Physics prospects of future high energy machines

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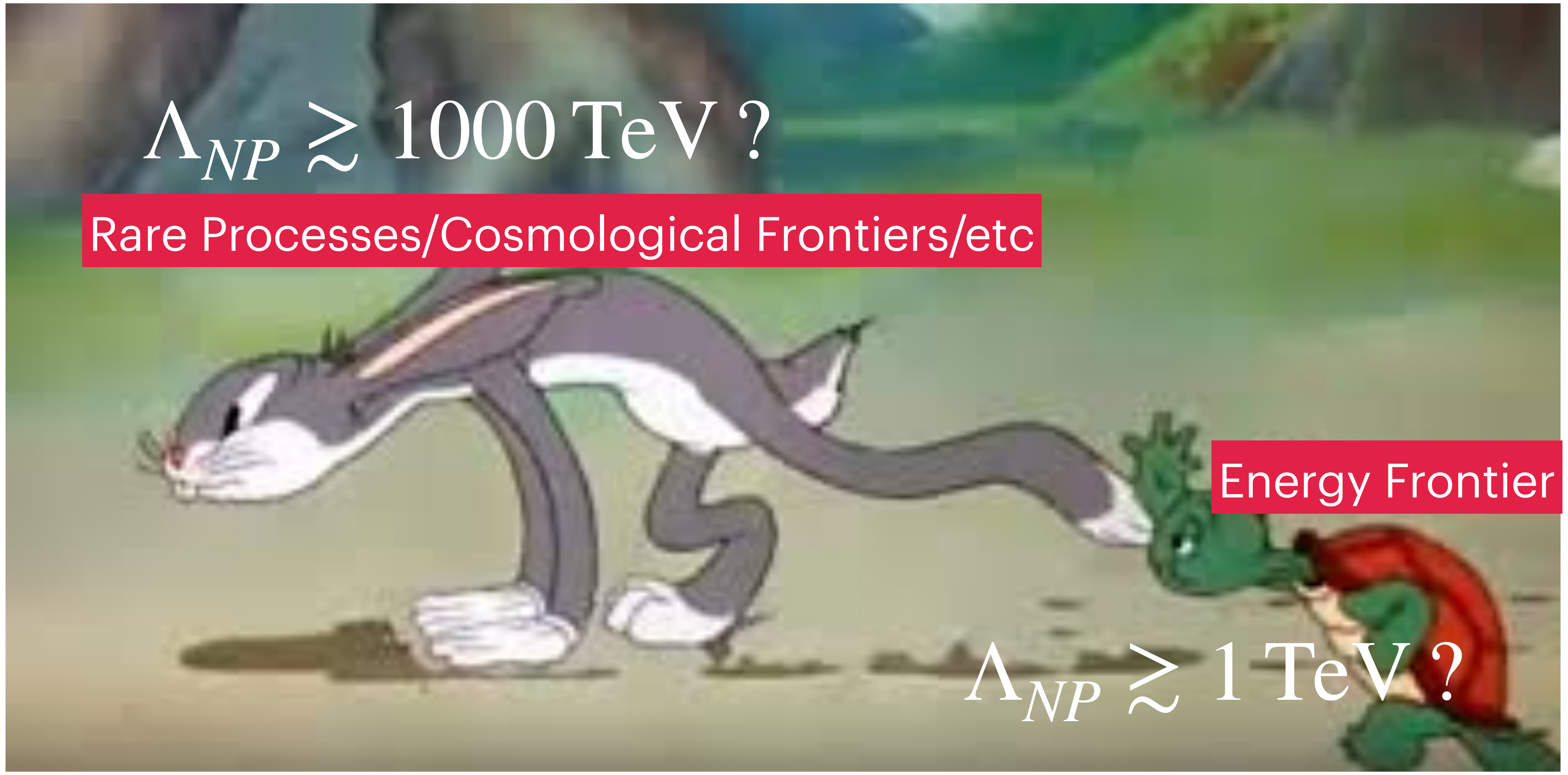
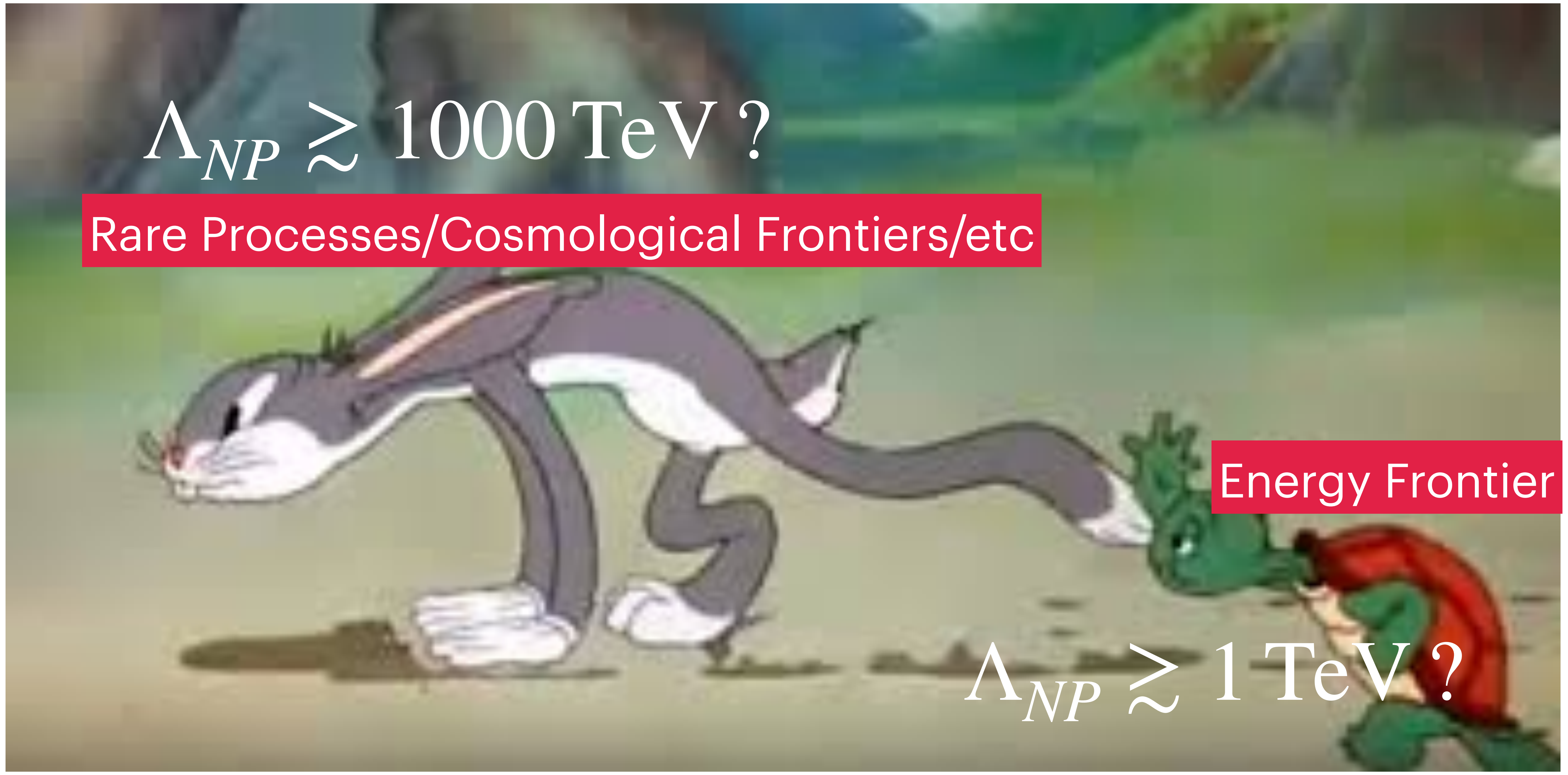
Intersections in Snowmass language



What do High Energy Colliders Bring?

Intersections in Snowmass language

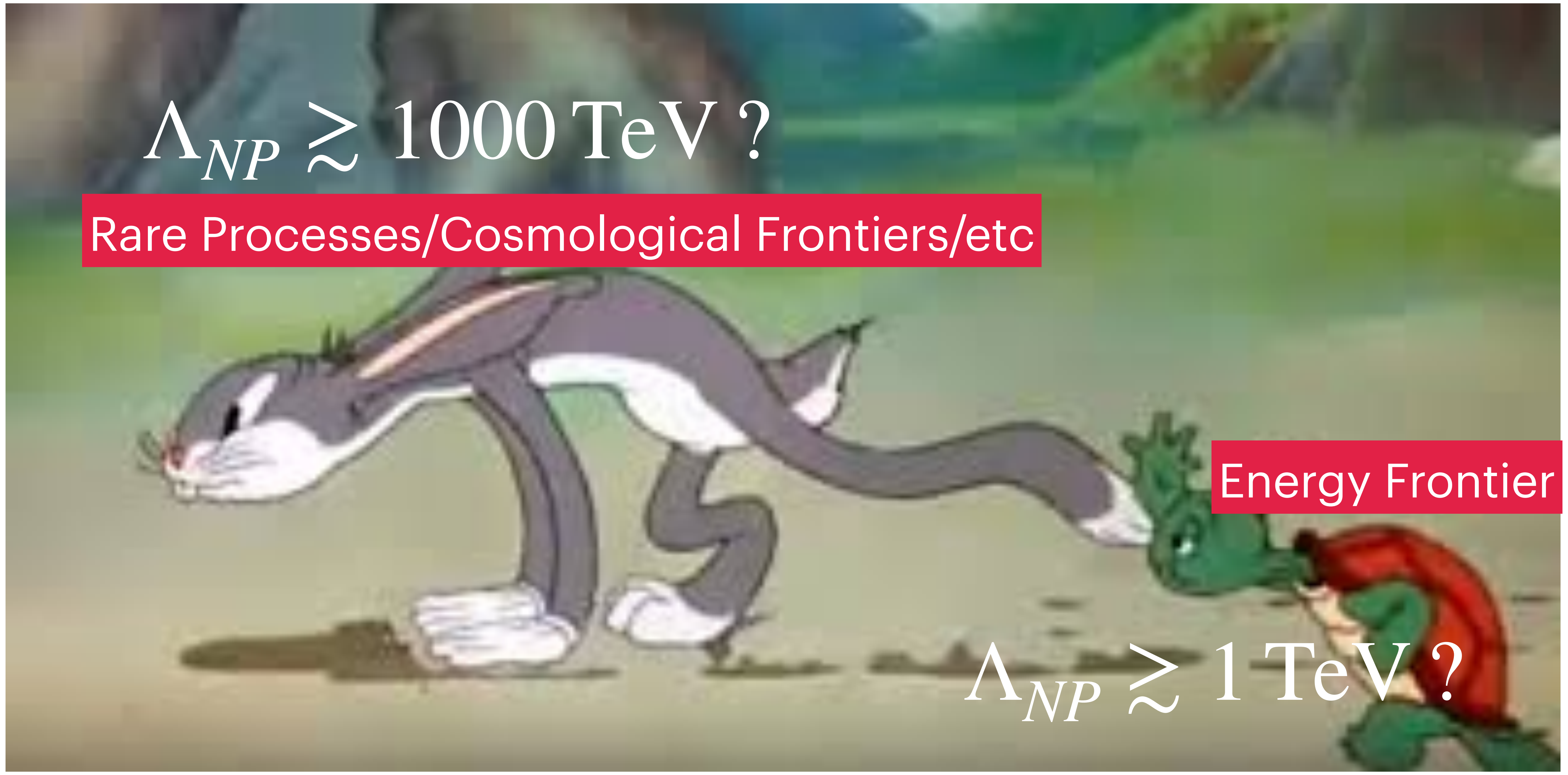


What do High Energy Colliders Bring?

We of course want to bring an all of the above strategy for understanding our universe

Indirect hints need followed by direct probes (e.g $(g-2)_\mu$, m_W, flavor etc)

Intersections in Snowmass language

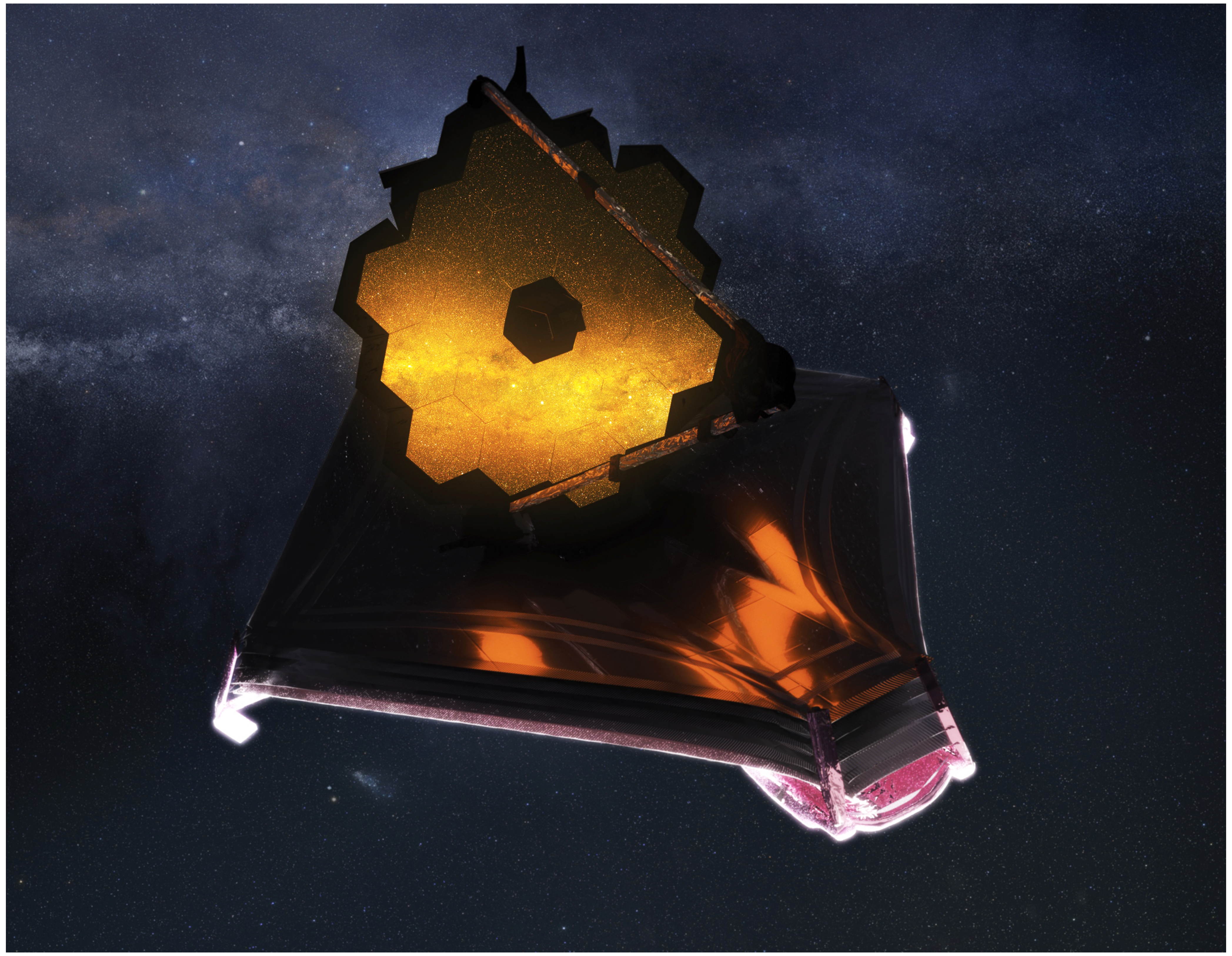


What do High Energy Colliders Bring?

Many aspects of the SM are untested experimentally and *need* high energy colliders

Answers to some of our deepest questions about the universe likely reside at the shortest distances

Nevertheless at the broadest level colliders are for scientific exploration of the unknown



Just like telescopes take us to the largest distances

Colliders are our microscopes to the shortest distances

The downside…

	CME (TeV)	Lumi per IP (10^34)	Years, pre-project R&D	Years to 1st Physics	Cost Range (2021 B$)	Electric Power (MW)
FCCee-0.24	0.24	8.5	0-2	13-18	12-18	280
ILC-0.25	0.25	2.7	0-2	<12	7-12	140
CLIC-0.38	0.38	2.3	0-2	13-18	7-12	110
HELEN-0.25	0.25	1.4	5-10	13-18	7-12	110
CCC-0.25	0.25	1.3	3-5	13-18	7-12	150
CERC(ERL)	0.24	78	5-10	19-24	12-30	90
CLIC-3	3	5.9	3-5	19-24	18-30	~550
ILC-3	3	6.1	5-10	19-24	18-30	~400
MC-3	3	2.3	>10	19-24	7-12	~230
MC-FNAL	6-10	20	>10	19-24	12-18	O(300)
MC-10-IMCC	10-14	20	>10	>25	12-18	O(300)
FCChh-100	100	30	>10	>25	30-50	~560

From 2208.09552

They cost* a lot!

Physics and Cost are distinct issues and something our field is not unfamiliar with

Wilson's 1967 congressional testimony

SENATOR PASTORE Here we are, asking for $250 million to build a machine that is an experimental machine, in fundamental high energy physics, and we cannot be told exactly what we are trying to find out through that machine.

SENATOR PASTORE. Is there anything connected in the hopes of this accelerator that in any way involves the security of the country?

DR. WILSON. No, sir; I do not believe so.

SENATOR PASTORE. Nothing at all?

DR. WILSON. Nothing at all.

SENATOR PASTORE. It has no value in that respect?

DR. WILSON. It only has to do with the respect with which we regard one another, the dignity of men, our love of culture... It has to do with: Are we good painters, good sculptors, great poets? I mean all the things that we really venerate and honor in our country and are patriotic about. In that sense, this new knowledge has all to do with honor and country but it has nothing to do directly with defending our country except to help make it worth defending.

So, why new colliders?

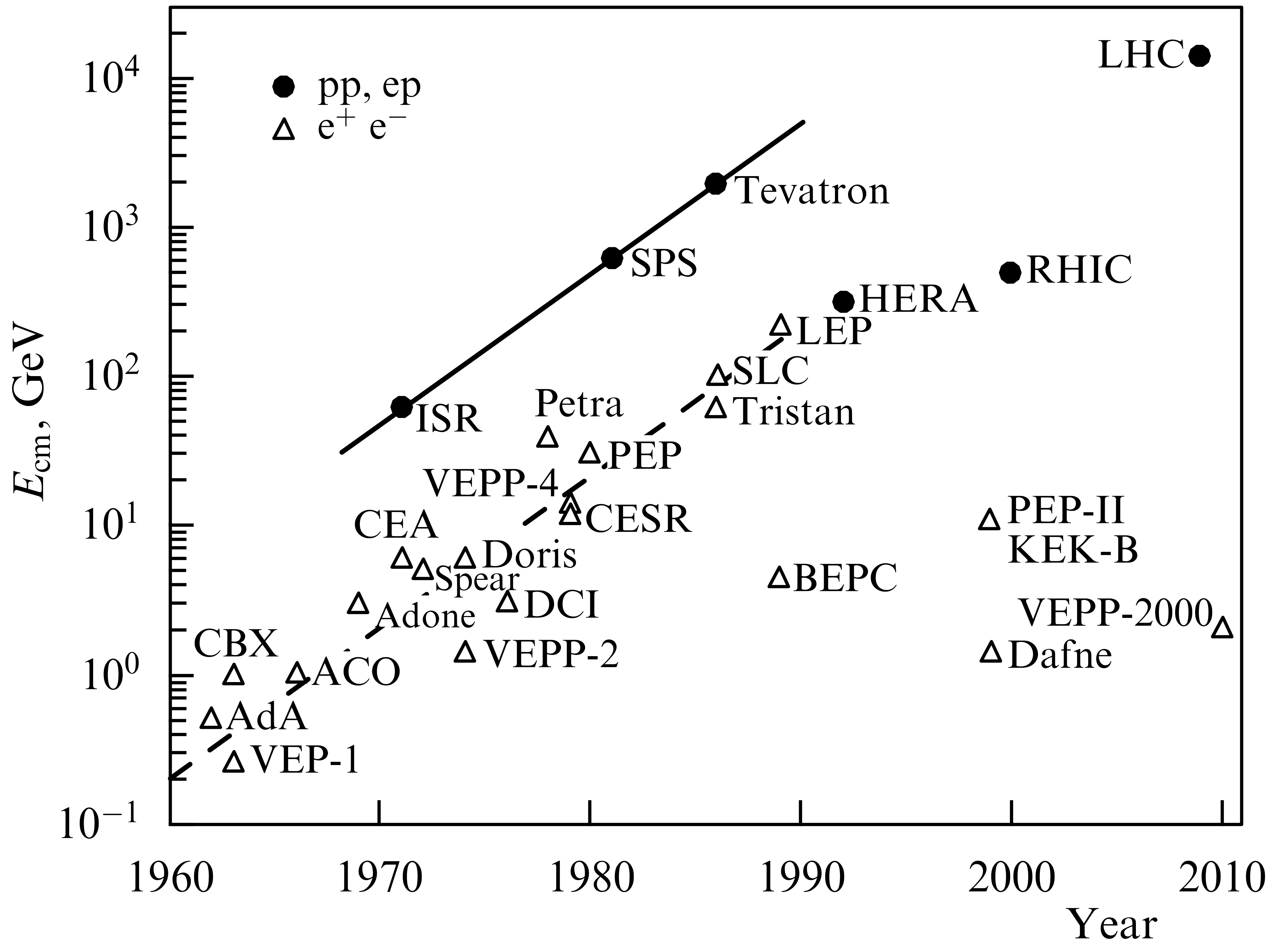
To boldly go where no one has gone before

So, why new colliders?

To boldly go where no one has gone before

But it's important to have a solid physics case as well
(and not just for funding purposes)

Colliders have been increasing in energy since their inception



(V. Shiltsev, 2012)

How high in Energy do we need to go?
What particles and what luminosity do we need?

Snowmass has given us a chance to reflect on this, but also to reflect historically…

HADRON HADRON COLLIDER GROUP*

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I. Introduction

The objective of this group was to make a rough assessment of the characteristics of a hadron-hadron collider which could make it possible to study the 1 TeV mass scale. Since there is very little theoretical guidance for the type of experimental measurements which could illuminate this mass scale, we chose to extend the types of experiments which have been done at the ISR, and which are in progress at the SPS collider to these higher energies. Initially we chose to call these experiments "bellwether experiments" for reasons of convenience. In the absence of any alternative predictions we assumed that the cross sections for these standard experiments could be obtained either by extrapolating perturbative QCD models of hadrons to center of mass energies of 40 TeV or by extrapolating phenomenological parameterization of data obtained from experiments done in the center of mass energy range of 20 to 60 GeV to 40 TeV. For each bellwether we asked up to what mass (or momentum transfer Q) could a significant (> 100) number of events be seen in 10^7 seconds. While it is unlikely

Snowmass 1982

We're *still* trying to implement colliders similar to these 40 years later if you're familiar with FCC or ILC

PHYSICS WITH LINEAR COLLIDERS IN THE TEV CM ENERGY REGION

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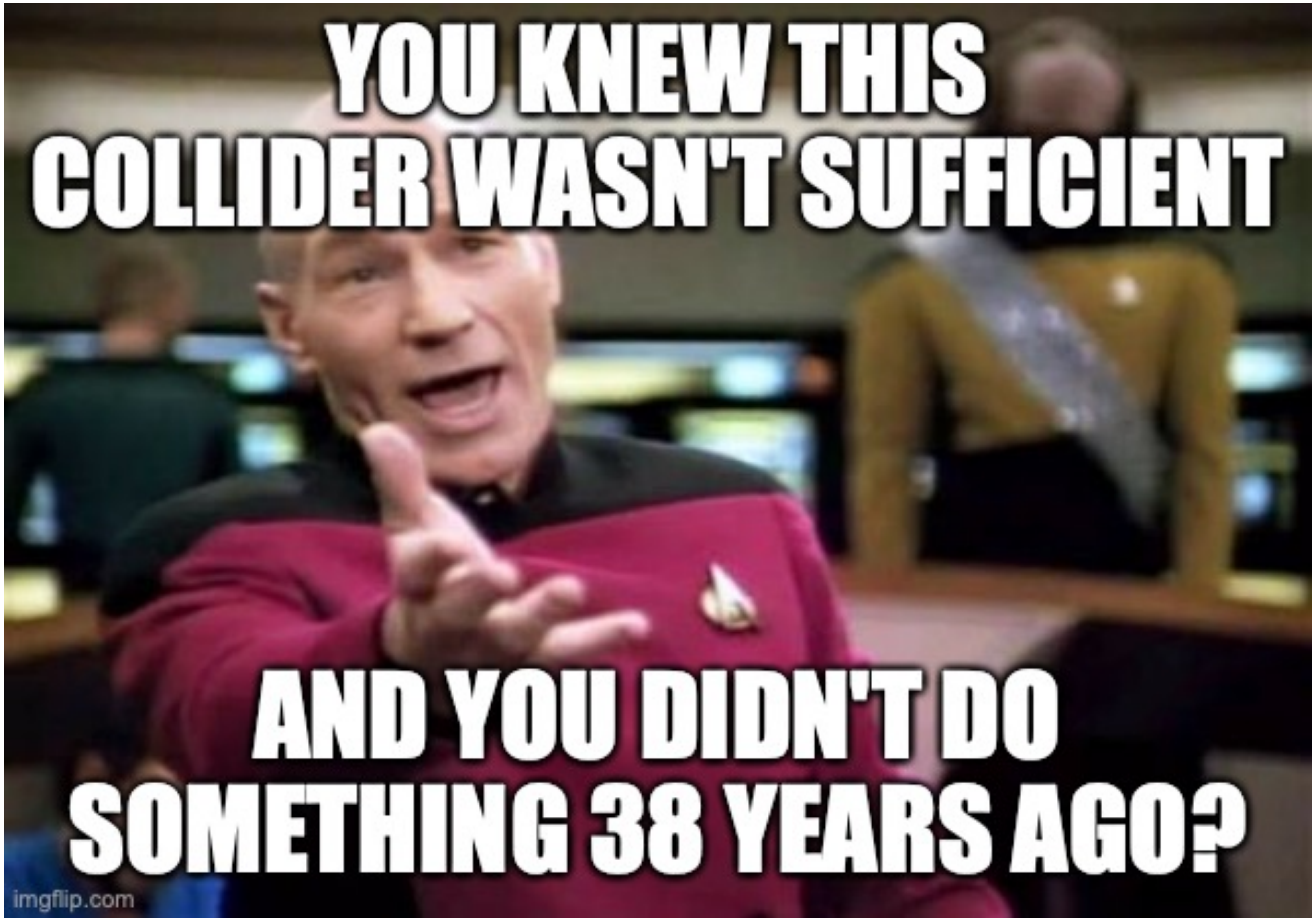
Design Goals

The physics as described in previous sections calls for maximum center-of-mass energies of at least 1000 GeV and possibly above. We will therefore explore the parameters of linear colliders from about 400 GeV up to 2000 GeV. As we mentioned before, the luminosity is limited by the electrical power available to the collider. In this study we have arbitrarily assumed a maximum electrical power of

$$P_{AC} = 100 \text{ MW} \qquad \text{(VII.1)}$$

Snowmass 1982

So this is both a depressing wake up call, but also has nothing really changed in 40 years?



#Snowmass1982 #Snowmass2058

**Don’t let this be our fate, a lot has changed
Experimentally and Theoretically!**

In particular one giant change occurred 10 years!

In fact this was already identified in the *LAST* P5 process which had the following science drivers:

- Use the Higgs boson as a new tool for discovery
- Pursue the physics associated with neutrino mass
- Identify the new physics of dark matter
- Understand cosmic acceleration: dark energy and inflation
- Explore the unknown: new particles, interactions, and physical principles

Foundational Physics Cases

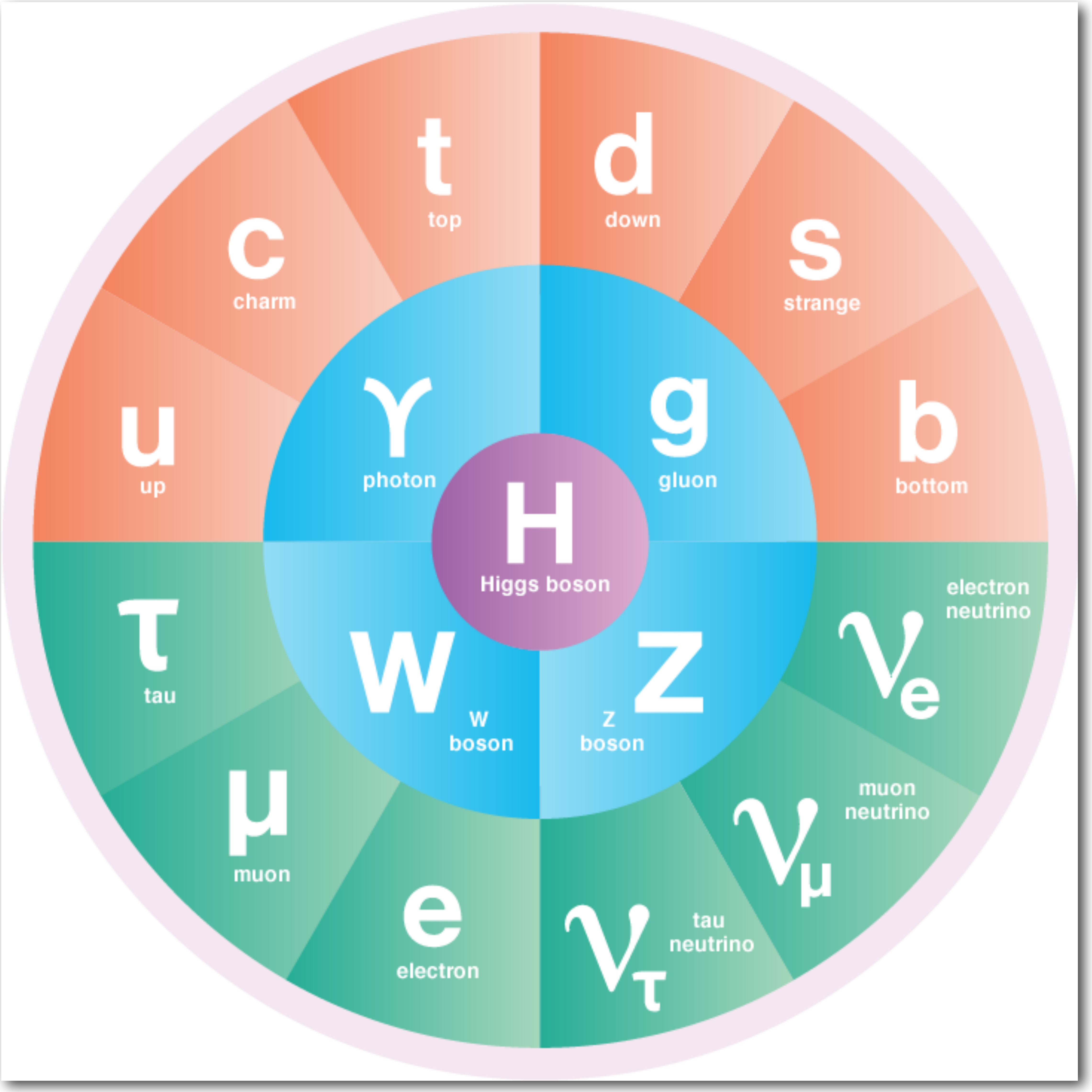
Foundational Physics Cases

BSM/
UNKNOWN

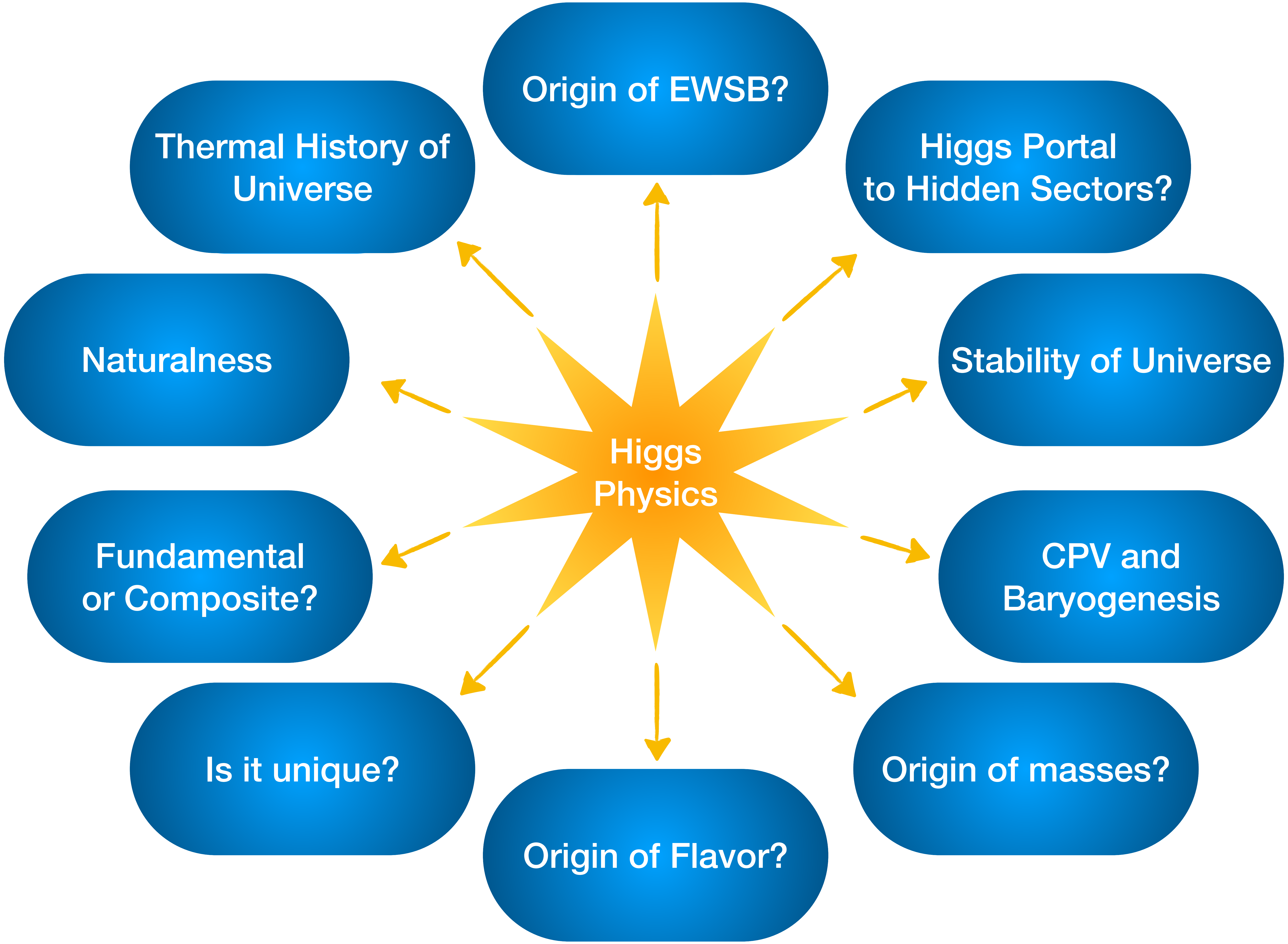
This is important, but is the Higgs enough to carry a collider since BSM is never guaranteed?

Yes.


The Higgs is the most important particle in the Standard Model
CHANGE MY MIND
imgflip.com

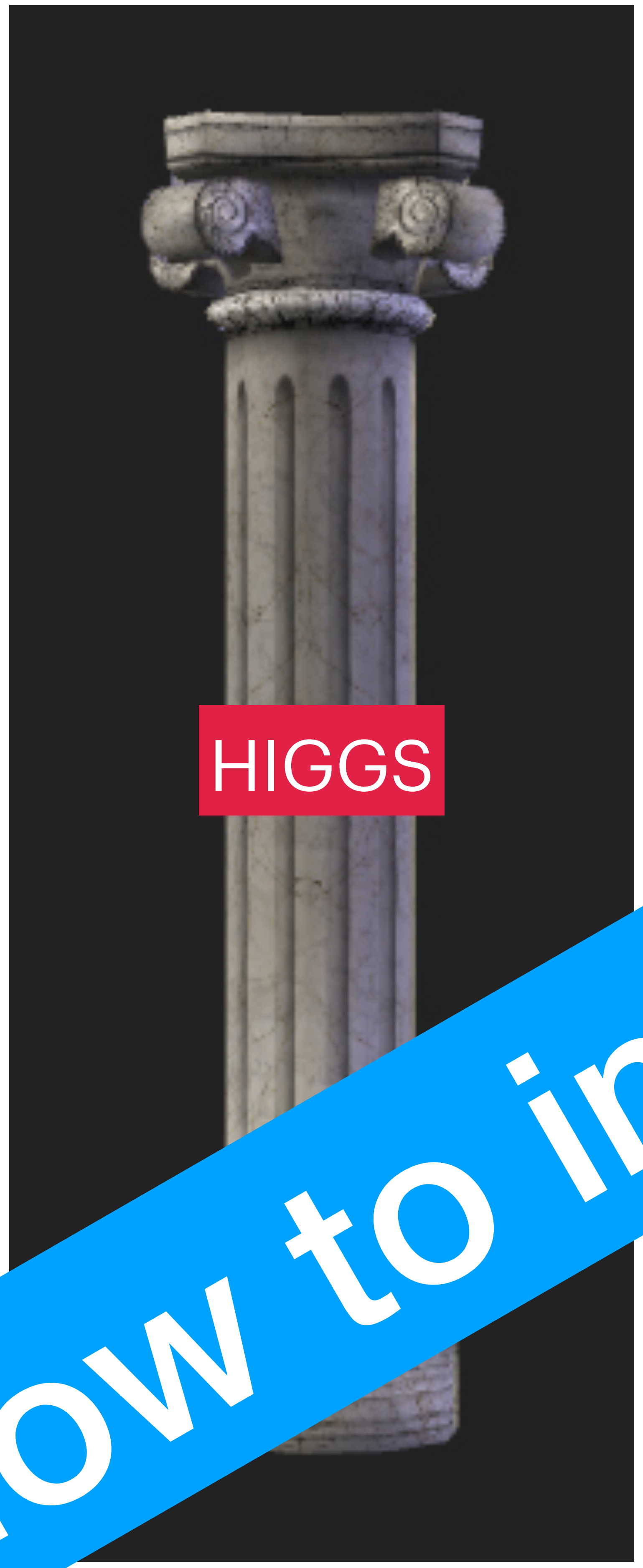


We're used to seeing this centrality of the Higgs figure, but sometimes the Higgs gets a overlooked as just the last piece of the SM



“The Higgs *is* new physics, we’ve never seen anything like it before” N.Arkani-Hamed

Foundational Physics Cases



How to implement this vision?

Foundational Physics Cases

Precision

Energy

A 2 collider solution continuing the path collider physics has been on?

Since then (1990s), the paths of different colliders have diverged: **hadron colliders continued the quest for record high energies** in particle reactions and the LHC was built at CERN, while in parallel highly productive **e+e− colliders called particle factories focused on precise exploration of rare phenomena at** ***much lower energies***.

(V. Shiltsev, F. Zimmermann 2021 Reviews of Modern Physics)

“Higgs Factory” + Energy Frontier Machine

There have been many proposals for how to implement this vision

FCC
hh ee he

CEPC -SPPC

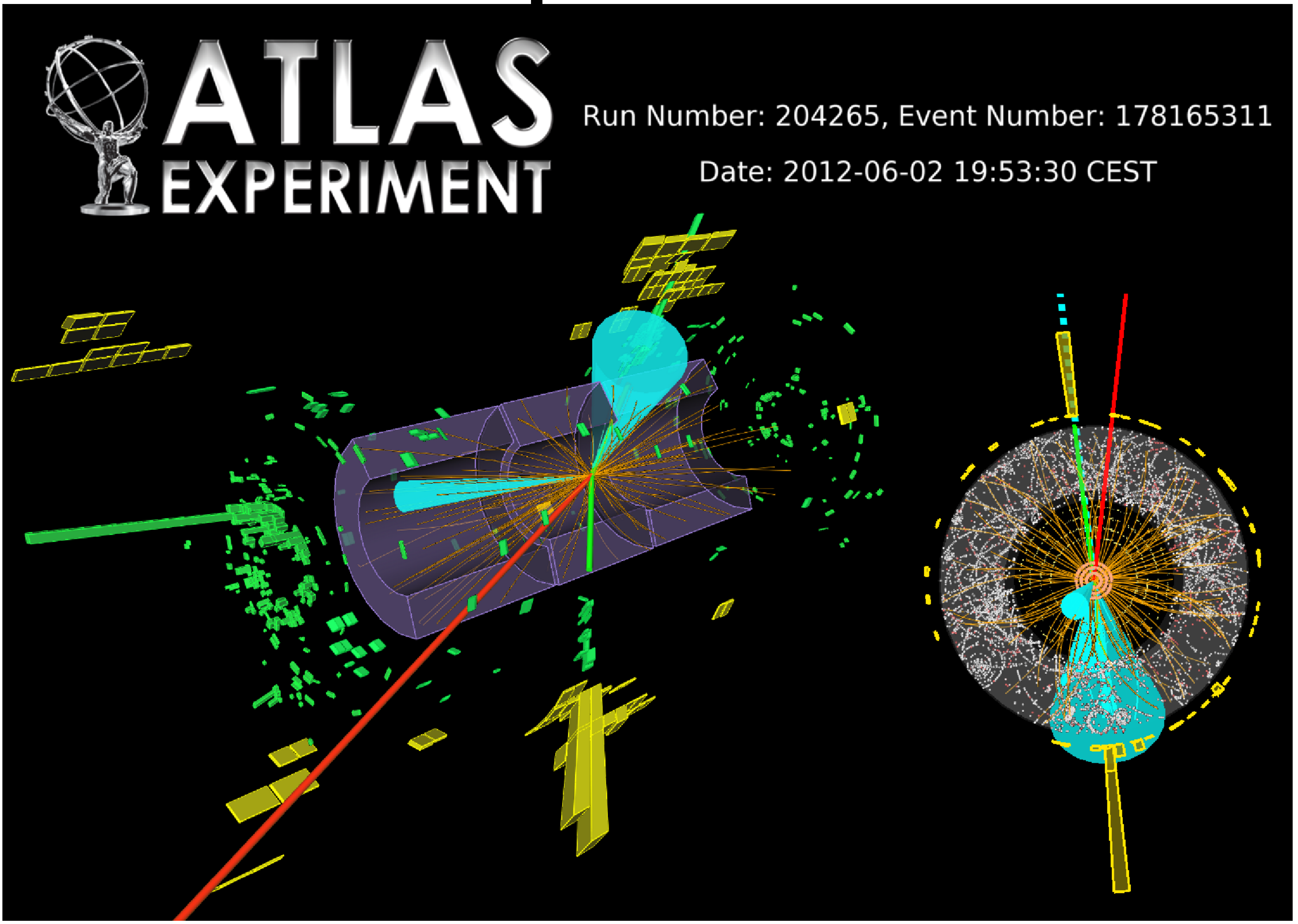
ILC
CLIC

It’s a logical vision

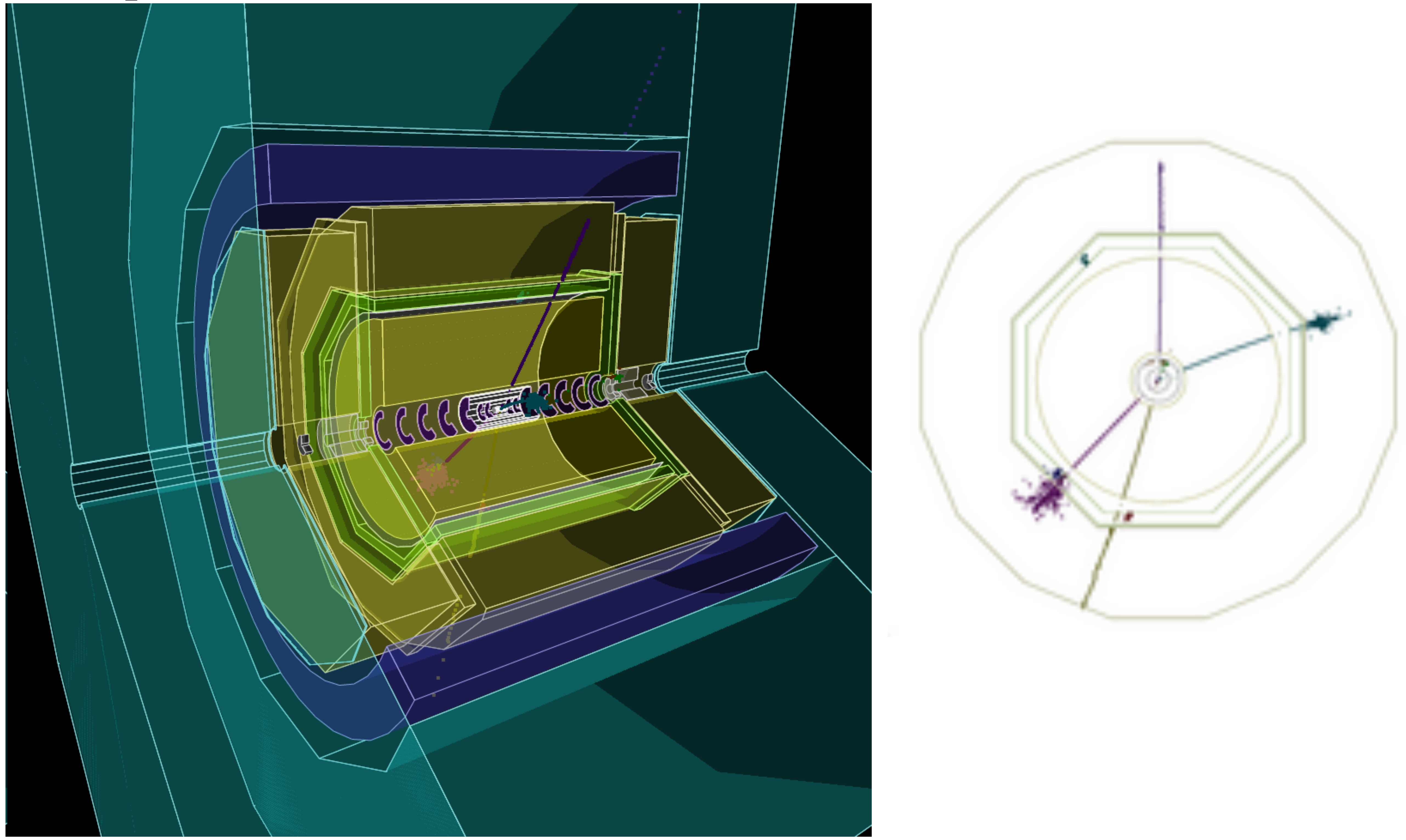
- Lepton colliders collide ***fundamental particles -*** that exploit the full energy and don’t have large QCD backgrounds (but electrons are hard to get high energy and high luminosity)

- Hadron colliders collide ***composite particles -*** that generate large QCD backgrounds and you use a fraction of the energy of beam for physics (but can get to high energy and luminosity)

Visual event level difference - Lepton Colliders are “precision factories”



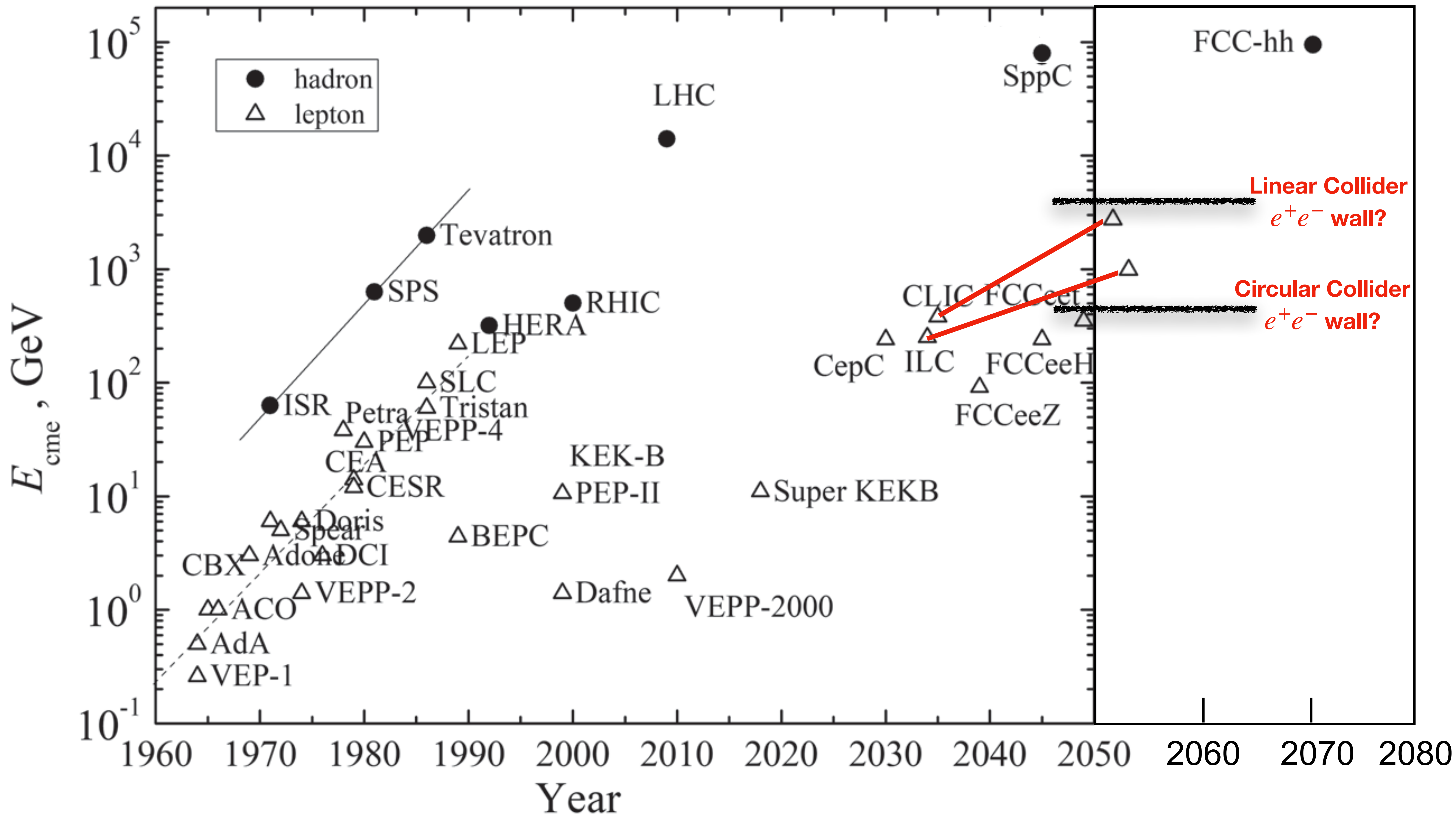
ATLAS VBF $h \rightarrow \tau^+\tau^-$ candidate event



ILC - ILD 250 GeV $e^+e^- \rightarrow Zh \rightarrow \mu^+\mu^-h$

This doesn’t reflect that the size of *backgrounds* are also orders of magnitude smaller as well for leptons, HL-LHC will have 100x more Higgs bosons than ILC but still won’t measure it better for most things!

Extending to future colliders



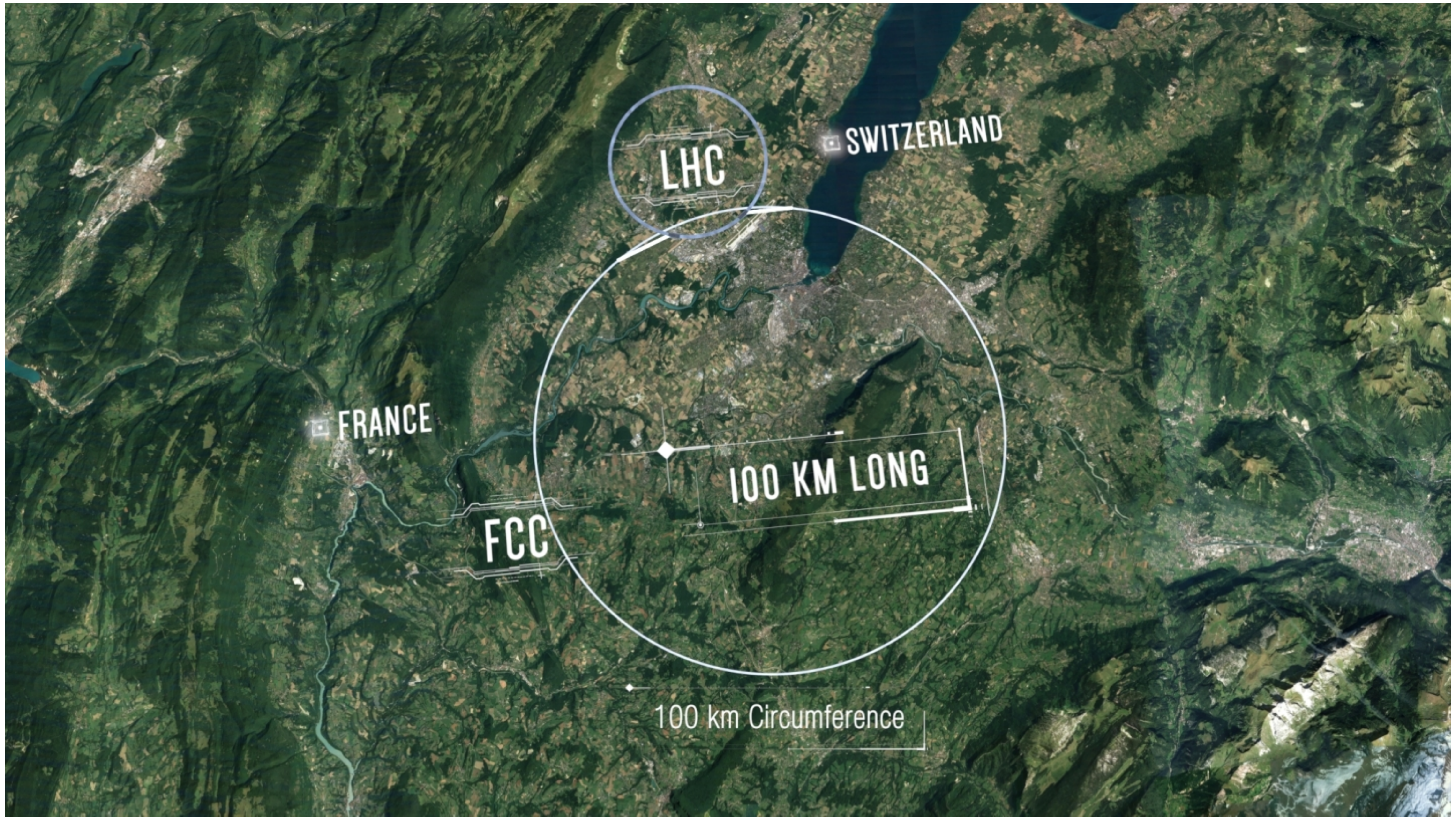
Is this the only option?

Pros and Cons

- We have the technology to build an e+e- Higgs factory today, but we don’t have a project yet…

- Most everyone in this room won’t be alive for a FCC-hh turn on

- Size and sustainability

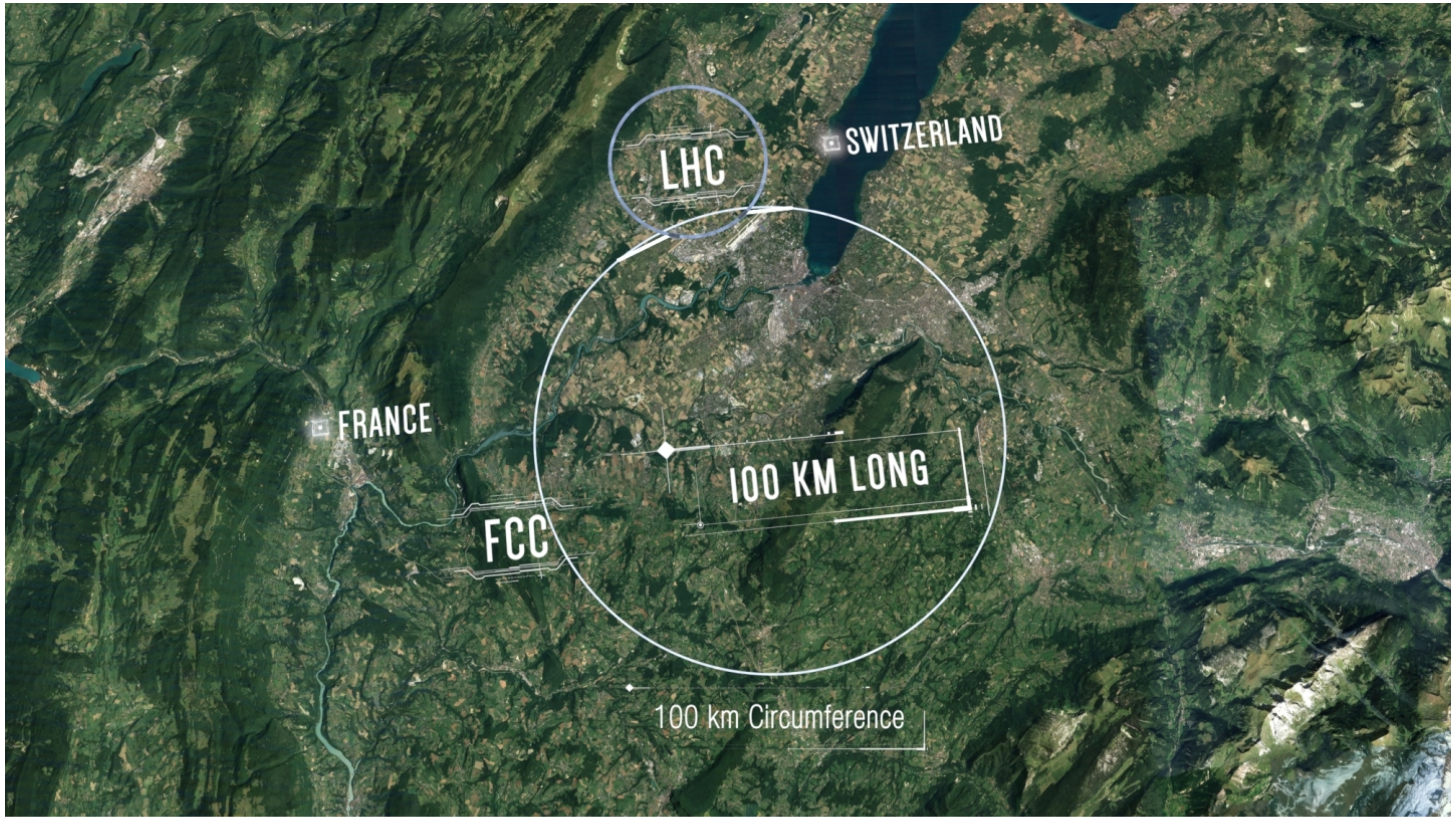


Pros and Cons

- We have the technology to build an e+e- Higgs factory today, but we don't have a project yet… (more ideas C^3, HELEN, LEP3 etc)

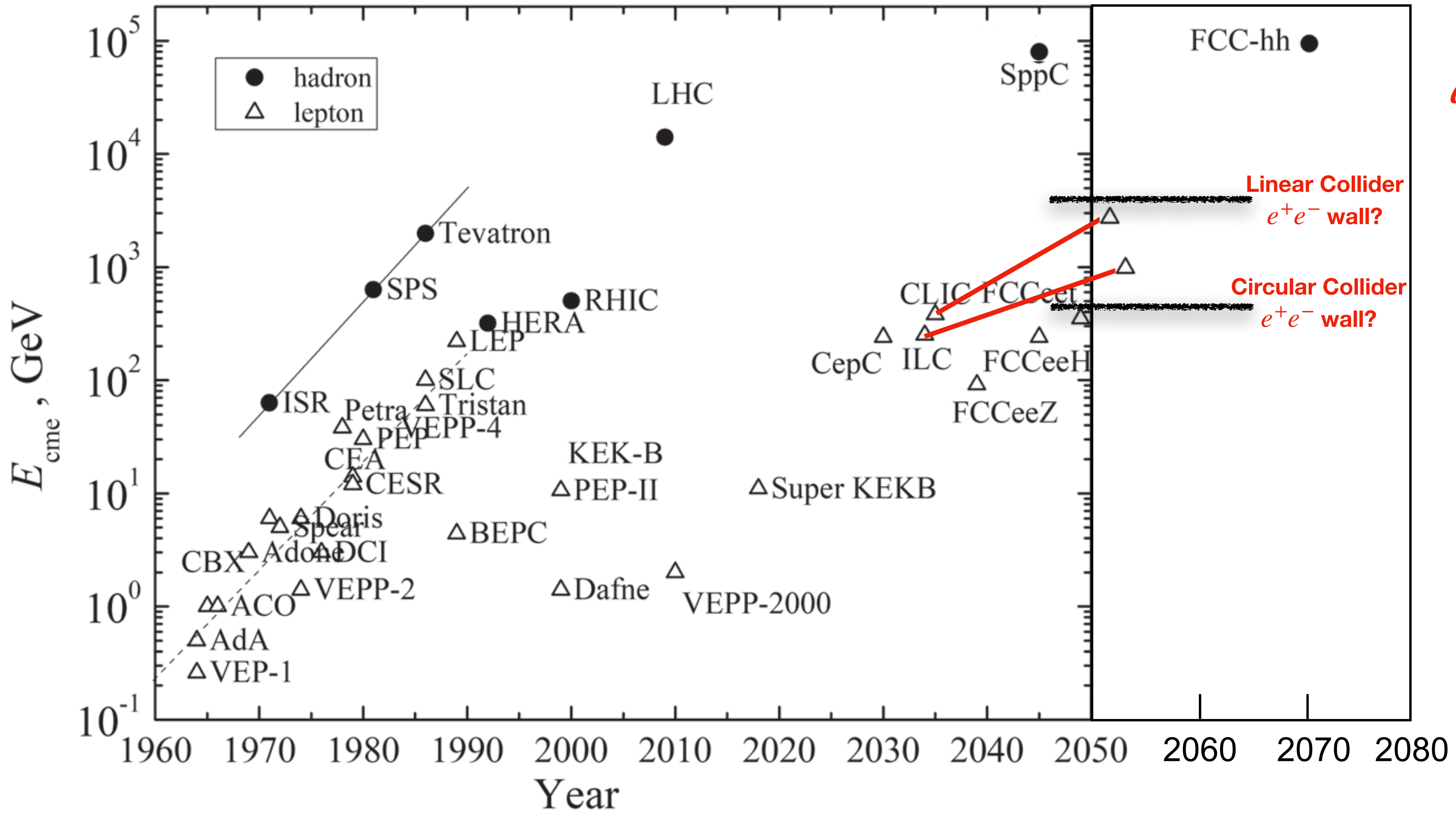
- Most everyone in this room won't be alive for a FCC-hh turn on

- Size and sustainability



Extending to Future Colliders

Are hadrons the only path higher?




MARVEL STUDIOS
WHAT IF...?
LEPTONS COULD REACH HIGHER
ENERGY MORE QUICKLY AND SUSTAINABLY
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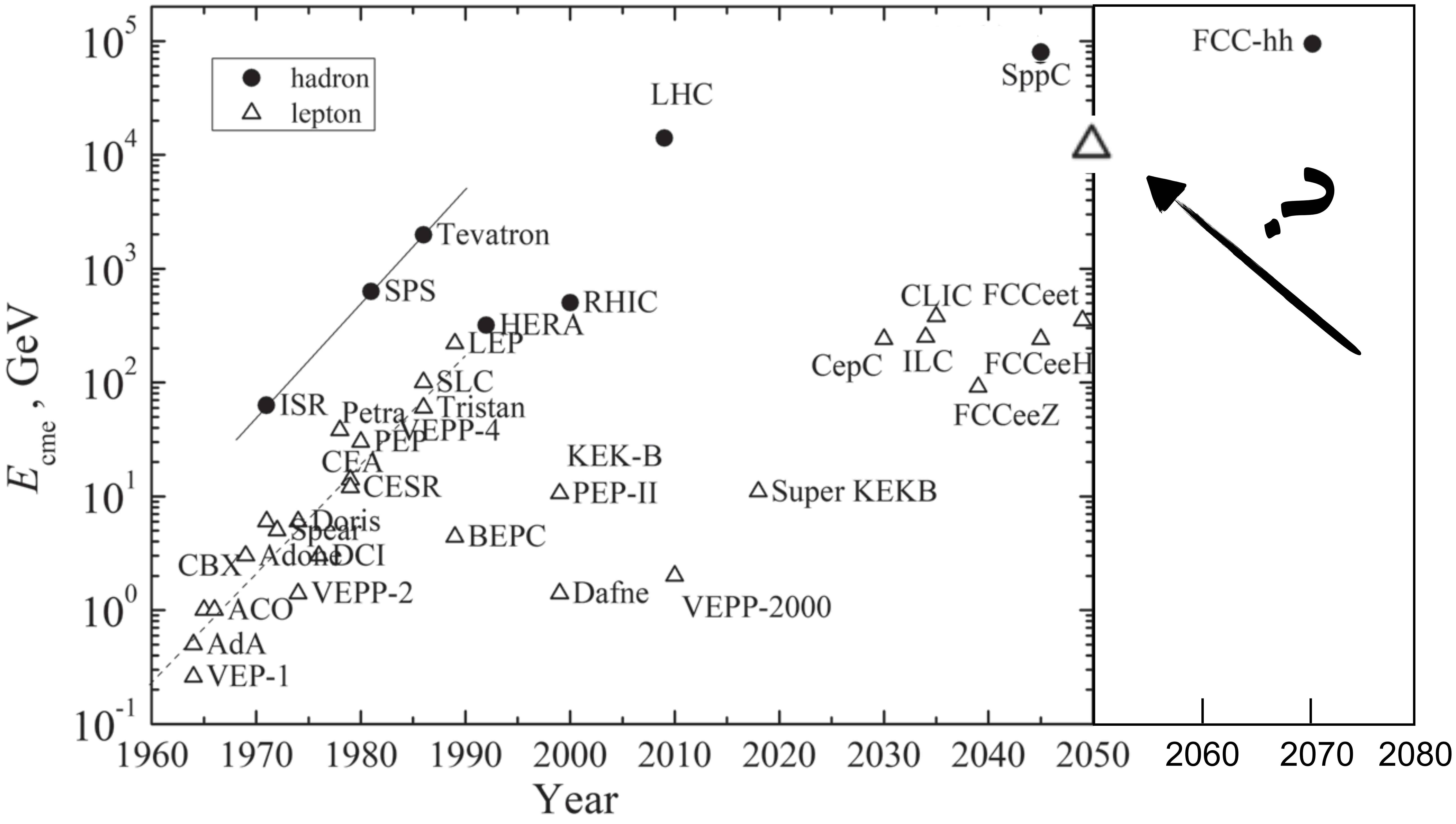
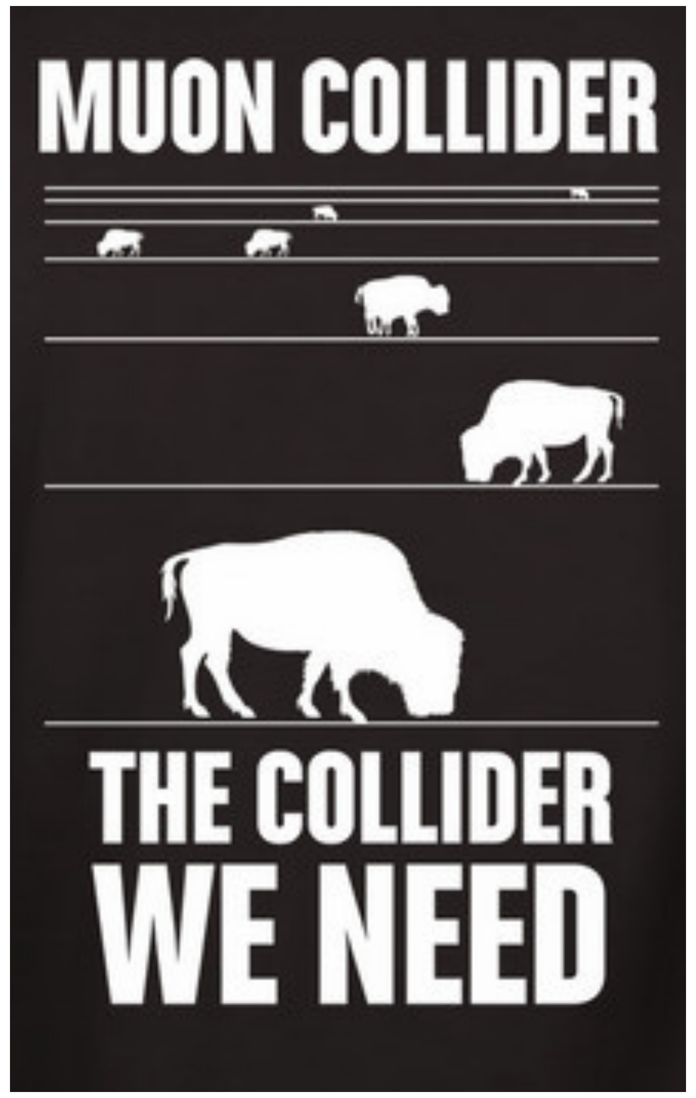
Extending to Future Colliders





Protons vs Muons
extending the Marvel theme

Brute Force

Reach in an intelligent new way

Two immediate questions

- **First question:** *How on earth is this possible?*
  - New technology and R&D is needed for Muon colliders, but no showstoppers have been identified
- **Second question:** How high of scale do we need for a physics case since we are colliding *fundamental* particles not composite ones?
  - We'll see, but a good target is $\mathcal{O}(10)$ TeV 10/ab

So we potentially have multiple paths for colliders: e,μ, p

What are the physics prospects?

Let's start with Higgs factories they go past HL-LHC and shed light on the Higgs, *but there's still a lot to do*!

Energy Frontier Higgs Factory First Stages

EF benchmarks		y_u	y_d	y_s	y_c	y_b	y_t	y_e	y_μ	y_τ	Gauge Couplings: Tree	Gauge Couplings: Loop induced	Higgs Width	λ_3	λ_4
	LHC/HL-LHC	$> \mathcal{O}(1)$	$> \mathcal{O}(1)$	$> \mathcal{O}(1)$	$\mathcal{O}(1)$	$\mathcal{O}(.1)$	$\mathcal{O}(.1)$	$> \mathcal{O}(1)$	$\mathcal{O}(.1)$	$\mathcal{O}(.1)$	$\mathcal{O}(.01)$	$\mathcal{O}(.01)$	$\mathcal{O}(.1)$	$\mathcal{O}(1)$	$> \mathcal{O}(1)$
Higgs Factory + HL-LHC	ILC/C^3 250	$> \mathcal{O}(1)$	$> \mathcal{O}(1)$	$> \mathcal{O}(1)$ *	$\mathcal{O}(.01)$	$\mathcal{O}(.01)$	$\mathcal{O}(.01)$	$> \mathcal{O}(1)$	$\mathcal{O}(.1)$	$\mathcal{O}(.01)$	$\lesssim \mathcal{O}(10^{-3})$	$\mathcal{O}(.01)$	$\mathcal{O}(.01)$	$\mathcal{O}(1)$	$> \mathcal{O}(1)$
Higgs Factory + HL-LHC	CLIC 380	$> \mathcal{O}(1)$	$> \mathcal{O}(1)$	?	$\mathcal{O}(.1)$	$\mathcal{O}(.01)$	$\mathcal{O}(.01)$	$> \mathcal{O}(1)$	$\mathcal{O}(.1)$	$\mathcal{O}(.01)$	$\mathcal{O}(.01)$	$\mathcal{O}(.01)$	$\mathcal{O}(.01)$	$\mathcal{O}(1)$	$> \mathcal{O}(1)$
Higgs Factory + HL-LHC	FCC-ee 240	$> \mathcal{O}(1)$	$> \mathcal{O}(1)$	?	$\mathcal{O}(.01)$	$\mathcal{O}(.01)$	$\mathcal{O}(.01)$	$> \mathcal{O}(1)$	$\mathcal{O}(.1)$	$\mathcal{O}(.01)$	$\lesssim \mathcal{O}(10^{-3})$	$\mathcal{O}(.01)$	$\mathcal{O}(.01)$	$\mathcal{O}(1)$	$> \mathcal{O}(1)$
Higgs Factory + HL-LHC	CEPC 240	$> \mathcal{O}(1)$	$> \mathcal{O}(1)$	?	$\mathcal{O}(.01)$	$\mathcal{O}(.01)$	$\mathcal{O}(.01)$	$> \mathcal{O}(1)$	$\mathcal{O}(.1)$	$\mathcal{O}(.01)$	$\lesssim \mathcal{O}(10^{-3})$	$\mathcal{O}(.01)$	$\mathcal{O}(.01)$	$\mathcal{O}(1)$	$> \mathcal{O}(1)$

Order of Magnitude for Fractional Uncertainty $\lesssim \mathcal{O}(10^{-3})$ $\mathcal{O}(.01)$ $\mathcal{O}(.1)$ $\mathcal{O}(1)$ $> \mathcal{O}(1)$? **No study Beyond HL-LHC**

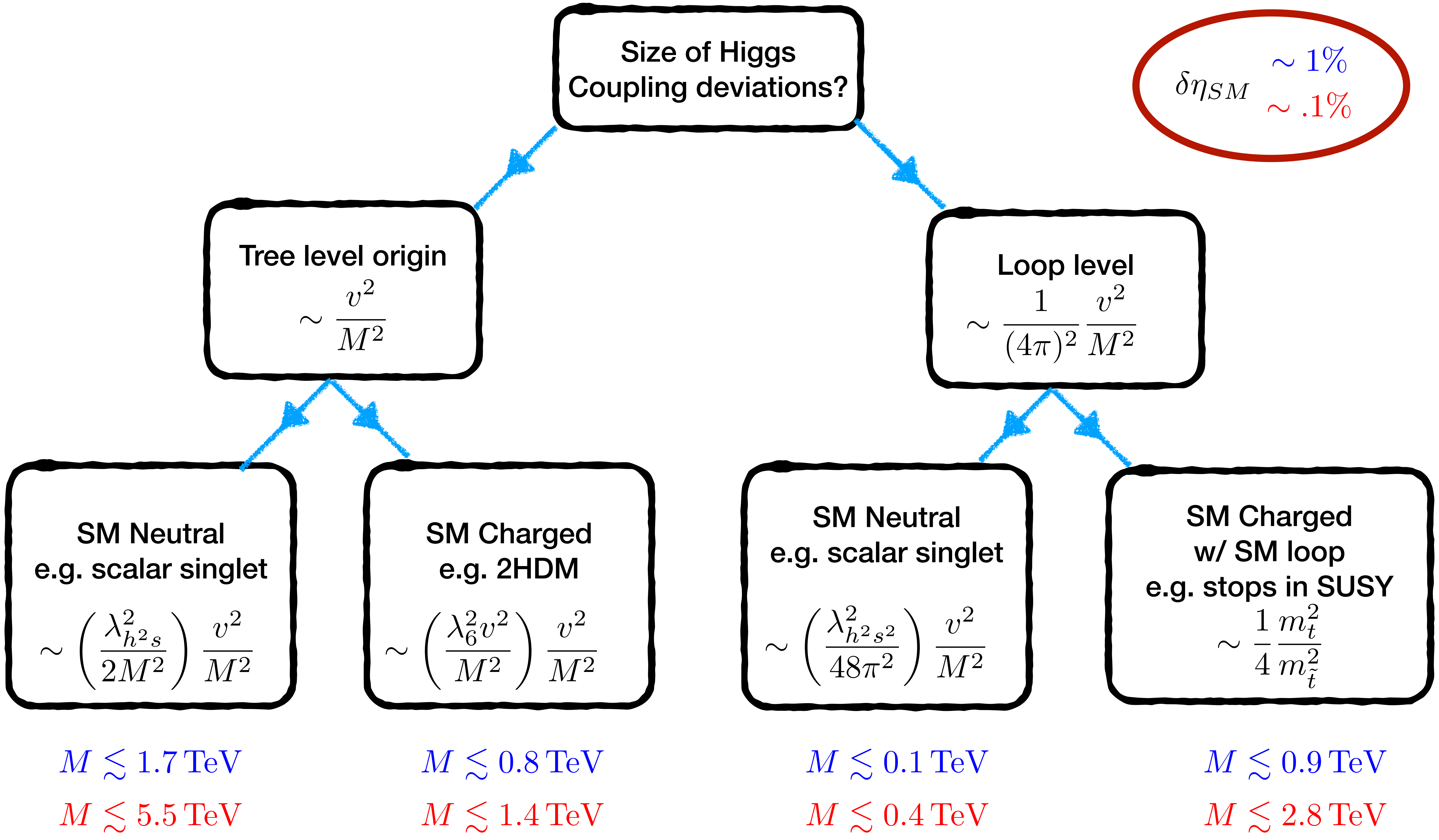
Higgs Factories are *also* discovery machines!

Especially considering they are EW Factories as well (e.g. TeraZ or GigaZ etc)

Remember that *any* deviation implies new physics

Standard Model balances on arbitrary Higgs Sector

But what scale can it imply?



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

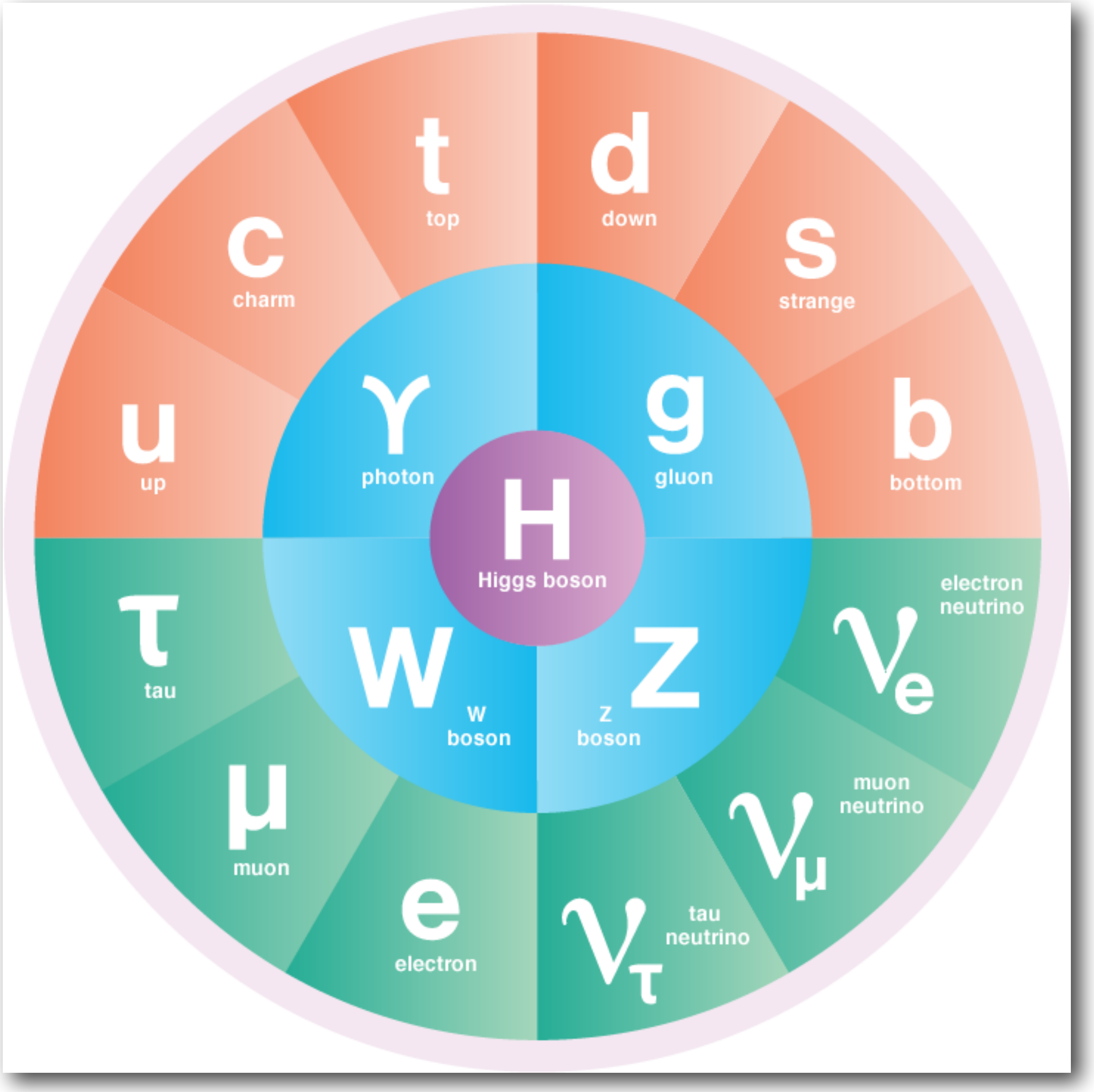
Higgs factories probe the few TeV scale

This sets two possible scales

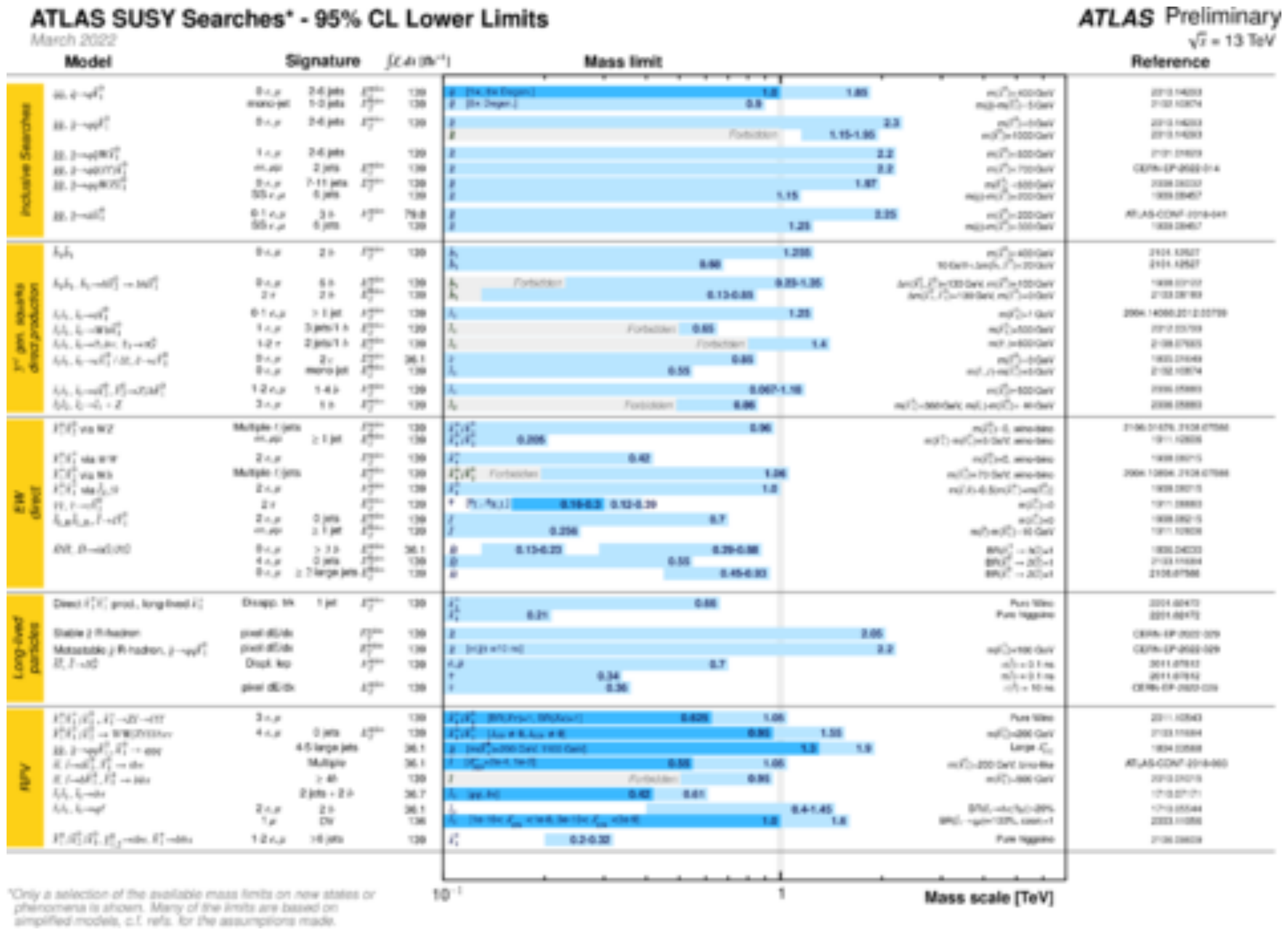
1) What we'd need to test deviations

2) What we'd want to push beyond

High Energy Collider Scales



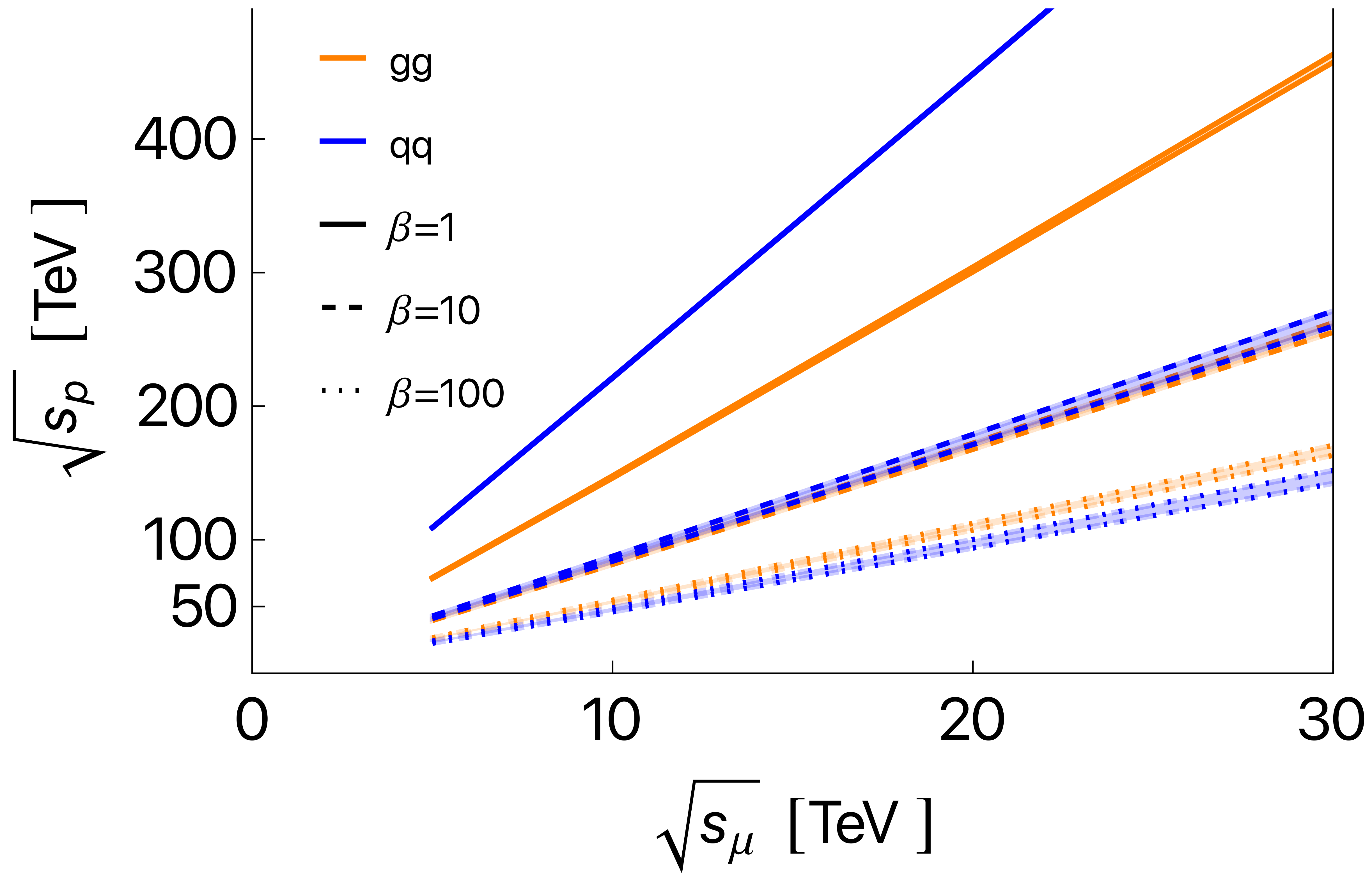
Higgs factories set a scale whether deviation is observed or not



No clear signs of BSM directly at LHC thus far

Reaching the 10+ TeV scale lets you go beyond(or test) the LHC and Higgs Factories

Protons vs Muons



A 10 TeV muon collider can easily go beyond 100 TeV pp depending on the process (and vice versa)

Rule of thumb in $2 \to 2$

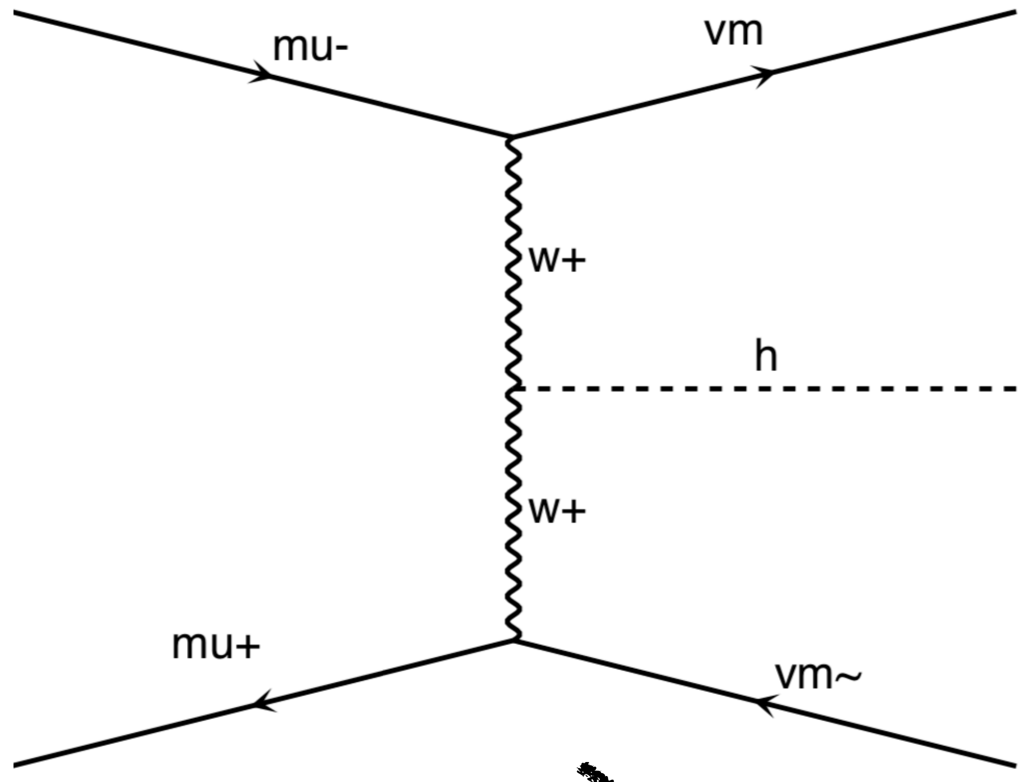
Discovery reach to $M \sim \dfrac{\sqrt{s}}{2}$

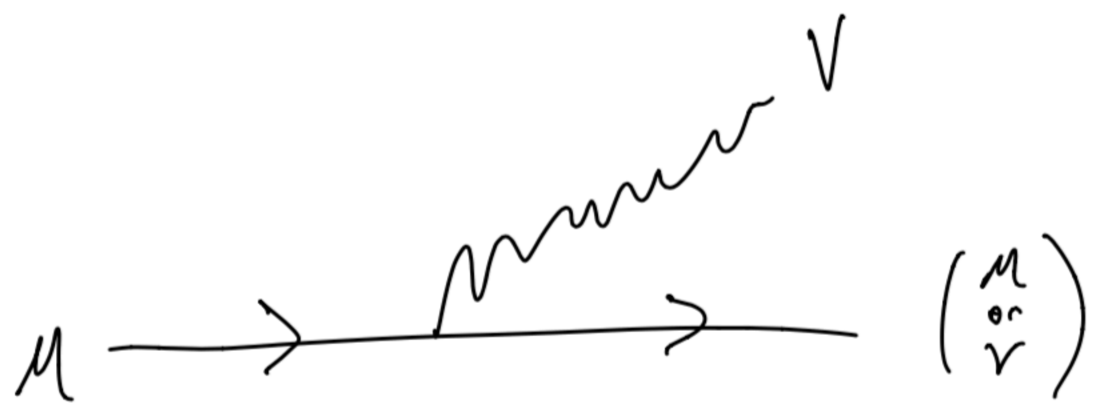
10 TeV ***is not the limit*** - just the study point for what is thought to be doable on paper already

Part of R&D is finding how high it can be pushed

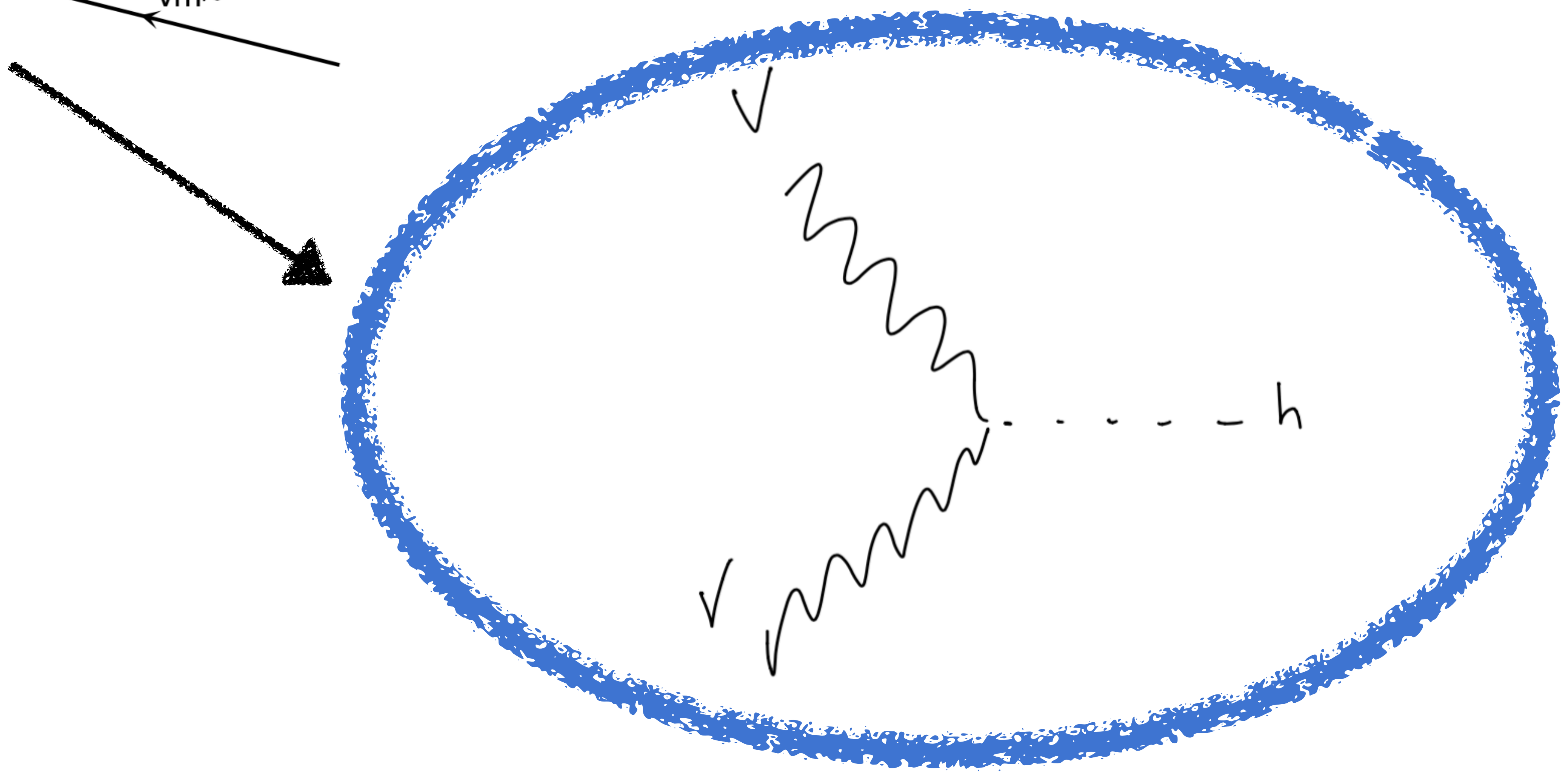
High Energy Muon Colliders
are more than just muon collisions

Can think of this as VV to H fusion, with VV initial states (PDF like for hadron colliders)





Vector Boson really wants to be soft or collinear....



This allows for an *enhanced* Higgs and EW production at high E since $\sigma \sim \log E_{CM}^2$

High energy colliders allow us to push our understanding of the Higgs even further

Energy Frontier Benchmarks Integrated Staging

	EF benchmarks	y_u	y_d	y_s	y_c	y_b	y_t	y_e	y_μ	y_τ	Gauge Couplings: Tree	Gauge Couplings: Loop induced	Higgs Width	λ_3	λ_4
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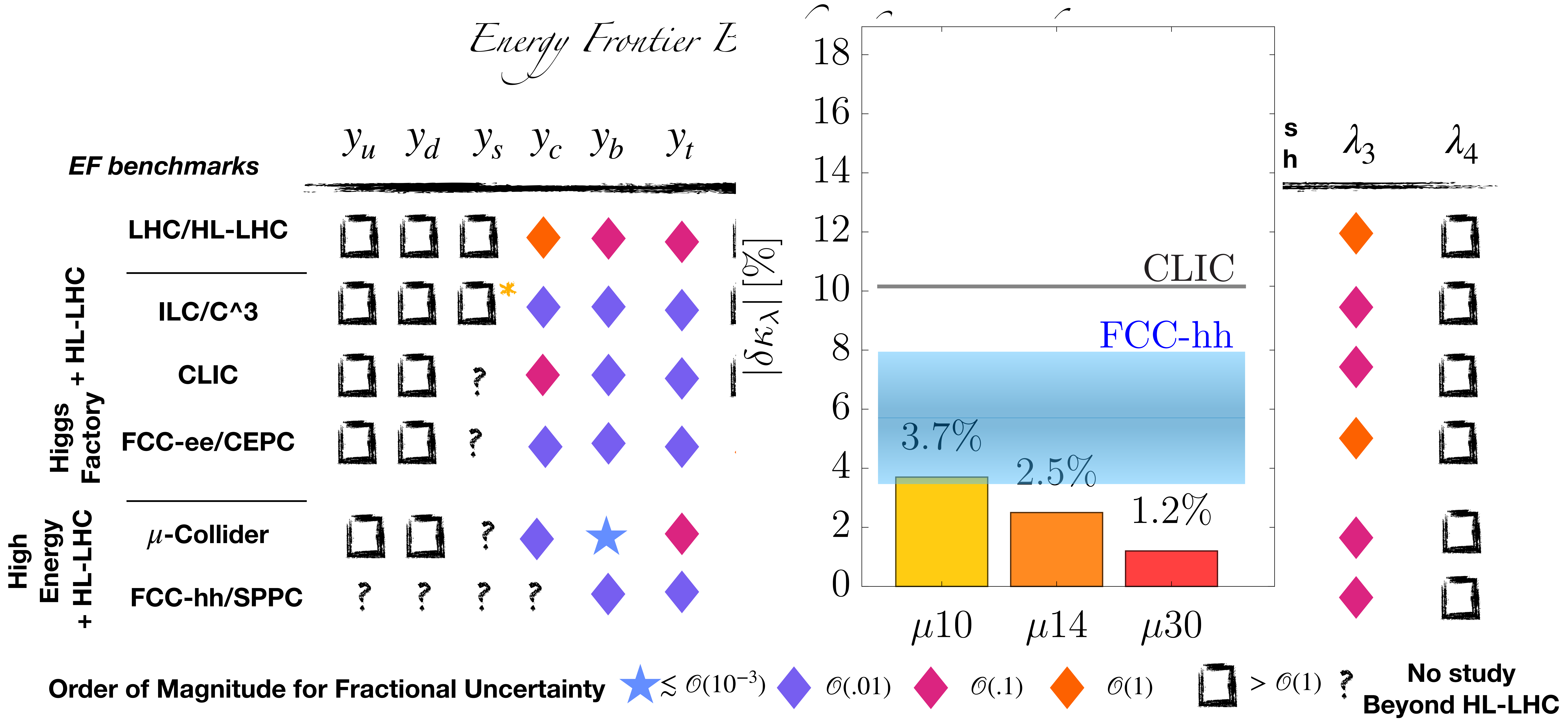
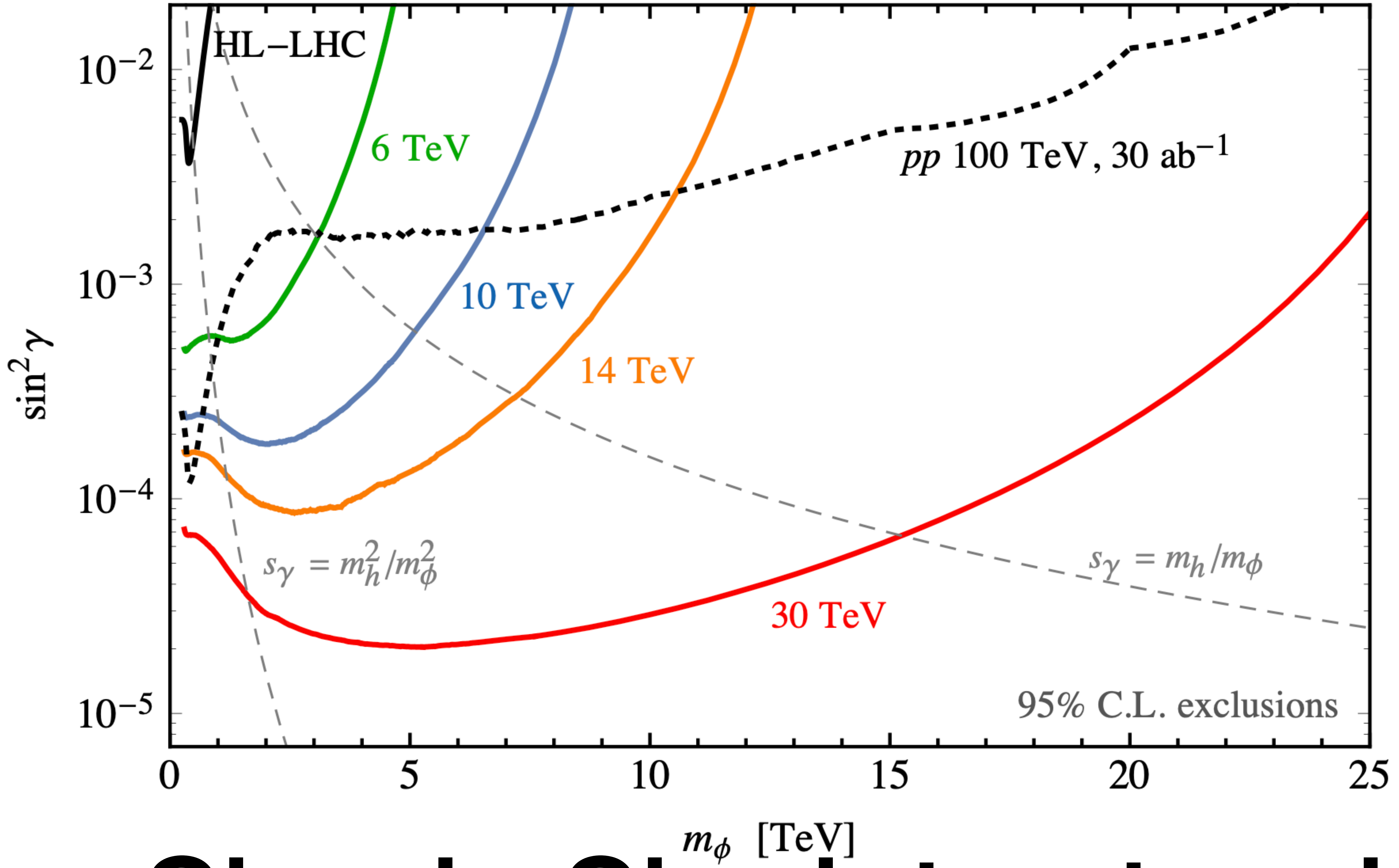
Higgs Factory + HL-LHC	ILC/C^3	$>\mathcal{O}(1)$	$>\mathcal{O}(1)$	$>\mathcal{O}(1)$ *	$\mathcal{O}(.01)$	$\mathcal{O}(.01)$	$\mathcal{O}(.01)$	$>\mathcal{O}(1)$	$\mathcal{O}(.1)$	$\mathcal{O}(.01)$	$\lesssim\mathcal{O}(10^{-3})$	$\mathcal{O}(.01)$	$\mathcal{O}(.01)$	$\mathcal{O}(.1)$	$>\mathcal{O}(1)$
Higgs Factory + HL-LHC	CLIC	$>\mathcal{O}(1)$	$>\mathcal{O}(1)$	?	$\mathcal{O}(.1)$	$\mathcal{O}(.01)$	$\mathcal{O}(.01)$	$>\mathcal{O}(1)$	$\mathcal{O}(.1)$	$\mathcal{O}(.01)$	$\mathcal{O}(.01)$	$\mathcal{O}(.01)$	$\mathcal{O}(.01)$	$\mathcal{O}(.1)$	$>\mathcal{O}(1)$
Higgs Factory + HL-LHC	FCC-ee/CEPC	$>\mathcal{O}(1)$	$>\mathcal{O}(1)$	?	$\mathcal{O}(.01)$	$\mathcal{O}(.01)$	$\mathcal{O}(.01)$	$\mathcal{O}(1)$	$\mathcal{O}(.1)$	$\mathcal{O}(.01)$	$\lesssim\mathcal{O}(10^{-3})$	$\mathcal{O}(.01)$	$\mathcal{O}(.01)$	$\mathcal{O}(1)$	$>\mathcal{O}(1)$
High Energy + HL-LHC	μ-Collider	$>\mathcal{O}(1)$	$>\mathcal{O}(1)$	?	$\mathcal{O}(.01)$	$\lesssim\mathcal{O}(10^{-3})$	$\mathcal{O}(.1)$	$>\mathcal{O}(1)$	$\mathcal{O}(.01)$	$\mathcal{O}(.01)$	$\lesssim\mathcal{O}(10^{-3})$	$\mathcal{O}(.01)$	$\mathcal{O}(.01)$	$\mathcal{O}(.1)$	$>\mathcal{O}(1)$
High Energy + HL-LHC	FCC-hh/SPPC	?	?	?	?	$\mathcal{O}(.01)$	$\mathcal{O}(.01)$	?	$\mathcal{O}(.01)$	$\mathcal{O}(.01)$	$\lesssim\mathcal{O}(10^{-3})$	$\lesssim\mathcal{O}(10^{-3})$	?	$\mathcal{O}(.1)$	$>\mathcal{O}(1)$

Order of Magnitude for Fractional Uncertainty ★ $\lesssim\mathcal{O}(10^{-3})$ ◆ $\mathcal{O}(.01)$ ◆ $\mathcal{O}(.1)$ ◆ $\mathcal{O}(1)$ □ $>\mathcal{O}(1)$? **No study Beyond HL-LHC**

High energy colliders allow us to push our understanding of the Higgs even further



High energy muons let us push forwards numerous BSM directions as well!

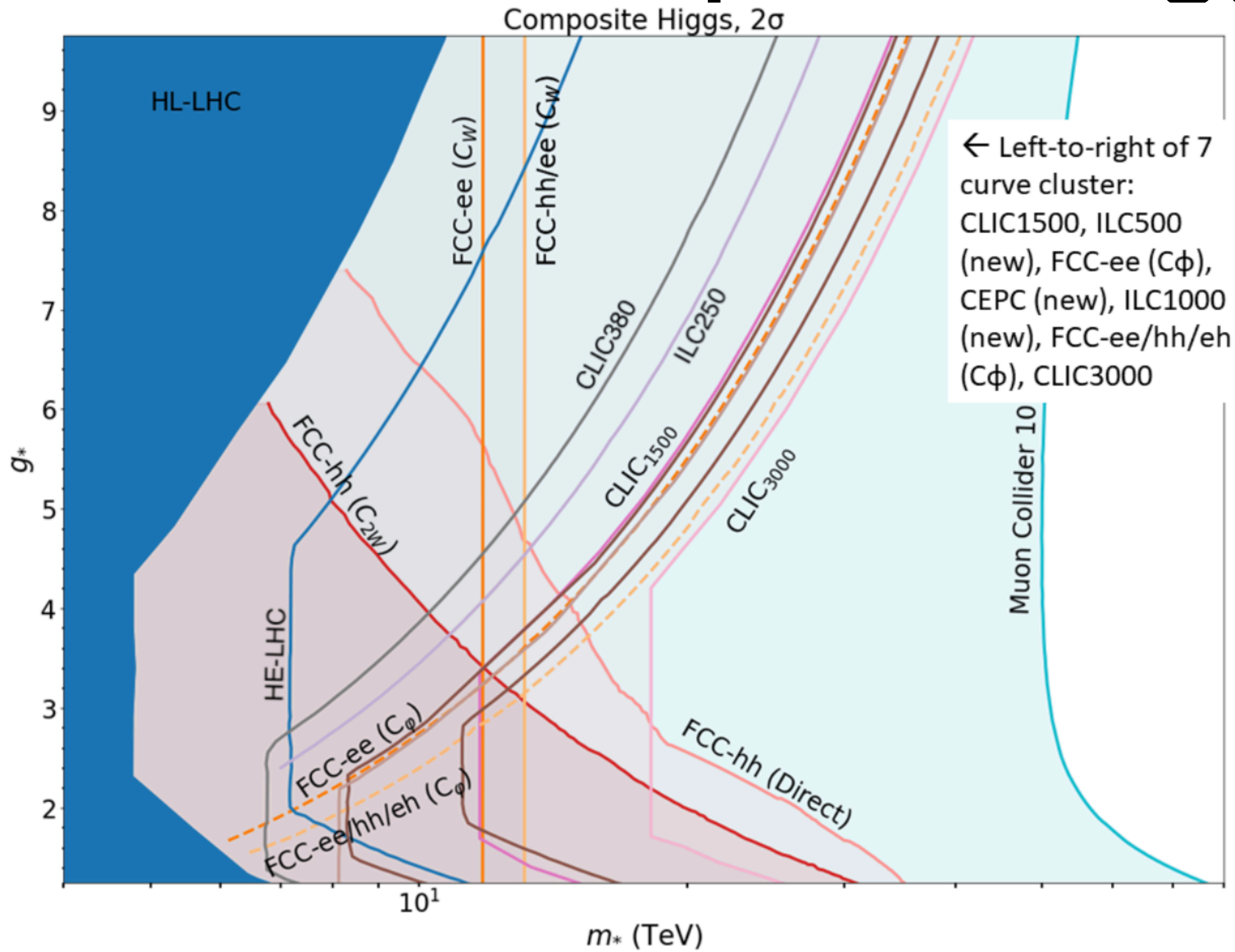


10 TeV very complementary with FCC-hh, 30 TeV blows away other ideas

Can map to Neutral Naturalness Reach/Dark Sectors

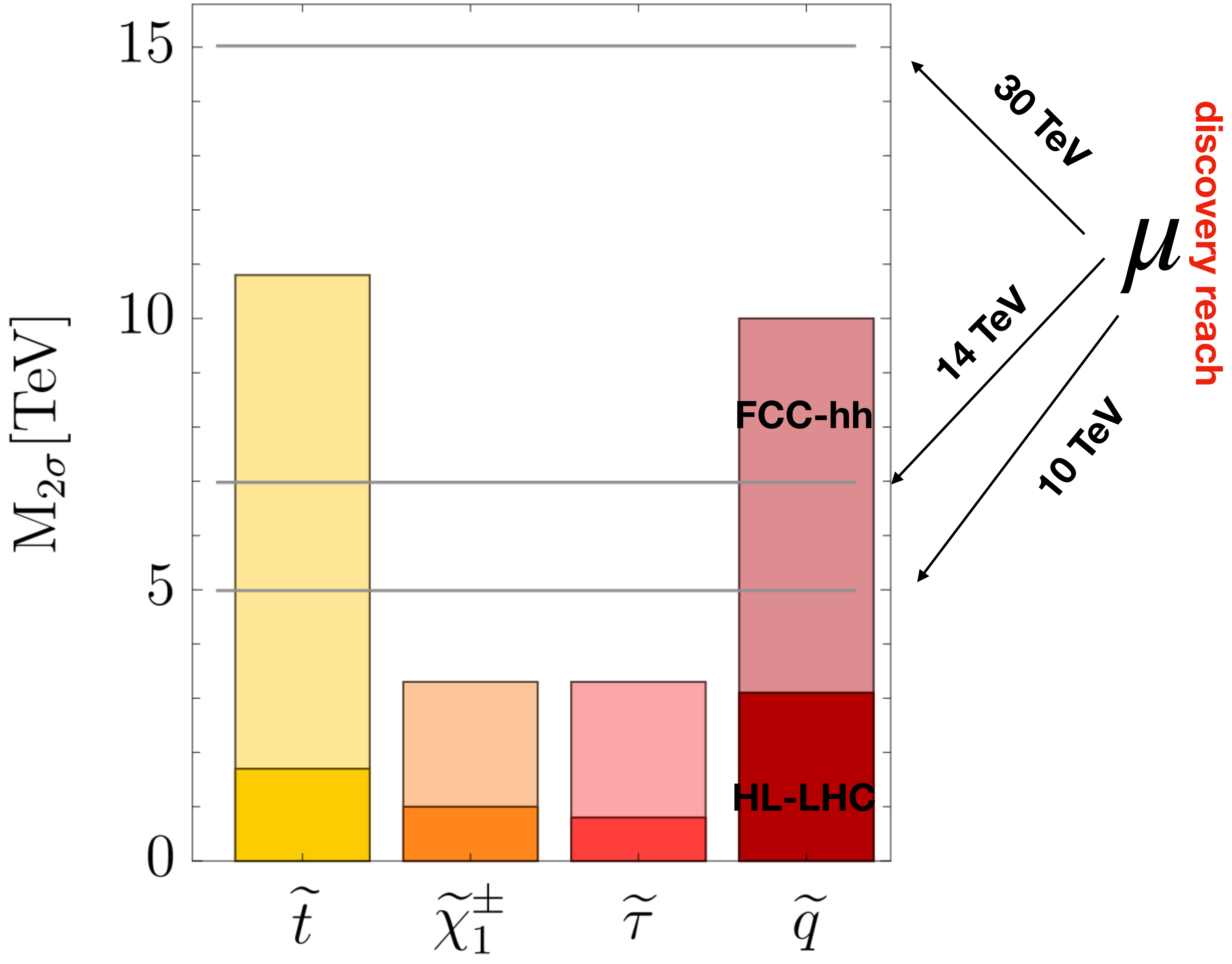
Simple Singlet extension of SM

Composite Higgs



A 10 TeV High Energy Muon Collider extends significantly beyond FCC-hh

Naturalness and Supersymmetry Example

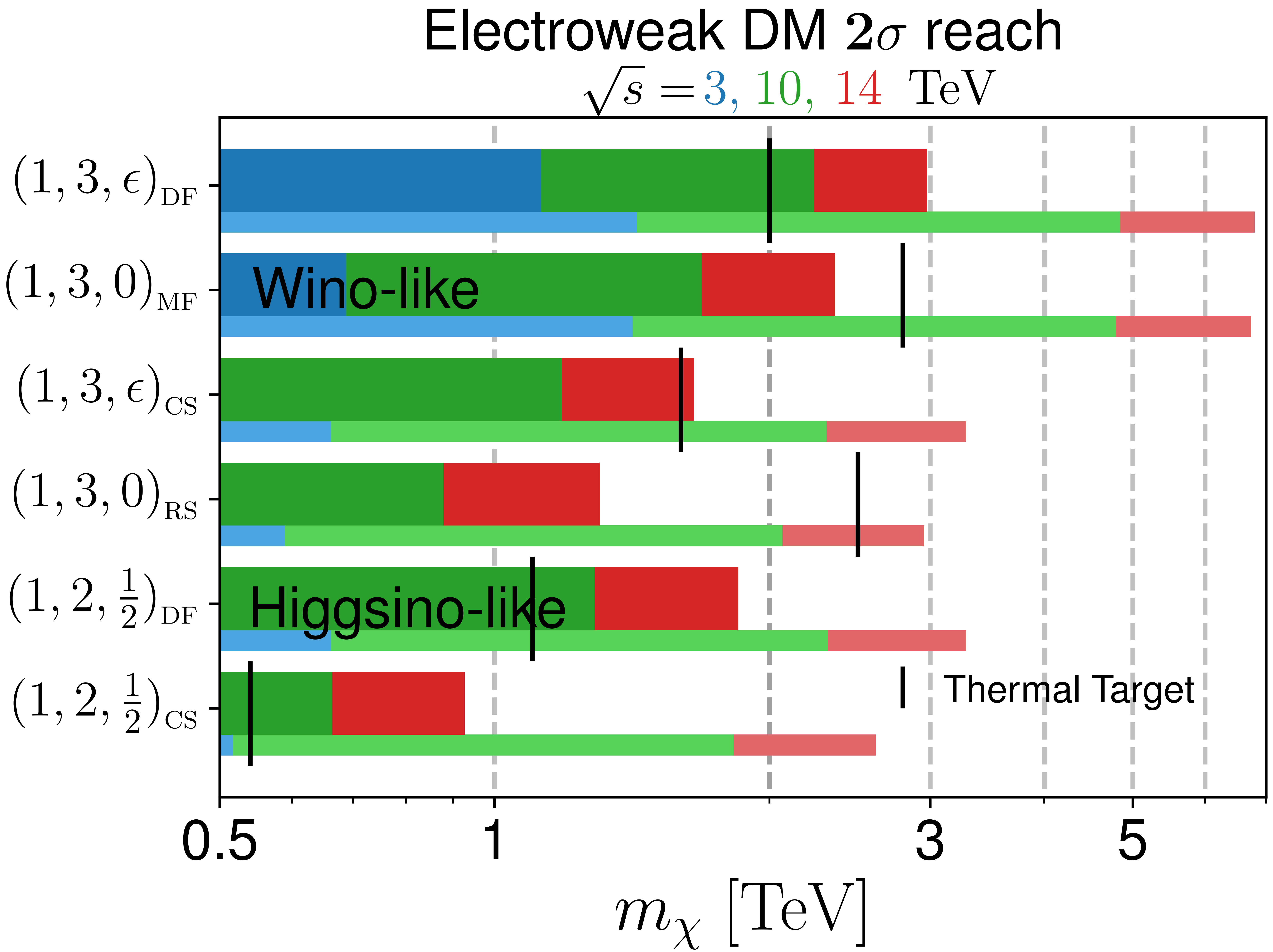


The Higgs at 125 GeV already suggested the SUSY scale was high, e.g. Stops ~ 10 TeV

In this case FCC-hh is superior to 10 TeV for Stop Searches, but for 20 TeV muons the case would be reversed

In realistic models - EWinos/ Sleptons tend to be TeV scale which is WELL within reach of a 10 TeV muon collider

WIMP DM - some cases colliders are better suited!



High Energy Muon colliders $\geq$10 TeV can discover the canonical targets!

I’ve given a lightning overview of physics prospects at future colliders

Lot of options for e+e- Higgs factories

Now we have 2 viable options for the highest energy protons and muons

The muon collider is particularly attractive

It could finally allow us to break the precision/energy dichotomy that we've been stuck with for decades now

It does it in the smallest most sustainable package *and* naturally dovetails with DUNE and a potential Fermilab vision of the future (also could be done at CERN IMCC)

Not surprisingly this matches well with the Snowmass Energy Frontier Vision

Resource needs and plan for the five year period starting 2025:

1. Prioritize HL-LHC physics program,
2. Establish a targeted e^+e^- Higgs Factory detector R&D program for US participation in a global collider,
3. Develop an initial design for a first stage Tev-scale Muon Collider in the US, with pre-CDR document at the end of this period,
4. Support critical detector R&D towards EF multi-TeV Colliders.

Resource needs and plan for the five year period starting 2030:

1. Continue strong support for the HL-LHC physics program,
2. Support construction of a e^+e^- Higgs Factory,
3. Demonstrate principal risk mitigation and deliver CDR for a first stage TeV-scale muon collider.

Resource needs and plan after 2035:

1. Evaluate continuing HL-LHC physics program to the conclusion of archival measurements,
2. Begin and support the physics program of the Higgs Factories,
3. Demonstrate readiness to construct and deliver TDR for a first-stage TeV-scale muon collider, 4. Ramp up funding support for detector R&D for EF multi-TeV Colliders.

Conclusions

- Higgs factories are ready and we should pursue them wherever we can ASAP - They have the most obvious pressing physics case to study the *most* unique particle in universe we know, the Higgs

- Energy Frontier colliders allow us to understand *even more* about the Higgs and are a genuine BSM microscope to the shortest distances but it needs R&D investment now (but there's no reason the horizon couldn't be 20 years not 50 years in the case of the muon collider)

Conclusions

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And now we wait for P5 and NAS panels to see what the US contributions could be!

Extra slides

High Energy Lepton Collider Physics Case

- Most all the work in the last 2 years for the physics case is based on a **10+ TeV muon collider** - there is an ongoing integrated design study and an ability to do full simulation. Lots of excitement due to CERN LDG accelerator roadmap showing ~20 years to start given R&D support

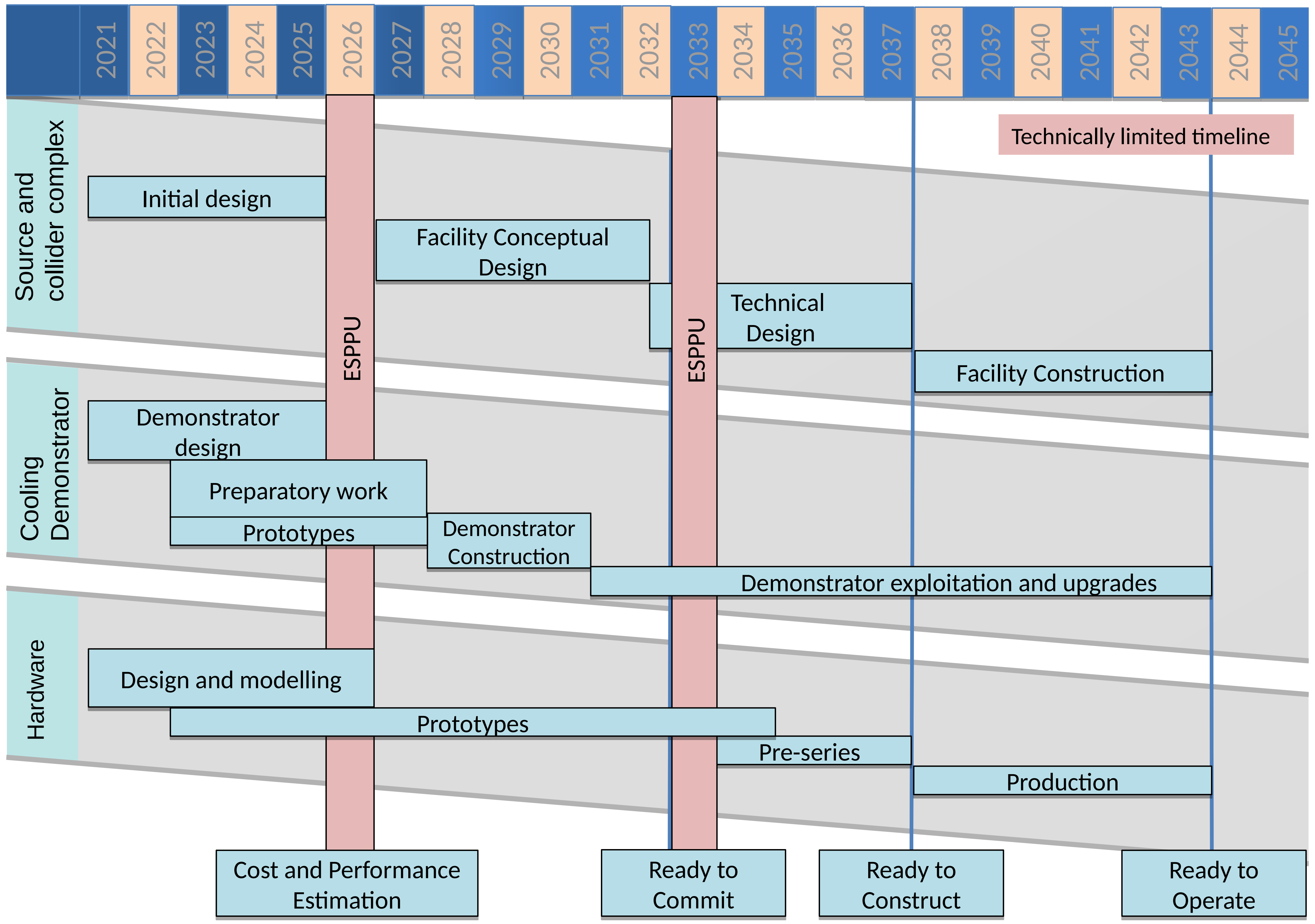


Fig. 5.3: A technically limited timeline for the muon collider R&D programme.

If an electron based WFA collider has:

e^+e^-

Same energy

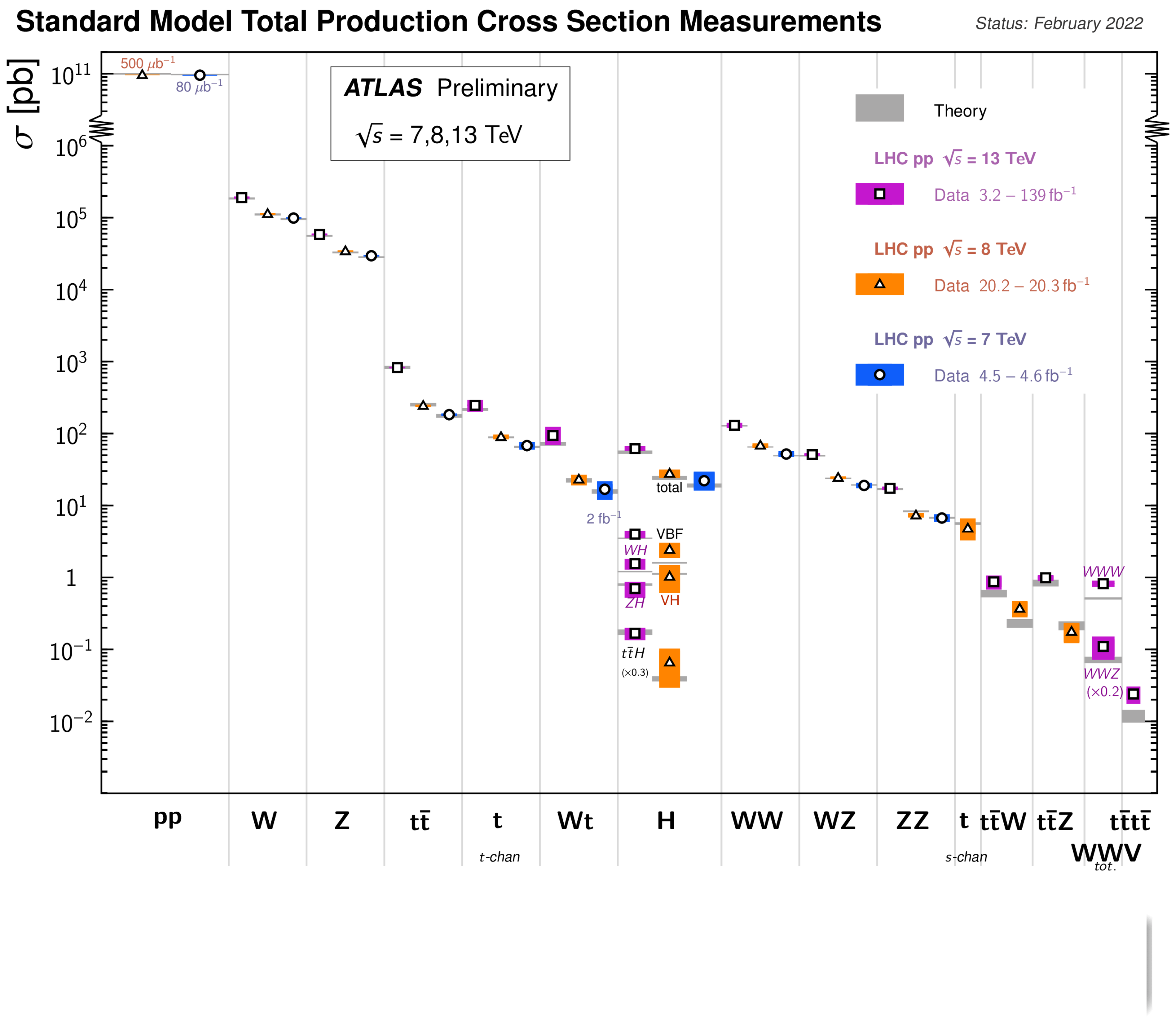
Same luminosity

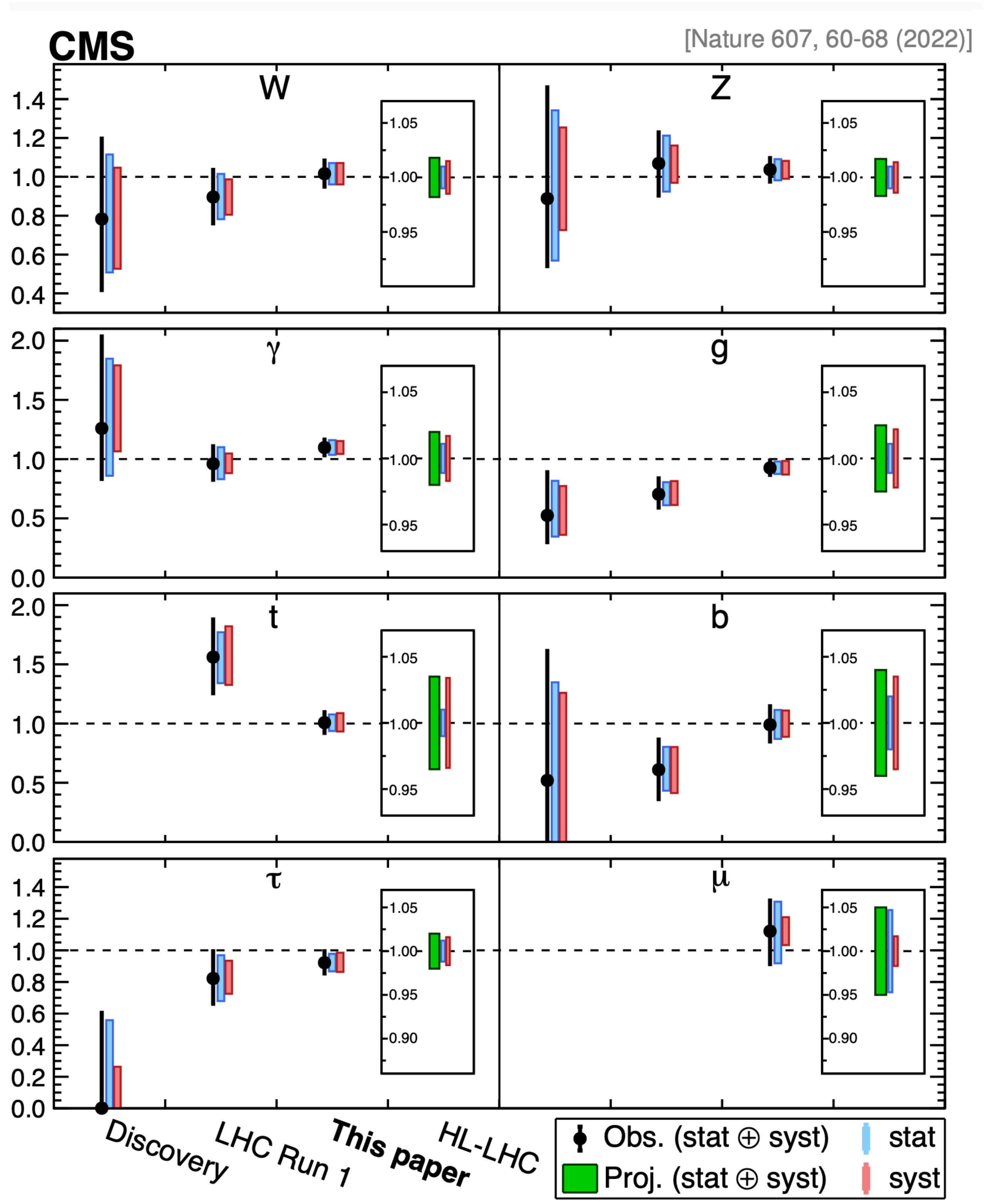
Same beam quality

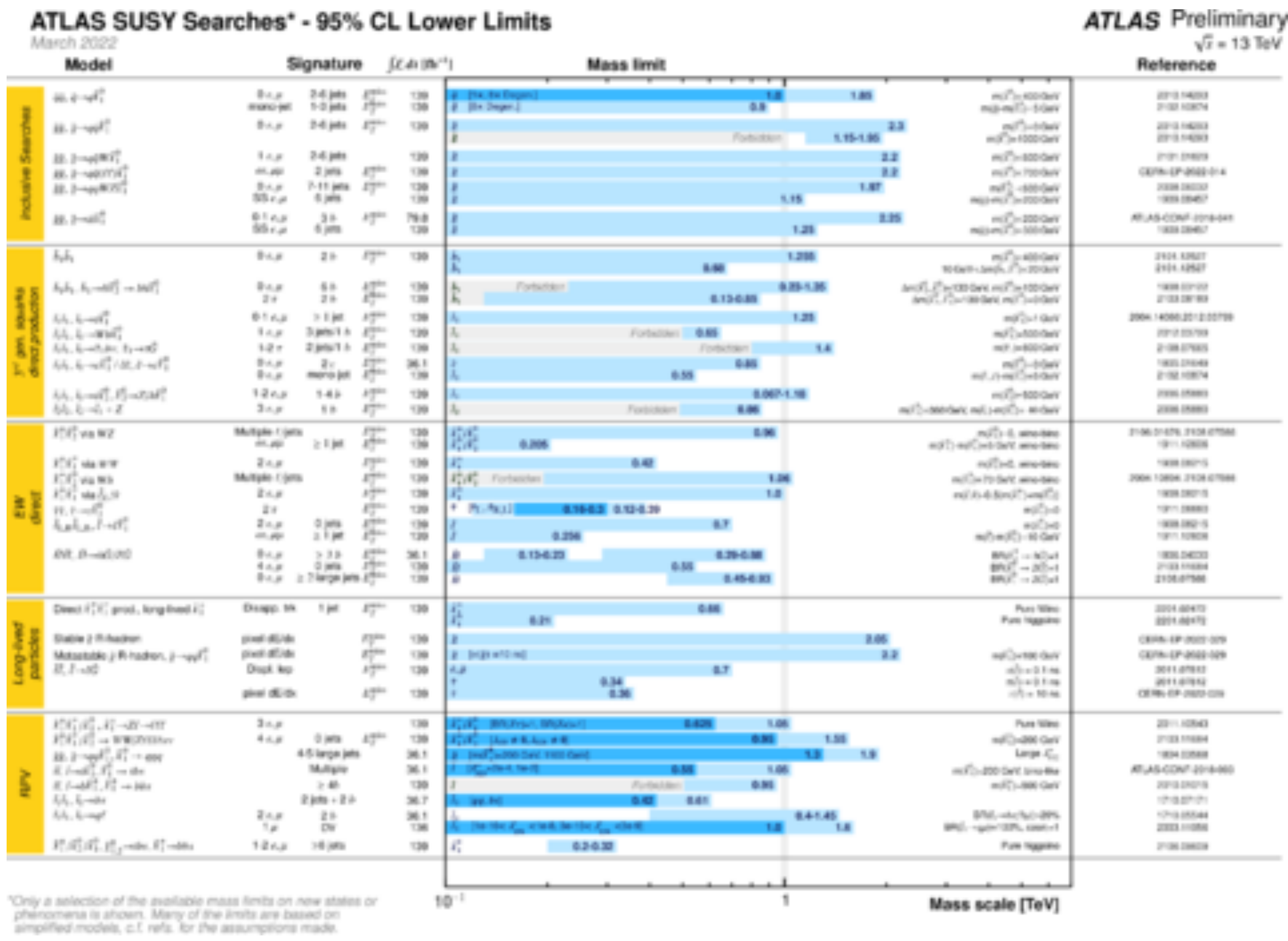
Then physics case should be approximately the same!

Timelines/differences are in ITF/AF

The LHC has given us more than just the Higgs





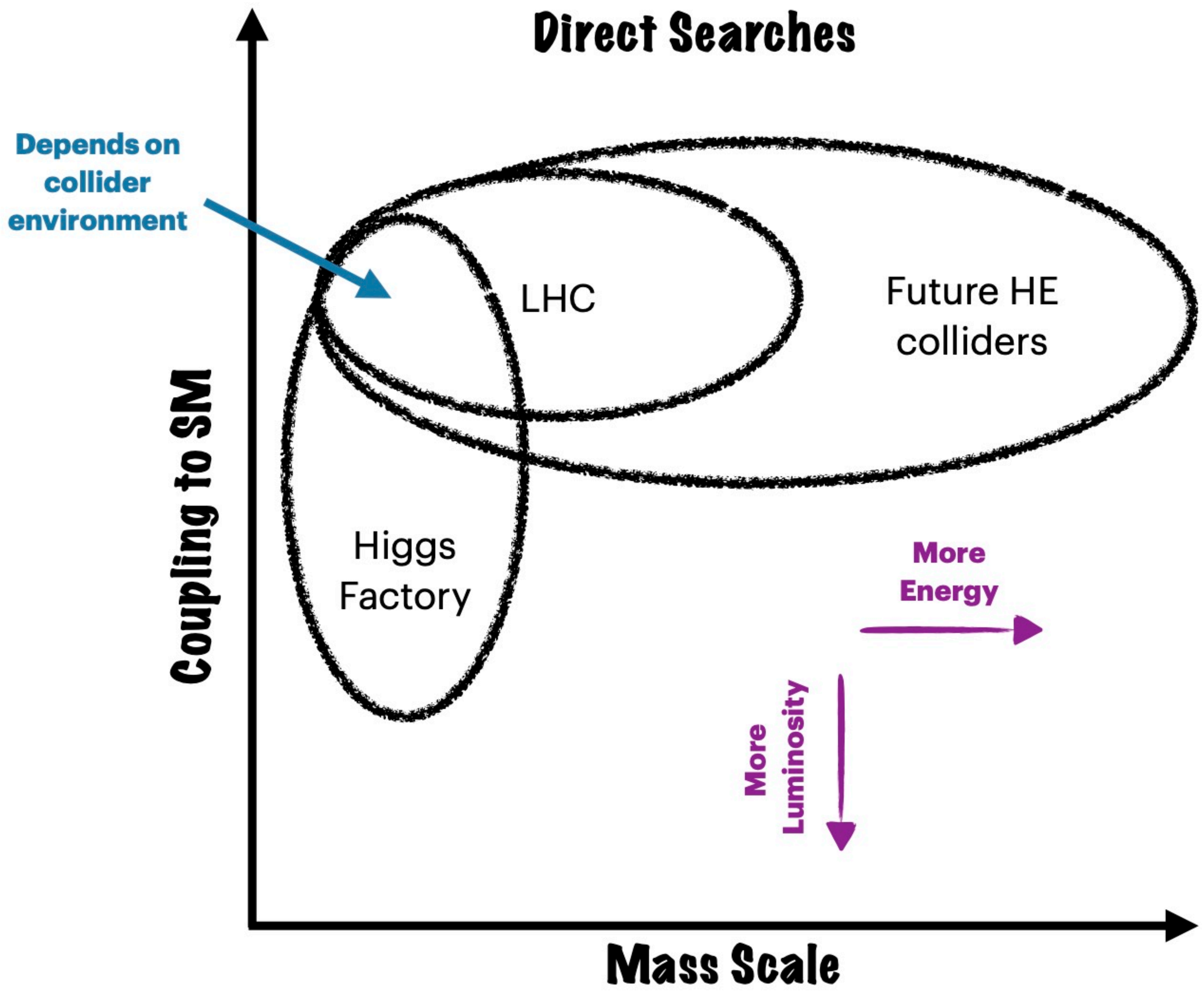


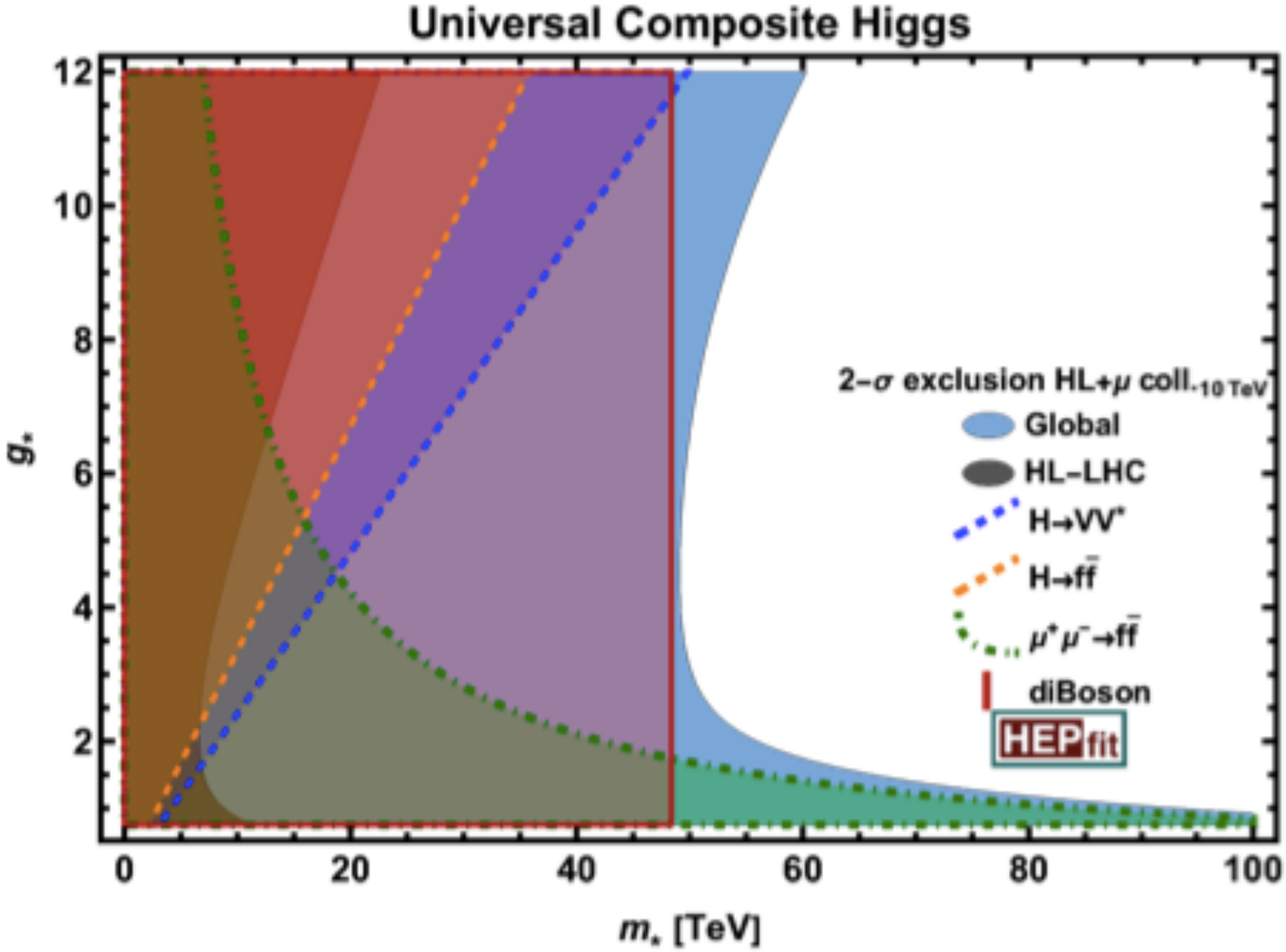
Wonderful SM agreement

Higgs looks SM-like so far

No clear signs of BSM

Higgs Factories are *also* discovery machines!
Especially considering they are also EW Factories as well (e.g. TeraZ or GigaZ etc)




Universal Composite Higgs
2−σ exclusion HL+μ coll.10 TeV
Global
HL−LHC
H→VV*
H→ff̄
μ⁺μ⁻→ff̄
diBoson
HEPfit
g*
m* [TeV]
0
20
40
60
80
100
2
4
6
8
10
12

	Higgs Factory	MC-3TeV	MC-10TeV
CM energy $\sqrt{s}$, TeV	0.125	3	10
Luminosity per IP, $10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$	0.008	2.3	20
Collider circumference, km	0.3	4.5	10
Number of IPs	1	2	2
Number of bunches	1	1	1
Repetition rate, HZ	15	5	5
Bunch charge N_μ, 10^{12}	4	2.2	1.8
Bunch length, mm	63	5	1.5
Bet-function at IP β^*, mm	17	5	1.5
R.m.s. beam size at IP, μm	75	3	0.9
Avg. power to beams, MW	0.05	10.5	28.8

Table 22: Main parameters of Muon Colliders.