BSM Theory

Patrick Meade
Yang Institute for Theoretical Physics
Stony Brook University

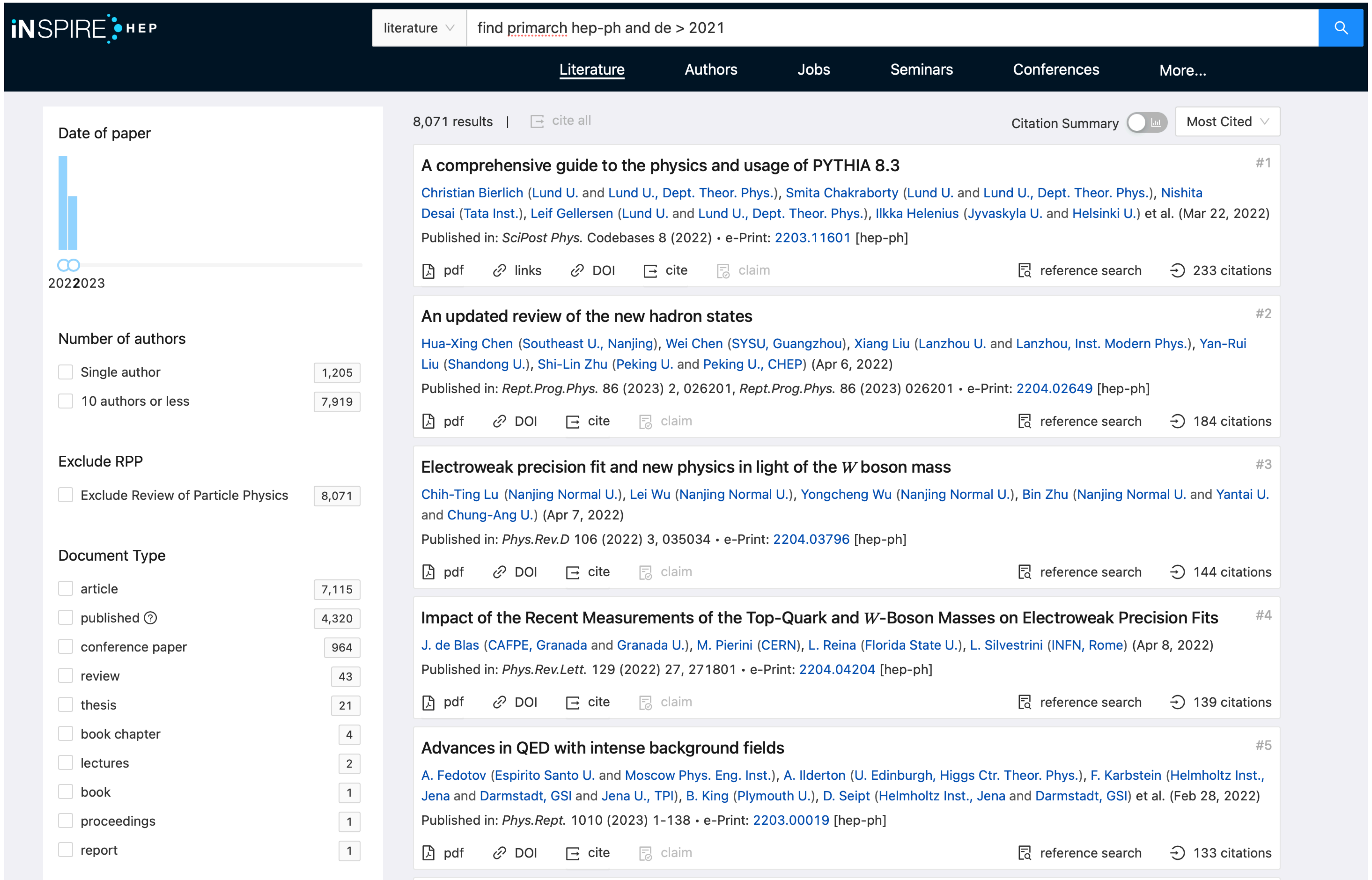
EPS-HEP 2023

Huge topic but not much explicit guidance

Hitoshi Murayama artistic impression circa 2000s

I clearly can’t cover all this!

What’s new in BSM theory since the last EPS?



Unless you really believe in the CDF measurement not much “trending” from citations alone

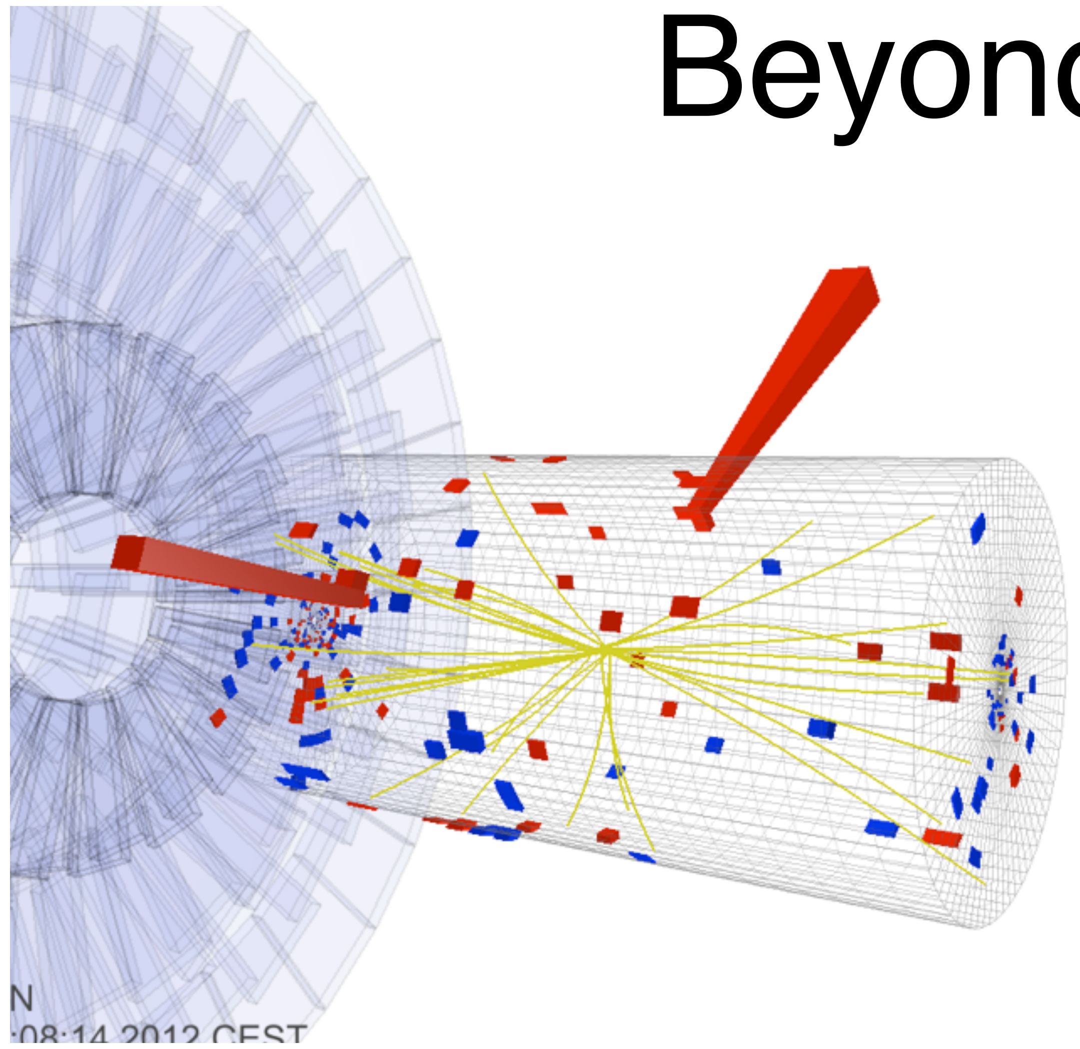
What about experimental guidance for BSM theory directions?

What about historical guidance since this talk exists at every incarnation in the last 10 years?

Naturalness after LHC8

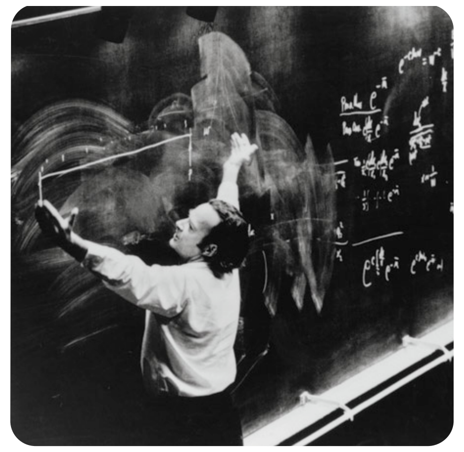
G.F. Giudice

HEP 2013
Stockholm
18-24 July 2013
(info@eps-hep2013.eu)



Beyond the SM

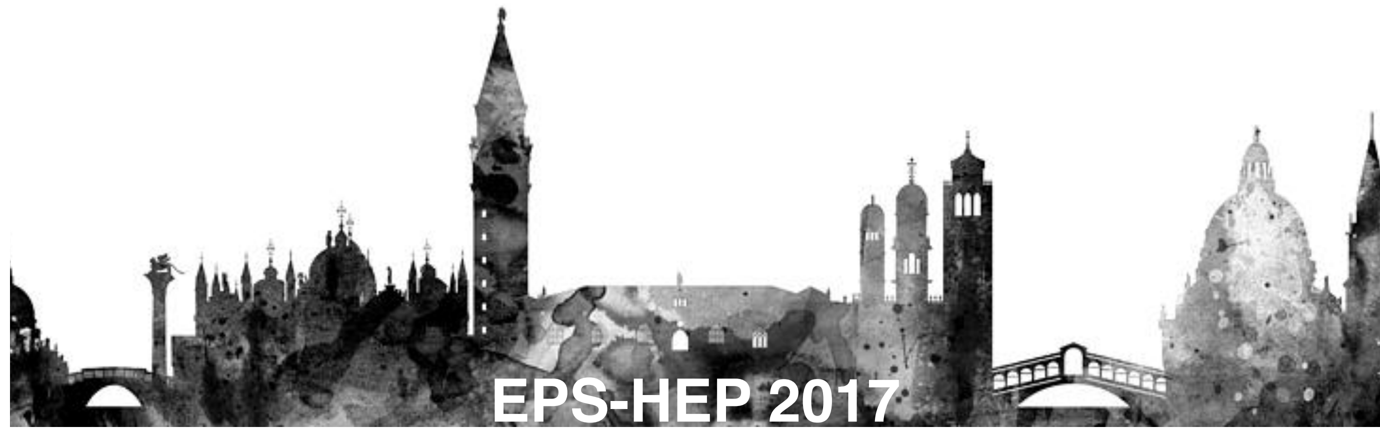
Andreas Weiler
DESY/CERN/TUM



EPS-HEP 2015

SUSY and BSM Theory after LHC16

Nathaniel Craig
UC Santa Barbara



Beyond Standard Model Theory

Giuliano Panico
Università di Firenze and INFN Firenze

Beyond Standard Model Theory

Anson Hook
University of Maryland

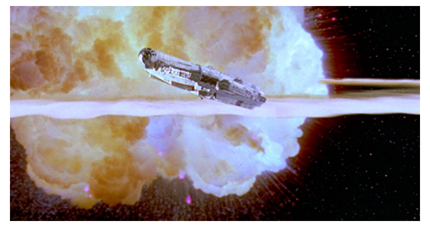
EPS-HEP 2021

Conclusions

- Naturalness is deeply rooted in EFT approach to physical phenomena
- Testing naturalness in Higgs has far-reaching consequences for particle physics

IR Naturalness

- Most welcome outcome
- New physics is guaranteed
- Heavy casualties after LHC8 …



Conclusions

- Run1 left the most motivated natural models in a somewhat bruised state
- Run2 will be a big jump in sensitivity
- The first 10 fb-1 will explore new territory
- Looking forward to exciting times and (hopefully) some guidance from experiment

Conclusions

- LHC16 null results push generic conventional solutions to the hierarchy problem to the % level or below.
- Conventional ideas still worth pursuing, but BSM theory for the hierarchy problem is approaching a paradigm shift.

Null results an invitation for exploration:

- Data motivates new ideas in old theory frameworks…
- …and pursuing entirely new theory frameworks.
- Invariably leads to new experimental signatures & directions.
- New ideas emerging, many ambitious directions to explore…

Conclusions

Last years saw *explosion* of research directions in BSM physics

Naturalness remains an important question and fruitful guideline…

- (minimal) classical scenarios under pressure
- several alternatives are being explored

… but a **broader search program** is clearly necessary

- many open questions in SM
- new search strategies at colliders (eg. model independent approach)
- beyond-collider probes

Conclusion

Age old solutions to age old problems

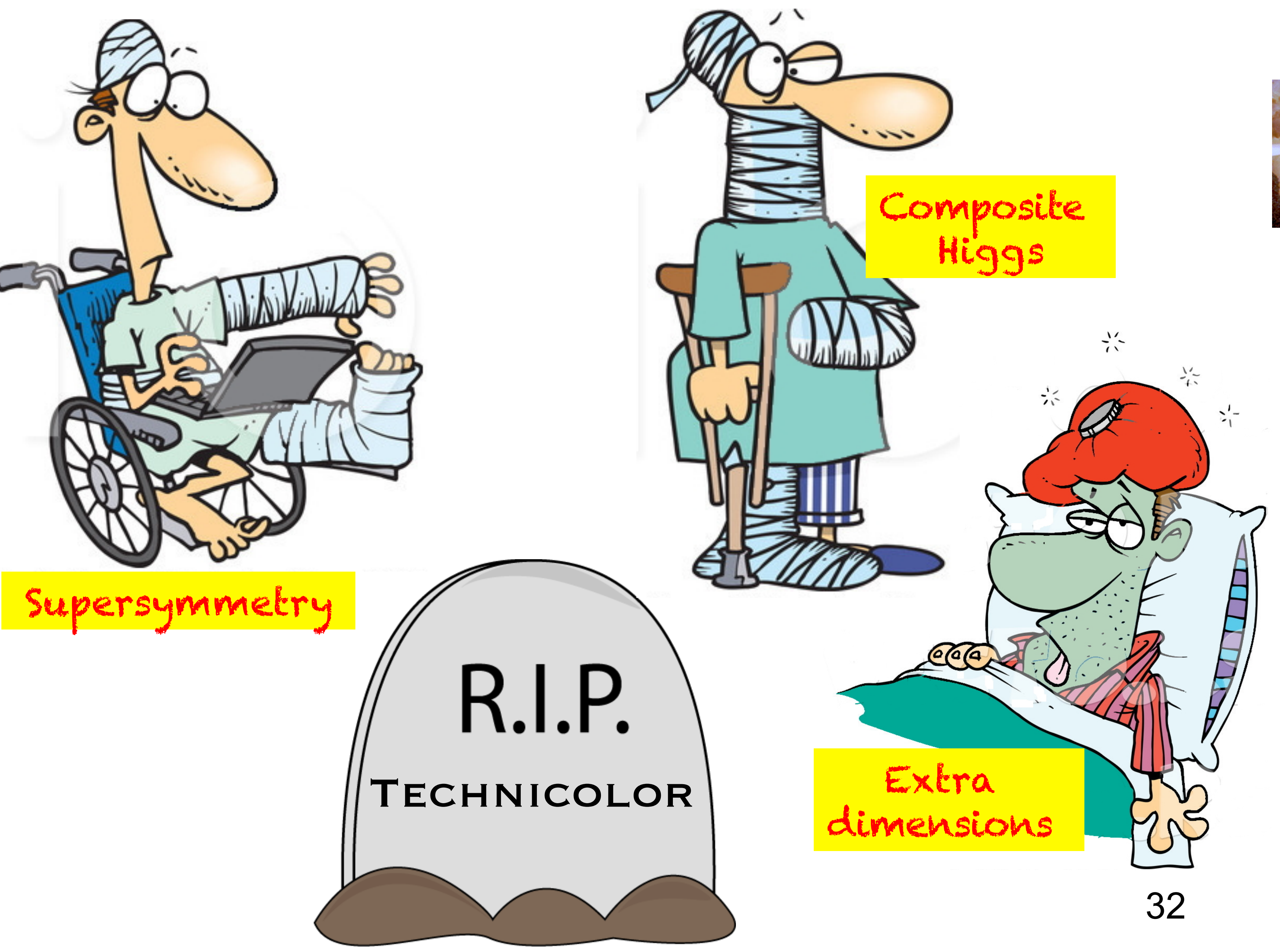
Compositeness **Historical**

"Axion" approach can relax the Higgs mass small

Find via axion type experiments

Maybe TeV scale is not the mass scale of new particles but instead the field value of new physics

Find via high precision/density/intensity experiments



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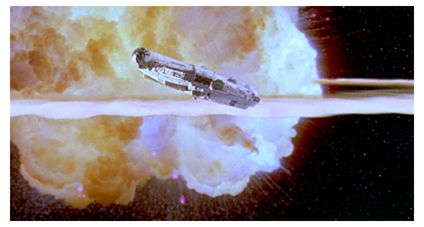

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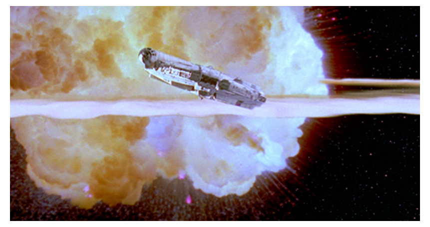

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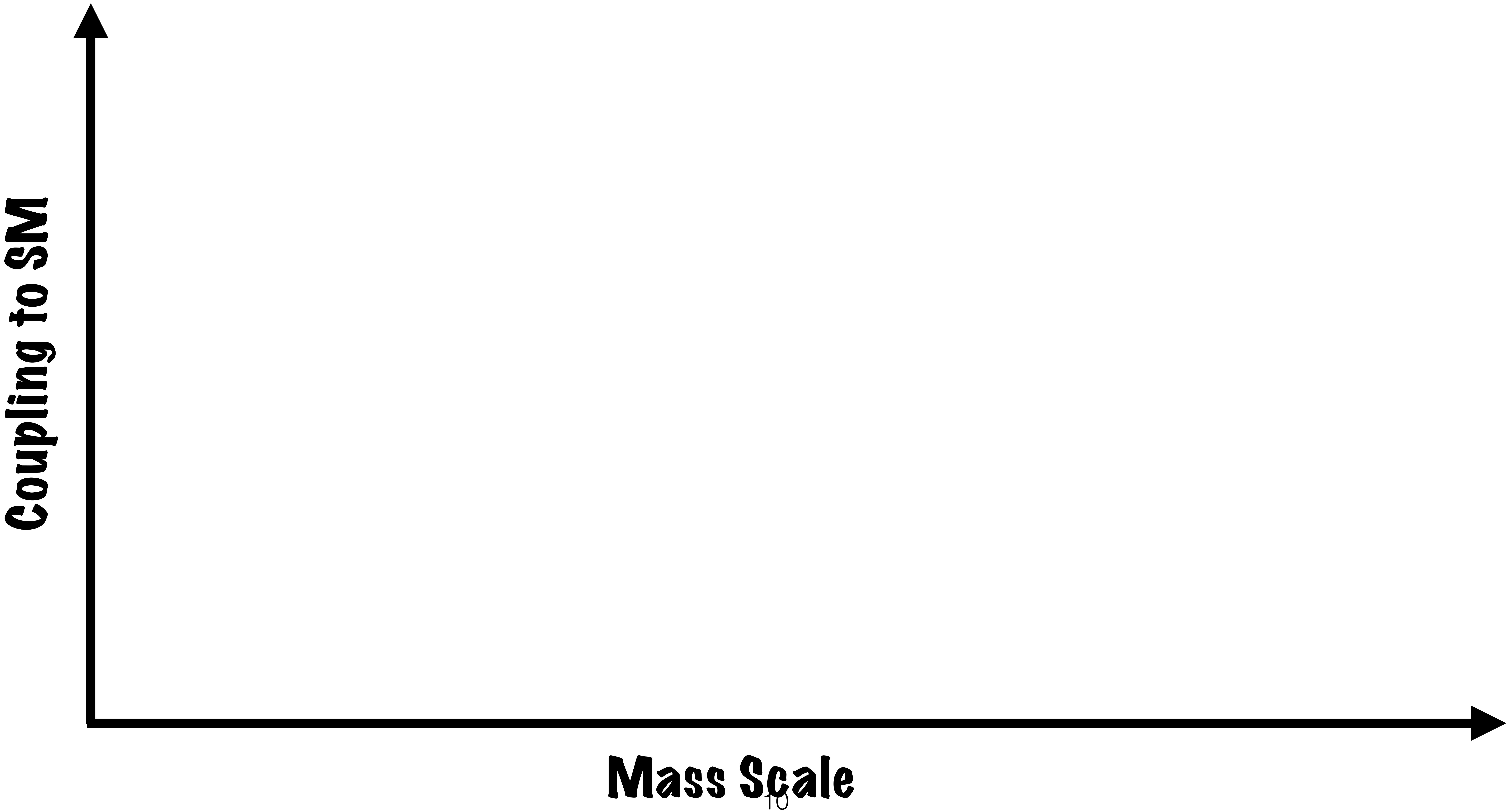
NATURALNESS + expand your horizons

Breaking a decade long tradition…

- I am *not* going to talk about naturalness in any great detail today
- I *am* going to talk about expanding theoretical horizons, but not a specific direction
    - Specific goal of how to connect searches and precision measurements for BSM theories
    - How do big ideas/questions map to space of observables so we can make sure to maximize (HL-)LHC and future experiments

From as “model-independent” point of view, where’s the new physics and how do we find it?



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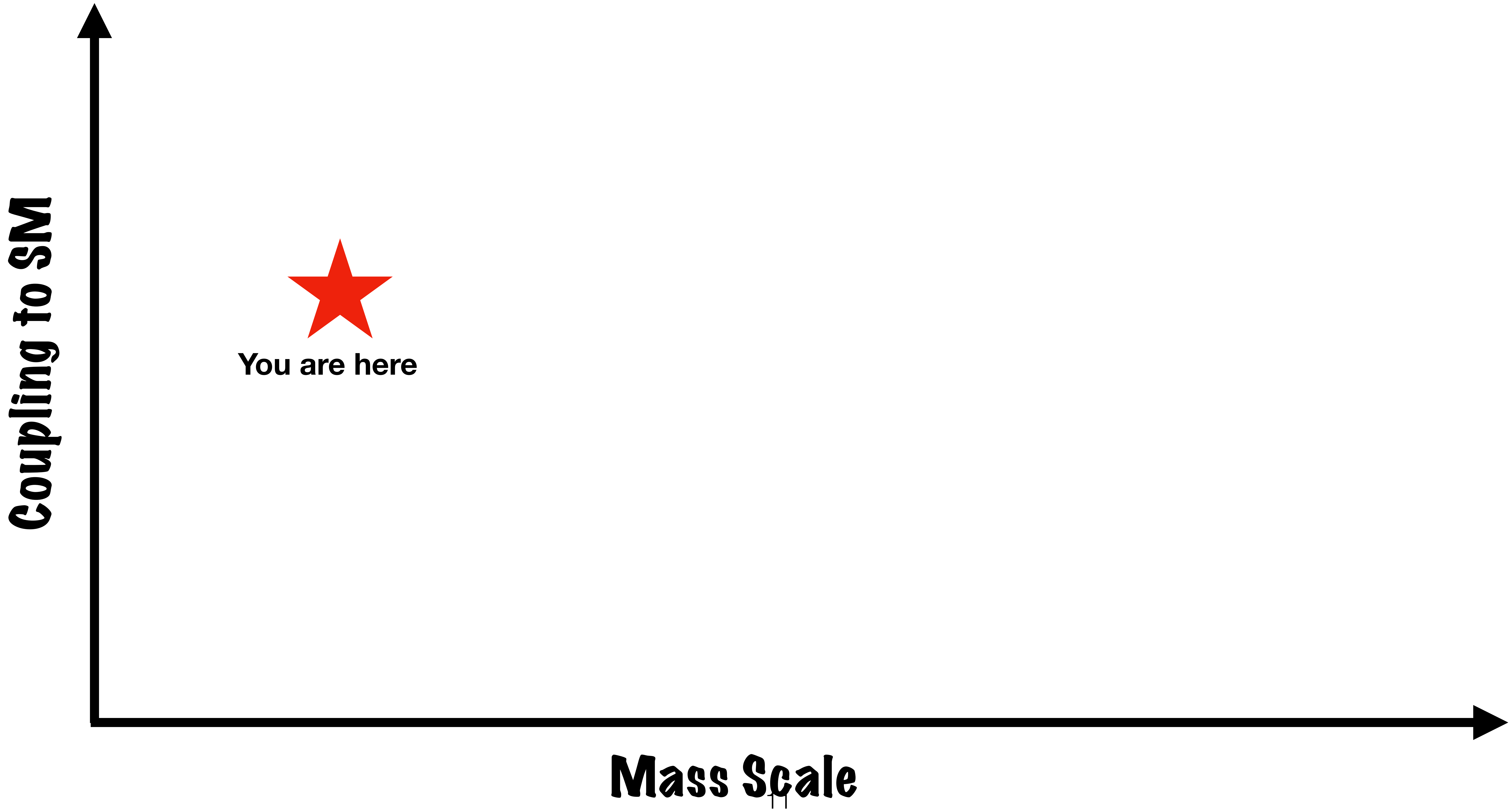

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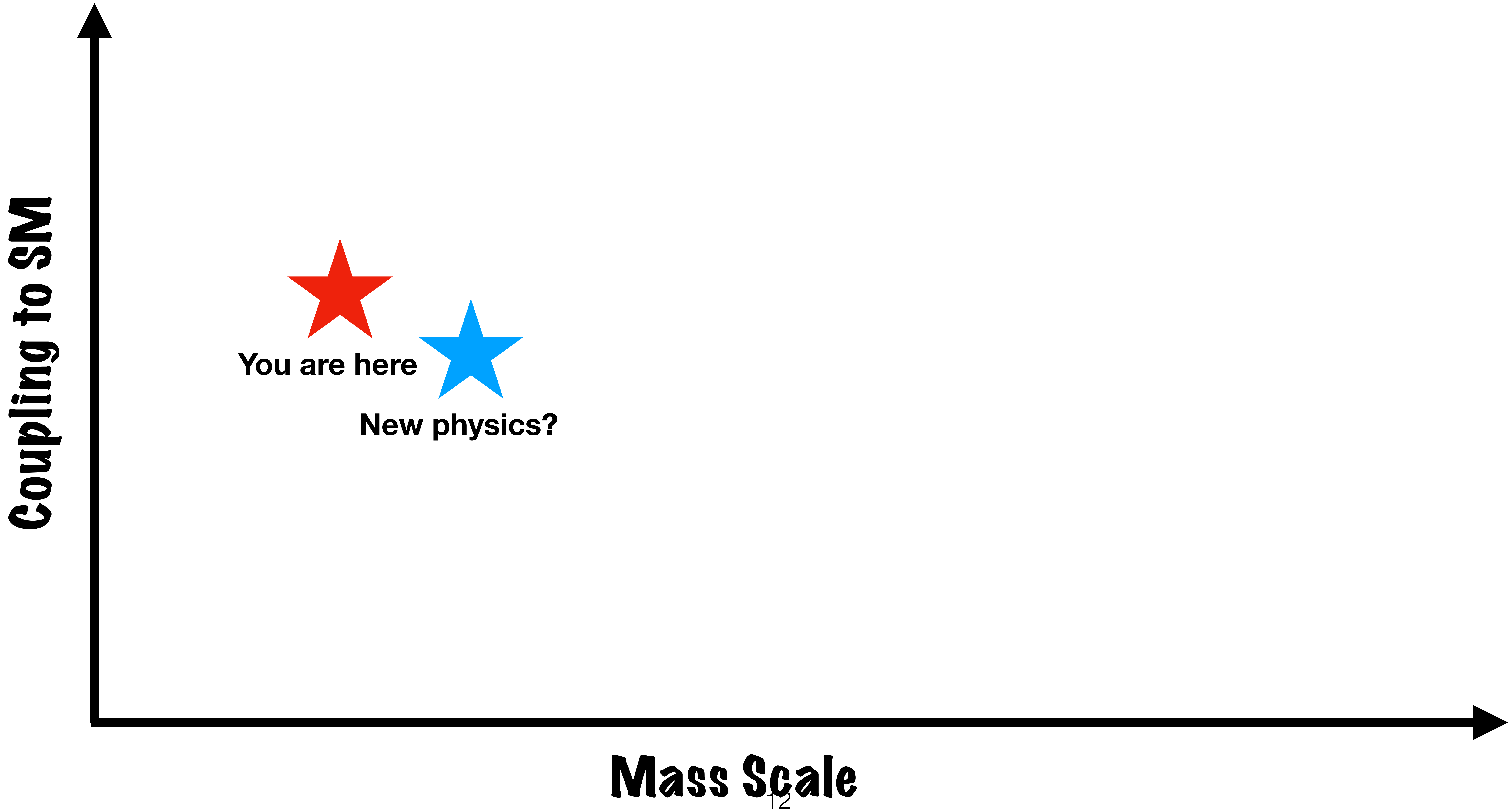

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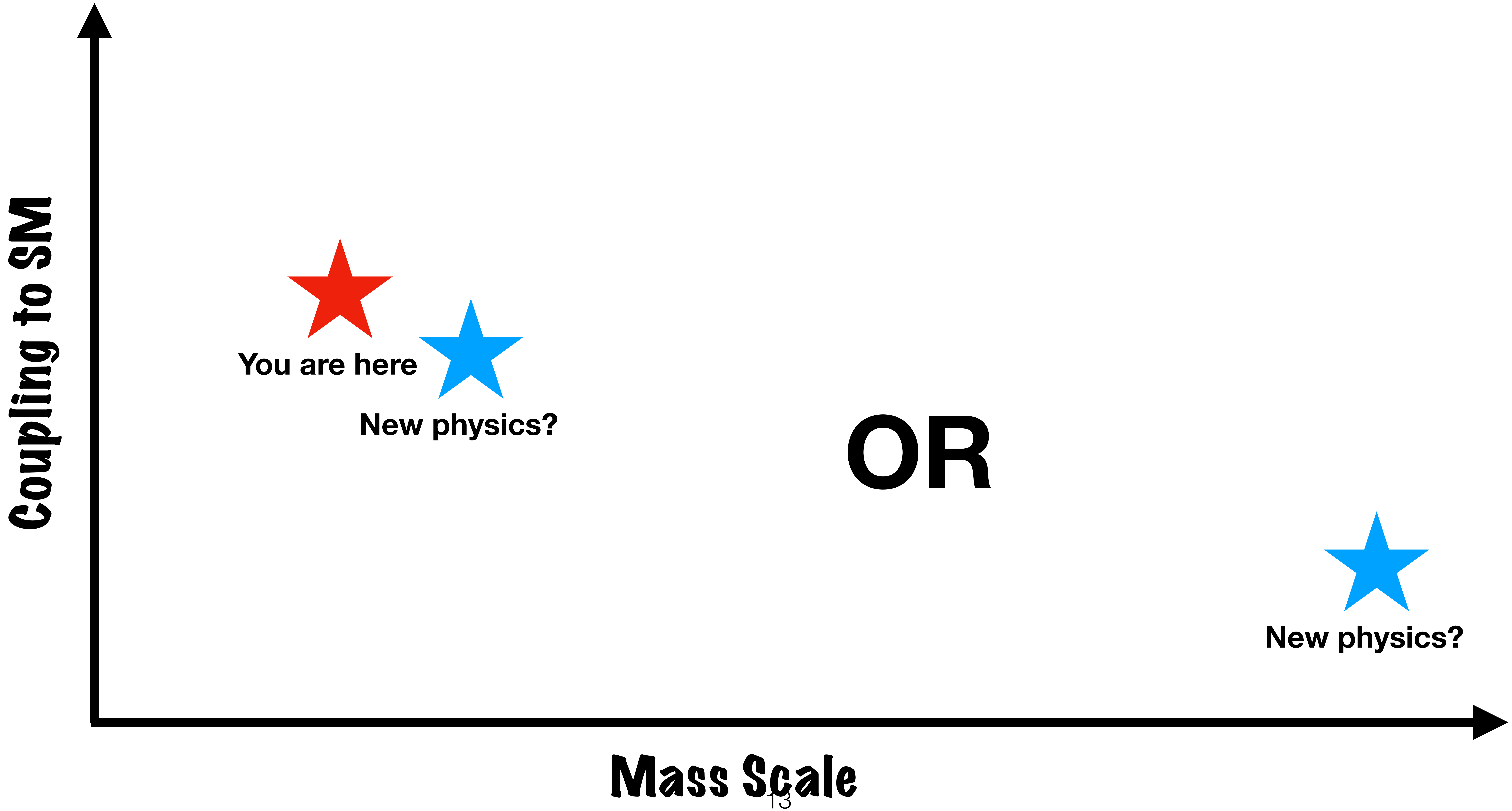

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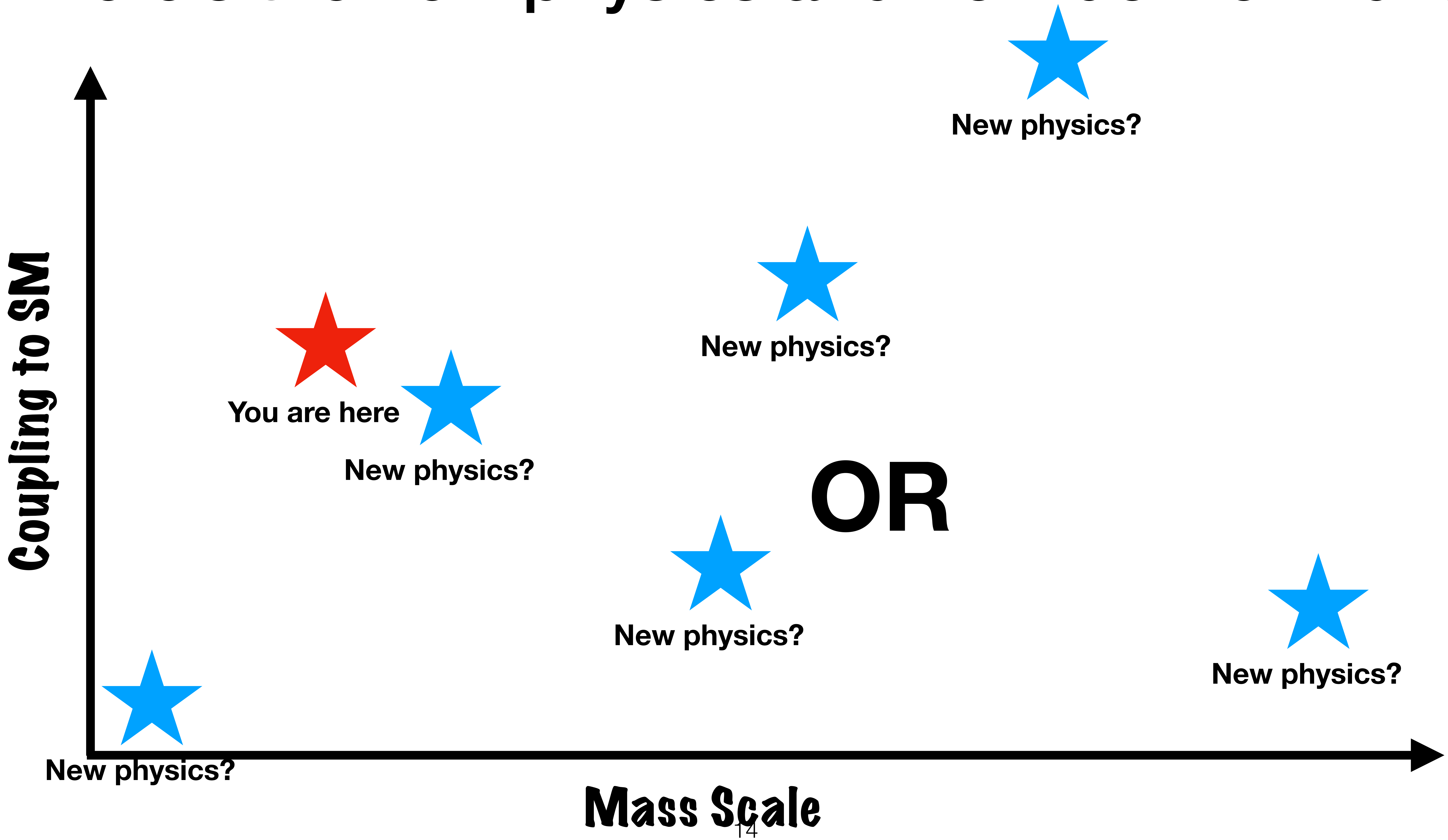
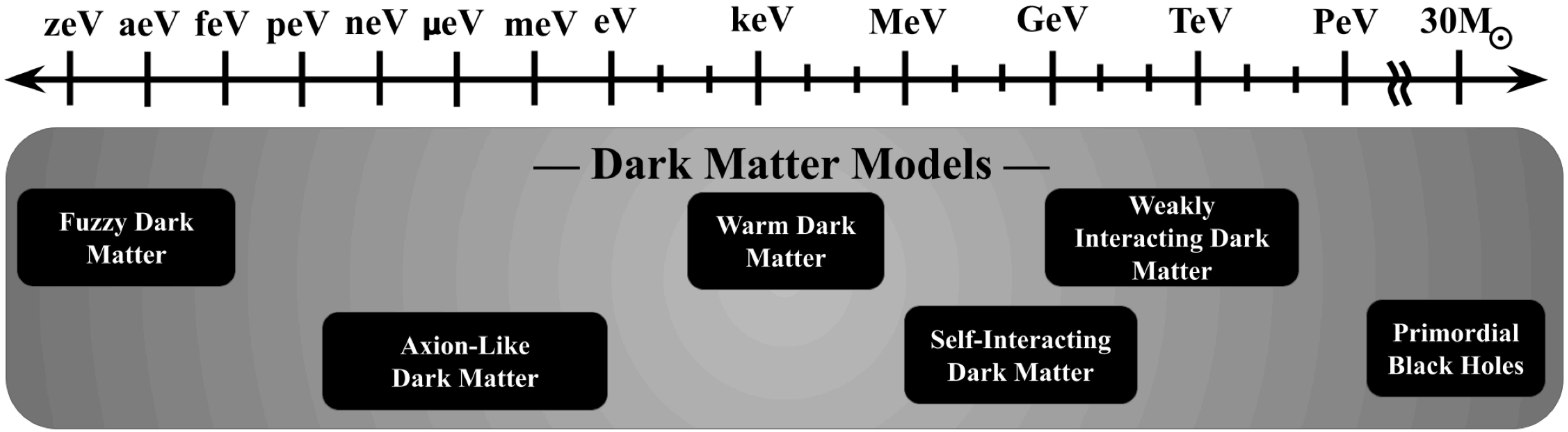


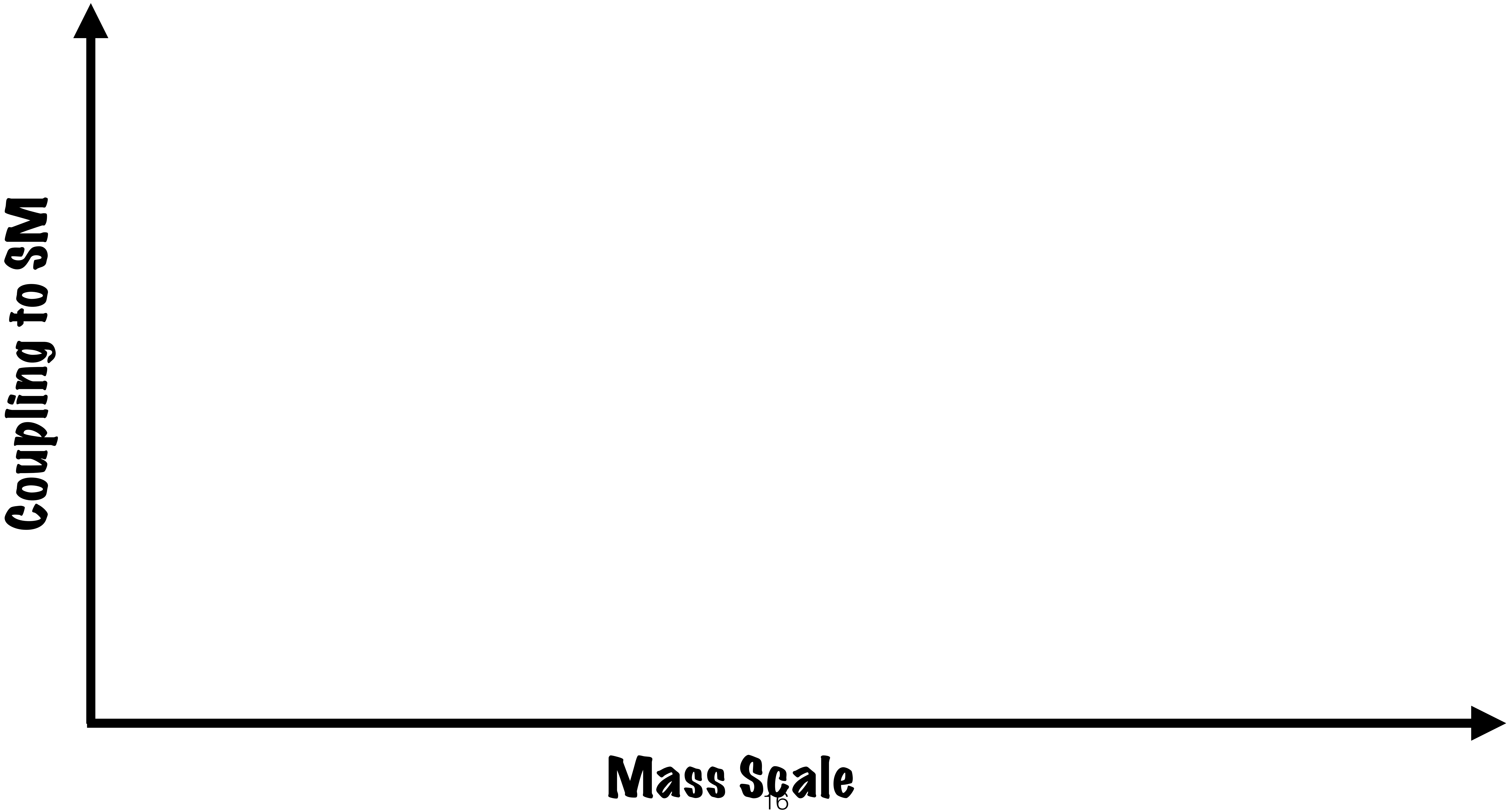
This is an abstraction but it comes up time and time again regardless of the deep particle physics question we ask



2209.08215 Snowmass CF TG report

Are some questions sharper and lead to more specific experimental targets? Are there general theory considerations to narrow the space?

This is a big space, and it would be nice to give theoretical guidance to experimentalists



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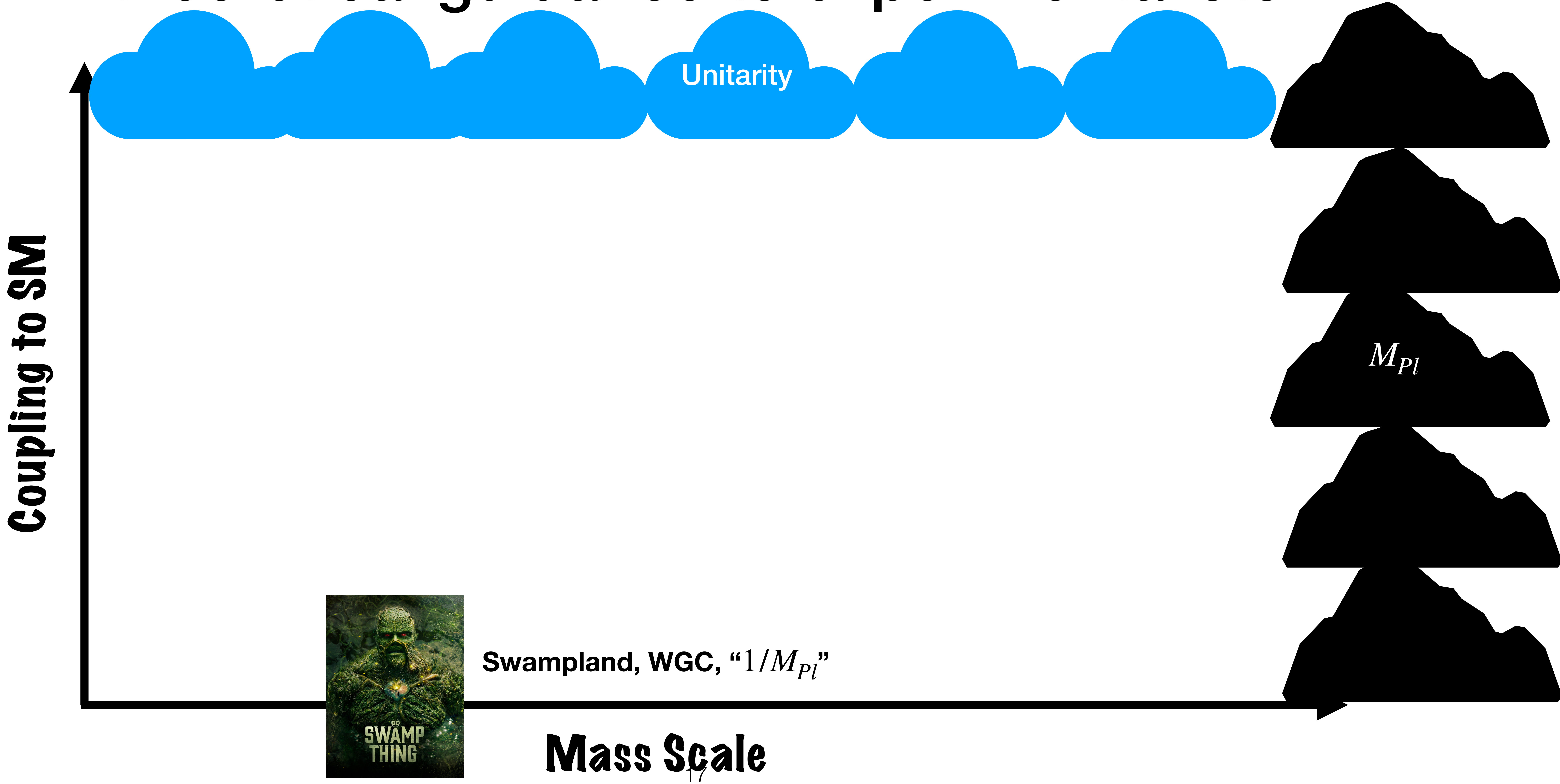

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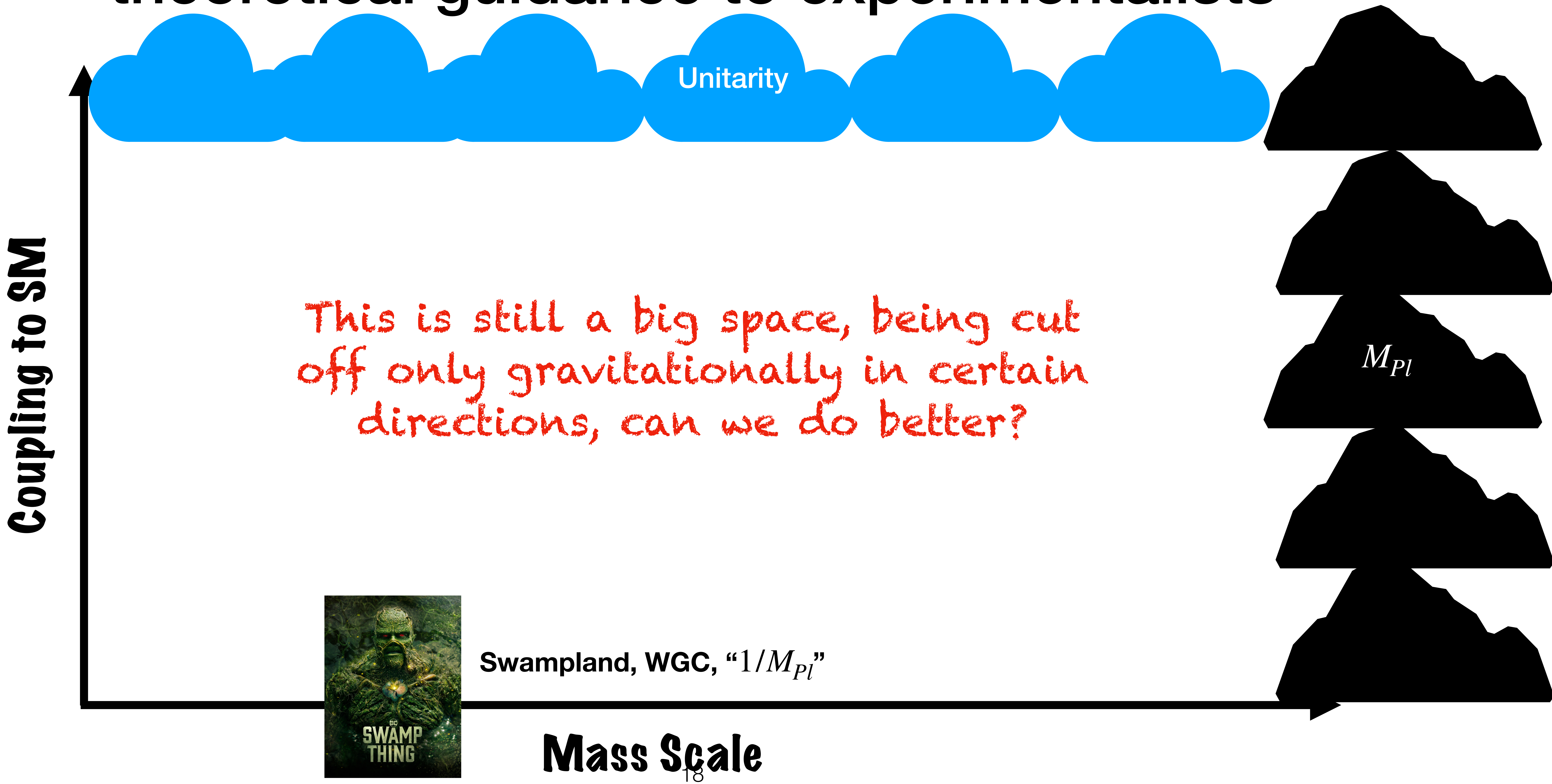
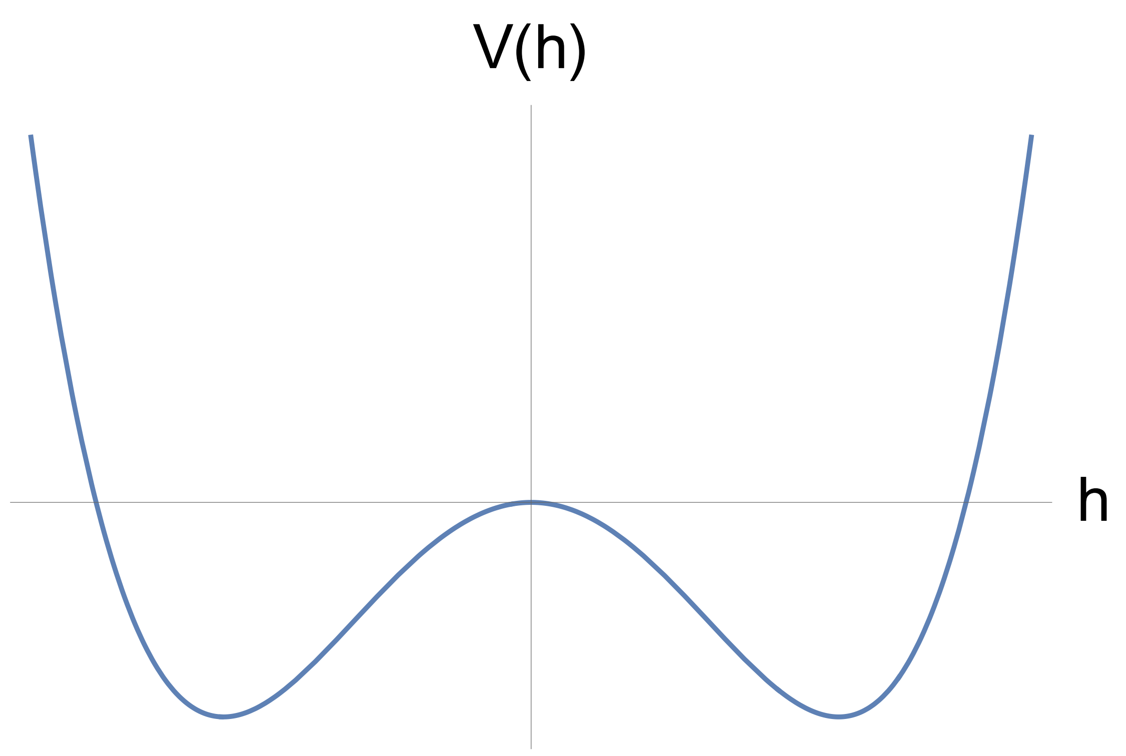
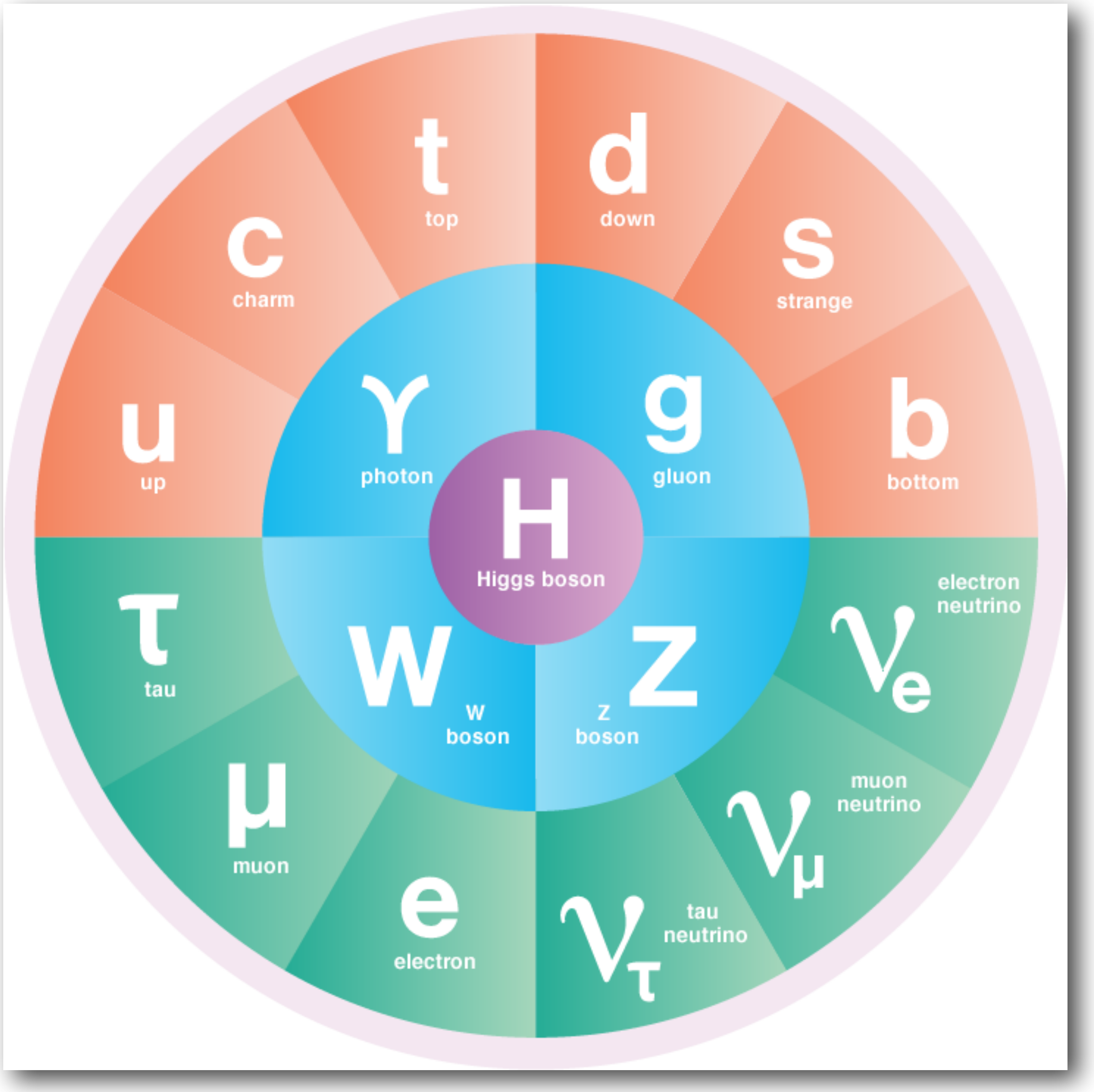


Yes, if we focus: EWSB and the Higgs





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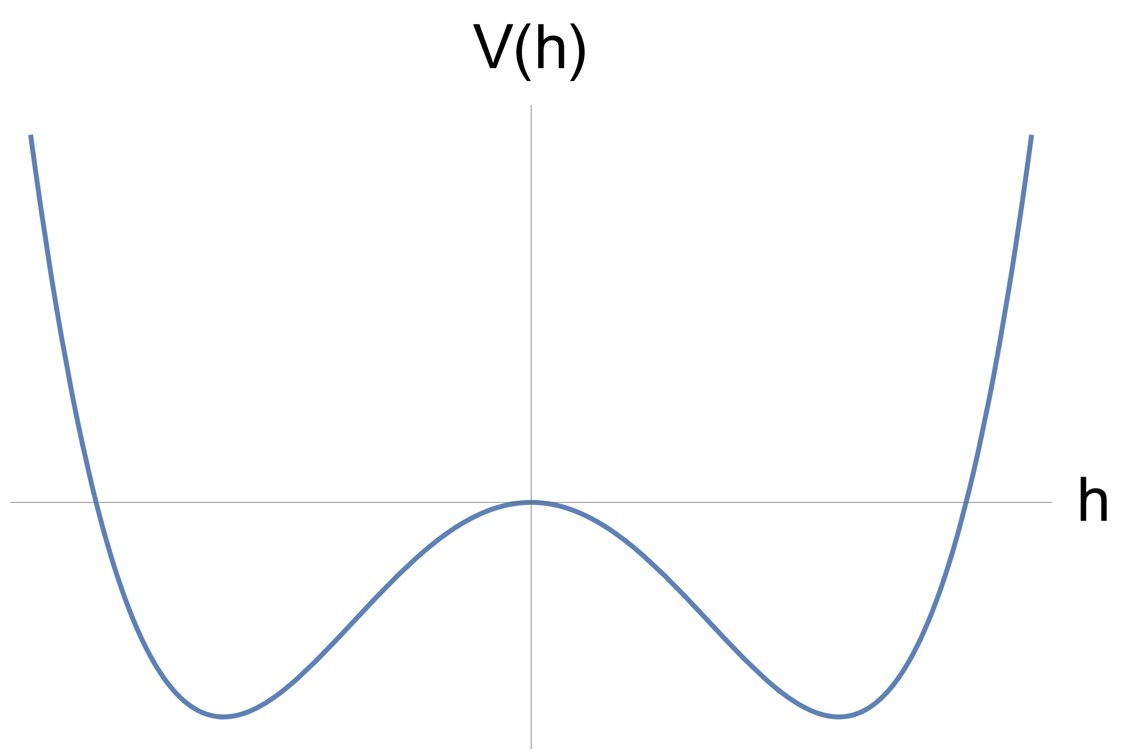
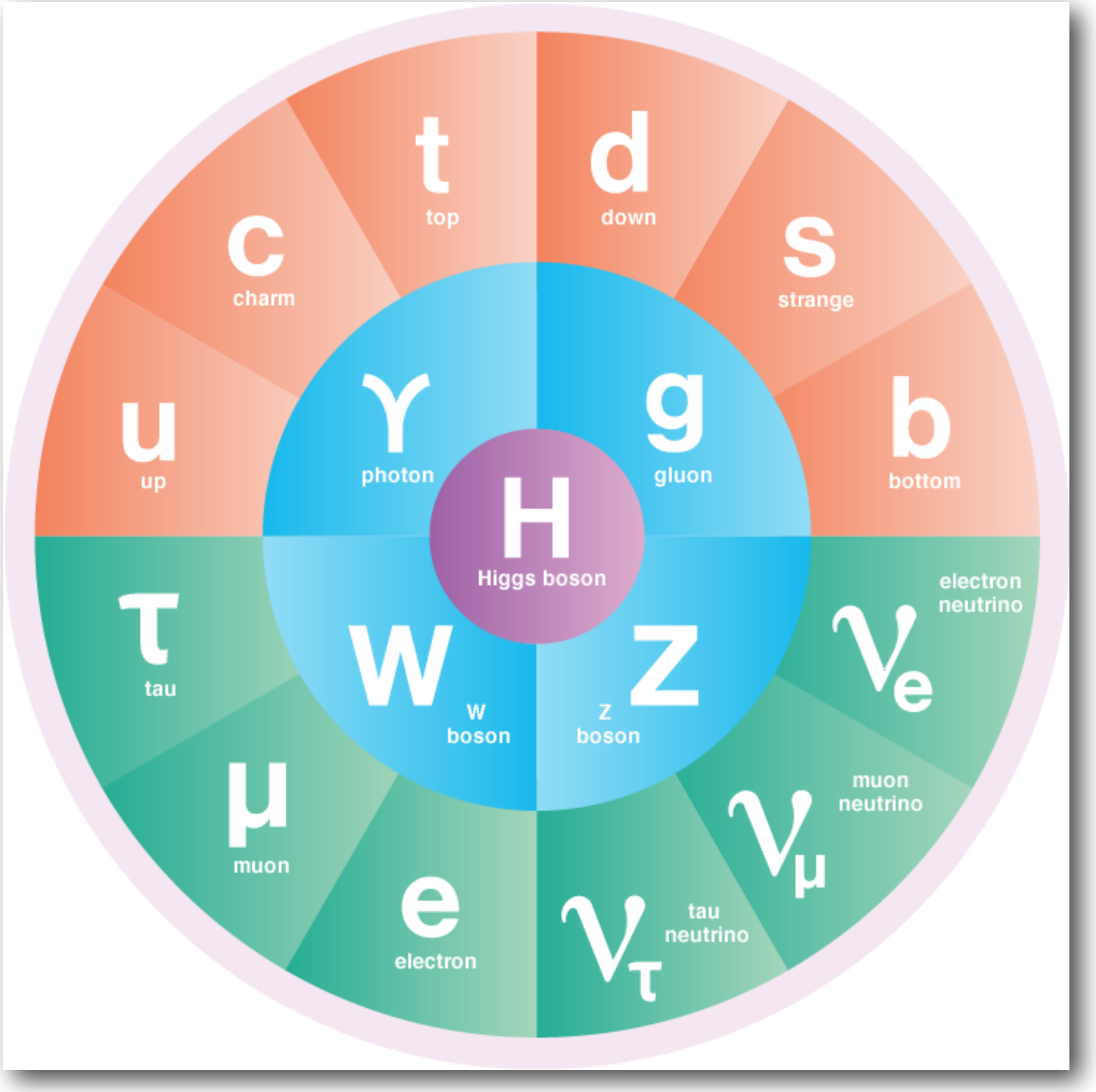
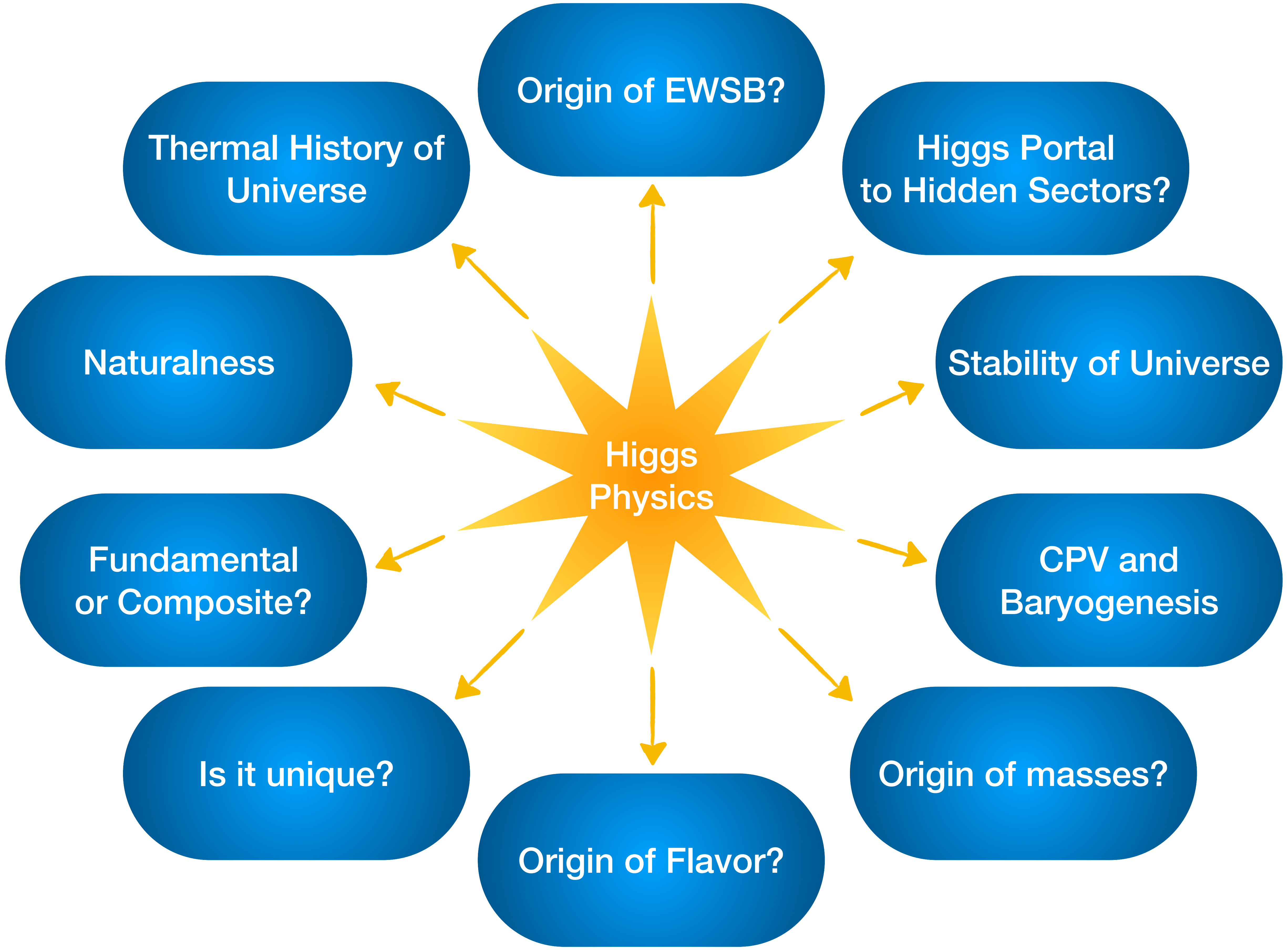




Doesn’t it look very SM like and the SM is now “complete”

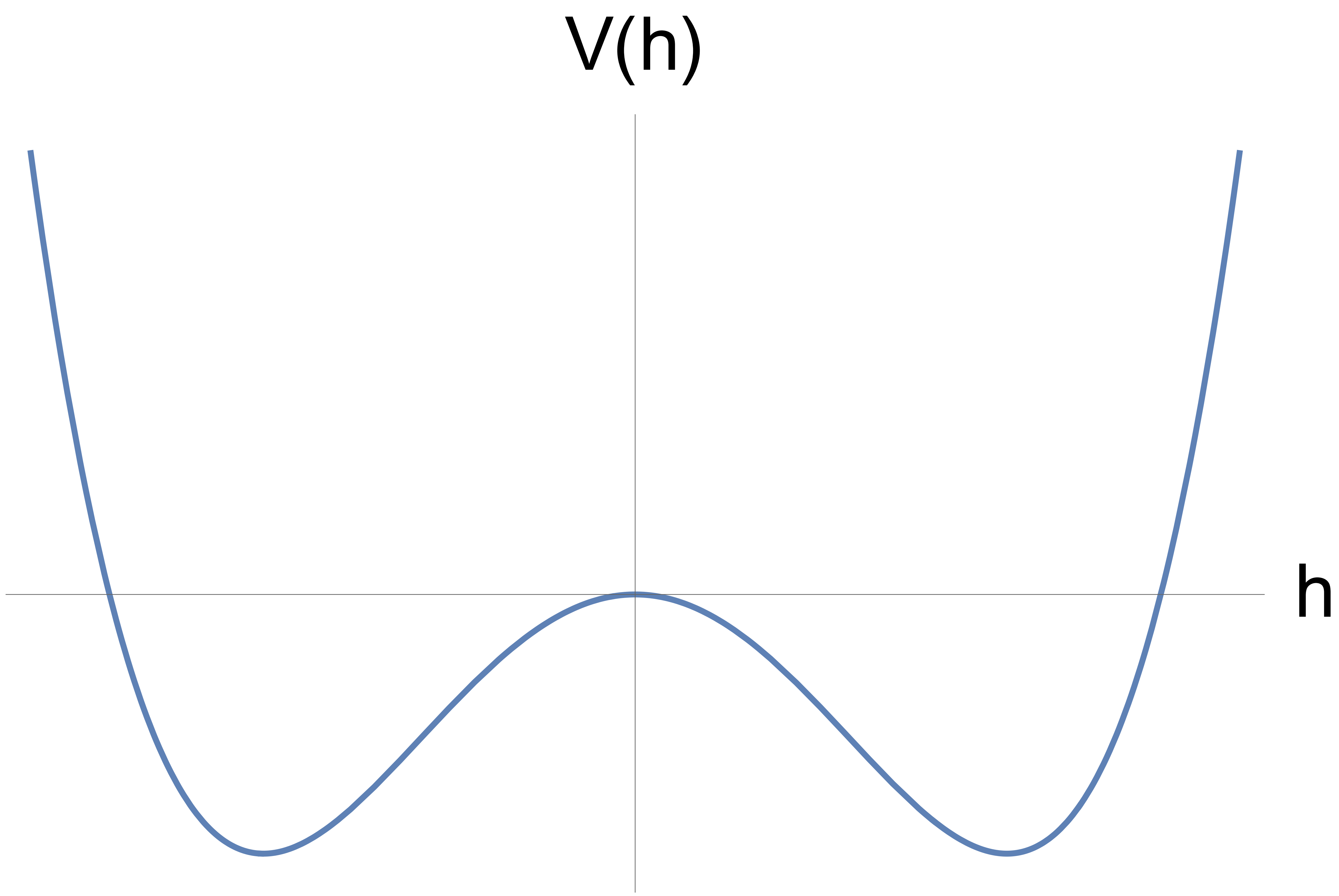
The Higgs is under appreciated for how connected is to so many deep BSM questions



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

Why do you think there were 10 years of EPS plenary talks on naturalness?? The Higgs is *really* strange!

I'm not going to go through all these, even though I'd love to assign a Pedro Pascal meme to all of them



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

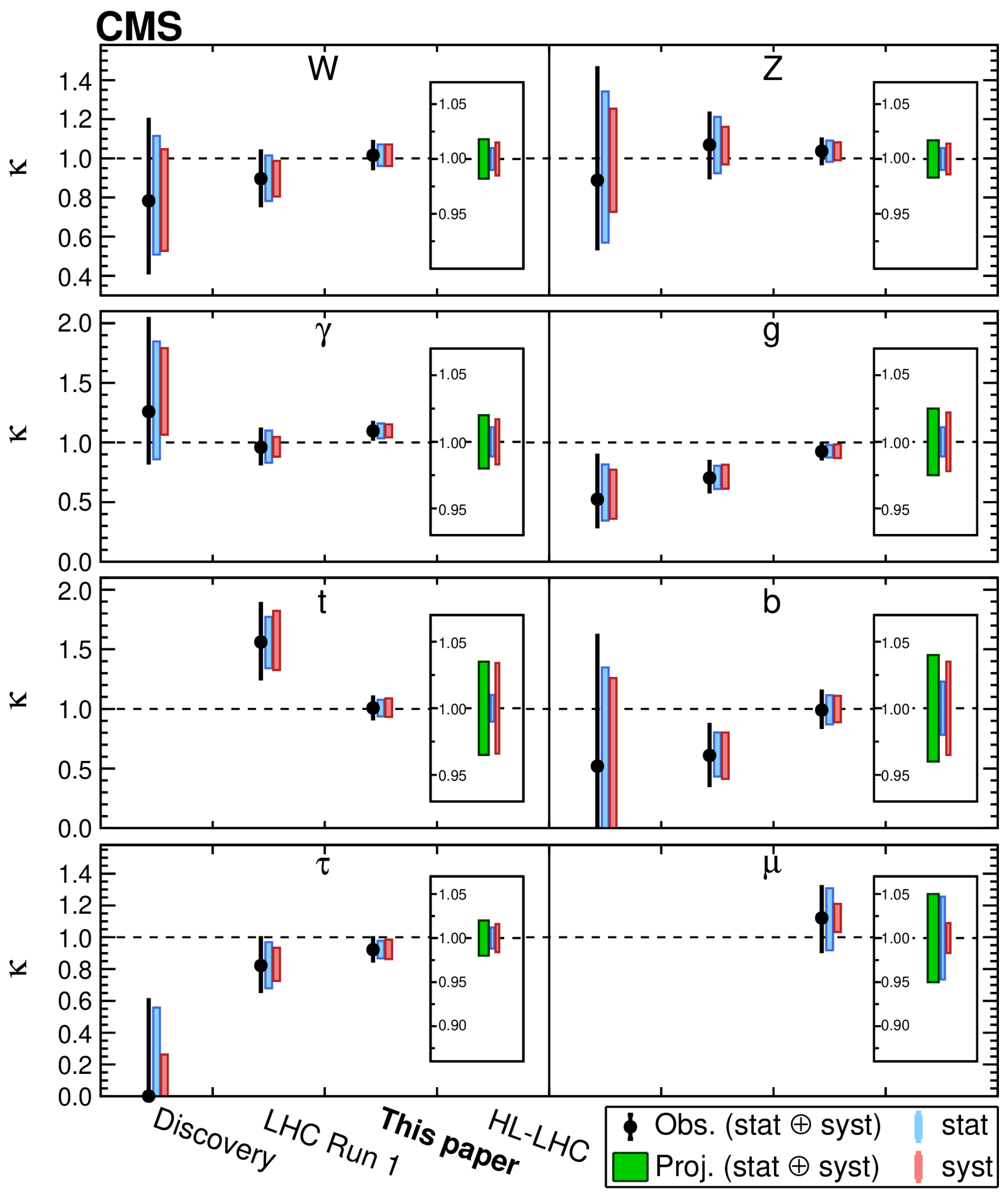
Nevertheless, isn't Higgs physics primarily about precision now?

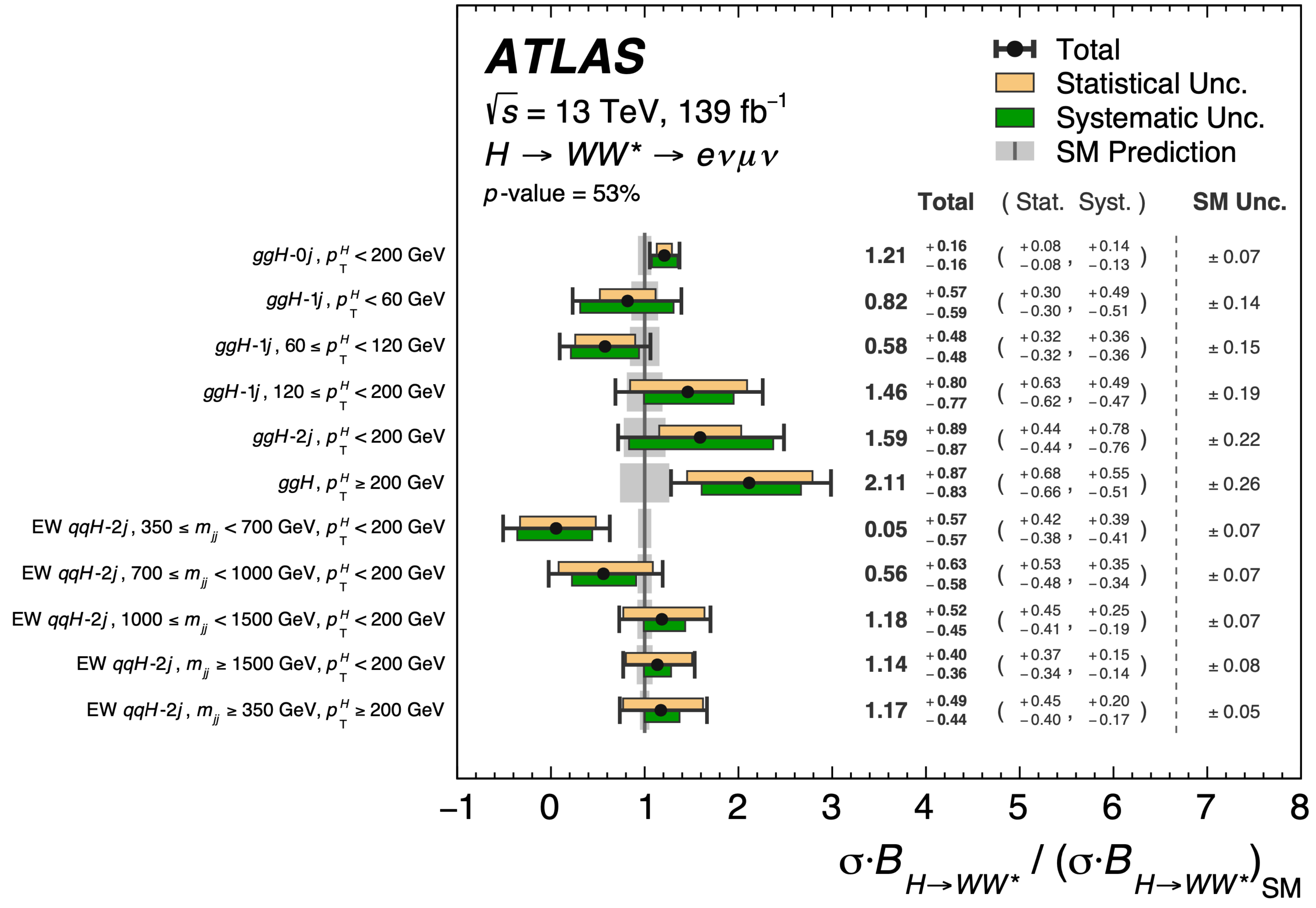
"kappa" fits

$$\kappa_i \equiv \frac{g_i}{g_i^{SM}}$$

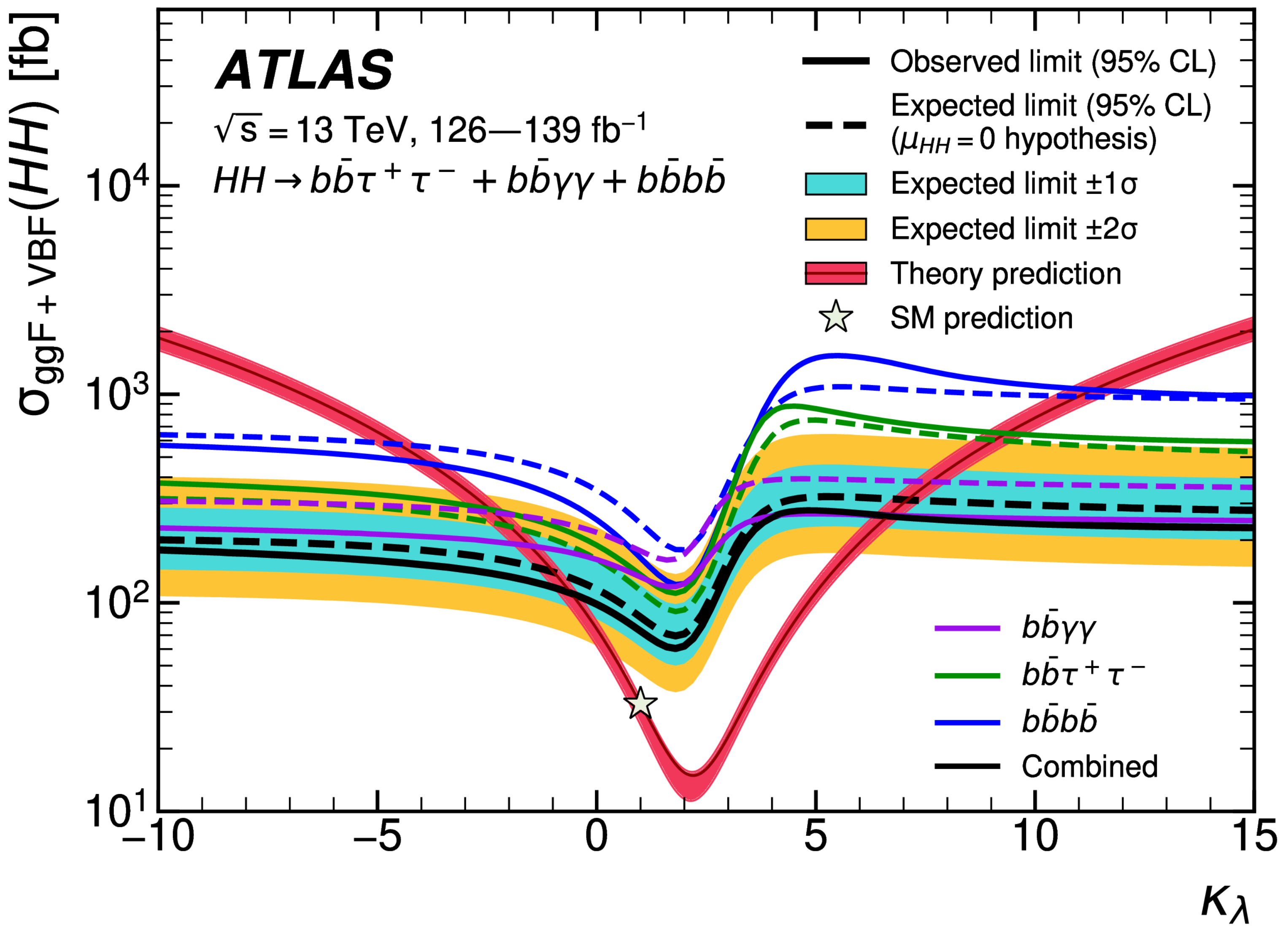
EFT fits, SMEFT/HEFT etc

$$\frac{c}{\Lambda^2}(QH\bar{u})H^2$$





STXS bins

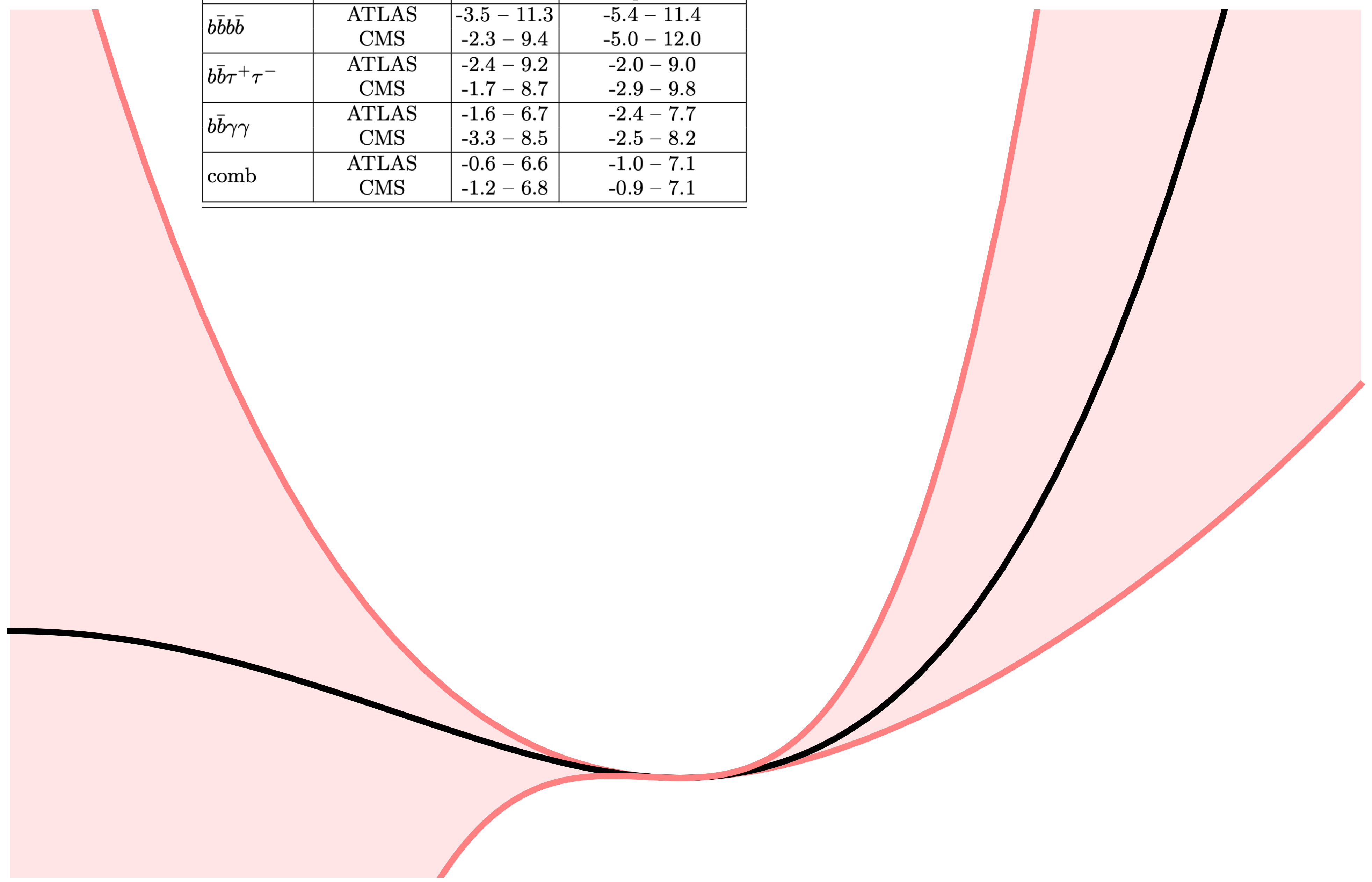


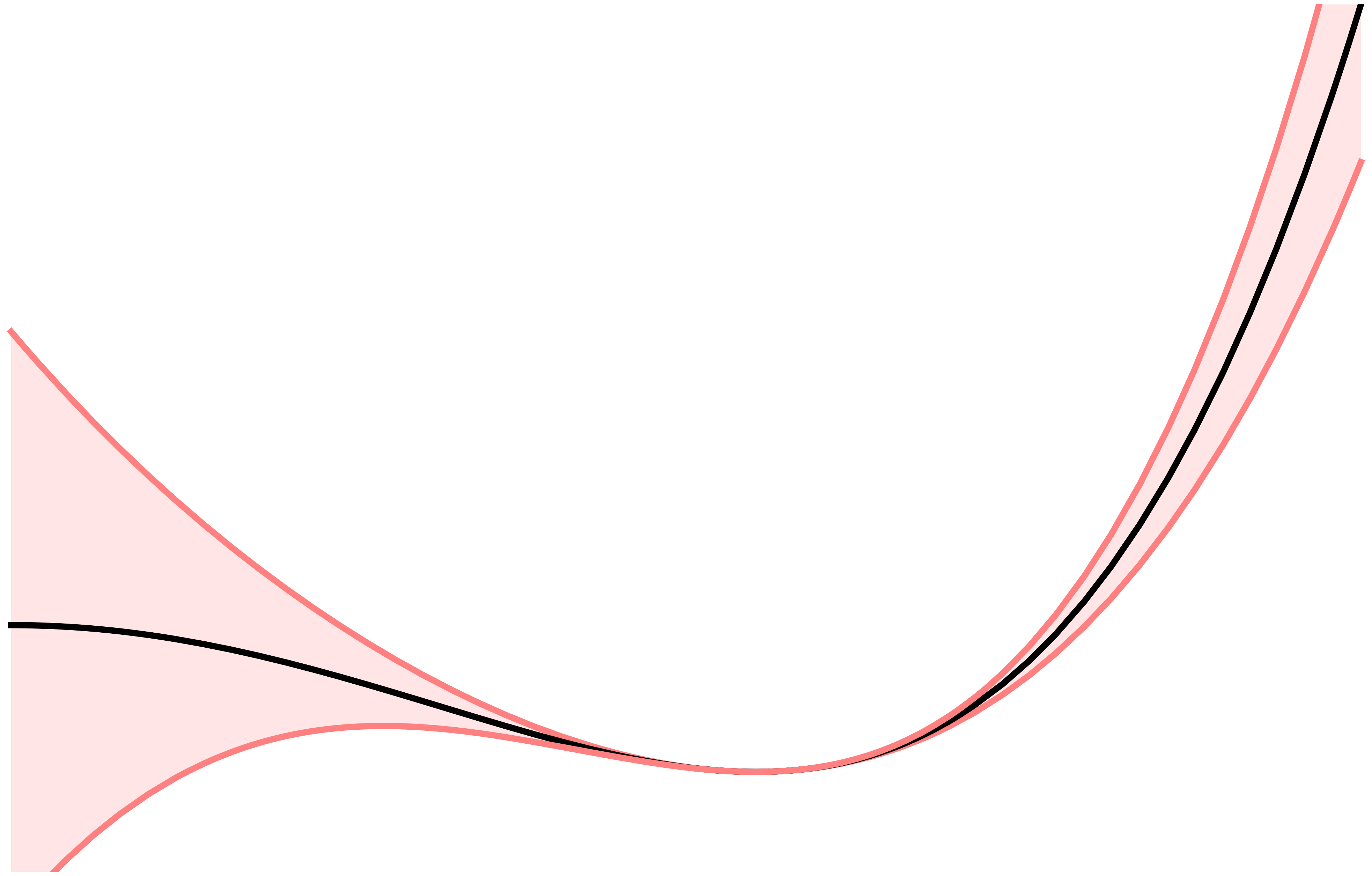
Higgs self interactions/"Holy grail" measurement of HL-LHC

If the questions center on the Higgs, do we need to do more than sit back and wait for more data for more precision (or a Higgs factory)?

Snowmass EF Higgs Topical Report
2209.07510

Final state	Collaboration	allowed κ_λ interval at 95% CL	
		observed	expected
$b\bar{b}b\bar{b}$	ATLAS	-3.5 – 11.3	-5.4 – 11.4
	CMS	-2.3 – 9.4	-5.0 – 12.0
$b\bar{b}\tau^+\tau^-$	ATLAS	-2.4 – 9.2	-2.0 – 9.0
	CMS	-1.7 – 8.7	-2.9 – 9.8
$b\bar{b}\gamma\gamma$	ATLAS	-1.6 – 6.7	-2.4 – 7.7
	CMS	-3.3 – 8.5	-2.5 – 8.2
comb	ATLAS	-0.6 – 6.6	-1.0 – 7.1
	CMS	-1.2 – 6.8	-0.9 – 7.1



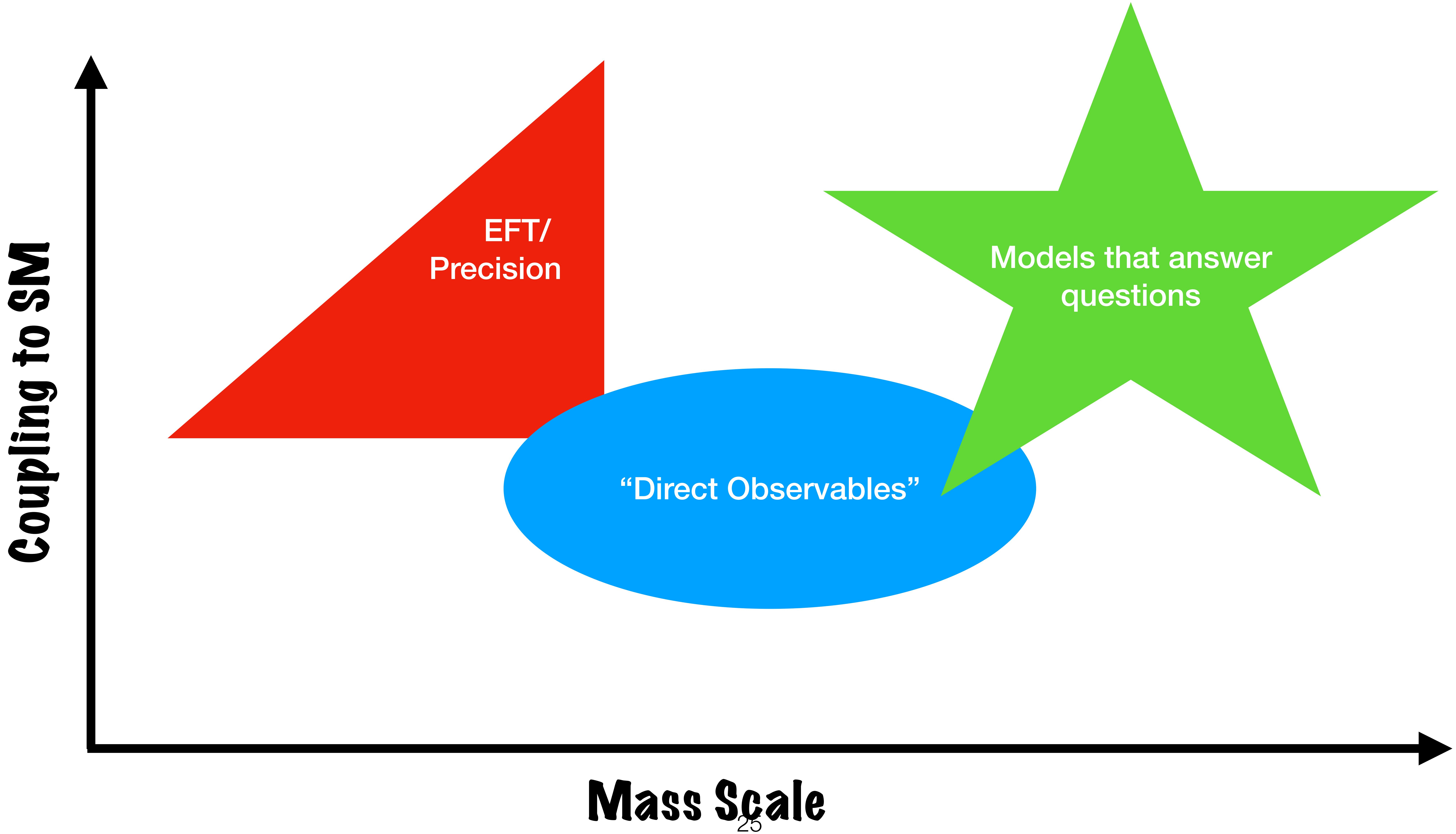


H/T N.Craig, R. Petrossian-Byrne

Current LHC ⟶ **HL-LHC**

What precision is sufficient to answer the big questions, and is it all that we care about?

To answer this we need to go further and understand this abstract space better and where observables and predictions fit



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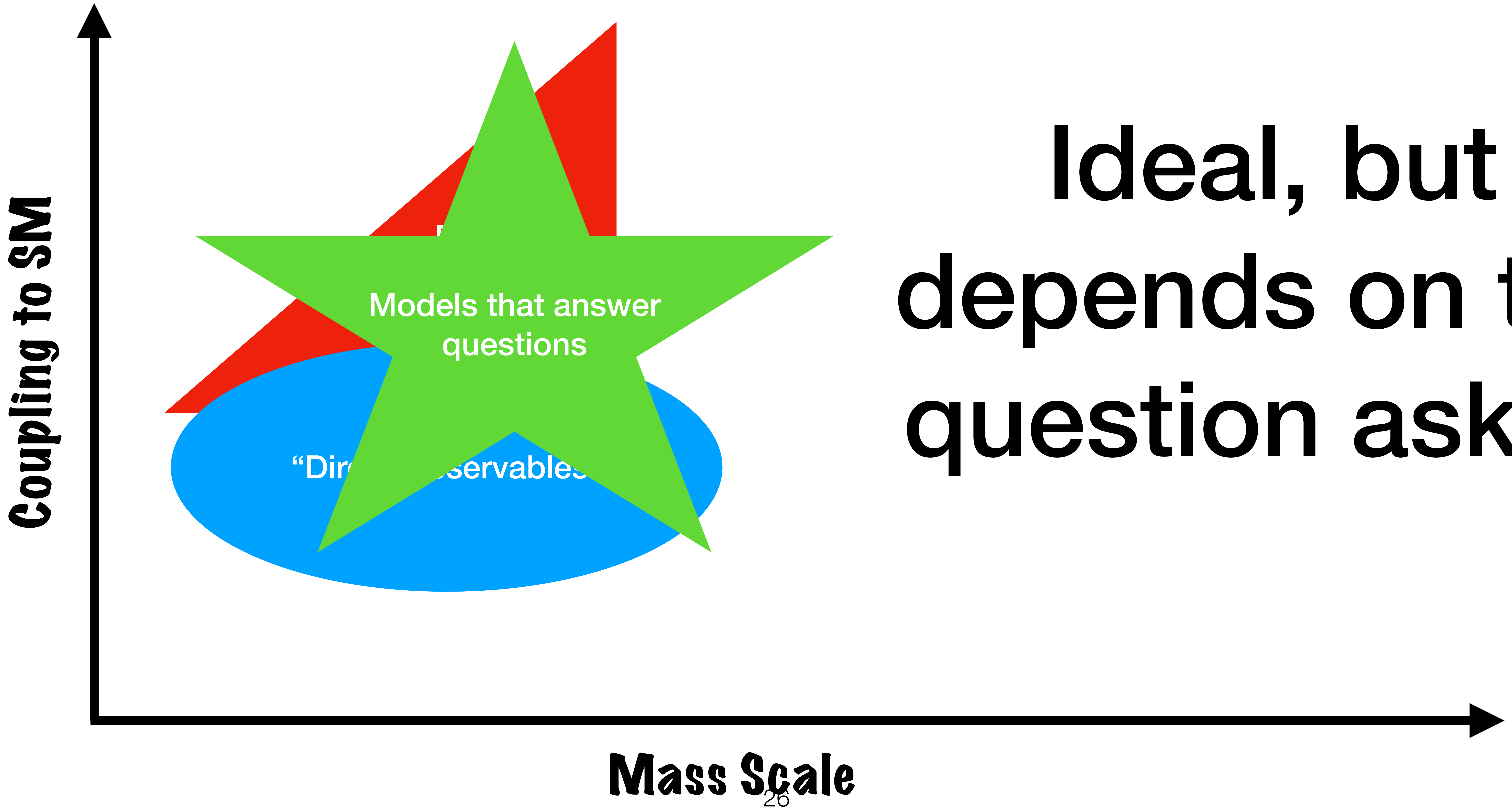


Ideal, but depends on the question asked

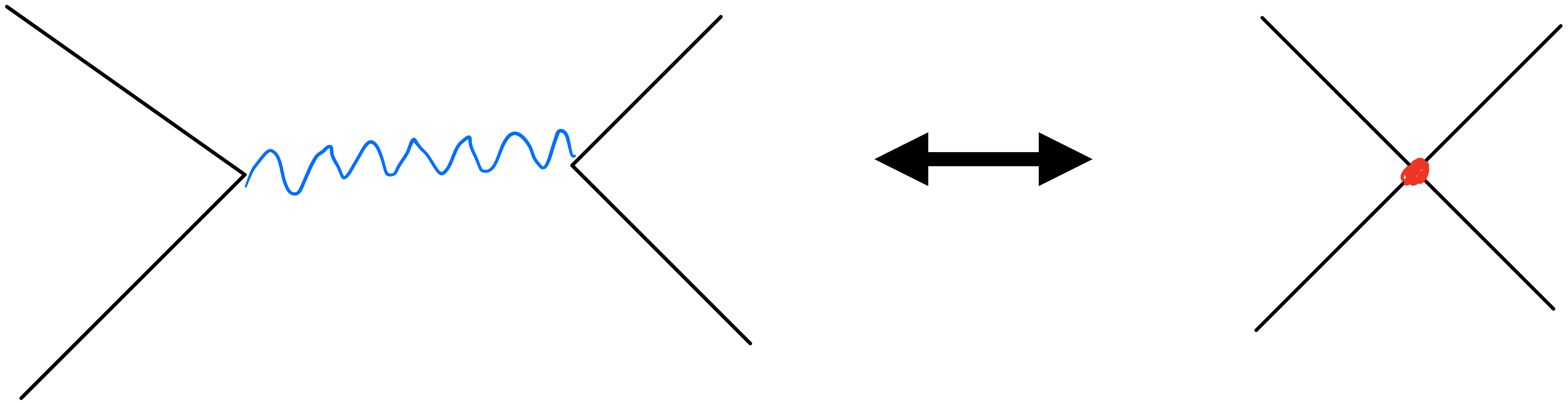
How do we figure out the overlap?

- BSM solutions can span a large space
- Direct observables can be viewed as solution dependent
- Indirect/precision is more “model independent” so let’s start by reverse engineering

EFT $\longrightarrow$ UV models

Why is this a good strategy?

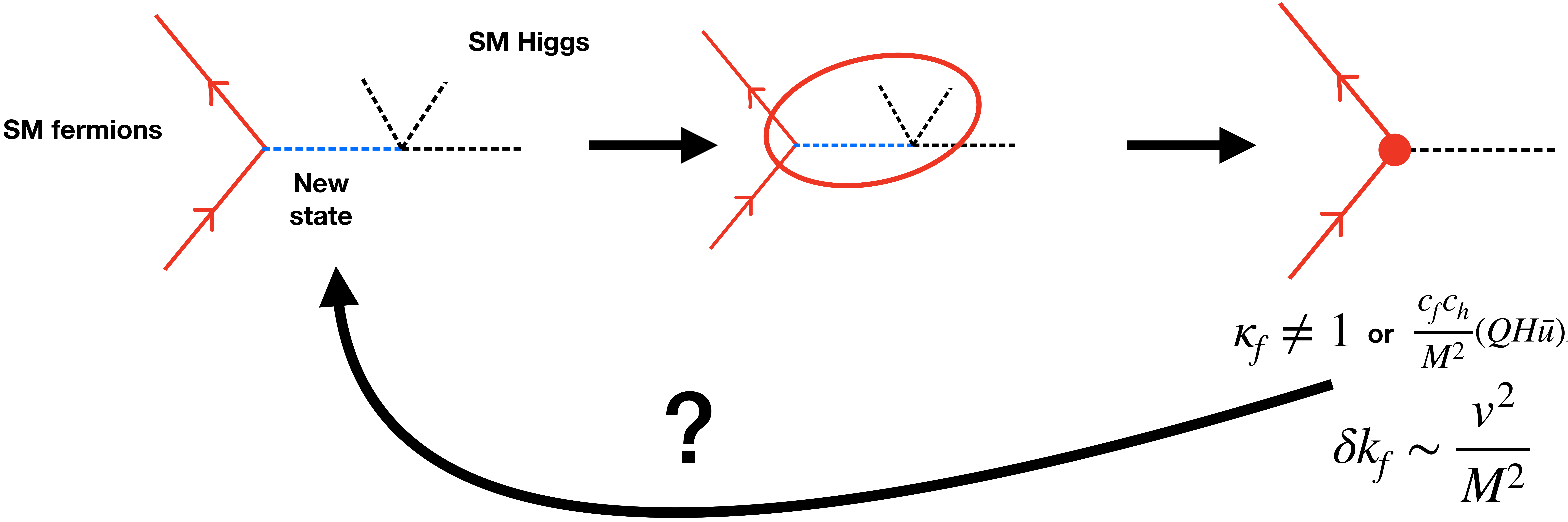
Every QFT describing our universe is an EFT, but an EFT doesn't tell us everything (it's *not* model independent)



$$\sim \mathscr{L}_{QED} + \frac{1}{\Lambda^2}\left(\bar{\psi}\gamma^{\mu}\psi\right)^2$$

Most everyone in this room is familiar with Fermi theory of Weak interactions but we can use EFTs as a tool much more broadly

For example in models of modified EWSB



$\kappa_f \neq 1$ or $\frac{c_f c_h}{M^2}(QH\bar{u})H^2$

$$\delta k_f \sim \frac{v^2}{M^2}$$

Where this maps in the coupling/mass plane depends on the precision of the observable when viewed in this direction

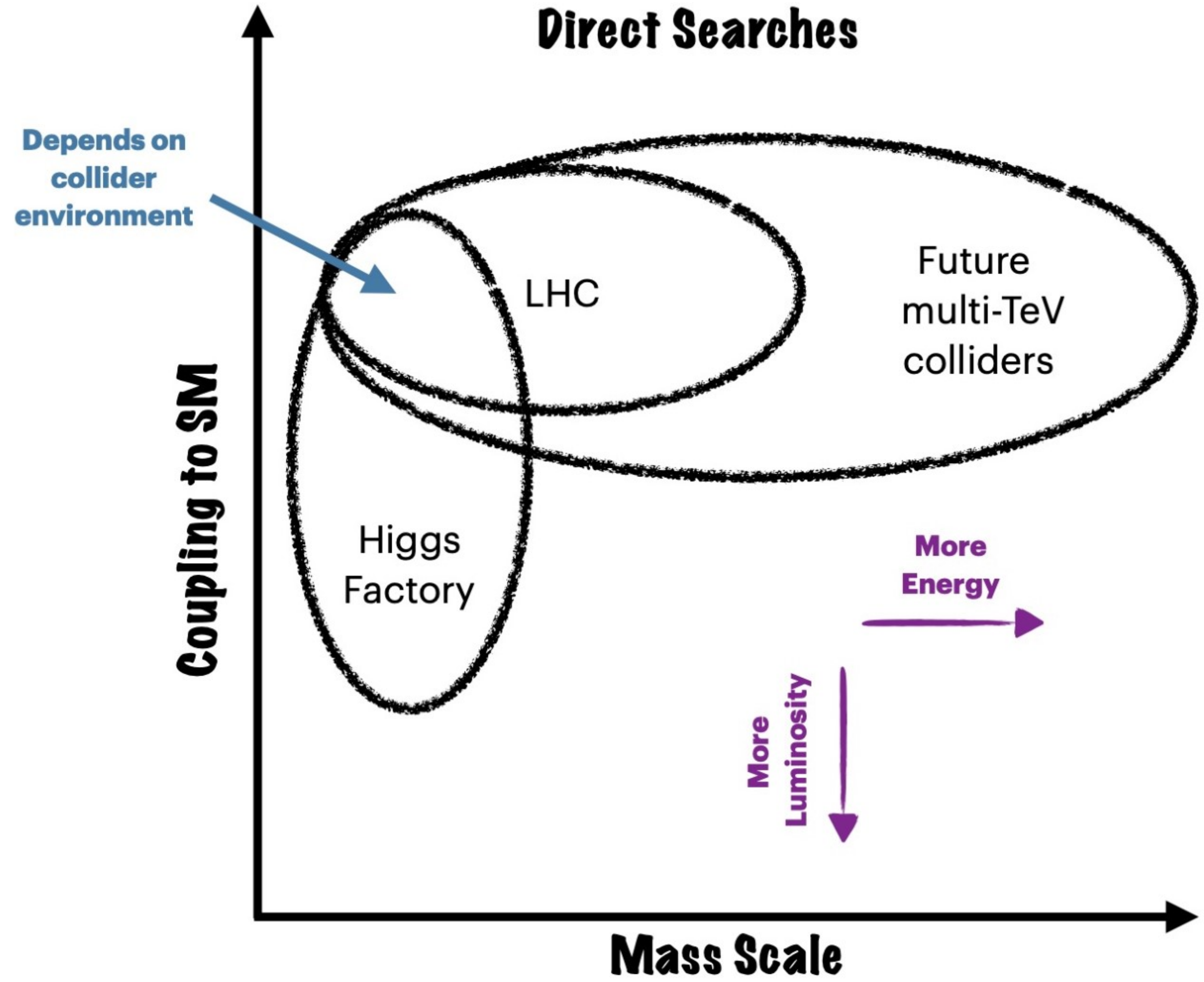
Precision and Energy are inexorably linked

We need to understand this mapping otherwise just using EFT logic could inadvertently sell the LHC short

Mapping to UV QFTs gives correlated observables that naively are distinct or not captured from EFT POV

This holds for *future* colliders as well

This concept is of course straightforward to think of in the context of direct searches

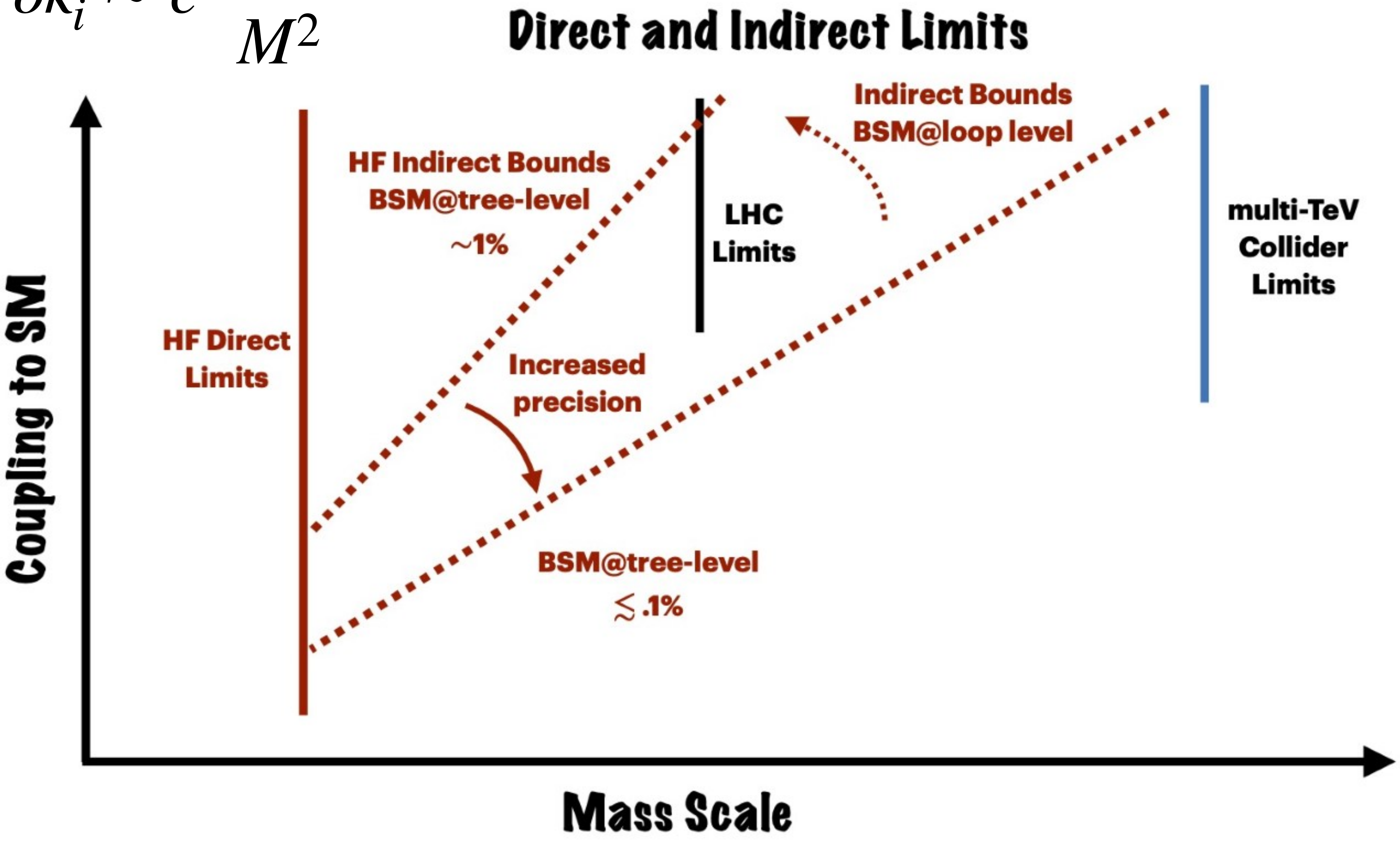


Snowmass EF Report
M. Narain, et al 2211.11084

More energy = more reach

When overlaying precision bounds, you have to think more carefully

$$\delta\kappa_i \sim c^2 \frac{v^2}{M^2}$$



When do precision Higgs factories actually extend beyond the HL-LHC for Higgs physics?

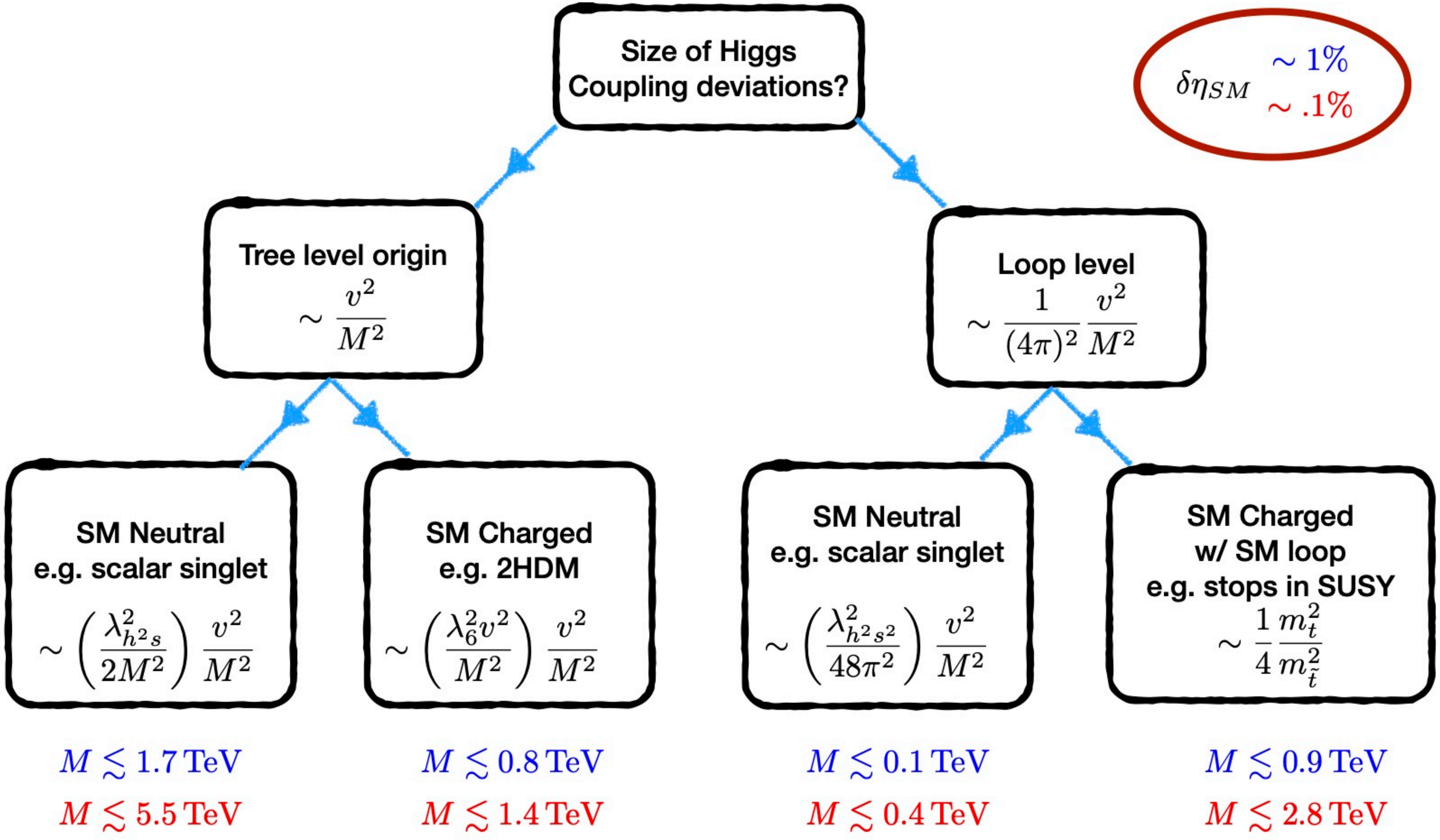
Naively almost always from precision, but it doesn't have to be!

This has been very schematic so let's look at *numbers*

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

For HL-LHC a few % (or much worse) you have the ability to look at Higgs precision "directly" there's a lot of overlap!

Whether the EFT is even a valid description of course also comes into question and depends on the collider



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

I’d like to show 4 vignettes of how this works

- I don’t have a full mapping, just like we don’t know the space of all BSM theories, so it’s the best I can do for now and hopefully inspires ideas
- We can learn from examples how the mapping works and the benefits of precision and energy
- I am going this route because I care about discovering new physics, not precision for precision’s sake
- It matters a lot for the planning of the future for HEP. Worst case scenario for our field is spending billions without fully understanding what we’ve already explored

1) Higgs Precision and Flavor

- I want to start with this example because it's normally thought of as the most difficult

- The Higgs of course is the source of *all* flavor in the Standard Model so it's a natural place to ask if that's really true

- Experimentally you can always search for flavor violating couplings but it's *very* difficult to make consistent theories that aren't ruled out by dedicated flavor experiments

- Typically for EW to TeV scale physics we make assumptions like Minimal Flavor Violation (MFV) which results in the interesting questions sticking to the 3rd generation, like naturalness

Spontaneous Flavor Violation (SFV)

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

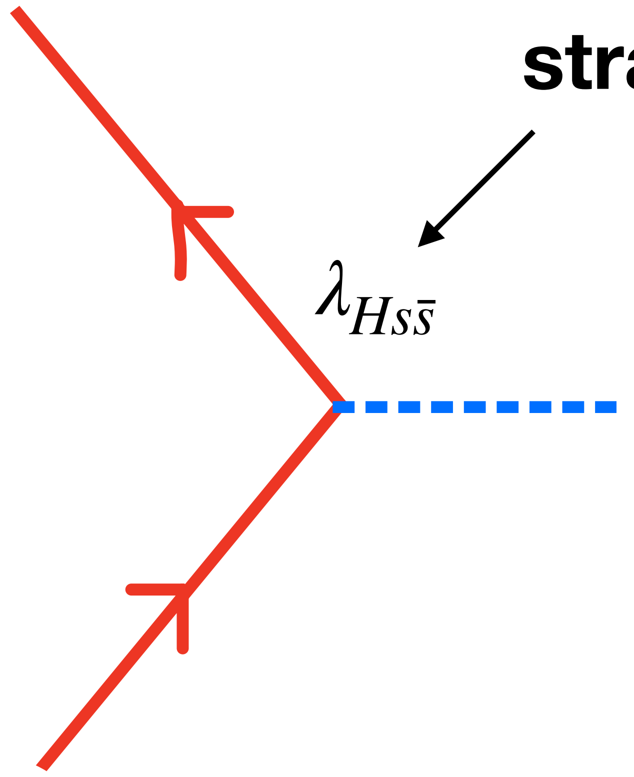
New physics *can* couple in a strongly flavor dependent way if it is aligned in the down-type quark or up-type quark sectors

For example: I could have a new BSM state at the *EW scale* that just couples to RH strange quarks and nothing else at tree level - perfectly consistent *despite* EFT flavor bounds on Kaon mixing naively setting a scale of *10000 TeV*

This is symmetry protected, and there are simple UV completions!
This is *really* opening up to space of theoretically possible ideas

SFV is general but let's apply this to the Higgs with a 2HDM

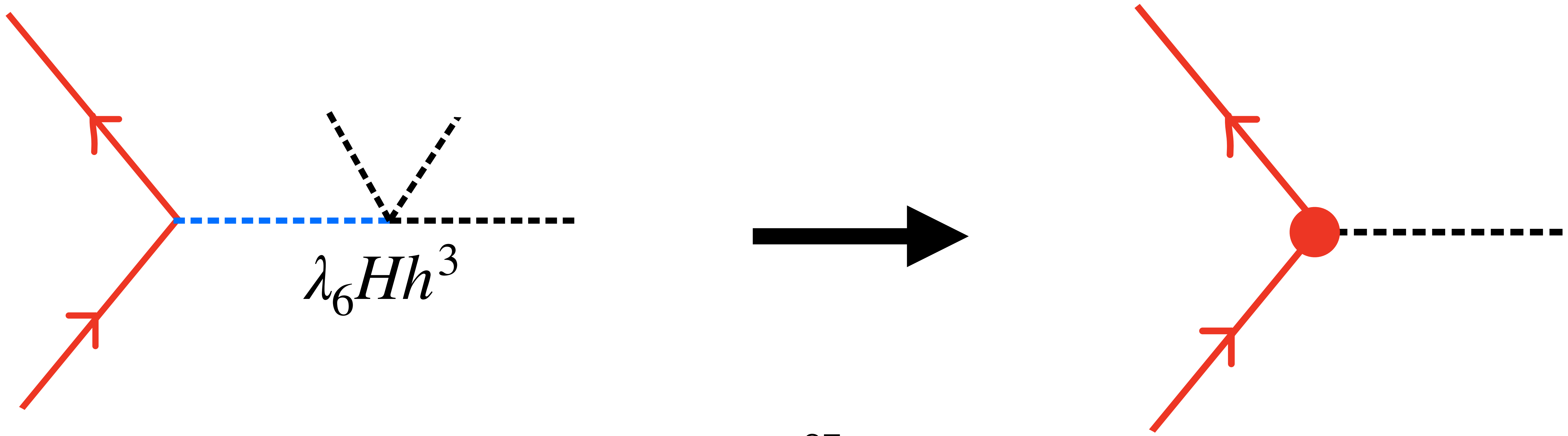
Nothing to do with SM strange Yukawa



H - 2nd Higgs doublet

If this was all there was, then an amusing signal generator for strange jet resonances

It *can* modify "SM" Higgs strange couplings



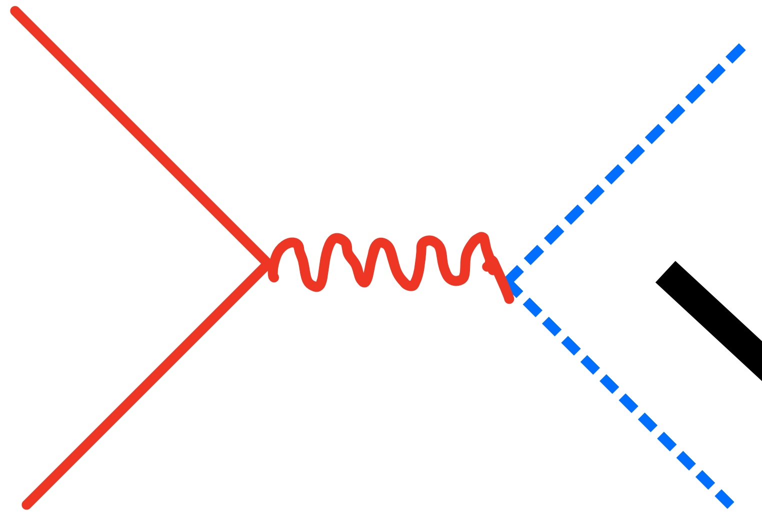
$$\sim \frac{1}{\Lambda^2}(sh\bar{s})h^2$$

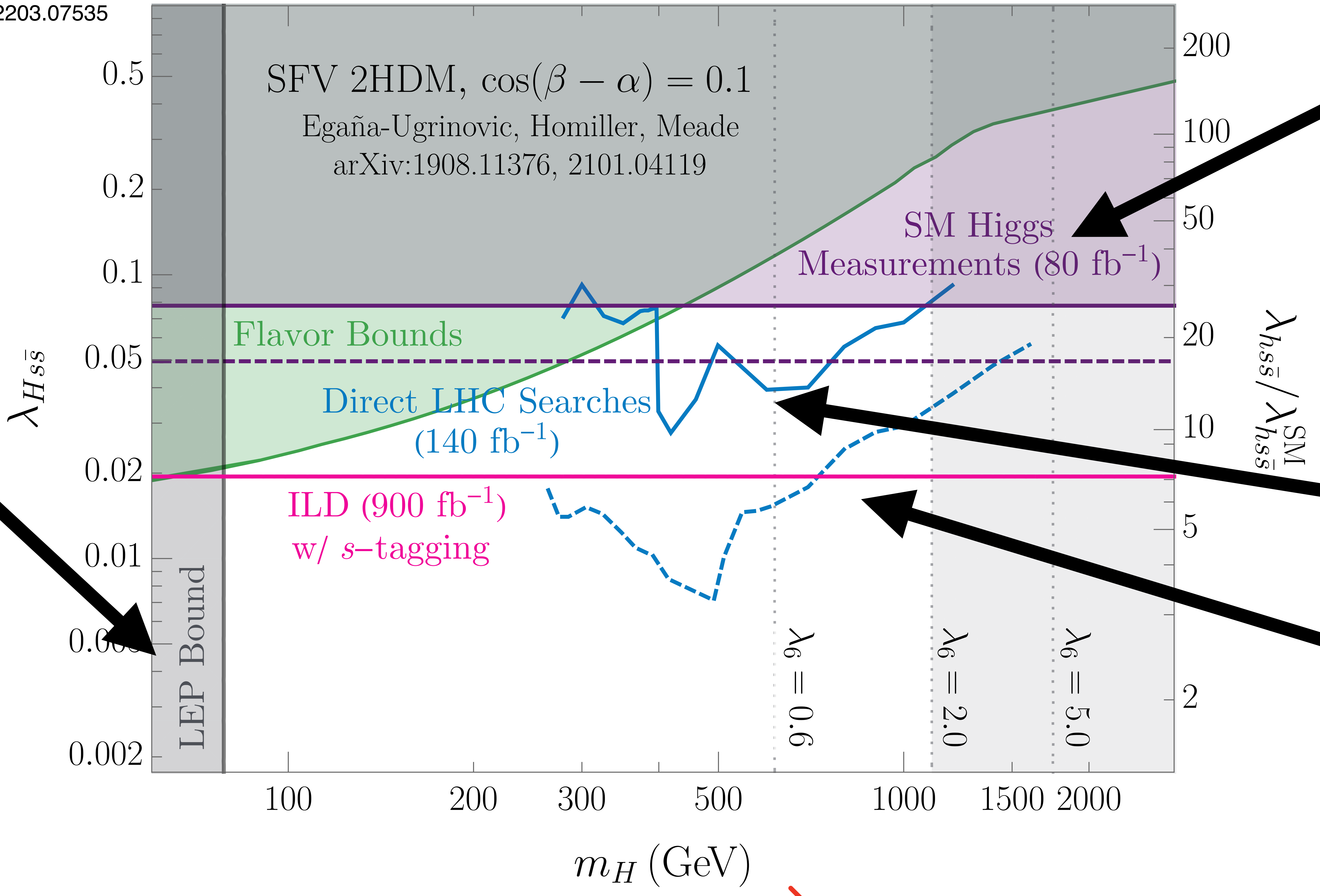
That's not the only signal!

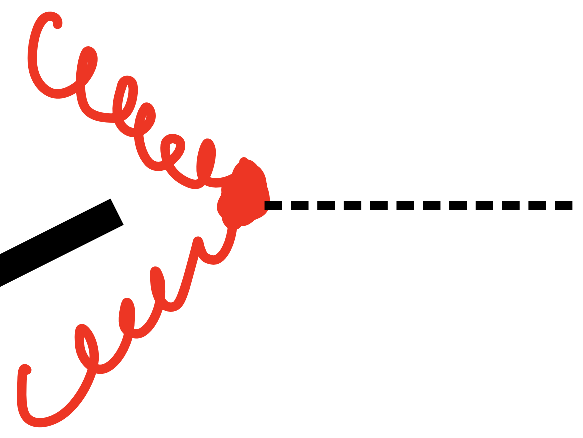
A. Albert et al
2203.07535

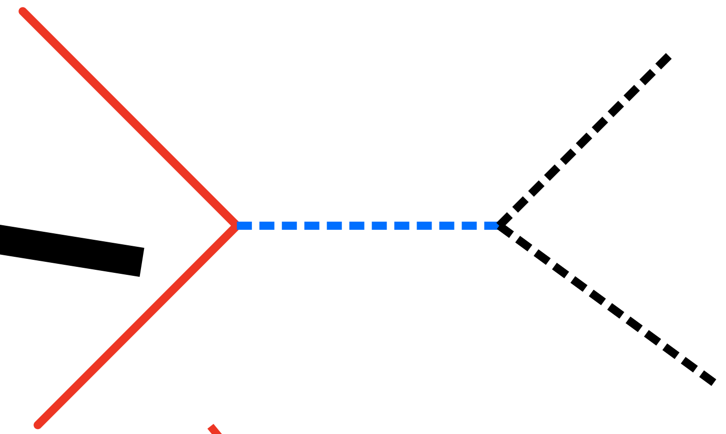
You wouldn't understand all this *just* from EFT

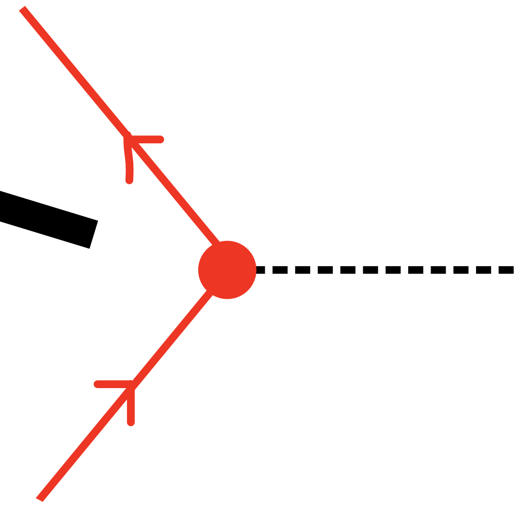
$$\frac{1}{\Lambda^2}(sh\bar{s})h^2$$



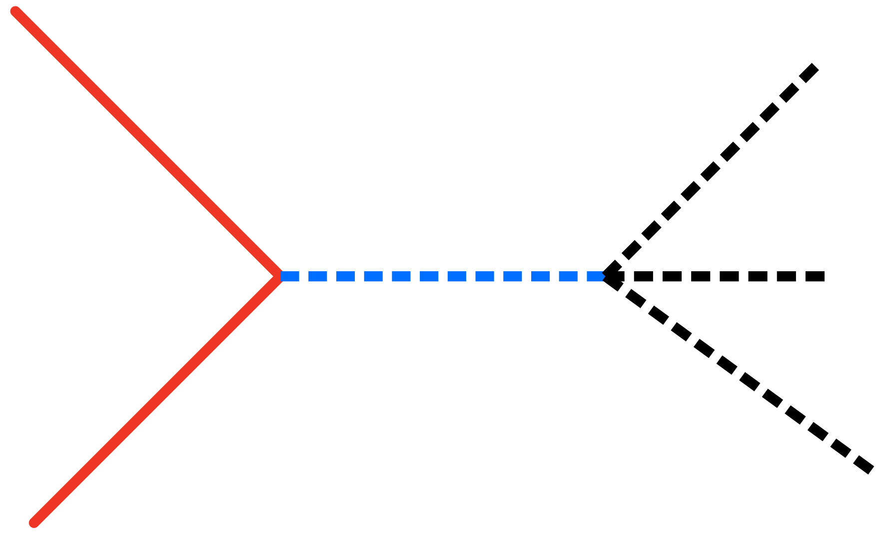








Resonant di-Higgs sets the current strongest LHC bound on deviations of the strange Yukawa!



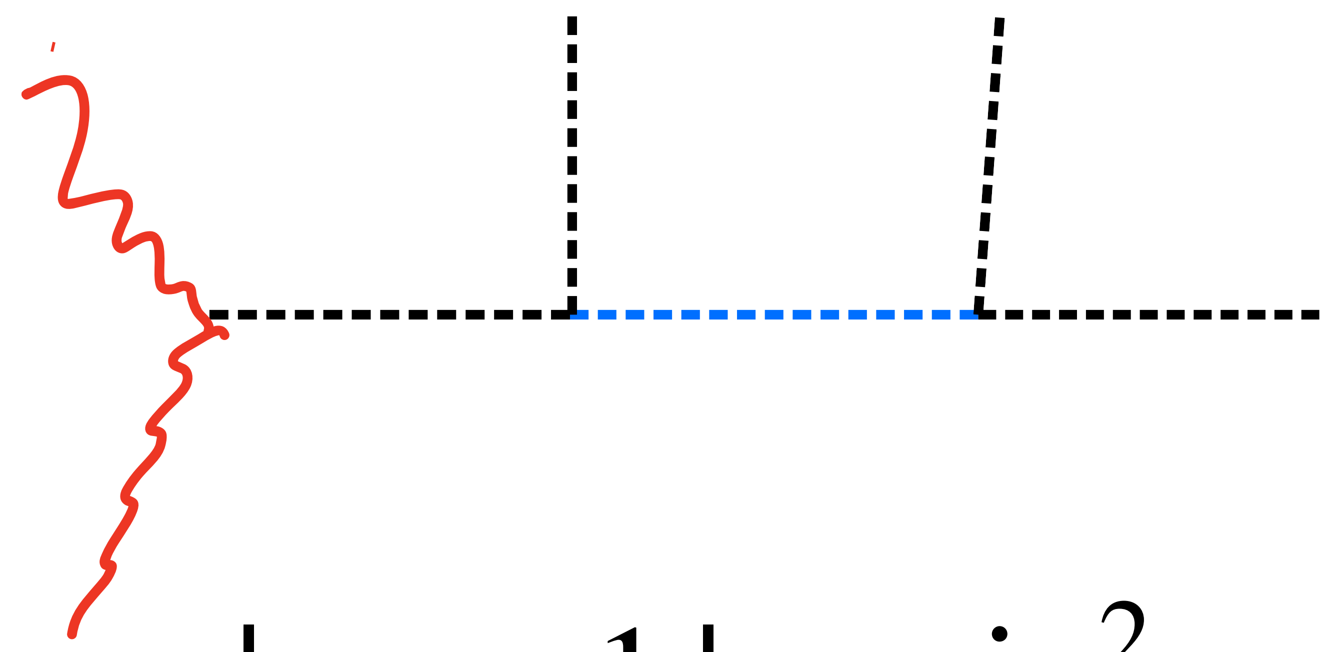
Prospects for tri-Higgs at the HL-LHC

2) EW phase transition, Neutral Naturalness, Higgs Portal

Add a scalar singlet to the SM

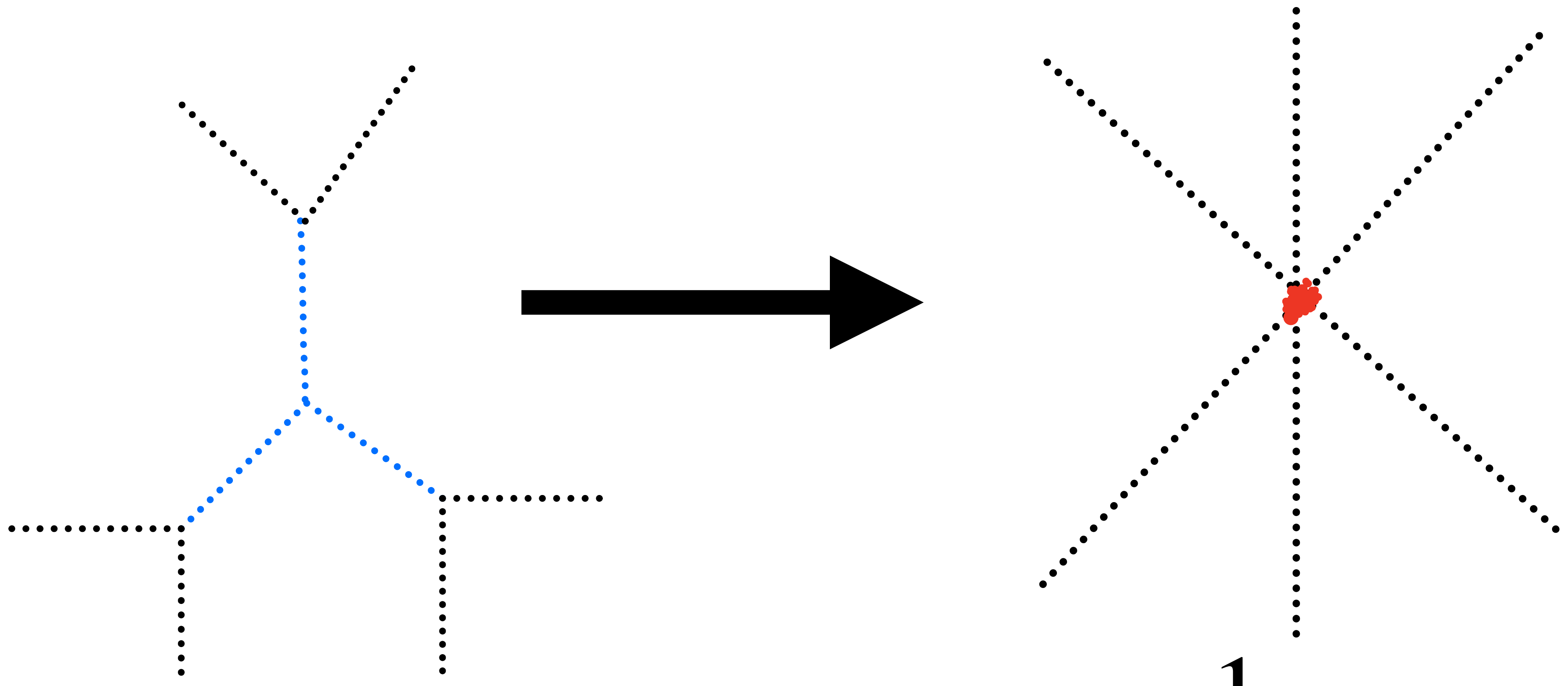
$$\mathscr{L} \supset \lambda_{h^2\phi} h^2 \phi + \lambda_{h^2\phi^2} h^2 \phi^2$$

There can be multiple couplings but effectively reduces to either a mixing angle/mass or coupling/mass



$$|\kappa_V - 1| = \sin^2\gamma$$

All couplings inherited from Higgs!

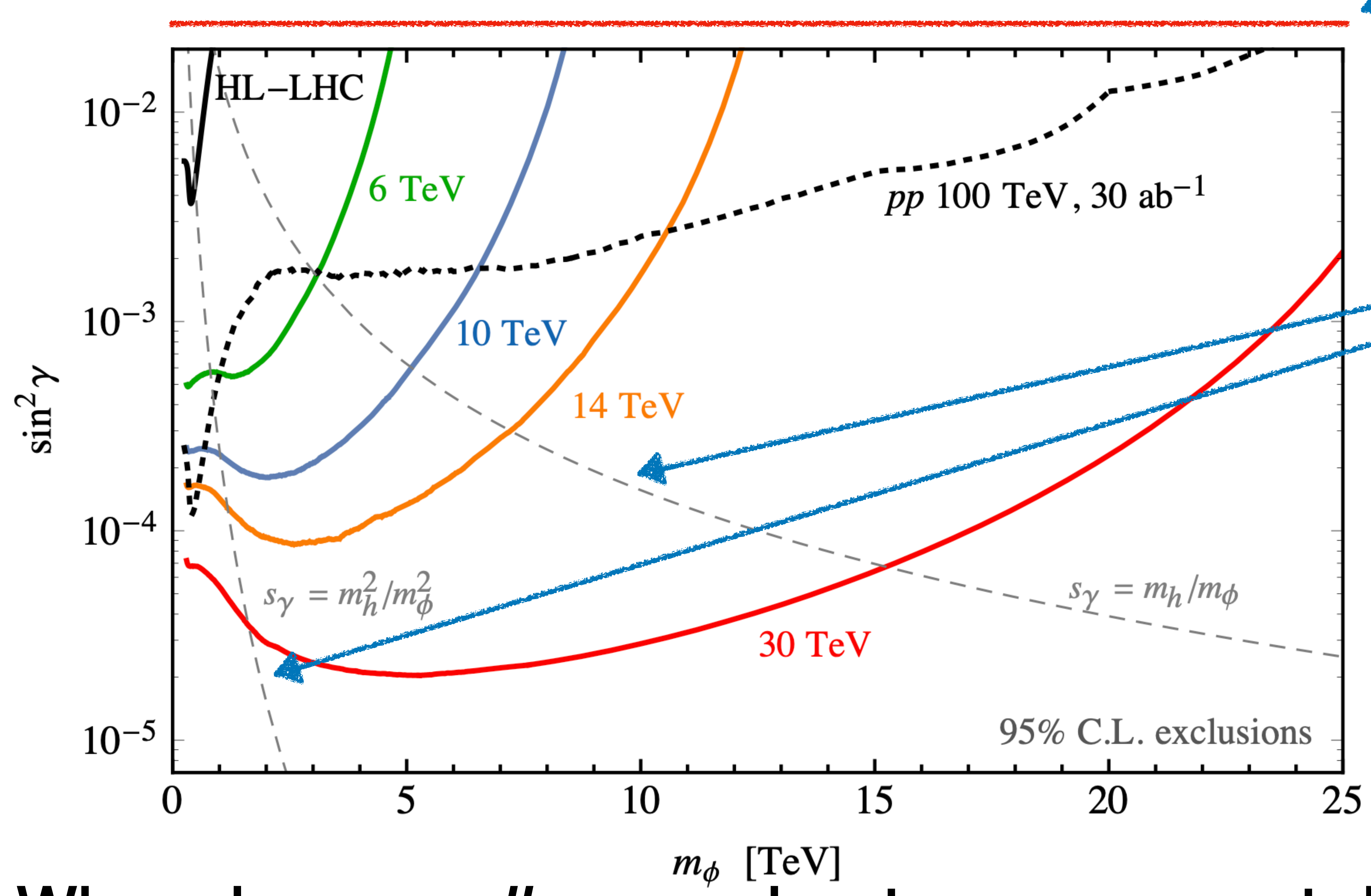


$$\frac{1}{\Lambda^2} H^6$$

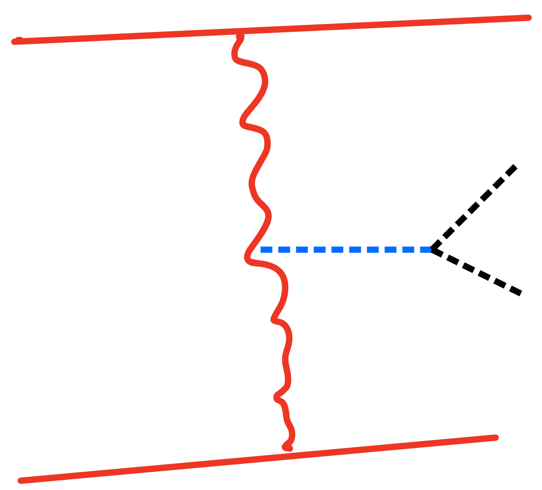
EW phase transition, Neutral Naturalness, Higgs Portal

A. Alit et al
2103.14043

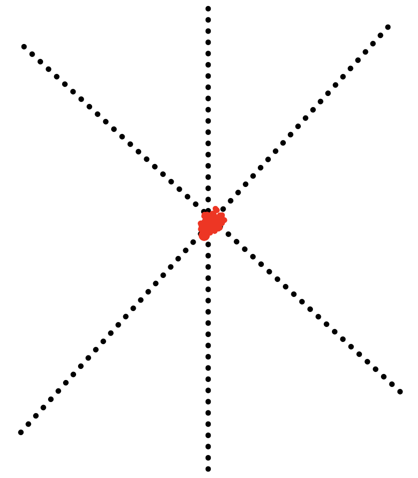
HL-LHC Higgs precision projections



Focus on model lines



Direct search is almost always stronger



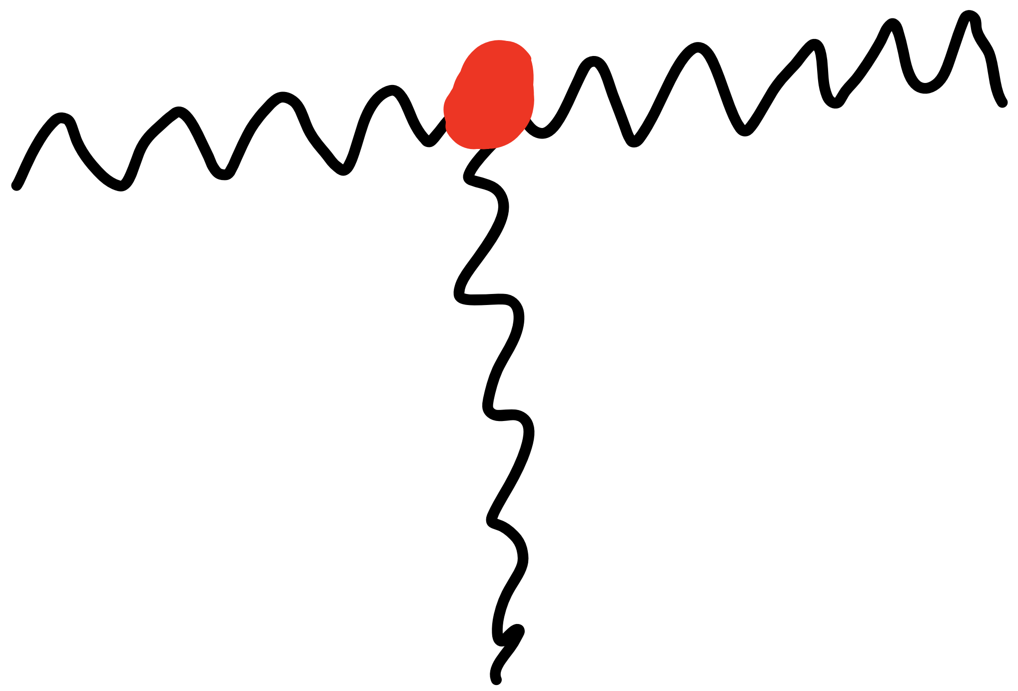
When do we *really* care about non-resonant di-Higgs (λ_3) for its own sake?

Interesting to think about in more general setups beyond singlet, e.g. composite Higgs

See G. Durieux et al, 2110.06941 for recent extensions

3) Modified W/Z gauge couplings

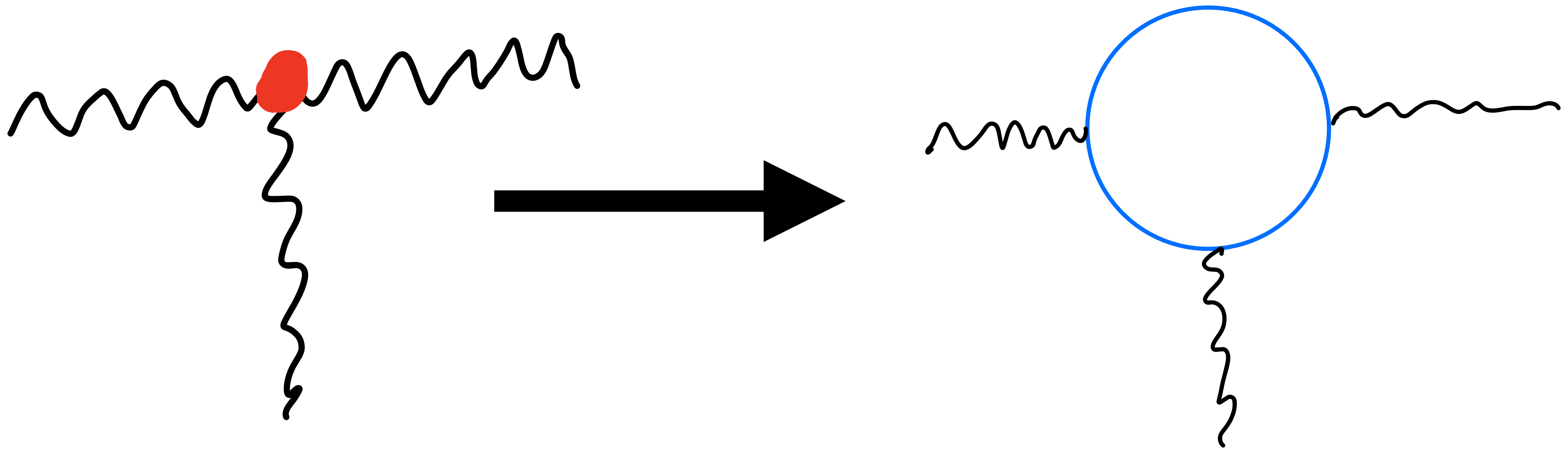
Not directly Higgs precision but at the same time if we are asking questions about EWSB we expect deviations



$$\frac{c_W}{\Lambda^2} W^3_{\mu\nu} + \frac{c_B}{\Lambda^2} D_\mu h^\dagger B^{\mu\nu} D_\nu h + \frac{c_W}{\Lambda^2} D_\mu h^\dagger S^{\mu\nu} D_\nu h$$

From EFT perspective at dimension 6 there are 3 operators that can modify these coupling

However, from Arzt et al (1995) you *can't* generate these from integrating out a heavy state at tree-level



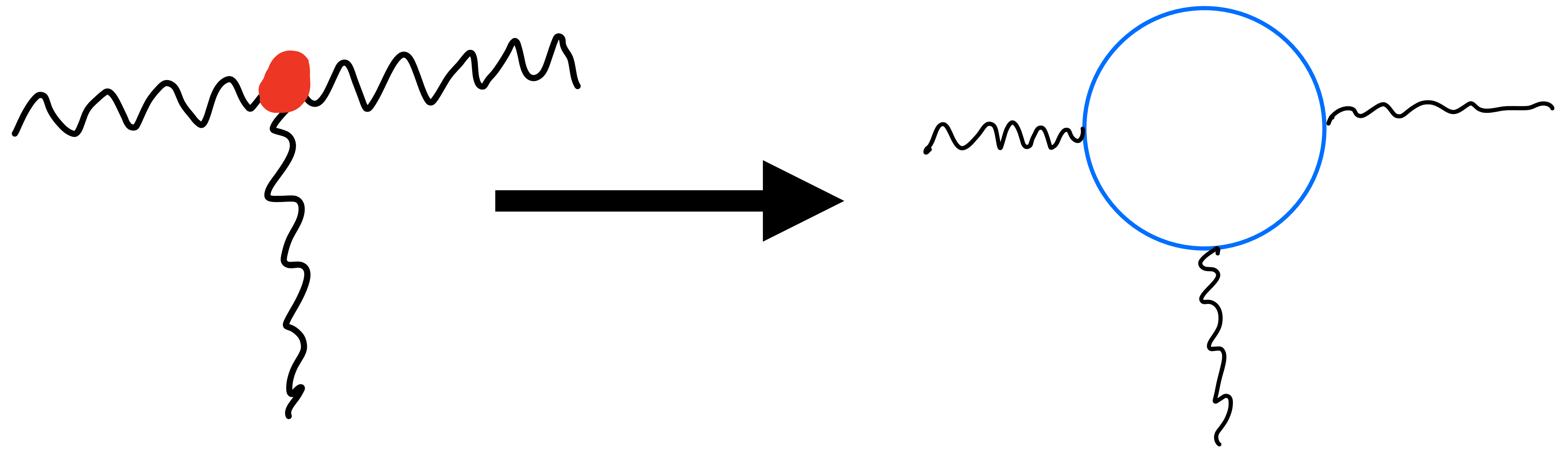
$$\frac{c}{\Lambda^2} \sim \frac{g^3}{16\pi^2 M^2}$$

Validity of EFT at dim 6 versus precision?

Other observables, new EW charged multiplets!

Modified W/Z gauge couplings

Not directly Higgs precision but at the same time if we are asking questions about EWSB we expect deviations



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Validity of EFT at dim 6 versus precision?

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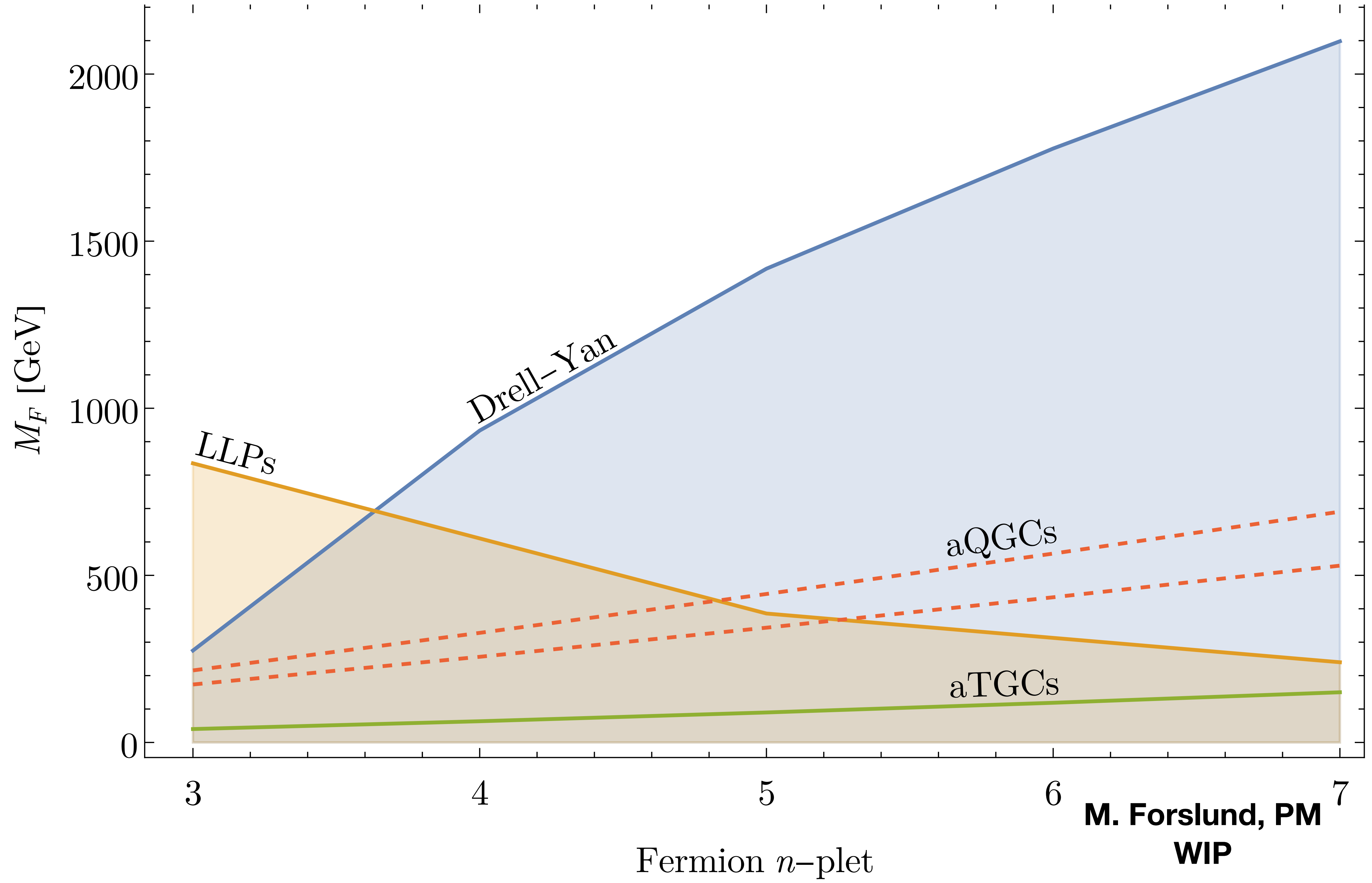
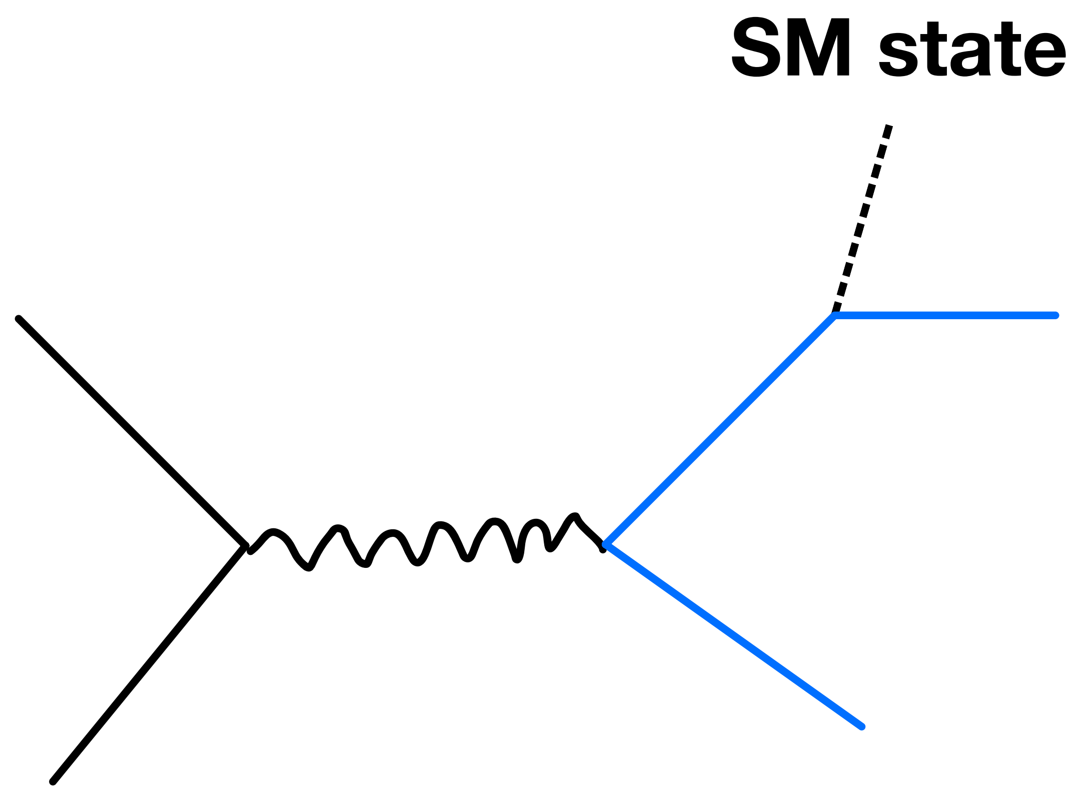


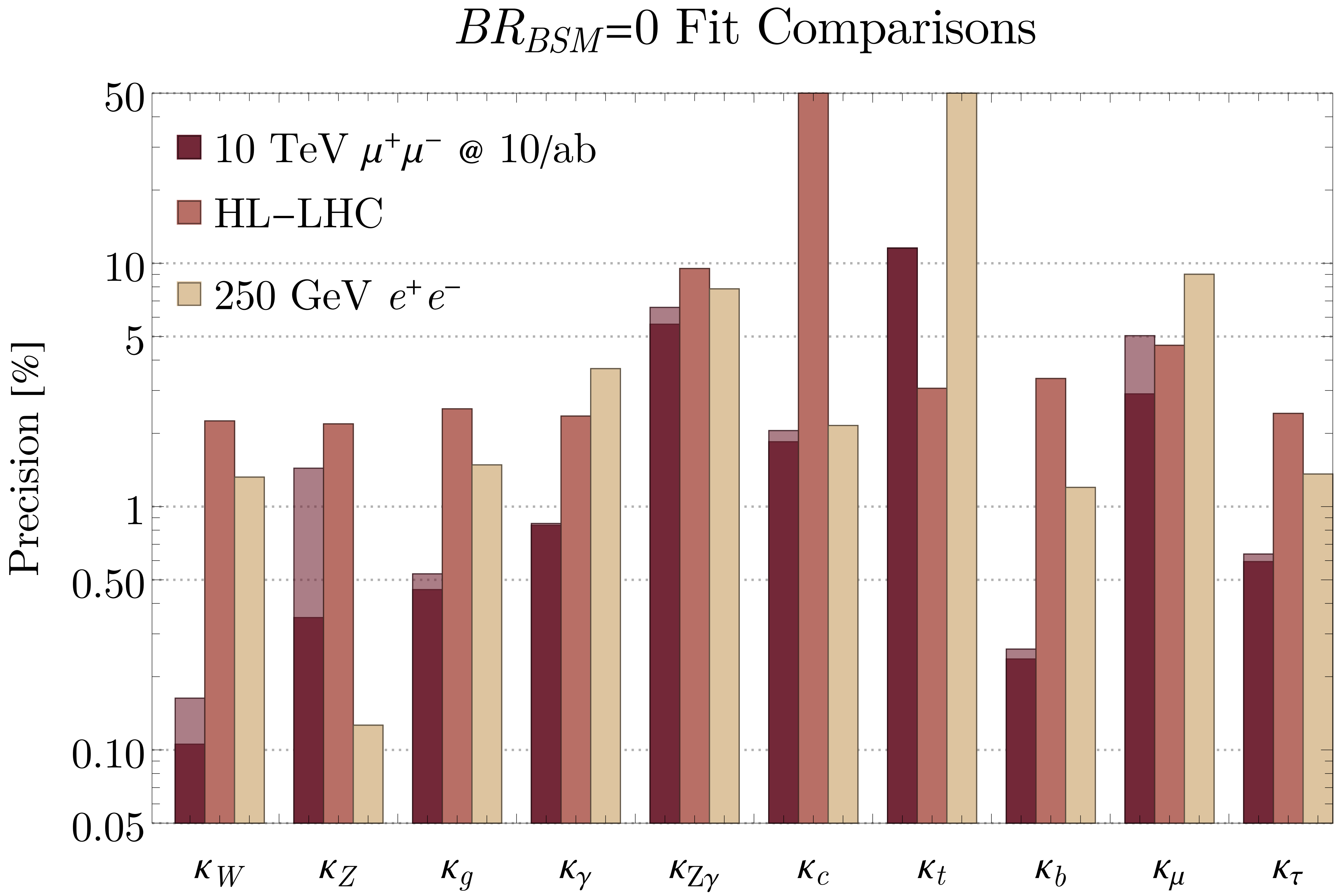


Small splitting (no new couplings) = LLP observables!

LLP always more powerful than aTGCs and consistent!

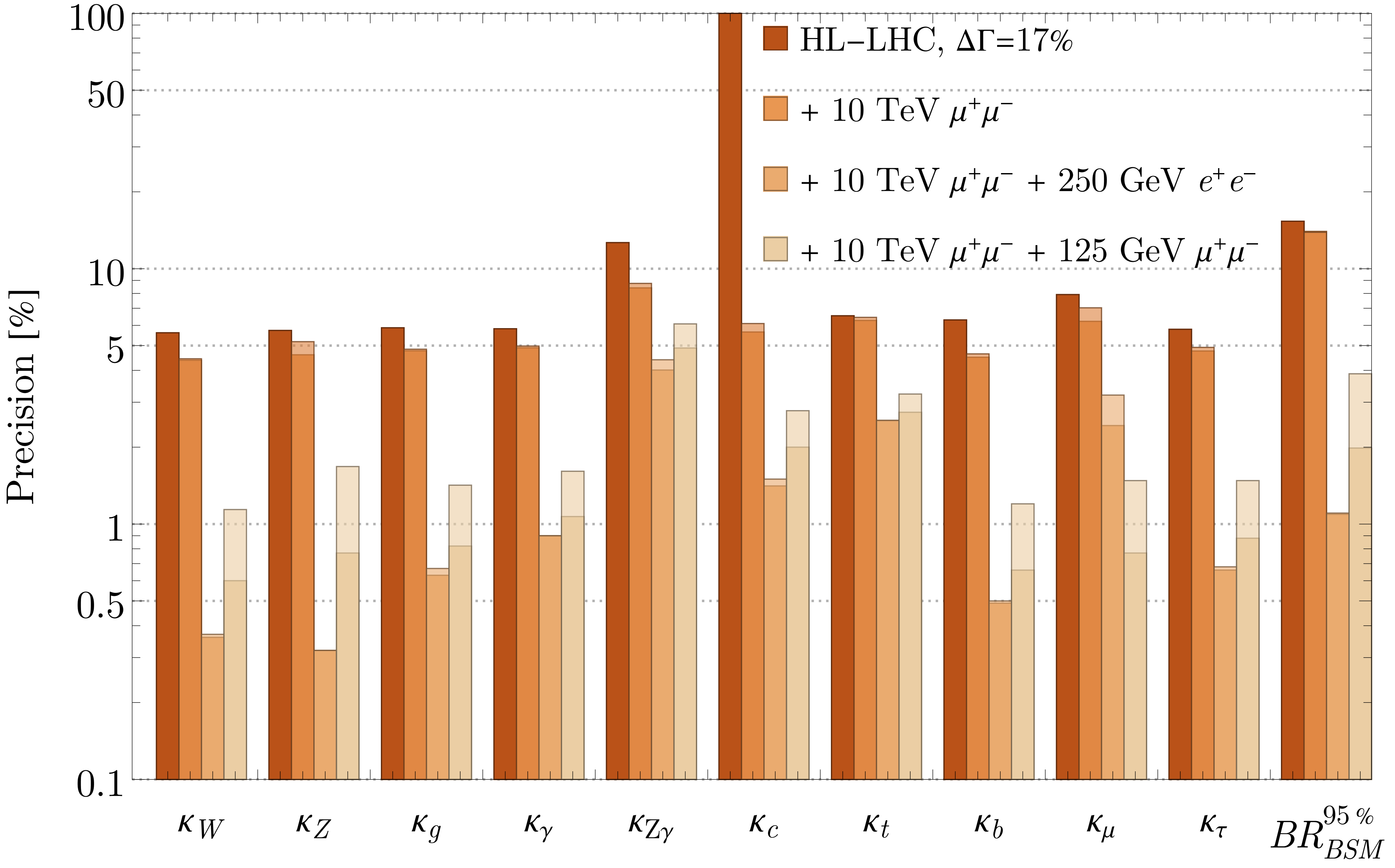
Extend UV model bring in more observables including Higgs physics!

4) Higgs fits with new colliders



$$\sigma(i \to H \to j) \sim \frac{g_i^2 g_j^2}{\Gamma_H}$$

Floating width naively



Well known flat direction

$$\mu_{i\to H\to j} = \frac{\sigma_{i\to H} \times BR^{SM}_{H\to j}}{\sigma^{SM}_{i\to H} \times BR^{SM}_{H\to j}} = \kappa^2(1 - BR_{BSM})$$

All $\kappa > 1$ *and* $BR_{BSM} \neq 0$

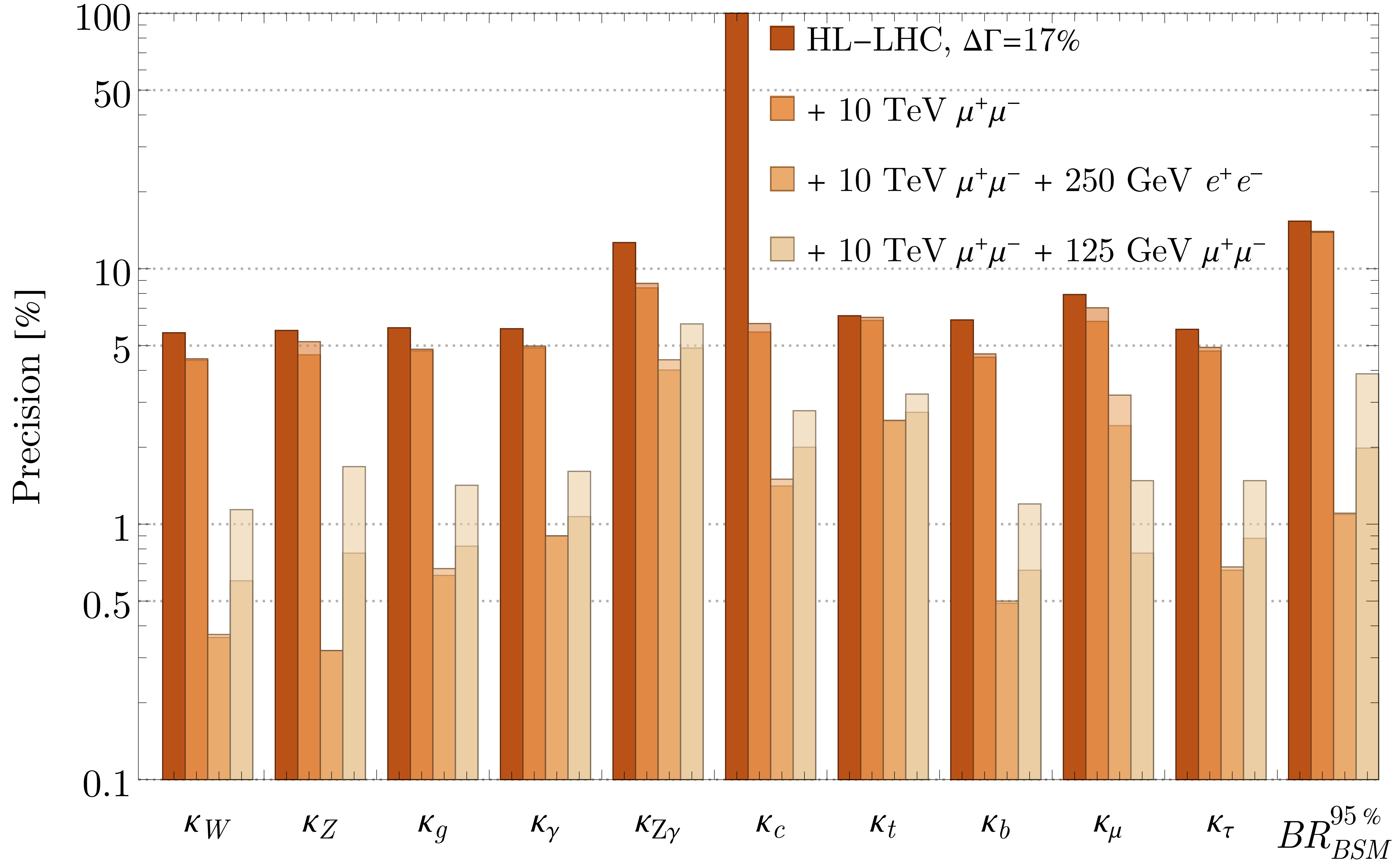
Higgs factories are great, because they let you make inclusive measurements (e^+e^-) or direct width scans (125 GeV $\mu^+\mu^-$)

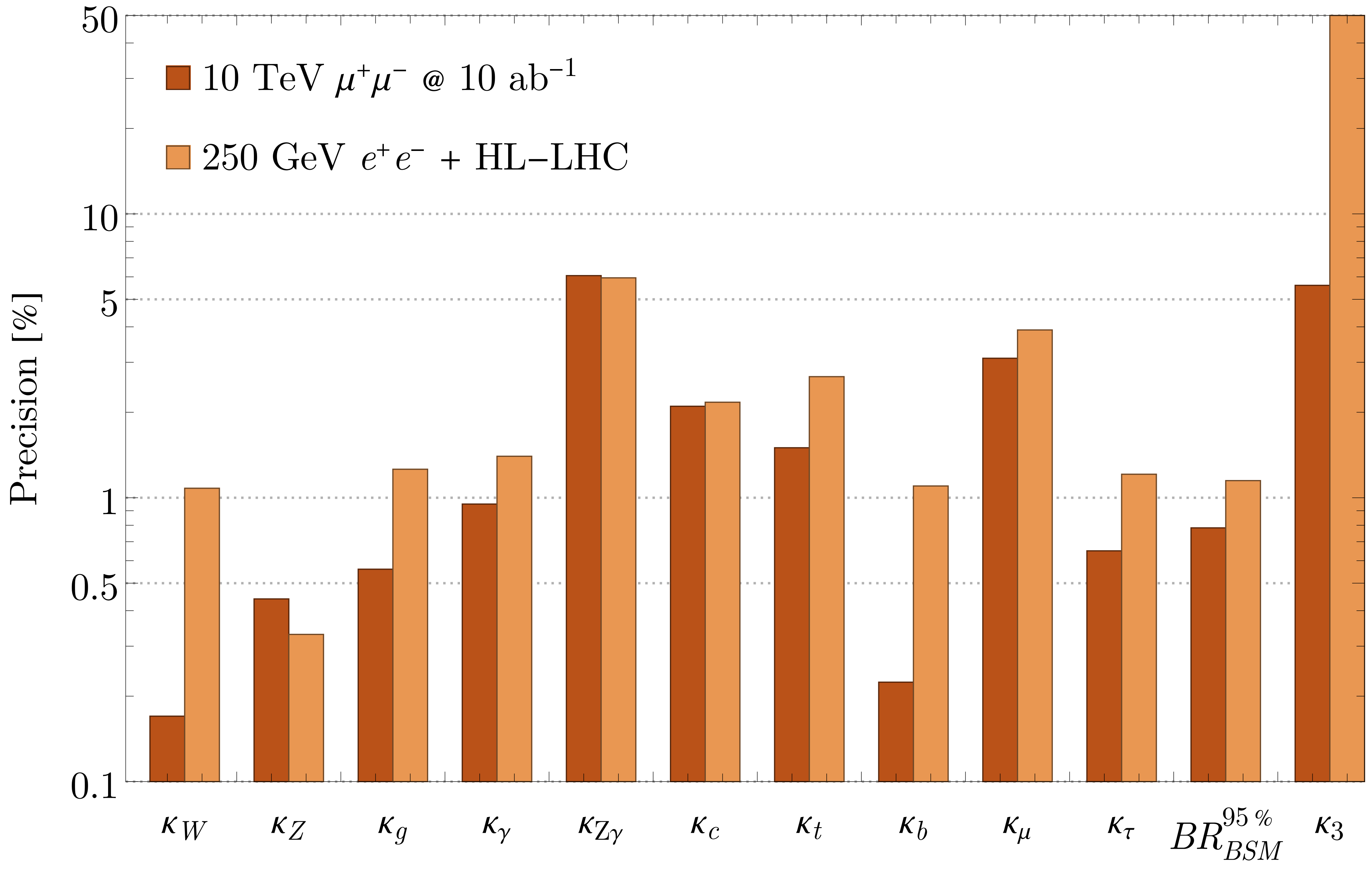
What if we didn't have a Higgs factory before a High Energy Muon Collider?

What is the space of QFTs that generate all $\kappa > 1$ *and* $BR_{BSM} \neq 0$?

From bottom up precision perspective *I can't answer this*

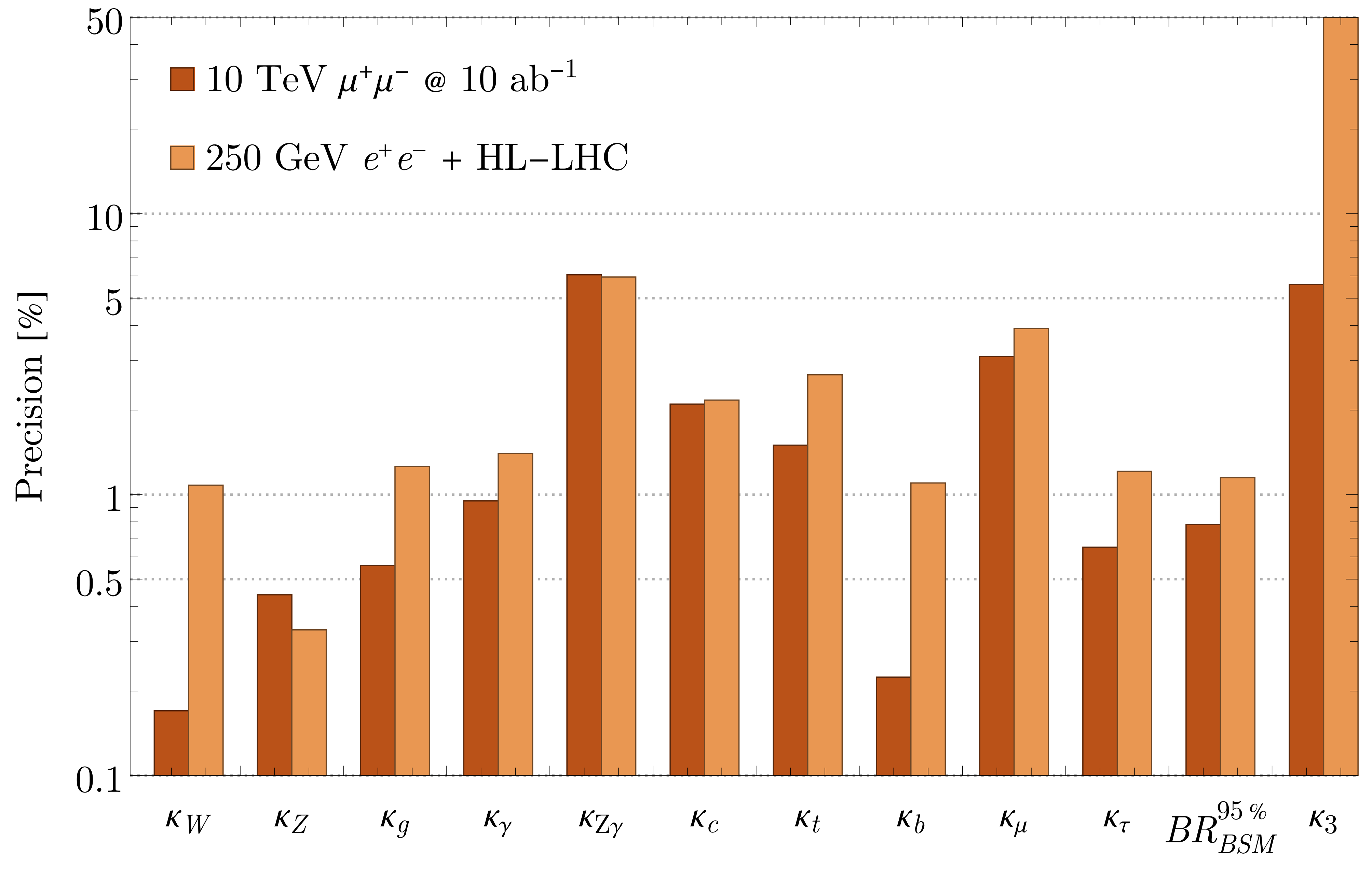
From top down, I need higher SU(2) representations that can look like EFT at low energy and not run into EWPT

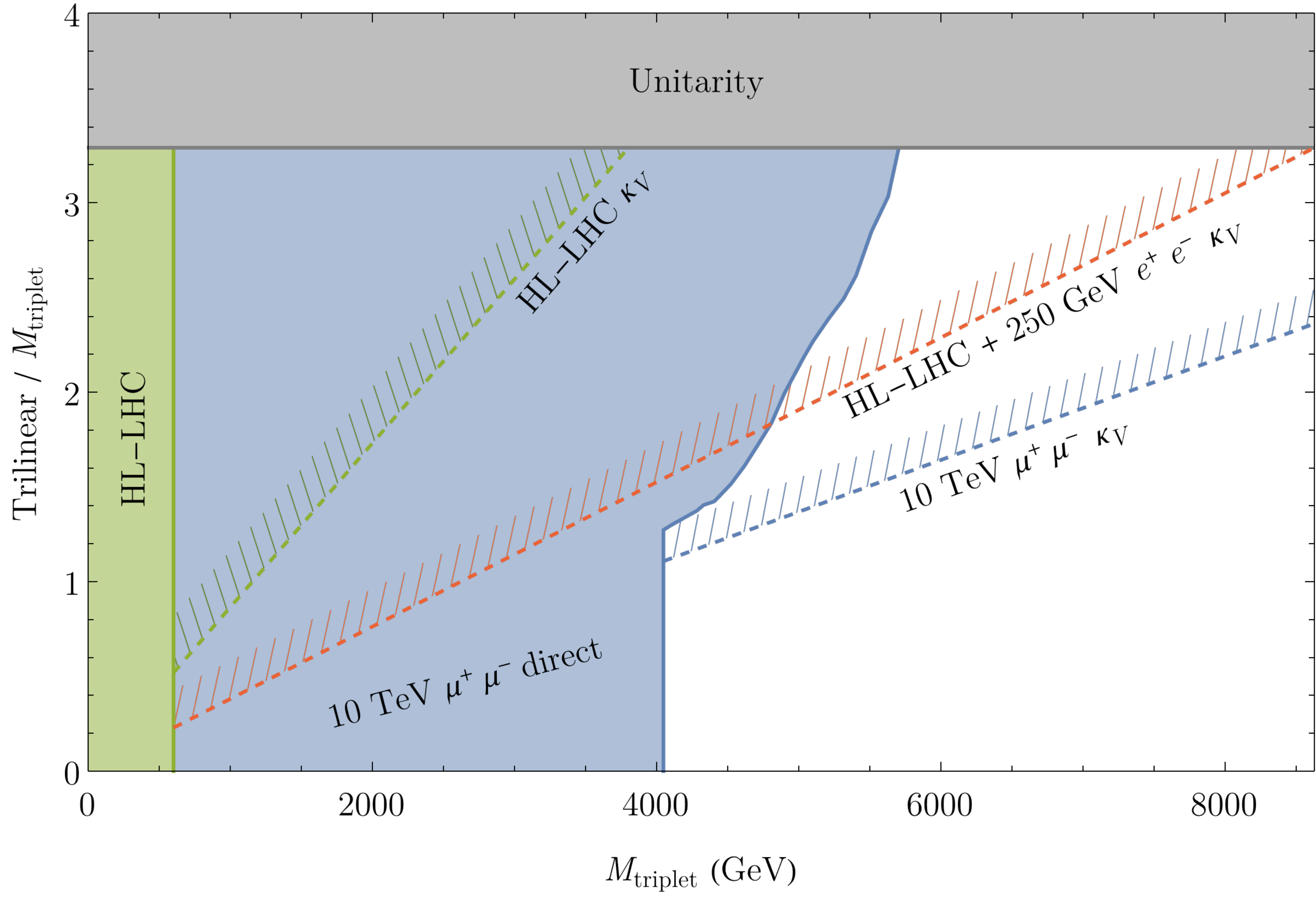




By understanding space of QFTs we realize that EFT logic can be misleading

However the message can be extended even further like in vignettes 1-3





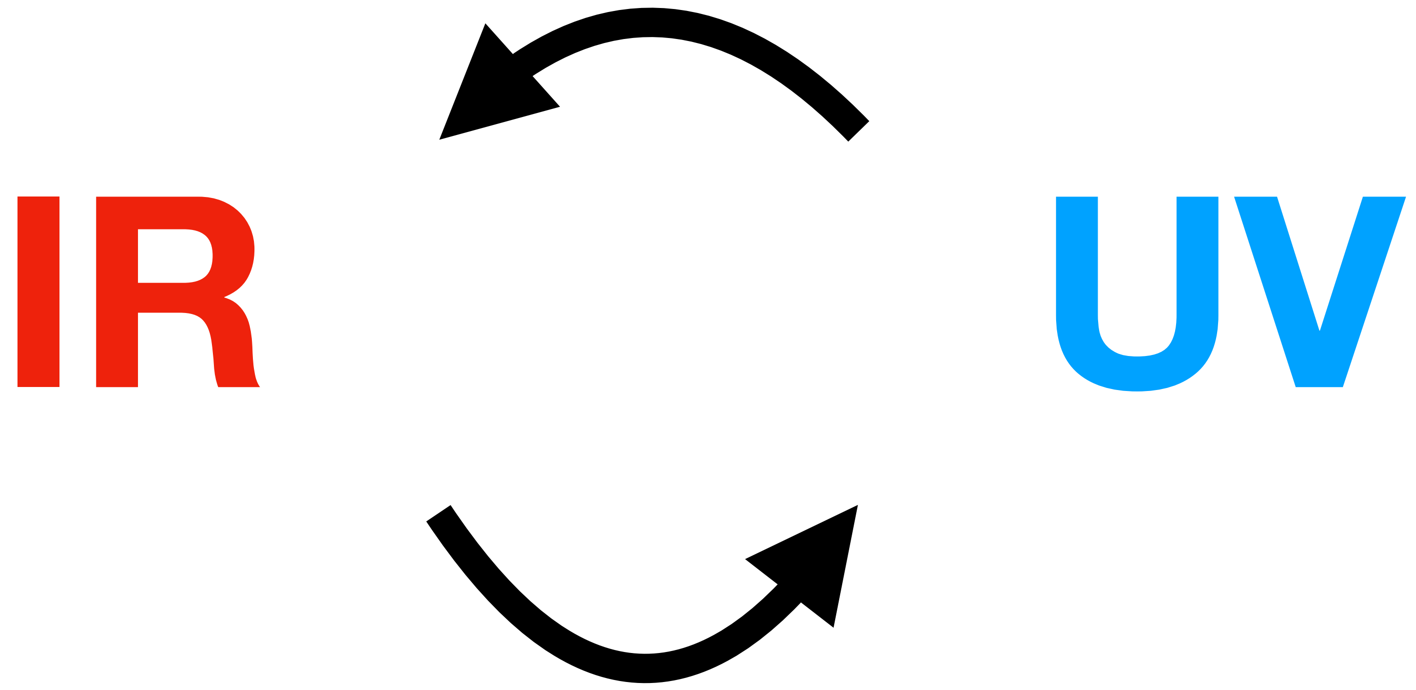
The overlaps of Energy vs Precision can be understood

IF you map onto simplified models of extended EWSB

Conclusions

- Precision and EFT alone aren’t enough to understand the space of BSM theories tested for EWSB, we must go beyond - BSM theory matters!

- Understanding the interplay, especially if we care about finding *new* things at the LHC or future colliders, is absolutely crucial!



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- There’s a whole potential program of “simplified models” for Higgs physics that can better quantify the reach of the LHC, offer new observables *and* cover our deep question about particle physics!
- There’s been a lot of theoretical progress but hopefully we really nail this before the next European strategy update to make the best choices!

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And naturalness still matters, feel free to go back to it in 2025!