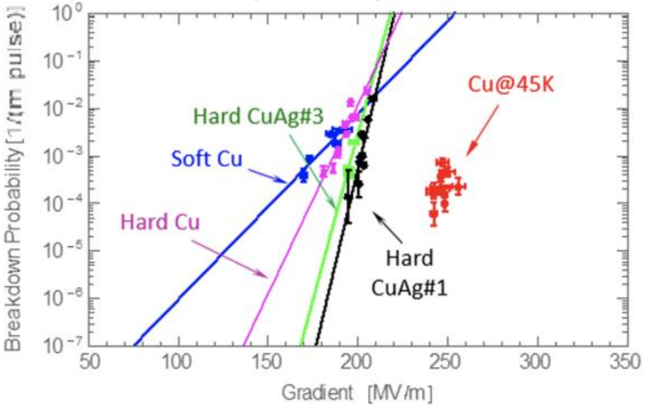


Electric field magnitude produced when RF manifold feeds alternating cells equally

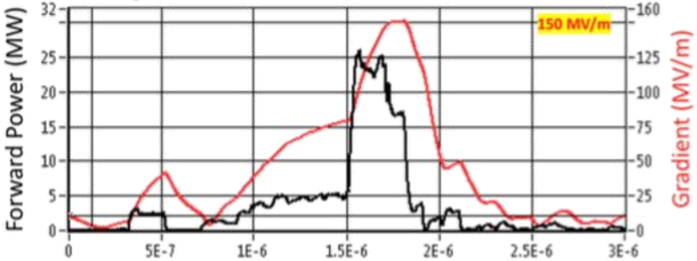
First C^3 structure at SLAC

Cryogenic operation improves performance

[Cahill et al, PRAB 21.10 (2018): 102002](#)



High Gradient Operation at 150 MV/m



[Bane et al, arXiv 1807.10195](#)

X-band Prototype

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Synergies With X-Ray Photon Sources

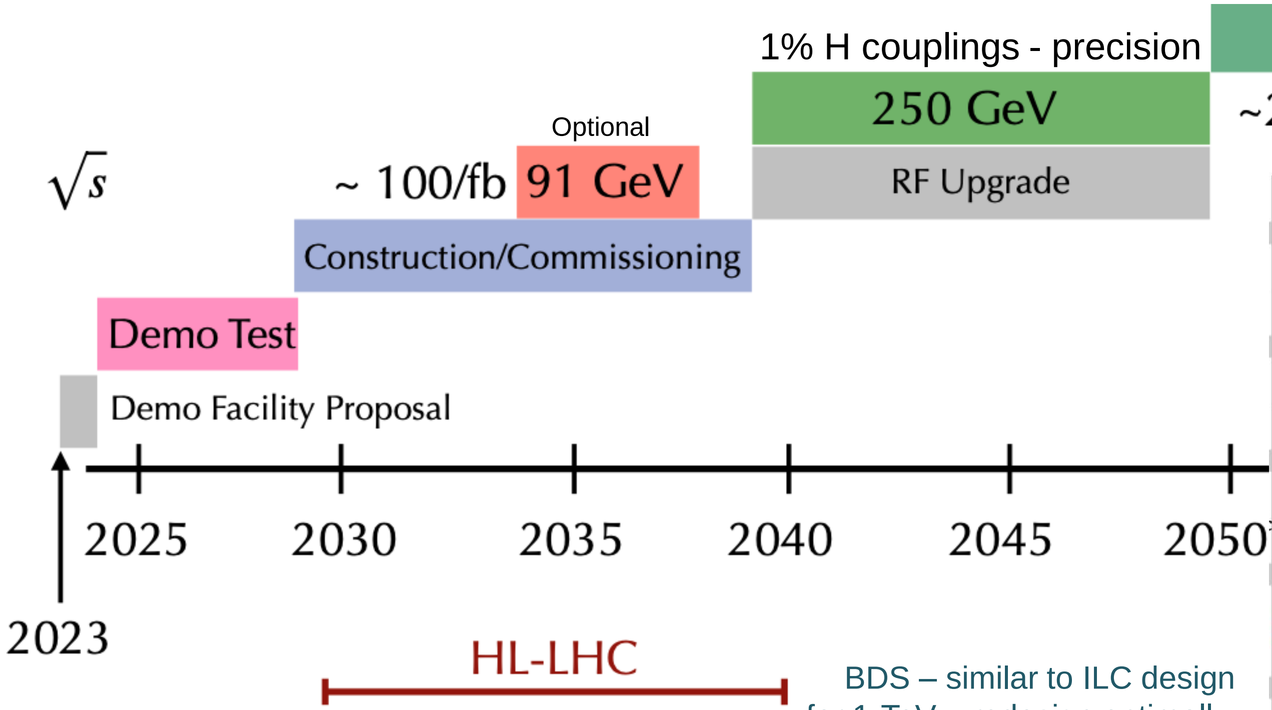
The vast majority of ~30,000 currently operating accelerators globally are electron accelerators.

Electron accelerator R&D ranges from industrial applications to the cutting-edge development of ultimate storage rings and linear accelerator based XFELs.

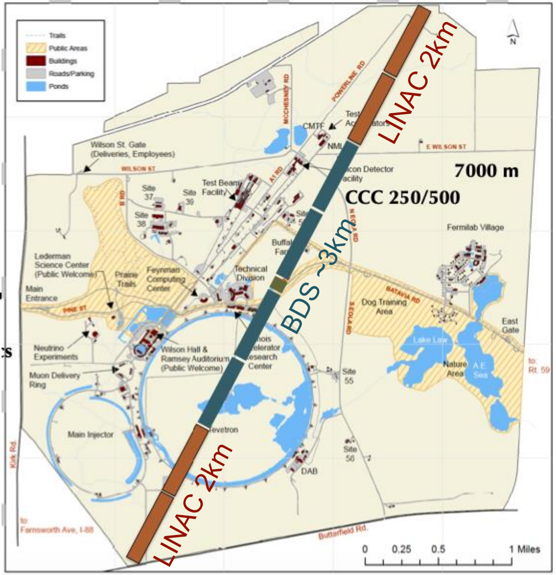
This fortunate situation allows e^+e^- colliders to leverage these global efforts to provide a viable path to a collider reducing the R&D costs to the HEP budget.

Possibly an interesting option for the African Light Source based on Inverse Compton

C³ – $\sqrt{s} = 250 - 550$ GeV – Potential Coordinates



BDS – similar to ILC design for 1-TeV – redesign optimally.



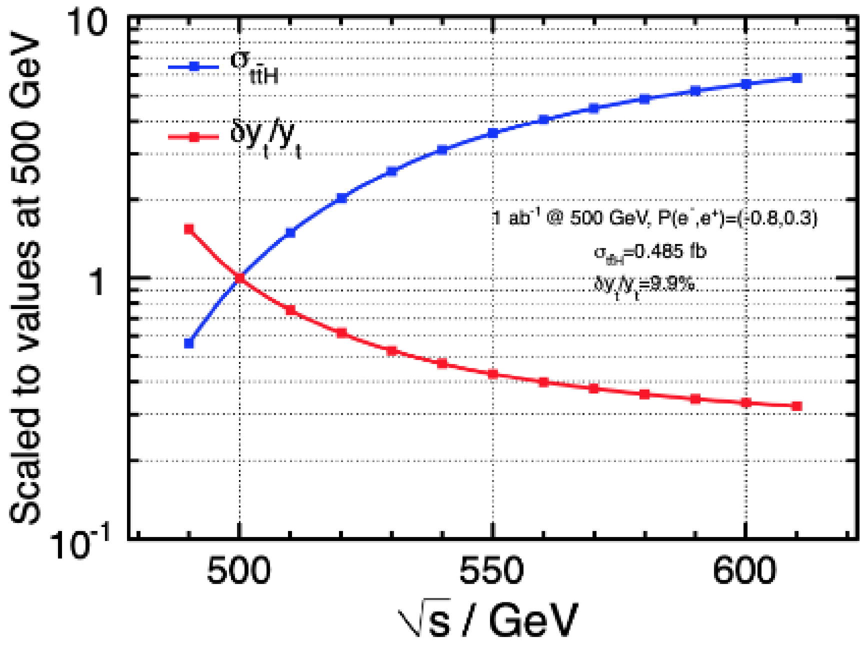
Can fit in FNAL site with BDS improvements

Higgs Couplings from Factories

Higgs Coupling (%)	HL-LHC	ILC250 + HL-LHC	ILC500 +HL-LHC	ILC1000 + HL-LHC	FCC-ee + HL-LHC	CEPC240 + HL-LHC	CEPC360 +HL-LHC	CLIC380 + HL-LHC	CLIC3000 +HL-LHC
hZZ	1.5	.22	.17	.16	.17	.074	.072	.34	.22
hWW	1.7	.98	.20	.13	.41	.73	.41	.62	1
$hb\bar{b}$	3.7	1.06	.50	.41	.64	.73	.44	.98	.36
$h\tau^+\tau^-$	3.4	1.03	.58	.48	.66	.77	.49	1.26	.74
$hgg.$	2.5	1.32	.82	.59	.89	.86	.61	1.36	.78
$hc\bar{c}$	-	1.95	1.22	.87	1.3	1.3	1.1	3.95	1.37
$h\gamma\gamma$	1.8	1.36	1.22	1.07	1.3	1.68	1.5	1.37	1.13
$h\gamma Z$	9.8	10.2	10.2	10.2	10	4.28	4.17	10.26	5.67
$h\mu^+\mu^-$	4.3	4.14	3.9	3.53	3.9	3.3	3.2	4.36	3.47
$ht\bar{t}$	3.4	3.12	2.82	1.4	3.1	3.1	3.1	3.14	2.01
Γ_{tot}	5.3	1.8	.63	.45	1.1	1.65	1.1	1.44	.41

Top-Yukawa and Higgs Self-Coupling

Advantages of Energy Reach



Double Higgs production

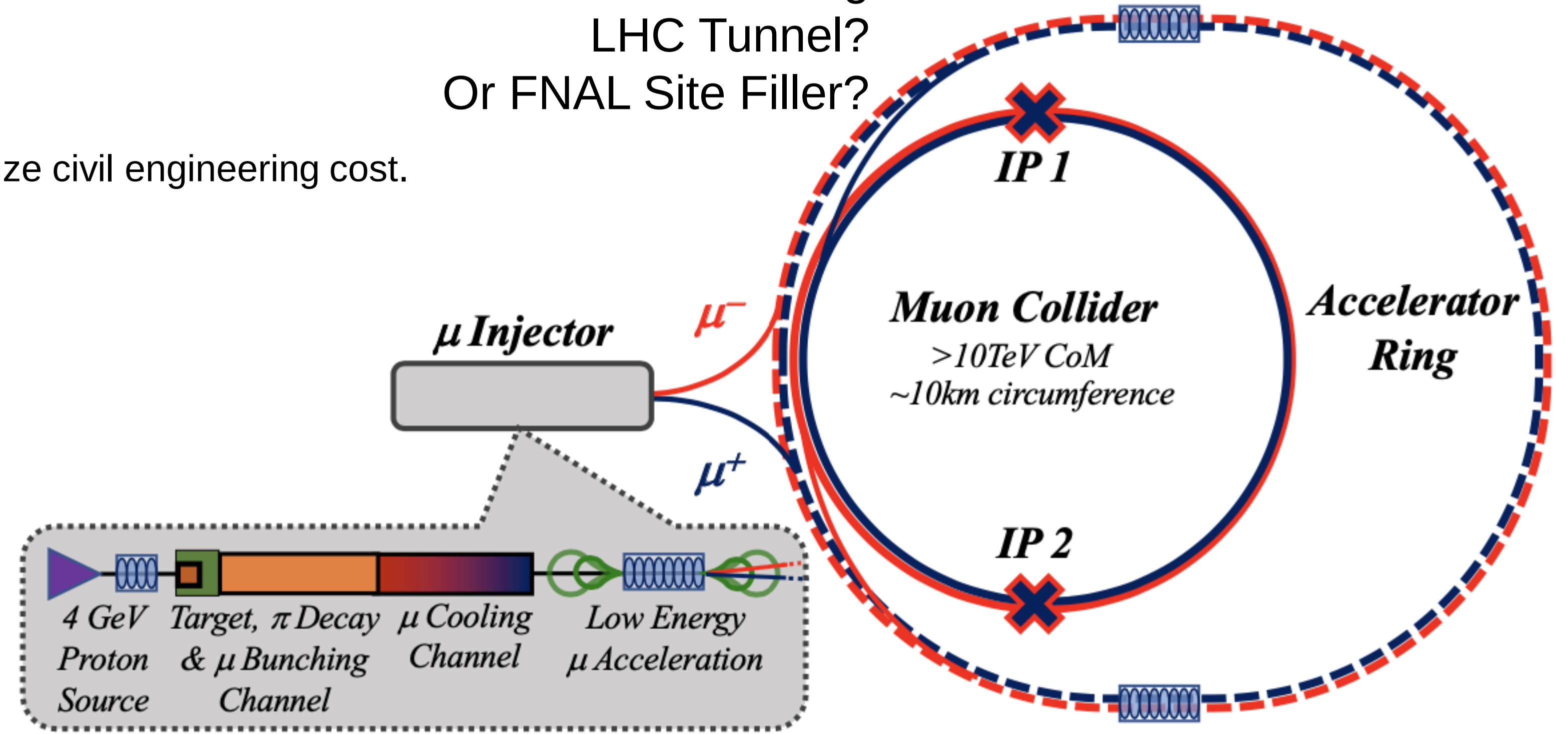
E_{CM} (TeV)	Precision of λ_{HHH}
HL-LHC	50%
ILC 0.5, C3 0.55	20%
CLIC 1.5	36%
CLIC 3	9%
μC10, FCC-hh	4%

Oh! Lord of Rings!!
Can’t we get to 10 TeV in one swoop?

Innovative Muon Collider Concepts
Energy Efficient Path to O(10)-TeV Colliders

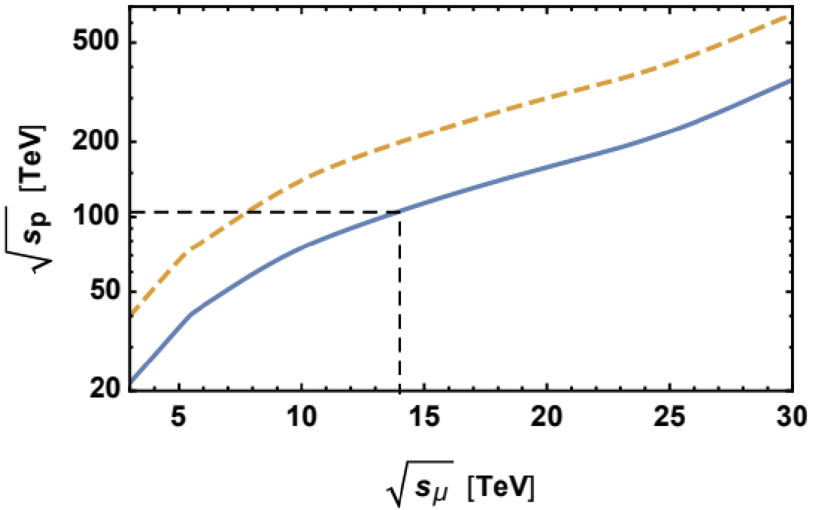
Accelerator Ring
LHC Tunnel?
Or FNAL Site Filler?

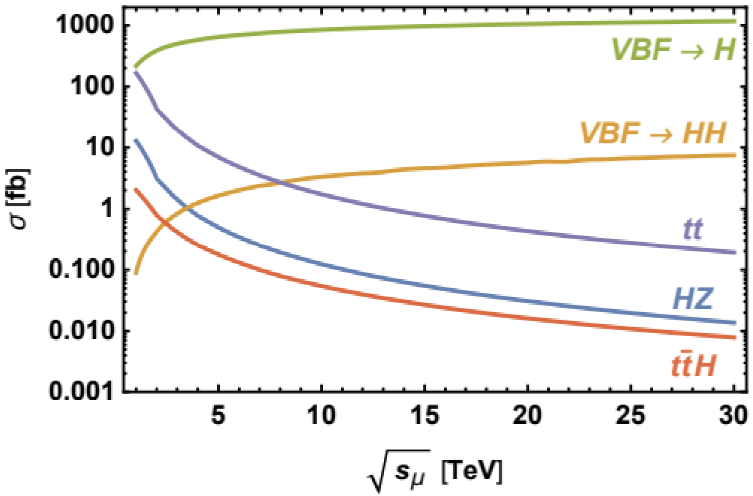
Minimize civil engineering cost.



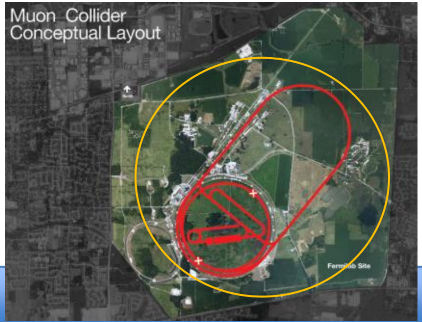
Muon Collider Advantages

arxiv:1901.06150

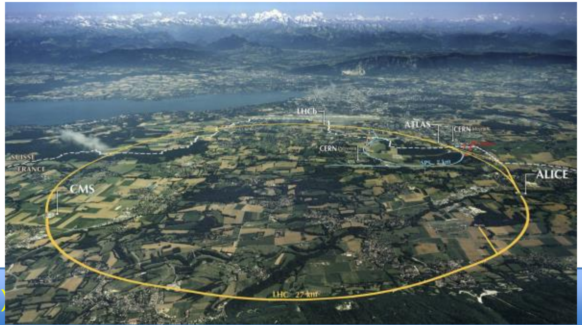




6-10 TeV machine can fit on Fermilab site



15 TeV machine can fit in LHC/CERN tunnel



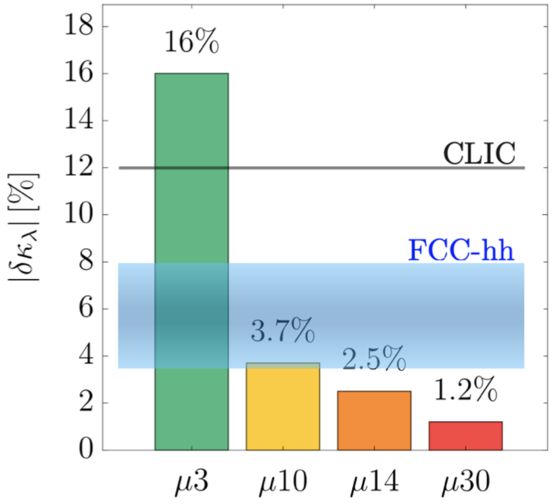
Precision physics

Higgs coupling sensitivities k-framework

	HL-LHC	HL-LHC +10 TeV	HL-LHC +10 TeV + ee
κ_W	1.7	0.1	0.1
κ_Z	1.5	0.4	0.1
κ_g	2.3	0.7	0.6
κ_γ	1.9	0.8	0.8
κ_c	-	2.3	1.1
κ_b	3.6	0.4	0.4
κ_μ	4.6	3.4	3.2
κ_τ	1.9	0.6	0.4
$\kappa_{Z\gamma}^*$	10	10	10
κ_t^*	3.3	3.1	3.1

* No input used for μ collider

1σ sensitivities (in %) from a 10-parameter fit in the k-framework at a 10 TeV muon collider with 10 ab^{-1} , compared with HL-LHC. The effect of measurements from a 250 GeV e^+e^- Higgs factory is also reported.

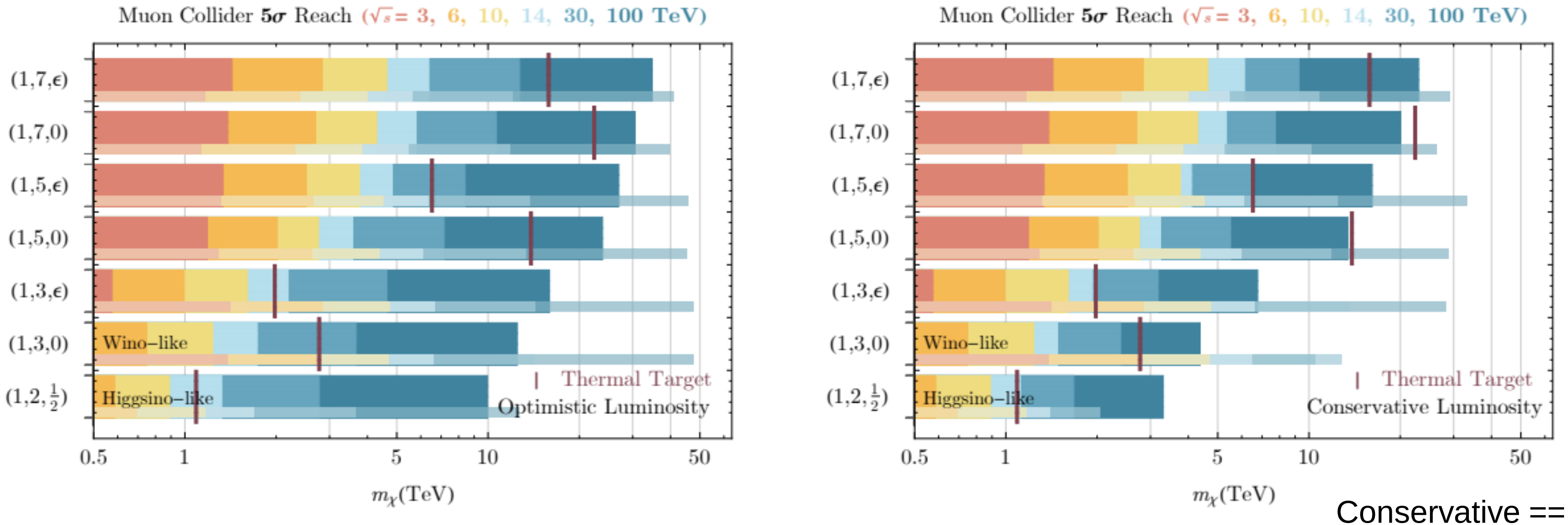


High-energy muon colliders open the way to direct measurements of the Higgs trilinear self-coupling, λ_3, and at above 10 TeV, even the potential observation of multi-Higgs production, which is sensitive to the quartic self-coupling. We find that the precision in the determination of λ_3 of the 3 TeV muon collider would substantially benefit from an increase in the total luminosity by a factor$\sim$ 2 with respect to the proposed benchmark of 0.9 ab^{-1}, suppressing a second mode in the likelihood for λ_3 and allowing a determination at the 15% level. Percent level uncertainties will be achieved at the higher energy stages.

Dark Matter Reach

[Higgs Smashers Guide, arXiv: 2103.14043](https://arxiv.org/abs/2103.14043)

Discovery potential for 10-TeV scale WIMPs for a variety of color/ew/hypercharge multiplets



Conservative == $10ab^{-1}$

Towards Muon Collider

Critical concepts to demonstrate

- Target Solenoid
  - Similar Low Temp Superconductor parameters to ITER Central Solenoid
  - Performance can be improved with a radiation resistant HTS or Cu insert
- Muon 6D Cooling
  - MICE Demonstration of Emittance Cooling
  - High gradient demonstration of RF operating in Tesla-class magnetic fields
  - Cooling channel concepts and detailed simulation consistent with operational targets
- Muon Final Cooling
  - Advances in HTS conductor/cable/magnet technology
  - High Field User Magnet program operationally demonstrating magnet parameters that are rapidly approaching the MC requirements

Towards Muon Collider …

Critical concepts to demonstrate

- Muon Acceleration
  - Significant recent advancement in HTS-based fast-ramping magnets
  - Focused effort on studying the integrated magnet/power supply efficiency issues for TeV-scale acceleration
- Collider and Detector
  - Detailed studies of backgrounds that may impact physics
  - Detector performance studies now demonstrate the ability to successfully measure key processes
  - Concepts in development to manage off-site neutrino radiation issues

See dedicated JINST Volume for key references:
Muon Accelerators for Particle Physics (MUON)

Muon Collider Challenges …

10+ TeV is NEW Territory ➪ Key Areas of Investigation:

Evaluation of physics potential (including detector technology)

- Impacts of beam induced background

Neutrino Flux Mitigation

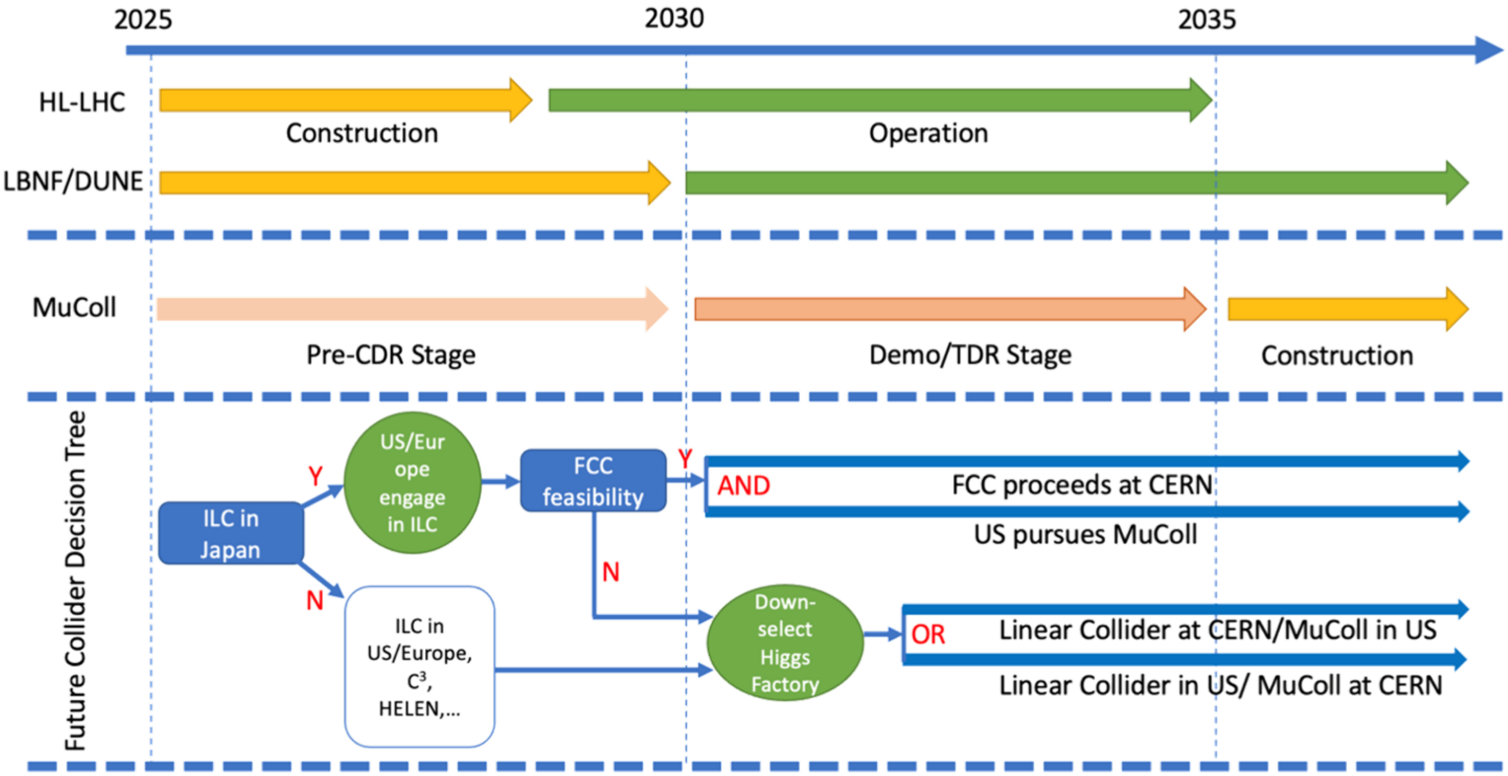
- Straight accelerator sections produce intense ν beam - safety

High Energy Systems

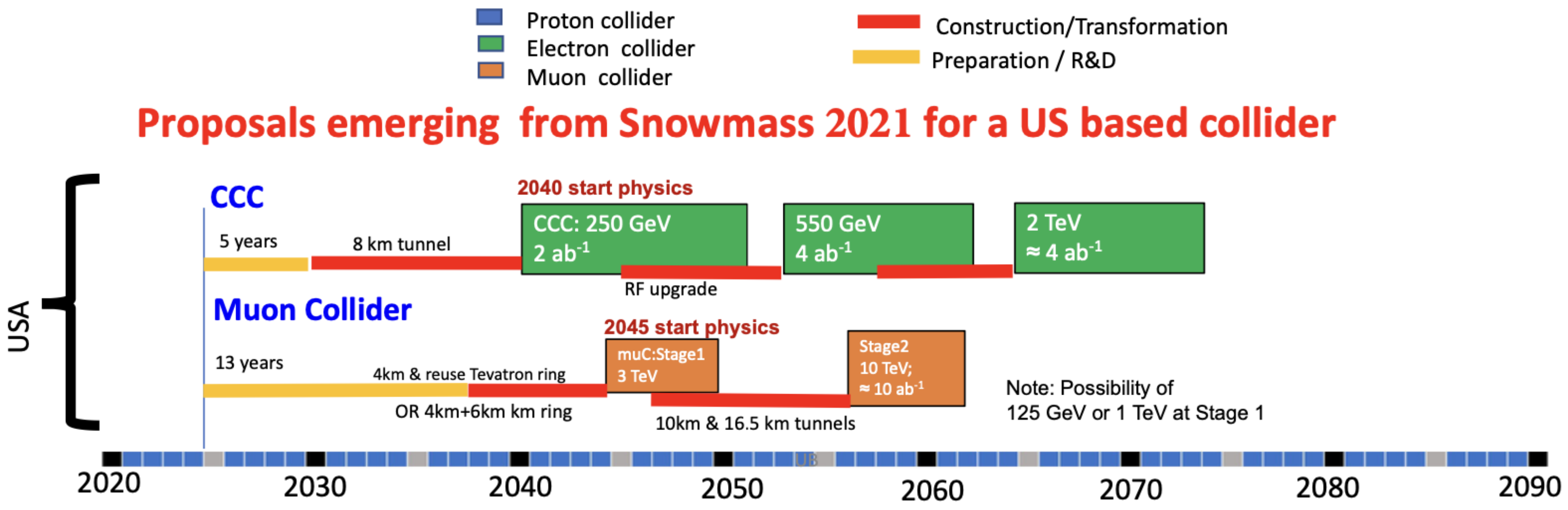
- Acceleration sections can impact the energy reach due to cost, power, technical risk, and impact on beam quality
- 10+ TeV Collider designs must be developed and fully evaluated

Cooling string demonstration to verify high brightness μ beam delivery

Path Forward



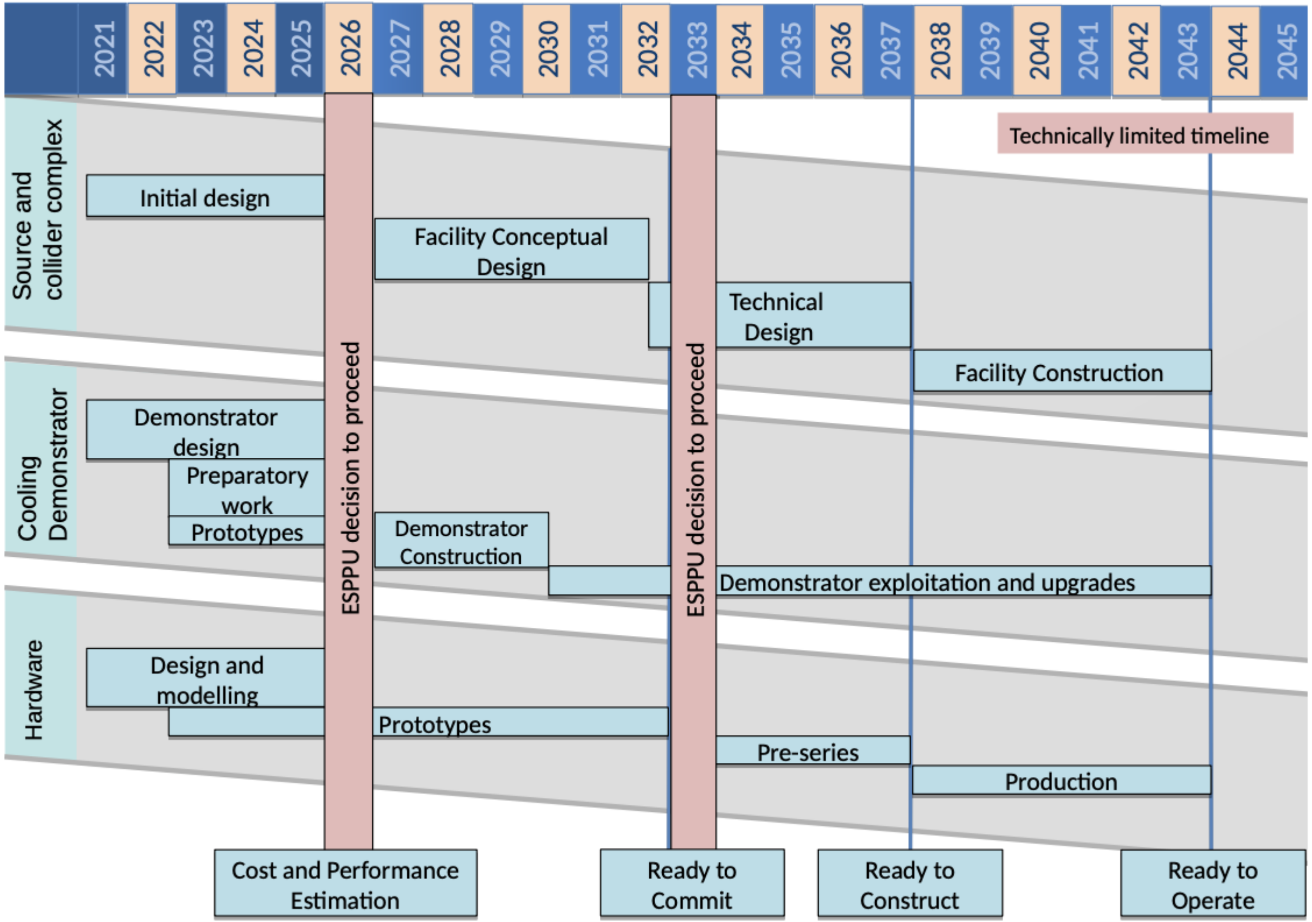
Summary + Invitation



Welcome African participation in studies – starting with simulations

Accelerators, detector technologies, machine-detector interface …

Studentships, Fractional postdocs, Guest & Visitor programs …



CERN-based International Muon Collider Collaboration ”timeline”

Fig. 2: A technically limited timeline for the Muon Collider R&D programme