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 +
2023 Particle Physics Project Prioritization Panel (P5) discussions

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

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

https://web.slac.stanford.edu/c3/

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],

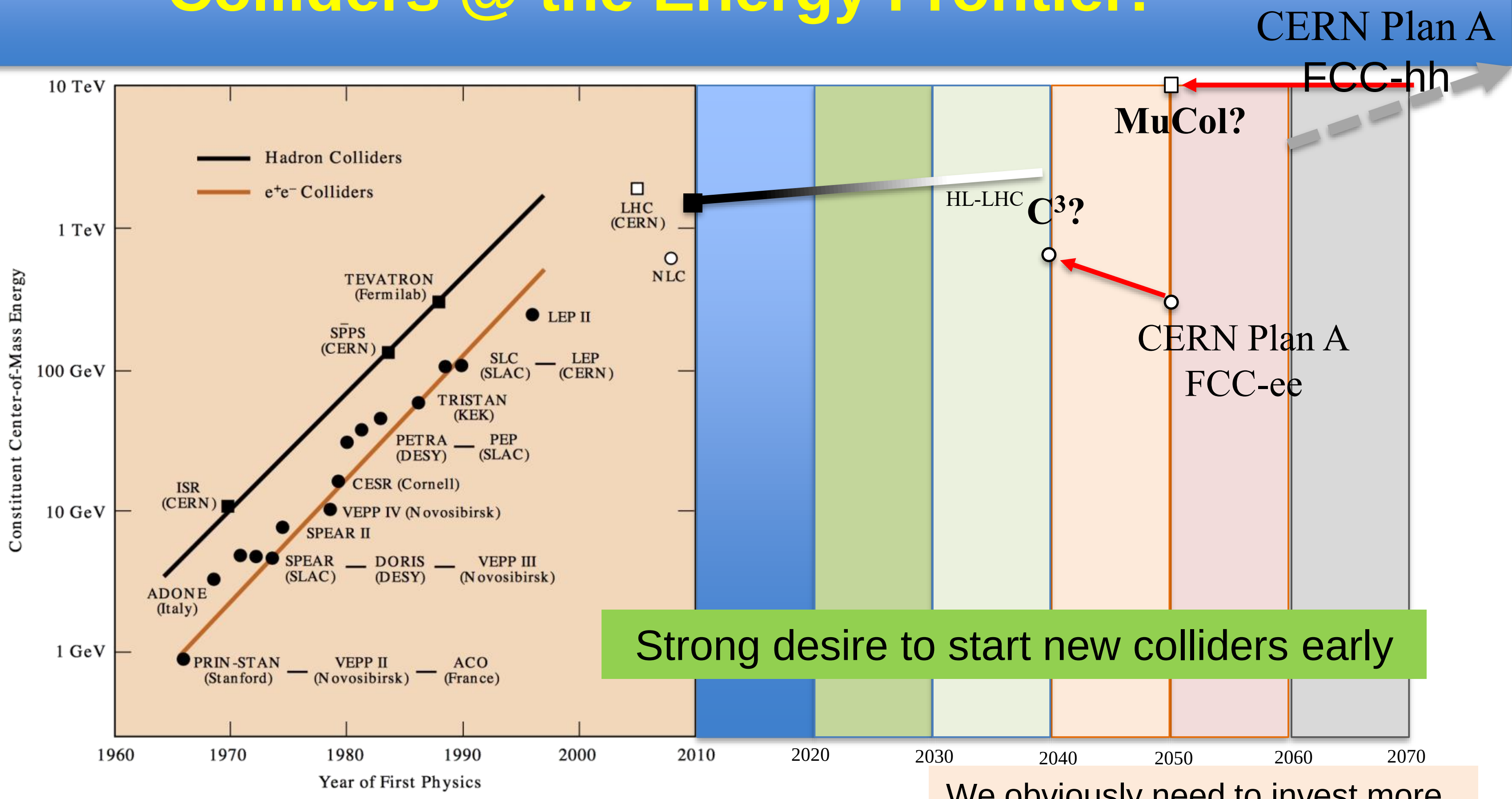
https://www.muoncollider.us/
https://muoncollider.web.cern.ch/

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!

http://www.slac.stanford.edu/pubs/beamline/27/1/27-1-panofsky.pdf



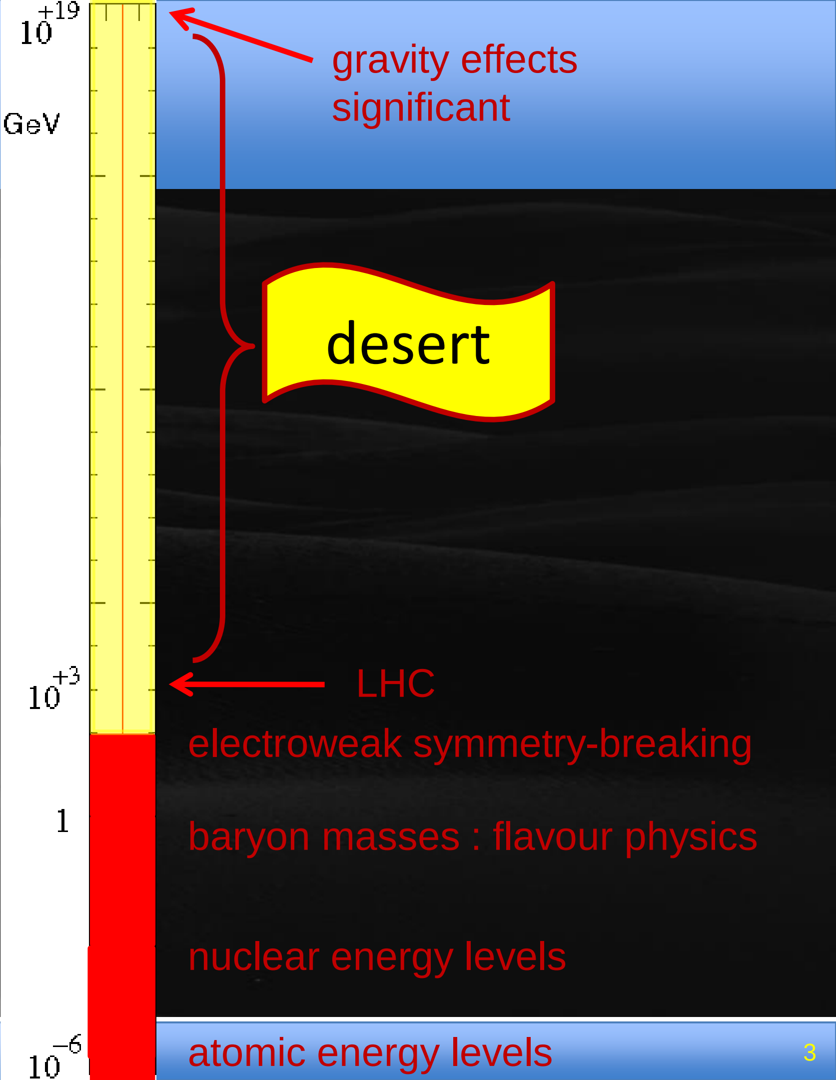
Strong desire to start new colliders early

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

Why go to new Colliders?

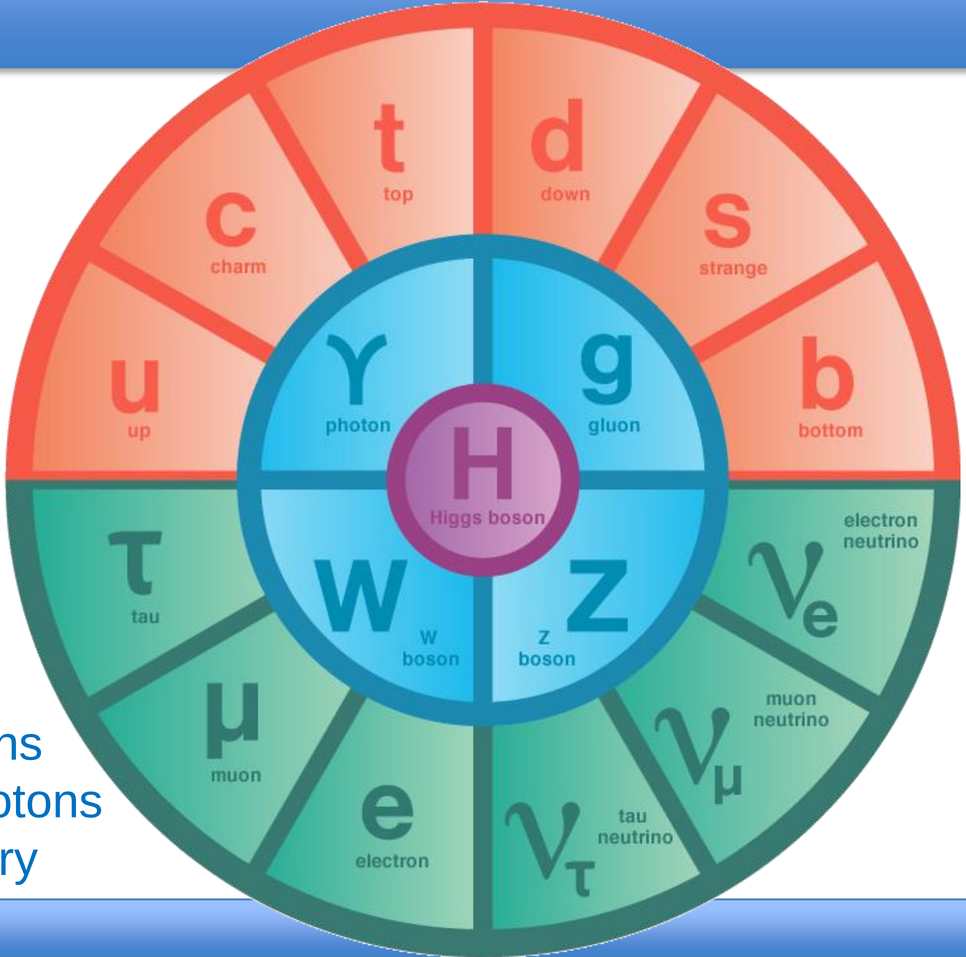
Standard model of particle physics works well at the LHC scales, although some key aspects of observed cosmological phenomena are left unexplained.

Yes, we are in the dark.



Higgs is Central

First Fermions discovered were electrons in 19th century



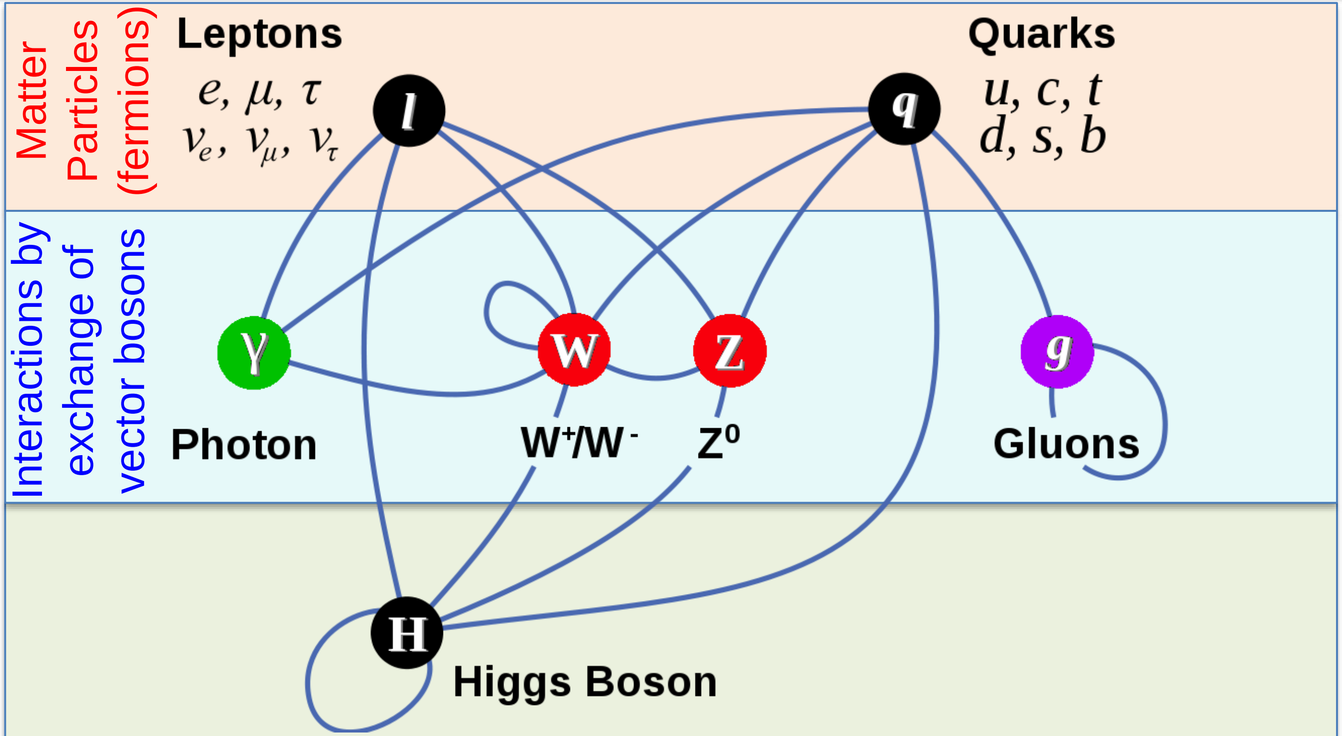
First Scalar boson discovered, the Higgs, was in 2012!

Higgs is Edifice on which the Standard Model is built.

First Vector-bosons discovered were photons also in 19th century

Higgs Will Likely Play a Central Role in guiding us out of this Darkness

Particles & Interactions of The Standard Model



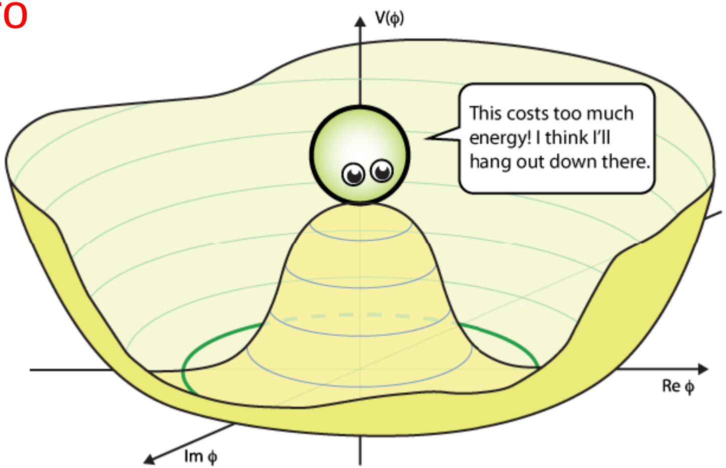
The edifice on which SM is built: The complex scalar doublet, with non-zero VEV, results in masses for W^+/W^- and the Z & massive Higgs. Fermions also get mass interacting with H.

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!!

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

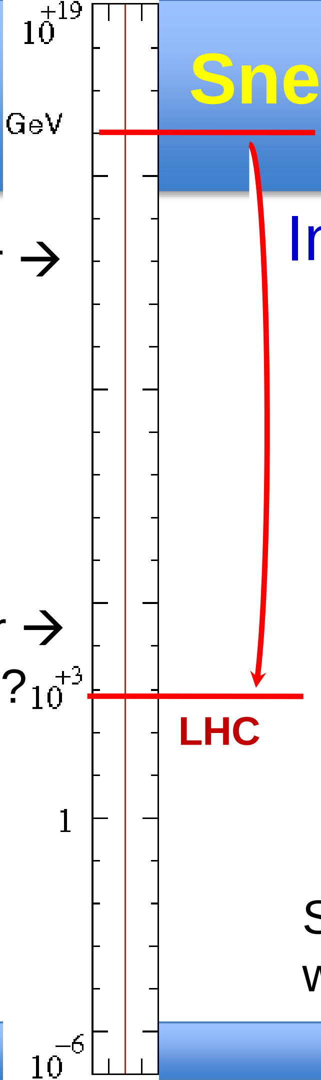
$$\text{For } \mu^2 < 0, \quad \text{minimum } v = \sqrt{-\frac{\mu^2}{2\lambda}}$$

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

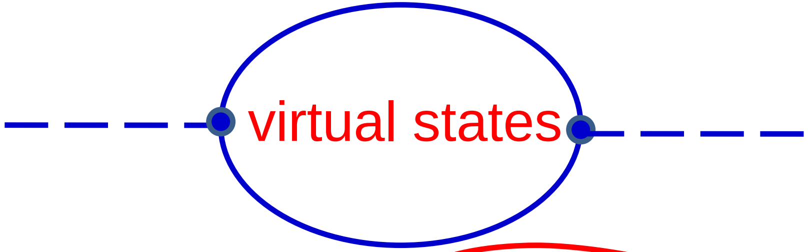
Sneak Peek into the Desert

Flavor sector → new physics

Higgs sector → new physics?



In the language of quantum field theory...



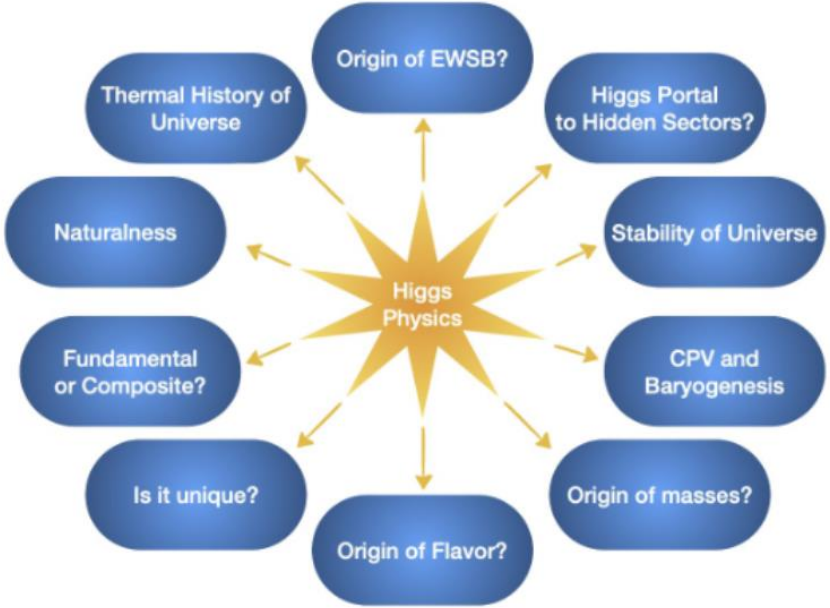
$$m \to m + \delta m(Q^2)$$

$$g \to g + \delta g(Q^2)$$

...our window into the desert

Scalar Higgs boson mass corrections would be very large with only the particle content of the Standard Model

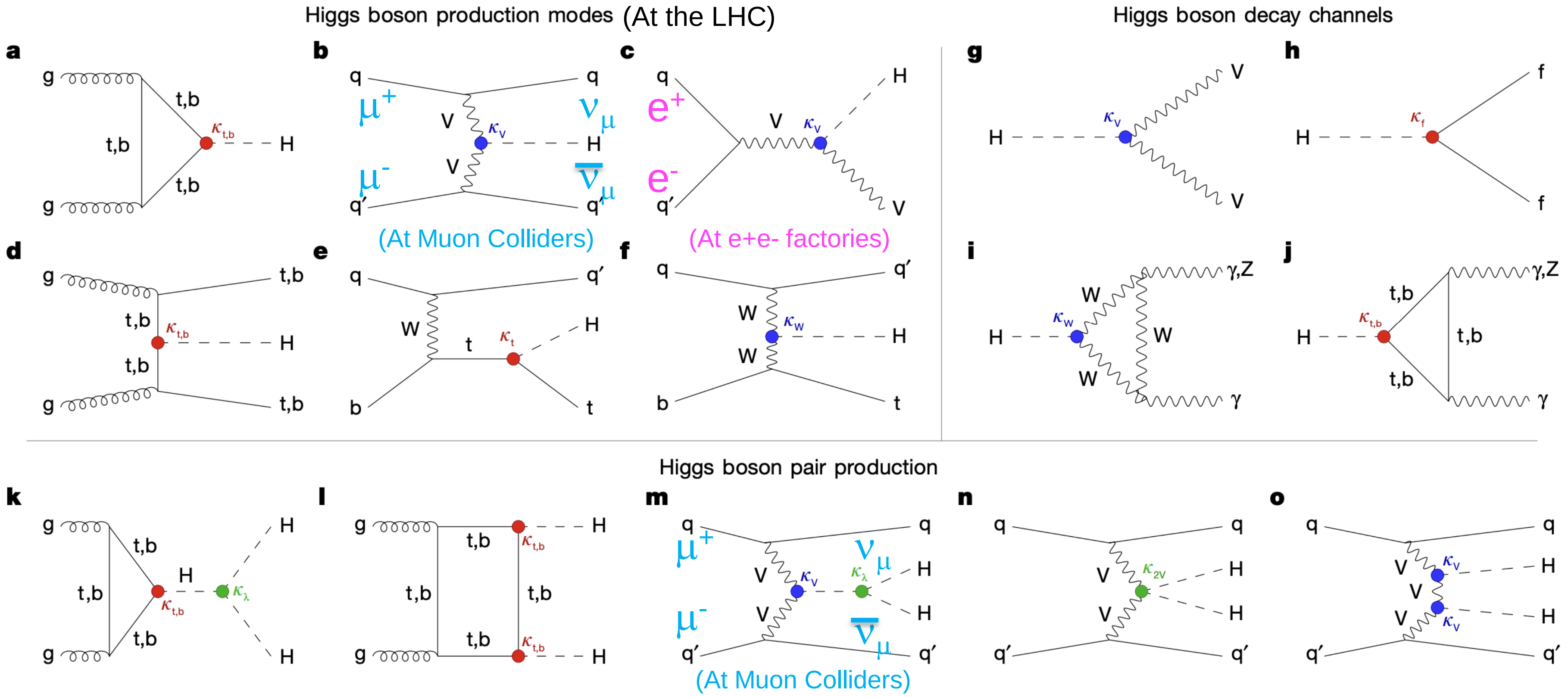
Higgs Central to Many Fundamental Topics



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

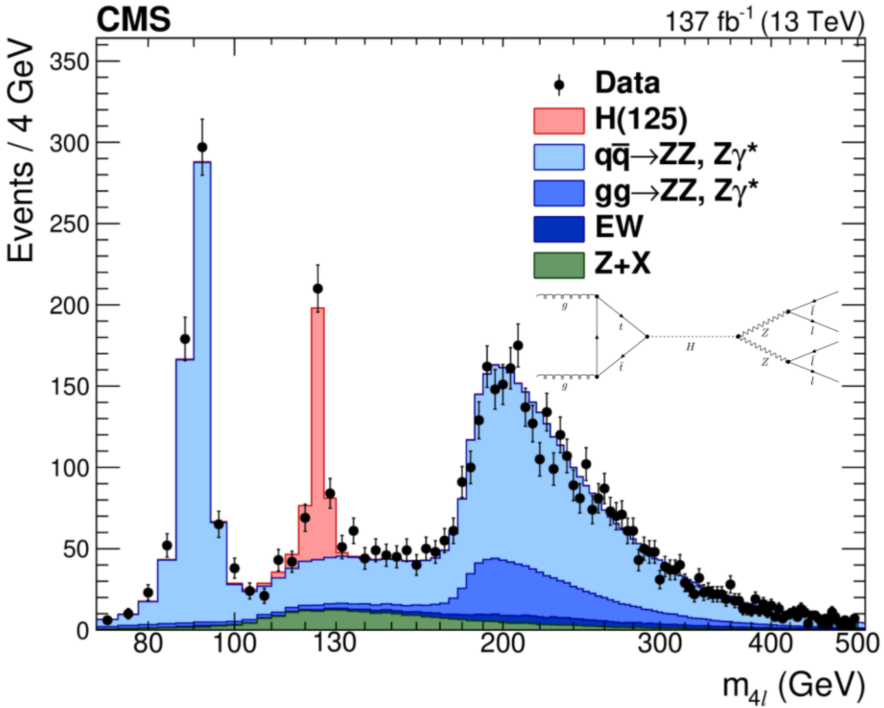
$e^+ e^-$ Higgs Factory ➔ Energy Frontier (10 TeV) Muon Collider

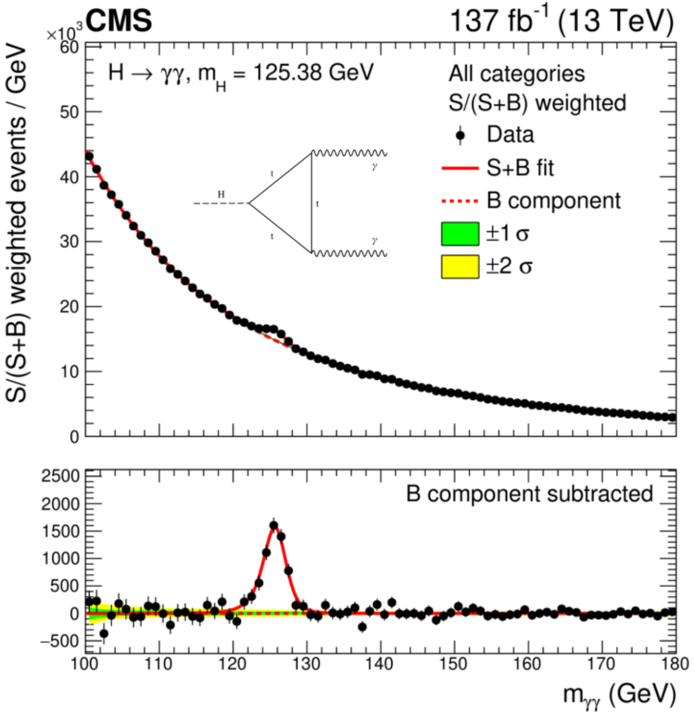
Higgs Boson Couplings, Production and Decays



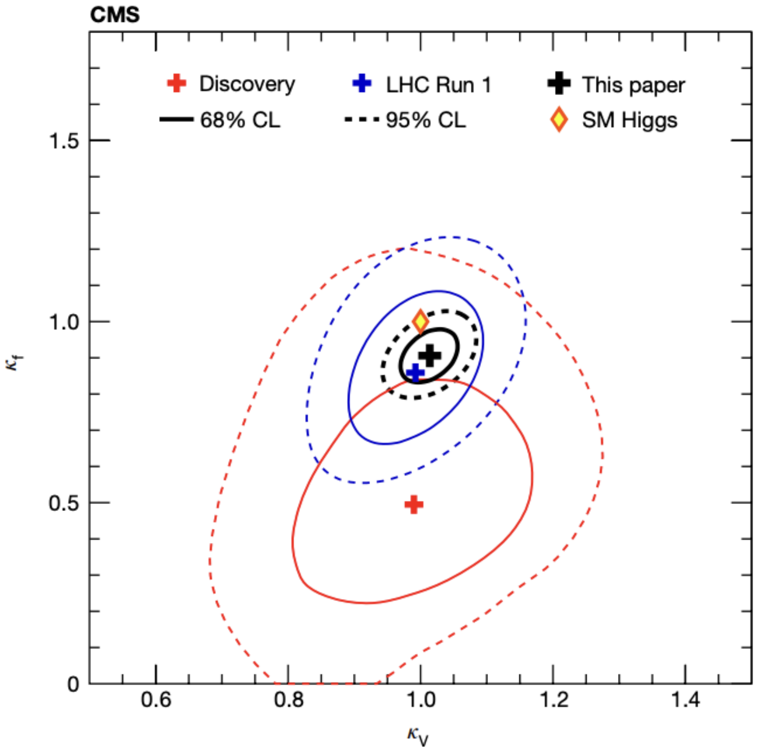
Current Status of Golden Channels @ LHC

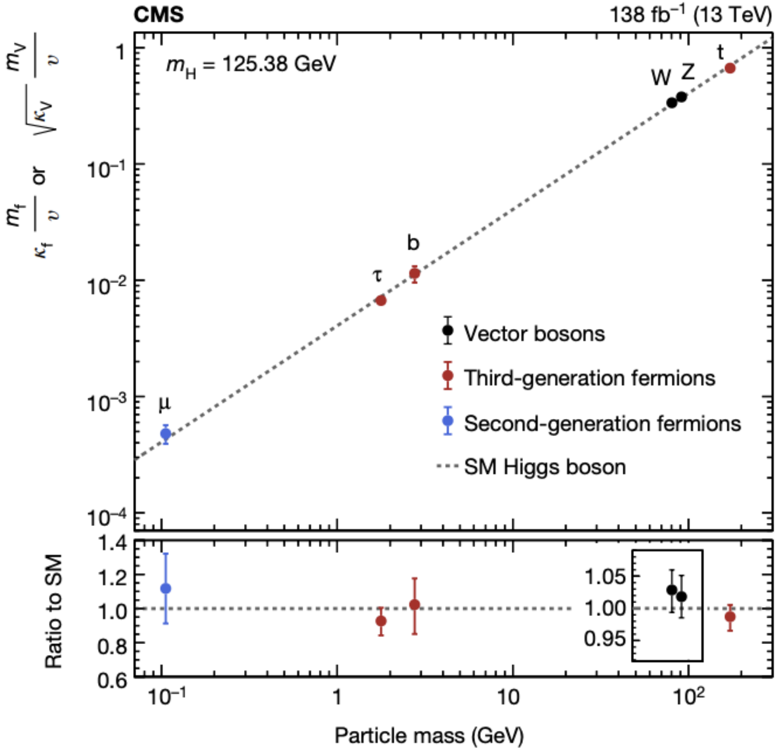
Our Higgs boson data sets are enabling detailed studies of the SM





Current Status of Higgs Couplings

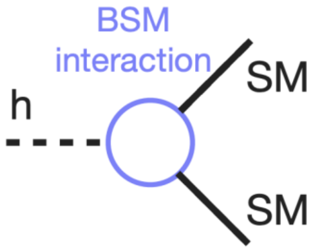




Discrepancies at this level if any would imply <1 TeV scale new physics – we did not see either

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

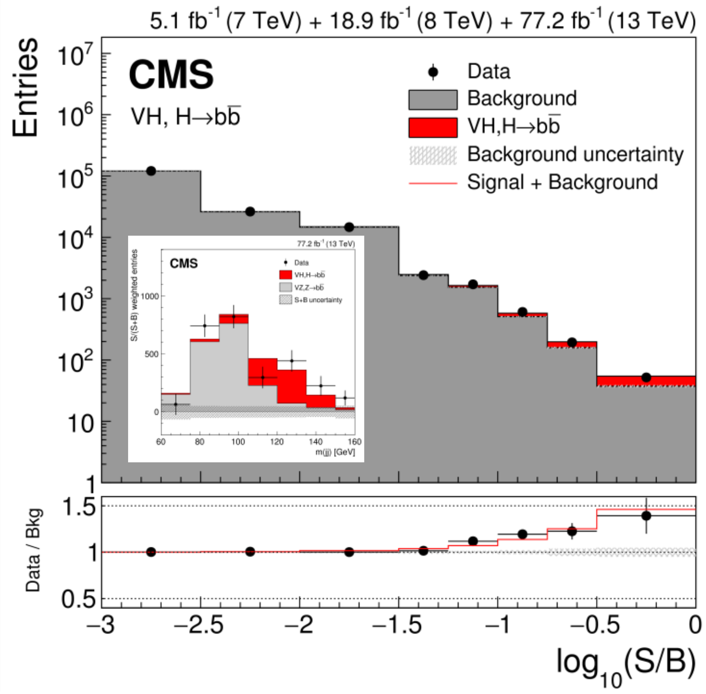
Can we use precision measurements to indirectly probe new physics at higher energies?
Are higgs couplings to SM particles modified?



		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

Why an electron-positron collider?



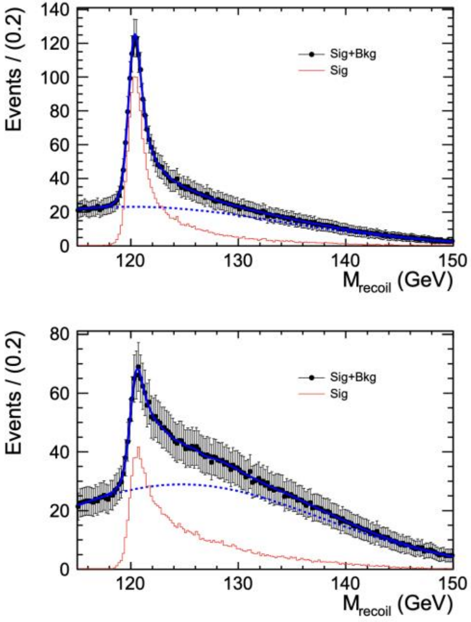
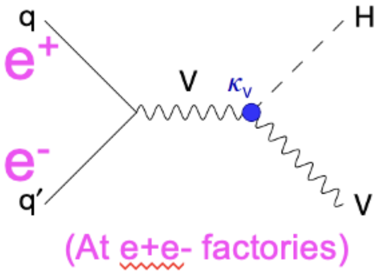


Figure 24: Reconstructed Higgs mass spectrum together with the sum of underlying background for the *Model Independent Analysis* for the $\mu\mu X$-channel (top) and eeX-channel (bottom). The polarisation mode is $e^-_L e^+_R$. The lines show the fits using the Simplified Kernel Estimation fitting formula to the signal and a polynomial of second order to the background as explained in the text.



Recoil mass at electron positron collider

Higgs to anything over background

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

Implementation Task Force
Evaluated Collider Types

Circular Colliders e^+e^-

- From $\sqrt{s} = M_Z \rightarrow M_{WW} \rightarrow M_{Z+H} \rightarrow M_{tt}$
- Tera-Z, millions of H – very high luminosity
- ”Upgrade” to pp-machine for high energy

Proton Colliders (FCC-hh, SPPS/China ~100 TeV, 10s ab^{-1})

Linear Colliders e^+e^-

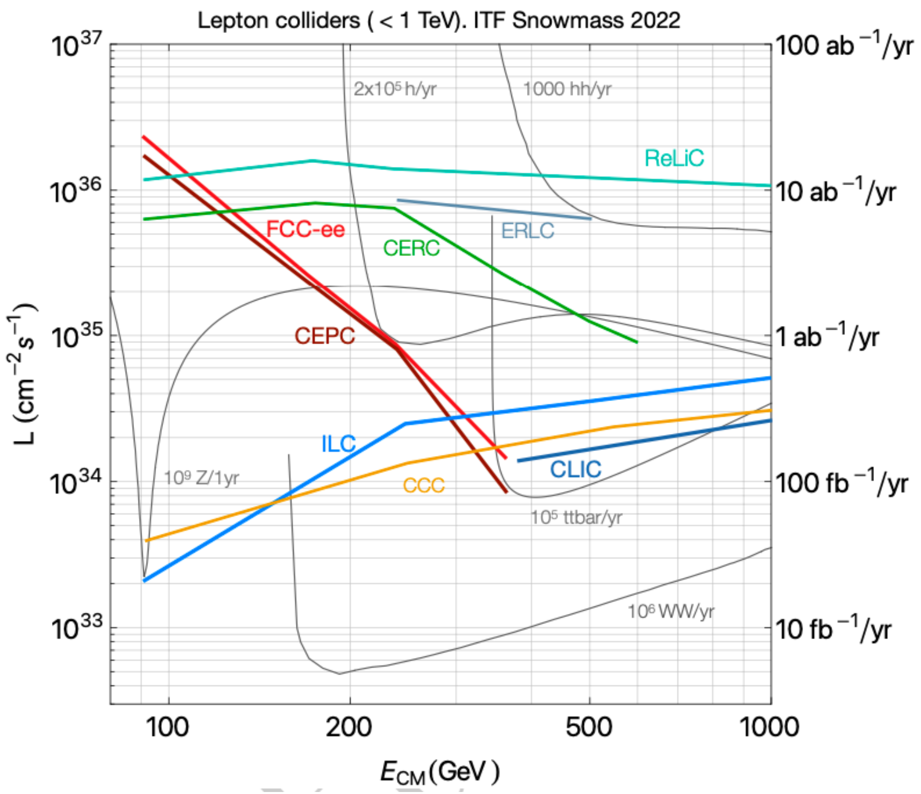
- Polarization, Energy Reach
- From $\sqrt{s} = M_Z \rightarrow M_{WW} \rightarrow M_{Z+H} \rightarrow 550\ \mathrm{GeV}$
- Upgraded / Expanded facilities: $\sqrt{s} \rightarrow 3\ \mathrm{TeV}$
- Advanced technologies: $\sqrt{s} \rightarrow 15\ \mathrm{TeV}$ (much R&D needed)

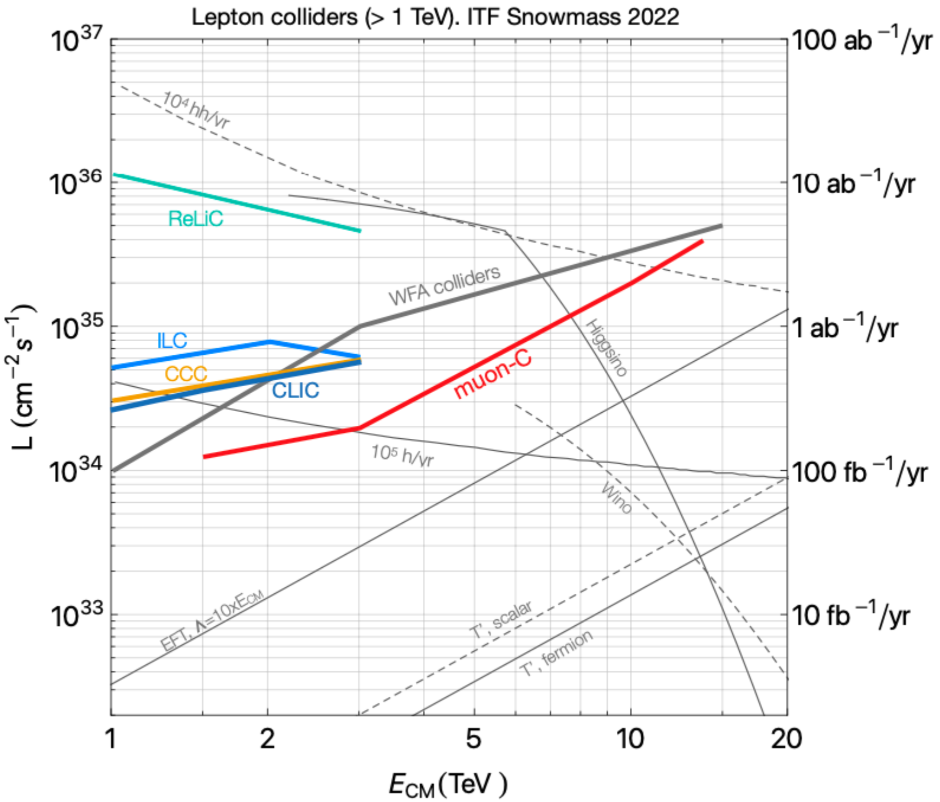
Muon Colliders (10 TeV, 10 ab^{-1})

- Revived interest in high-energy option due to recent advances

Collider	Type
FCC-ee (0.24 TeV)	Circular
CEPC (0.24 TeV)	Circular
CERC (0.24 TeV)	Circular
ILC (0.25 TeV)	Linear
CLIC (0.38 TeV)	Linear
CLIC (3 TeV)	Linear
C^3 (0.25 TeV)	Linear
ReLiC (0.24 TeV)	Linear
ERLC (0.24 TeV)	Linear
ILC (3 TeV)	Linear
C^3 (3 TeV)	Linear
ReLiC (3 TeV)	Linear
WFA (3 TeV)	Linear
WFA-flat (15 TeV)	Linear
WFA-round (15 TeV)	Linear

Lepton collider Luminosity vs $\sqrt{s}$ Landscape

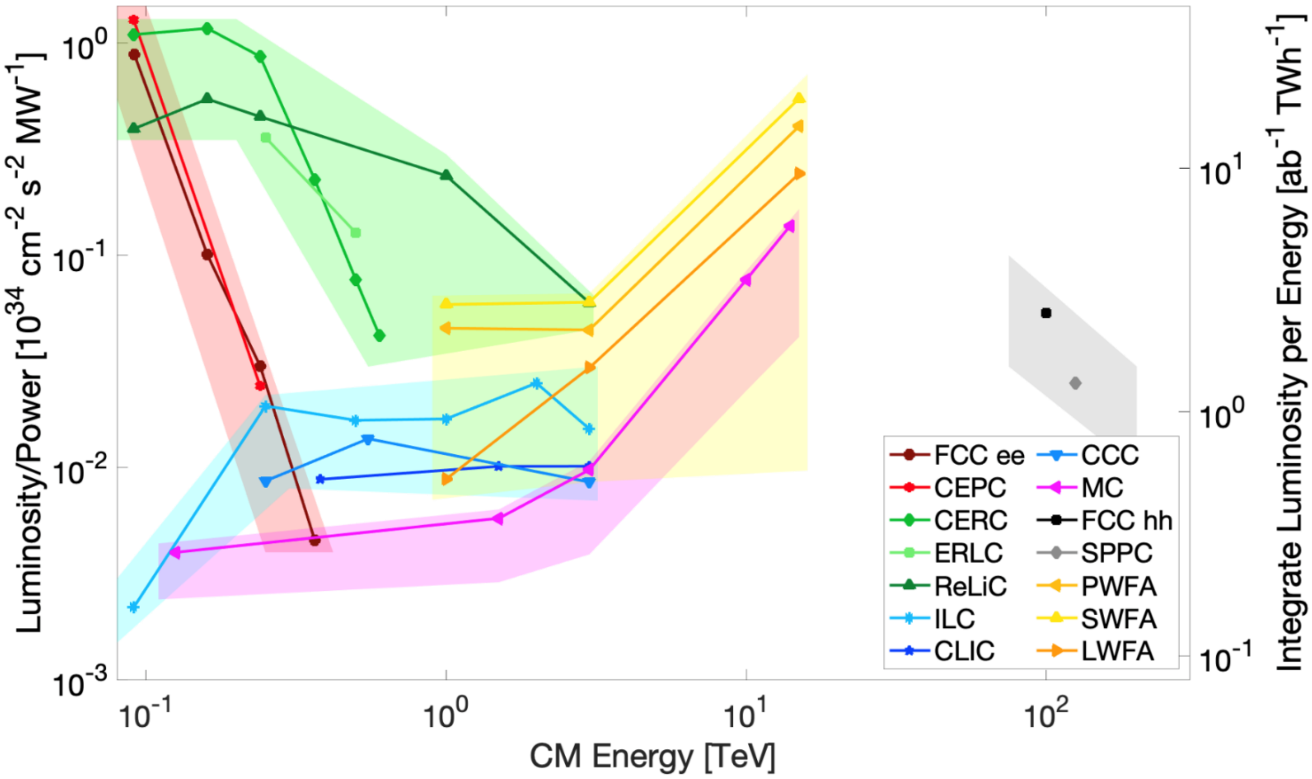




Luminosity / Power vs Energy from ITF

Points computed from proponent submitted parameters table

Uncertainty band is ITF judgement based on many considerations: technical design status, risk assessment, …



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

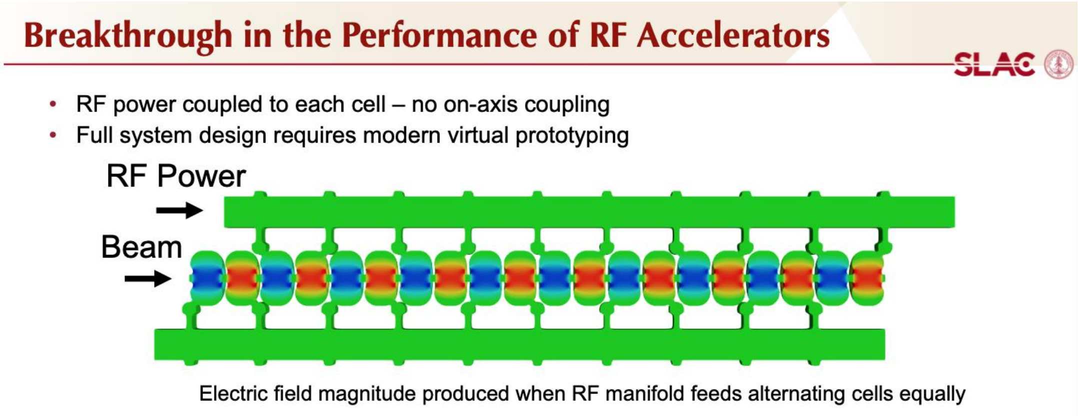
Higgs Factory Physics Timeline vis-à-vis Integrated Luminosity

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		

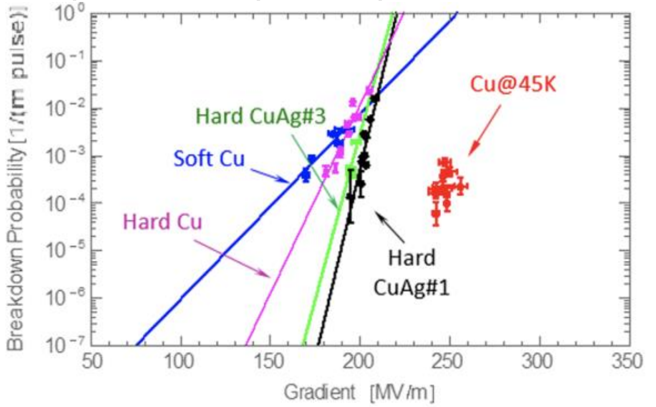
C3 – Cool Copper Collider – New Option

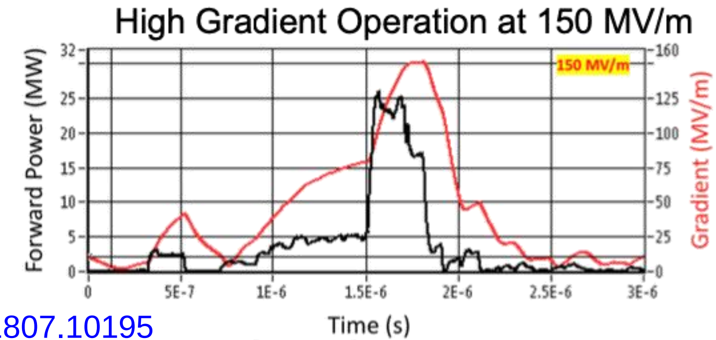


First C³ structure at SLAC

Cryogenic operation improves performance

Cahill et al, PRAB 21.10 (2018): 102002





Bane et al, arXiv 1807.10195

X-band Prototype

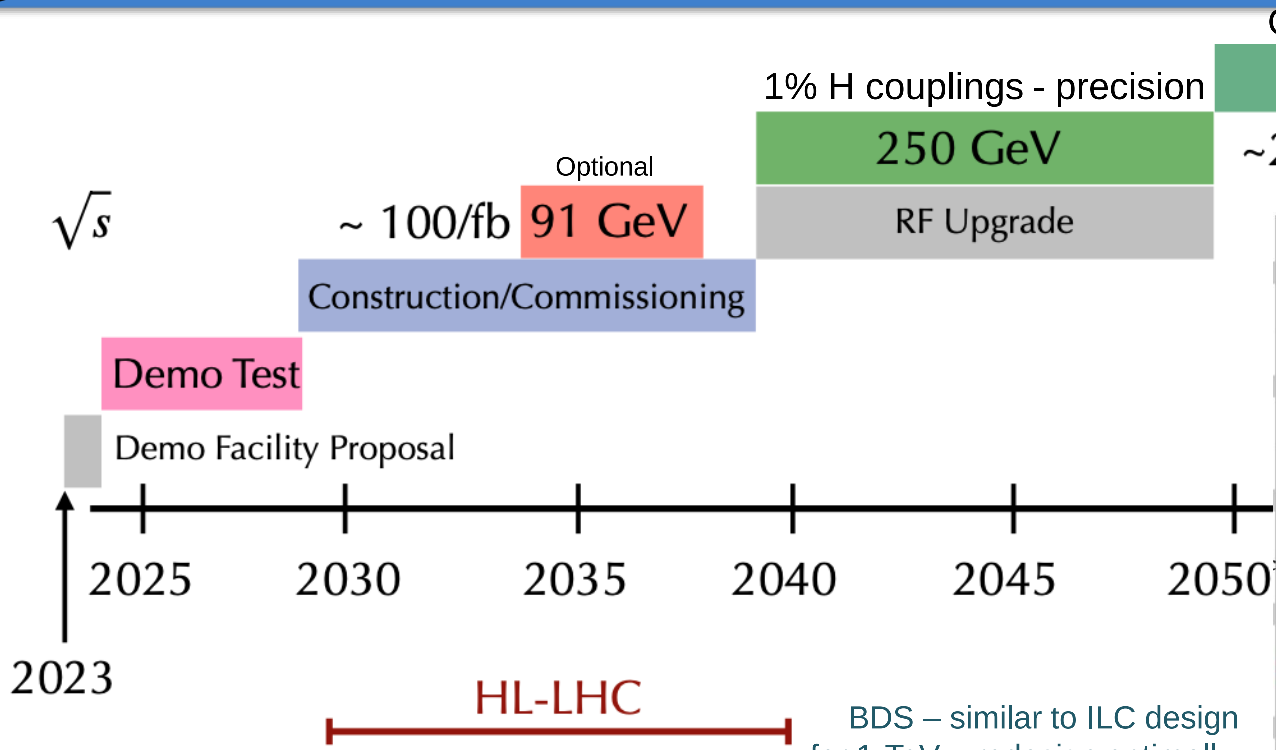
Synergies With X-Ray Photon Sources

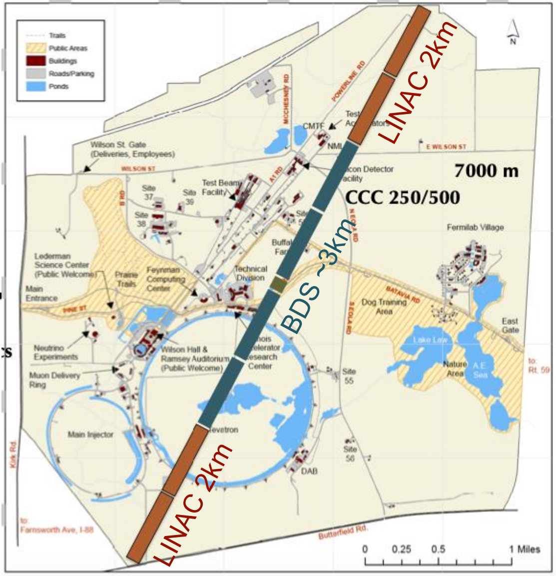
The vast majority of ~30,000 currently operating accelerators globally are electron accelerators.

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.

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





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

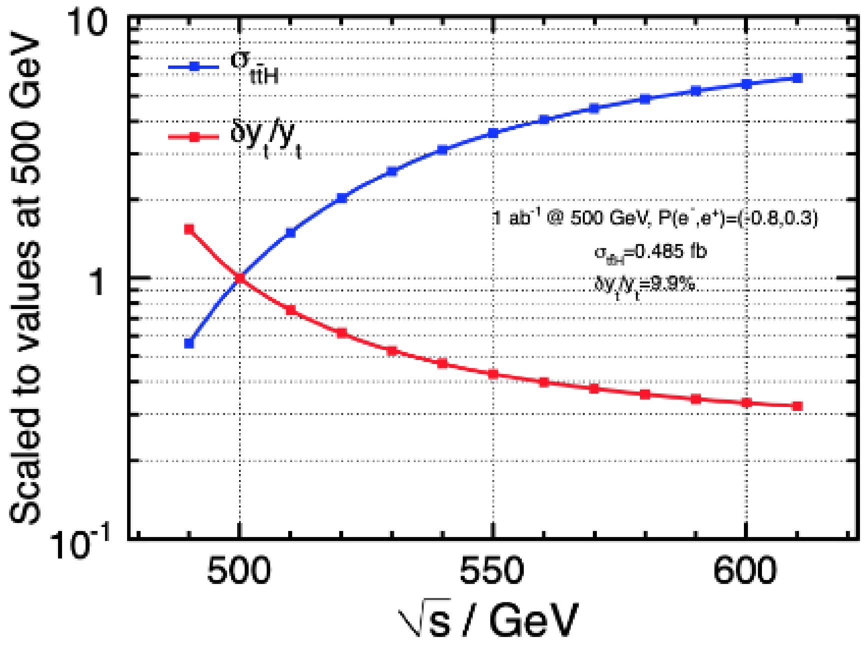
Can fit in FNAL site with BDS improvements

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%

Electroweak Observables

GigaZ is a big improvement over current status

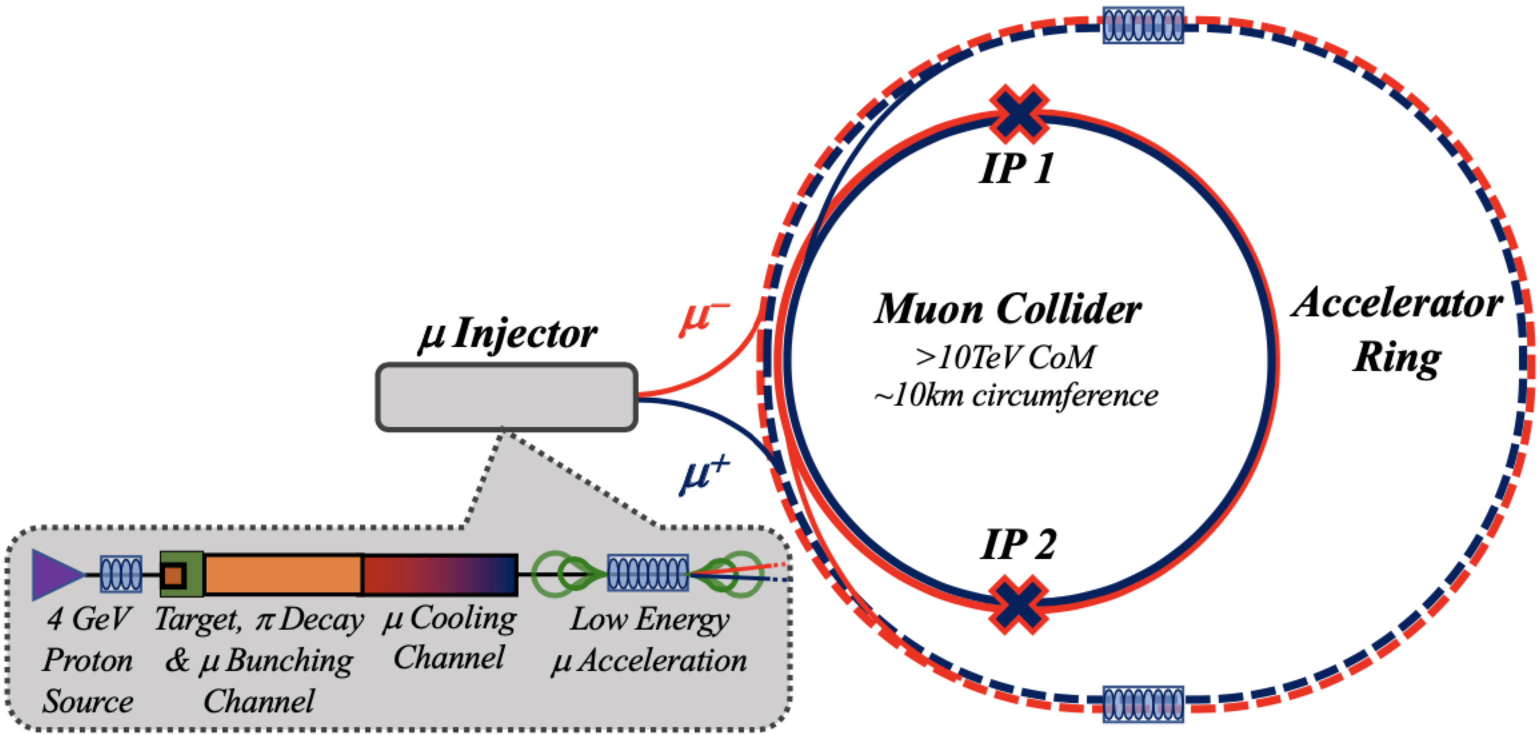
FCC-ee TeraZ suggests even bigger leap forward in precision

Quantity	current	ILC250	ILC-GigaZ	FCC-ee	CEPC	CLIC380
$\Delta\alpha(m_Z)^{-1}$ ($\times 10^3$)	17.8*	17.8*		3.8 (1.2)	17.8*	
Δm_W (MeV)	12*	0.5 (2.4)		0.25 (0.3)	0.35 (0.3)	
Δm_Z (MeV)	2.1*	0.7 (0.2)	0.2	0.004 (0.1)	0.005 (0.1)	2.1*
Δm_H (MeV)	170*	14		2.5 (2)	5.9	78
$\Delta\Gamma_W$ (MeV)	42*	2		1.2 (0.3)	1.8 (0.9)	
$\Delta\Gamma_Z$ (MeV)	2.3*	1.5 (0.2)	0.12	0.004 (0.025)	0.005 (0.025)	2.3*
ΔA_e ($\times 10^5$)	190*	14 (4.5)	1.5 (8)	0.7 (2)	1.5 (2)	64
ΔA_μ ($\times 10^5$)	1500*	82 (4.5)	3 (8)	2.3 (2.2)	3.0 (1.8)	400
ΔA_τ ($\times 10^5$)	400*	86 (4.5)	3 (8)	0.5 (20)	1.2 (20)	570
ΔA_b ($\times 10^5$)	2000*	53 (35)	9 (50)	2.4 (21)	3 (21)	380
ΔA_c ($\times 10^5$)	2700*	140 (25)	20 (37)	20 (15)	6 (30)	200
$\Delta\sigma^0_{\mathrm{had}}$ (pb)	37*			0.035 (4)	0.05 (2)	37*
δR_e ($\times 10^3$)	2.4*	0.5 (1.0)	0.2 (0.5)	0.004 (0.3)	0.003 (0.2)	2.7
δR_μ ($\times 10^3$)	1.6*	0.5 (1.0)	0.2 (0.2)	0.003 (0.05)	0.003 (0.1)	2.7
δR_τ ($\times 10^3$)	2.2*	0.6 (1.0)	0.2 (0.4)	0.003 (0.1)	0.003 (0.1)	6
δR_b ($\times 10^3$)	3.1*	0.4 (1.0)	0.04 (0.7)	0.0014 ($<$ 0.3)	0.005 (0.2)	1.8
δR_c($\times 10^3$)	17*	0.6 (5.0)	0.2 (3.0)	0.015 (1.5)	0.02 (1)	5.6

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

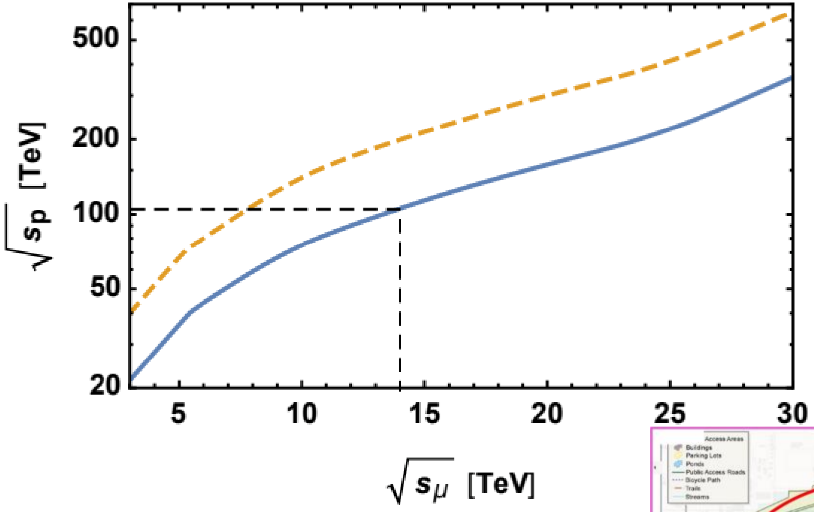
Innovative Muon Collider Concepts

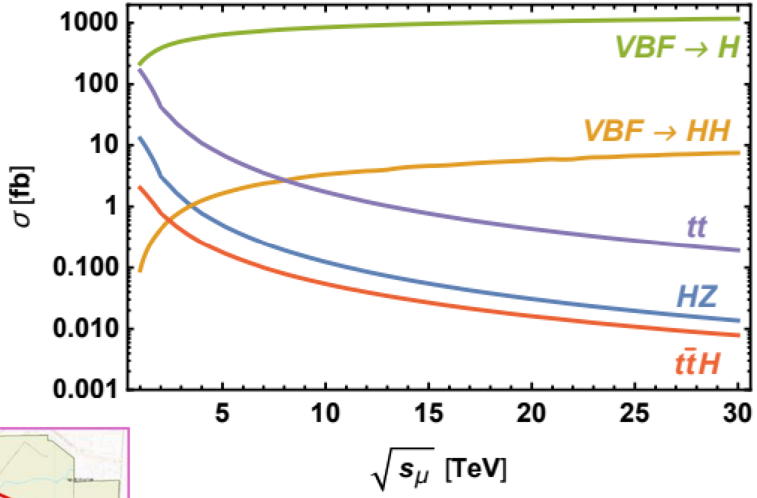
Energy Efficient Path to O(10)-TeV Colliders



Muon Collider Advantages

arxiv:1901.06150



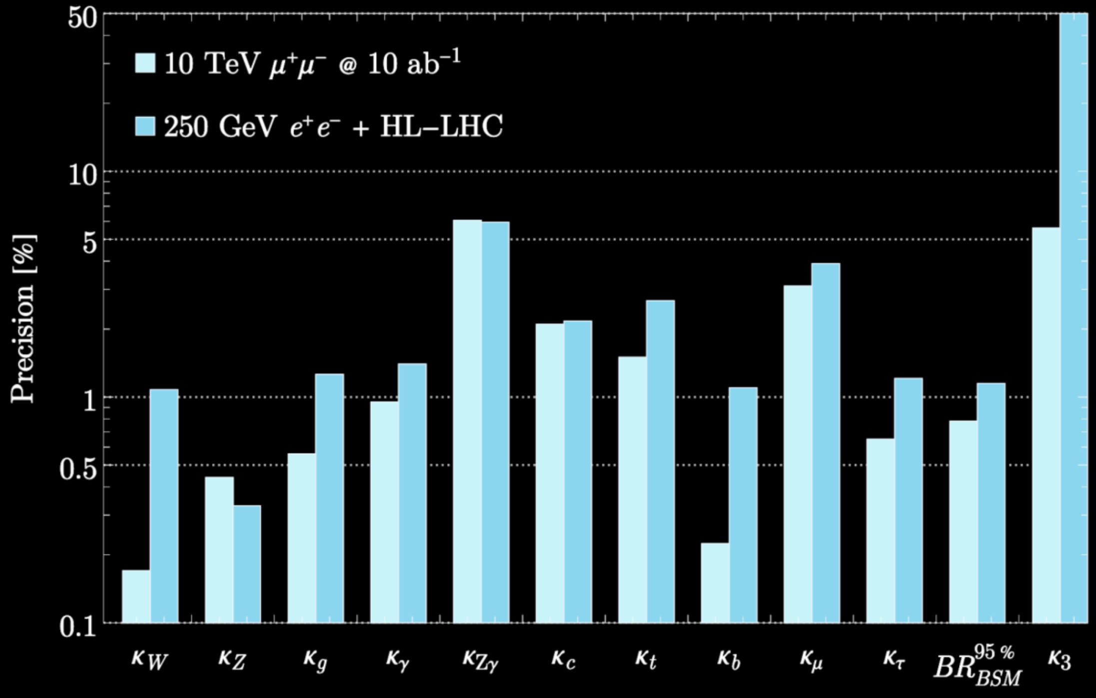


6-10 TeV muon collider can fit on FNAL site

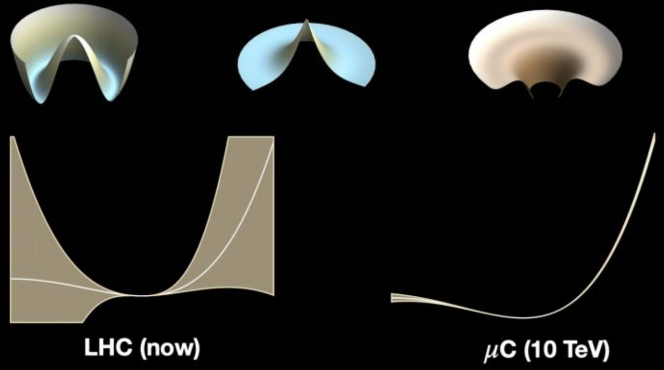
Accelerator ring would be a FNAL site filler

Reduced civil engineering costs compared to pp-machines

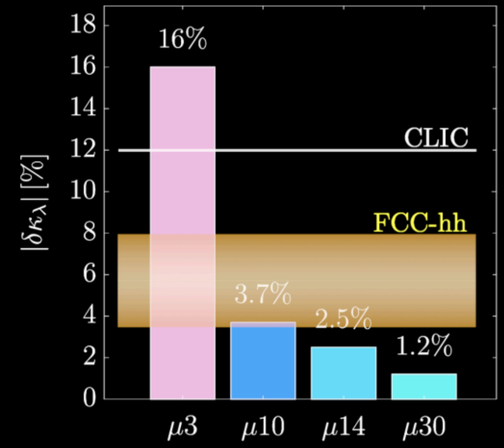
Higgs Precision & Di-Higgs Potential



[Forslund & Meade, 2308.02633]



[Accettura et al. 2303.08533]



Sub-percent deviations of Higgs couplings will be observable at muon collider too

Muon Collider Prospects: Heavy Scalar Singlet

Higgs Smashers Guide, arXiv: 2103.14043

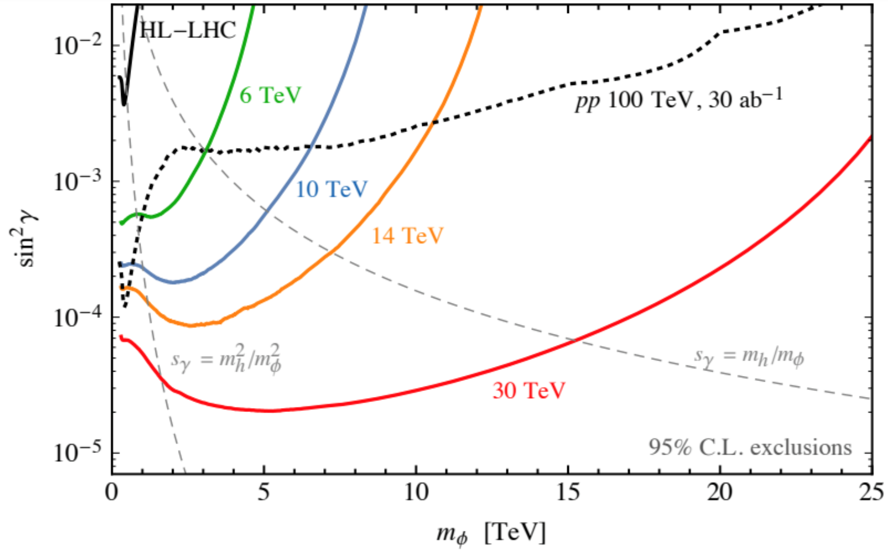


Figure 14: Exclusions on the mixing angle of a generic scalar singlet, $\sin^2\gamma = \kappa_V - 1$, as a function of the singlet mass m_ϕ for the various collider benchmarks (colored lines). The expected limits at HL-LHC (solid) and a FCC-hh (dashed) are shown as black lines for comparison. The thin dashed lines indicate the two possible scalings of the mixing angle with m_ϕ in realistic models with fixed coupling.

Higgs Compositeness & Minimal Z' – Another place where Muon Collider Shines

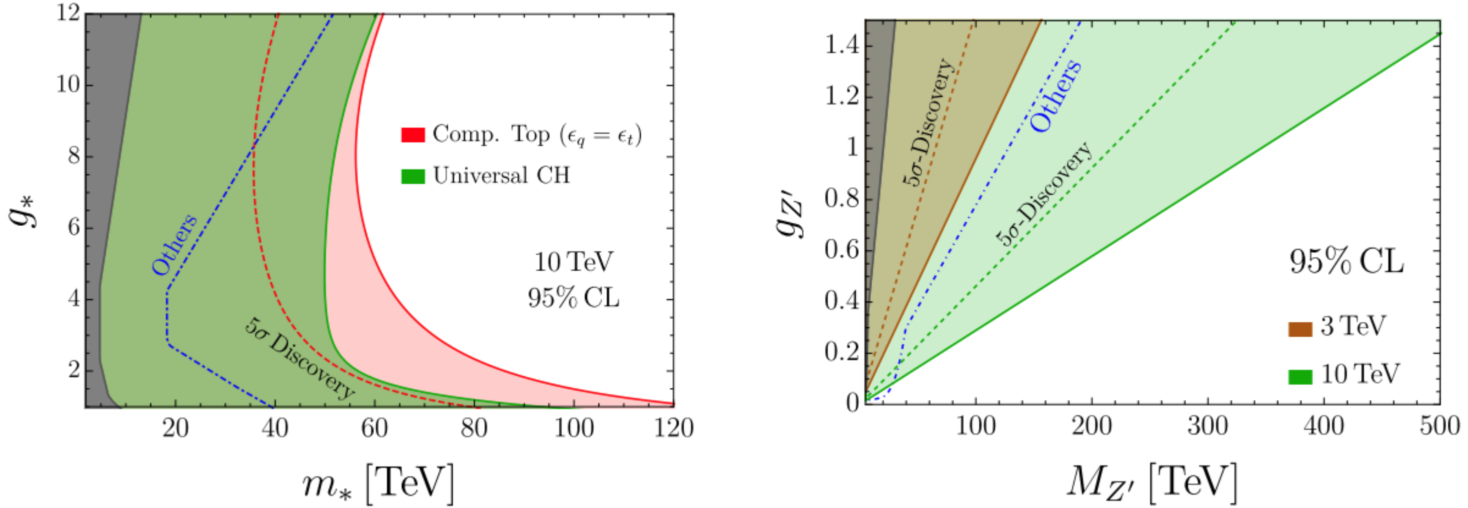
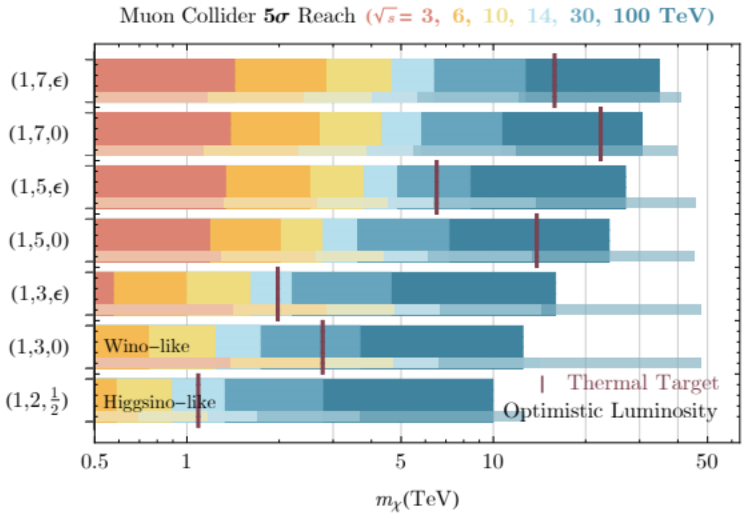


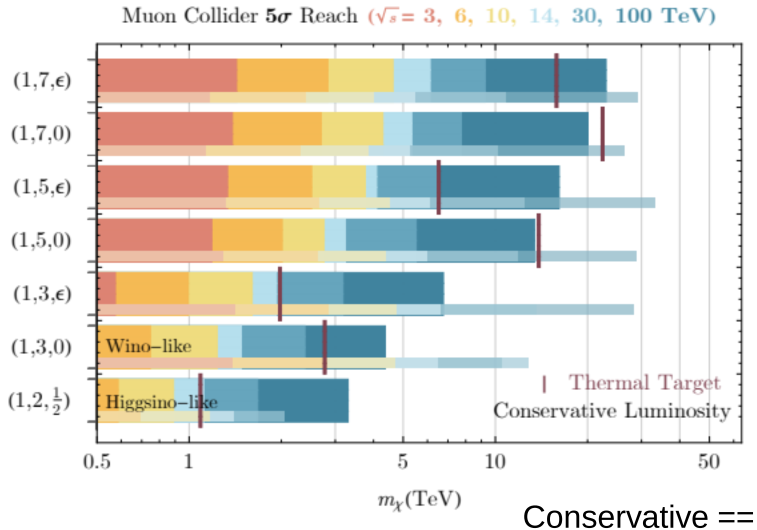
Fig. 6: Left panel: 95% reach on the Composite Higgs scenario from high-energy measurements in di-boson and di-fermion final states [26]. The green contour display the sensitivity from "Universal" effects related with the composite nature of the Higgs boson and not of the top quark. The red contour includes the effects of top compositeness. Right panel: sensitivity to a minimal Z' [26]. Discovery contours at 5σ are also reported in both panels.

Dark Matter Reach

[Higgs Smashers Guide, arXiv: 2103.14043]

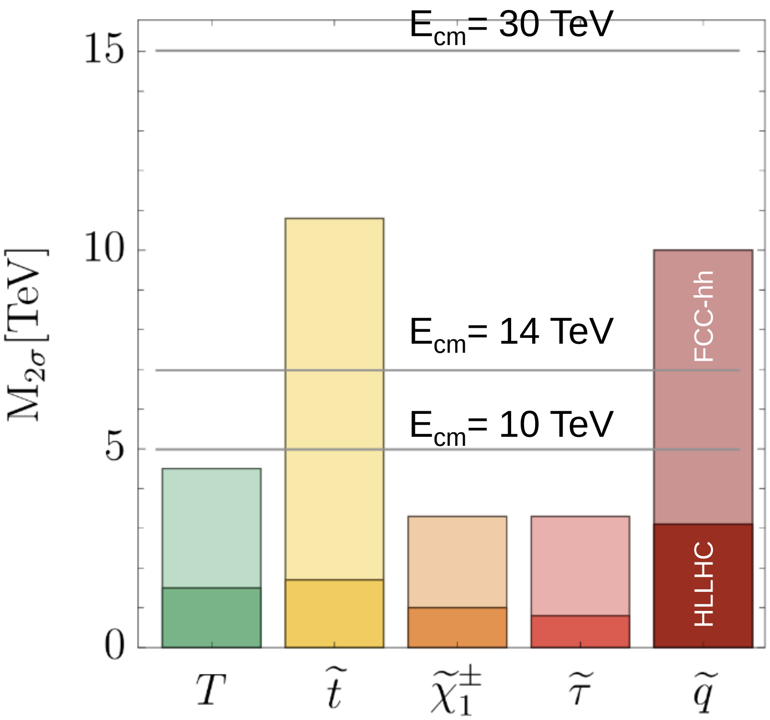
Discovery potential for 10-TeV scale WIMPs for a variety of color/ew/hypercharge multiplets





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

SUSY sparticle Searches



Of course, FCC-hh wins in colored particle case over 10 TeV μCol

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

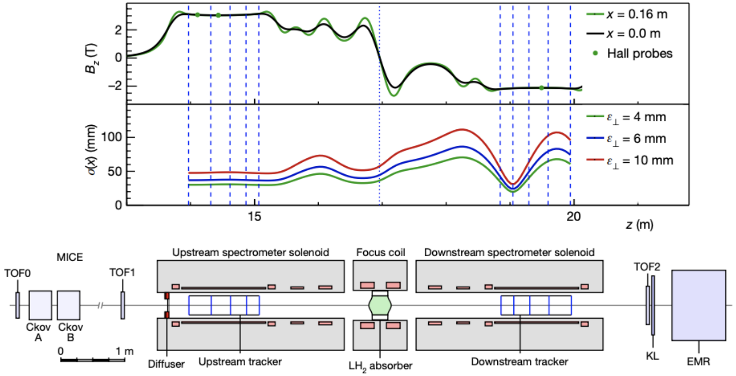
- Muon Acceleration
  - Significant recent advancement in HTS-based fast-ramping magnets
  - Focused effort on studying the integrated magnet/power supply efficiency issues for TeV-scale acceleration
- Collider and Detector
  - Detailed studies of backgrounds that may impact physics
  - Detector performance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

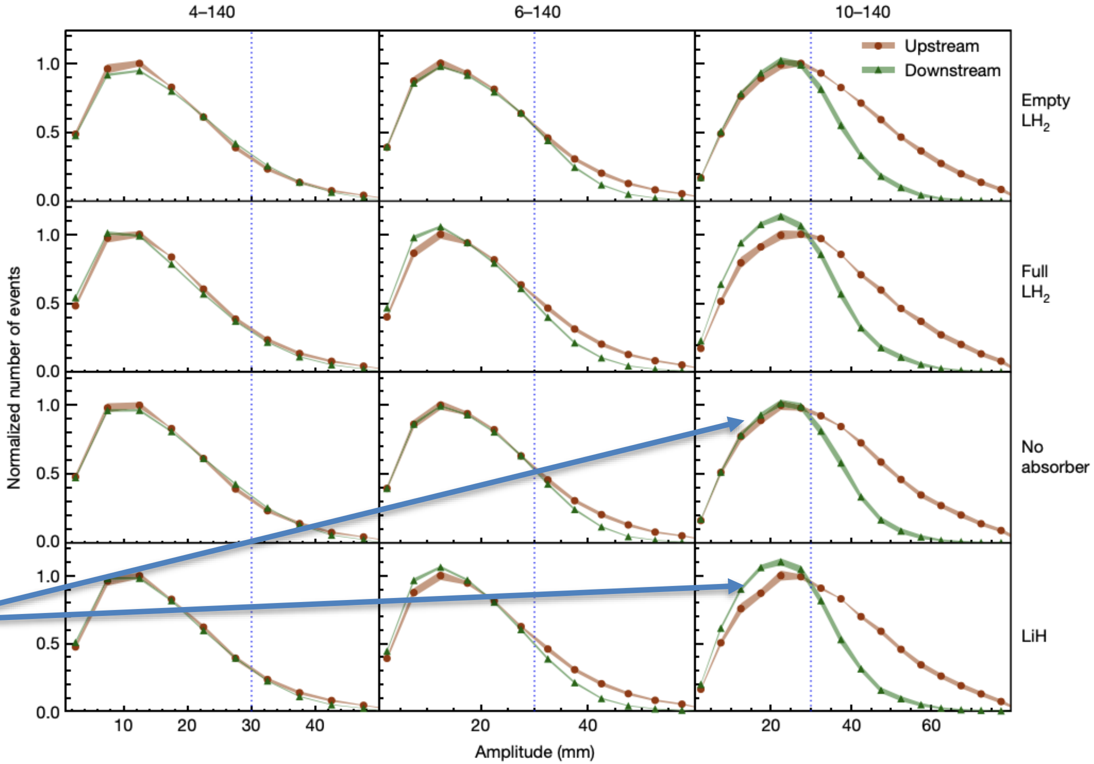
See dedicated JINST Volume for key references:
Muon Accelerators for Particle Physics (MUON)

Beam Production : Demonstration of Ionization Cooling

[Nature, Vol 578, P53]

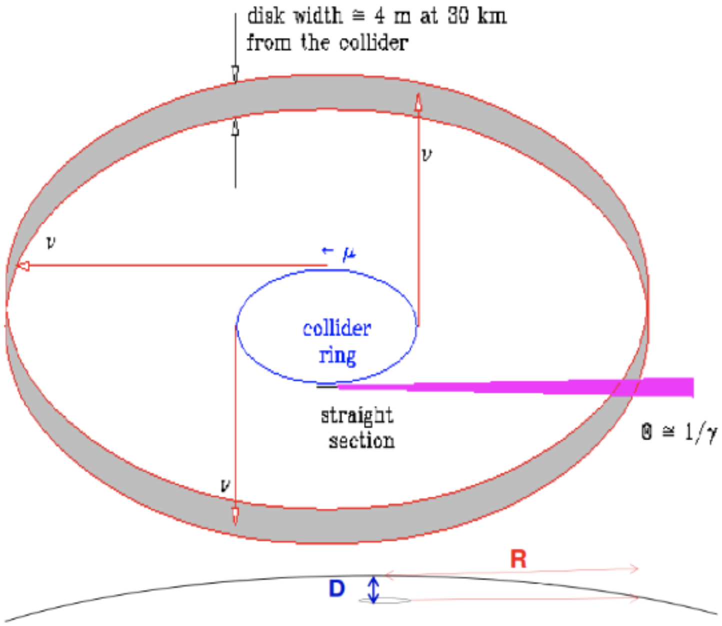
MICE





Increase in particle counts at smaller amplitude with low-Z absorber in place

Neutrino Background?



$$R = \sqrt{2R_{earth}D}$$

Muon Collider Accelerator Challenges

Neutrino Radiation Mitigation

Mokhov & Van Ginneken

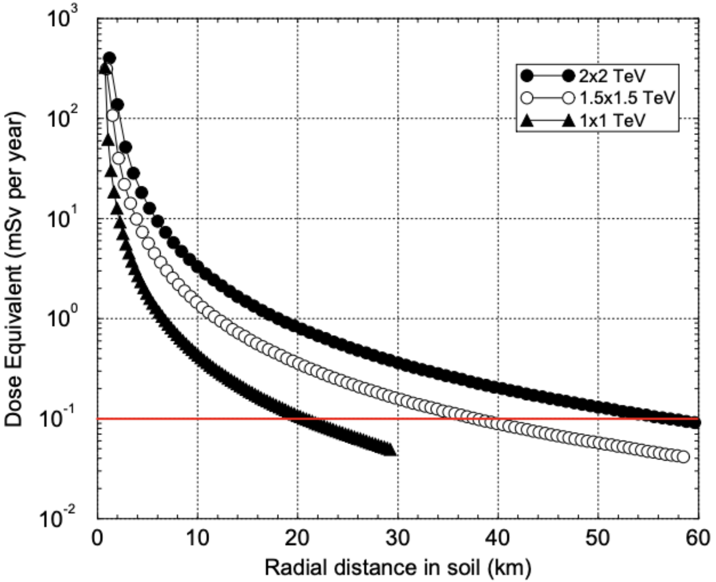


Figure 4: Maximum dose equivalent in TEP embedded in soil in high-energy muon collider orbit plane with 1.2×10^{21} decays per year *vs* distance from ring center.

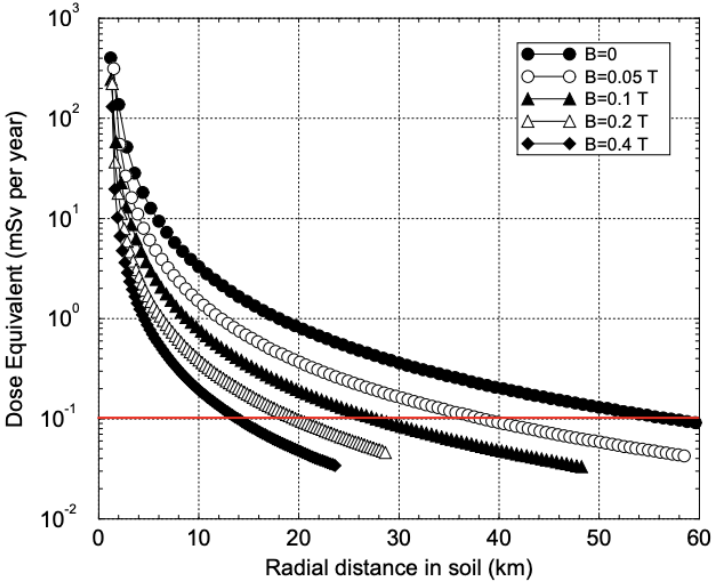


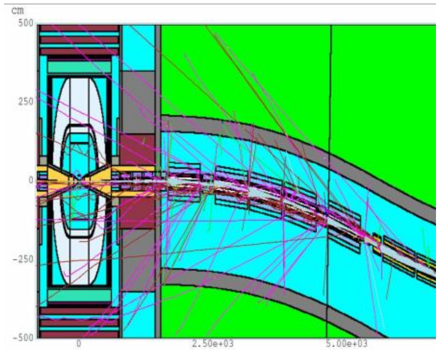
Figure 5: Average dose in TEP located in orbit plane *vs* distance from ring center in soil around a 2+2 TeV muon collider with 1.2×10^{21} decays per year for five values of vertical wave field.

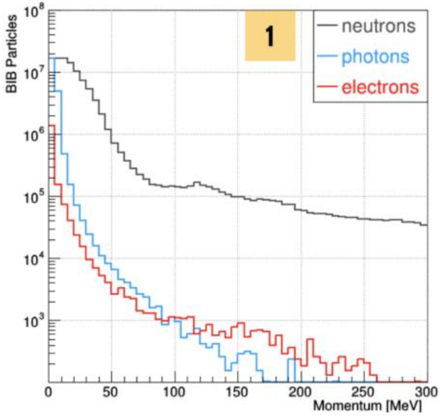
Higher the collider energy the deeper the ring needs to be.

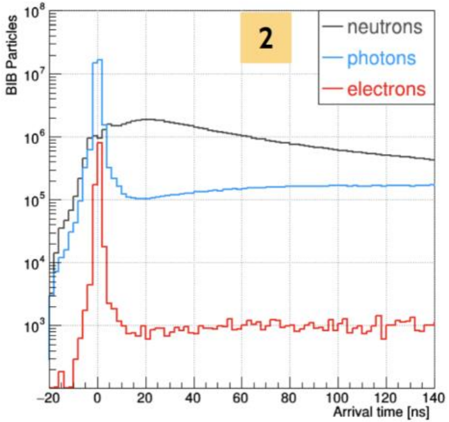
Magnetic field to dither the orbit also helps.

LHC Tunnel is 100m deep.

Muon Collider Challenges – Beam Induced Background







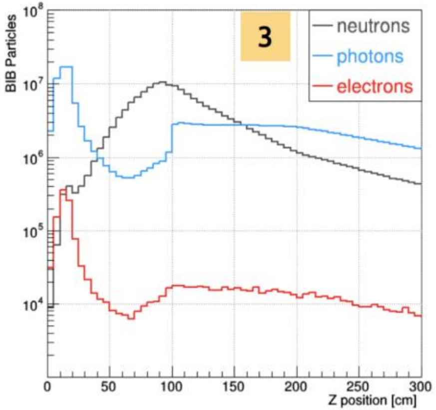
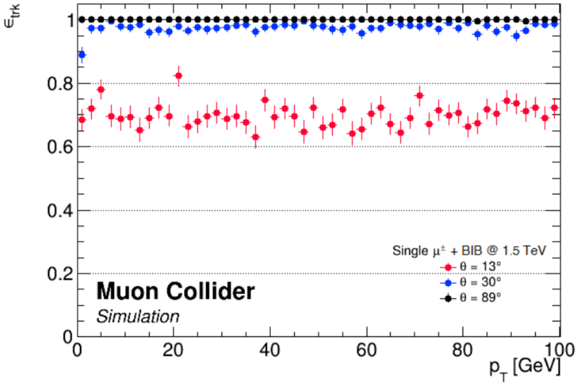


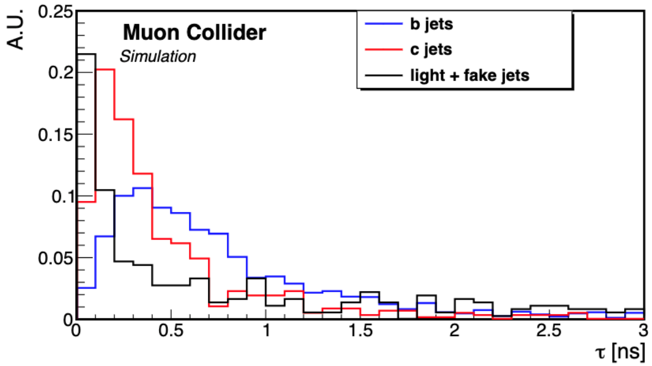
Figure: by N.Bartosik

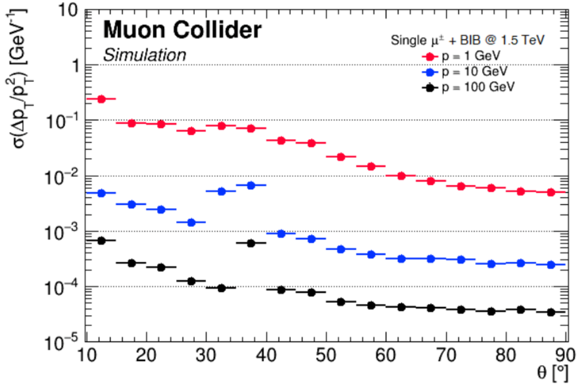
Mitigation Strategies needed in spite of the optimized conical absorber

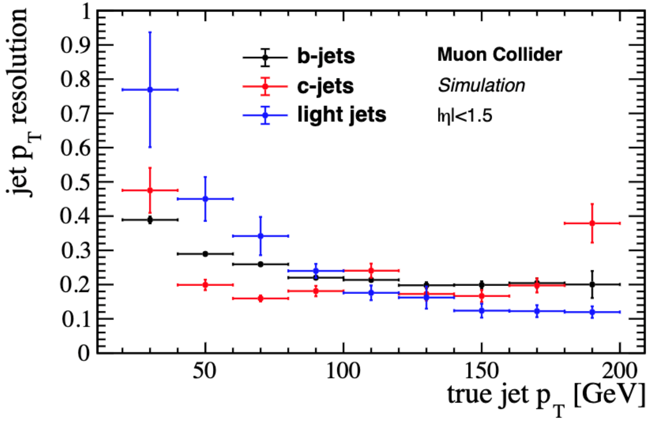
- Highly segmented detectors
- Timing cuts and energy cuts
- Doublet tracker design a la CMS tracker

Can we reconstruct stuff?









Muon Collider Challenges

Increased Accelerator R&D is the Key

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

Evaluation of physics potential (including detector technology)

- Impacts of beam induced background

Neutrino Flux Mitigation

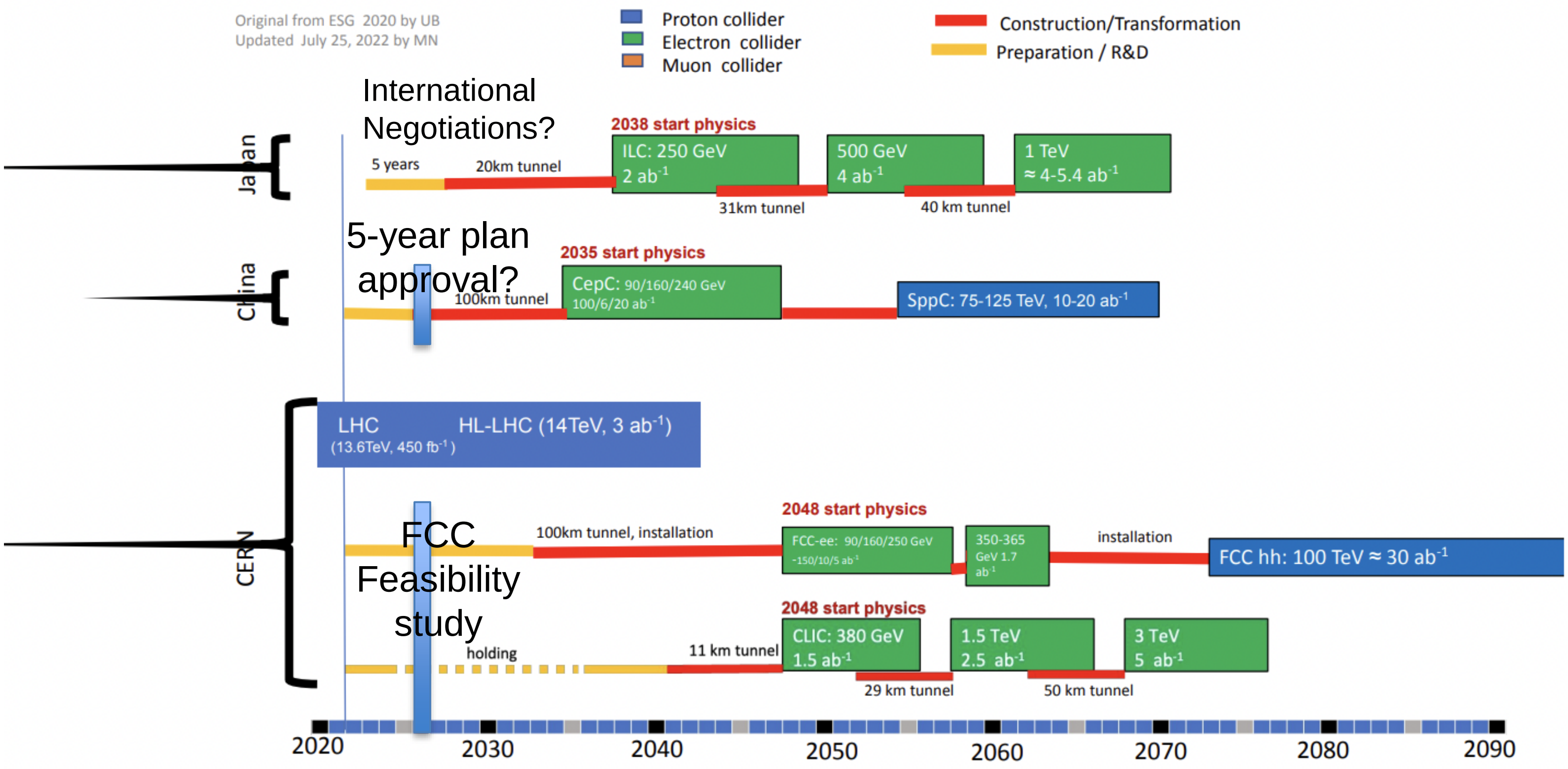
- Straight accelerator sections produce intense ν beam - safety

High Energy Systems

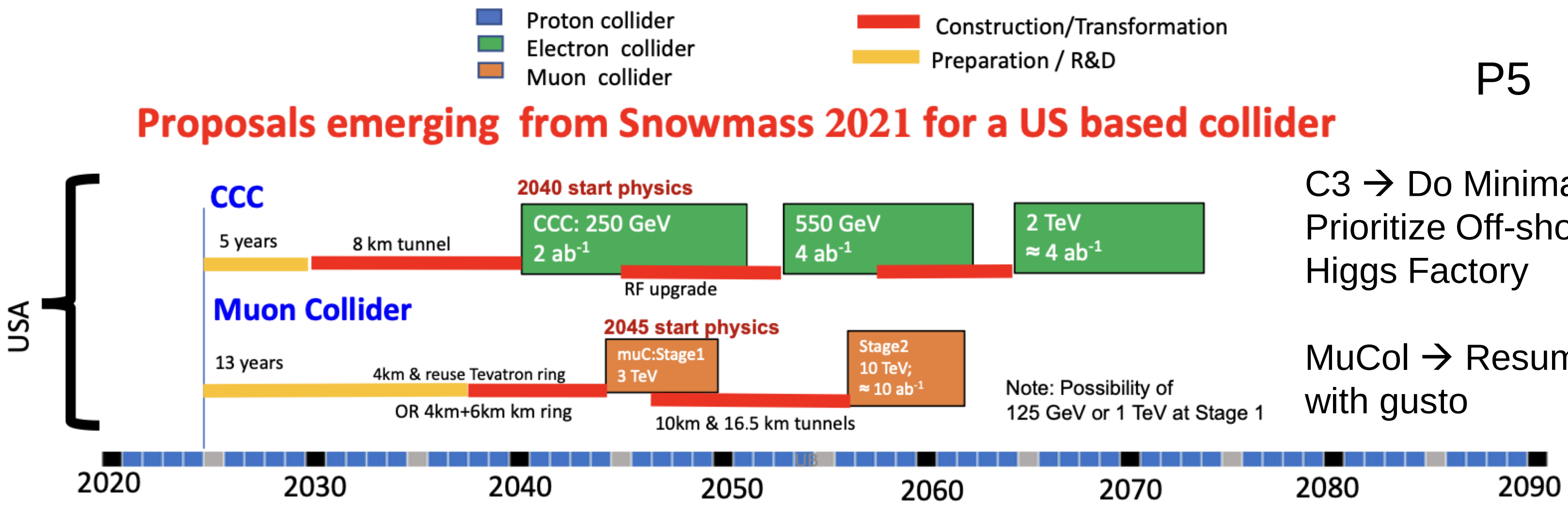
- Acceleration sections can impact the energy reach due to cost, power, technical risk, and impact on beam quality
- 10+ TeV Collider designs must be developed and fully evaluated

Cooling string demonstration to verify high brightness μ beam delivery

Summary – Asia & Europe



Summary + Invitation



P5

C3 → Do Minimal R&D
Prioritize Off-shore
Higgs Factory

MuCol → Resume R&D
with gusto

Welcome *your* participation in studies – starting with simulations
Accelerators, detector technologies, machine-detector interface …
Biggest need is accelerator workforce – ideal place for our young to start

Another Invitation!

Lepton Photon 2025, Madison, Wisconsin, USA

Aug 25 – 29, 2025
Monona Convention Center
America/Chicago timezone

Enter your search term

https://agenda.hep.wisc.edu/event/2188/

Please ask for US Visa letter ~now if you need one