Physics Synergies Muon Colliders

Isobel Ojalvo

PRINCETON UNIVERSITY

Physics Goals

Science Drivers from the Energy Frontier Executive Summary

- EF aims at investigating the fundamental physics of the Universe at the highest energies or – equivalently – the shortest timescales after the Big Bang
- We investigate open questions and explore the unknown using various probes to discover and characterize the nature of new physics, through the breadth and multitude of collider physics signatures

We need to use both energy reach and precision measurements to push beyond the 1 TeV scale in our exploration

The quest for new physics will be thus conducted in a two-tier approach: 1) looking for indirect evidence of beyond-the-Standard-Model physics (BSM) through precision measurements of the properties of the Higgs boson and other SM particles

2) Searching for direct evidence of BSM physics at the energy frontier, reaching multi-TeV scales

The Higgs Boson IS Special!

The discovery of the Higgs in 2012 was an important milestone for HEP

- As far as we know, the Higgs has no spin, no charge, no structure
- It provides an exciting program for precision measurements and searches
- Many of us are still excited about it and others, especially scientists, should be excited about it!

"A self-interacting Higgs (as SM predicts) would be unlike anything yet seen in nature; all other interactions change particle identity"

Higgs

Precision measurements
- mass, width
- spin, CP, couplings
- off-shell coupling, width
- differential distributions

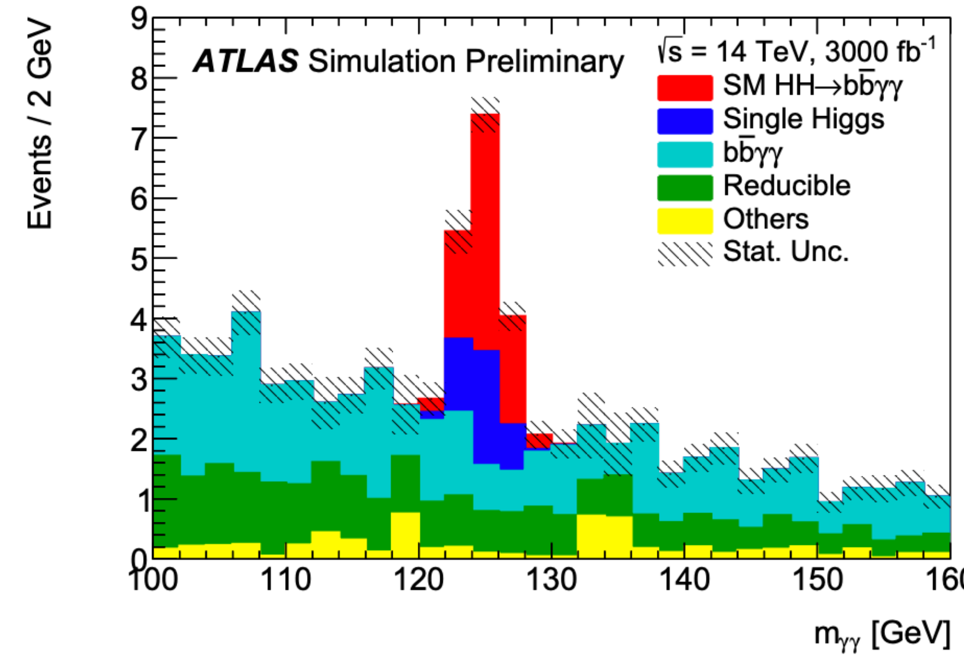
Tool for Discovery
- portal to BSM
- portal to hidden sector
- portal to DM

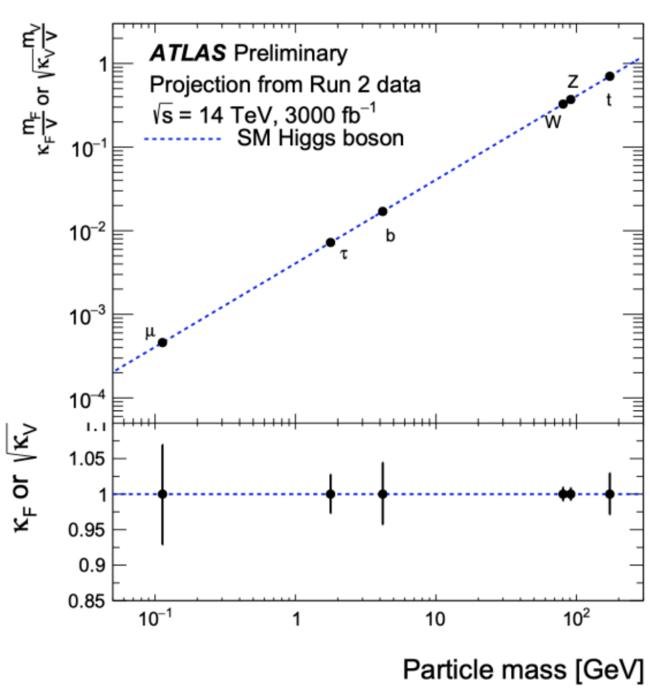
SM or BSM?
- Higgs Doublets
- Higgs Singlets
- Composite Higgs

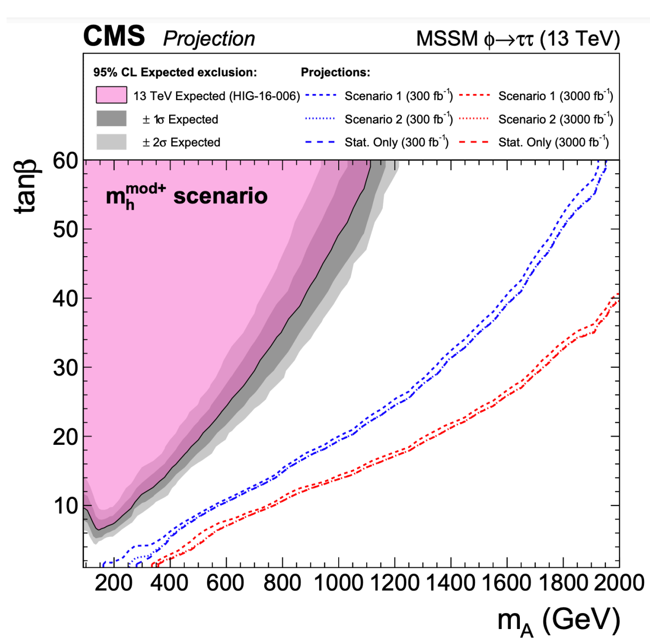
Rare / beyond SM decays
- $H \rightarrow Z\gamma$
- $H \rightarrow \mu\mu$
- $H \rightarrow cc$
- $H \rightarrow \tau\mu, \tau e, e\mu$
- $H \rightarrow J/\Psi\gamma, \Upsilon\gamma$, ...

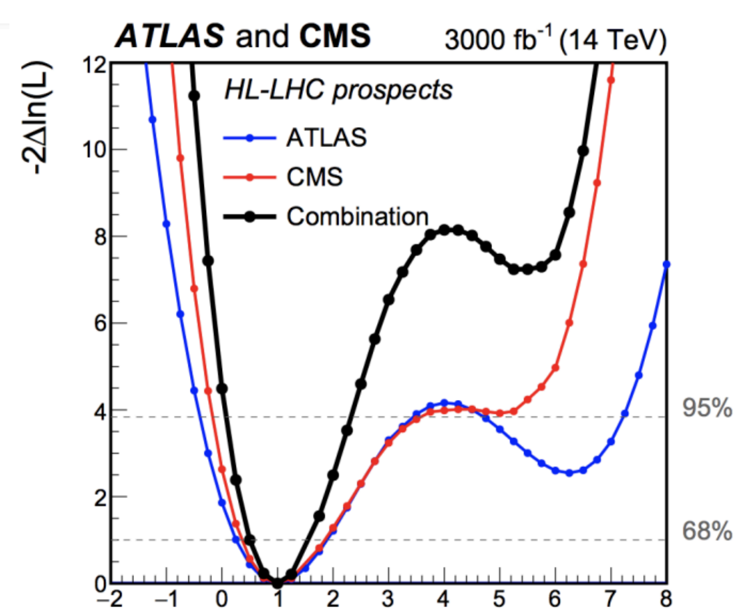
HL-LHC Benchmark

The HL era of LHC will dramatically expand the physics reach for Higgs physics:
- 2-4% precision for many of the Higgs couplings
- much larger uncertainties on Z and charm and ~50% on the self-coupling

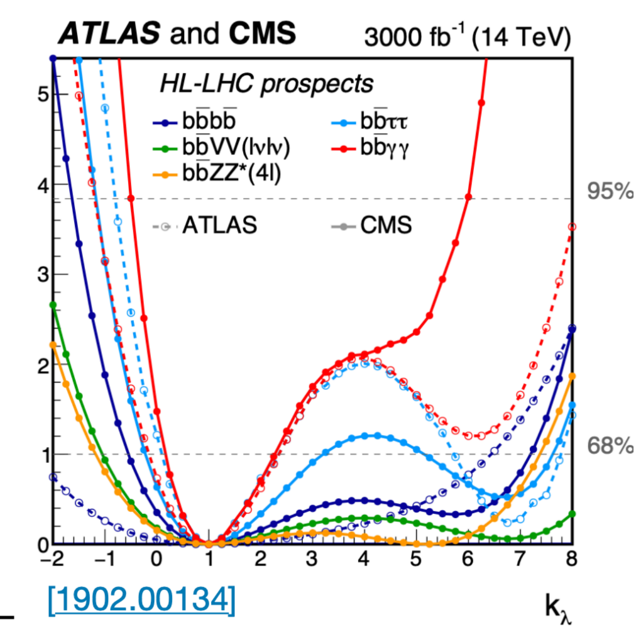








$$k_\lambda = \frac{\lambda}{\lambda_{SM}}$$



[1902.00134]

Where to look?

Two holes in understanding the Higgs after the HL-LHC

$$-\mu^2 H^\dagger H + \lambda \left(H^\dagger H\right)^2$$

Higgs potential (self-coupling)

$$\lambda^u_{ij} Q_i H \bar{u}_j - \lambda^d_{ij} Q_i H^c \bar{d}_j$$

Light flavor Yukawas

Extended scalar sectors
EW phase transition
Baryogenesis
Hierarchy Problem
…
…

Flavor Puzzle
Strong CP Problem
Baryogenesis
Extended scalar sectors
…
…

Status at Higgs Factories (Initial Stage)

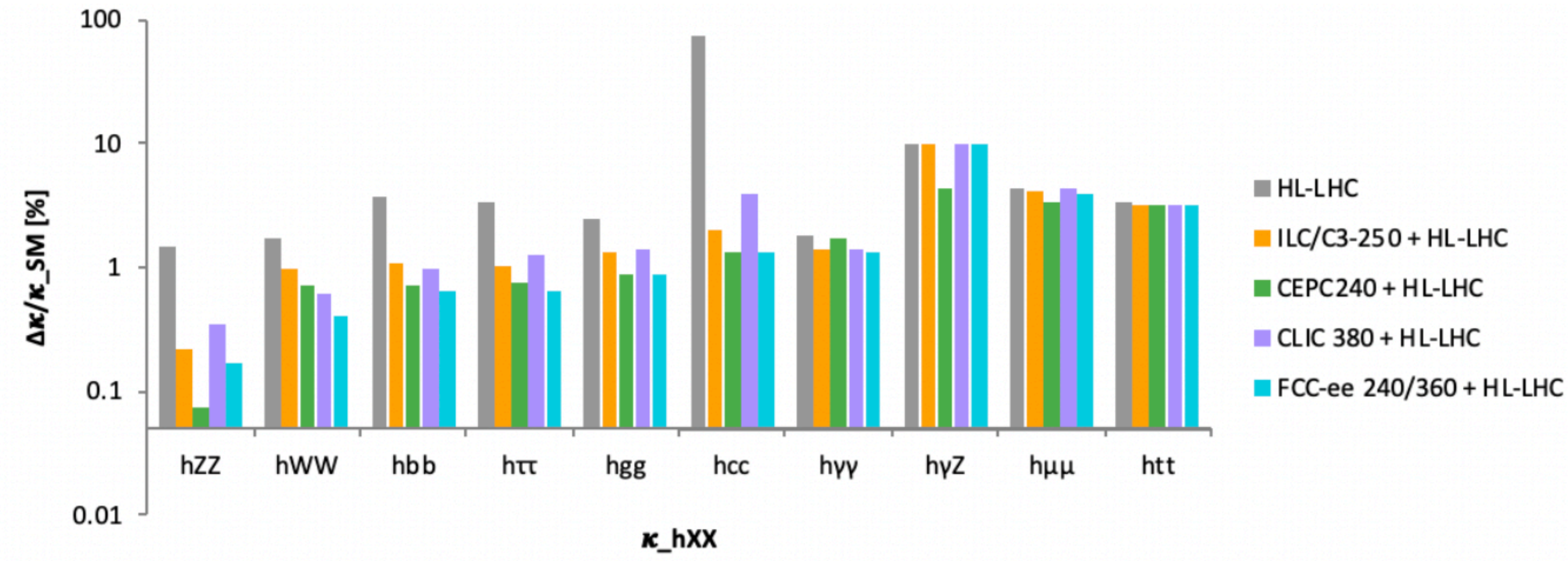
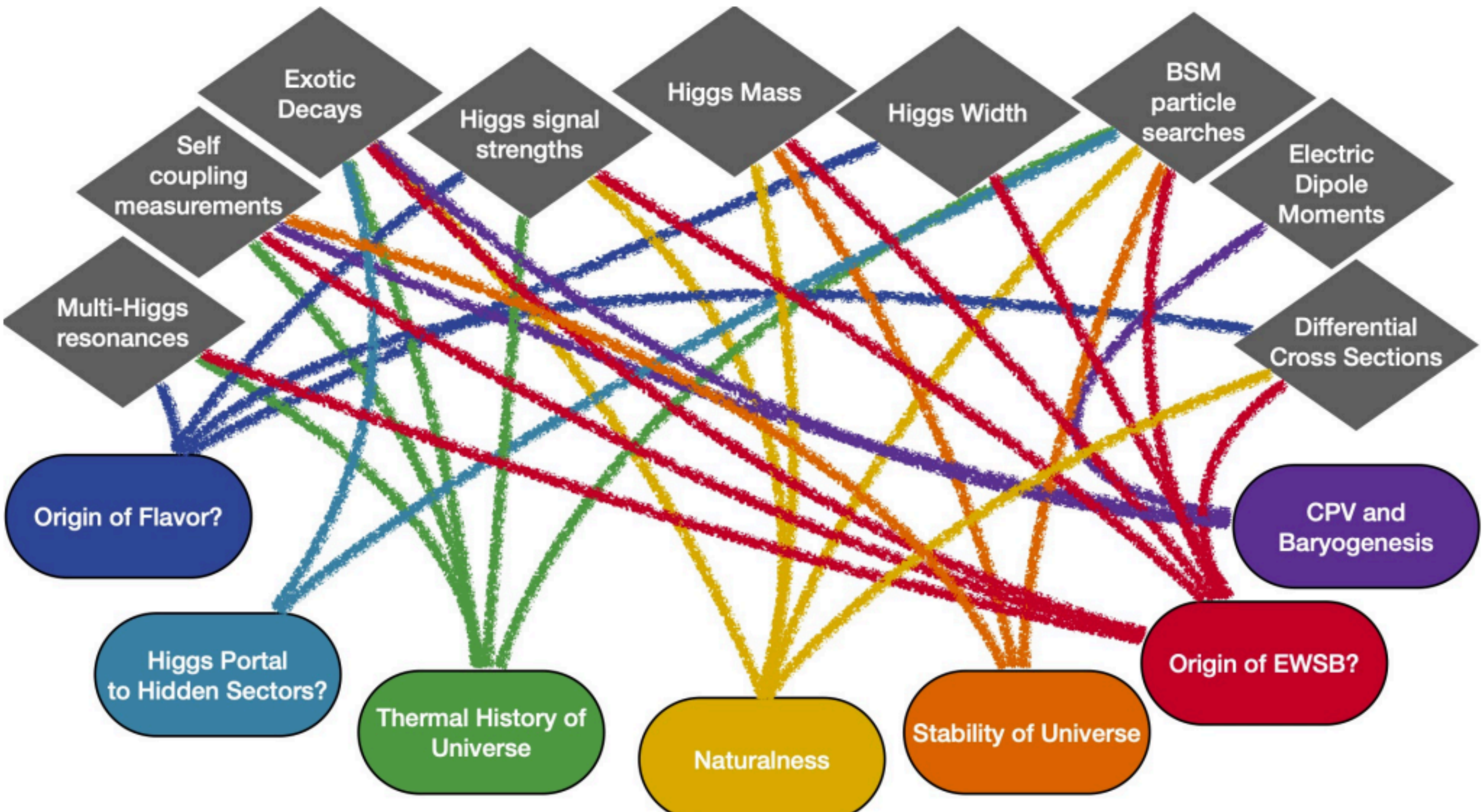


Figure 1-7. *Projected relative Higgs-coupling measurements in % when combined with HL-LHC results. All values assume no BSM decay modes. In addition, only the following collider stages are shown: 3 ab^{-1} and two interaction points (IPs), ATLAS and CMS, for the HL-LHC at 14 TeV, 2 ab^{-1} and 1 IP at 250 GeV for ILC/C^3, 20 ab^{-1} and 2 IP at 240 GeV for CEPC, 1 ab^{-1} and 1 IP at 380 GeV for CLIC, and 5 ab^{-1} and 4 IPs at 240 GeV for FCC-ee. Note that the HL-LHC κ_{hcc} projection uses only the CMS detector and is an upper bound [30].*

What do the Couplings tell us?

No need to tell this group how important the Higgs is to HEP…



Where will BSM physics lie?

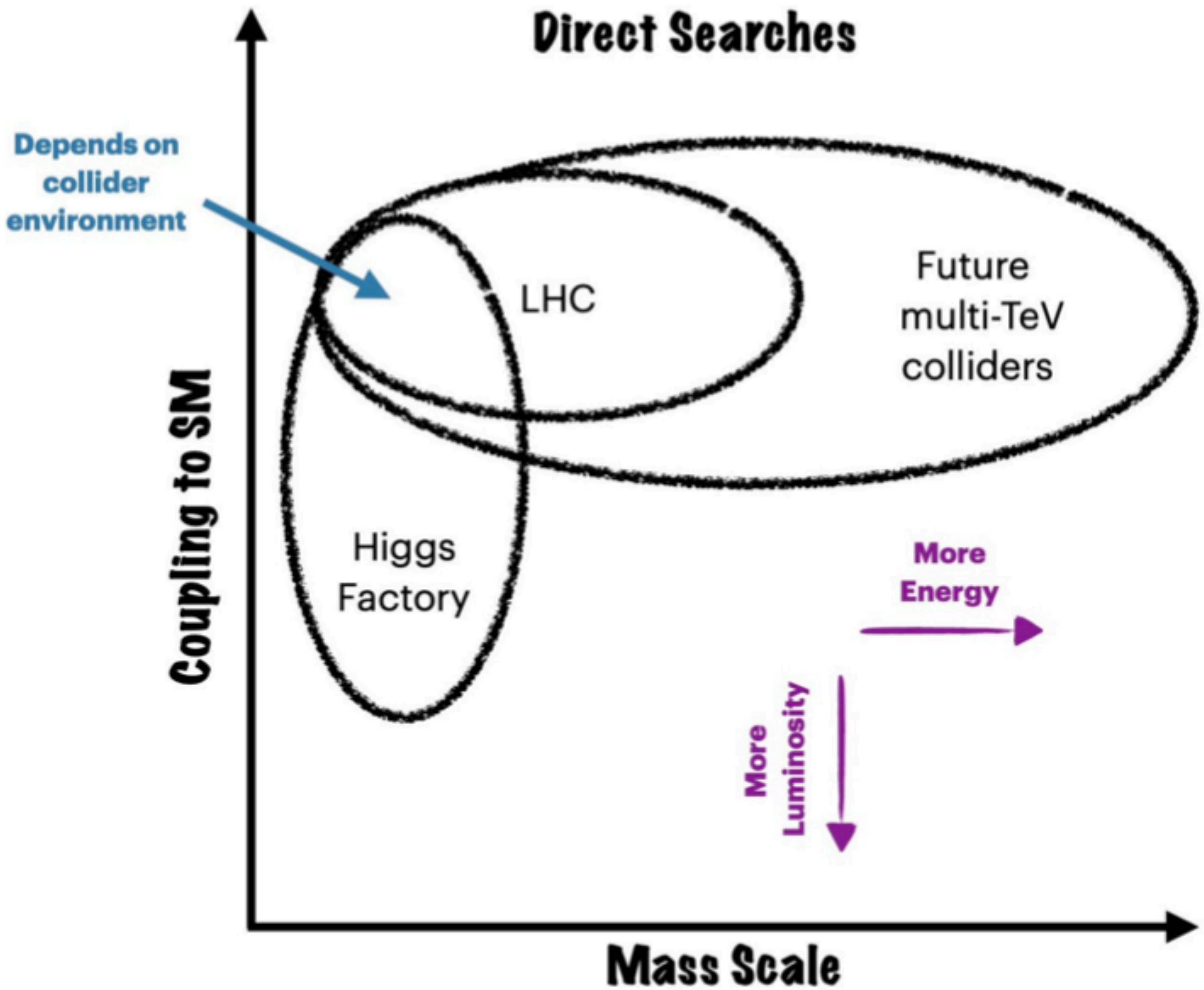


Figure 1-2. *The direct coverage of various colliders in the schematic space of coupling to the SM versus mass scale of BSM physics. "Higgs factory" and "multi-TeV colliders" correspond to a generic option among the ones listed in Table 1-1 and Table 1-2 respectively.*

What do the Couplings tell us?

Size of Higgs Coupling deviations?

$\delta\eta_{SM}$ $\sim 1\%$ / $\sim .1\%$

$$\delta\eta_{SM} \sim c_\eta \frac{v^2}{M^2}$$

Tree level origin

$$\sim \frac{v^2}{M^2}$$

- **SM Neutral** e.g. scalar singlet: $\sim \left(\frac{\lambda^2_{h^2 s}}{2M^2}\right)\frac{v^2}{M^2}$
  - $M \lesssim 1.7\,\text{TeV}$
  - $M \lesssim 5.5\,\text{TeV}$
- **SM Charged** e.g. 2HDM: $\sim \left(\frac{\lambda^2_6 v^2}{M^2}\right)\frac{v^2}{M^2}$
  - $M \lesssim 0.8\,\text{TeV}$
  - $M \lesssim 1.4\,\text{TeV}$

Loop level

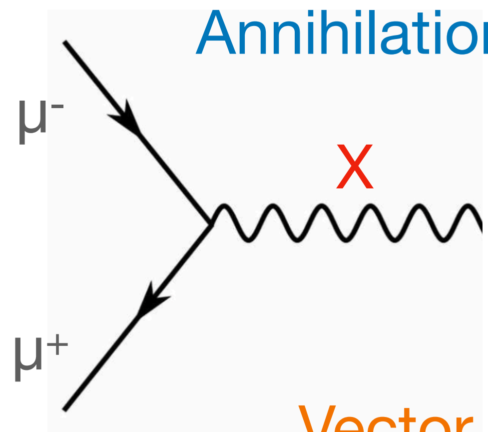
$$\sim \frac{1}{(4\pi)^2}\frac{v^2}{M^2}$$

- **SM Neutral** e.g. scalar singlet: $\sim \left(\frac{\lambda^2_{h^2 s^2}}{48\pi^2}\right)\frac{v^2}{M^2}$
  - $M \lesssim 0.1\,\text{TeV}$
  - $M \lesssim 0.4\,\text{TeV}$
- **SM Charged** w/ SM loop e.g. stops in SUSY: $\sim \frac{1}{4}\frac{m_t^2}{m_{\tilde{t}}^2}$
  - $M \lesssim 0.9\,\text{TeV}$
  - $M \lesssim 2.8\,\text{TeV}$

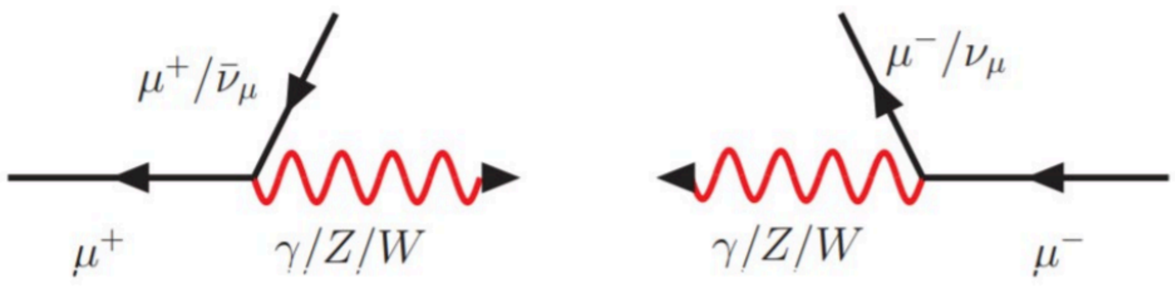
Conservative Scaling for Upper Limit on Mass Scale Probed by Higgs Precision

A machine **beyond** a Higgs Factory should try to go **beyond** these Mass Scales

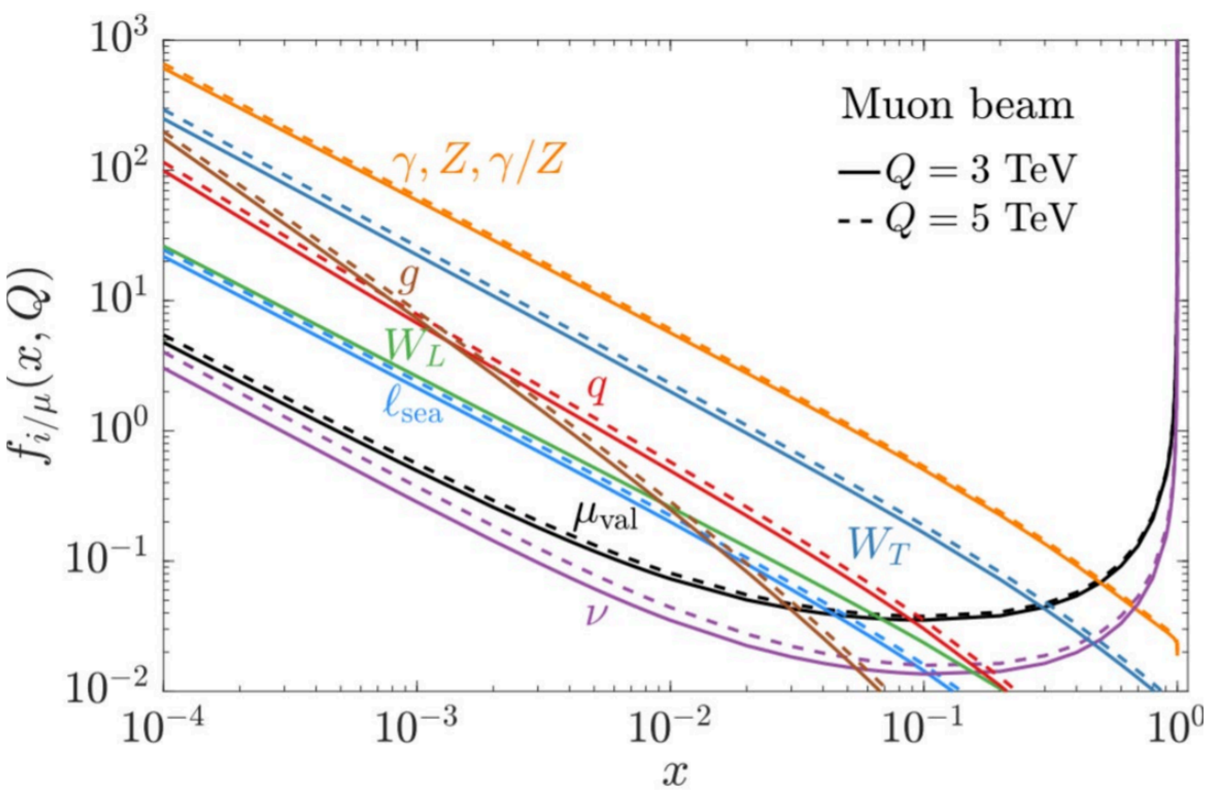
Why a Muon Collider?

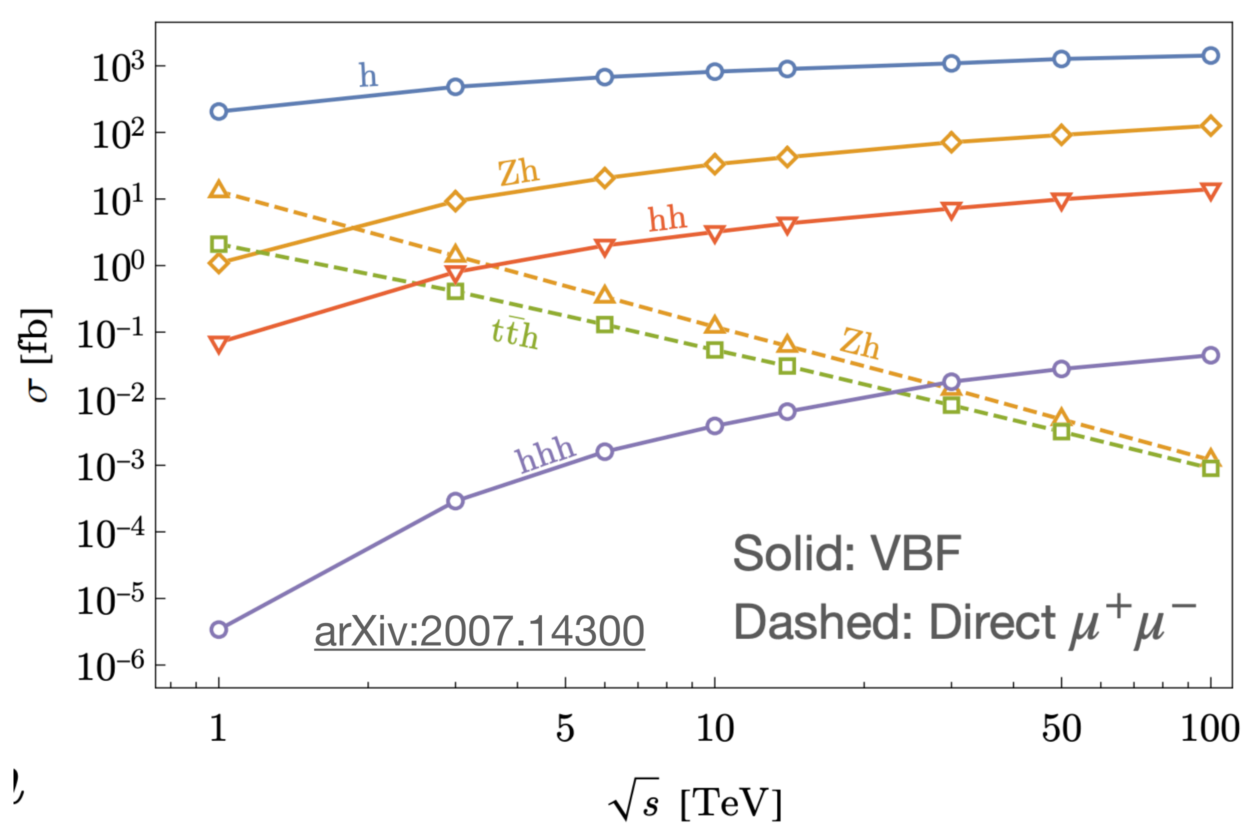


Vector Boson Fusion



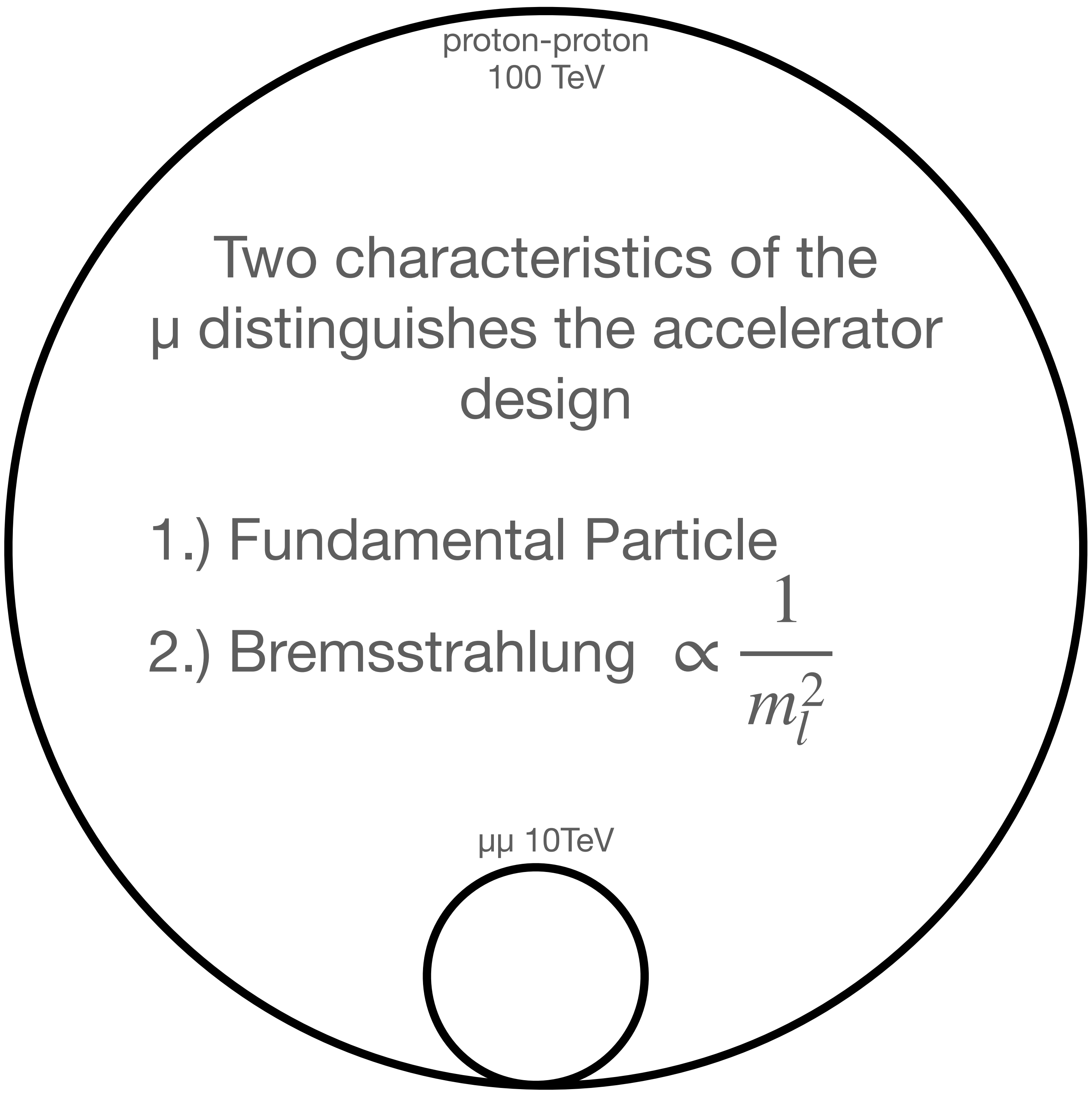
Two main processes:
Annihilation, Vector Boson Fusion





Why a Muon Collider?

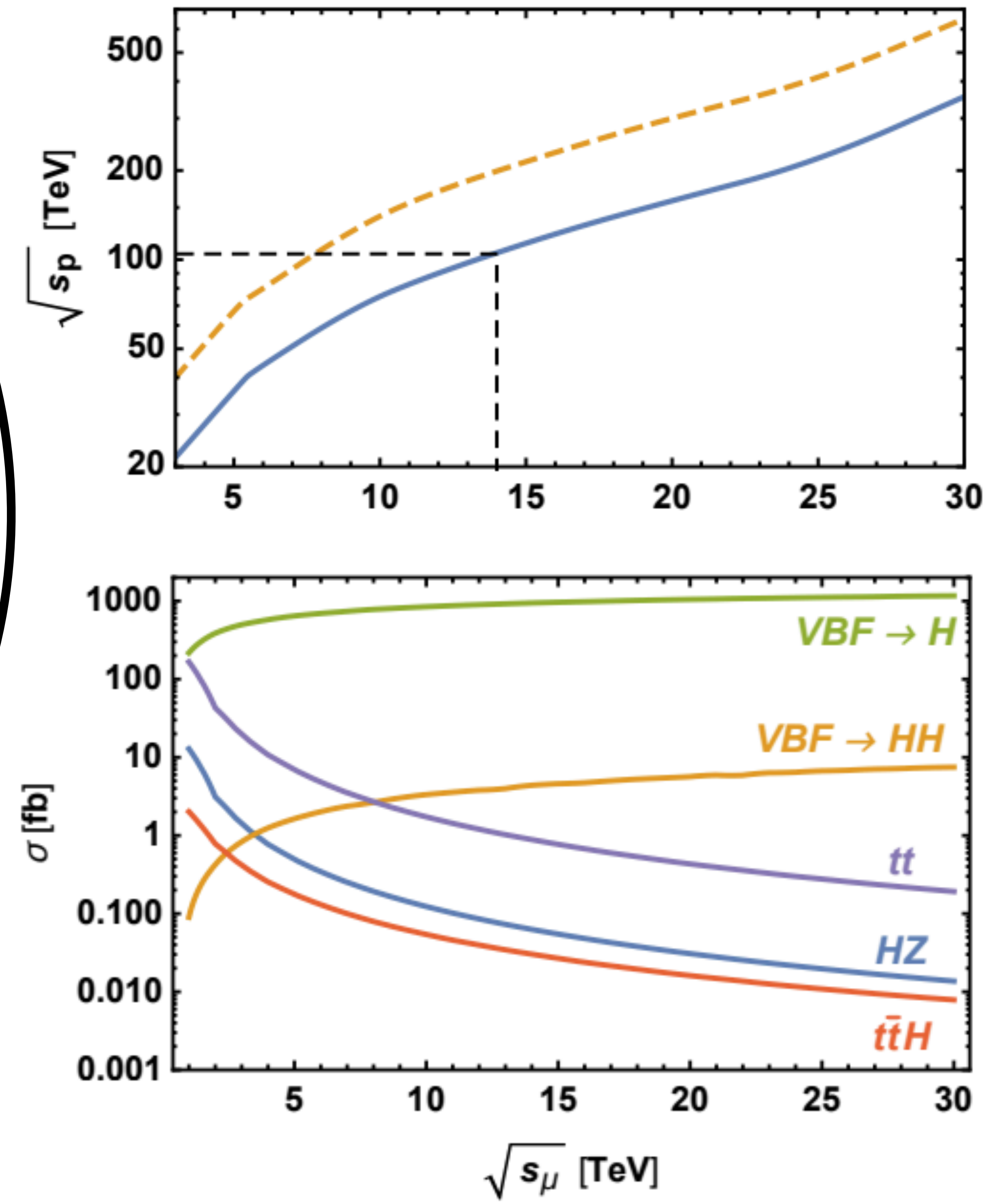
Unlike protons, they are fundamental!



Two characteristics of the μ distinguishes the accelerator design

1.) Fundamental Particle

2.) Bremsstrahlung $\propto \frac{1}{m_l^2}$



1901.06150

Protons vs. Muons

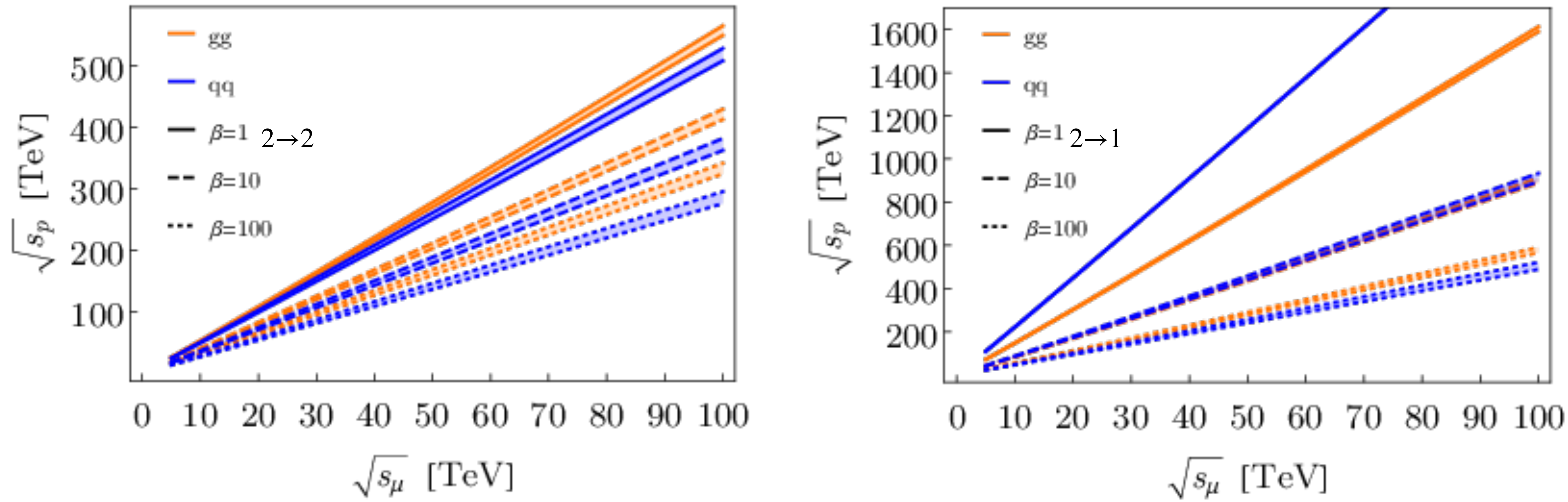


Figure 1: The c.m. energy $\sqrt{s_p}$ in TeV at a proton-proton collider versus $\sqrt{s_\mu}$ in TeV at a muon collider, which yield equivalent cross sections. Curves correspond to production via a gg (orange) or $q\bar{q}$ (blue) initial state at the proton-proton collider, while production at the muon collider is determined by $\mu^+\mu^-$. The partonic cross sections are related by $\beta \equiv [\hat{\sigma}]_p/[\hat{\sigma}]_\mu$. The bands correspond to two different choices of proton PDF sets, `NNPDF3.0 LO` (as in [32]) and `CT18NNLO`. The left (right) panel is for $2 \to 1$ ($2 \to 2$) scattering.

Comparing SM Higgs Background

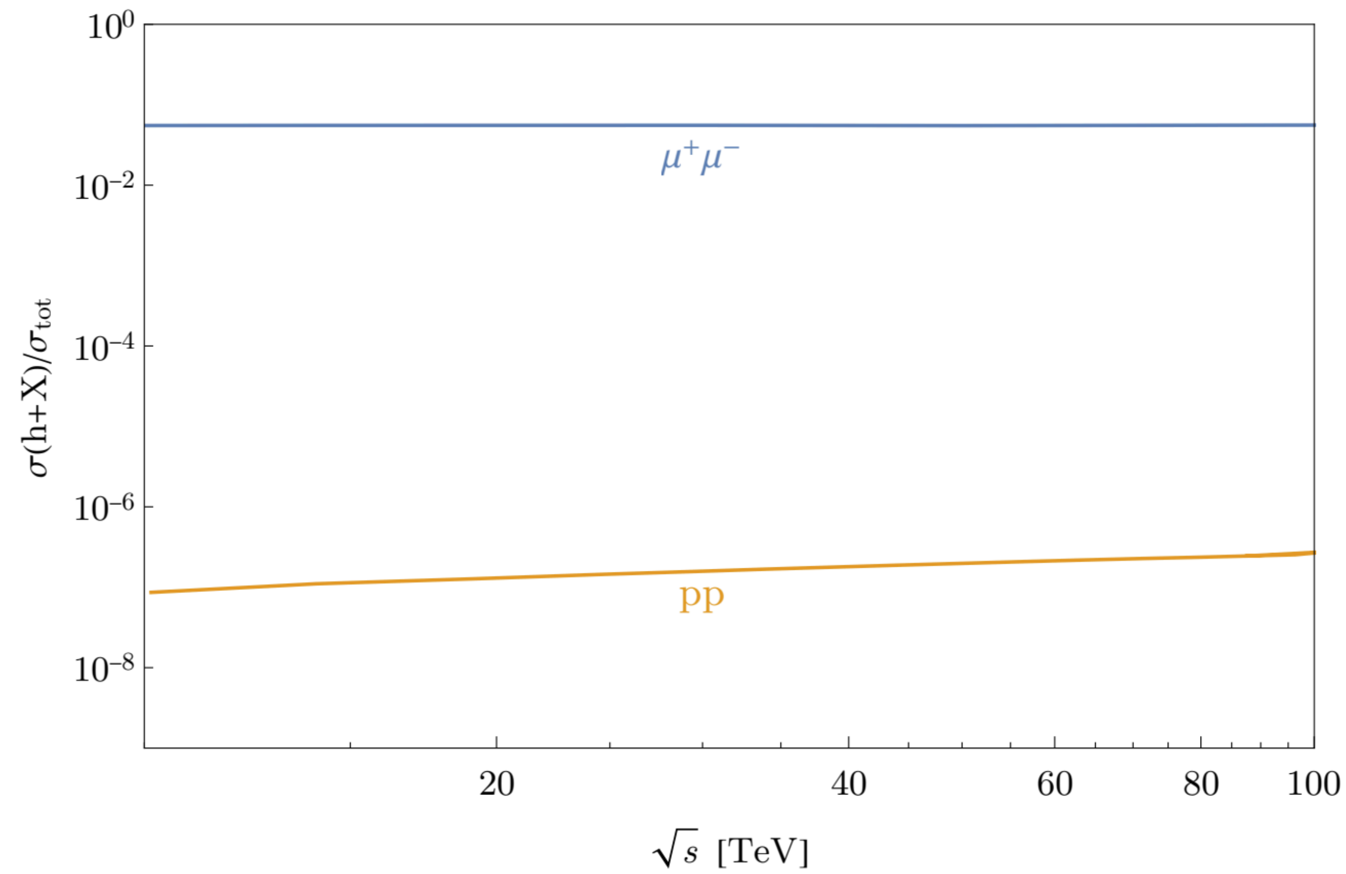
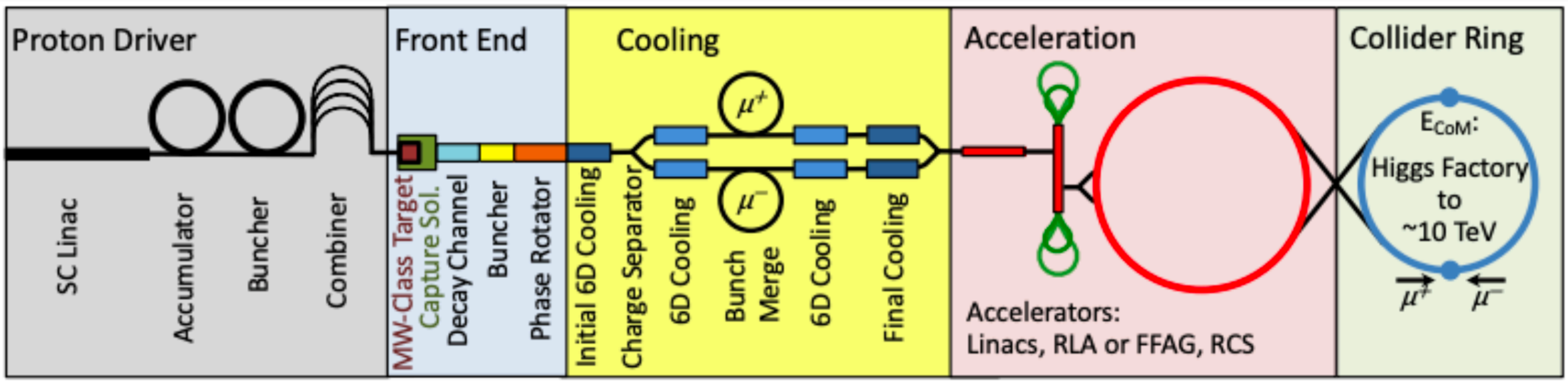
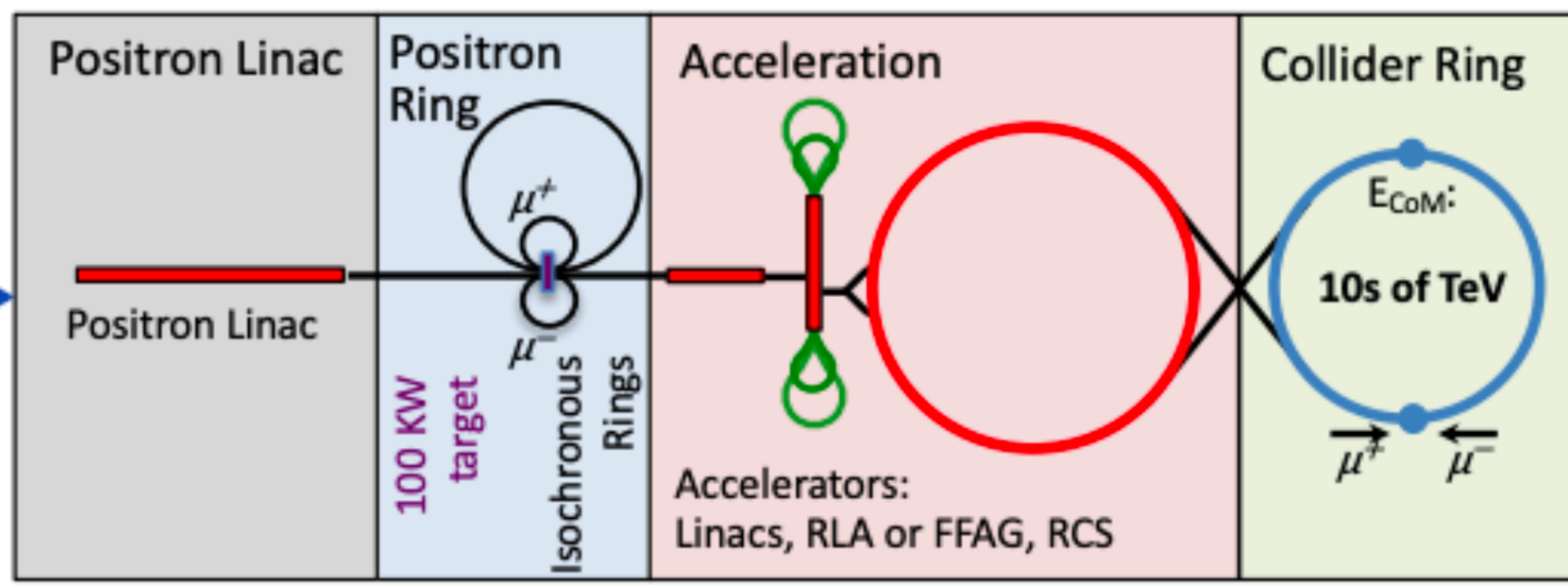


Figure 4: Higgs production cross section $\sigma(h + X)$ as a fraction of a representative "total" cross section σ_{tot} for $\mu^+\mu^-$ and pp colliders. For $\mu^+\mu^-$ colliders, we compute Higgs production using the LO cross section for $\mu^+\mu^- \to h + \nu\bar{\nu}$, while the "total" cross section σ_{tot} is taken to be the rate for single electroweak boson production, which is dominated by VBF production of W, Z, h, γ at these energies. For pp colliders we take the Higgs production cross section to be the N3LO cross section for $gg \to h$ [50] presented in [51], while the "total" cross section σ_{tot} is taken to be the $pp \to b\bar{b}$ cross section computed by MCFM [52].

Muon Collider Concepts



Low EMmittance Muon Accelerator (LEMMA):
10^{11} μ pairs/sec from e^+e^- interactions. The small production emittance allows lower overall charge in the collider rings – hence, lower backgrounds in a collider detector and a higher potential CoM energy due to neutrino radiation.



Muon Collider Luminosity vs. Energy

Comparing Luminosity in MAP vs. CLIC

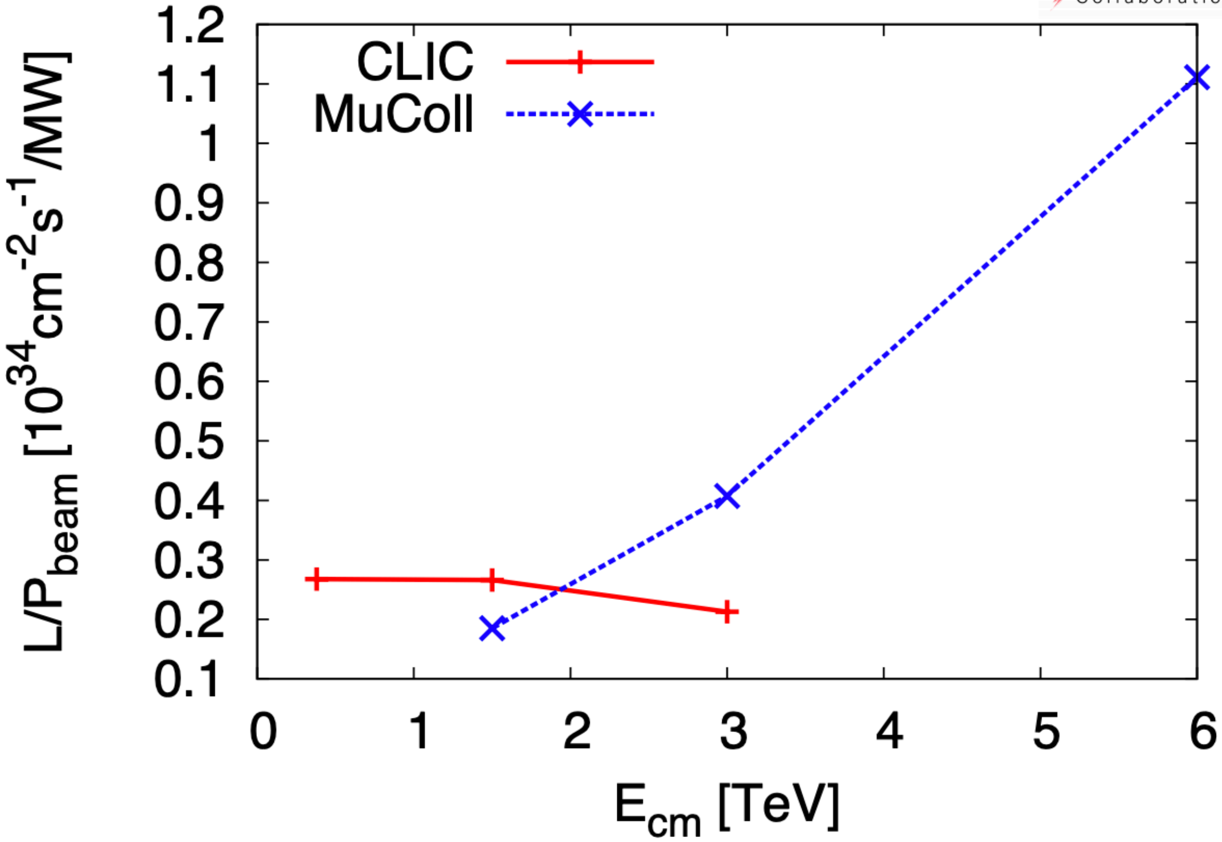
Linear colliders: Luminosity per beam power is independent of collision energy for same technology

CLIC is at the limit of what one can do (decades of R&D)

No obvious way to improve

$$\mathcal{L} \propto \frac{N}{\sqrt{\beta_x \epsilon_x}} \frac{1}{\sqrt{\beta_y \epsilon_y}} P_{beam}$$

Note: normalised emittances used, they do not decrease with energy



Muon collider: Luminosity per beam power can increase with energy

Potential for high energies

$$\mathcal{L} \propto \gamma \langle B \rangle \sigma_\delta \frac{N_0}{\epsilon \epsilon_L} f_r N_0 \gamma$$

D. Schulte

Beyond Initial Stage

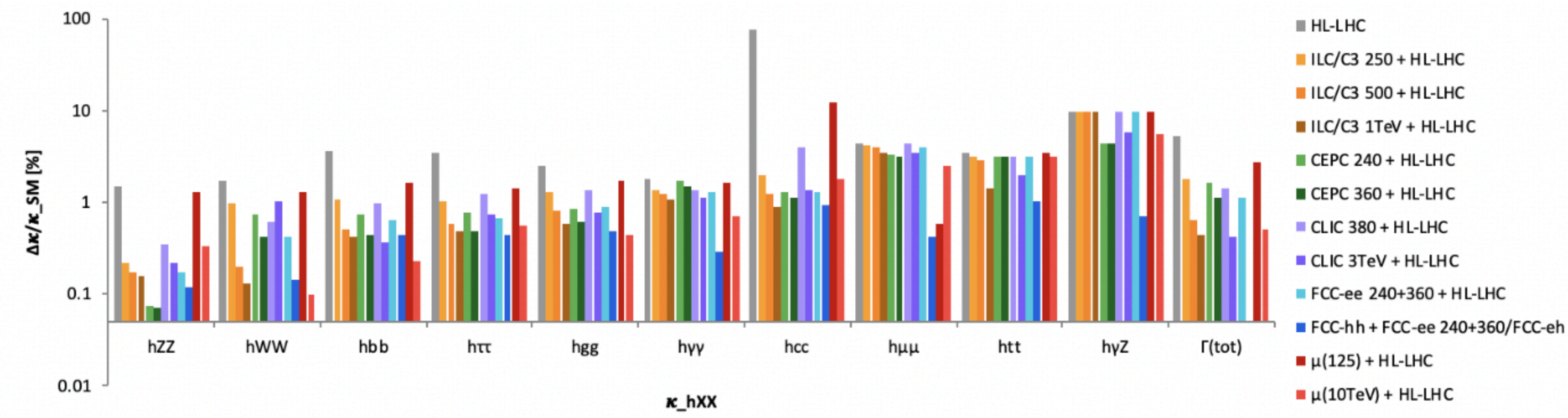


FIG. 20: Relative Higgs coupling measurements in % when combined with HL-LHC results. All values assume no beyond the Standard Model decay modes of the Higgs boson. The energies and luminosities are those defined in Table IV A.

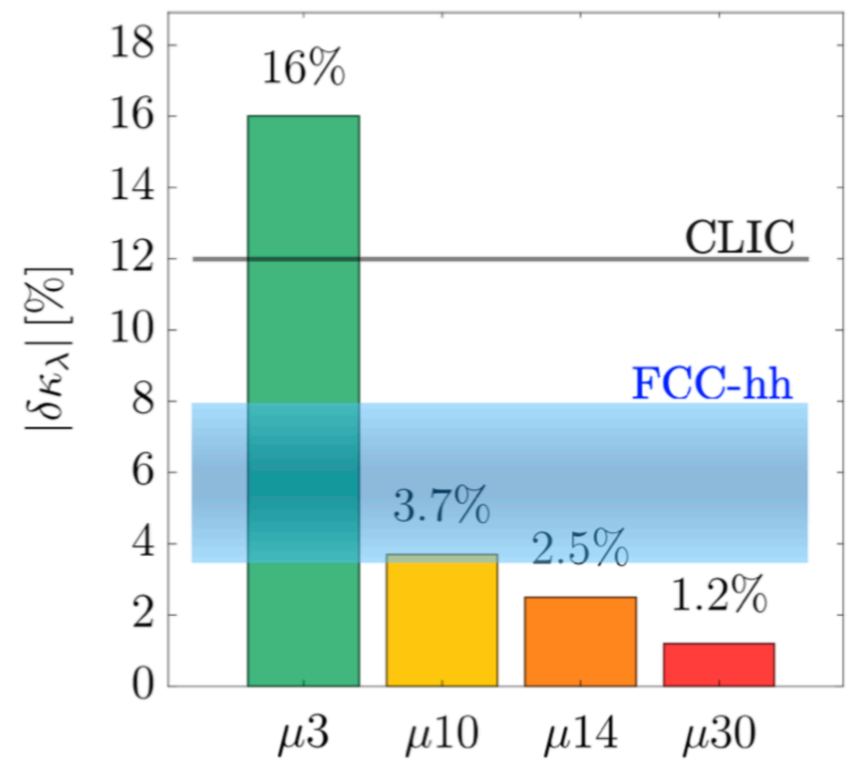
Muon Collider Detector Concepts

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

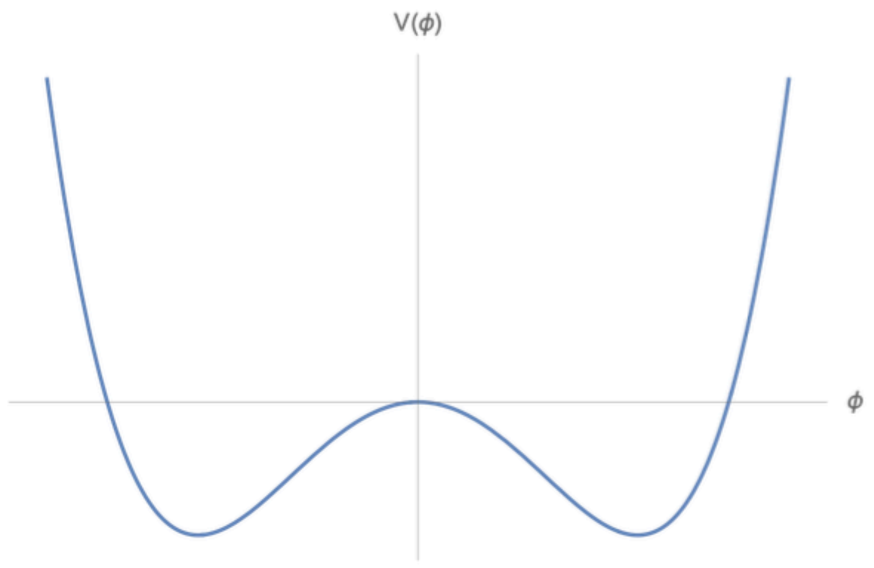
* No input used for μ collider

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~ 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.

Higgs Potential/Self Coupling

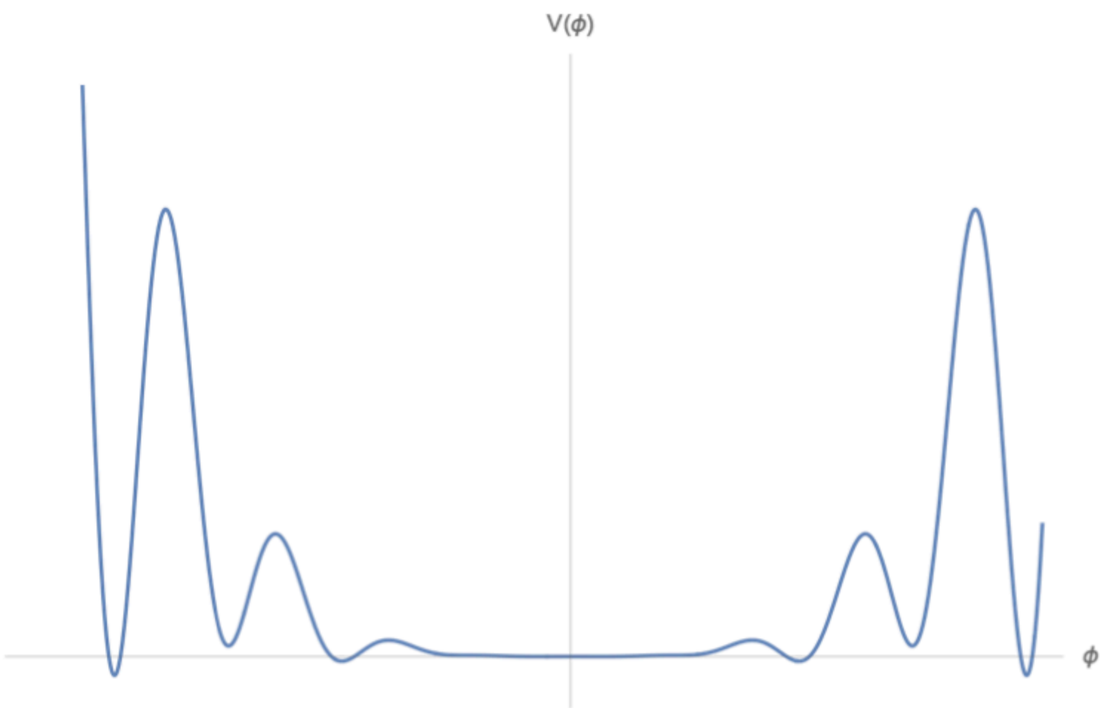


$$V(\phi) = -\frac{\mu^2}{2}\phi^2 + \frac{\lambda}{4}\phi^4$$

The negative sign is put by hand.
Why?

Maybe the Higgs *isn't* fundamental?

Maybe the Higgs *is* fundamental but there is still dynamics at play?



Timelines

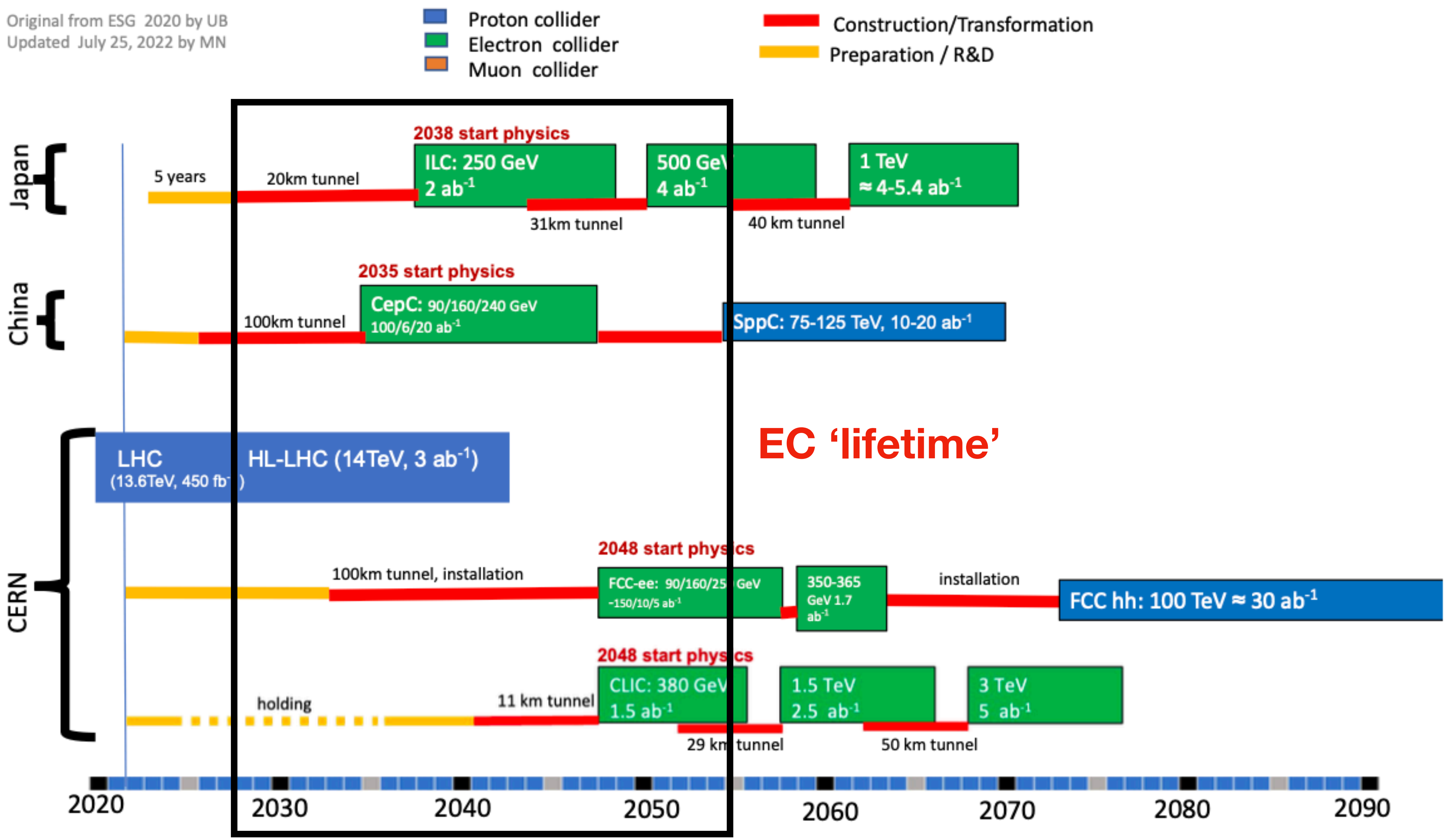
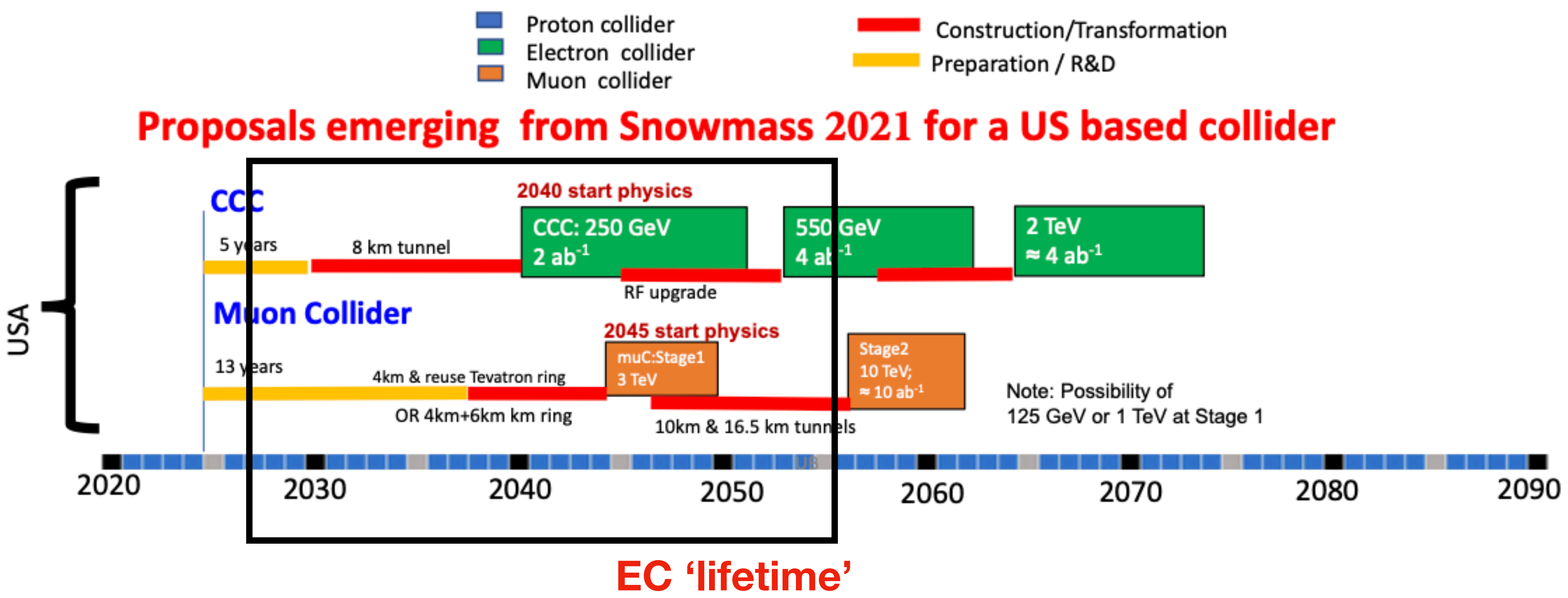


Figure A-1. *Projected timelines for R&D, construction, and physics operations for some of the leading proposed future collider options.*

Timelines



Proton collider
Electron collider
Muon collider
Construction/Transformation
Preparation / R&D
Proposals emerging from Snowmass 2021 for a US based collider
USA
CCC
5 years
8 km tunnel
2040 start physics
CCC: 250 GeV
2 ab-1
RF upgrade
550 GeV
4 ab-1
2 TeV
≈ 4 ab-1
Muon Collider
13 years
4km & reuse Tevatron ring
OR 4km+6km km ring
2045 start physics
muC:Stage1
3 TeV
10km & 16.5 km tunnels
Stage2
10 TeV;
≈ 10 ab-1
Note: Possibility of
125 GeV or 1 TeV at Stage 1
2020
2030
2040
2050
2060
2070
2080
2090
EC 'lifetime'

Conclusions

The next 5-40 years will be an exciting time in Collider Physics!

Snowmass process is marching on
- Finalize studies and make worthwhile comparisons
- Advocate to our scientific colleagues
- Advocate to the public, our funding agencies and governments

Our goal should be to create a comprehensive international program that welcomes all with know-how and interest