Physics Case for Lepton Colliders

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

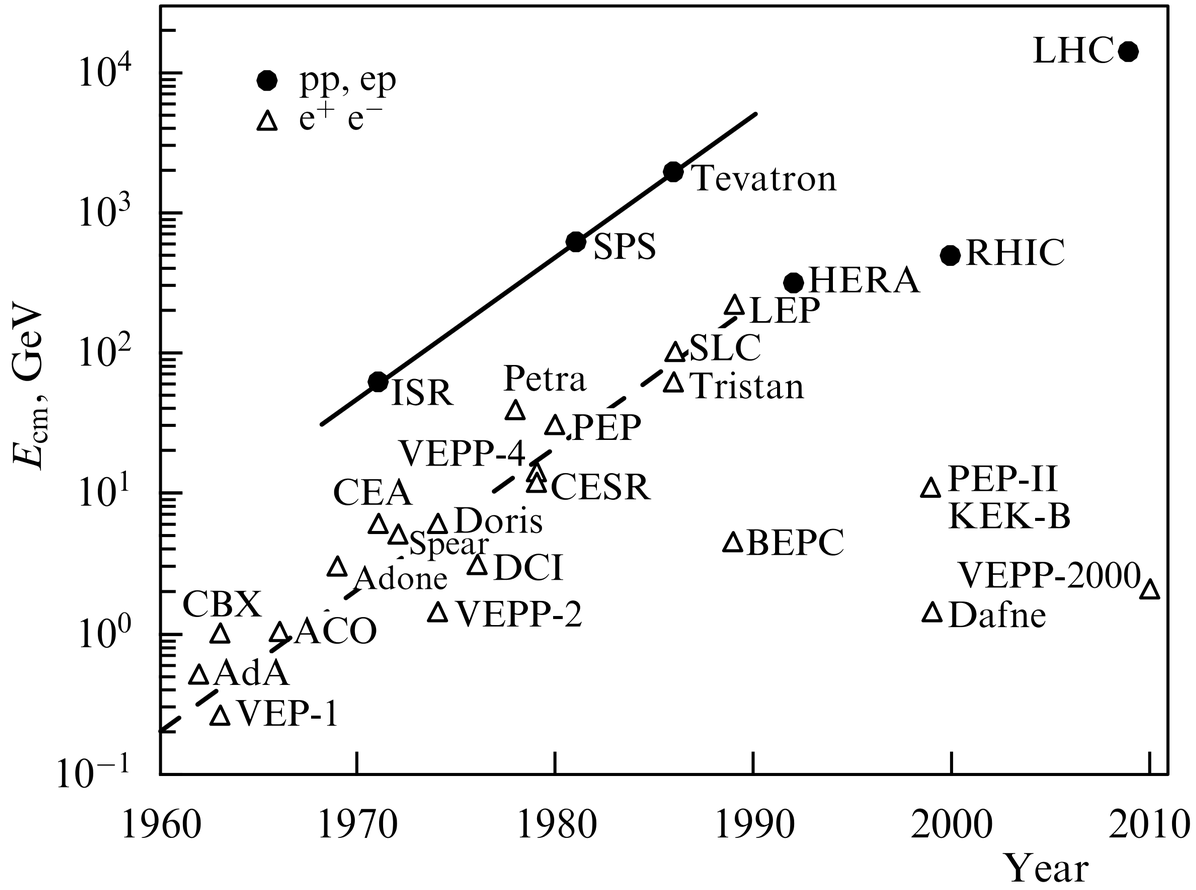
A leptonic vision for the future

A leptonic vision for the future

All in 20 minutes, and hopefully at a level mostly appropriate to all frontiers!

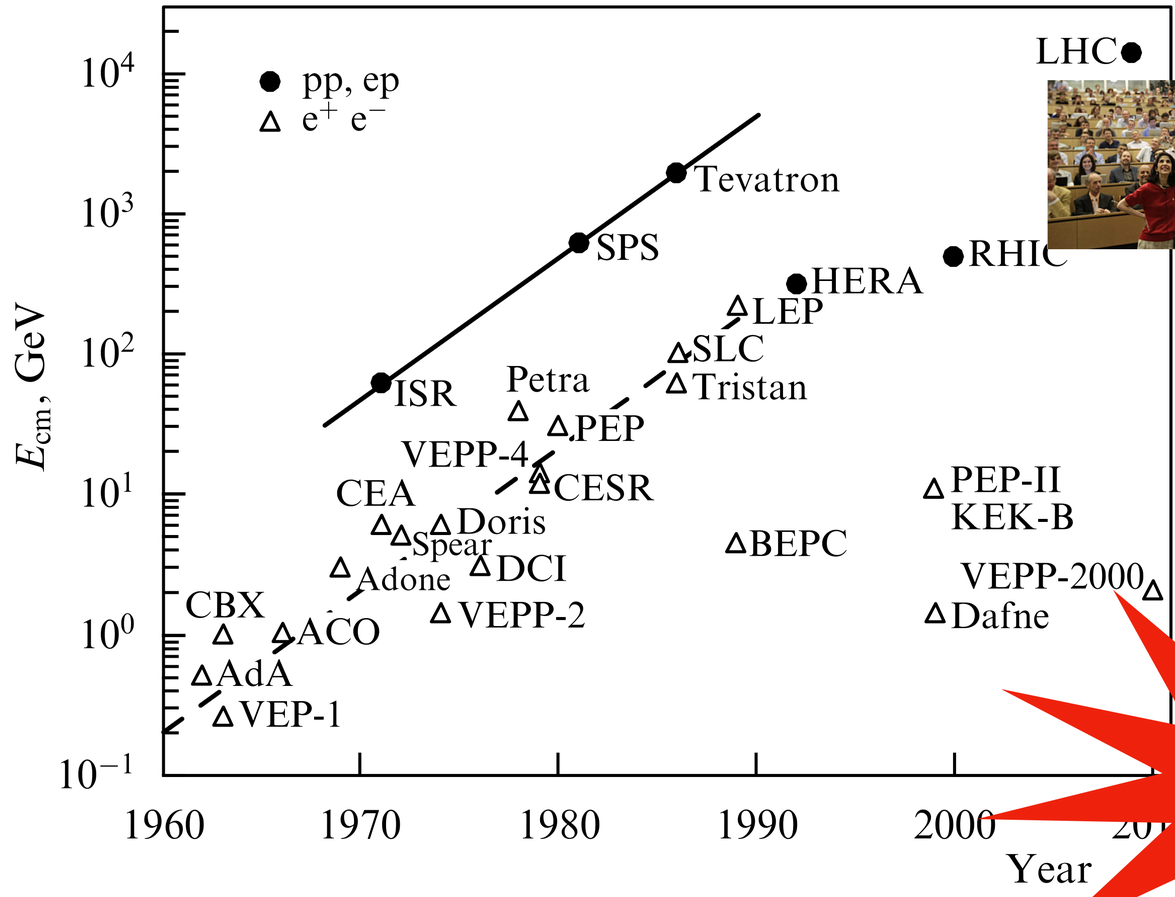
For experts: please look for more details in the forum reports, other whitepapers and the Q&A, or bug a convener during CSS!

Lepton colliders have always been around, so why are we having this session on them *now*? And what's *new*?



(V. Shiltsev, 2012)

Lepton colliders have always been around, so why are we having this session on them ***now***? And what's ***new***?



(V. Shiltsev, 2012)

1) Higgs discovery
2) Results of LHC to now
3) New ideas for e and μ

Higgs Discovery

Wait a minute the Higgs isn’t new is it? Didn’t we just have the 10th anniversary…

Wait a minute the Higgs isn't new is it? Didn't we just have the 10th anniversary…

That's actually the point!

For the last several decades there has been an interplay/divergence of lepton and hadron colliders

> 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)**

In EF: "Today's signal is tomorrow's background"

For AF: "Today's high energy is tomorrow's low energy"

"The Higgs needs a factory!" (Tao Han, every year) of course there's more motivation than this…

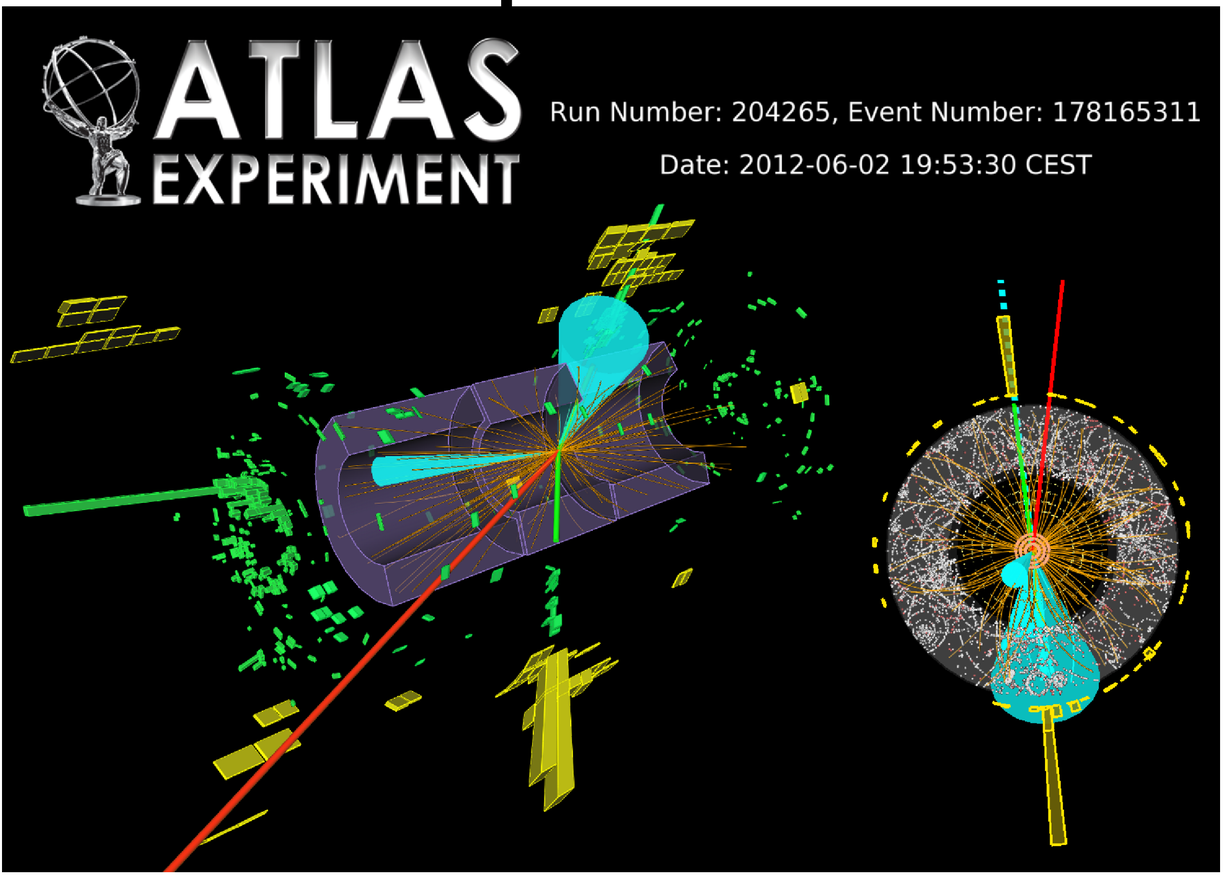
There are many motivations for a Higgs/EW Factory AF, EF, and TF perspectives

Most basic difference:

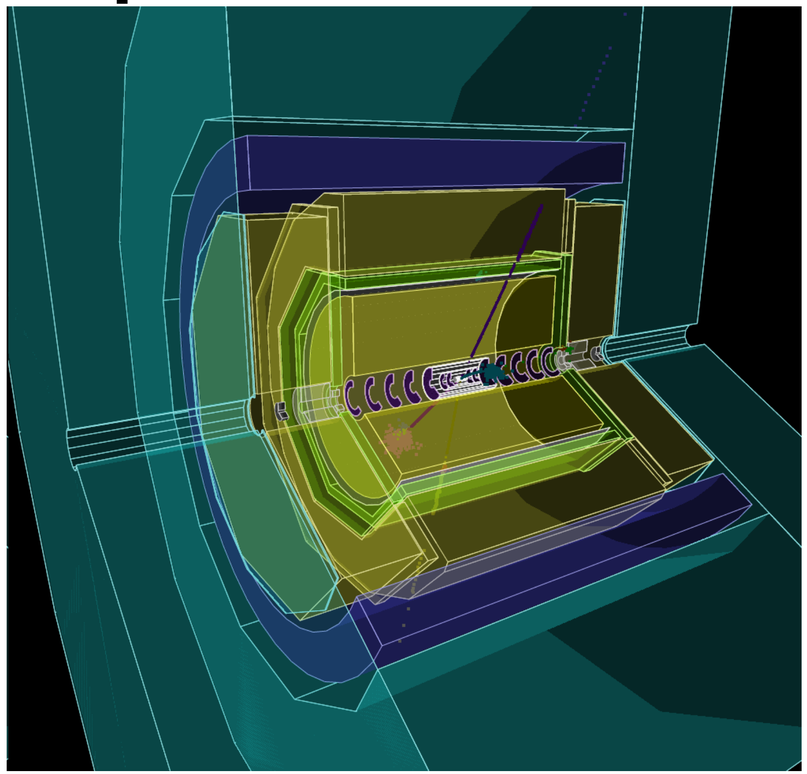
- Hadron colliders collide ***composite particles -*** that generate large QCD backgrounds and you use a fraction of the energy of beam for physics

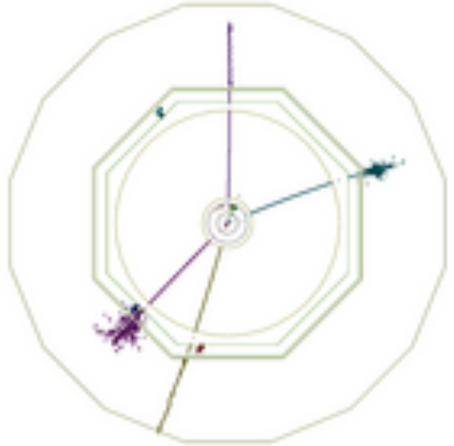
- Lepton colliders collide ***fundamental particles -*** that exploit the full energy and don’t have large QCD backgrounds

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



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





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

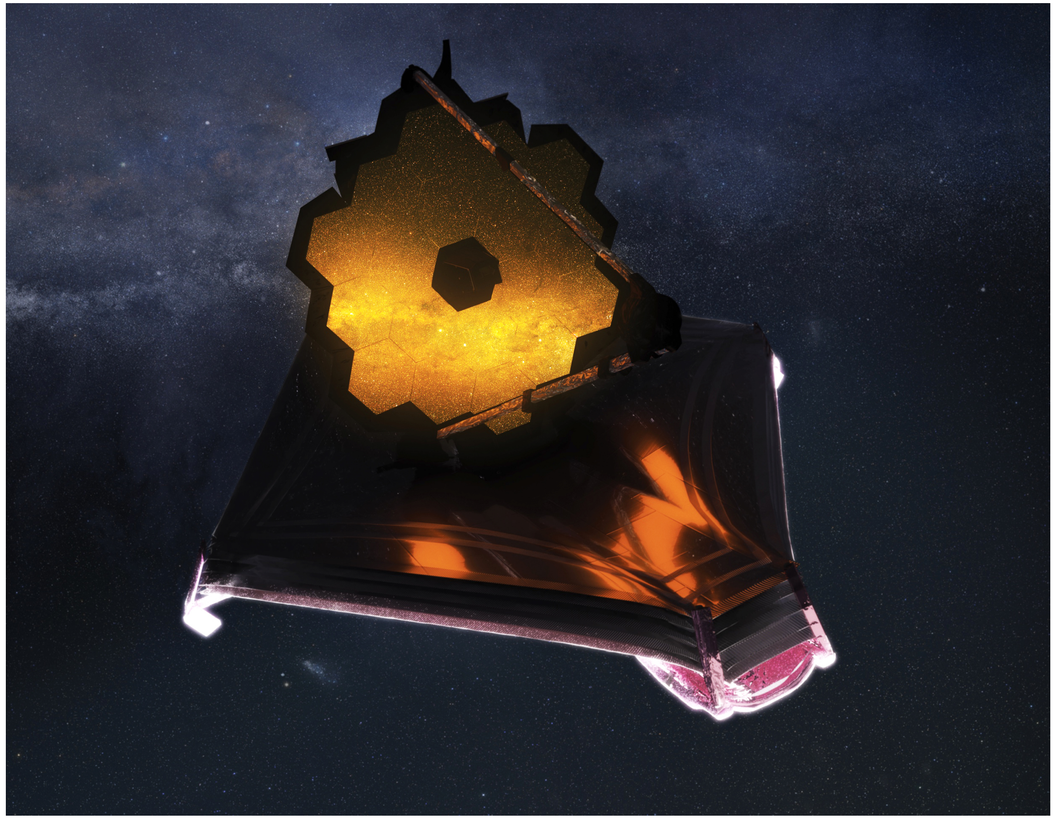
This doesn’t reflect that the size of *backgrounds* are also orders of magnitude smaller as well for leptons

There are many proposals for Higgs/ EW factories, but are they the end of the road for EF lepton colliders?

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)

After all we do want to be ready to go to higher energies!



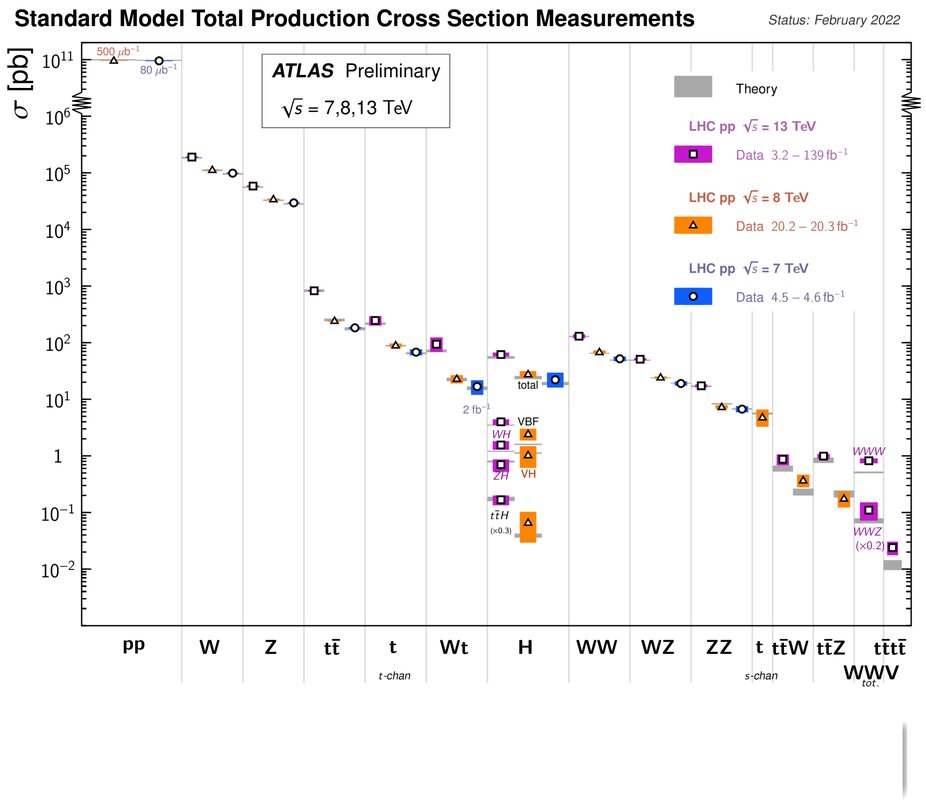
Just like telescopes take us to the largest distances

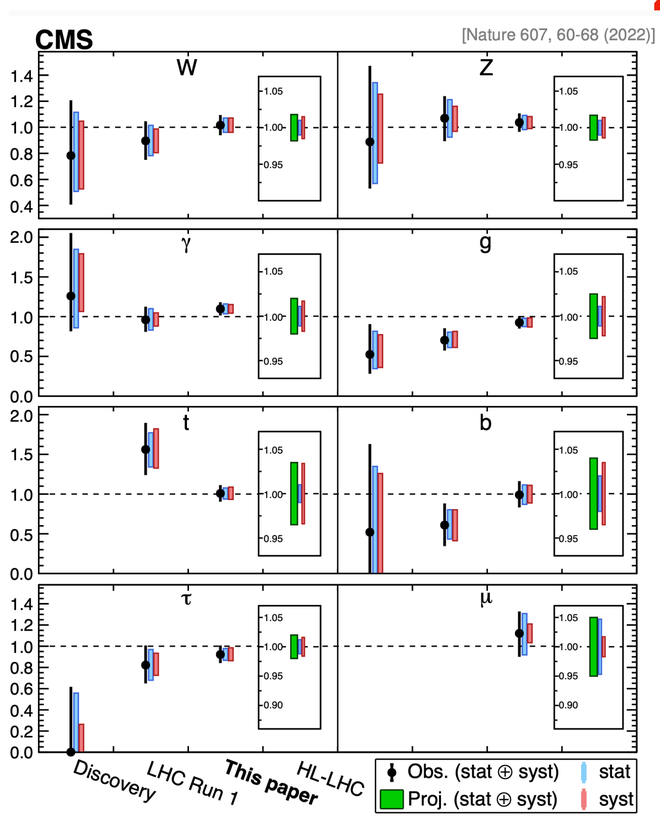
Colliders are our microscopes to the shortest distances

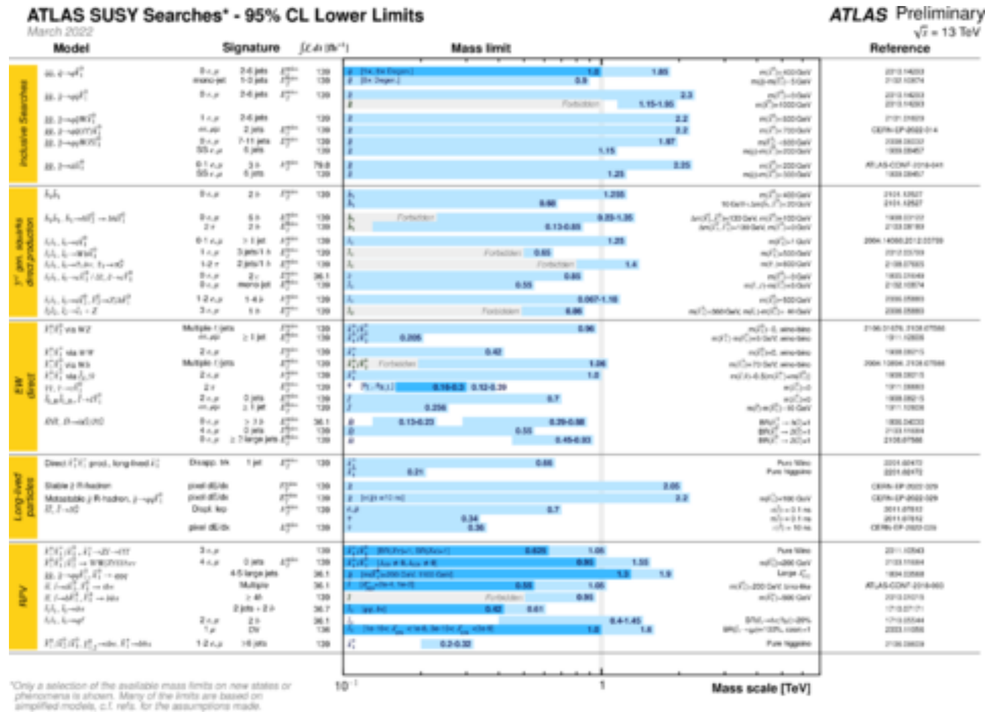
After all we do want to be ready to go to higher energies!

1)Higgs discovery

2)Results of LHC to now







Wonderful SM agreement

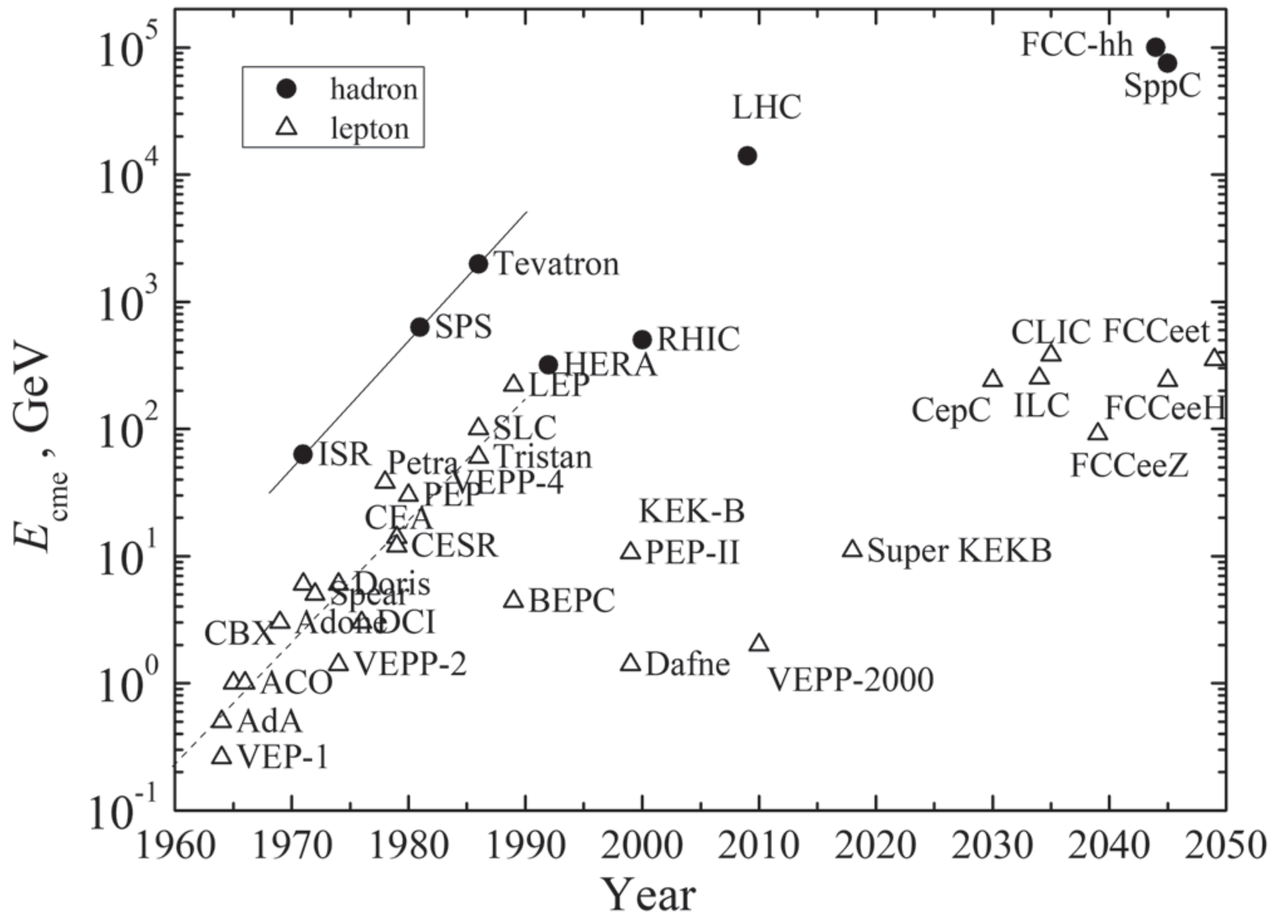
Higgs looks SM-like so far

No clear signs of BSM

There *are* beautiful visions that continues the lepton/hadron divergence and let us go higher in Energy

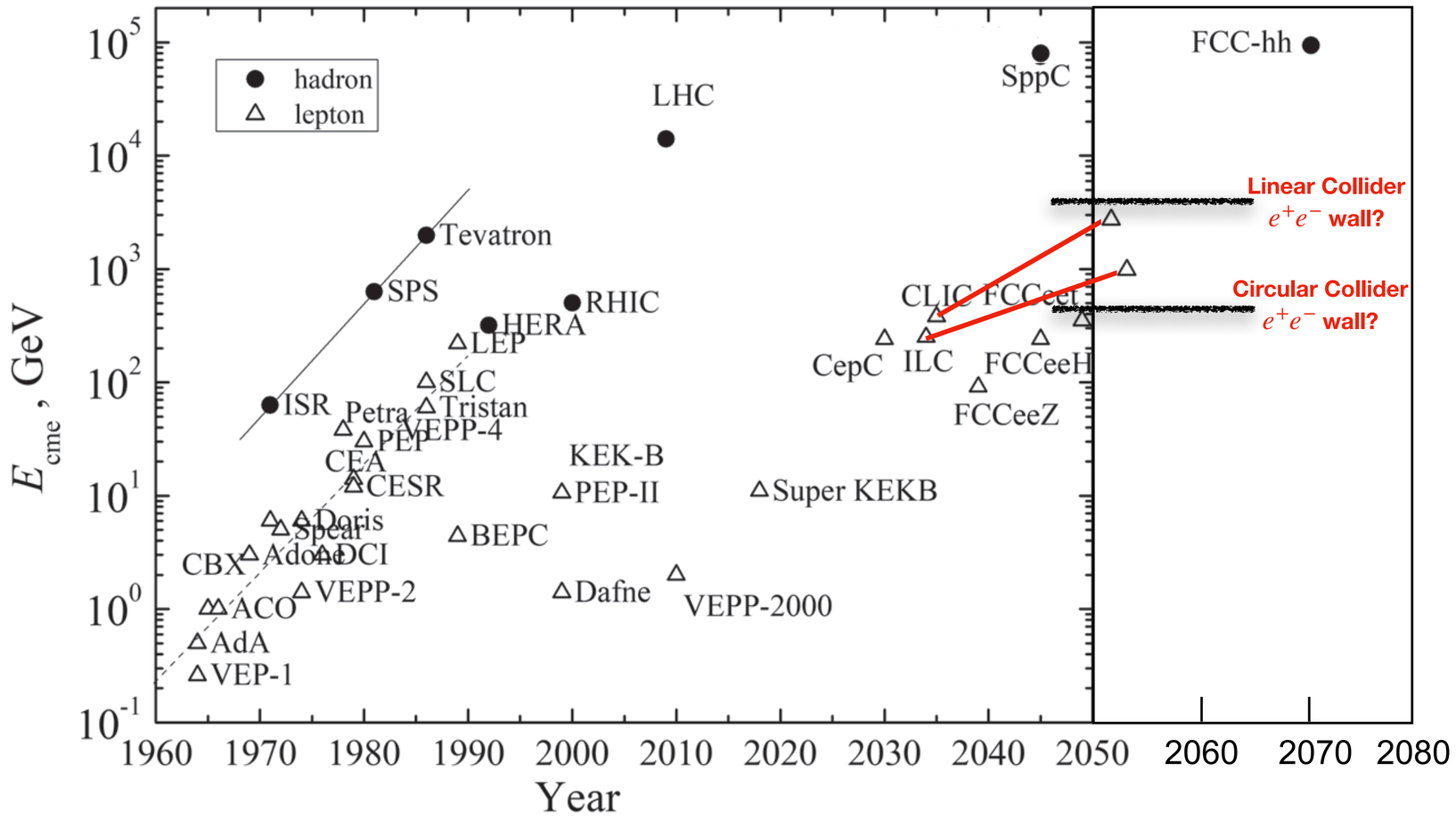
-SPPC

This is reflected in this updated plot



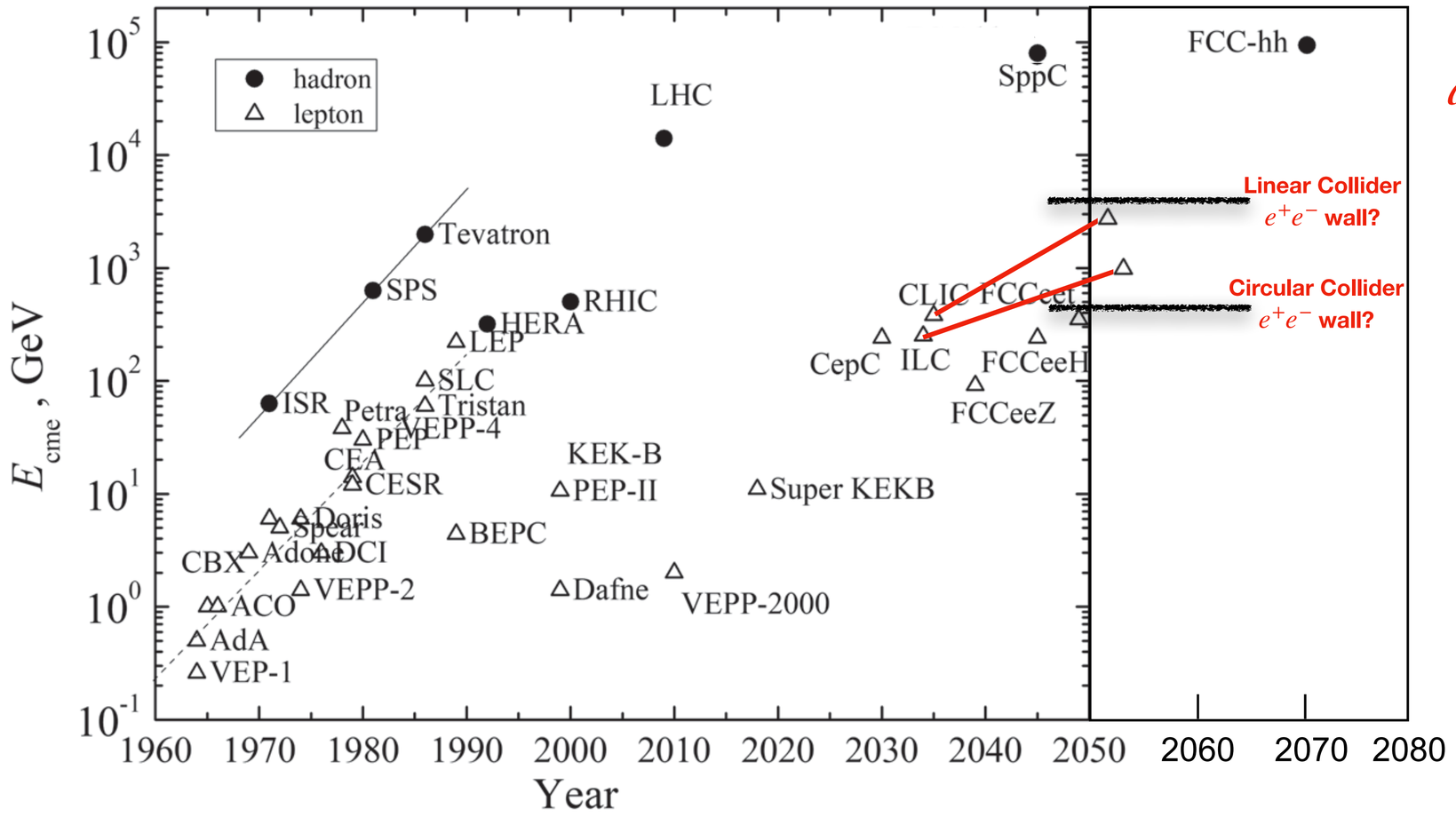
(V. Shiltsev, F. Zimmermann 2021 Reviews of Modern Physics)

This is reflected in this updated plot



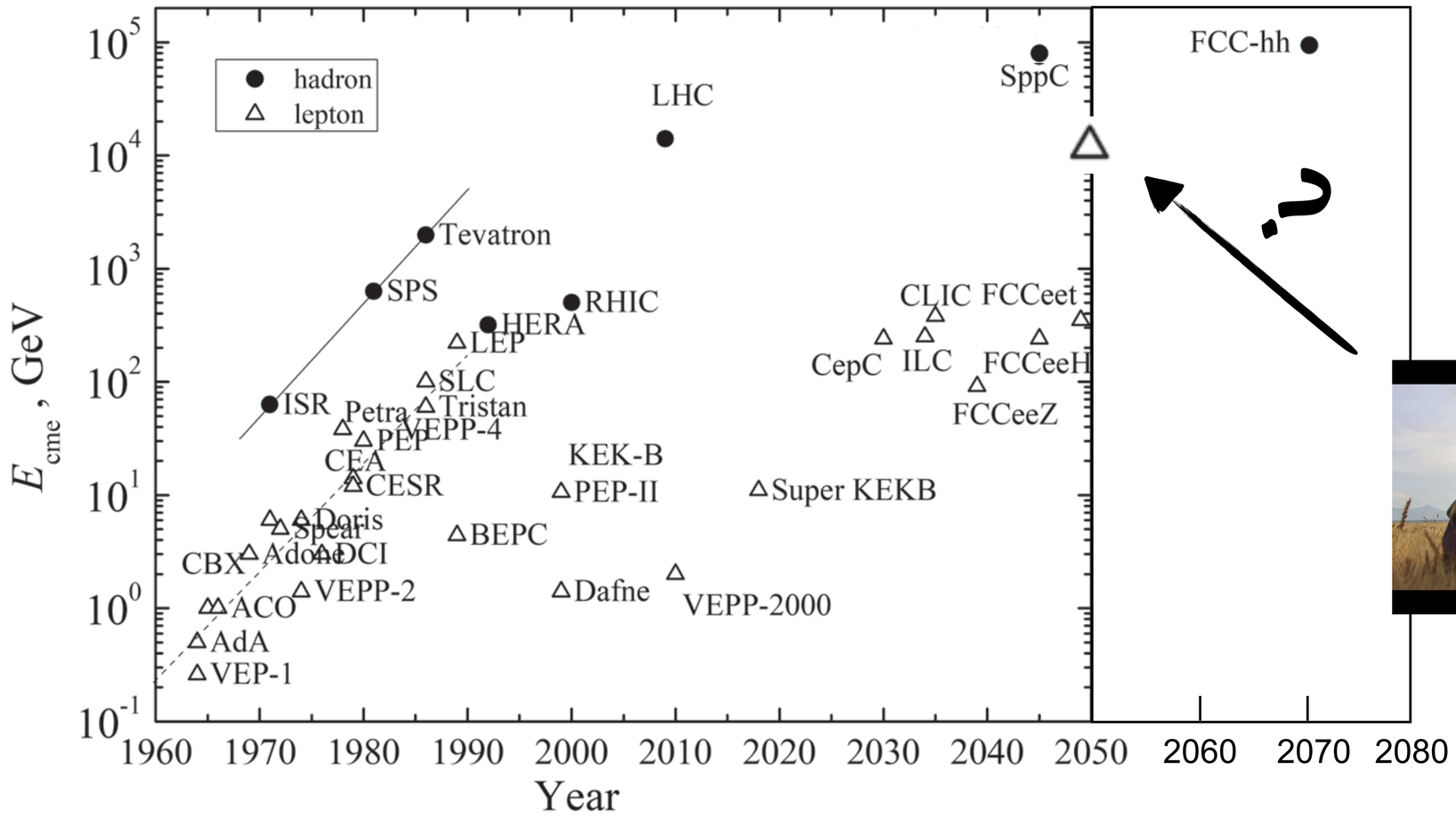
This is reflected in this updated plot

Are hadrons the only path higher?




MARVEL STUDIOS
WHAT IF...?
LEPTONS COULD REACH HIGHER ENERGY MORE QUICKLY AND SUSTAINABLY
imgflip.com

This is reflected in this updated plot



Two immediate questions

1) Higgs discovery

2) Results of LHC to now

3) New ideas for e and μ

- **First question:** *How on earth is this possible?*
  - New technology and R&D is needed: Muon colliders or WFA based e+e-
- **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

A leptonic vision for the future

Higgs Factories

ILC

C^3

CLIC

FCC-ee

CEPC

…

More in e^+e^- forum talk

Possible $\mu^+\mu^-$ staging

New ideas here too!

High Energy

10+ TeV μCollider

More in $\mu^+\mu^-$ forum talk

10+ TeV WFA e^+e^- collider

This actually matches well with the EF vision (Section 2.8.7)

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.

A leptonic vision for the future

Higgs Factories

ILC

C^3

CLIC

FCC-ee

CEPC

...

More in e^+e^- forum talk

Possible $\mu^+\mu^-$ staging

High Energy

10+ TeV μCollider

More in $\mu^+\mu^-$ forum talk

10+ TeV WFA e^+e^- collider

So what are the physics cases?

A leptonic vision for the future

Higgs Factories

ILC

C^3

CLIC

FCC-ee

CEPC

...

More in e^+e^- forum talk

Possible $\mu^+\mu^-$ staging

High Energy

10+ TeV μCollider

More in $\mu^+\mu^-$ forum talk

10+ TeV WFA e^+e^- collider

So what are the physics cases?

Higgs Factories - Well known physics case

Higgs is Really New Physics!

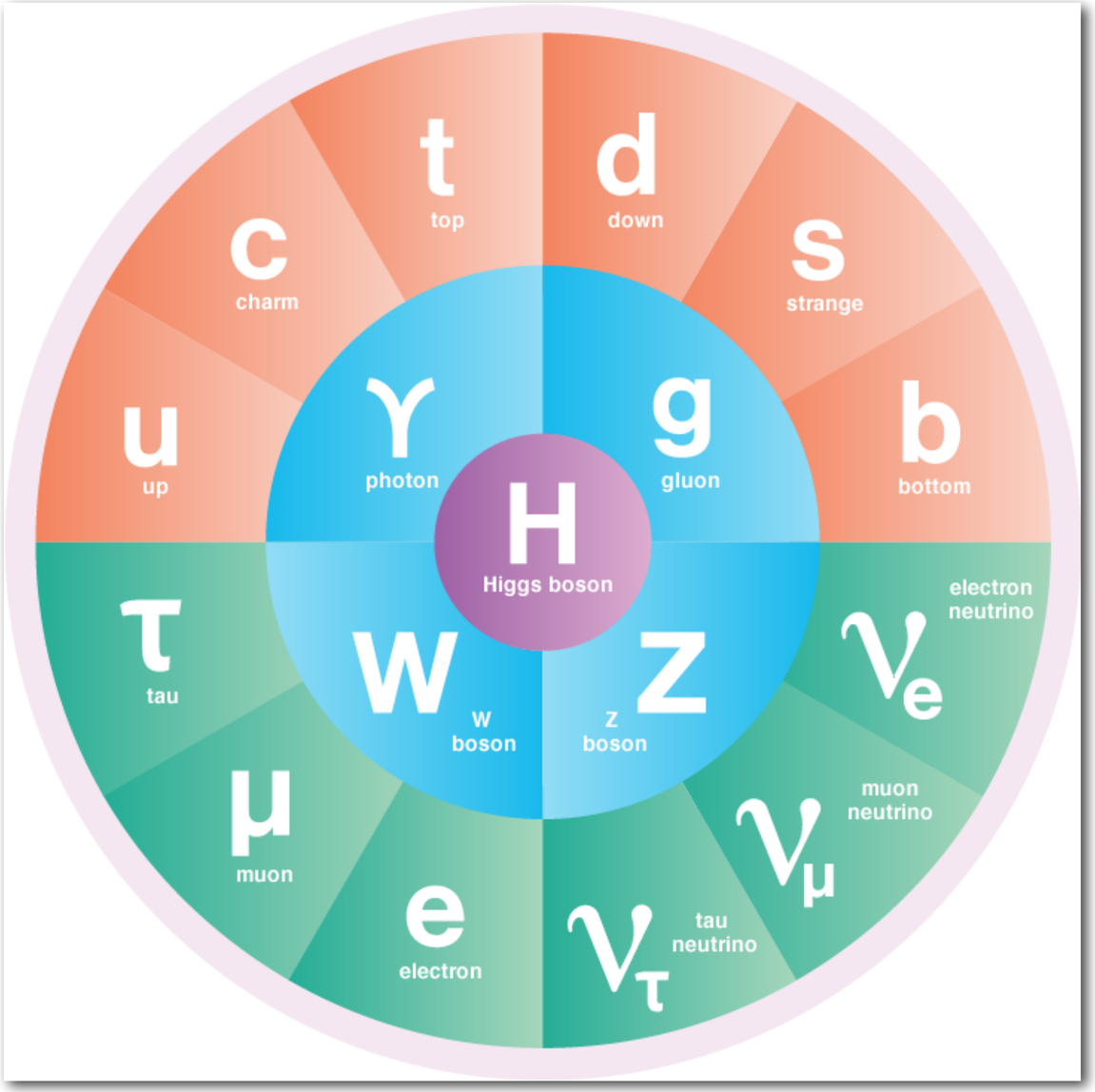
* We've never seen anything like it
* Harbinger of Profound New Principles at work in quantum vacuum

PUT IT UNDER MICROSCOPE

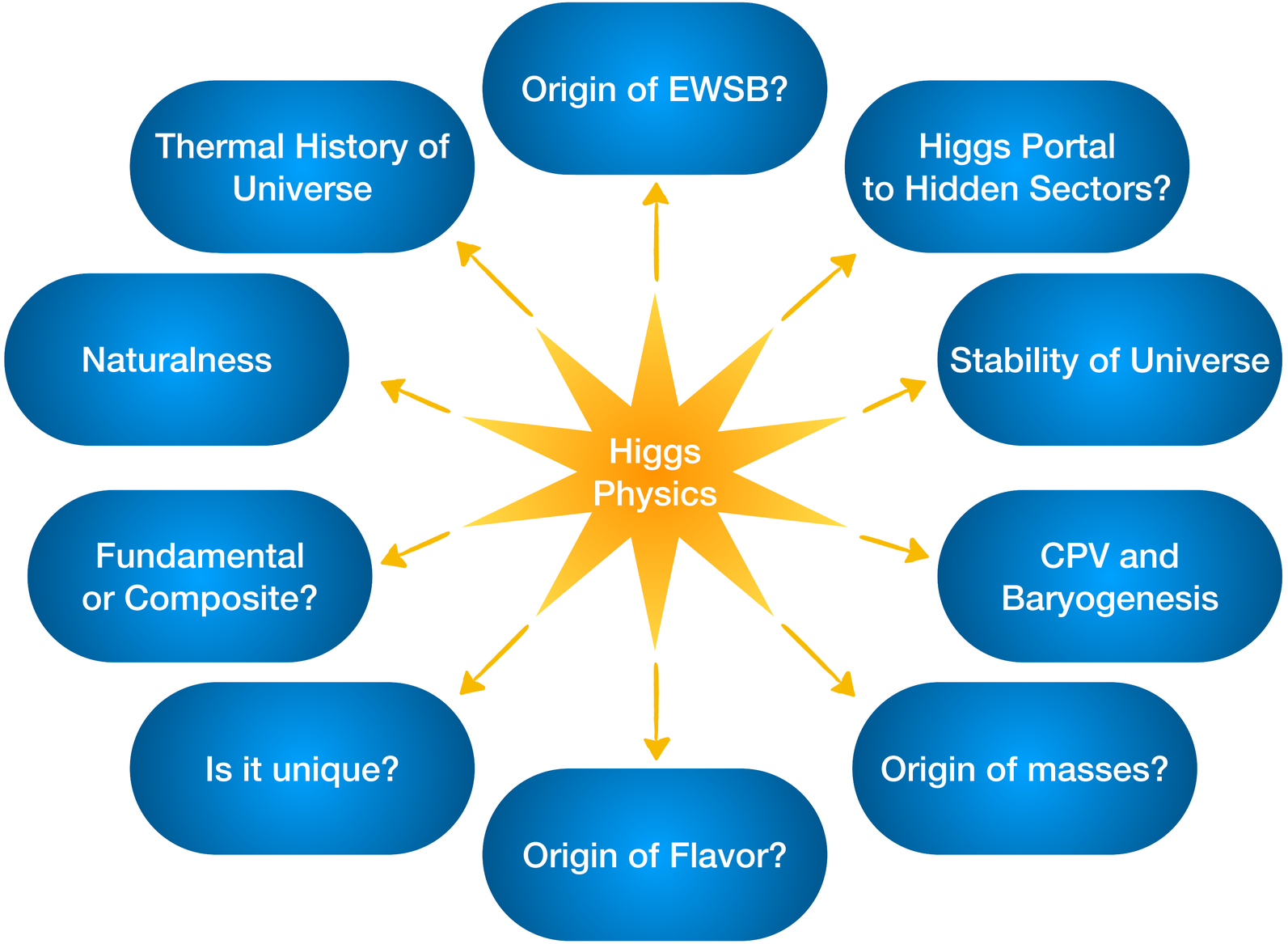
STUDY IT TO DEATH

Nima Arkani-Hamed Conclusions from Higgs 10th Anniversary CERN talk

Also see Sally Dawson's colloquium this Saturday Afternoon!



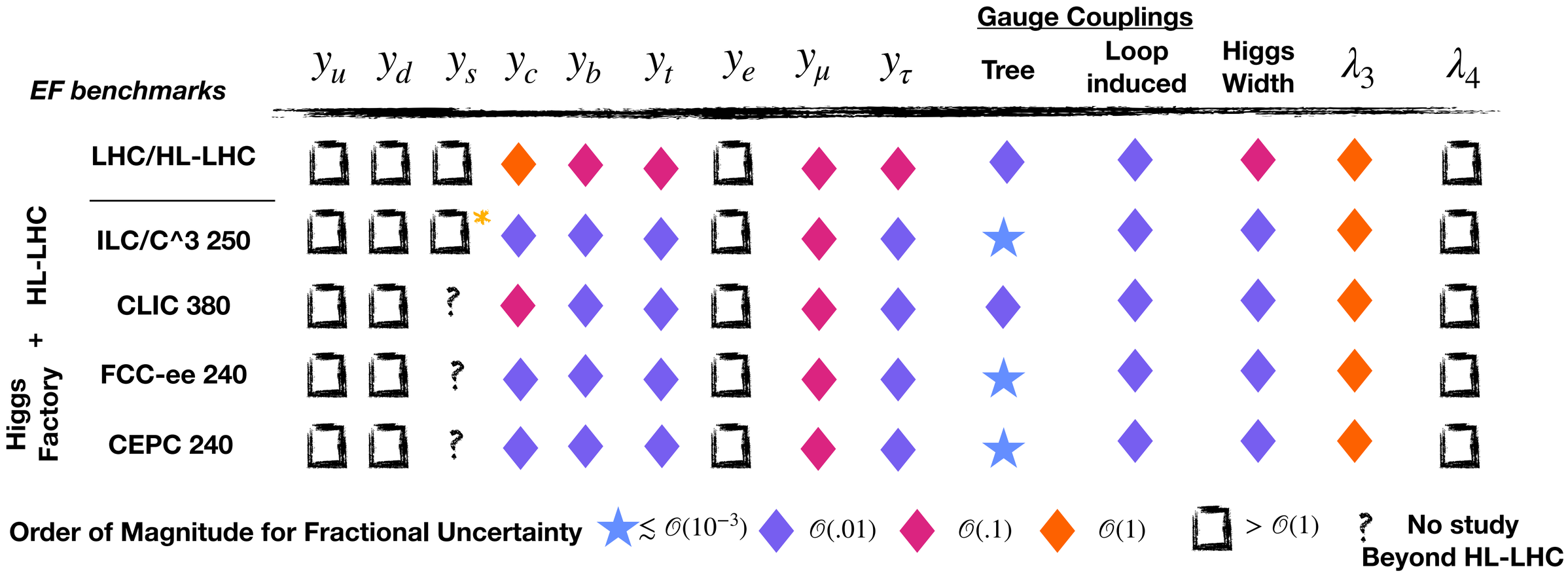
We've all probably seen this figure with the Higgs being the last piece of the SM and now we're done?



In reality we've just started (even 10 years on) given how unique the Higgs truly is!

Higgs factories let us study it to death, *but there's still a lot to do*!

Energy Frontier Higgs Factory First Stages



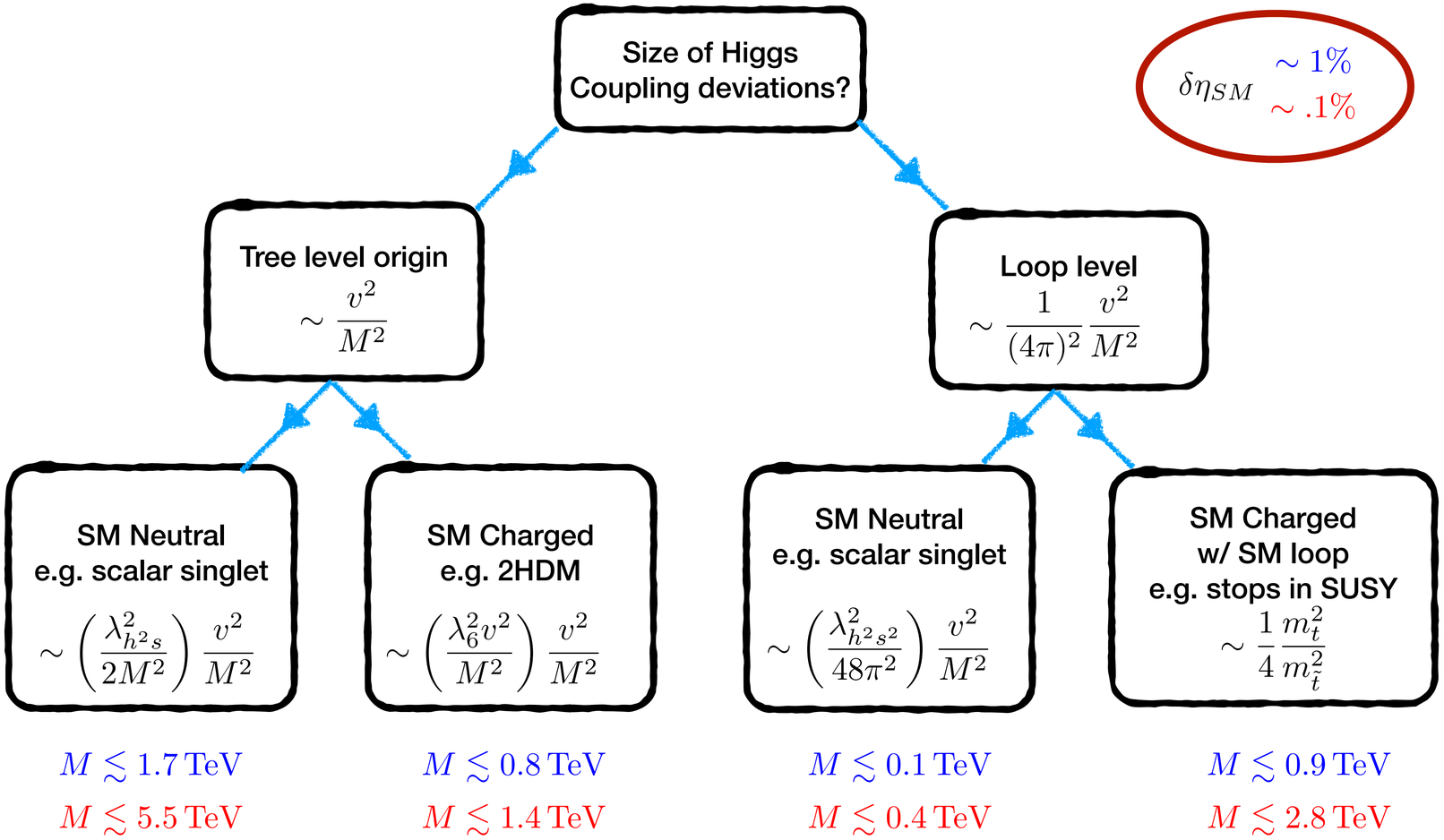
Higgs Factories are *also* discovery machines!

Especially considering they are also 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

A leptonic vision for the future

Higgs Factories

ILC

C^3

CLIC

FCC-ee

CEPC

...

More in e^+e^- forum talk

Possible $\mu^+\mu^-$ staging

High Energy

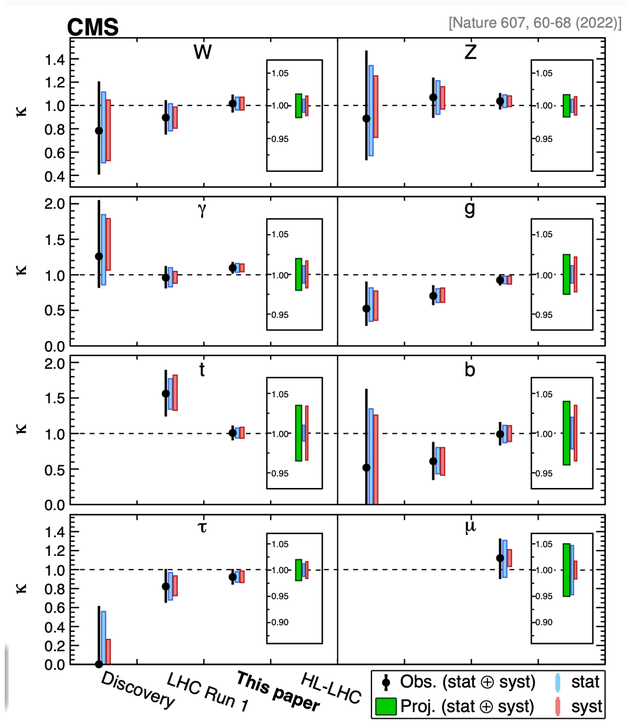
10+ TeV μCollider

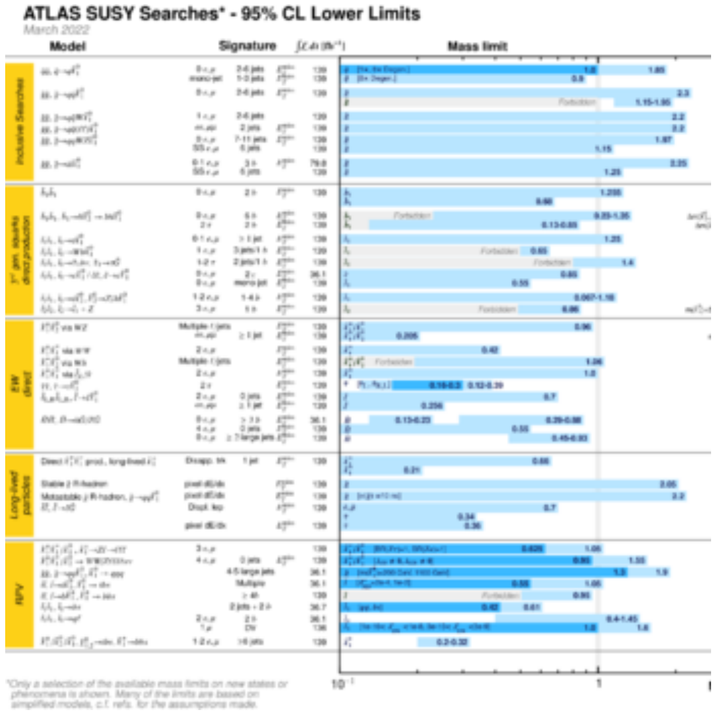
More in $\mu^+\mu^-$ forum talk

10+ TeV WFA e^+e^- collider

So what are the physics cases?

High Energy Lepton Collider - Physics Case





Preparing to go to high energies is obvious, and there is just as strong of physics case here as e.g. FCC-hh, but what are the scales that are particular interesting?

Higgs looks SM-like so far

No clear signs of BSM

Also see Simone Pagan Griso's colloquium this Saturday Afternoon!

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

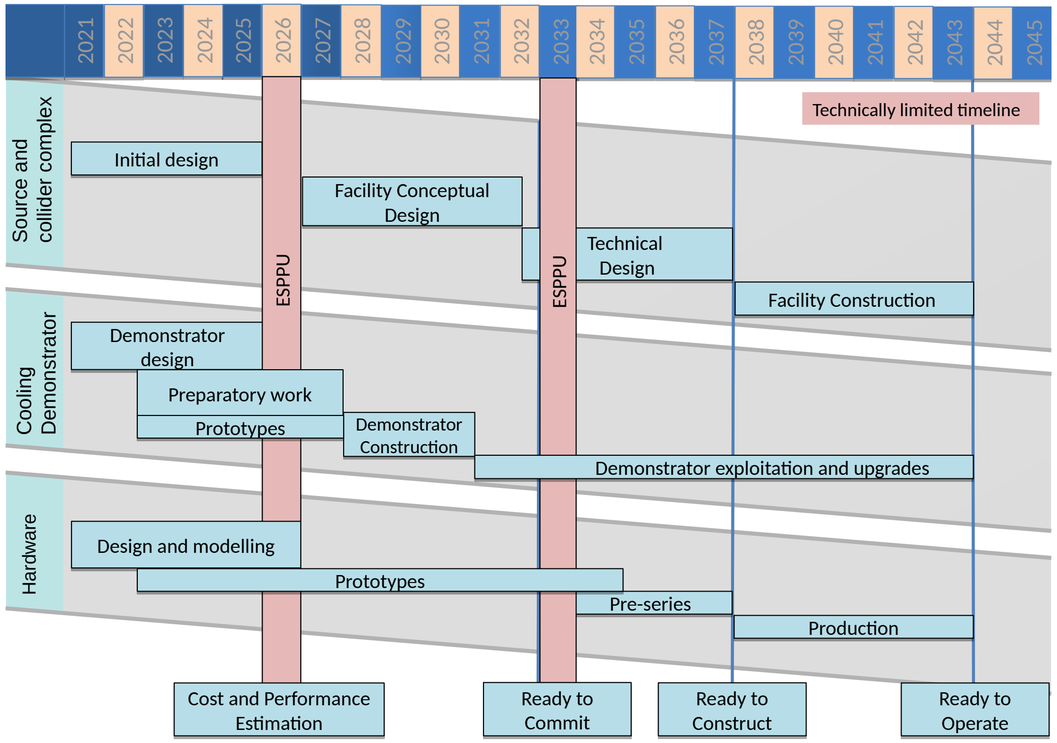


Fig. 5.3: A technically limited timeline for the muon collider R&D programme.

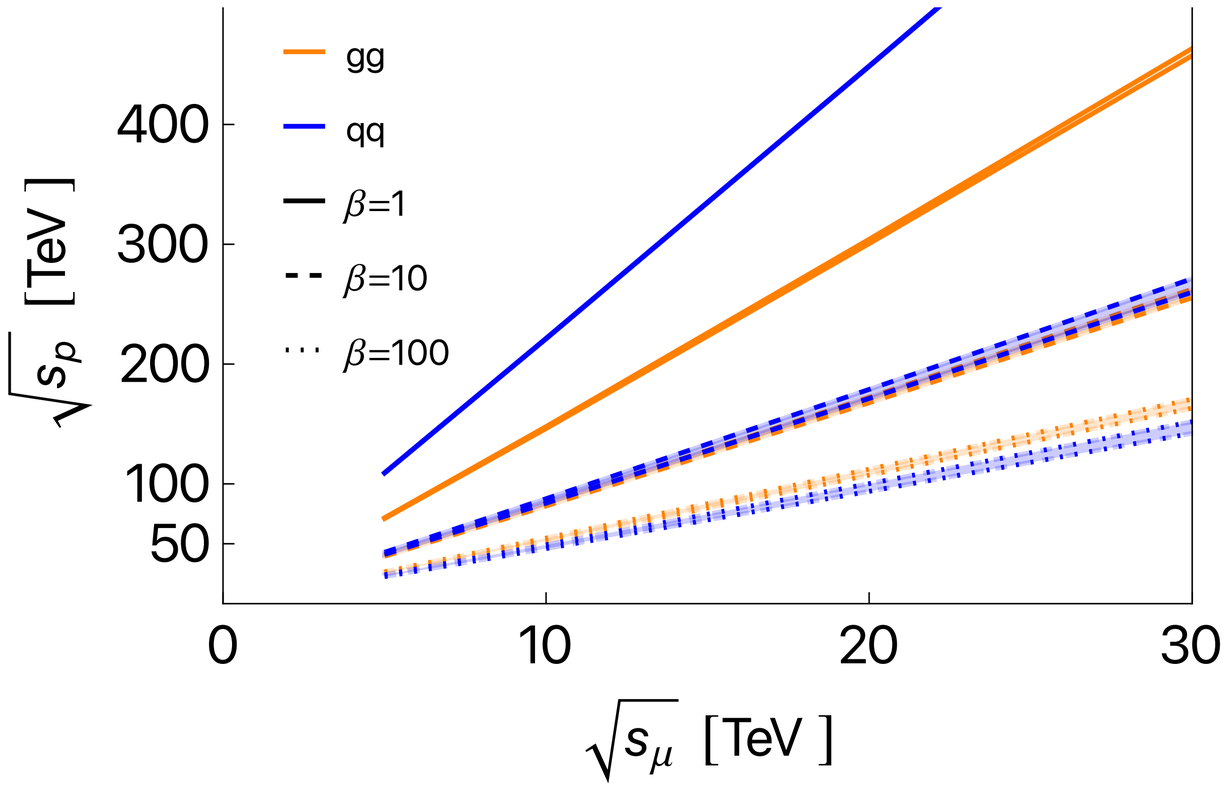
If an electron based WFA collider has:

e^+e^-

Same energy
Same luminosity
Same beam quality
Then physics case should be approximately the same!

Timelines/differences are in ITF/AF

Benefit is that you get to use the full energy of the collider



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

Rule of thumb in $2 \to 2$

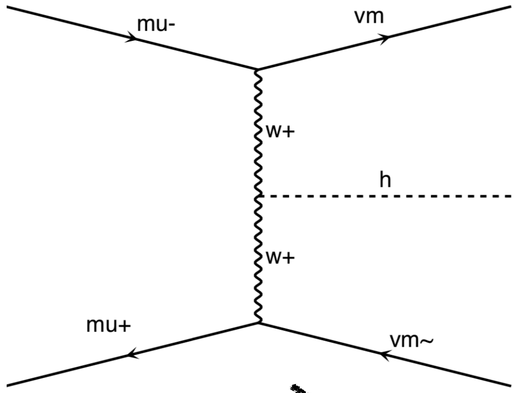
Discovery reach to $M \sim \frac{\sqrt{s}}{2}$

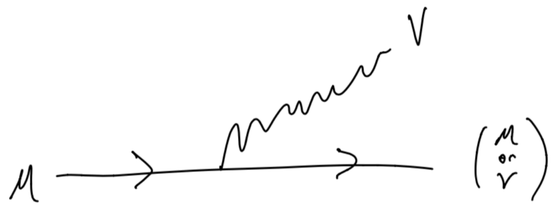
10 TeV ***is not the limit*** - just the study point for what is thought to be doable on paper already

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

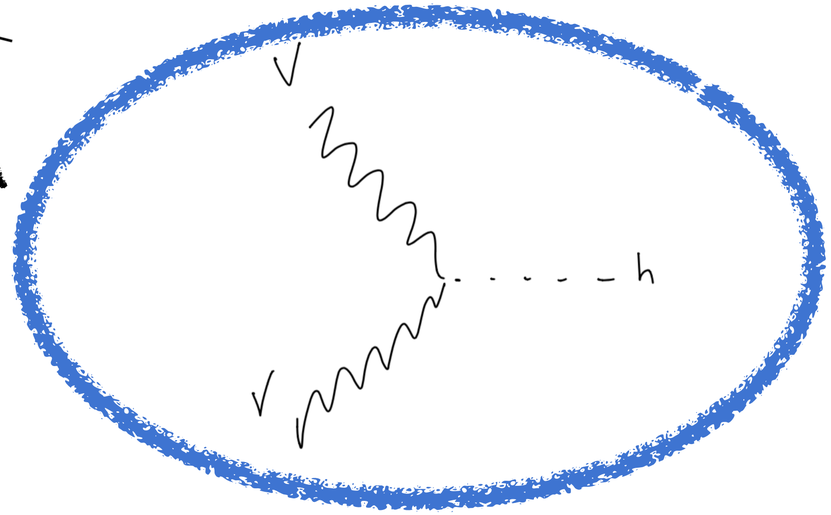
High Energy Lepton Colliders
are more than just lepton collisions

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





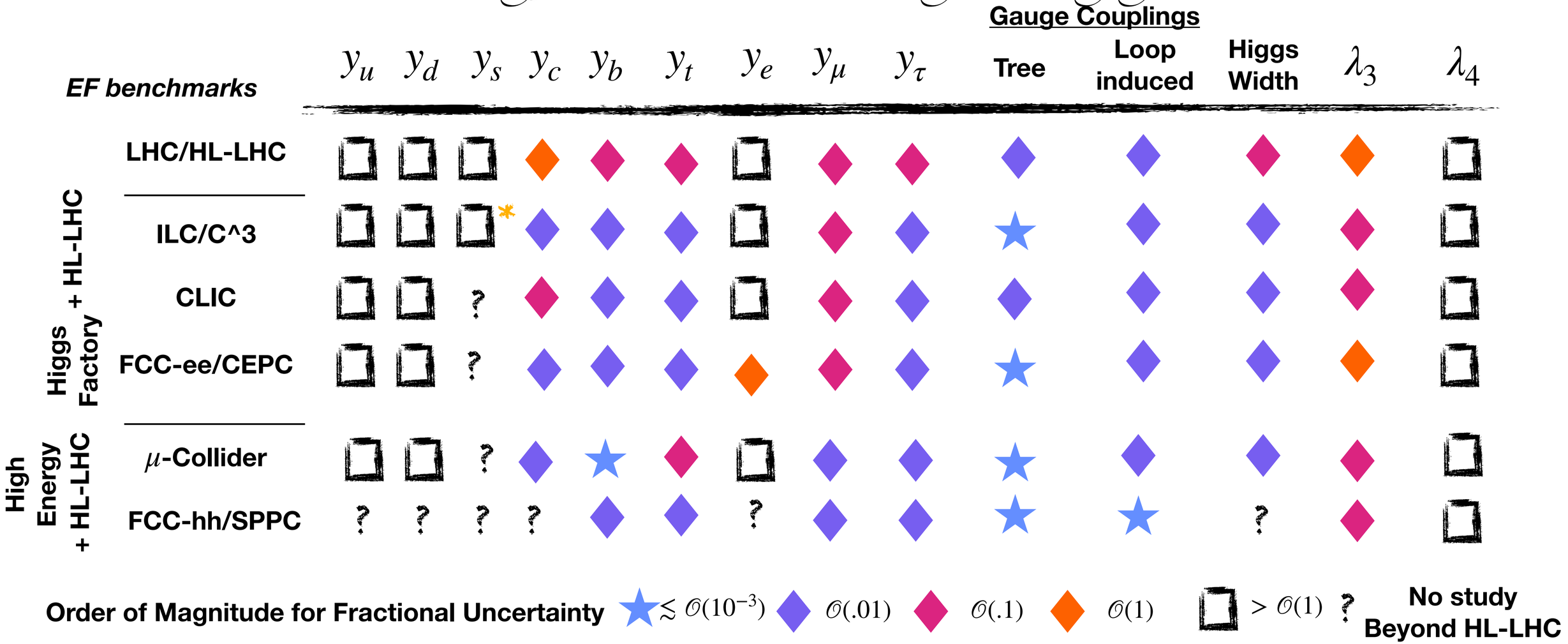
Vector Boson really wants to be soft or collinear....



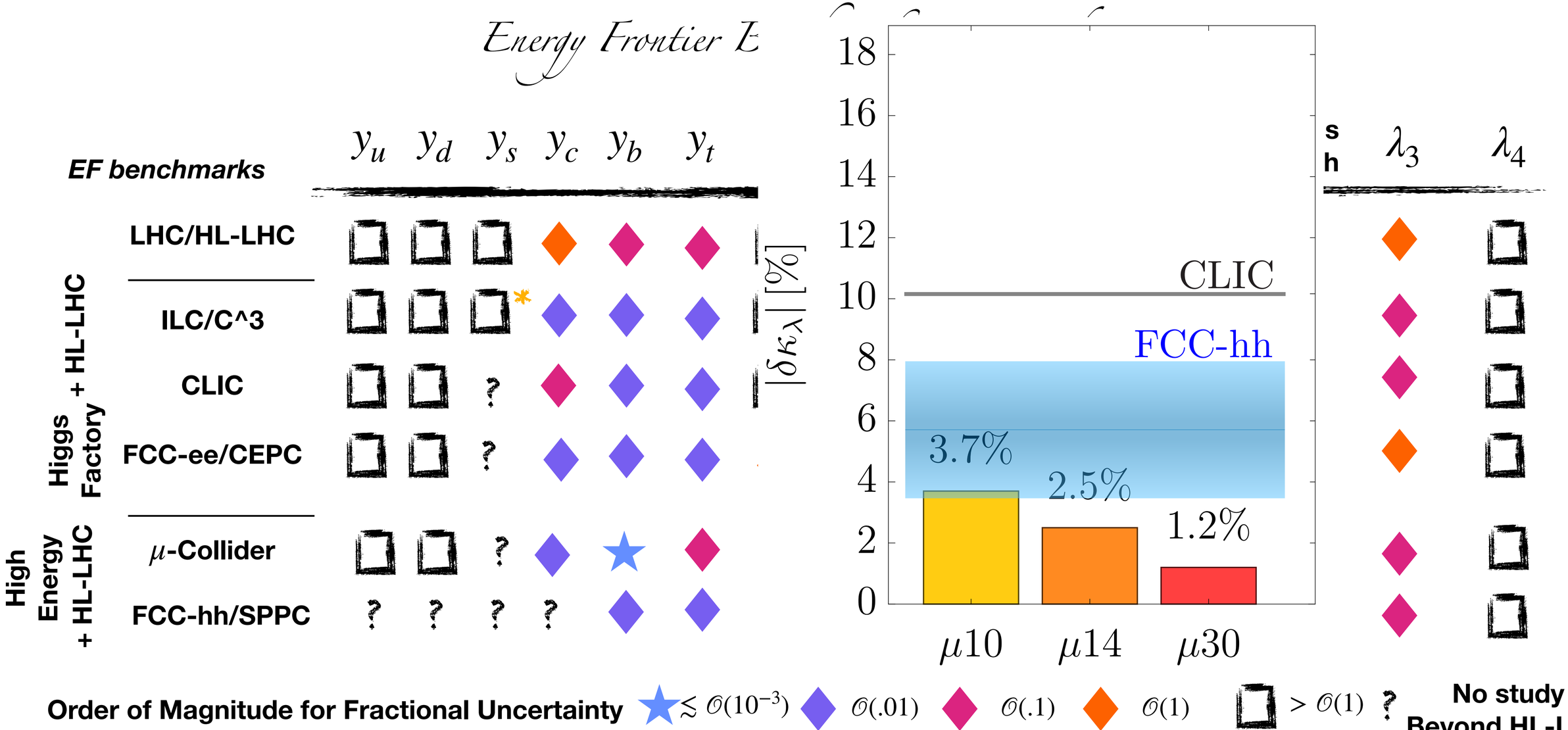
This allows for an *enhanced* Higgs and EW production at high E since $\sigma \sim \log E^2_{CM}$

High energy leptons allows us to push forwards on understanding the Higgs

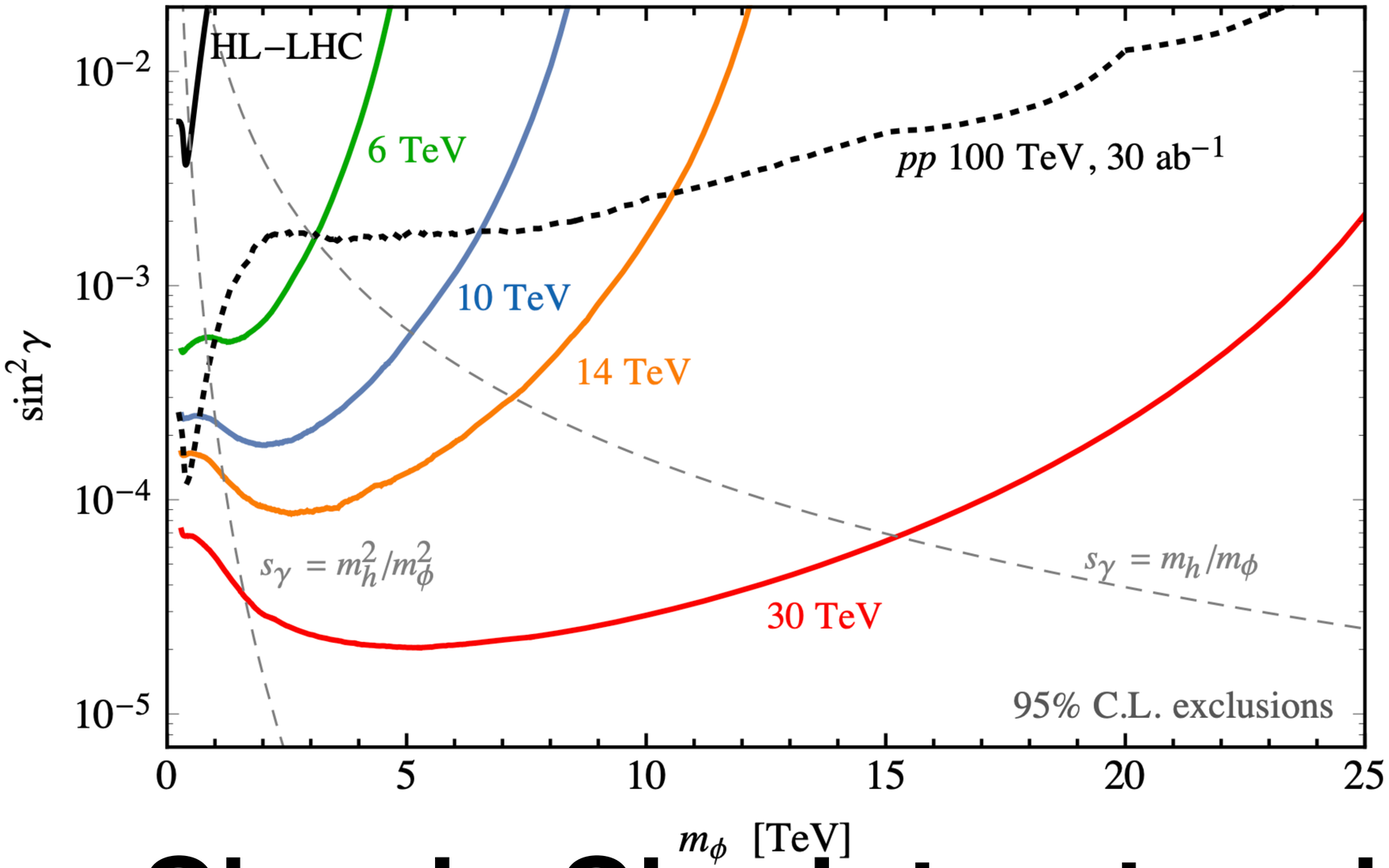
Energy Frontier Benchmarks Integrated Staging



High energy leptons allows us to push forwards on understanding the Higgs



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

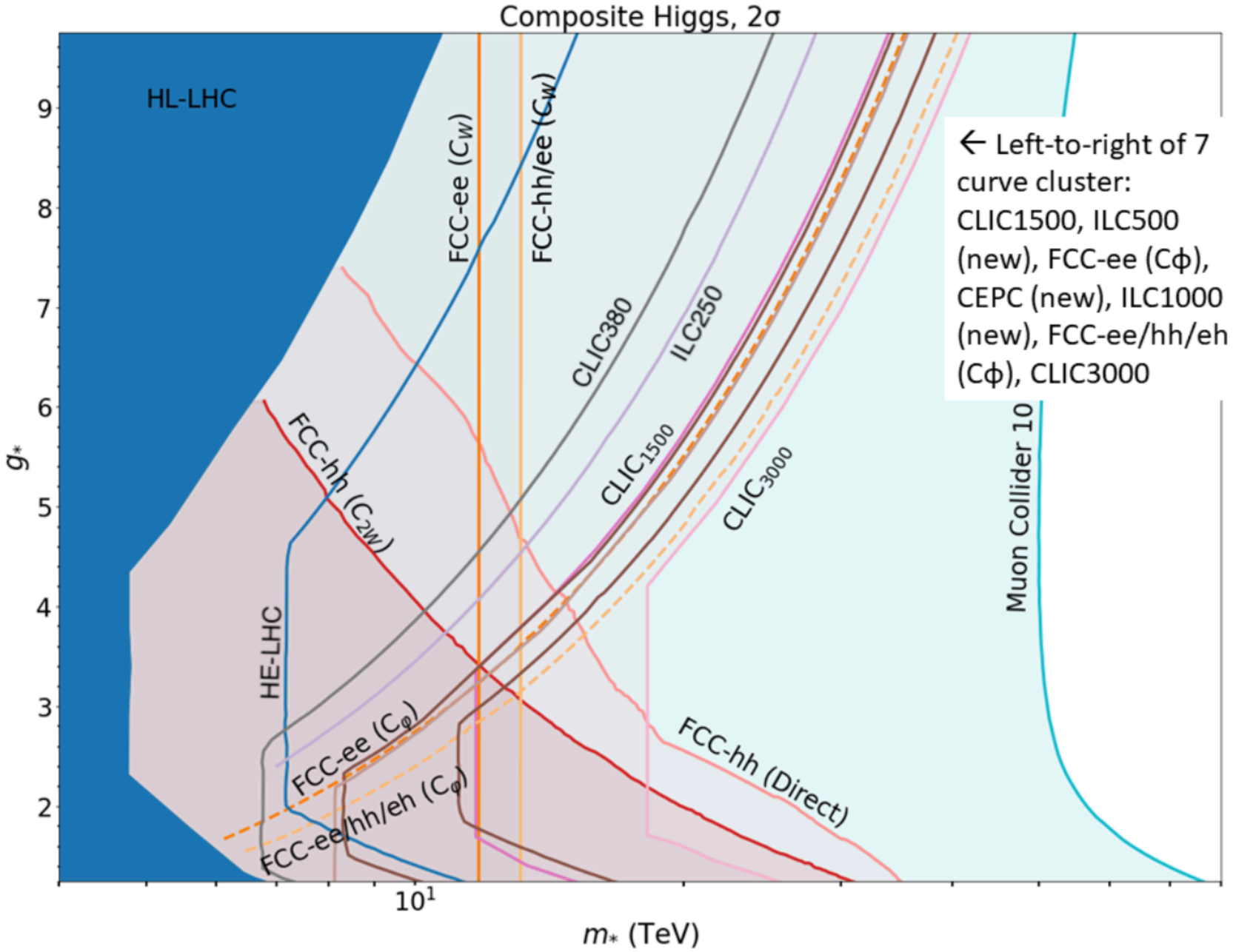


10 TeV very complementary with FCC-hh, 30 TeV blows away other ideas

Can map to Neutral Naturalness Reach

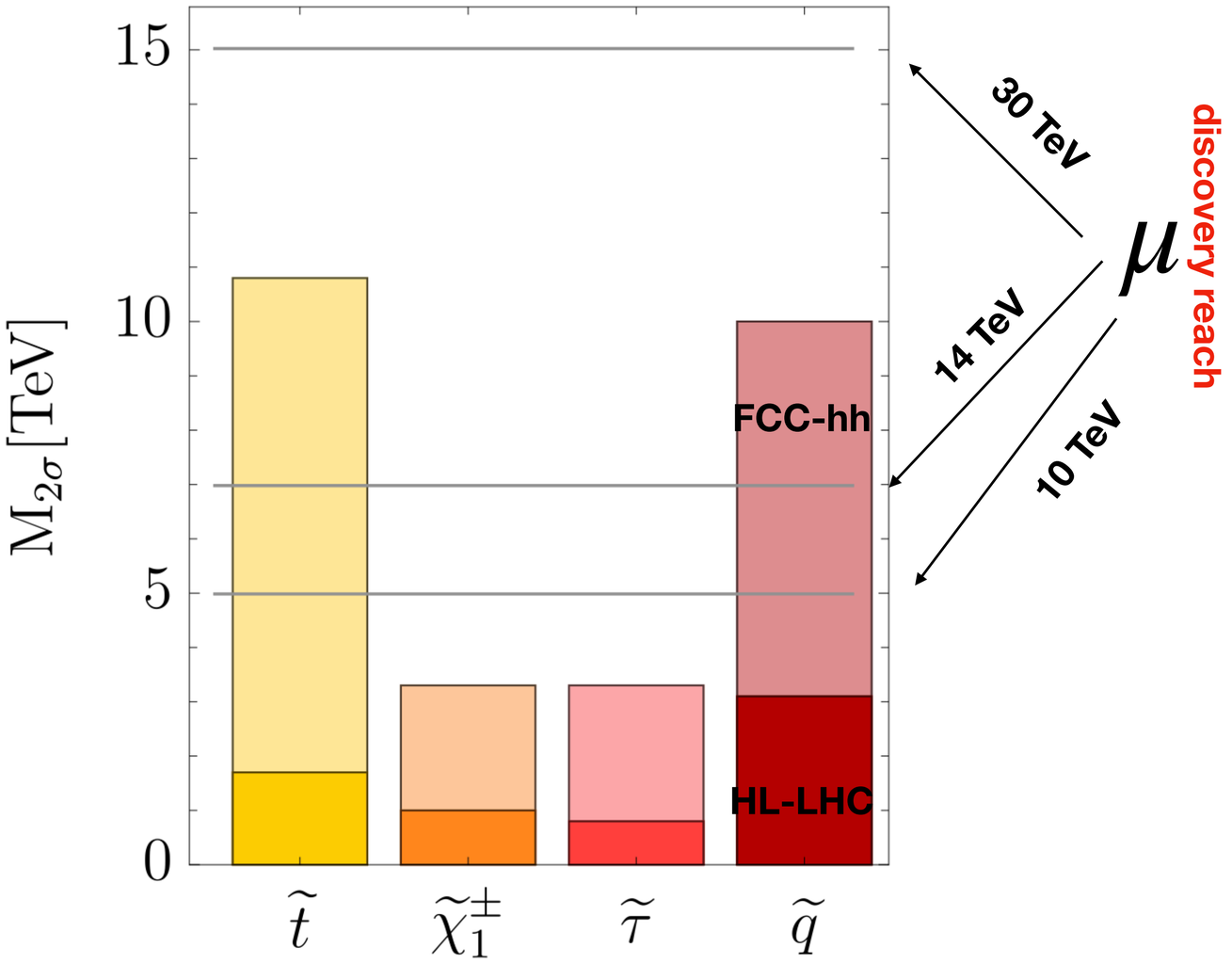
Simple Singlet extension of SM

Composite Higgs



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

Naturalness and Supersymmetry Example

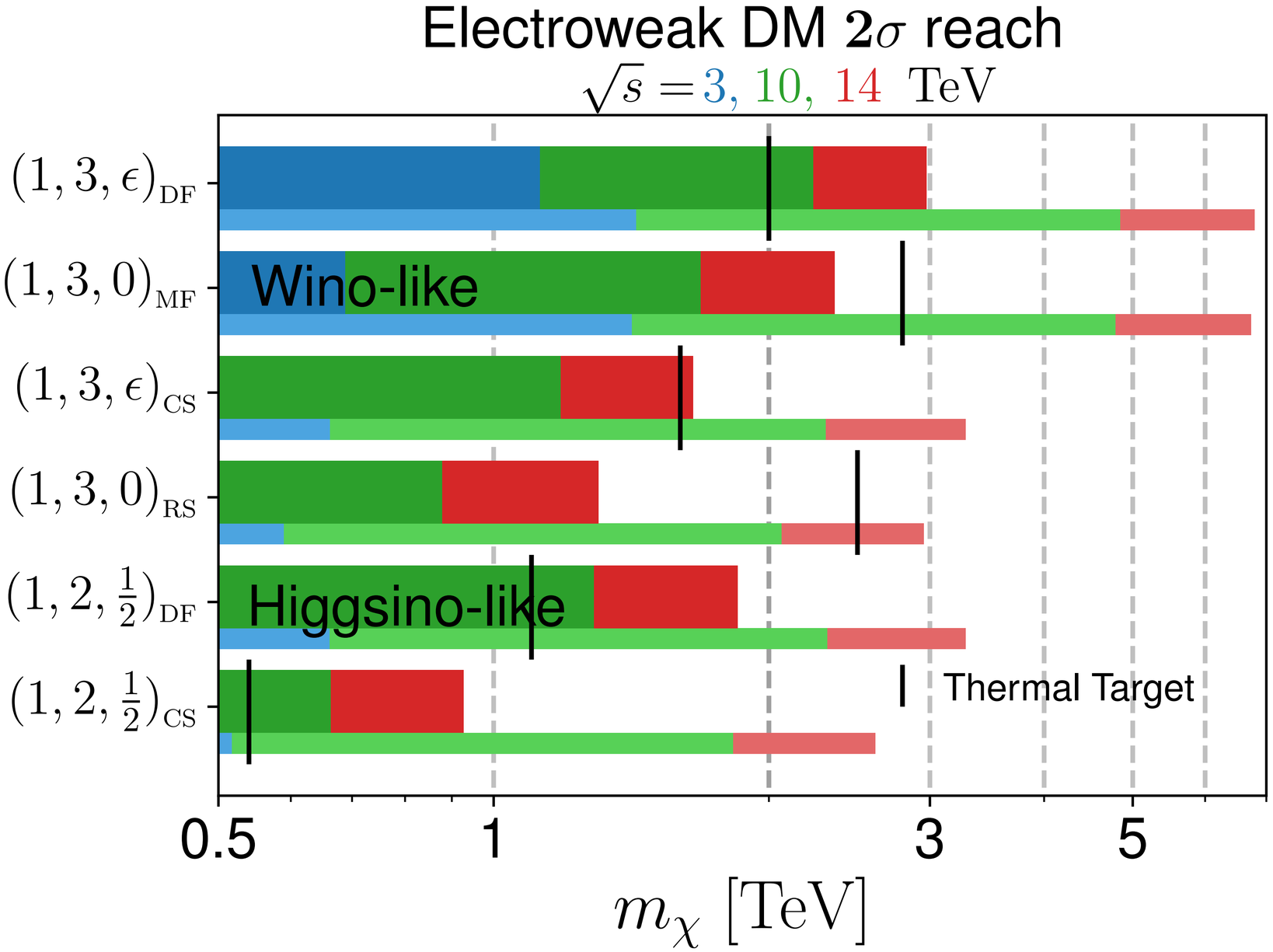


The Higgs at 125 GeV already suggested the SUSY scale was high, e.g. Stops ~ 10 TeV

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

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

WIMP DM - some cases colliders are better suited!



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

High Energy Lepton Collider - Physics Case

A high energy lepton collider *could* allow one to break the energy/precision dichotomy that has arisen in the past decades - but *needs* R&D to support this alternative path

Moreover it gives a compelling alternative vision for the future!

Conclusions

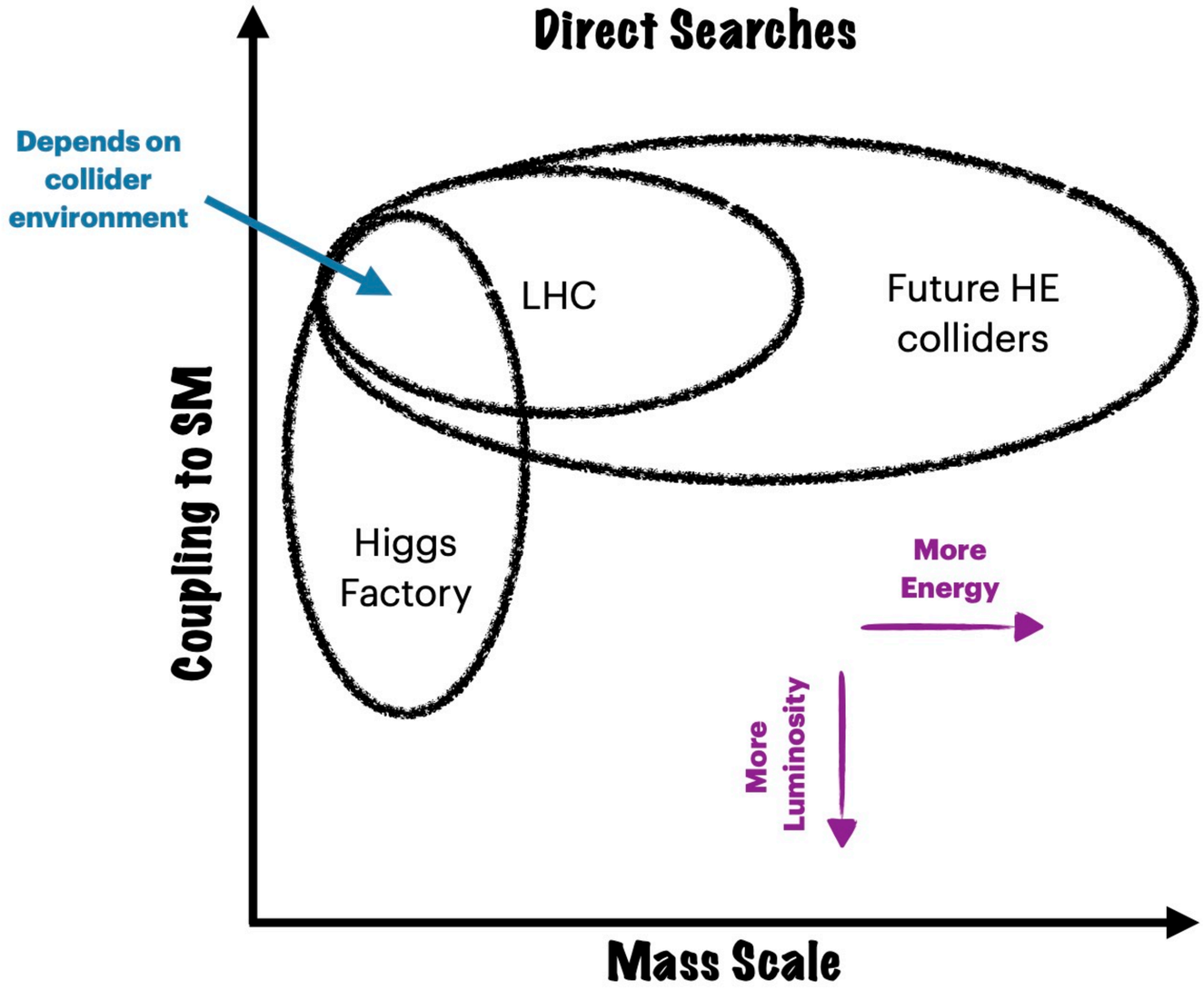
- Lepton colliders are *amazing* precision tools *but also* can be discovery machines
- ***"Low Energy" Higgs/EW lepton colliders*** have the most obvious pressing physics case to study the *most* unique particle in universe we know, the Higgs
  - Provides both precision for understanding Higgs and discovery windows for BSM portals
- ***"High Energy" lepton colliders*** allow us to understand *even more* about the Higgs and are a genuine BSM microscope to the shortest distances like hadron colliders - but with completely different technology
  - Moreover, they can break the classic precision/energy dichotomy and "include" the lower energies as well

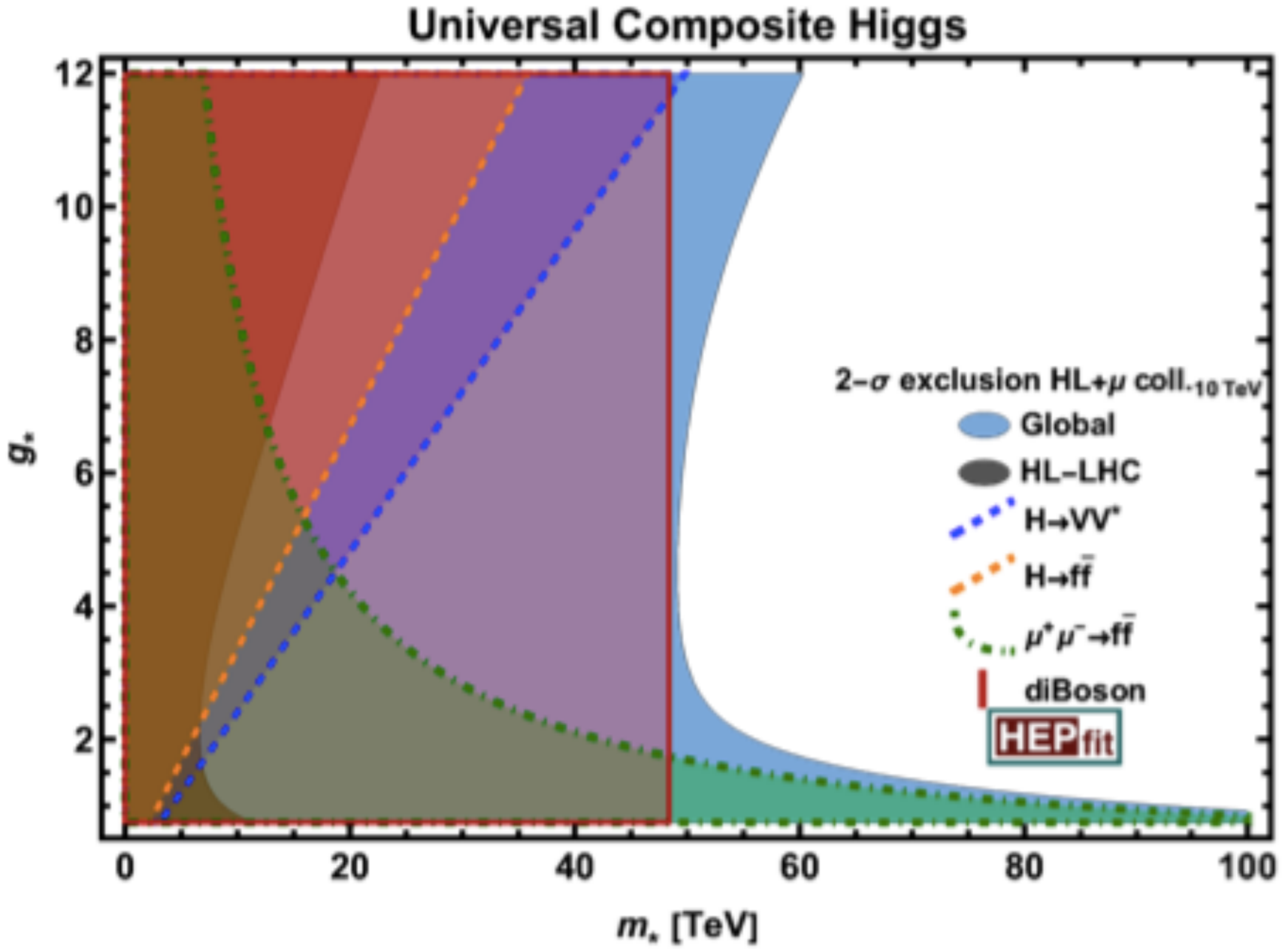
Conclusions

- Matching with the EF vision
  - “Low energy” e+e- colliders are either shovel ready, or close to it, and many options - **we must pursue it ASAP, wherever we can**
  - “High energy” lepton colliders require *new* concepts and **we must invest R&D *now*** if we want an alternative path to the highest energies (and especially in context of having a future US HE collider)
    - HE leptons *could* leapfrog protons into our lifetimes (<2070, eg μ’s) and provide complementary or superseding physics depending on COM energy in a smaller more sustainable footprint

Backup

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




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