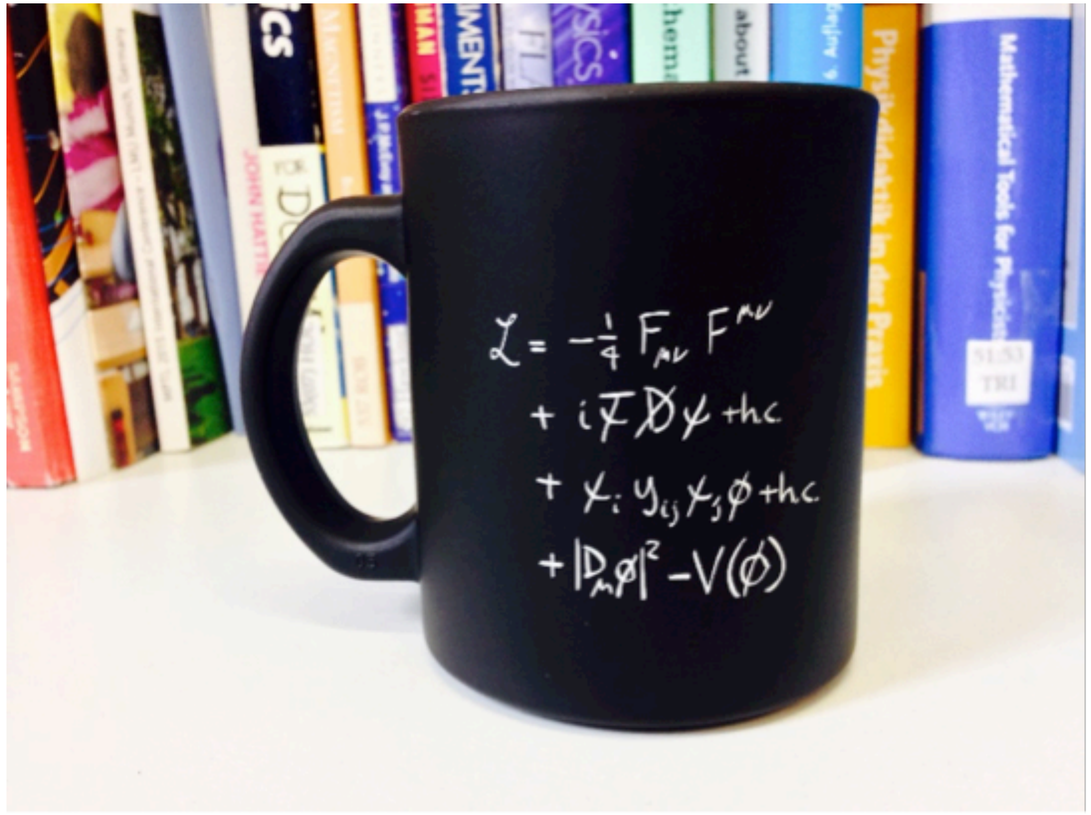
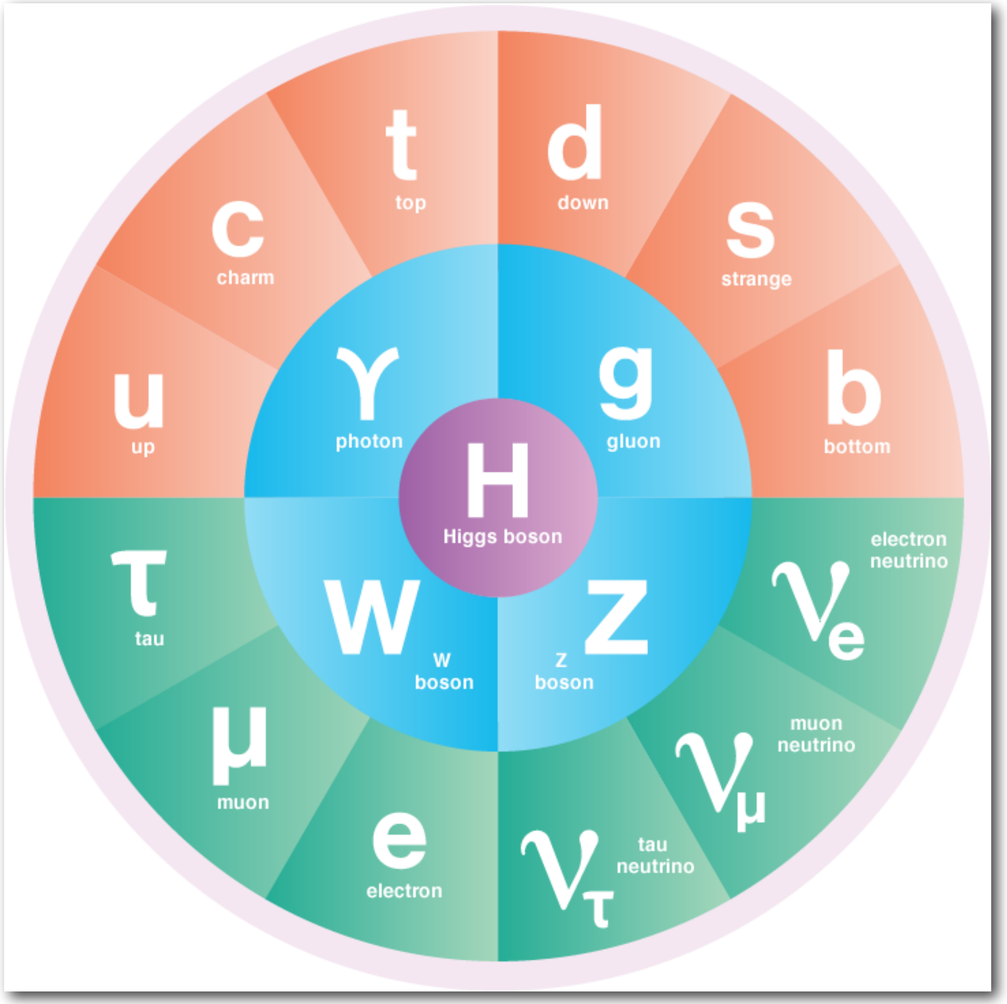
Higgs Physics at Future Colliders

Patrick Meade
C.N. Yang Institute for Theoretical Physics
Stony Brook University

The Standard Model is Complete!





Why Higgs Physics at a future collider?

The Higgs brings more questions than answers

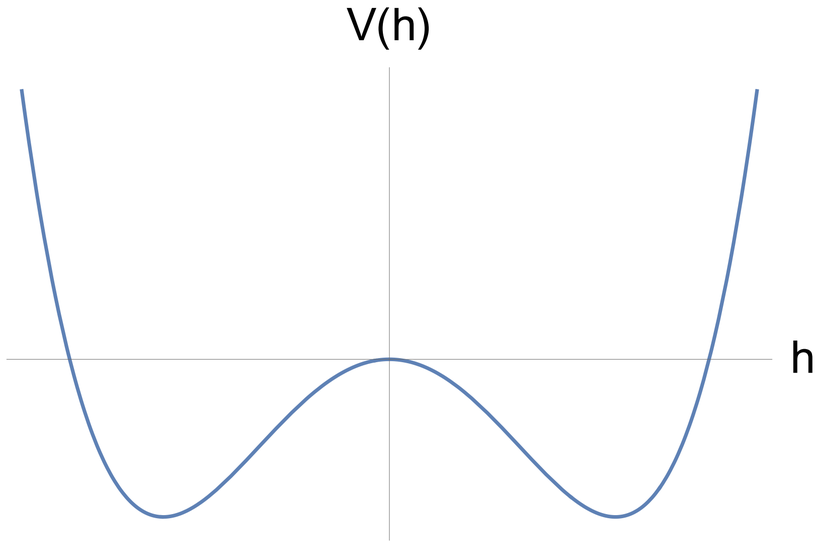
Unfortunately the LHC hasn’t provided the answers as of *yet*

Why were/are we waiting for future colliders then?

At some level we didn’t realize *how* weird the universe is until the LHC and we hadn’t made the case for future colliders

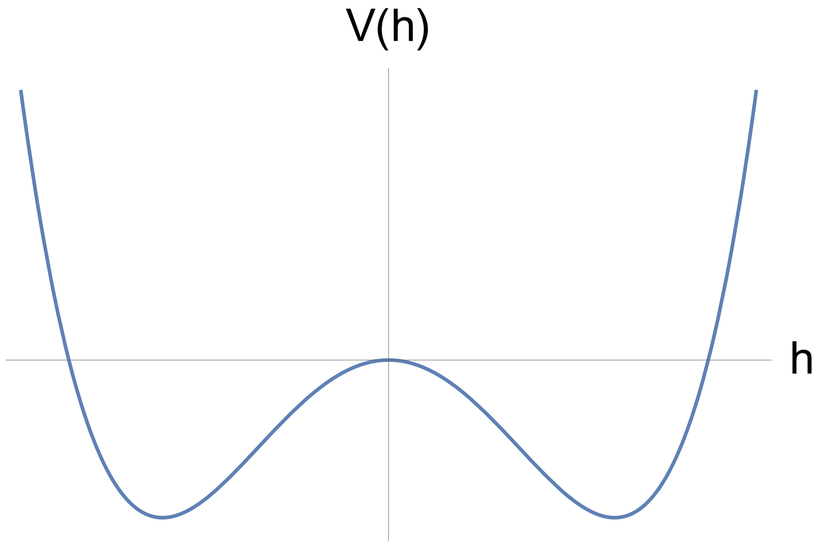
(theorists including myself are to blame)

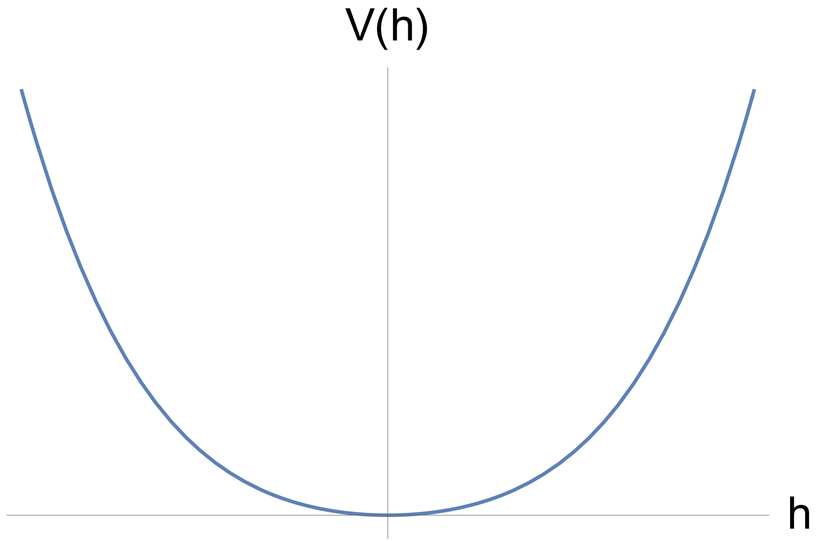
How fundamental and how confusing the Higgs is easy to understand just from the potential in the SM from the physicist point of view



$$V(h) \sim -\mu^2 h^2 + \lambda h^4$$

Why does EWSB occur?

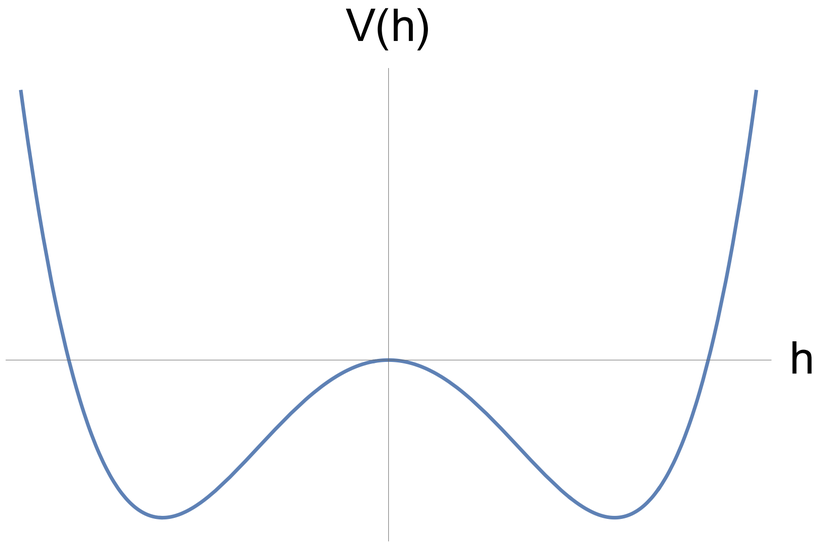




$$V(h) \sim -\mu^2 h^2 + \lambda h^4$$

$$V(h) \sim +\mu^2 h^2 + \lambda h^4$$

The SM is predicated on the spontaneous breaking of the EW symmetry, we do it by hand with the dumbest possible choice!



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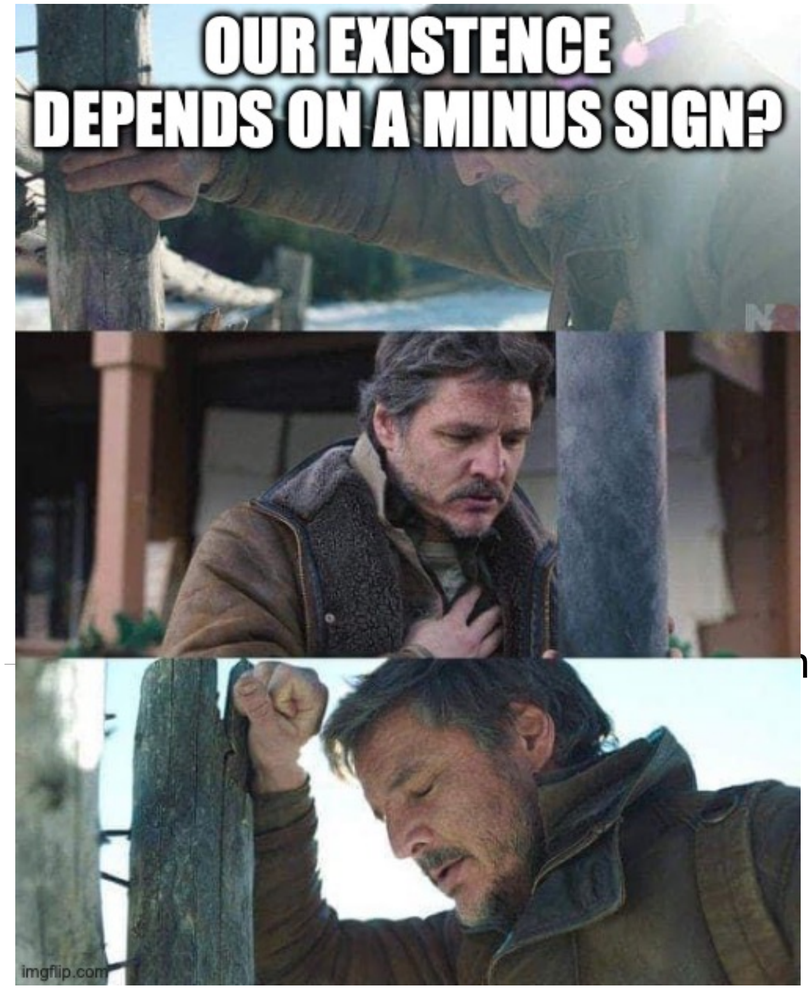
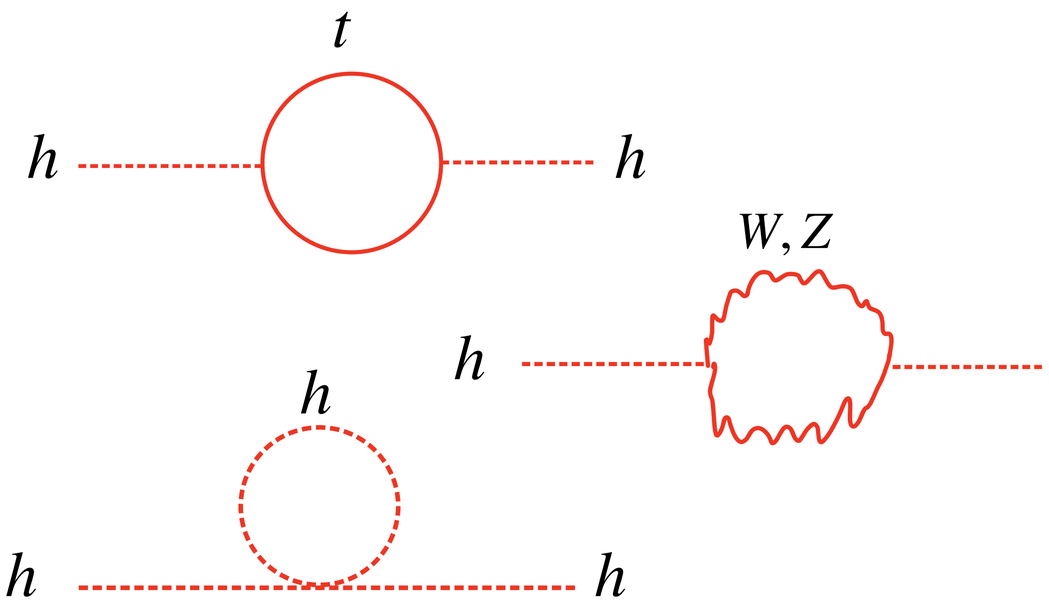


Life is due to a minus sign…

Closely related question, *why* does EWSB occur *at the scale it does*? AKA naturalness



UV scale, could be the Planck scale without new physics!

$$m_h^2 \sim \mu^2 + \Lambda^2$$

The scale of EWSB is quadratically sensitive to any new UV physics scale Λ

If the Higgs is elementary quantum corrections behave differently for it *than any other fundamental particle!*

Closely related question, *why* does EWSB occur *at the scale it does*? AKA naturalness

UV scale, could be the Planck scale without new physics!

$$m_h^2 \sim \mu^2 + \Lambda^2$$

Our universe seems incredibly fine-tuned to have big things in it!

Many theorists were already trying to solve the next step *beyond* the Higgs *before* the Higgs discovery because the idea of it *is* so weird/unique

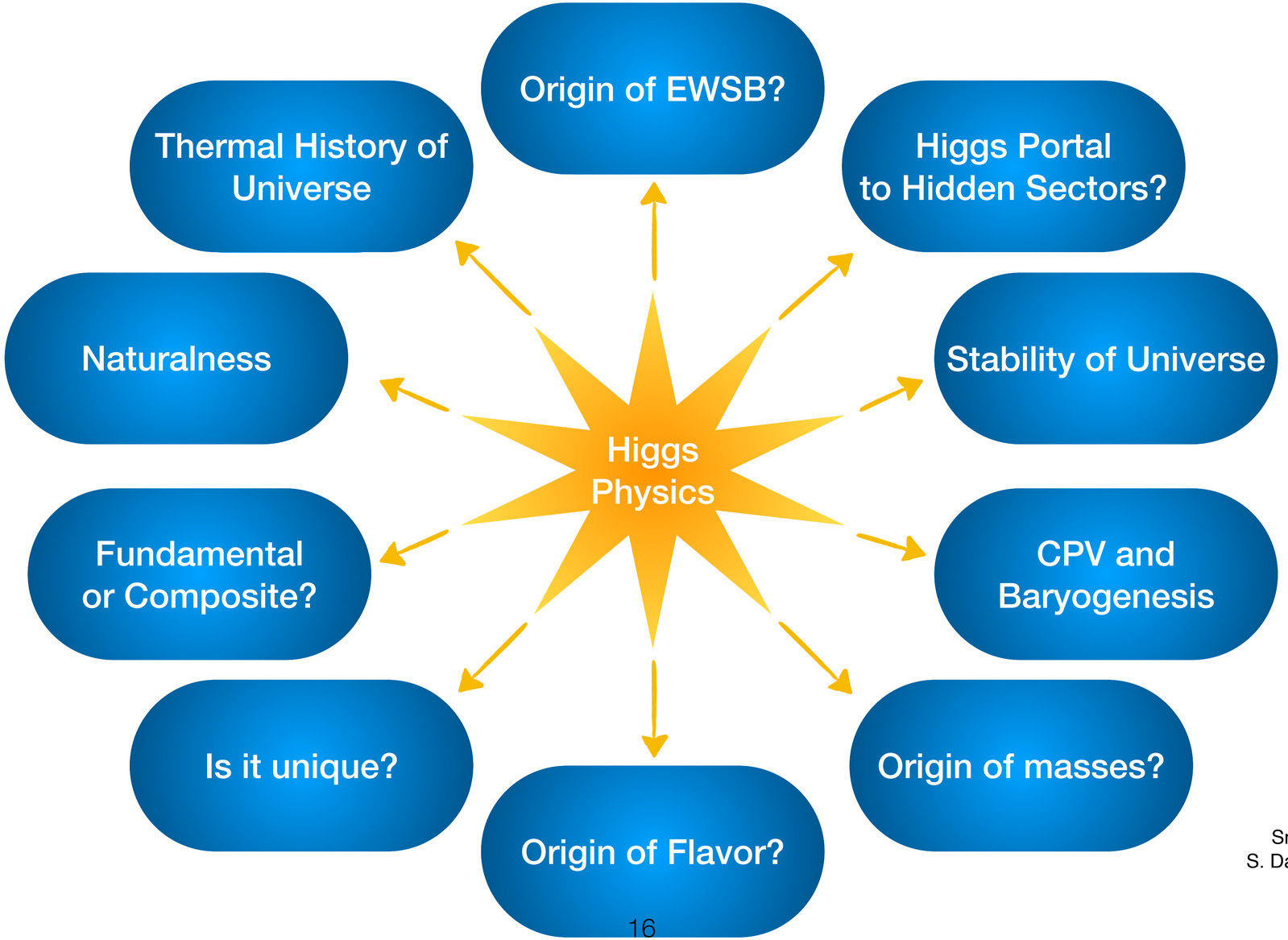
(e.g. supersymmetry, extra dimensions, composite Higgs, little Higgs, etc)

Nevertheless we're starting to improve how we explain to more general audiences how fundamental the Higgs is

AI prompt: Peter Higgs bringing life into existence in the universe

The Higgs field is responsible for the existence of all life!

The centrality of the Higgs in the SM *also* puts it at the forefront of many of our deepest questions about our universe at a technical level

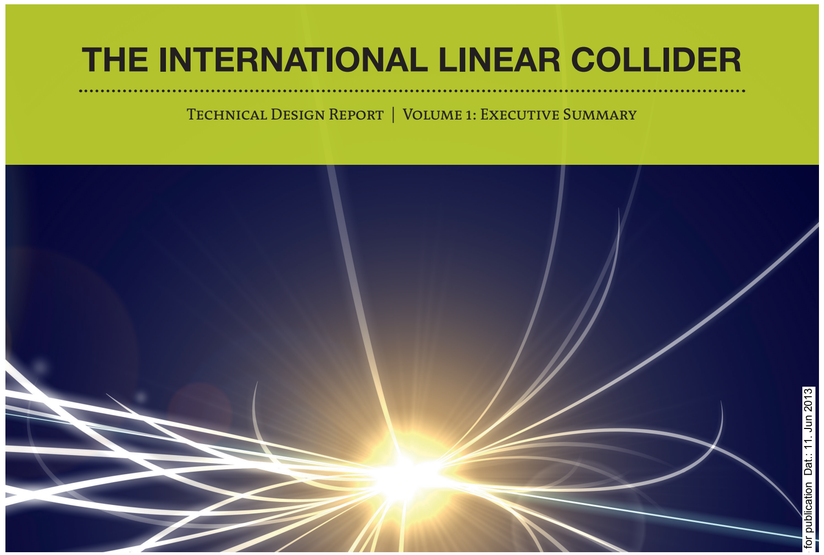


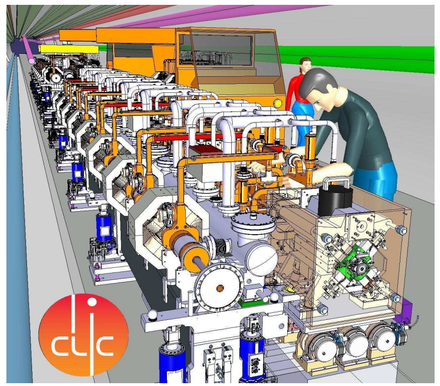
Snowmass EF Higgs Topical Report
S. Dawson, PM, I. Ojalvo, C. Vernieri et al
2209.07510

Therefore let’s look under the Higgs lamppost to try to answer our questions

Historically when we want to study a particle in depth we make a “factory”

Fortunately there are many “shovel ready” options (see next talk for more details)





A MULTI-TEV LINEAR COLLIDER
BASED ON CLIC TECHNOLOGY
CLIC CONCEPTUAL DESIGN REPORT

+ other concepts that are close

CEPC

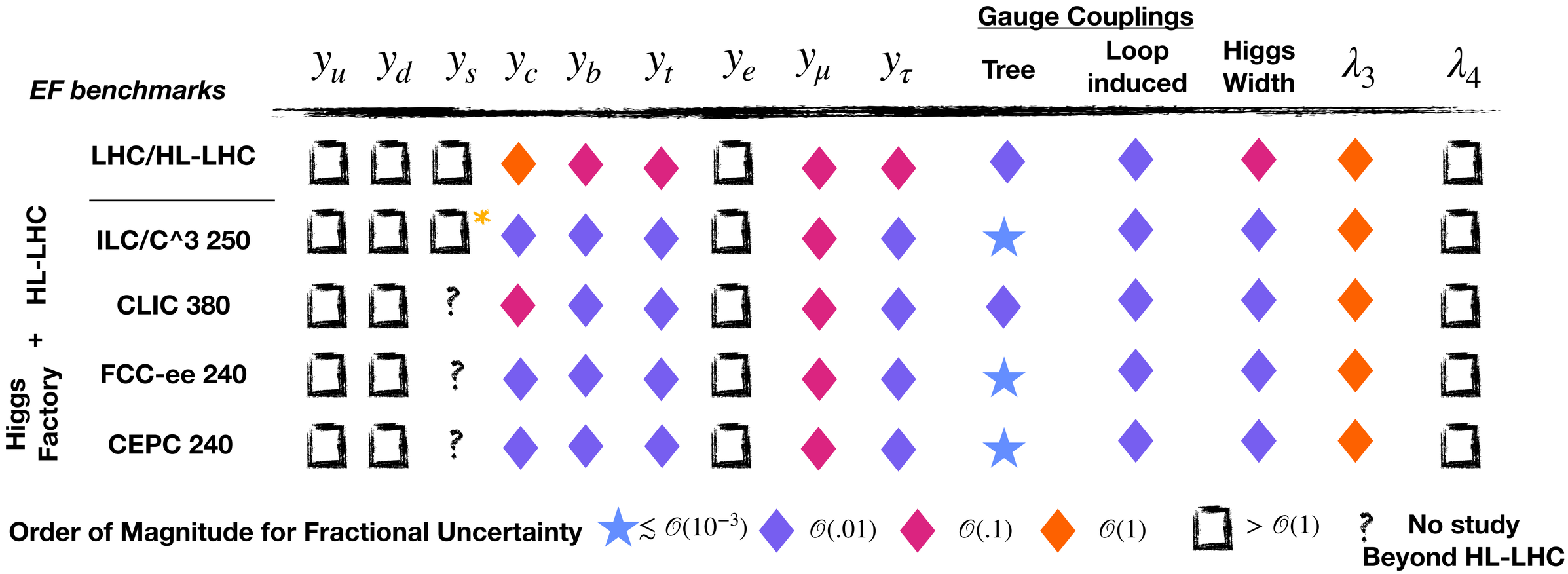
Technical Design Report

Accelerator

Do they all do the job?

Indeed they all fit the bill and improve on LHC

Energy Frontier Higgs Factory First Stages



P5:

c. An offshore Higgs factory, realized in collaboration with international partners, in order to reveal the secrets of the Higgs boson. The current designs of FCC-ee and ILC meet our scientific requirements. The US should actively engage in feasibility

But what does it mean: do Higgs factories do the job?

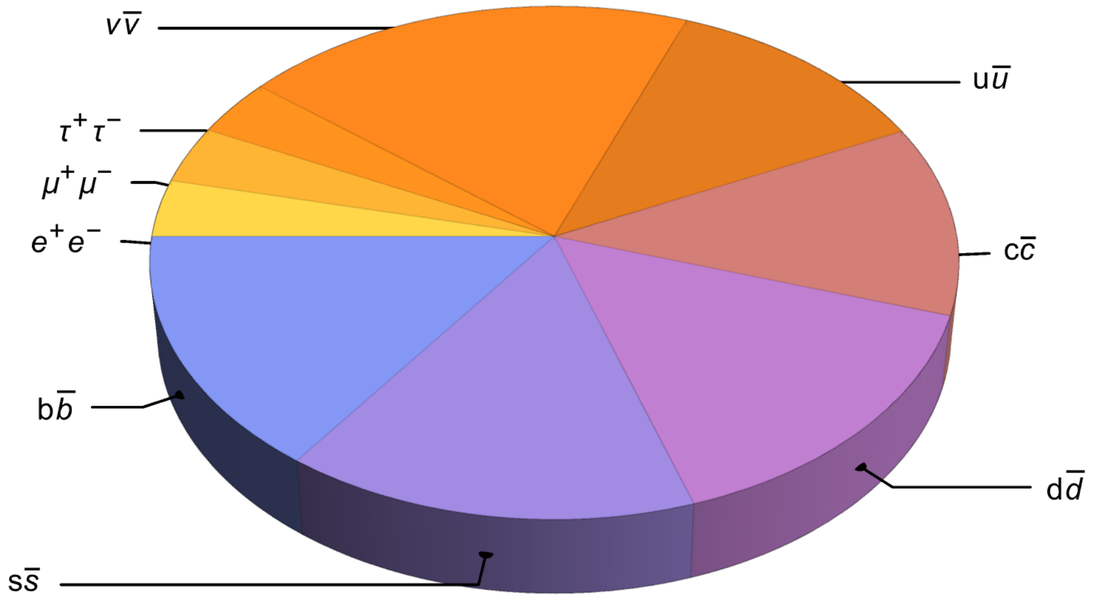
One definition could be: do we measure all Higgs couplings to high precision?

The SM Higgs is an unprecedented particle.

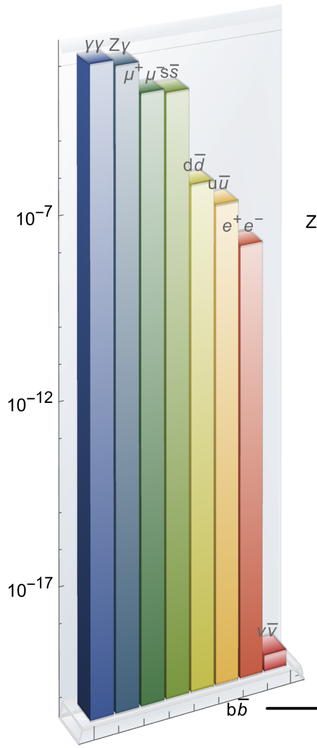
LEP was a Z boson factory and produced ~ 17 Million Z bosons

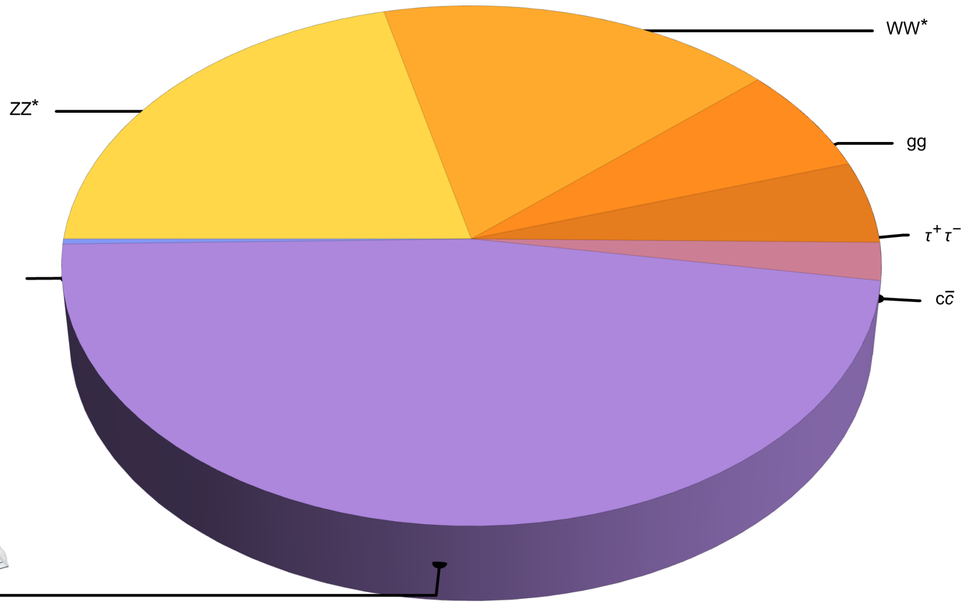
Higgs Factories produce ~ 1 Million Higgs bosons

Z boson Branching Fractions



Higgs boson Branching Fractions

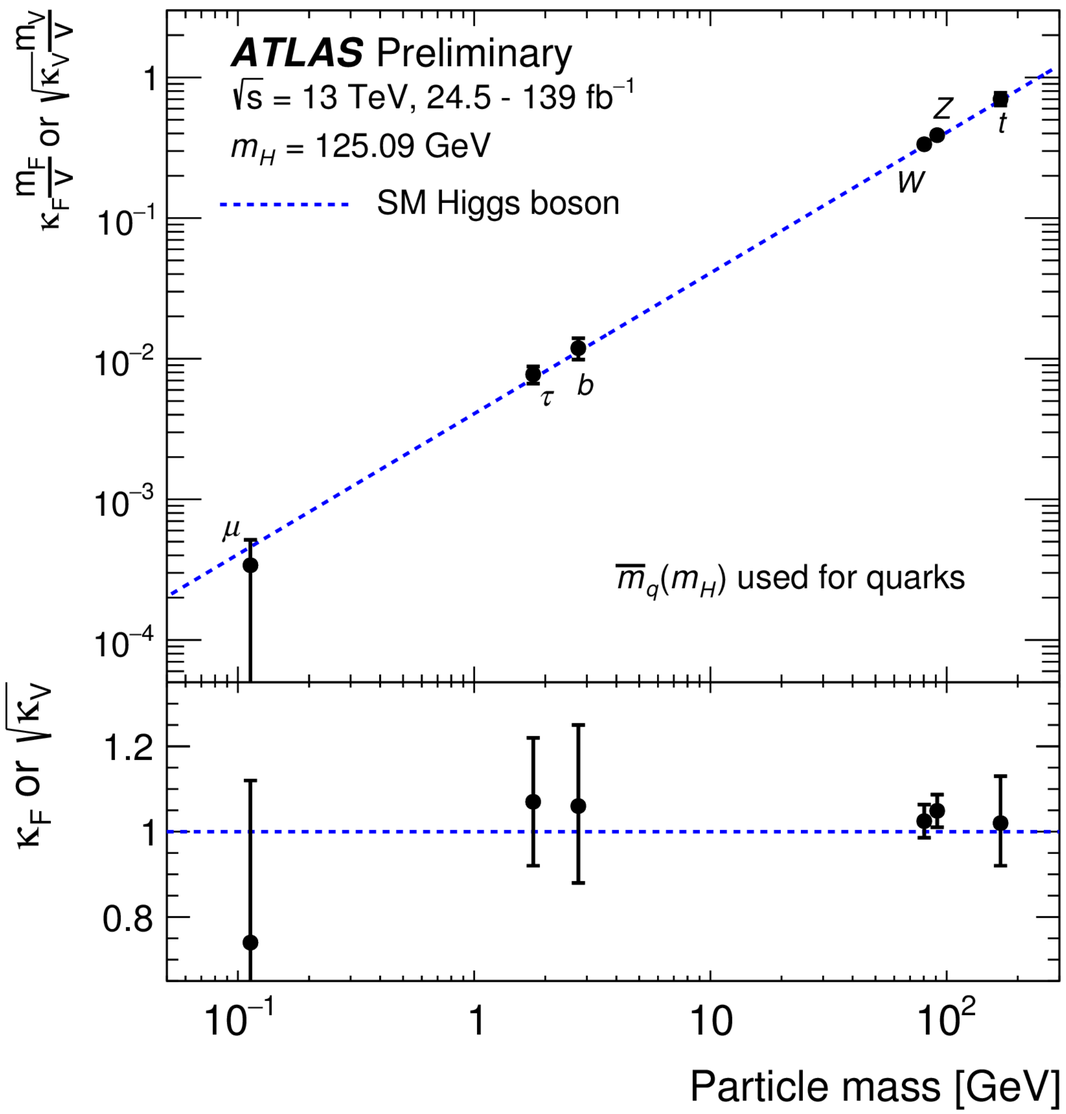




All major Branching Fractions are $\gtrsim \mathcal{O}(1\%)$

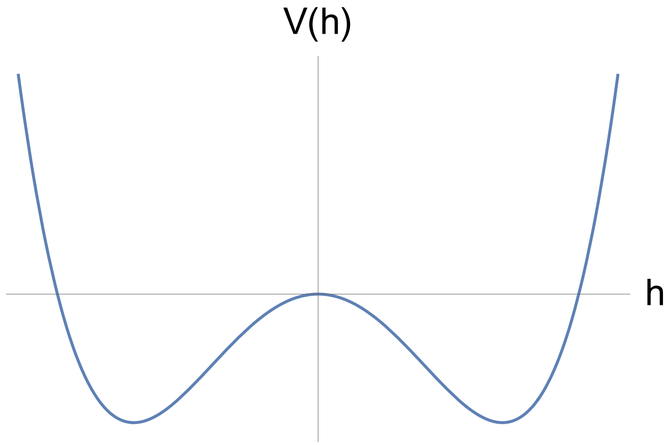
The *same* Higgs Branching Fractions span 8 to 20 ORDERS OF MAGNITUDE or more!

A Higgs factory is a great <u>start</u> but we need to plan for the future as well!



Unfortunately no one has a clue how to make at least a Zetta(10^{21})-Higgs Factory to attempt to complete this plot, but can we go further than MegaHiggs?

This also extends to the new types of couplings that only the Higgs has and we've never seen before (AKA studying its potential)



$$\left.\frac{\partial V(h)}{\partial h}\right|_{h=v} = 0$$

$$\left.\frac{\partial^2 V(h)}{\partial h^2}\right|_{h=v} = m_h^2$$

+ more derivatives = self-interactions

Experimentally we look for multi-Higgs production

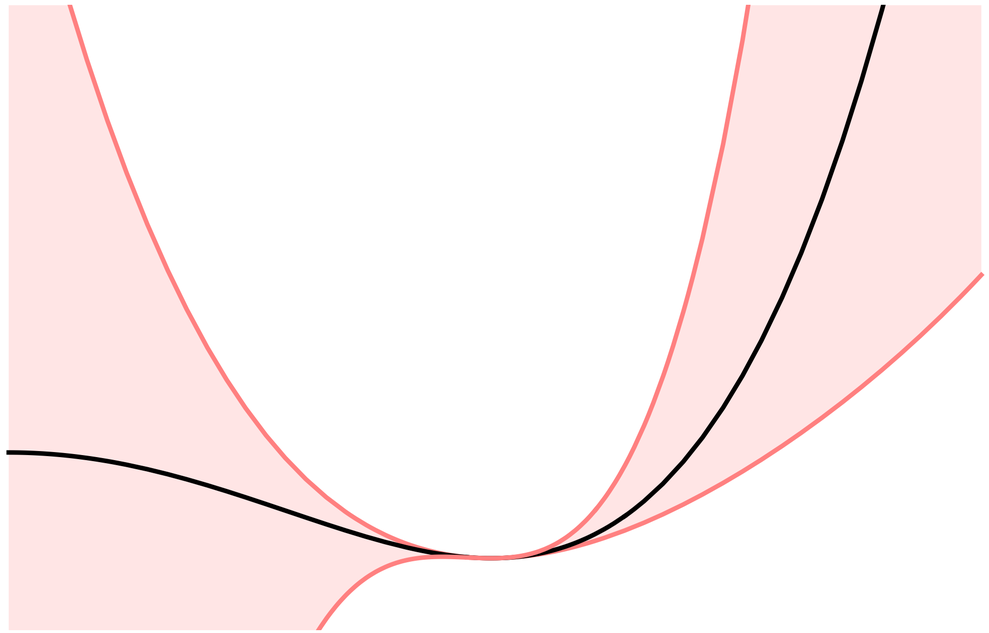
$$V(h) \sim -\mu^2 h^2 + \lambda h^4$$

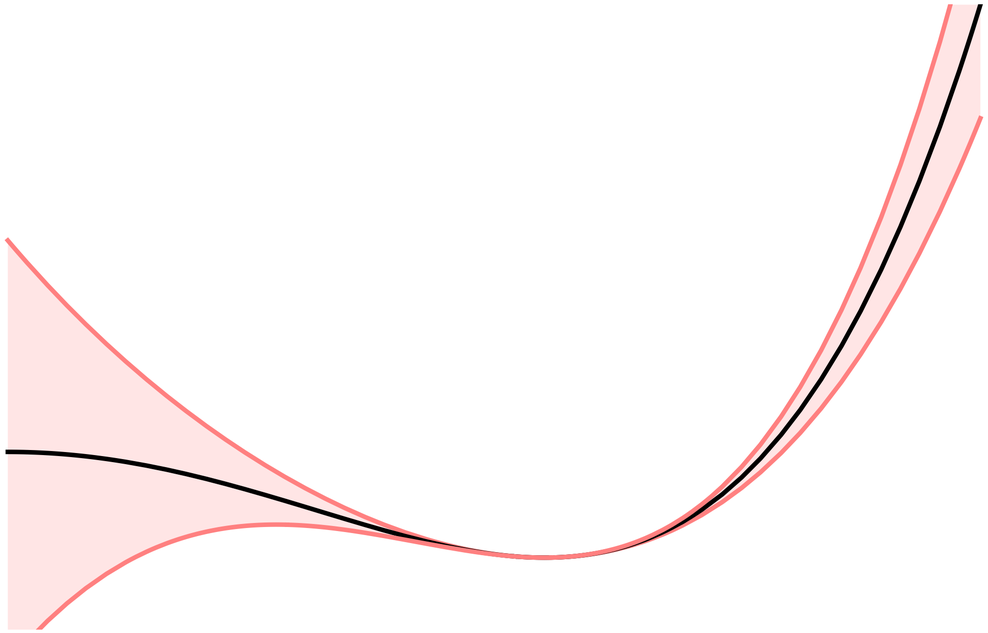
κ_λ sensitivity first

$\lambda_{hhh} \sim \lambda v$

$\lambda_{hhhh} \sim \lambda$

Visually this is more striking than giving you a table first, but we're still a long way from nailing down the SM potential even with HL-LHC





H/T N.Craig, R. Petrossian-Byrne

Current LHC → **HL-LHC**

However, it's hard to improve with only a low energy Higgs factory (and more model dependency comes in)

κ_λ sensitivity

collider	Indirect-h	hh	combined
HL-LHC [78]	100-200%	50%	50%
$\mathrm{ILC}_{250}/\mathrm{C}^3$-250 [51, 52]	49%	–	49%
CLIC_{380} [54]	50%	–	50%
FCC-ee [55]	33%	–	33%

Snowmass Higgs report 2209.07510

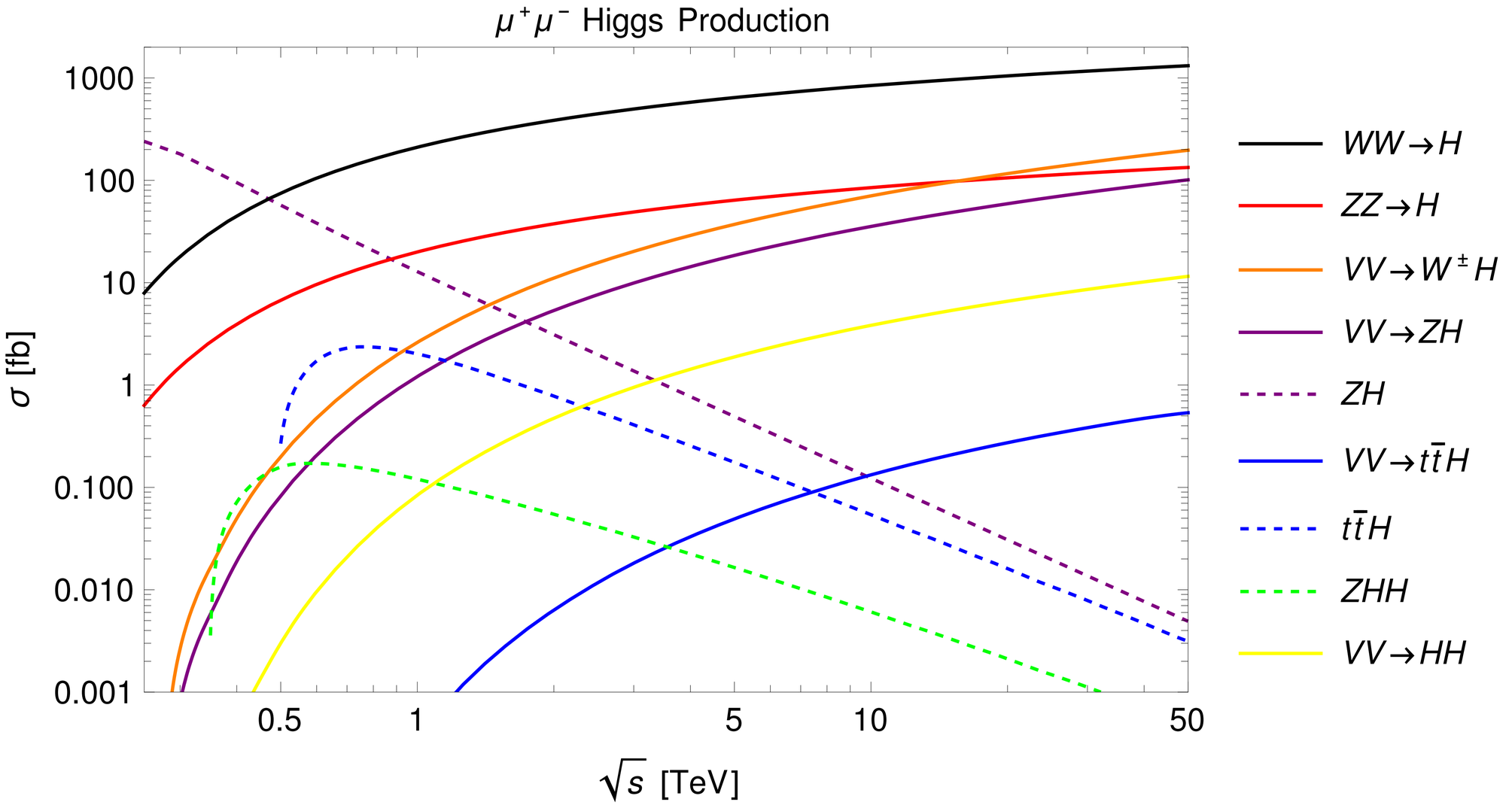
So if we need more Higgs, Di-Higgs, and $N > 2$ Higgs events what do we do?

MORE ENERGY!

Hard to increase (power and time are precious)

$$N_{ev} = \mathscr{L}\sigma$$

Lepton colliders *can* Increase this at high Energy



Similar concept to LHC/FCC-hh for why *more* Energy means *more* Higgs!

Outcome of US strategy process (Snowmass/P5)

Higgs Factory

10 TeV PCM

Recommendation 2: Construct a portfolio of major projects that collectively study nearly all fundamental constituents of our universe and their interactions, as well as how those interactions determine both the cosmic past and future.

c) An offshore Higgs factory, realized in collaboration with international partners, in order to reveal the secrets of the Higgs boson. The current designs of FCC-ee and ILC meet our scientific requirements.

"Now"

Recommendation 4: Invest in a comprehensive initiative to develop the resources—theoretical, computational, and technological—essential to realizing our 20-year strategic vision. This includes an aggressive R&D program that, while technologically challenging, could yield revolutionary accelerator designs that chart a realistic path to a 10 TeV pCM collider.

20ish years 10 TeV $\mu^+\mu^-$

50ish years (w/context) 100 TeV pp

more? years 10 TeV WFA

Linear colliders could also go in between depending on Higgs factory

Outcome of US strategy process (Snowmass/P5)

Higgs Factory

10 TeV ?

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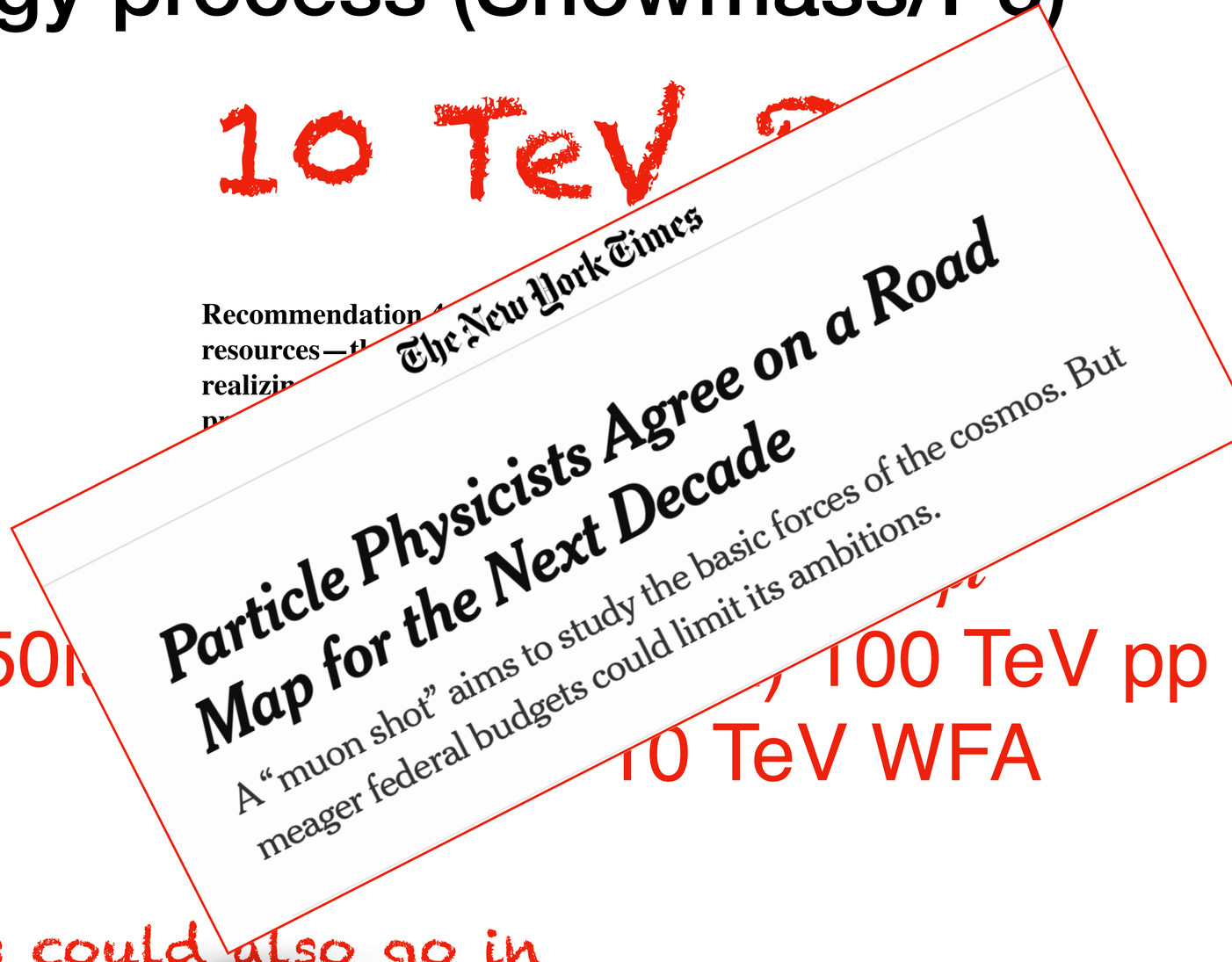

The New York Times

Particle Physicists Agree on a Road Map for the Next Decade

A "muon shot" aims to study the basic forces of the cosmos. But meager federal budgets could limit its ambitions.

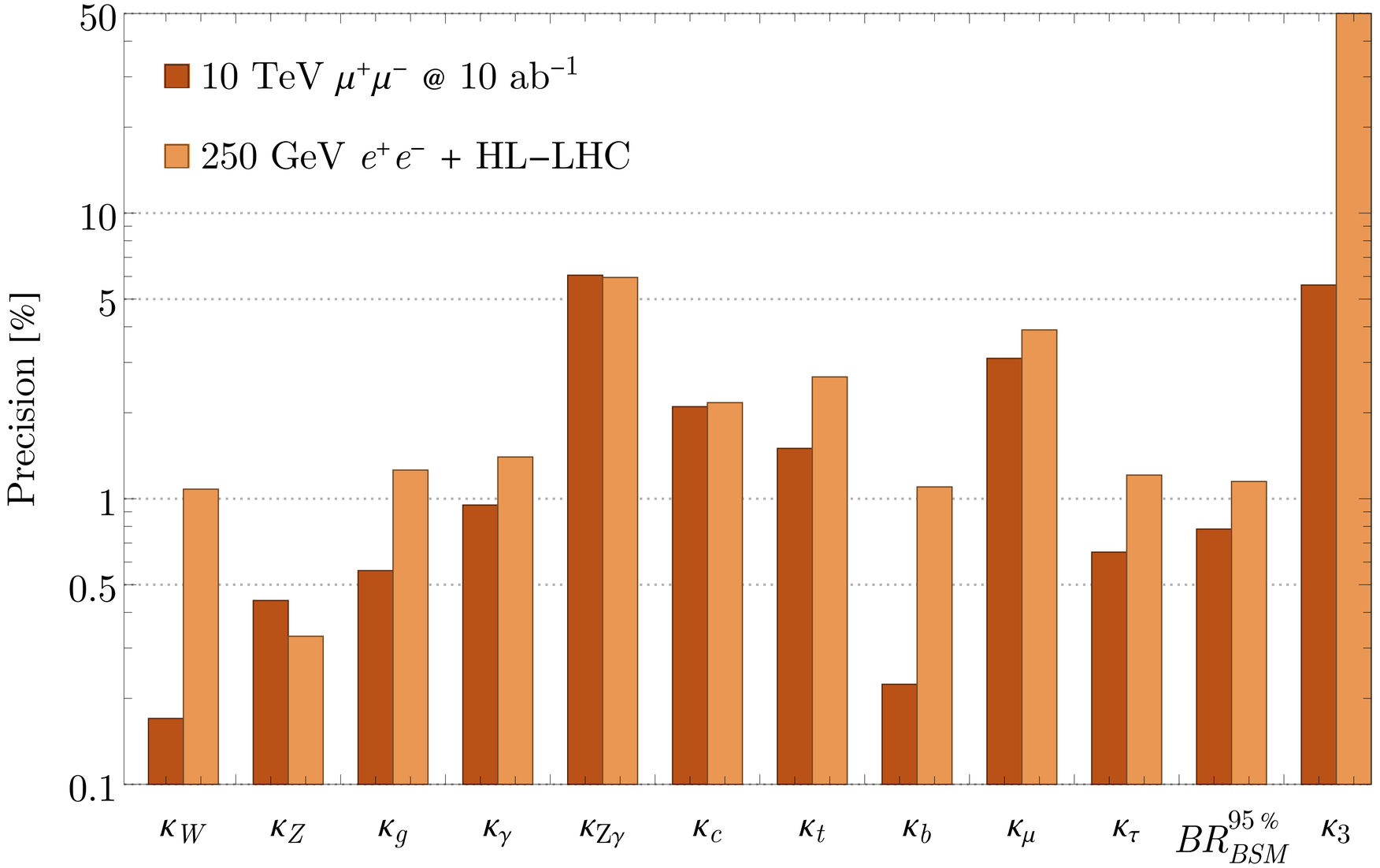
50

100 TeV pp

10 TeV WFA

Linear colliders could also go in between depending on Higgs factory

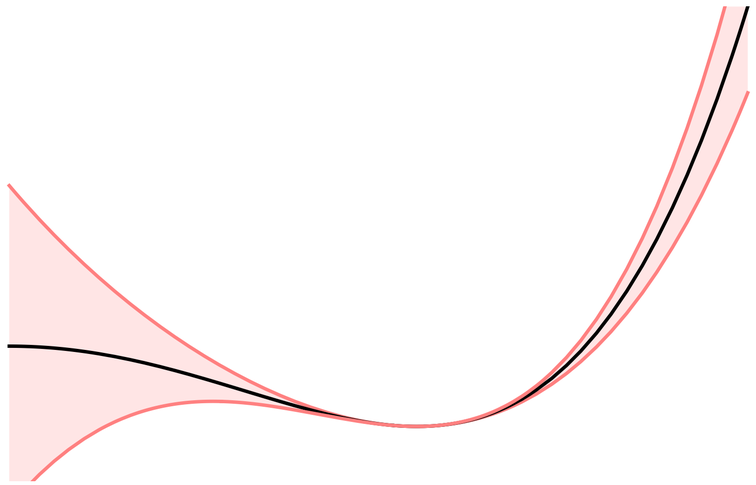
What does that buy you?



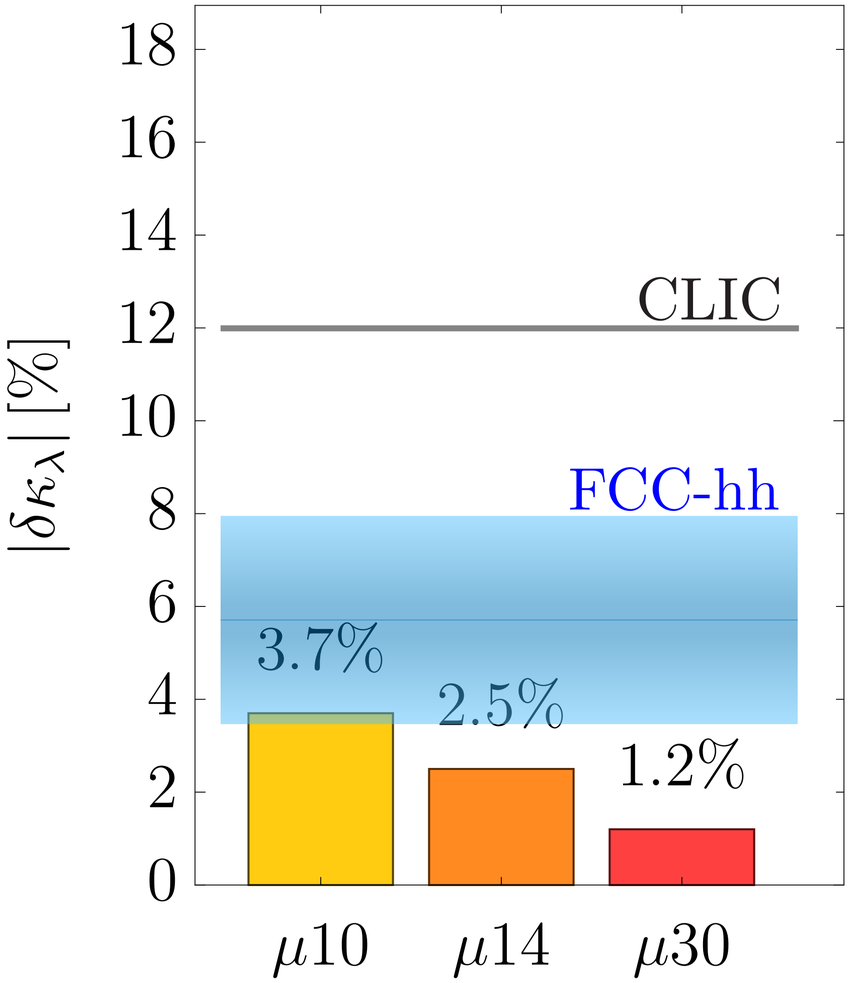
2308.02633 M.Forslund, PM

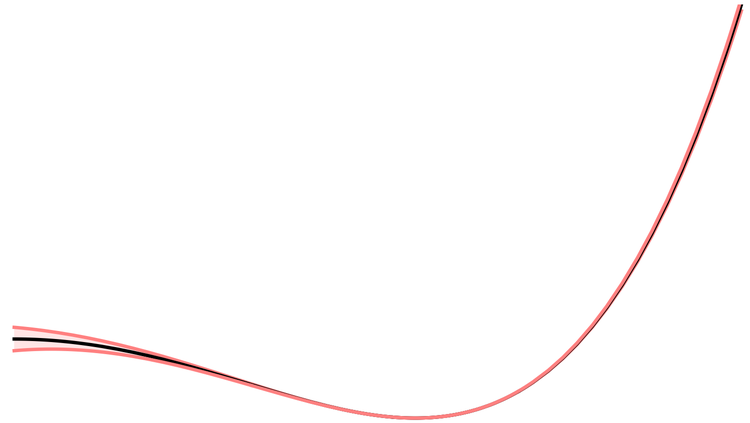
See also great talk by Alessandro Montella from earlier this week

What does that buy you?



HL-LHC



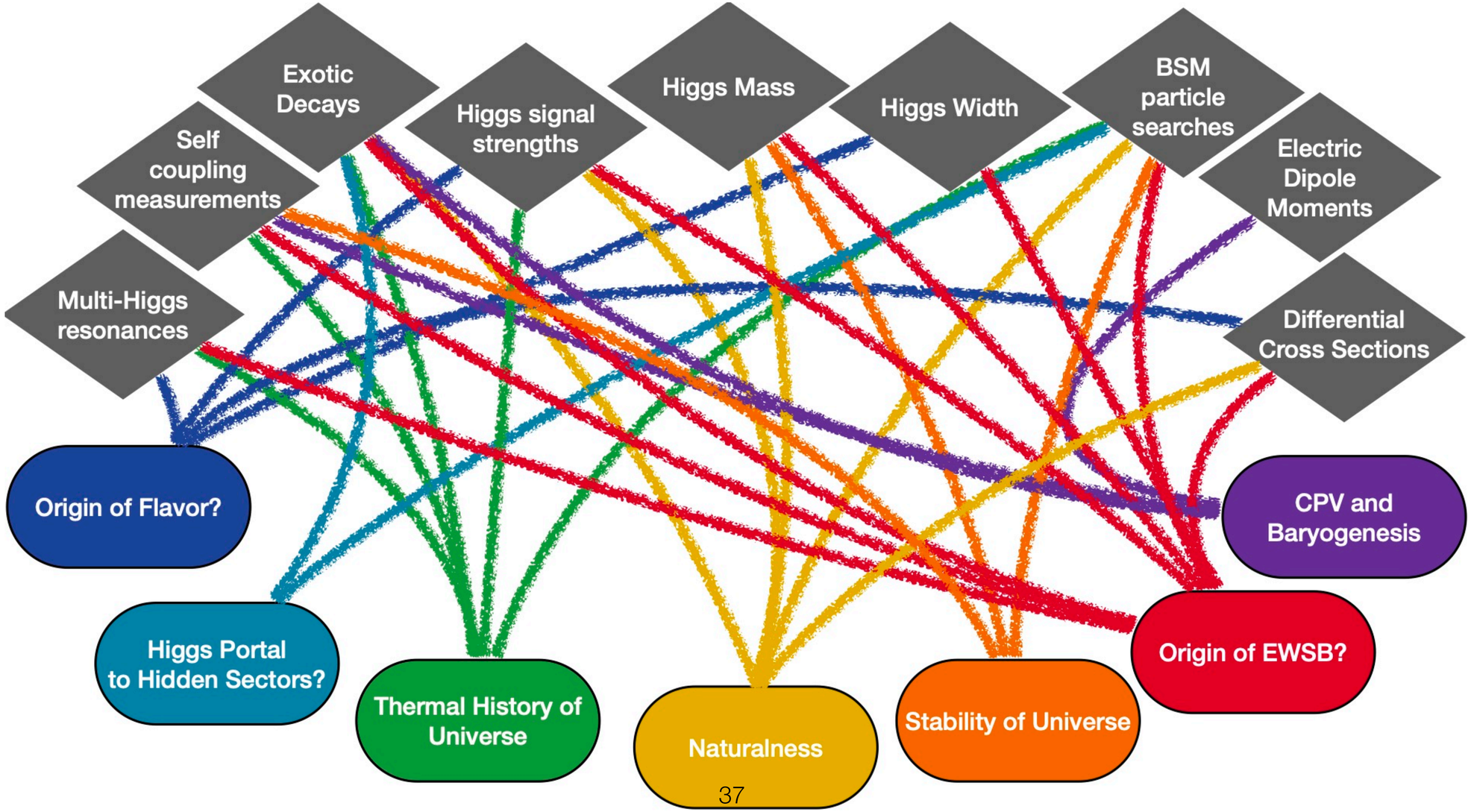


10 TeV μCol

High energy provides a way to higher precision Higgs physics (and physics beyond the Higgs) - but does it matter?

Is there a threshold on precision where we actually answer questions we care about?

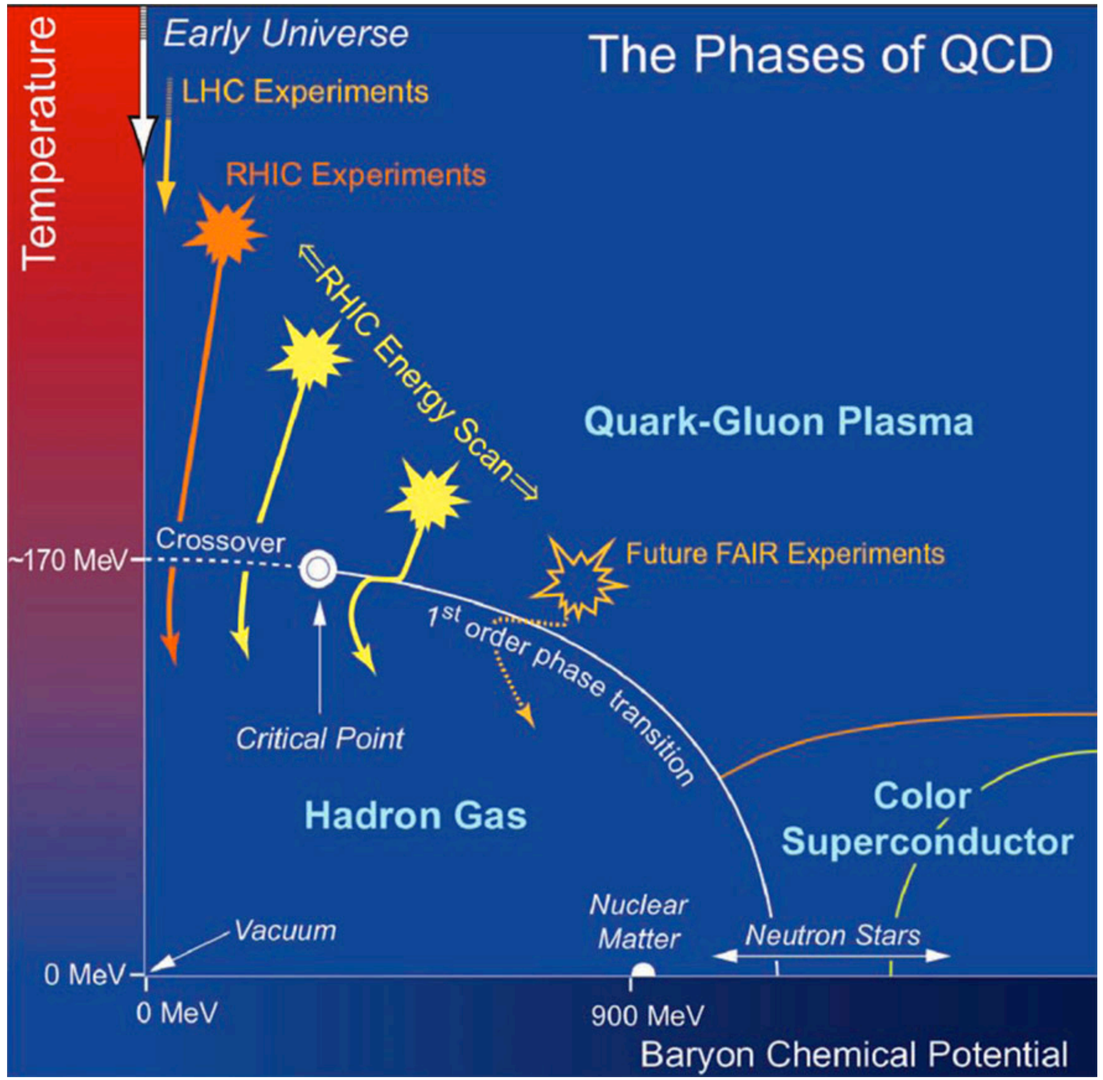
We know we can connect questions to observables, but what's the threshold of *precision* we need to achieve?



It’s very hard to create a no lose theorem based on precision alone.

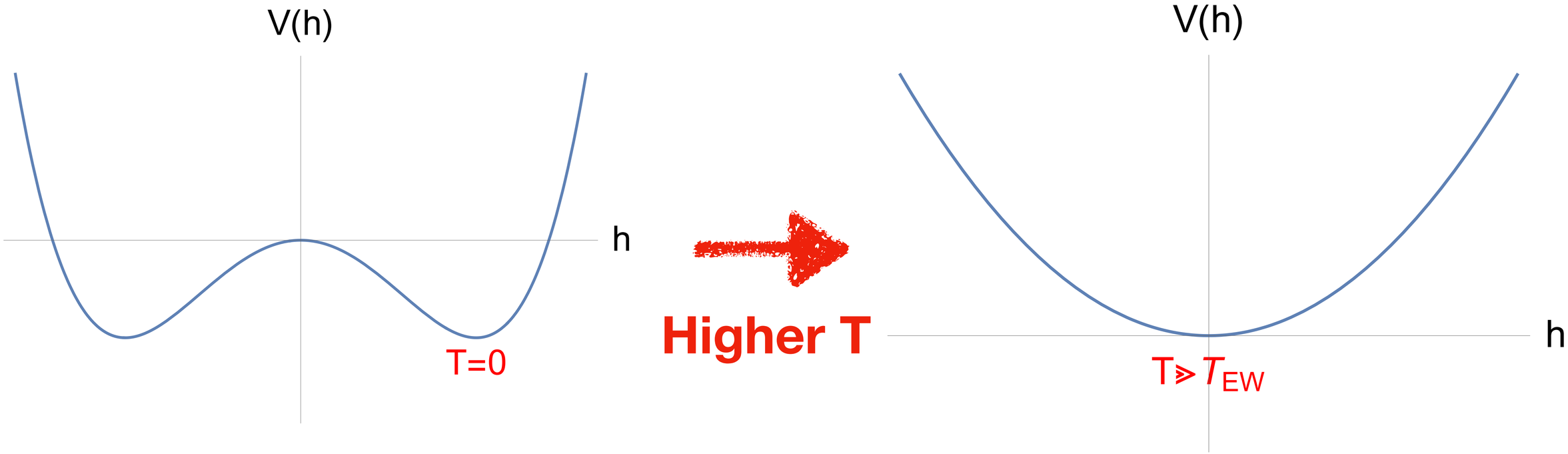
Mapping out the phase diagram of EW symmetry breaking in the early universe

(STAR whitepaper)



We can play a similar game to our heavy ion friends (although not quite as directly)

Next era in SM history is the “Electroweak Phase Transition”



Can we test this by testing the T=0 potential?

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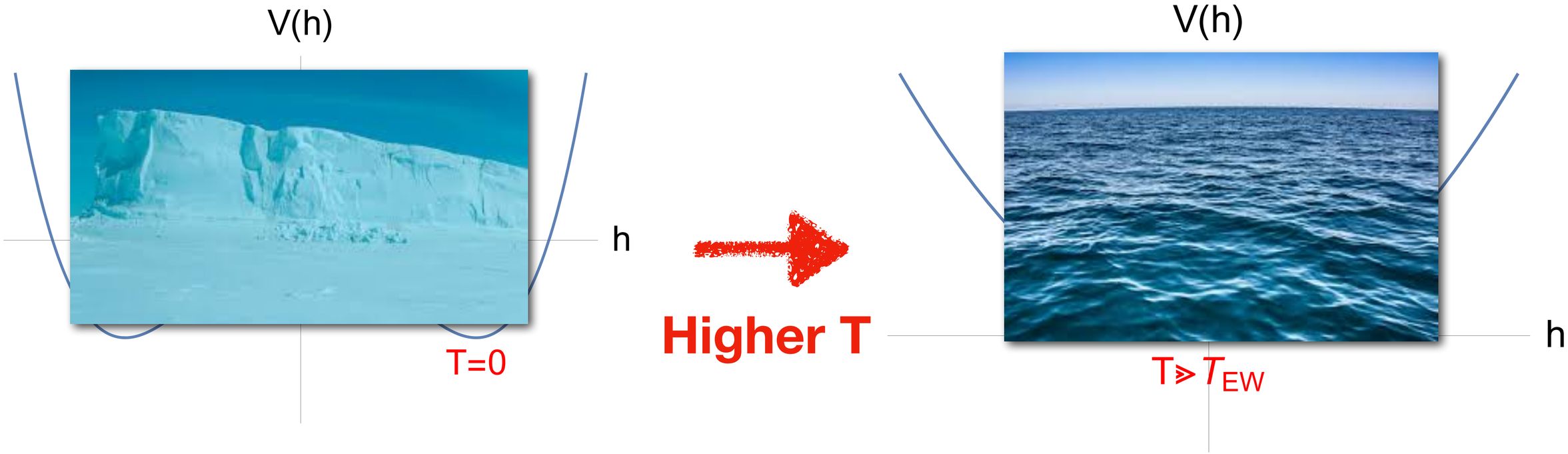
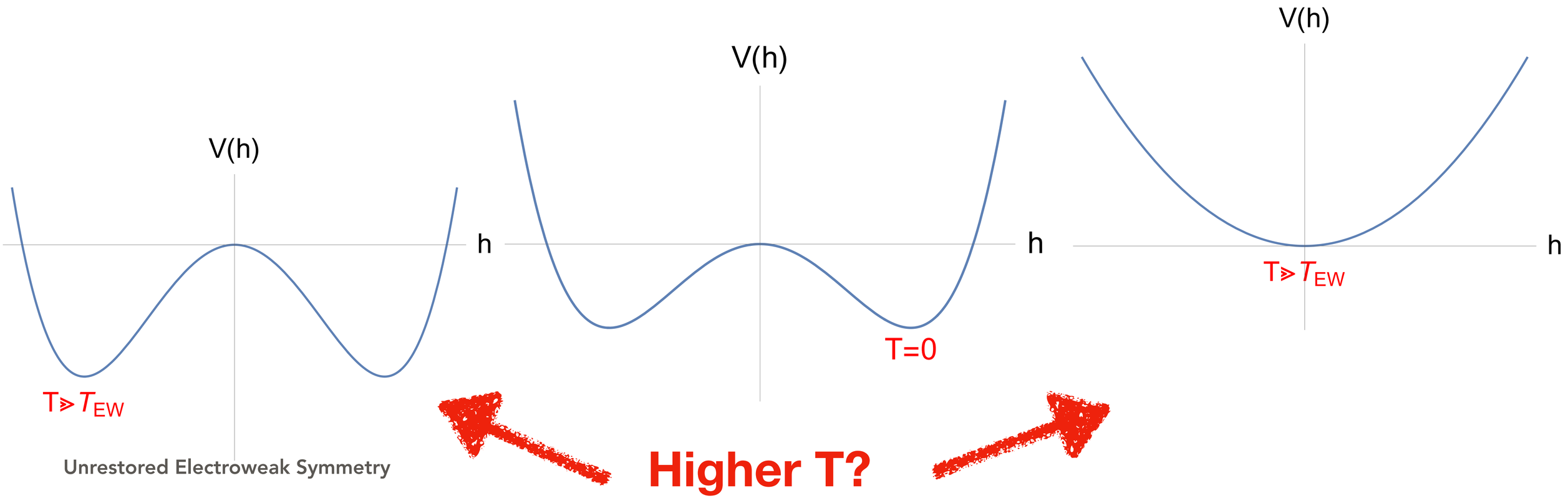


Can we test this by testing the T=0 potential? Yes*

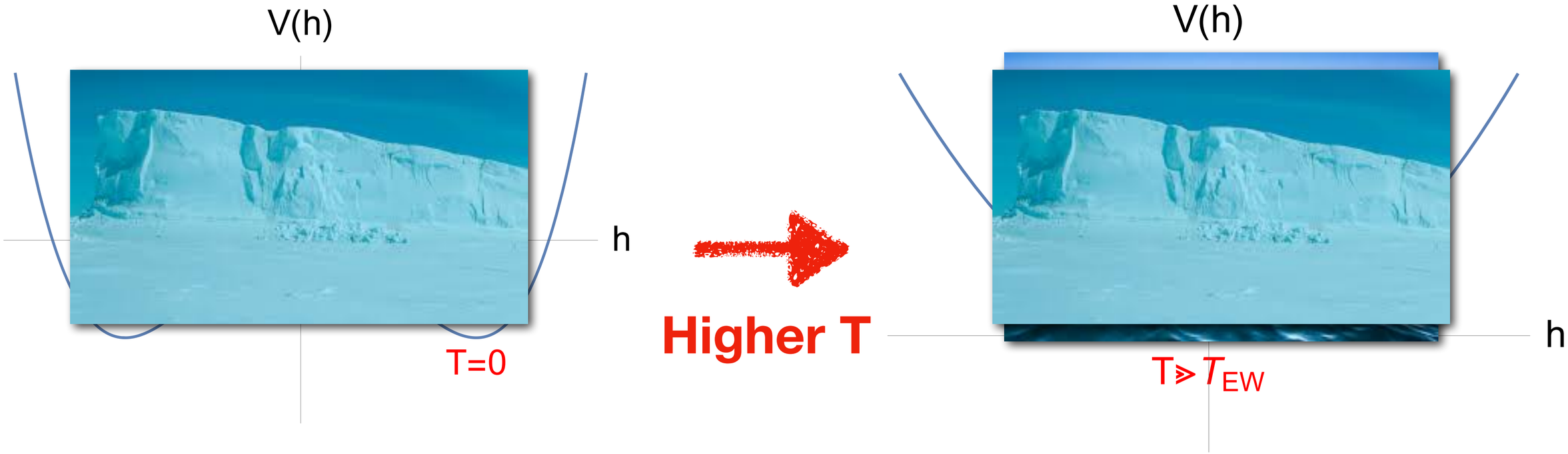
It turns out we don't even ***know*** that there was symmetry restoration at temperatures ≫ EW scale!



Unrestored Electroweak Symmetry

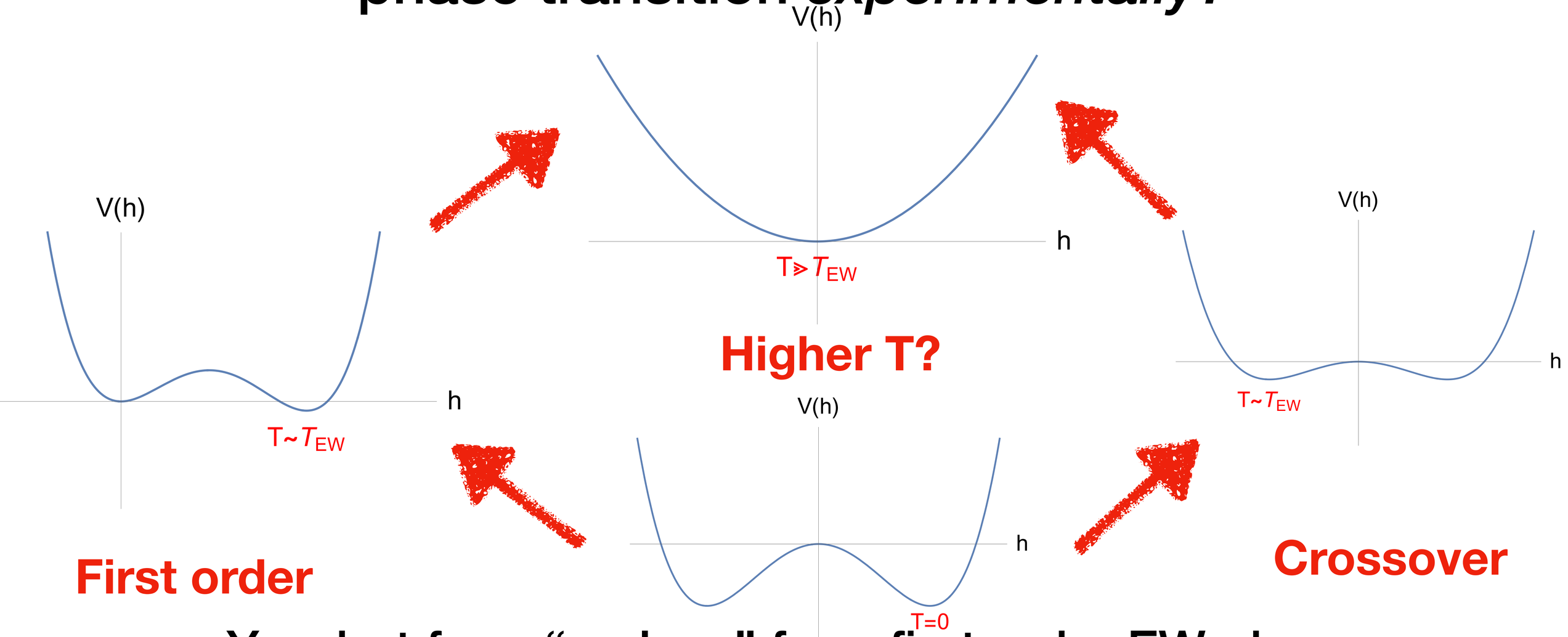
PM, H. Ramani
1807.07578

Next era in SM history is the “Electroweak Phase Transition”



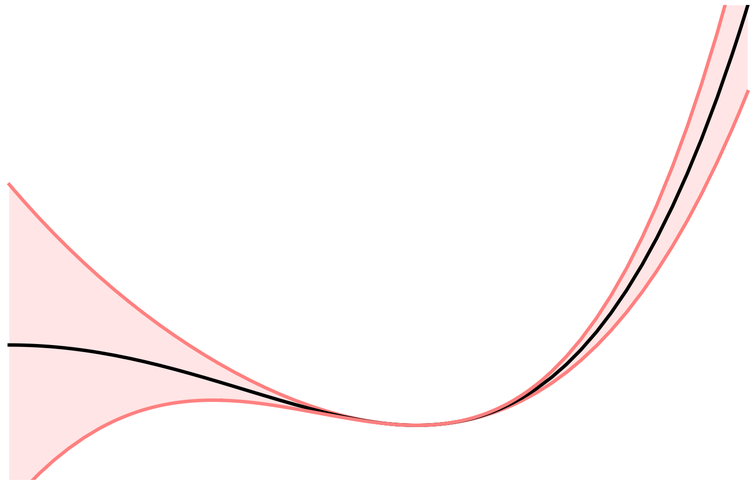
Can we test this by testing the T=0 potential? Yes*

If it was restored could we get at the **order** of the phase transition *experimentally?*

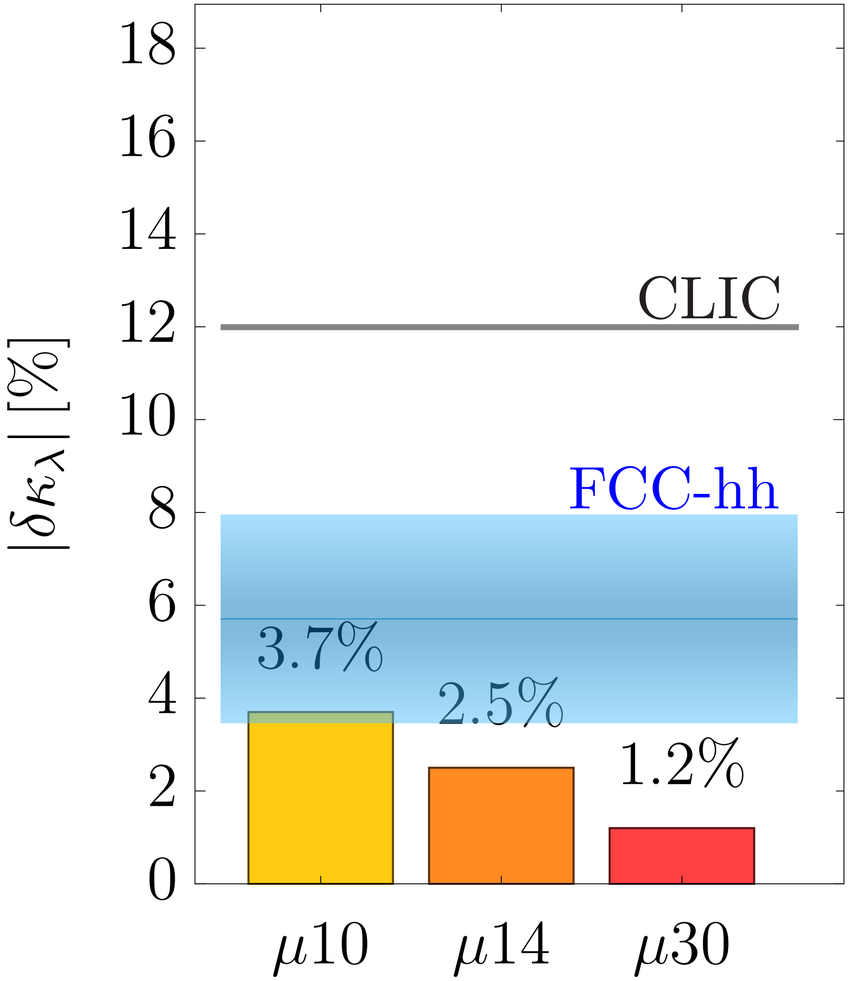


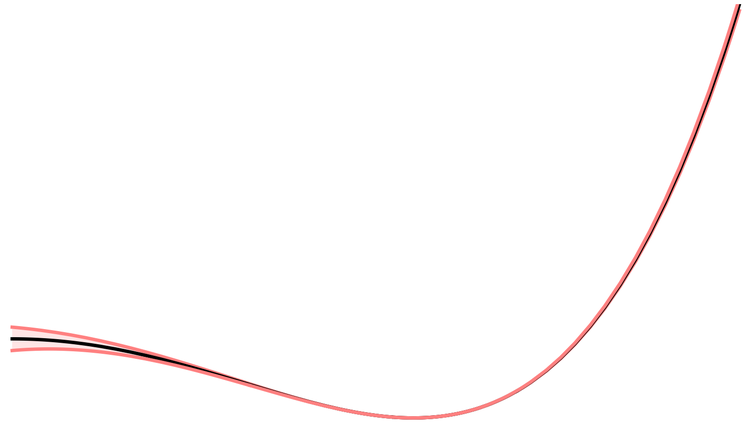
Yes, but for a “no lose” for a first order EW phase transition at the EW *scale* needs $\delta\kappa_\lambda \sim \mathcal{O}(\%)$

We need 10 TeV PCM for a “no lose” theorem



HL-LHC





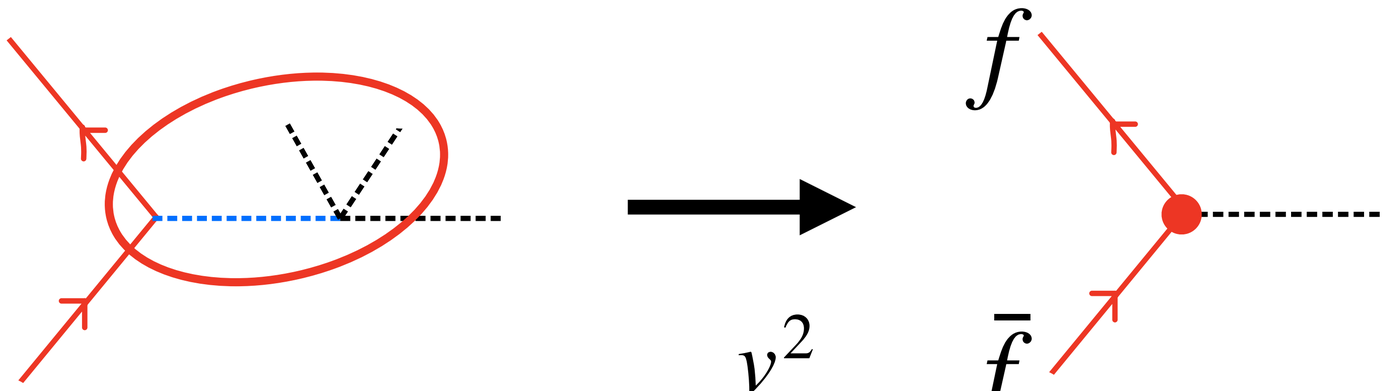
10 TeV μCol

What does precision mean more generally? And what does it let us probe?

There is no such thing as a model independent interpretation of precision:

not κ *nor* EFTs

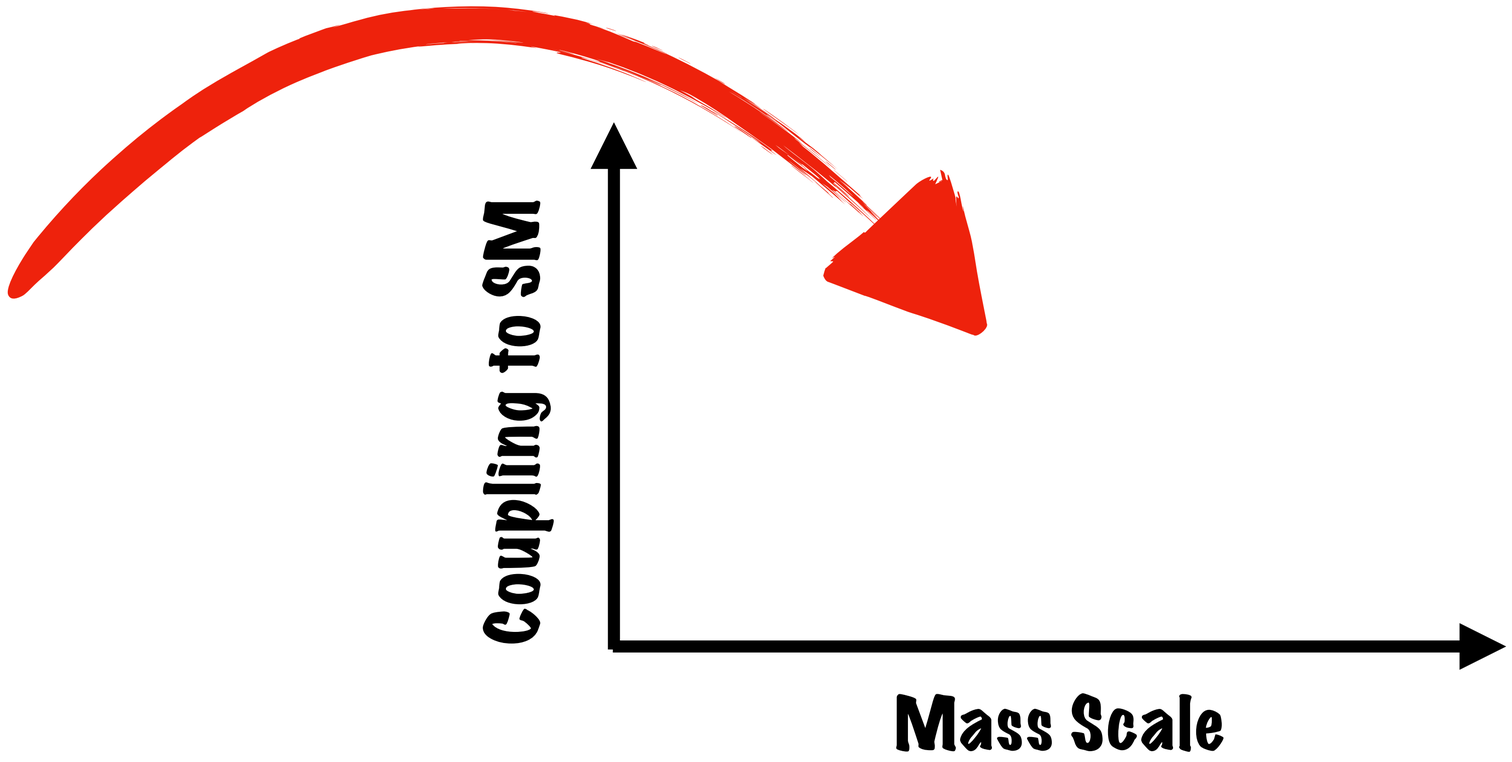
We like EFTs because they *can* systematically compress the seemingly infinite space of UV BSM theories, *provided* they are a valid description (e.g. $E \ll \Lambda$)



$$\delta\kappa \sim \frac{v^2}{M_{NP}^2}$$

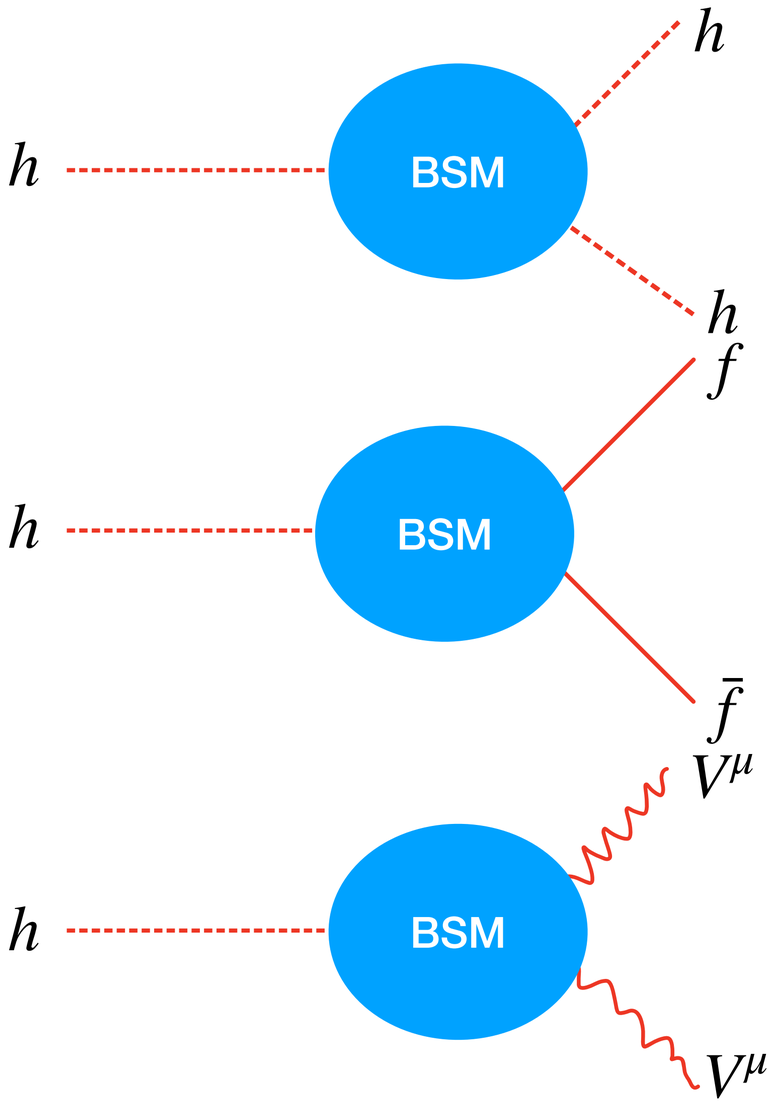
At a Higgs factory with high precision everything plays pretty nicely in EFT framework, but elsewhere? LHC, ILC, CLIC, FCC-hh, Muon Colliders?

For a given precision on Wilson coefficients



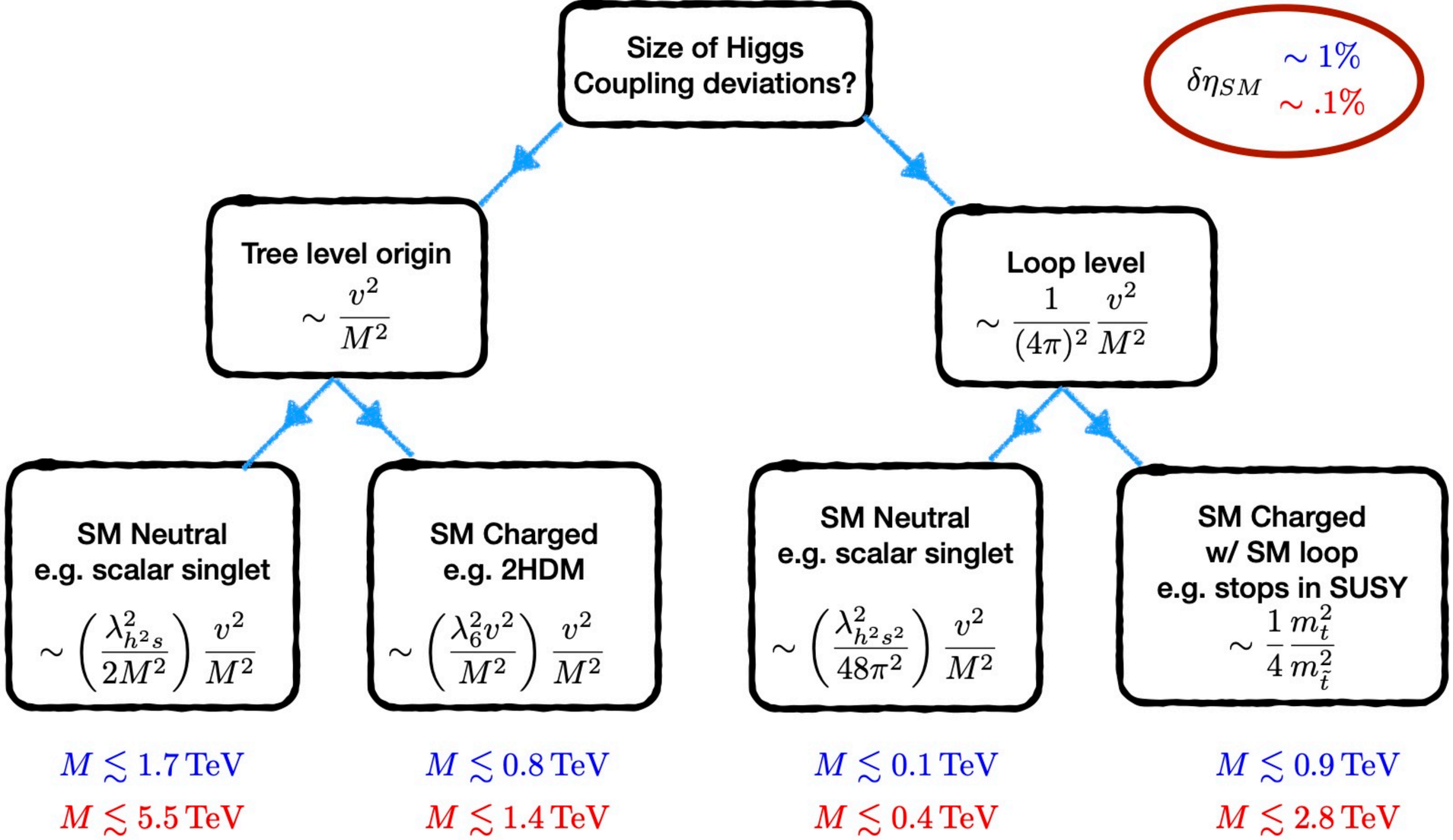
What is the mapping to possible BSM theories?

This is an exercise you can do just based on the *precision* of a Higgs observable, independent of collider!



What can BSM be?

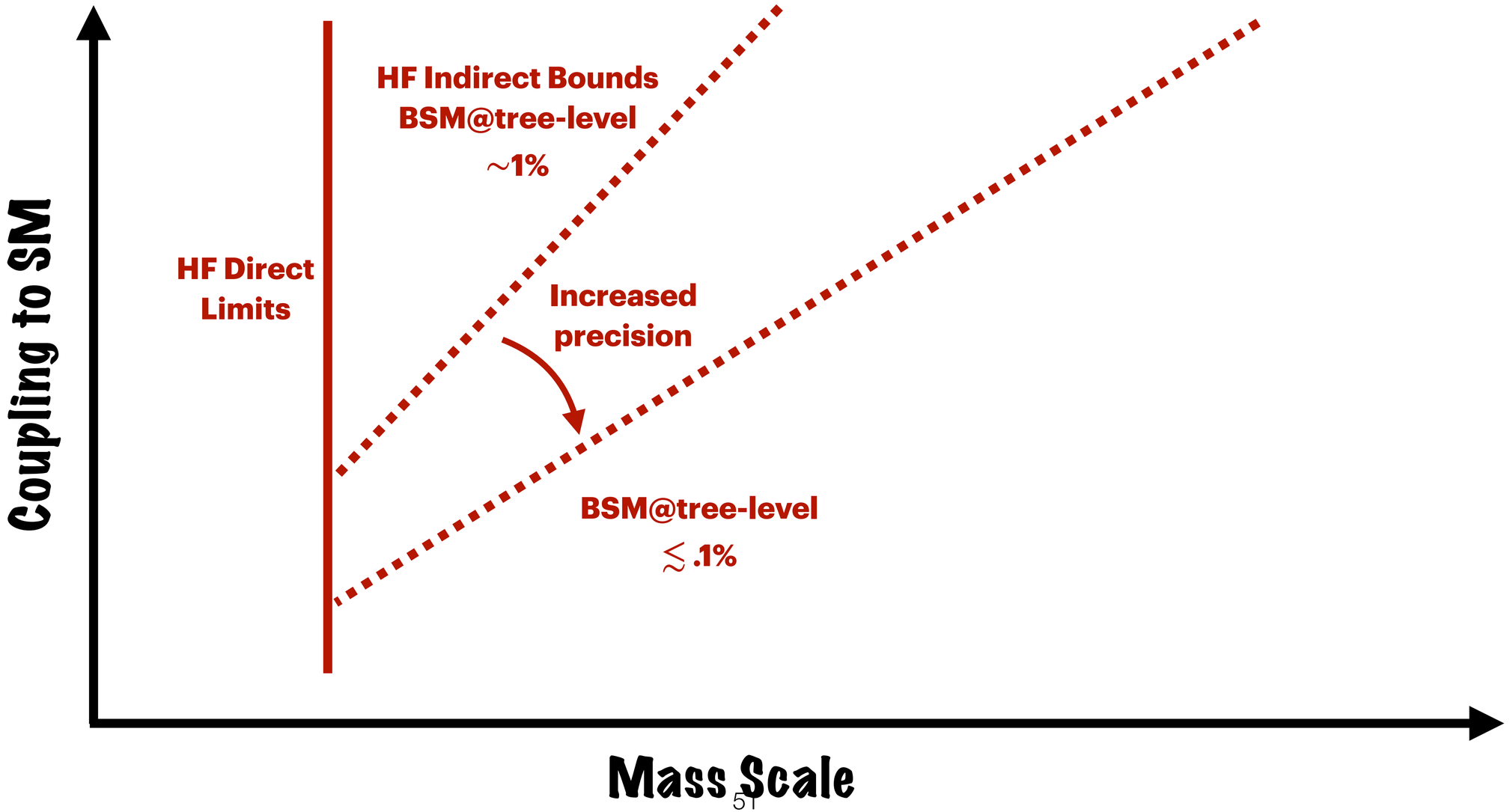
Something that couples at tree-level or loop-level to the SM!



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

These scales can be probed *directly* at the LHC, Linear Colliders, FCC-hh, Muon Collider

Where do other colliders live?



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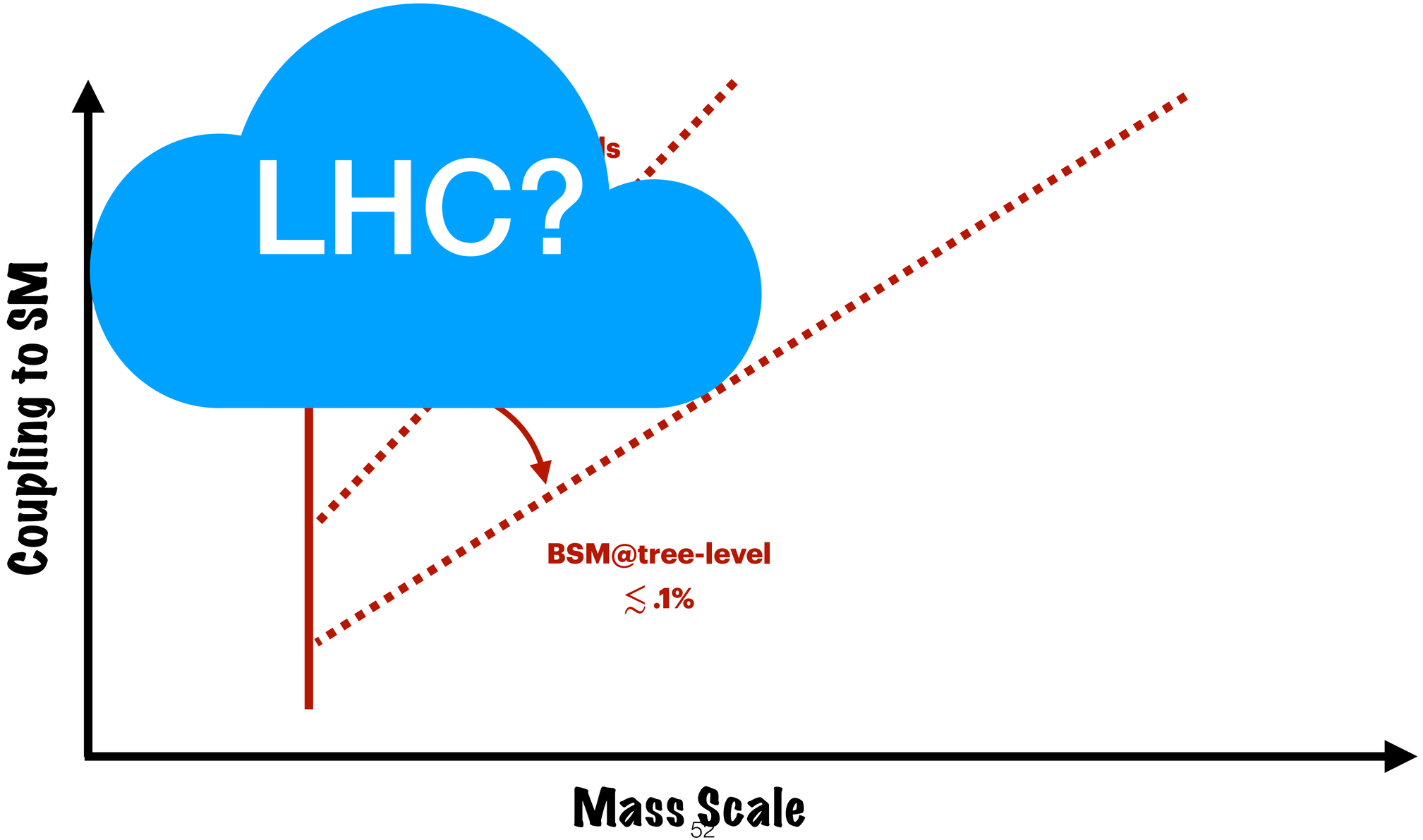

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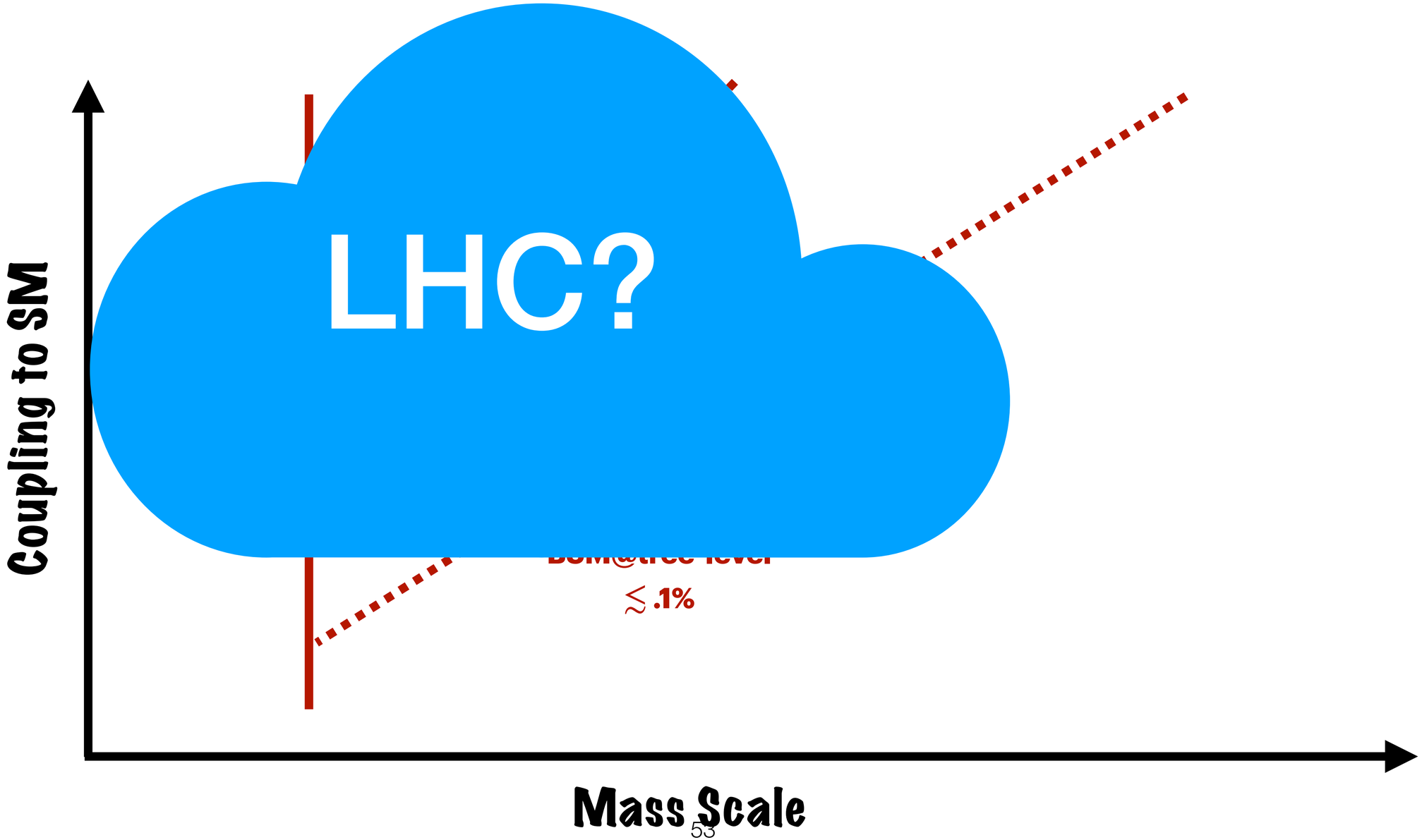
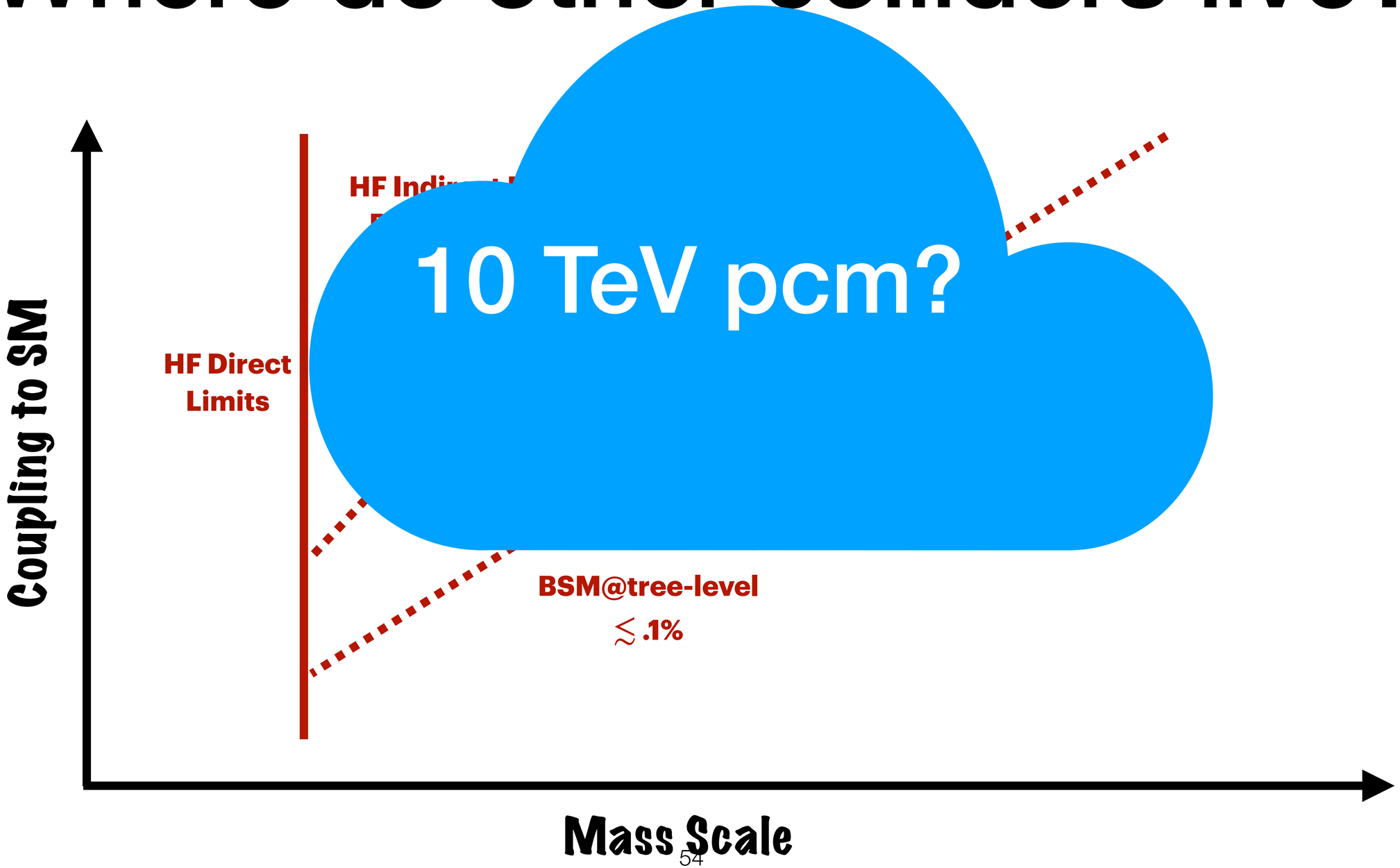


Where do other colliders live?



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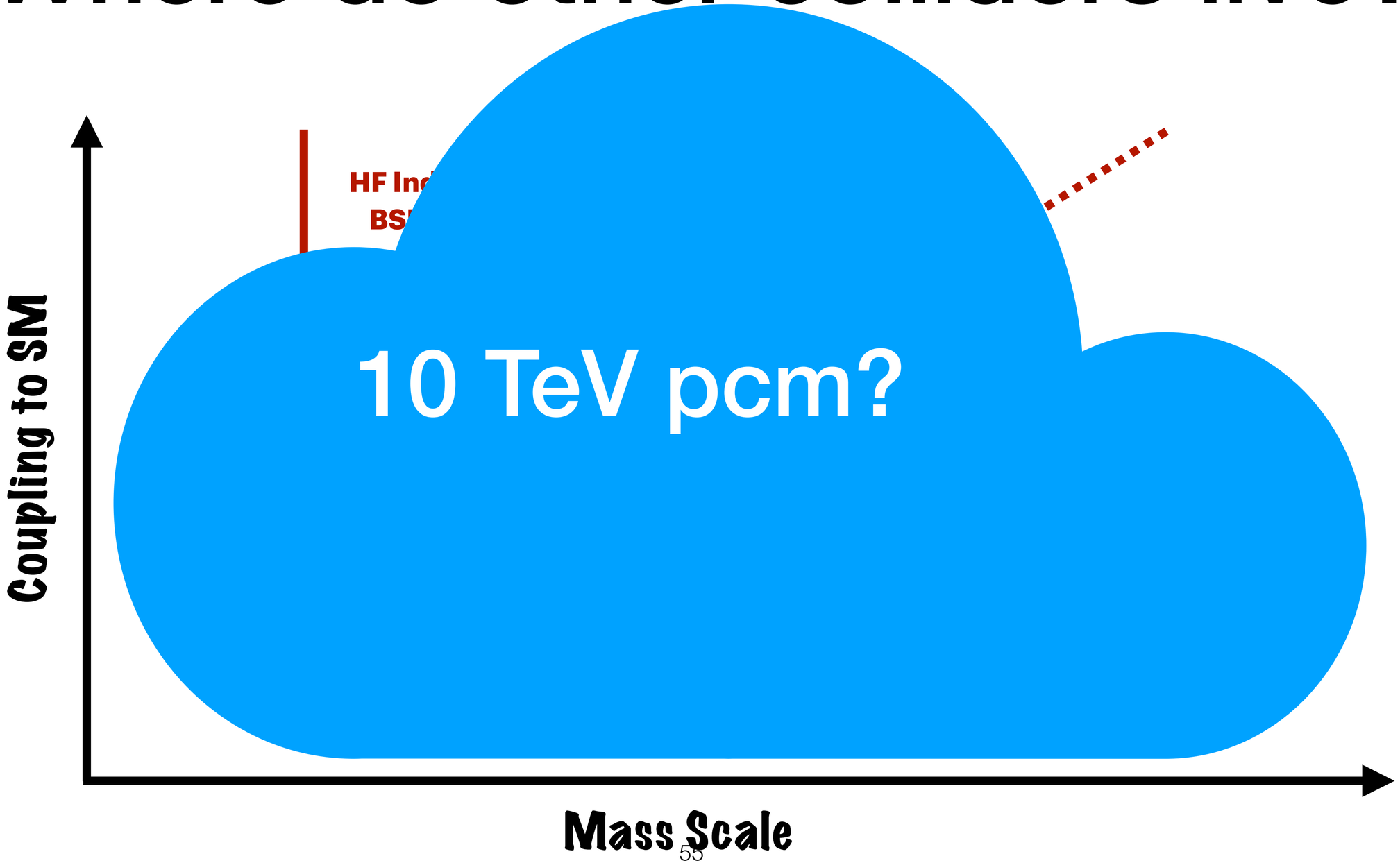
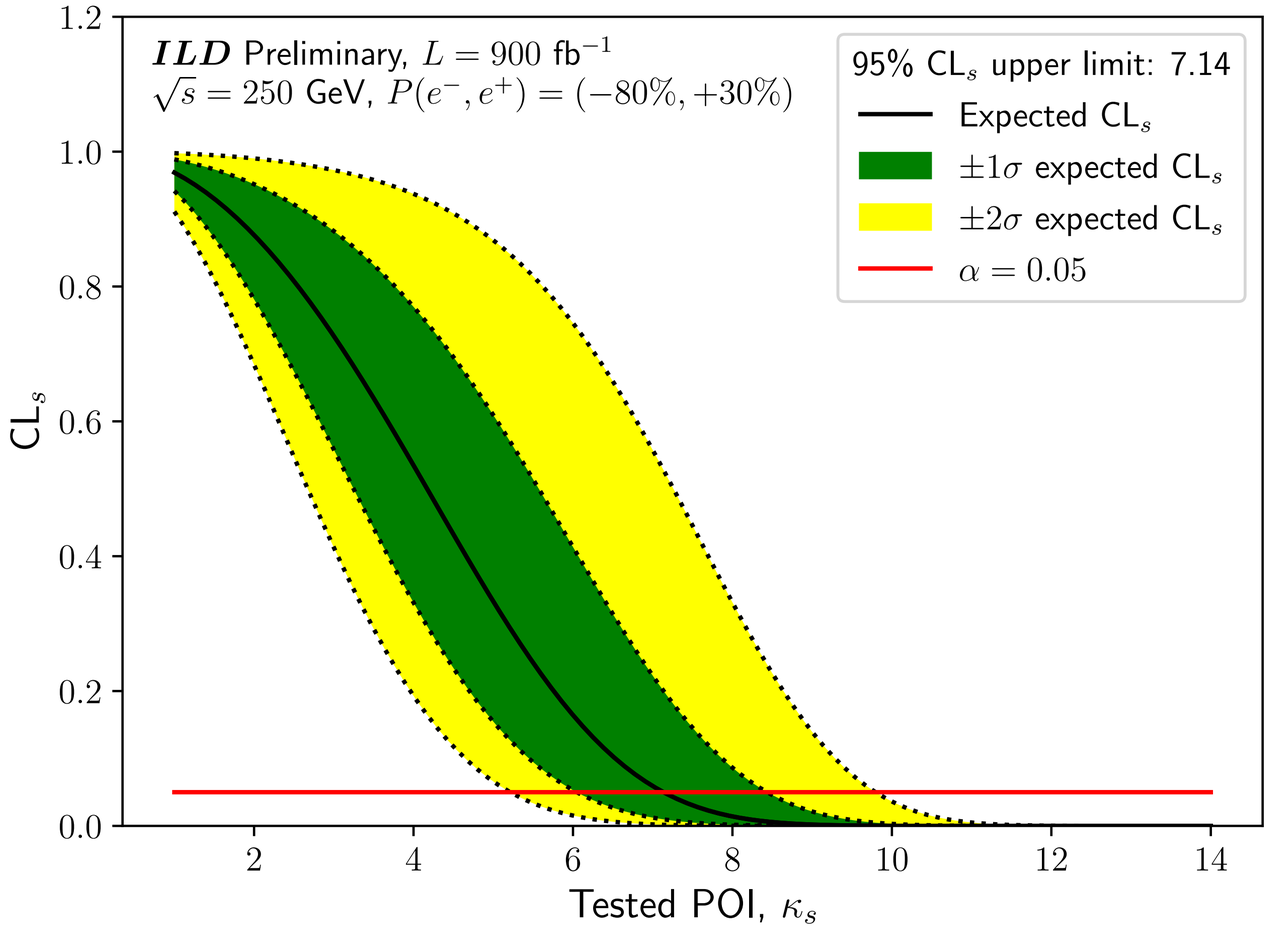


Concrete/Cute example how strange is the strange Yukawa?

$$\frac{1}{\Lambda^2}(sh\bar{s})h^2$$

Generically you should worry but you can reduce flavor constraints w/ Spontaneous Flavor Violation (SFV)

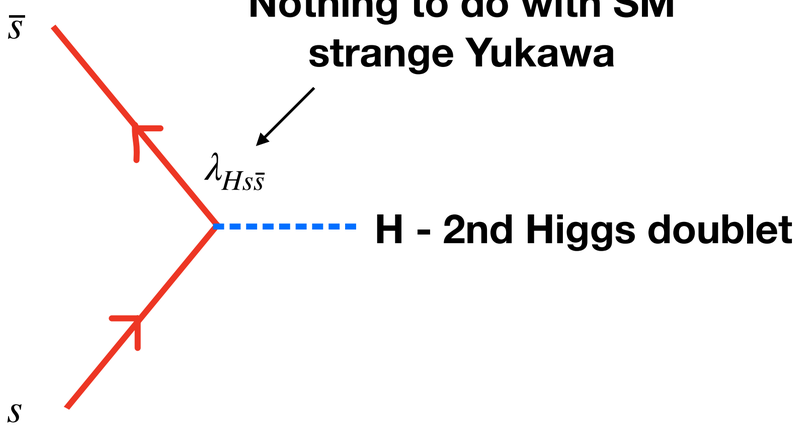


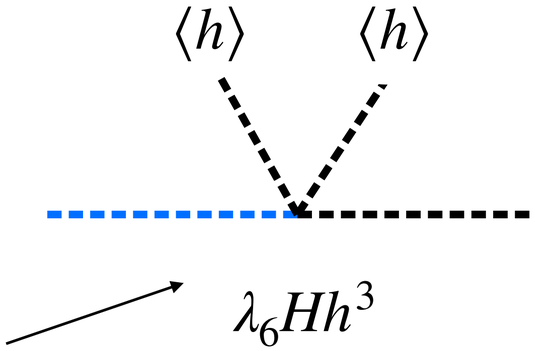
ILC Snowmass study
A. Albert et al
2203.07535

D. Egana-Ugrinovic, S. Homiller, PM
1811.00017,1908.11376,2101.04119

To generate such $\mathcal{O}$ you *need* BSM physics that couples to strange quarks differently *and* couples to the SM Higgs + symmetry (e.g. SFV 2HDM)

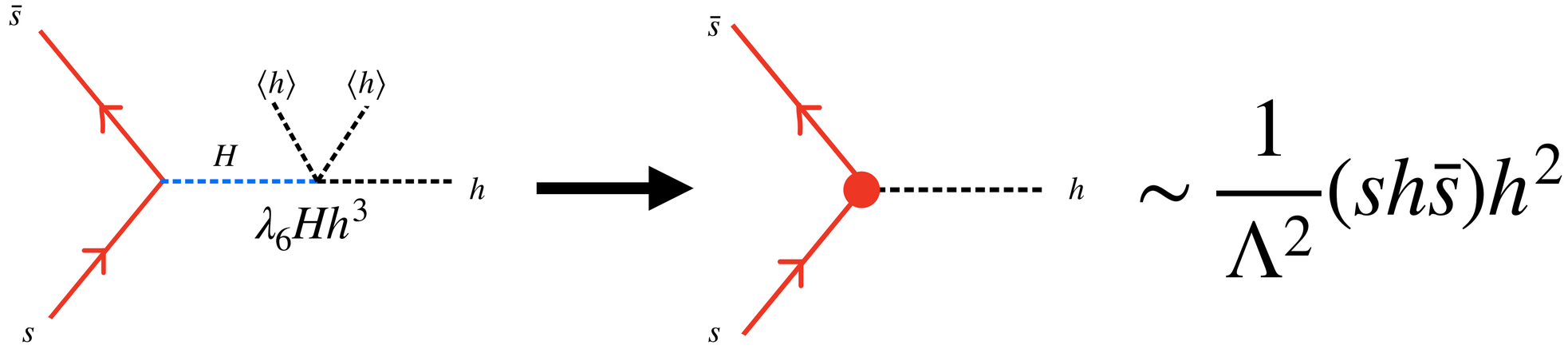
$$\frac{1}{\Lambda^2}(sh\bar{s})h^2$$





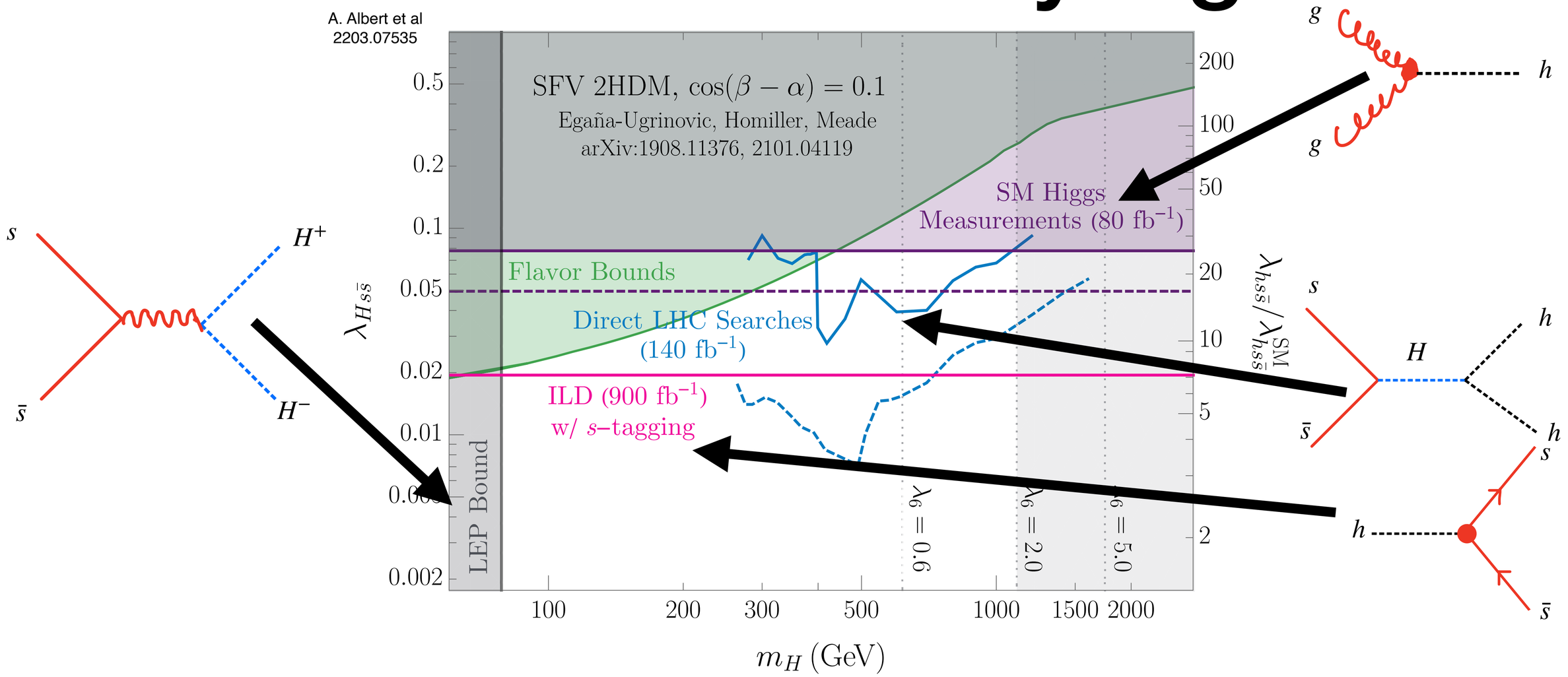
Coupling of 2nd Higgs doublet to our Higgs

Put them together and it can modify “SM Higgs” strange Yukawa



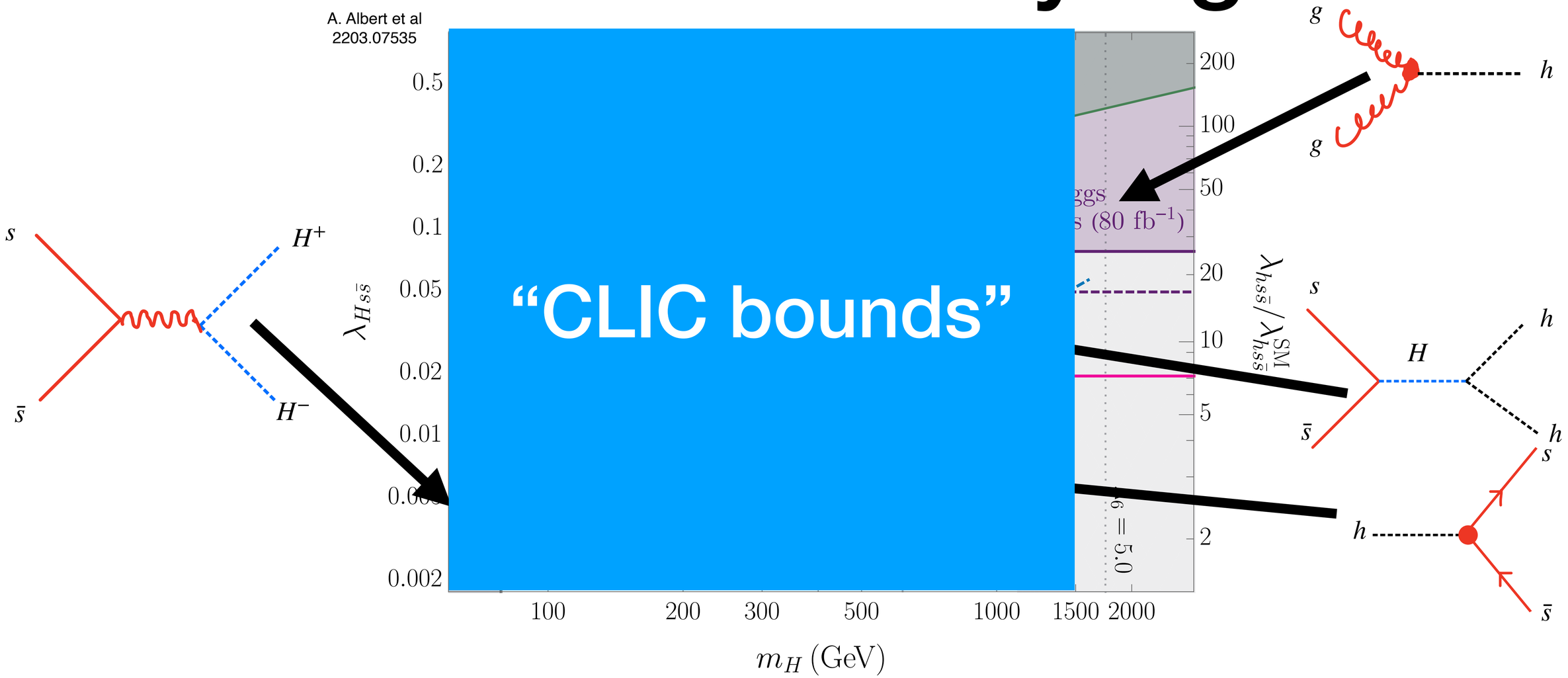
Simple parameter space:
mass, coupling to strange, mixing with Higgs

That's not the only signal!



Resonant di-Higgs sets the current strongest LHC bound on deviations of the strange Yukawa!

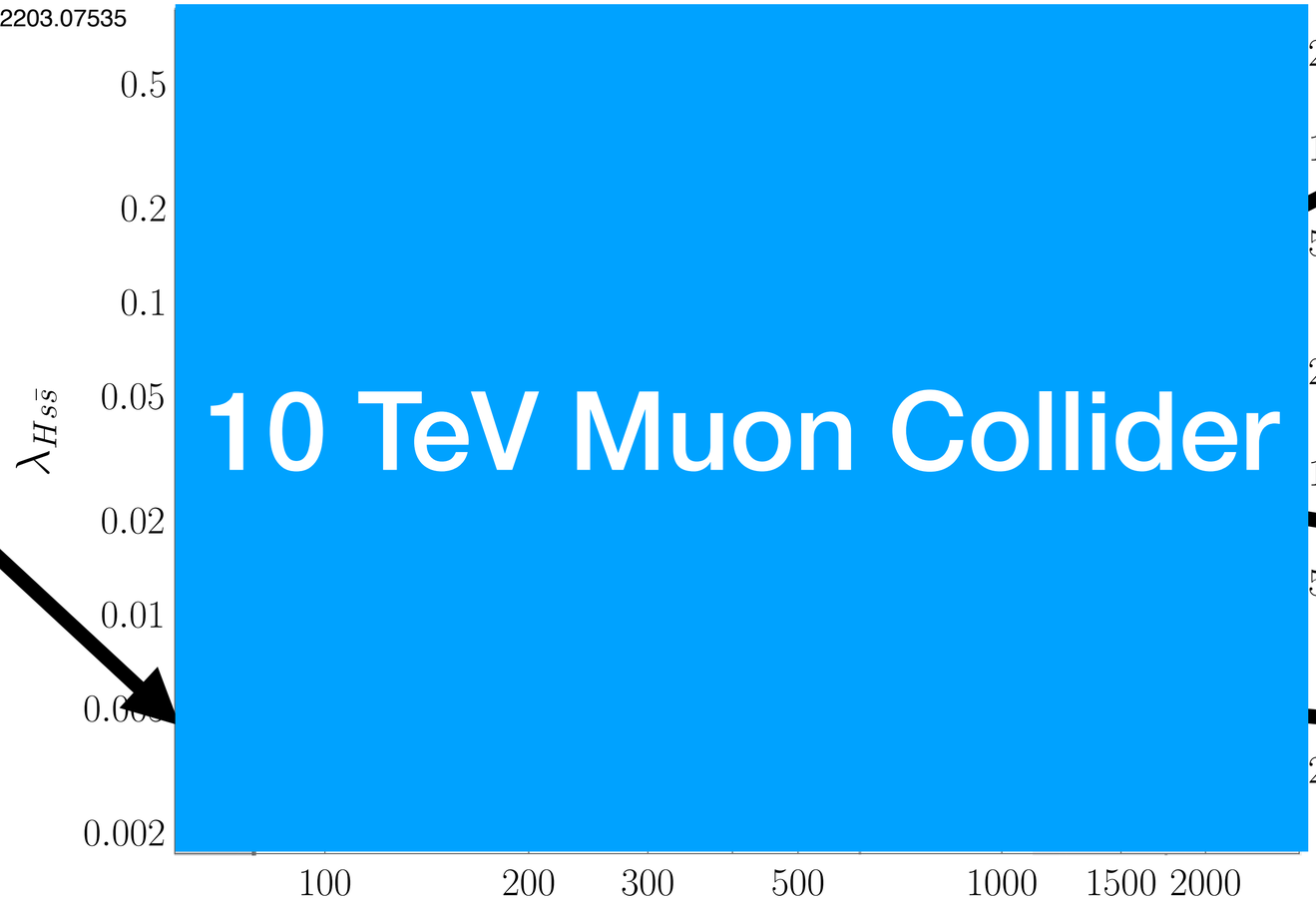
That's not the only signal!

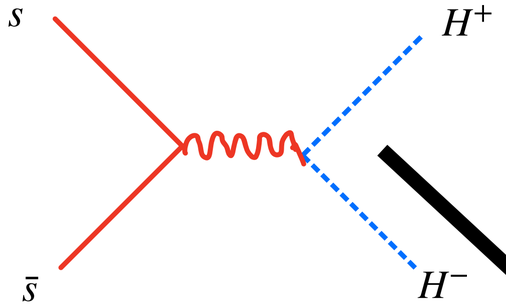


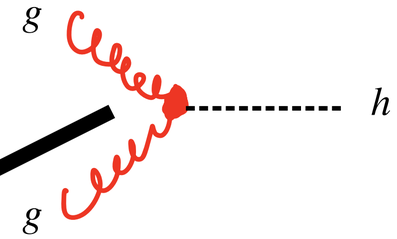
High energy colliders test Higgs physics in complementary and powerful ways!

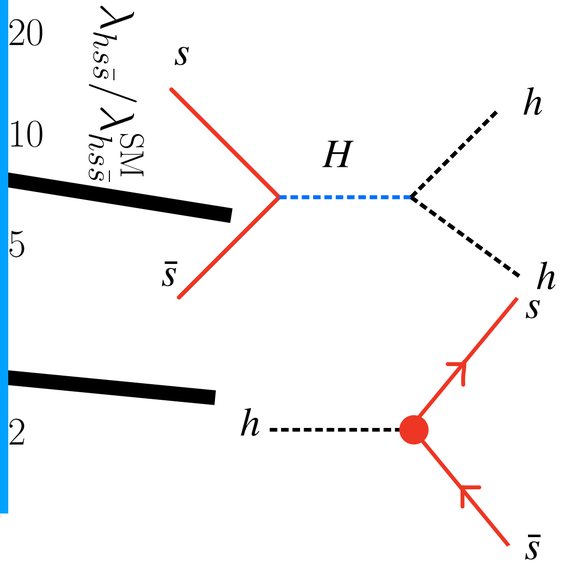
That's not the only signal!

A. Albert et al
2203.07535









High energy colliders test Higgs physics in complementary and powerful ways!

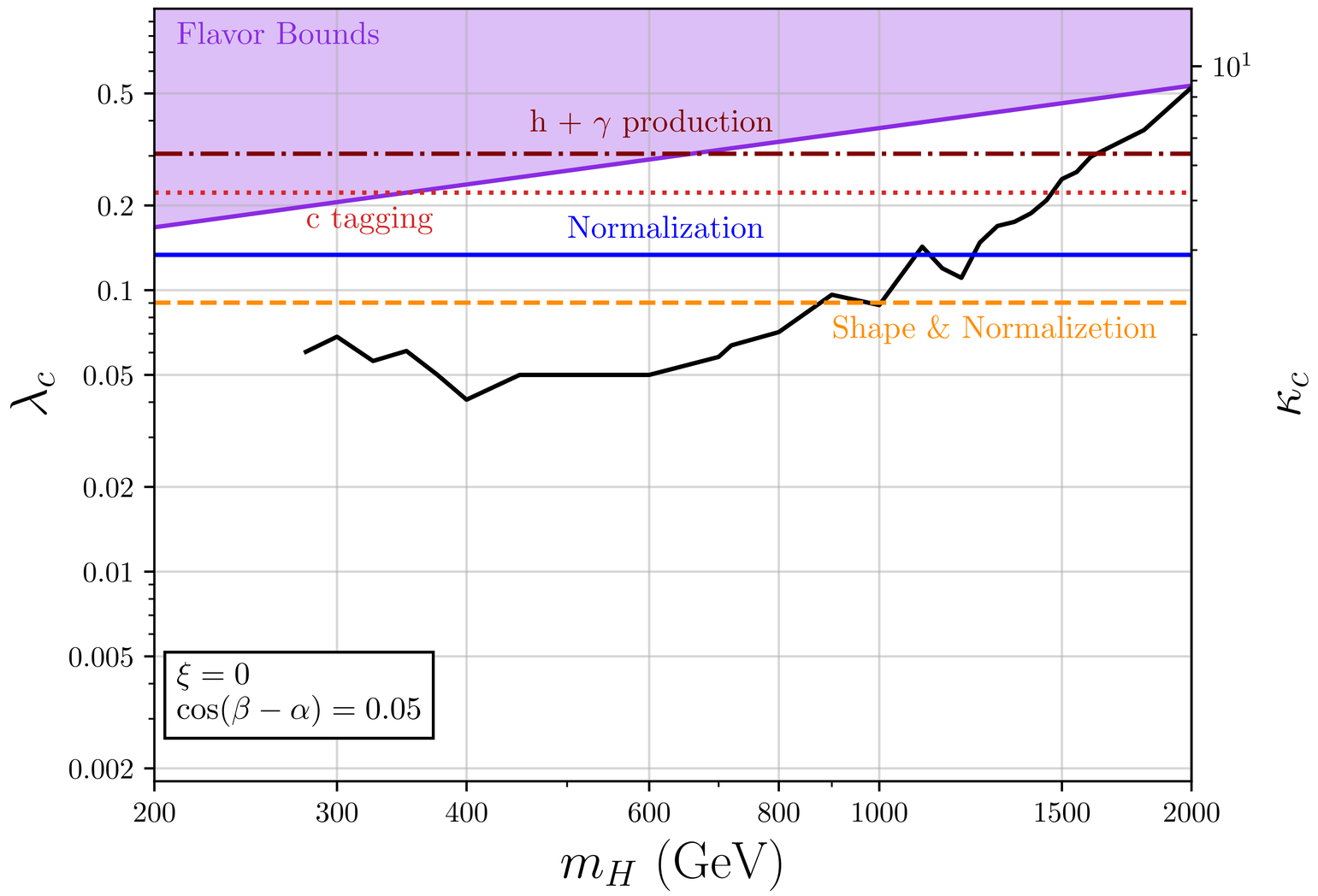
Can play a similar game for the Charm Yukawa

Experiment	Reference	$\mathcal{L}(fb^{-1})$	Constraints	Comments
ATLAS	[22]	139	$\lvert\kappa_c\rvert < 2.91$	Normalization
CMS	[25]	138	$\lvert\kappa_c\rvert < 2.92$	Normalization
ATLAS	[28]	139	$\kappa_c \in (-2.27, 2.27)$ $\kappa_c \in (-8.6, 17.3)$	(p_T measurement, Shape & Normalization) p_T measurement, Shape only
CMS	[29]	138	$\kappa_c \in (-6, 5.4)$	$h + \gamma$ associated production
CMS	[23]	138	$1.1 < \lvert\kappa_c\rvert < 5.5$	c-tagging
ATLAS	[30]	140	$\lvert\kappa_c\rvert < 4.2$	c-tagging
CMS	[31]	138	$\lvert\kappa_c\rvert < 38.1$	$h + c$ associated production
ATLAS	[21]	139	$\kappa_c/\kappa_\gamma \in (-153, 175)$	$h \to J/\psi\gamma$ decays
CMS	[32]	138	$\kappa_c \in (-7.5 \times 10^3, 7.7 \times 10^3)$	$h \to J/\psi Z$ decays

A. Giannakopoulou, PM, M. Valli
2410.05236

A lot more experimental effort and possibilities for LHC

How charming can the Higgs be?



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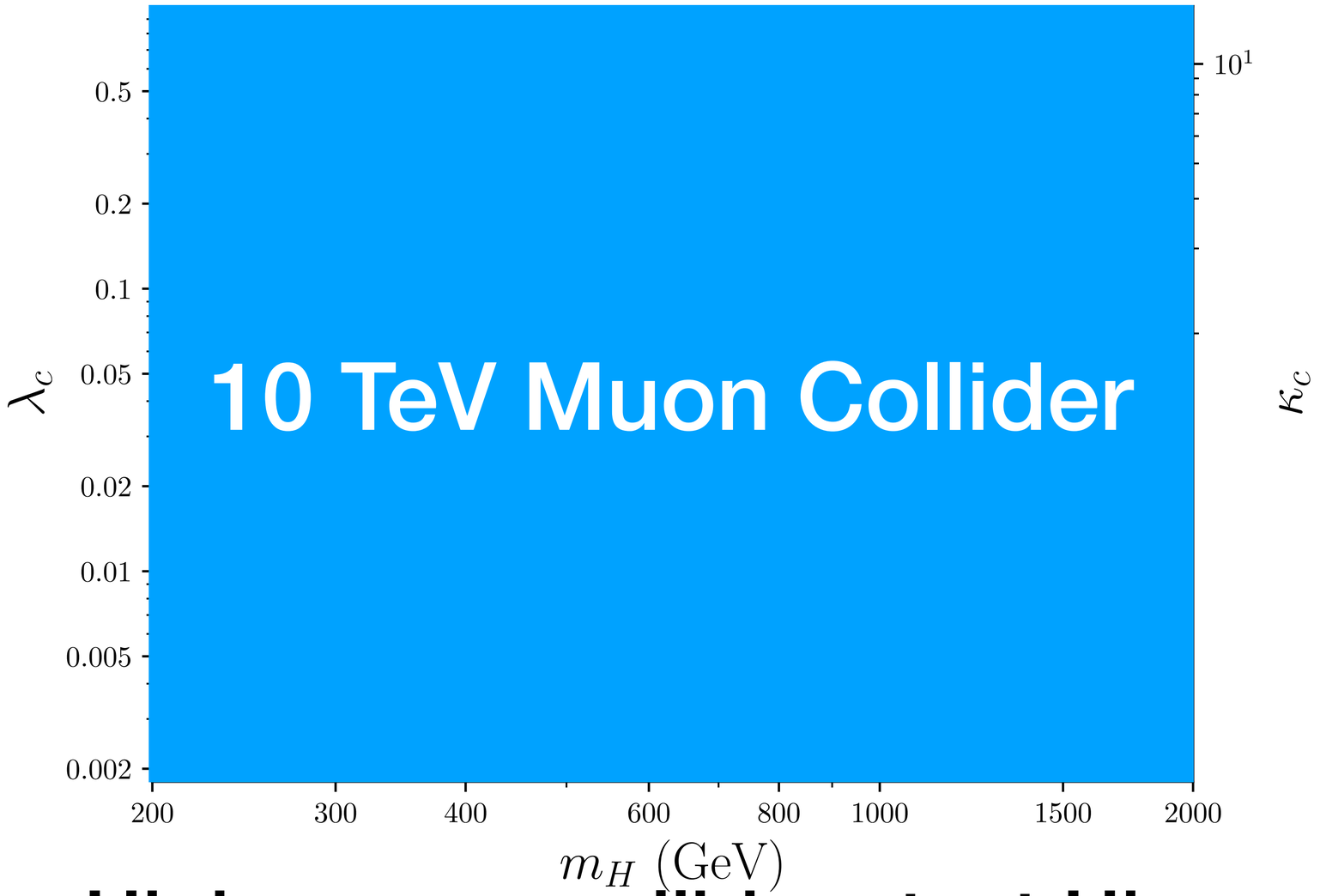
2410.05236

Strongest bounds are often from di-Higgs searches at the LHC!

How charming can the Higgs be?



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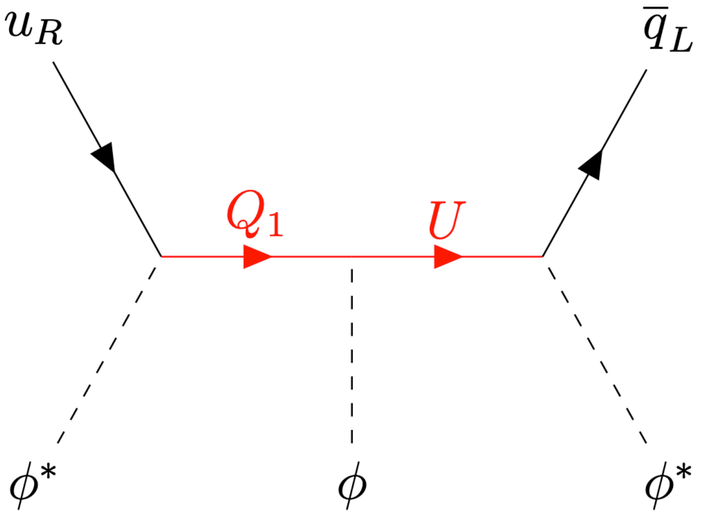
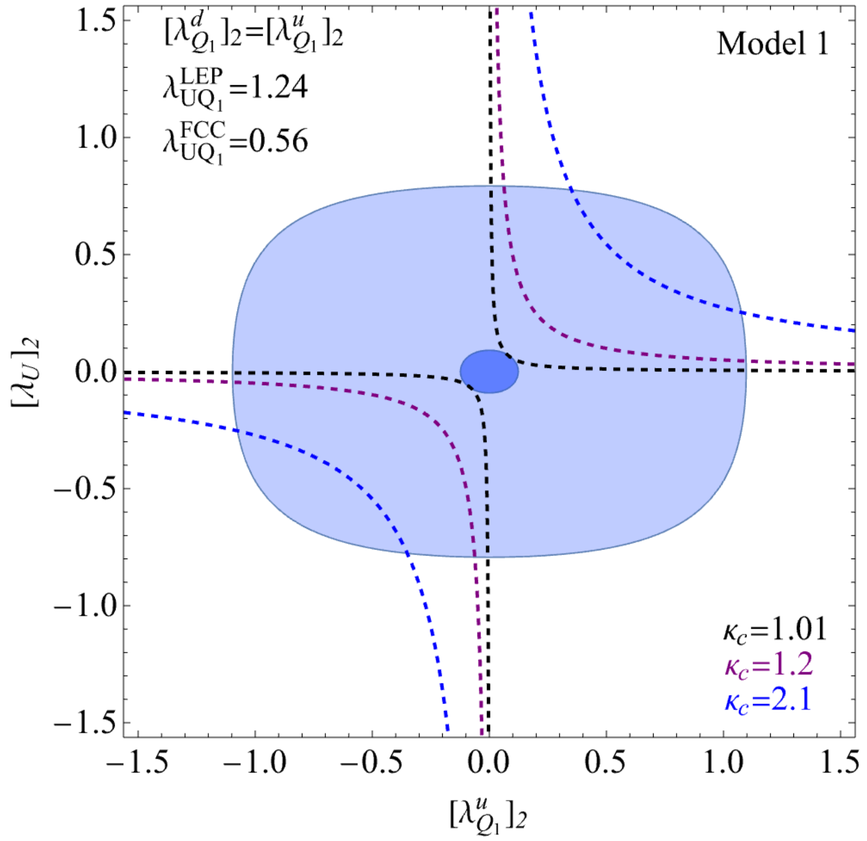
2410.05236

High energy colliders test Higgs physics in complementary and powerful ways!

Discrete other choice - VLQs

See great talk by Nudžeim Selimović from earlier this week





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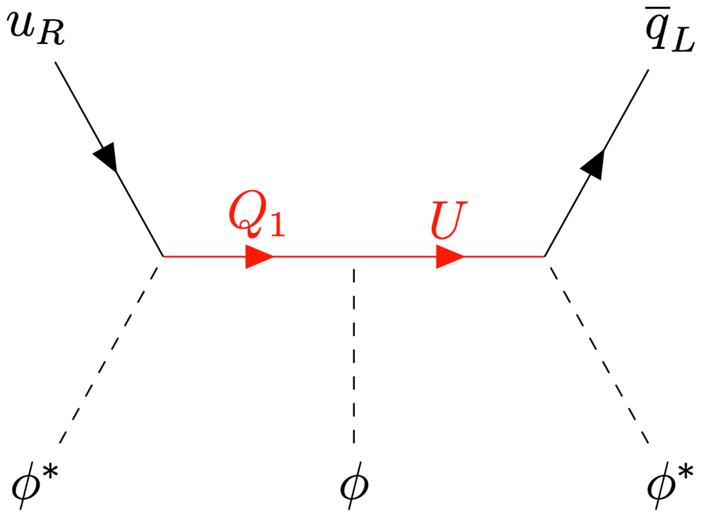

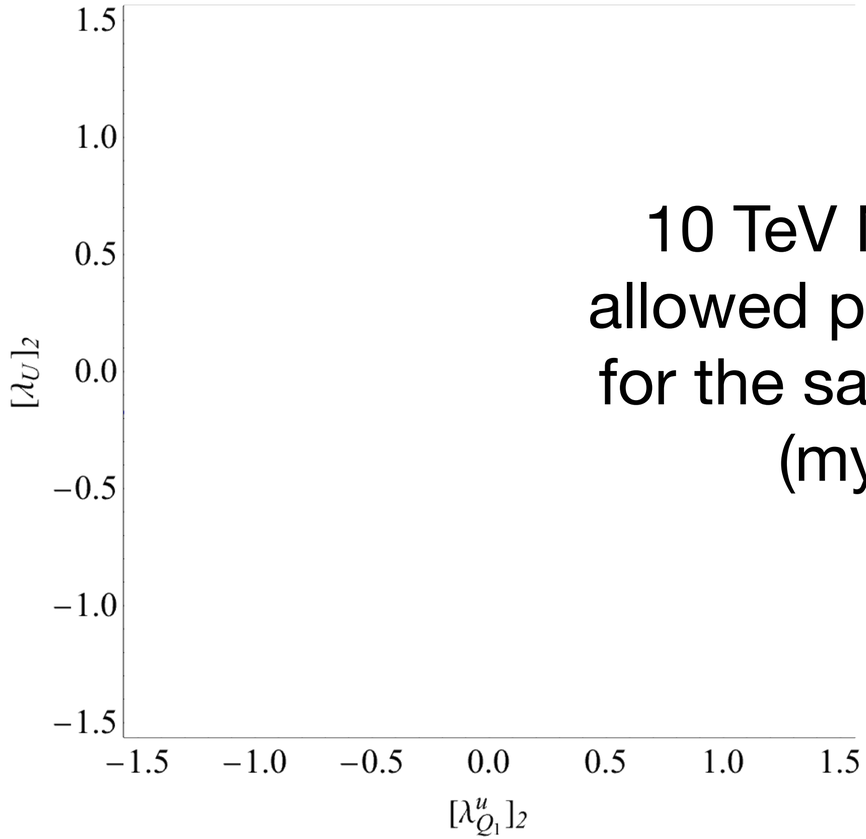

10 TeV Muon Collider allowed parameter space for the same parameters (my version)

This isn't *only* for shifts in Yukawa couplings, one can *systematically* study this for gauge couplings and Higgs self couplings with similar results

Lesson: We're just not deep into the decoupling regime with *precision* Higgs physics now ***or*** at the next proposed generation of colliders

Higgs physics is more than just Higgs physics!

Is there an alternative?

Simplified Models of EW symmetry breaking

- Systematic and finite set of models relevant to Higgs precision we're probing now or in the future
  - Still provides a layer to cover a large space of "complete" models by focusing on relevant DOF
- Can still use all the great technology that has been developed for EFTs over the last ~ decade
- Allows us to identify what the *full reach* of the LHC for understanding the Higgs - use all information not just Higgs precision subset
  - Allows one to also identify new search strategies or missing parts of experimental phase space at the LHC
- Allows one to compare future colliders on *even* footing

Conclusions

- The Higgs is the most unique particle we've found in nature, we need future colliders to study it better
  - We ALSO need to really ask what is the full reach of the LHC for Higgs physics?
- We need to think more about connecting physics questions to observables - it's not *just* "precision Higgs" ***or*** searches
  - There is a systematic way to combine these
- The energy of future colliders *really really* matters so we *must* do the R&D *worldwide* to get us to 10 TeV PCM (and higher)