Snowmass EF1/EF2 “Higgs Report” Theory

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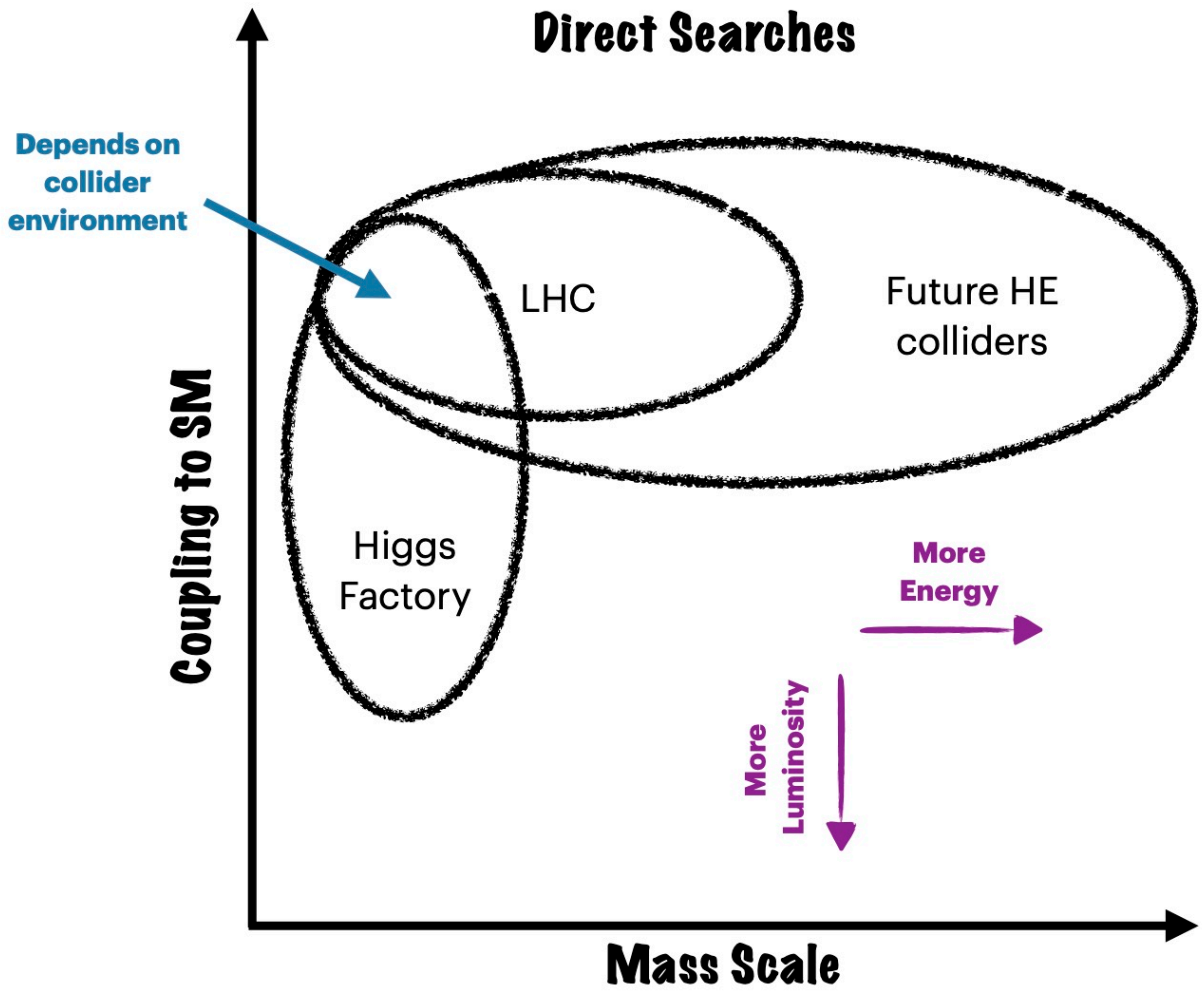
“Theory Side”

- Why we care about the Higgs and studying its properties in more details
- What theory is needed to understand the Higgs
- BSM side
  - What do we expect for Higgs precision
  - What can we say about BSM scenarios involving the Higgs
  - Complementarity of direct and indirect searches involving the Higgs

(See also tomorrow’s TF-EF cross frontier session)

Another way of saying this, take the section 2.2 of the EF report and apply it to the Higgs!



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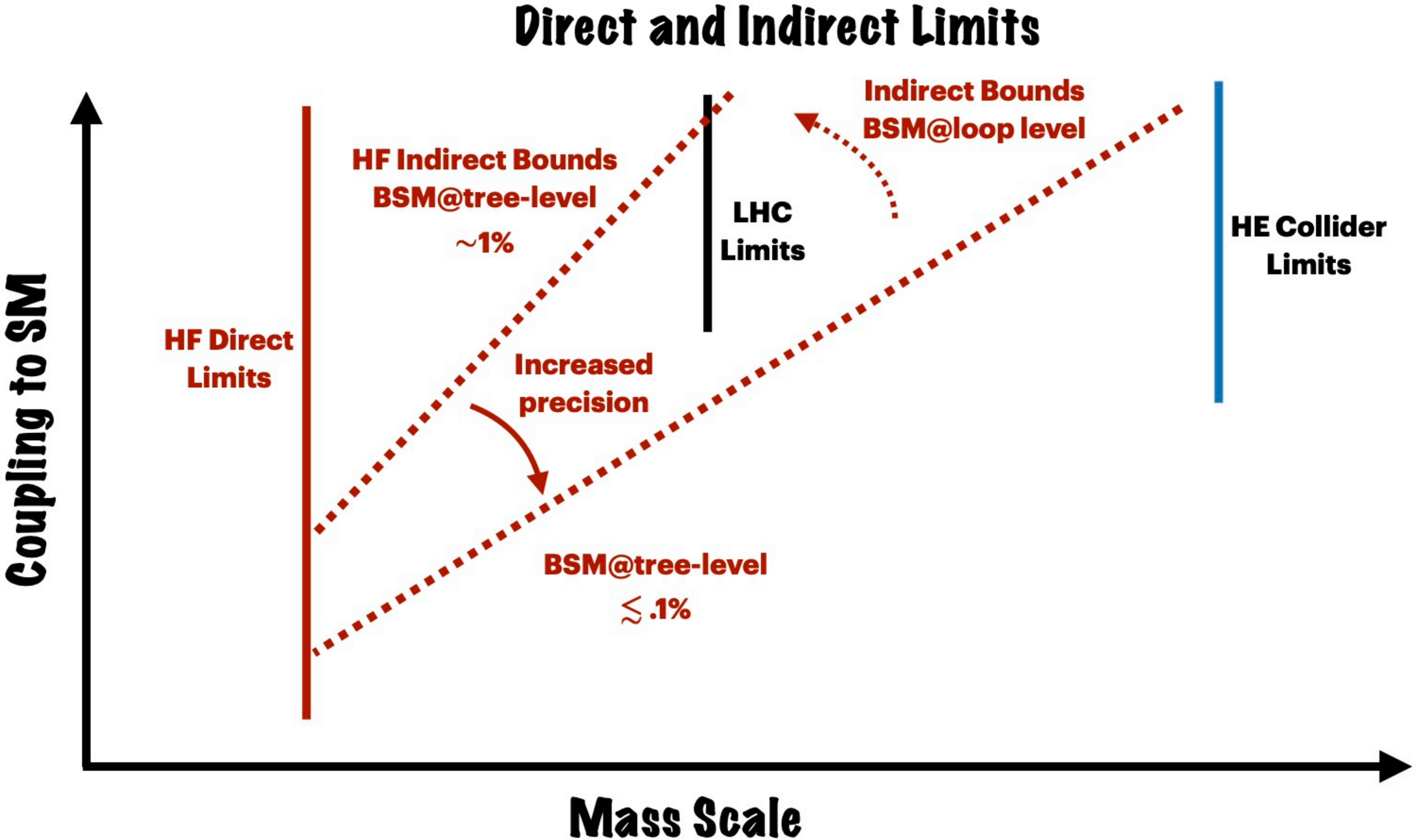
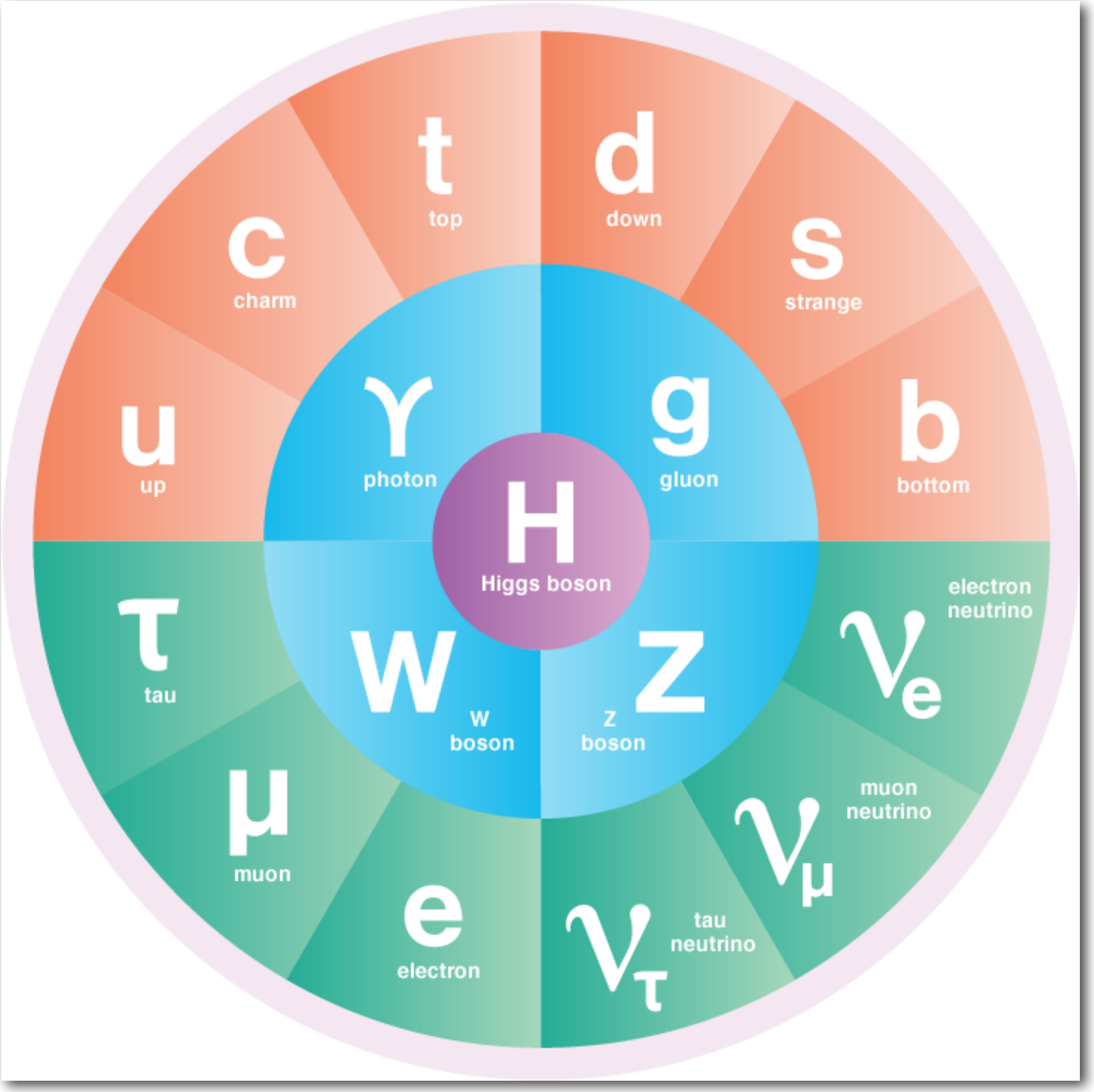


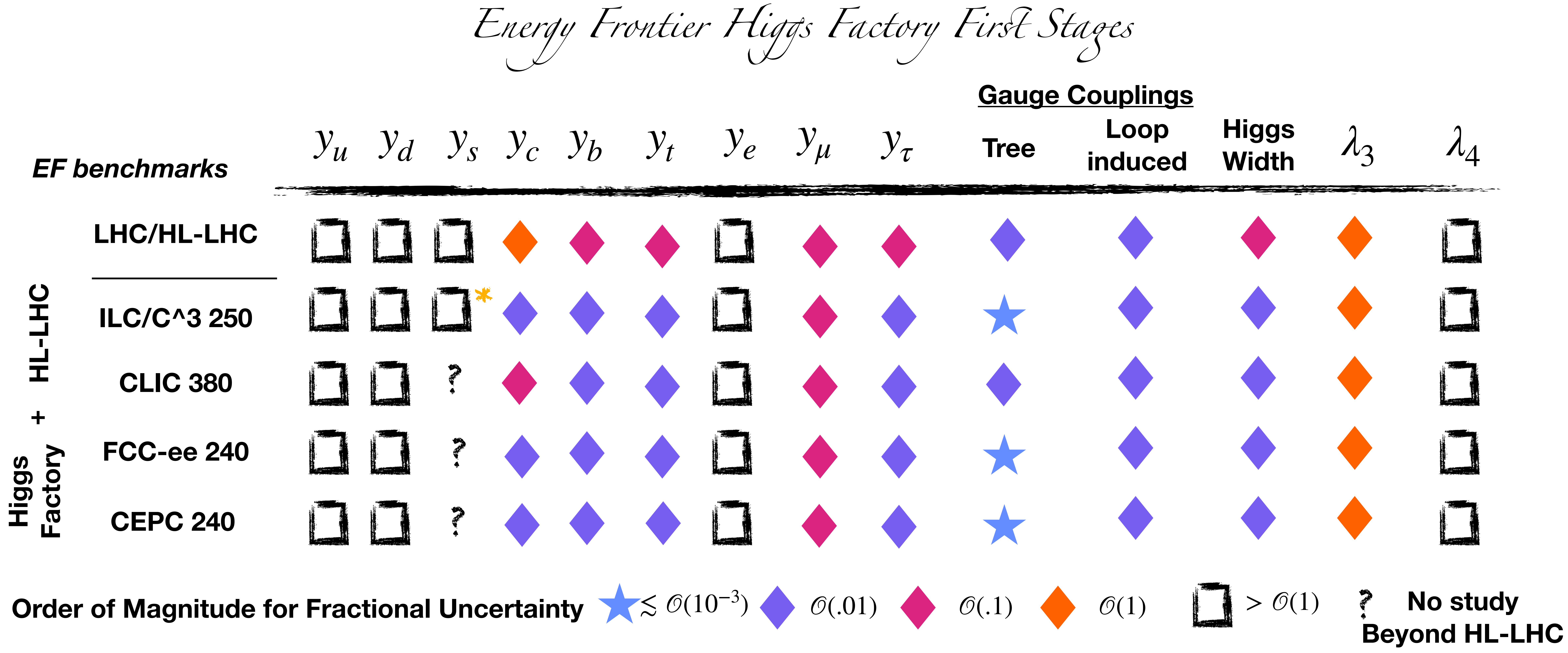
Why are you here? Because hopefully we all know the Higgs is the most unique ***AND*** central player in the Standard Model



We've all probably seen this figure with the Higgs being the last piece of the SM and now we're done?

Absolutely not! After all you just saw all the myriad of updated projections in Isobel's talk… But what do they mean? And when is it enough?

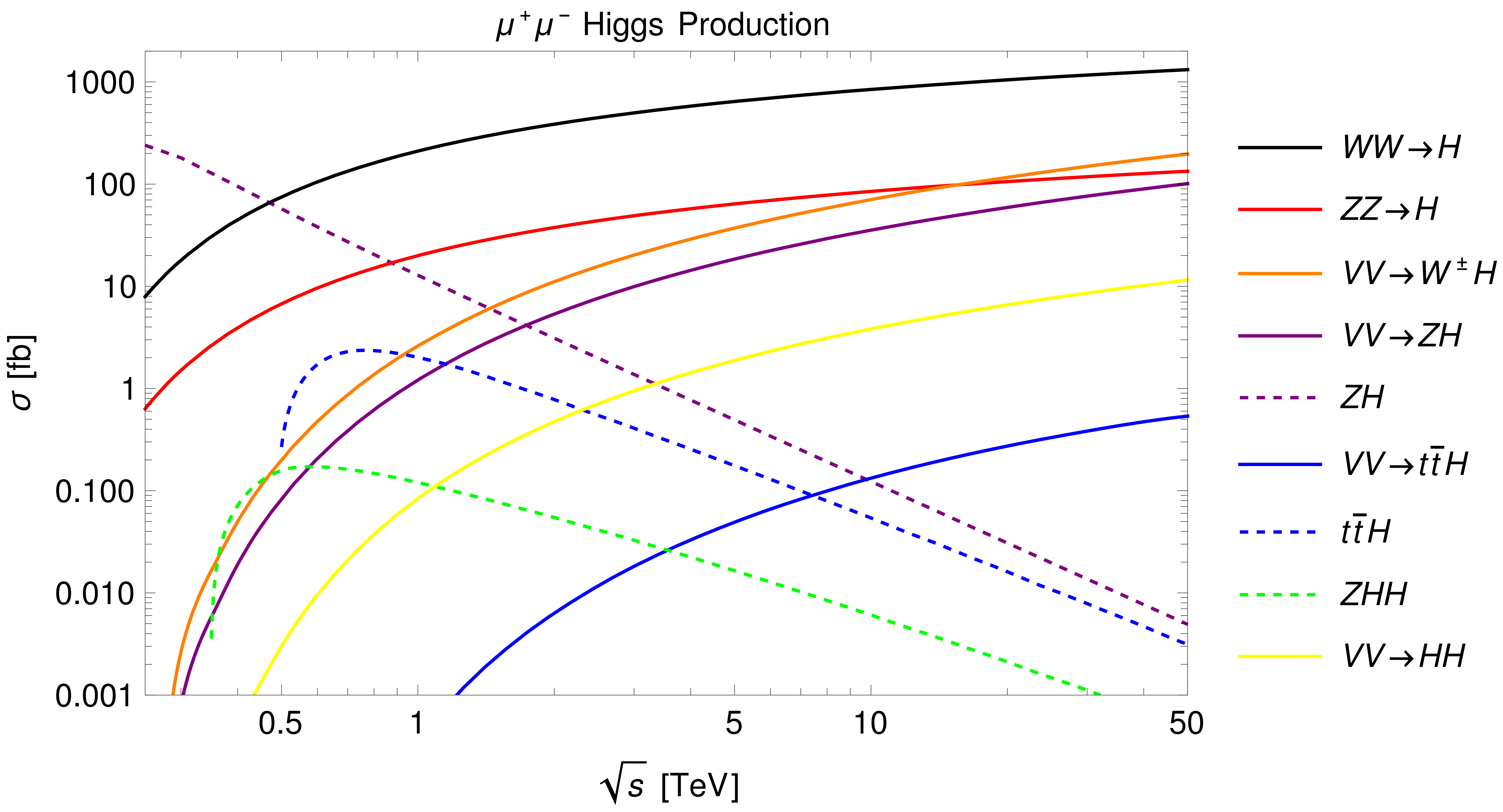
For example we can take a snapshot of all of the many many bar charts - after the first stages of proposed Higgs Factories



Clearly many parameters greatly improve compared to HL-LHC, but also many don’t even achieve O(1) accuracy

Okay, but that's just the first stages, what about our most futuristic plans at higher energies that have been studied during Snowmass?

More energy = More Higgses



This is for lepton colliders, but also true for hadron colliders, e.g. we have more gluons at lower x

How Many Higgs??

Take this with many grains of salt...

HL-LHC $\sim .35 \times 10^9$ End of LHC ~ O(100) million Higgses!

ILC250/350 $\sim .6 \times 10^6$

FCC-ee 240/365 $\sim 1.2 \times 10^6$

CEPC 240 $\sim 1.1 \times 10^6$

CLIC-380 $\sim .2 \times 10^6$

} Low energy e+e- Higgs factories
~ 1 million Higgs

ILC500/1000 $\sim 4.5 \times 10^6$

CLIC 1500/3000 $\sim 3.4 \times 10^6$

} Moderate energy e+e- Higgs factories
~ few million Higgs

FCC-hh $\sim 27 \times 10^9$ 27 billion Higgses

ESG run plans 1905.03764

Collider	Type	$\sqrt{s}$	$\mathscr{P}$ [%] $[e^-/e^+]$	N(Det.)	$\mathscr{L}_{\text{inst}}$ $[10^{34}]$ $\text{cm}^{-2}\text{s}^{-1}$	$\mathscr{L}$ $[\text{ab}^{-1}]$	Time [years]	Refs.	Abbreviation
HL-LHC	pp	14 TeV	-	2	5	6.0	12	[13]	HL-LHC
HE-LHC	pp	27 TeV	-	2	16	15.0	20	[13]	HE-LHC
FCC-hh$^{(*)}$	pp	100 TeV	-	2	30	30.0	25	[1]	FCC-hh
FCC-ee	ee	M_Z	0/0	2	100/200	150	4	[1]	
		$2M_W$	0/0	2	25	10	1-2		
		240 GeV	0/0	2	7	5	3		FCC-ee_{240}
		$2m_{top}$	0/0	2	0.8/1.4	1.5	5		FCC-ee_{365}
							(+1)		(1y SD before $2m_{top}$ run)
ILC	ee	250 GeV	±80/±30	1	1.35/2.7	2.0	11.5	[3, 14]	ILC_{250}
		350 GeV	±80/±30	1	1.6	0.2	1		ILC_{350}
		500 GeV	±80/±30	1	1.8/3.6	4.0	8.5		ILC_{500}
							(+1)		(1y SD after 250 GeV run)
		1000 GeV	±80/±20	1	3.6/7.2	8.0	8.5	[4]	ILC_{1000}
							(+1-2)		(1-2y SD after 500 GeV run)
CEPC	ee	M_Z	0/0	2	17/32	16	2	[2]	CEPC
		$2M_W$	0/0	2	10	2.6	1		
		240 GeV	0/0	2	3	5.6	7		
CLIC	ee	380 GeV	±80/0	1	1.5	1.0	8	[15]	CLIC_{380}
		1.5 TeV	±80/0	1	3.7	2.5	7		CLIC_{1500}
		3.0 TeV	±80/0	1	6.0	5.0	8		CLIC_{3000}
							(+4)		(2y SDs between energy stages)
LHeC	ep	1.3 TeV	-	1	0.8	1.0	15	[12]	LHeC
HE-LHeC	ep	1.8 TeV	-	1	1.5	2.0	20	[1]	HE-LHeC
FCC-eh	ep	3.5 TeV	-	1	1.5	2.0	25	[1]	FCC-eh

Speculative high energy options (run plans specified here)

Muon (or electron colliders)

6 TeV 4/ab $\sim 3.2 \times 10^6$

10 TeV 10/ab $\sim 9.5 \times 10^6$

14 TeV 20/ab $\sim 22 \times 10^6$

30 TeV 90/ab $\sim .12 \times 10^9$

100 TeV 100/ab $\sim .18 \times 10^9$

Millions to 100s of millions

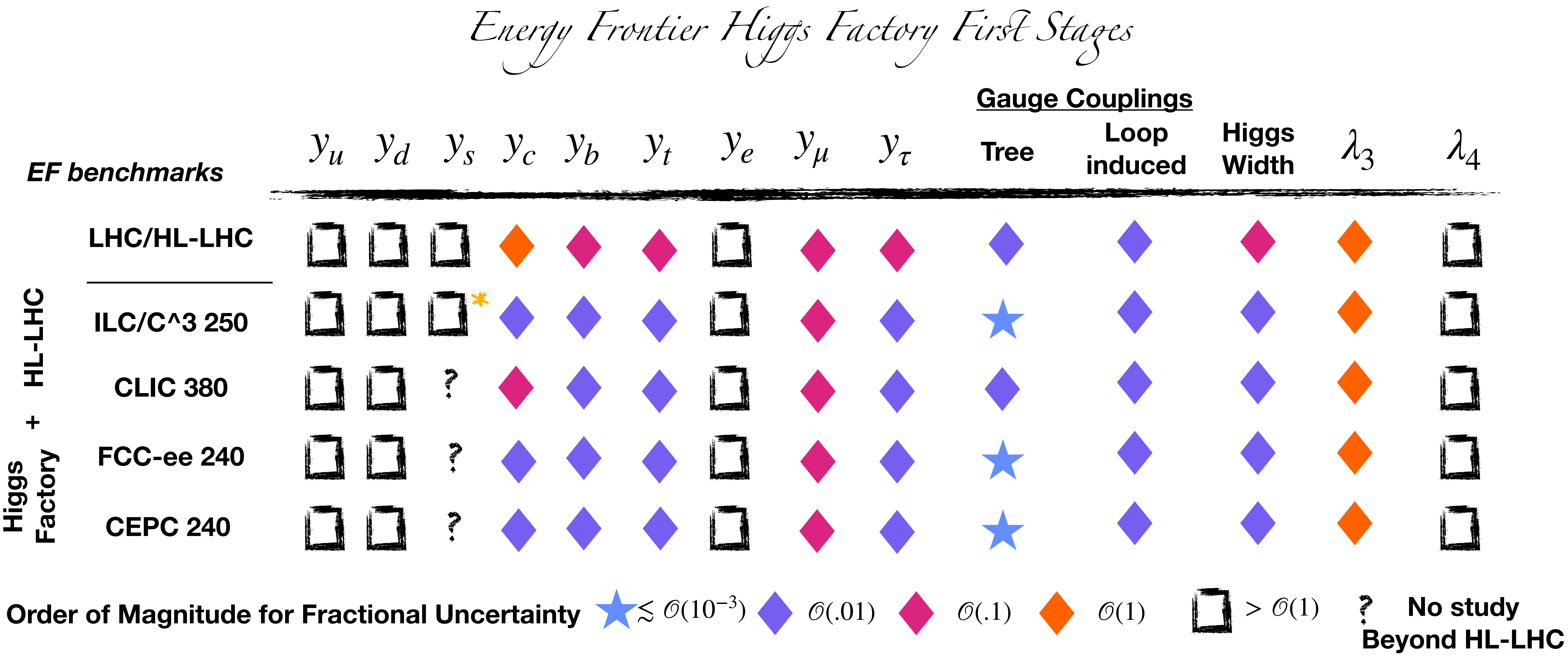
Collider in the sea

500 TeV 50/ab $\sim 400 \times 10^9$ Can approach a trillion Higgs

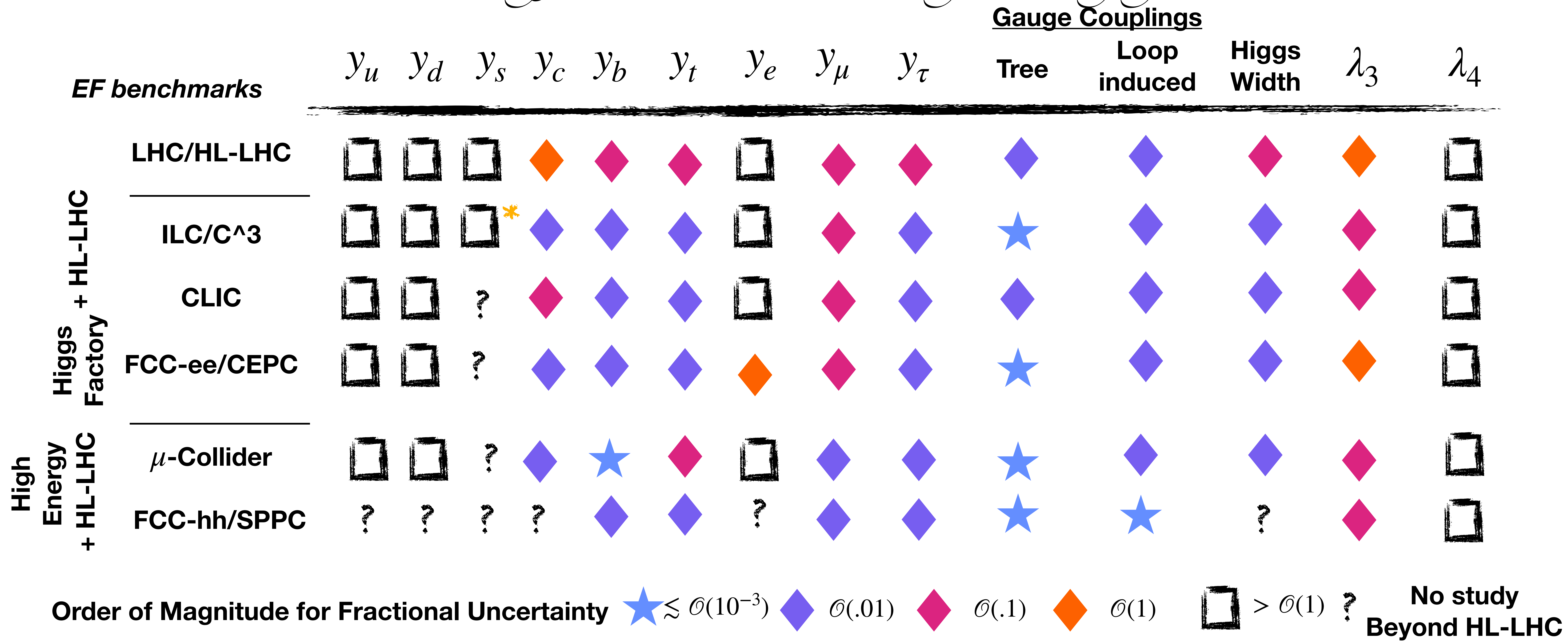
Different energies access different dominant processes (different physics you can access), have different experimental challenges

This is to understand orders of magnitude and what you *could* do *if* you could exploit them all!

Not surprising from this perspective why we have the same rough starting point with similar detector environs



Energy Frontier Benchmarks Integrated Staging



Big improvement with Energy, but also the SM is not even close to “complete” so we *must* press forwards

One thing to keep in mind always…

Gauge bosons are egalitarian

The Higgs is not.

LEP 17 M Z's

"Major" BFs $\mathcal{O}(\%)$

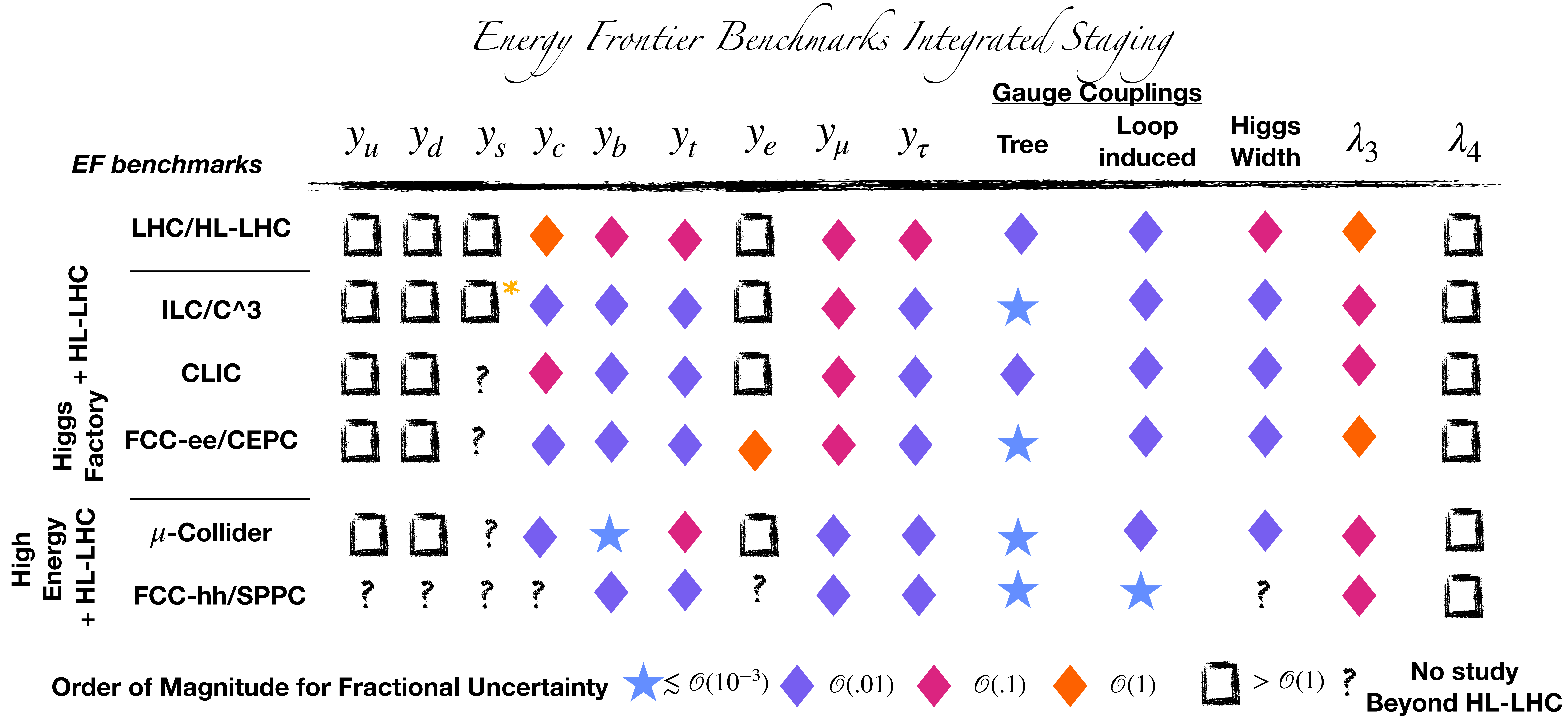
Higgs Factory $\mathcal{O}(1)$ M H's

"Major" $\gamma\gamma \sim 10^{-3}$ $\sim 10^{3}$ events

$\mu\mu \sim 10^{-4}$ $\sim 10^{2}$ events

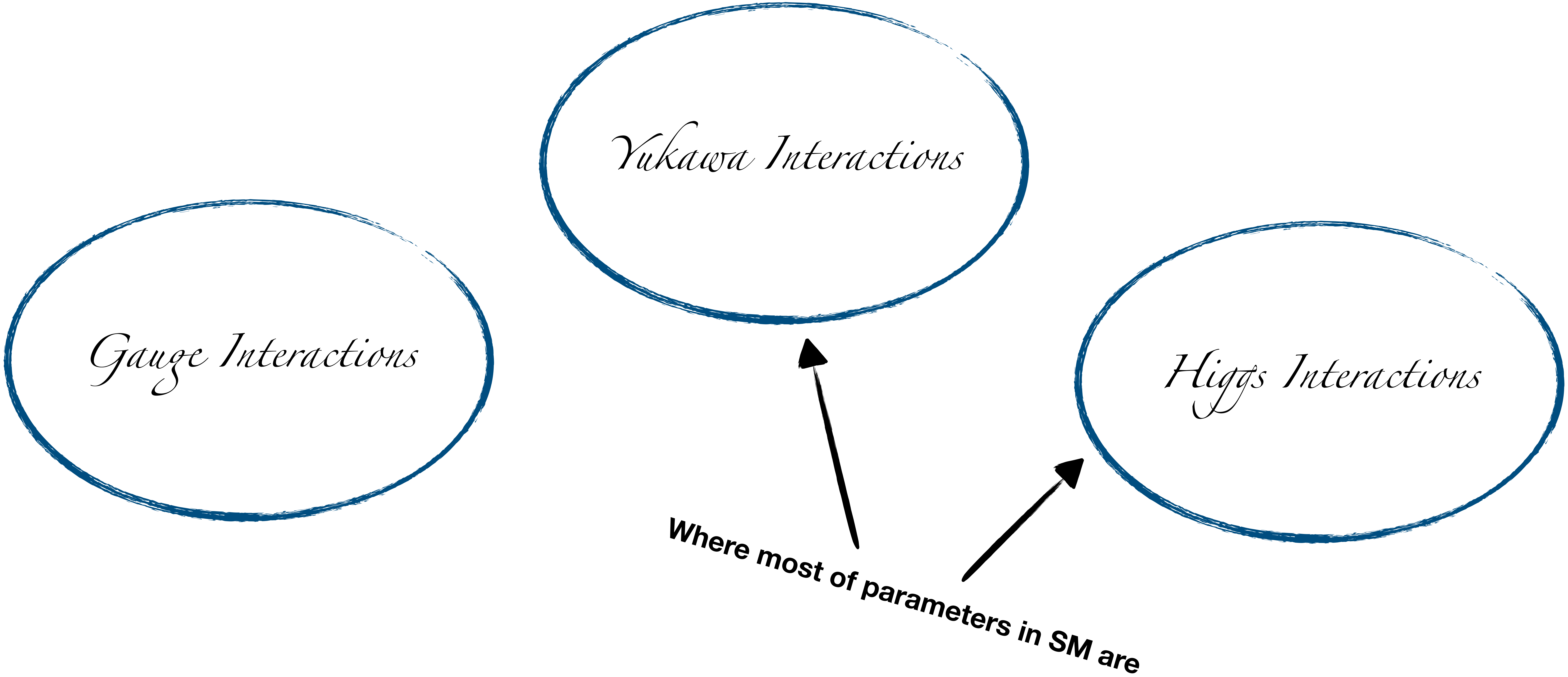
$ss \sim 10^{-4}$

$u/d/e \sim 10^{-8}$ CRAP!!



So what precision is enough?

Zeroth order answer… whenever we find a deviation!



Remember that *any* deviation implies new physics

Although parameters from Higgs are arbitrary the structure is delicately balanced once set

Therefore *any* deviation points to a scale where there *must* be new physics

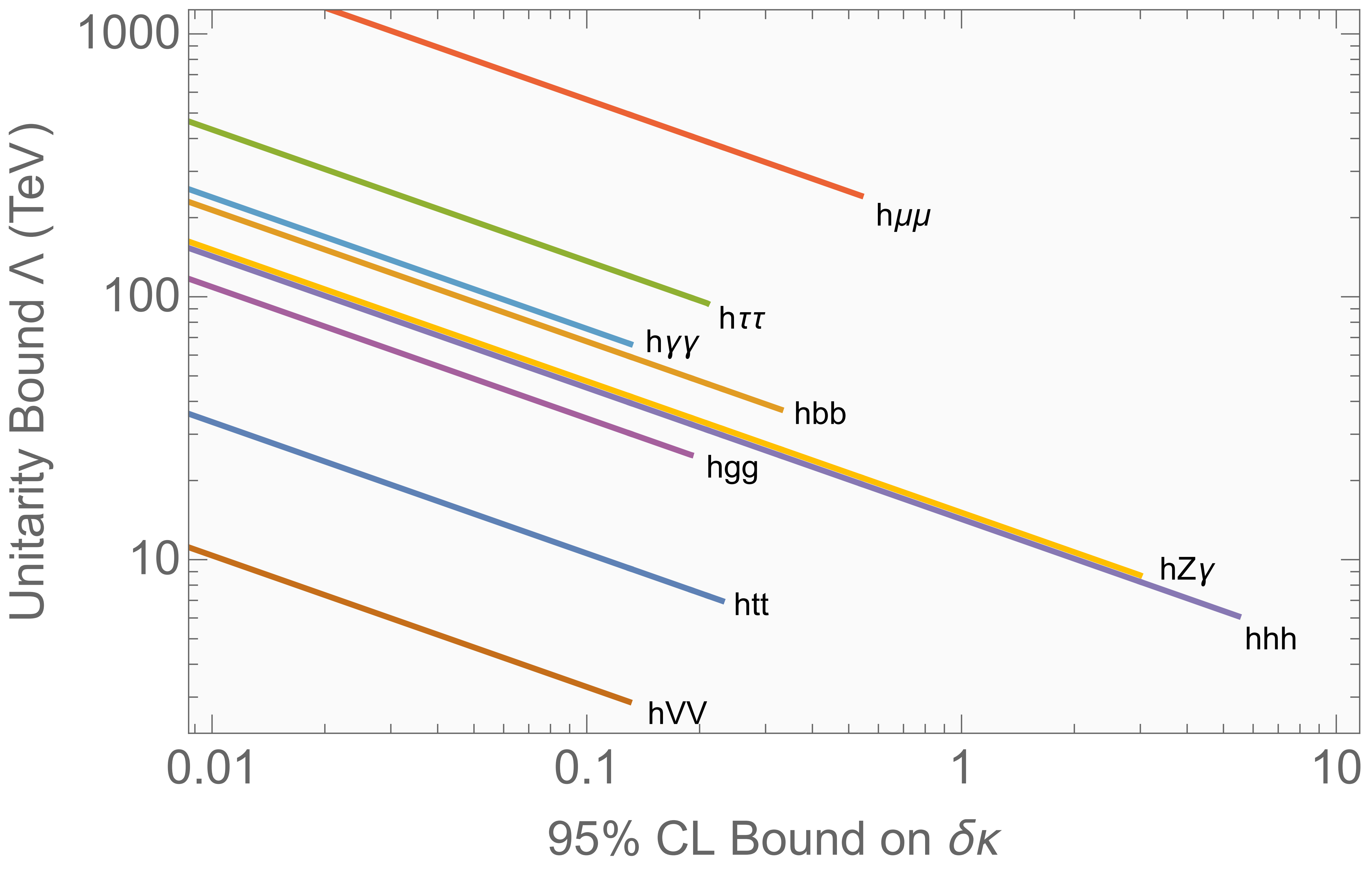


FIG. 27: Scale where unitarity is violated as a function of precision of Higgs coupling measurements. The bound is typically only saturated in strongly interacting scenarios and in specific models tends to be significantly lower.[77].

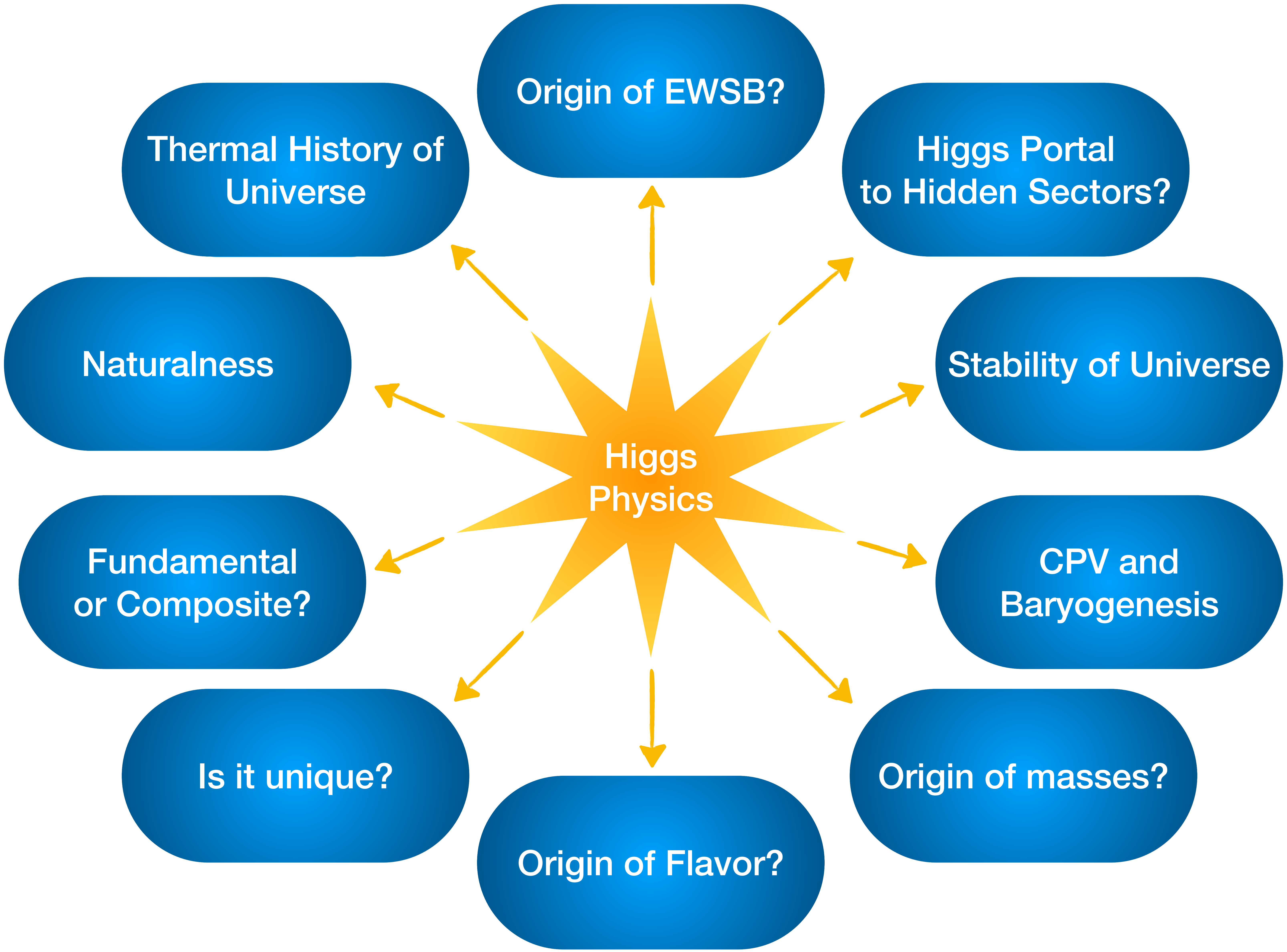
Similar to Lee-Quigg-Thacker Bounds that said the Higgs had to be there…

The reverse of this shouldn’t inspire doubt though…

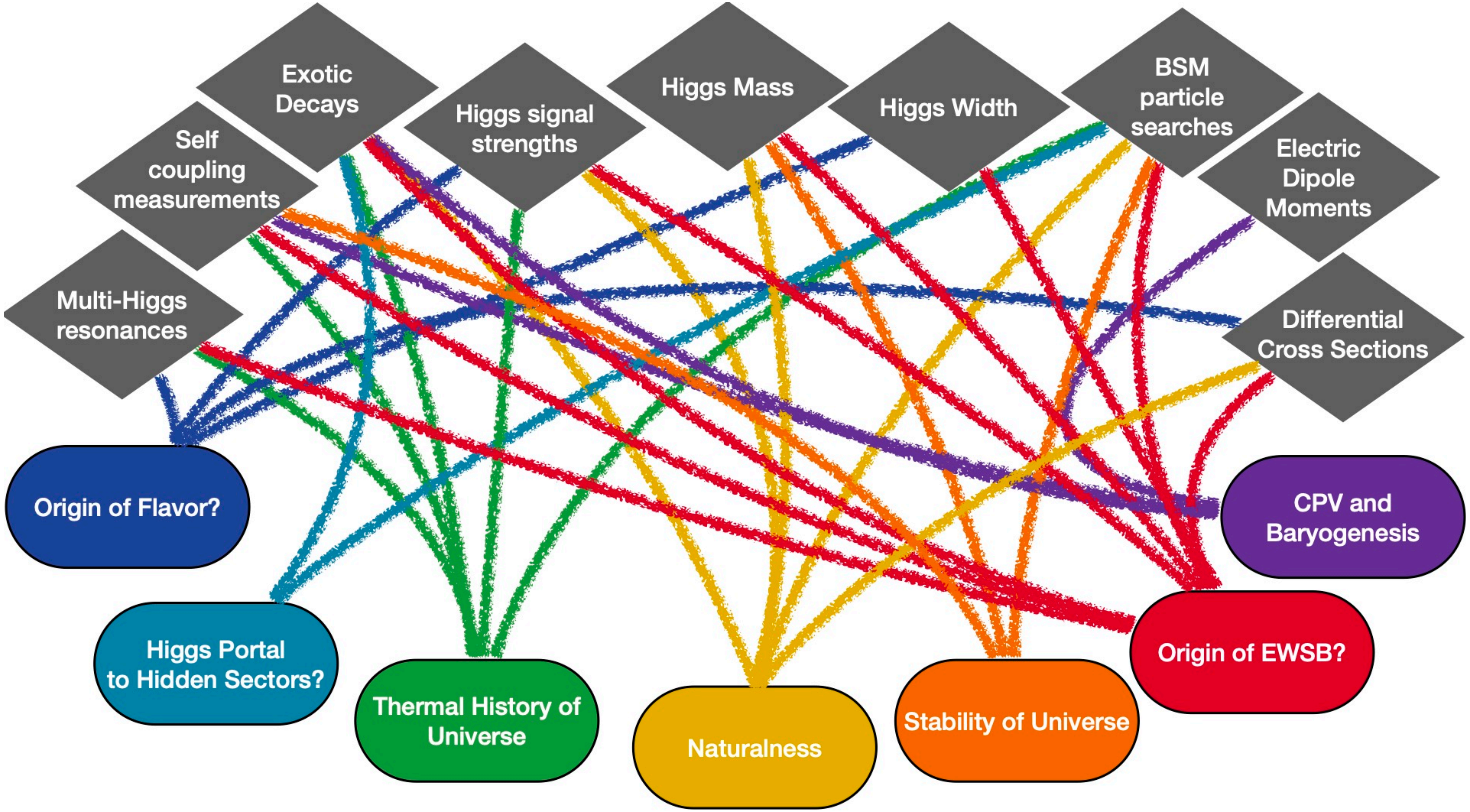
If we don’t see a deviation in the muon Yukawa this doesn’t mean all new physics is above 100 TeV!

Are there targets? Are there expected deviation sizes?

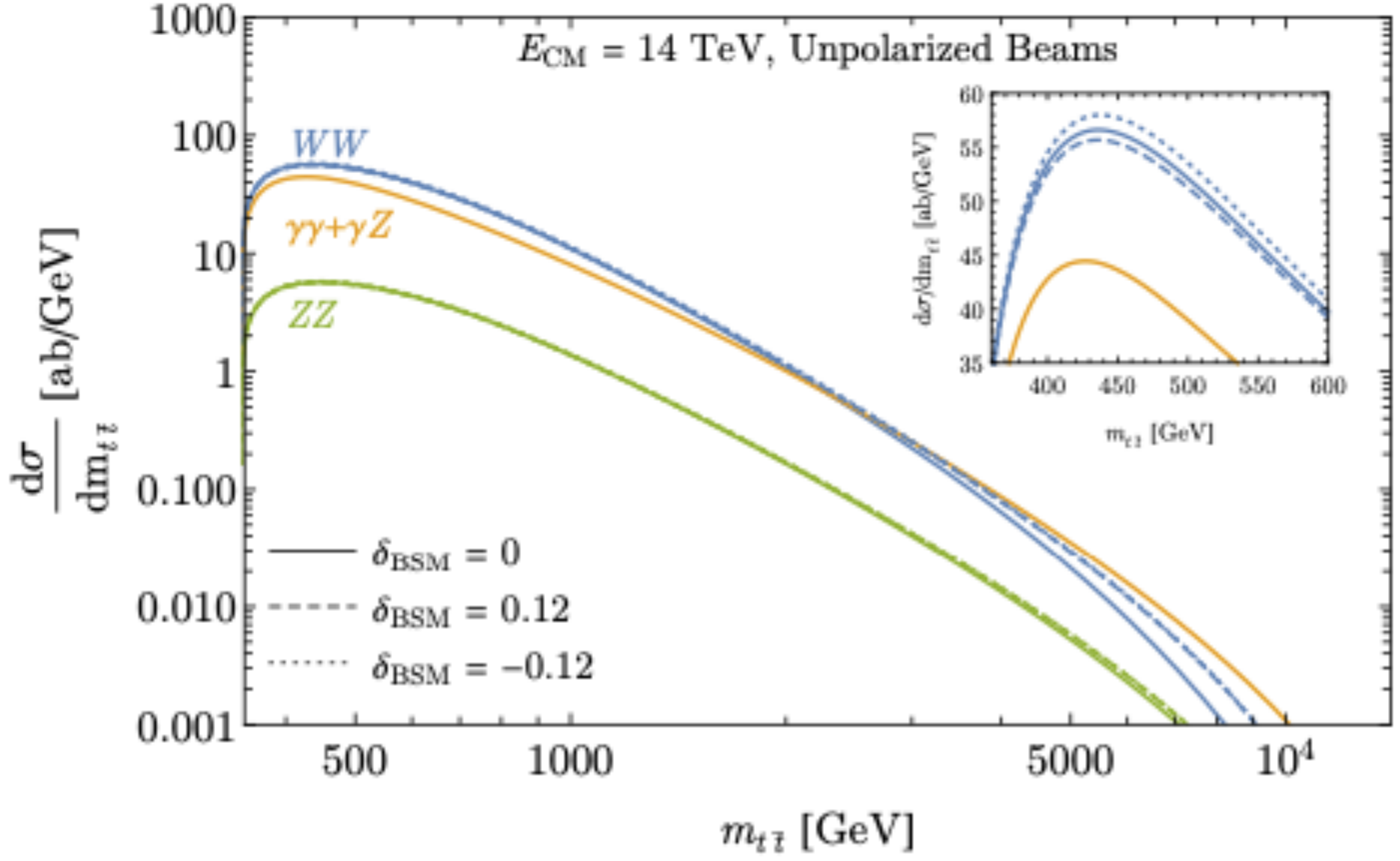
Why is the Higgs so central and important?

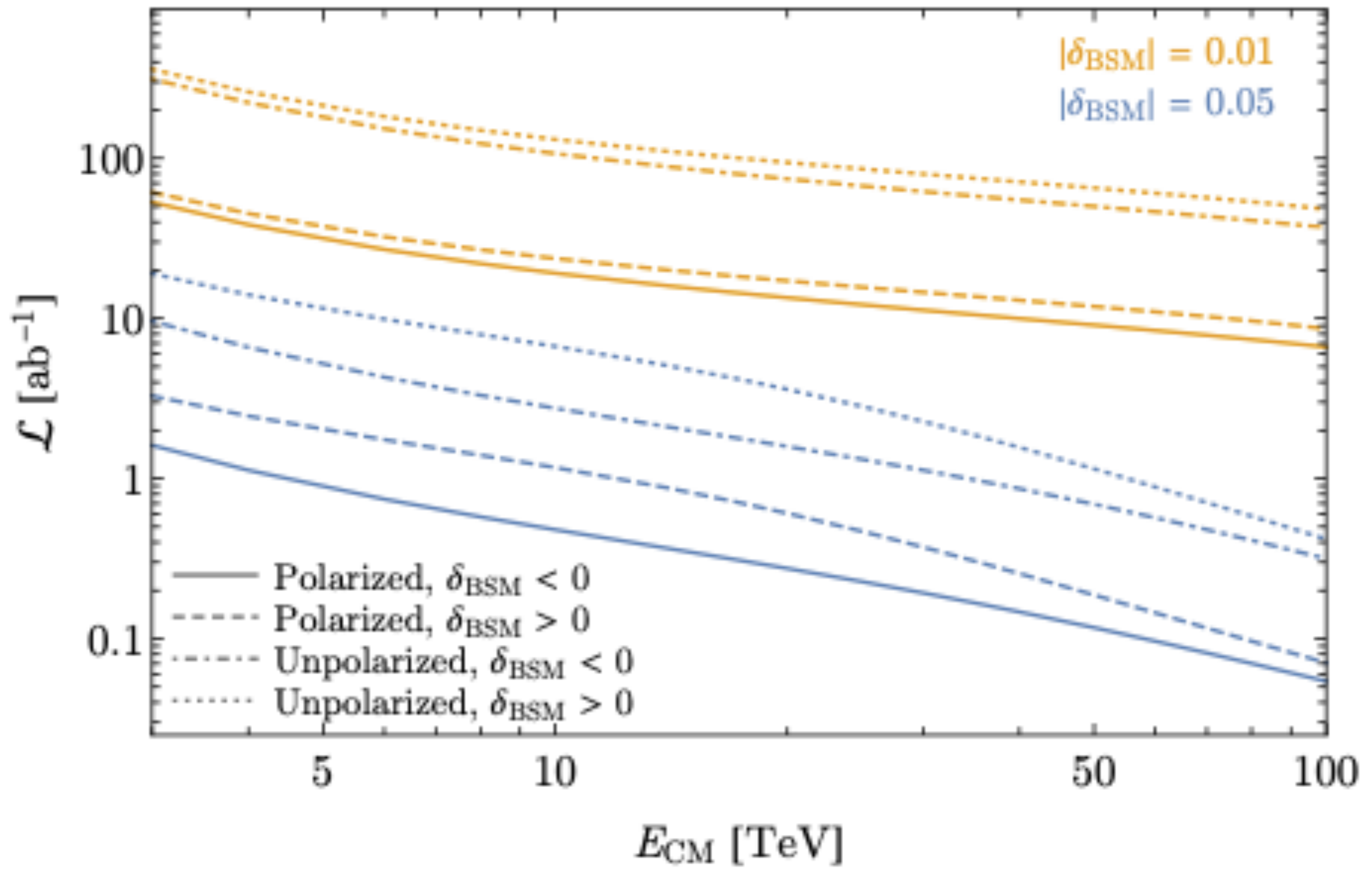


How do these ideas correlate to observables?



Future colliders offer new observables



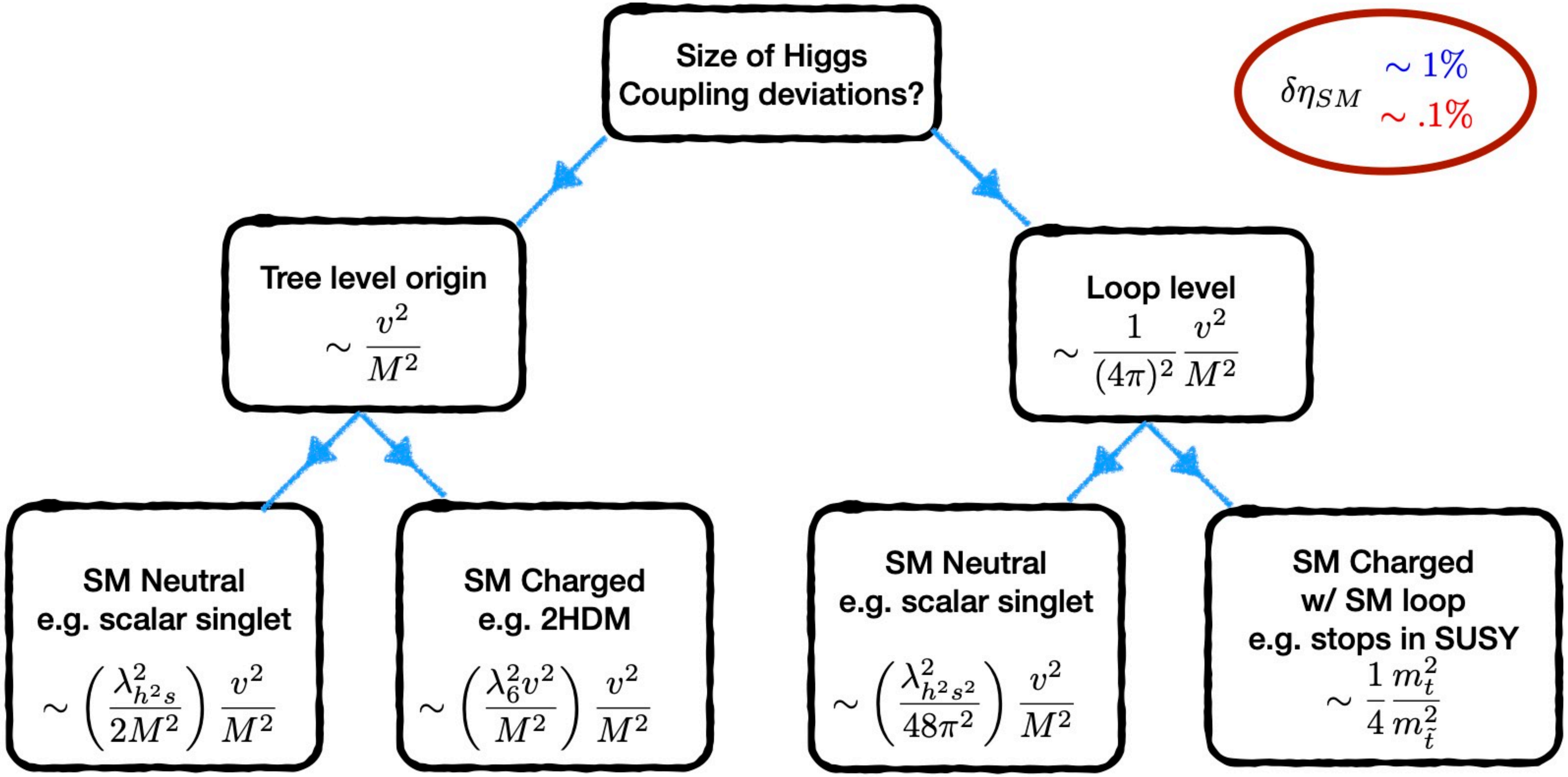


Higgs without Higgs Program

What are the expected size of the effects in the Higgs sector?

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

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



SM Neutral (tree)	SM Charged (tree)	SM Neutral (loop)	SM Charged (loop)
$M \lesssim 1.7\,\mathrm{TeV}$	$M \lesssim 0.8\,\mathrm{TeV}$	$M \lesssim 0.1\,\mathrm{TeV}$	$M \lesssim 0.9\,\mathrm{TeV}$
$M \lesssim 5.5\,\mathrm{TeV}$	$M \lesssim 1.4\,\mathrm{TeV}$	$M \lesssim 0.4\,\mathrm{TeV}$	$M \lesssim 2.8\,\mathrm{TeV}$

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

Also important to recall, SMEFT or HEFT doesn't *always* capture interesting physics

Scale *and* Precision matter

We'll give examples

So at this basic level…

- Big questions can connect to observables
- Observables measurable at the 1% to .1% (future colliders on the books) are typically testing up to the few TeV scale
    - Direct and Indirect complementarity clearly matters here!
- But what about some specific connections?

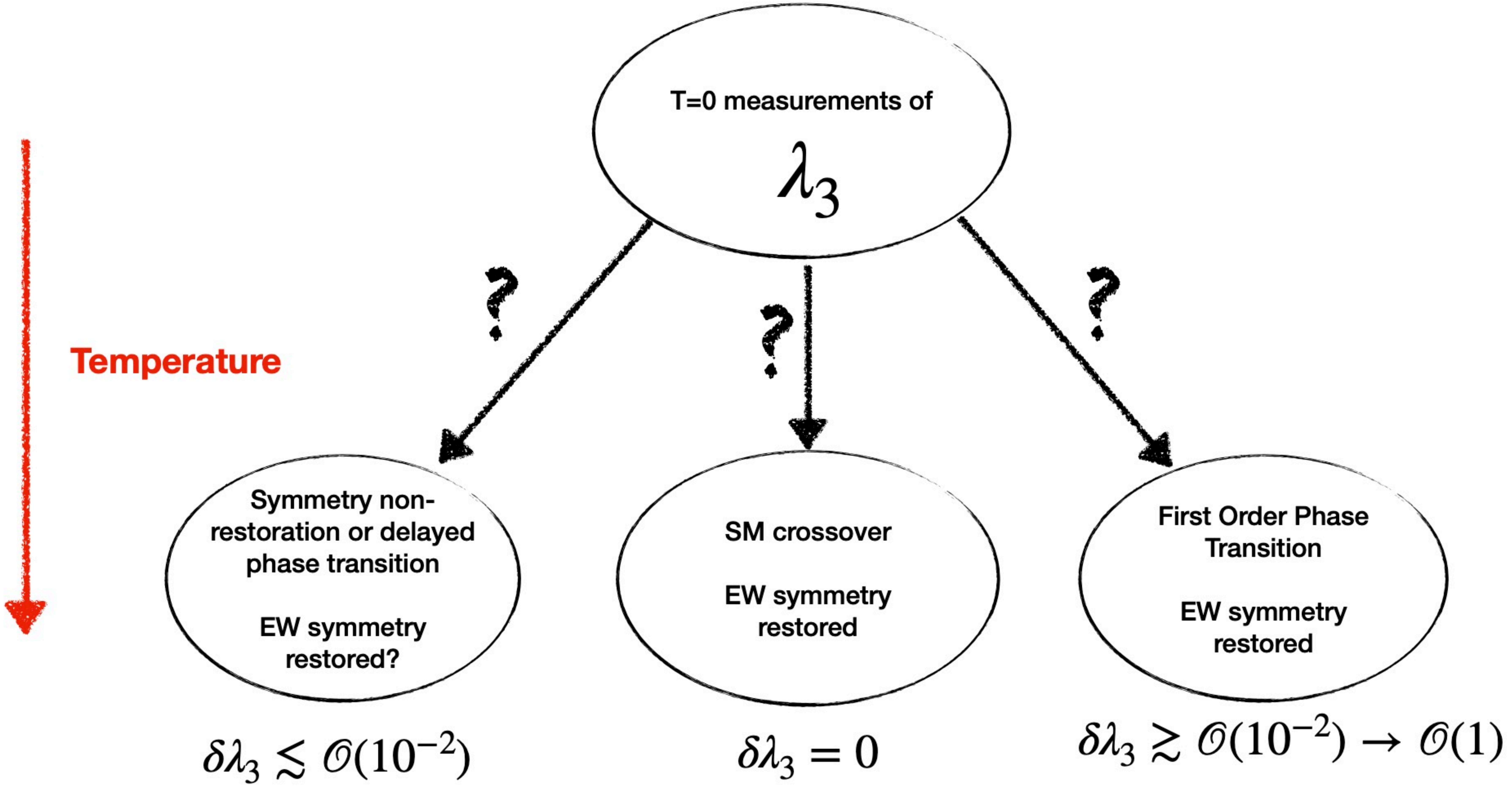
Naturalness

- Love it or Hate it - it's tied to our understanding of QFT and born out in applications of QFT

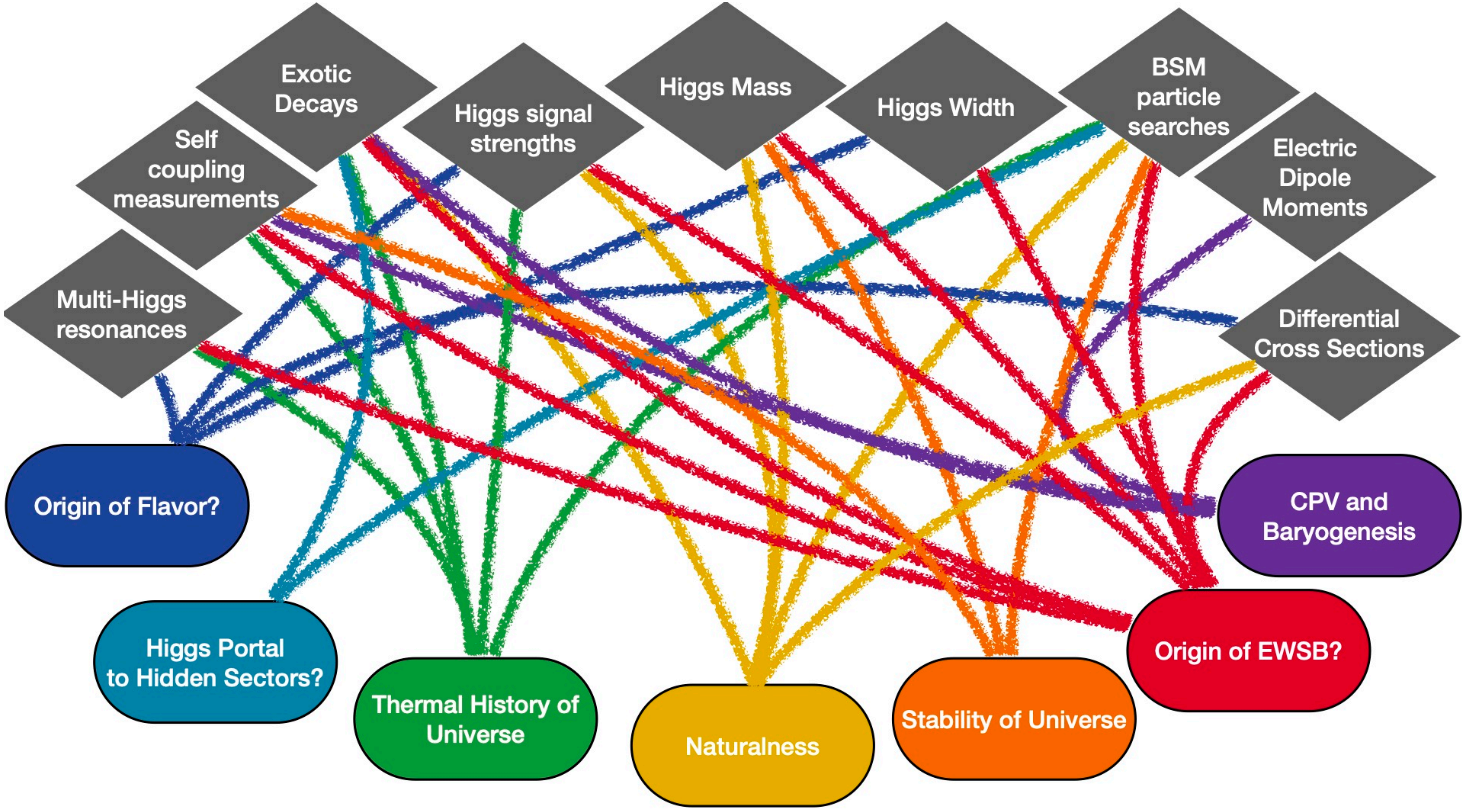
$$\epsilon = \frac{m_h^2}{\Delta m_h^2} \qquad\qquad \frac{\delta\eta_{SM}}{\eta_{SM}} \sim c\epsilon$$

- Hard to go too far without specific models - depending on type of contributions Soft, SuperSoft etc Direct searches or Indirect Searches can be more powerful tests of naturalness

Thermal History of Universe



Hard to give definite targets, and how to not confuse?



Higgs Inverse

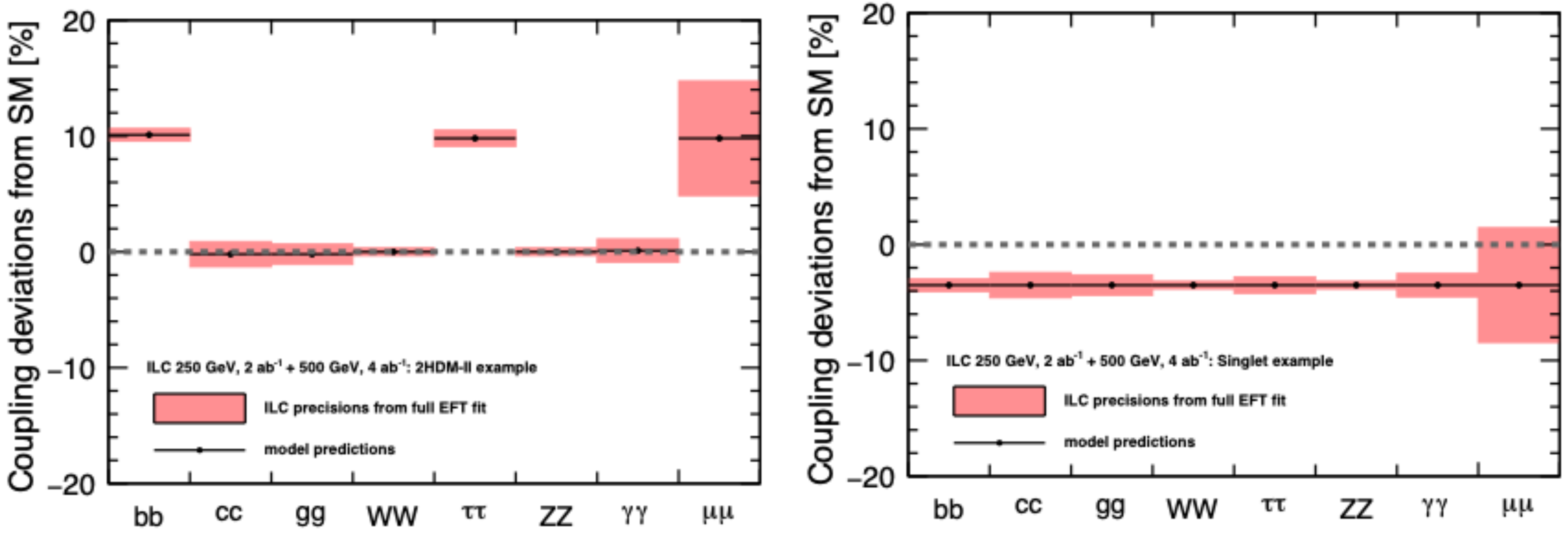


FIG. 29: An example from [49] demonstrating different patterns of Higgs deviations from different classes of models, in this case a 2HDM example and scalar singlet model.

Can be more systematic from this perspective

Singlet Extensions of SM Higgs Sector

$$\mathcal{L} \supset \lambda_{hhS}\phi^2 S + \lambda_{\phi S}\phi^2 S^2$$

Despite their simplicity there still is a lot of physics involved - but still effectively a mass/mixing or mass/coupling

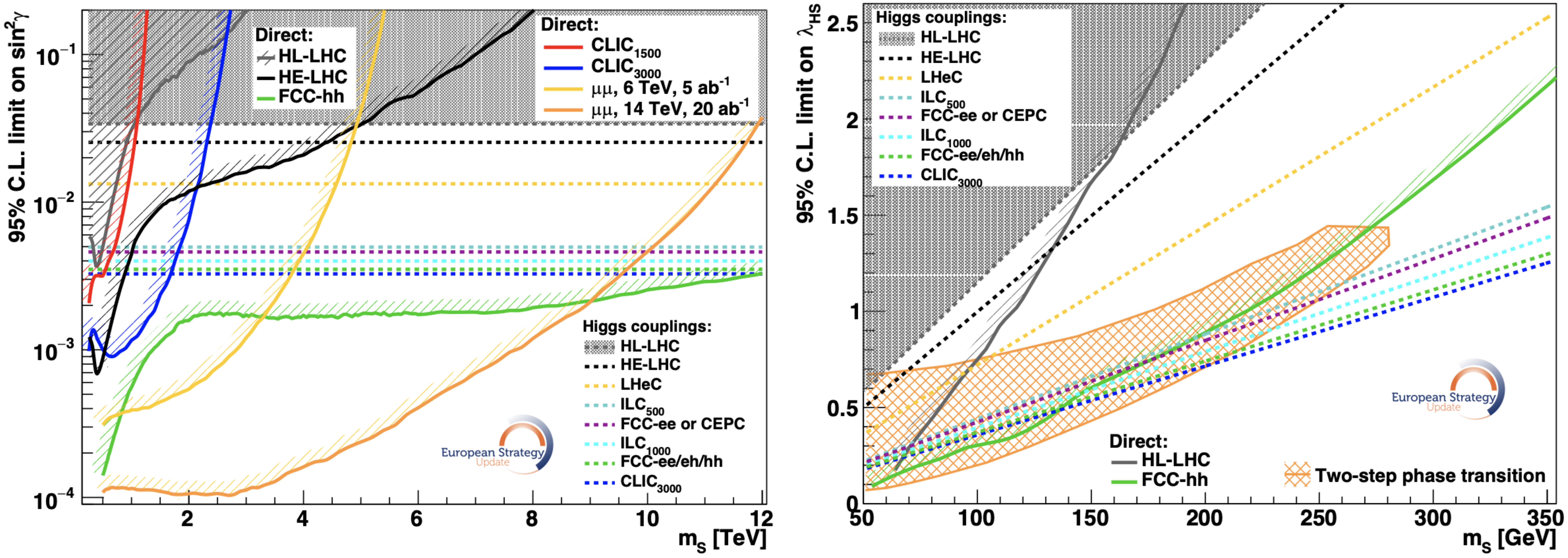


FIG. 31: This figure is from [78] Figure 8.11, where on the LHS the direct and indirect sensitivity to a singlet which mixes with the SM Higgs, while on the RHS it is the limit of no-mixing but also overlaid with regions of parameter space for a strong first-order phase transition.

Would be nice to update

Singlet Extensions of SM Higgs Sector

$$\mathcal{L} \supset \lambda_{hhS}\phi^2 S + \lambda_{\phi S}\phi^2 S^2$$

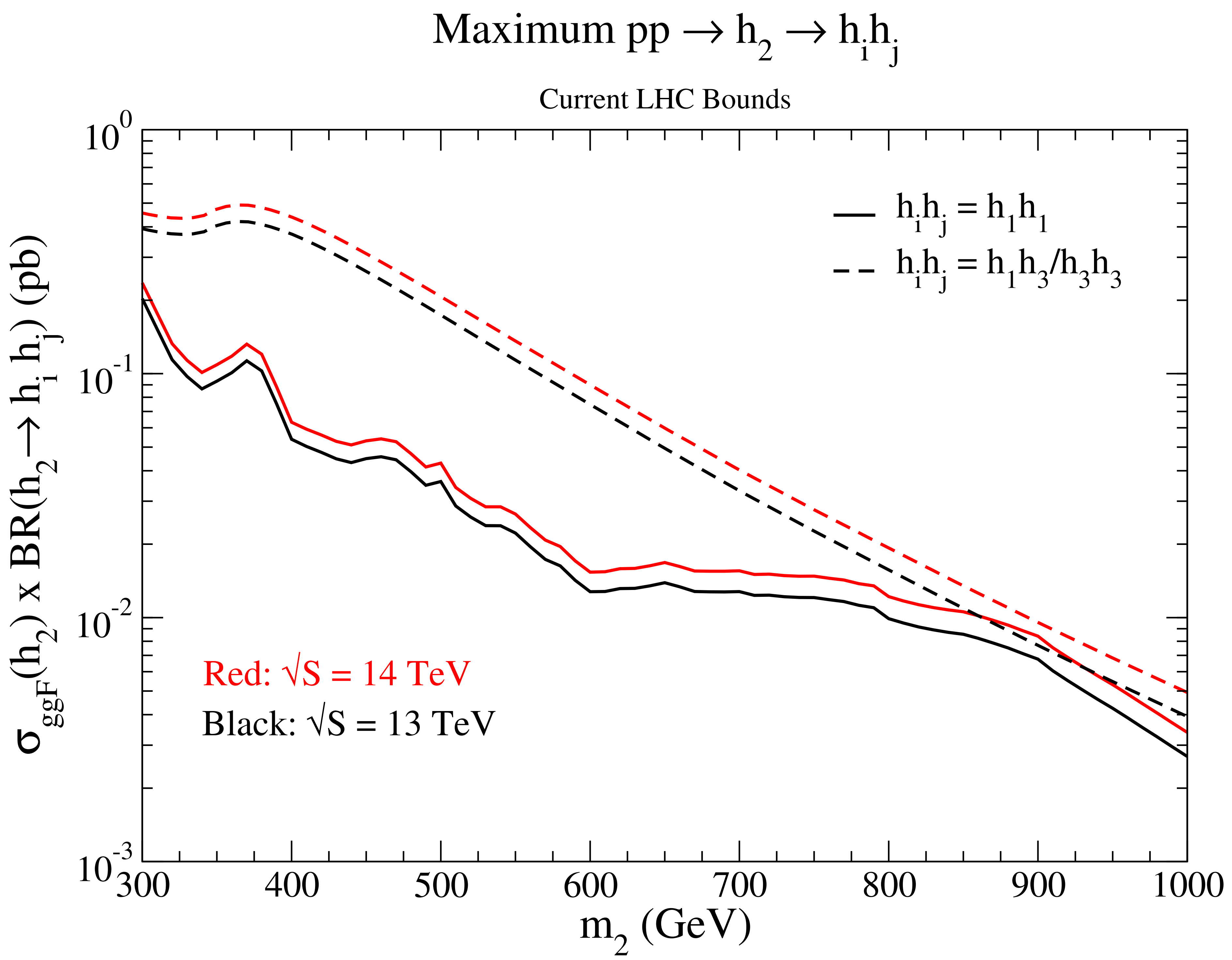


FIG. 30: Production of a pair of Higgs bosons in the complex singlet model. h_1 is the SM Higgs boson, and h_2, h_3 are new gauge singlet scalars. The maximum rates allowed by current LHC data are shown[89].

More nontrivial phenomenology investigated by a number of whitepapers

2HDM

Lots of new phenomena can occur because at renormalizable level you can couple to Fermions!

Typically classified by

$$\tan\beta \qquad \cos(\beta - \alpha)$$

$$\lambda_f^{(1)} = \frac{\sqrt{2}}{v} m_f, \qquad \lambda_f^{(2)} = \frac{\eta_f}{\tan\beta}\lambda_f^{(1)},$$

where η_f dictates the type of 2HDM, given in Table VIII, and m_f is the mass of fermion type f.

	Type-I	Type-II	Type-L	Type-F
η_u	1	1	1	1
η_d	1	$-\tan^2\beta$	1	$-\tan^2\beta$
η_l	1	$-\tan^2\beta$	$-\tan^2\beta$	1

This comes from Glashow-Weinberg Condition for avoiding FCNCs it is *NOT* a necessary condition

EFT subtleties w/2HDM

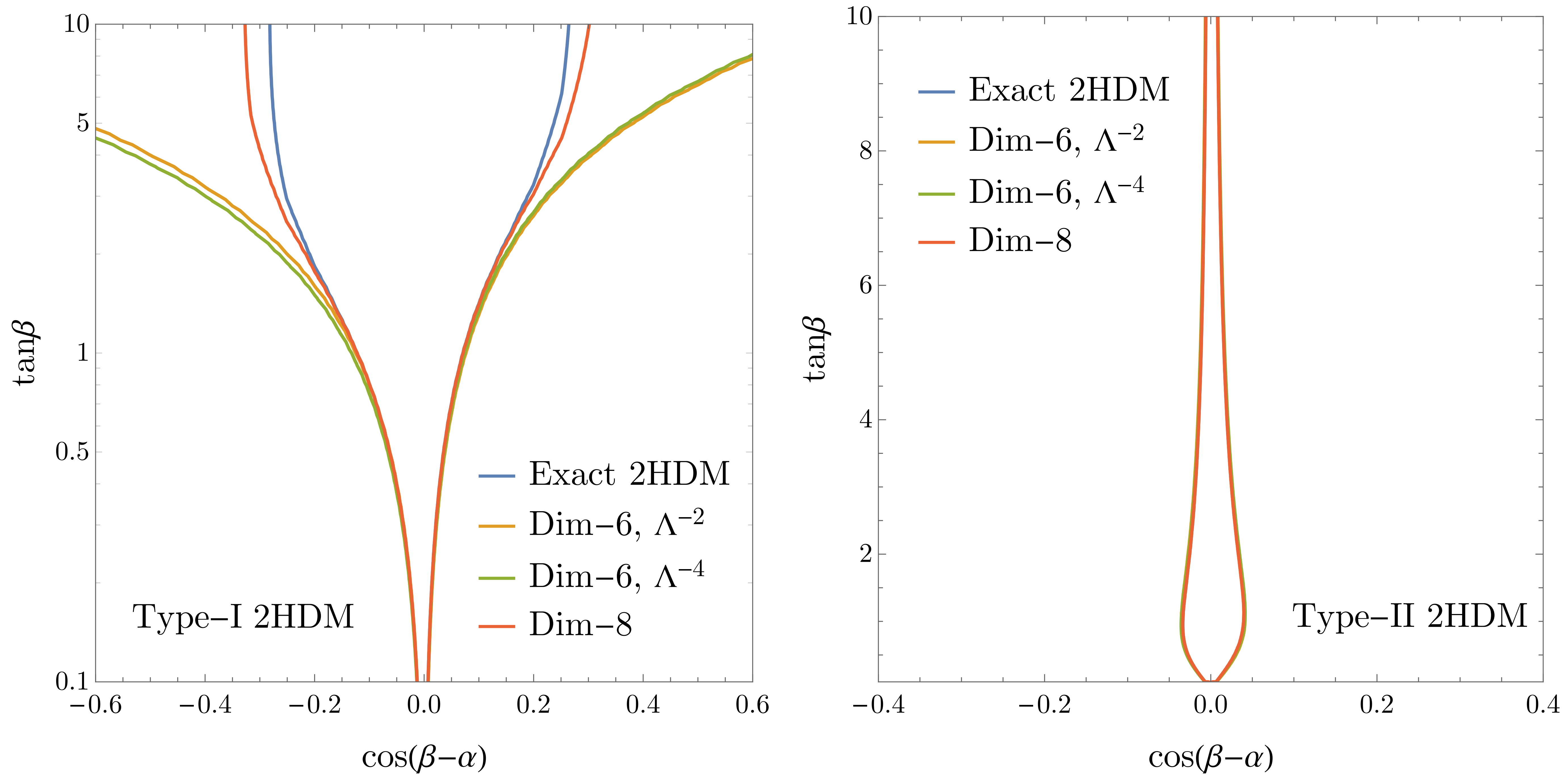


FIG. 32: Matching the 2HDM type-I and type-II to the SMEFT at dimension-6 and dimension-8[96].

HL-LHC 2HDM searches

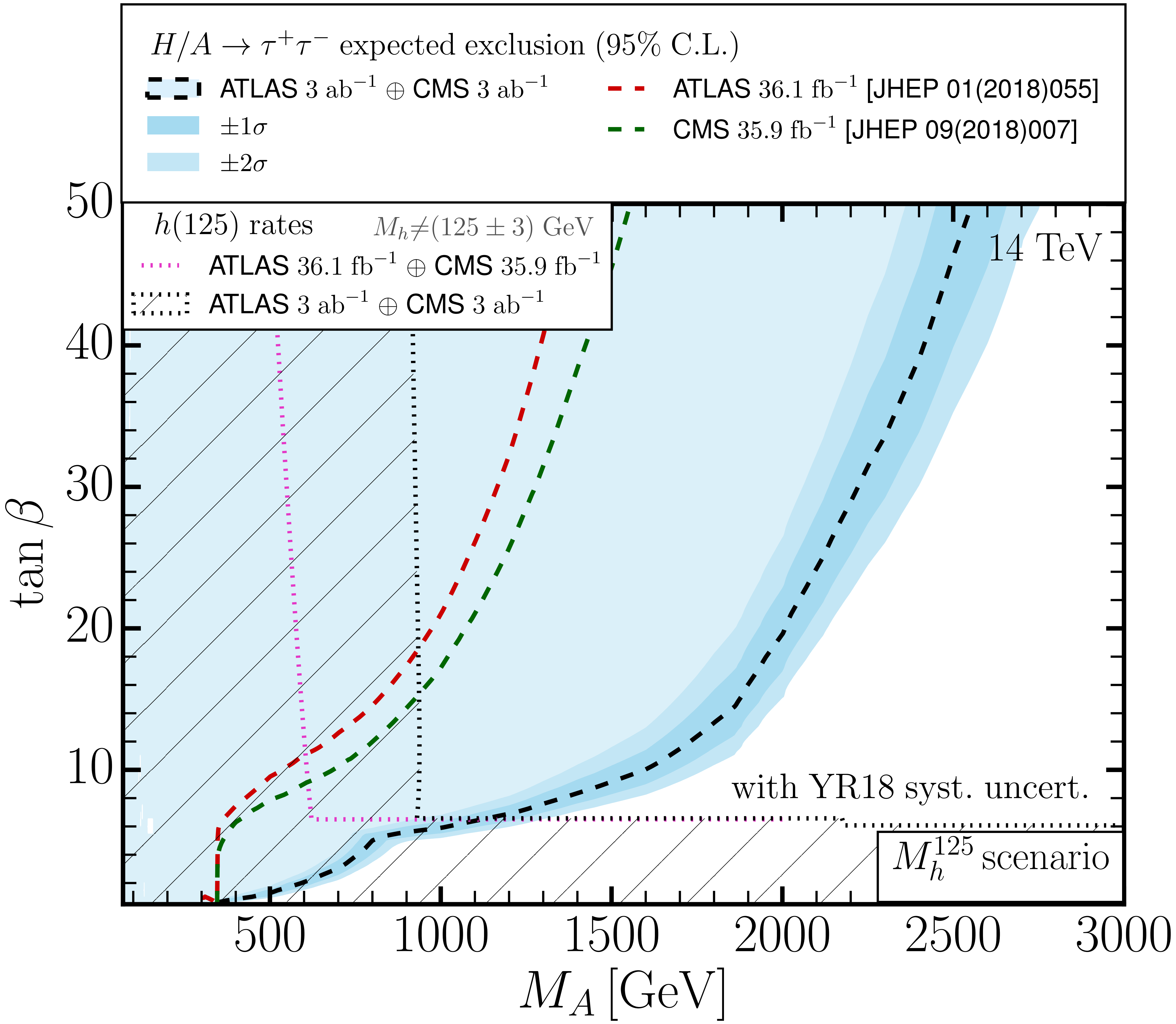


FIG. 34: Capability of HL-LHC to probe the scalar sector of the 2HDM[56].

2HDM future colliders

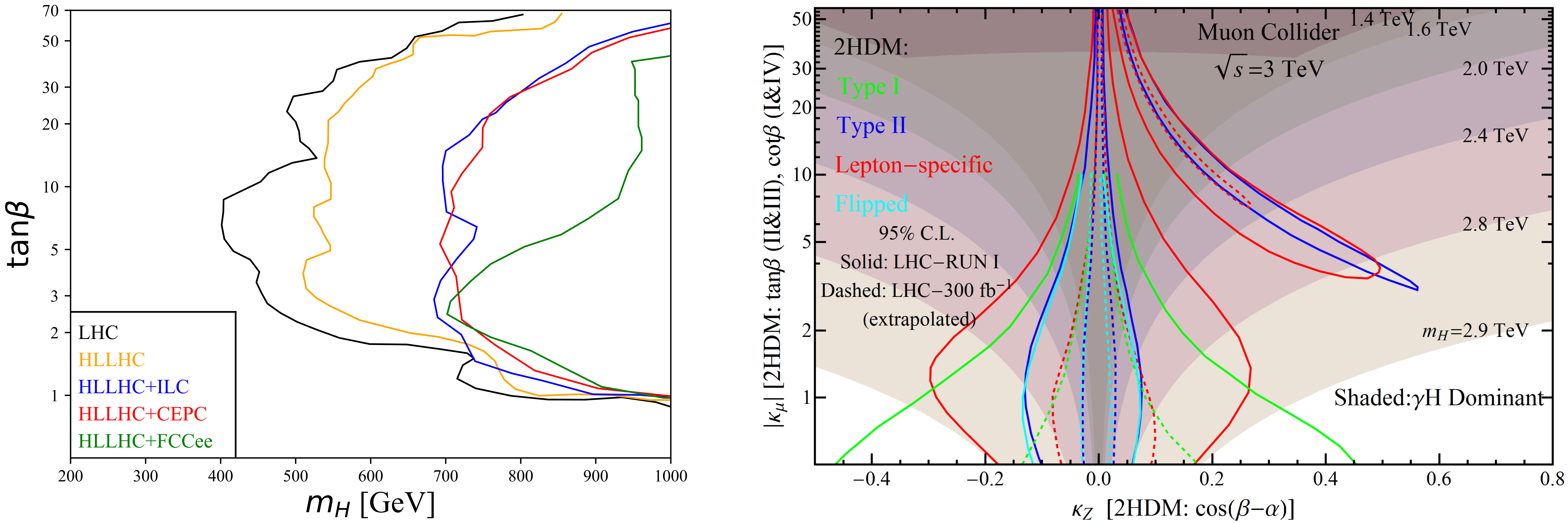
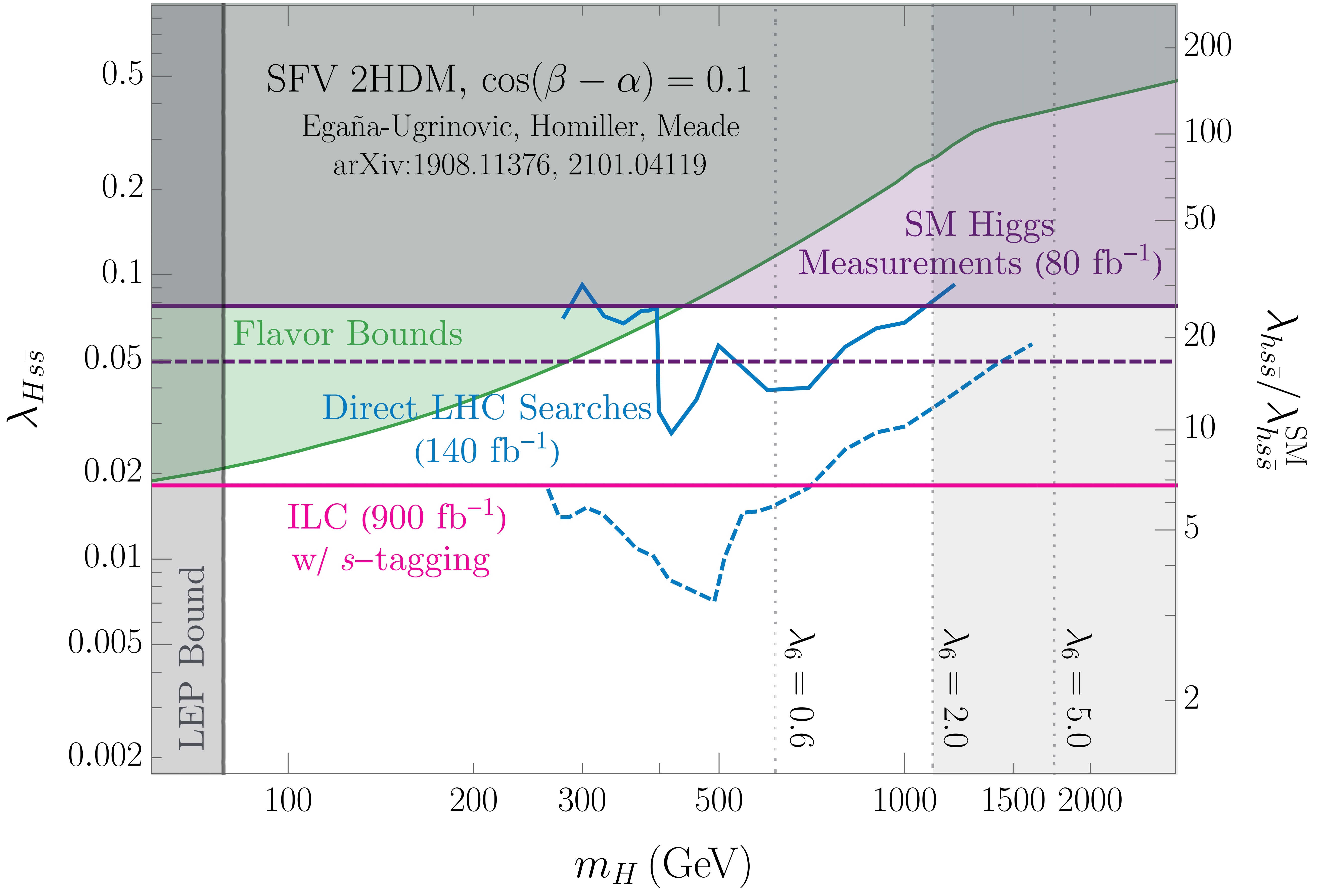


FIG. 33: Limits on the parameters of a 2HDM from precision Higgs couplings combined with HL-LHC results. LHS: Limits from future e^+e^- colliders[99]. RHS: Limits from a 3 TeV muon collider.

Would be nice to overlay

2HDM w/flavor beyond NFC

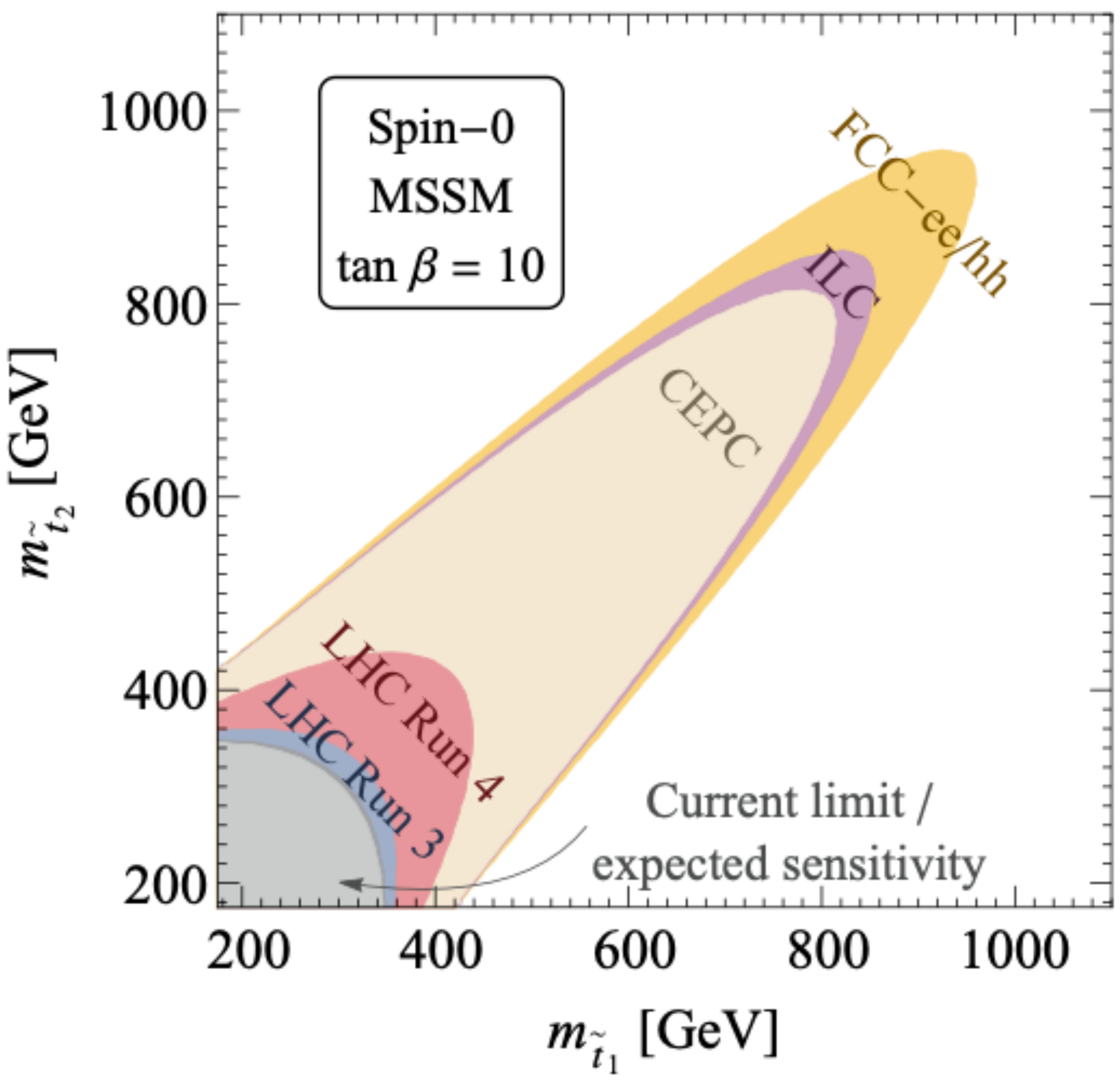
	up-type	down-type
MFV [100]	polynomial of SM Yukawas	polynomial of SM Yukawas
gFC [101, 102]	non-universally flavor aligned	non-universally flavor aligned
NFC (types I-IV) [92]	real proportional	real proportional
Aligned 2HDM [103, 104]	complex proportional	complex proportional
up-type SFV [105, 106]	real proportional	non-universally flavor aligned
down-type SFV [105, 106]	non-universally flavor aligned	real proportional



Also Flavorful Models and CPV in 2HDM section

FIG. 35: Probes of flavor violation in a 2HDM at future colliders[64].

New Physics in Higgs Loops



LHC direct already beyond FCC-ee/hh Higgs properties?

direct/indirect interplay

FIG. 36: The bounds on stop masses in the MSSM for a fixed value of tan β, for future e^+e^- colliders and the FCC-hh adapted from [113]. As can be seen even with the most precise Higgs measurements, the LHC has already probed this space albeit with assuming particular decay modes.

Exotic Higgs Decays

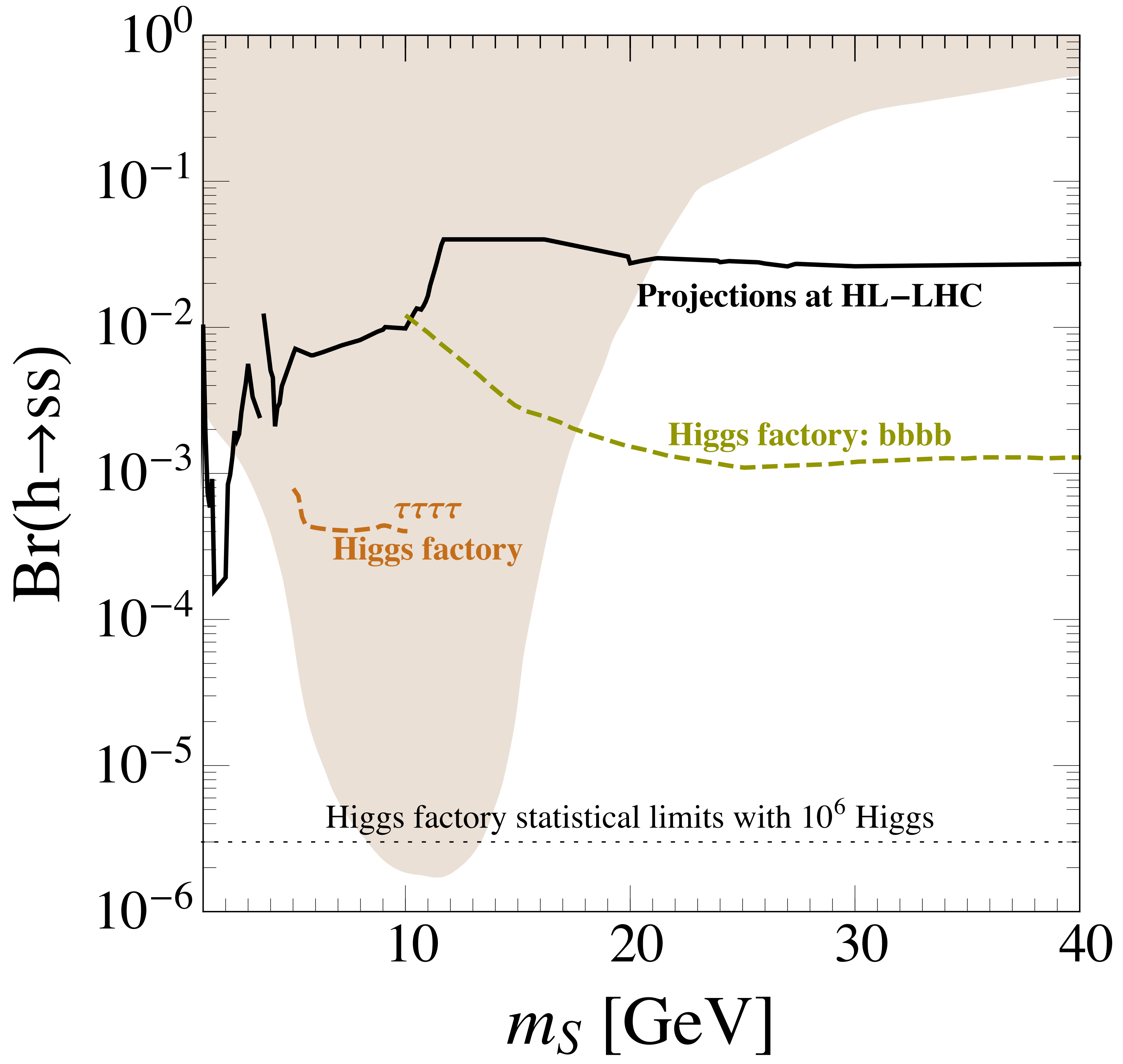


FIG. 37: Higgs portal model with $h \to SS$. The shaded region allows for an electroweak phase transition. From Ref [83].

Conclusions

- We’ve tried to emphasize how important the Higgs is and how connected to so many different SM issues and BSM possibilities
- We’ve tried to give context to what Higgs precision actually means
- We’ve tried to give a number of examples for what future colliders can do, as well as illustrating theory points that are new compared to European Strategy
- There’s still an enormous amount of work to be done on all fronts for the Higgs, but hopefully this gives a basis for where we are and why it’s **SO** crucial that we develop and construct experiments to study the Higgs to death!
- We welcome your questions, feedback, and any help in tweaking this to make the final version as strong as possible!