Physics at the Higgs factories: e^+e^-, circular and linear

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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

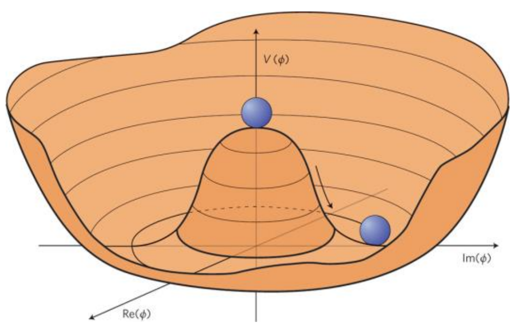
Why focusing on Higgs?

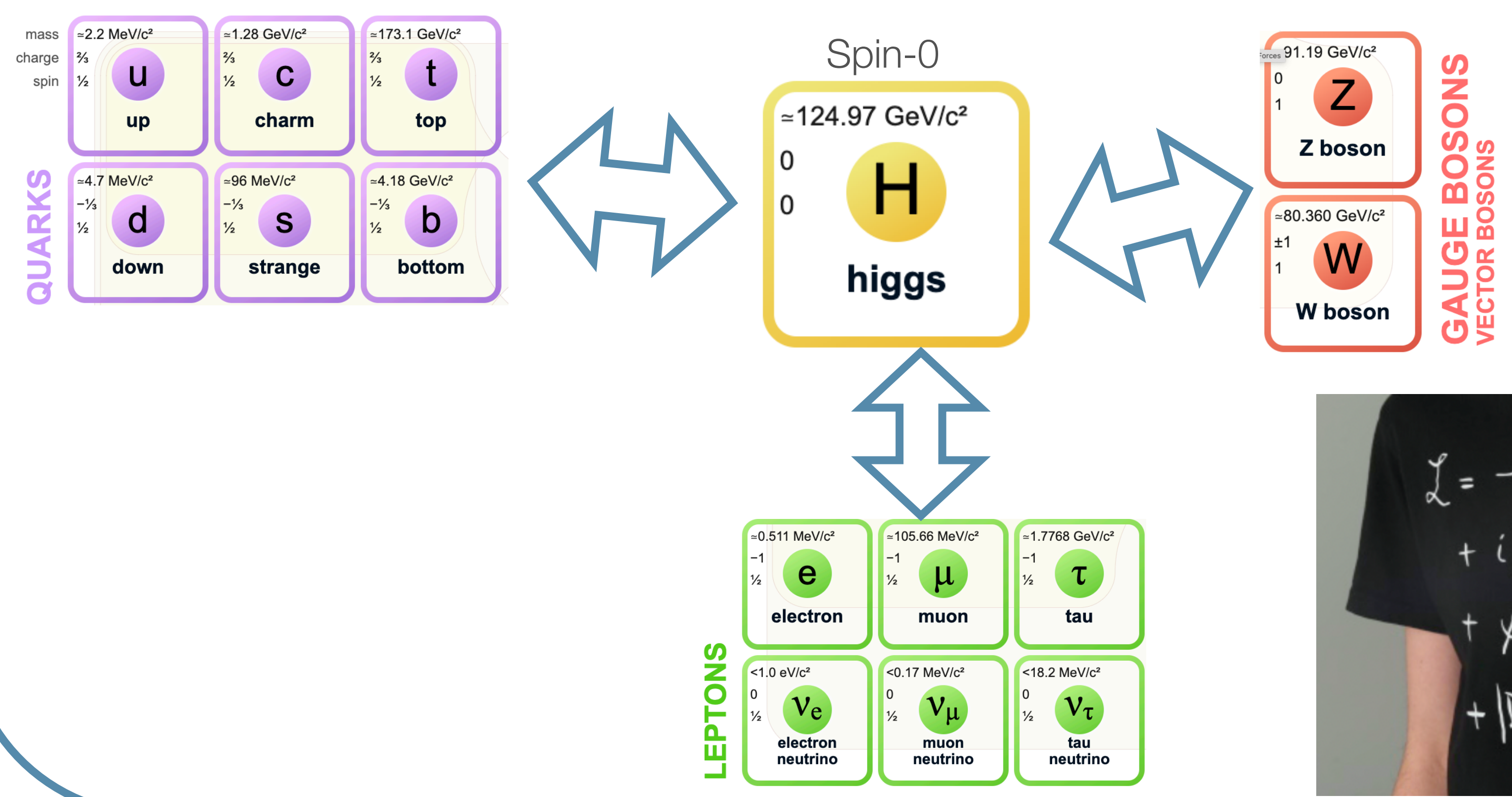
Higgs is simple.

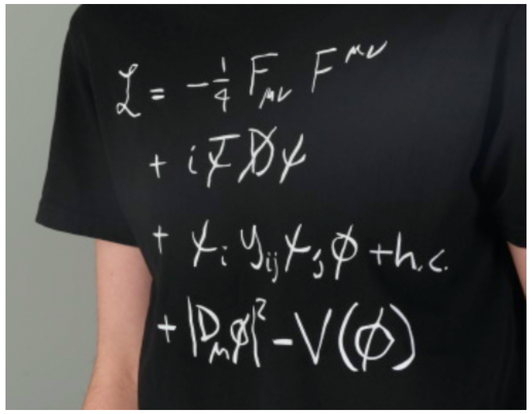
A simple “Mexican hat” potential.

⇒ 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.

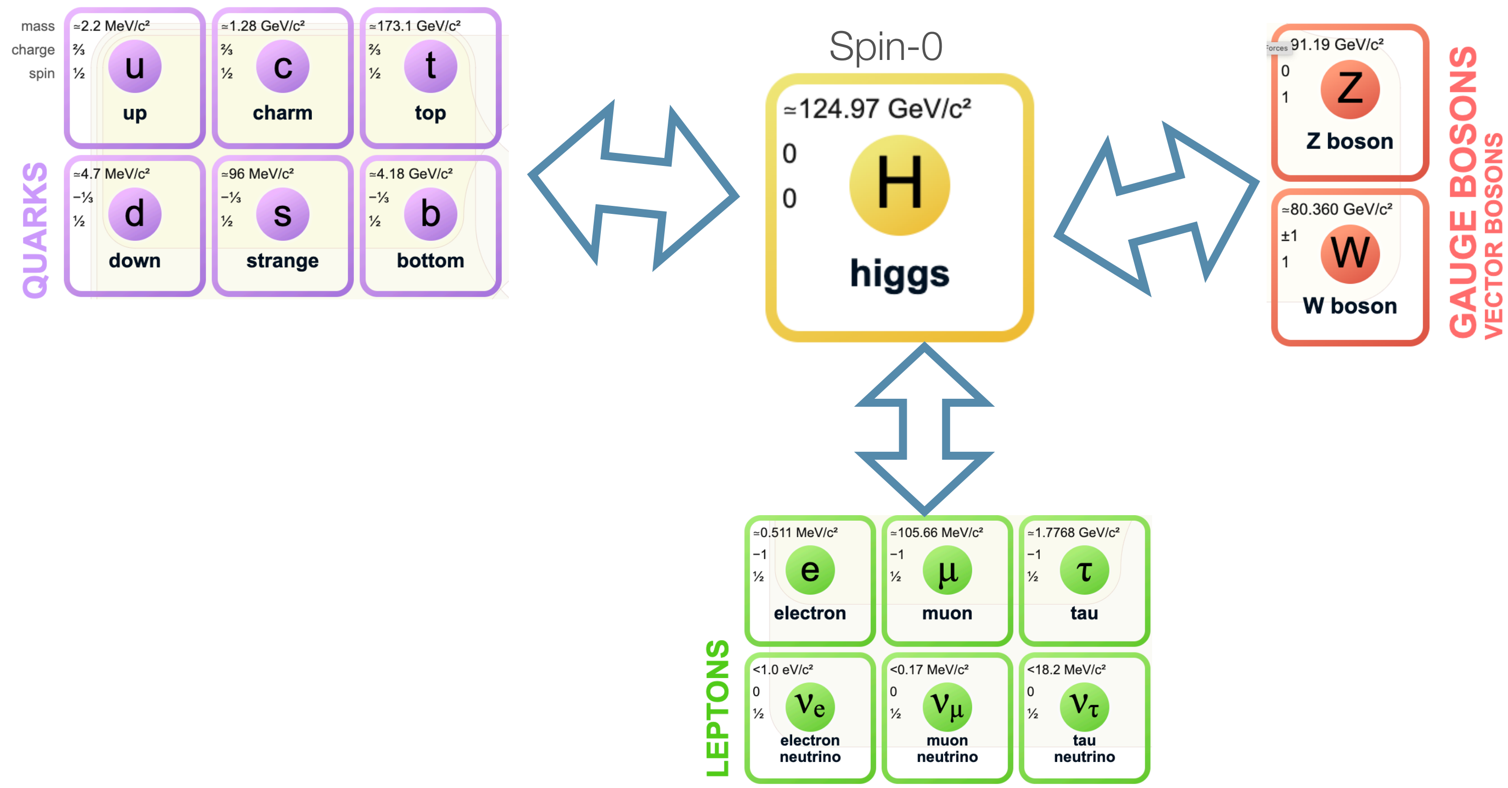
Different from other SM particles:
gauge boson (gauge symmetry), fermion (chiral symmetry)

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?



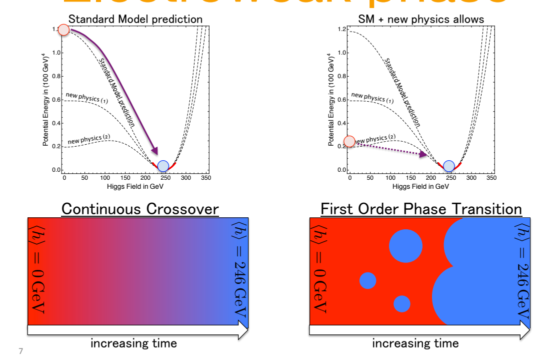
Higgs mechanism sets the masses of the SM particles

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

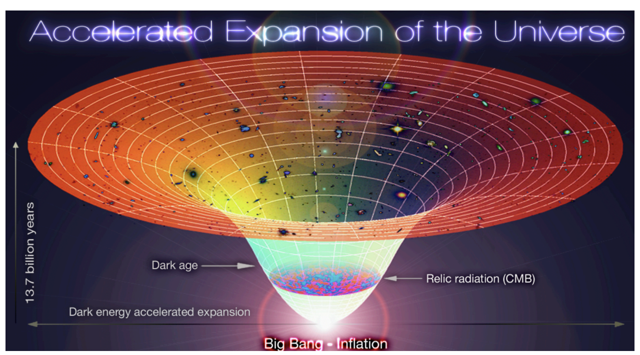
Higgs and everything else

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

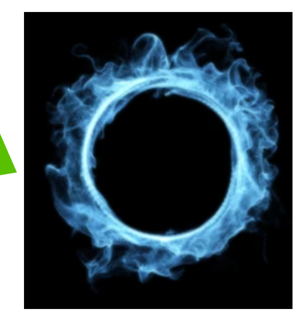
Matter > anti-matter
Electroweak phase



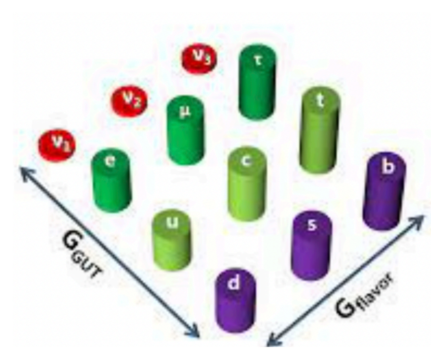
Higgs



Inflation, age of universe, …



The dark world

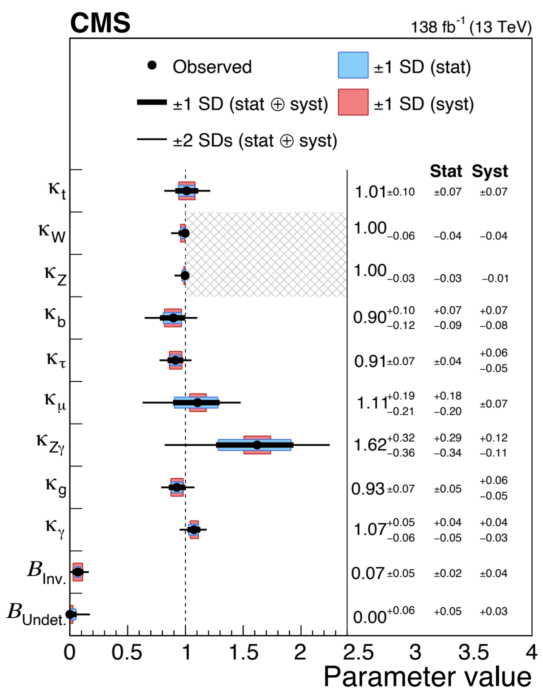


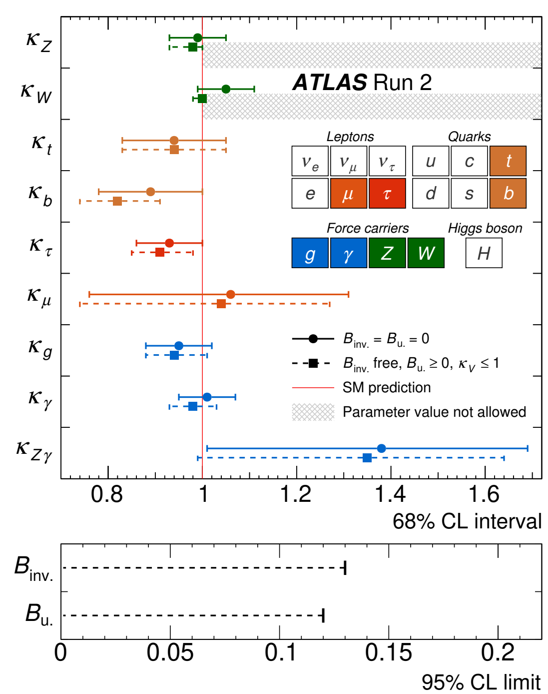
Flavor puzzle

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

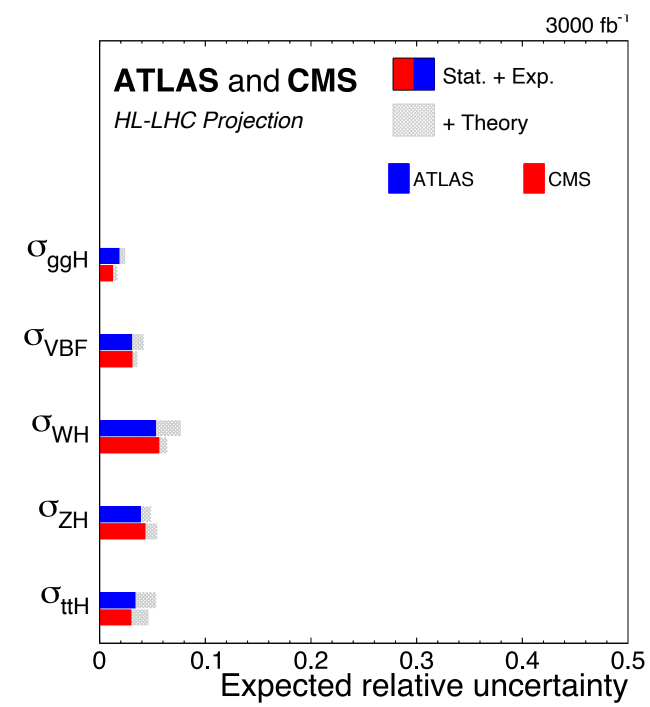
What do we know?

Higgs coupling other SM particles:





Eventually at the LHC



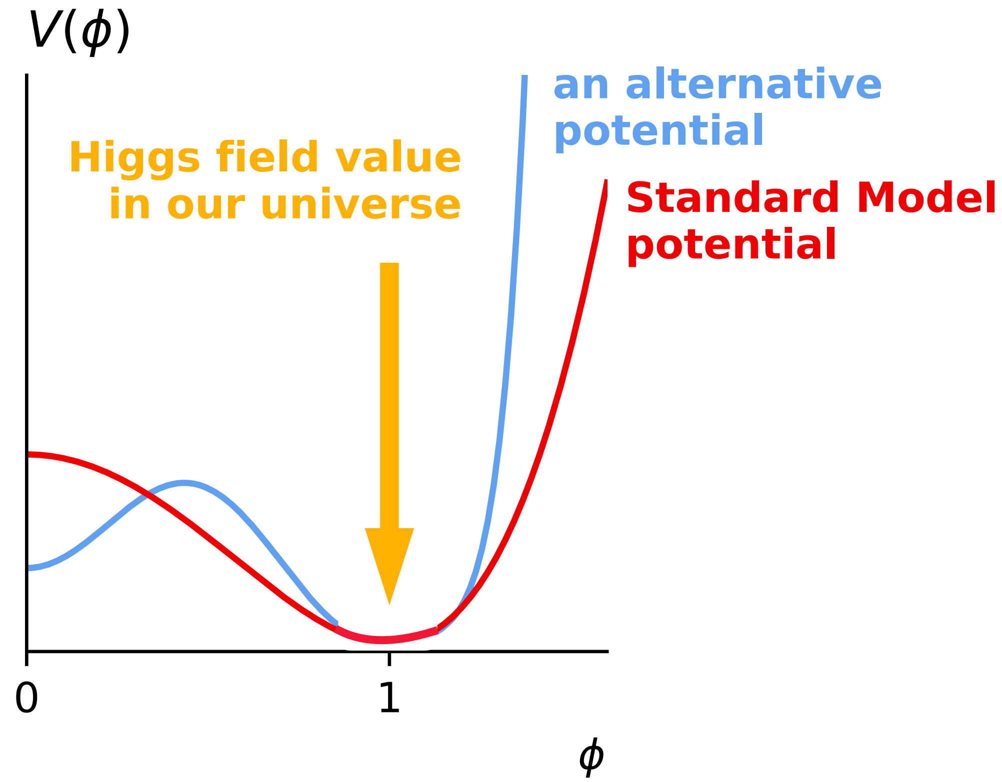
Higgs couplings. Presently, known to about 10%

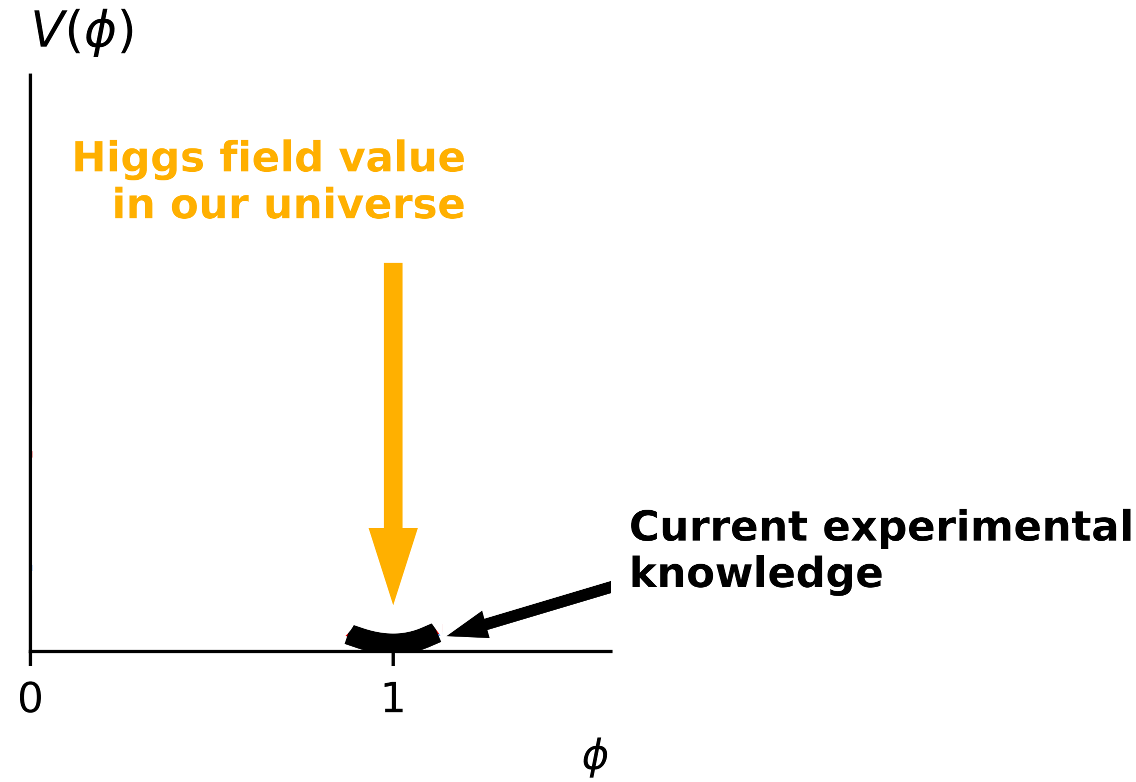
1- a few %

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

What do we know?

Higgs potential?

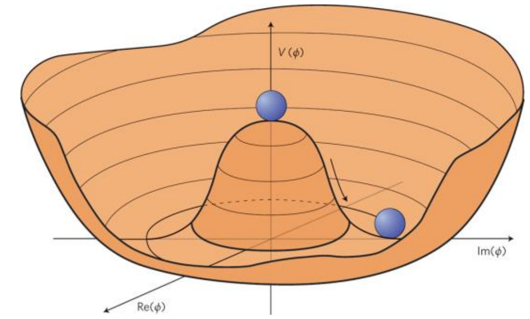


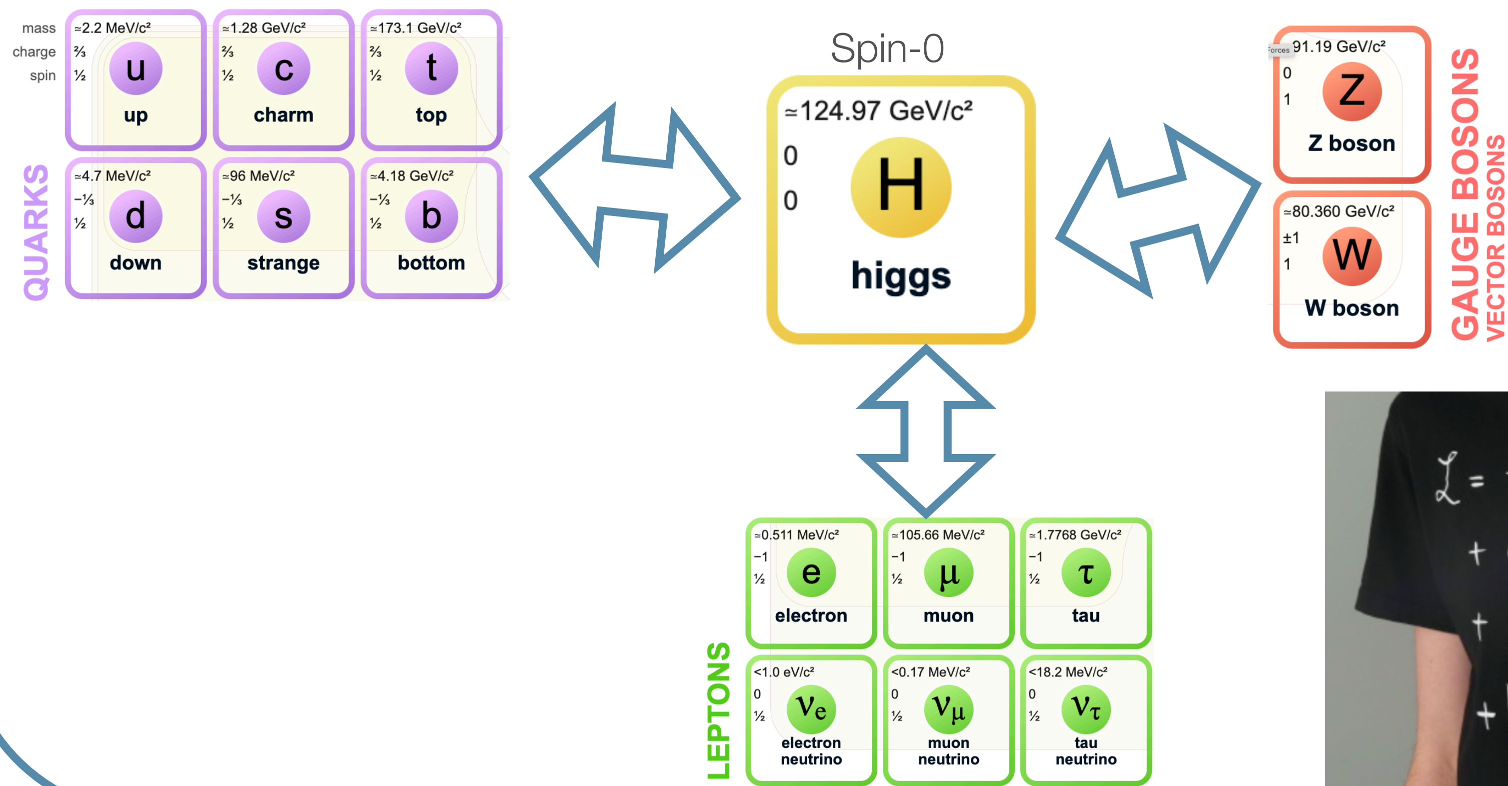


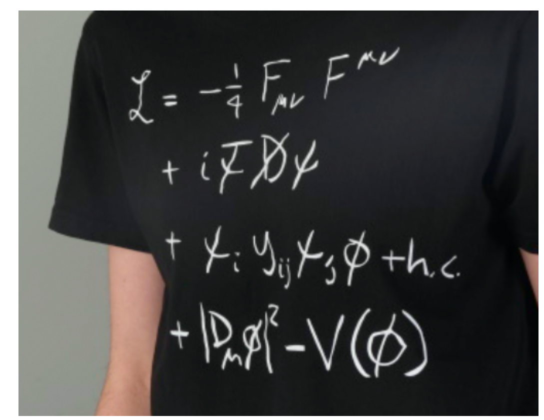
HL-LHC will make some progress.
But it won't clarify the picture.

A simple "Mexican hat" potential.

- ⇒ Electroweak symmetry breaking
- ⇒ gives masses of SM particles



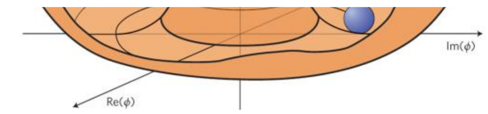


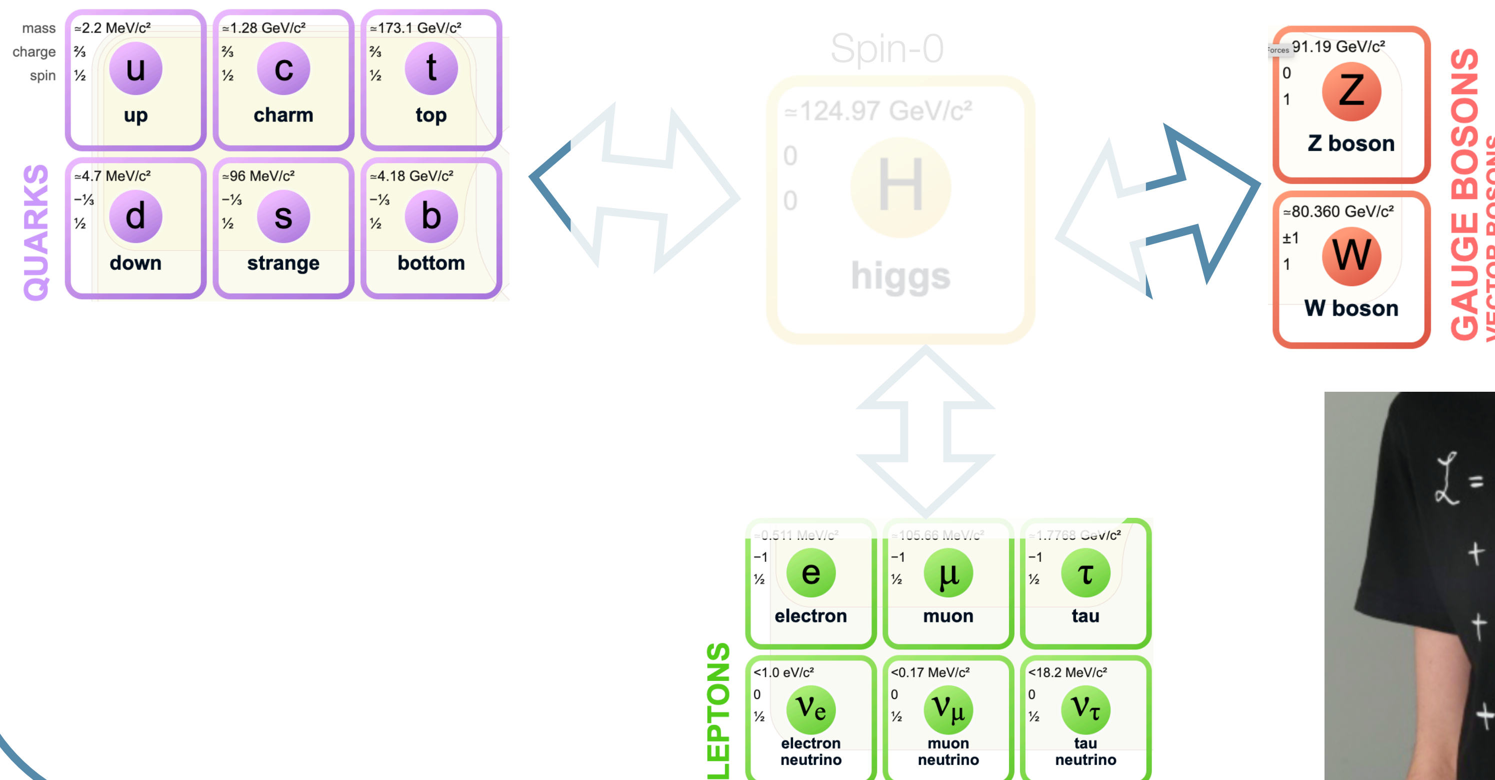


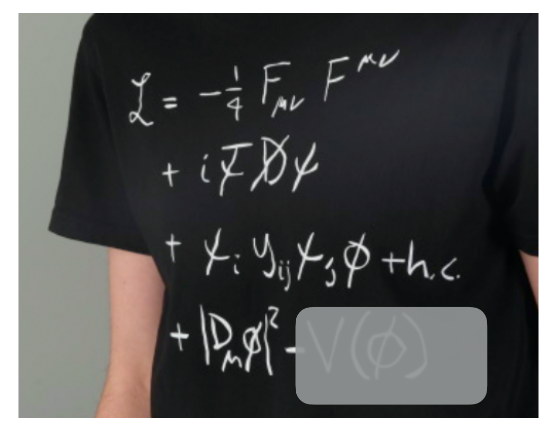
A simple “Mexican hat” potential ??

⇒ Electroweak symmetry breaking

⇒ gives masses of SM particles

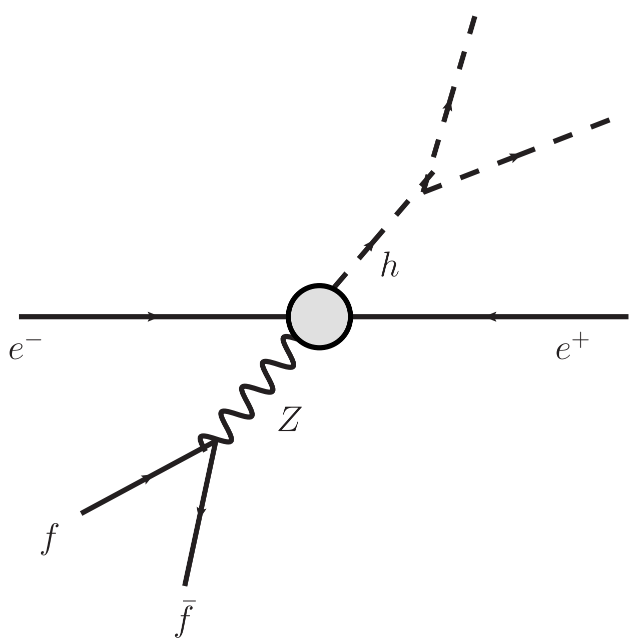




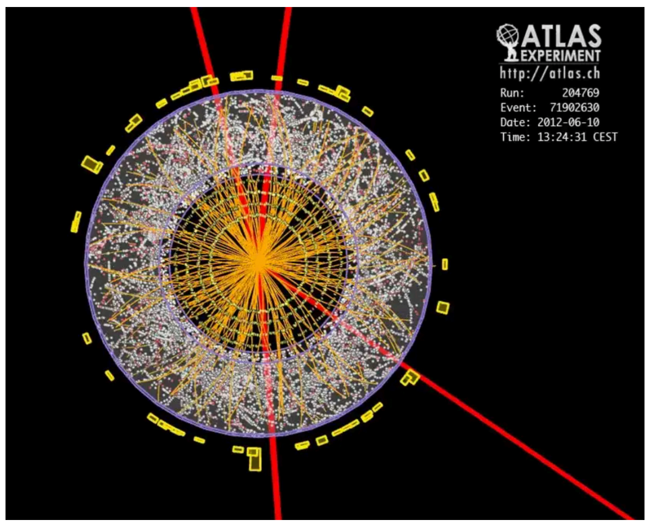


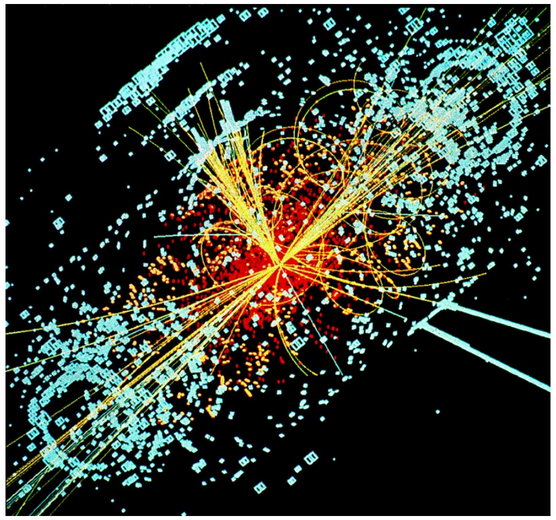
We need to know better!

Why e+e− Higgs factory?



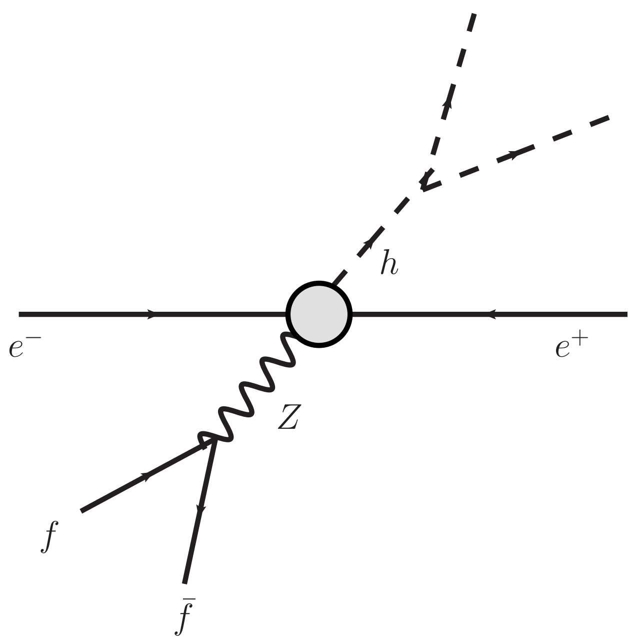
A much cleaner collision environment.
Good for precision measurement.

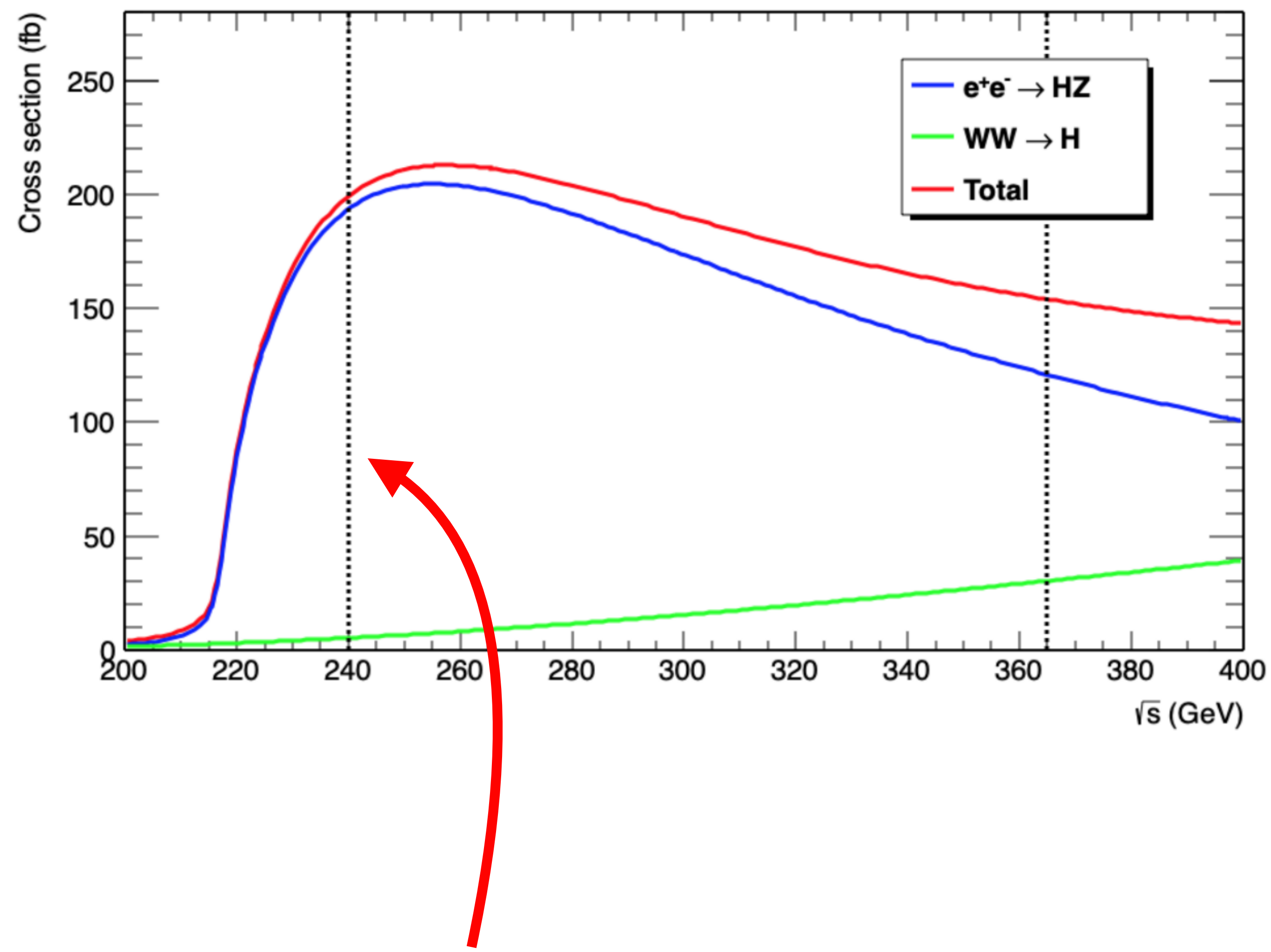




At the Large Hadron Collider

Why e+e− Higgs factory?

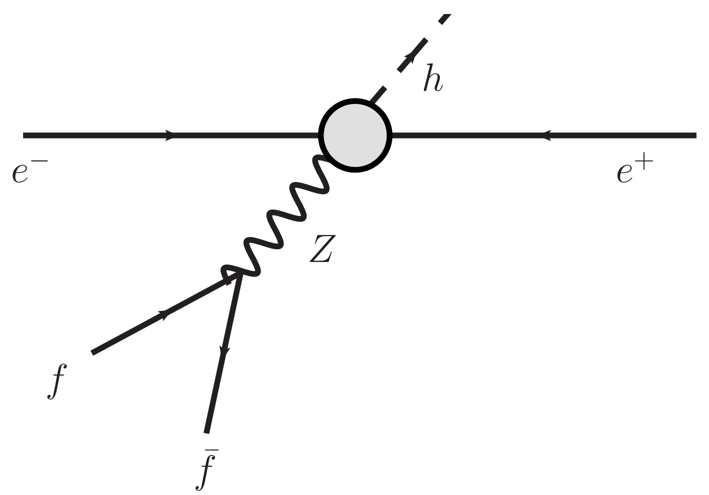


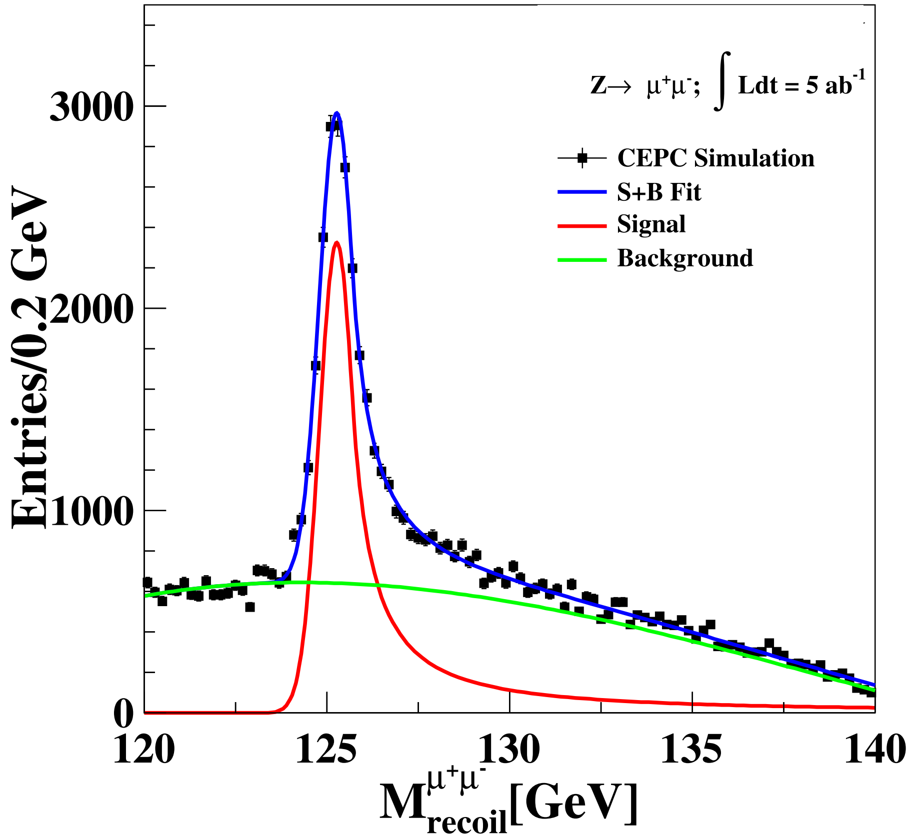


$E_{\text{CM}} \simeq 250$ GeV

"Sweet spot", most Higgs produced

Why e+e− Higgs factory?



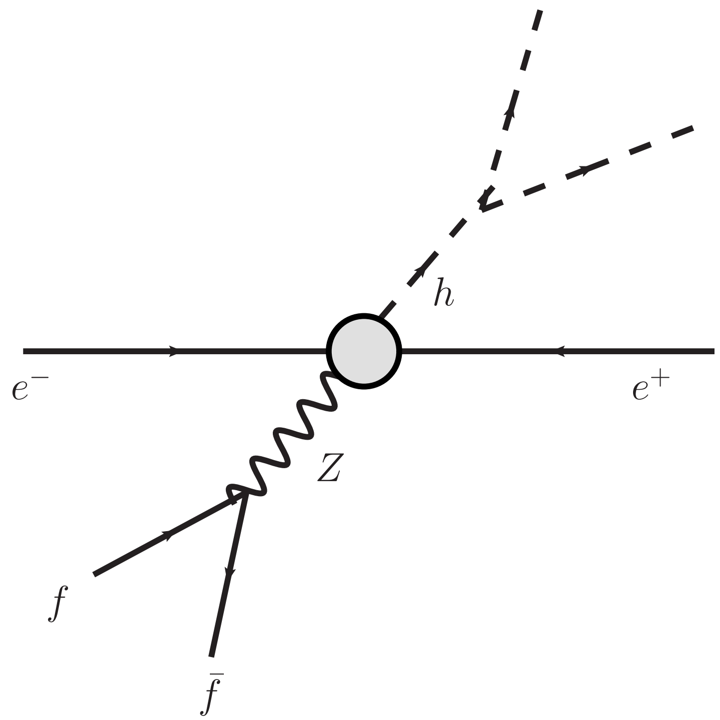


$$M^2_{\rm recoil} = (\sqrt{s} - E_{ff})^2 - p^2_{ff} = s - 2E_{ff}\sqrt{s} + m^2_{ff}$$

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, $\delta \equiv \dfrac{g_{\rm exp} - g_{\rm SM}}{g_{\rm SM}}$

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

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

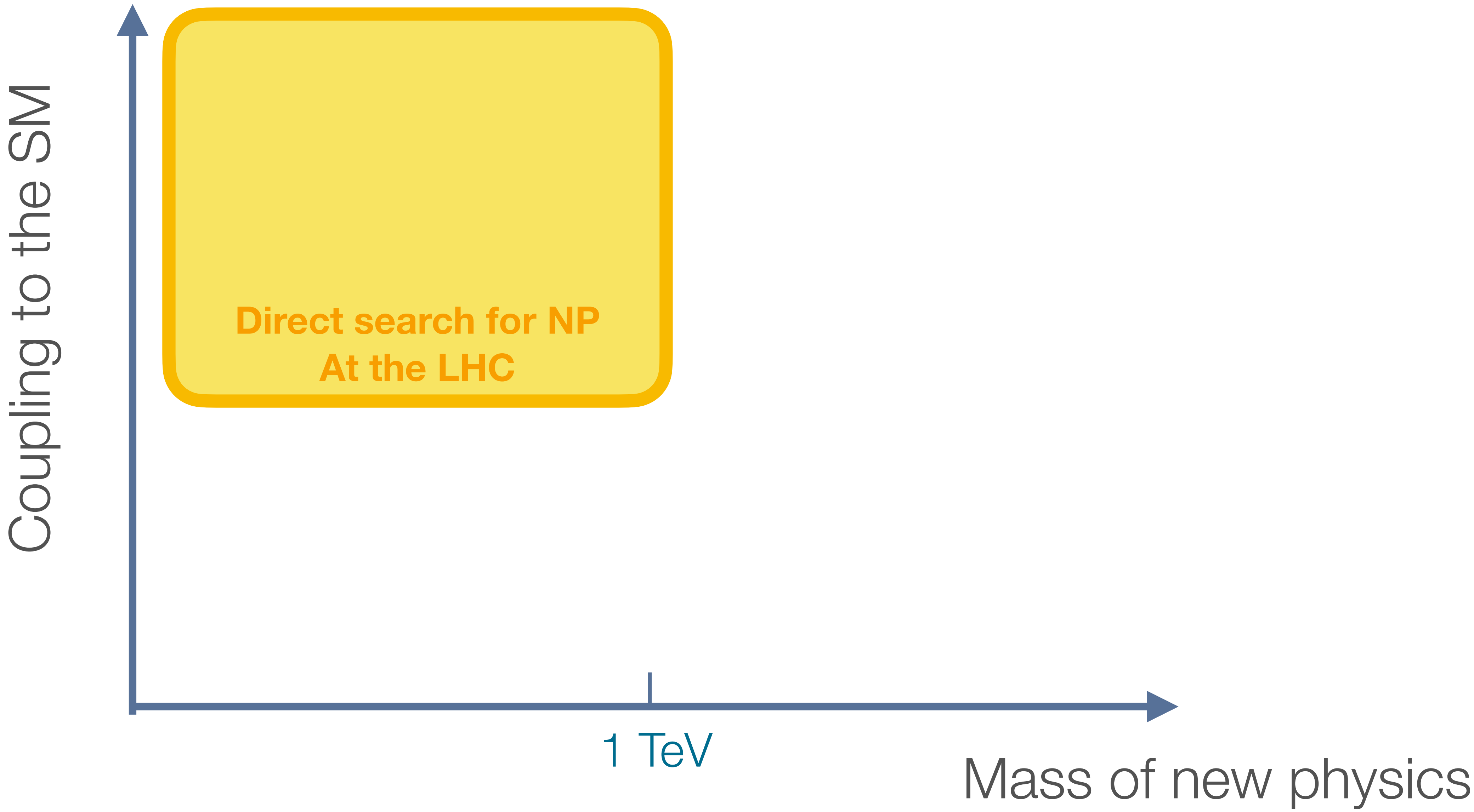
$M_{\rm new\ physics}$: mass scale of new physics

Measurement precision ⇒ sensitivity on δ ⇒ reach for NP

Our target

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

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



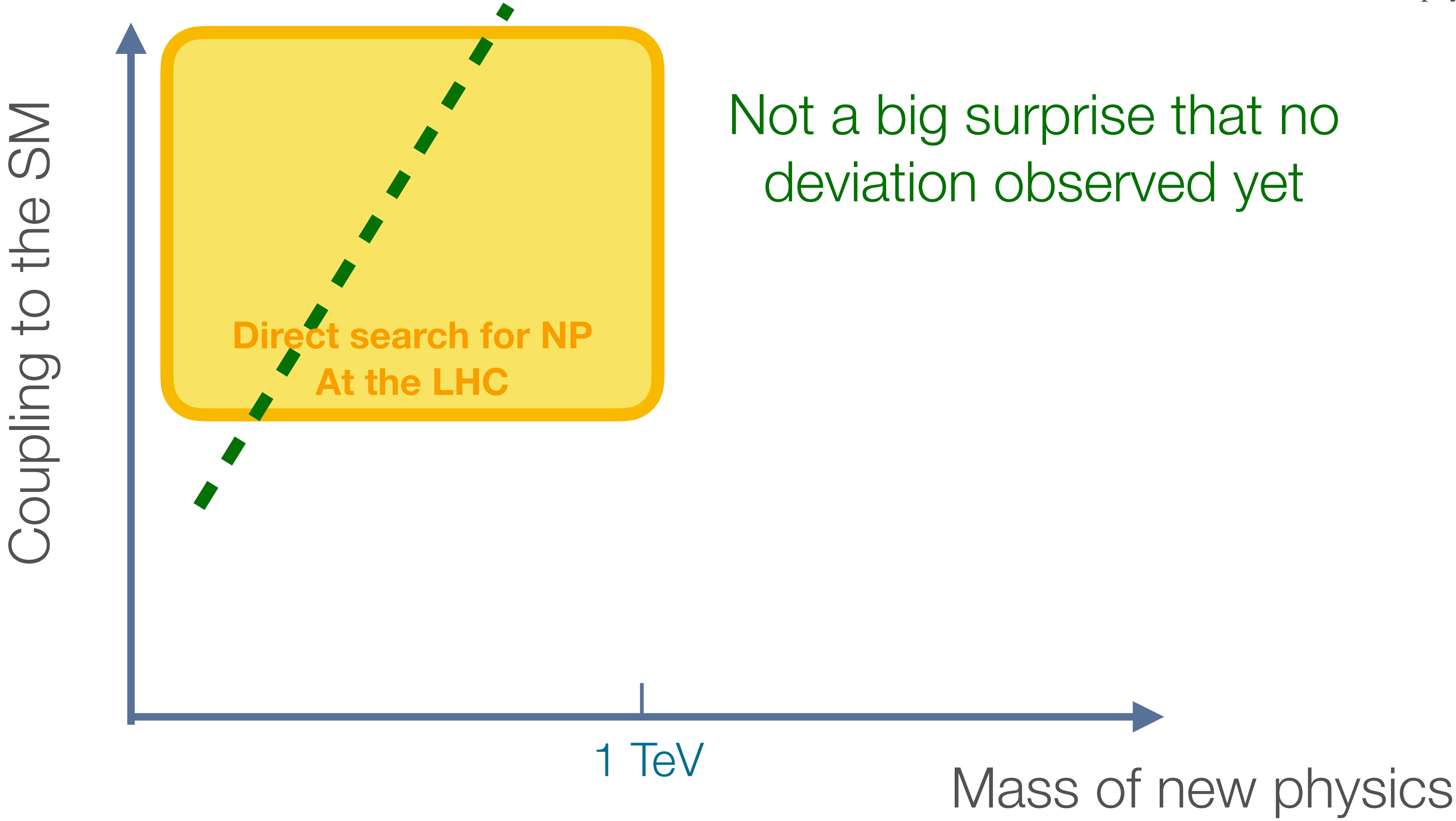
Our target

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

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

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

Not a big surprise that no deviation observed yet



Our target

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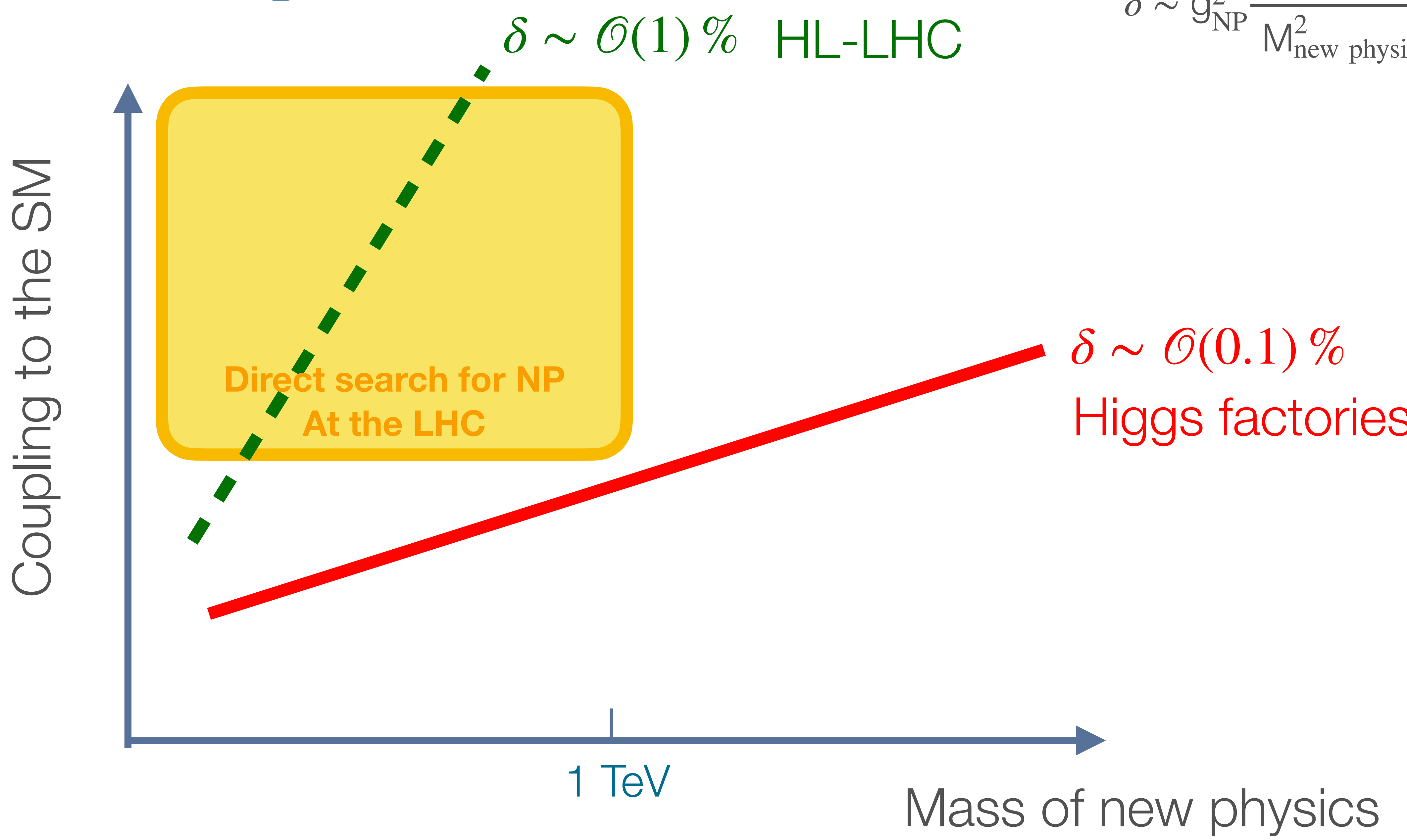
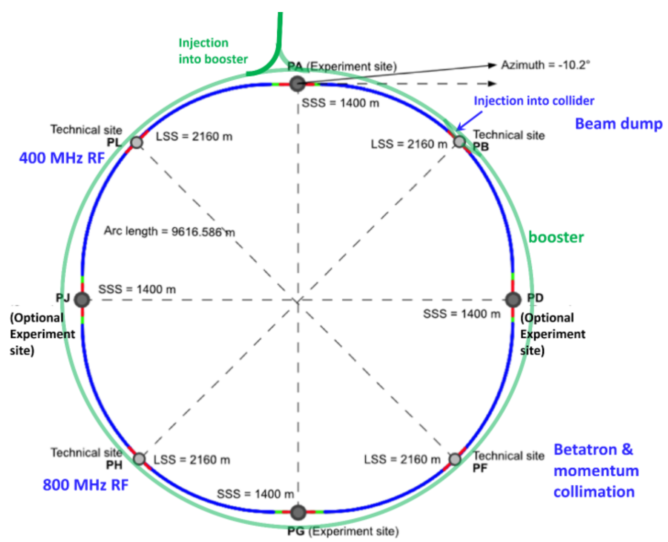
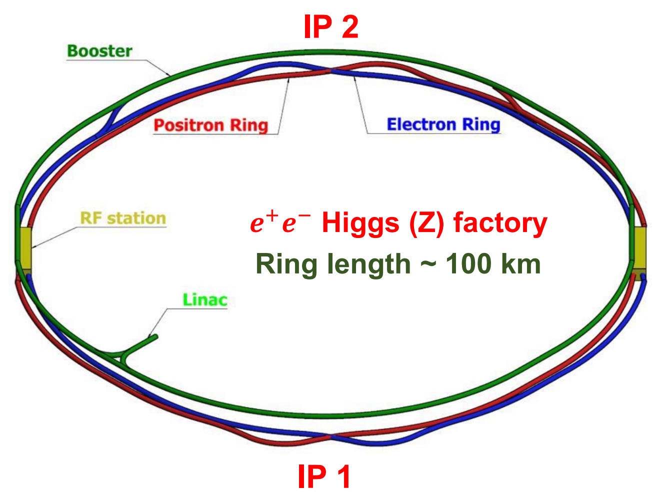


Higgs factories (e^+e^-)

Circular



FCC-ee

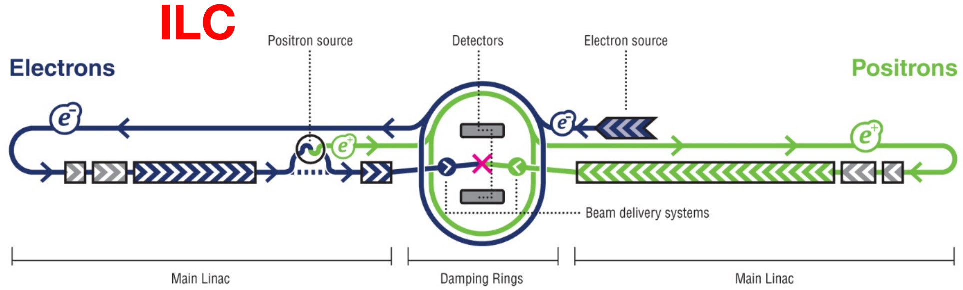


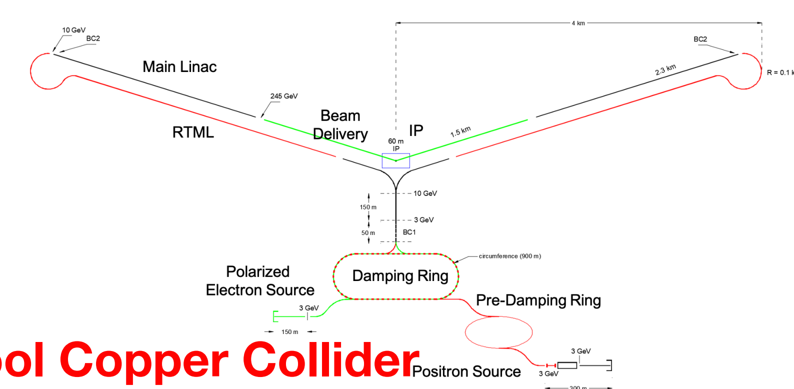
CEPC

+…

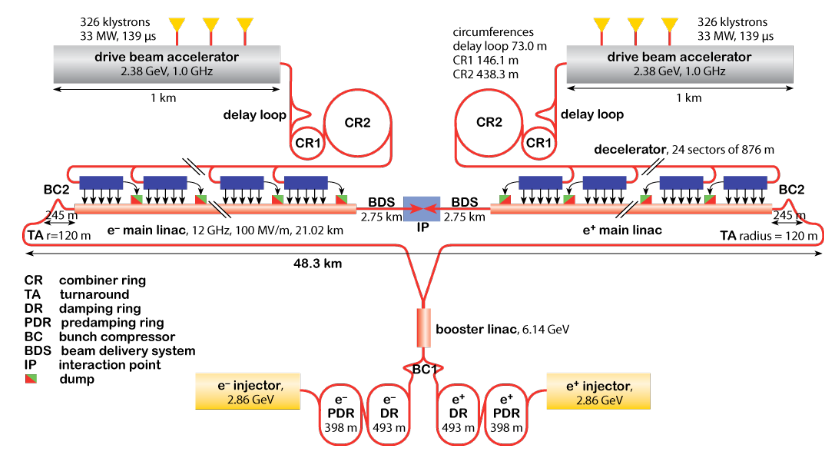
Linear

ILC



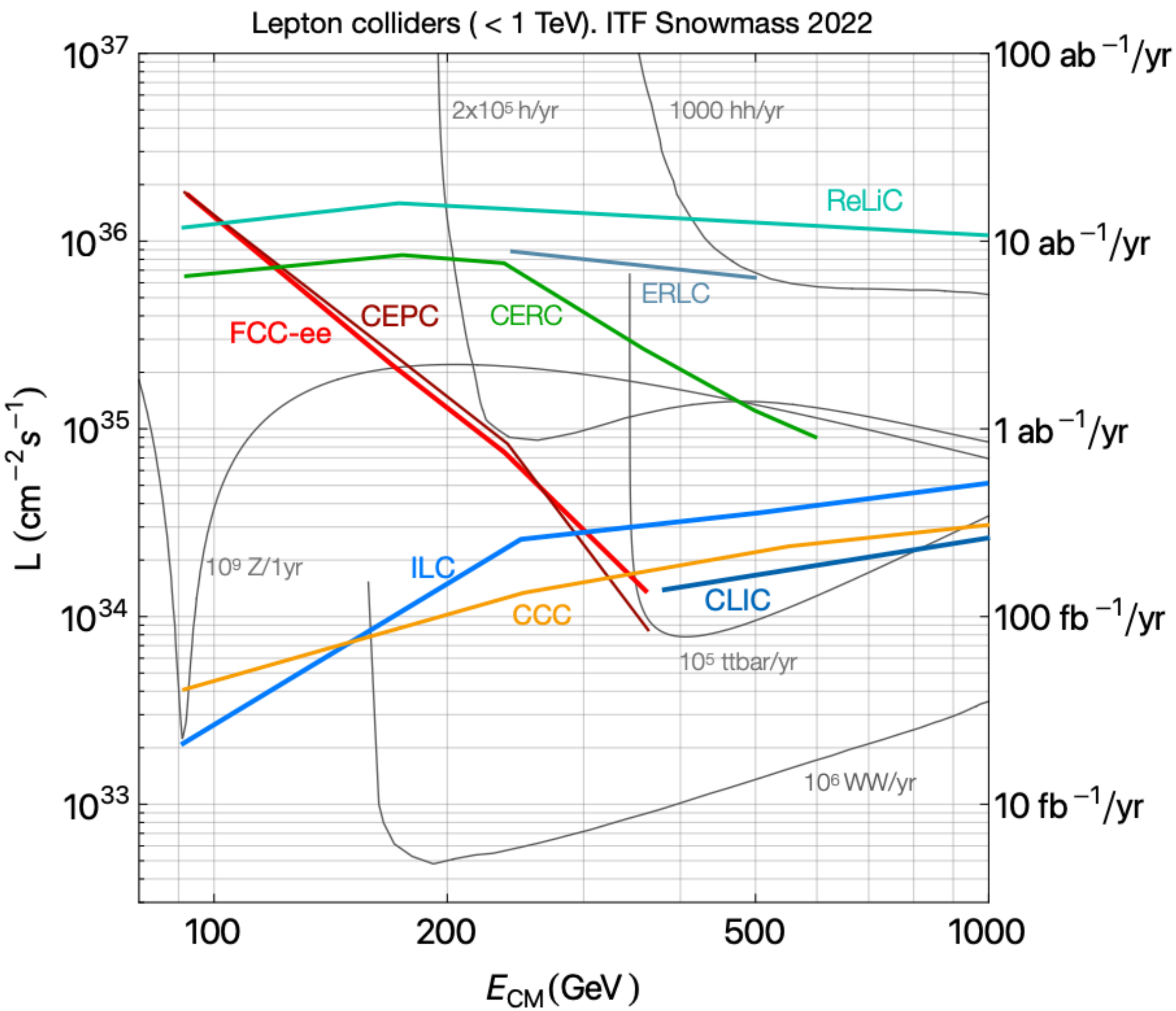


C^3 Cool Copper Collider



CLIC

Physics output



Main physics output:

10^6 Higgses

10^9 -10^{12} Zs

10^6 WW

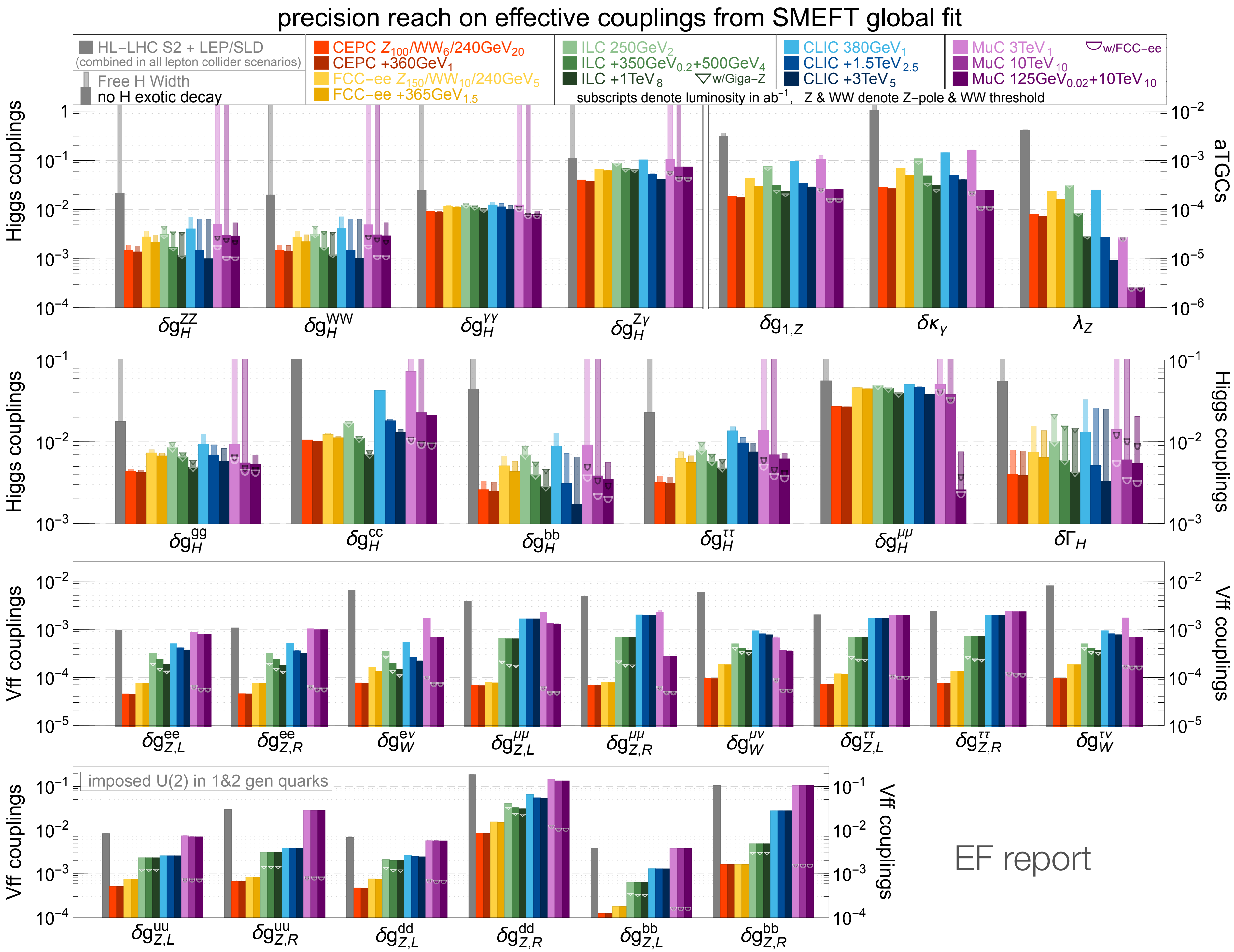
10^5 ttbar

Central theme: the electroweak scale

Performance of the Higgs factories:

Precision measurements Higgs and beyond

A full suite of measurements

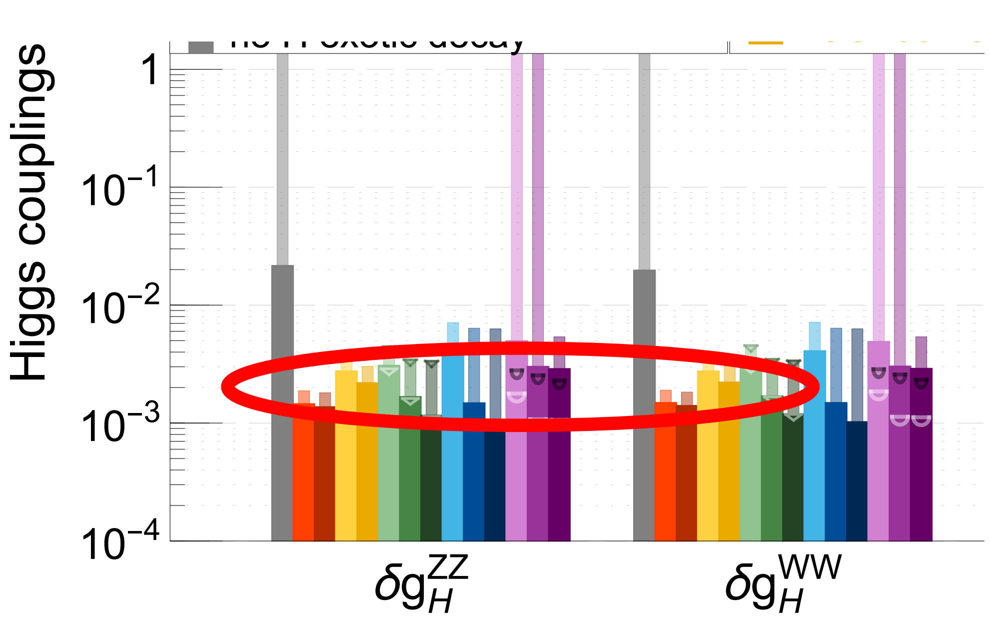


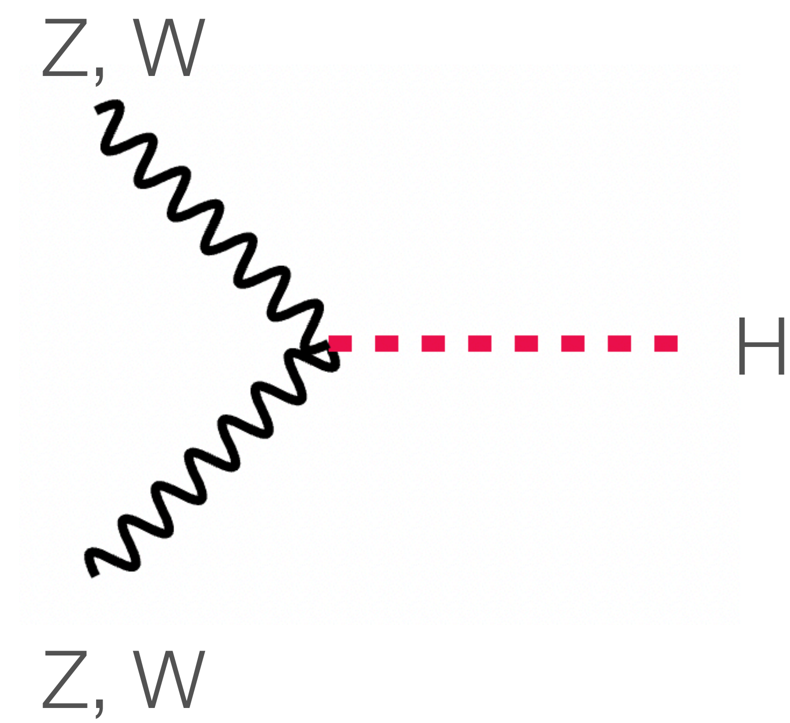
Based on:

Collider	$\sqrt{s}$	P [%] e^-/e^+	L_{int} ab^{-1}
ILC	250 GeV 350 GeV 500 GeV 1 TeV	$\pm80/\pm30$ $\pm80/\pm30$ $\pm80/\pm30$ $\pm80/\pm20$	2 0.2 4 8
ILC-GigaZ	m_Z	$\pm80/\pm30$	0.1
CLIC	380 GeV 500 GeV 1 TeV	$\pm80/0$ $\pm80/0$ $\pm80/0$	1 2.5 5
CEPC	m_Z $2m_W$ 240 GeV $2m_t$		60 / 100 3.6 / 6 12 / 20 – / 1
FCC-ee	m_Z $2m_W$ 240 GeV $2m_t$		150 10 5 1.5

EF report

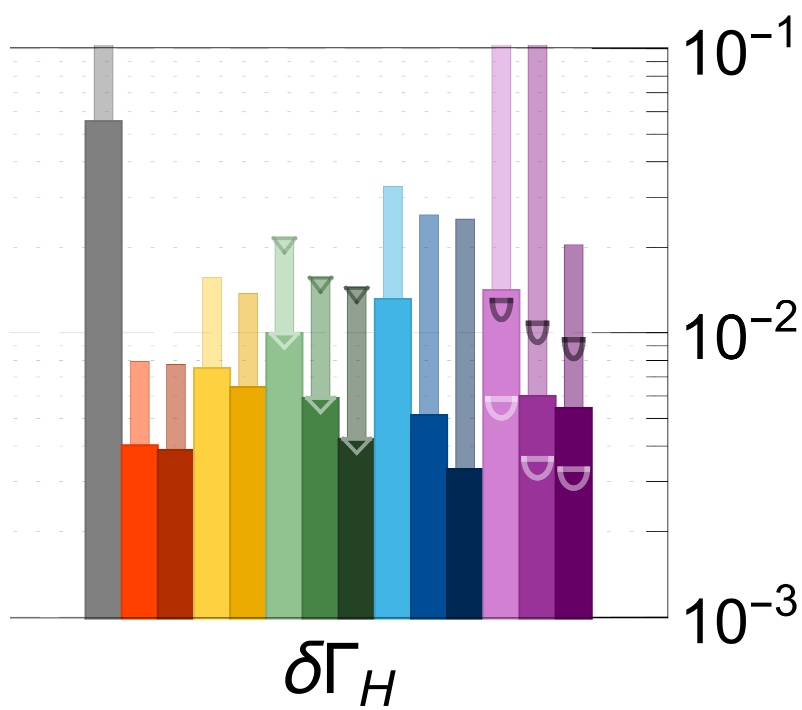
The Higgs measurements



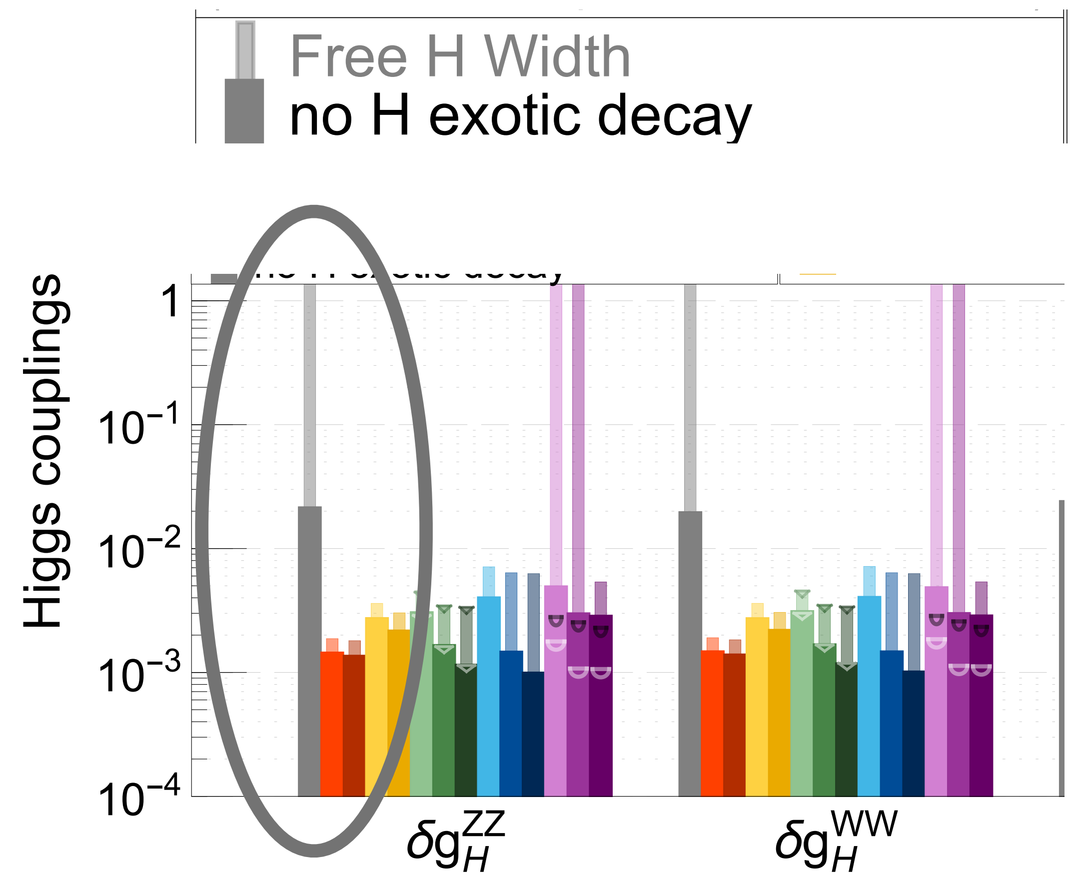


Measuring crucial Higgs coupling up to 10^{-3}

The Higgs measurements

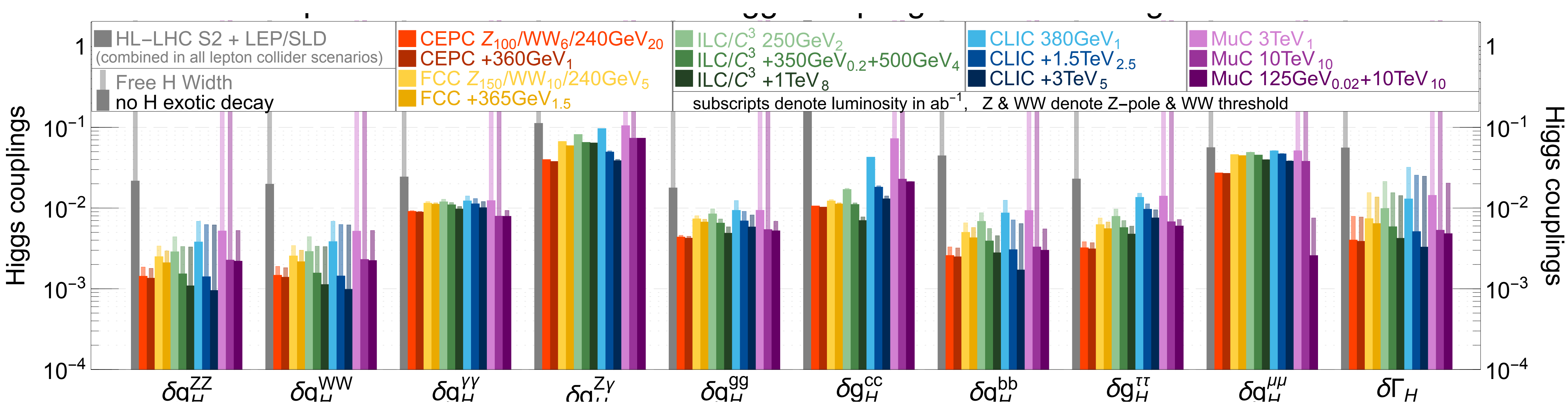


Higgs width measurement



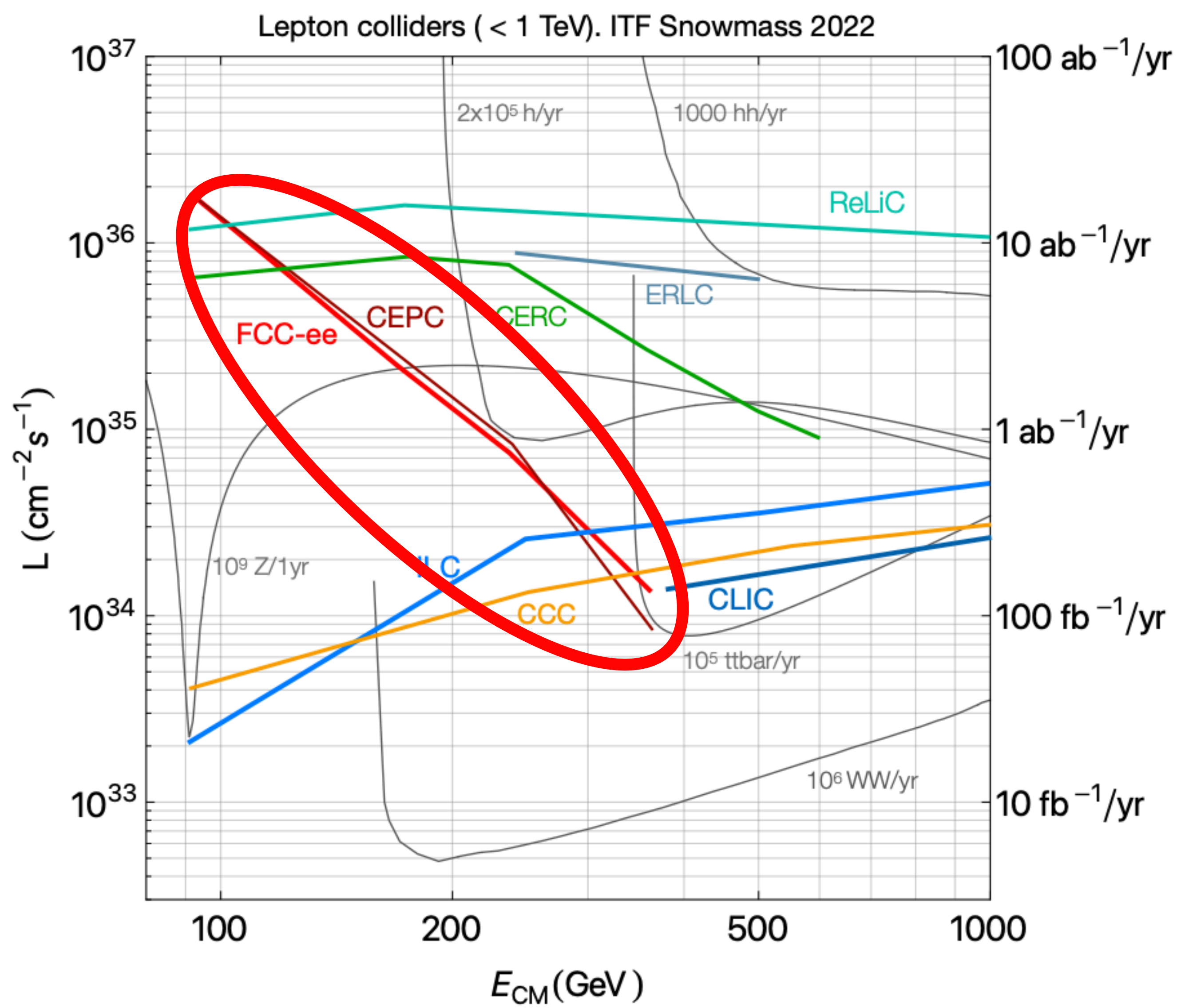
Significant impact on other coupling measurement

The Higgs measurements



Overall, a big step beyond the LHC

Circular



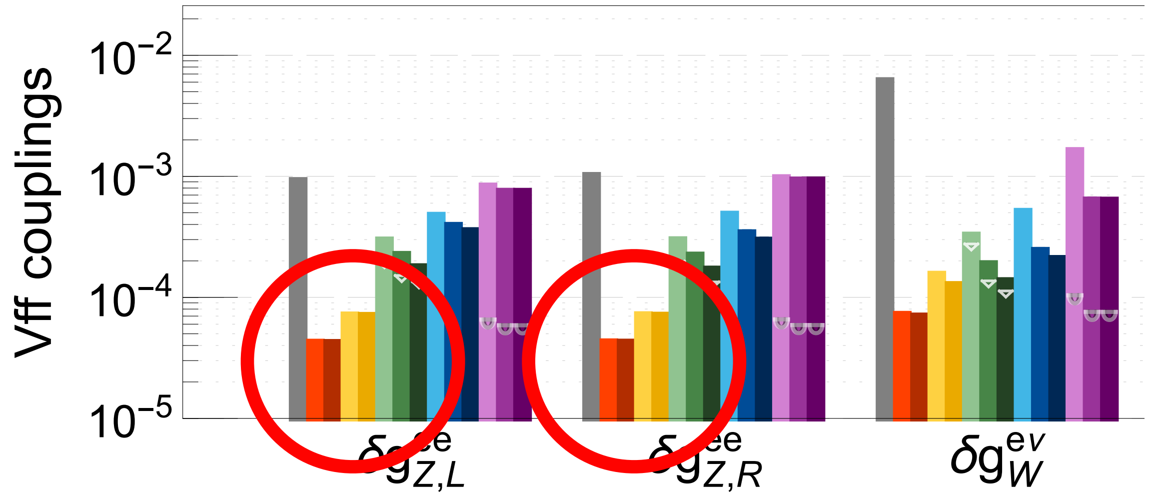
Higher luminosity.
⇒ more Higgs bosons!

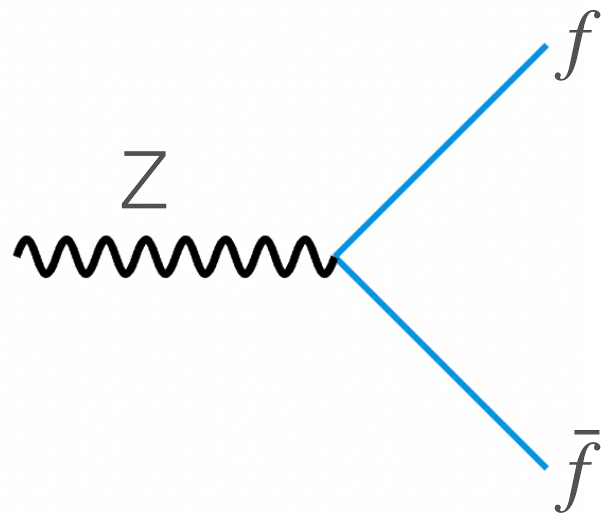
More W (10^6), Z (10^{12})

With more W, Zs

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

In comparison:
LEP has 10^{7} Zs

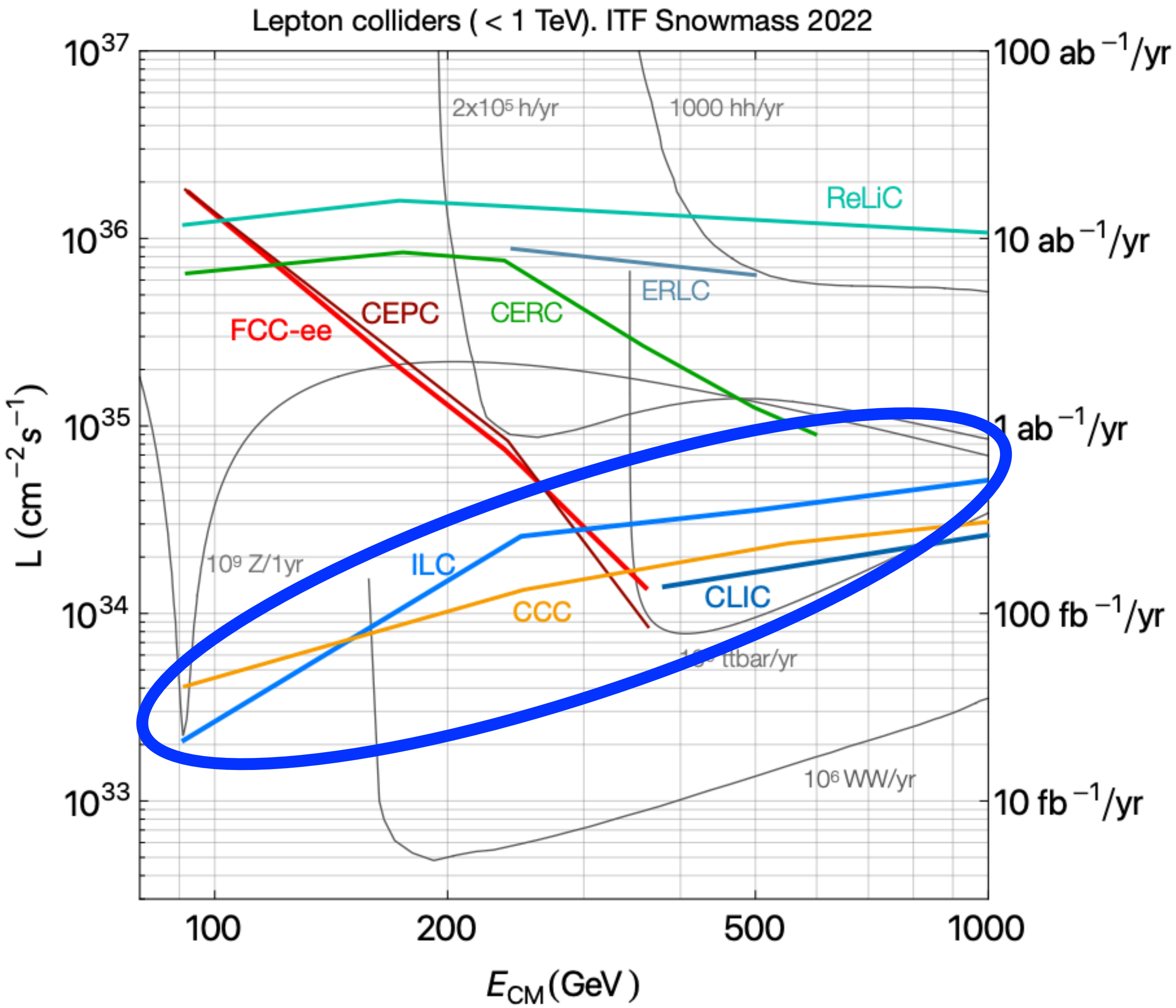




Precision on electroweak couplings: $10^{-3} \Rightarrow 10^{-4}$

Search for NP in exotic Z decays (more later)

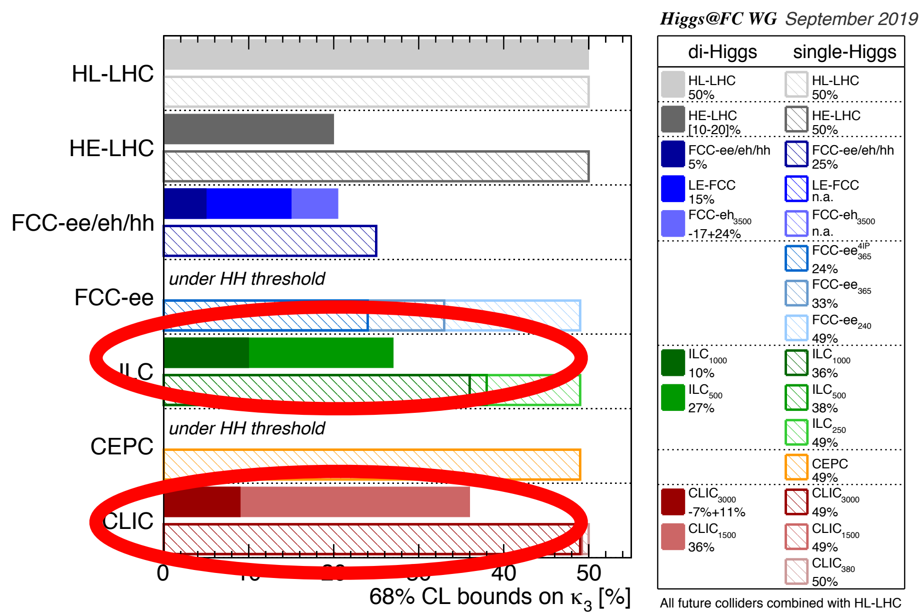
Linear

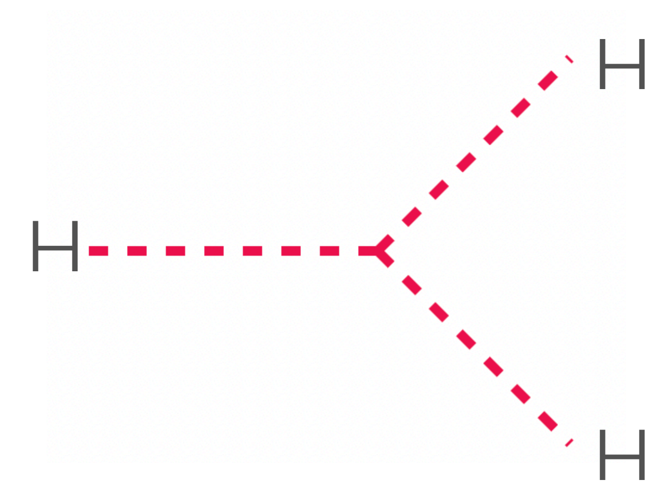


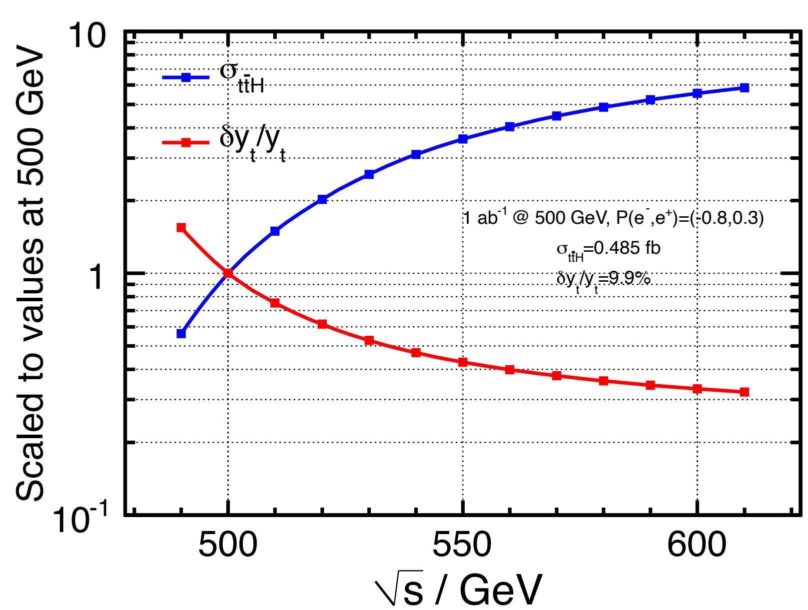
Longitudinal polarization.
Better at resolving certain signals

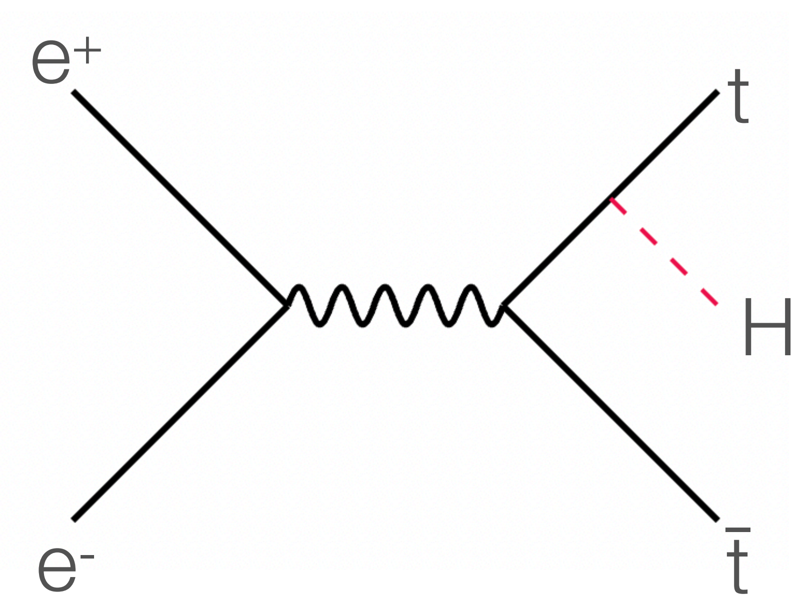
Can go to higher energies

At higher energies









Two excellent options!

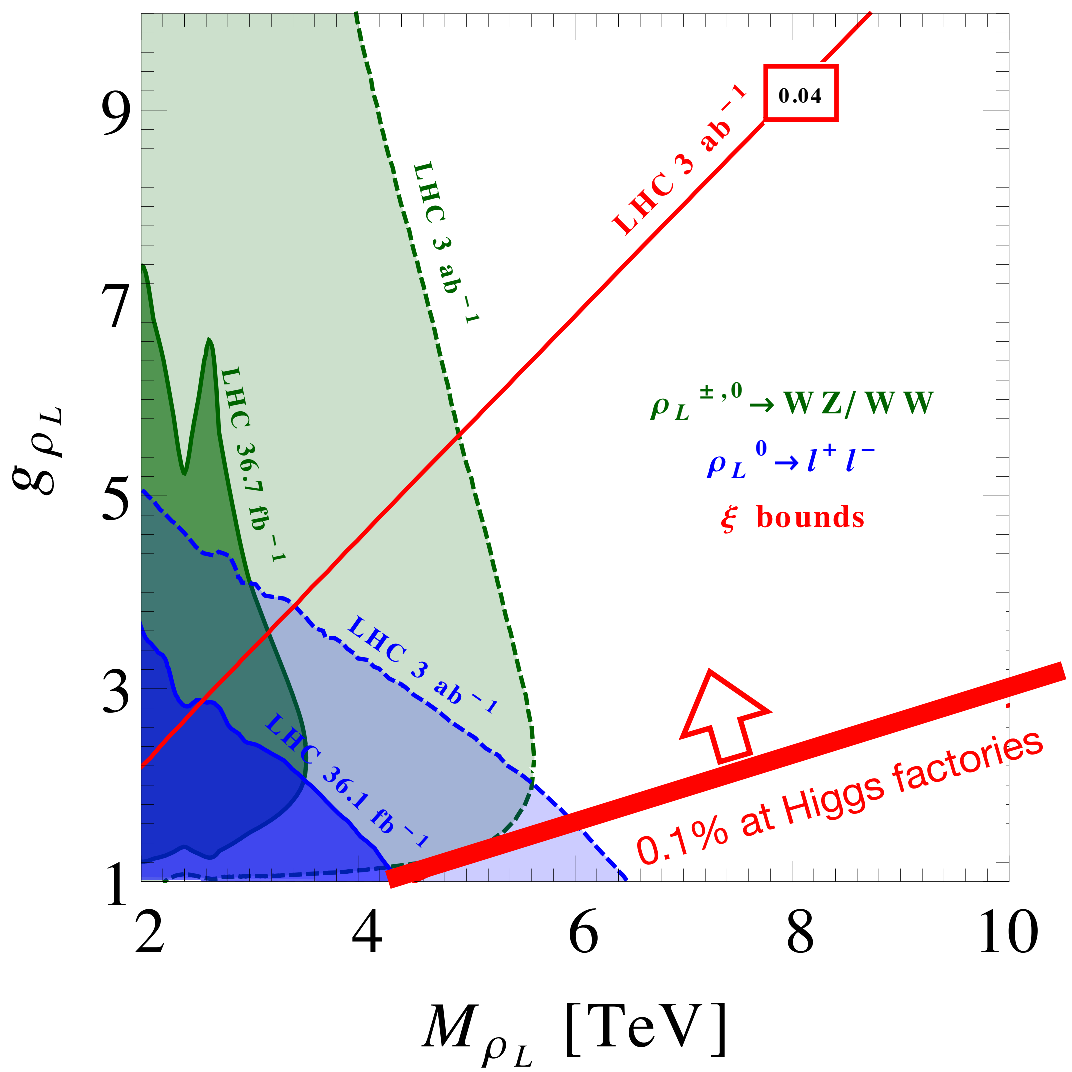
Great performances for Higgs measurements.

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

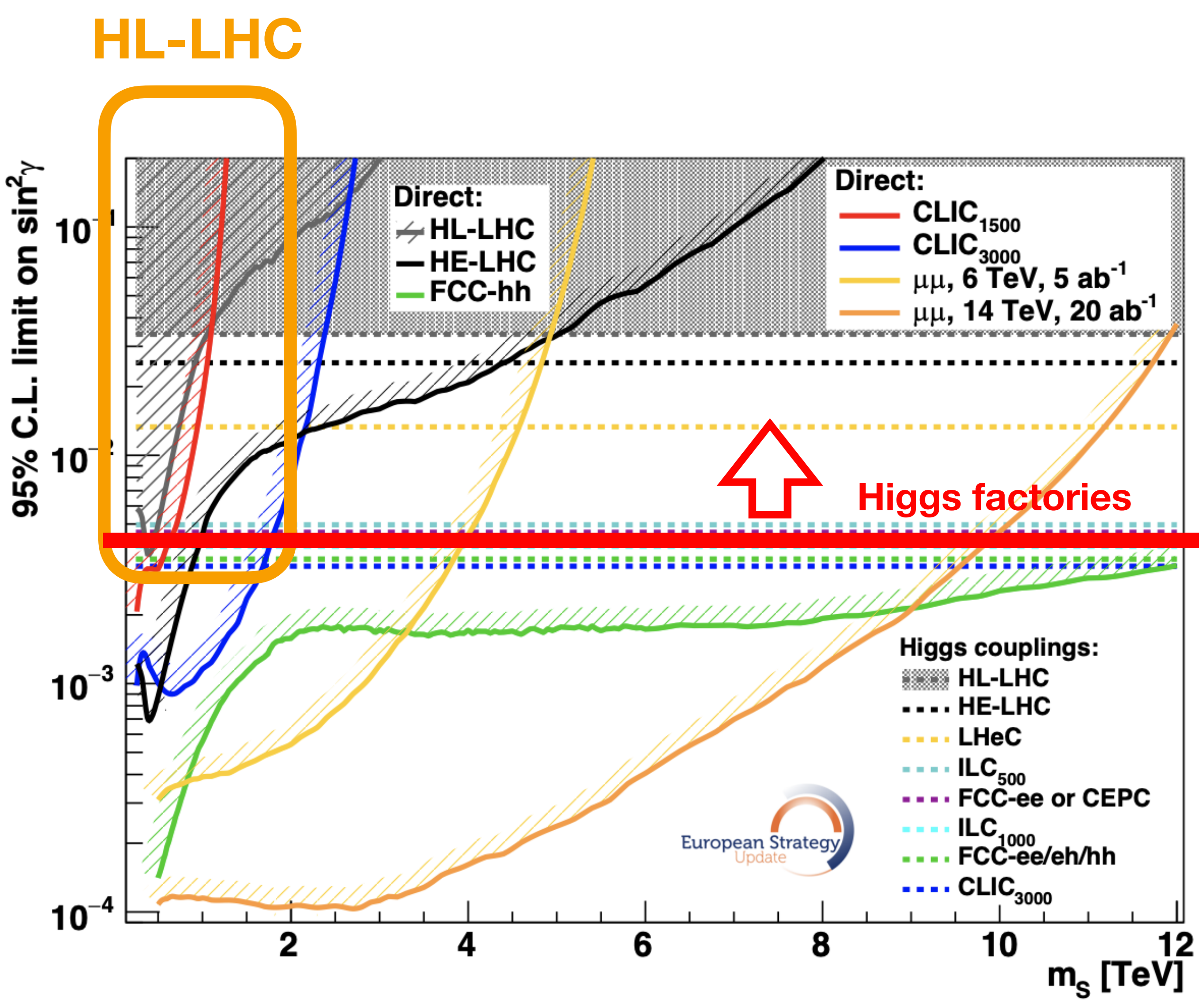
Direct search for composite resonances

Higgs coupling measurements

Composite ≠ elementary

Different couplings

Is the Higgs boson alone?

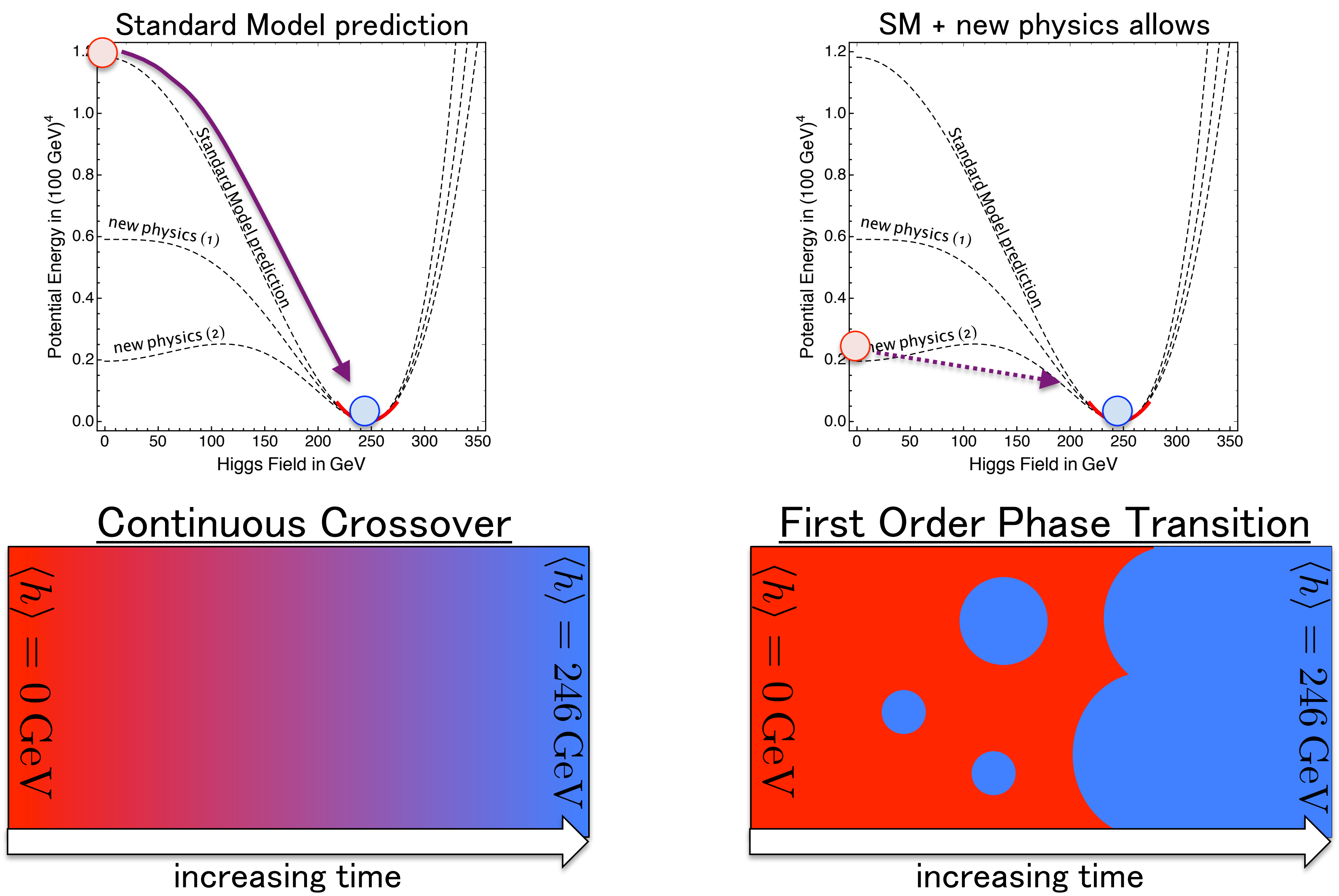


Maybe Higgs boson has some partners?

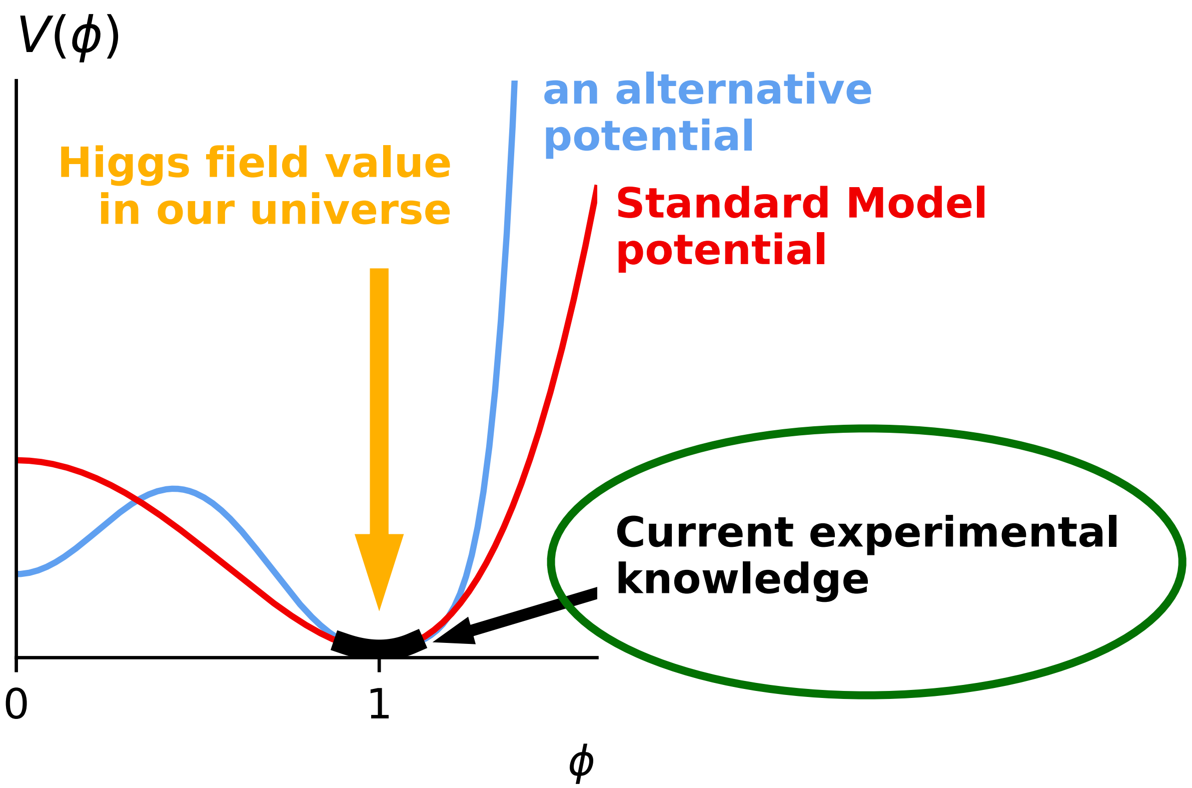
Will change Higgs behavior by interacting with it.

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

How does Higgs drive electroweak phase transition?

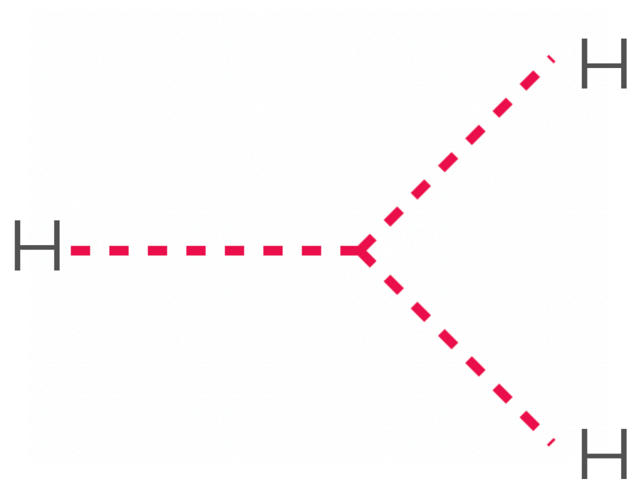


How does Higgs evolve in the early universe?

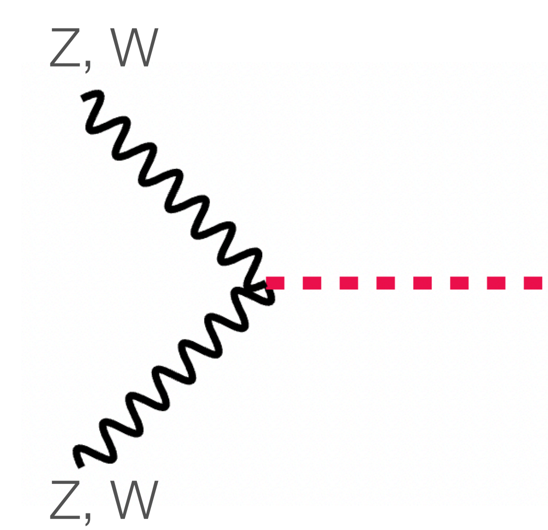


Need to go beyond this

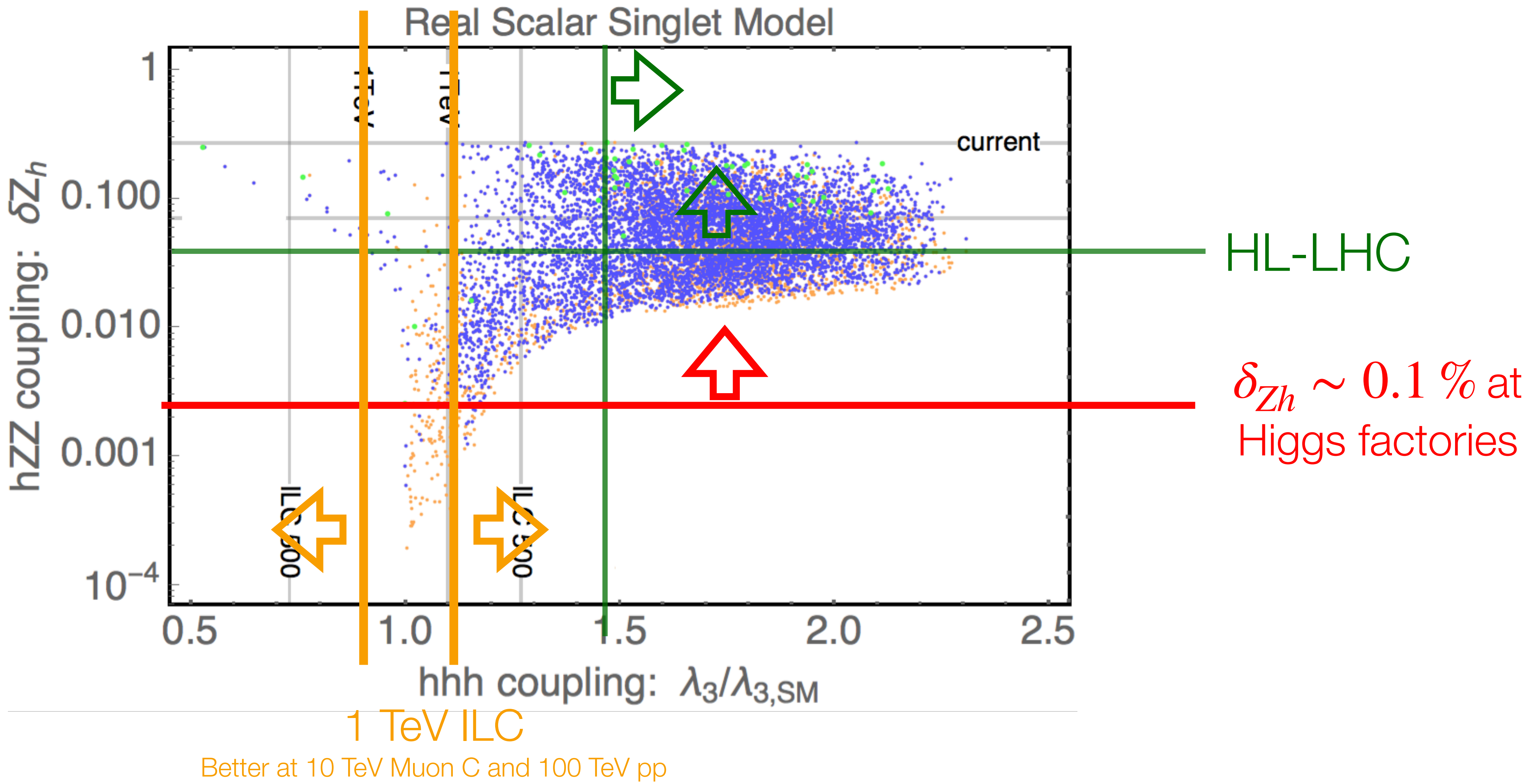
1. Self-coupling



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

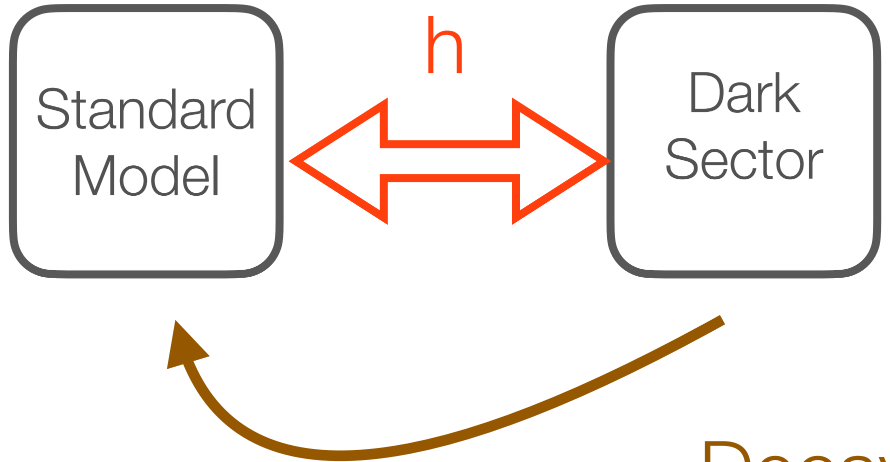
Other physics opportunities

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}
- New physics is light with very weak coupling.
  - Rare decays of H (clean), Z (large statistics).

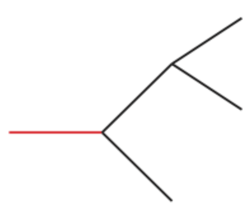
Higgs to dark sector?



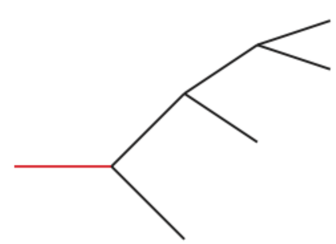
"Higgs portal"

Decay back to SM

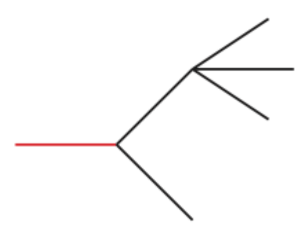
$h \to 2 \to 3$



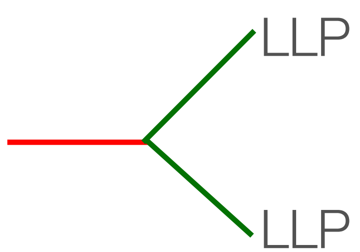
$h \to 2 \to 3 \to 4$



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

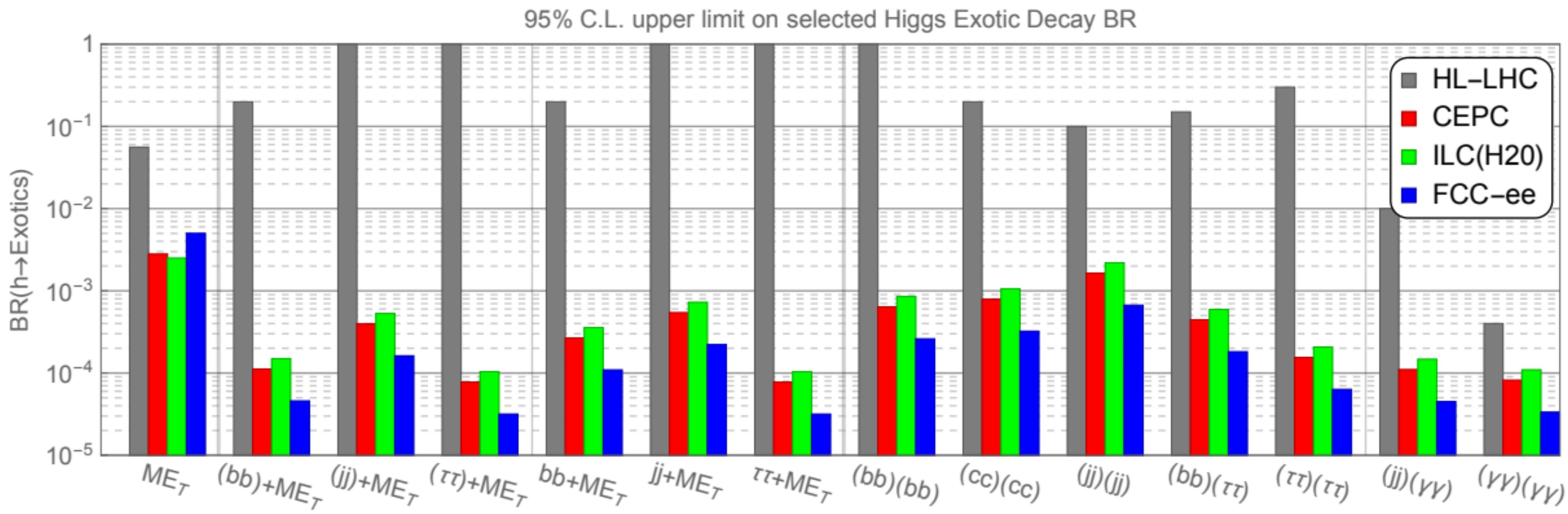


Long lived particles



....

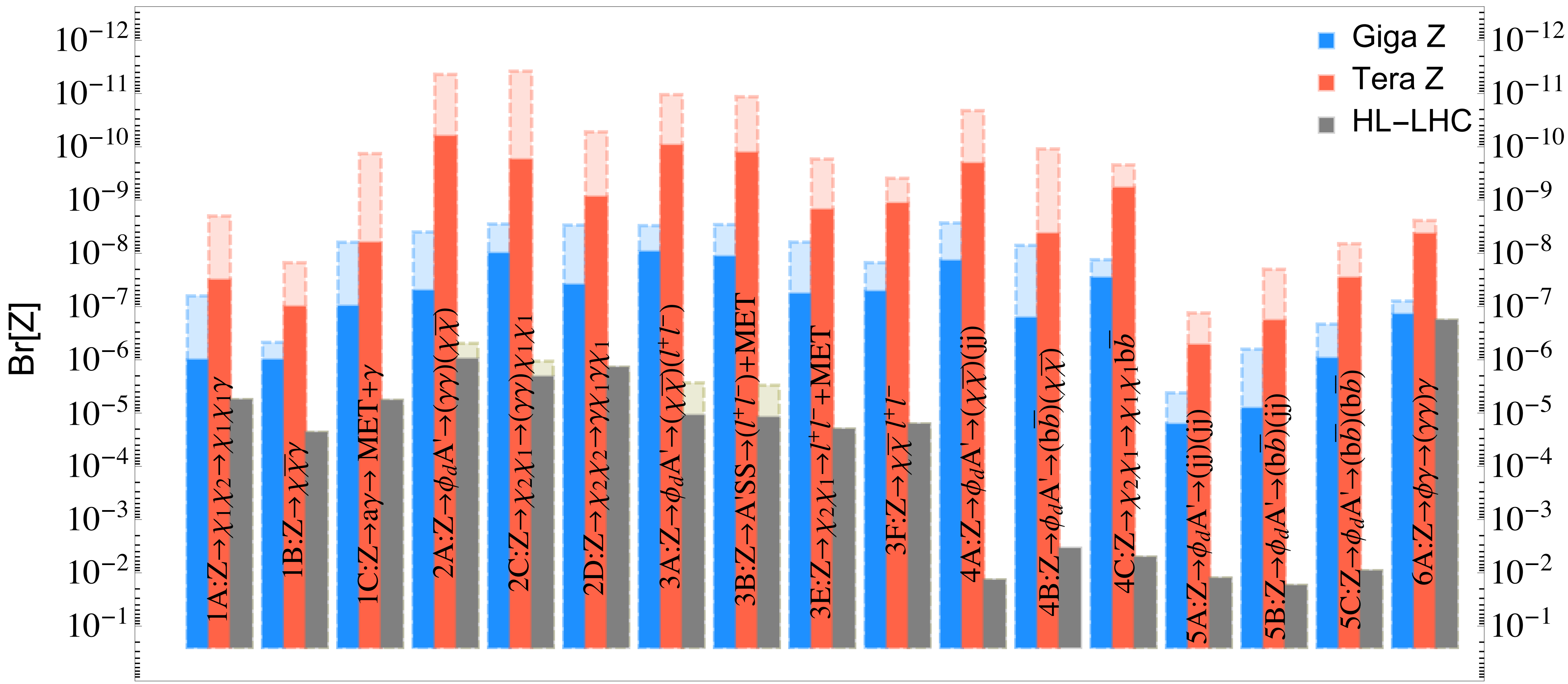
Higgs exotic decay



Complementary to hadron collider searches

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

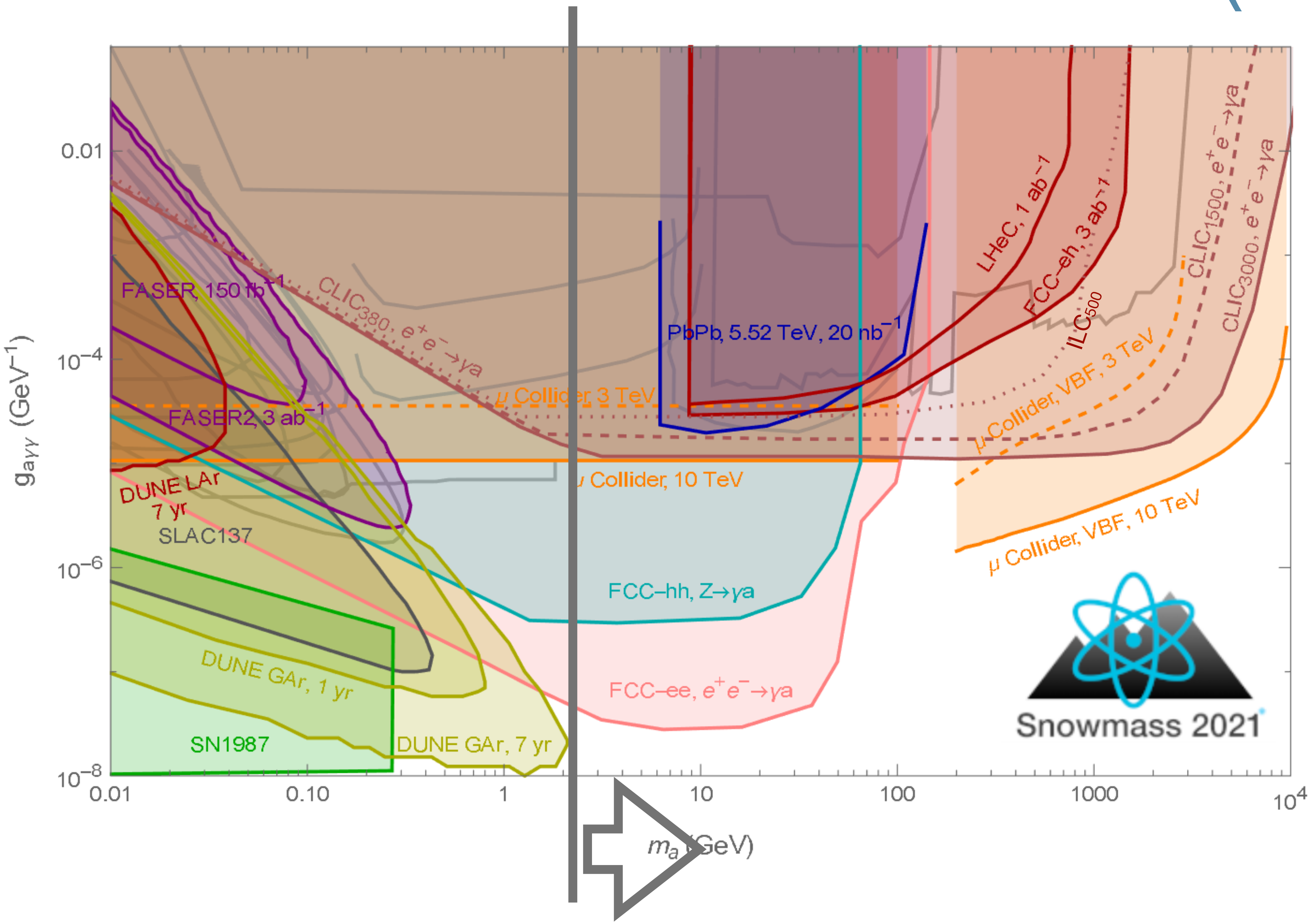
Rare Z decay at Tera-Z



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

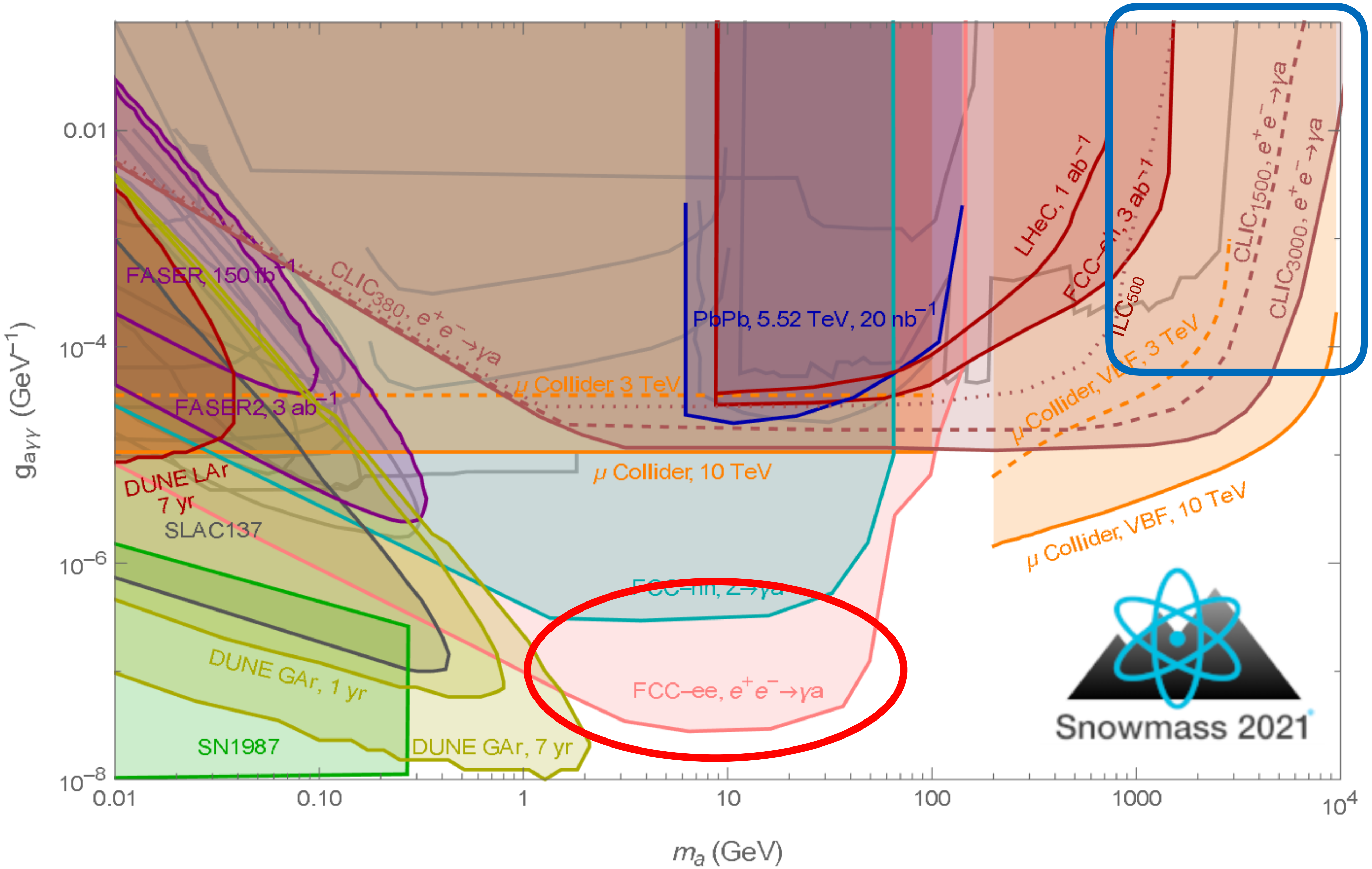
Sensitive to a variety of dark photon, dark scalar models.

Axion Like Particles (ALP)



High energy colliders probing higher mass regions.

Axion Like Particles (ALP)



Higher energies

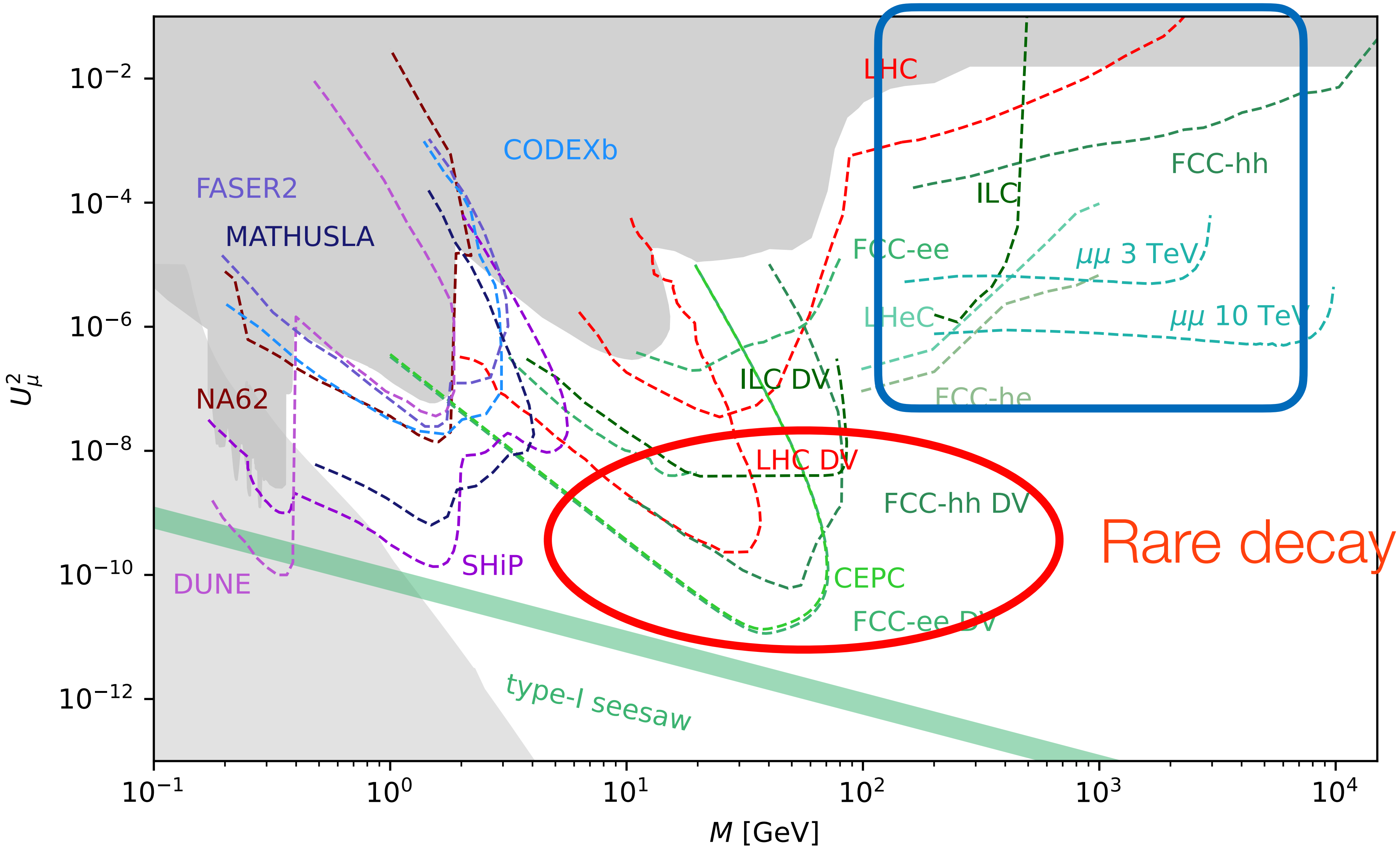
Reach scale with energy

Higgs factories

High luminosity, sensitive to weak signal

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}	$(50\,\text{ab}^{-1}$ on $\Upsilon(4S))$	3×10^{13}
B^0	6×10^{10}	3×10^{10}	$(50\,\text{ab}^{-1}$ on $\Upsilon(4S))$	3×10^{13}
B_s	2×10^{10}	3×10^{8}	$(5\,\text{ab}^{-1}$ 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}	$(50\,\text{ab}^{-1}$ on $\Upsilon(4S))$	

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

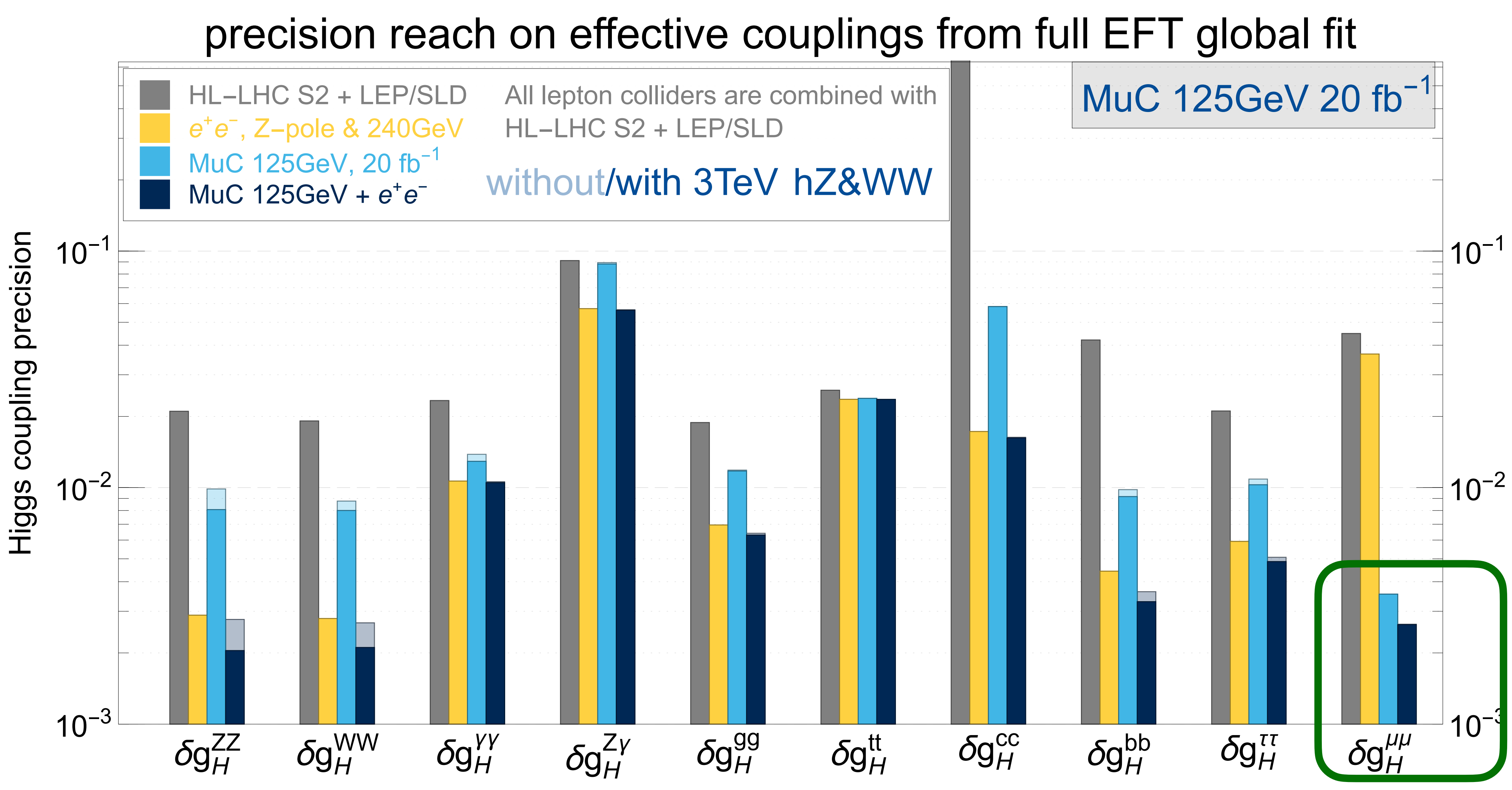
- Similar statistical sample of $B^{0,\pm}$, τ's at Belle 2 and CEPC
- Two order of magnitude more B_s at CEPC wrt to Belle 2
- b-baryon physics possible at the CEPC
- Limited possibilities for charm physics at Belle 2

Great place to probe rare flavor processes!

Other Higgs factories

* Muon Collider at 125 GeV. Good for Higgs-muon coupling measurement.

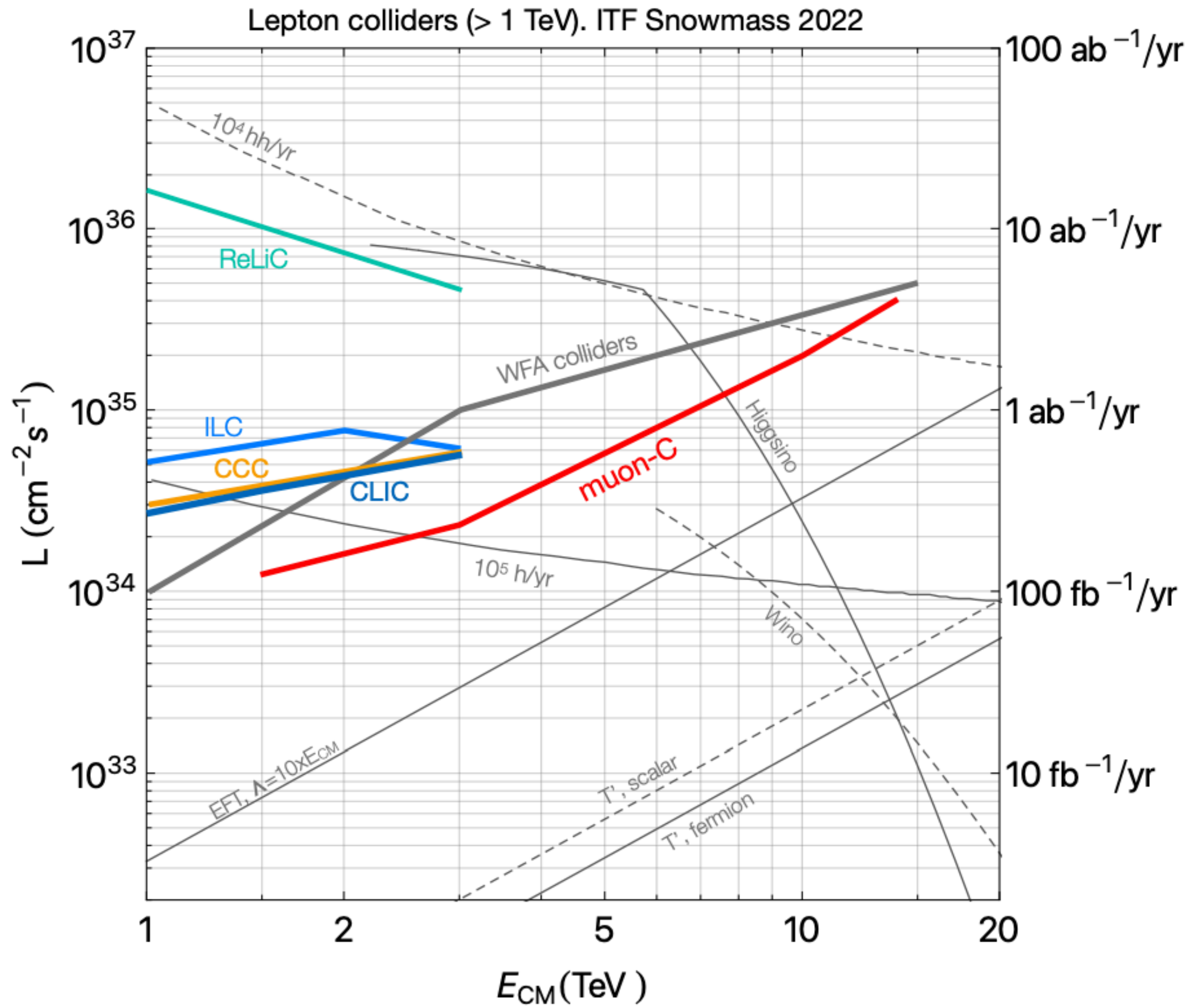
Muon Collider 125



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.
  - High energy pp, a lot more Higgs, but also noisier environment.
  - At muon collider Higgs production dominated by vector boson fusion, good yield.

Yield at higher energies



muon collider: $\mathscr{L} = \left(\frac{\sqrt{s}}{10\,\mathrm{TeV}}\right)^2 \times 10^{35}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$

E_{CM} (TeV):	1.5 TeV	3 TeV	6 TeV	10 TeV	30 TeV
Higgs production/10^7s	37,500	200,000	820,000	10^7	10^8

Muon collider vs the rest

κ-0 fit	HL-LHC	LHeC	HE-LHC S2	HE-LHC S2$'$	ILC 250	ILC 500	ILC 1000	CLIC 380	CLIC 1500	CLIC 3000	CEPC	FCC-ee 240	FCC-ee 365	FCC-ee/eh/hh	$\mu^+\mu^-$ 10000
κ_W	1.7	0.75	1.4	0.98	1.8	0.29	0.24	0.86	0.16	0.11	1.3	1.3	0.43	0.14	0.11
κ_Z	1.5	1.2	1.3	0.9	0.29	0.23	0.22	0.5	0.26	0.23	0.14	0.20	0.17	0.12	0.35
κ_g	2.3	3.6	1.9	1.2	2.3	0.97	0.66	2.5	1.3	0.9	1.5	1.7	1.0	0.49	0.45
κ_γ	1.9	7.6	1.6	1.2	6.7	3.4	1.9	98$\star$	5.0	2.2	3.7	4.7	3.9	0.29	0.84
$\kappa_{Z\gamma}$	10.	–	5.7	3.8	99$\star$	86$\star$	85$\star$	120$\star$	15	6.9	8.2	81$\star$	75$\star$	0.69	5.5
κ_c	–	4.1	–	–	2.5	1.3	0.9	4.3	1.8	1.4	2.2	1.8	1.3	0.95	1.8
κ_t	3.3	–	2.8	1.7	–	6.9	1.6	–	–	2.7	–	–	–	1.0	1.4
κ_b	3.6	2.1	3.2	2.3	1.8	0.58	0.48	1.9	0.46	0.37	1.2	1.3	0.67	0.43	0.24
κ_μ	4.6	–	2.5	1.7	15	9.4	6.2	320$\star$	13	5.8	8.9	10	8.9	0.41	2.9
κ_τ	1.9	3.3	1.5	1.1	1.9	0.70	0.57	3.0	1.3	0.88	1.3	1.4	0.73	0.44	0.59

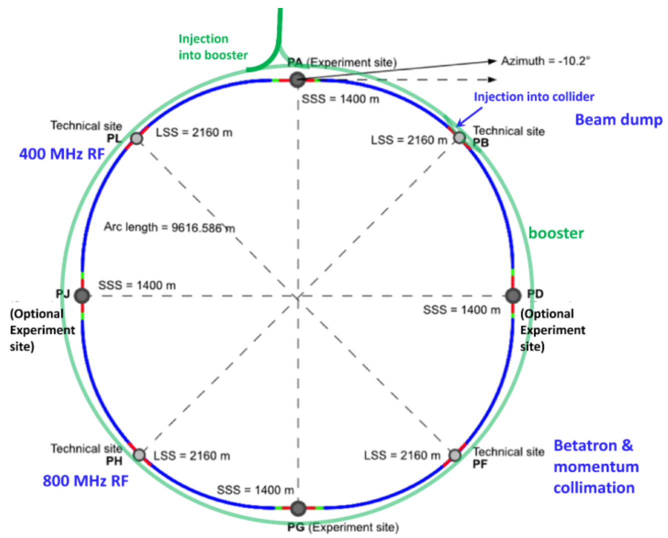
Summary

- 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.

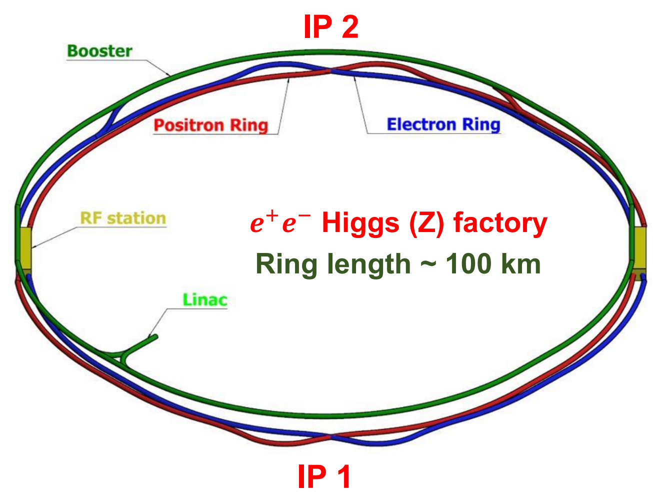
This is the clearest and most concrete argument for making progress, based on what we actually know.

With all these excellent options

Circular



FCC-ee

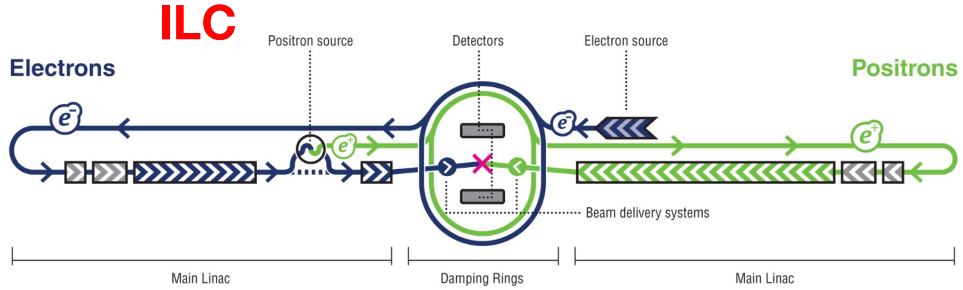


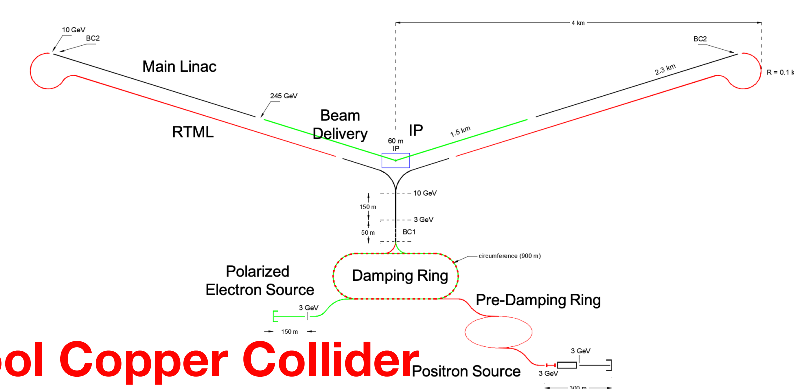
CEPC

+...

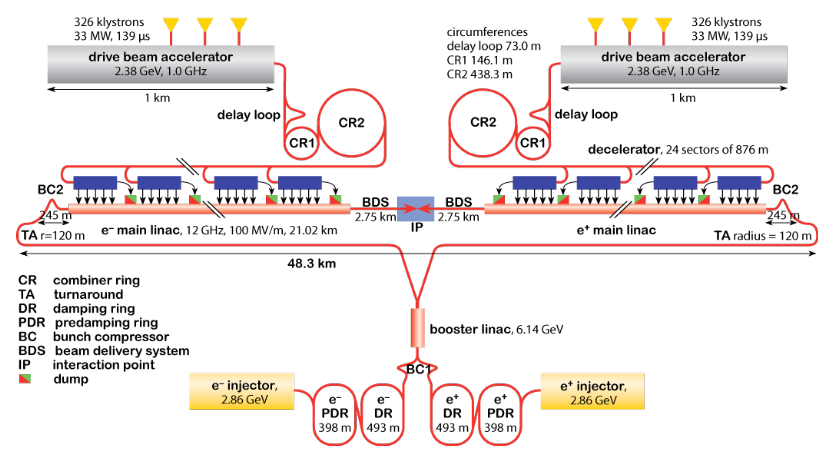
Linear

ILC





C^3 Cool Copper Collider



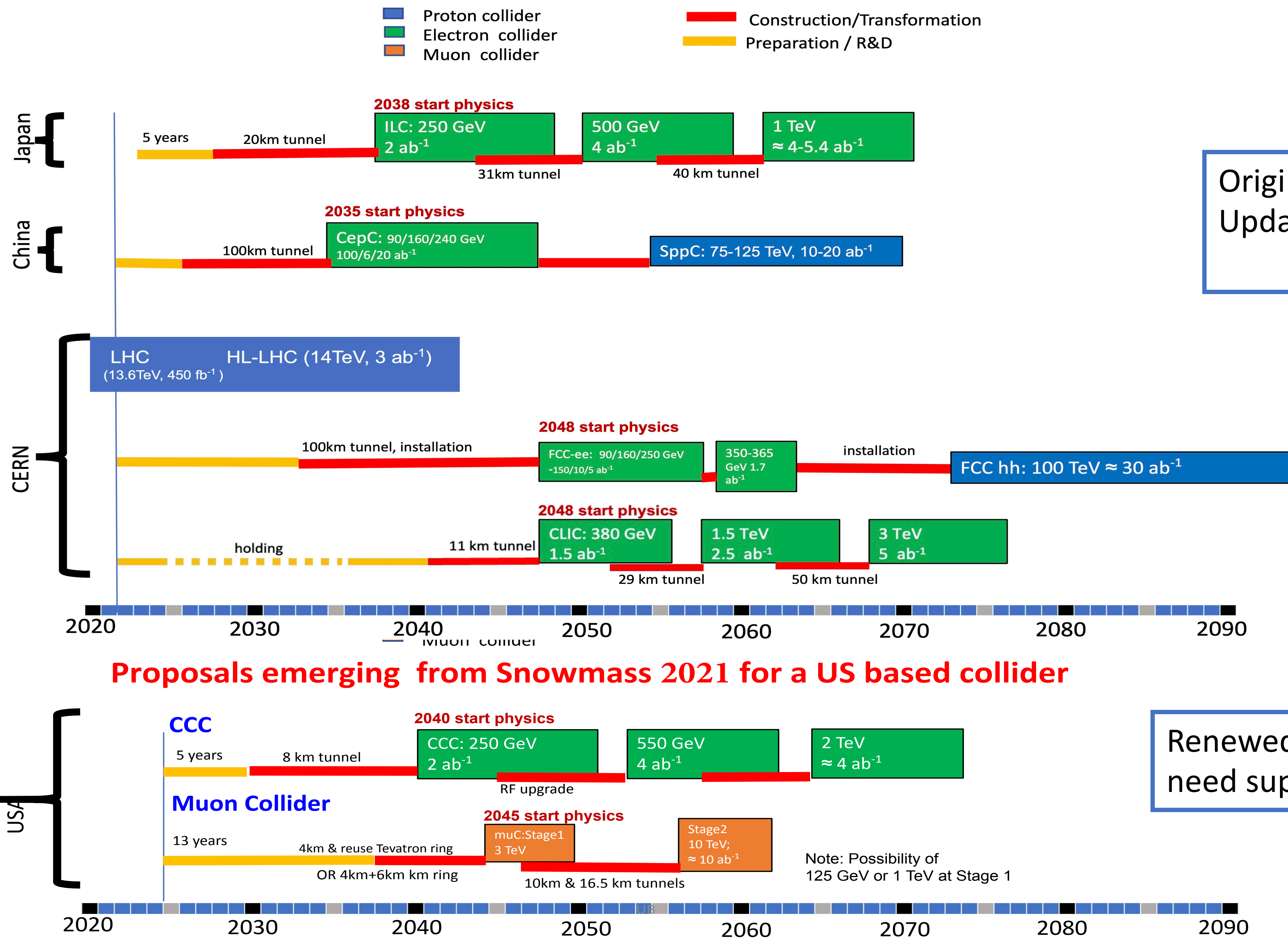
CLIC

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!

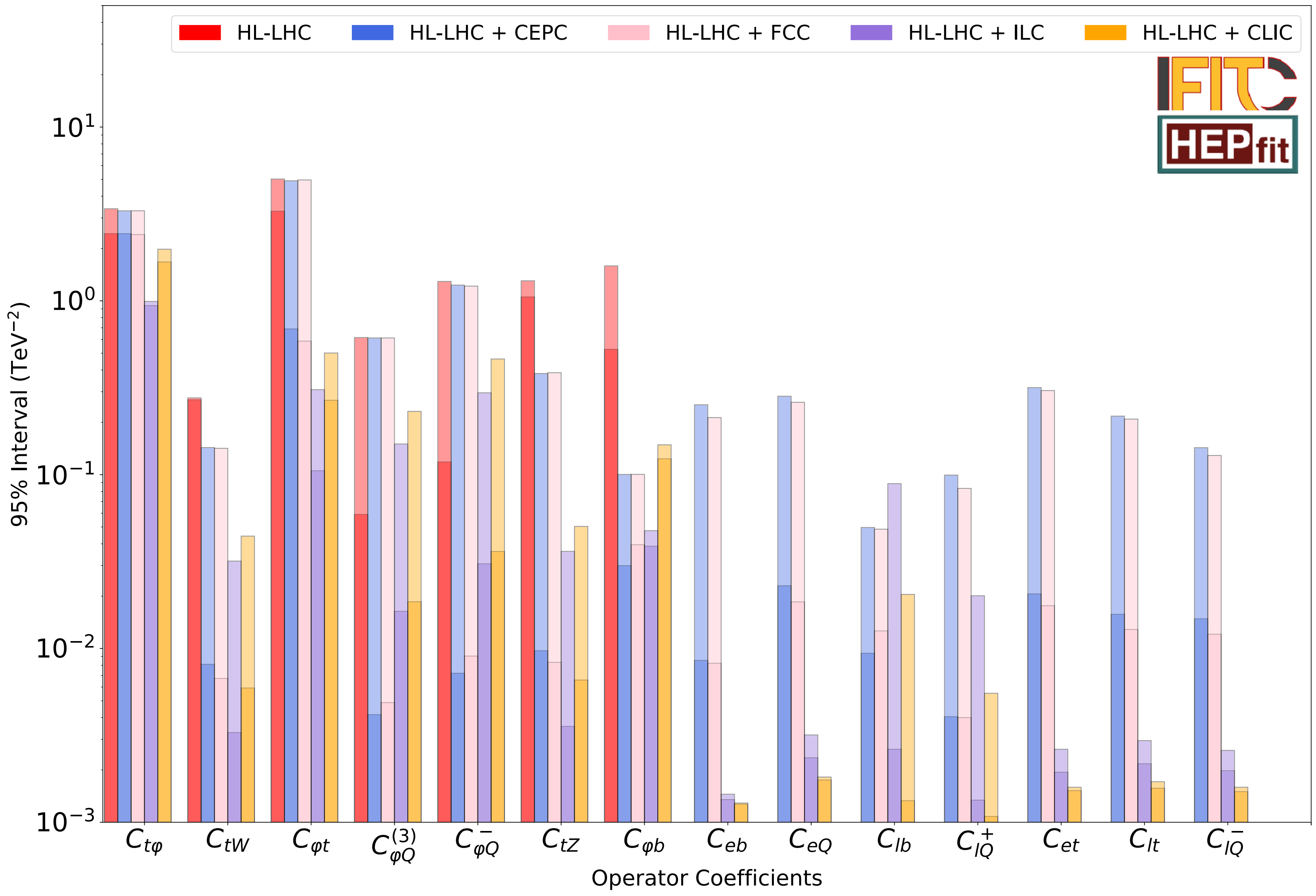
Extra

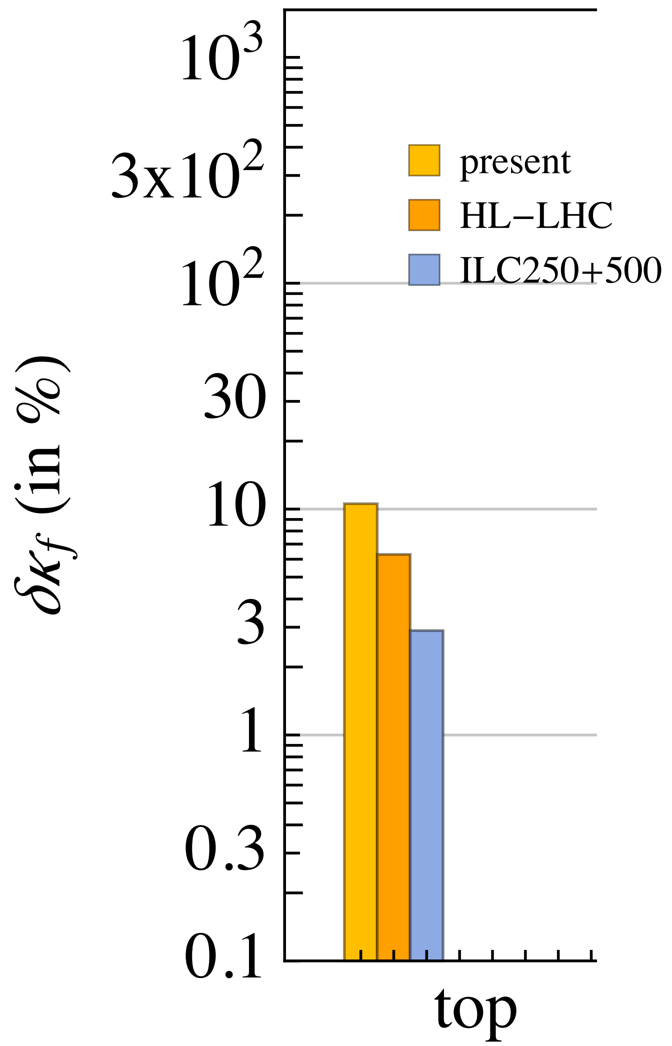


Original timeline from ESG
Updated during Snowmass 2021
(see EF Report)

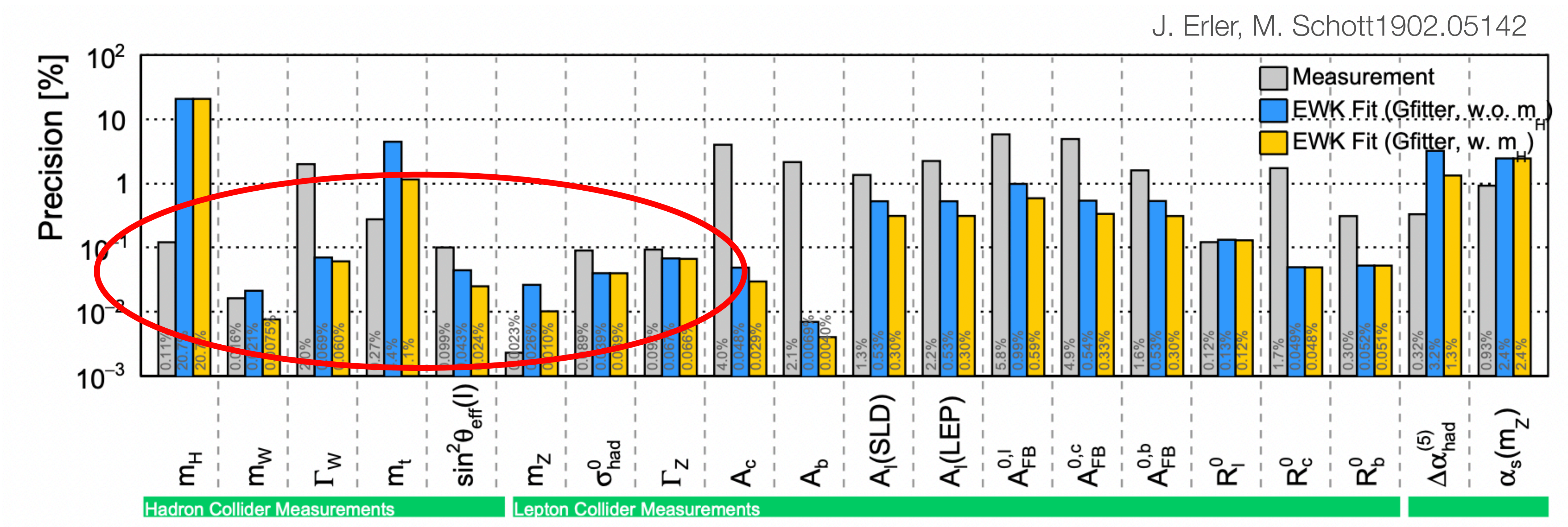
Renewed interest in lepton colliders: need supporting R&D in near future

Top quark coupling



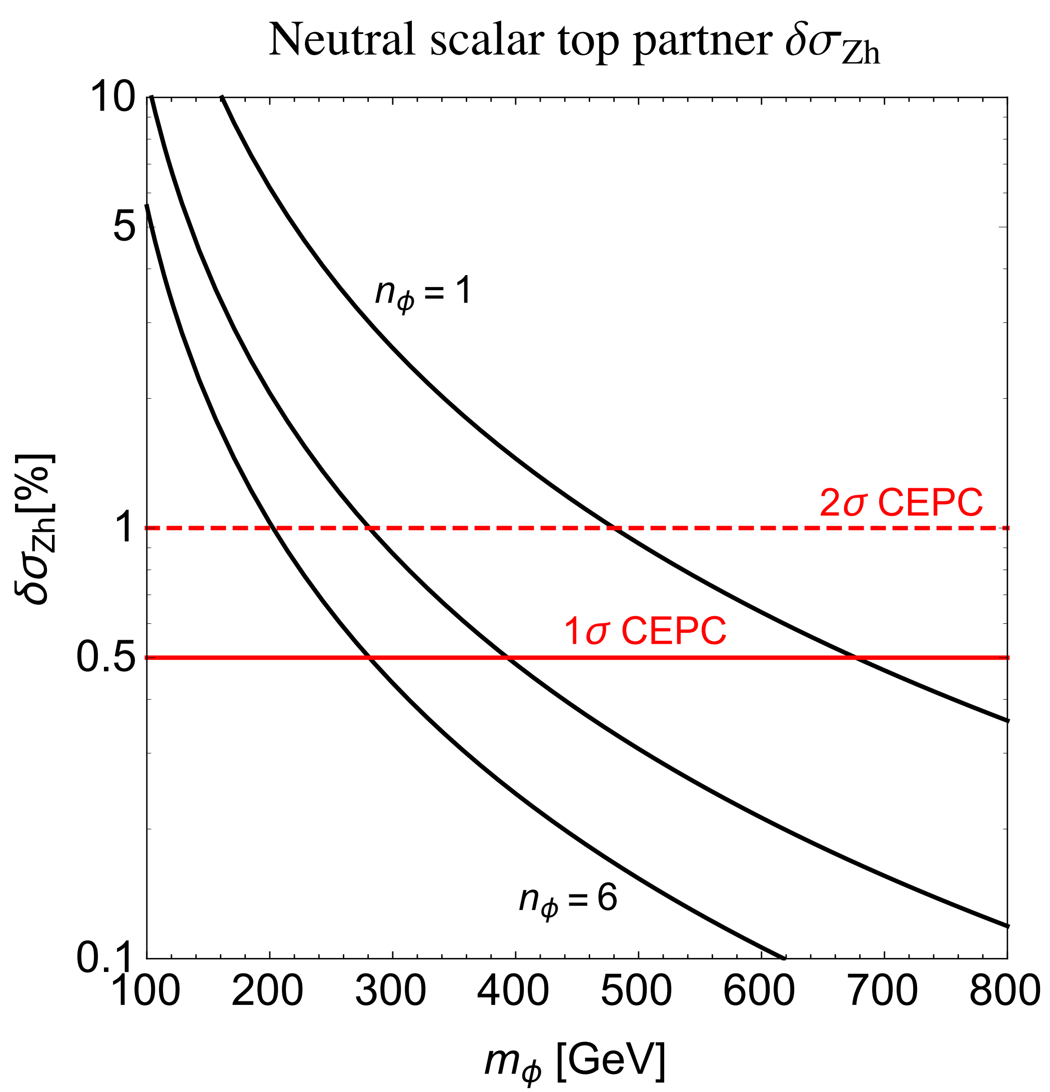


SM precision



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

Is the Higgs fine-tuned?

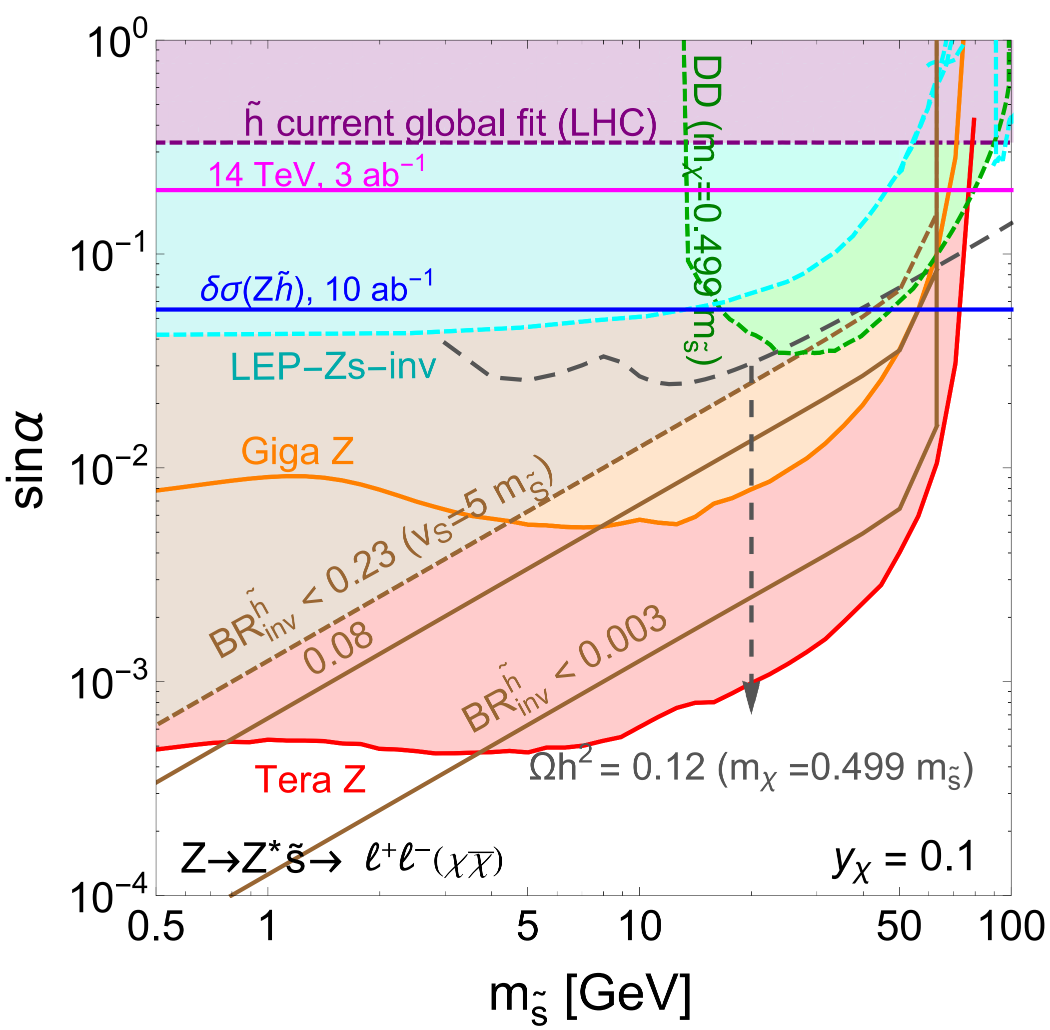


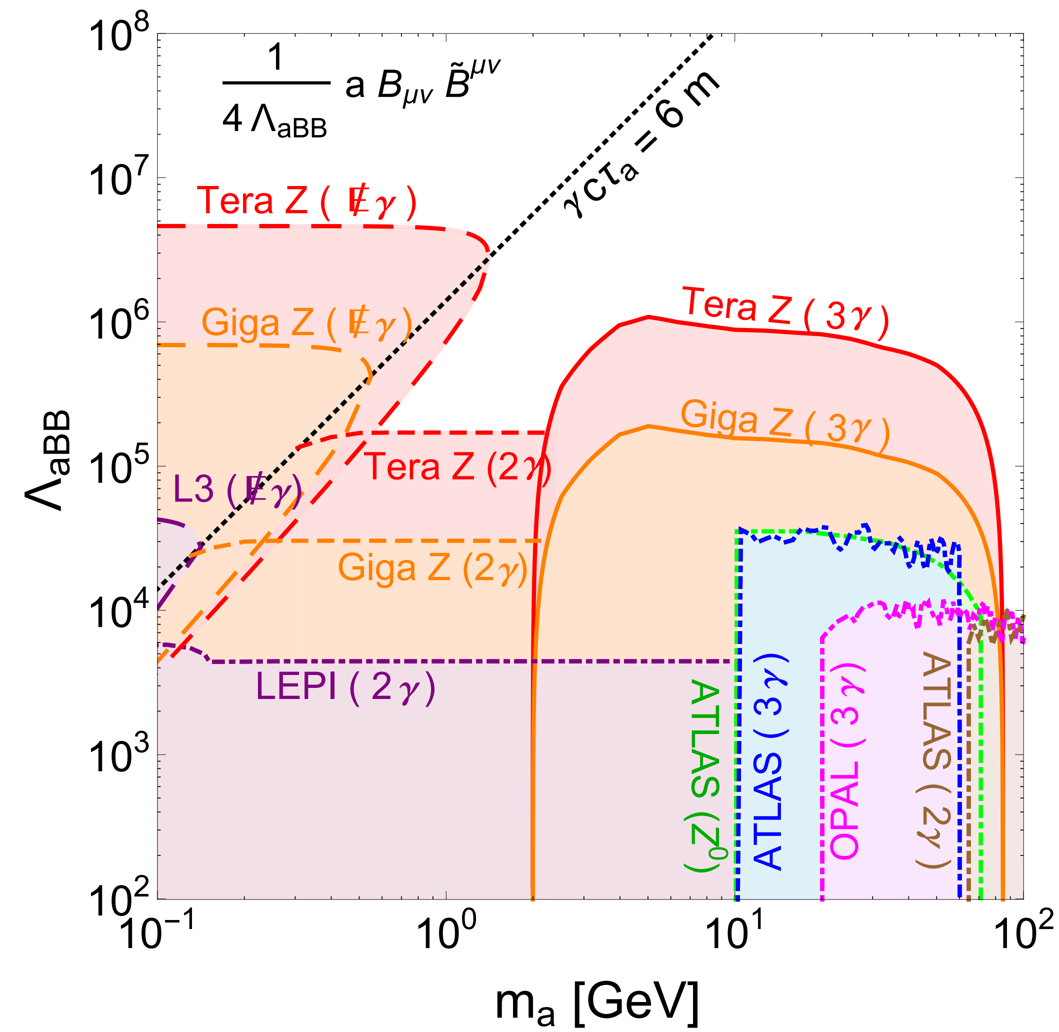
New physics is neutral, only couples to the Higgs

Neutral naturalness

Dark photon, dark scalar

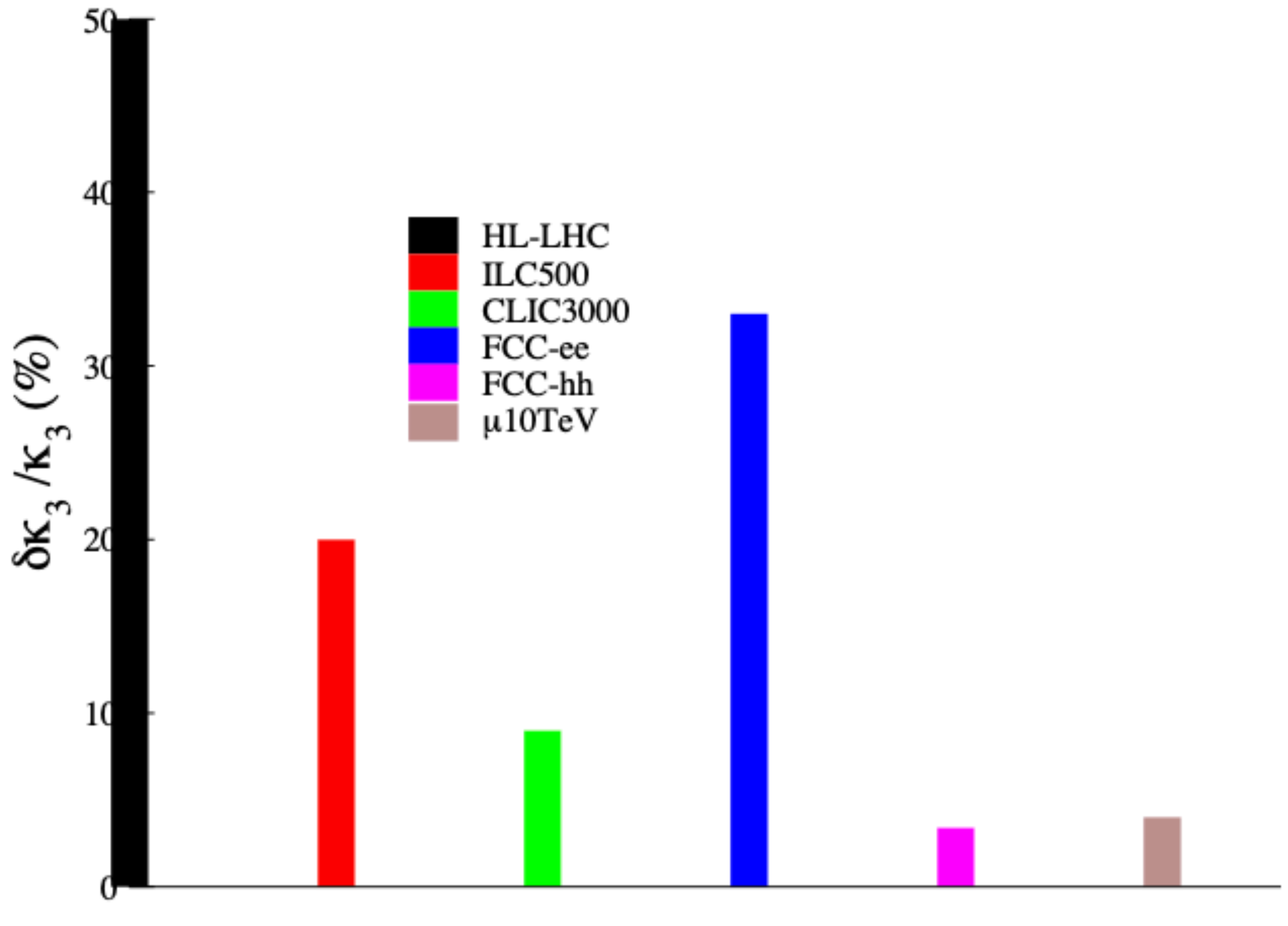
J. Liu, X.P. Wang, W. Xue, LTW



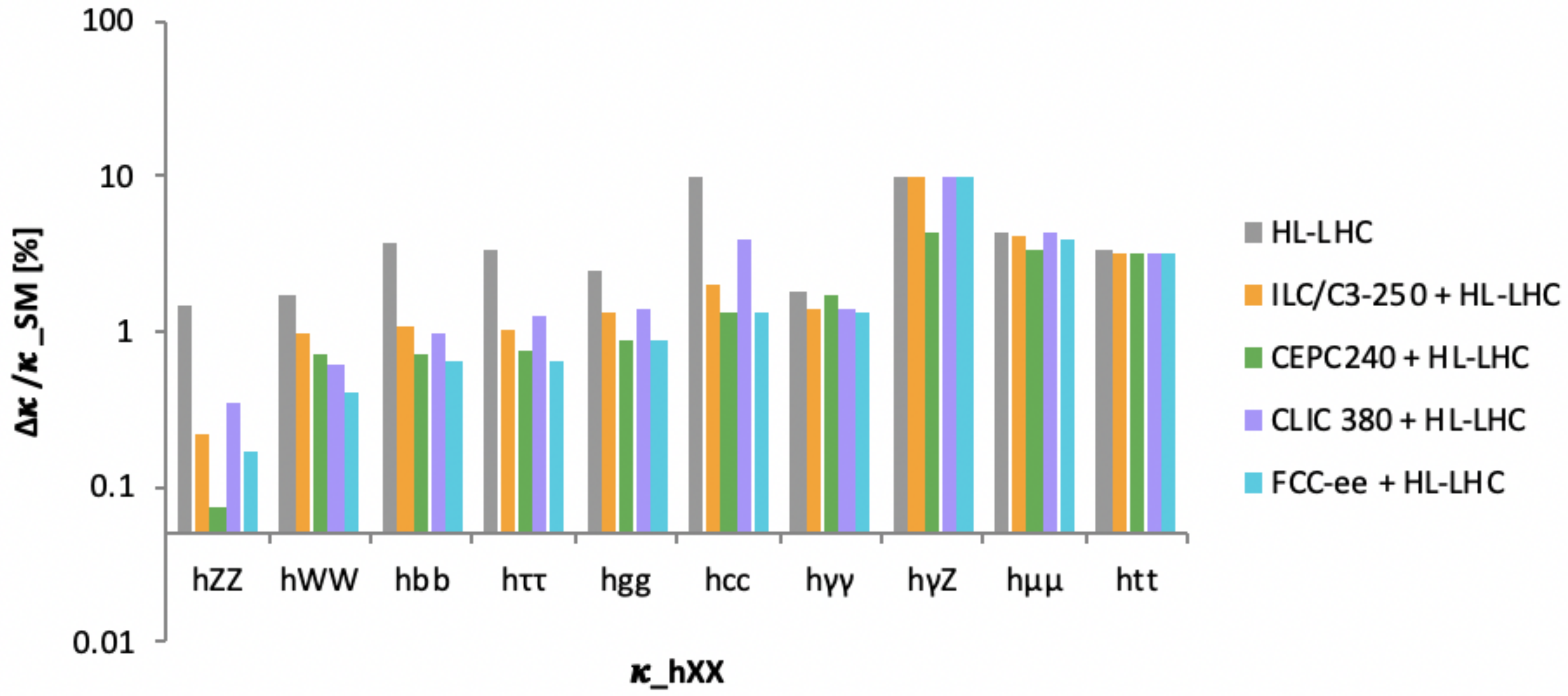


There are certainly many more scenarios to explore here.

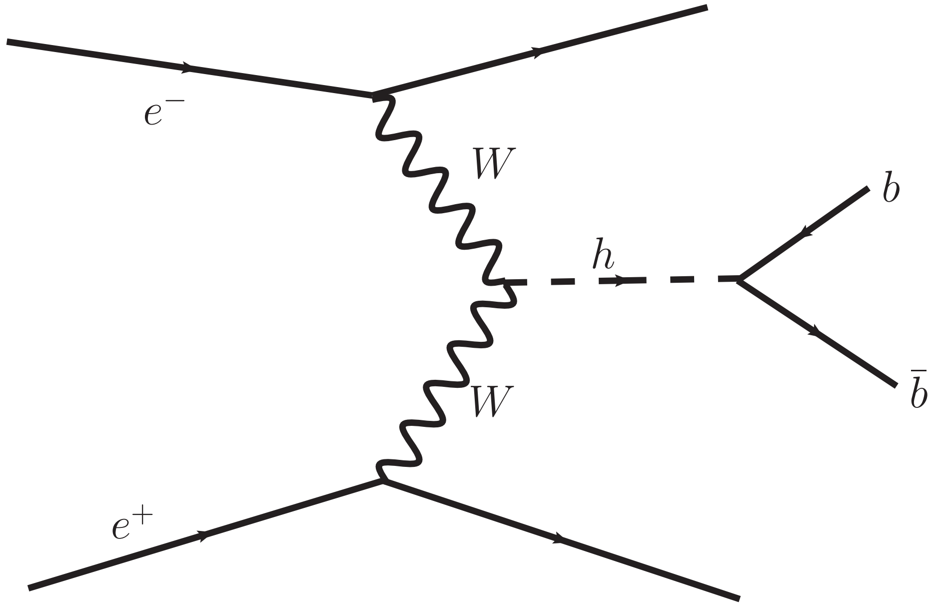
Higgs self-coupling



HL-LHC Higgs measurement

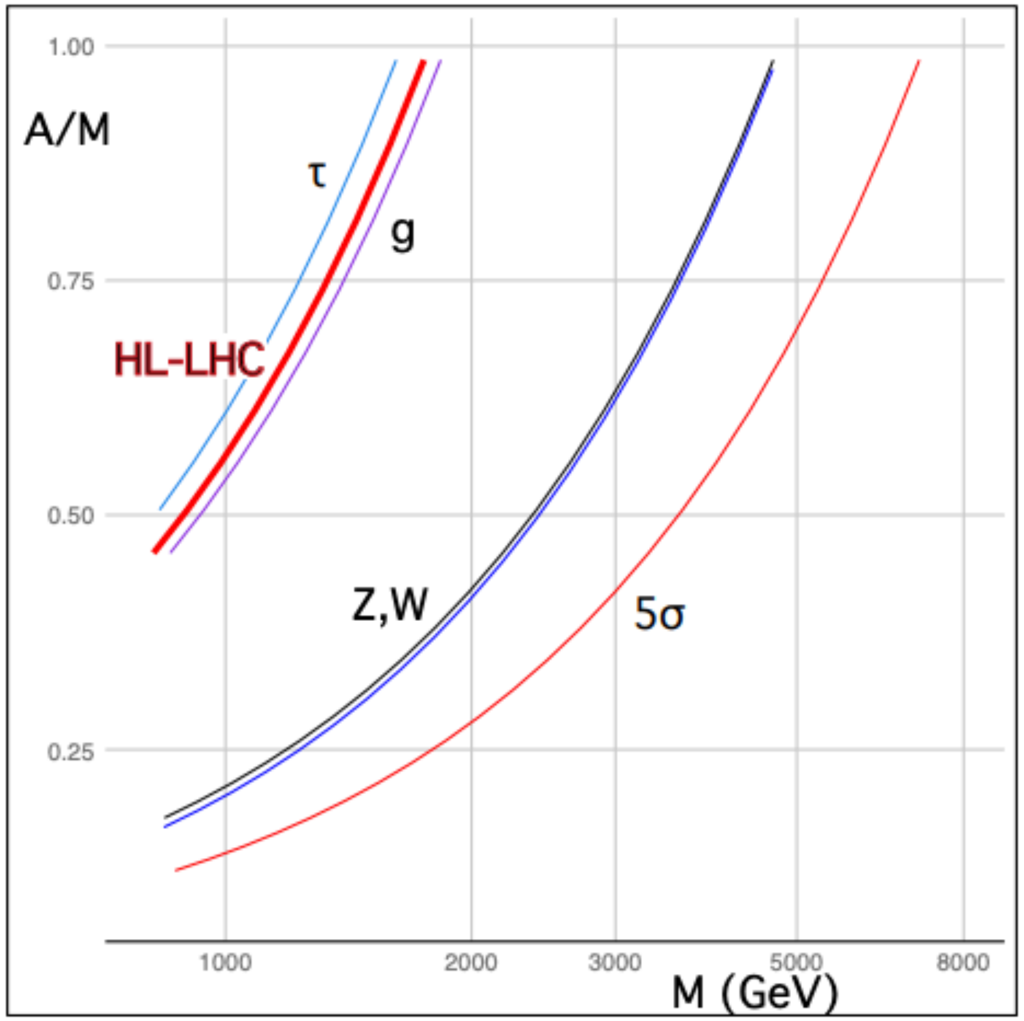


Higgs width from VBF

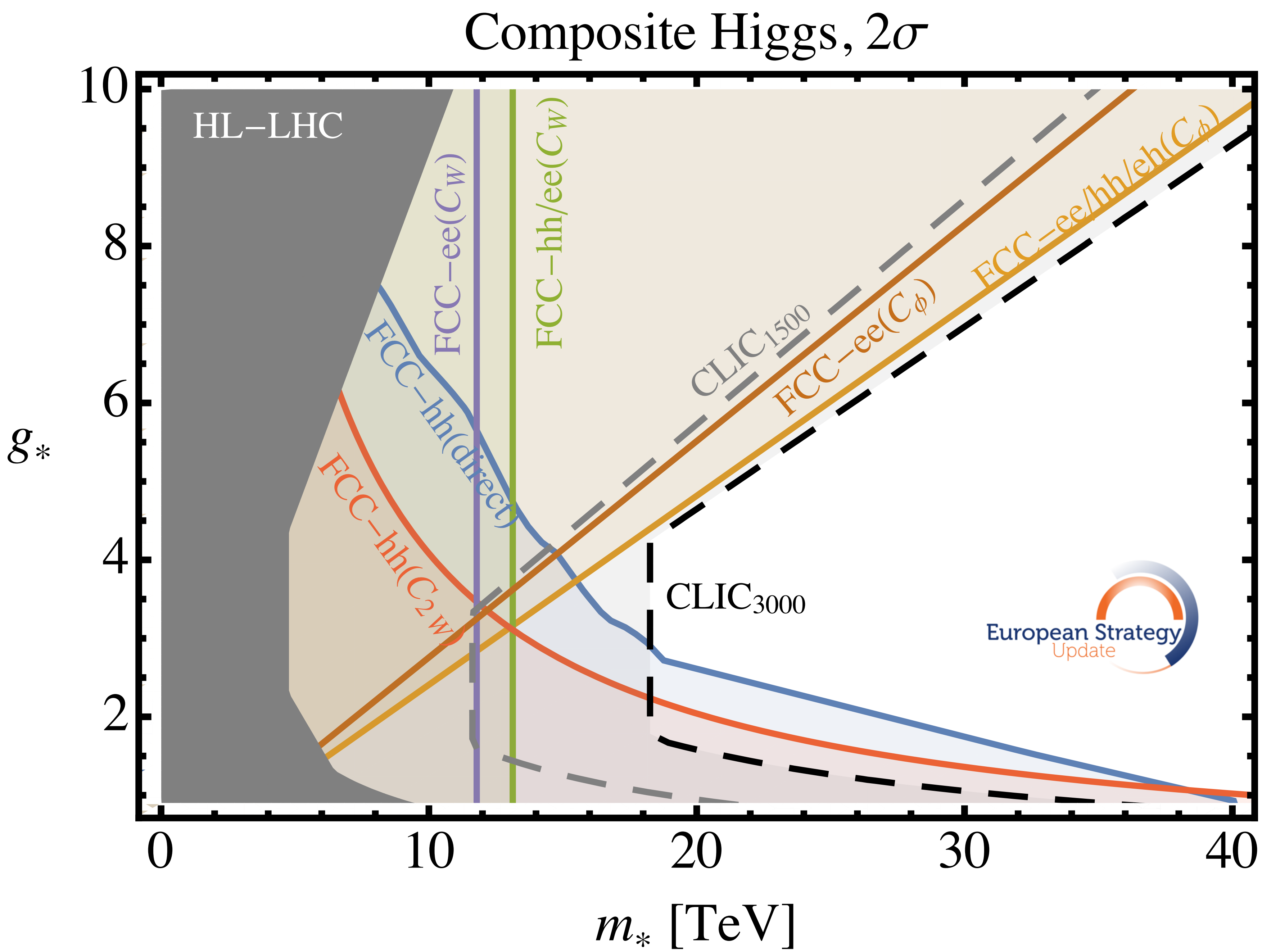


$$\Gamma_H \propto \frac{\Gamma(H \to bb)}{\mathrm{BR}(H \to bb)} \propto \frac{\sigma(\nu\nu H \to \nu\nu bb)}{\mathrm{BR}(H \to bb) \cdot \mathrm{BR}(H \to WW^*)}$$

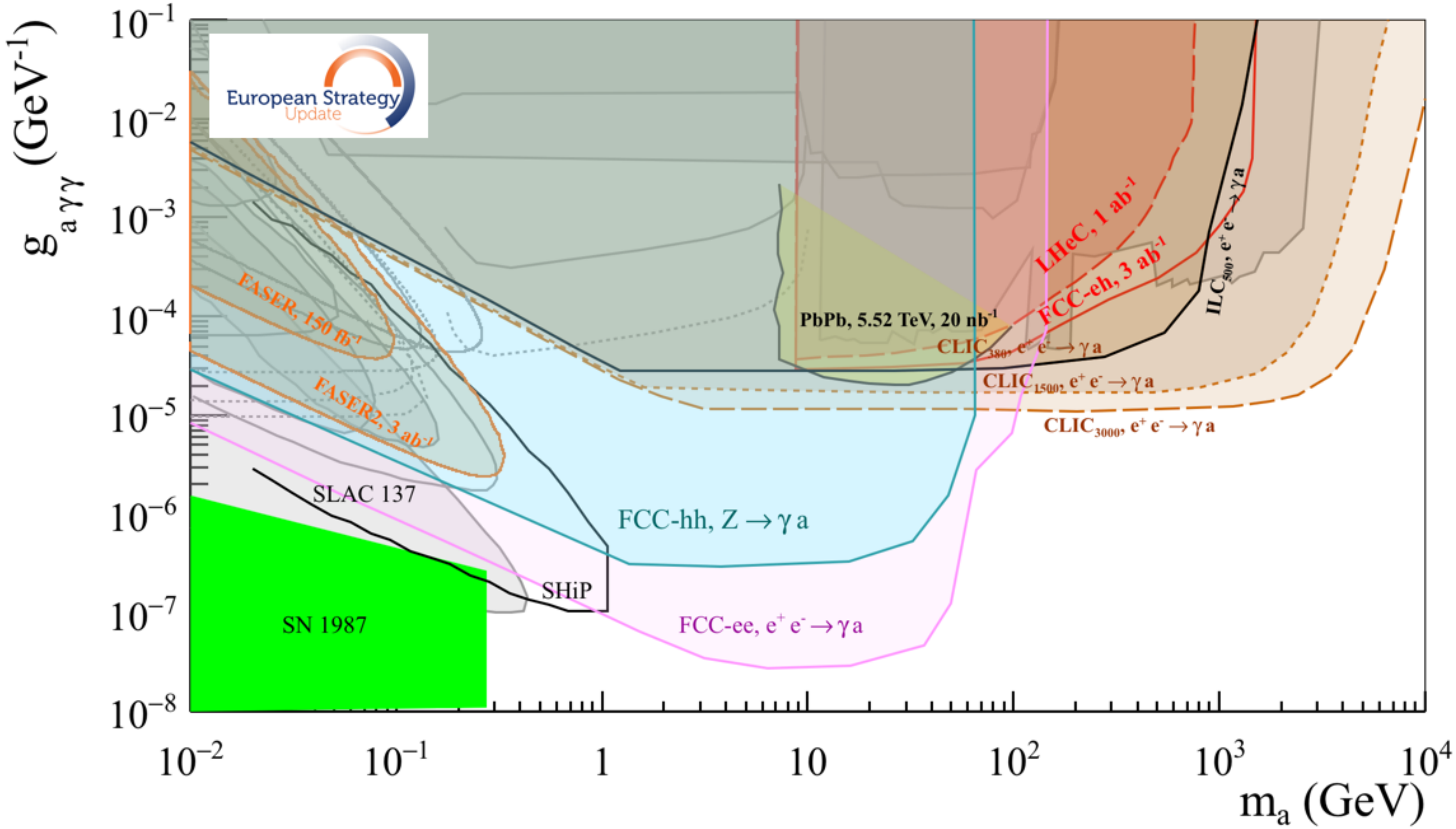
Higgs+singlet



Composite Higgs



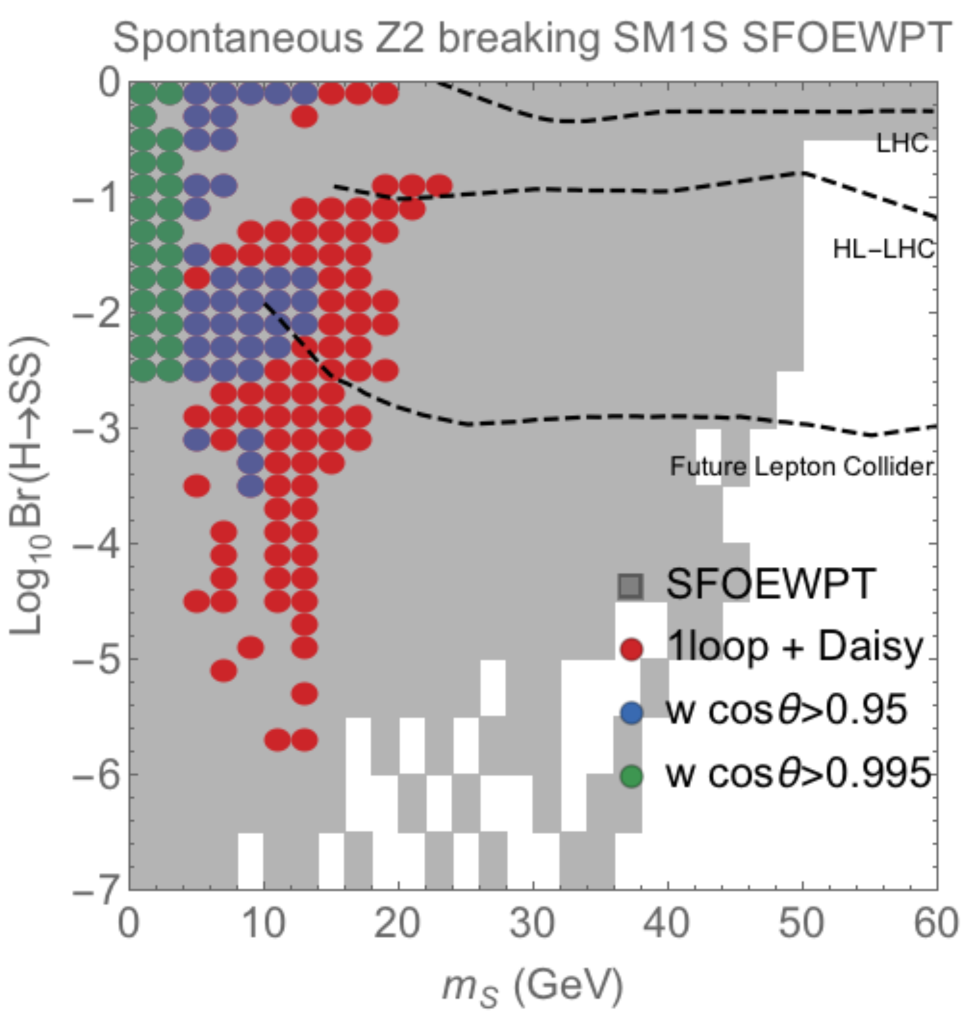
ALP

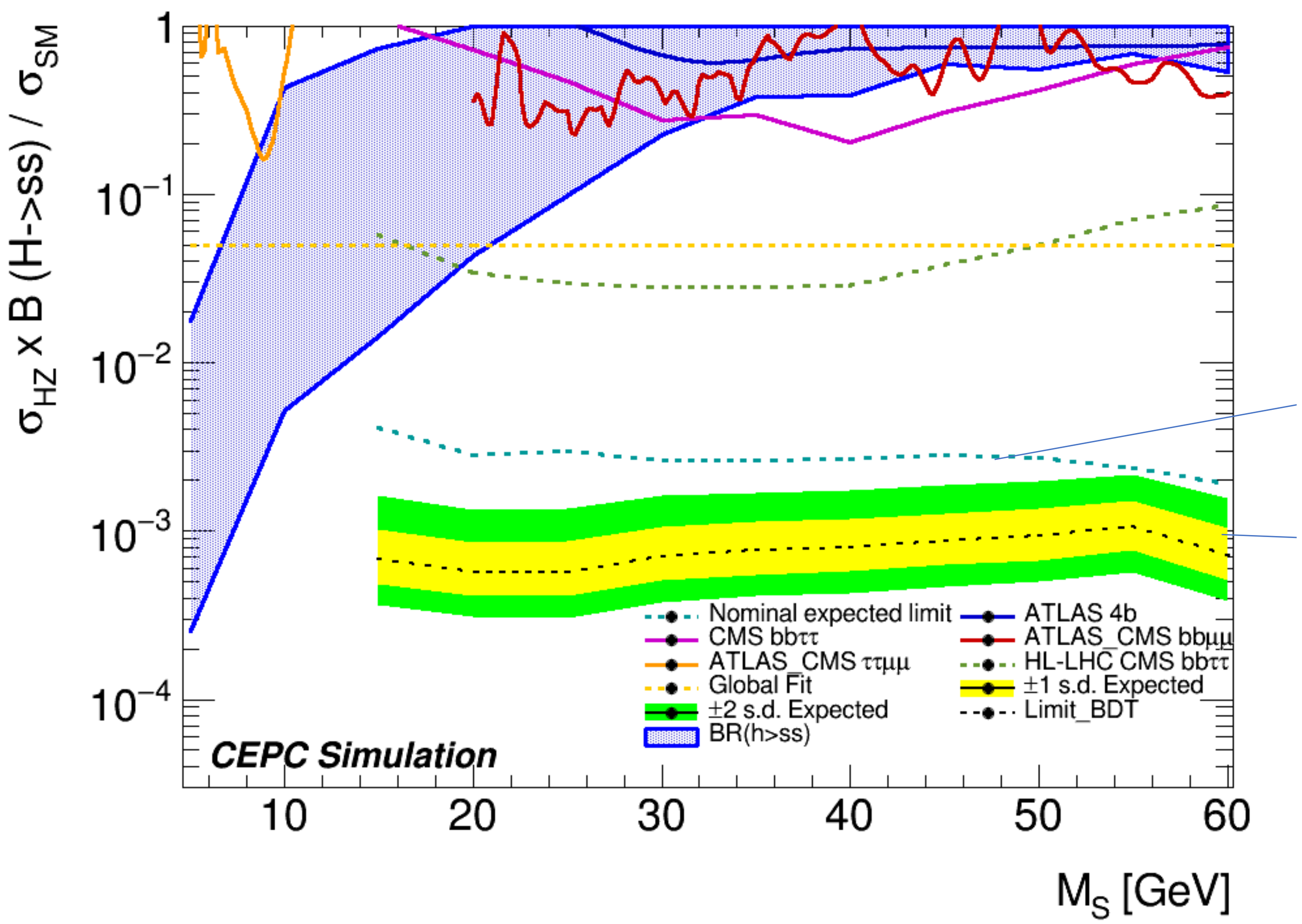


European Strategy Update
PbPb, 5.52 TeV, 20 nb^{-1}
LHeC, 1 ab^{-1}
FCC-eh, 3 ab^{-1}
ILC$_{500}$, $e^+e^- \to \gamma a$
CLIC$_{380}$, $e^+e^- \to \gamma a$
CLIC$_{1500}$, $e^+e^- \to \gamma a$
CLIC$_{3000}$, $e^+e^- \to \gamma a$
FASER, 150 fb^{-1}
FASER2, 3 ab^{-1}
FCC-hh, $Z \to \gamma a$
SLAC 137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

Example: EW phase transition

Singlet extension, h→ss





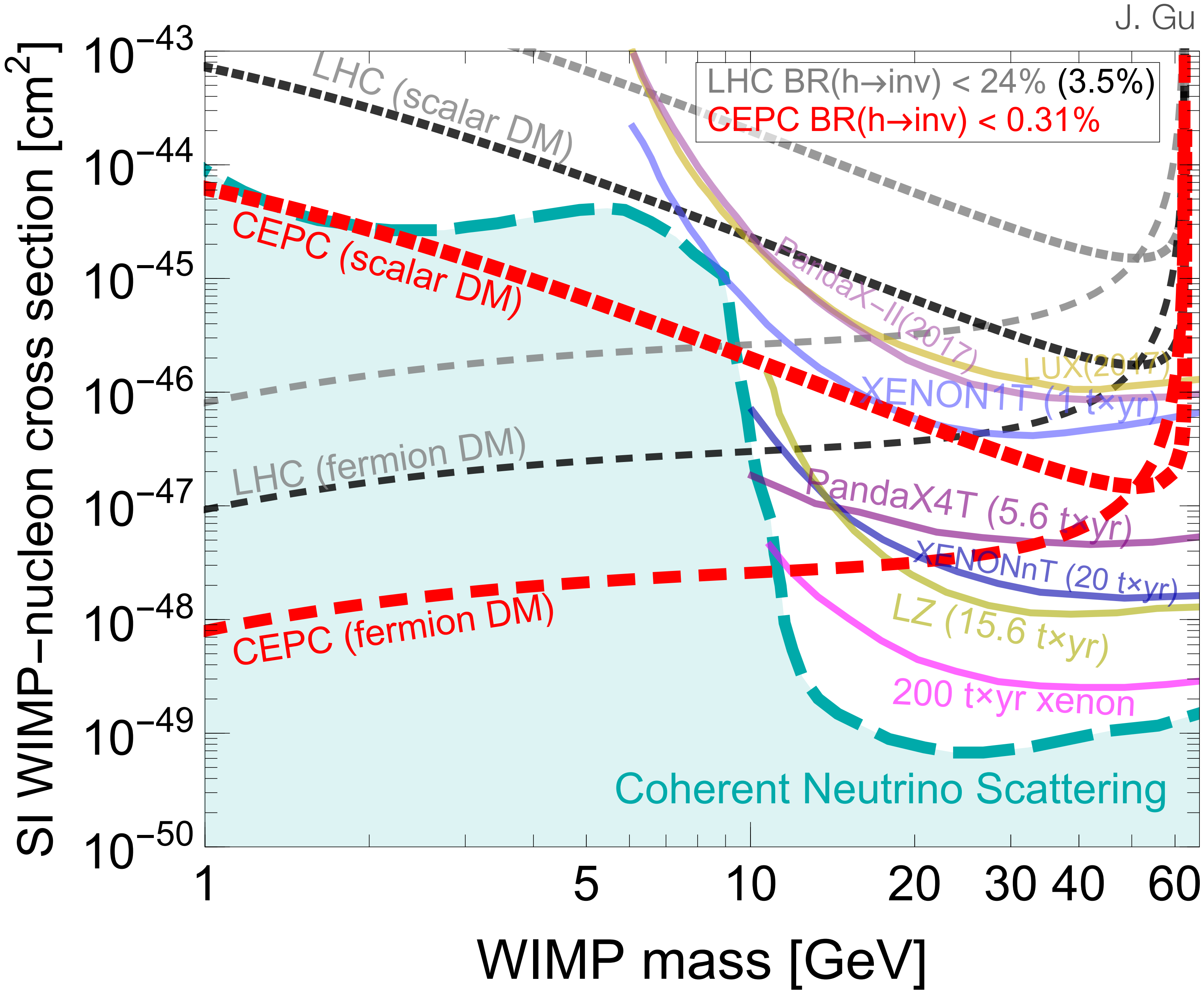
X. Zhu, talk at 2022 CEPC workshop

Carena, Liu, Wang, 1911.10206

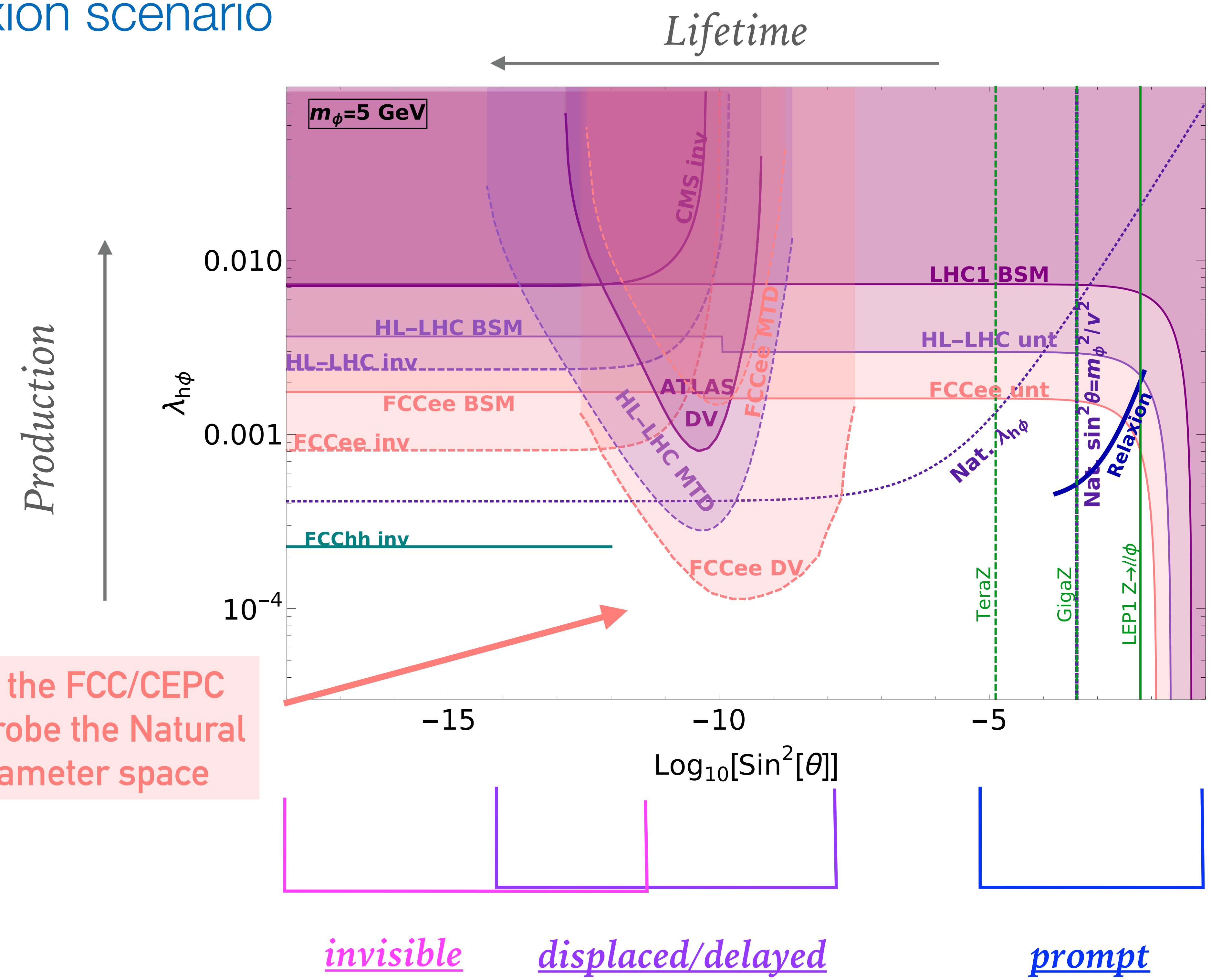
Kozaczuk, Ramsey-Musolf, Shelton, 1911.10210

Higgs portal dark matter

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



Relaxion scenario



Only the FCC/CEPC can probe the Natural parameter space

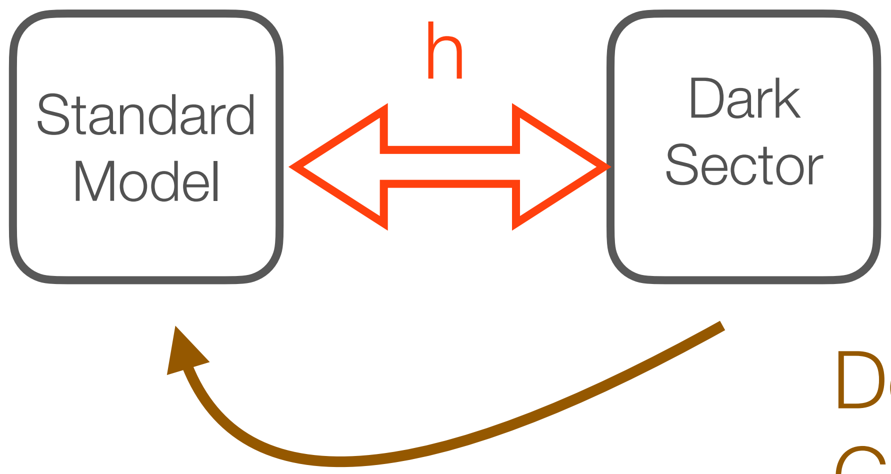
Alipour-Fard, Craig, Jiang, Koren, 1812.05588
Banerjee, Matsedonskyi, Kim, Perez, Safronova, 2004.02899
Fuchs, Matsedonskyi, Savoray and Schlaffer, 2008.12773

Talk by Savoray at CEPC 2021 workshop

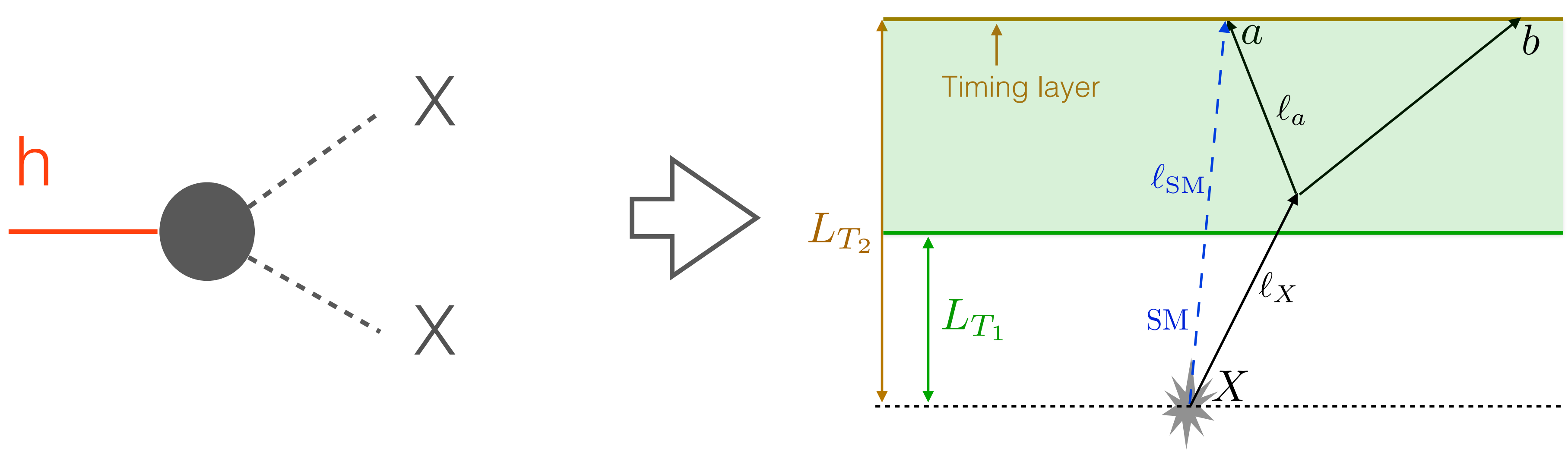
Fermilab


Public Access Areas
Buildings
Parking Lots
Ponds
Public Access Roads
Bicycle Path
Trails
Streams
Accelerator Test Areas
Wilson St. Gate
WILSON ST
Test Beam Facility
Silicon Detector Facility
Site 37
Site 39
Site 50
Site 38
Bison Pasture
Technical Division
Fermilab Village
Users Center
Main Entrance (Open to All Visitors)
Prairie Trails
Dog Training Area
Feynman Computing Center
Illinois Accelerator Research Center
Neutrino Area
Muon Area
Wilson Hall and Ramsey Auditorium (Public Welcome)
Site 55
Nature Area
Tevatron Collider (decommissioned)
Site 56
DZero Assembly Building
Butterfield Rd
No Entrance
© OpenStreetMap (and) contributors, CC-BY-SA

Long lived particle (LLP)

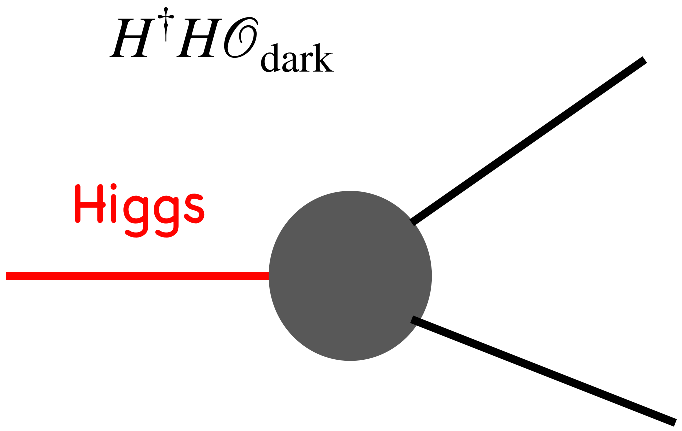


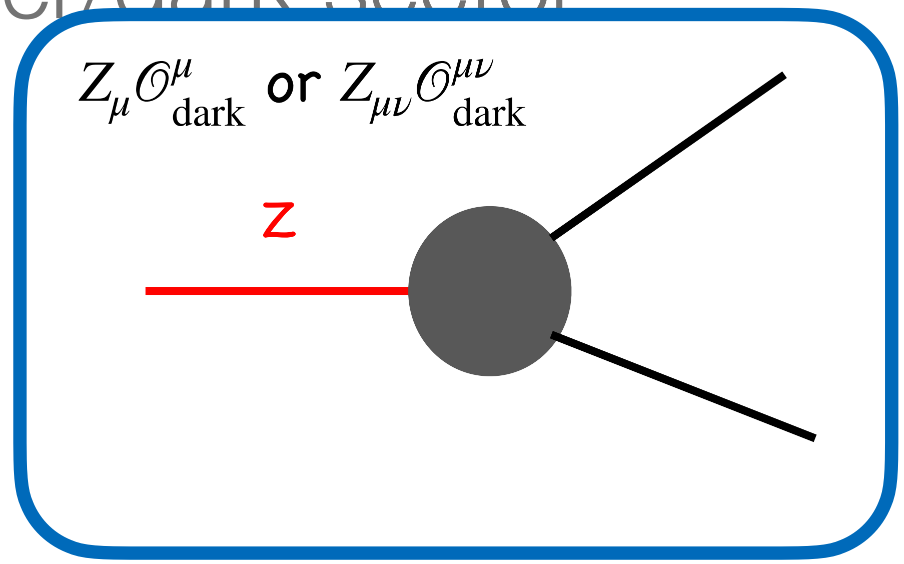
Decay back to SM
Can be long lived.
cτ can be 1 km or more

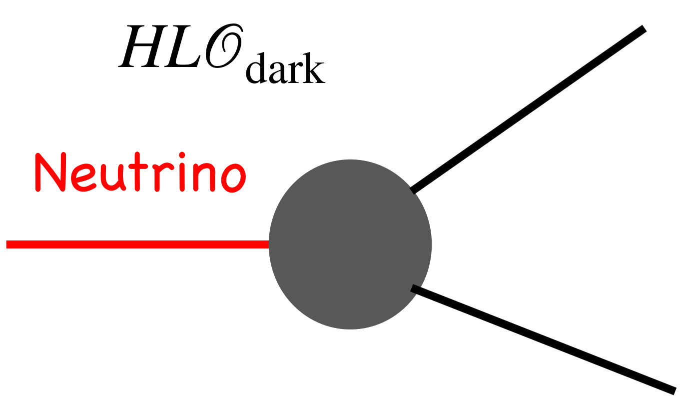


Windows into dark sector: portals

- Any known (SM) particle can in principle have small couplings to dark matter/dark sector



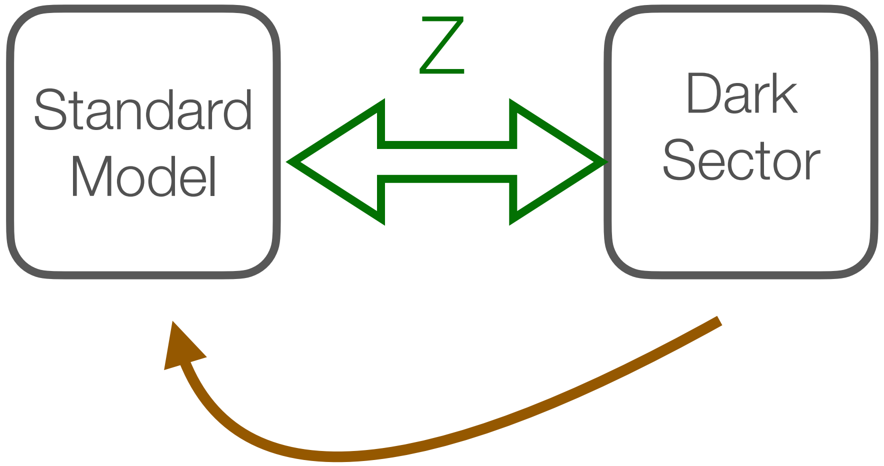




$\mathcal{O}_{\rm dark}$ = SM singlet

Higgs/Z factories, such as CEPC
Neutrino facilities, fixed target experiments…

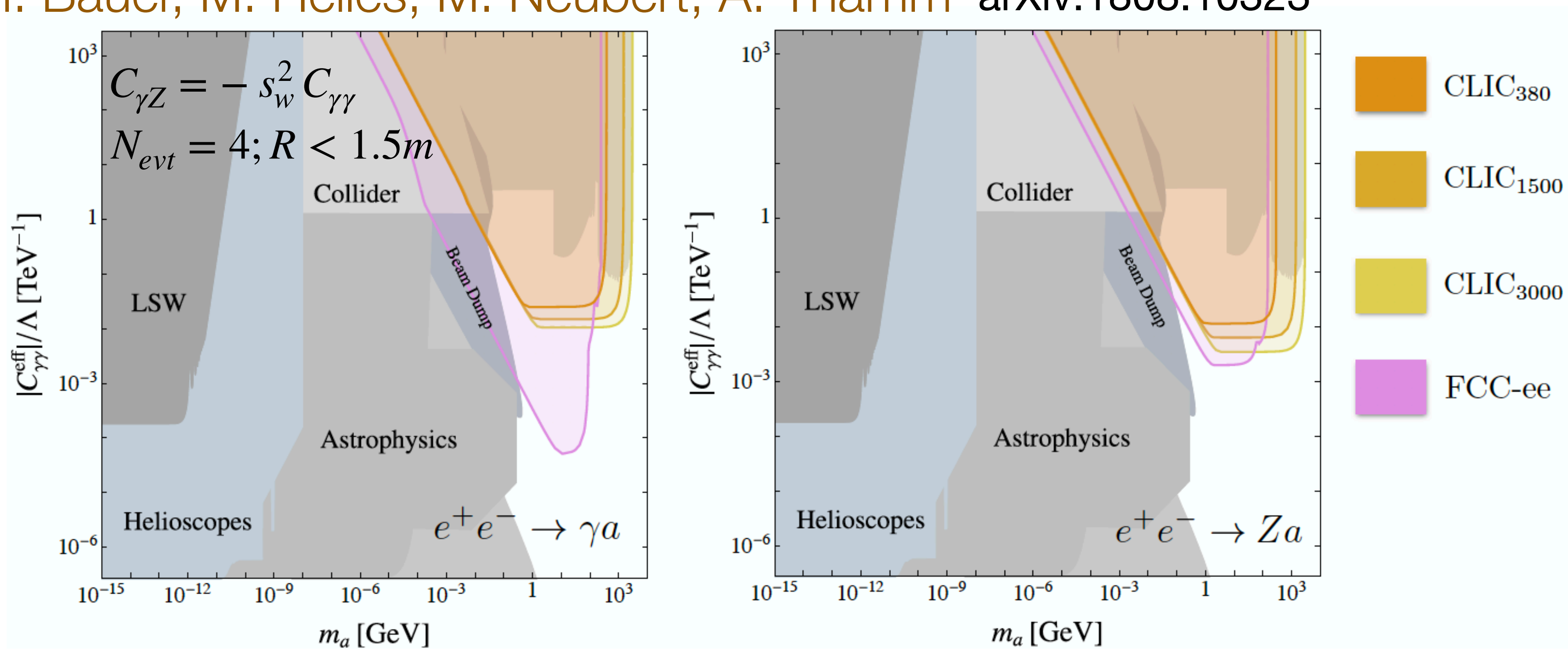
Z decay

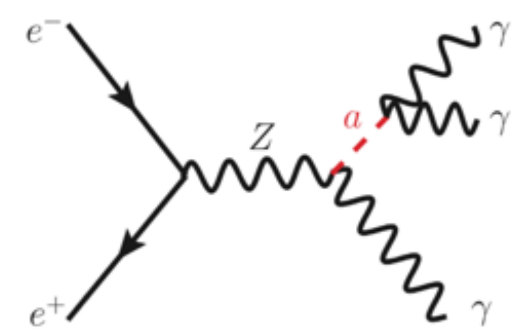


- 10^{12} Zs at the Z factories go a long way in probing the dark sector.

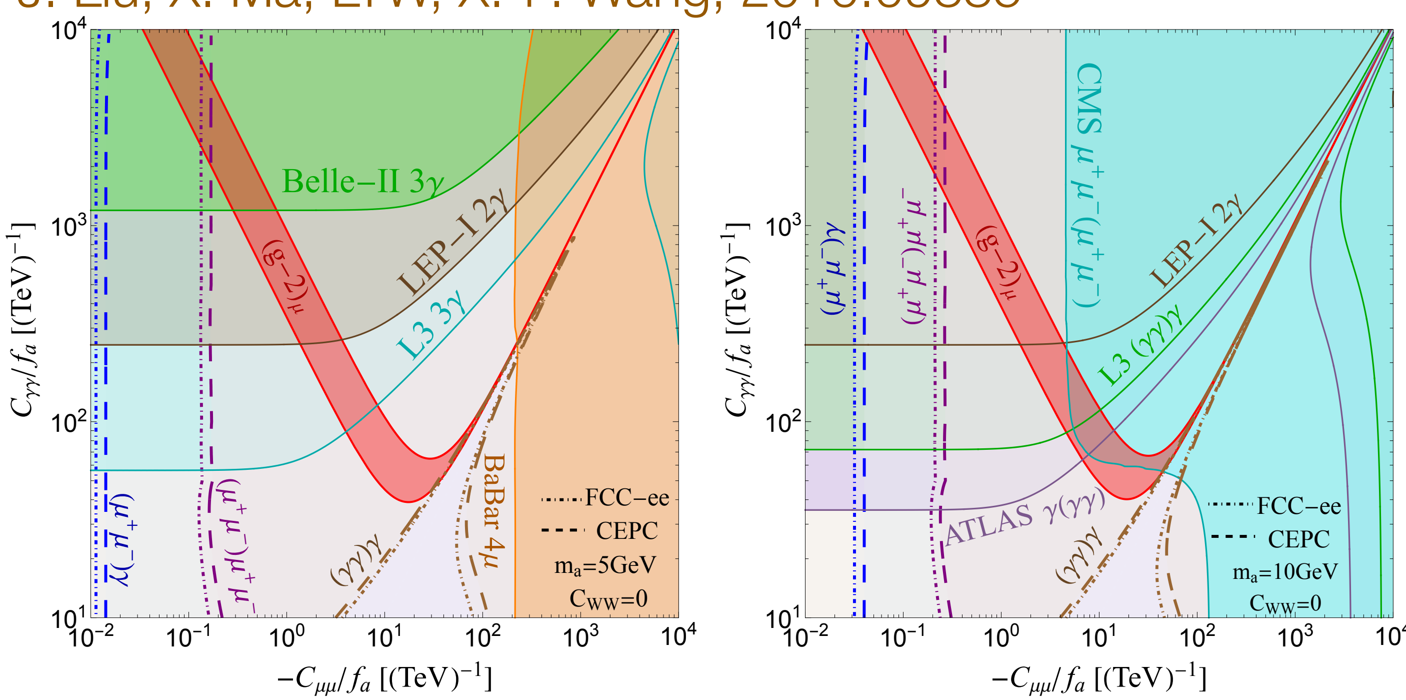
Axion like particles (ALPs)

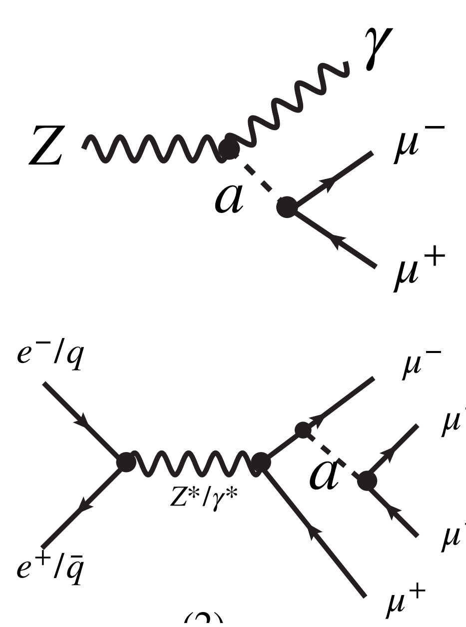
M. Bauer, M. Heiles, M. Neubert, A. Thamm arXiv:1808.10323





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

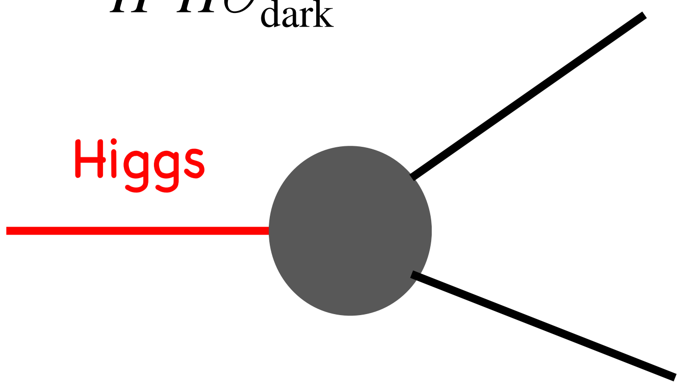




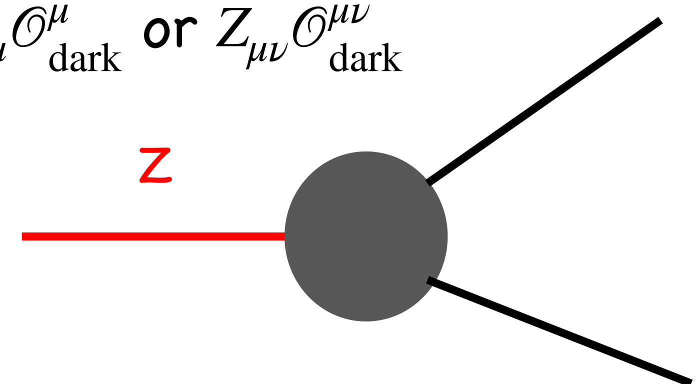
Windows into dark sector: portals

- Any known (SM) particle can in principle have small couplings to dark matter/dark sector.

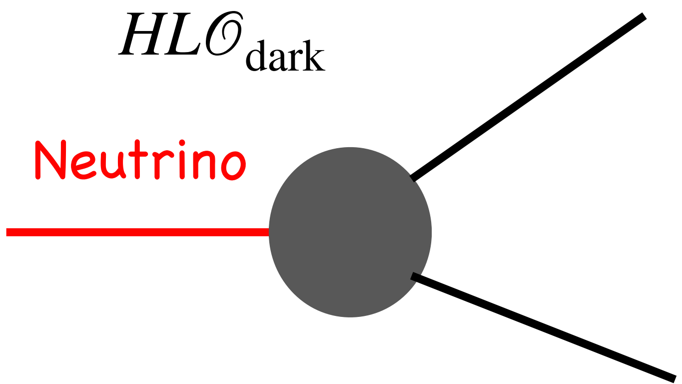
$H^{\dagger}H\mathcal{O}_{\text{dark}}$



$Z_{\mu}\mathcal{O}^{\mu}_{\text{dark}}$ or $Z_{\mu\nu}\mathcal{O}^{\mu\nu}_{\text{dark}}$



$HL\mathcal{O}_{\text{dark}}$



$\mathcal{O}_{\text{dark}}$ = SM singlet

Higgs/Z factories, such as CEPC

Neutrino facilities, fixed target experiments…

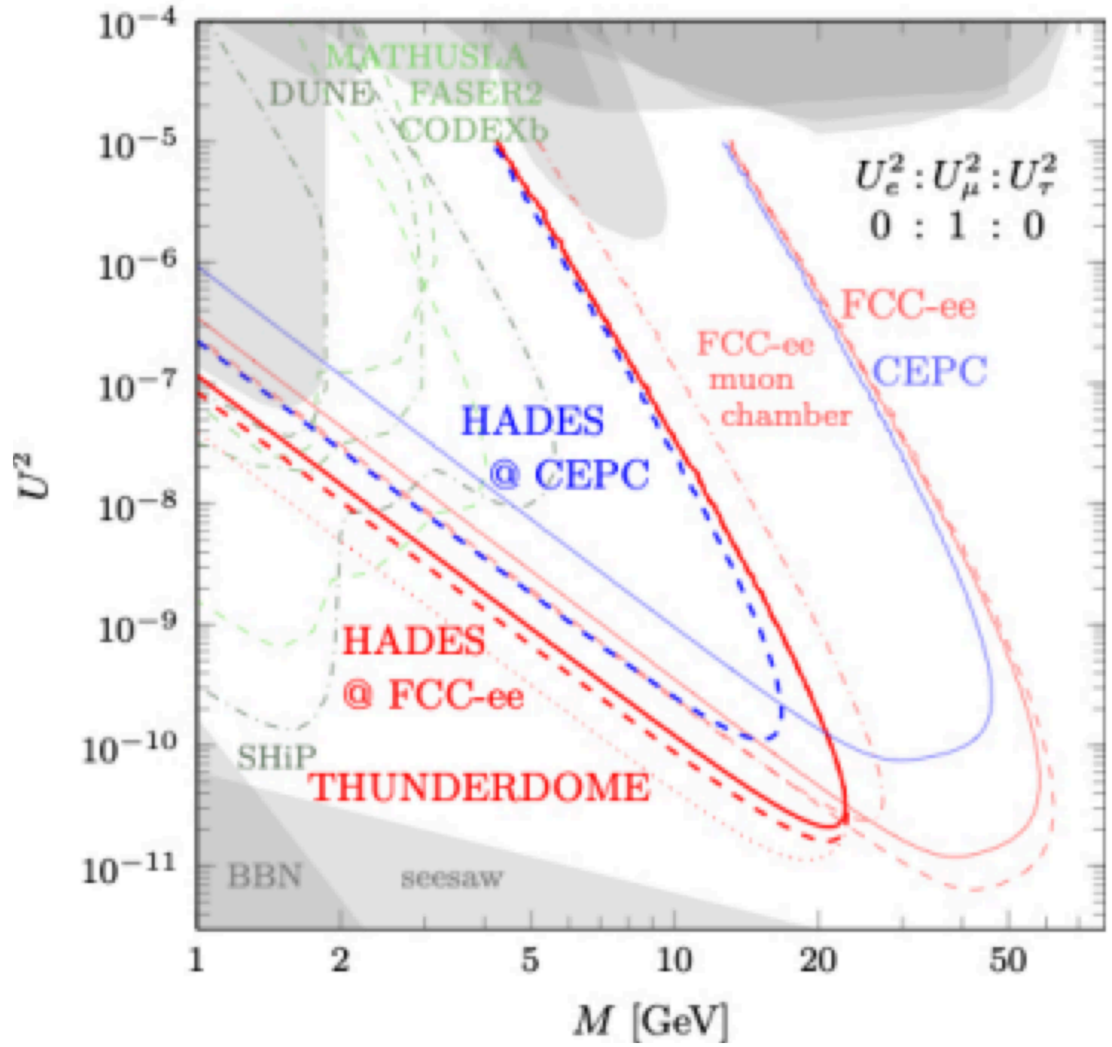
New detectors

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

An example proposal: HADES

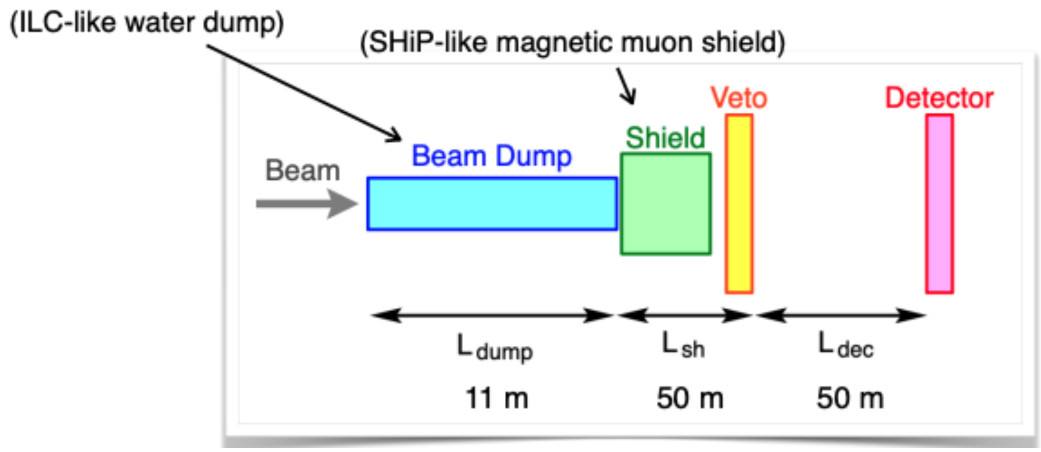
With extra instrumentation of detector cavern walls

2011.01005

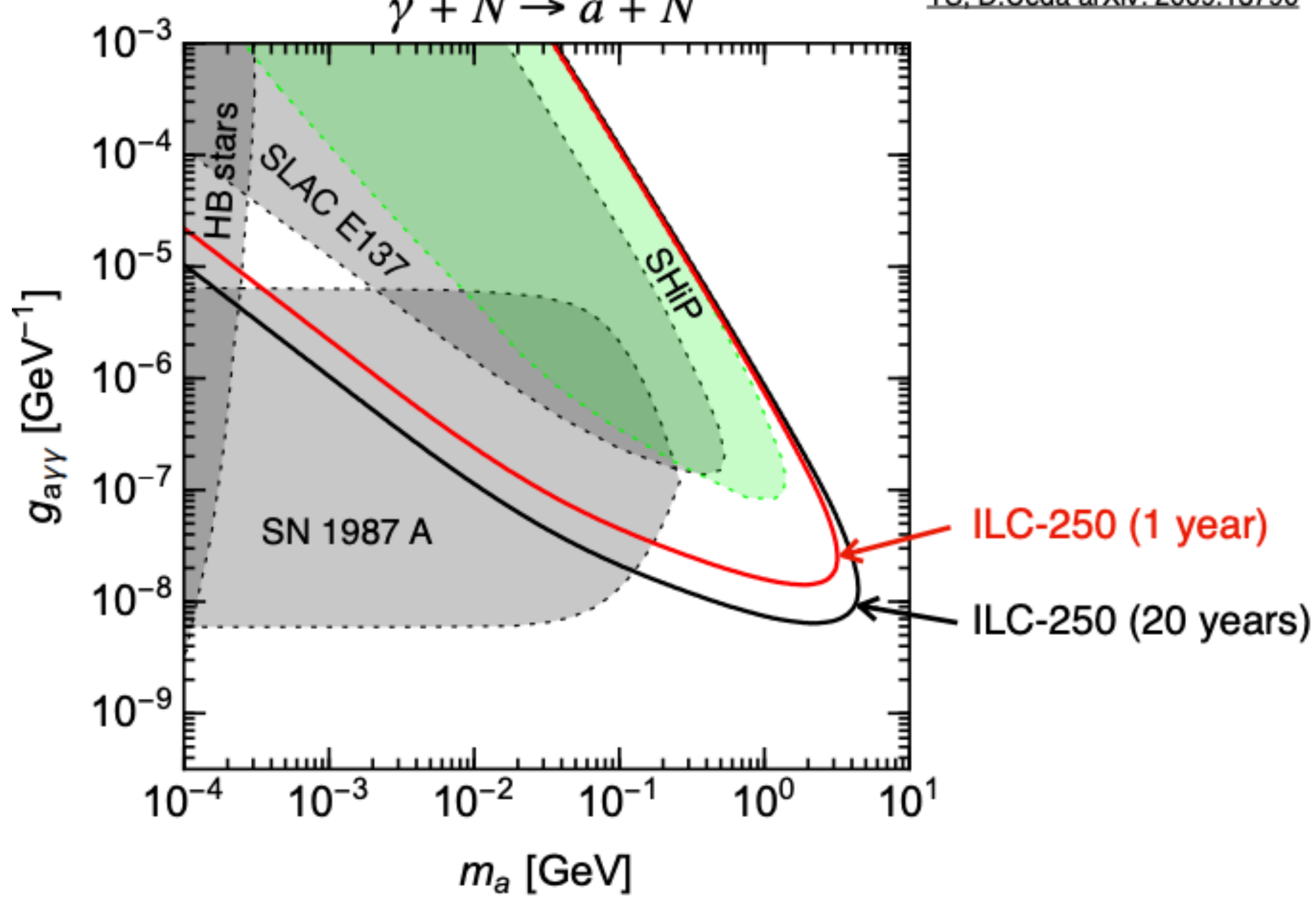


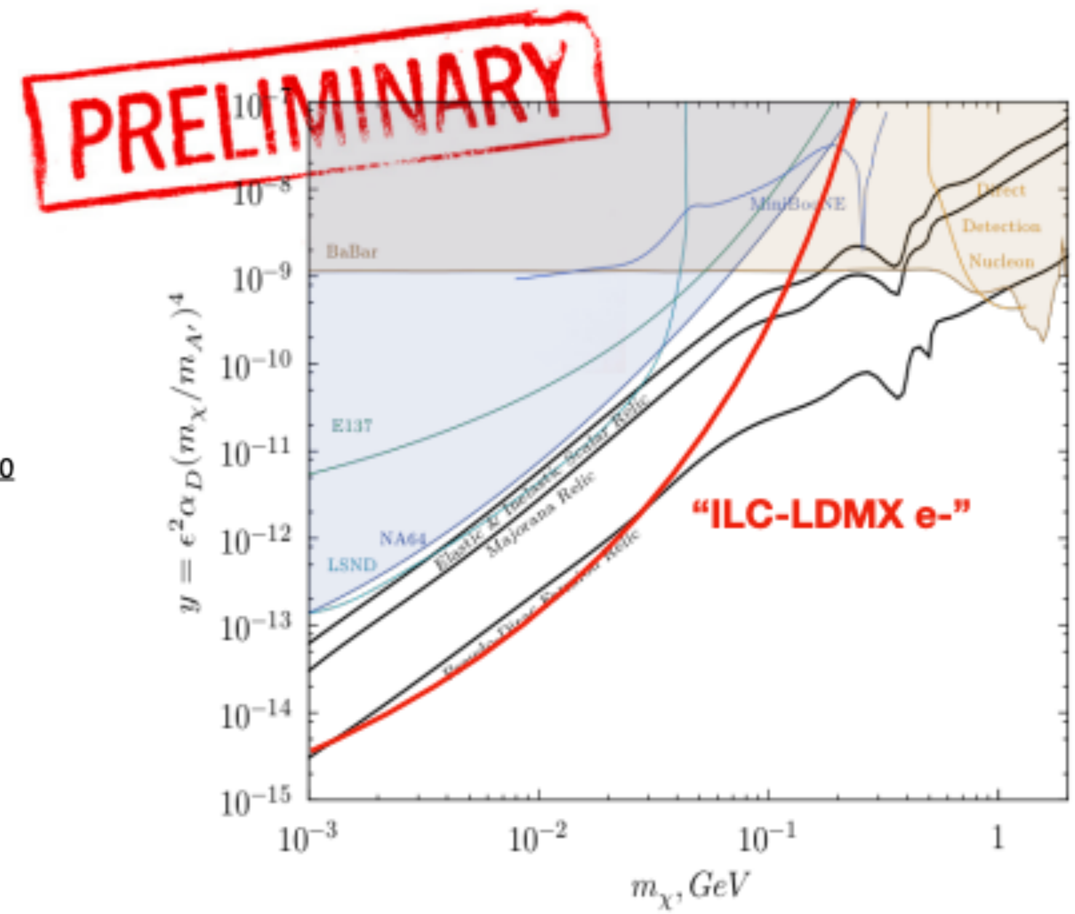
Beam dump?

Kanemura, Moroi, Tanabe, 1507.02809

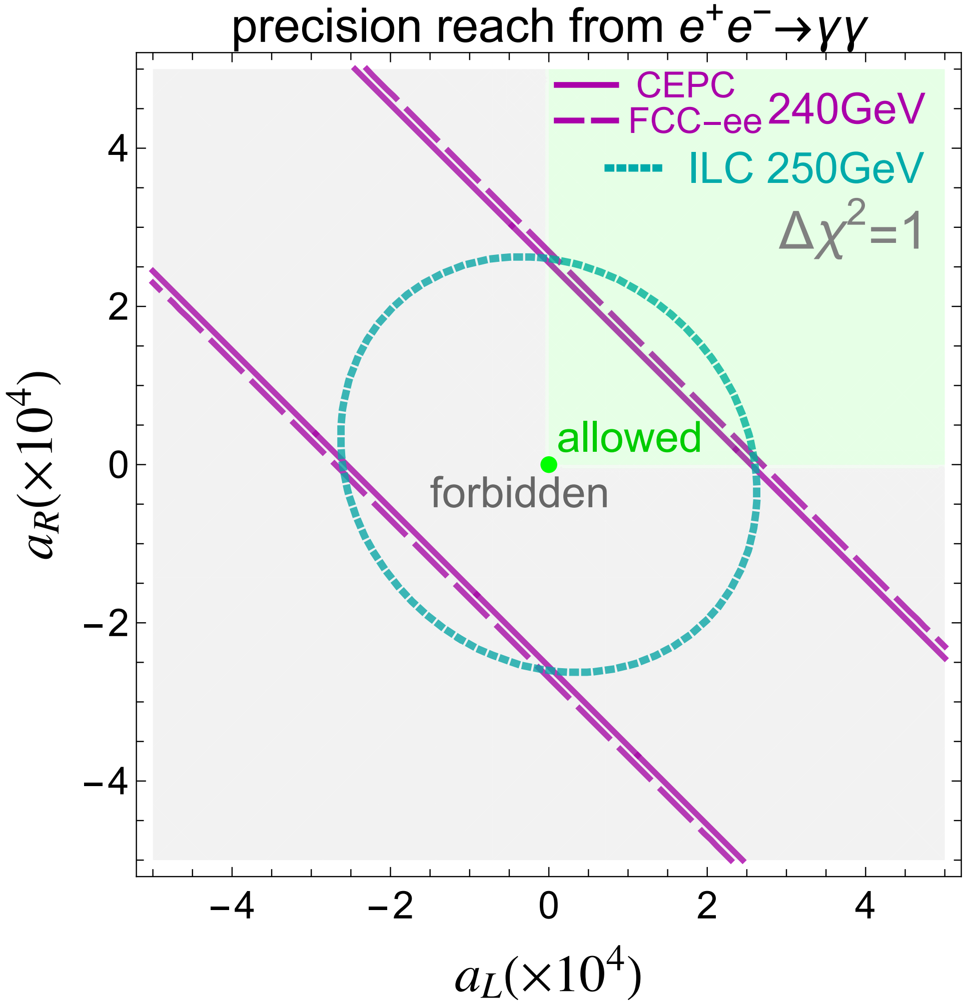


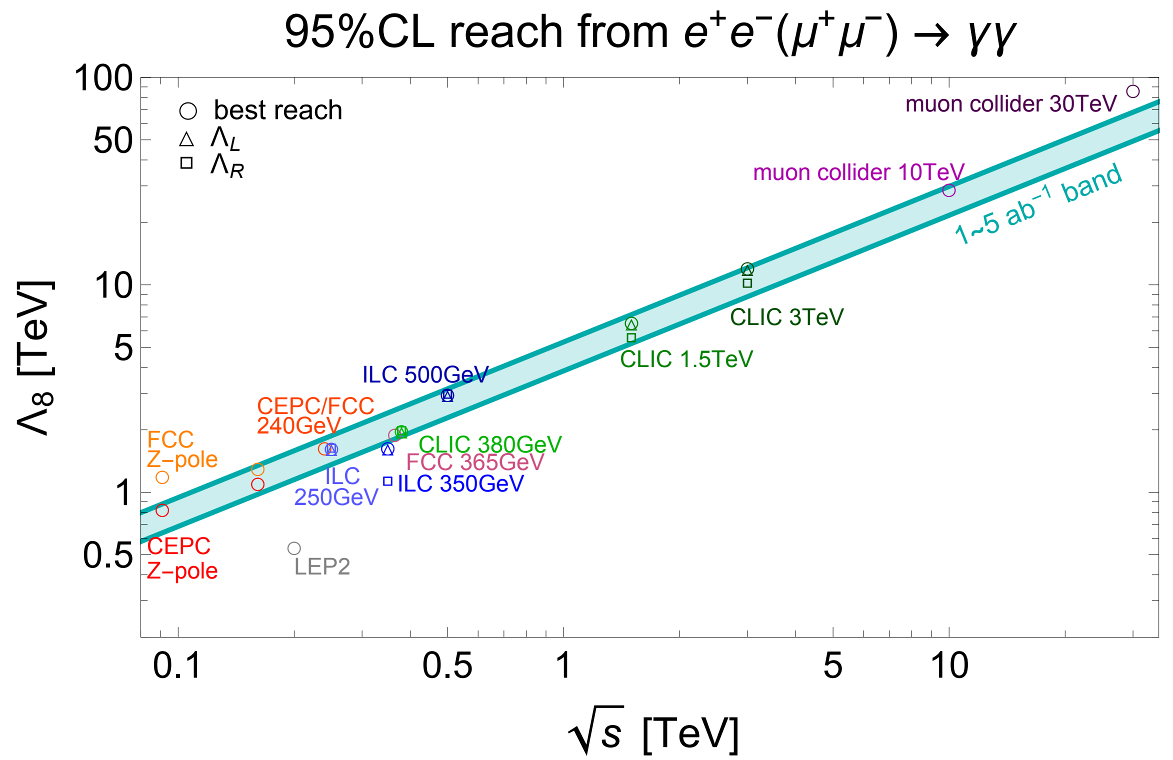
YS, D.Ueda arXiv: 2009.13790





Talk by M. Perelstein at LCWS 2021

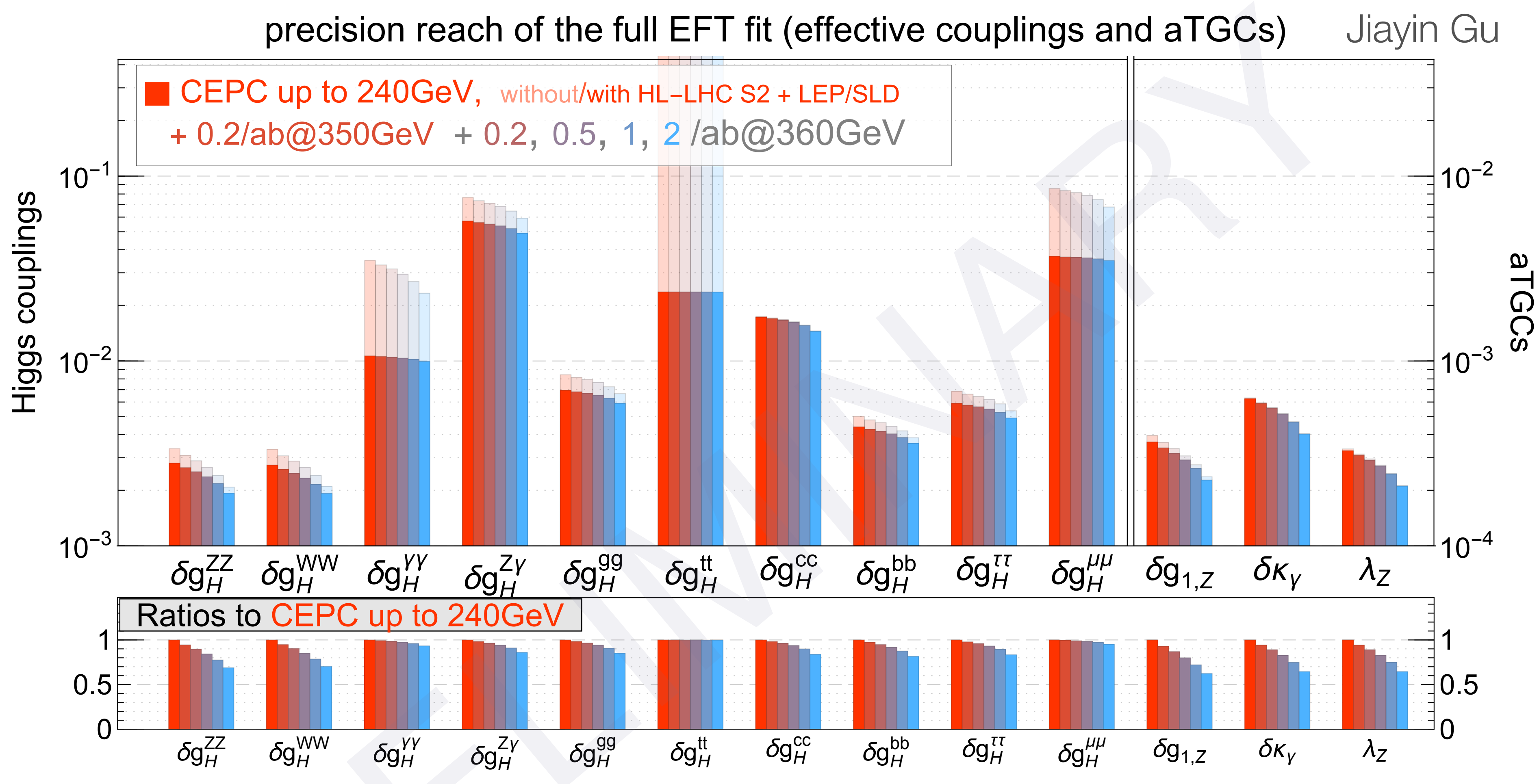




Can be used break degeneracies in the EFT fit.
Could also be an interesting test of the fundamental principles of QFT.

Other sensitive channels, interesting scenarios to test?

Better at higher energies



Gain up to a factor of a few

Even better if one can run at even higher energies.