Physics at the Higgs factories (circular and linear)

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P5 Town Hall Meeting on the Future of High Energy Physics. BNL April 13, 2023

2014 P5: Higgs as a new tool for discovery

In summary, **the EF supports a fast start for construction of an e^+e^- Higgs factory (linear or circular), and a significant R&D program for multi-TeV colliders (hadron and muon). The realization of a Higgs factory will require an immediate, vigorous and targeted detector R&D program, while the study towards multi-TeV colliders will need significant and long-term investments in a broad spectrum of R&D programs for accelerators and detectors.** These projects have the potential to be transformative as they will push the boundaries of our knowledge by testing the limits of the SM, and indirectly or directly discovering new physics beyond the SM.

- 2021-2022 Snowmass EF report

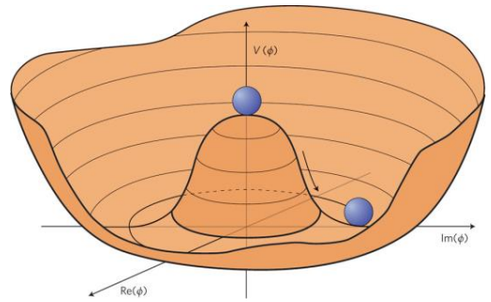
The goal of my talk:
Outline the physics argument behind this statement.

For more details: Snowmass reports European strategy update

Why focusing on Higgs?

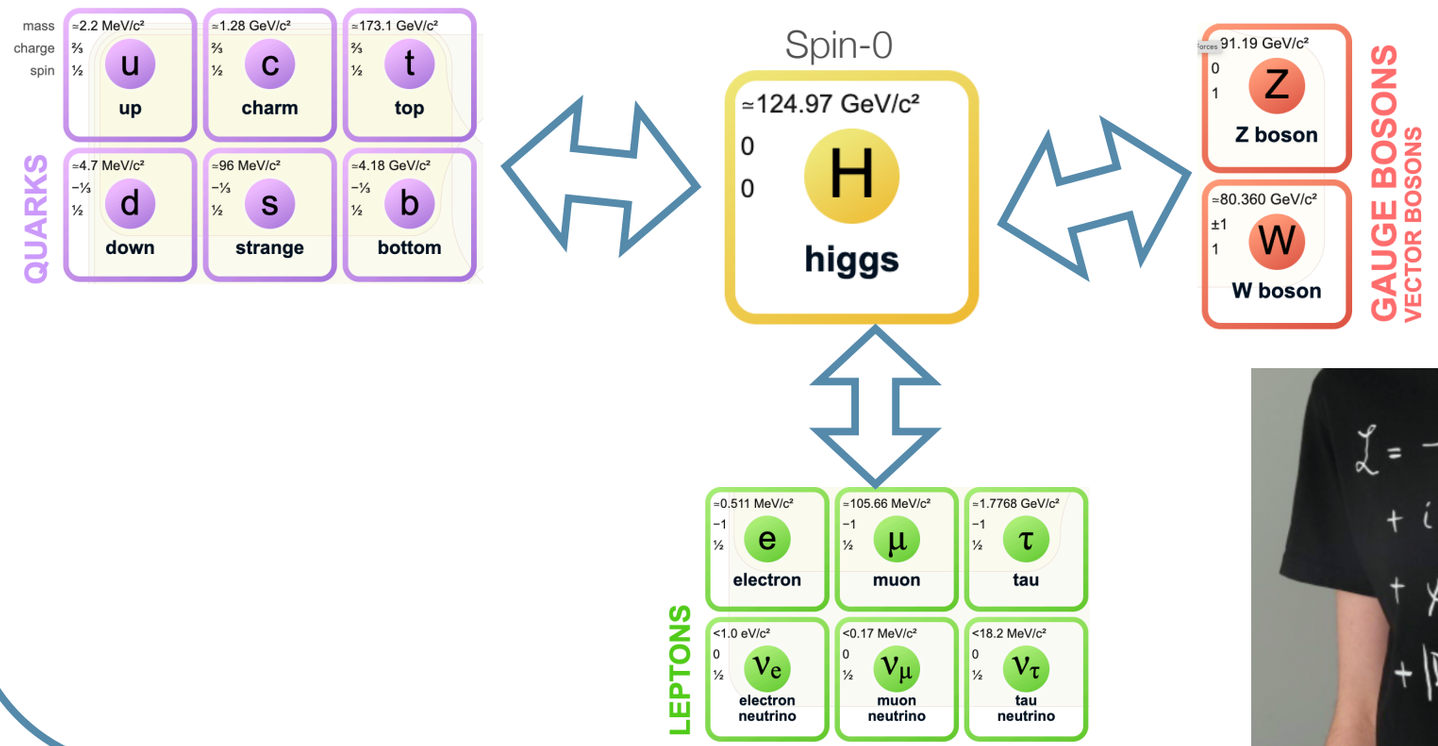
Higgs is simple.

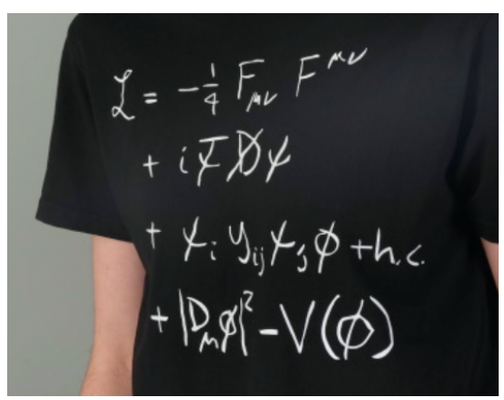
A simple “Mexican hat” potential.



⇒ Electroweak symmetry breaking

⇒ gives masses of SM particles





Why focusing on Higgs?

Yet, Higgs is confusing.

Sure, the math is simple.
It does not give us clues for a deeper understanding.

Different from other SM particles:
gauge boson (gauge symmetry), fermion (chiral symmetry)

Why focusing on Higgs?

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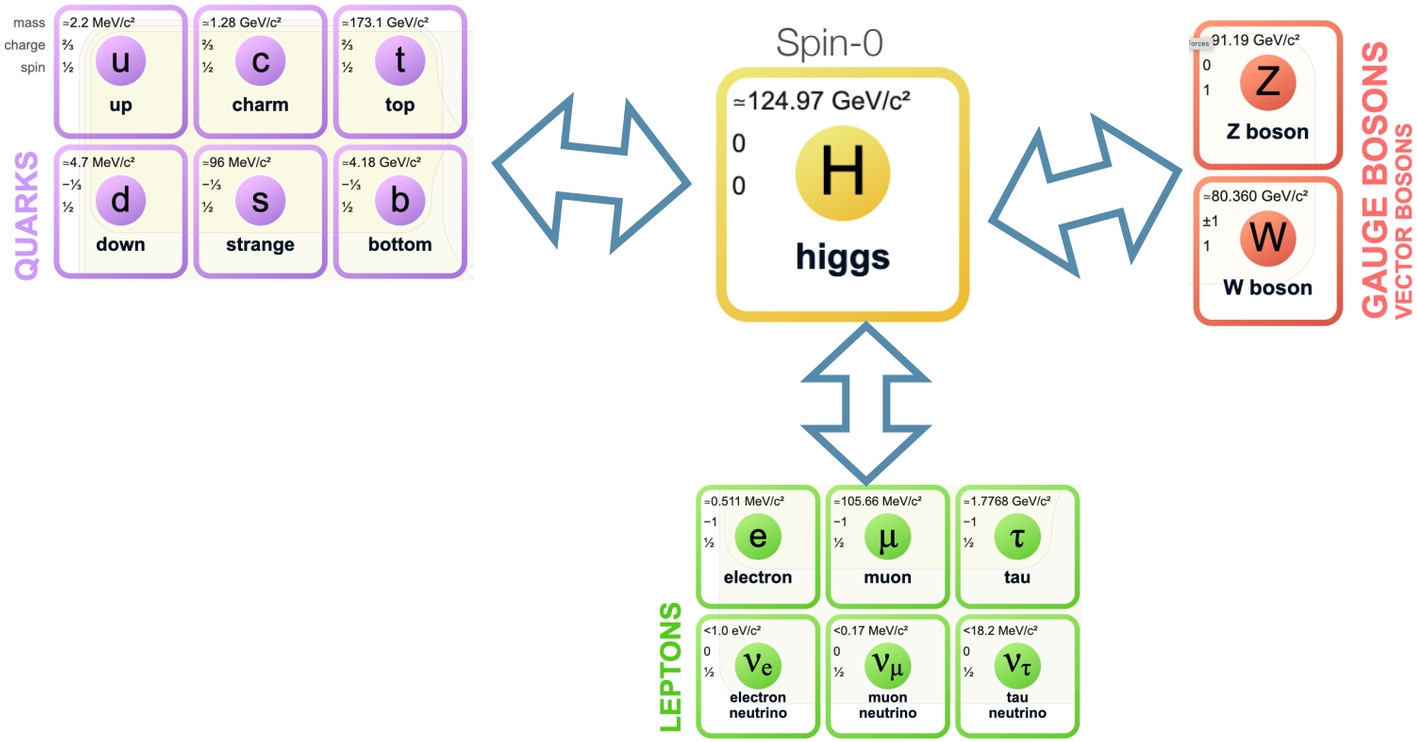
Different from other SM particles:
gauge boson (gauge symmetry), fermion (chiral symmetry)

Maybe not as simple as it seems?

Is it elementary (like electron) or composite (like proton or pion)?

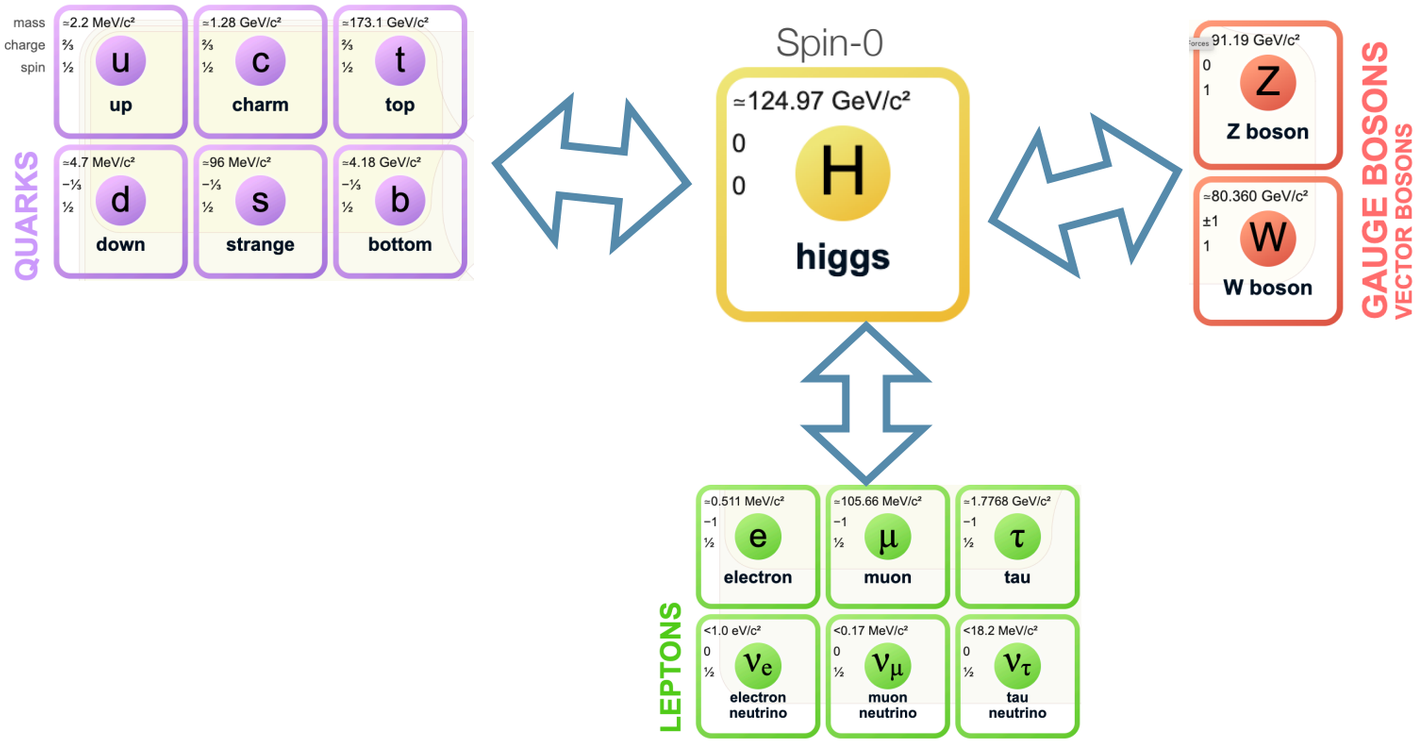
Is the Higgs the only spin-0 particle, or there are similar ones?

What sets the masses?



Higgs mechanism sets the masses of the SM particles

What sets the masses?



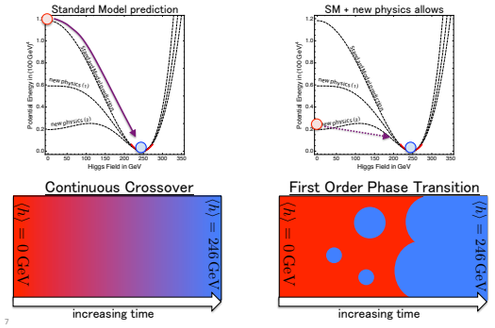
Higgs mechanism sets the masses of the SM particles

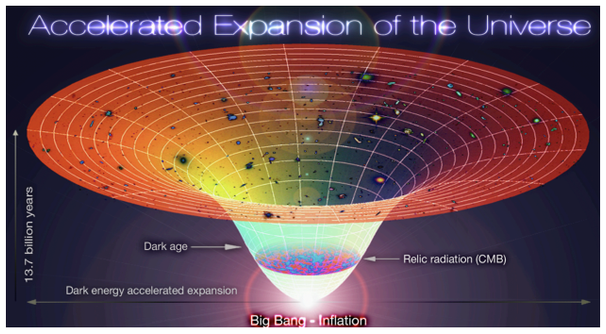
However, we can’t explain how this mass scale is set.
Why is it around 100 GeV?

Higgs and everything else

Weak interaction vs gravitation
10^2 vs 10^{18}

Matter > anti-matter
Electroweak phase

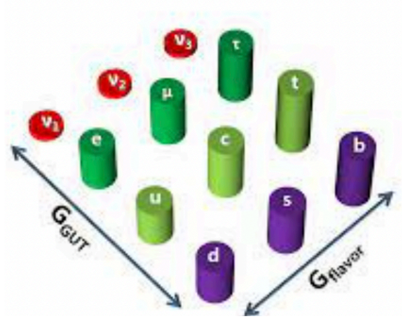




Inflation, age of universe, …

Higgs

The dark world



Flavor puzzle

Higgs and everything else

Weak interaction vs gravitation
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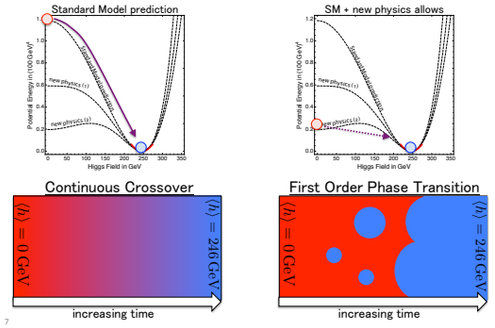

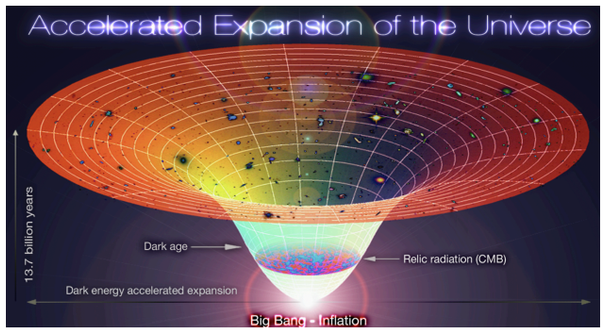

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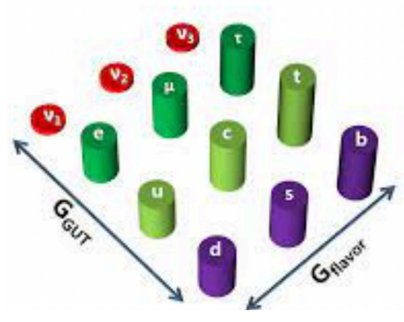
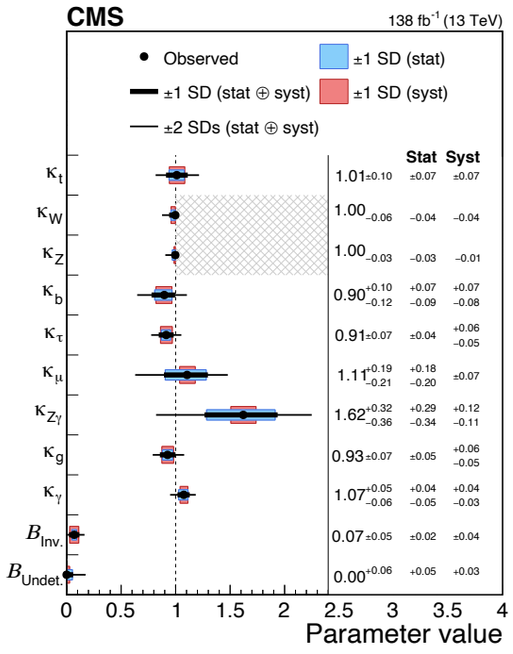


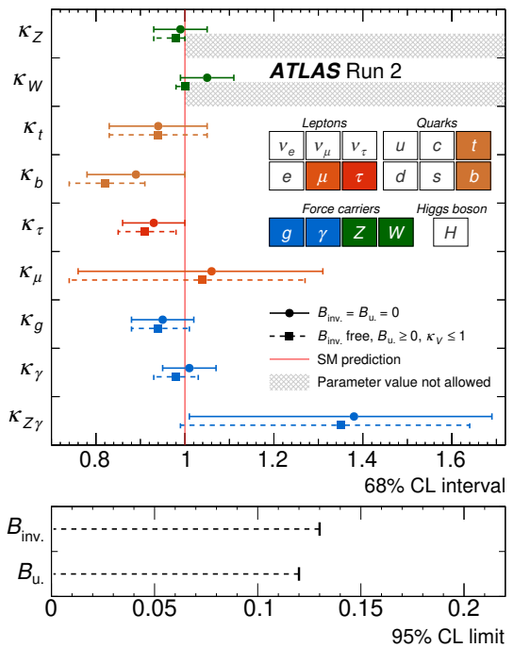
Flavor puzzle

Higgs is likely to play a role in many of these, but how?

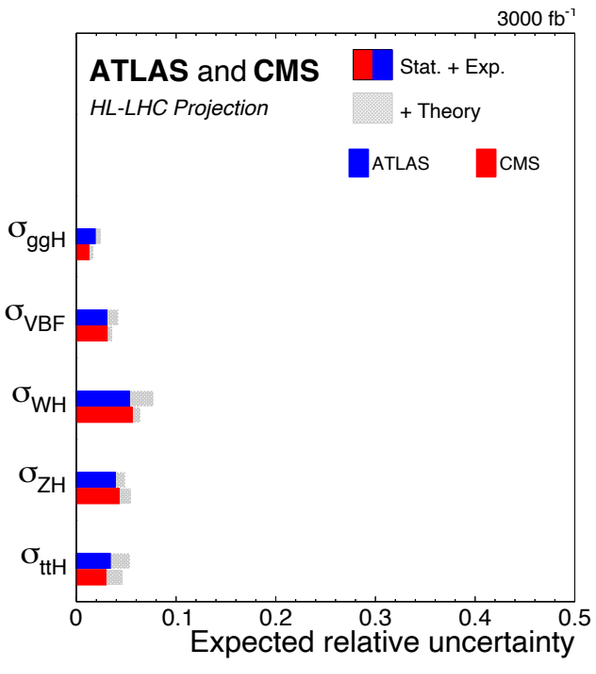
What do we know?

Higgs coupling other SM particles:





Eventually at the LHC



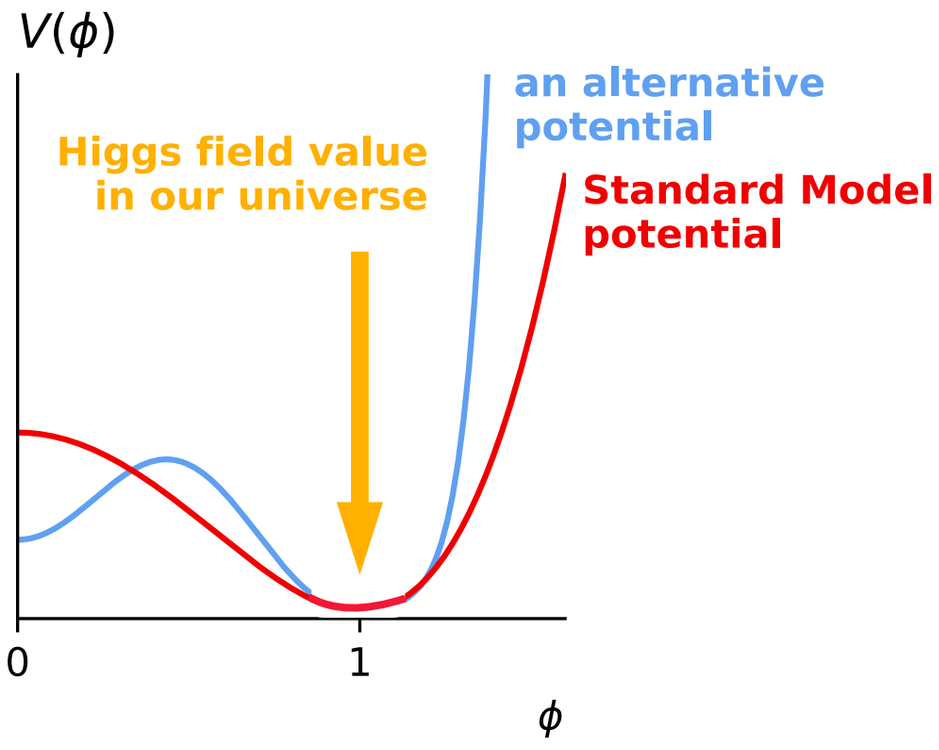
Higgs couplings. Presently, known to about 10%

1- a few %

Other electroweak couplings known to much better precision $\mathcal{O}(10^{-3})$.

What do we know?

Higgs potential?



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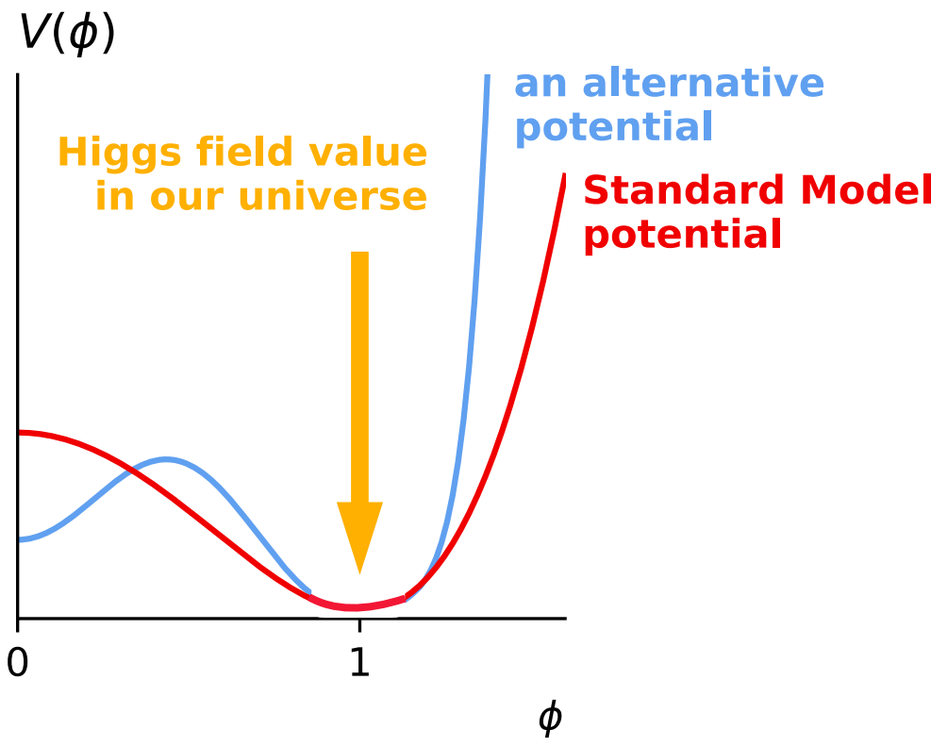
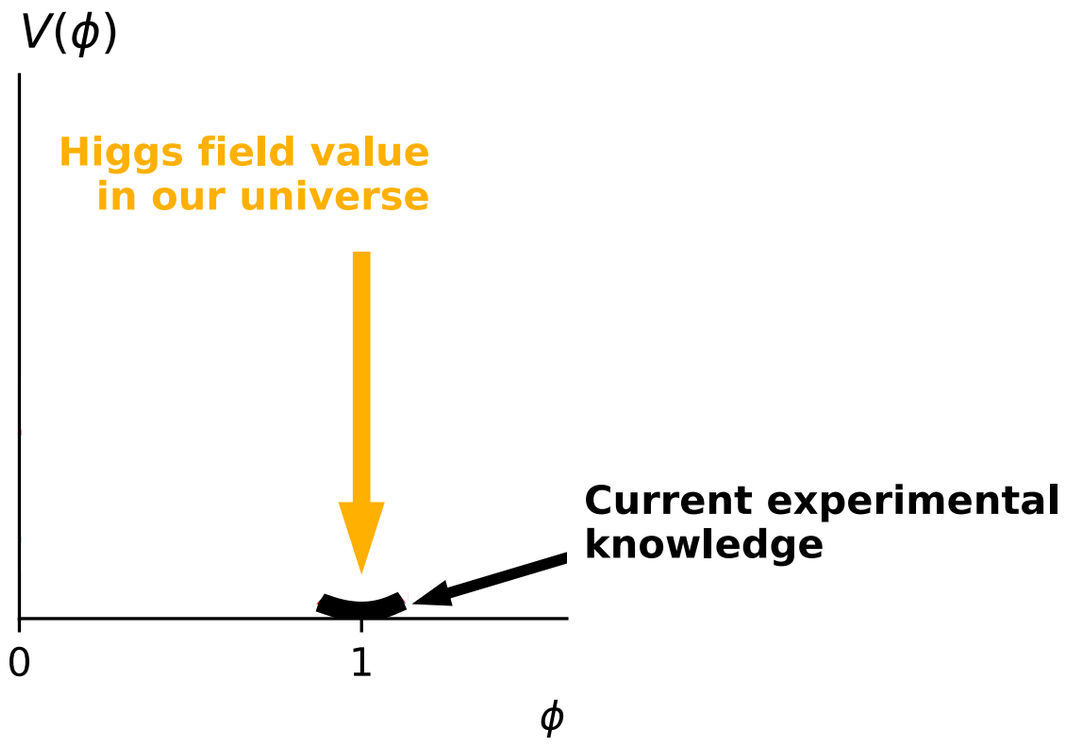
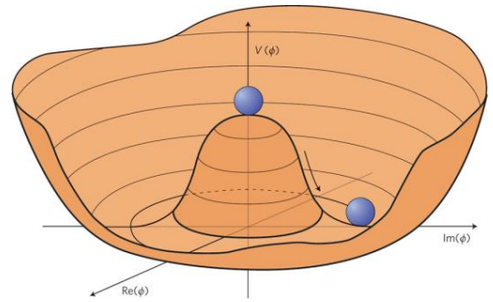




HL-LHC will make some progress.
But it won't clarify the picture.

A simple “Mexican hat” potential.



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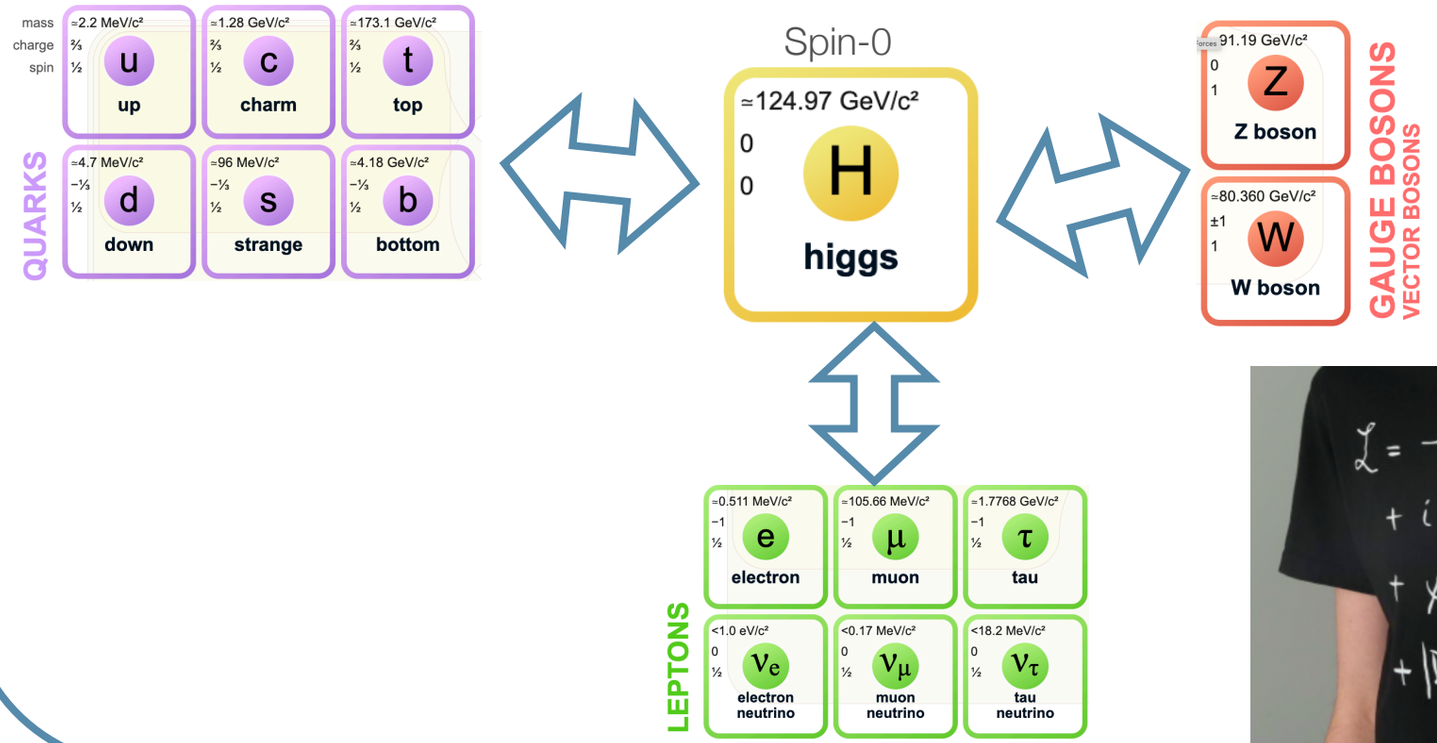
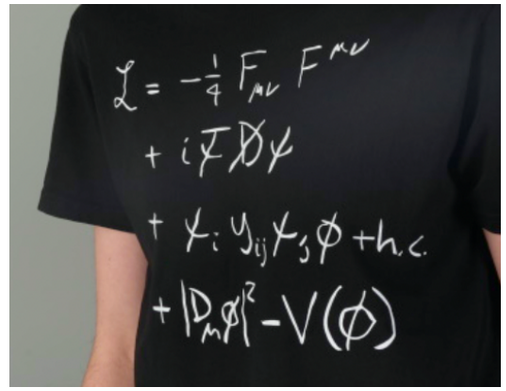
⇒ gives masses of SM particles





A simple “Mexican hat” potential ??

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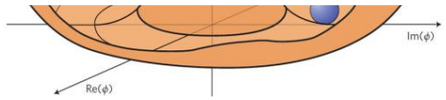
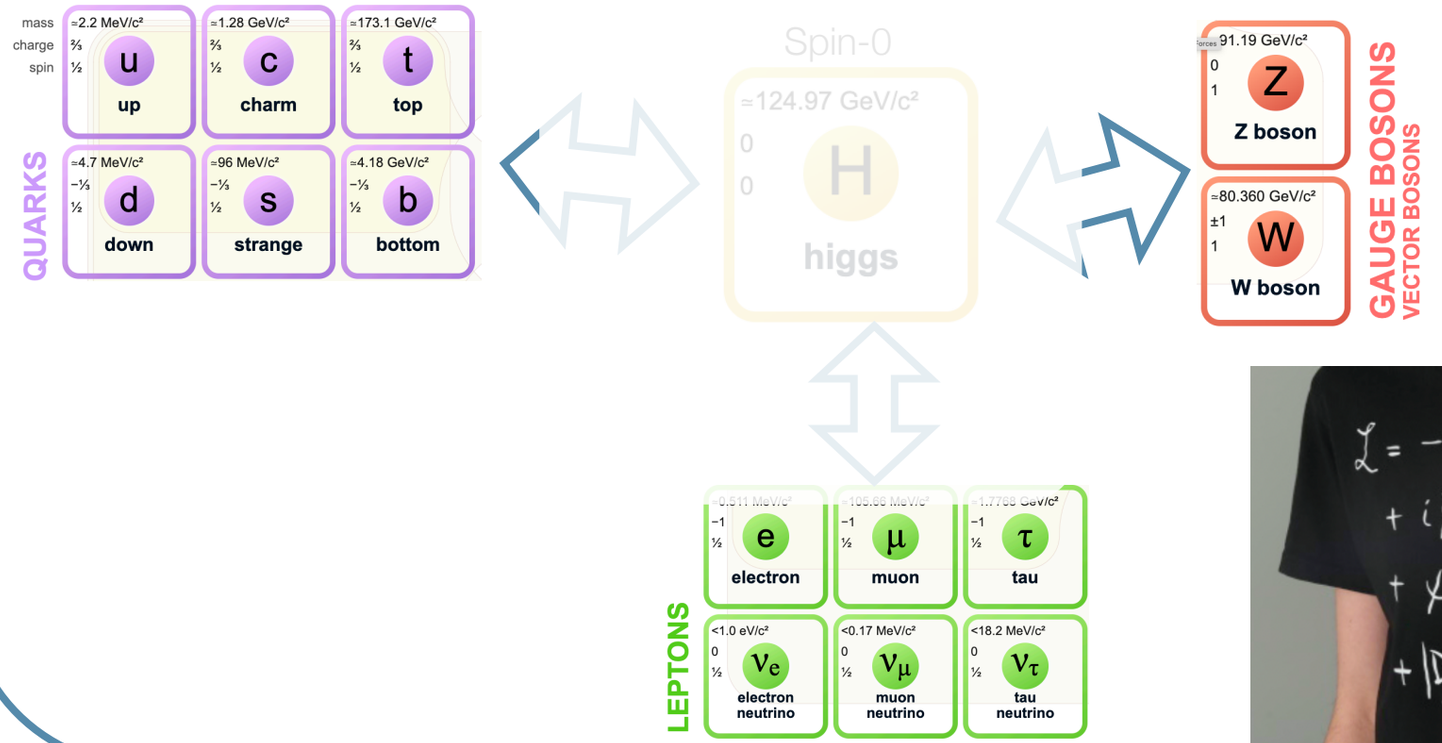
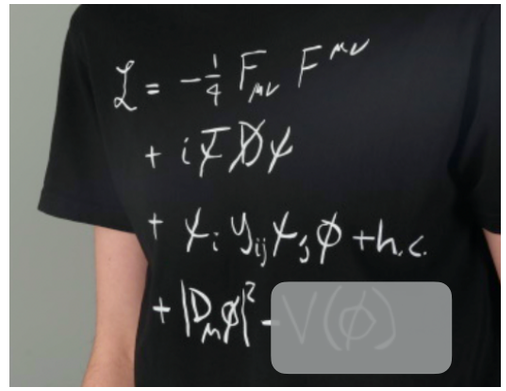
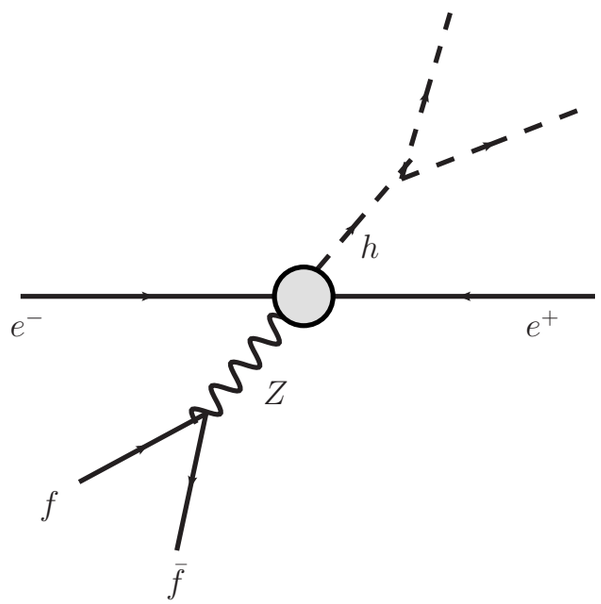




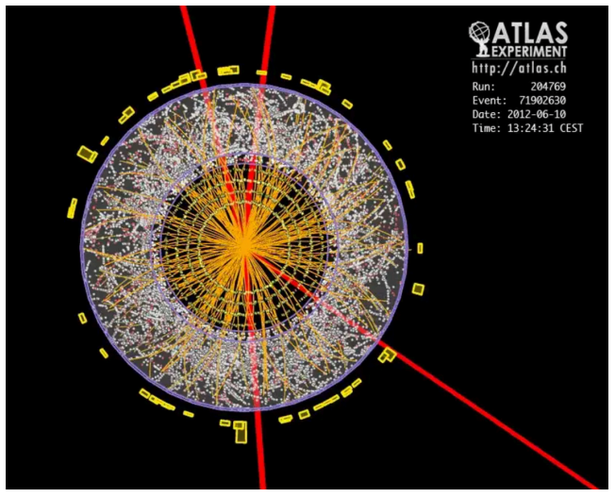


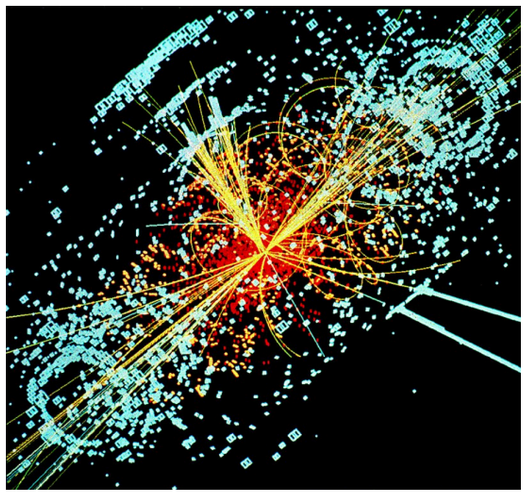
We need to know better!

Why e+e− Higgs factory?



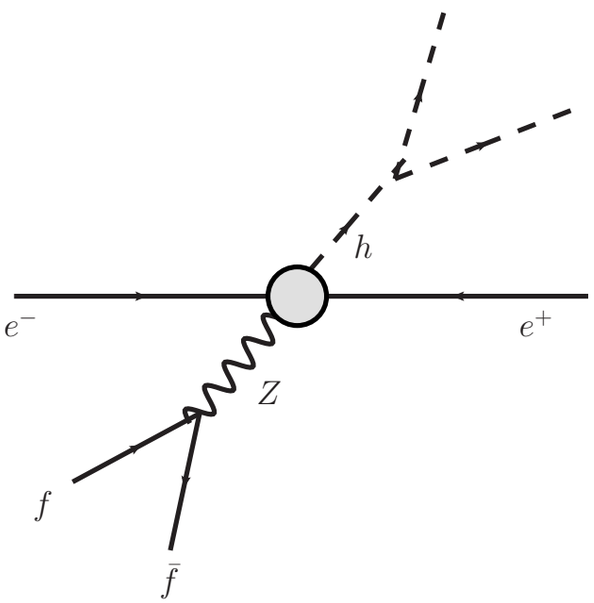
A much cleaner collision environment.
Good for precision measurement.

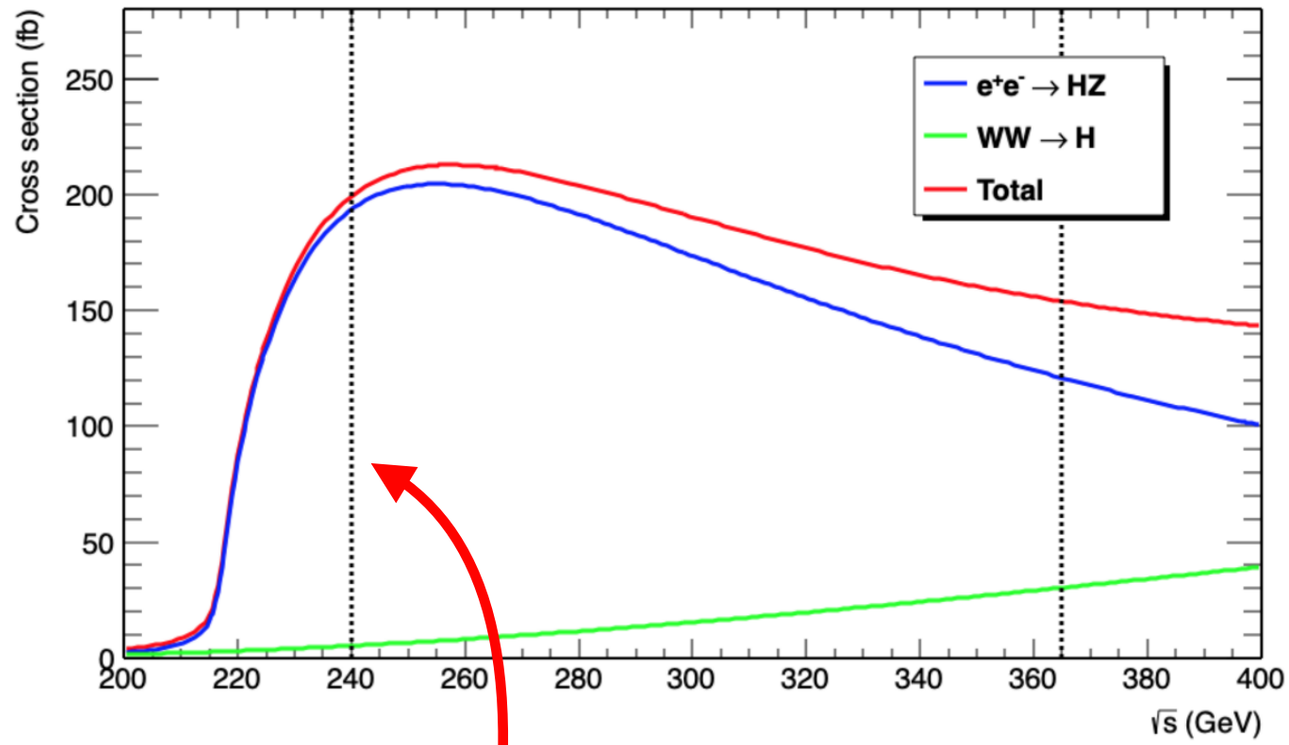




At the Large Hadron Collider

Why e+e− Higgs factory?

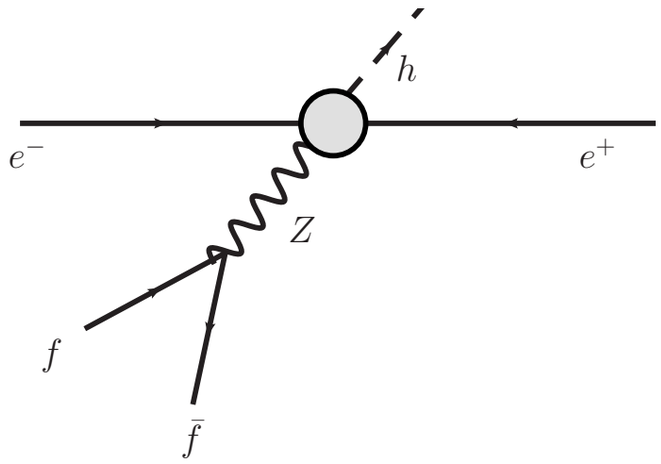


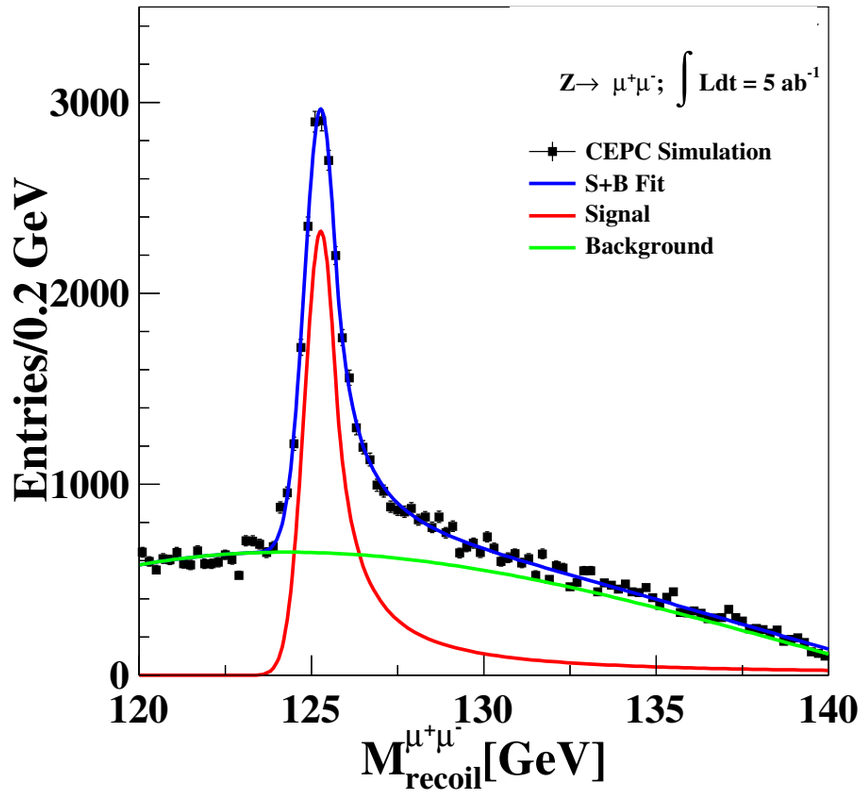


$E_{\mathrm{CM}} \simeq 250$ GeV

“Sweet spot”, most Higgs produced

Why e+e− Higgs factory?



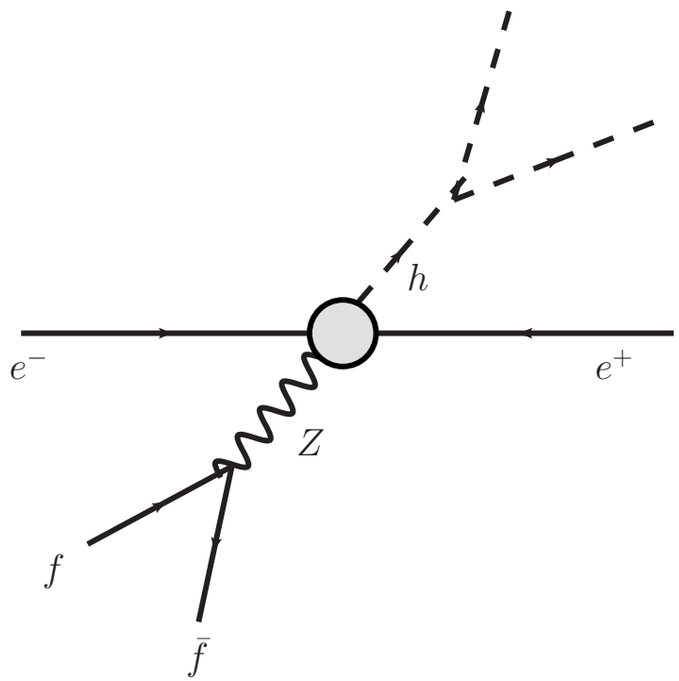


$$M^2_{\text{recoil}} = (\sqrt{s} - E_{ff})^2 - p^2_{ff} = s - 2E_{ff}\sqrt{s} + m^2_{ff}$$

Fully reconstructed Higgs boson without identifying decaying products

⇒ Great for measuring cross section $e^+e^- \to Zh$

Why e+e− Higgs factory?



$$\Gamma_H \propto \frac{\Gamma(H \to ZZ^*)}{\mathrm{BR}(H \to ZZ^*)} \propto \frac{\sigma(ZH)}{\mathrm{BR}(H \to ZZ^*)}$$

A precise total width measurement is possible.

1. An important Higgs property.
2. Crucial in interpreting other Higgs measurements.

Signal for new physics

Coupling deviation from the Standard Model, $\delta \equiv \dfrac{g_{\mathrm{exp}} - g_{\mathrm{SM}}}{g_{\mathrm{SM}}}$

Deviation generated by new physics: $\delta \sim g_{\mathrm{NP}}^2 \dfrac{(100\ \mathrm{GeV})^2}{M_{\text{new physics}}^2}$

g_{NP} : coupling of new physics to the SM

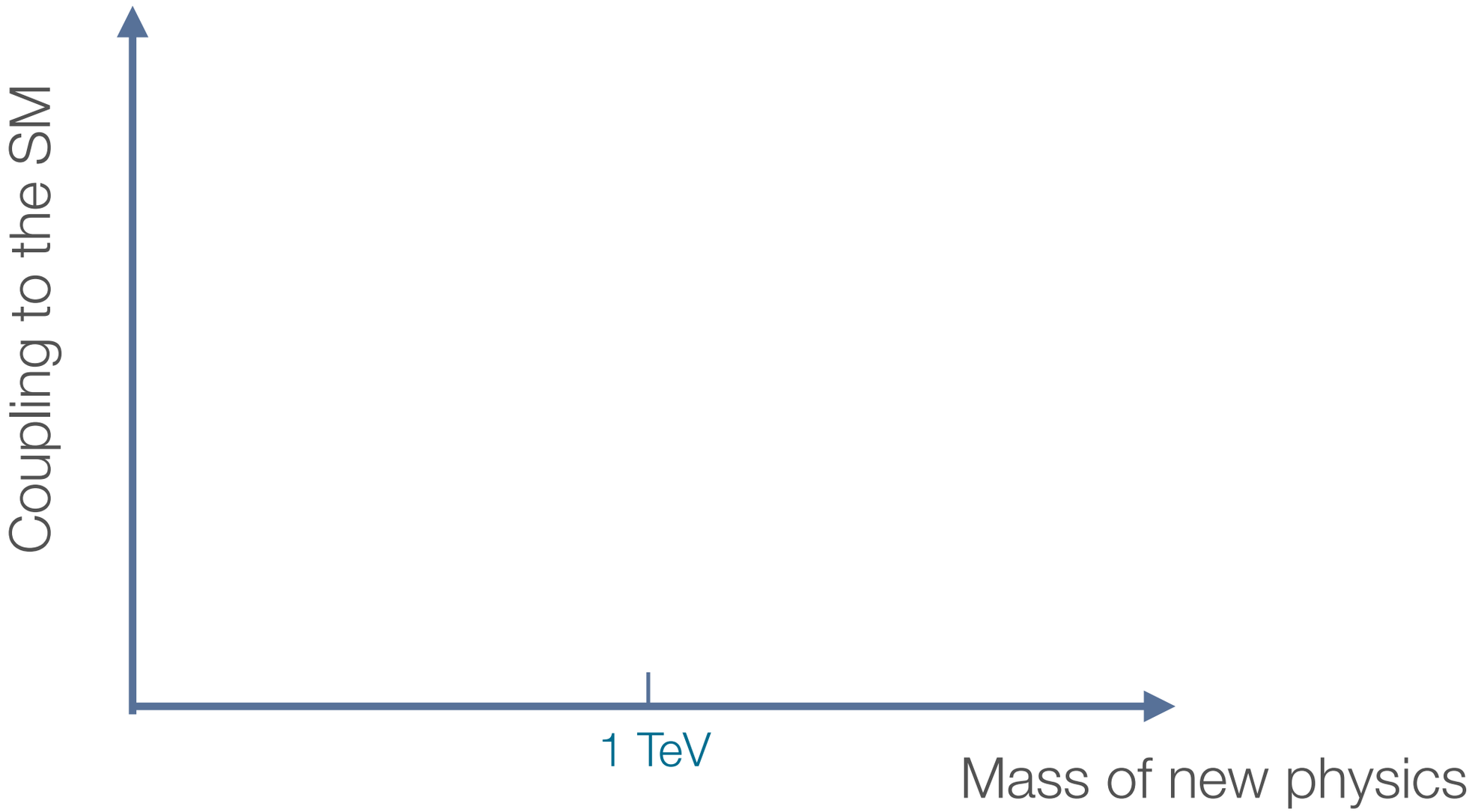
$M_{\text{new physics}}$: mass scale of new physics

Measurement precision ⇒ sensitivity on δ ⇒ reach for NP

Our target

$$\delta \equiv \frac{g_{exp} - g_{SM}}{g_{SM}}$$

$$\delta \sim g_{NP}^2 \frac{(100\ \text{GeV})^2}{M_{\text{new physics}}^2}$$



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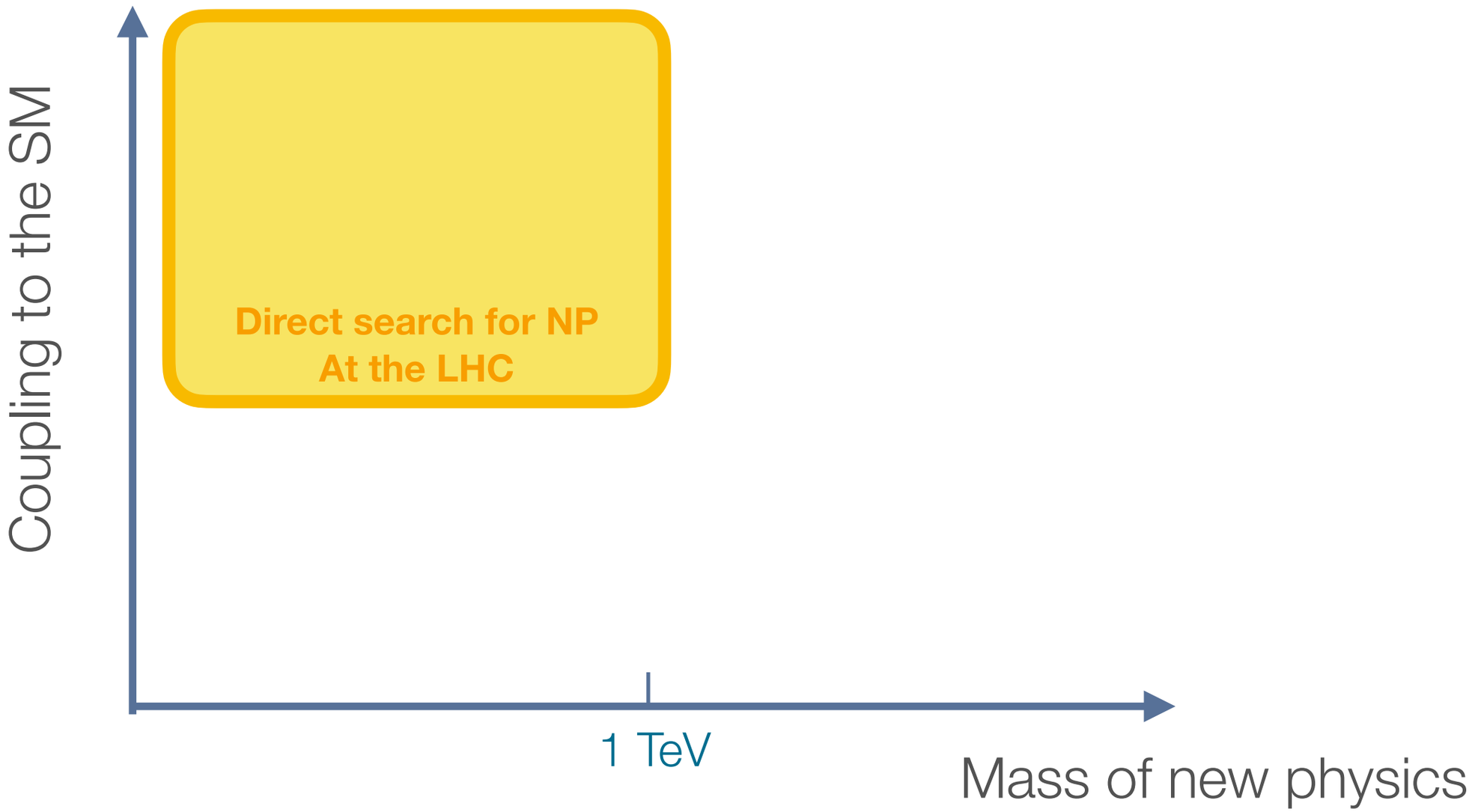

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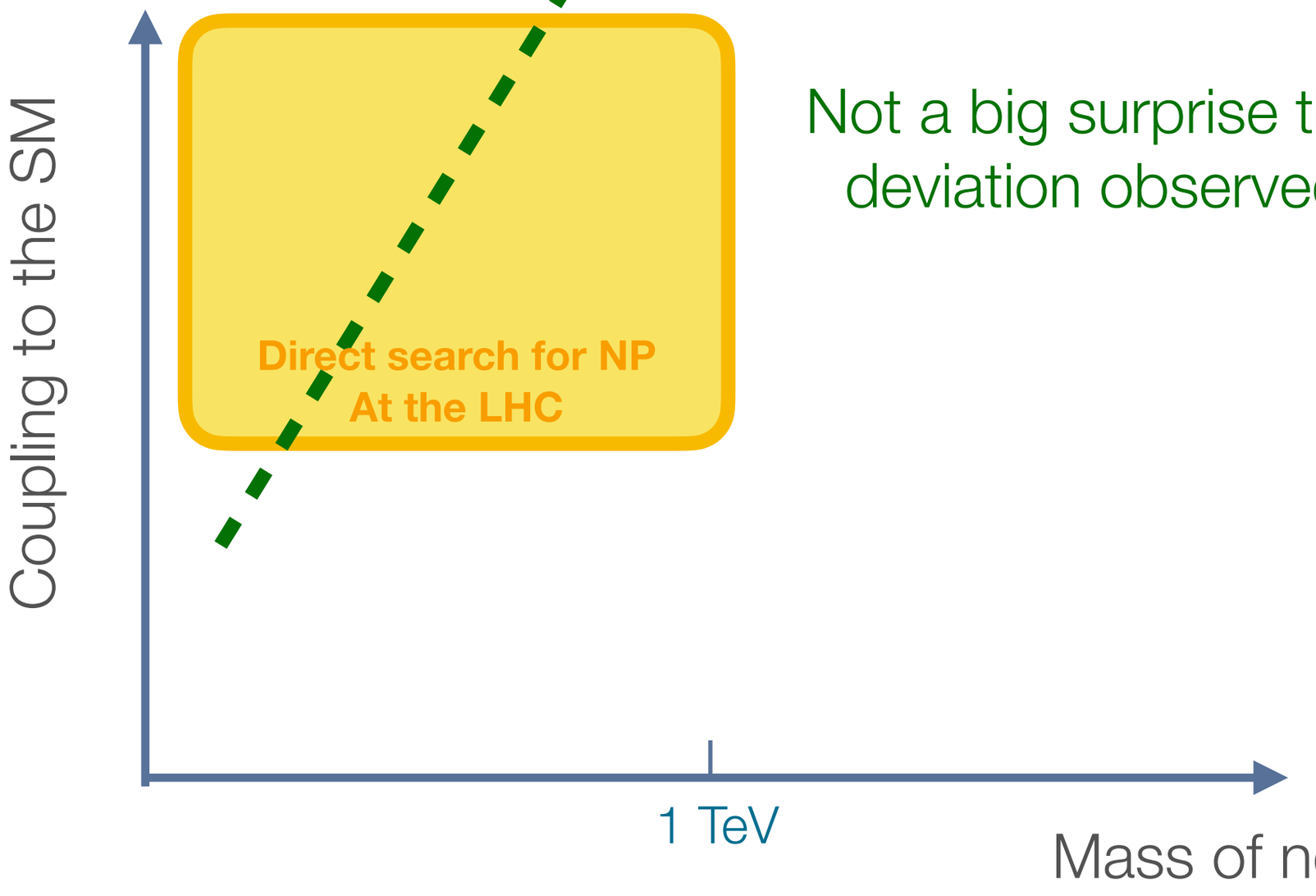
$$\delta \sim g_{NP}^2 \frac{(100\ \text{GeV})^2}{M^2_{\text{new physics}}}$$

$\delta \sim \mathcal{O}(1)\,\%$ HL-LHC



Not a big surprise that no deviation observed yet

Our target

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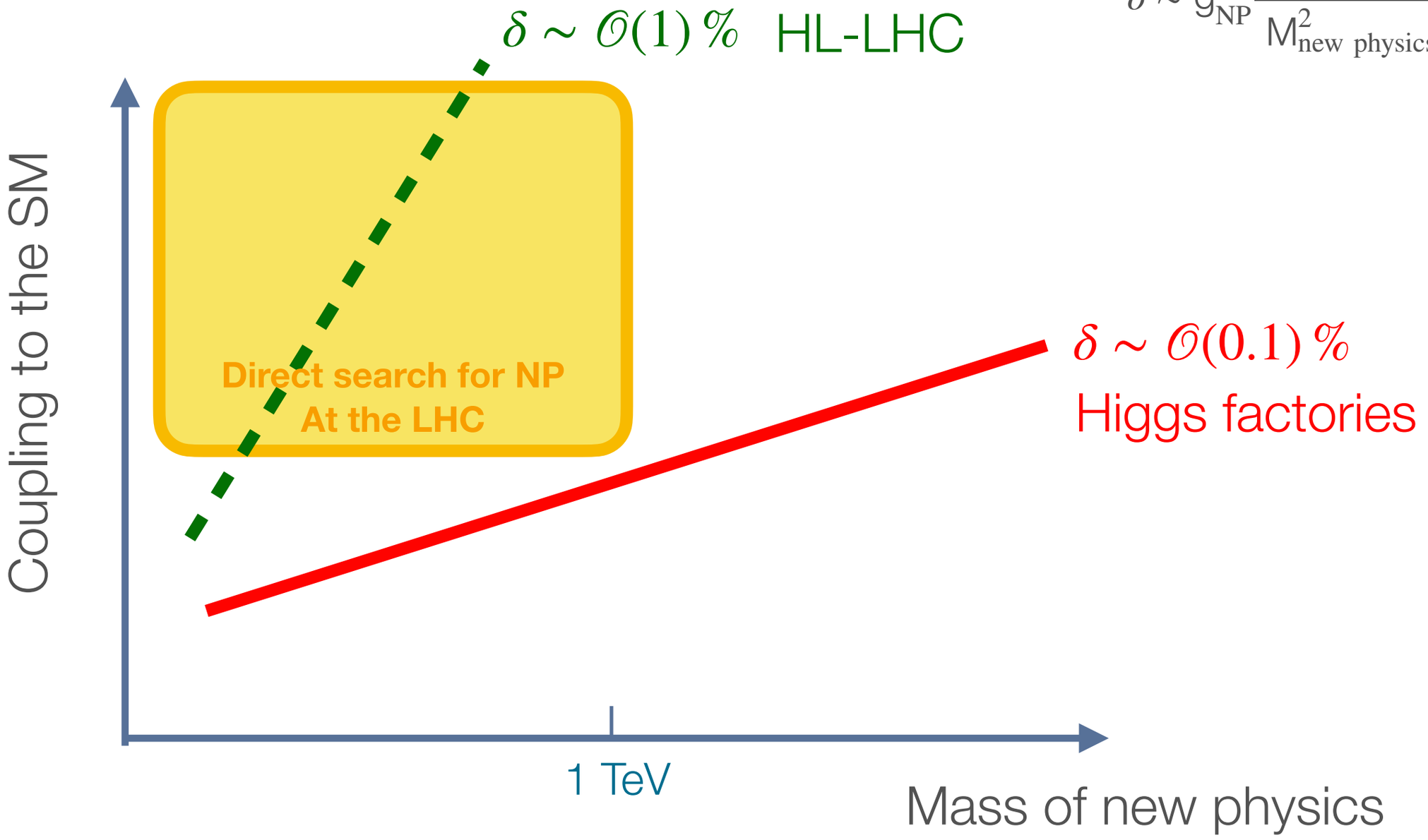
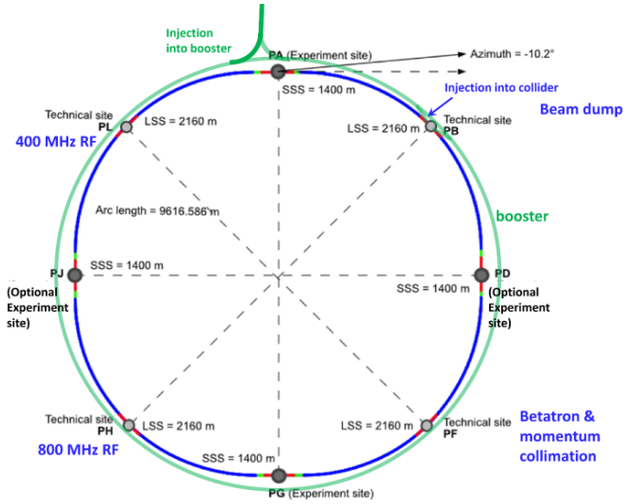
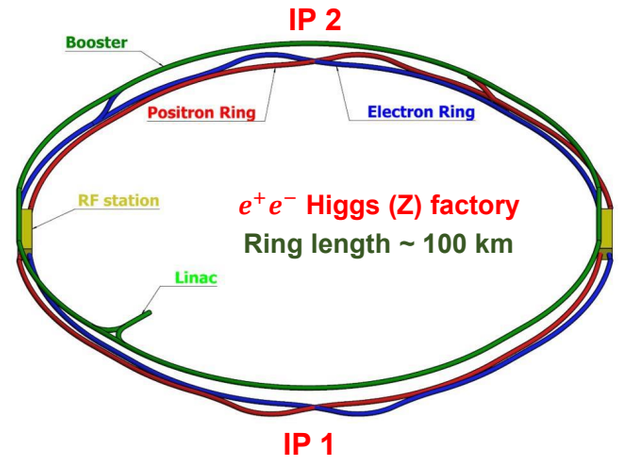


Higgs factories (e^+e^-)

Circular



FCC-ee

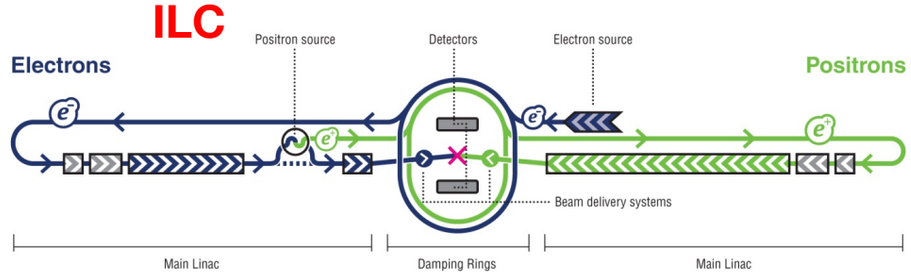


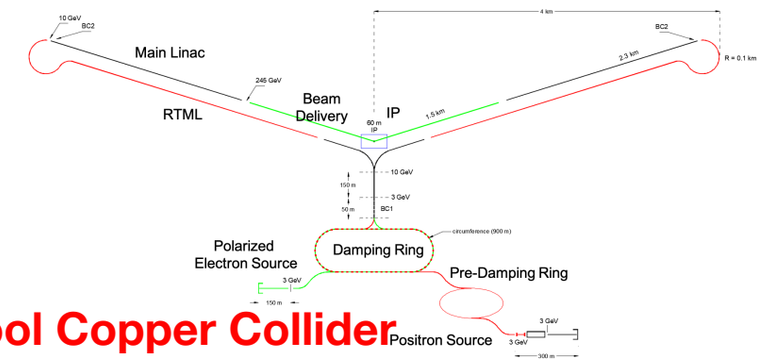
CEPC

+...

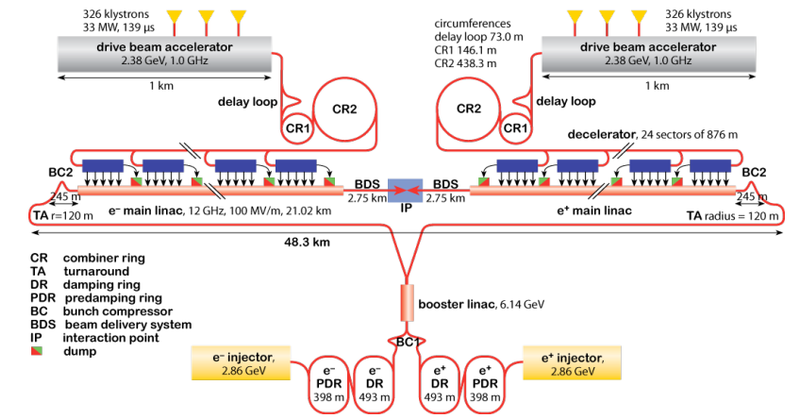
Linear

ILC



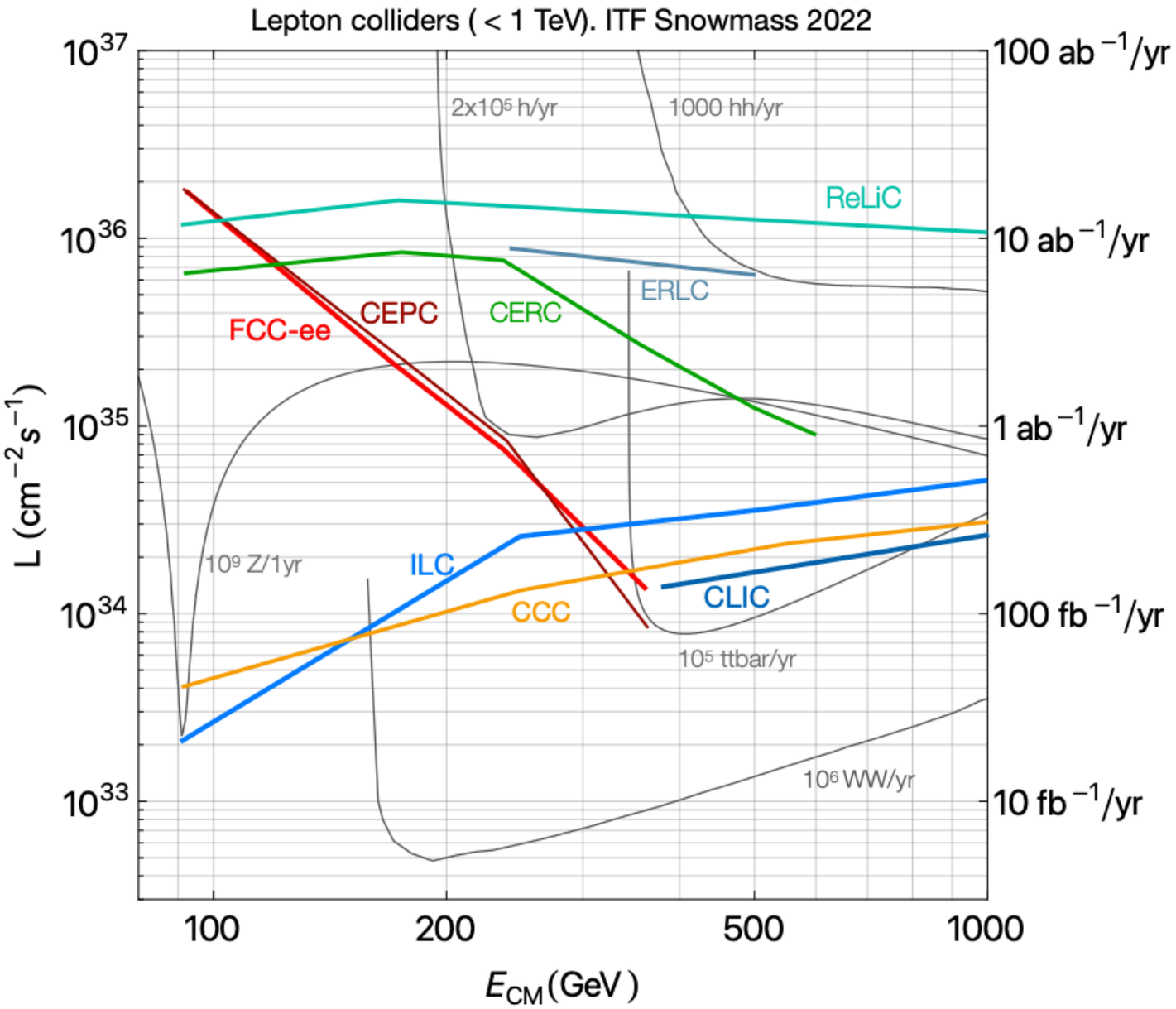


C^3 Cool Copper Collider



CLIC

Physics output



Main physics output:

10^6 Higgses

10^9 -10^{12} Zs

10^6 WW

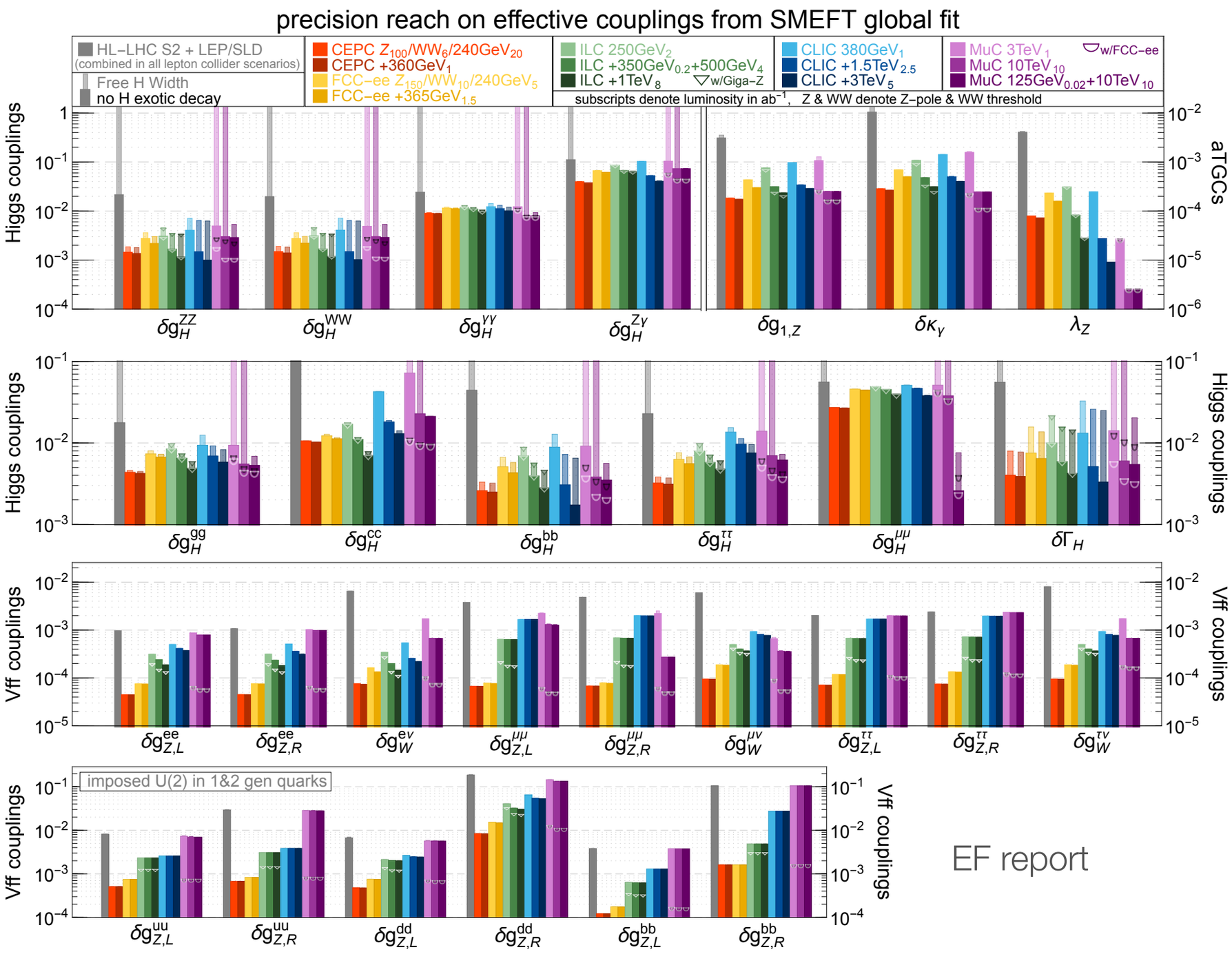
10^5 ttbar

Central theme: the electroweak scale

Performance of the Higgs factories:

Precision measurements Higgs and beyond

A full suite of measurements

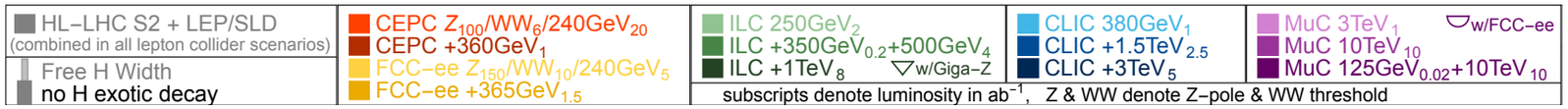


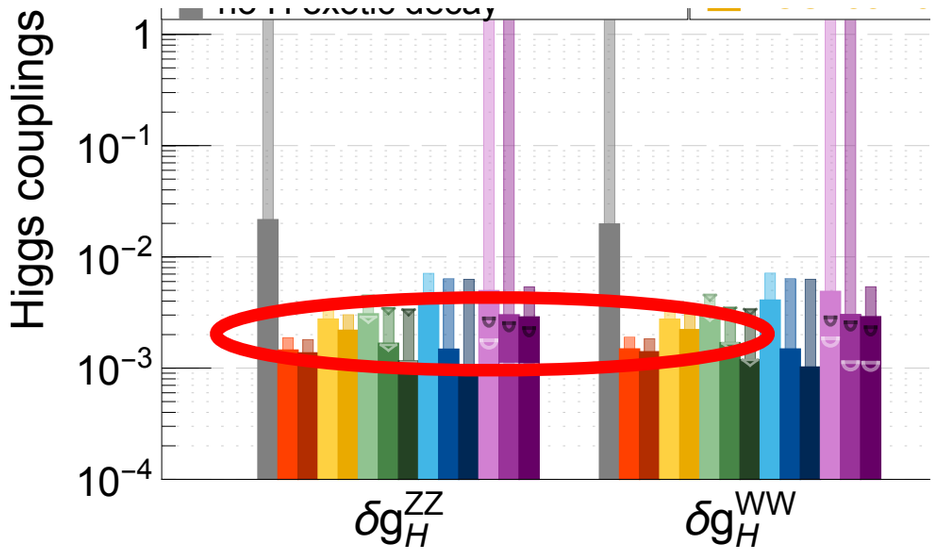
Based on:

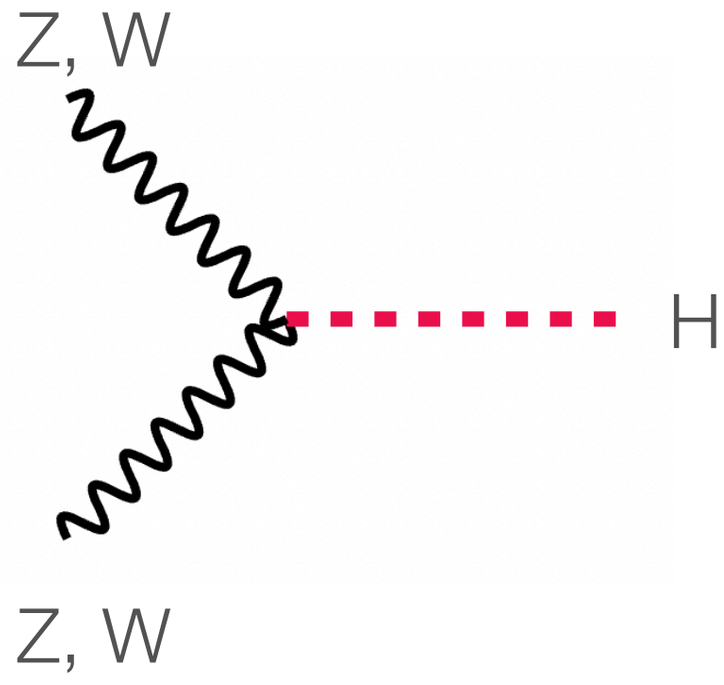
Collider	$\sqrt{s}$	P [%] e^-/e^+	L_{int} ab^{-1}
ILC	250 GeV	$\pm 80/\pm 30$	2
	350 GeV	$\pm 80/\pm 30$	0.2
	500 GeV	$\pm 80/\pm 30$	4
	1 TeV	$\pm 80/\pm 20$	8
ILC-GigaZ	m_Z	$\pm 80/\pm 30$	0.1
CLIC	380 GeV	$\pm 80/0$	1
	500 GeV	$\pm 80/0$	2.5
	1 TeV	$\pm 80/0$	5
CEPC	m_Z		60 / 100
	$2m_W$		3.6 / 6
	240 GeV		12 / 20
	$2m_t$		– / 1
FCC-ee	m_Z		150
	$2m_W$		10
	240 GeV		5
	$2m_t$		1.5

EF report

The Higgs measurements

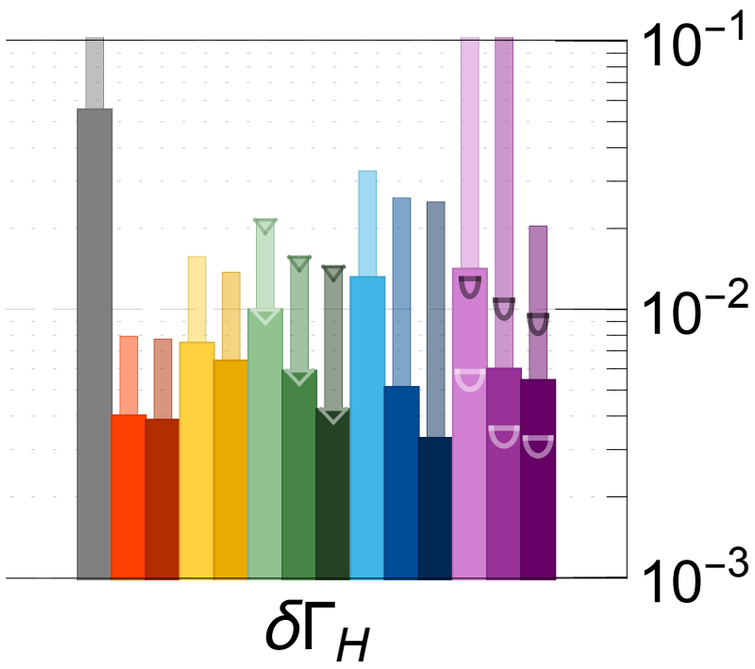






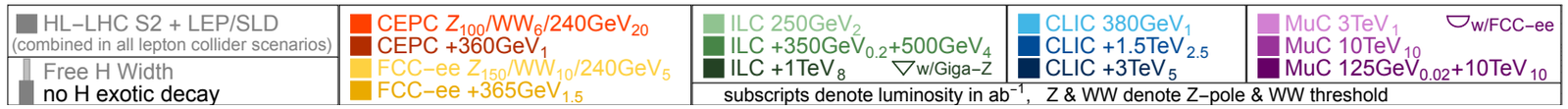
Measuring crucial Higgs coupling up to 10^{-3}

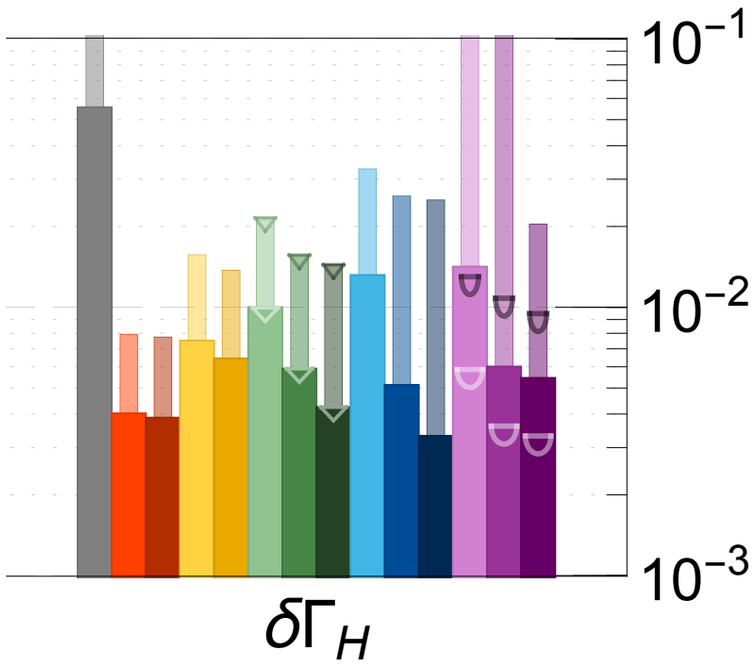
The Higgs measurements



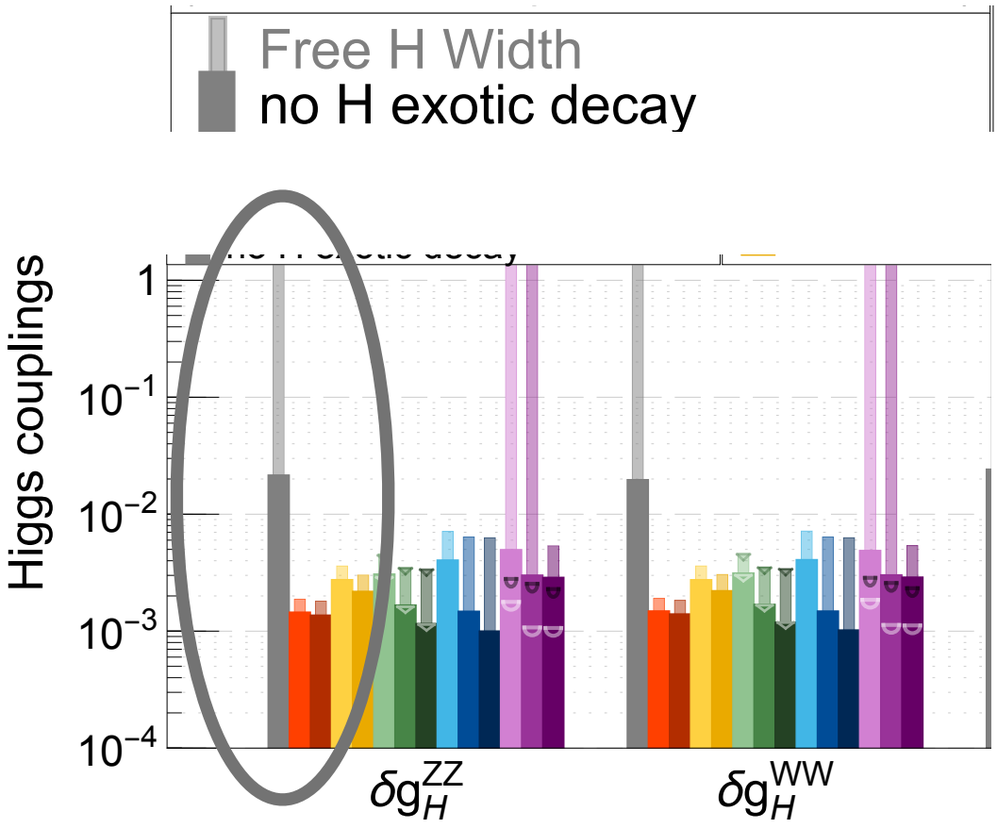
Higgs width measurement

The Higgs measurements



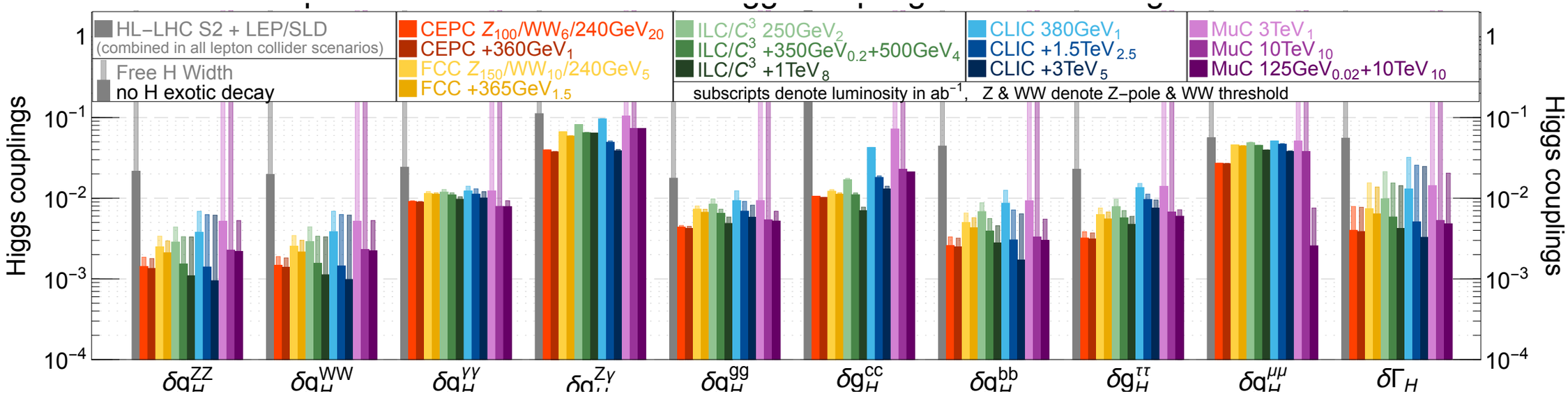


Higgs width measurement



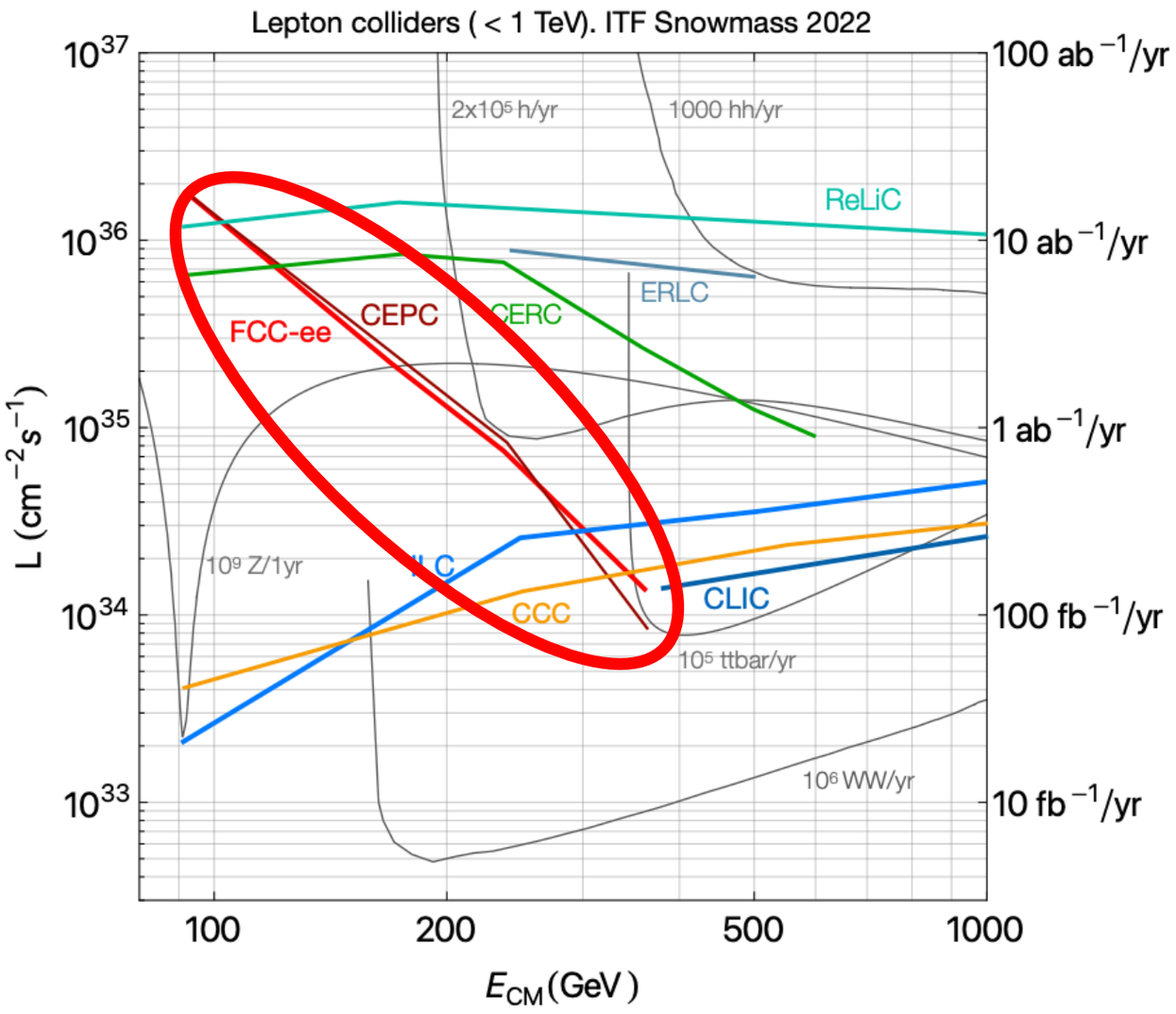
Significant impact on other coupling measurement

The Higgs measurements



Overall, a big step beyond the LHC

Circular



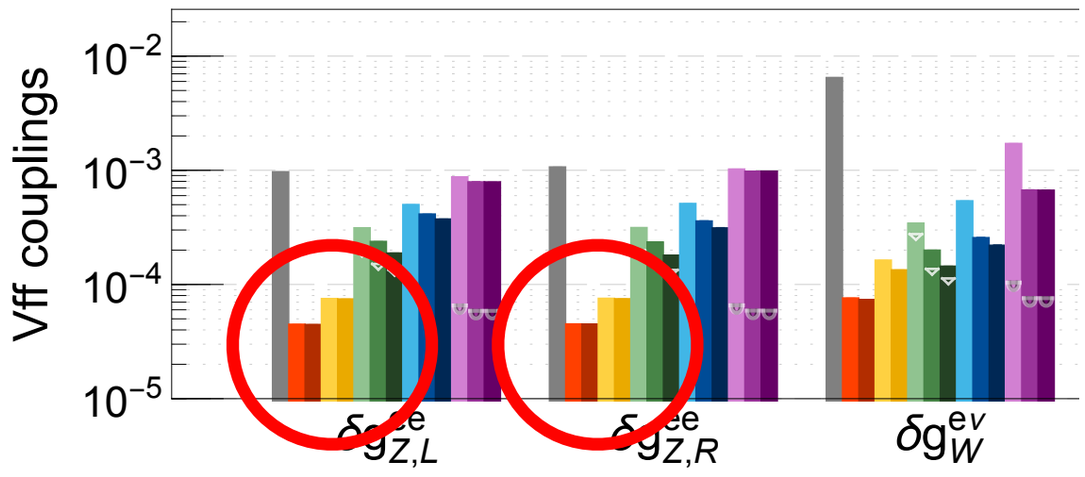
Higher luminosity.
⇒ more Higgs bosons!

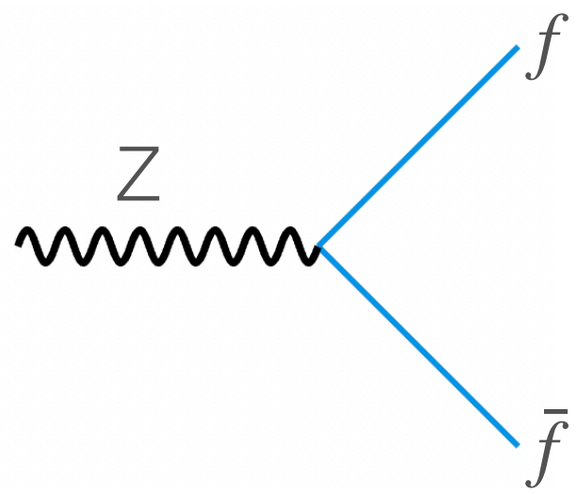
More W (10^6), Z (10^{12})

With more W, Zs

CircularHiggs factories:
10^{12} Zs 10^{6} WW

In comparison:
LEP has 10^{7} Zs

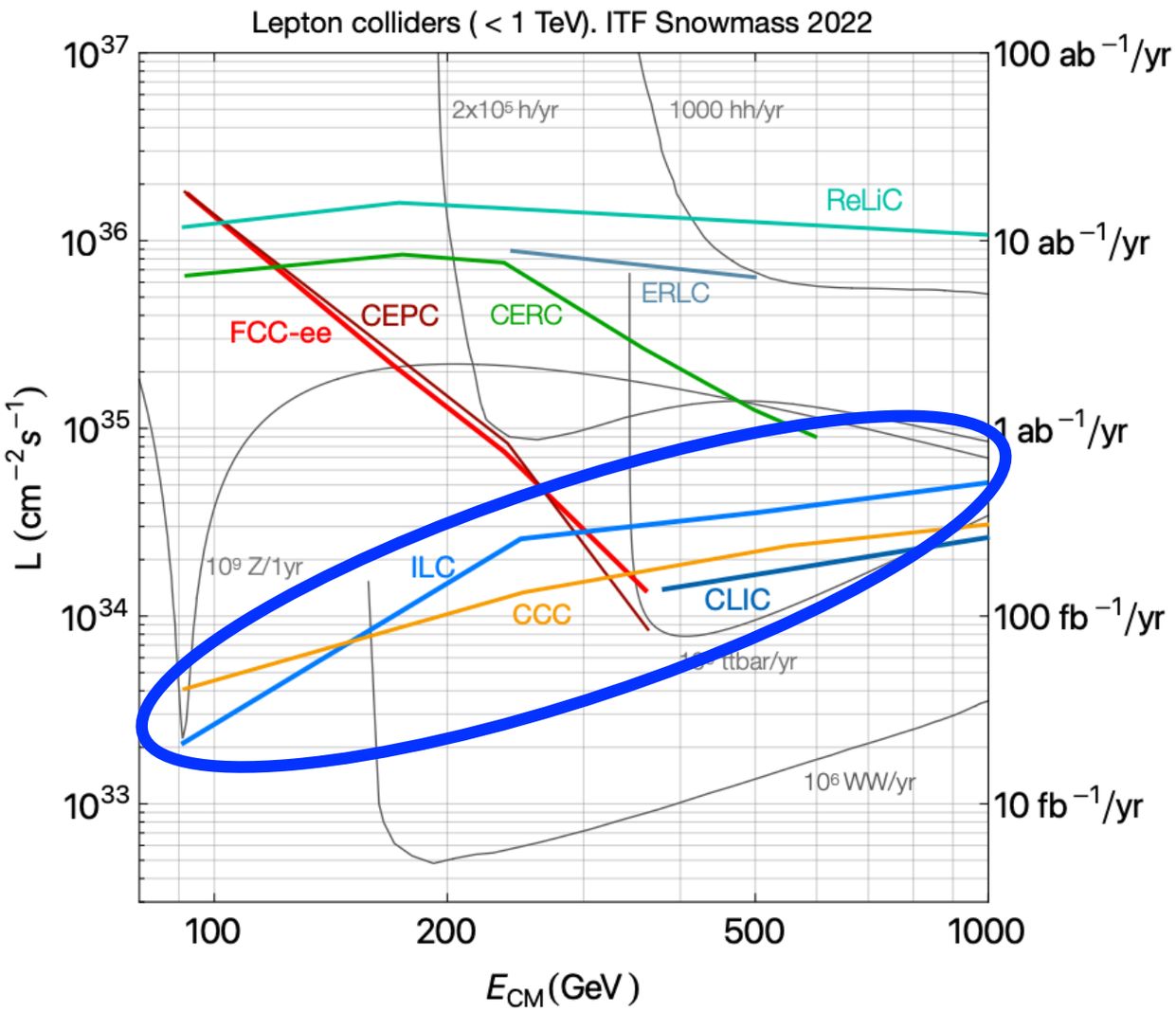




Precision on electroweak couplings: $10^{-3} \Rightarrow 10^{-4}$

Search for NP in exotic Z decays (more later)

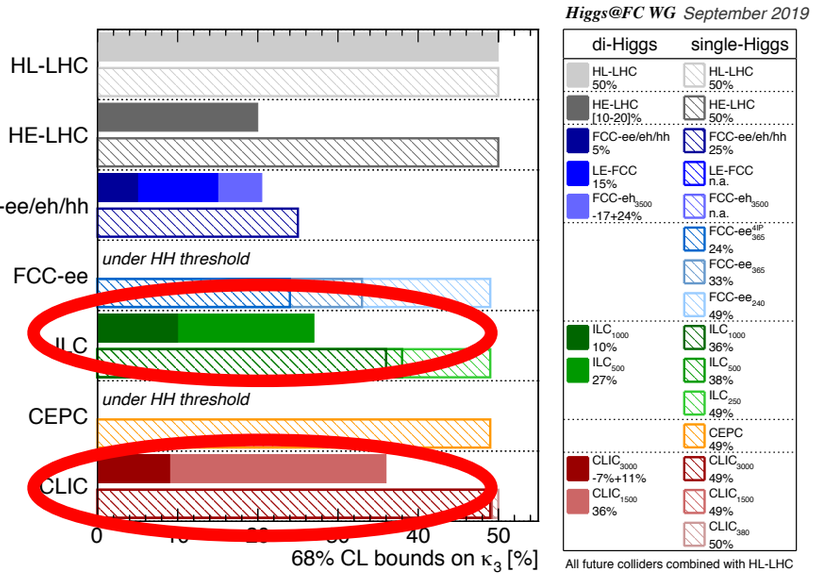
Linear

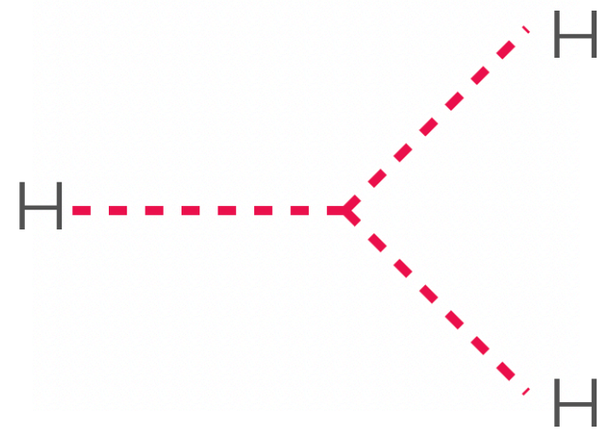


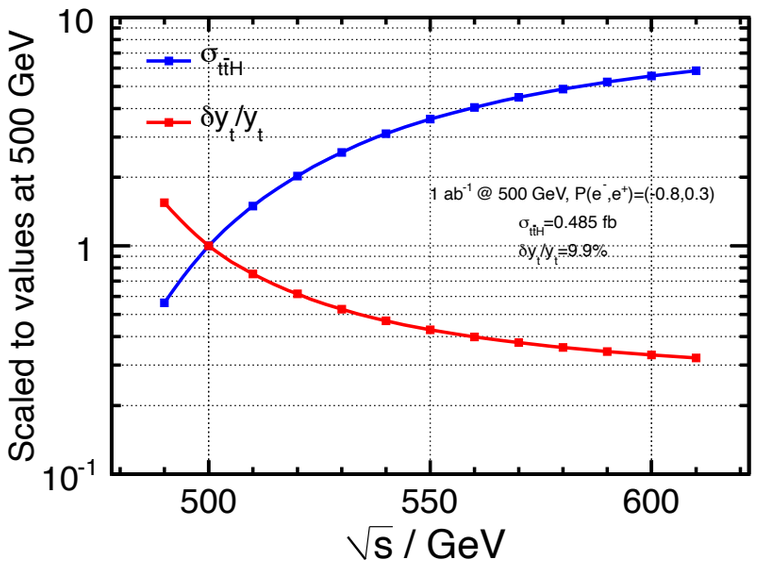
Longitudinal polarization.
Better at resolving certain signals

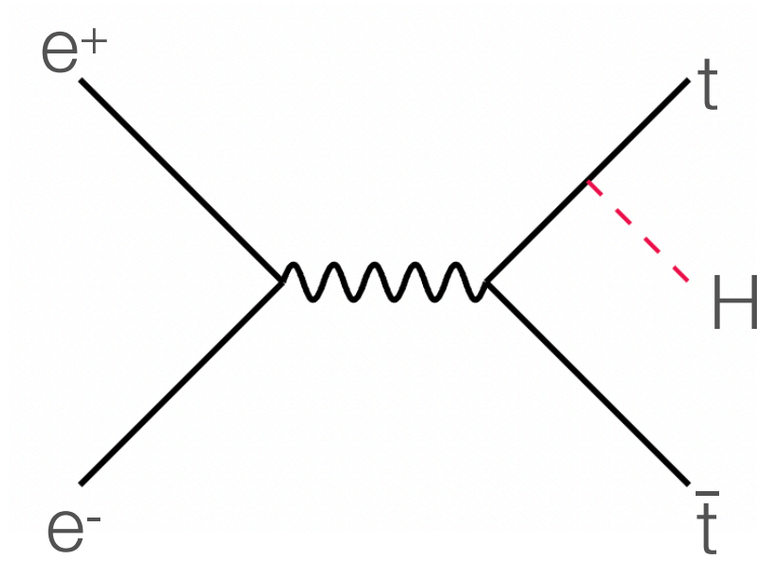
Can go to higher energies

At higher energies









Two excellent options!

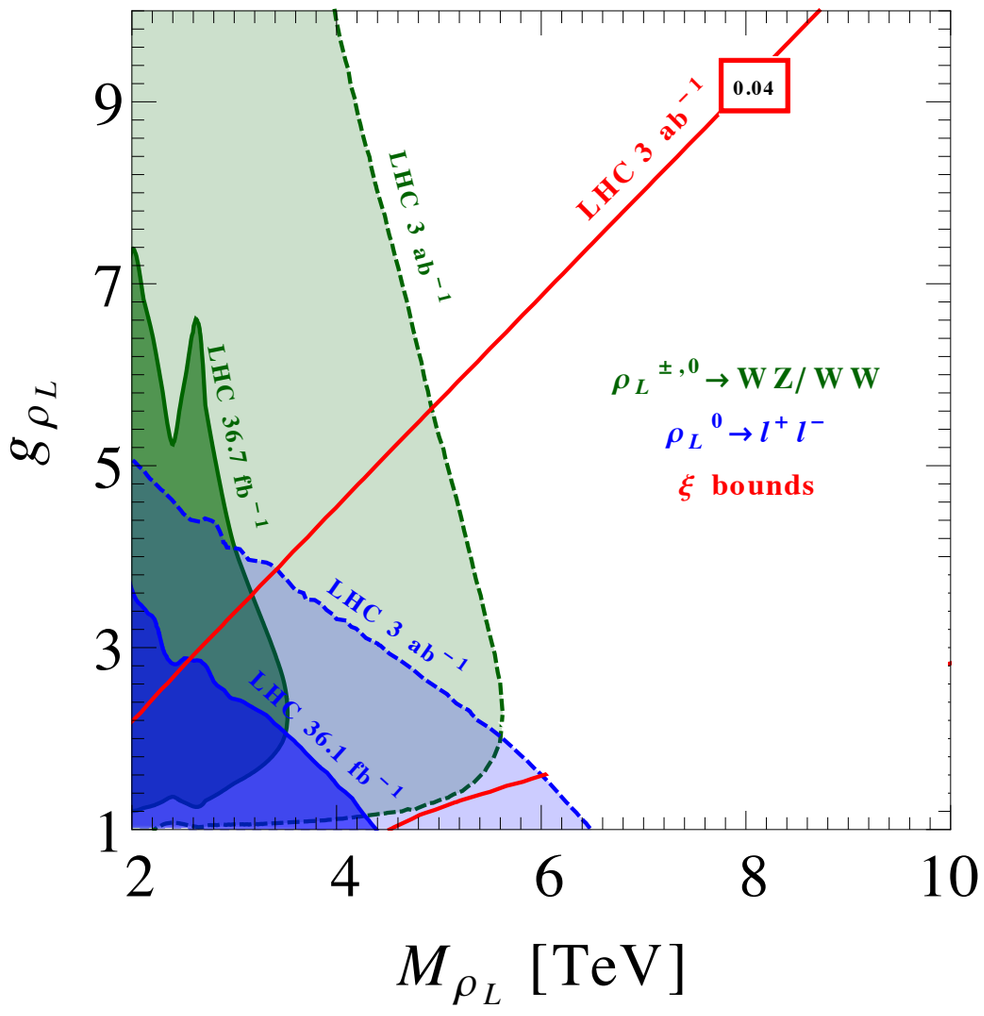
Great performances for Higgs measurements.

Different in additional physics program and prospects

What can we learn from these measurements

A sampler of some interesting cases (very brief)

Is the Higgs composite?



Perhaps the Higgs is similar to the pion?

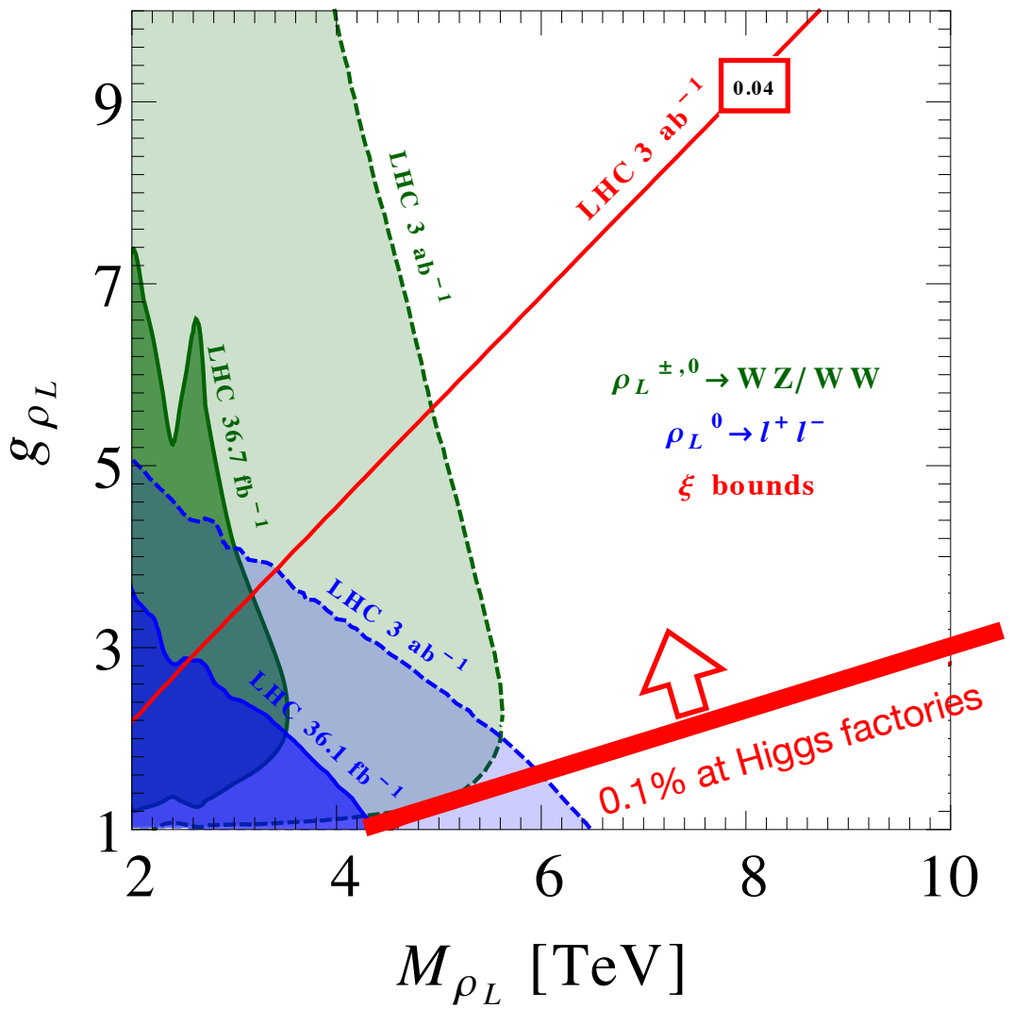
- Would make it naturally light, since it is not elementary.
- If so, will be other composite resonances

Direct search for composite resonances

Higgs coupling measurements

- Composite ≠ elementary
- Different couplings

Is the Higgs composite?



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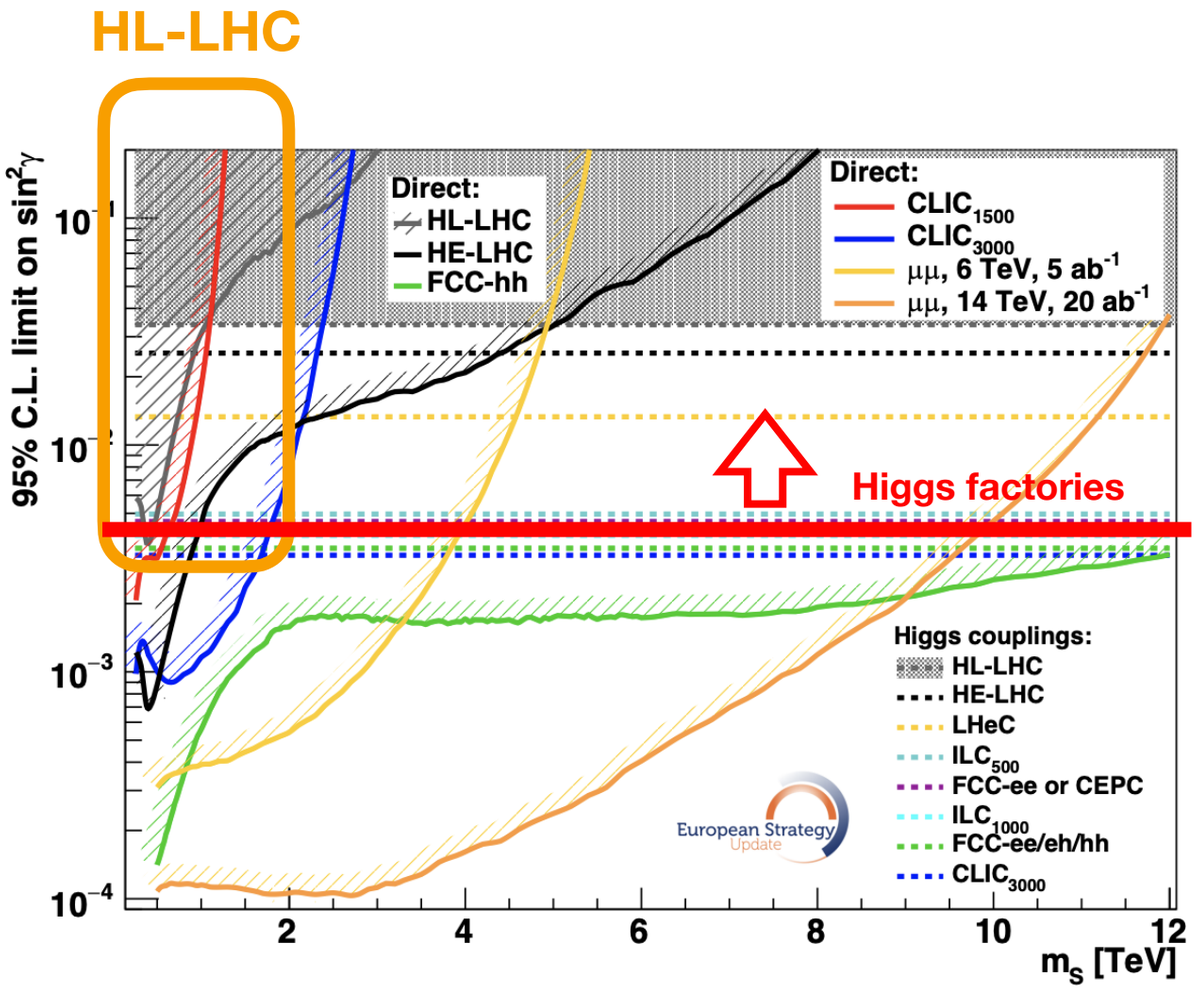
Direct search for composite resonances

Higgs coupling measurements

- Composite ≠ elementary
- Different couplings

Is the Higgs boson alone?

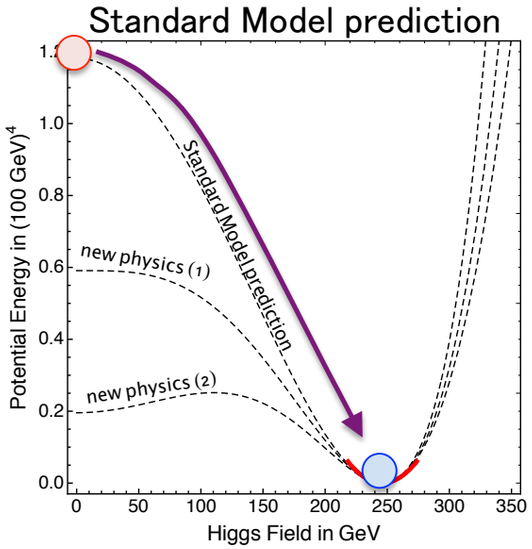


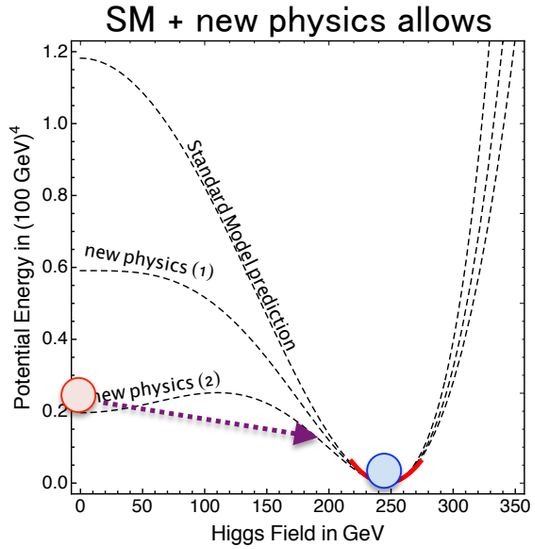
Maybe Higgs boson has some partners?

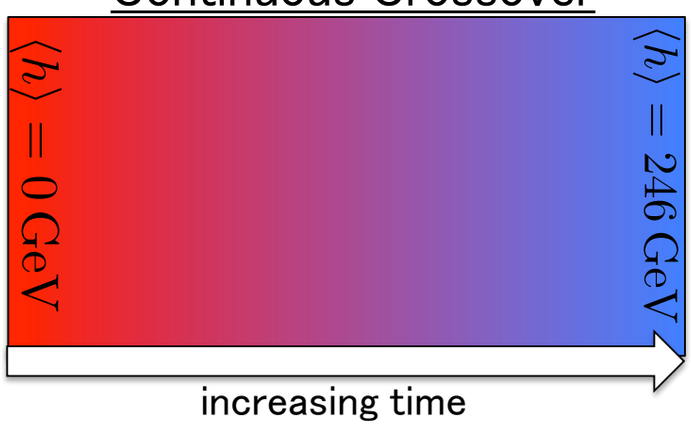
Will change Higgs behavior by interacting with it.

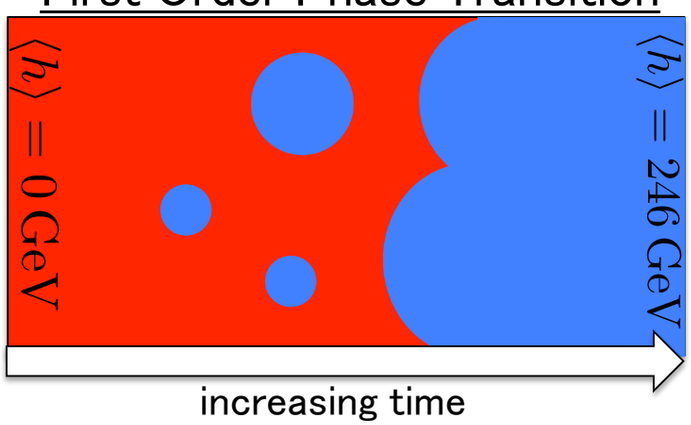
Simplest example:
Higgs coupling to one other spin-0 boson

How does Higgs drive electroweak phase transition?

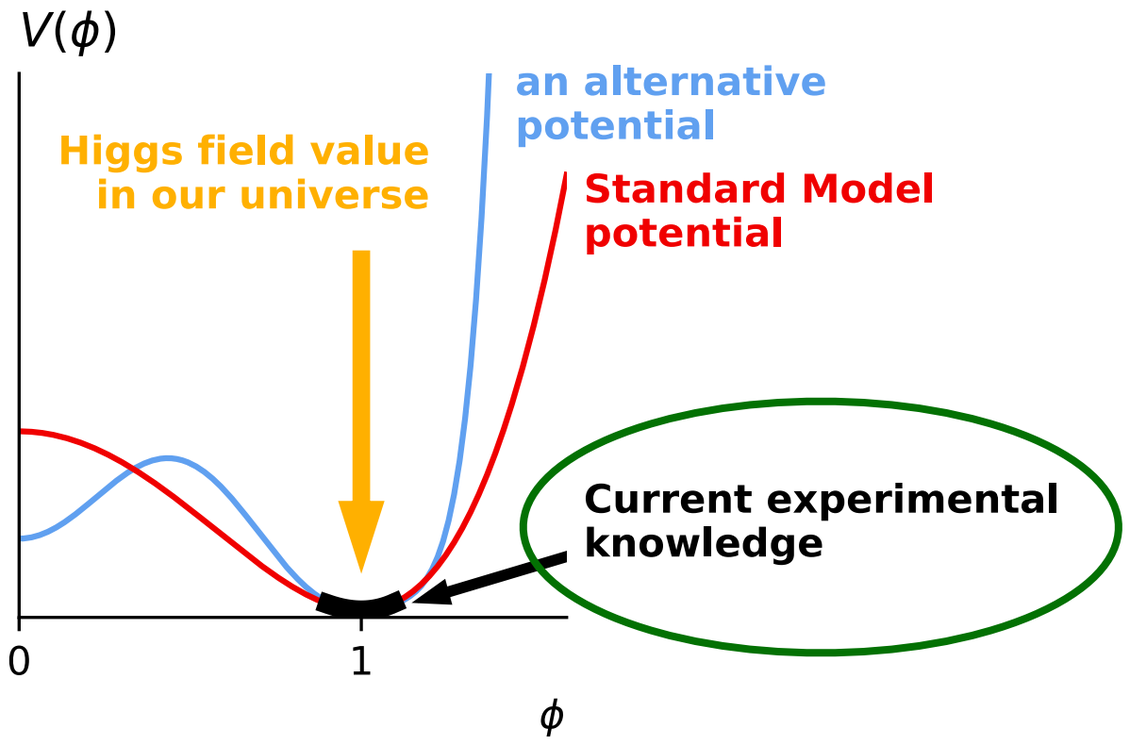




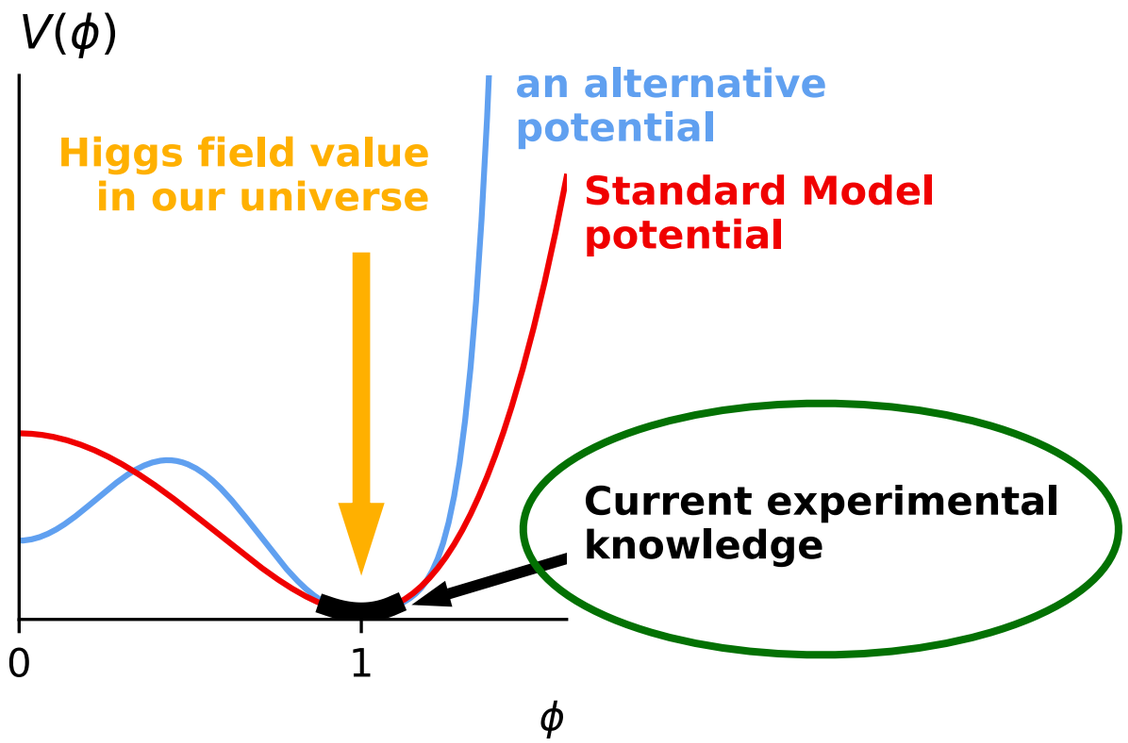




How does Higgs evolve in the early universe?

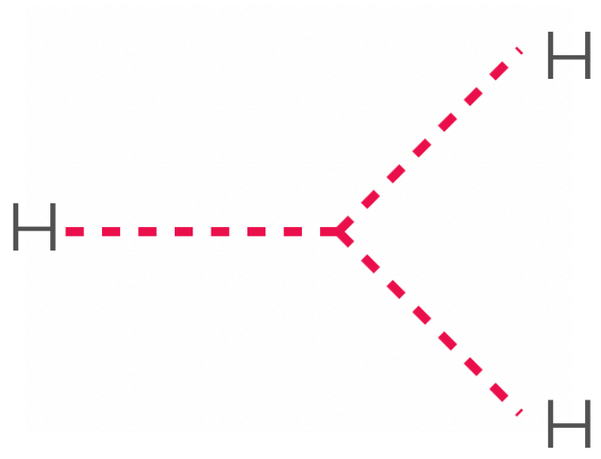


Need to go beyond this

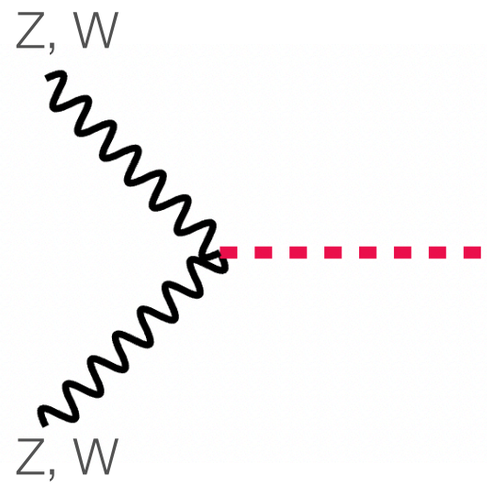


Need to go beyond this

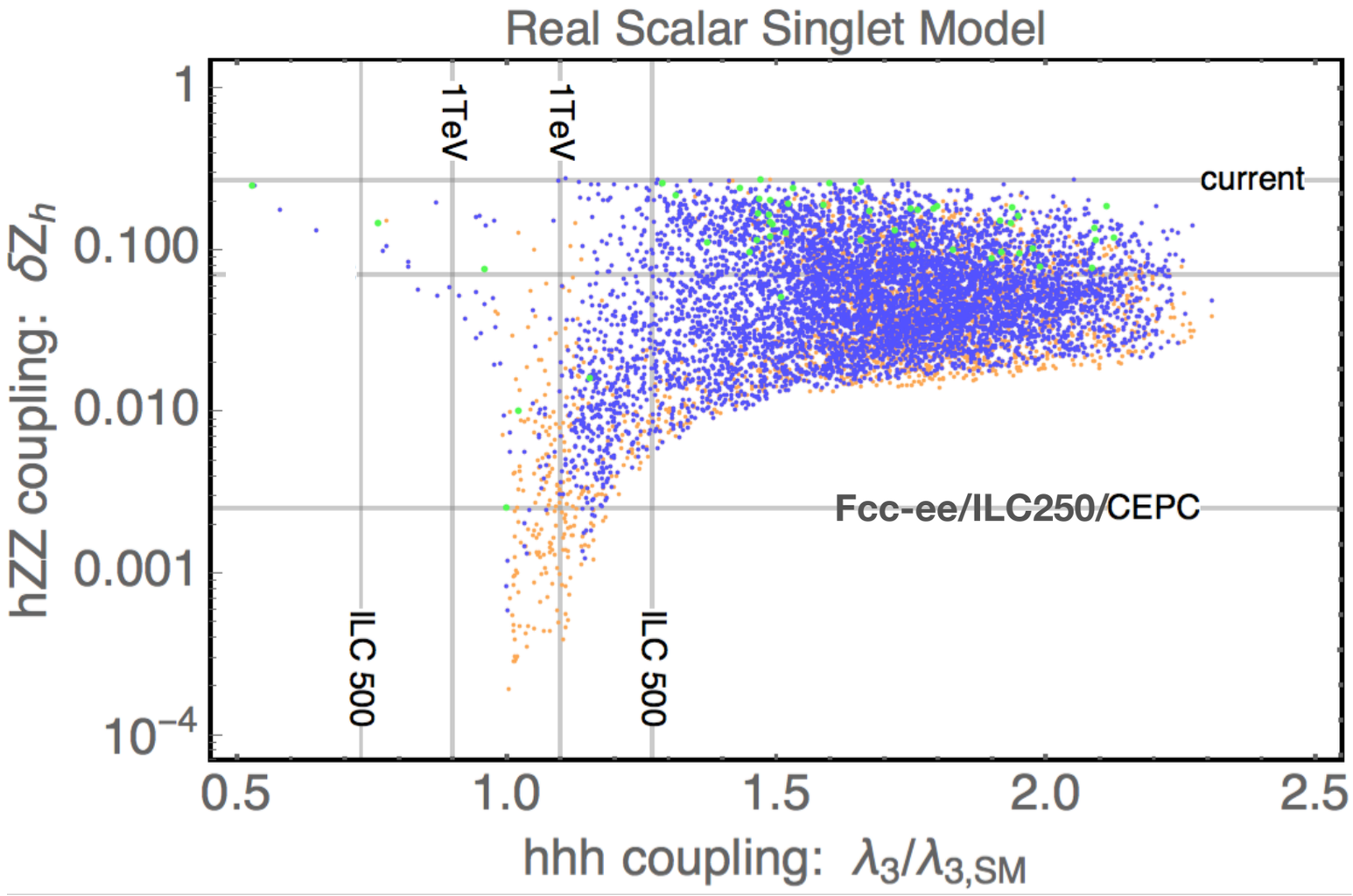
1. Self-coupling



2. New physics in the alternative scenario often induce changes in other Higgs coupling, such as hZ

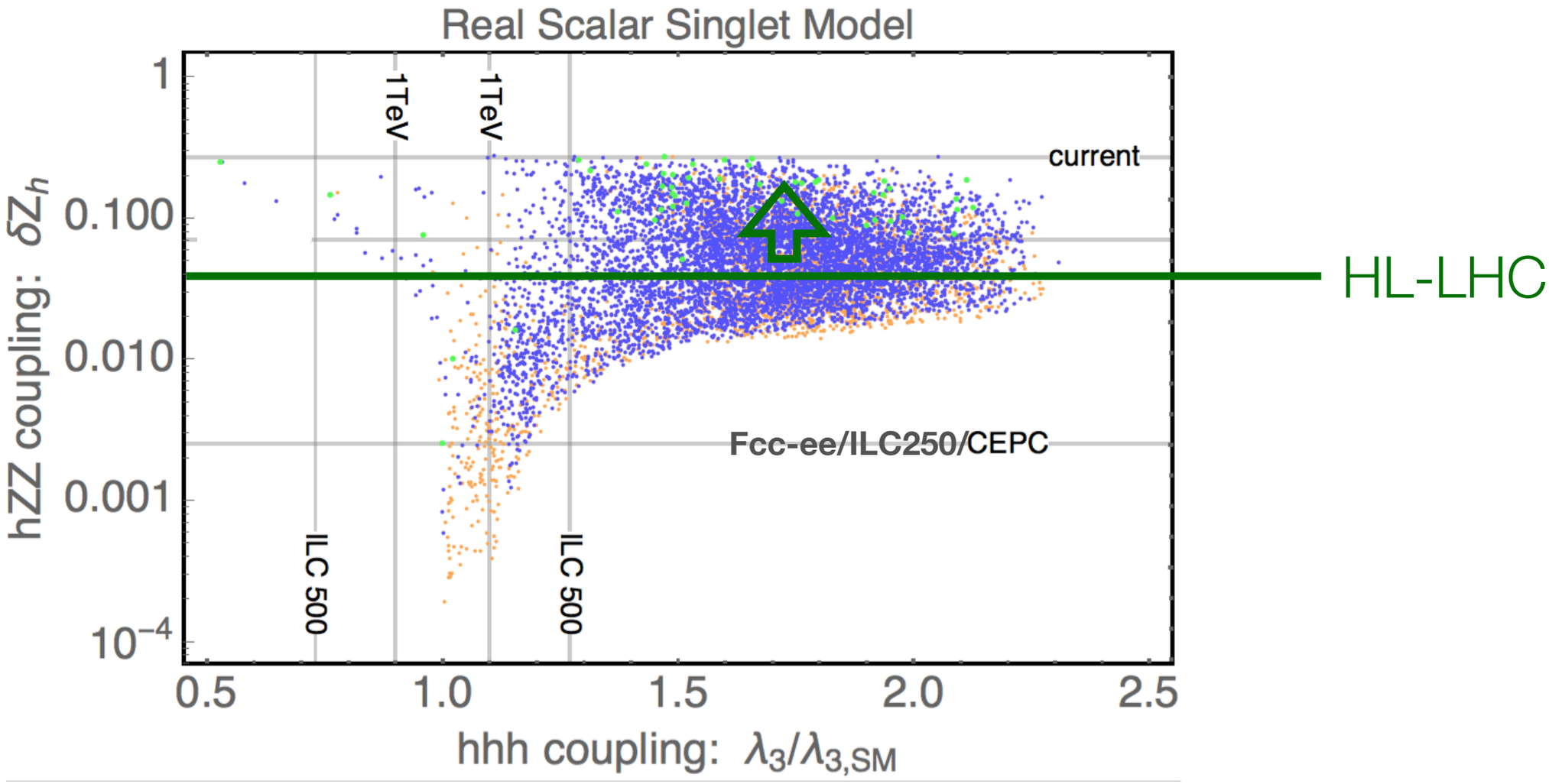


EW phase transition



A typical (simplest) model, Higgs mixes with a singlet

EW phase transition



A typical (simplest) model, Higgs mixes with a singlet

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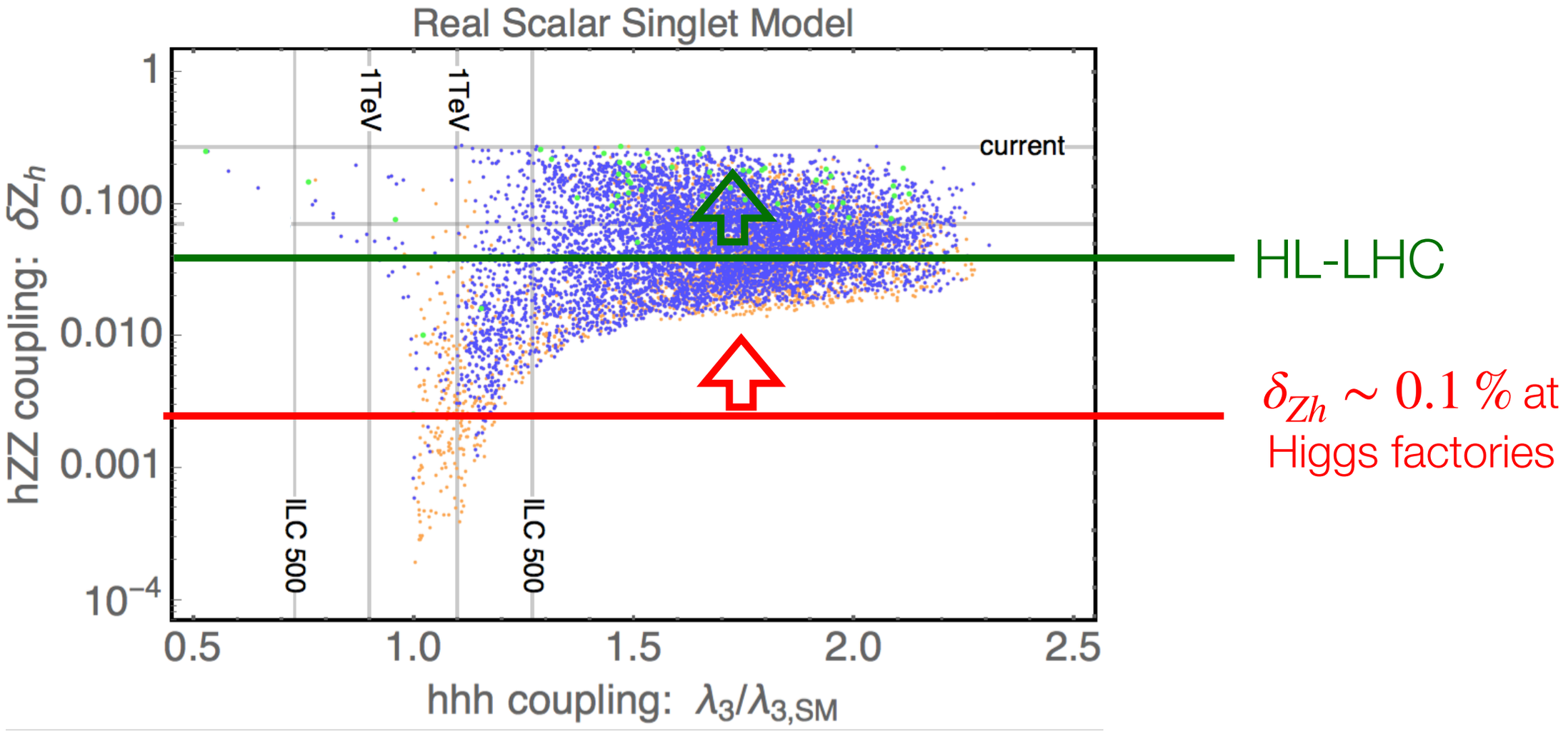

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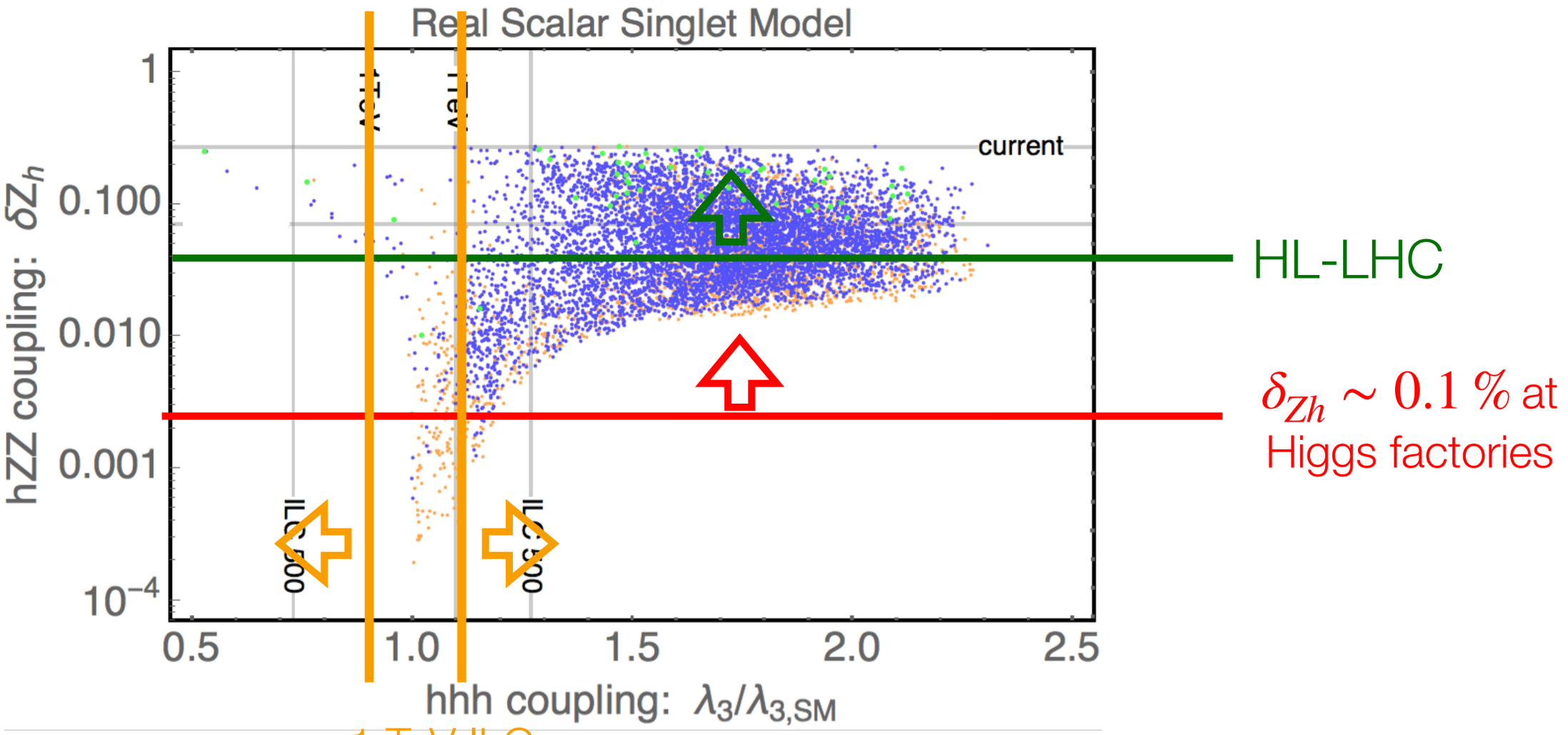


A typical (simplest) model, Higgs mixes with a singlet

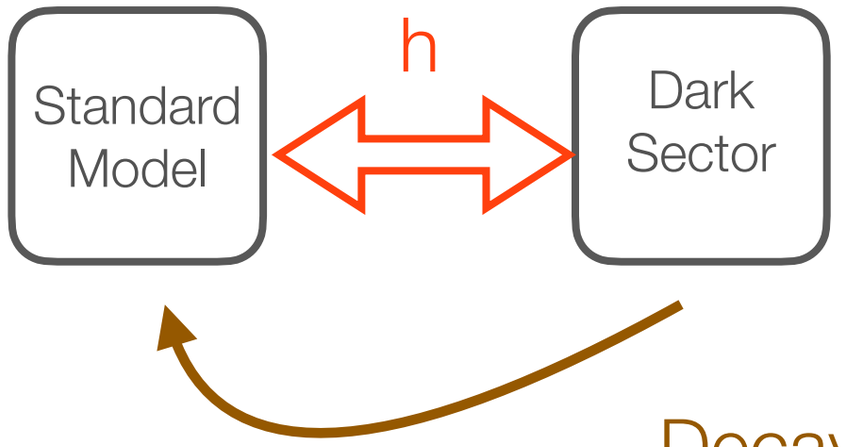
Other physics opportunities

Significantly enriches the physics program.

New physics searches at lepton colliders

- Precision measurement, virtual corrections to SM couplings of h, Z, W… (discussed above)
- Direct production, reach scales with E_{CM} More examples in P. Meade's talk
- New physics is light with very weak coupling.
  - Rare decays of H (clean), Z (large statistics).

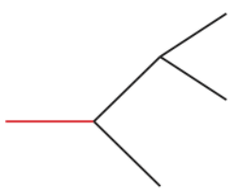
Higgs to dark sector?



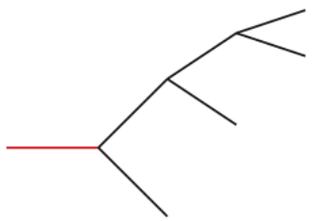
"Higgs portal"

Decay back to SM

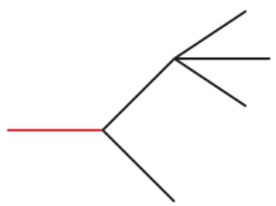
$h \to 2 \to 3$



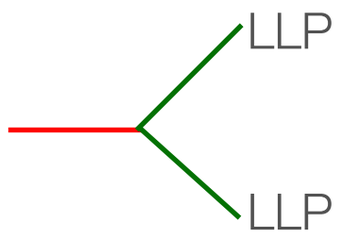
$h \to 2 \to 3 \to 4$



$h \to 2 \to (1+3)$

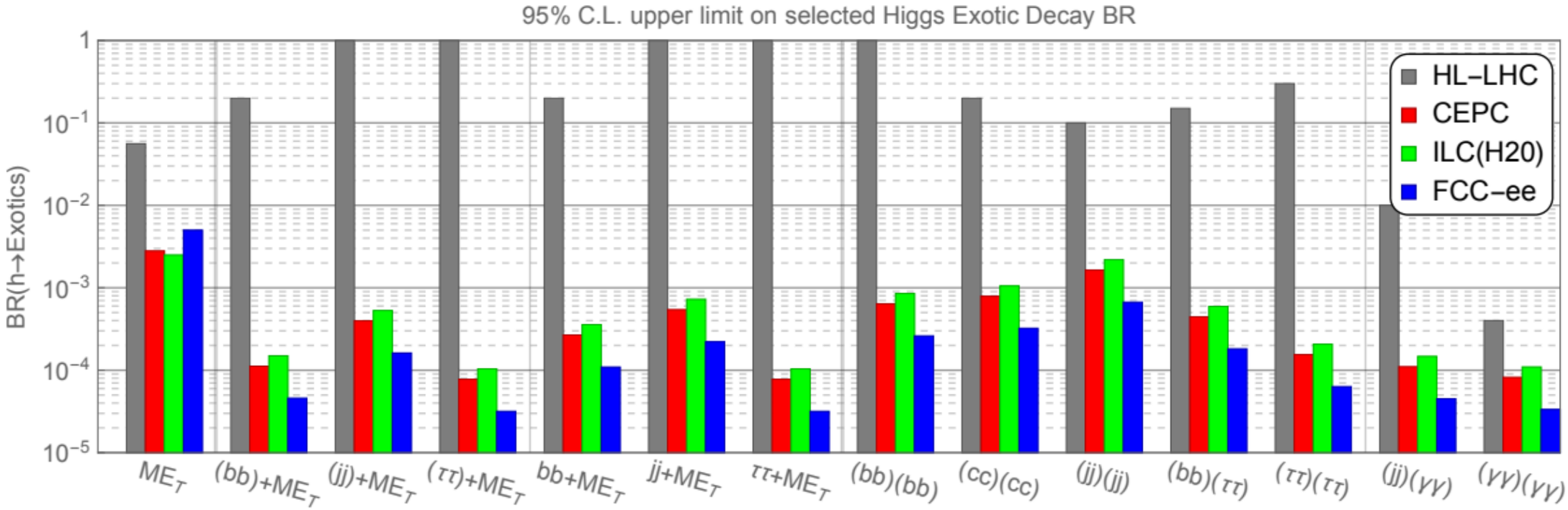


Long lived particles



....

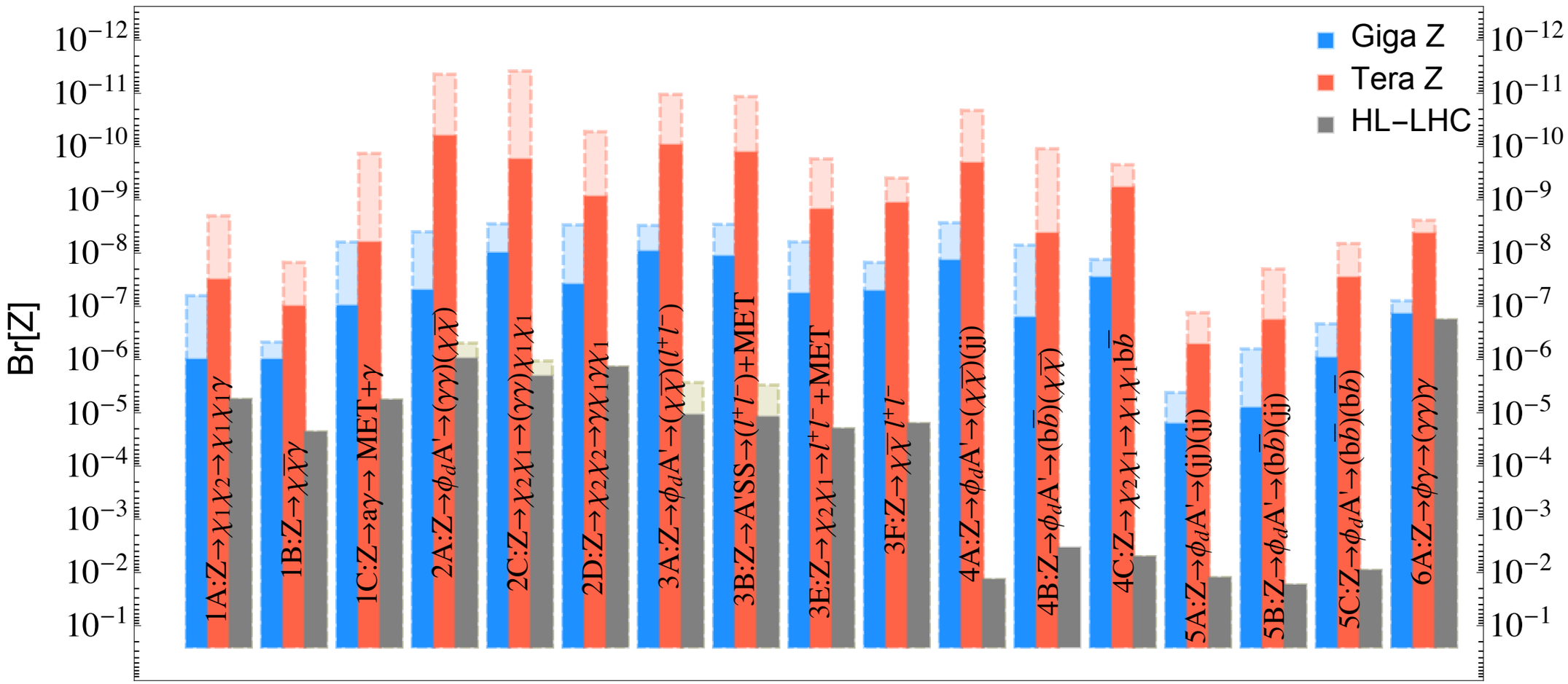
Higgs exotic decay



Complementary to hadron collider searches

Can probe interesting physics cases:
Hidden naturalness, dark matter, EW phase transition, …

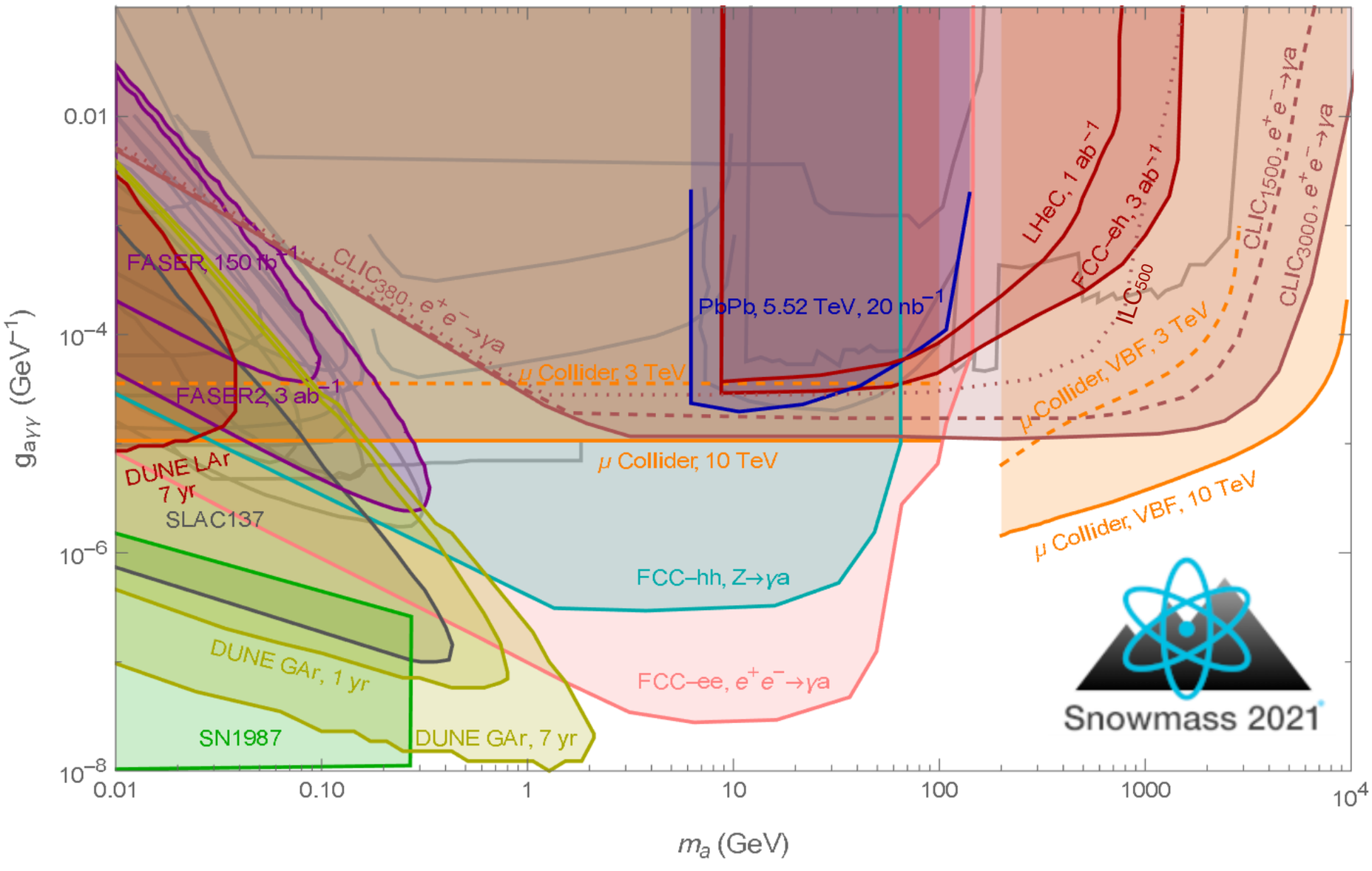
Rare Z decay at Tera-Z



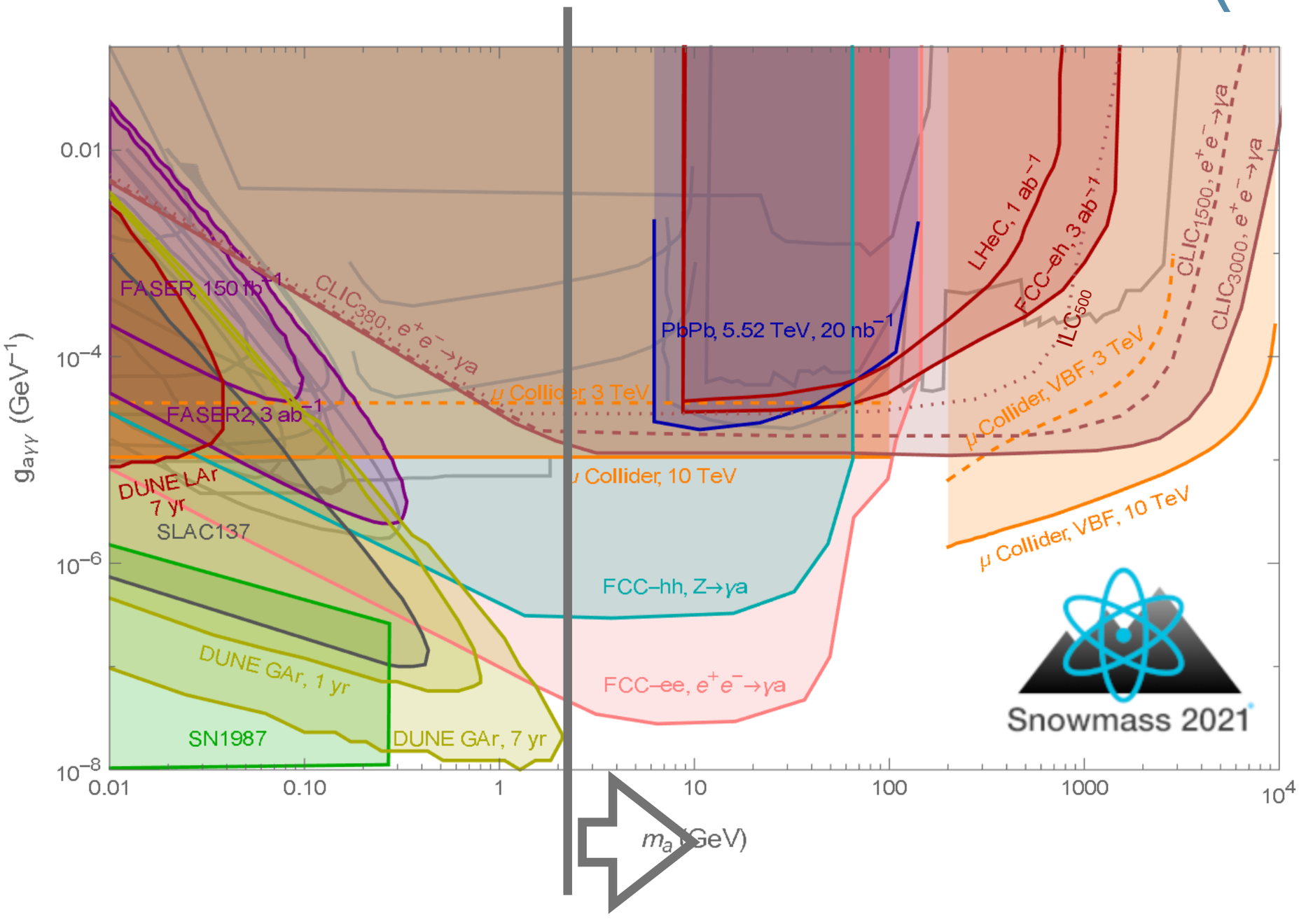
Probing exotic decay up to BR $\sim 10^{-11}$

Sensitive to a variety of dark photon, dark scalar models.

Axion Like Particles (ALP)

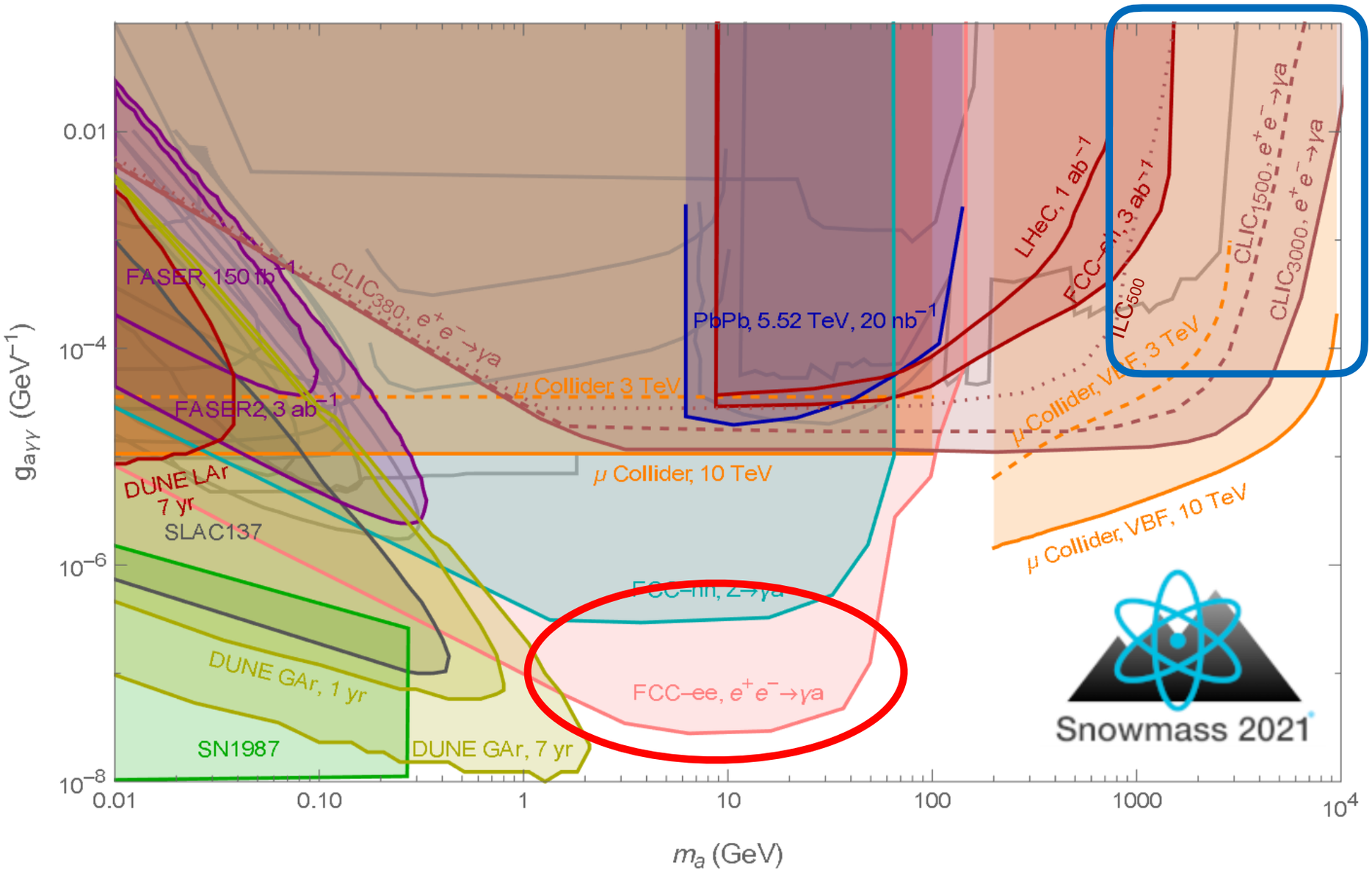


Axion Like Particles (ALP)



High energy colliders probing higher mass regions.

Axion Like Particles (ALP)



Higher energies

Reach scale with energy

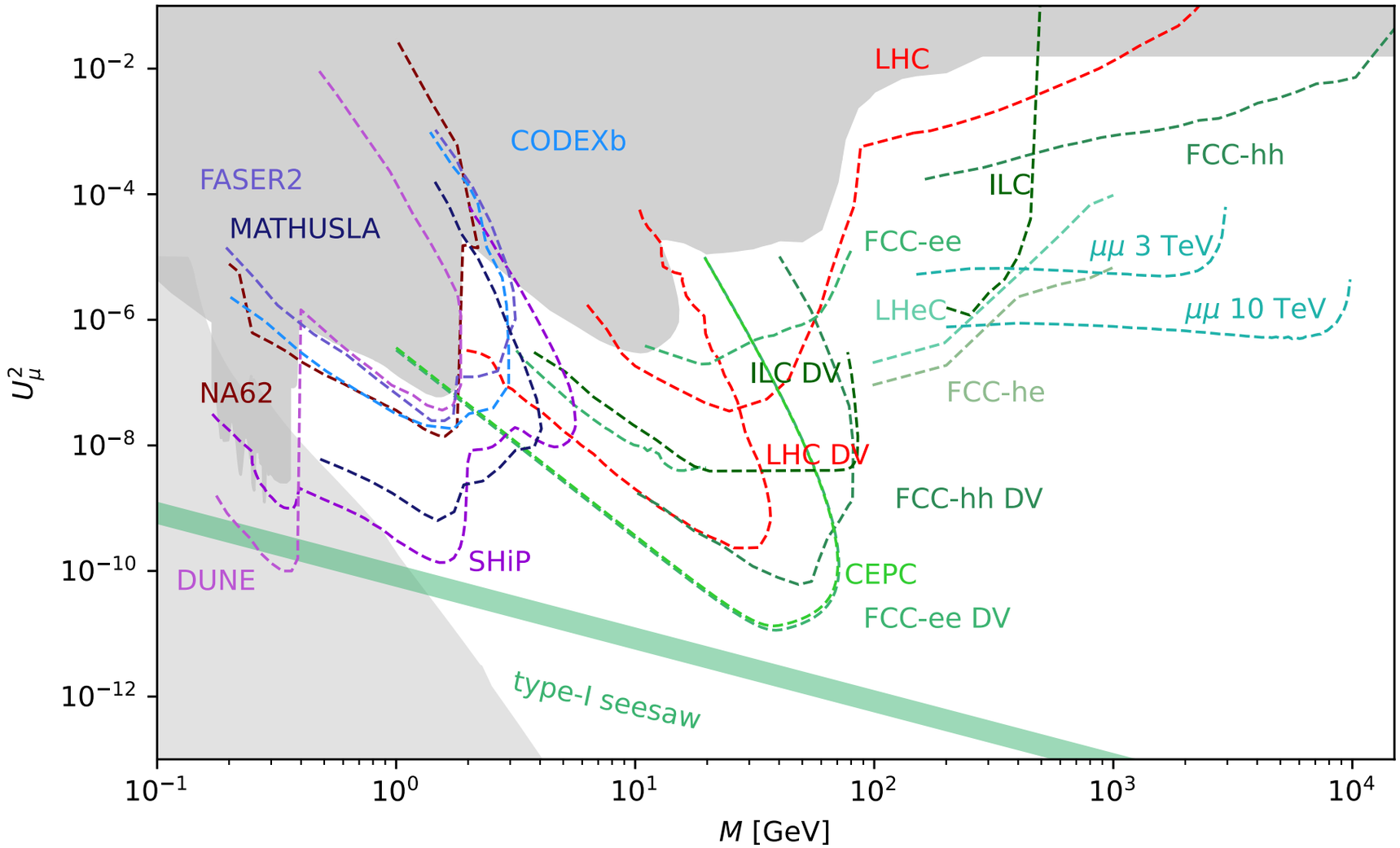
More examples in P. Meade's talk

Higgs factories

High luminosity, sensitive to weak signal

Heavy neutral lepton

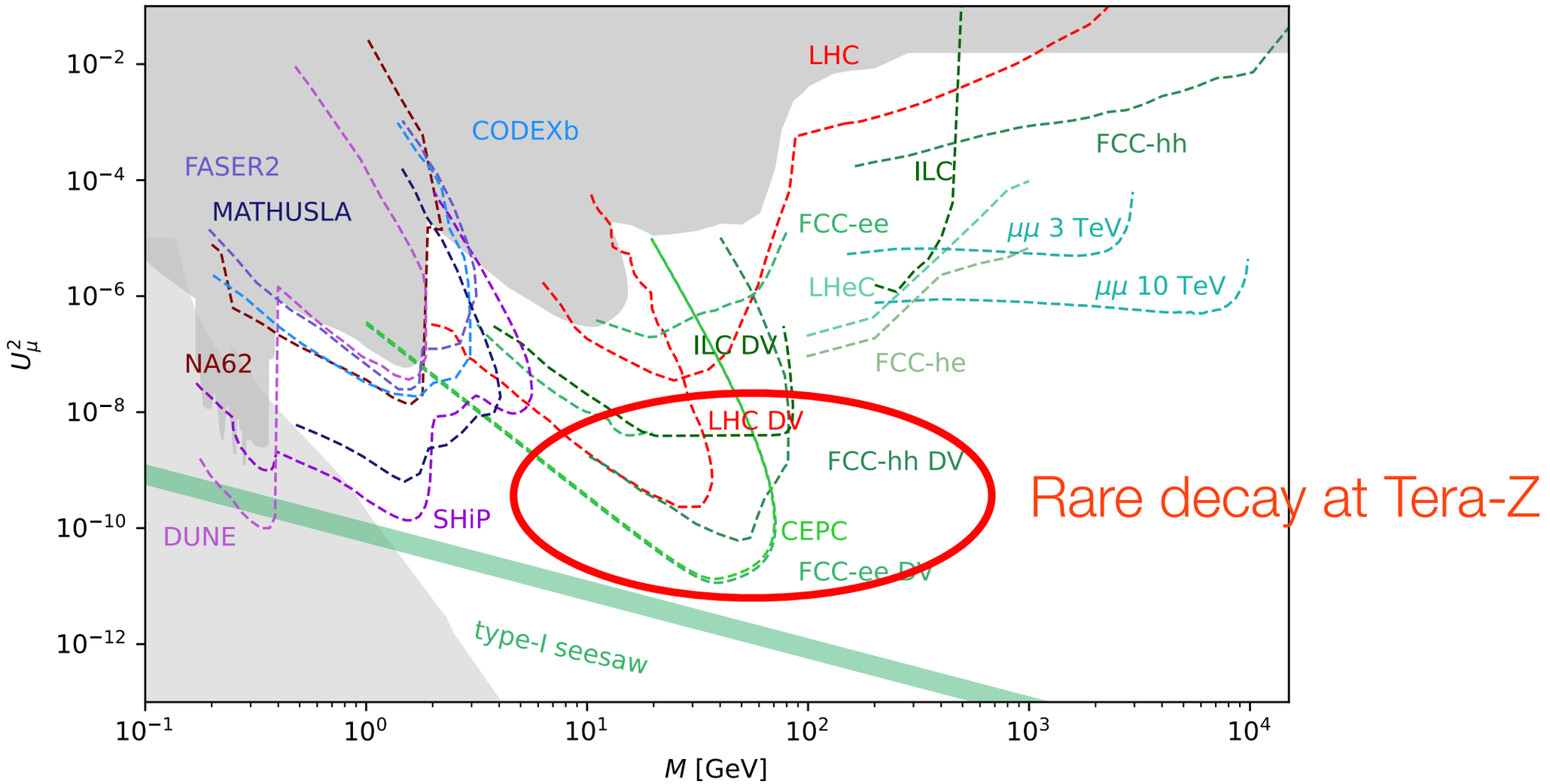
a.k.a. HNL, sterile neutrino, singlet fermion



Relation to neutrino mass?

Heavy neutral lepton

a.k.a. HNL, sterile neutrino, singlet fermion

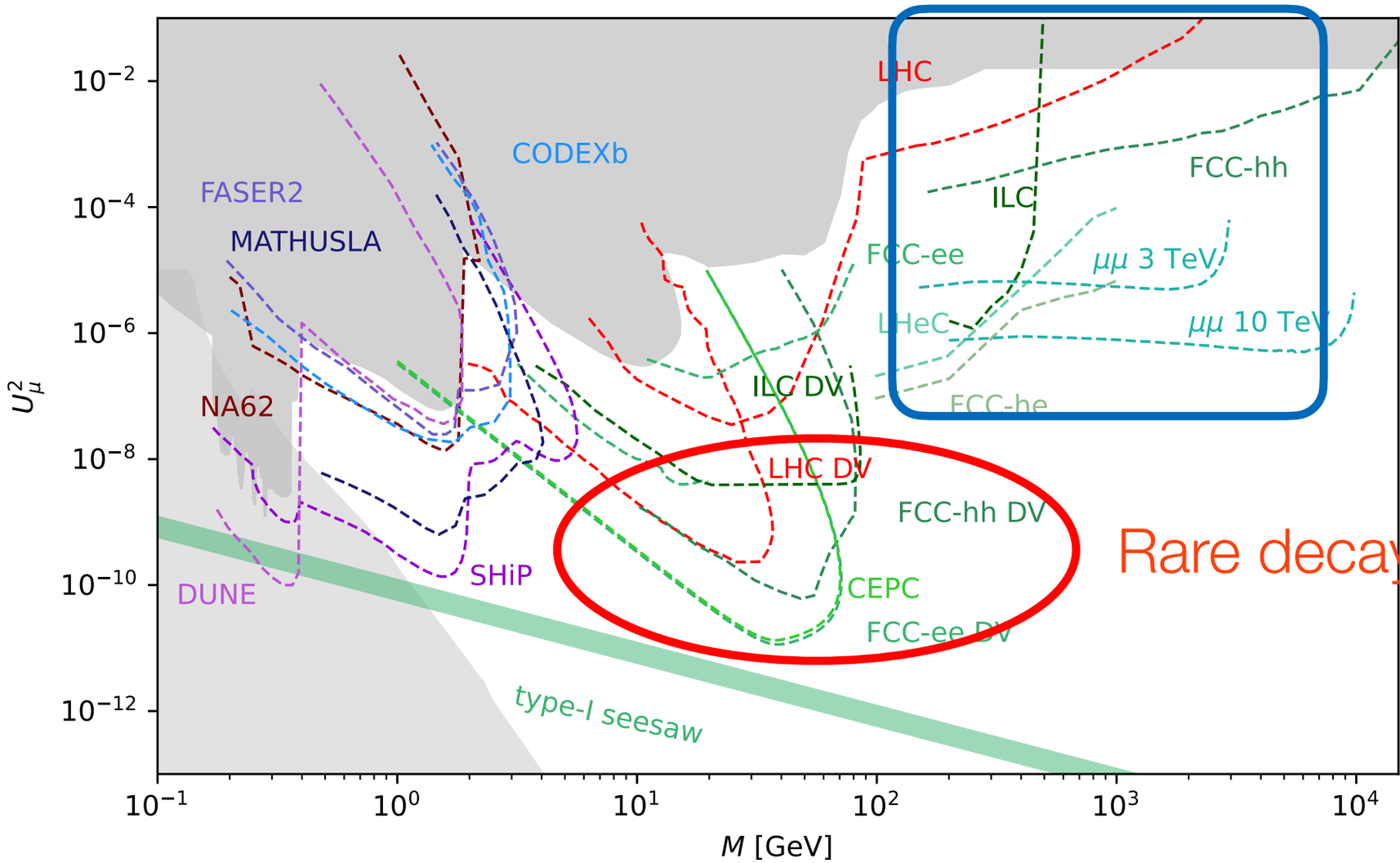


Rare decay at Tera-Z

Relation to neutrino mass?

Heavy neutral lepton

a.k.a. HNL, sterile neutrino, singlet fermion



Higher energies

Rare decay at Tera-Z

Relation to neutrino mass?

B, charm, hadron, τ at tera-Z

Particle production

Particle	@ Tera-Z	@ Belle II		@ LHCb
b hadrons				
B^+	6×10^{10}	3×10^{10}	($50\,\mathrm{ab}^{-1}$ on $\Upsilon(4S)$)	3×10^{13}
B^0	6×10^{10}	3×10^{10}	($50\,\mathrm{ab}^{-1}$ on $\Upsilon(4S)$)	3×10^{13}
B_s	2×10^{10}	3×10^{8}	($5\,\mathrm{ab}^{-1}$ on $\Upsilon(5S)$)	8×10^{12}
b baryons	1×10^{10}			1×10^{13}
Λ_b	1×10^{10}			1×10^{13}
c hadrons				
D^0	2×10^{11}			
D^+	6×10^{10}			
D_s^+	3×10^{10}			
Λ_c^+	2×10^{10}			
τ^+	3×10^{10}	5×10^{10}	($50\,\mathrm{ab}^{-1}$ on $\Upsilon(4S)$)	

From CEPC's CDR using fragmentation ratios from Amhis et al, 17

- Similar statistical sample of $B^{0,\pm}$, τ's at Belle 2 and CEPC
- Two order of magnitude more B_s at CEPC wrt to Belle 2
- b-baryon physics possible at the CEPC
- Limited possibilities for charm physics at Belle 2

Great place to probe rare flavor processes!

Other Higgs factories

- Muon Collider at 125 GeV. Good for Higgs-muon coupling measurement.
- High energy pp collider and muon collider are also good Higgs factories. P. Meade's talk

Summary

- Higgs boson is *there.* It is *important*, and yet *mysterious.*
  - *Need a better picture to understand it!*
- Higgs factory reaches beyond the LHC. And *complementary* to LHC searches.

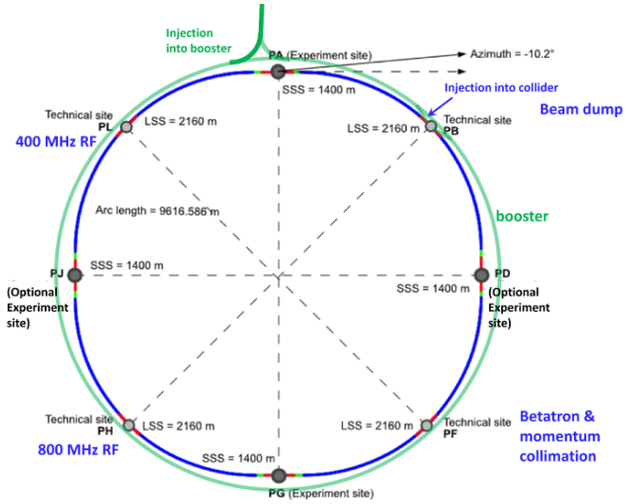
Summary

- Higgs boson is *there.* It is *important*, and yet *mysterious.*
  - *Need a better picture to understand it!*
- Higgs factory reaches beyond the LHC. And *complementary* to LHC searches.

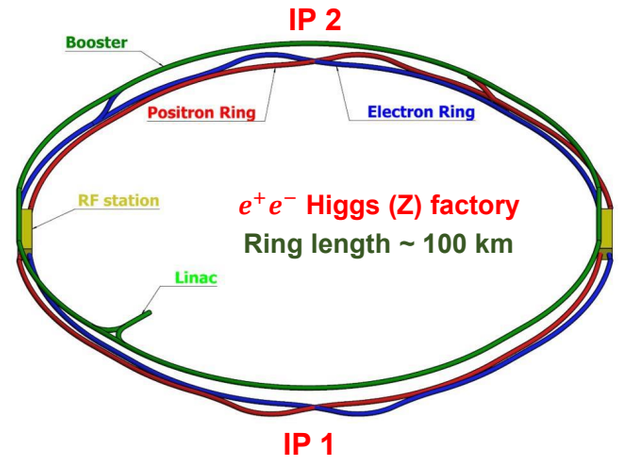
This is the clearest and most concrete argument for making progress, based on what we actually know.

With all these excellent options

Circular



FCC-ee

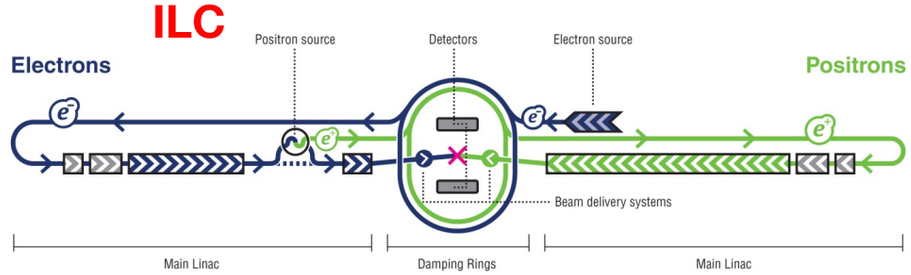


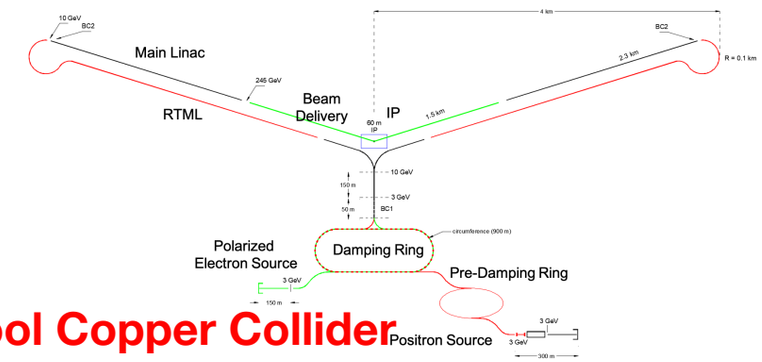
CEPC

+…

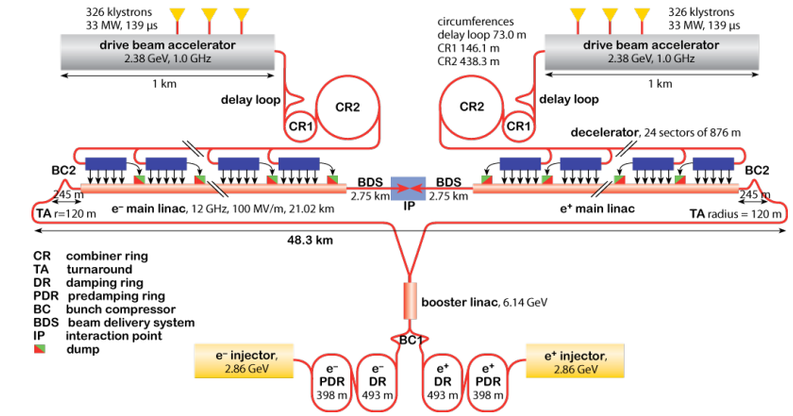
Linear

ILC





C^3 Cool Copper Collider



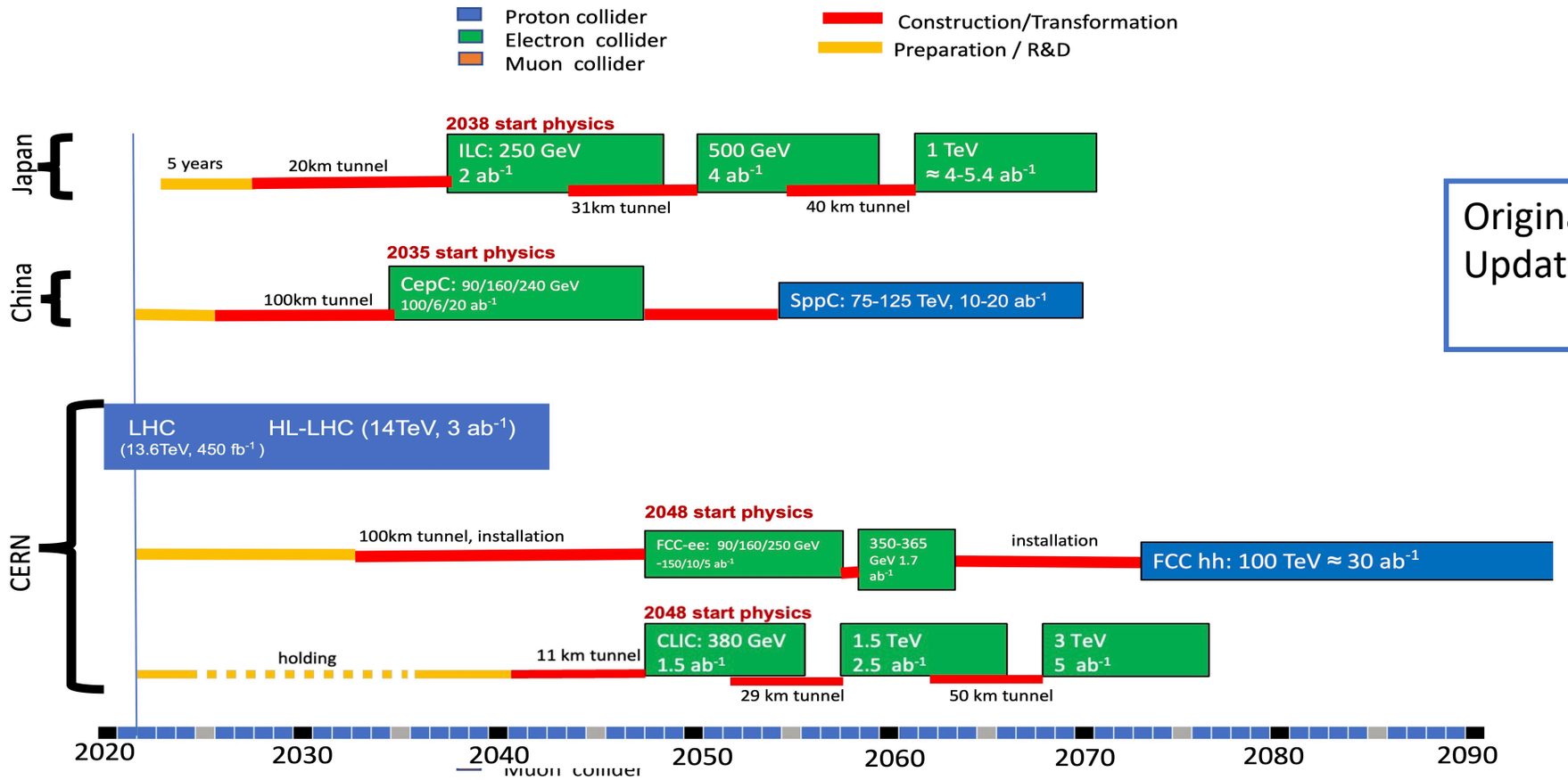
CLIC

2014 P5: Higgs as a new tool for discovery

In summary, **the EF supports a fast start for construction of an e^+e^- Higgs factory (linear or circular), and a significant R&D program for multi-TeV colliders (hadron and muon). The realization of a Higgs factory will require an immediate, vigorous and targeted detector R&D program, while the study towards multi-TeV colliders will need significant and long-term investments in a broad spectrum of R&D programs for accelerators and detectors.** These projects have the potential to be transformative as they will push the boundaries of our knowledge by testing the limits of the SM, and indirectly or directly discovering new physics beyond the SM.

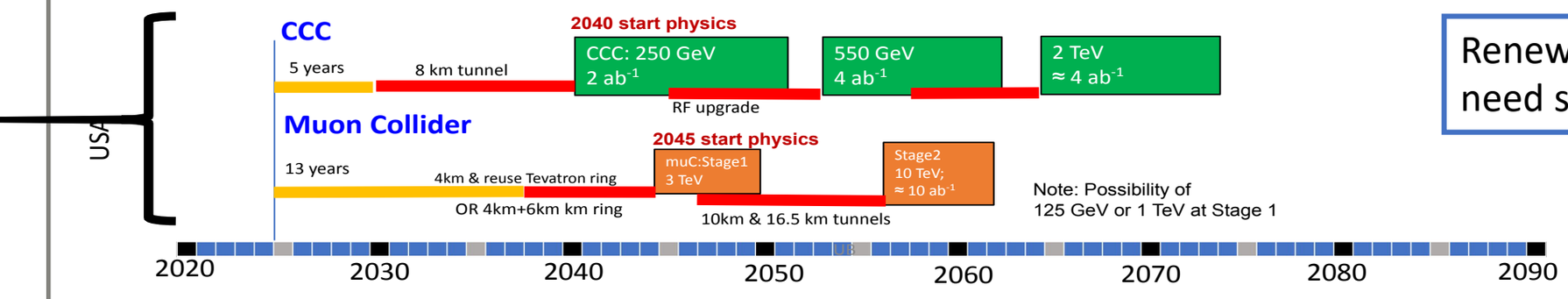
We should do it ASAP!

Extra



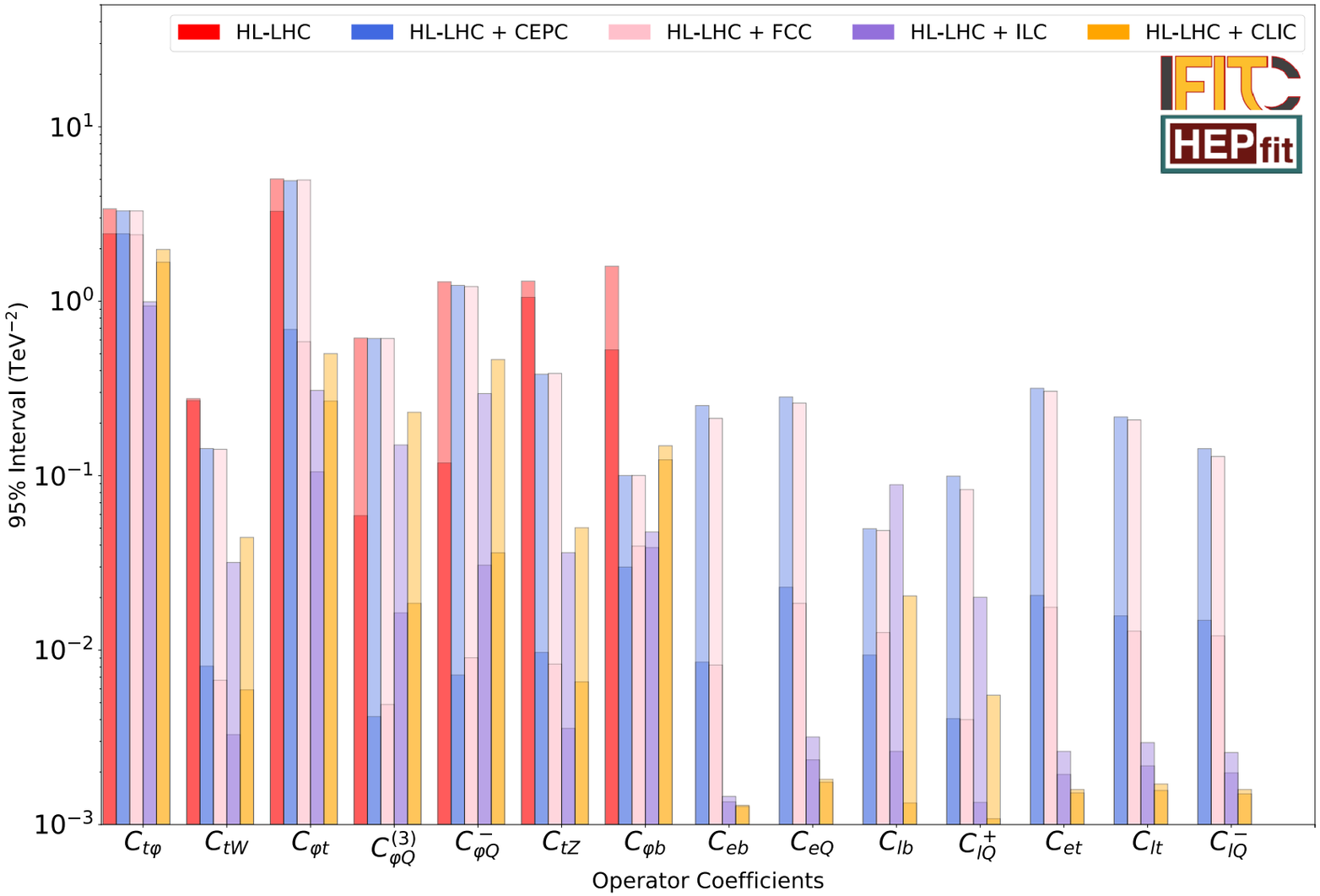
Original timeline from ESG
Updated during Snowmass 2021
(see EF Report)

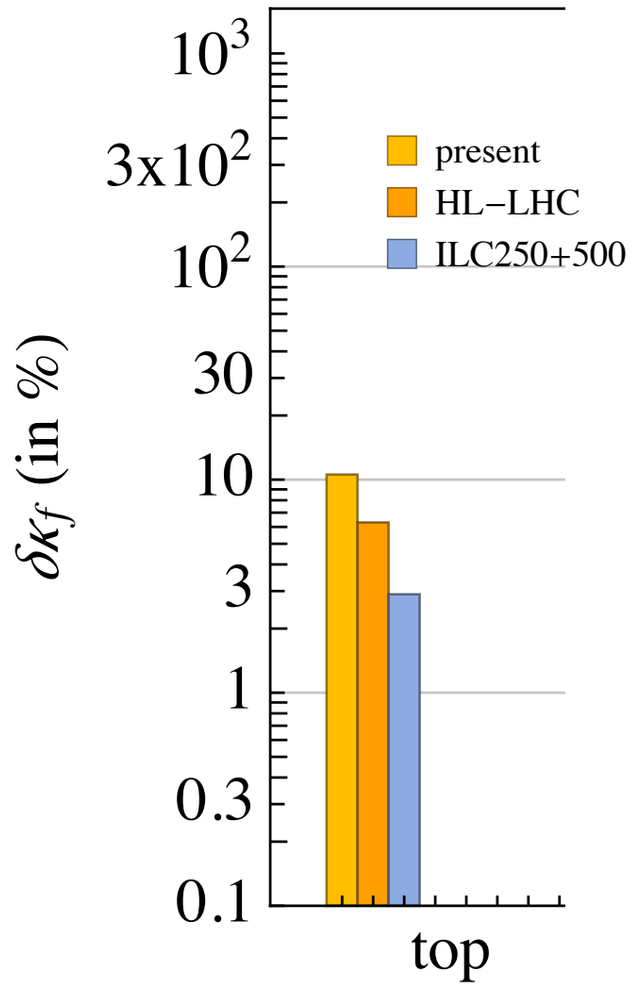
Proposals emerging from Snowmass 2021 for a US based collider



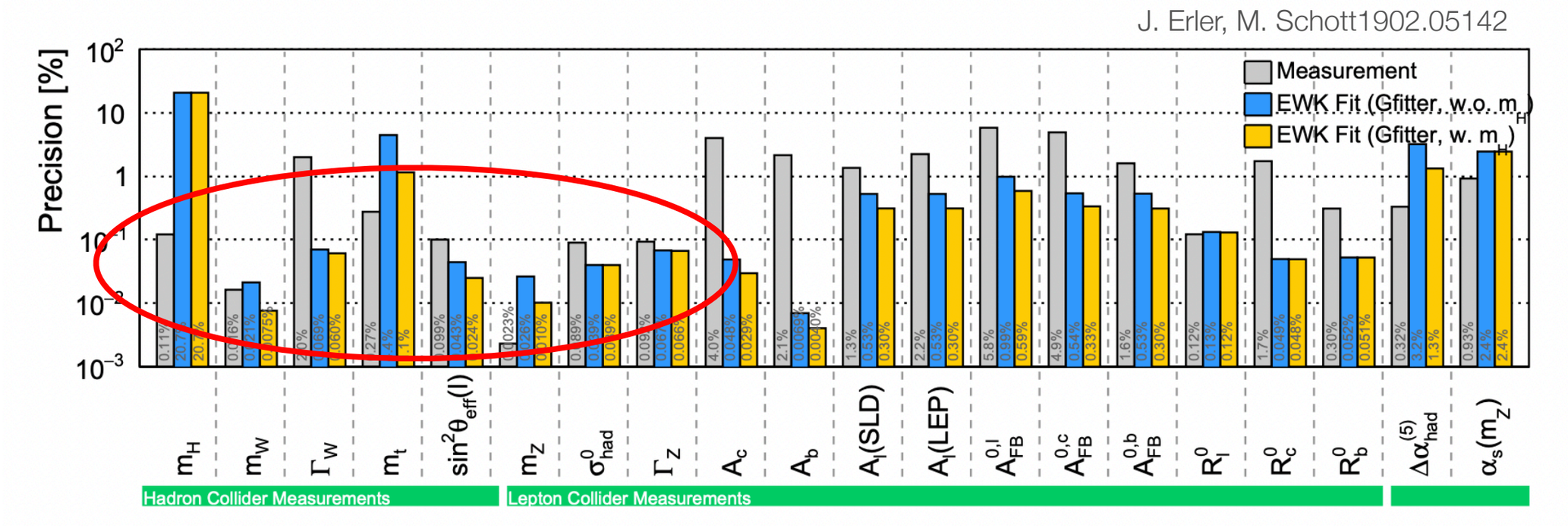
Renewed interest in lepton colliders:
need supporting R&D in near future

Top quark coupling



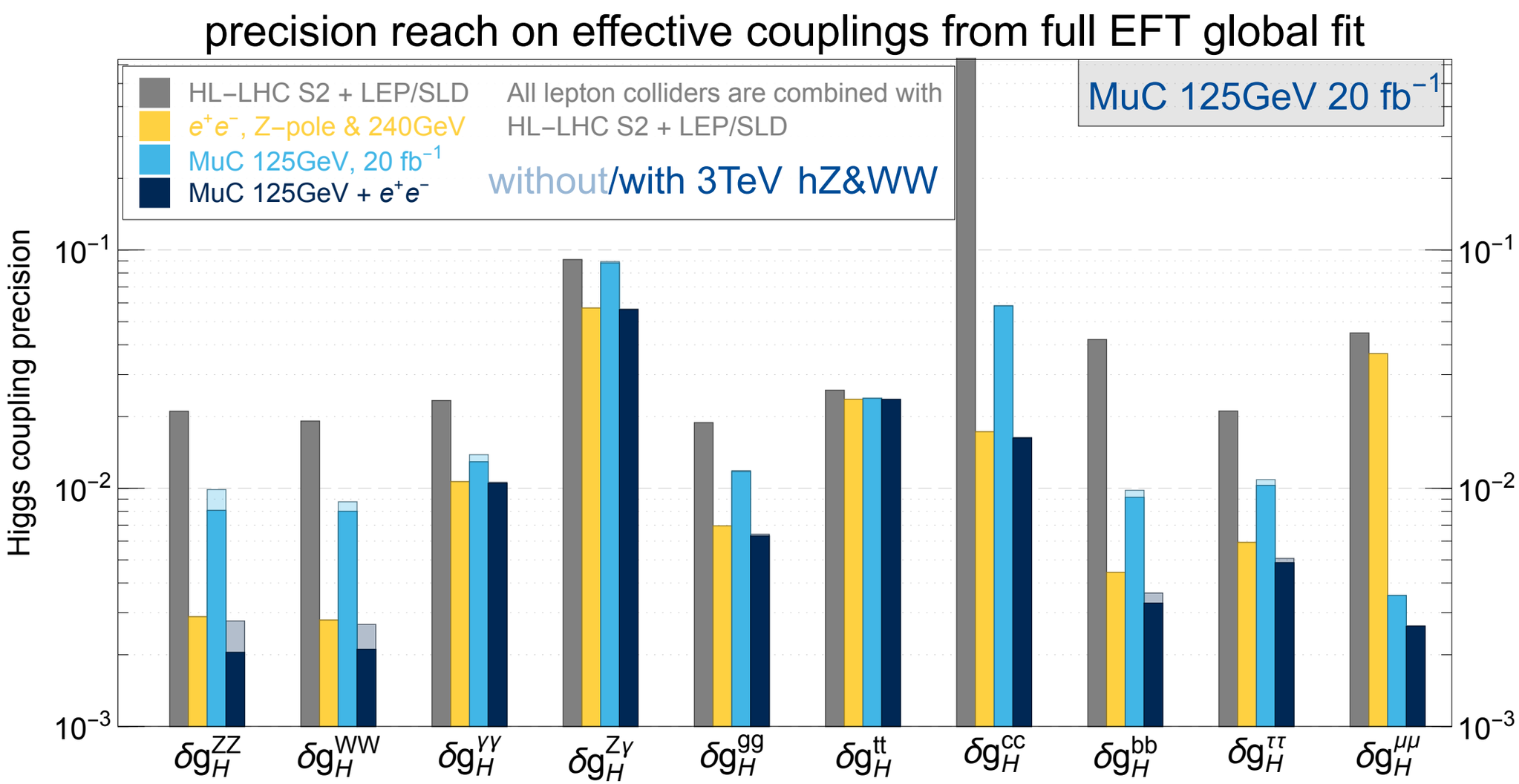


SM precision

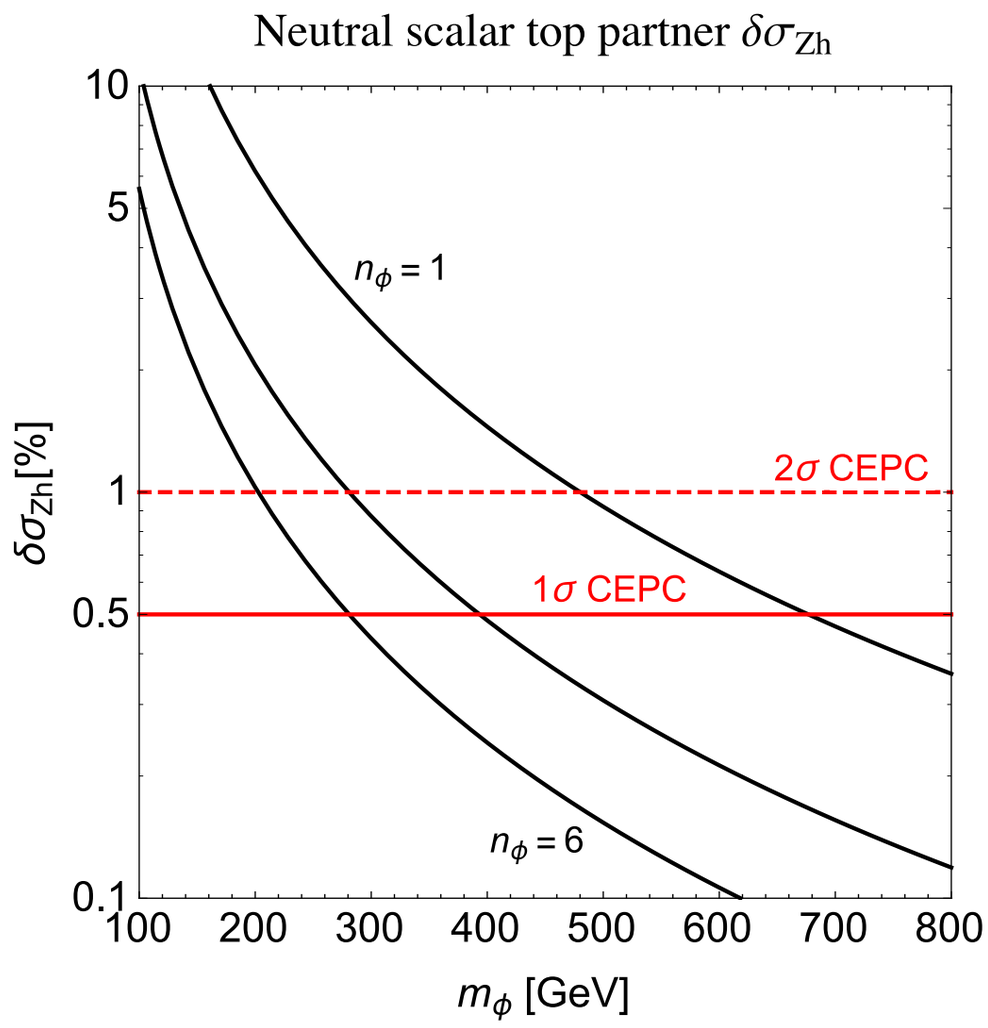


Other SM couplings measured better than 10^{-3}

Muon Collider 125



Is the Higgs fine-tuned?

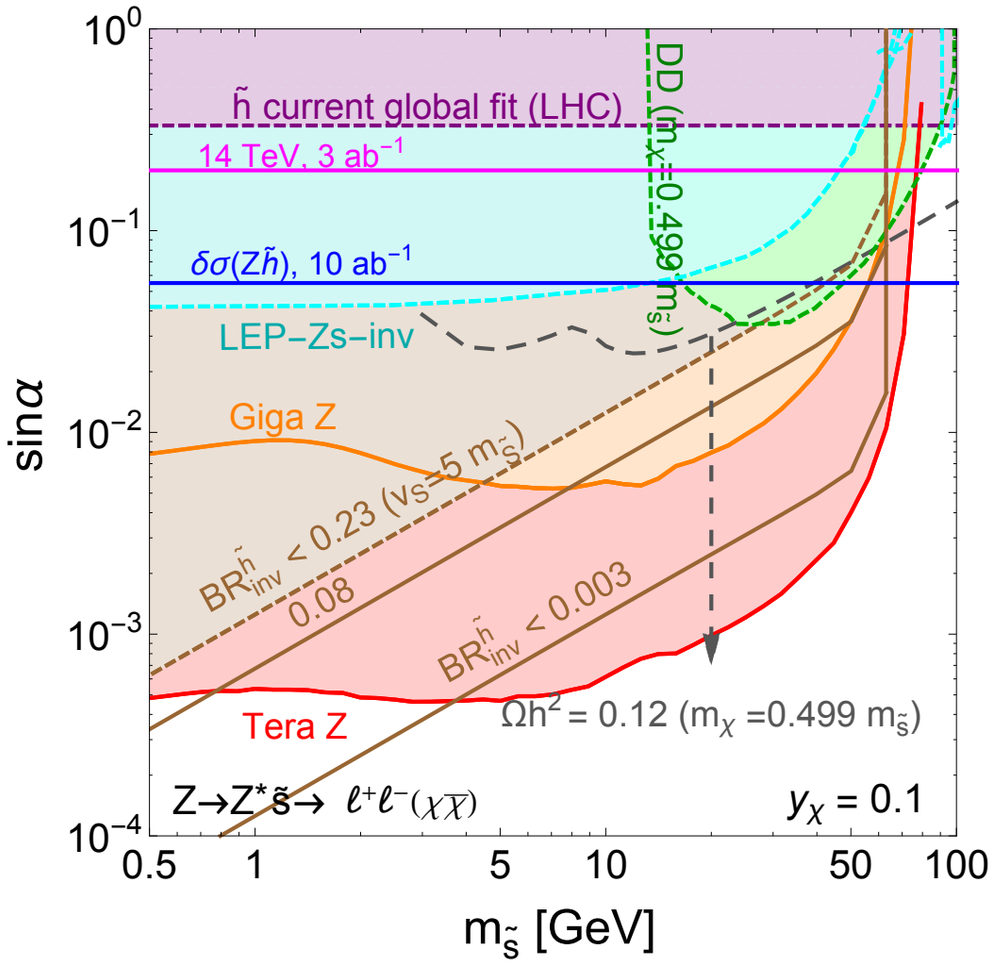


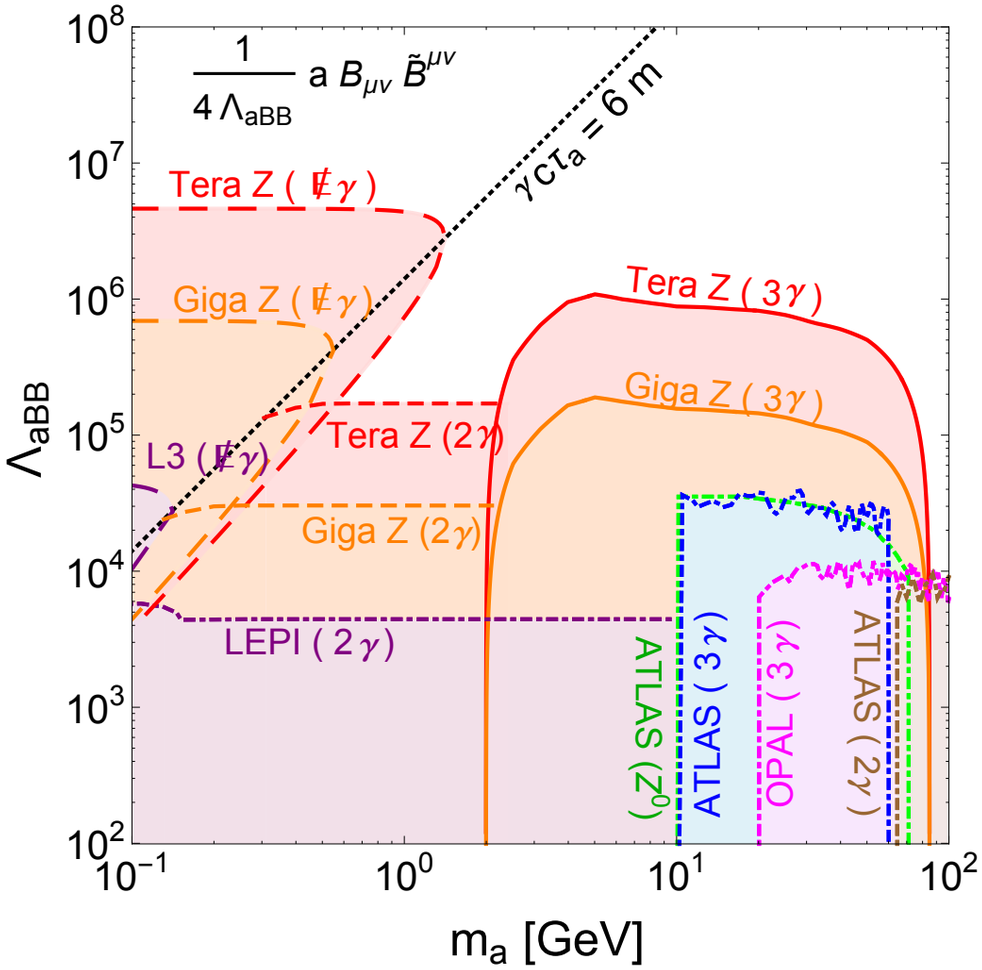
New physics is neutral, only couples to the Higgs

Neutral naturalness

Dark photon, dark scalar

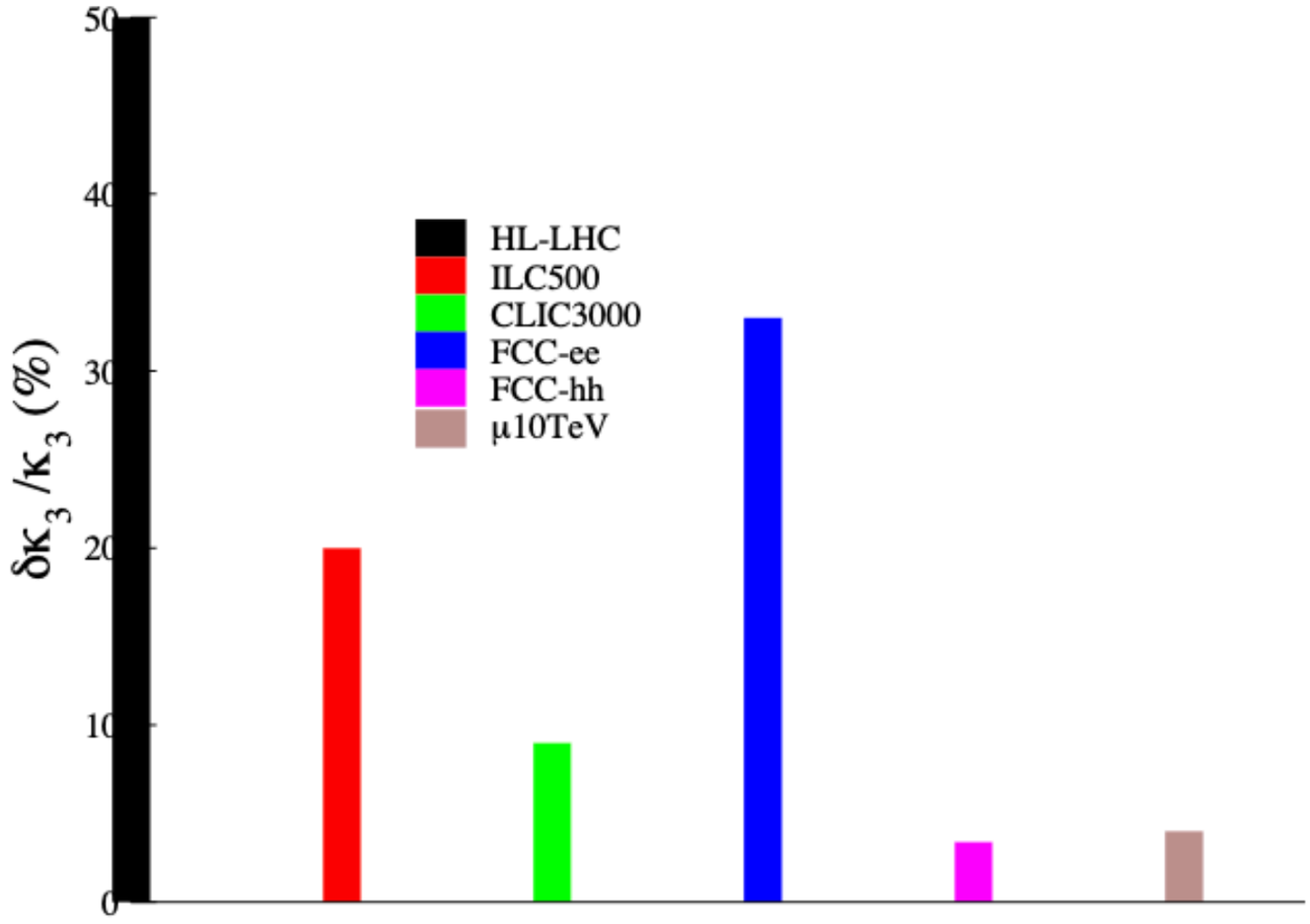
J. Liu, X.P. Wang, W. Xue, LTW



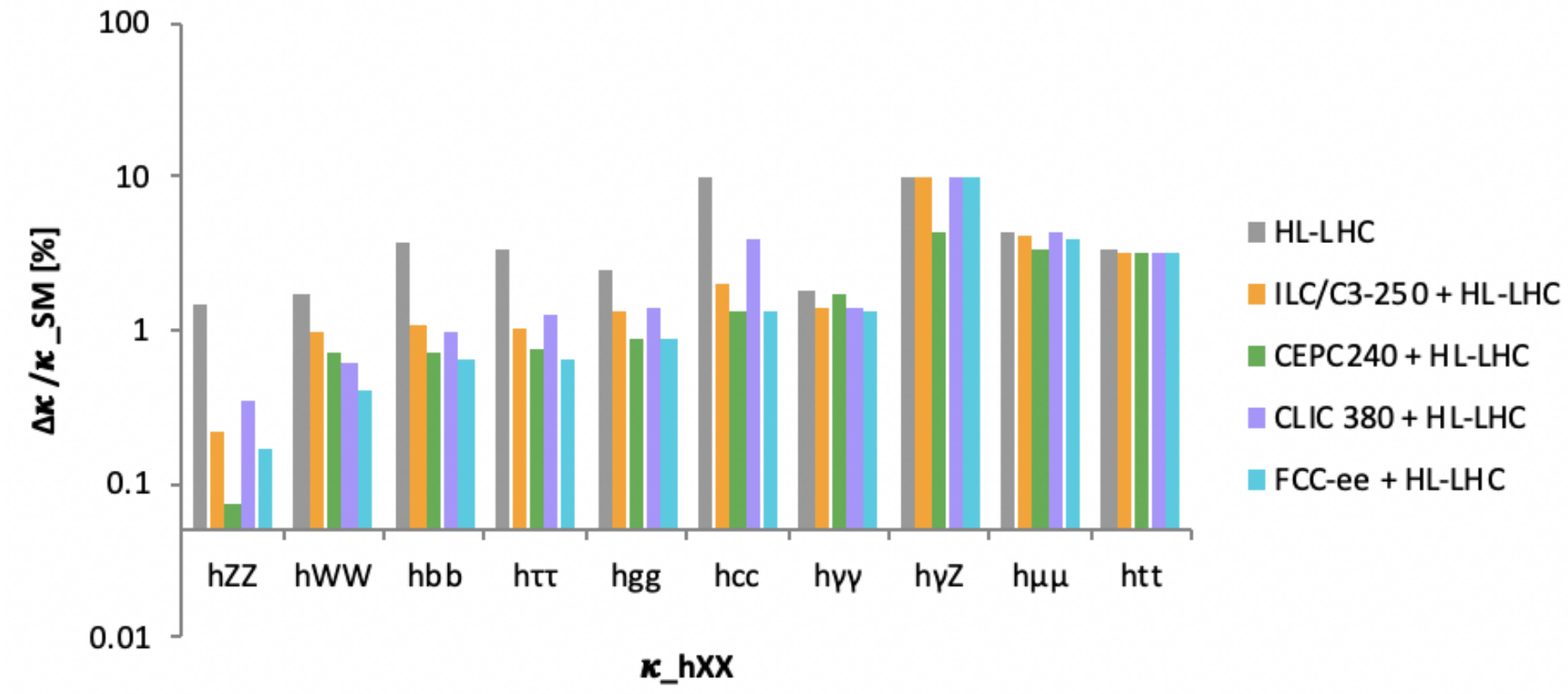


There are certainly many more scenarios to explore here.

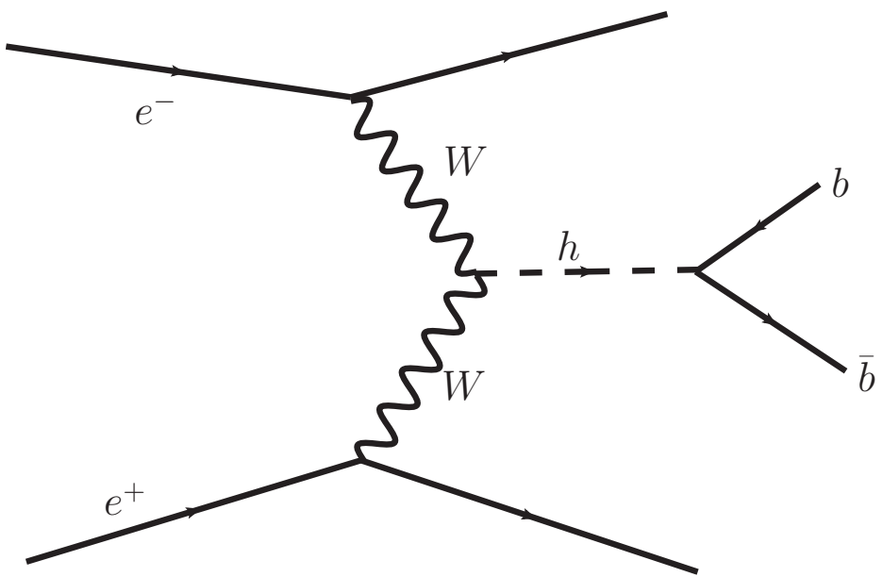
Higgs self-coupling



HL-LHC Higgs measurement

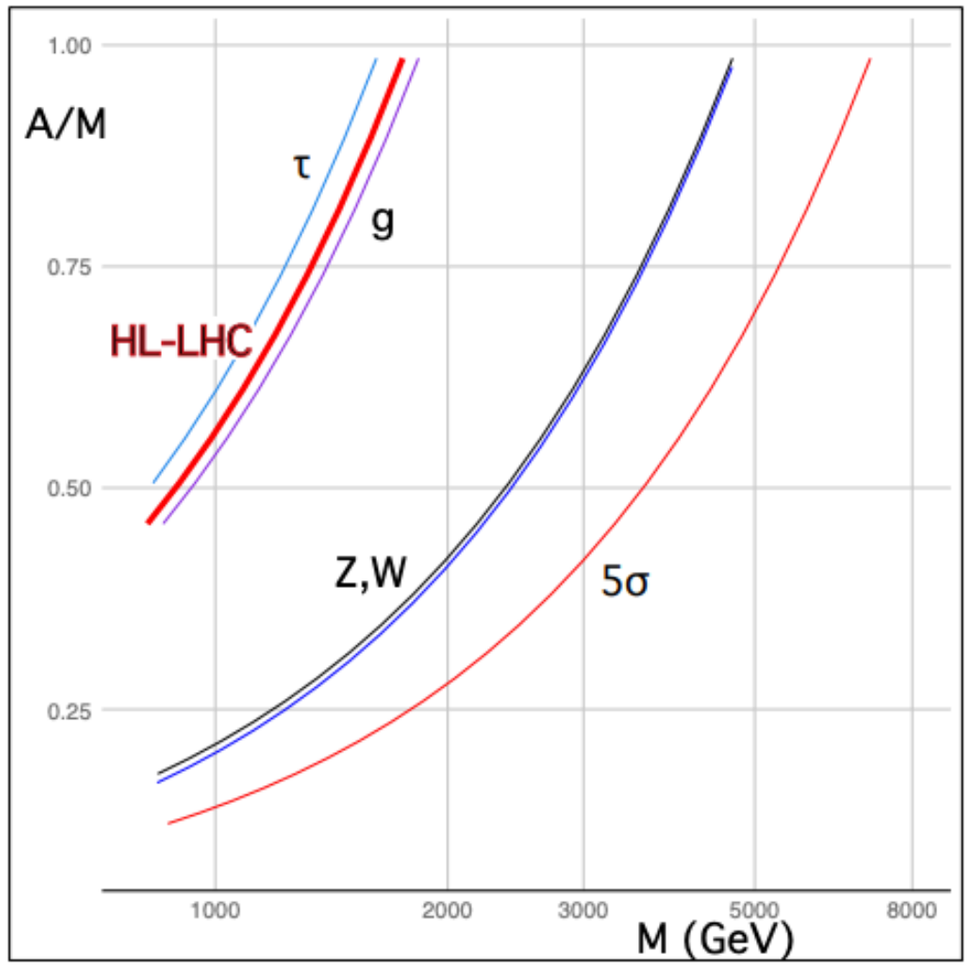


Higgs width from VBF

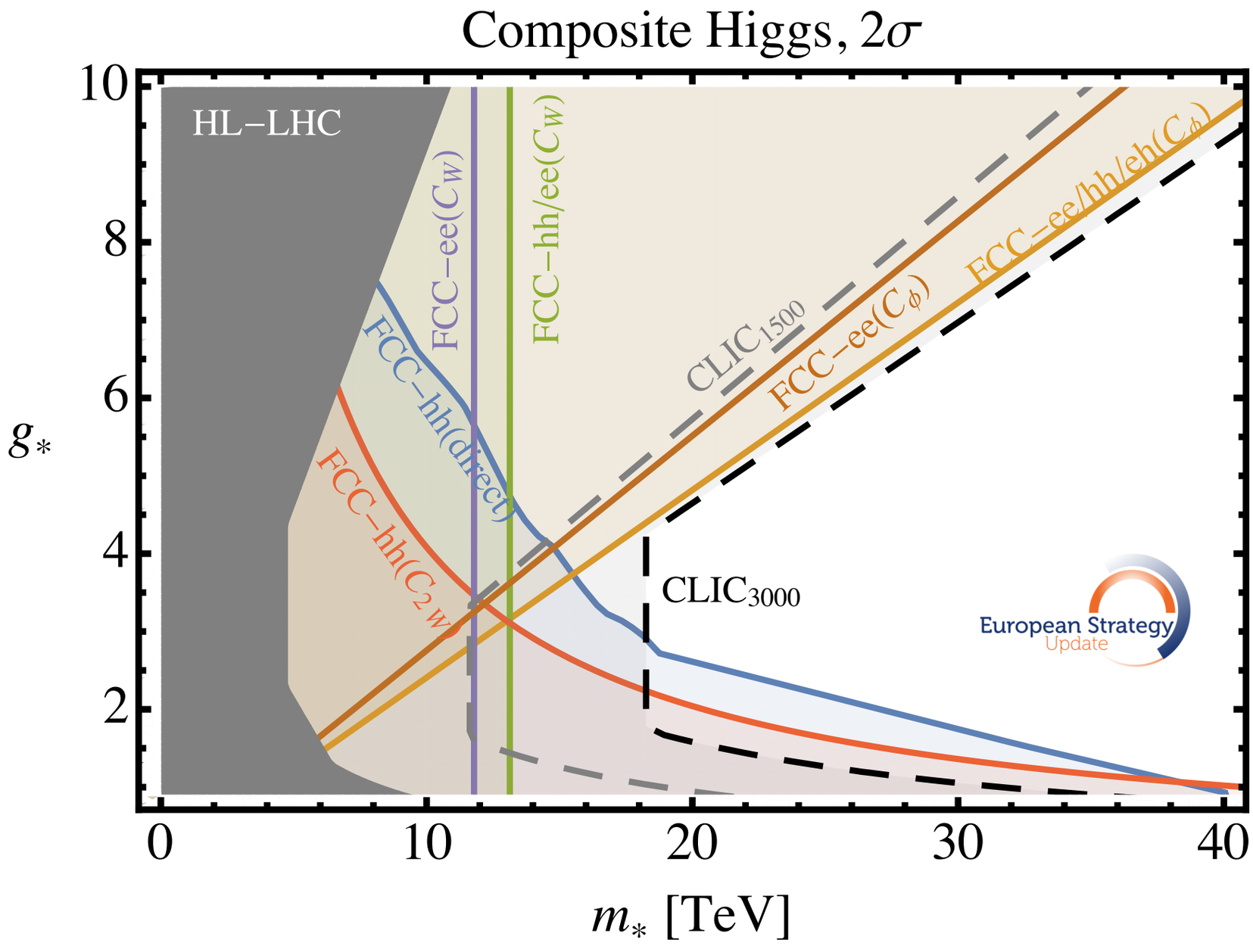


$$\Gamma_H \propto \frac{\Gamma(H \to bb)}{\mathrm{BR}(H \to bb)} \propto \frac{\sigma(\nu\nu H \to \nu\nu bb)}{\mathrm{BR}(H \to bb) \cdot \mathrm{BR}(H \to WW^*)}$$

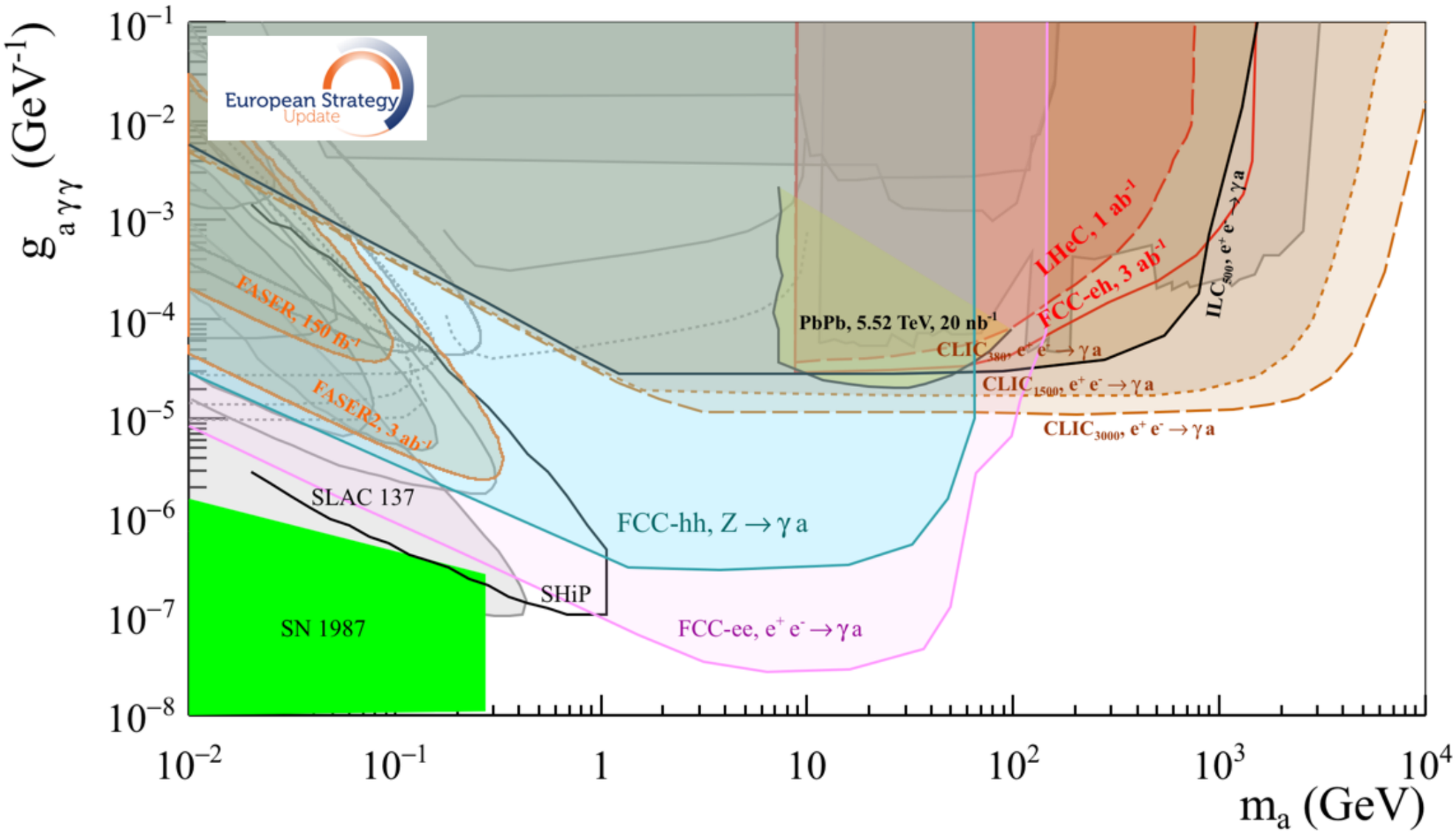
Higgs+singlet



Composite Higgs

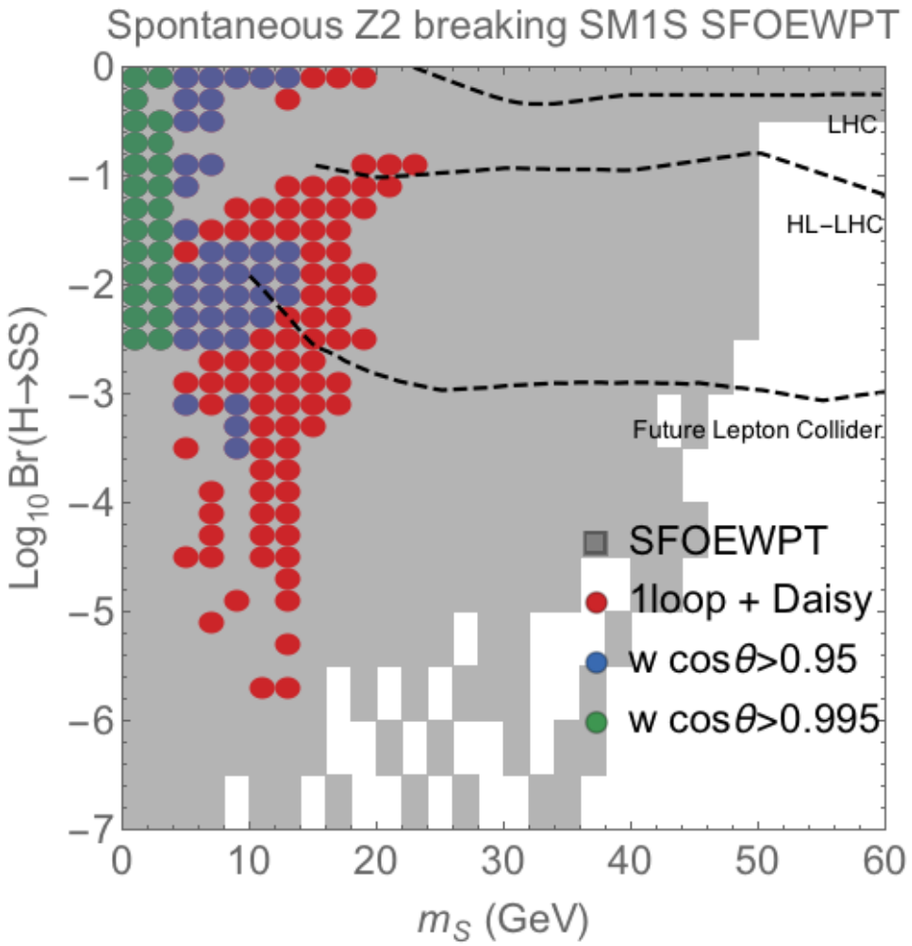


ALP

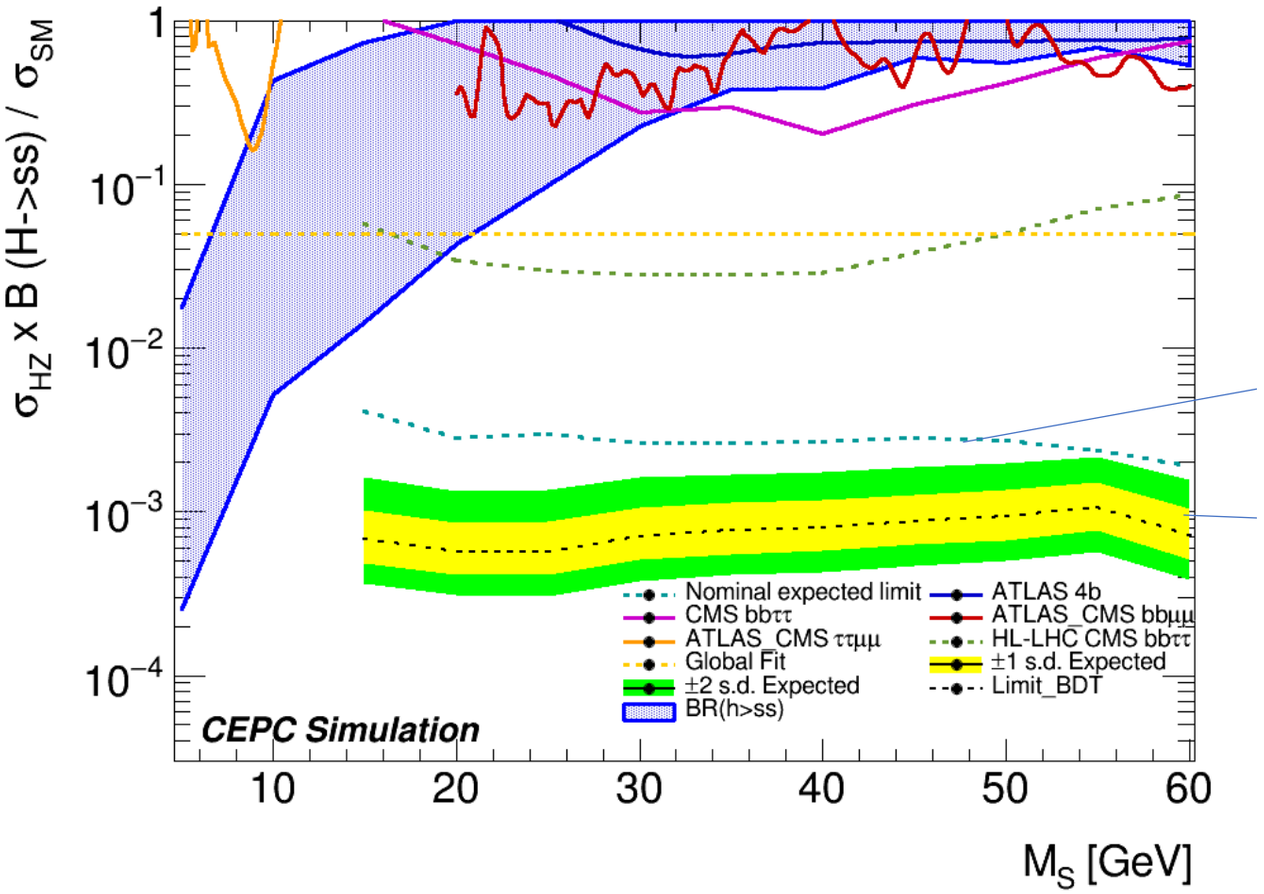

European Strategy
Update
$g_{a\gamma\gamma}$ (GeV^{-1})
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
FASER, 150 fb^{-1}
FASER2, 3 ab^{-1}
SLAC 137
SHiP
SN 1987
FCC-hh, Z → γ a
FCC-ee, e$^+$ e$^-$ → γ a
PbPb, 5.52 TeV, 20 nb^{-1}
LHeC, 1 ab^{-1}
FCC-eh, 3 ab^{-1}
ILC$_{500}$, e$^+$ e$^-$ → γ a
CLIC$_{380}$, e$^+$ e$^-$ → γ a
CLIC$_{1500}$, e$^+$ e$^-$ → γ a
CLIC$_{3000}$, e$^+$ e$^-$ → γ a
10^{-2}
10^{-1}
1
10
10^2
10^3
10^4
m_a (GeV)

Example: EW phase transition

Singlet extension, h→ss



Carena, Liu, Wang, 1911.10206

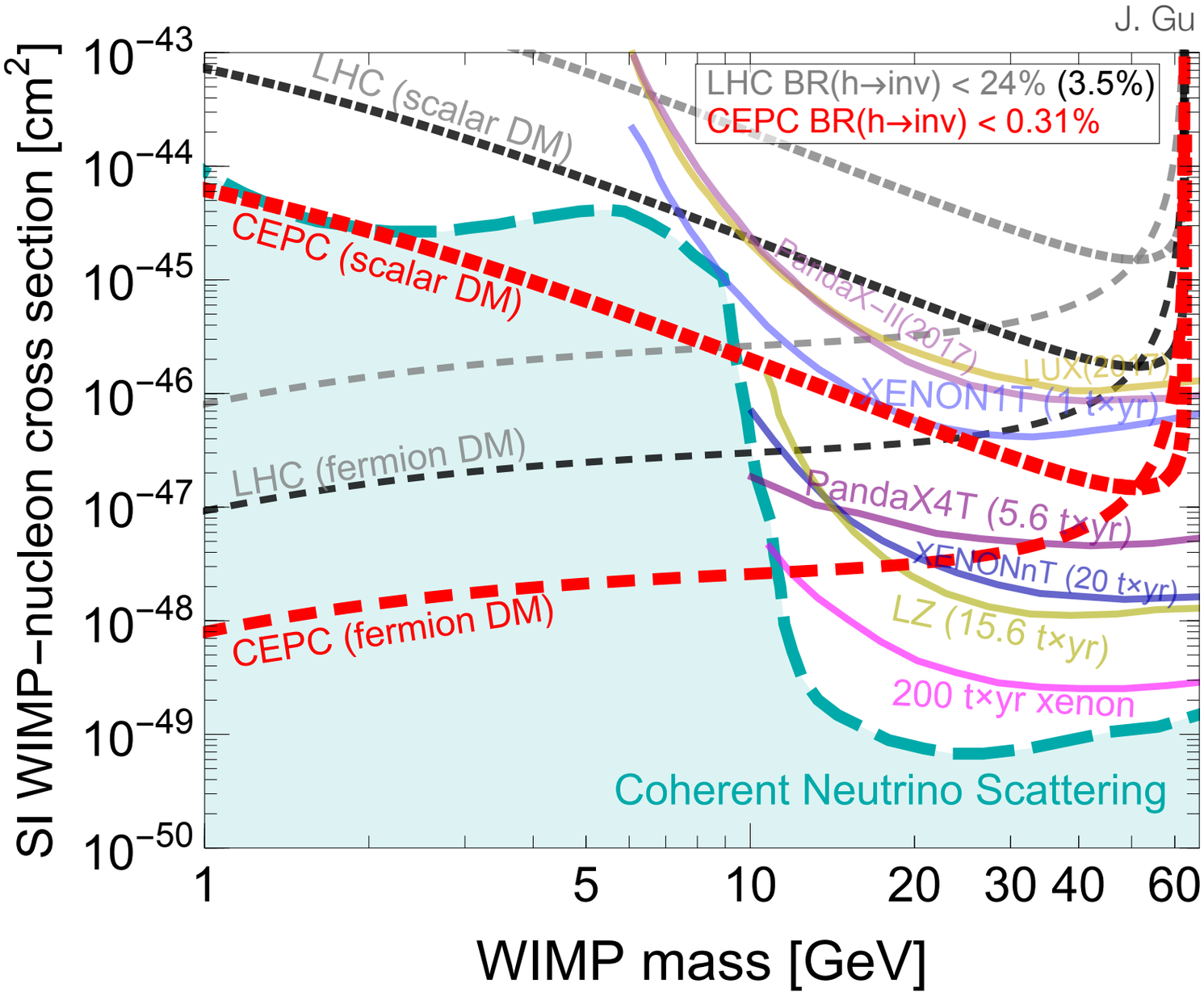


X. Zhu, talk at 2022 CEPC workshop

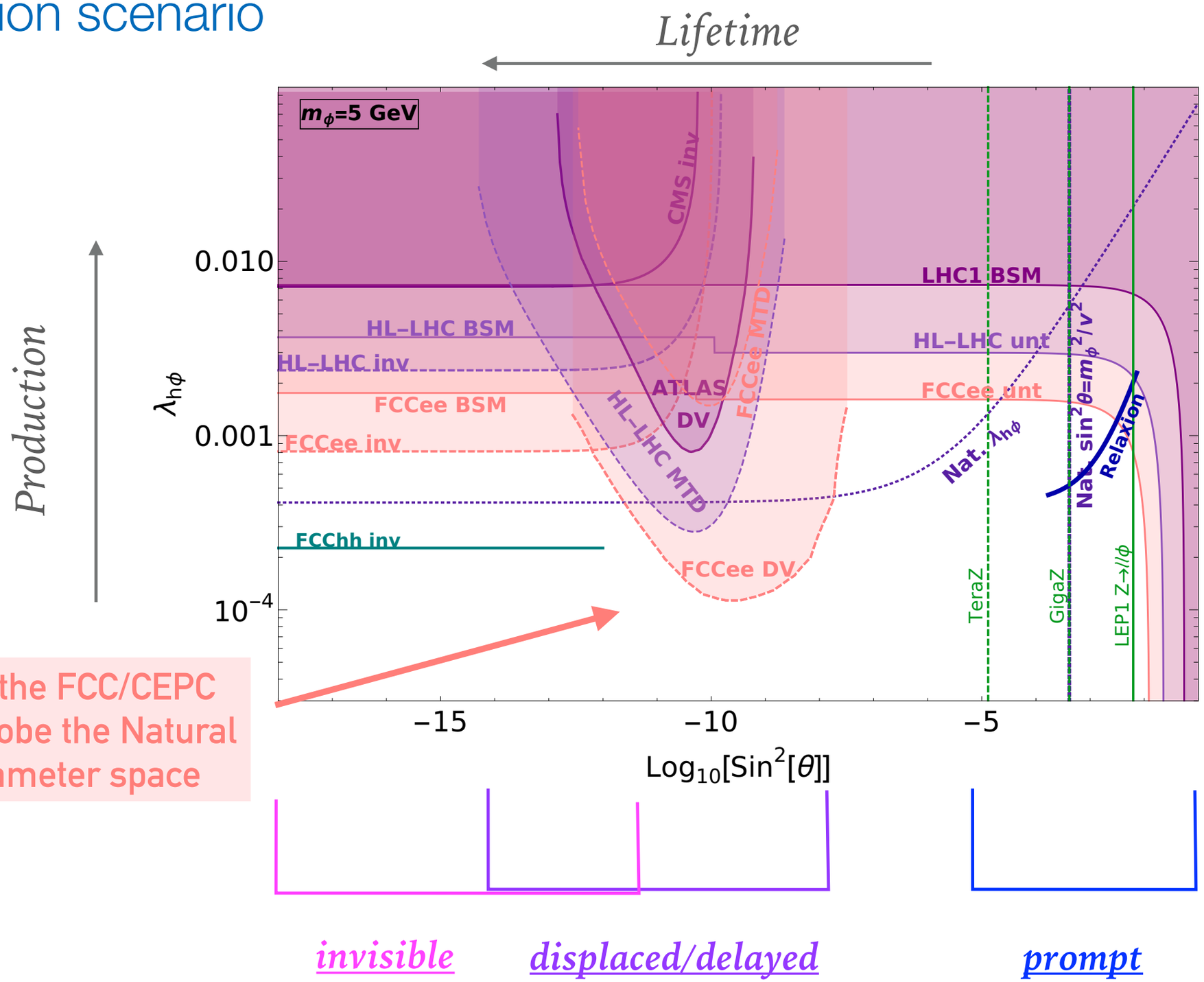
Kozaczuk, Ramsey-Musolf, Shelton, 1911.10210

Higgs portal dark matter

$$\mathcal{O} = H^\dagger H X_{\rm dm} X_{\rm dm} \quad \Rightarrow \quad h \to X_{\rm dm} X_{\rm dm}$$



Relaxion scenario



Only the FCC/CEPC can probe the Natural parameter space

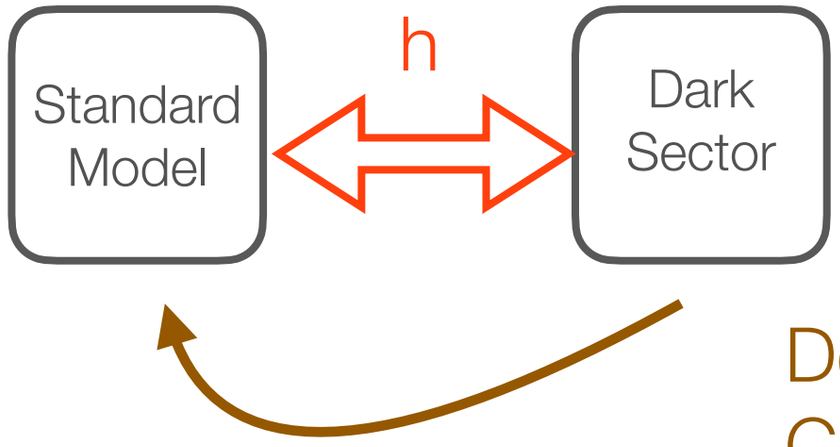
Alipour-Fard, Craig, Jiang, Koren, 1812.05588
Banerjee, Matsedonskyi, Kim, Perez, Safronova, 2004.02899
Fuchs, Matsedonskyi, Savoray and Schlaffer, 2008.12773

Talk by Savoray at CEPC 2021 workshop

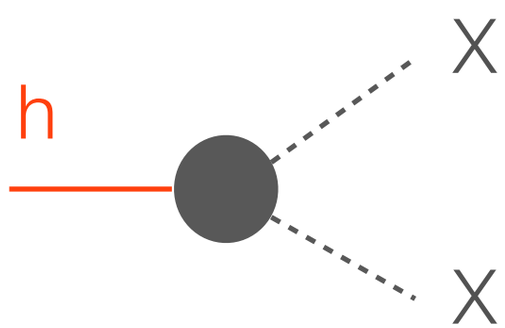
Fermilab

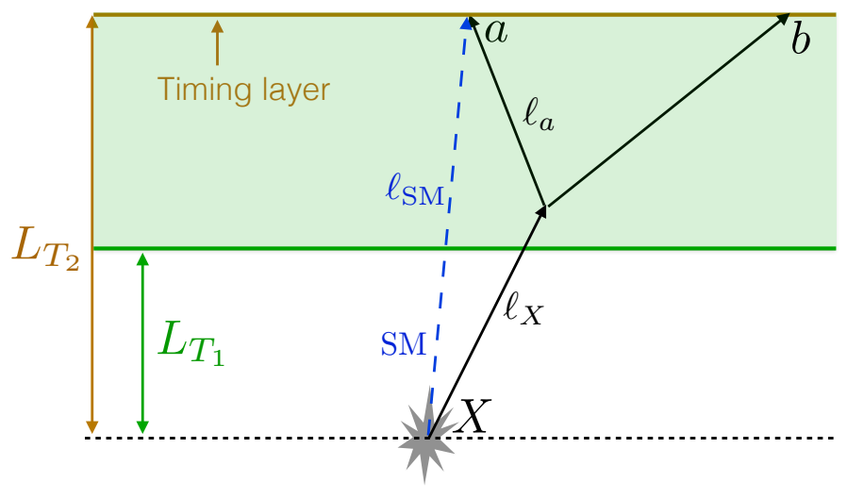

Public Access Areas
Buildings
Parking Lots
Ponds
Public Access Roads
Bicycle Path
Trails
Streams
WILSON ST
McCHESNEY RD
DISCOVER RD
Accelerator Test Areas
Test Beam Facility
Silicon Detector Facility
Site 37
Site 39
Site 38
Site 50
W BATAVIA RD
Bison Pasture
Prairie Trails
Main Entrance (Open to All Visitors)
Technical Division
PINE ST
BATAVIA RD
Dog Training Area
Users Center
Fermilab Village
Feynman Computing Center
Illinois Accelerator Research Center
Wilson Hall and Ramsey Auditorium (Public Welcome)
Neutrino Area
Muon Area
Site 55
Nature Area
Main Injector Particle Accelerator
Tevatron Collider (decommissioned)
Site 56
DZero Assembly Building
Kirk Rd
Butterfield Rd
© OpenStreetMap (and) contributors, CC-BY-SA

Long lived particle (LLP)



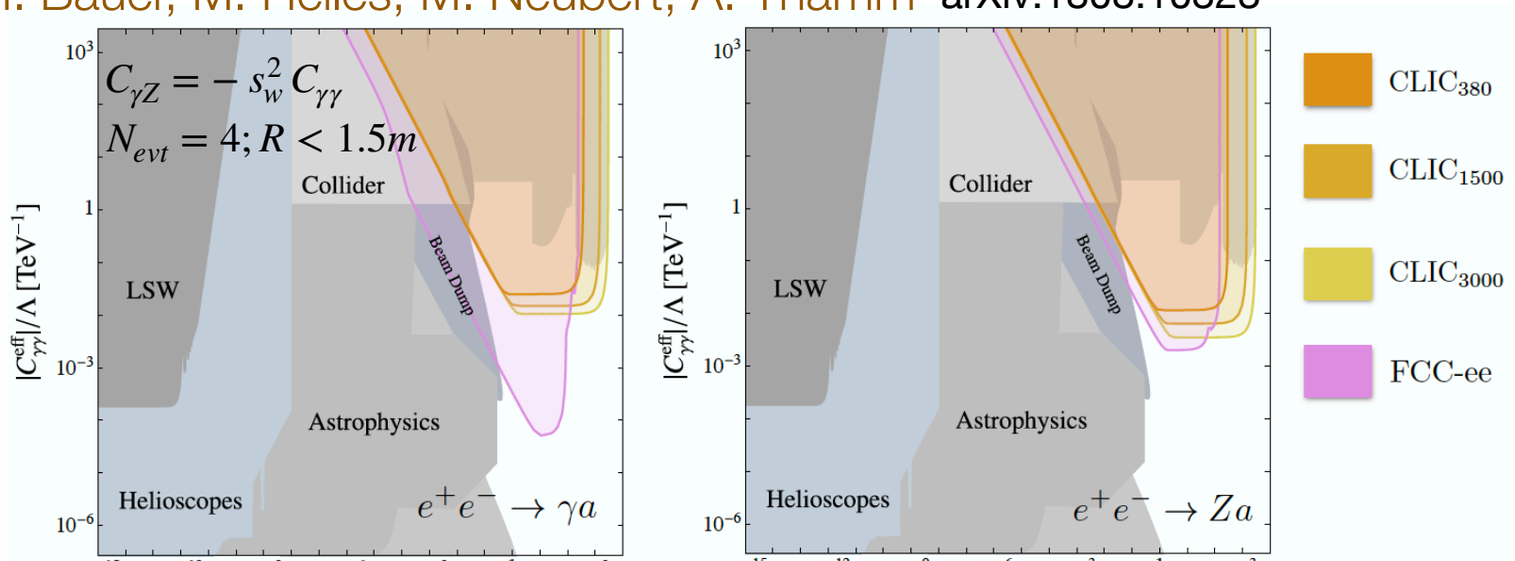
Decay back to SM
Can be long lived.
cτ can be 1 km or more

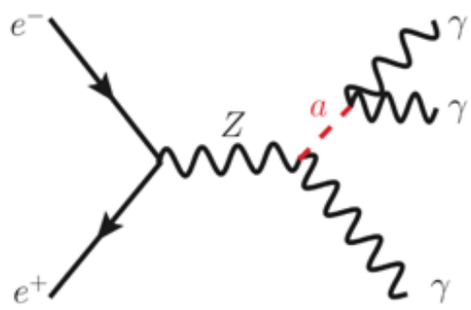




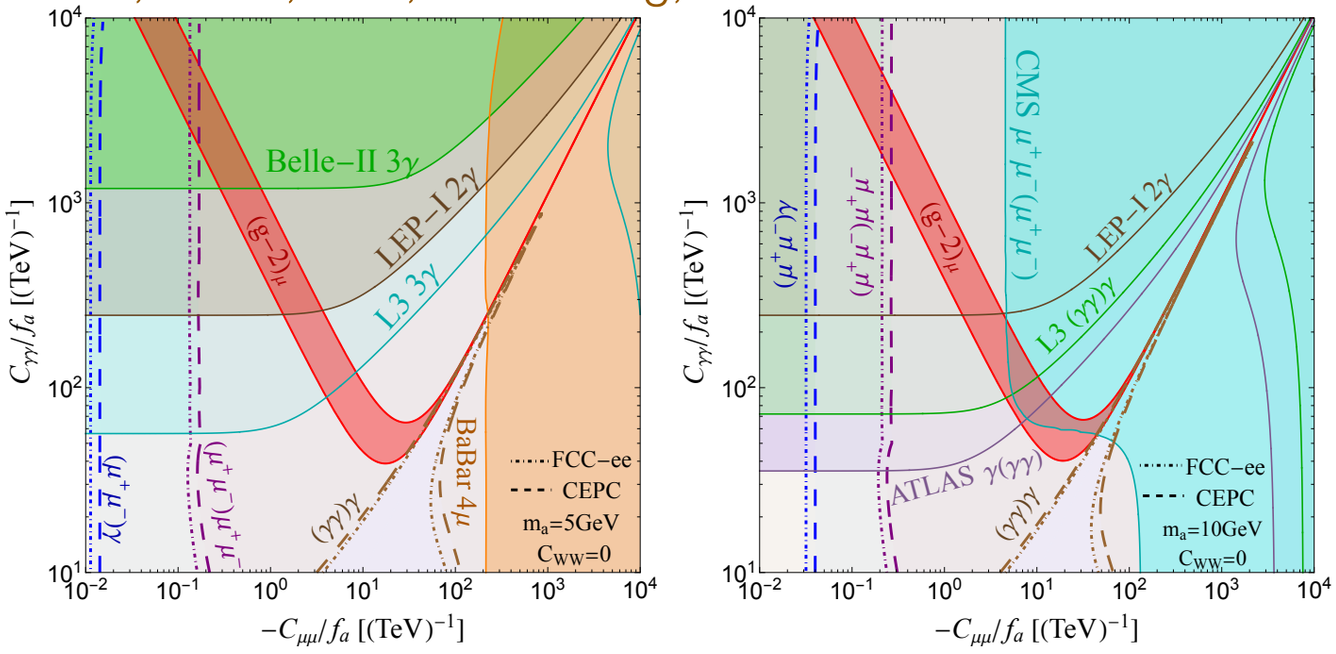
Axion like particles (ALPs)

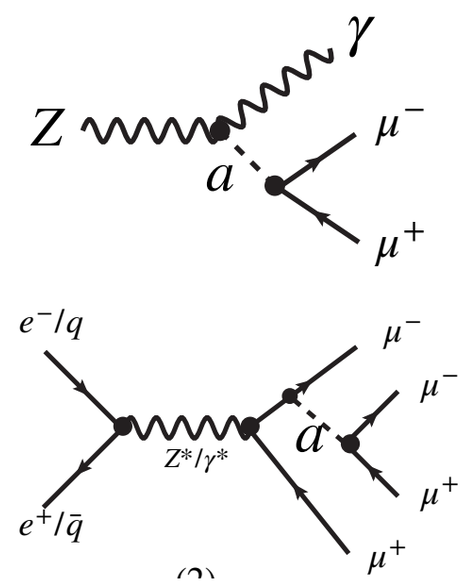
M. Bauer, M. Heiles, M. Neubert, A. Thamm arXiv:1808.10323





J. Liu, X. Ma, LTW, X.-P. Wang, 2010.09335





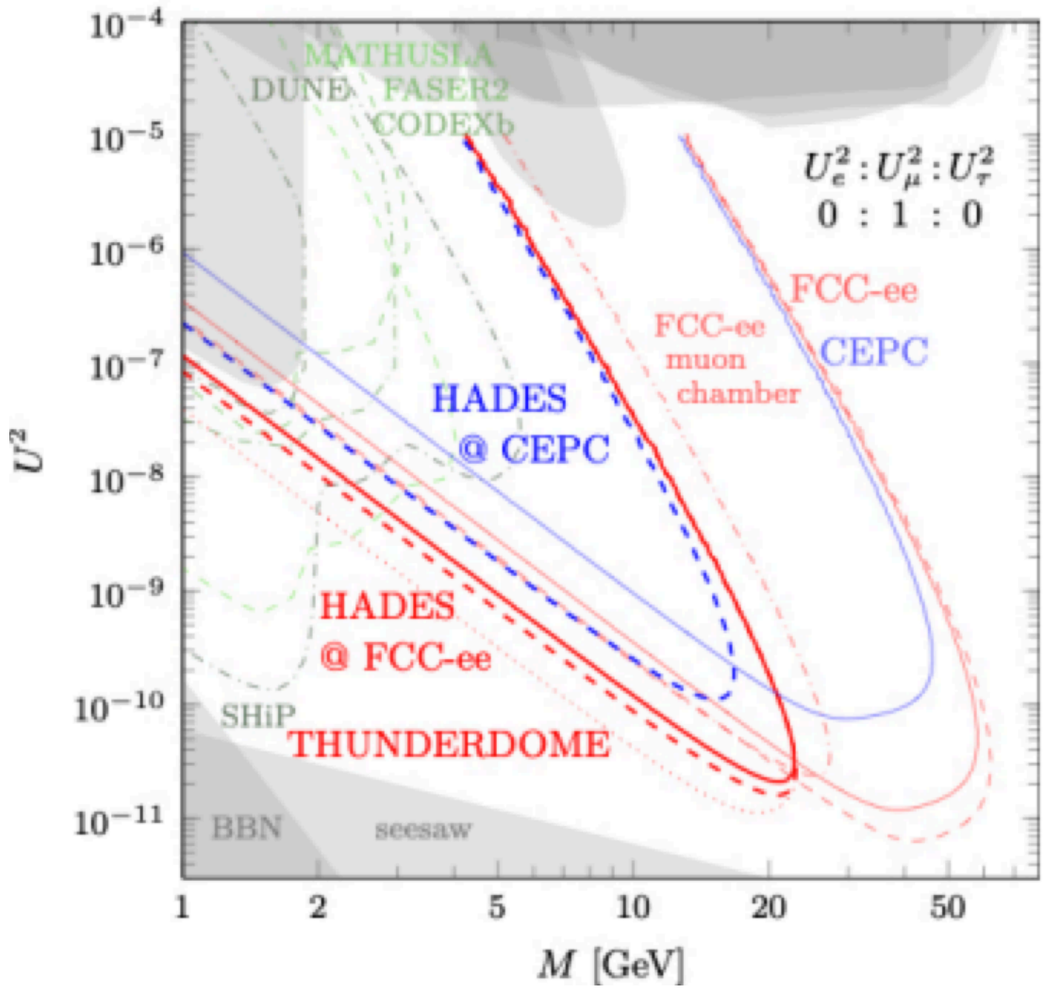
New detectors

- LHC has proposals for dedicated detectors of LLP searches.
  - CODEX, FASER, MATHUSLA.
- Similar for lepton colliders?

An example proposal: HADES

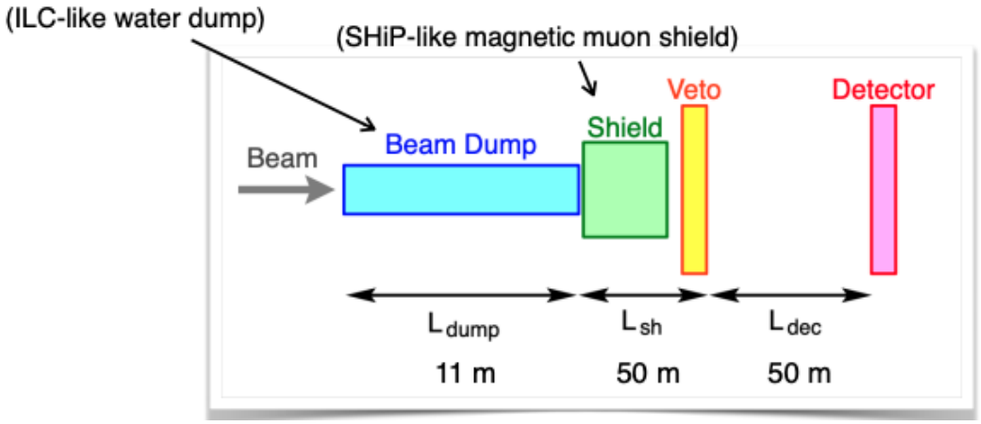
With extra instrumentation of detector cavern walls

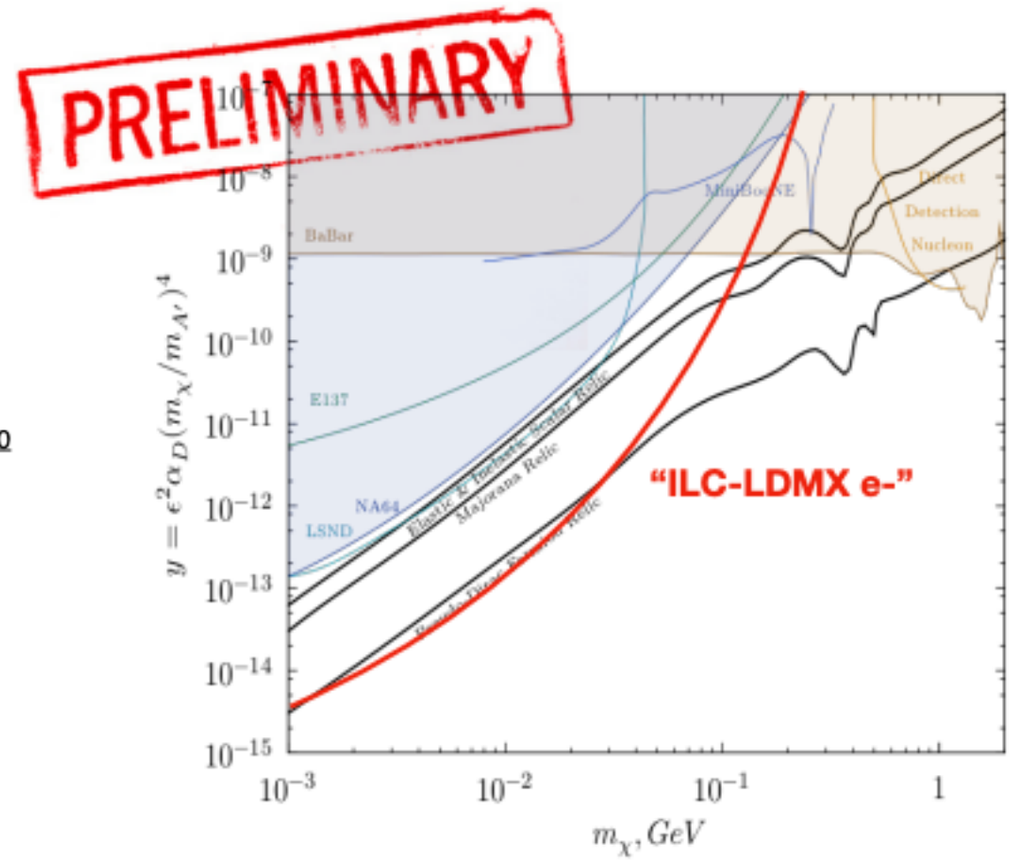
2011.01005



Beam dump?

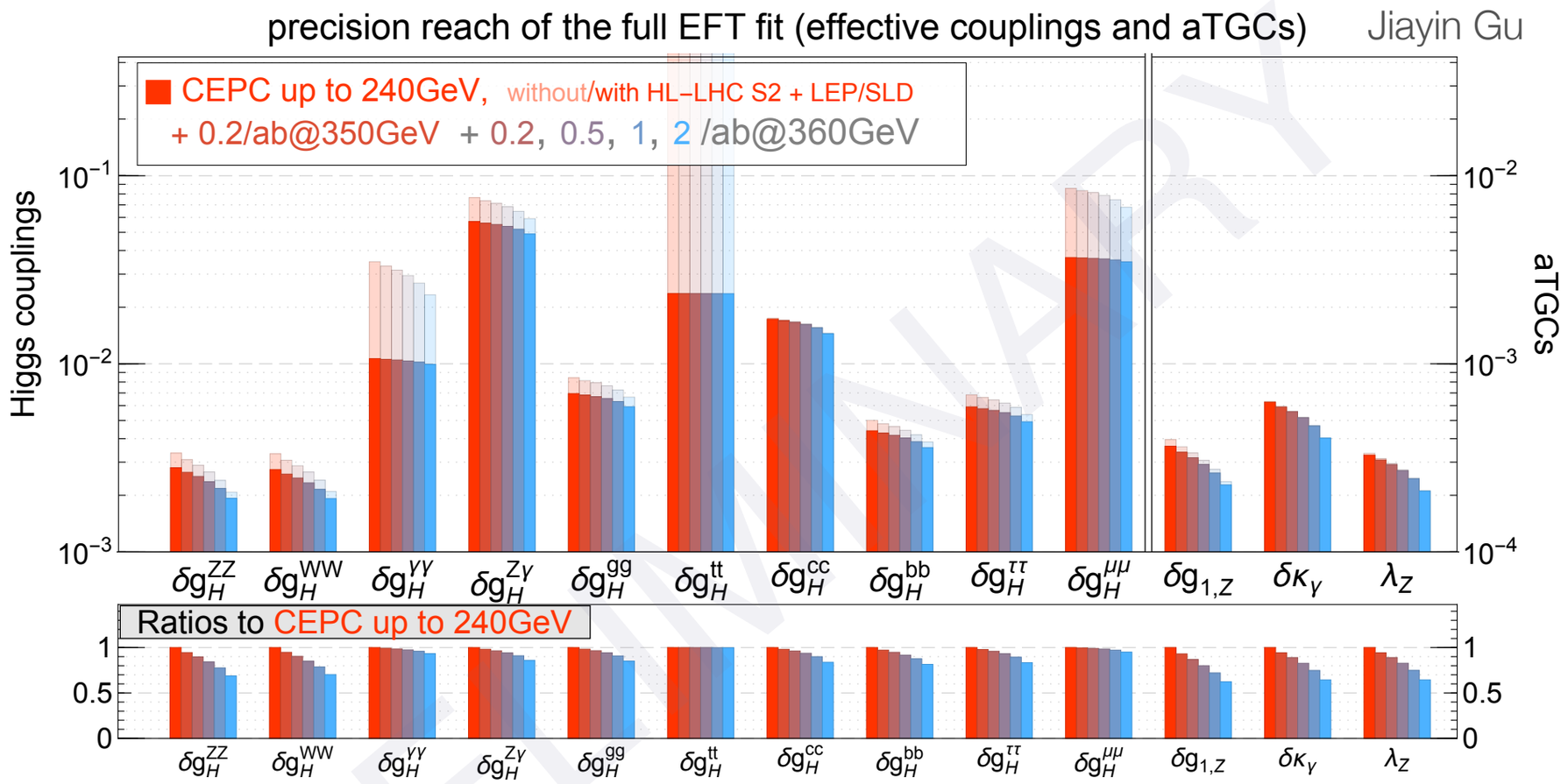
Kanemura, Moroi, Tanabe, 1507.02809





Talk by M. Perelstein at LCWS 2021

Better at higher energies



Gain up to a factor of a few

Even better if one can run at even higher energies.