

Why is FCC-ee interesting

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It's happening

3. The next CERN flagship collider project

- A. The electron–positron Future Circular Collider (FCC-ee) is recommended as the preferred option for the next flagship collider at CERN.*
- B. A descoped FCC-ee is the preferred alternative option for the next flagship collider at CERN.*



Helps to focus the attention!

This talk

- * A brief overview/review of the physics program.

See the Feasibility Study Report for more details.

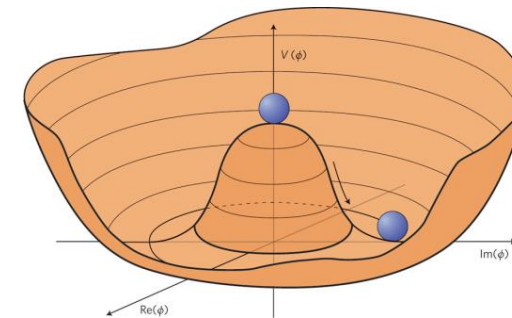
Why focusing on Higgs?

Higgs is simple.

A simple “Mexican hat” potential.

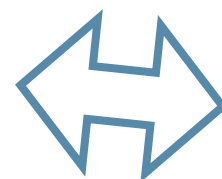
⇒ Electroweak symmetry breaking

⇒ gives masses of SM particles



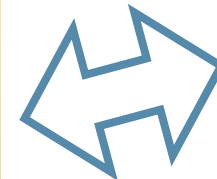
QUARKS

mass charge spin	$\approx 2.2 \text{ MeV}/c^2$ $\frac{2}{3}$ $\frac{1}{2}$ u up	$\approx 1.28 \text{ GeV}/c^2$ $\frac{2}{3}$ $\frac{1}{2}$ c charm	$\approx 173.1 \text{ GeV}/c^2$ $\frac{2}{3}$ $\frac{1}{2}$ t top
	$\approx 4.7 \text{ MeV}/c^2$ $-\frac{1}{3}$ $\frac{1}{2}$ d down	$\approx 96 \text{ MeV}/c^2$ $-\frac{1}{3}$ $\frac{1}{2}$ s strange	$\approx 4.18 \text{ GeV}/c^2$ $-\frac{1}{3}$ $\frac{1}{2}$ b bottom



Spin-0

$\approx 124.97 \text{ GeV}/c^2$ 0 0 H higgs

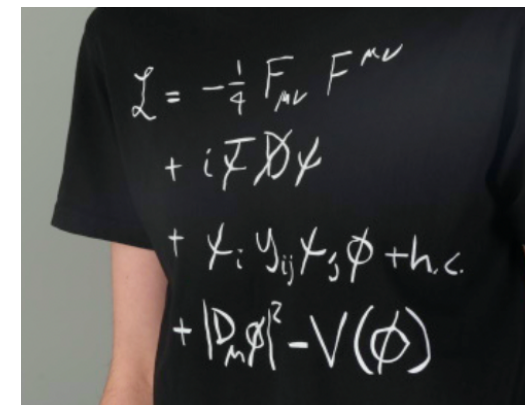


$\approx 91.19 \text{ GeV}/c^2$ 0 1 Z Z boson
$\approx 80.360 \text{ GeV}/c^2$ ± 1 1 W W boson

GAUGE BOSONS
VECTOR BOSONS

LEPTONS

$\approx 0.511 \text{ MeV}/c^2$ -1 $\frac{1}{2}$ e electron	$\approx 105.66 \text{ MeV}/c^2$ -1 $\frac{1}{2}$ μ muon	$\approx 1.7768 \text{ GeV}/c^2$ -1 $\frac{1}{2}$ τ tau
$< 1.0 \text{ eV}/c^2$ 0 $\frac{1}{2}$ ν_e electron neutrino	$< 0.17 \text{ MeV}/c^2$ 0 $\frac{1}{2}$ ν_μ muon neutrino	$< 18.2 \text{ MeV}/c^2$ 0 $\frac{1}{2}$ ν_τ tau neutrino



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)

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Different from other SM particles:

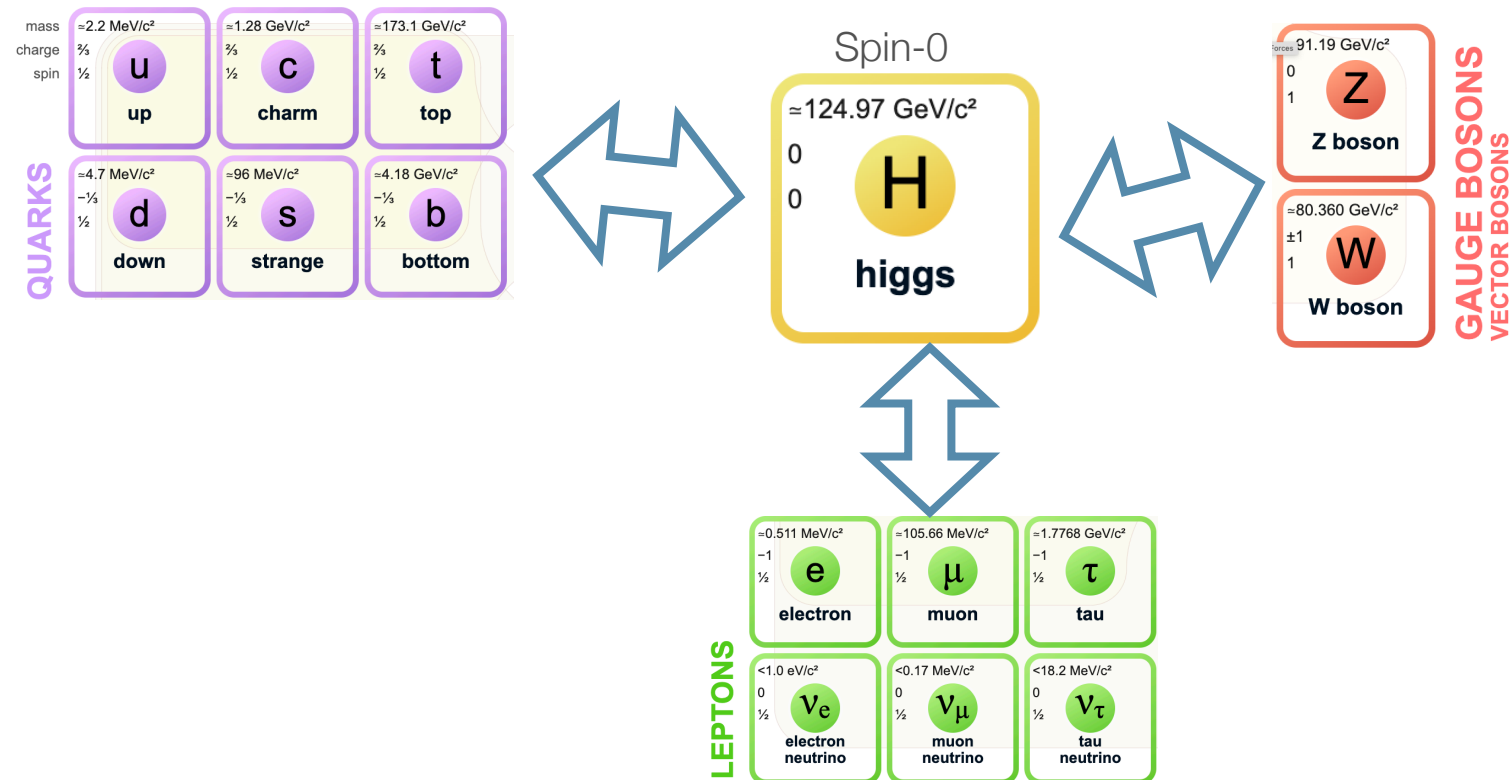
gauge boson (gauge symmetry), fermion (chiral symmetry)

Maybe not as simple as it seems?

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

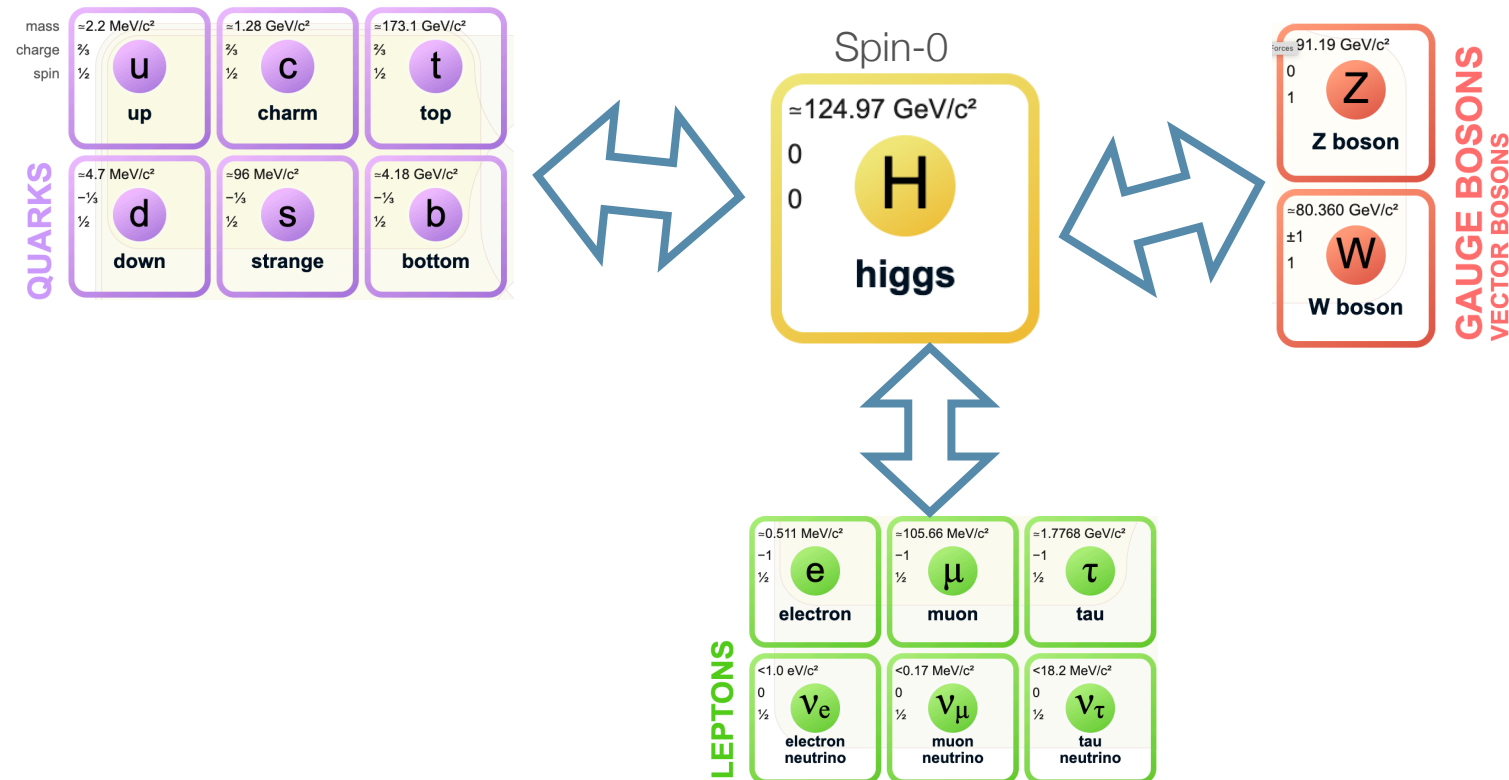
Is the Higgs the only spin-0 particle, or there are similar ones?

What sets the masses?



Higgs mechanism sets the masses of the SM particles

What sets the masses?



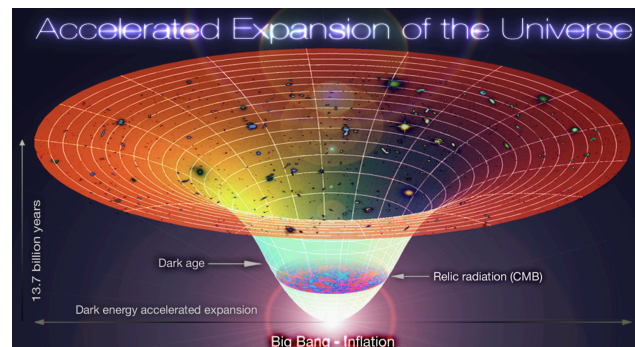
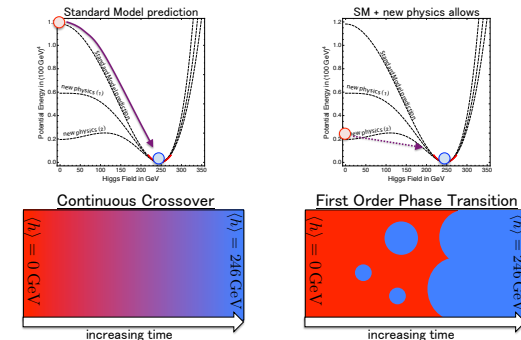
Higgs mechanism sets the masses of the SM particles

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

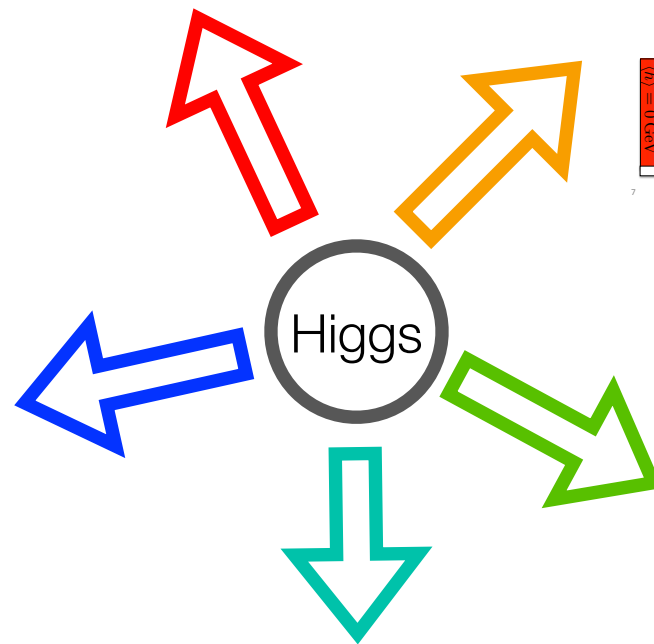
Higgs and everything else

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

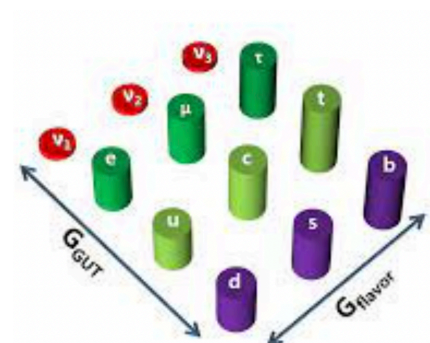
Matter > anti-matter
Electroweak phase



Inflation, age of
universe, ...



The dark world

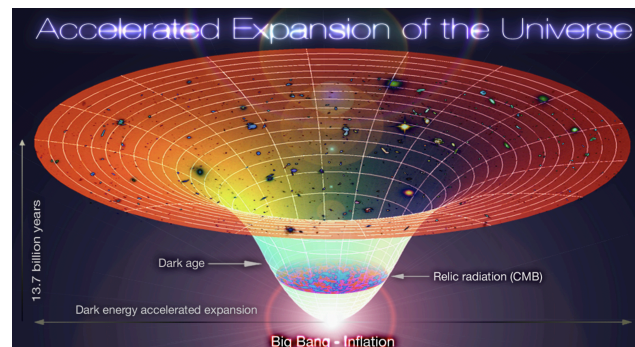
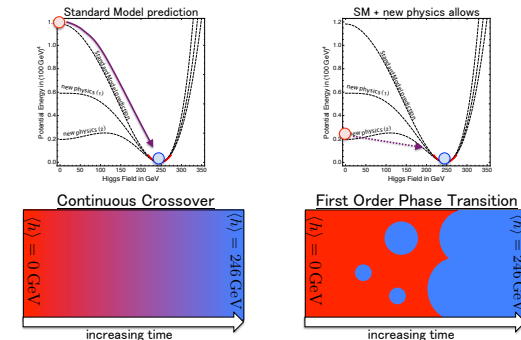


Flavor puzzle

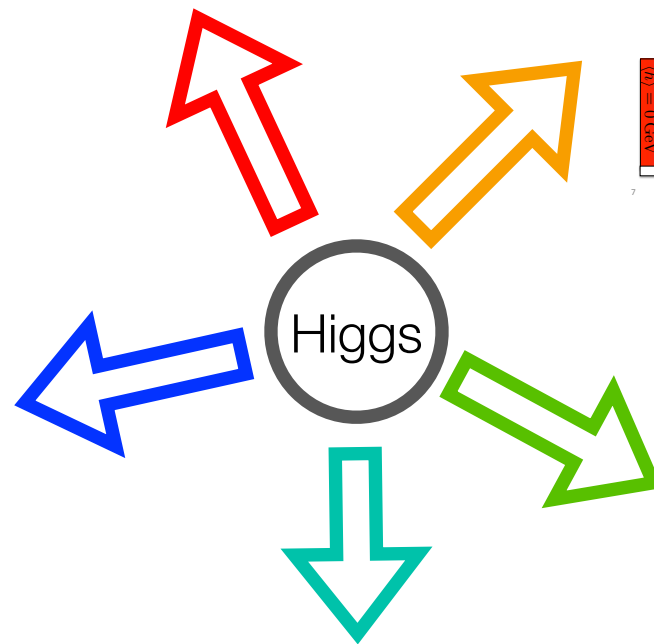
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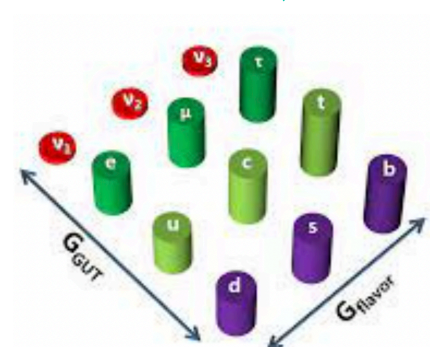
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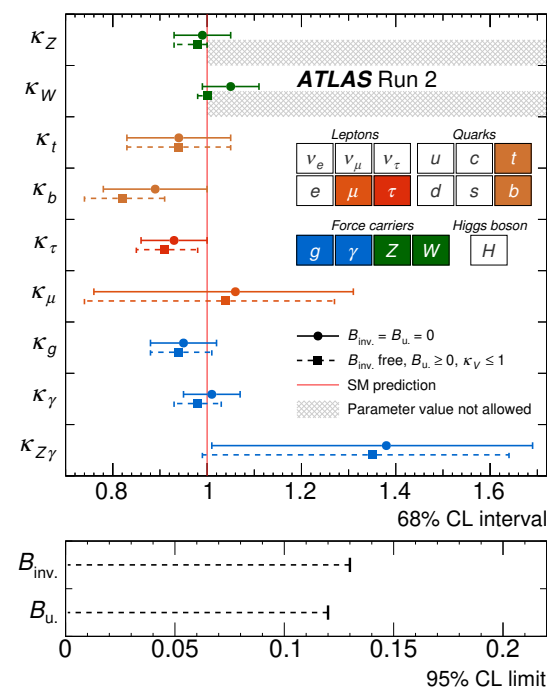
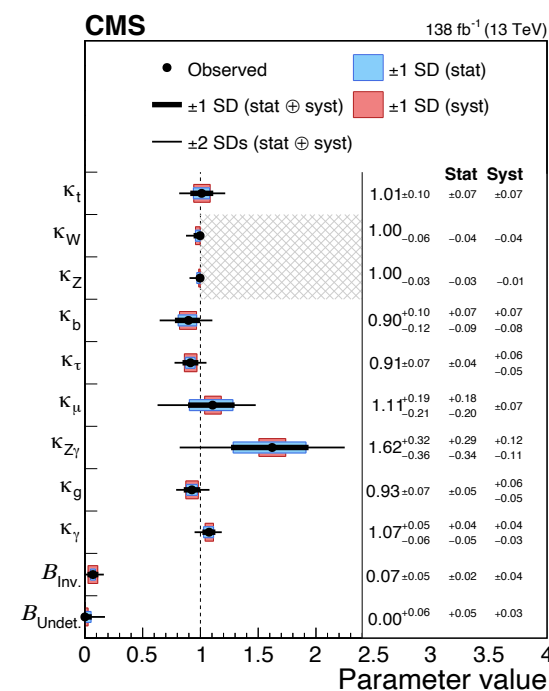


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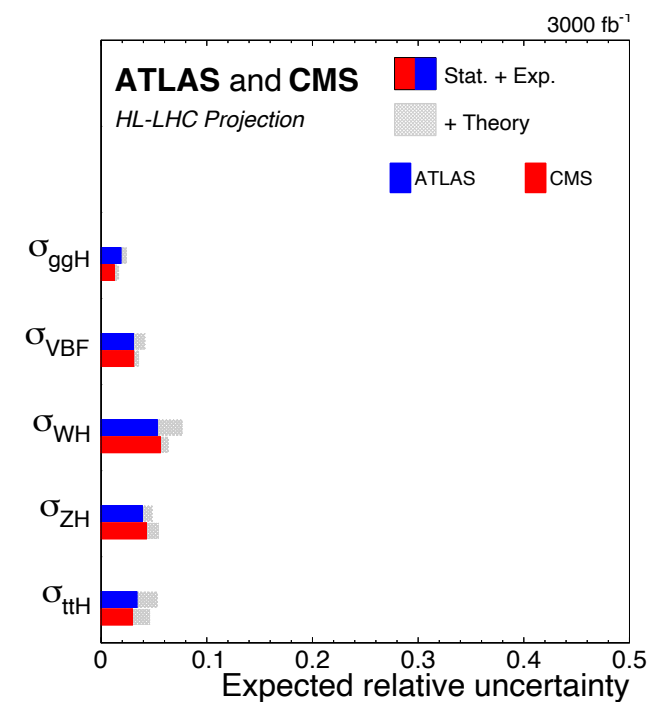
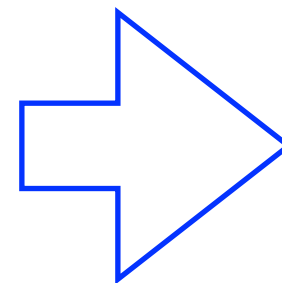
Higgs is likely to play a role in many of these, but **how**?

What do we know?

Higgs coupling other SM particles:



Eventually at the LHC



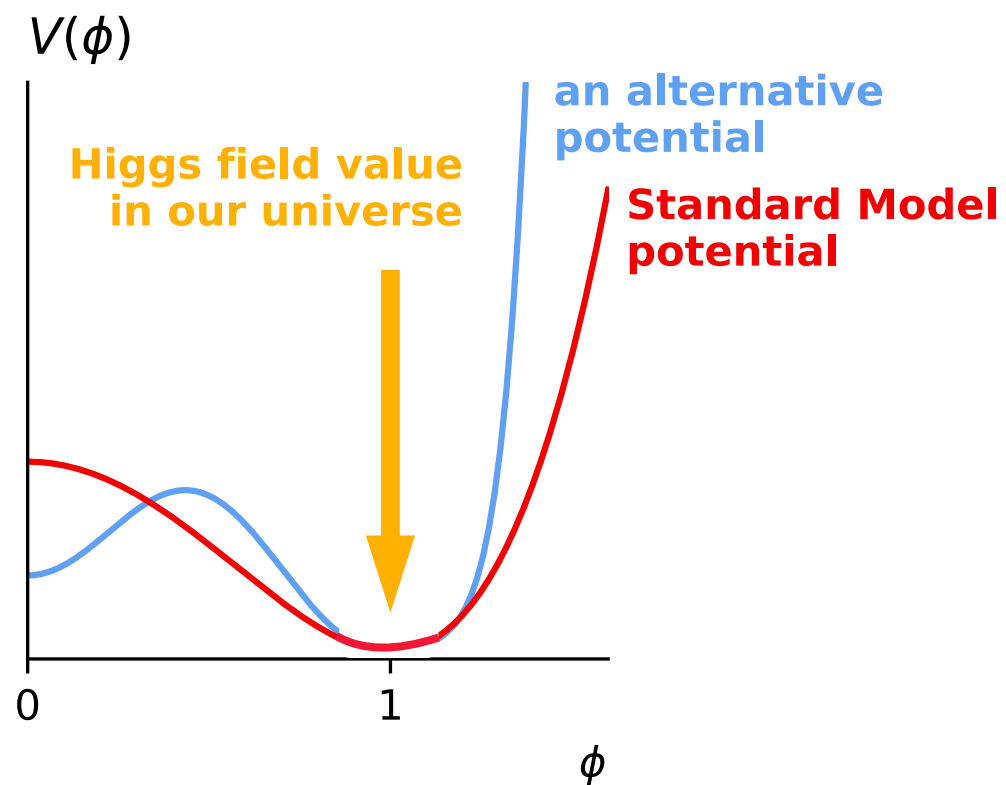
Higgs couplings. Presently, known to about 10%

1- a few %

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

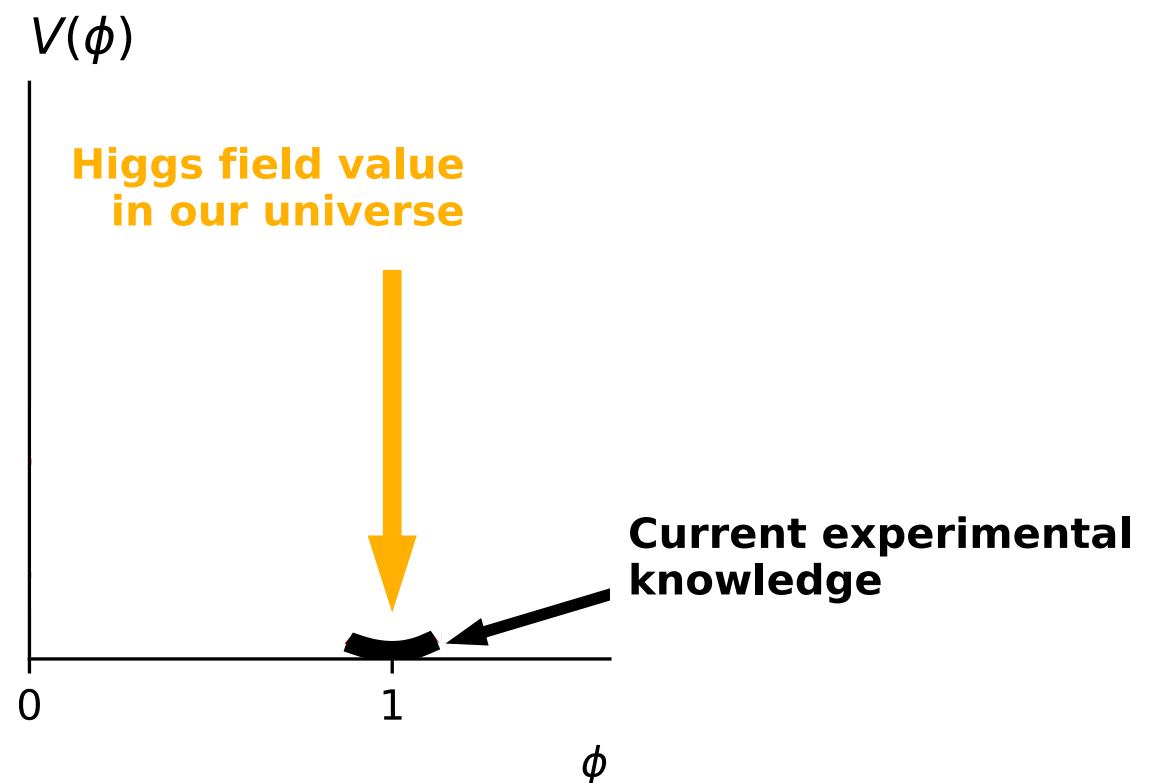
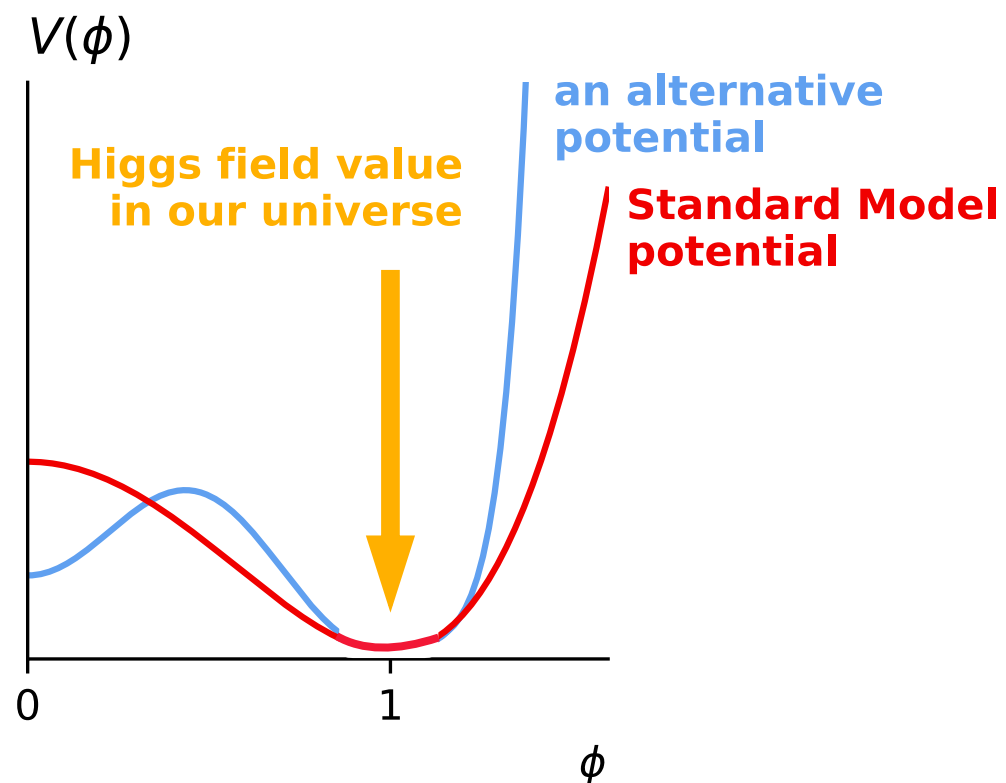
What do we know?

Higgs potential?



What do we know?

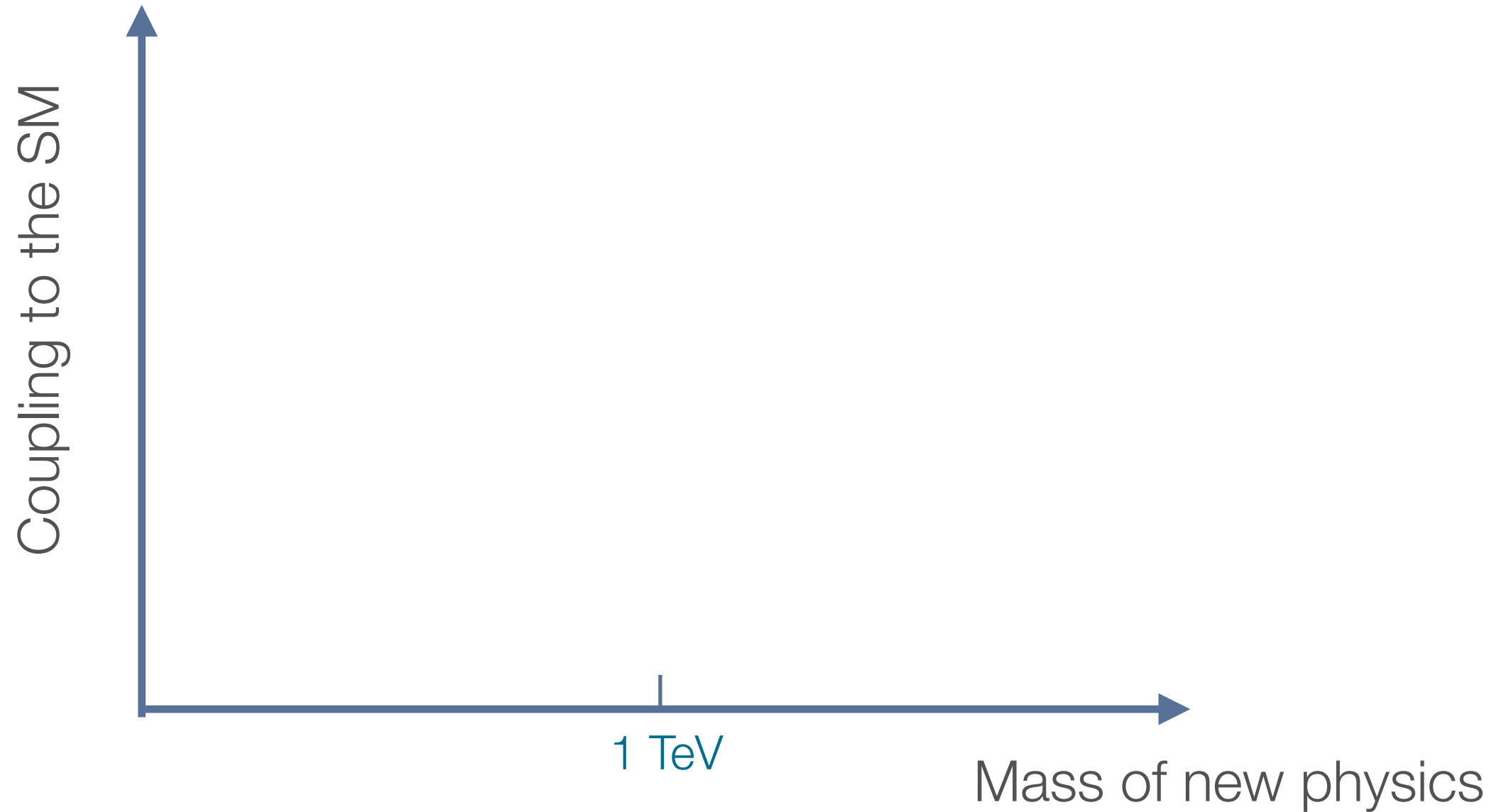
Higgs potential?



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

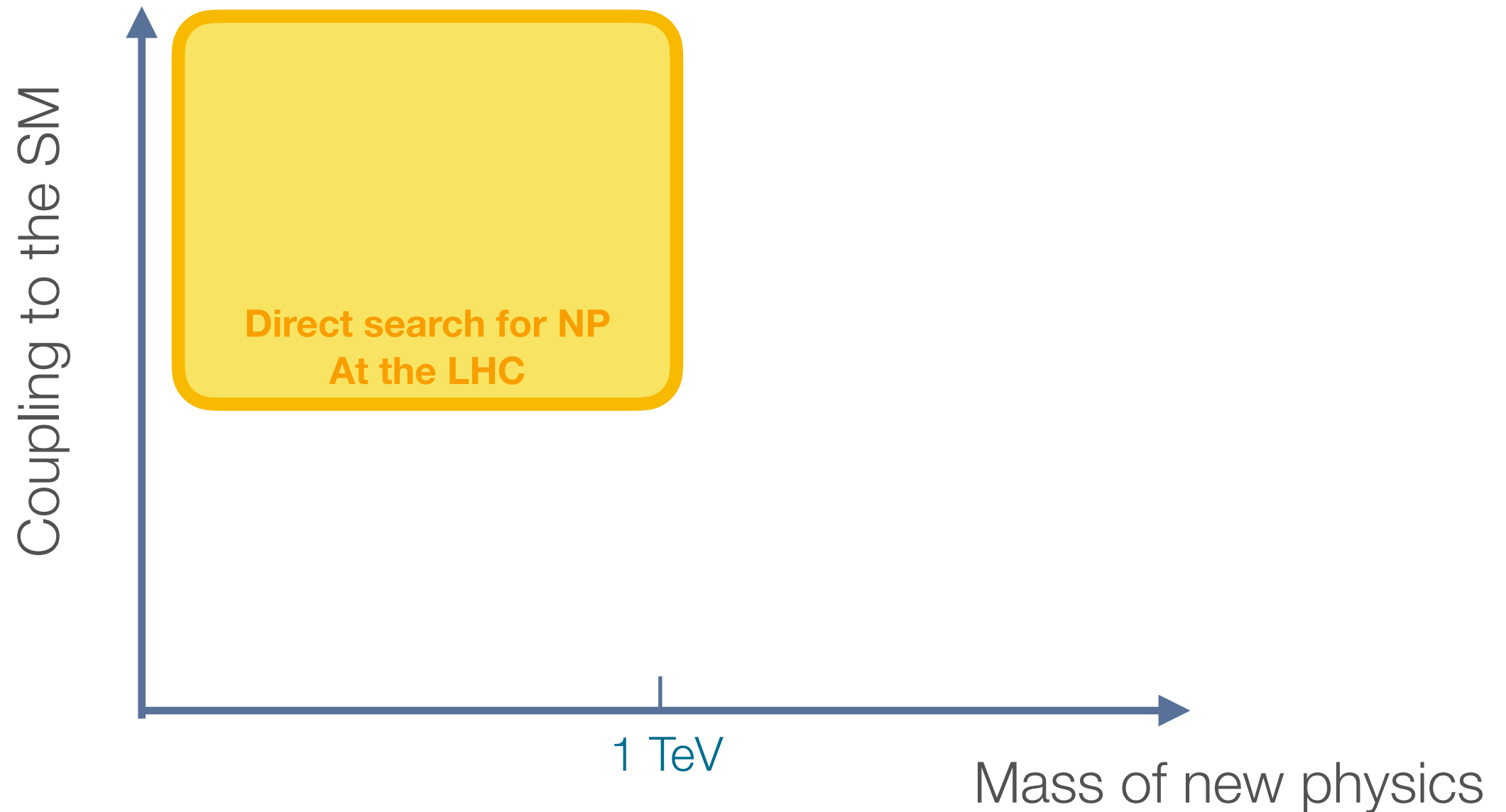
Our target

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



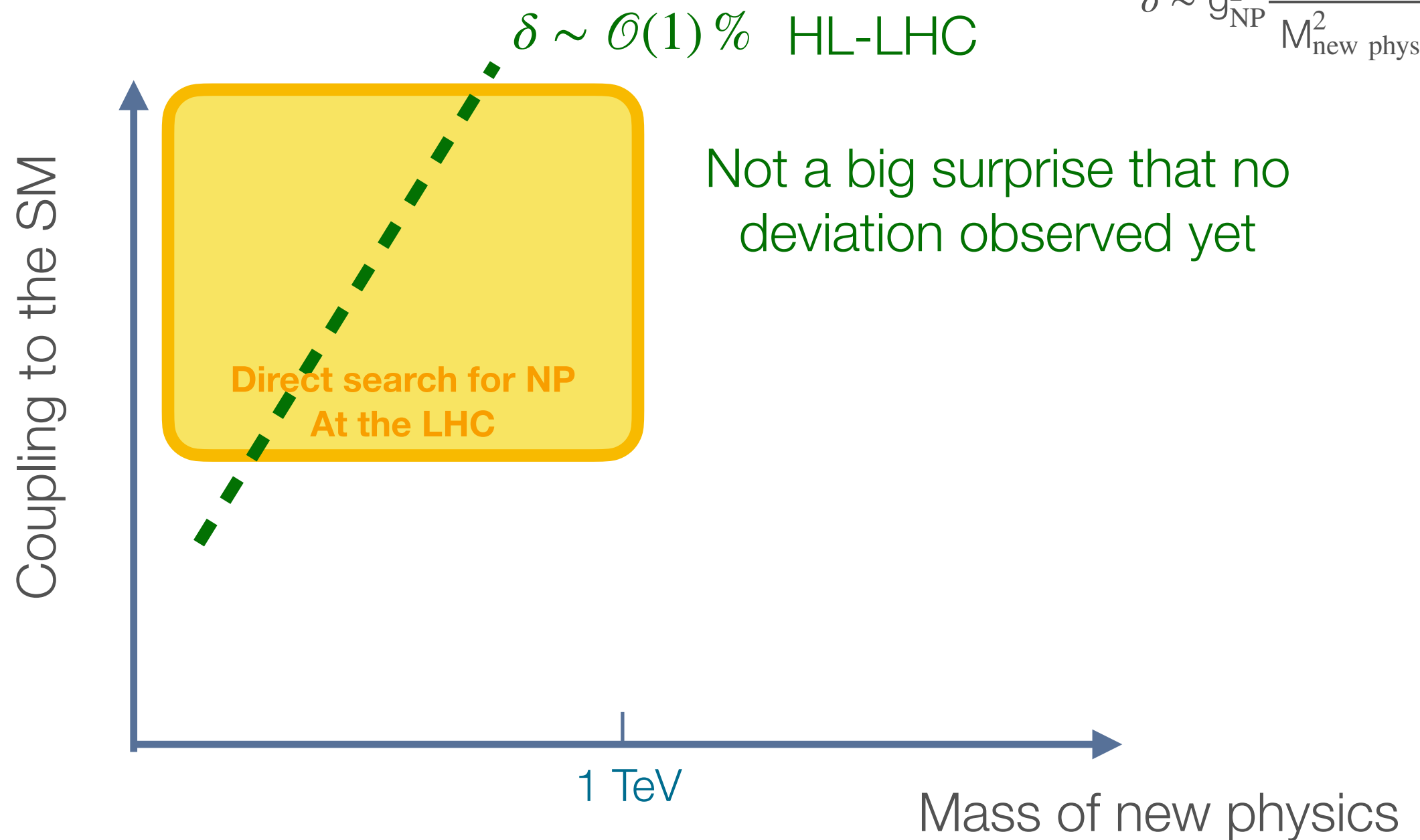
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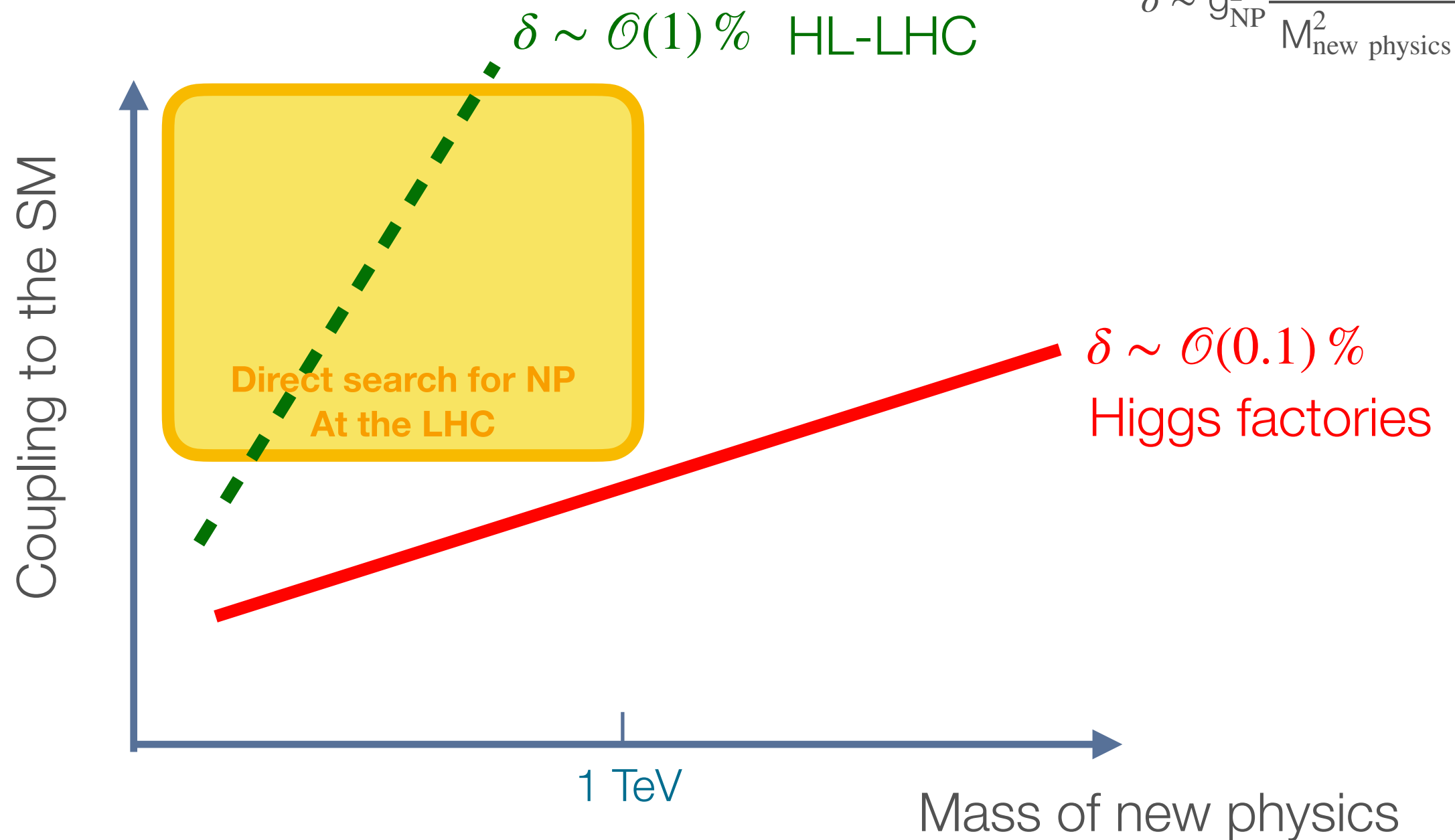
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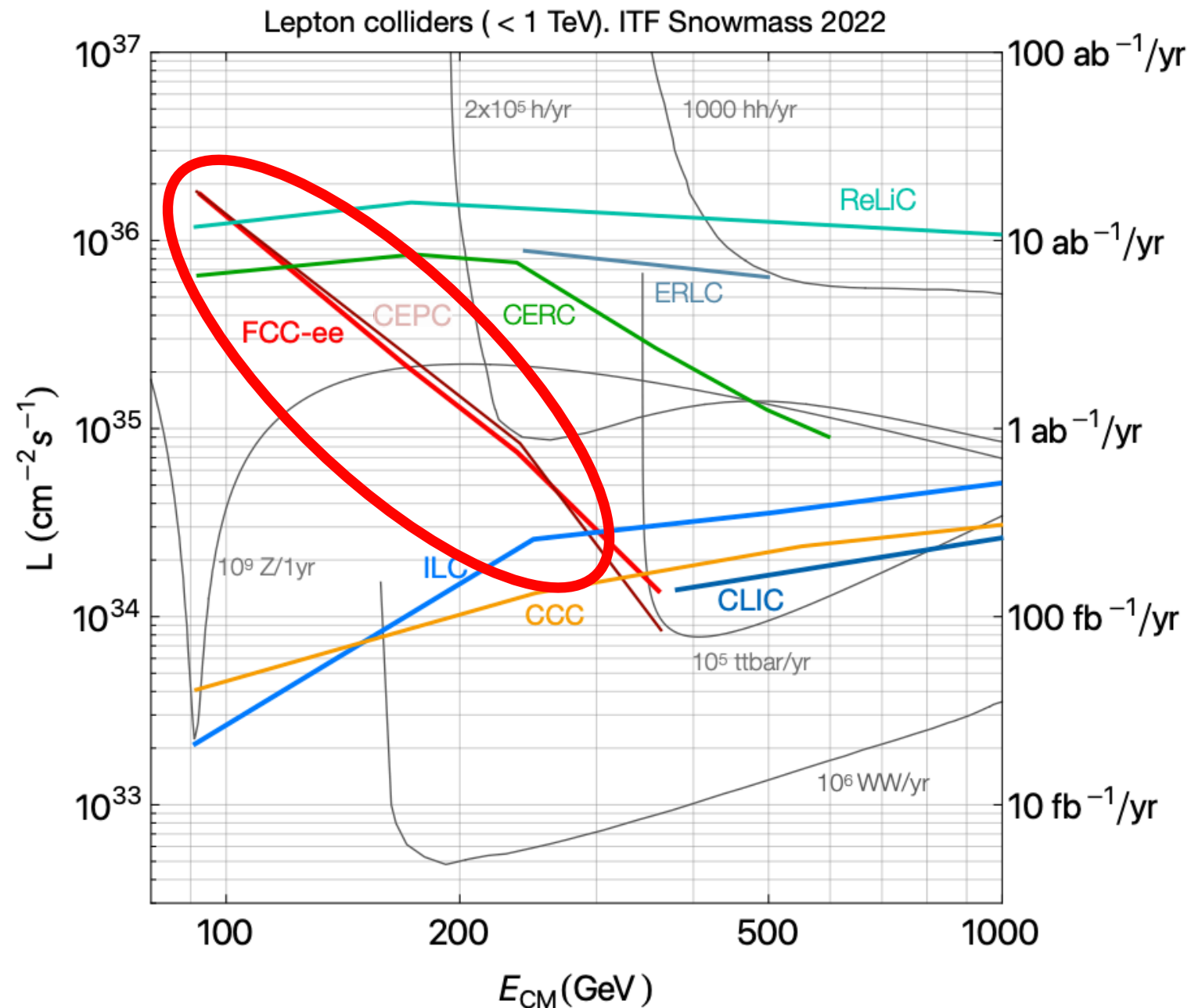


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Physics output



Main physics output:

10^6 Higgses

$> 10^{12}$ Zs

10^6 WW

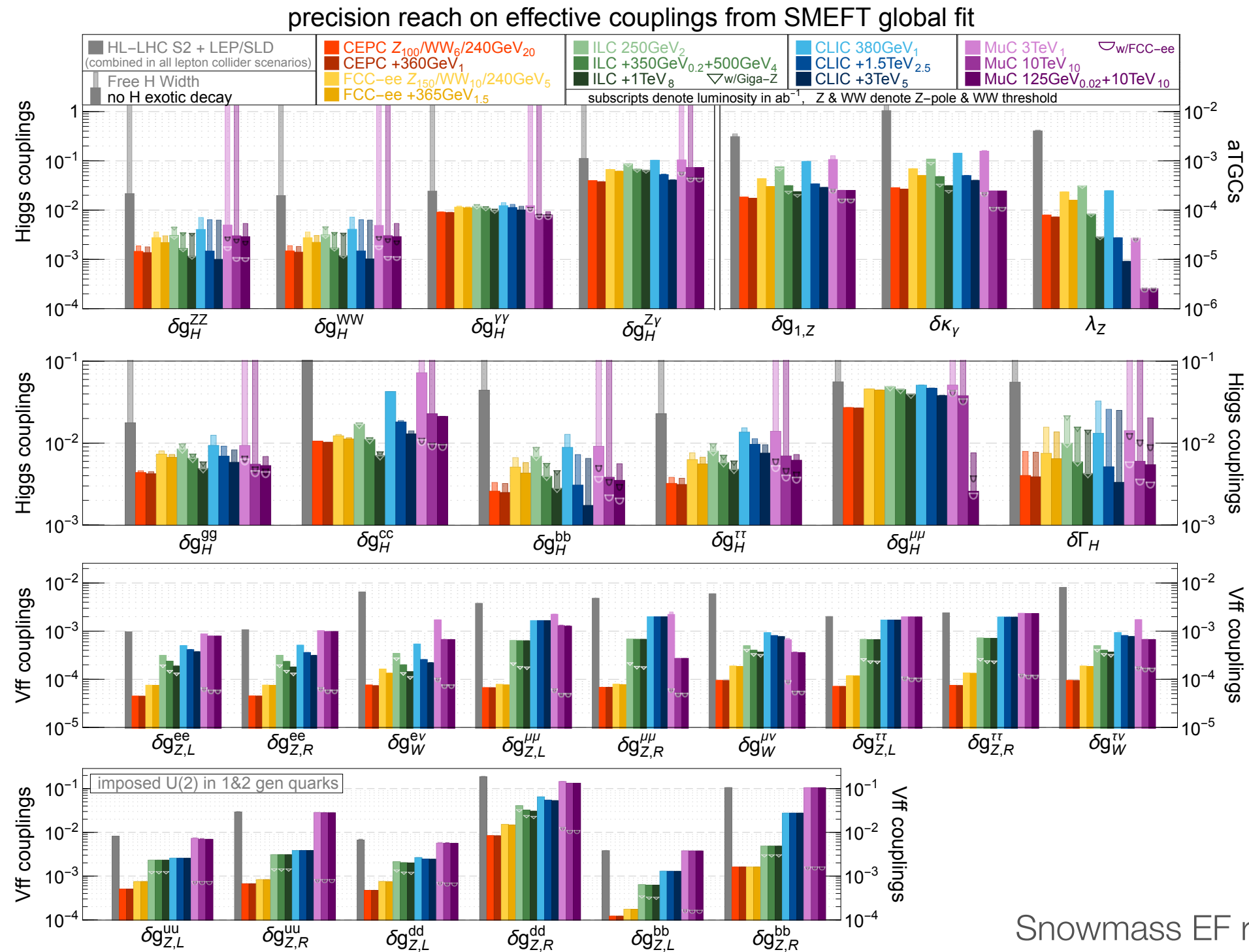
10^5 ttbar

Central theme: the electroweak scale

Performance:

Precision measurements Higgs and
beyond

A full suite of measurements

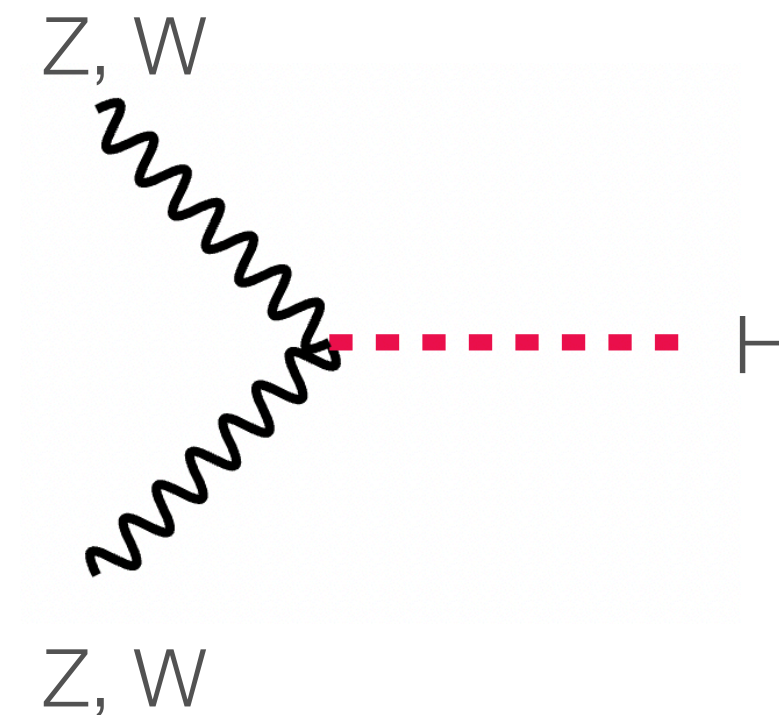
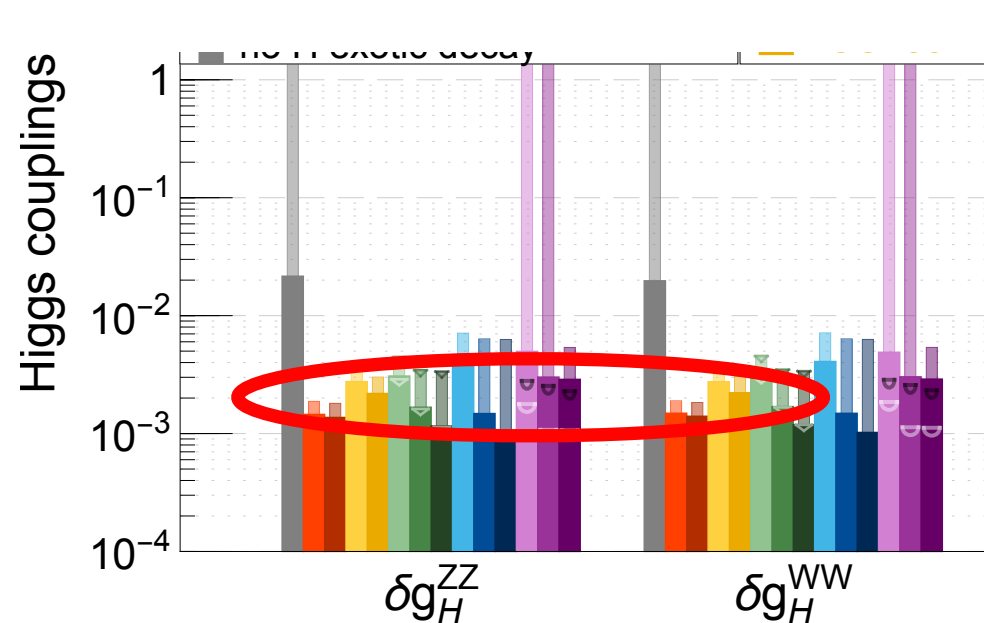


Snowmass EF report

The Higgs measurements

■ HL-LHC S2 + LEP/SLD (combined in all lepton collider scenarios)	■ CEPC Z ₁₀₀ /WW ₆ /240GeV ₂₀ ■ CEPC +360GeV ₁	■ ILC 250GeV ₂ ■ ILC +350GeV _{0.2} +500GeV ₄ ■ ILC +1TeV ₈	■ CLIC 380GeV ₁ ■ CLIC +1.5TeV _{2.5} ■ CLIC +3TeV ₅	■ MuC 3TeV ₁ ■ MuC 10TeV ₁₀ ■ MuC 125GeV _{0.02} +10TeV ₁₀
■ Free H Width ■ no H exotic decay	■ FCC-ee Z ₁₅₀ /WW ₁₀ /240GeV ₅ ■ FCC-ee +365GeV _{1.5}	▽ w/Giga-Z		▽ w/FCC-ee

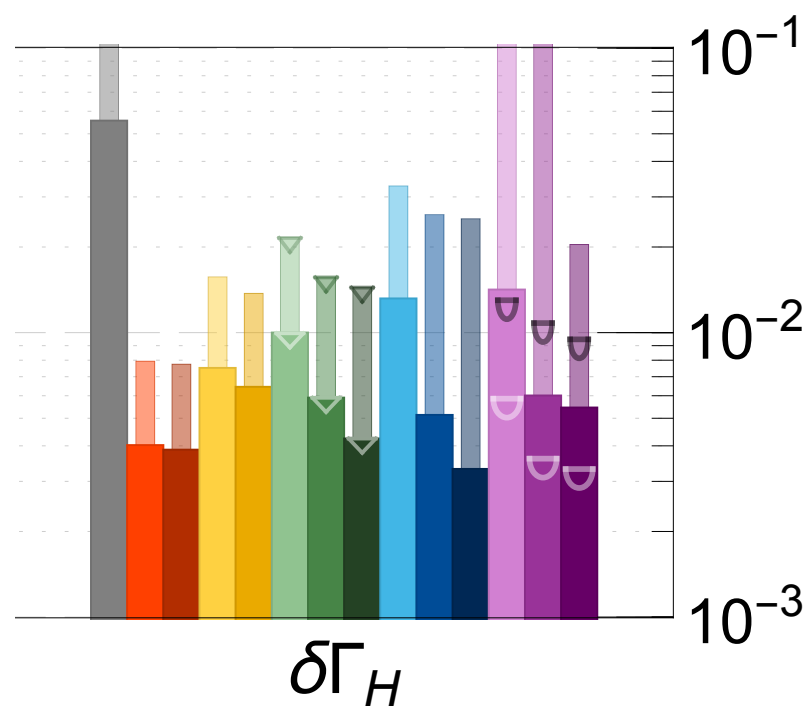
subscripts denote luminosity in ab⁻¹, Z & WW denote Z-pole & WW threshold



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

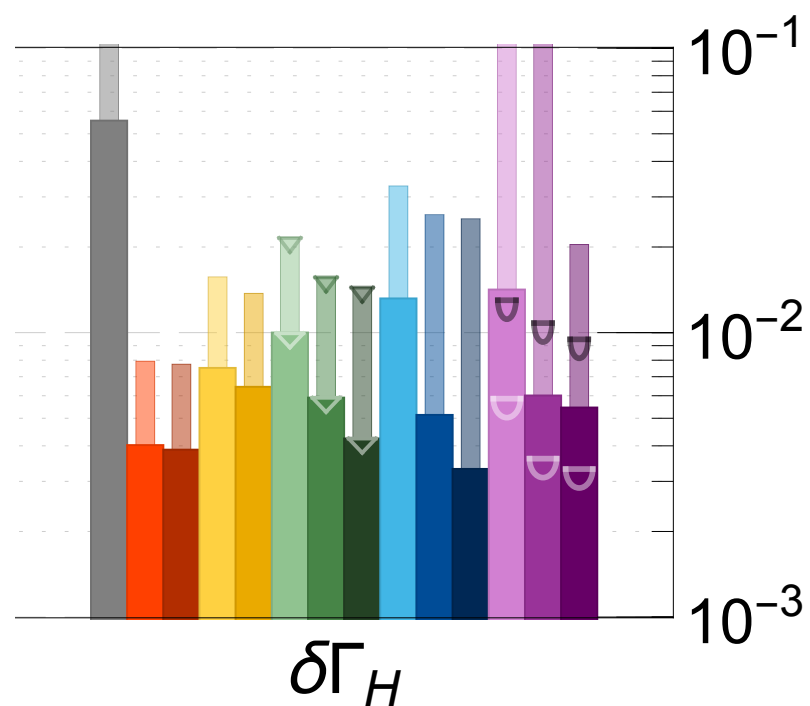
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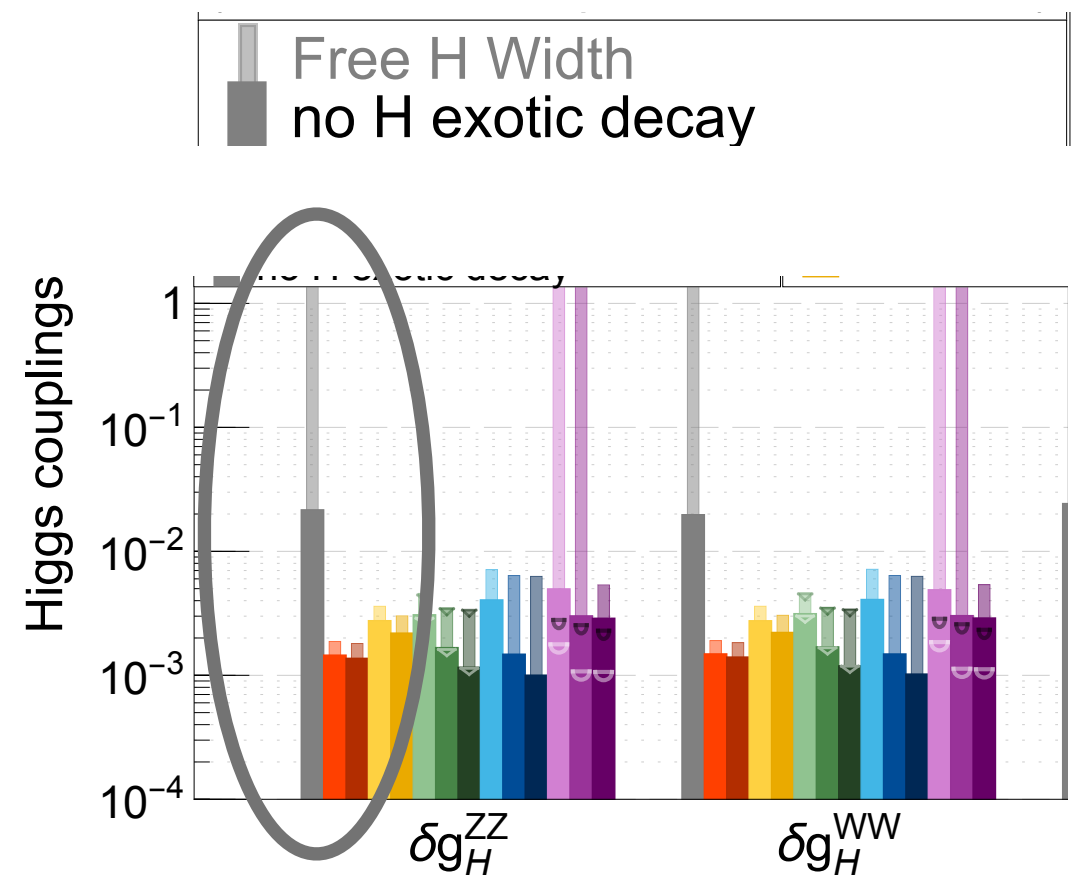


Higgs width measurement

The Higgs measurements

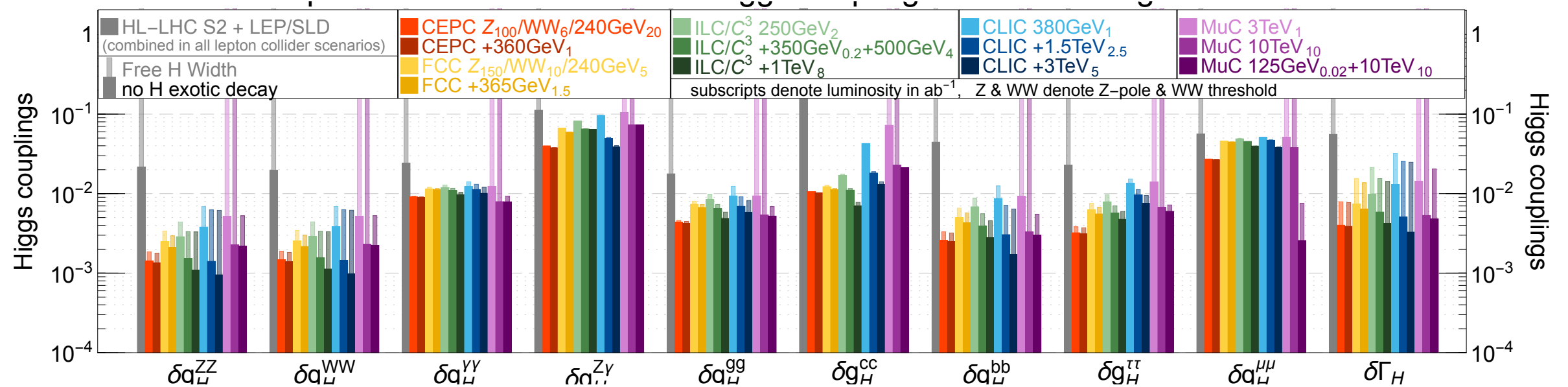


Higgs width measurement



Significant impact on other coupling measurement

The Higgs measurements



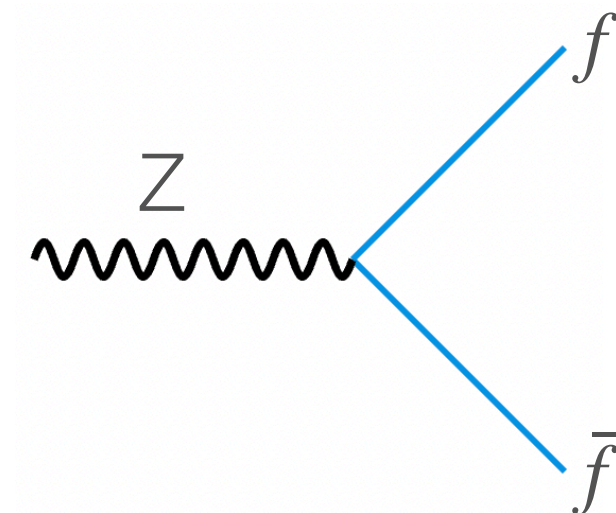
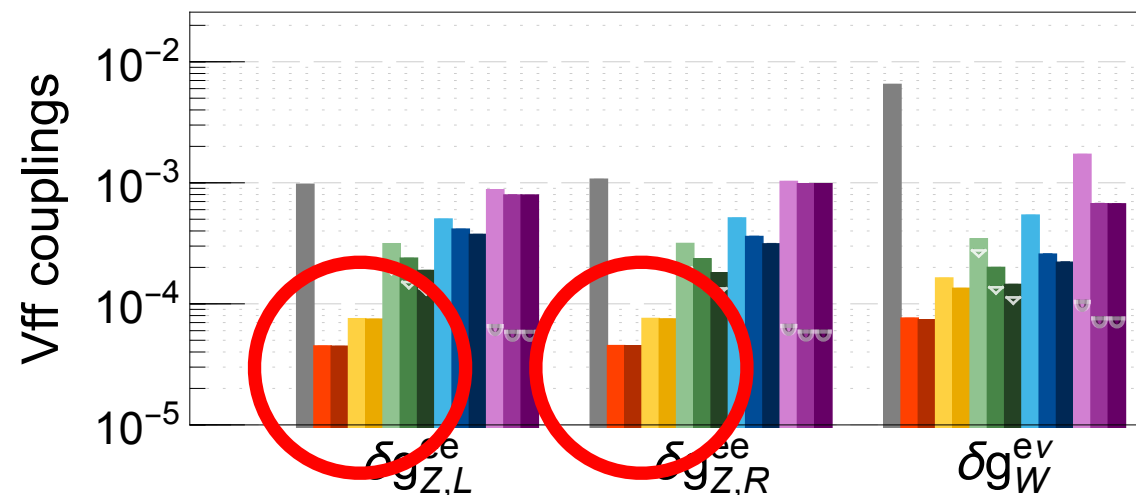
Overall, a big step beyond the LHC

With more W, Z, and tops

FCC-ee

10^{12} Zs 10^6 WW 10^5 tt

In comparison:
LEP has 10^7 Zs



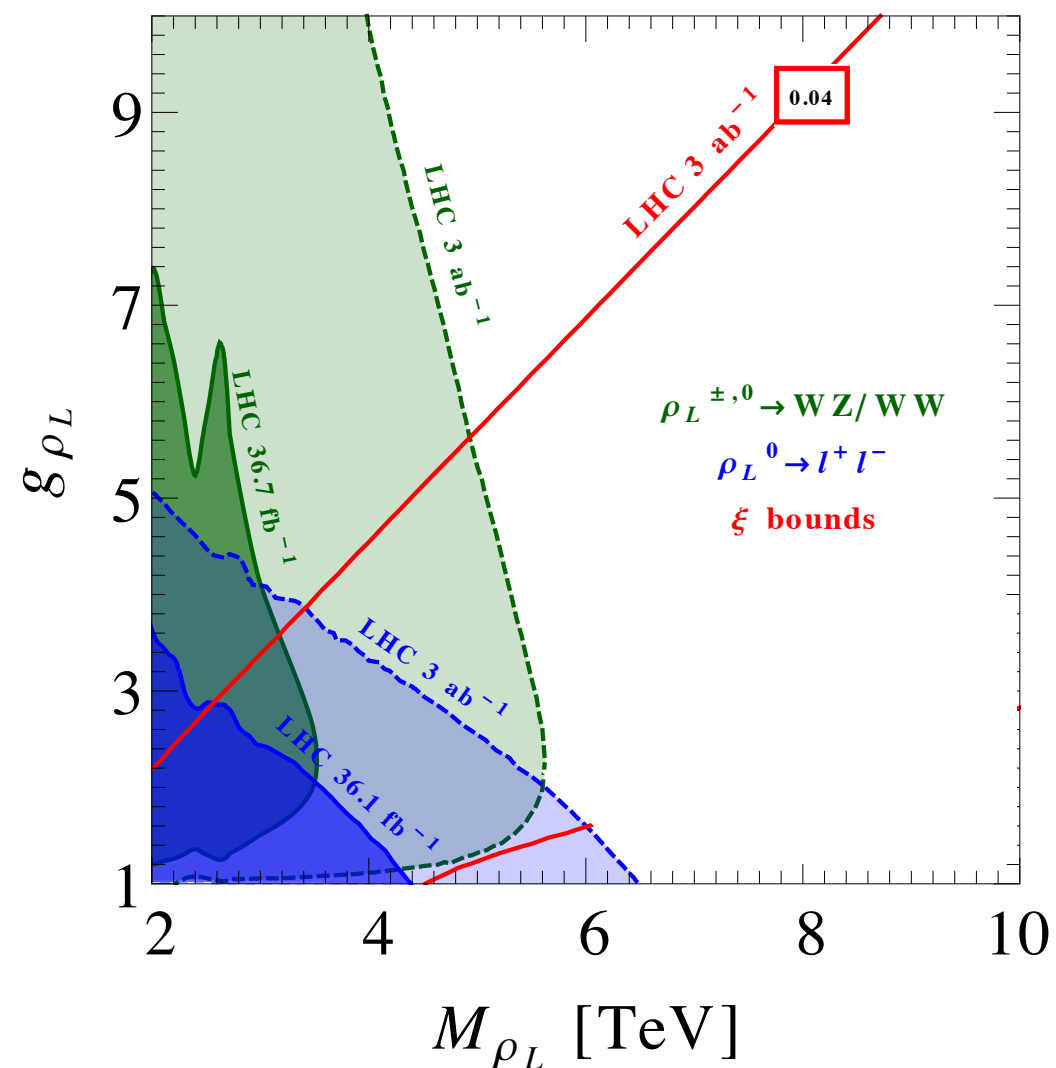
Precision on electroweak couplings: $10^{-3} \Rightarrow 10^{-4}$

Search for NP in exotic Z decays (more later)

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

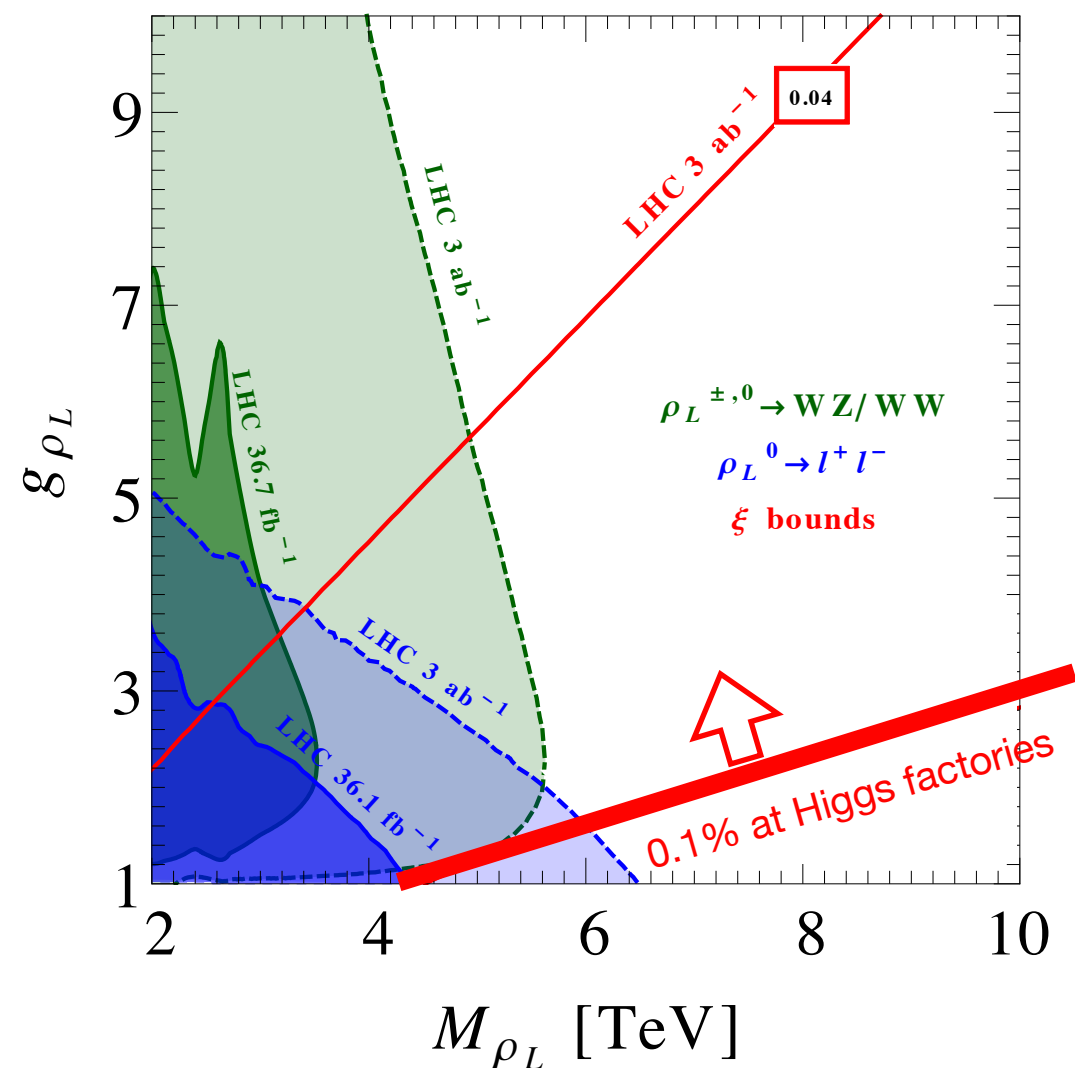
Direct search for composite resonances

Higgs coupling measurements

Composite $\neq$ elementary

Different couplings

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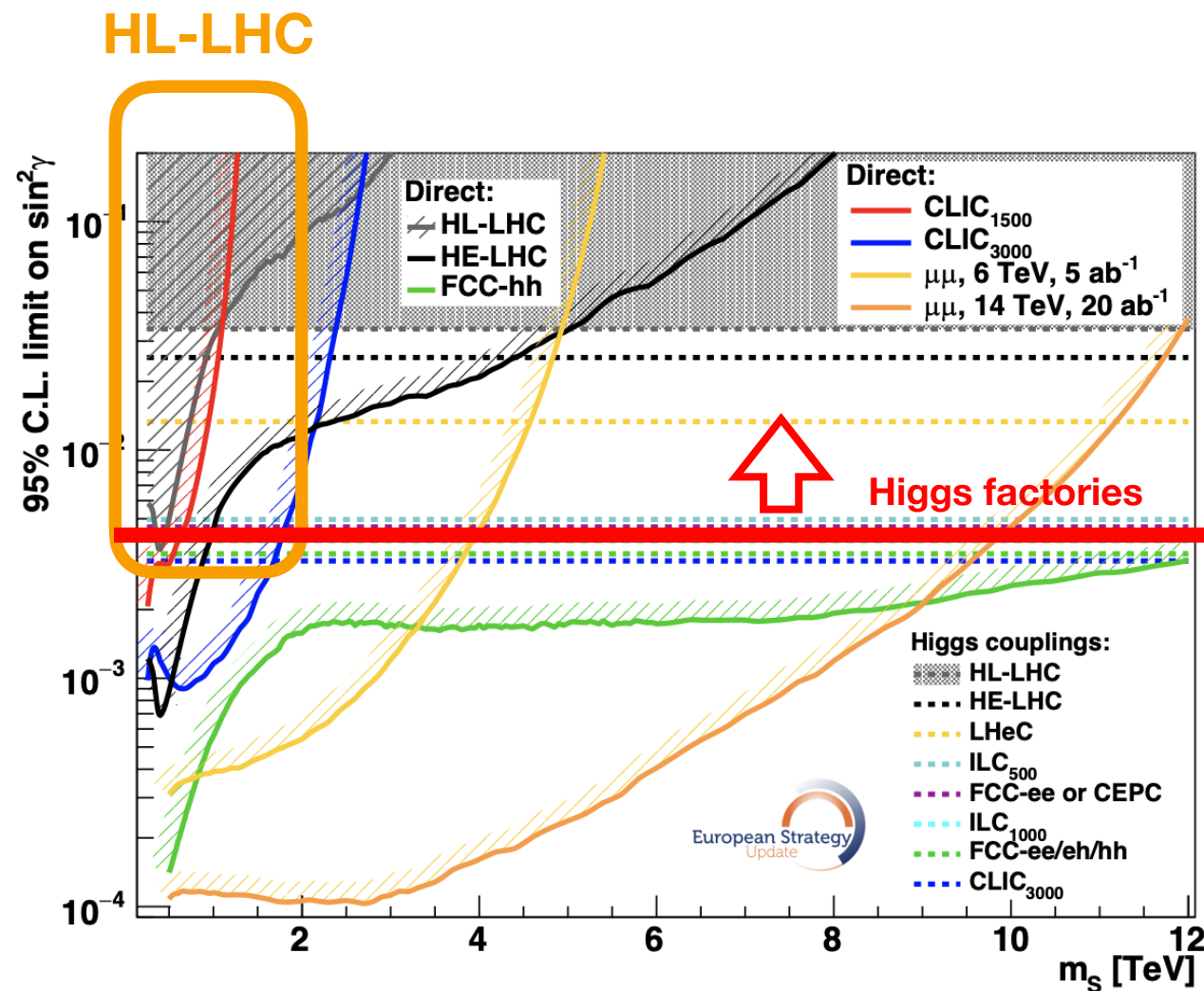
Direct search for composite resonances

Higgs coupling measurements

Composite $\neq$ elementary

Different couplings

Is the Higgs boson alone?

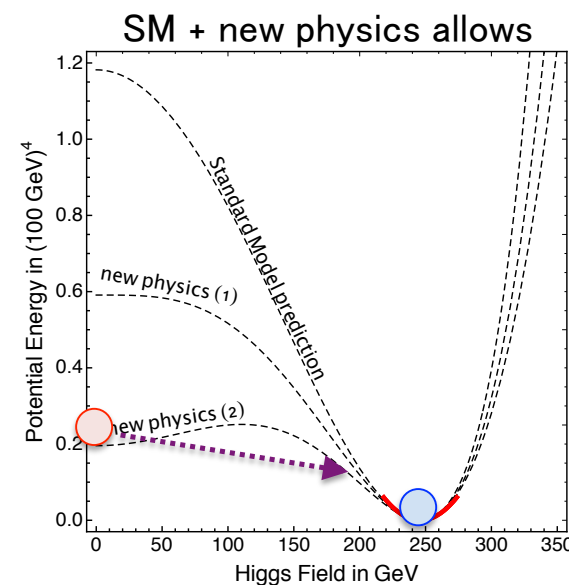
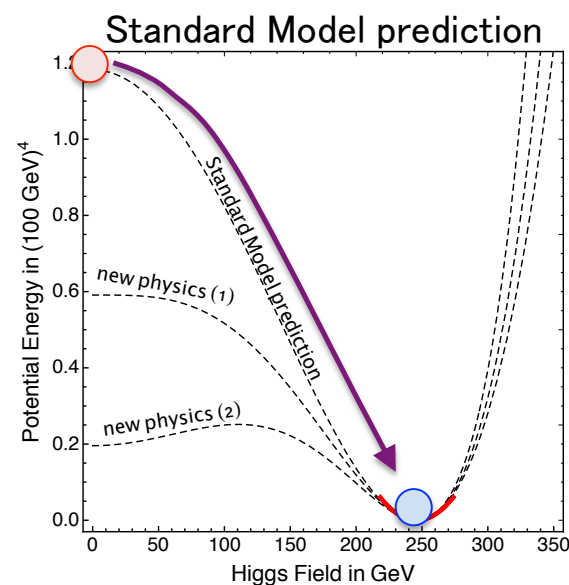


Maybe Higgs boson has some partners?

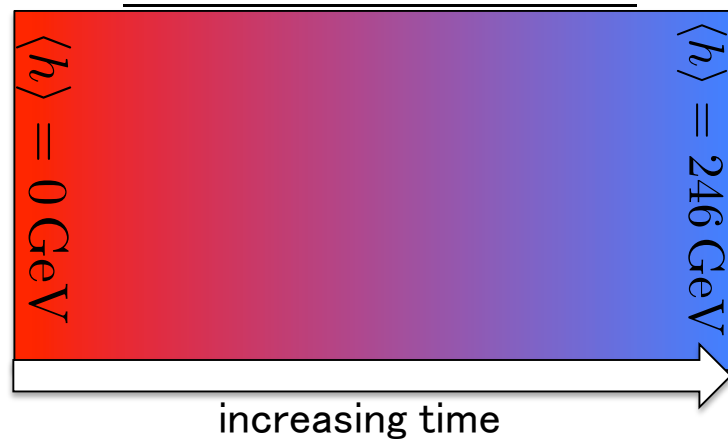
Will change Higgs behavior by interacting with it.

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

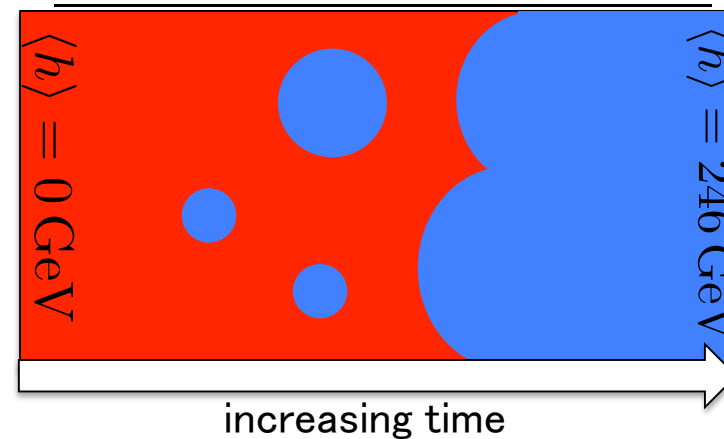
How does Higgs drive electroweak phase transition?



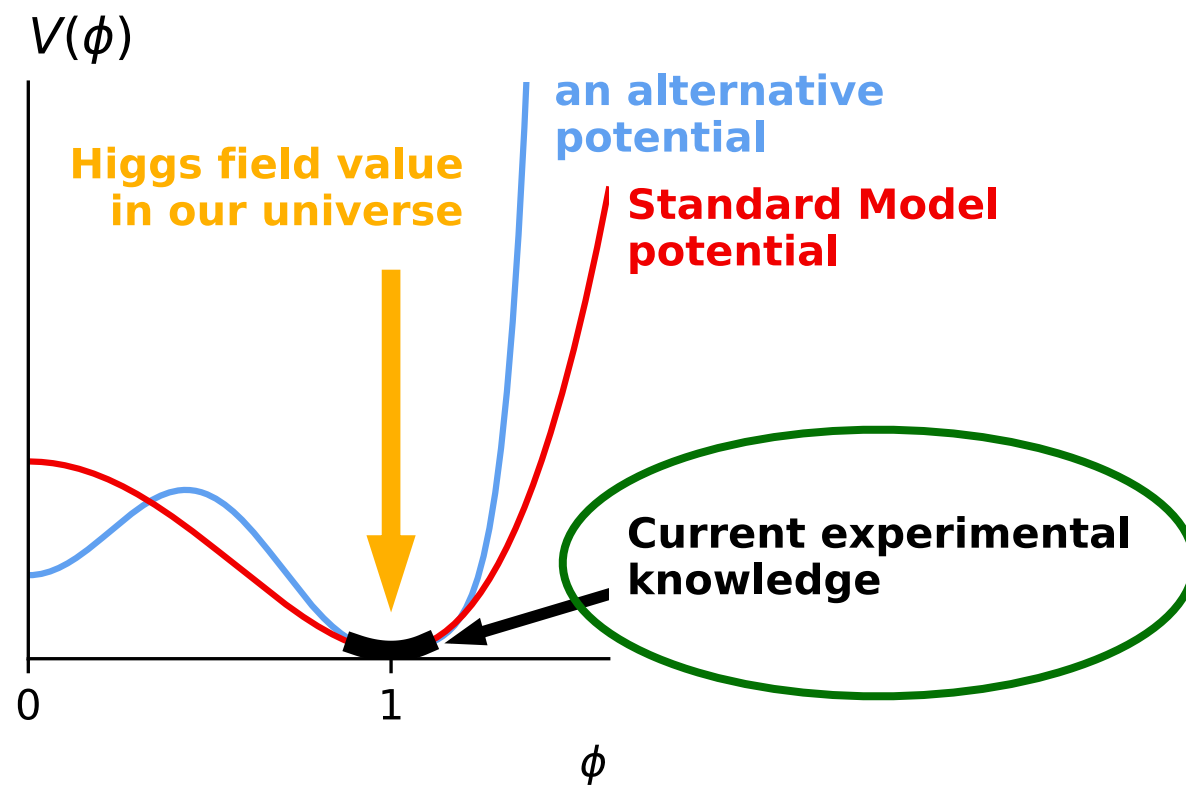
Continuous Crossover



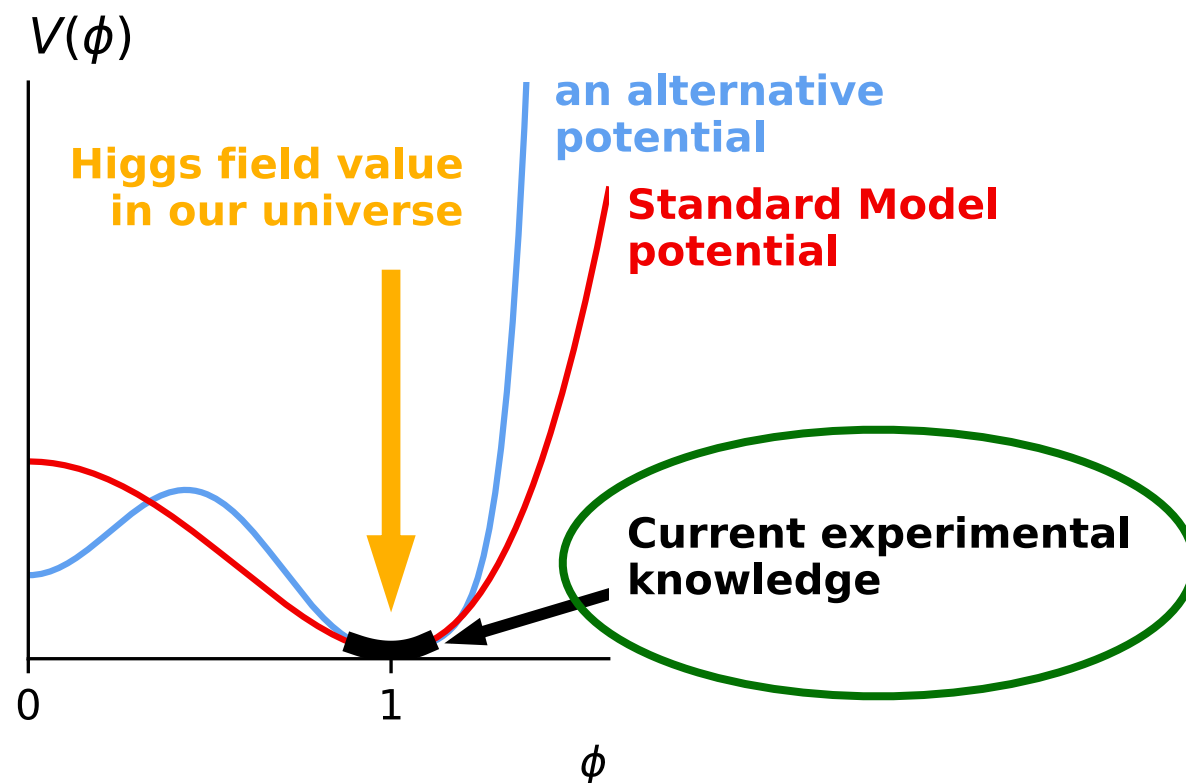
First Order Phase Transition



How does Higgs evolve in the early universe?

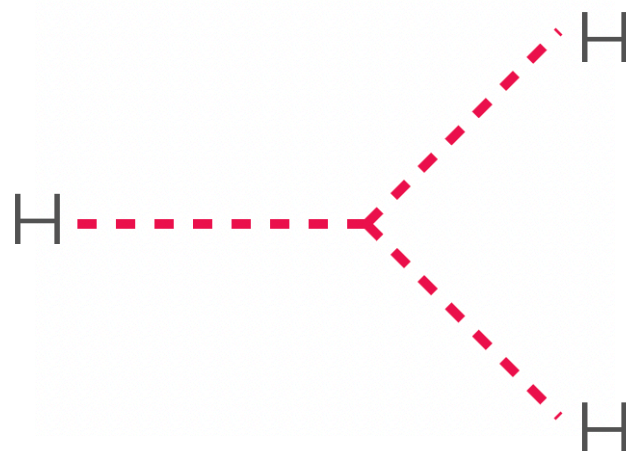


Need to go beyond this

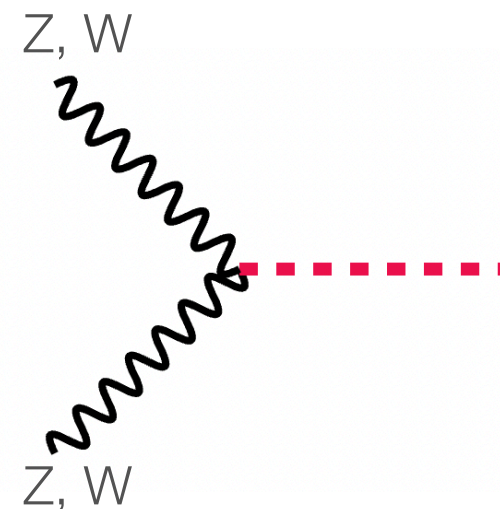


Need to go beyond this

1. Self-coupling

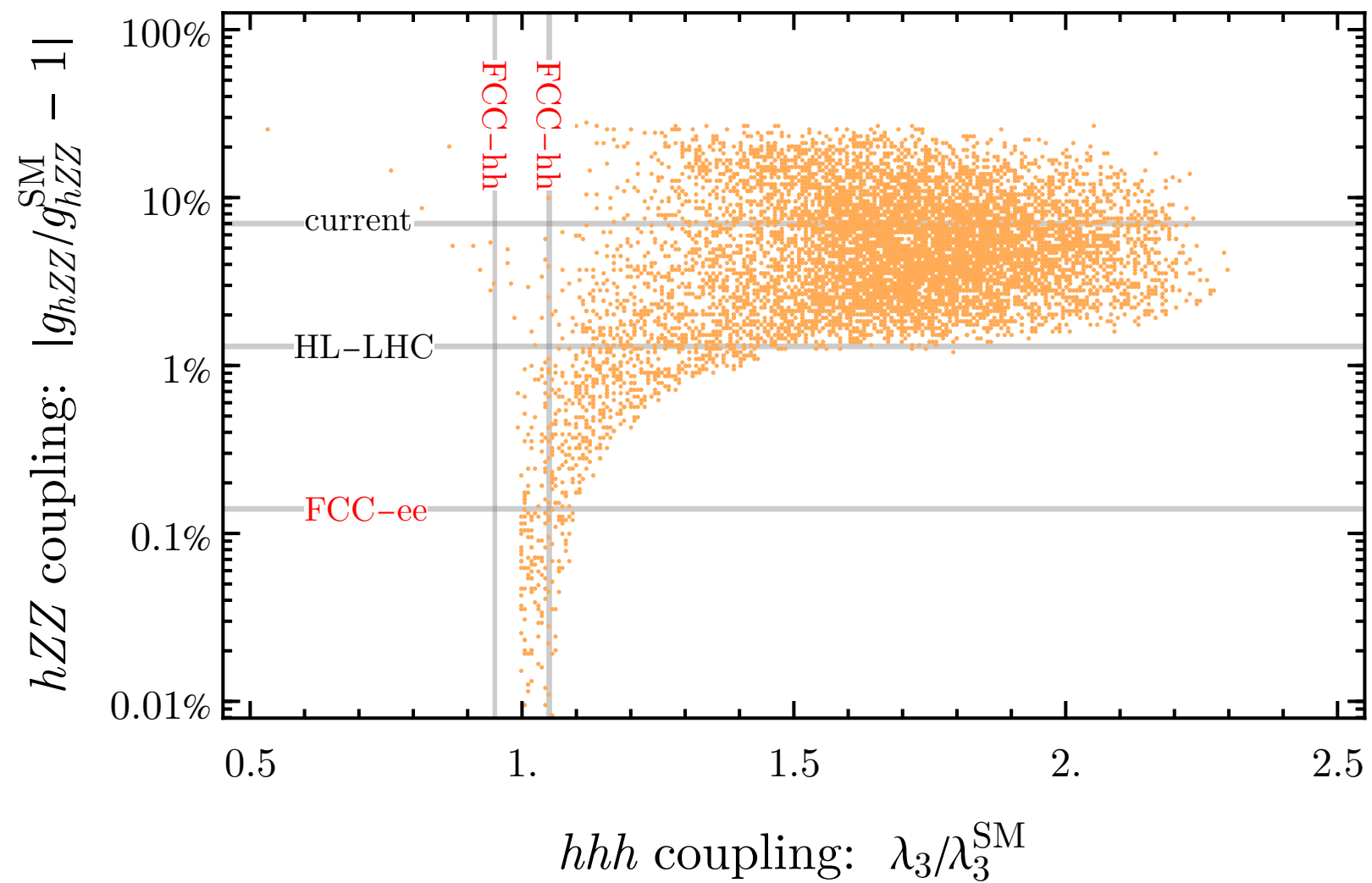


2. New physics in the alternative scenario often induce changes in other Higgs coupling, such as hZ



EW Phase transition

Real Scalar Singlet Model



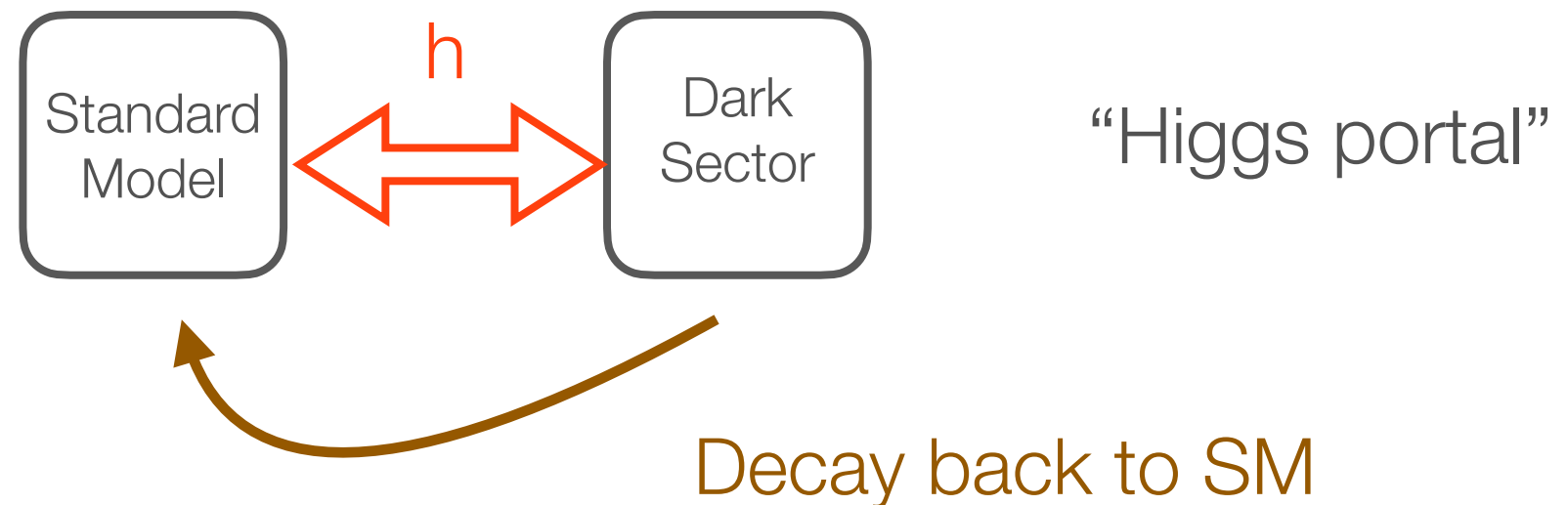
Other physics opportunities

Significantly enriches the physics program.

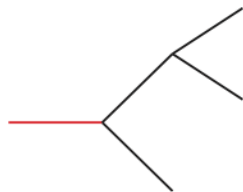
New physics searches at lepton colliders

- * 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).

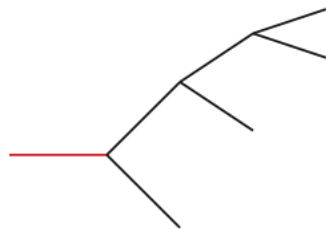
Higgs to dark sector?



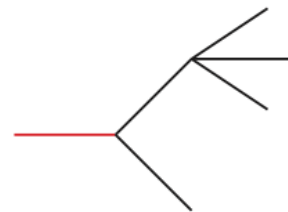
$h \rightarrow 2 \rightarrow 3$



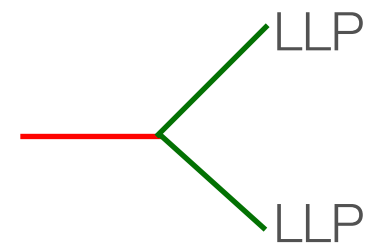
$h \rightarrow 2 \rightarrow 3 \rightarrow 4$



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

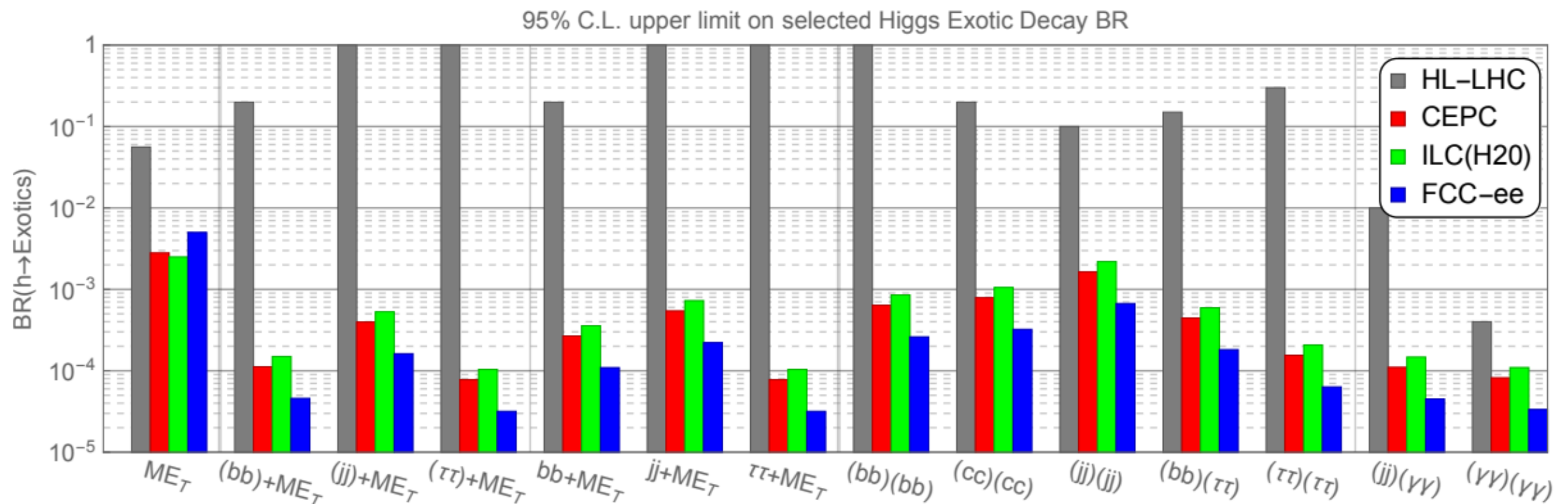


Long lived particles



....

Higgs exotic decay

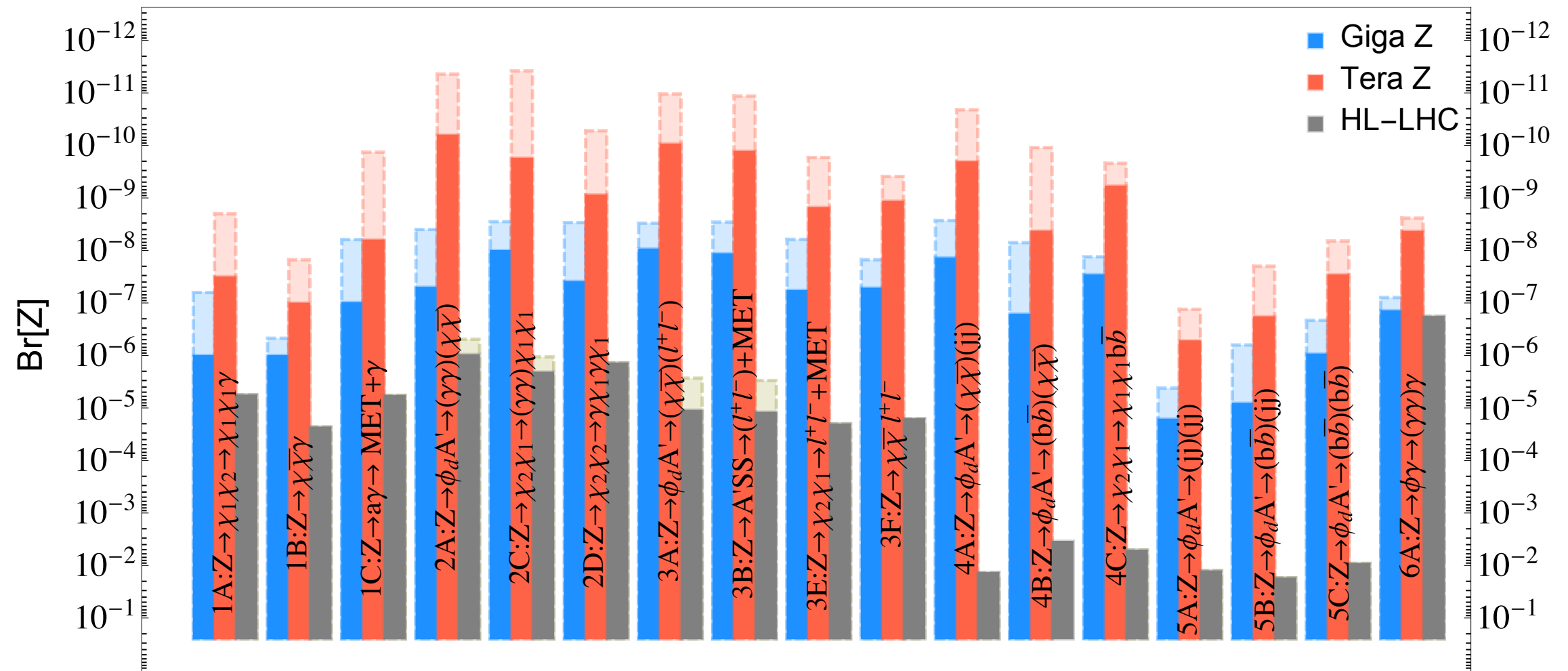


Complementary to hadron collider searches

Can probe interesting physics cases:

Hidden naturalness, dark matter, EW phase transition, ...

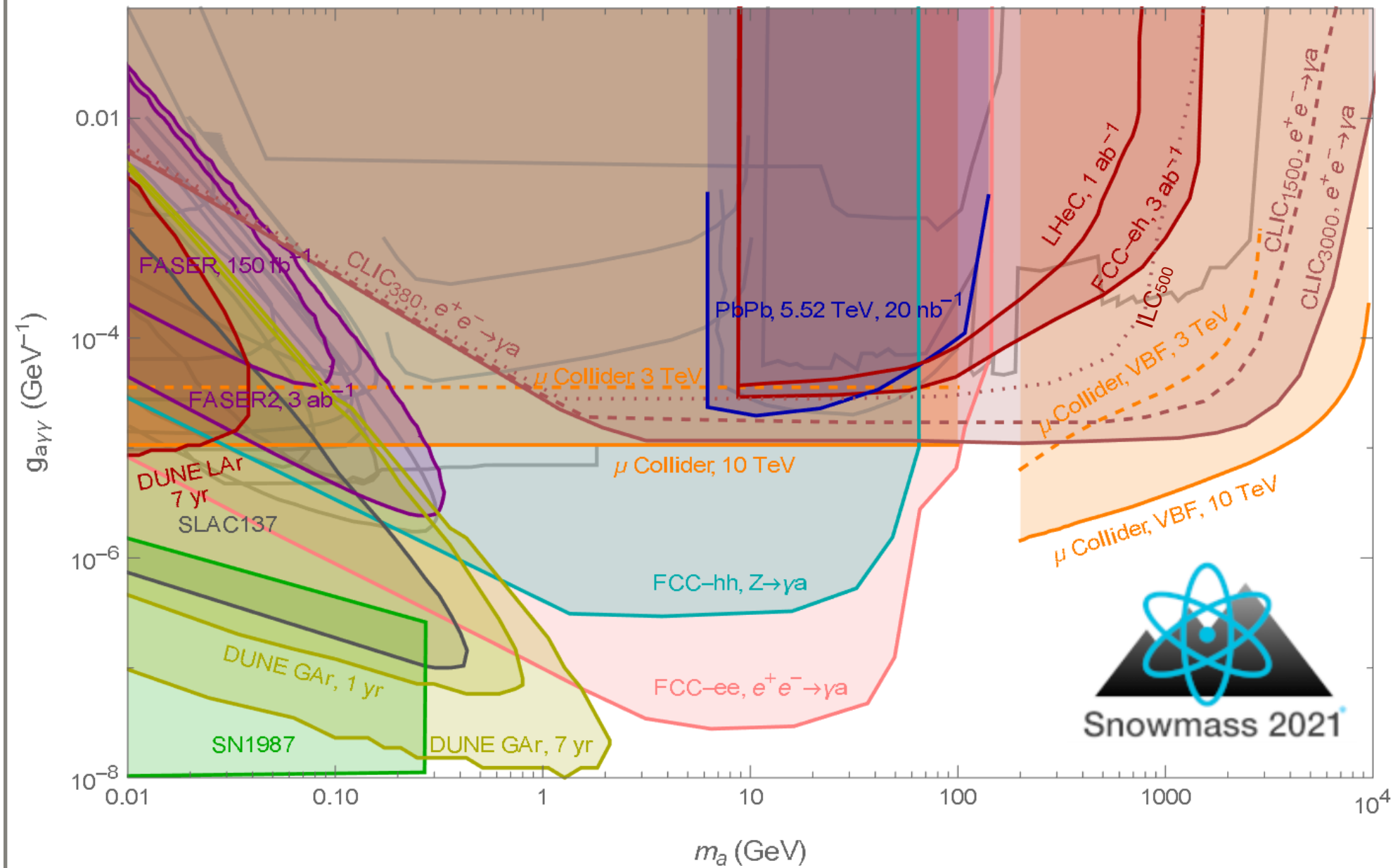
Rare Z decay at Tera-Z



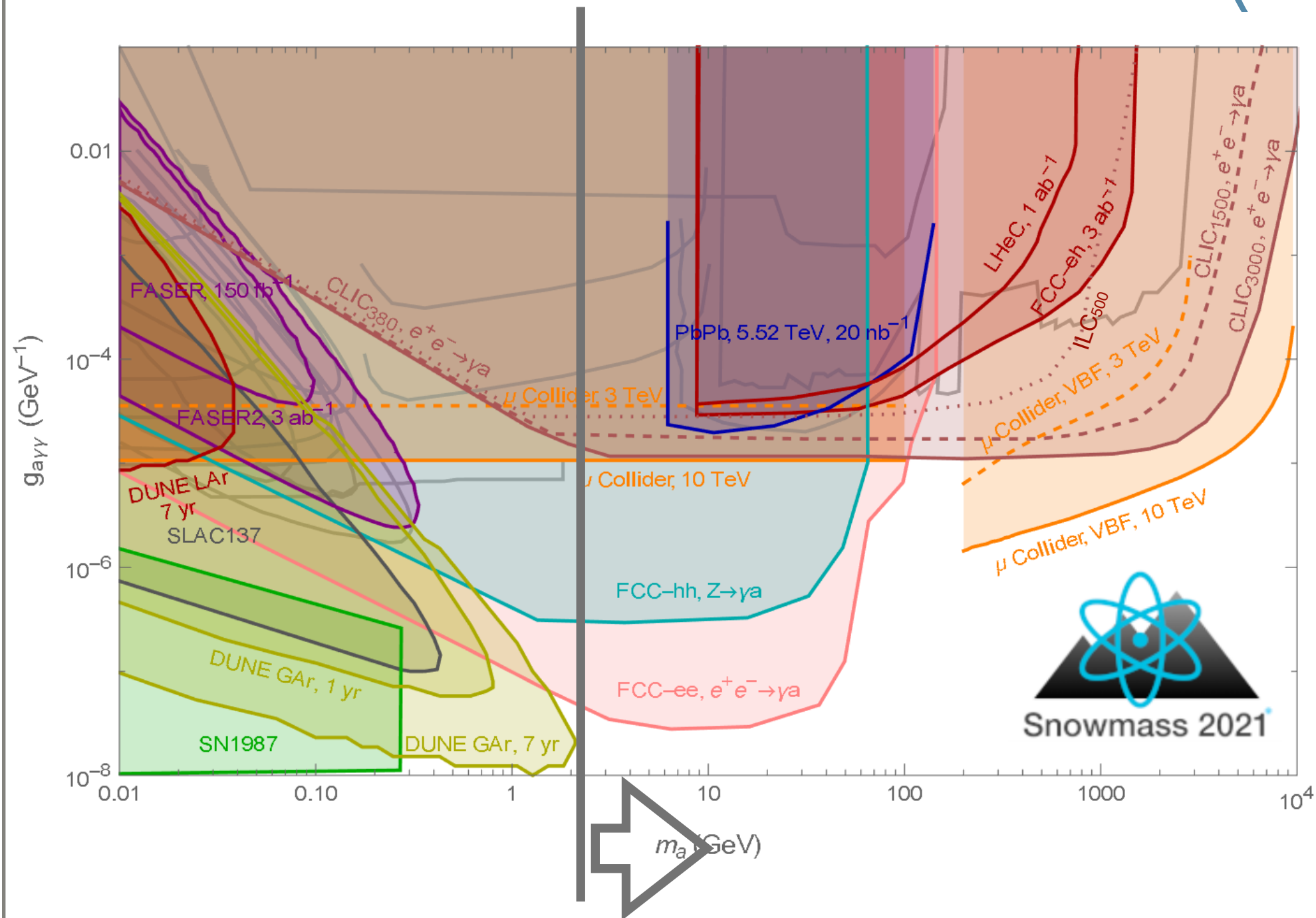
Probing exotic decay up to $\text{BR} \sim 10^{-11}$

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

Axion Like Particles (ALP)

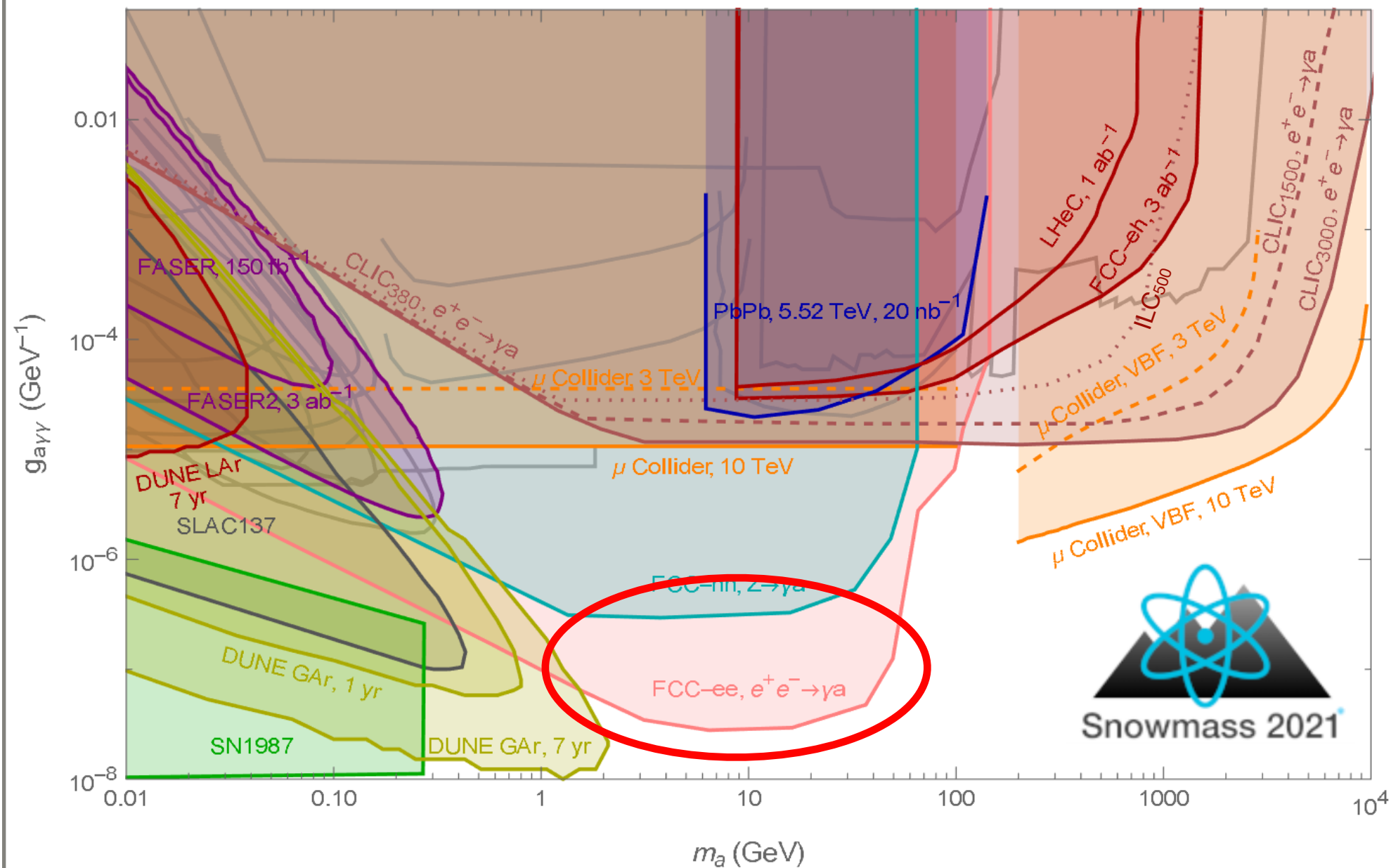


Axion Like Particles (ALP)



High energy colliders probing higher mass regions.

Axion Like Particles (ALP)

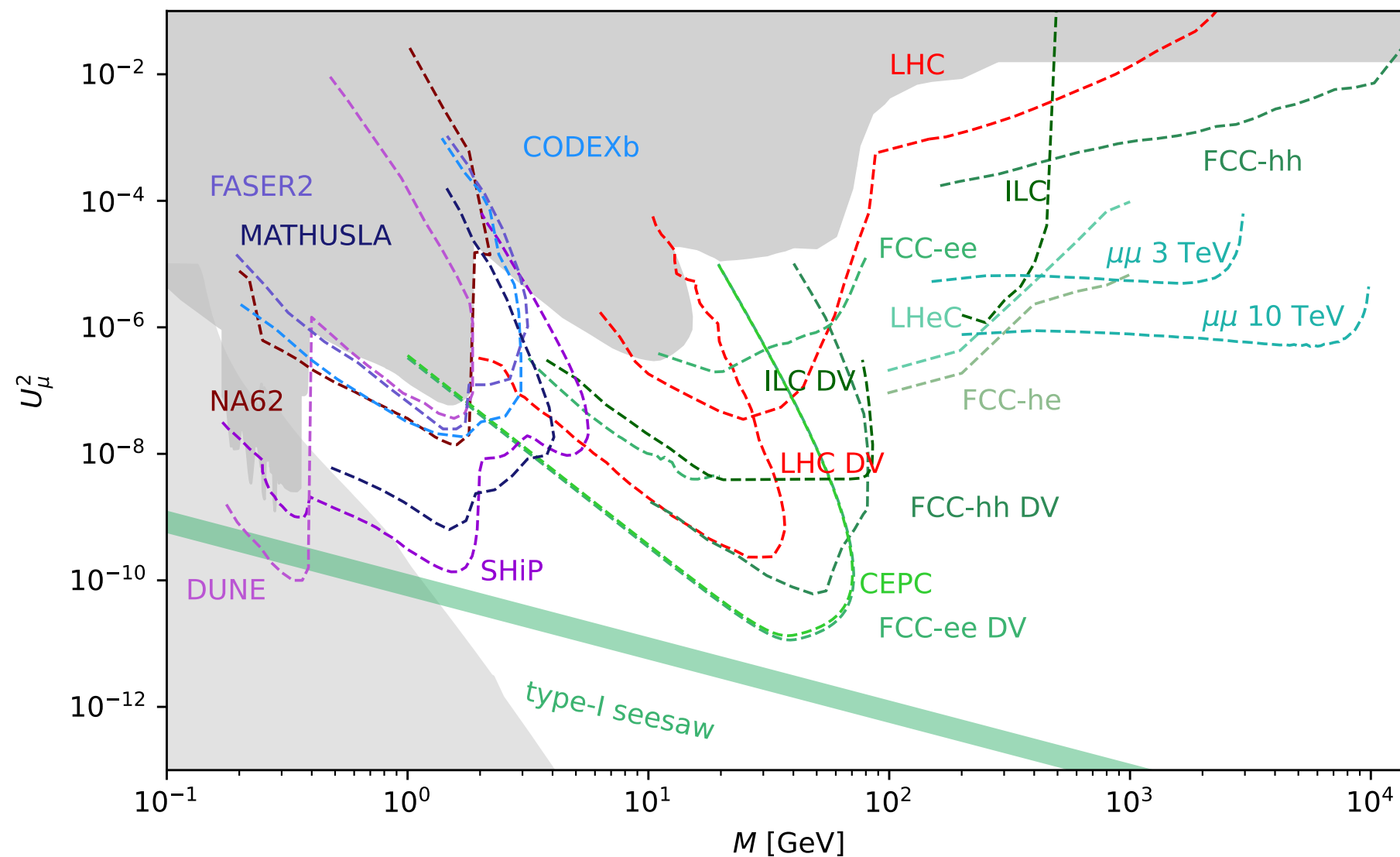


Higgs factories

High luminosity, sensitive to weak signal

Heavy neutral lepton

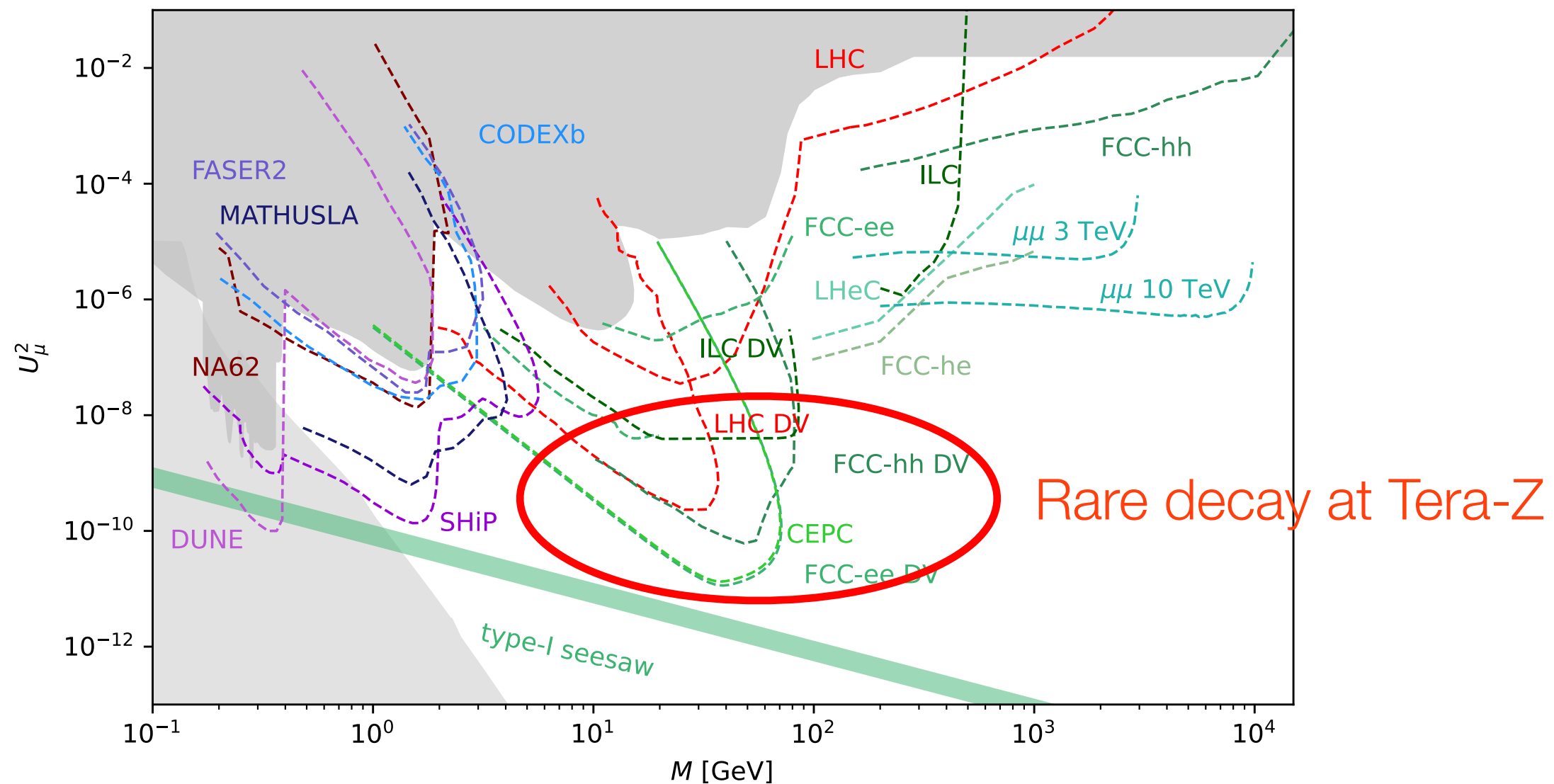
a.k.a. HNL, sterile neutrino, singlet fermion



Relation to neutrino mass?

Heavy neutral lepton

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

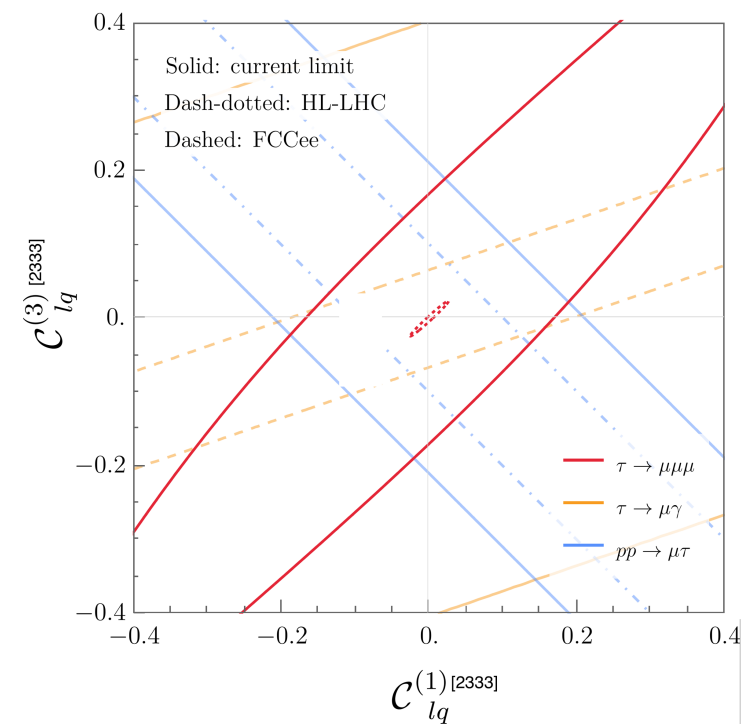
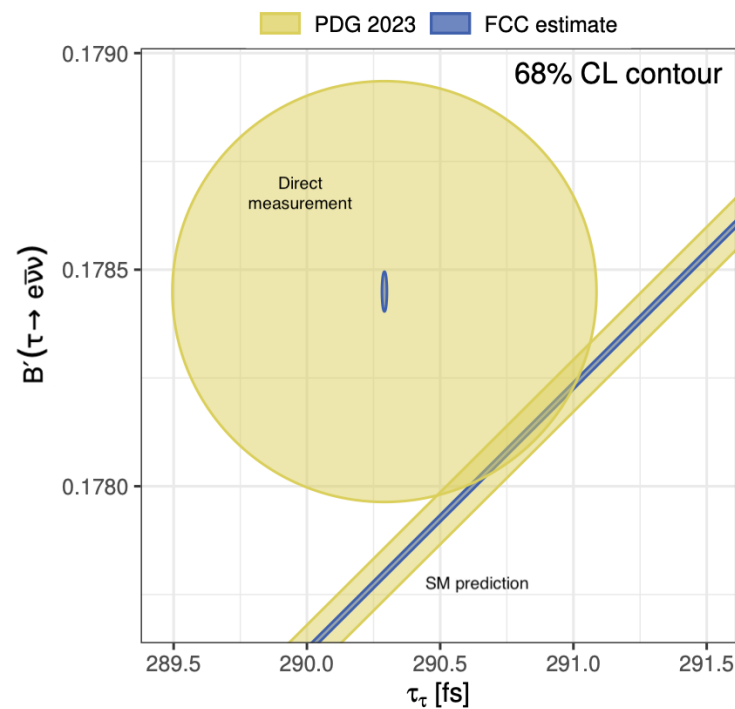


Relation to neutrino mass?

B, charm, hadron, τ at tera-Z

Table 6: Yields of heavy-flavoured particles produced at FCC-ee for 6×10^{12} Z decays [190].

Particle species	B^0	B^+	B_s^0	Λ_b	B_c^+	$c\bar{c}$	$\tau^-\tau^+$
Yield ($\times 10^9$)	370	370	90	80	2	720	200



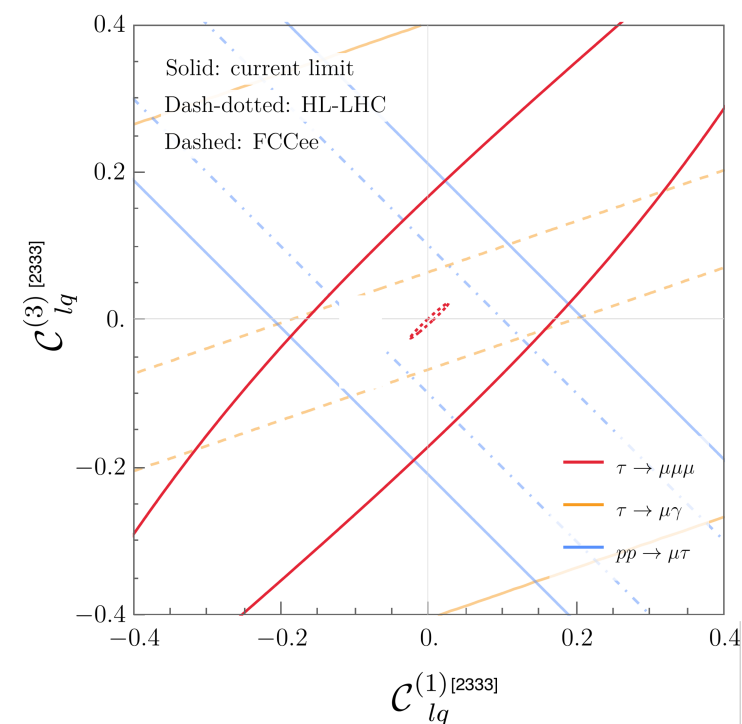
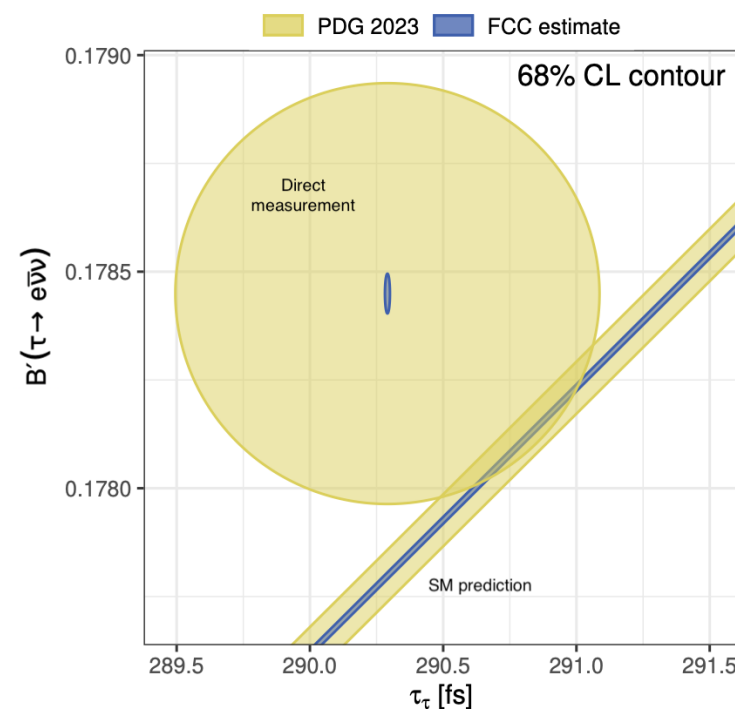
See Zoltan's talk

B, charm, hadron, τ at tera-Z

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Yield ($\times 10^9$)	370	370	90	80	2	720	200

A lot of opportunities!



See Zoltan's talk

Basic physics case:

- * Higgs boson is *there*. It is *important*, and yet *mysterious*.
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This is the clearest and most concrete argument for making progress, based on what we actually know.

Next steps

- * Big picture, main physics goals clear.
 - * Good benchmarks for detector and machine design and optimization.

Next steps

- * A lot of EFT studies.
- * More thinking on UV completions can lead to better connection to specific couplings and measurements.
 - * e.g. compositeness $\leftrightarrow$ Higgs-Z coupling.
 - * e.g. fermion mass $\leftrightarrow$ Higgs-top, Z-top/bottom couplings

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→ better benchmarks

Next steps

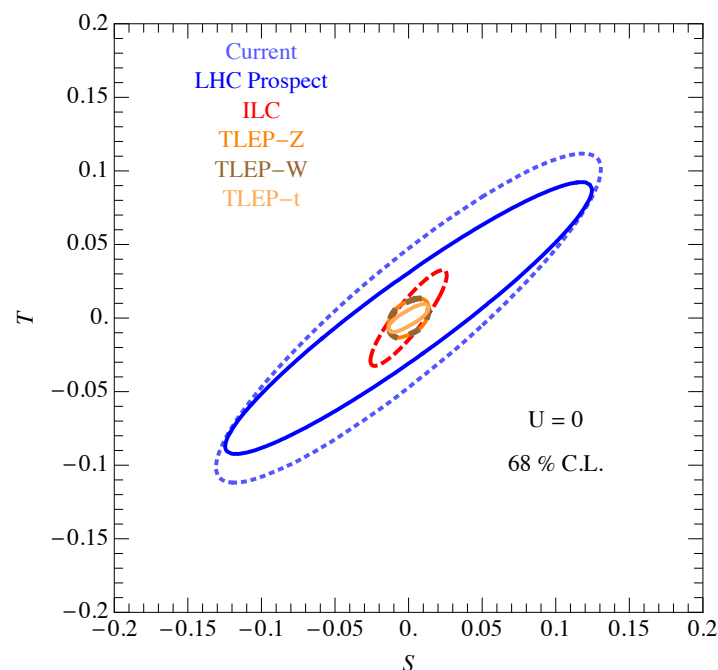
- * Many studies based on the optimal scenarios

Next steps

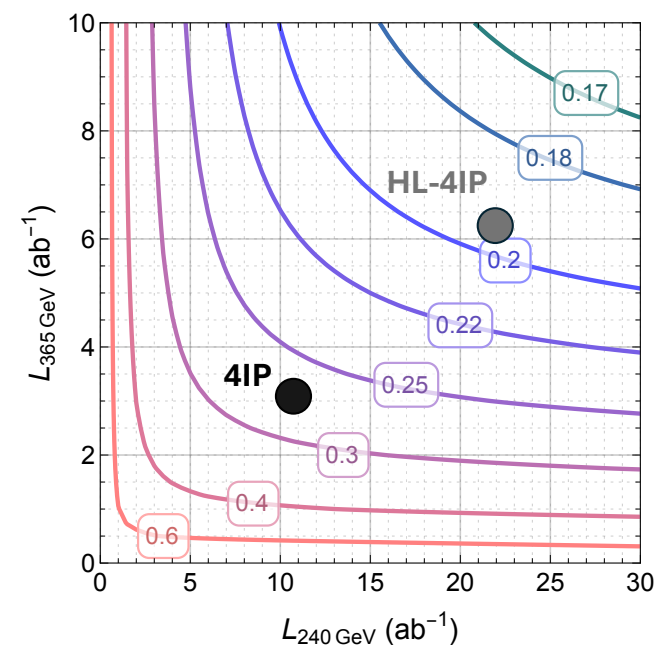
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Next steps

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Fan, Reece, LTW, 2014



Feasibility Studies

It's happening

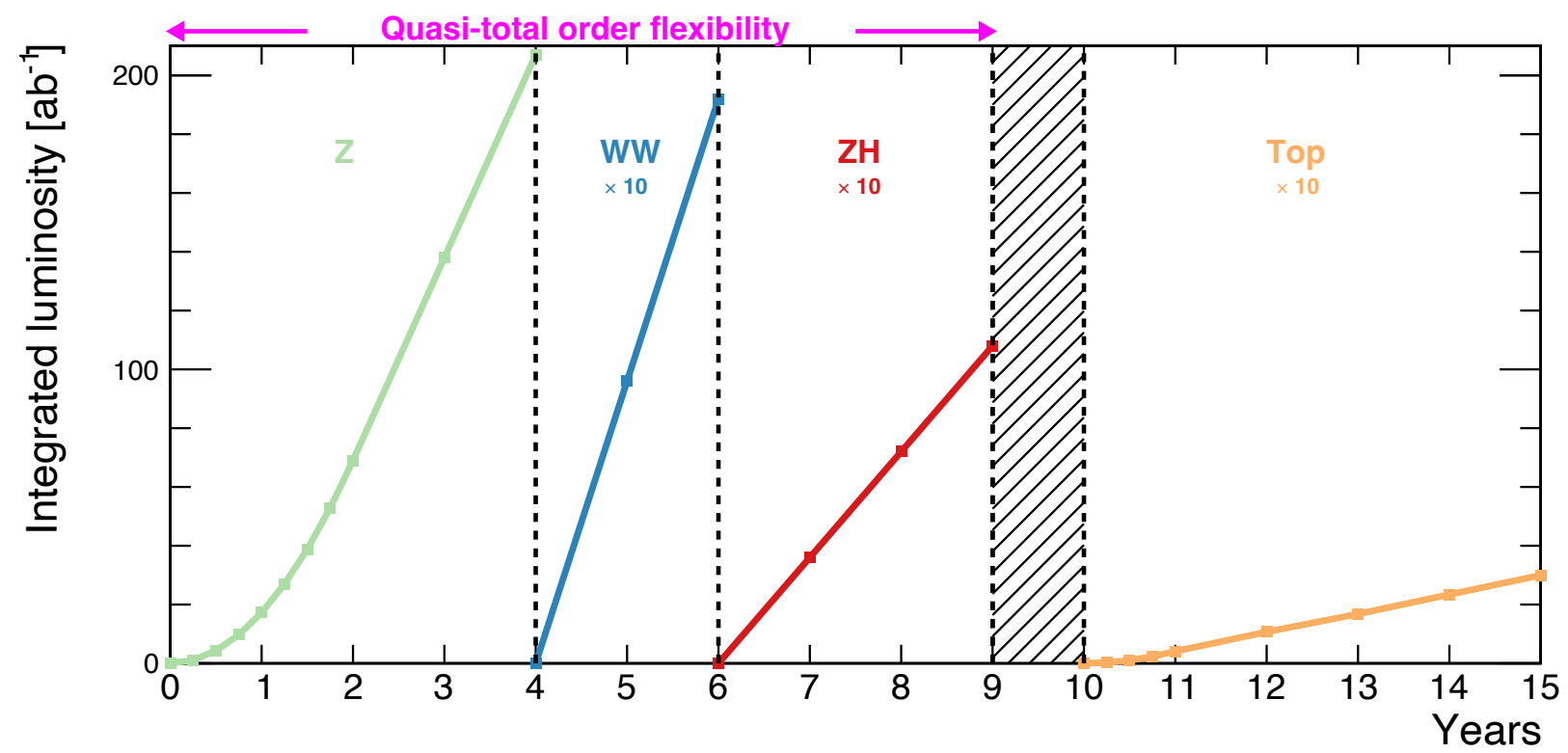
3. The next CERN flagship collider project

- A. The electron–positron Future Circular Collider (FCC-ee) is recommended as the preferred option for the next flagship collider at CERN.*
- B. A descoped FCC-ee is the preferred alternative option for the next flagship collider at CERN.*

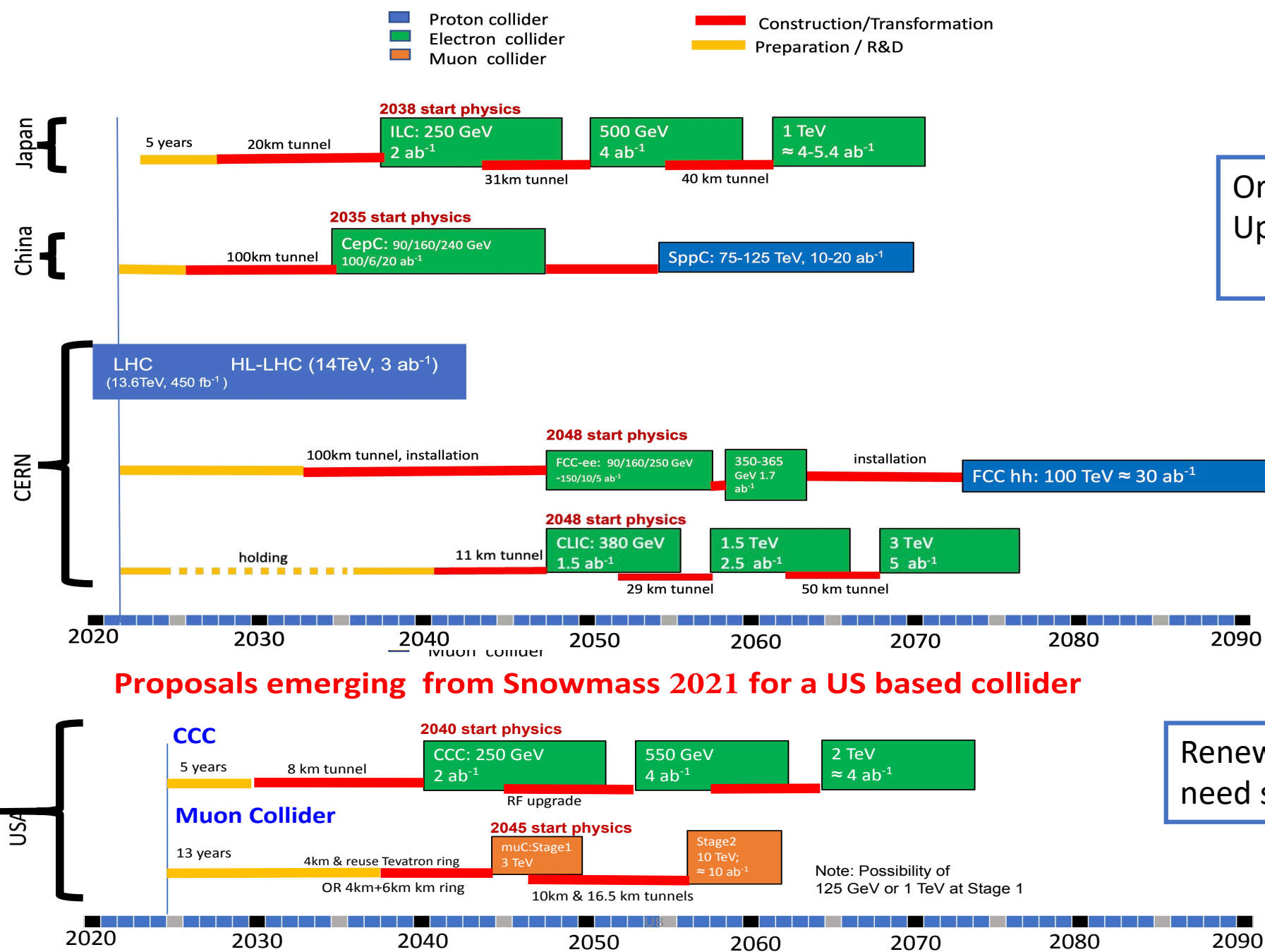


We (theorists) should also keep up!

Extra



Observable	present value	$\pm$	uncertainty	FCC-ee Stat.	FCC-ee Syst.	Comment and leading uncertainty
m_Z (keV)	91 187 600	$\pm$	2000	4	100	From Z line shape scan Beam energy calibration
Γ_Z (keV)	2 495 500	$\pm$	2300	4	12	From Z line shape scan Beam energy calibration
$\sin^2 \theta_W^{\text{eff}} (\times 10^6)$	231,480	$\pm$	160	1.2	1.2	From $A_{\text{FB}}^{\mu\mu}$ at Z peak Beam energy calibration
$1/\alpha_{\text{QED}}(m_Z^2) (\times 10^3)$	128 952	$\pm$	14	3.9 0.8	small tbc	From $A_{\text{FB}}^{\mu\mu}$ off peak From $A_{\text{FB}}^{\mu\mu}$ on peak QED&EW uncert. dominate
$R_\ell^Z (\times 10^3)$	20 767	$\pm$	25	0.05	0.05	Ratio of hadrons to leptons Acceptance for leptons
$\alpha_S(m_Z^2) (\times 10^4)$	1 196	$\pm$	30	0.1	1	Combined R_ℓ^Z , Γ_{tot}^Z , σ_{had}^0 fit
$\sigma_{\text{had}}^0 (\times 10^3)$ (nb)	41 480.2	$\pm$	32.5	0.03	0.8	Peak hadronic cross section Luminosity measurement
$N_v (\times 10^3)$	2 996.3	$\pm$	7.4	0.09	0.12	Z peak cross sections Luminosity measurement
$R_b (\times 10^6)$	216 290	$\pm$	660	0.25	0.3	Ratio of $b\bar{b}$ to hadrons
$A_{\text{FB}}^{b,0} (\times 10^4)$	992	$\pm$	16	0.04	0.04	b-quark asymmetry at Z pole From jet charge
$A_{\text{FB}}^{\text{pol},\tau} (\times 10^4)$	1 498	$\pm$	49	0.07	0.2	τ polarisation asymmetry τ decay physics
τ lifetime (fs)	290.3	$\pm$	0.5	0.001	0.005	ISR, τ mass
τ mass (MeV)	1 776.93	$\pm$	0.09	0.002	0.02	estimator bias, ISR, FSR
τ leptonic ($\mu\nu_\mu\nu_\tau$) BR (%)	17.38	$\pm$	0.04	0.00007	0.003	PID, π^0 efficiency
m_W (MeV)	80 360.2	$\pm$	9.9	0.18	0.16	From WW threshold scan Beam energy calibration
Γ_W (MeV)	2 085	$\pm$	42	0.27	0.2	From WW threshold scan Beam energy calibration
$\alpha_S(m_W^2) (\times 10^4)$	1 010	$\pm$	270	2	2	Combined R_ℓ^W , Γ_{tot}^W fit
$N_v (\times 10^3)$	2 920	$\pm$	50	0.5	small	Ratio of invis. to leptonic in radiative Z returns
m_{top} (MeV)	172 570	$\pm$	290	4.2	4.9	From $t\bar{t}$ threshold scan QCD uncert. dominate
Γ_{top} (MeV)	1 420	$\pm$	190	10	6	From $t\bar{t}$ threshold scan QCD uncert. dominate
$\lambda_{\text{top}}/\lambda_{\text{top}}^{\text{SM}}$	1.2	$\pm$	0.3	0.015	0.015	From $t\bar{t}$ threshold scan QCD uncert. dominate
ttZ couplings		$\pm$	30%	0.5–1.5 %	small	From $\sqrt{s} = 365$ GeV run

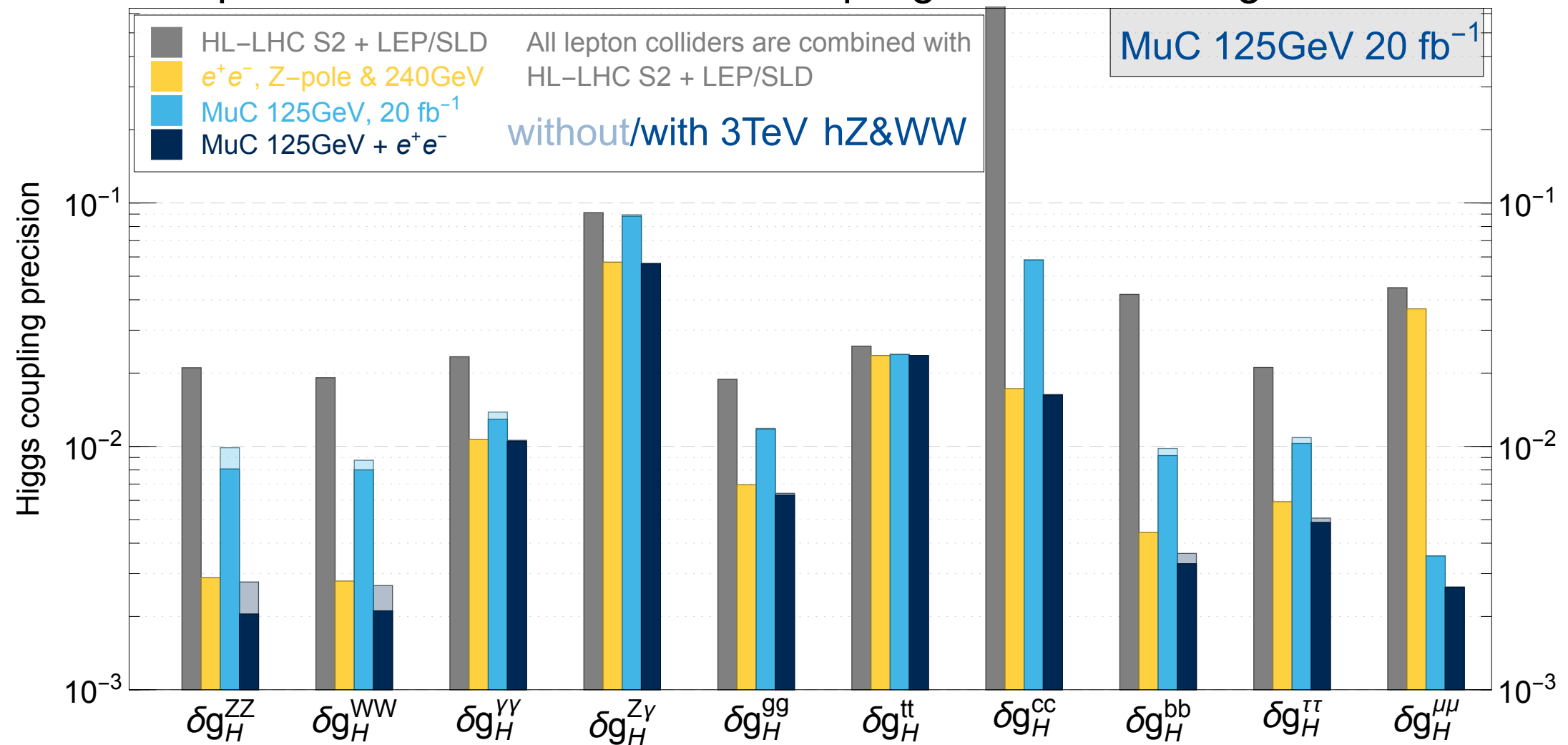


Original timeline from ESG
Updated during Snowmass 2021
(see EF Report)

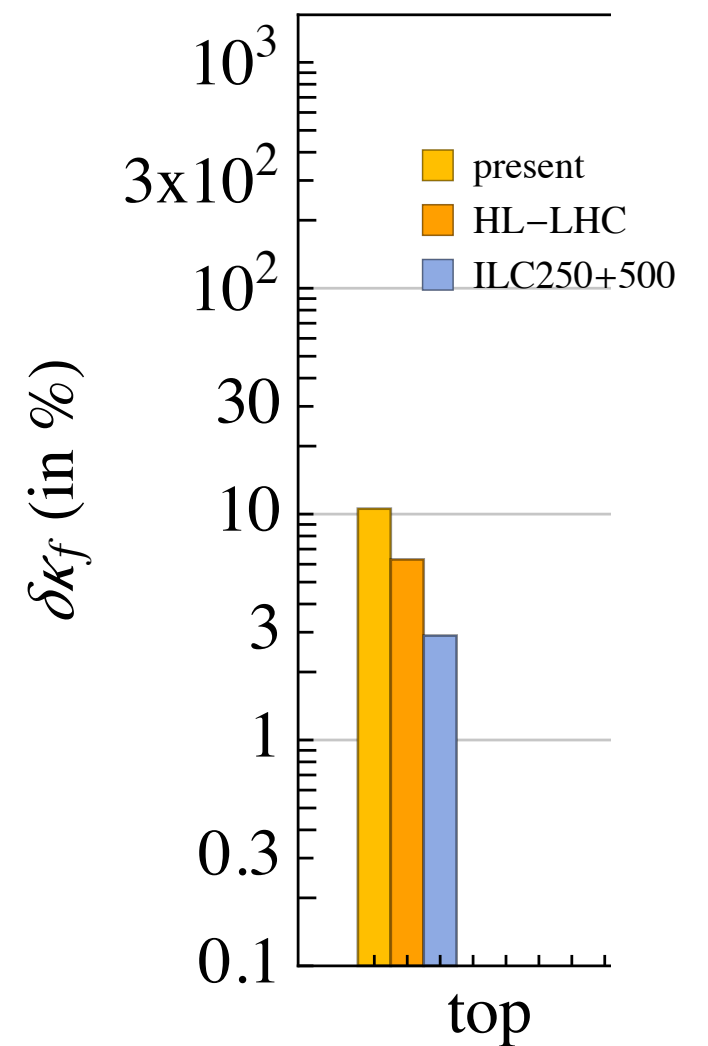
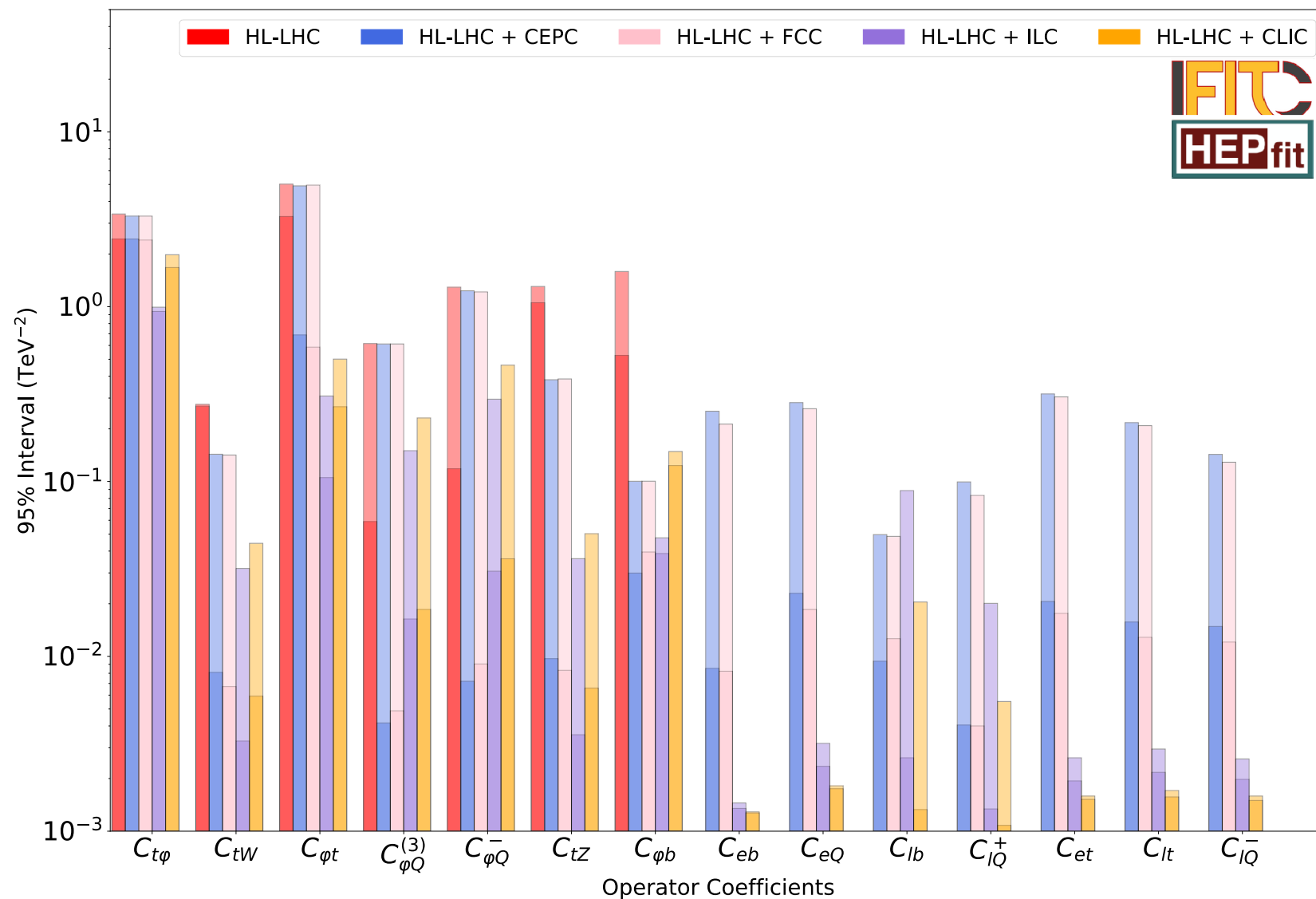
Renewed interest in lepton colliders:
need supporting R&D in near future

Muon Collider 125

precision reach on effective couplings from full EFT global fit

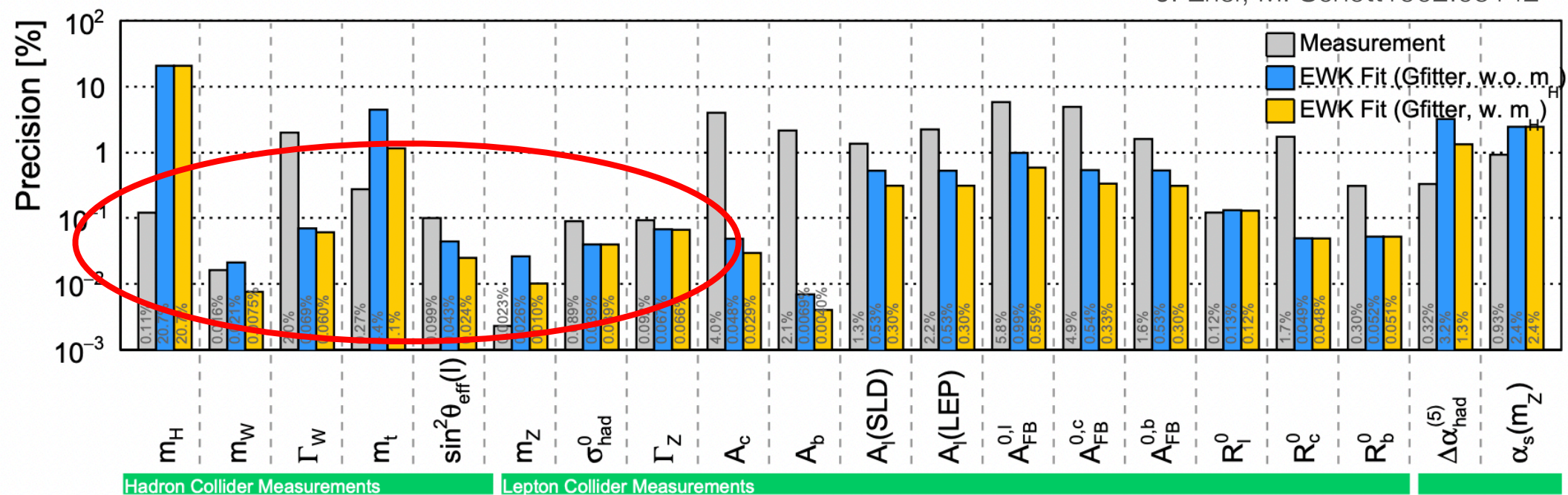


Top quark coupling



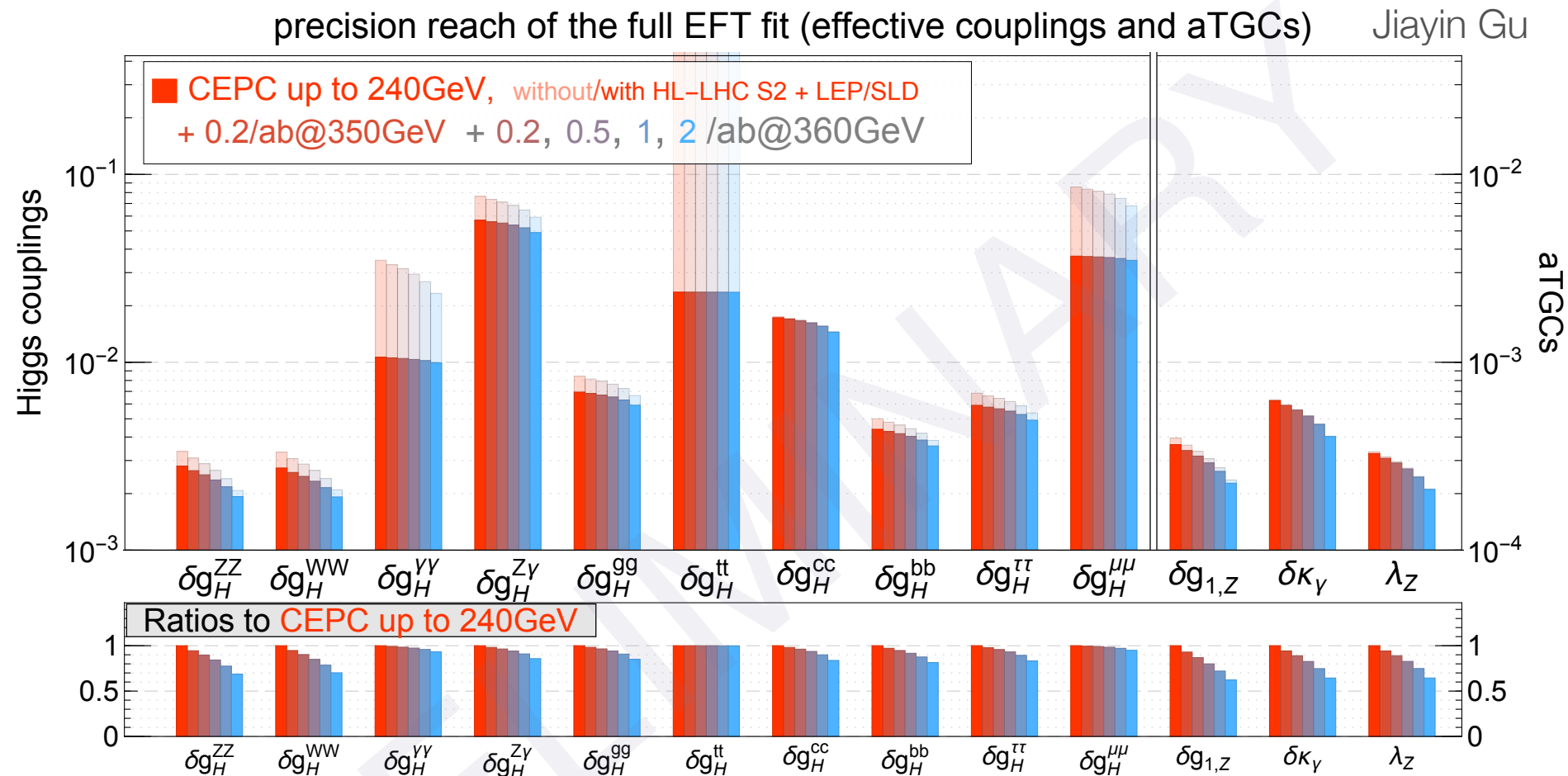
SM precision

J. Erler, M. Schott 1902.05142



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

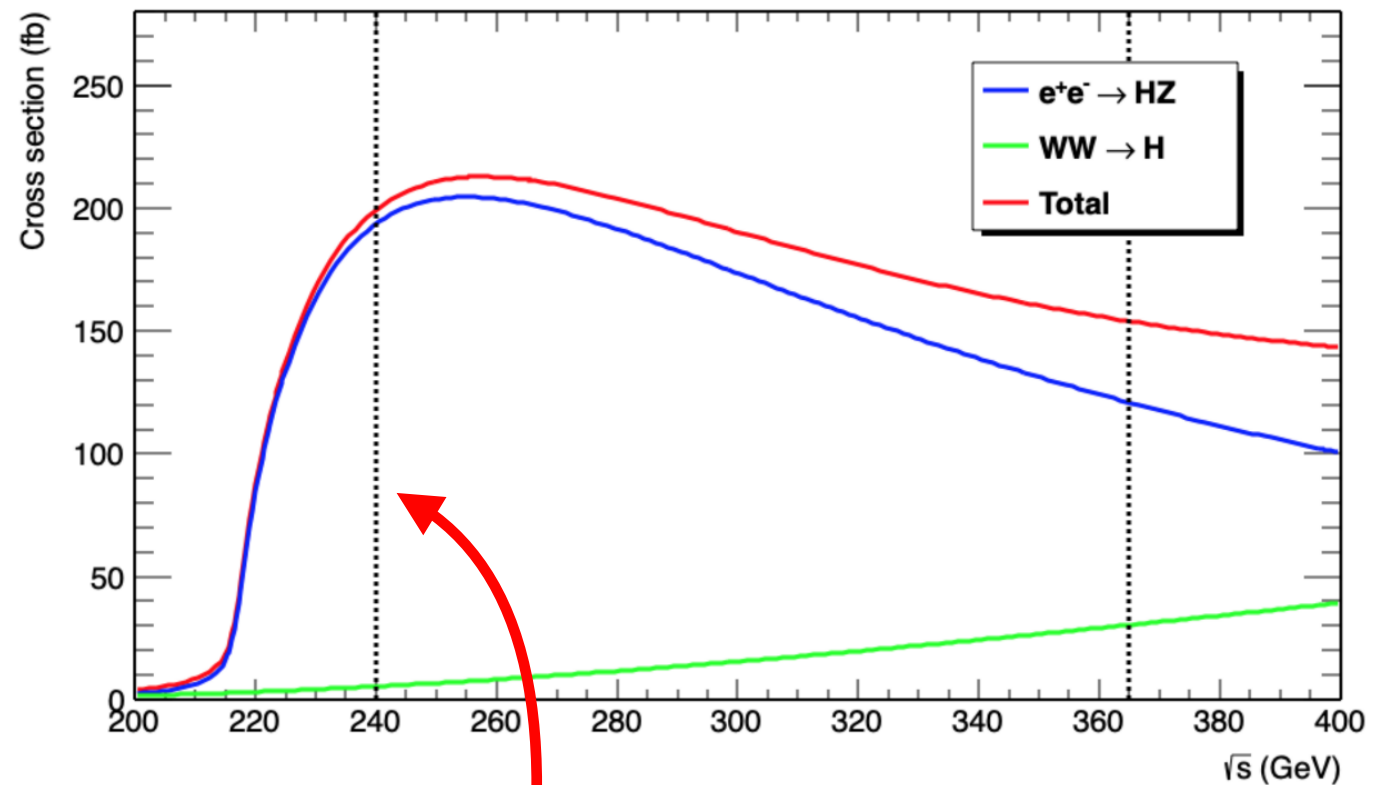
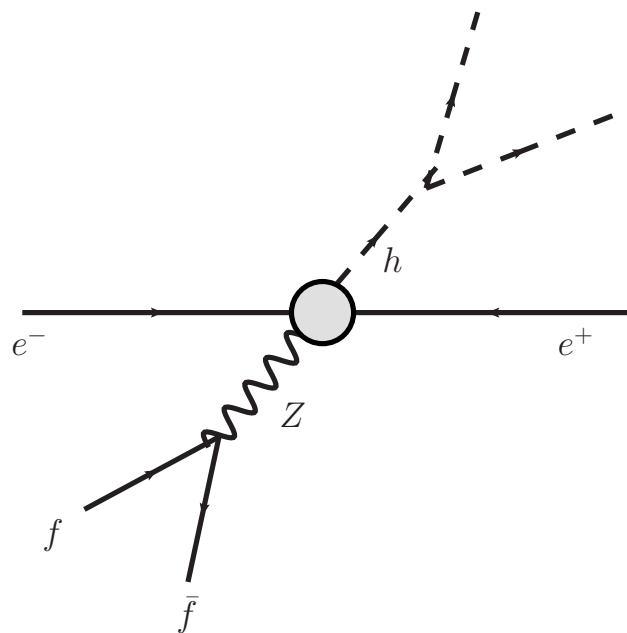
Better at higher energies



Gain up to a factor of a few

Even better if one can run at even higher energies.

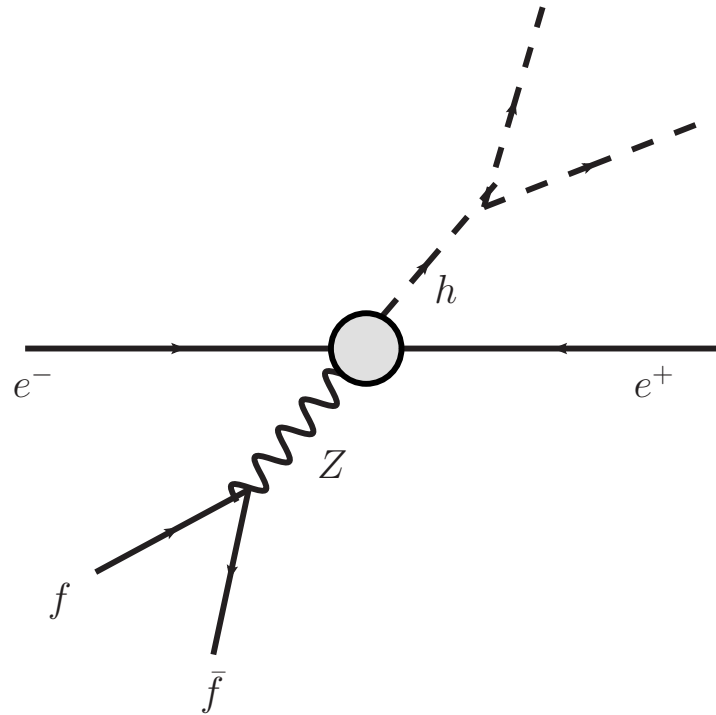
Why e^+e^- Higgs factory?



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

“Sweet spot”, most Higgs produced

Why e^+e^- Higgs factory?

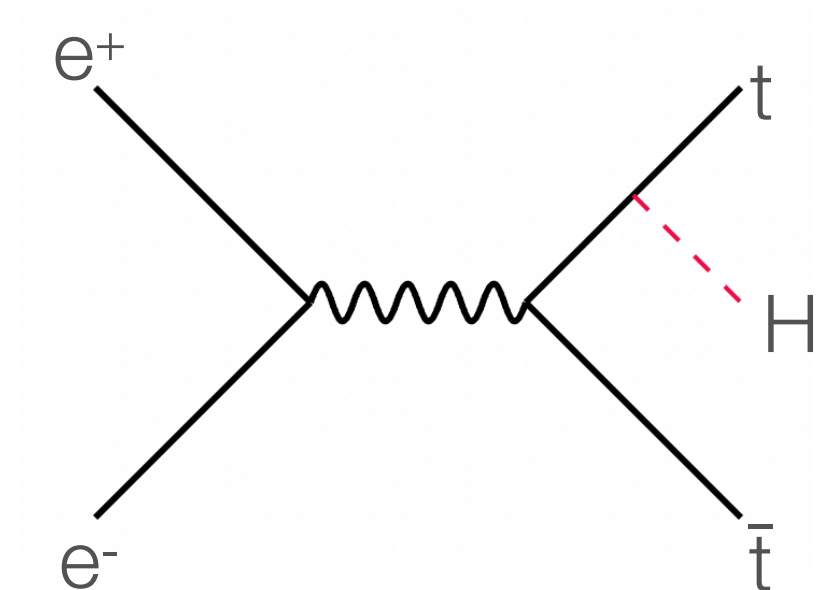
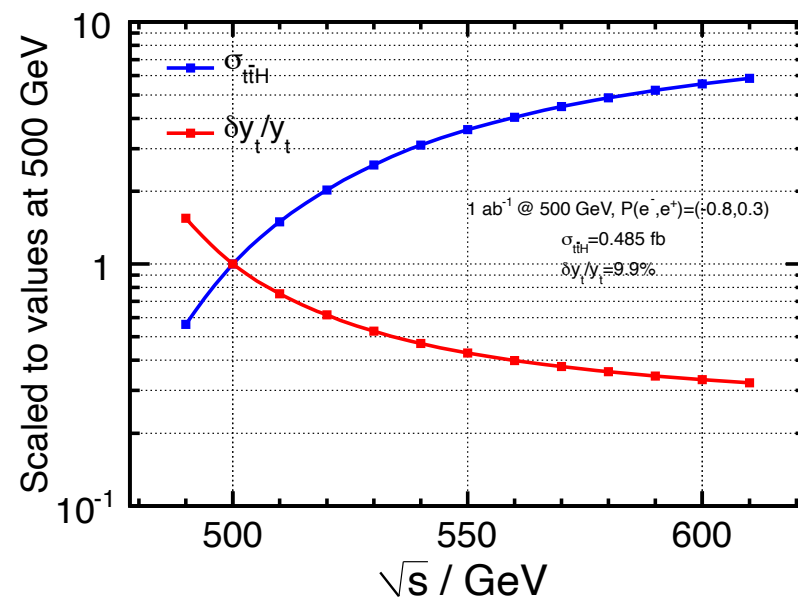
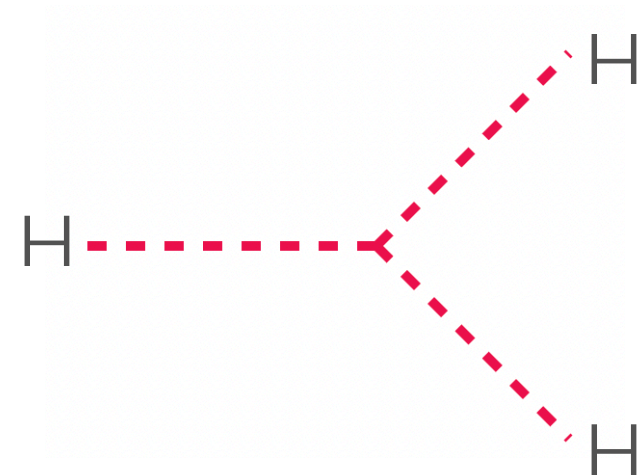
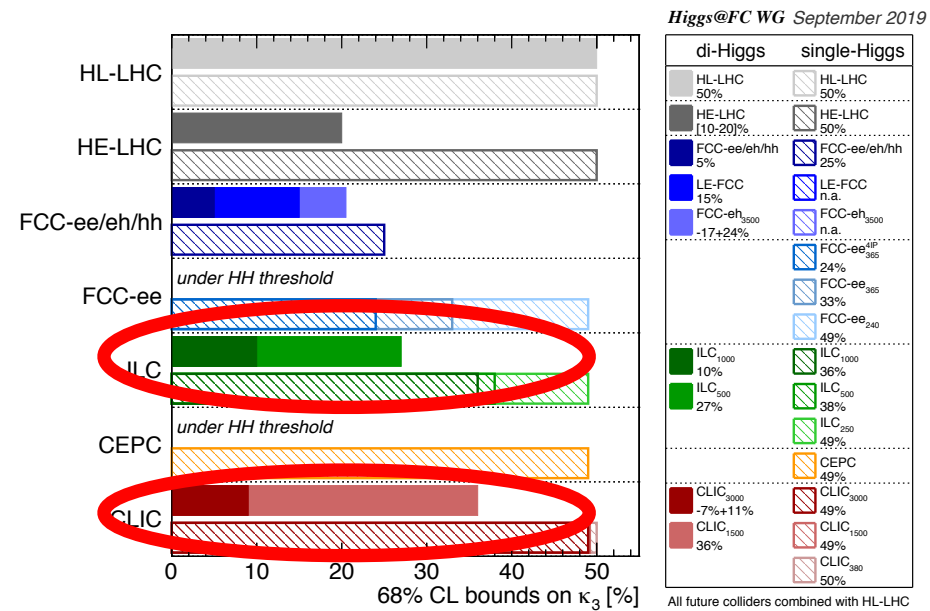


$$\Gamma_H \propto \frac{\Gamma(H \rightarrow ZZ^*)}{\text{BR}(H \rightarrow ZZ^*)} \propto \frac{\sigma(ZH)}{\text{BR}(H \rightarrow ZZ^*)}$$

A precise total width measurement is possible.

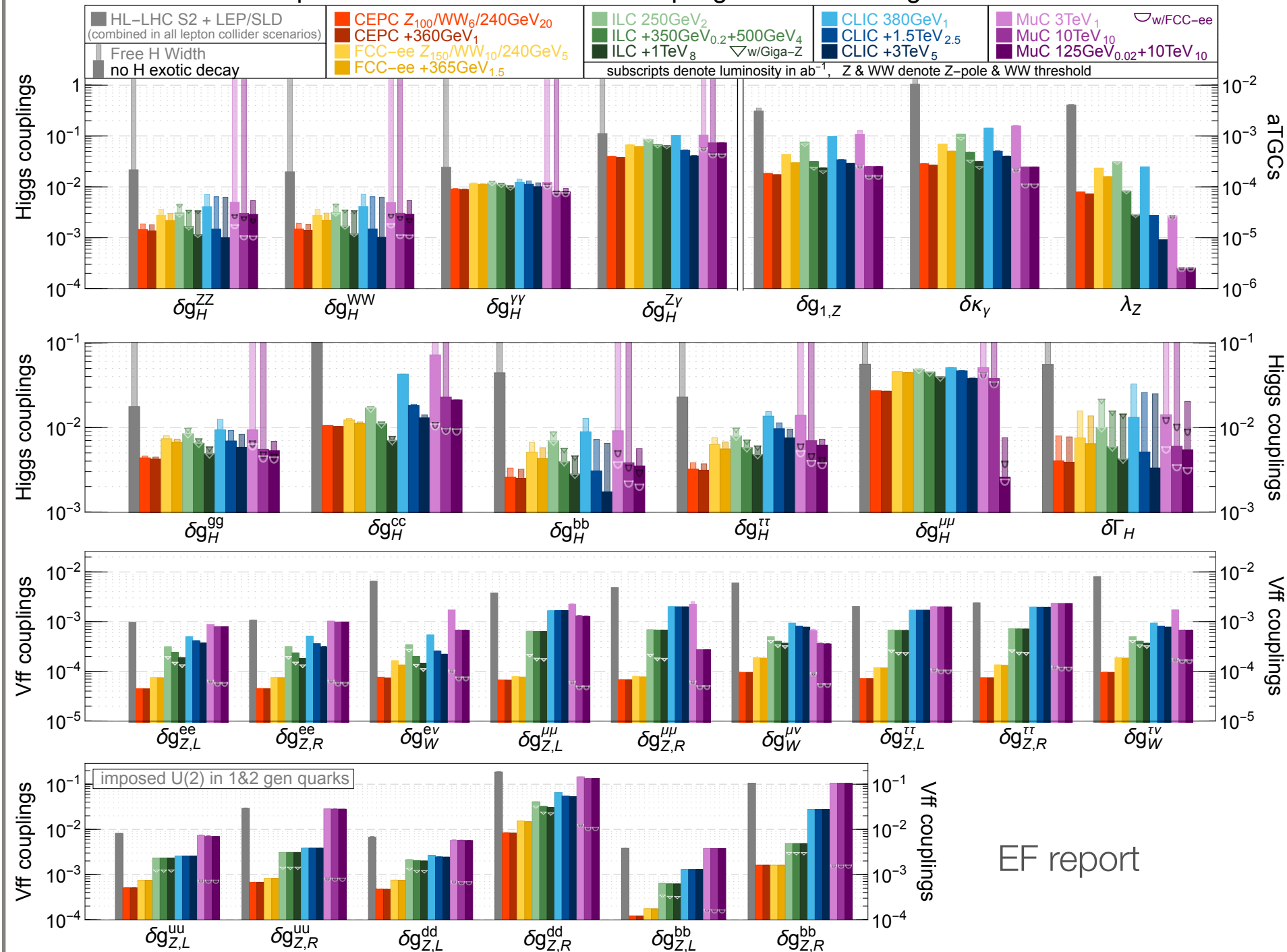
1. An important Higgs property.
2. Crucial in interpreting other Higgs measurements.

At higher energies



A full suite of measurements

precision reach on effective couplings from SMEFT global fit



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