Future e^+e^- and muon colliders

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

Why do we care about these colliders?

Why do we care about these colliders?

As the next to the last talk, hopefully you already know all the answers, but maybe you've been distracted…

Any new collider project attempts some sort of optimization

Physics we'd like to study

Colliders we can build

Colliders we could build in X years

Any new collider project attempts some sort of optimization

Ideally we have full overlap

Physics we'd like to study

Colliders we can build

Colliders we could build in X years

Any new collider project attempts some sort of optimization

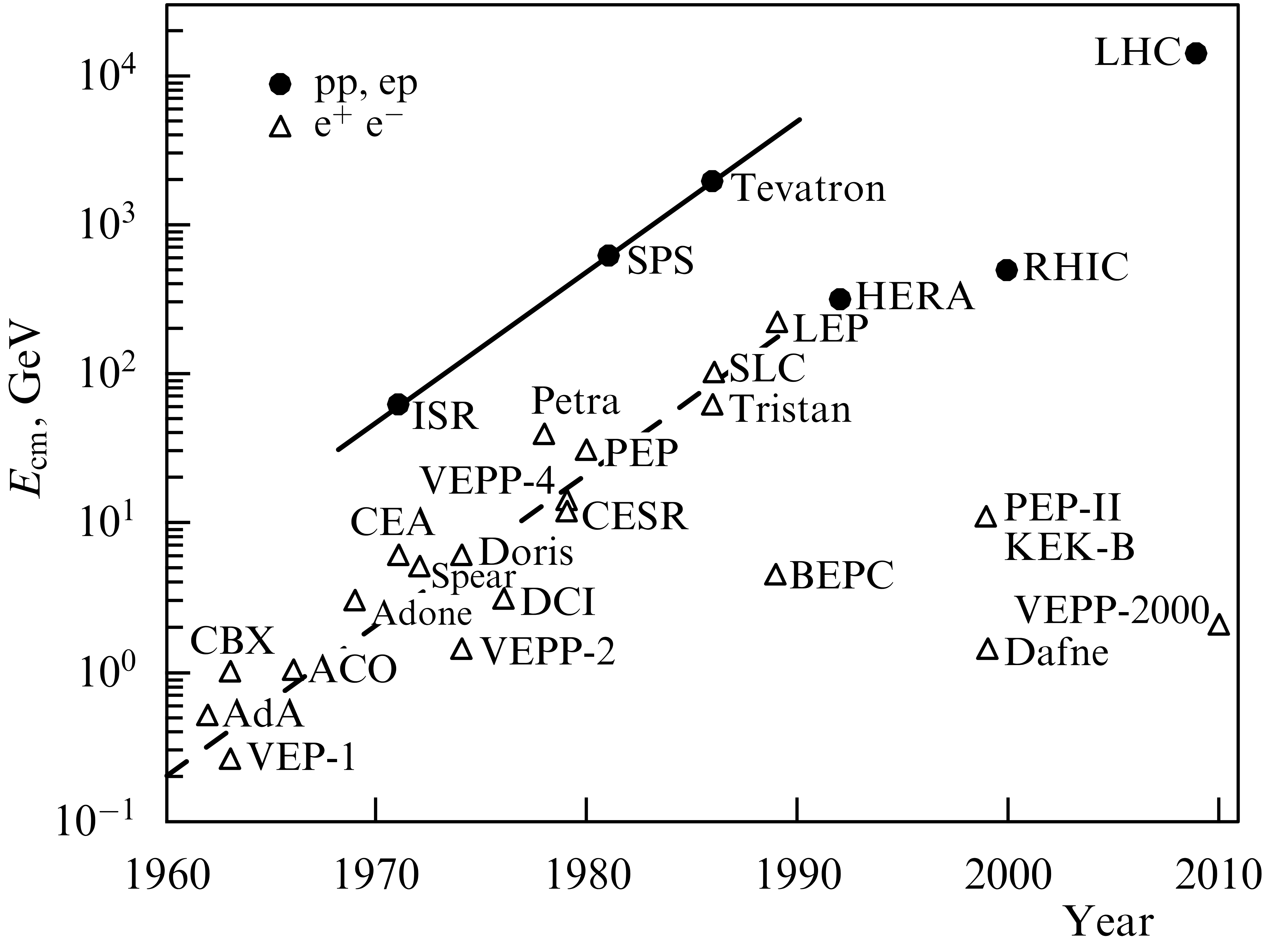
Physics we'd like to study

In practice we have to really understand this

Colliders we can build

Colliders we could build in X years

This dance has played out over many decades following a bifurcation based on particle type



(V. Shiltsev, 2012)

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***.

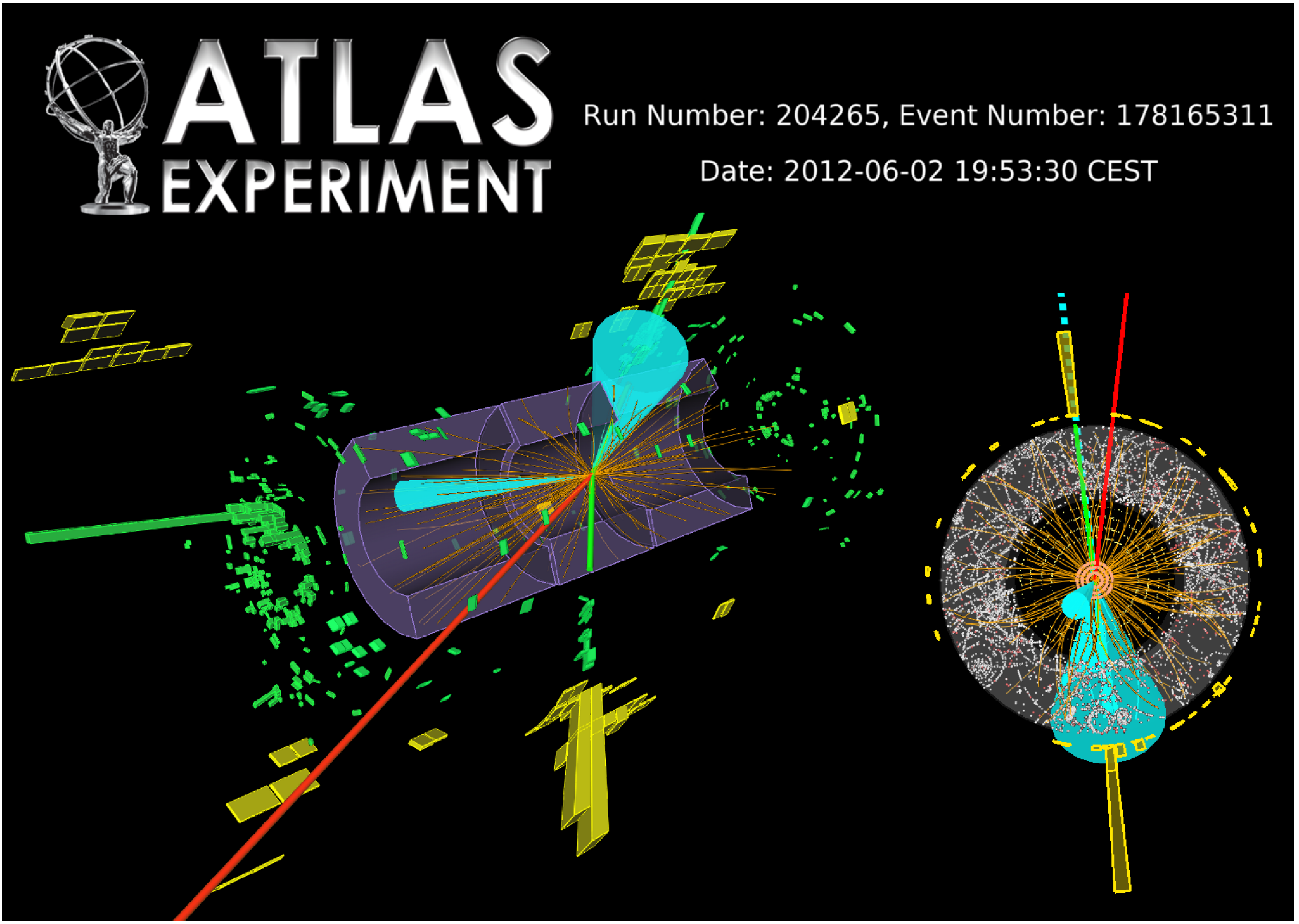
(V. Shiltsev, F. Zimmermann 2021 Reviews of Modern Physics)

Most basic difference:

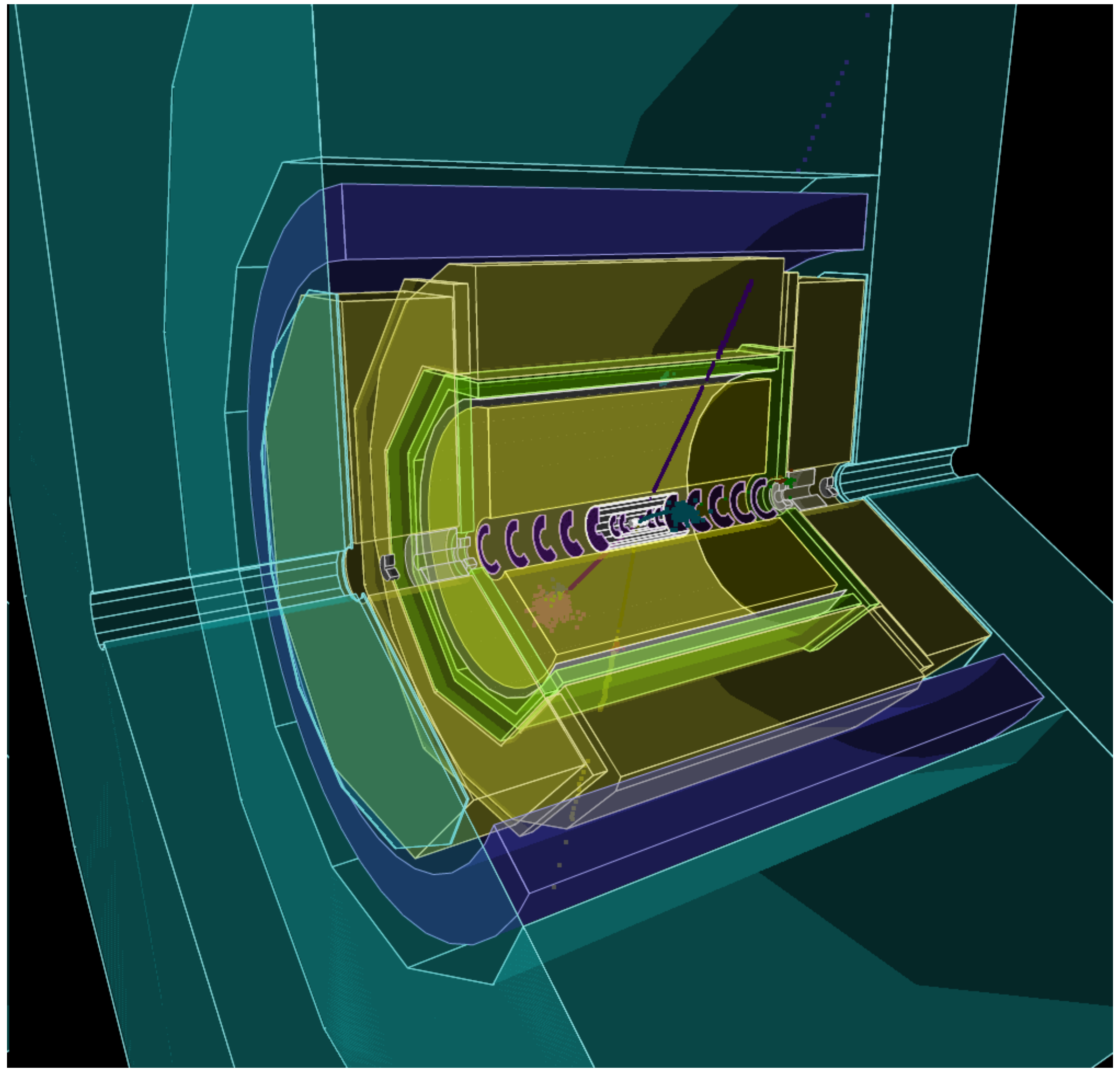
- Electron colliders collide ***fundamental particles -*** that exploit the full energy and don't have large QCD backgrounds - BUT they suffer from synchrotron radiation and beamstrahlung from small mass

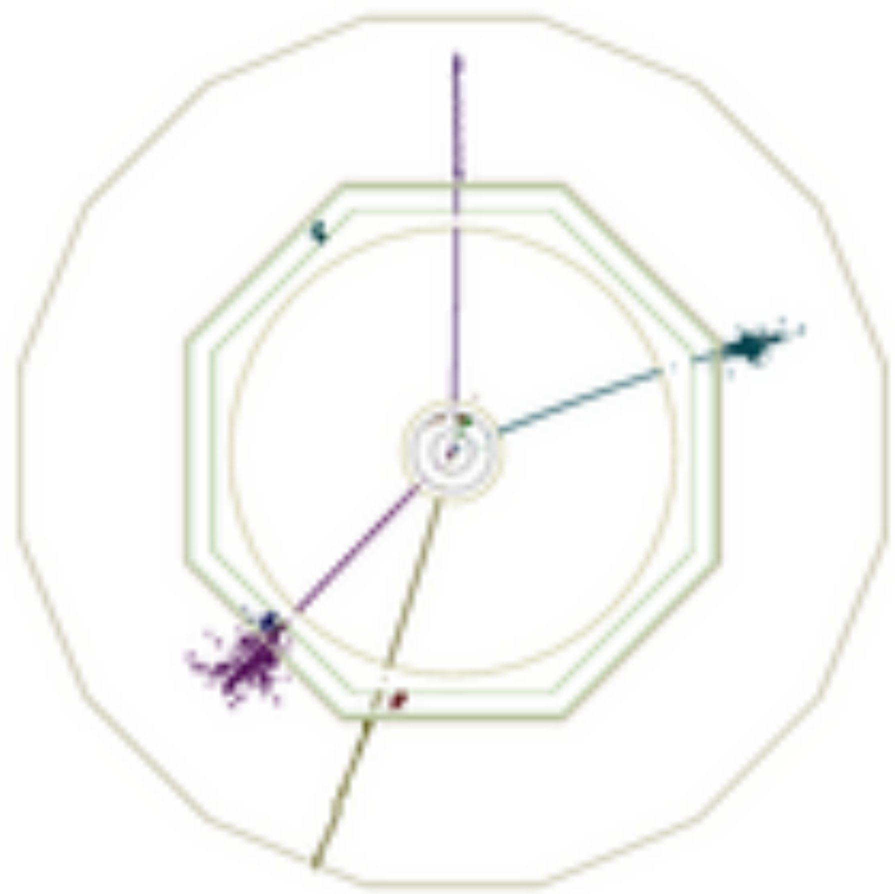
- Proton colliders collide ***composite particles -*** that generate large QCD backgrounds and you use a fraction of the energy of beam for physics - BUT they have a much larger mass and avoid synchrotron radiation

If you have a physics target, you can see by eye that electrons are easier!



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

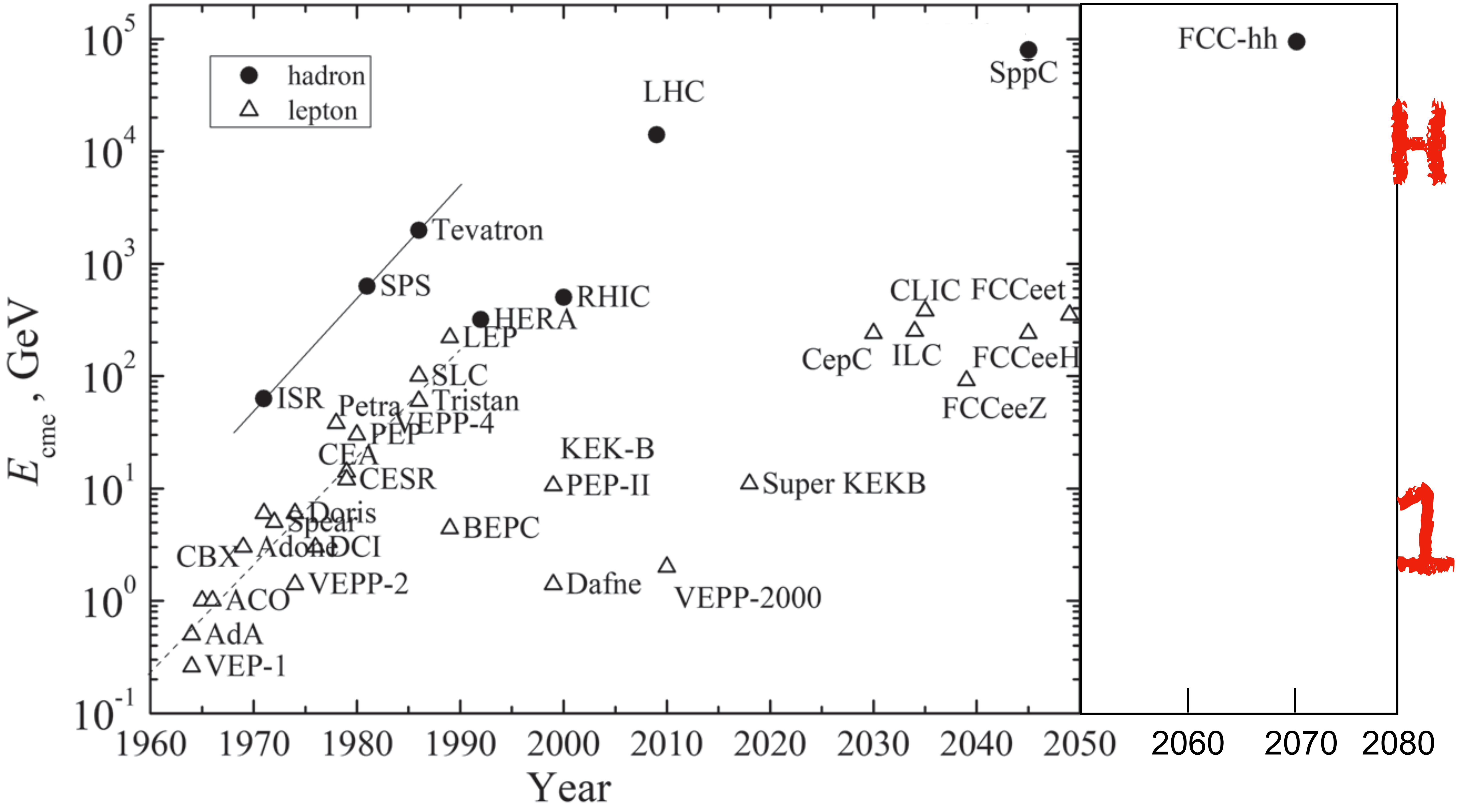




ILC - ILD 250 GeV $e^+e^- \to Zh \to \mu^+\mu^-h$

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

Therefore hopefully it will continue with CEPC/SPPC or FCC-ee/hh



Higgs Factory

10 TeV PCM

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

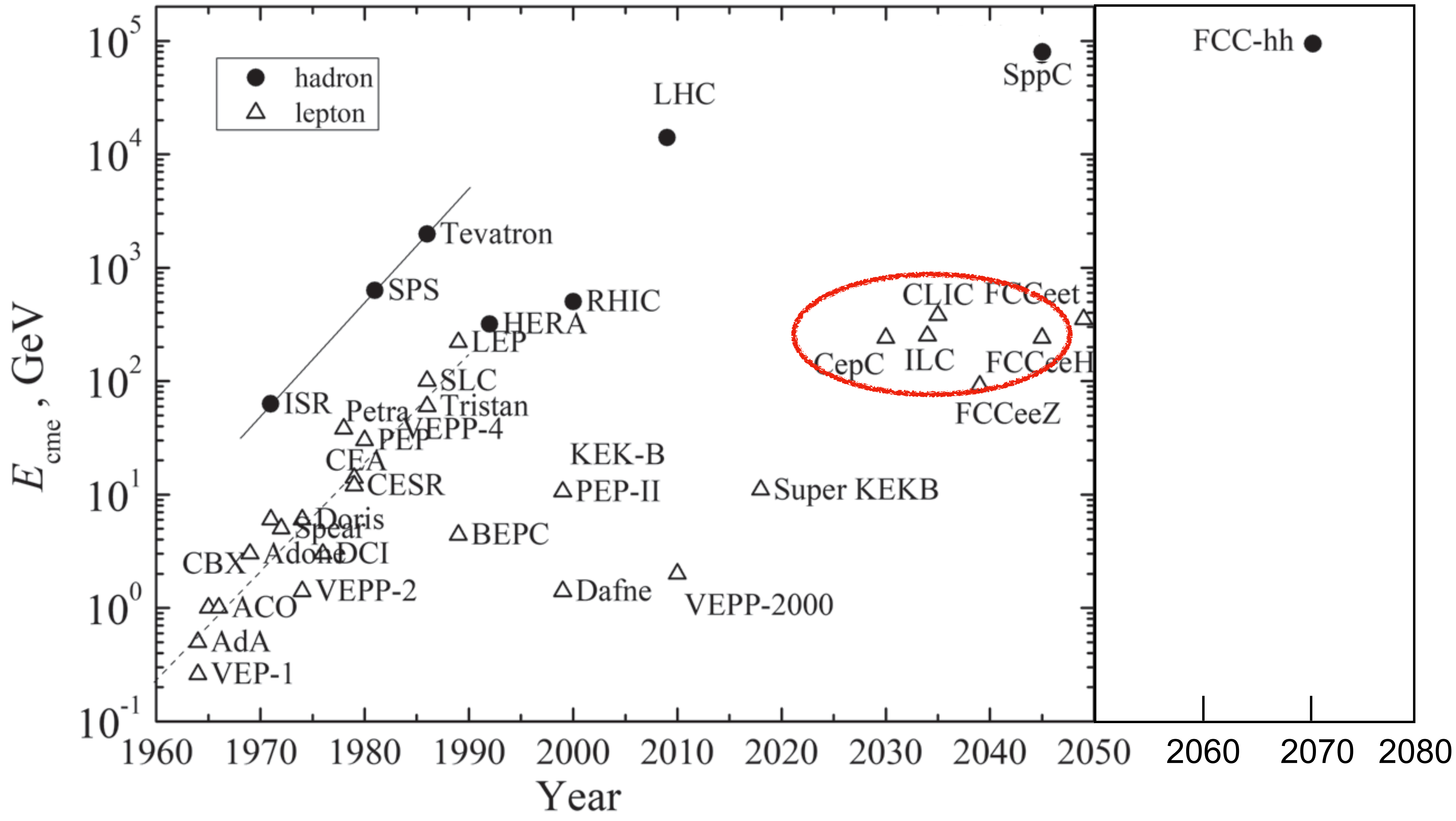
BUT, since this talk is about e^+e^- and $\mu^+\mu^-$ colliders, it turns out there are other possibilities as well:

The accelerator landscape is more nuanced

The physics capabilities are more varied

The physics needs have evolved with more data driving new efforts! (Both theoretical and experimental data)

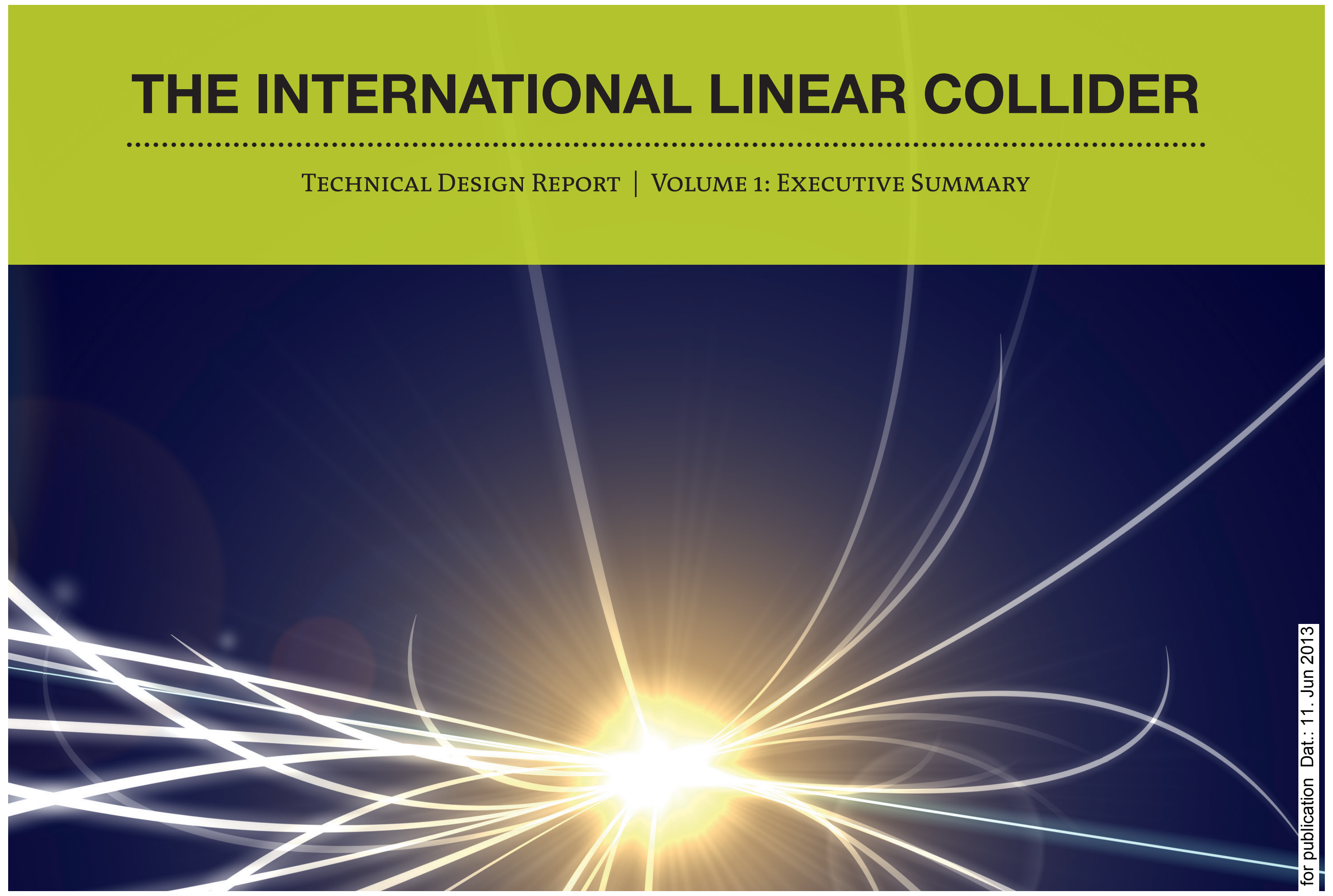
What's a Higgs Factory?

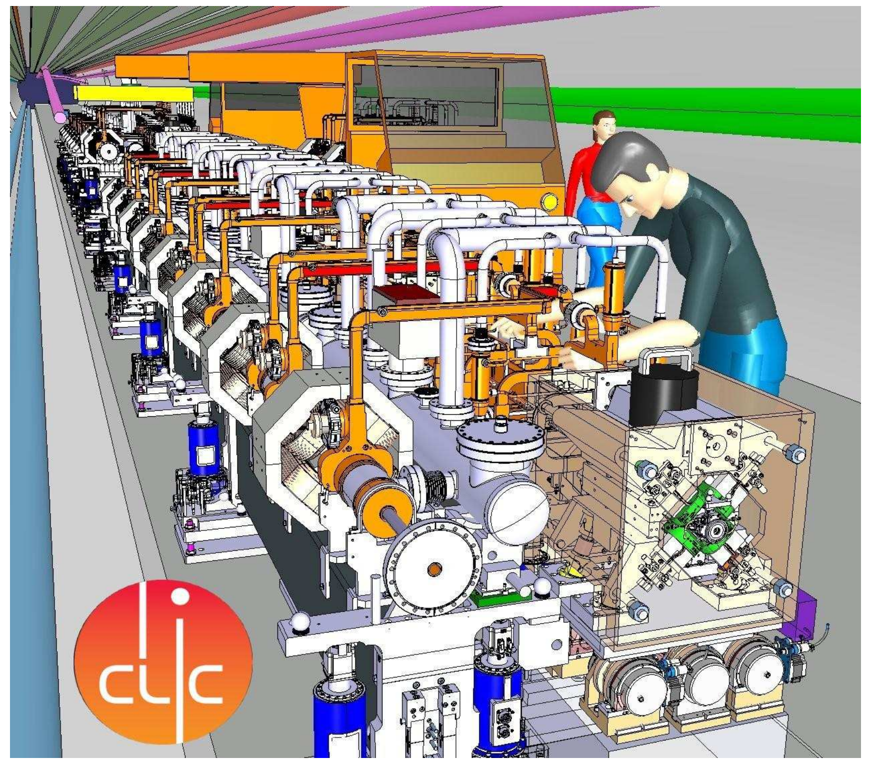


(V. Shiltsev, F. Zimmermann 2021 Reviews of Modern Physics)

An e^+e^- collider dominated by ZH production

These are also the *only* machines we know how to build “tomorrow”





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?

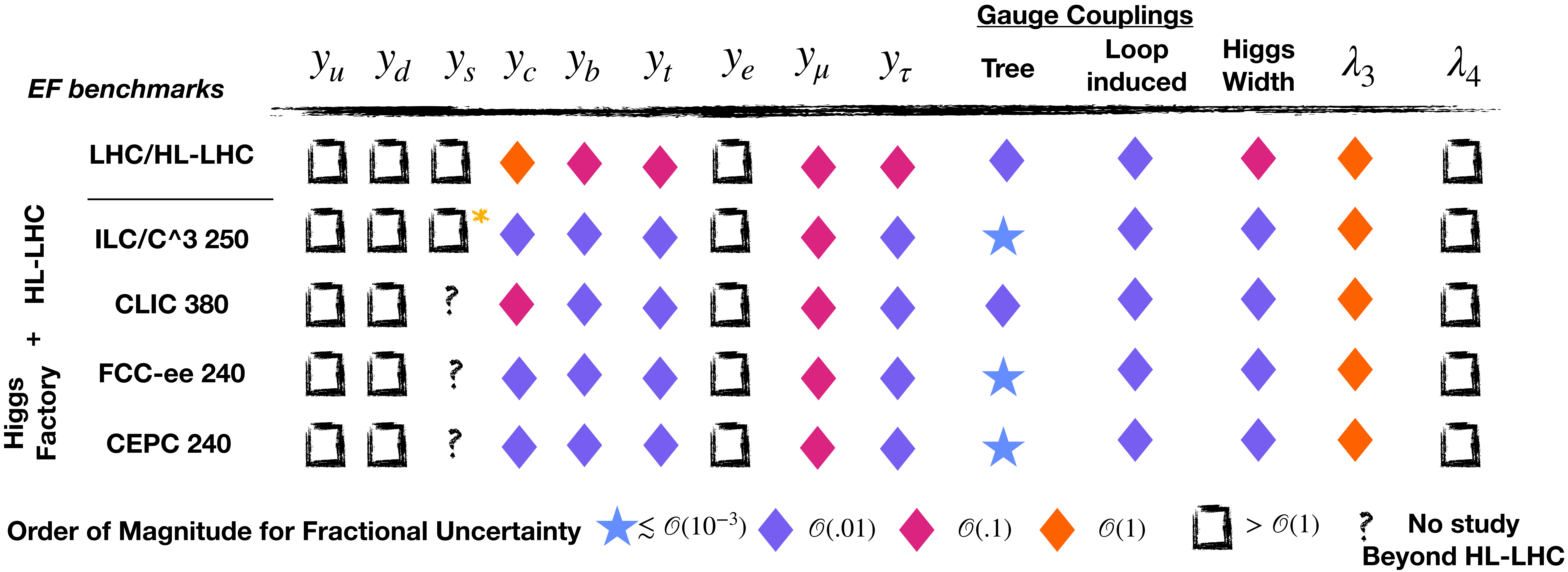
I have a strong dislike of showing tables of EFT operators or coupling modifiers

The difference between an uncertainty on g_{hXX} of 1.2% vs 1.1% makes no real *qualitative* difference probing the scale of new physics

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

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

Are all Higgs factories created equal? NO!

Circular

Beam gets reused for higher lumi

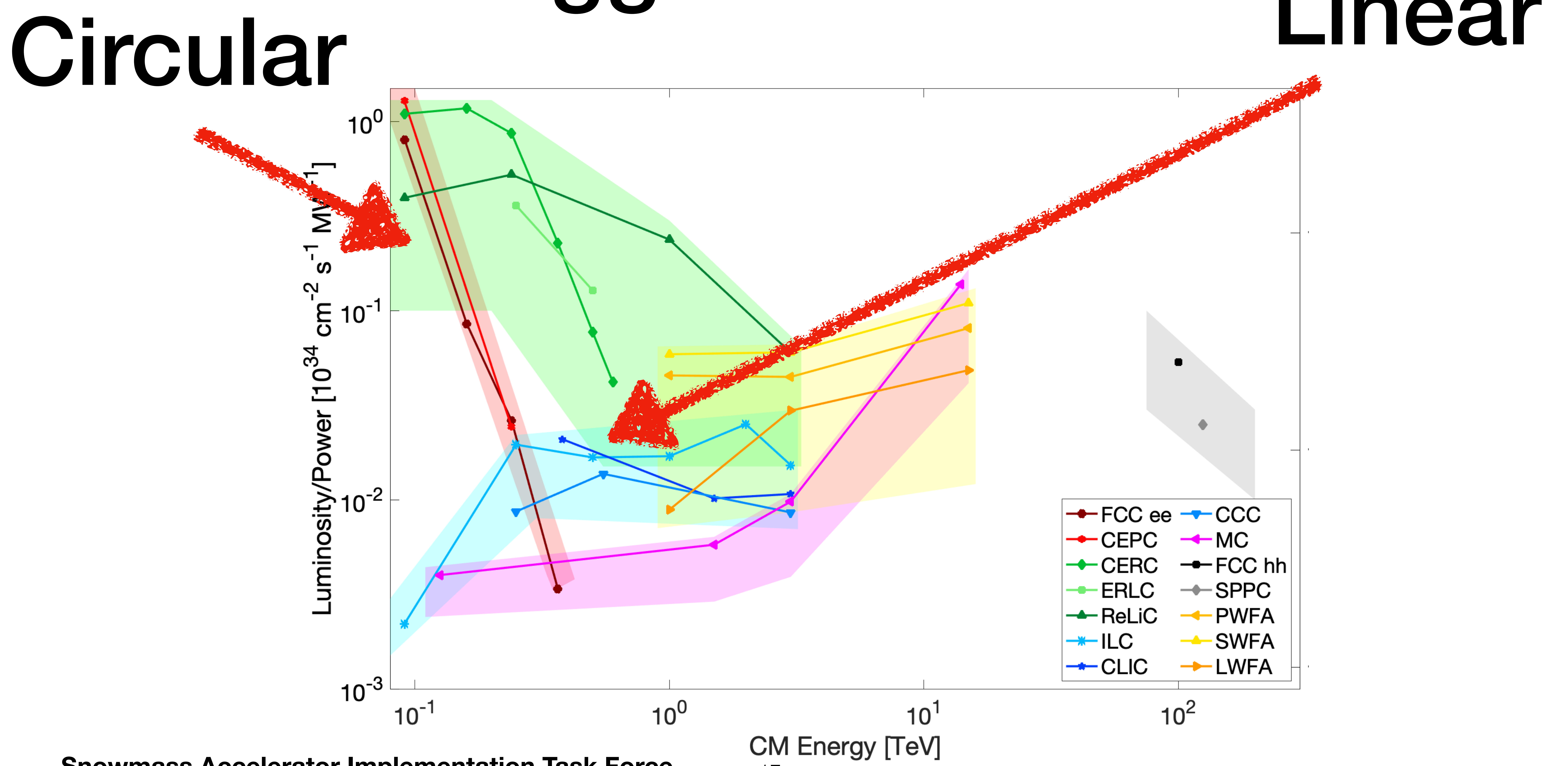
Beam goes in a circle, so synchrotron radiation limits energy reach

Linear

1 pass only - Lower lumi

Avoids synchrotron radiation - *can* go to higher Energy

Higgs factories

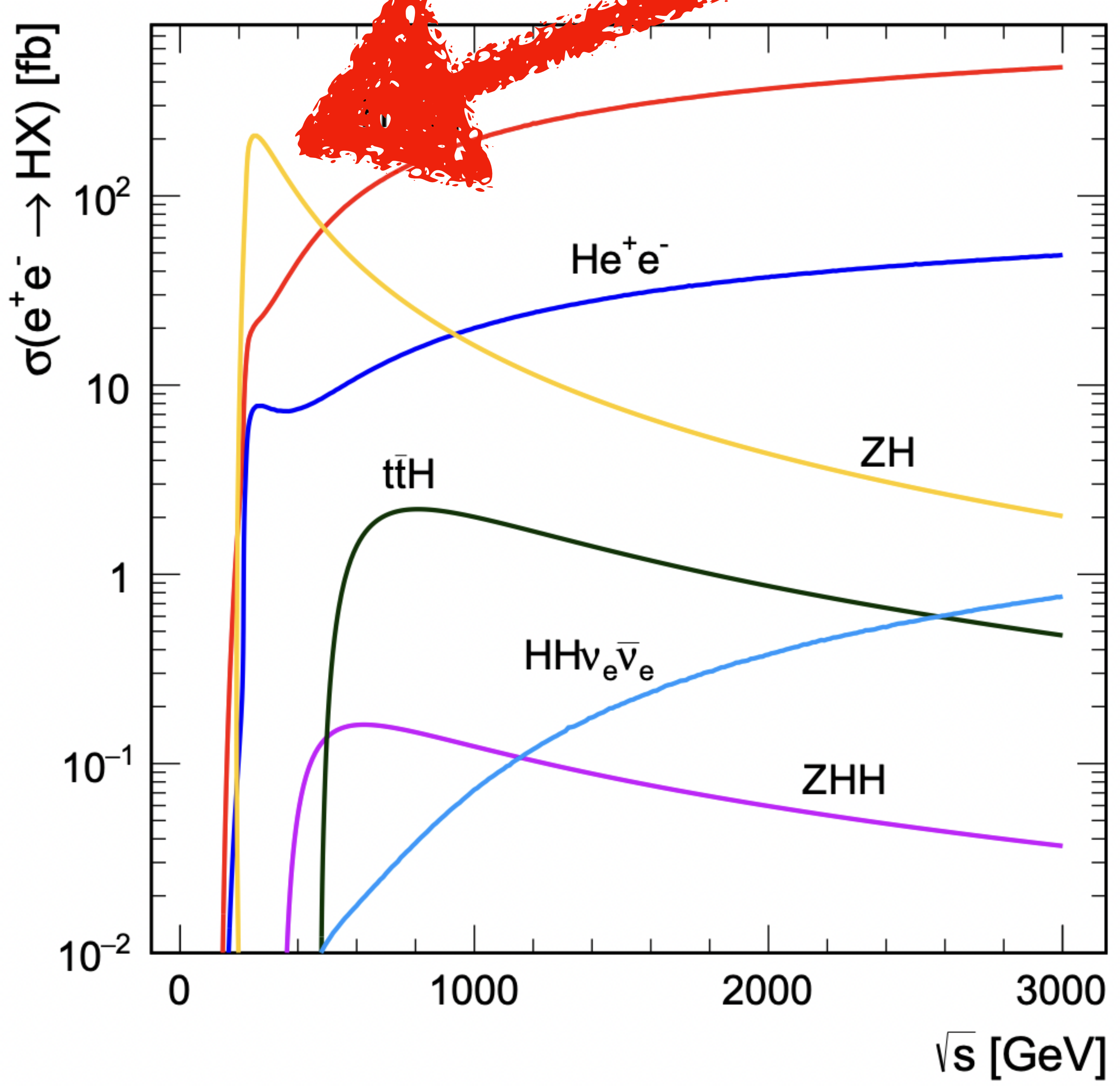


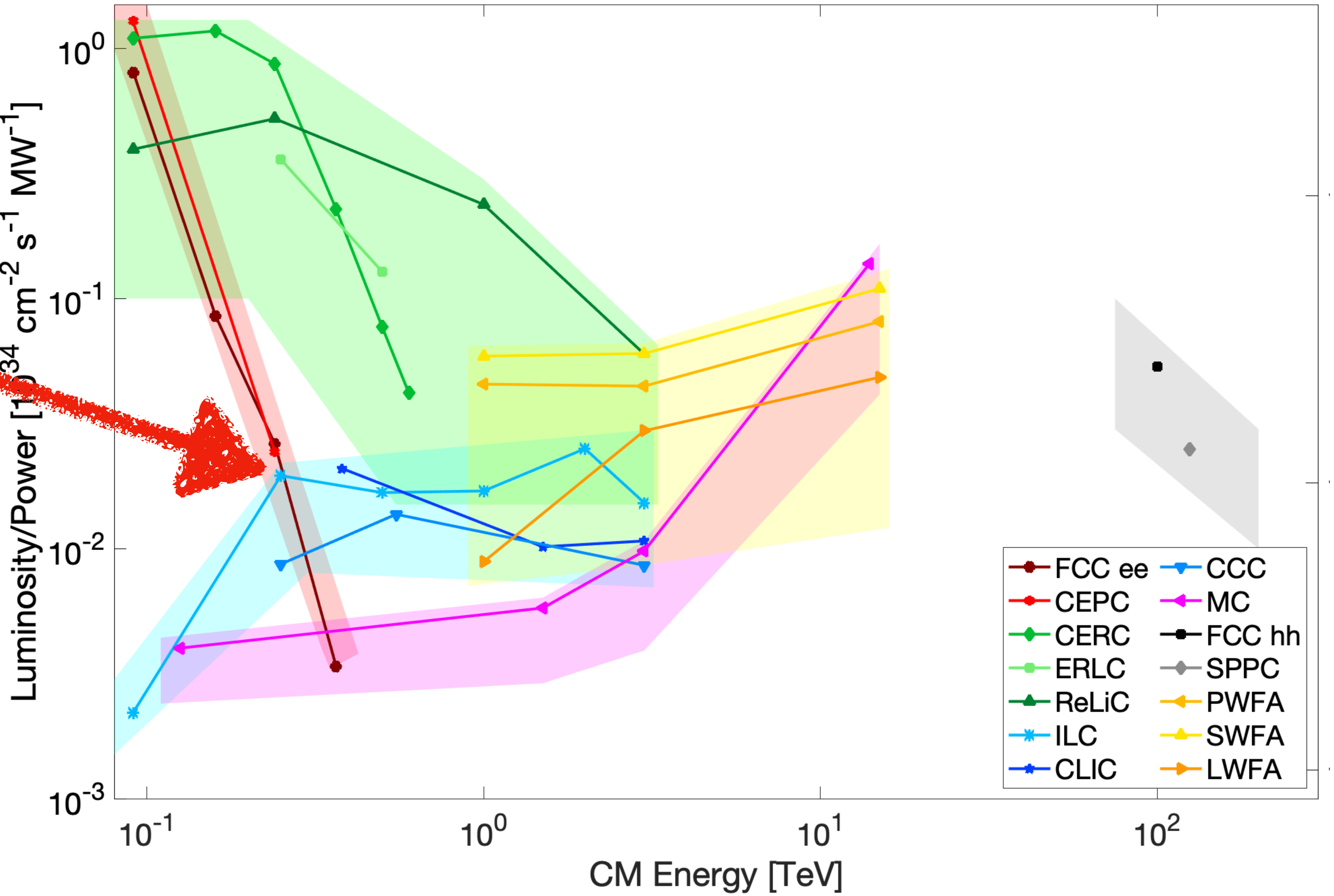
Snowmass Accelerator Implementation Task Force

Higgs factories

If power consumption/ run plans similar it's not surprising that the Higgs factory physics is similar

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



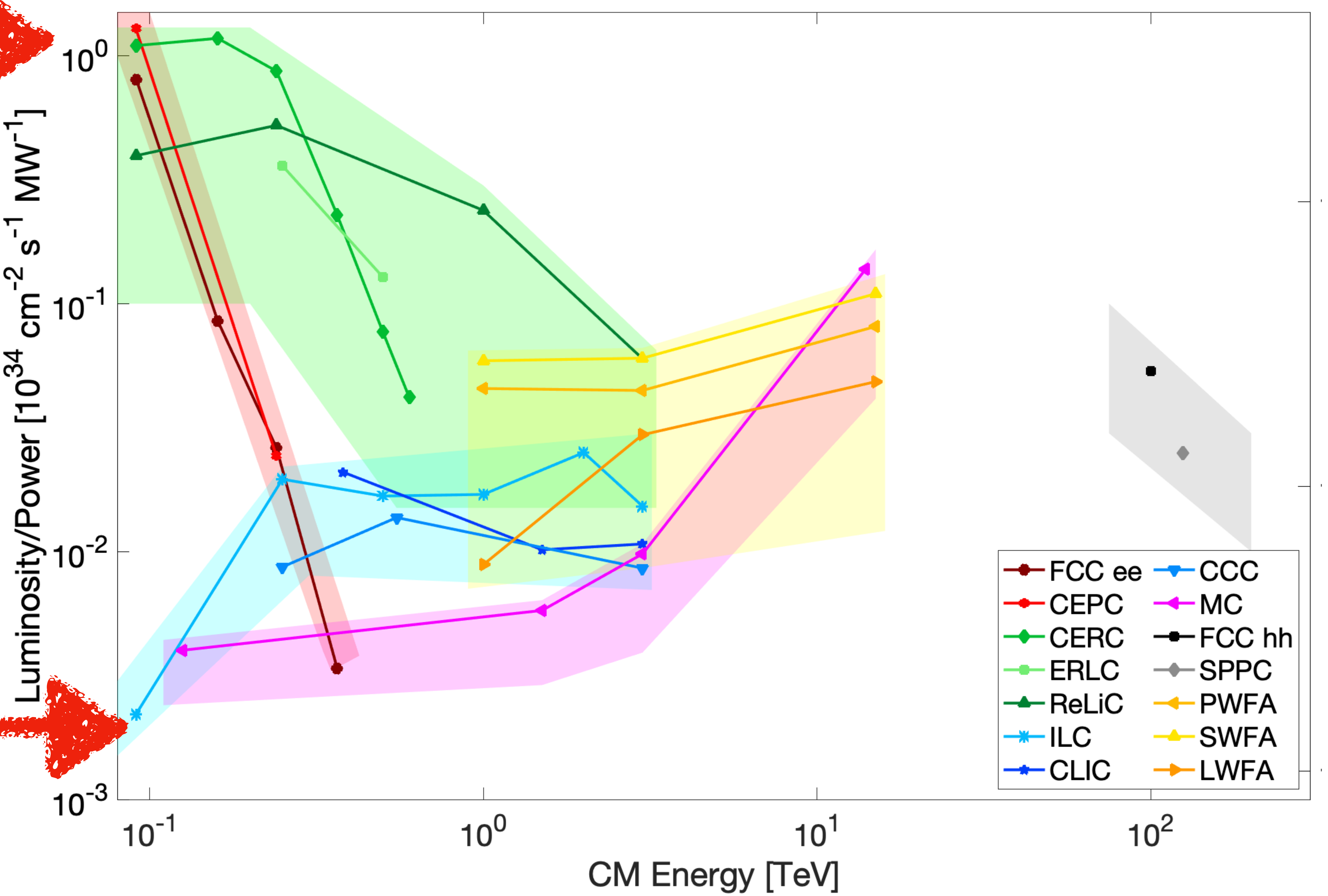


Snowmass Accelerator Implementation Task Force

Z factories - the type of "Higgs" Factory matters!

TeraZ

GigaZ



Snowmass Accelerator Implementation Task Force

Z factories - the type of “Higgs” Factory matters!

- Flavor physics - TeraZ allows one to go an order of magnitude beyond Belle II
- Light BSM physics - TeraZ allows to probe rare Z decays better (e.g. HNL)
- EW precision - TeraZ is an enormous jump (although polarization helps a LC)

Aside: Why can we do so well with Z factories now?

LEP1 had $\mathcal{O}(10^7)$ Z bosons

FCC-ee proposes $\mathcal{O}(10^{12})$ Z bosons!

Cross section is the same so we need a factor of 10^5 on Luminosity!

Modern Z-factories

Is CERN planning to consume 5 orders of magnitude more power in a few decades??? NO!

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Does digging an $\mathcal{O}(100)$ km tunnel make all the difference? NO!

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$$P_{sync}^{loss} \sim \left(\frac{E}{m}\right)^4 \frac{1}{R} \qquad \frac{27\,\text{km}}{91\text{km}} \sim 1/3$$

Synchrotron power loss is only about a factor of 3 better $\neq 10^5$

Modern Z-factories

Enabled by accelerator physicists!

LEP1 beam current ~mA

FCC-ee beam current ~ A

NC→SRF!

RF power efficiency $\sim 10^3$

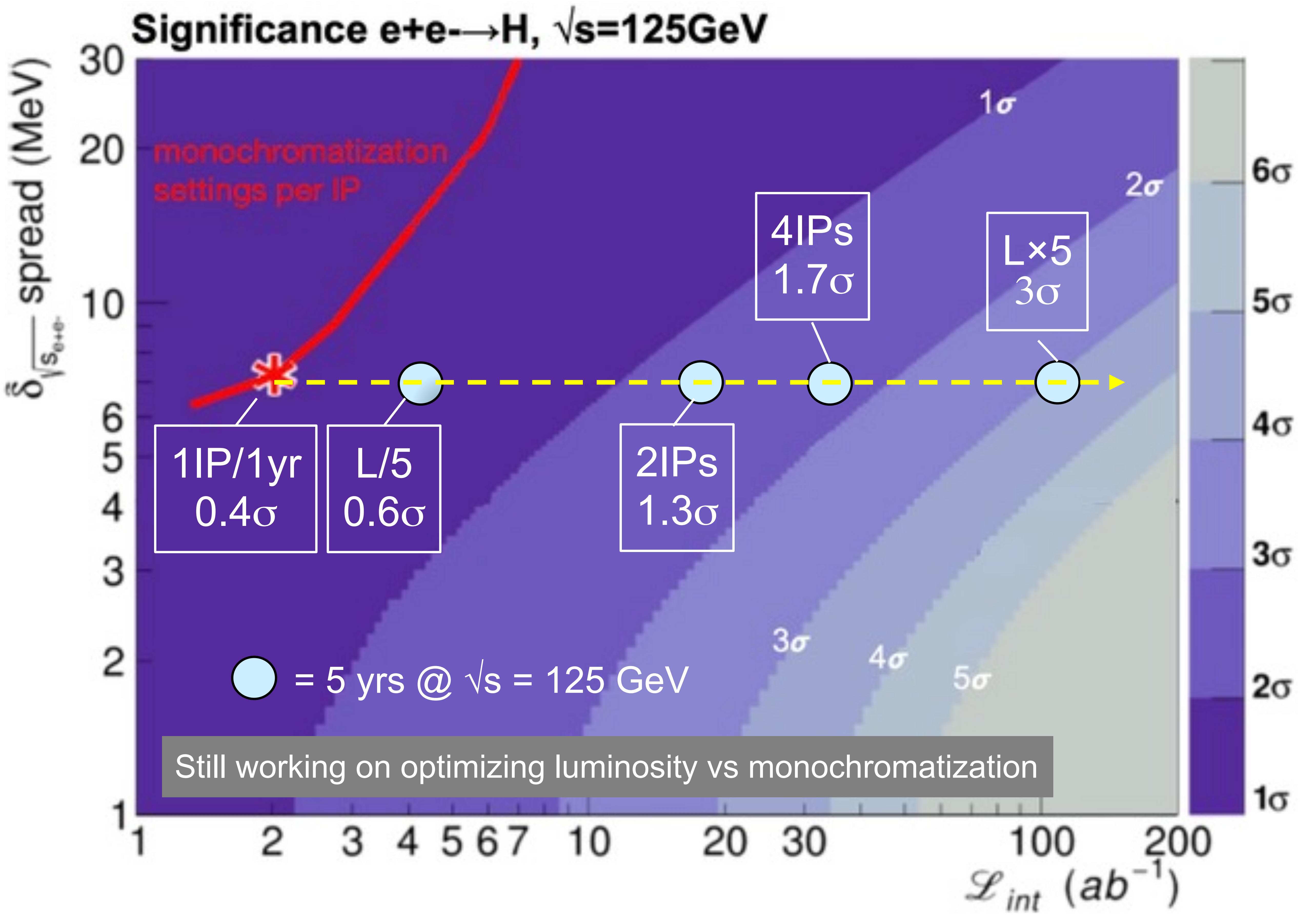
Crab Cavity + Final Focus $\sim 10^2$

You could in principle do TeraZ up to 240 GeV in a LEP length tunnel
(of course no detailed implementation study exists)

Does *not* mean you can do entire FCC-ee program in LEP tunnel, eventually you run out of room for RF and other tricks!

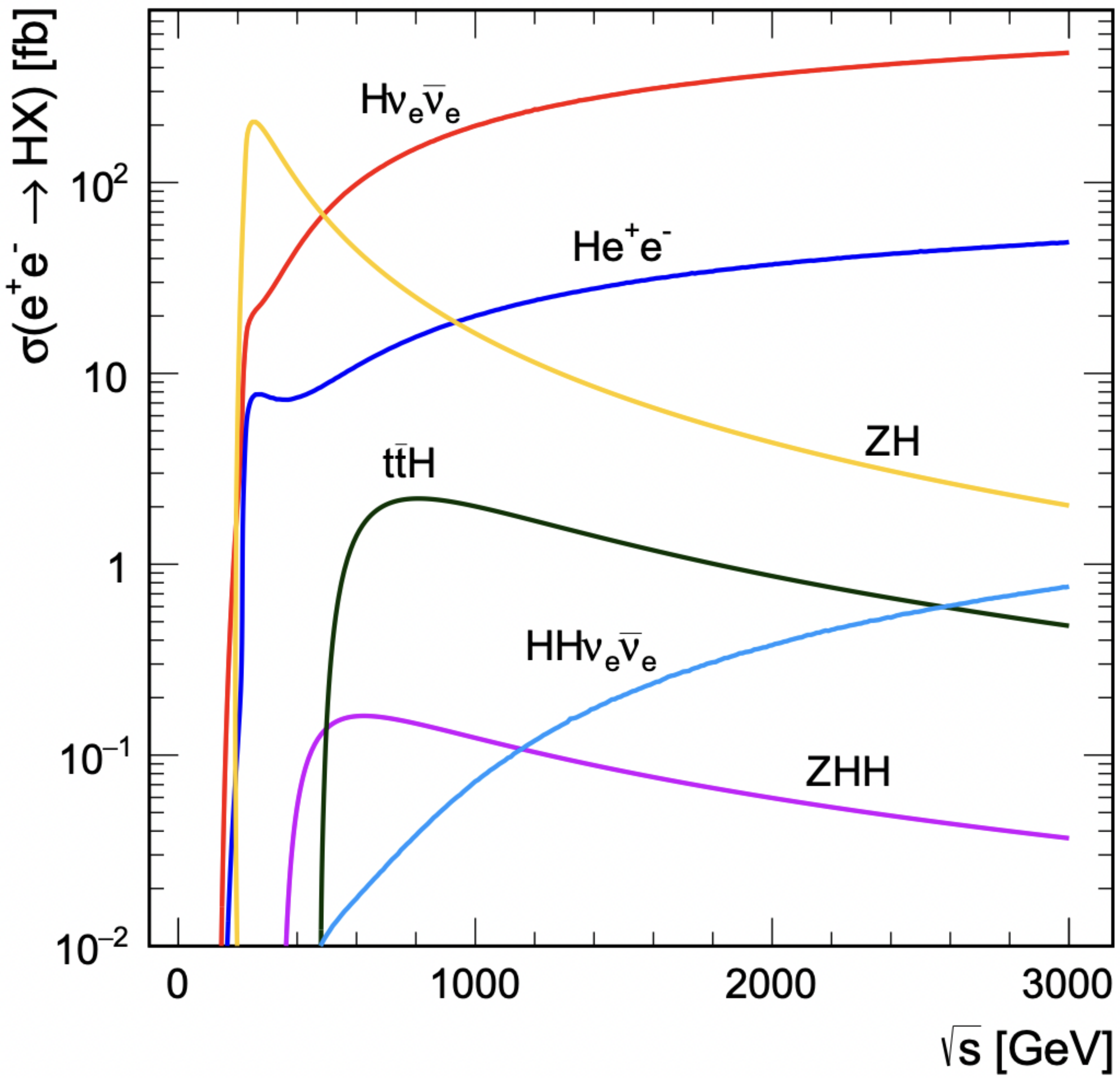
Circular e^+e^- colliders also have another potential trick - electron Yukawa

See C. Grojean's talk



I know of no models where it is relevant *yet*, but still super cool to get close to the 1st generation, should be a target for theory and experiment!

If a circular e^+e^- collider can do so much beyond a “Higgs factory”, are linear e^+e^- colliders uninteresting? No!!!



New processes at higher energies

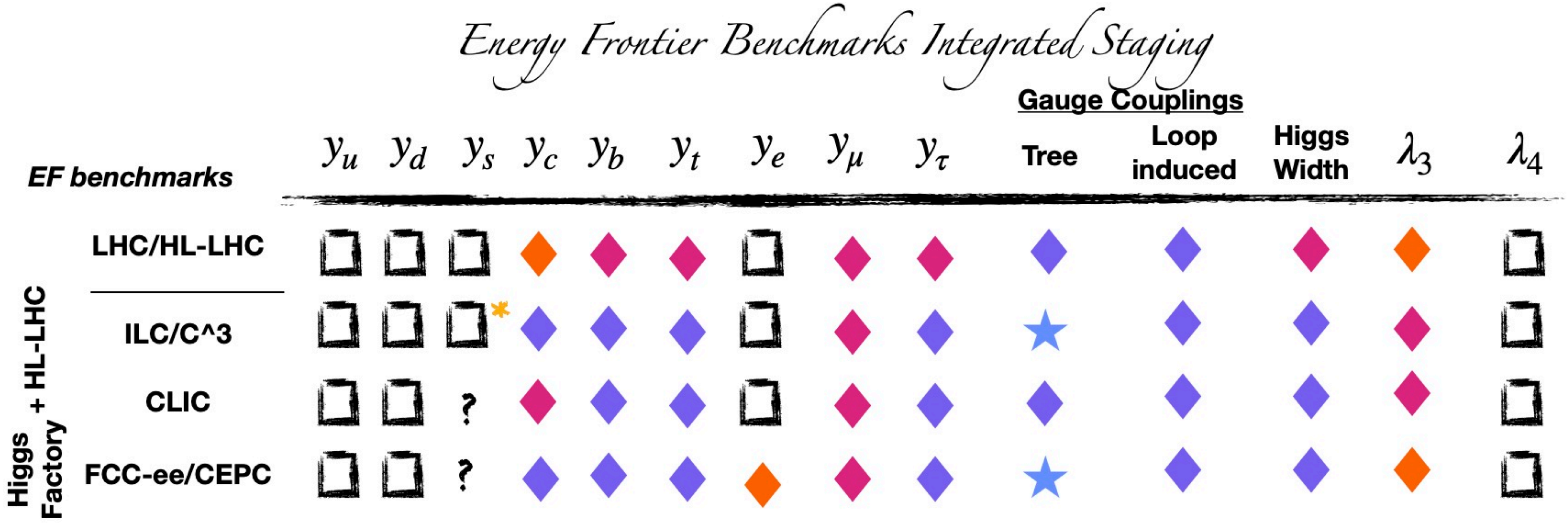
New processes means new measurement possibilities

κ_λ sensitivity

collider	Indirect-h	hh	combined
HL-LHC [78]	100-200%	50%	50%
ILC_{250}/C^3-250 [51, 52]	49%	—	49%
ILC_{500}/C^3-550 [51, 52]	38%	20%	20%
$CLIC_{380}$ [54]	50%	—	50%
$CLIC_{1500}$ [54]	49%	36%	29%
$CLIC_{3000}$ [54]	49%	9%	9%
FCC-ee [55]	33%	—	33%

Snowmass Higgs report 2209.07510

Linear colliders and Higgs physics



Is that all?

One general theme we've heard this week, how do you think of precision? Coupling modifiers, SMEFT/HEFT, Toy Model, Full Model?

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Coupling modifiers, SMEFT/HEFT, Toy Model, Full Model?

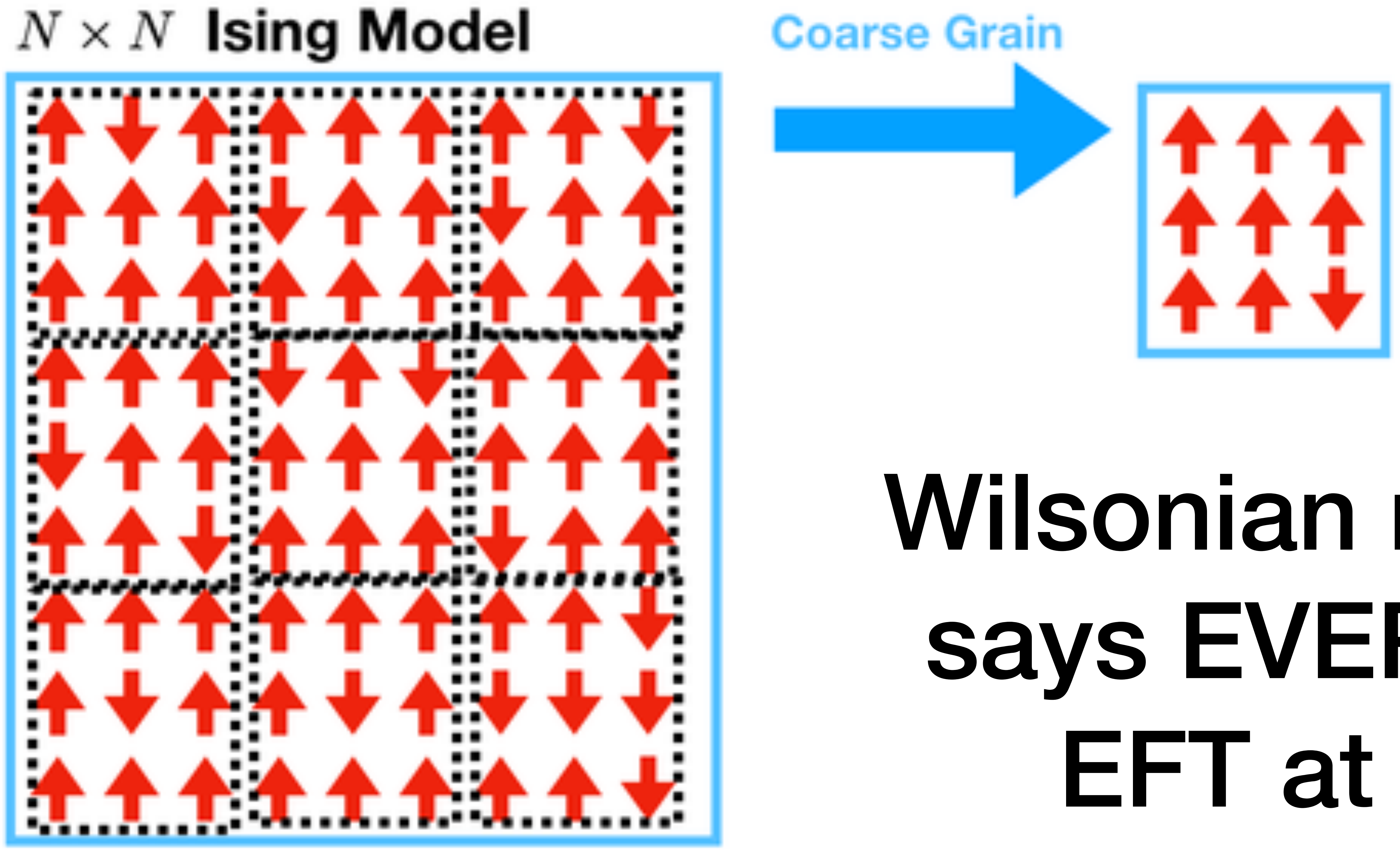
There is no such thing as a model independent interpretation!

One general theme we've heard this we… o
you think of precision…
Coupling modifiers, SMEFT/HE… odel, Full
Mod…

SMEFT IS <u>A</u> MODEL, NOT MODEL INDEPENDENT

There is… ch thing as a model i… endent interpretation!

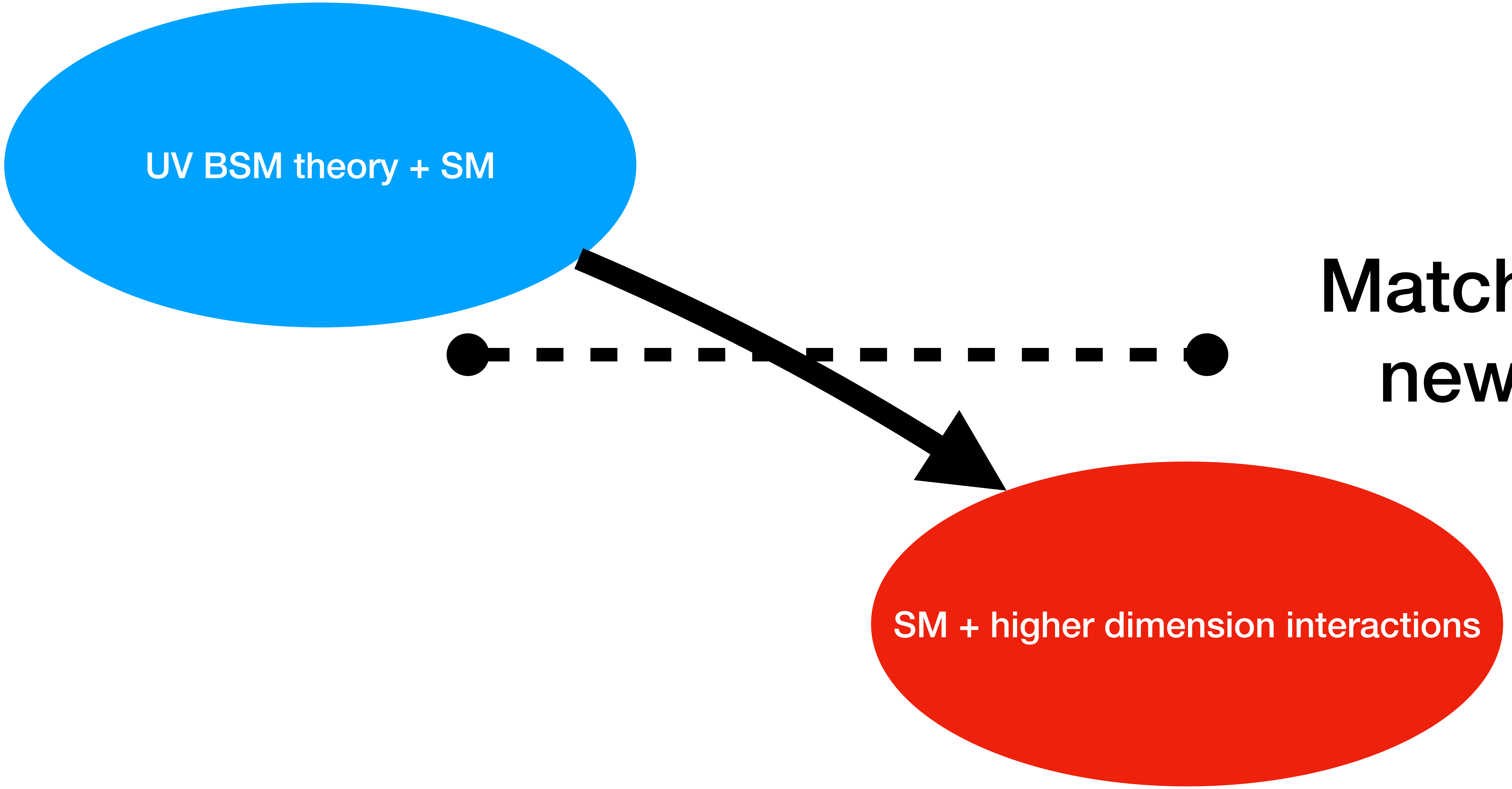
Our modern understanding of QFT is based on Wilsonian Renormalization



Wilsonian renormalization says EVERYTHING is an EFT at low energy!

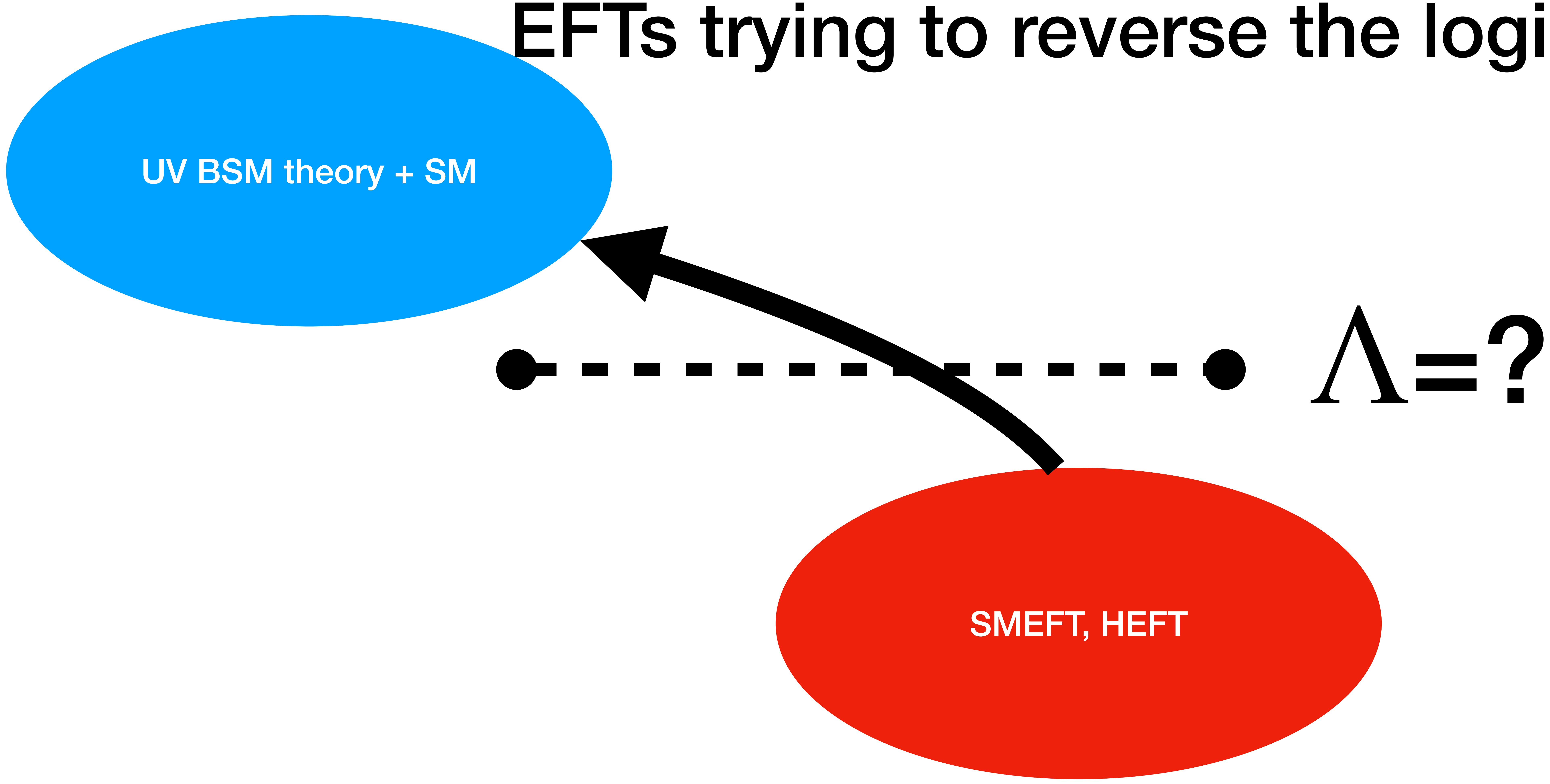
Why it works *systematically* is that all higher dimension operators contribute as $\sim \left(\frac{E}{\Lambda}\right)^{\#>0}$

This is why regardless of BSM physics



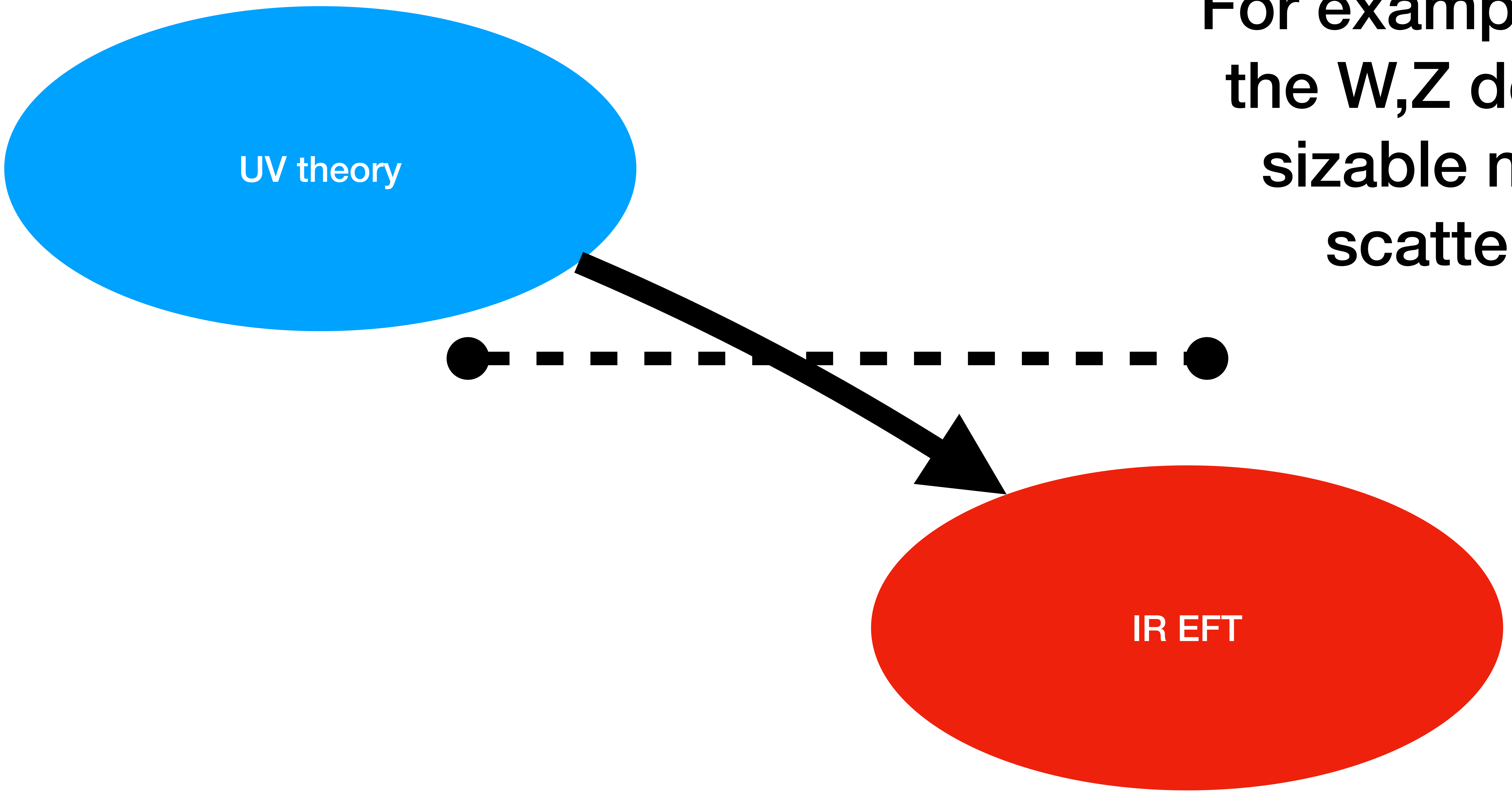
Matching scale, like a new particle mass

This led to a modern renaissance for the LHC and EFTs trying to reverse the logic



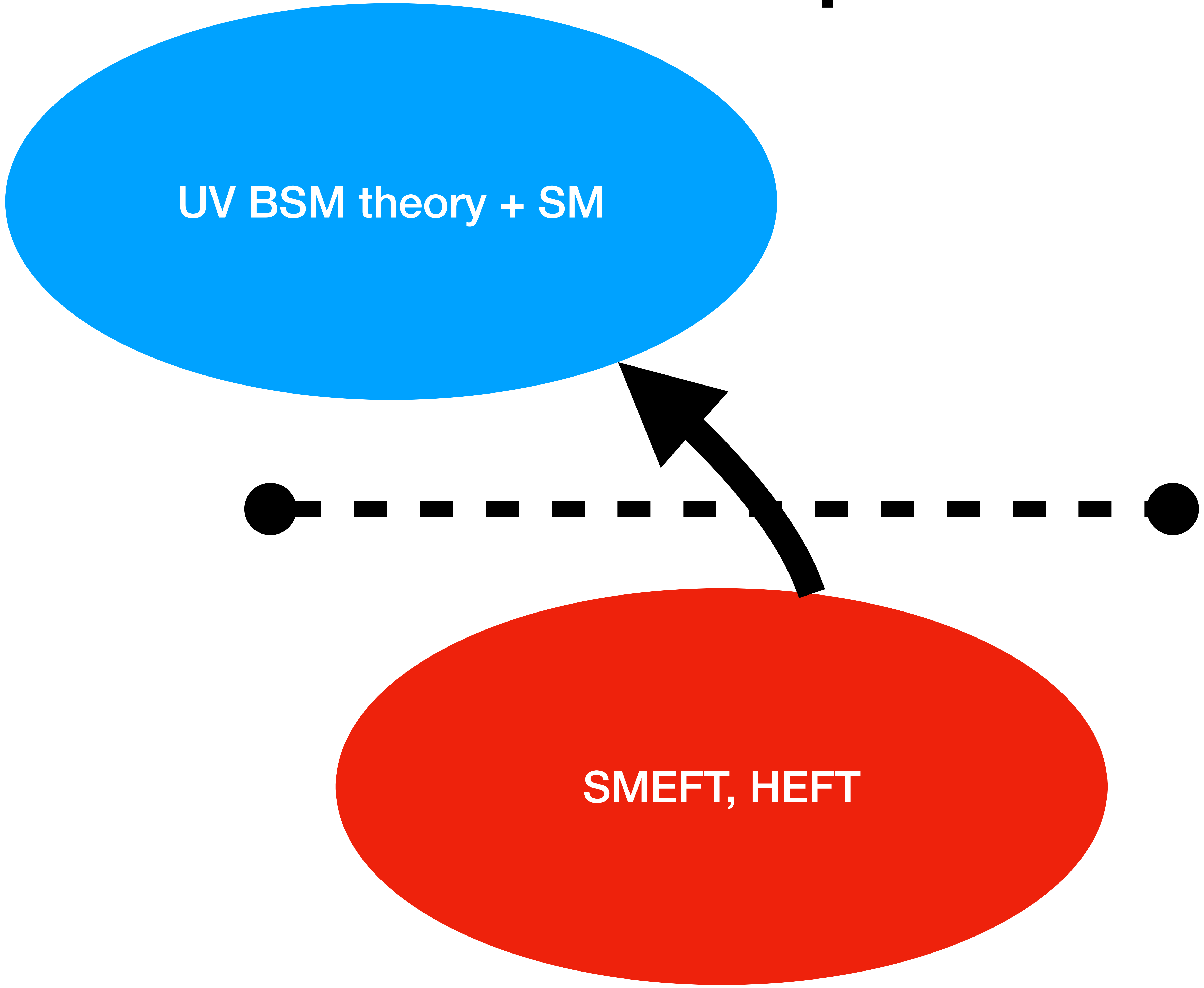
However the RGE flow is irreversible!

EFTs are not model independent



For example, integrating out the W,Z doesn't give you a sizable new gluon gluon scattering operator!

From bottom up measurements you know this too!



$$\Lambda = ?$$

Flavor

$$\frac{C_s}{\Lambda^2} s\bar{d}s\bar{d} \longrightarrow \Lambda \gtrsim 10^4\,\text{TeV}$$

$$\frac{C_c}{\Lambda^2} c\bar{u}c\bar{u} \longrightarrow \Lambda \gtrsim 10^3\,\text{TeV}$$

$$\frac{C_b}{\Lambda^2} b\bar{d}b\bar{d} \longrightarrow \Lambda \gtrsim 10^4\,\text{TeV}$$

EWPT

$$\frac{C_T}{\Lambda^2} (H^\dagger D_\mu H)^2 \longrightarrow \Lambda \gtrsim 10\,\text{TeV}$$

You must make model dependent assumptions to use it, otherwise you are guaranteed to see nothing at the LHC or future colliders!

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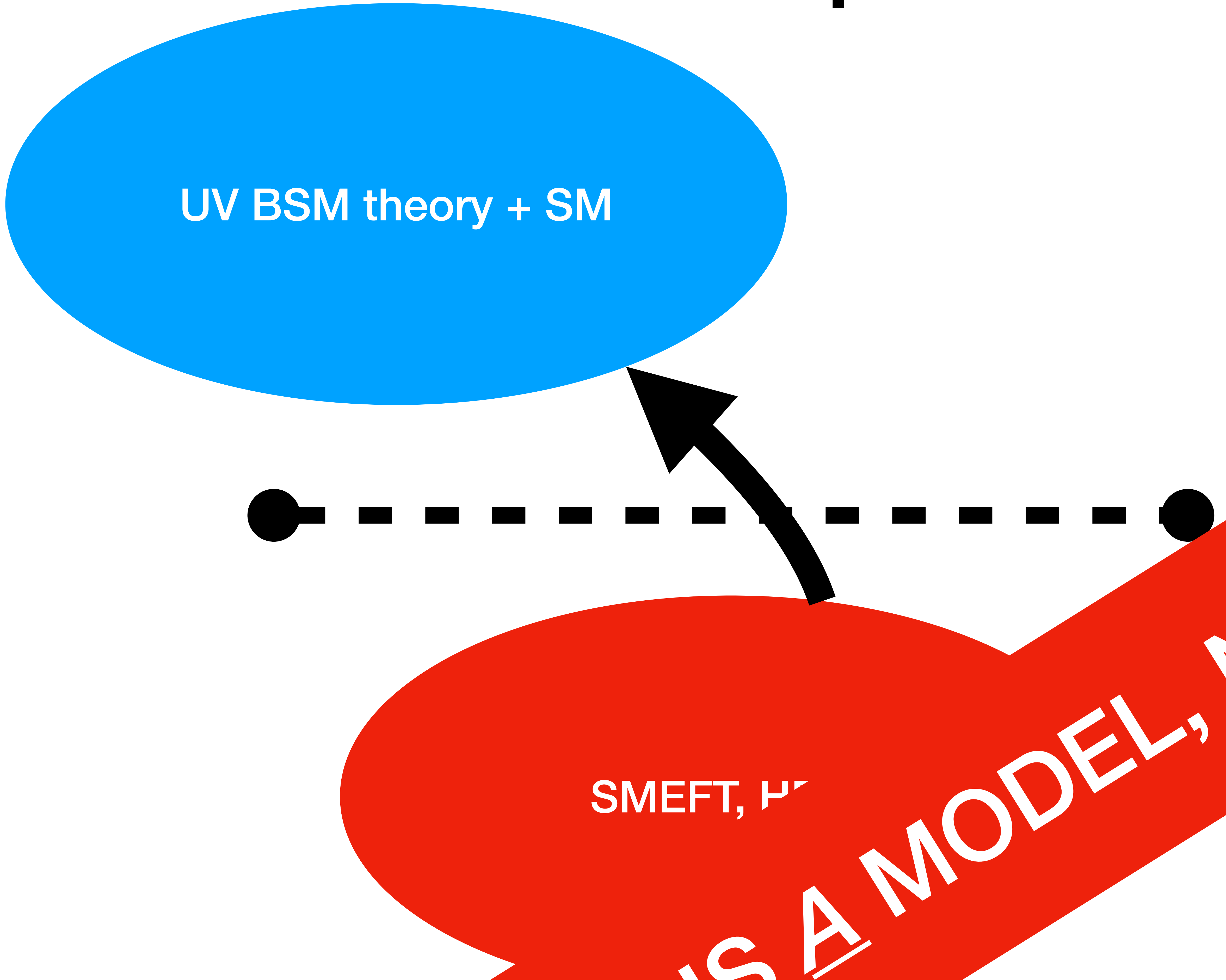


Λ=?

C ... $\Lambda \gtrsim 10^4\,\mathrm{TeV}$

$\longrightarrow$ $\Lambda \gtrsim 10^3\,\mathrm{TeV}$

$\frac{C_b}{\Lambda^2} b\bar{d}b\bar{d}$ $\longrightarrow$ $\Lambda \gtrsim 10^4\,\mathrm{TeV}$

Flavor

$\frac{C_T}{\Lambda^2}(H^\dagger D_\mu H)^2$ $\longrightarrow$ $\Lambda \gtrsim 10\,\mathrm{TeV}$

EWPT

SMEFT IS A MODEL, NOT MODEL INDEPENDENT

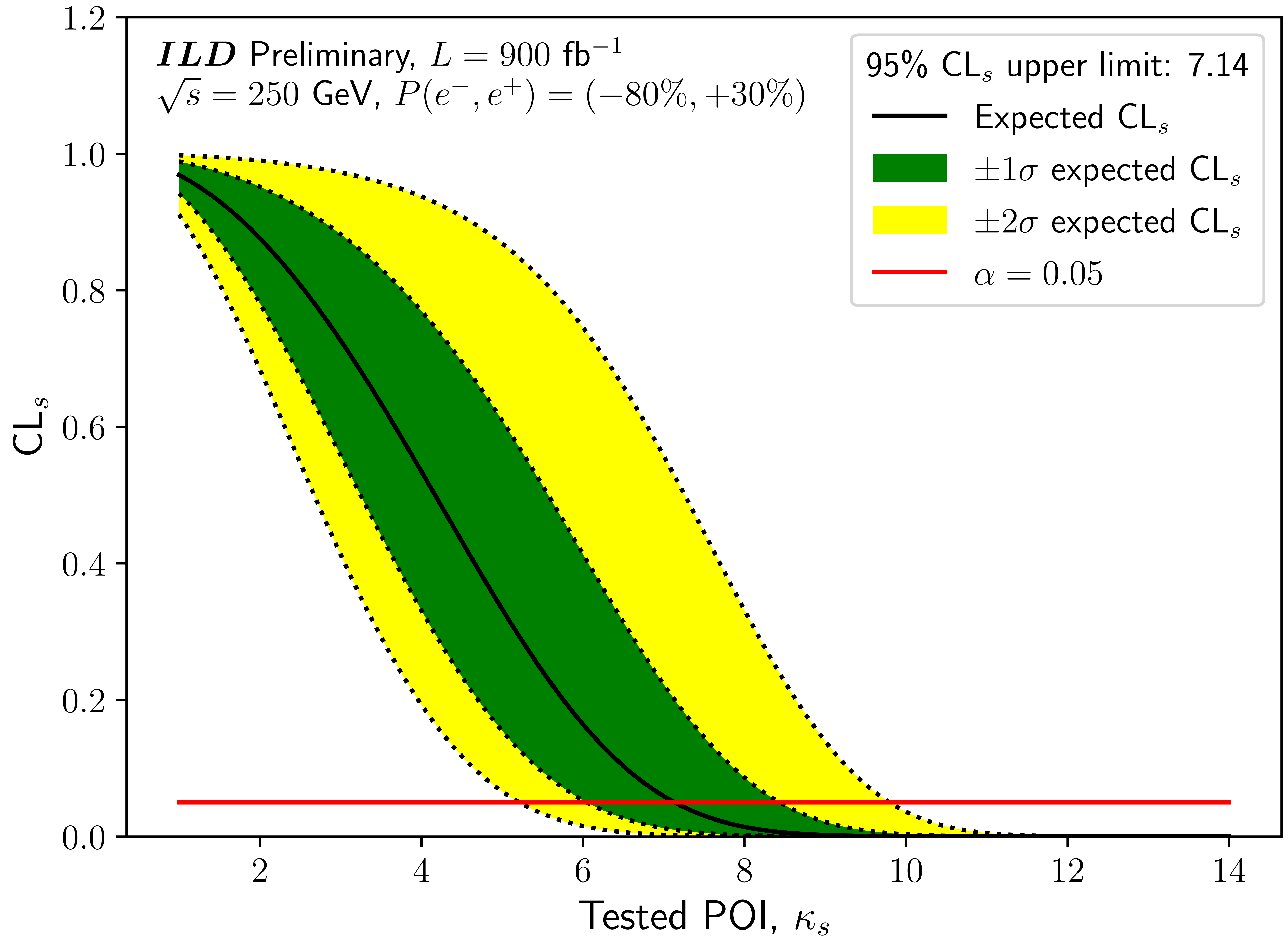
You [...] make model dependent assumptions to use it, otherwise you [...]re guaranteed to see nothing at the LHC or future colliders!

Therefore if I want to talk about *implications* of precision I need to know the types of UV physics that can map to certain types of operators or observables!

Let's look at a particular example to see how this works, and why a Linear Collider can have other advantages in Higgs Physics

Higgs physics isn't just EFT/couplings: Cute example is the strange Yukawa

This was done for ILC, but should be applicable to FCC-ee/CEPC (ECFA/ESPPU)

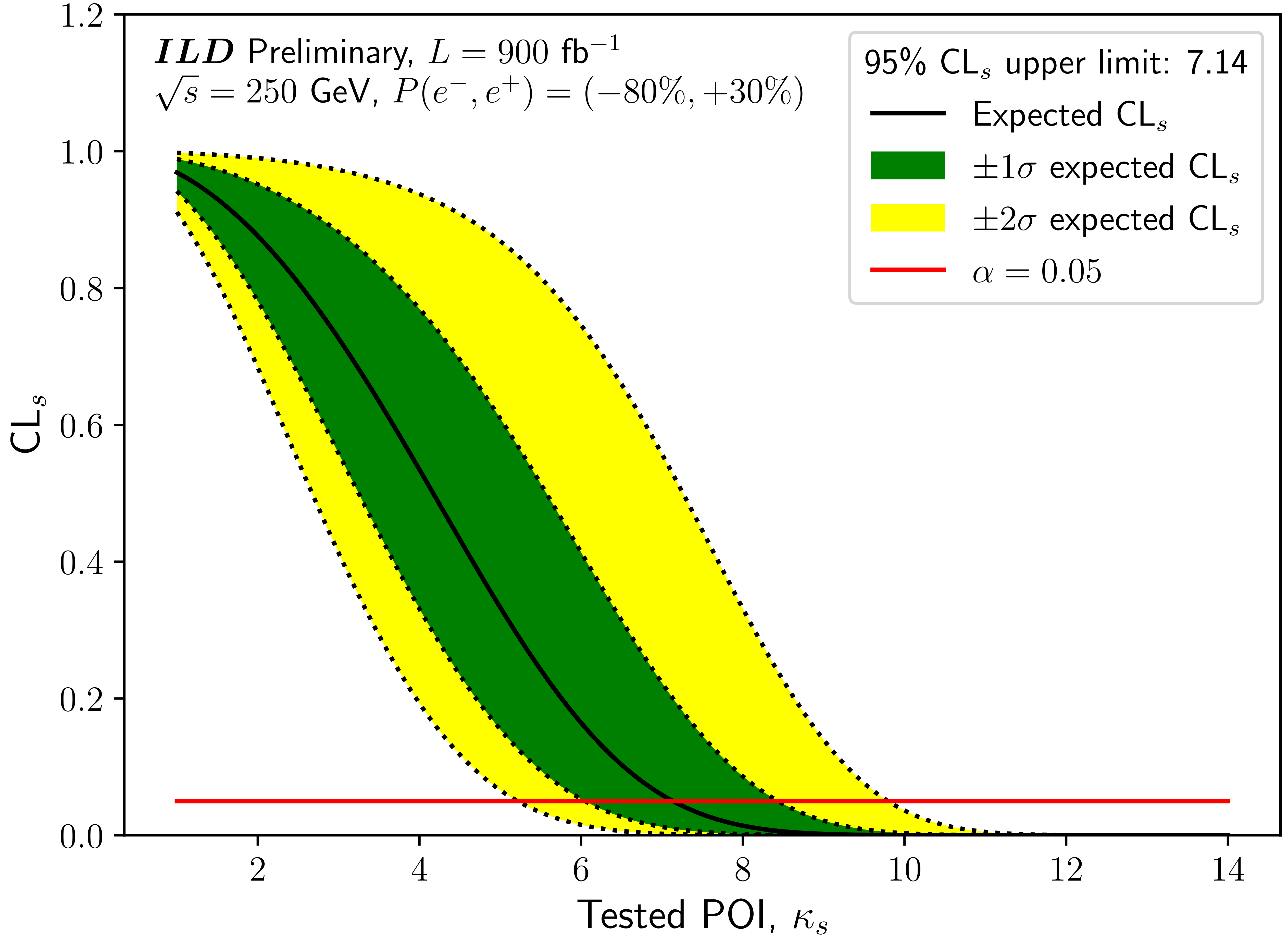


ILC Snowmass study
A. Albert et al
2203.07535

Higgs physics isn't just EFT/couplings: Cute example is the strange Yukawa

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

We've heard about MFV, U(2) etc from very nice SMEFT talks this week, so do we ever care about this precision?



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To generate such $\mathcal{O}$ or effect, you *need* BSM physics that couples to strange quarks *and* couples to the Higgs

+

symmetry/dynamics to avoid Flavor bounds

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symmetry/dynamics to avoid Flavor bounds

Spontaneous Flavor Violation (SFV)

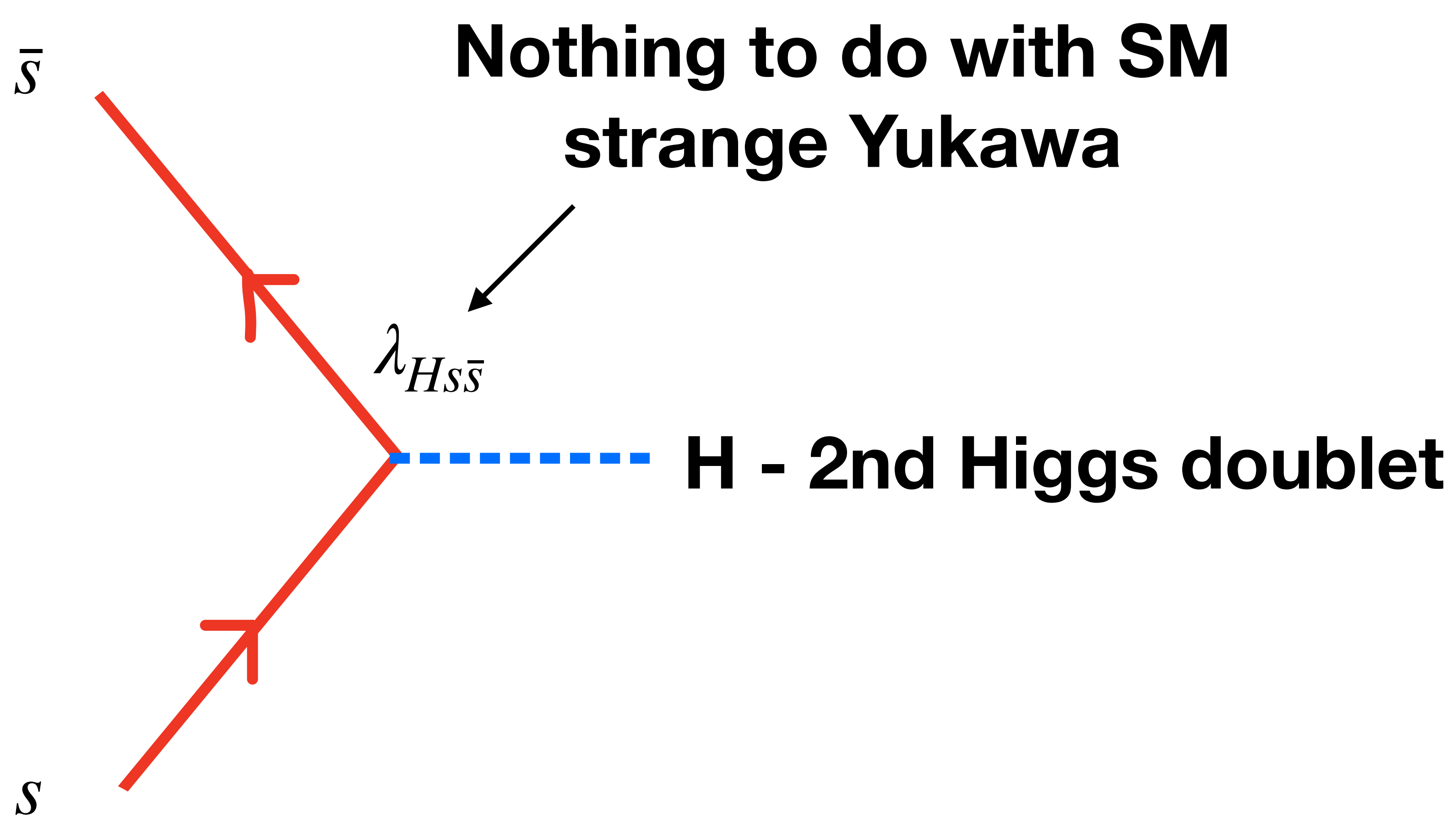
D. Egana-Ugrinovic, S. Homiller, PM
1811.00017,1908.11376,2101.04119

New physics *can* couple in a strongly flavor dependent way if it is aligned in the down-type quark or up-type quark sectors with a *sufficient symmetry* to protect it: SFV provides this *beyond* Aligned Flavor Violation

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*

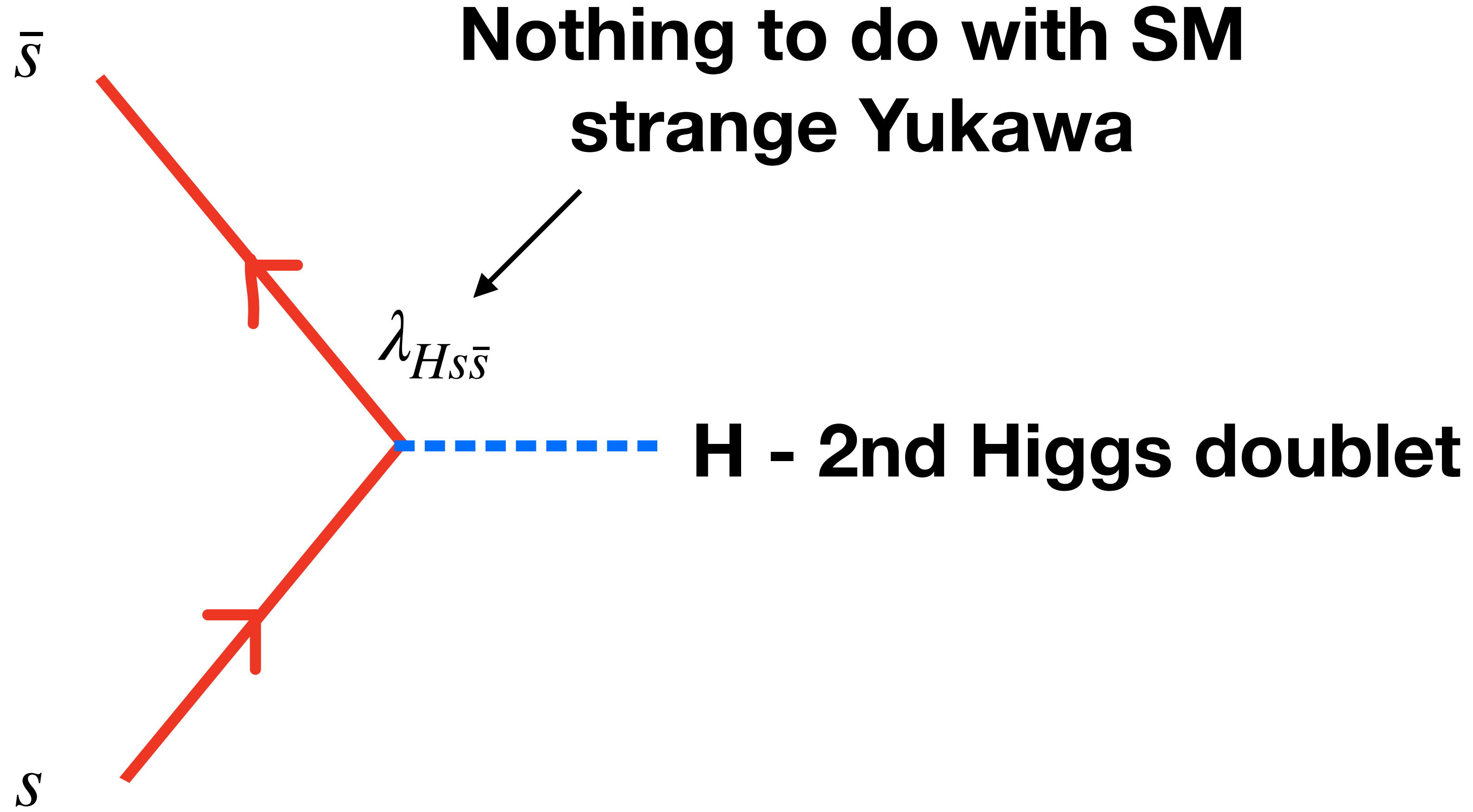
This is symmetry protected, and there are simple UV completions!

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



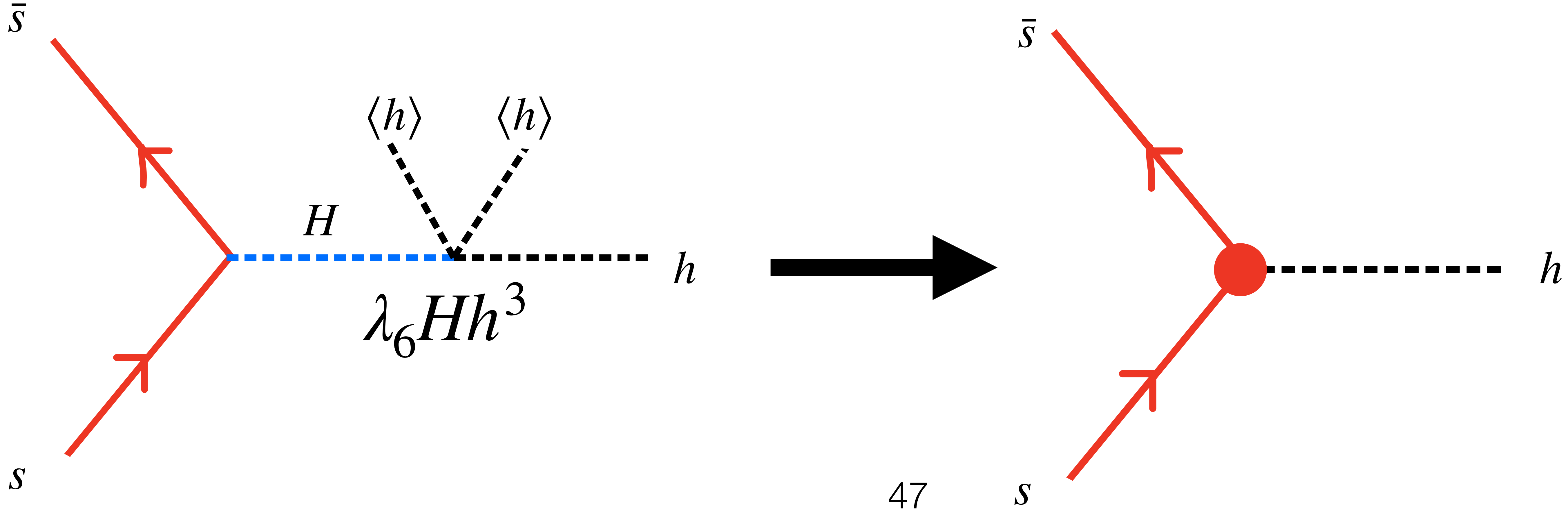
If this was all there was, then an amusing signal generator for strange jet resonances

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



It *can* modify "SM" Higgs strange couplings

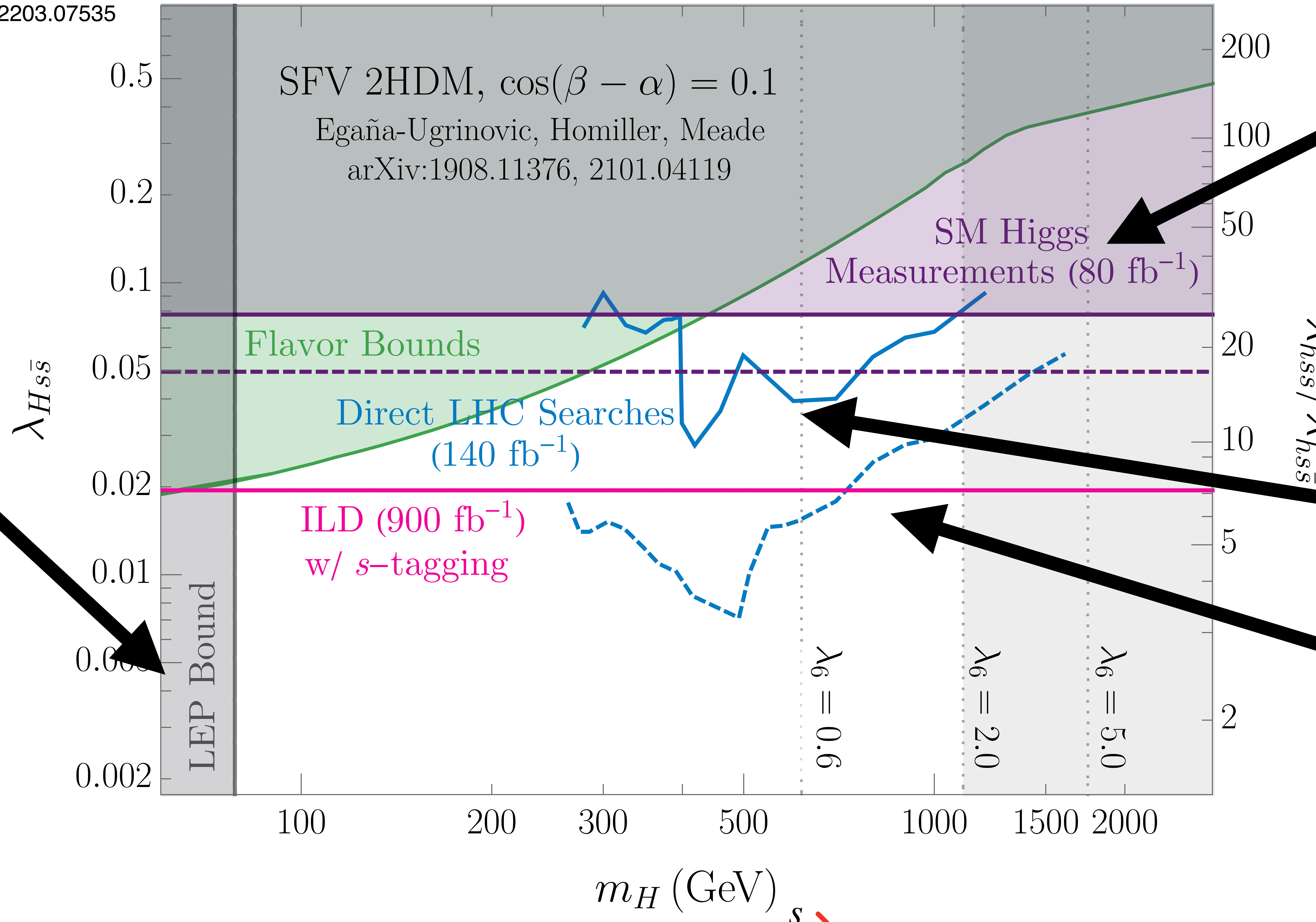
Simple parameter space: mass, coupling to strange, mixing with Higgs

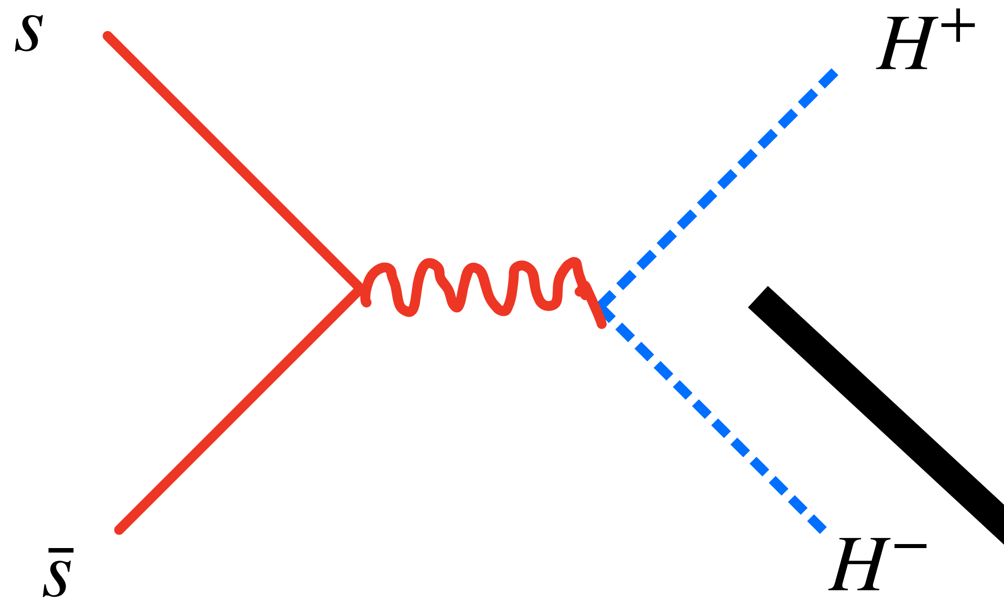


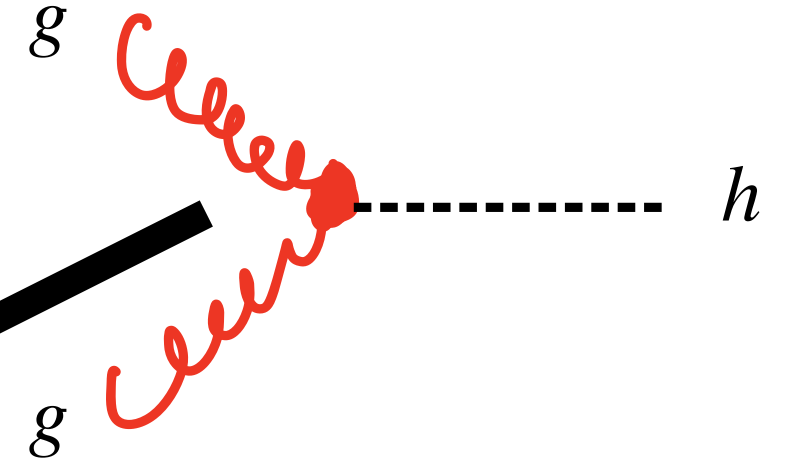
$$\sim \frac{1}{\Lambda^2}(sh\bar{s})h^2$$

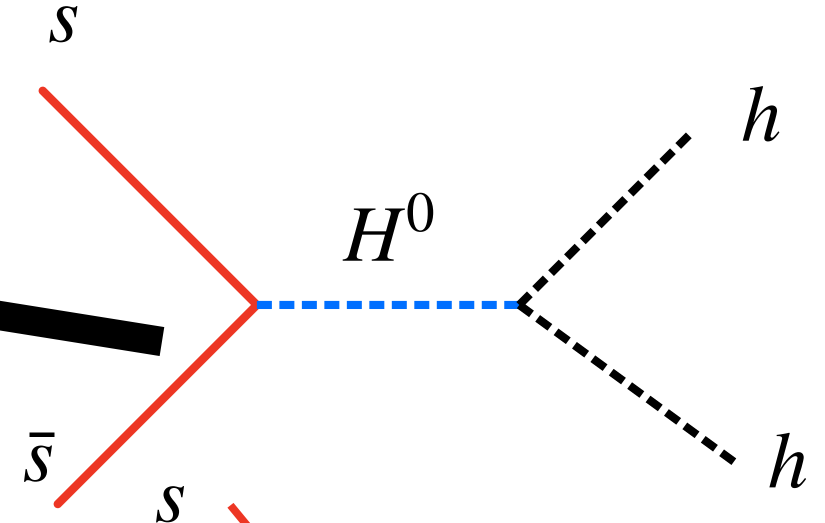
That's not the only signal!

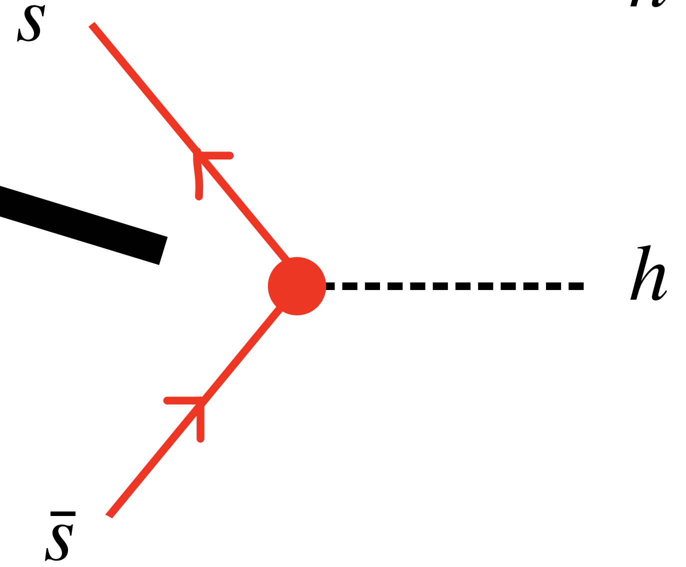
A. Albert et al
2203.07535



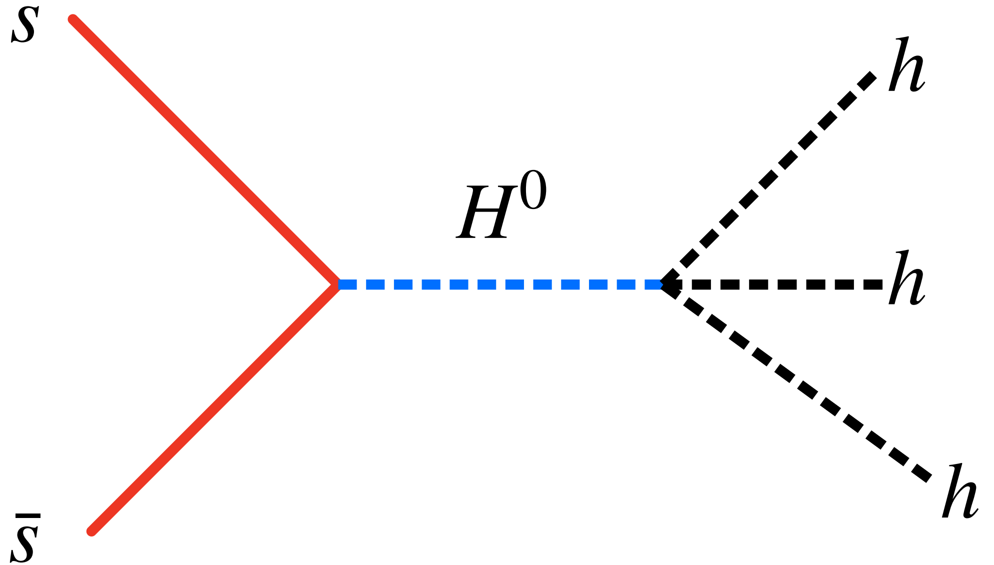






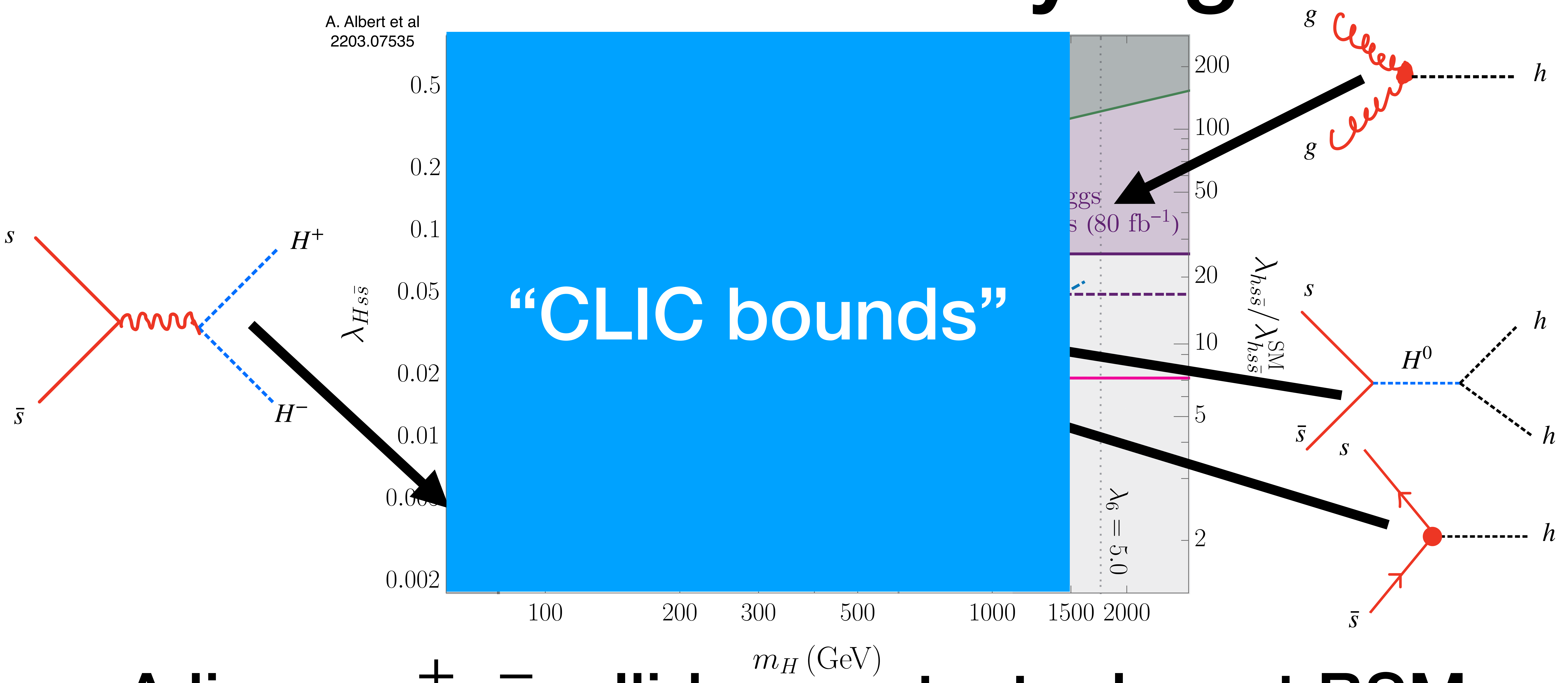


Resonant di-Higgs sets the current strongest LHC bound on deviations of the strange Yukawa!



Prospects for *tri*-Higgs at the HL-LHC

That's not the only signal!



A linear e^+e^- collider can test relevant BSM Higgs physics directly

“Higgs Factories”

Circular

Flavor Physics
Rare Z decays (BSM search)
EW program
Higgs Program
Potential new big tunnel!

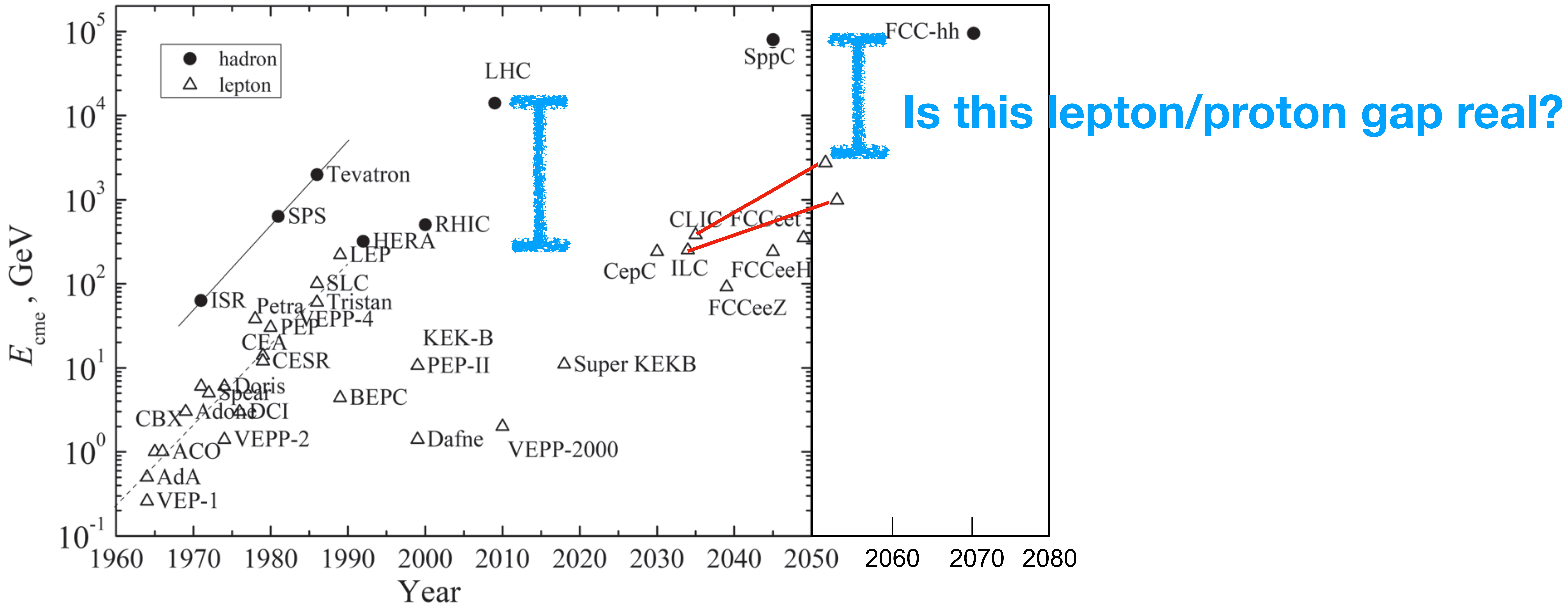
Linear

EW program
Higgs Program
Di-Higgs/Higgs Potential
Testing BSM EW physics directly

Both options are great *and* complementary:
If CEPC then ILC or CLIC immediately?

What about muons? Where do they fit in?

Let’s go back to our collider plot



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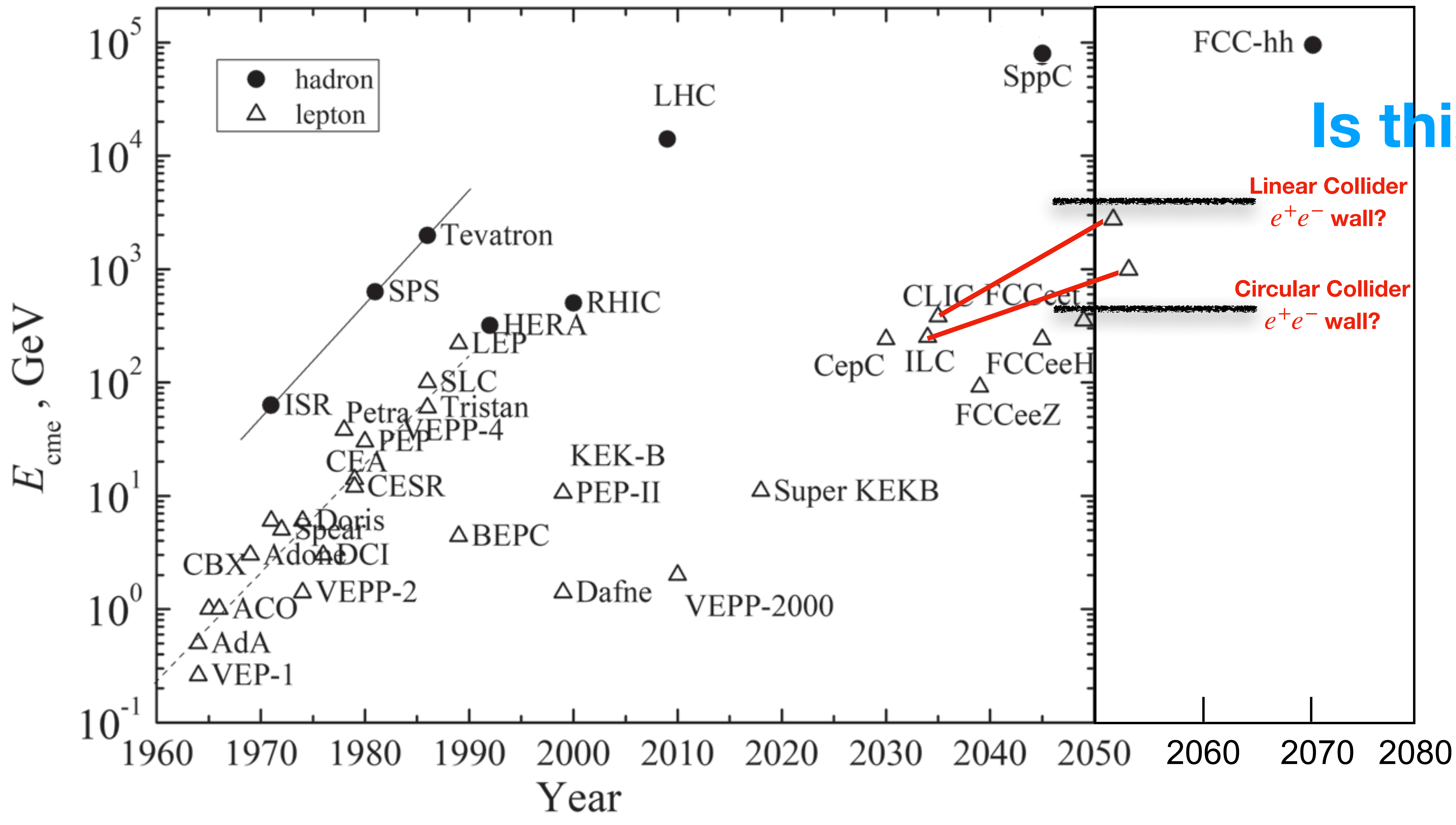

Is this lepton/proton gap real?

YES

***IF* we stick with current technology**

What technologies can fill the gap?

Avoid synchrotron radiation of circular e^+e^- colliders

Muon Collider

High Energy + High Lumi in small ring

Once muons are cooled, much more like "conventional" collider

Pheno and full sim studies done

Many synergies with neutrino physics and dovetails well with Fermilab

Avoid infinitely long linear e^+e^- colliders

WFA

High energy in short package

Understanding Lumi and Power consumption w/staging still open question

Don't have enough info to do real pheno/exp studies *yet*

What technologies can fill the gap?

Avoid synchr
radiation of circu
colliders

Muon Co

High Energy + H

Once muons are co
more like "conventio

Pheno and full si
done

Many synergies with ne
and dovetails well w

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/FA

short package

Lumi and Power
staging still open
stion

gh info to do real
studies *yet*

Wh… p?

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radia… ers

Mu…

High E… ackage

Once muons … imi and Power

more like “co… aging still open

Pheno and … on

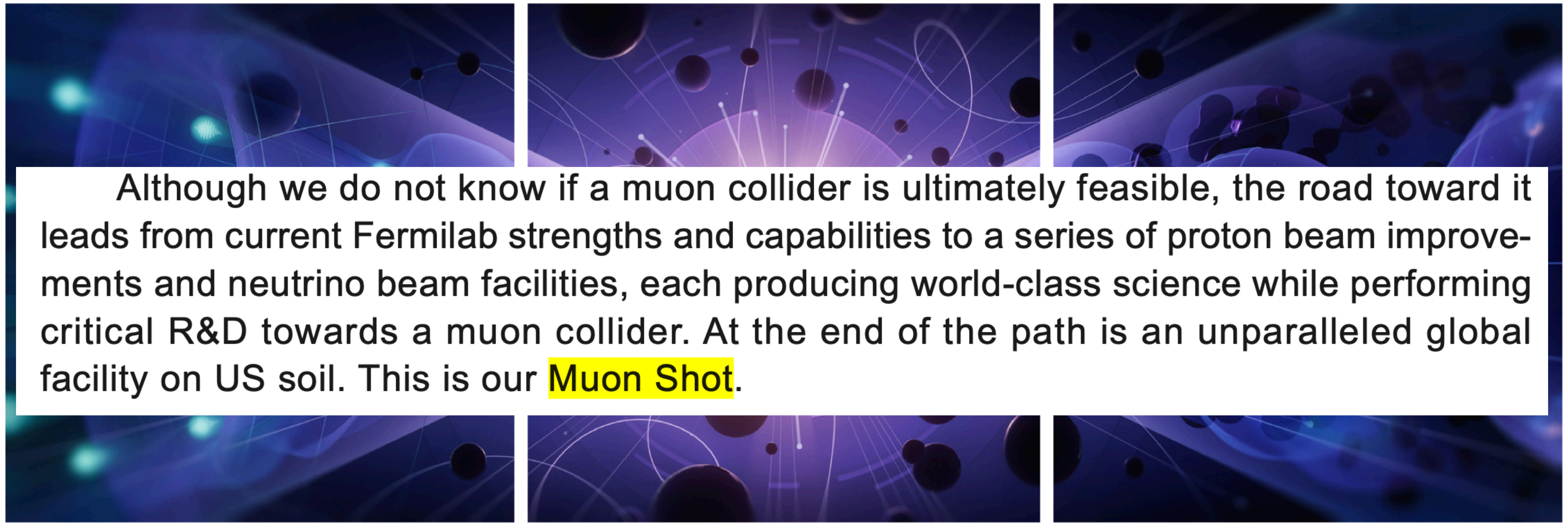
Many synergies … h info to do real

and dovetail … studies *yet*

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.



Although we do not know if a muon collider is ultimately feasible, the road toward it leads from current Fermilab strengths and capabilities to a series of proton beam improvements and neutrino beam facilities, each producing world-class science while performing critical R&D towards a muon collider. At the end of the path is an unparalleled global facility on US soil. This is our Muon Shot.

Decipher the Quantum Realm

Explore New Paradigms in Physics

Illuminate the Hidden Universe

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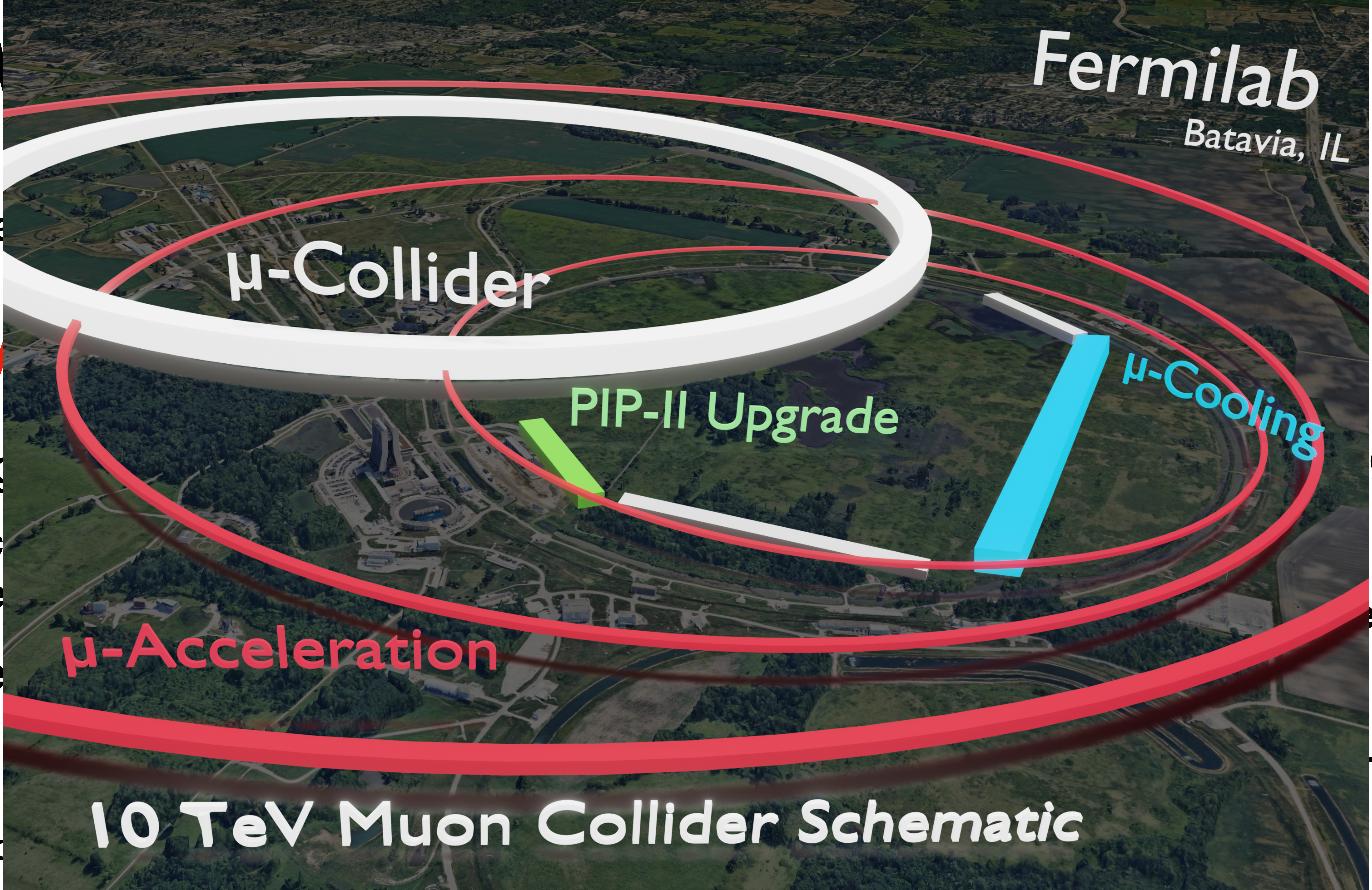


Why is it so important to fill this gap?

- **We *already* have good reason to think we *need* to get to higher energy - both from data and theory - so we better make sure we can!**

- FCC-hh and SPPC follow the LEP/LHC paradigm - but we don't know for sure if we can build detectors to get the physics out - 2070 makes it easy to not focus on it for now, but should we put all our eggs in one basket?

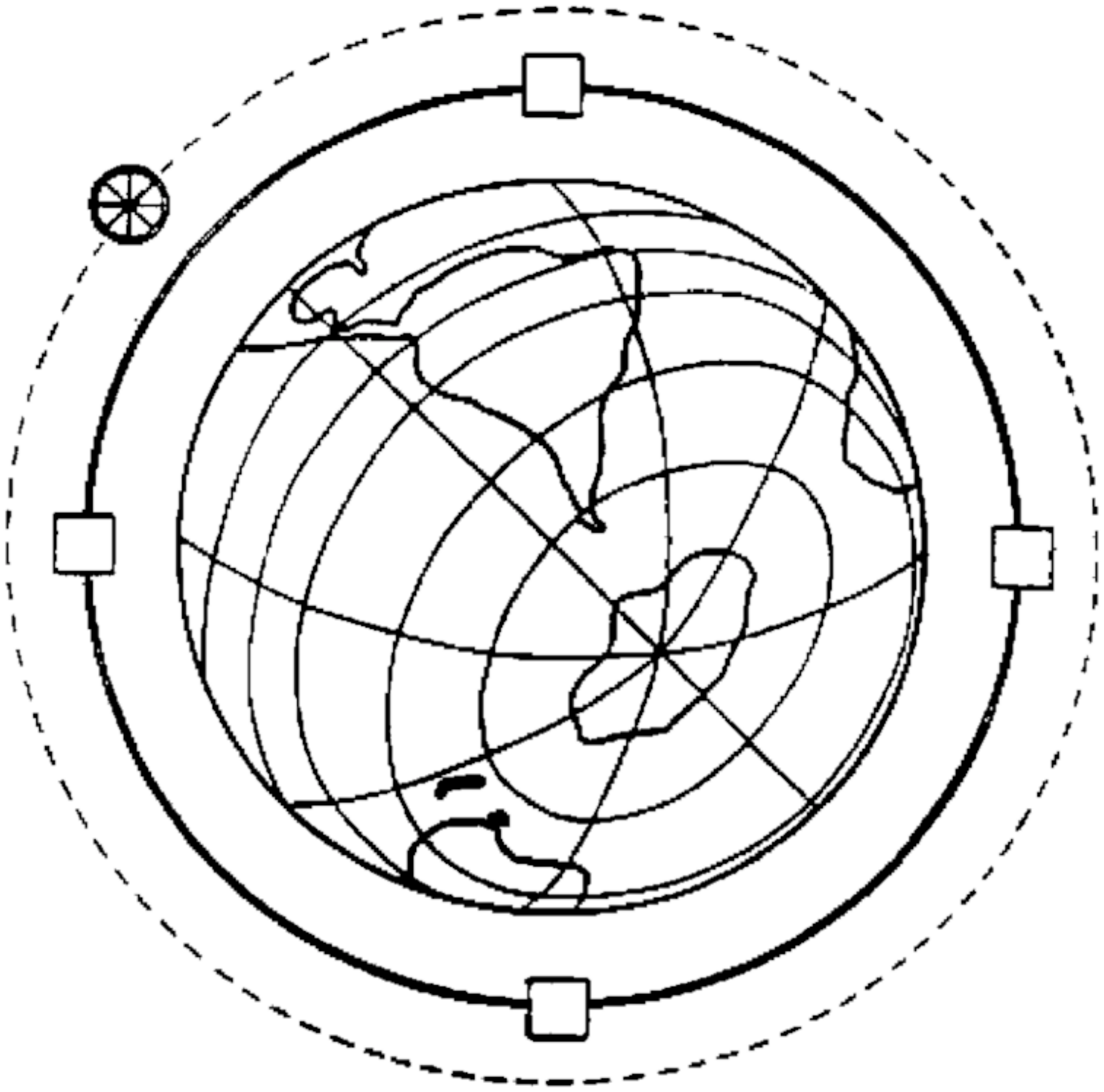
- What is the ultimate limit of protons?

  - Have to keep going bigger - sustainability and political issues

  - QM tells us we need to increase lumi roughly quadratically if we want to increase energy of our colliders, is this feasible?

  - pp total cross section increases with $\sqrt{s}$, do our beams burn off too fast and power consumption spirals eventually?

Even if we had the resources, it's not clear how far we can go without supporting broad R&D

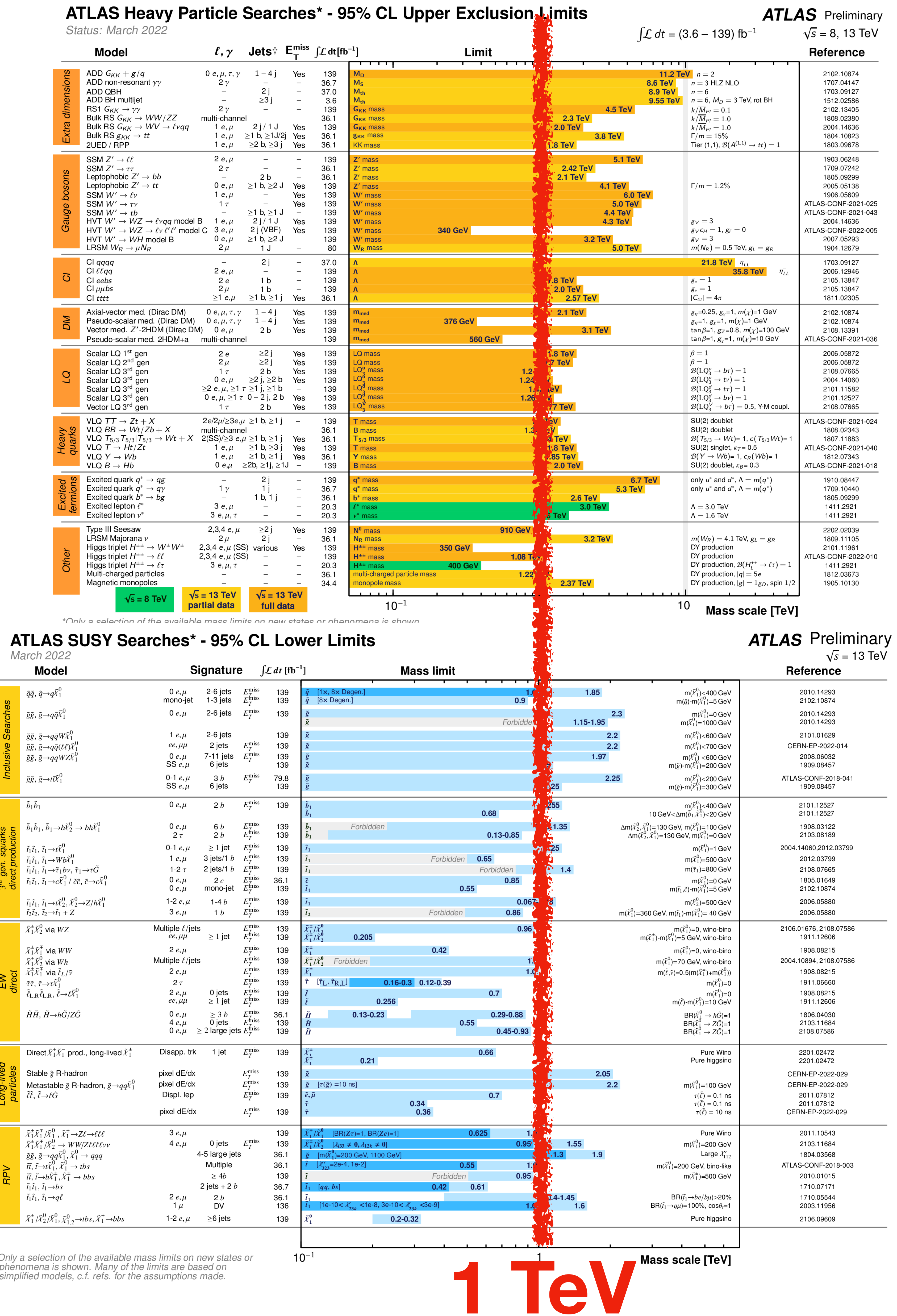


We can dream big like Fermi, but whether we can do it even if we had the resources is a different story

Why do we *need* higher energy?

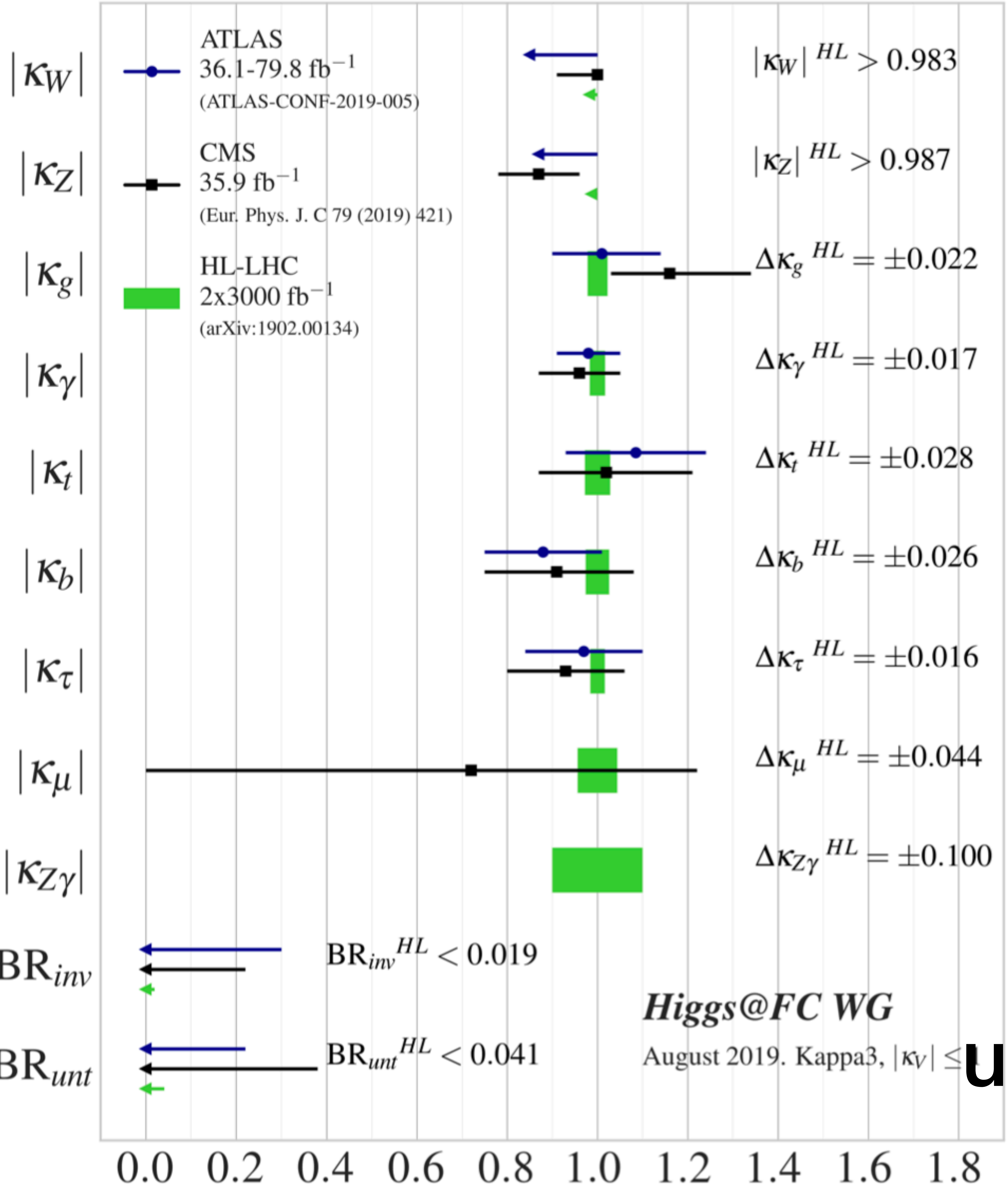
- LHC dataset so far: Lack of BSM evidence
- Preparing for Higgs Factory Results
- Completing the Standard Model
- Higgs Mass + SUSY
- Minimal Dark Matter
- Electroweak Phase Transition

Lessons learned from the LHC so far

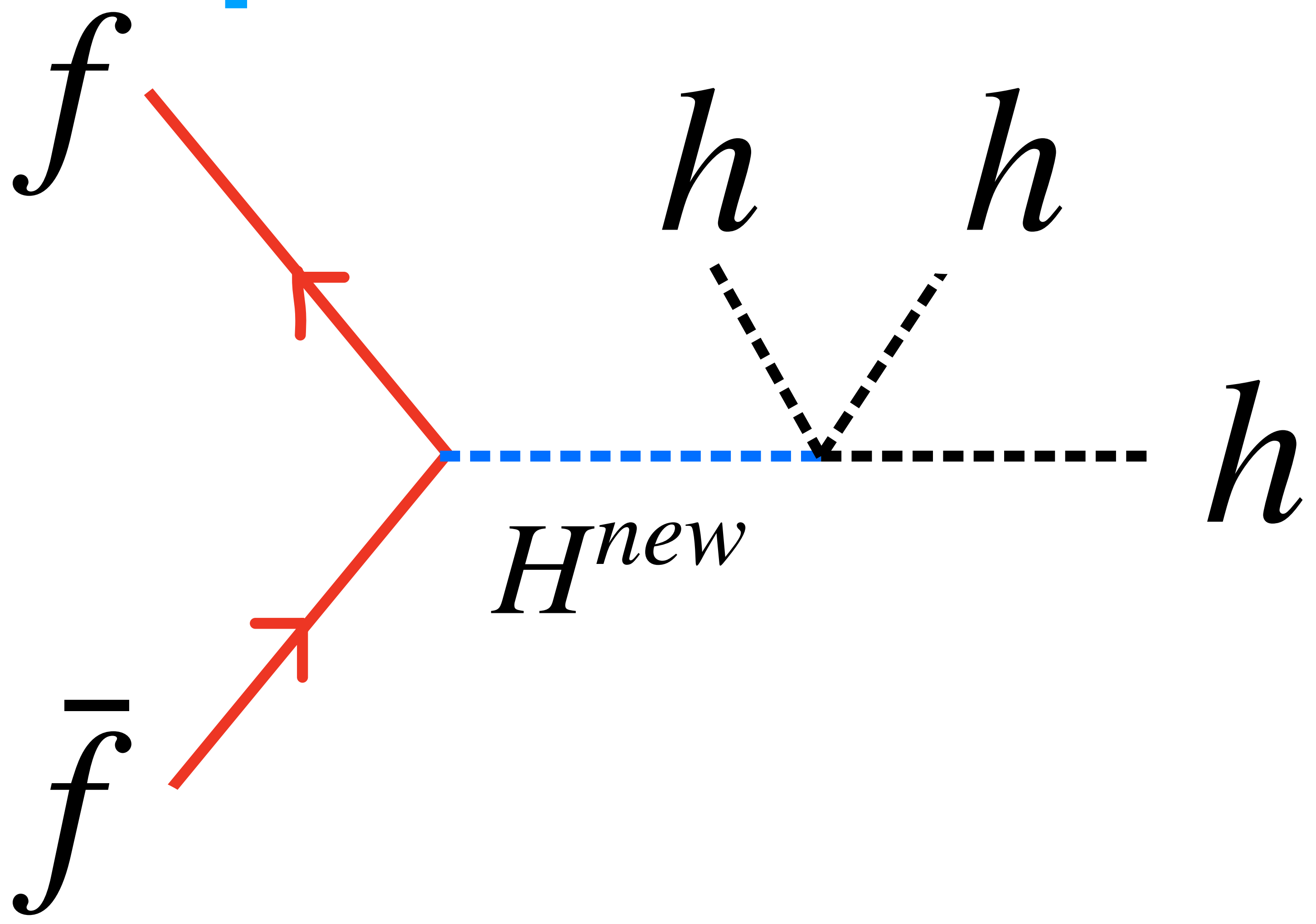


Direct searches for new phenomena beyond the Standard Model roughly tells us that we are already probing up to the $\gtrsim$ 1 TeV scale

Lessons learned from the LHC so far

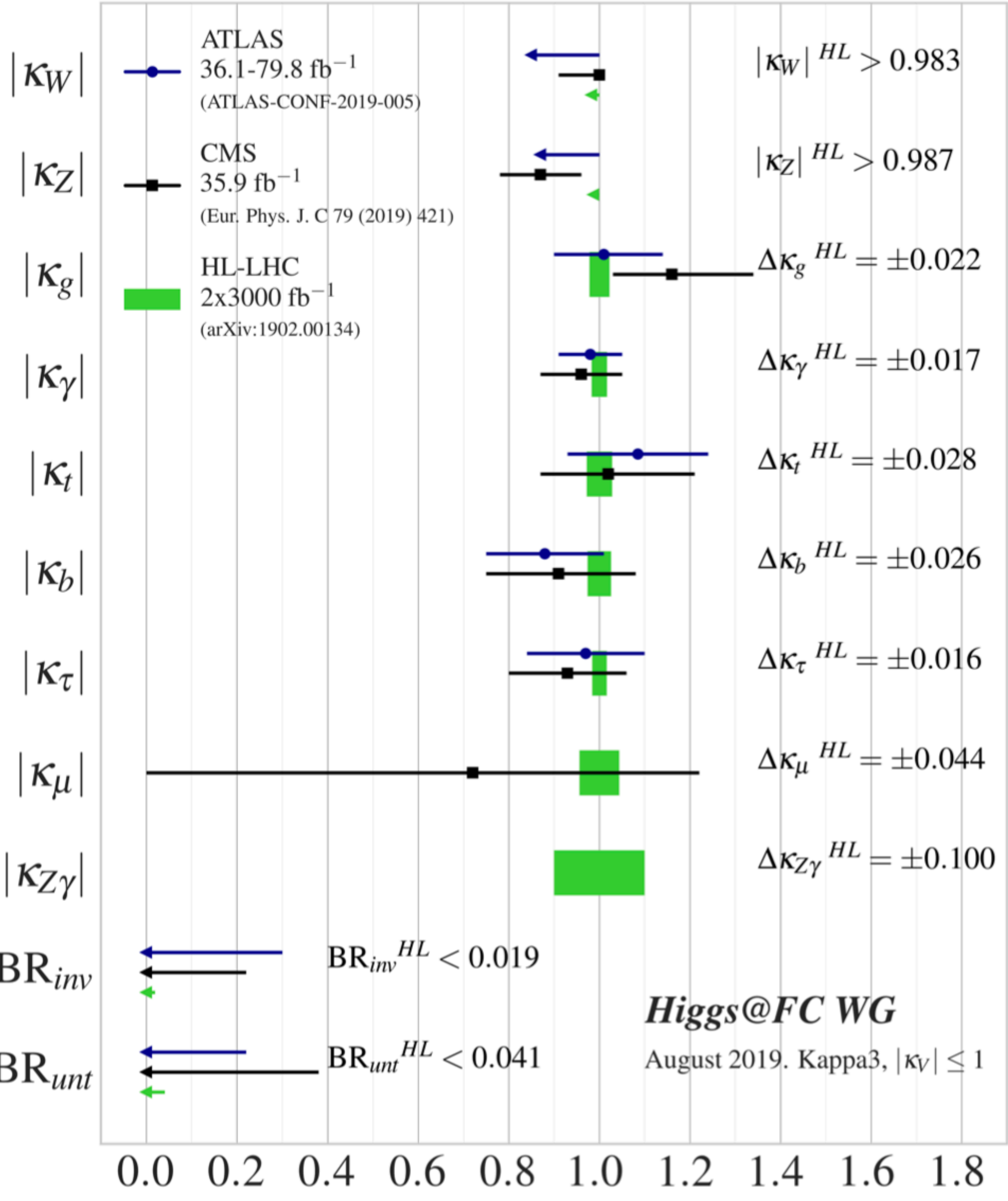


Can probe new physics indirectly as well and it implies a *scale*

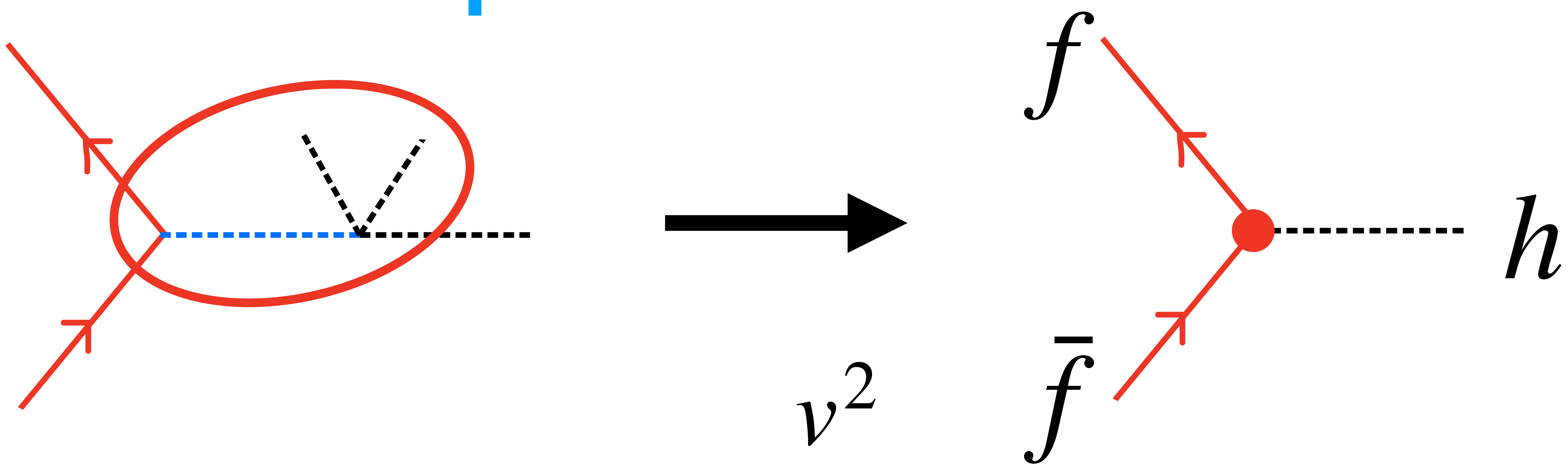


More complicated UV physics can be understood quantitatively at low energies using Wilsonian RGE/EFT techniques

Lessons learned from the LHC so far



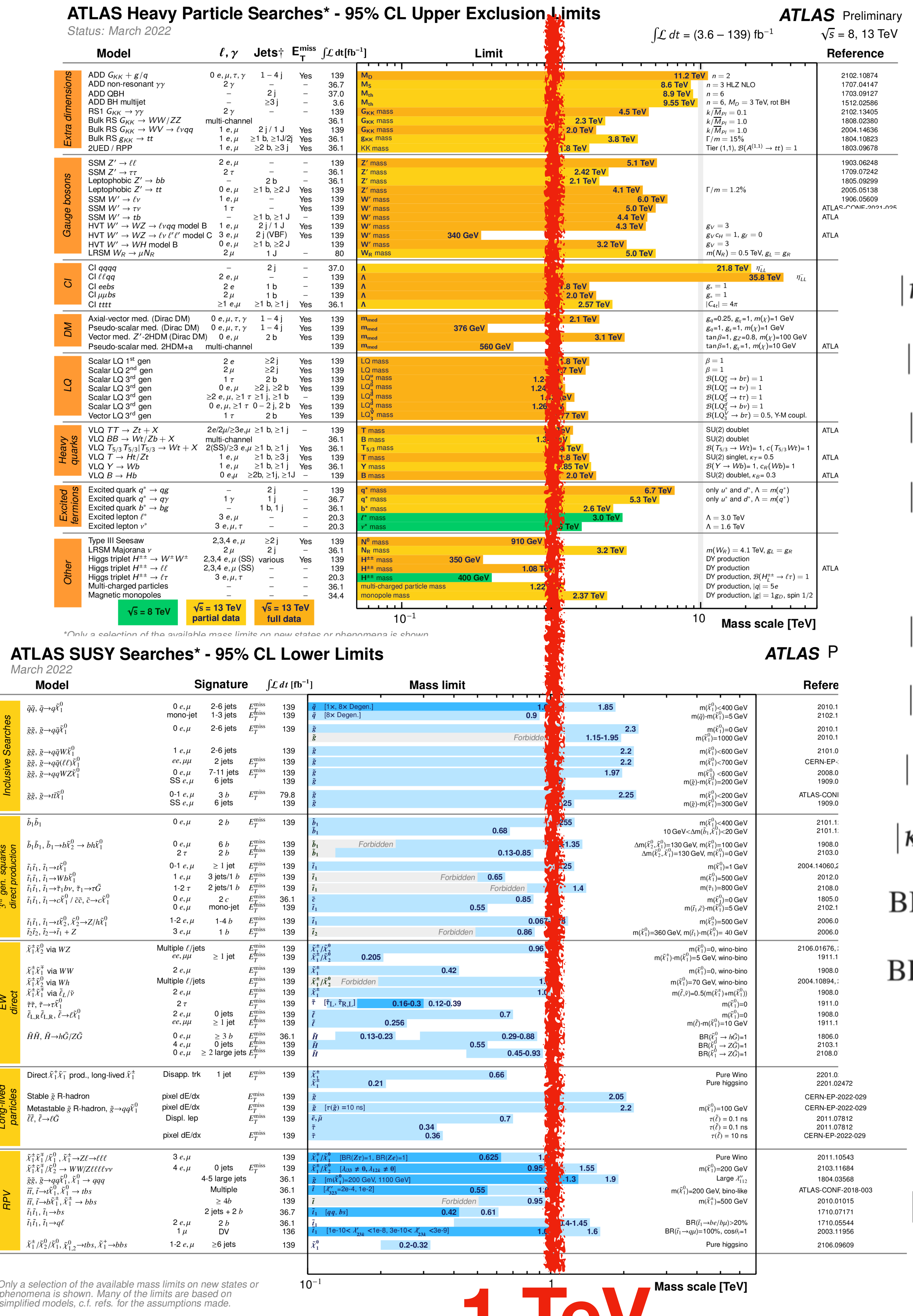
Can probe new physics indirectly as well and it implies a *scale*



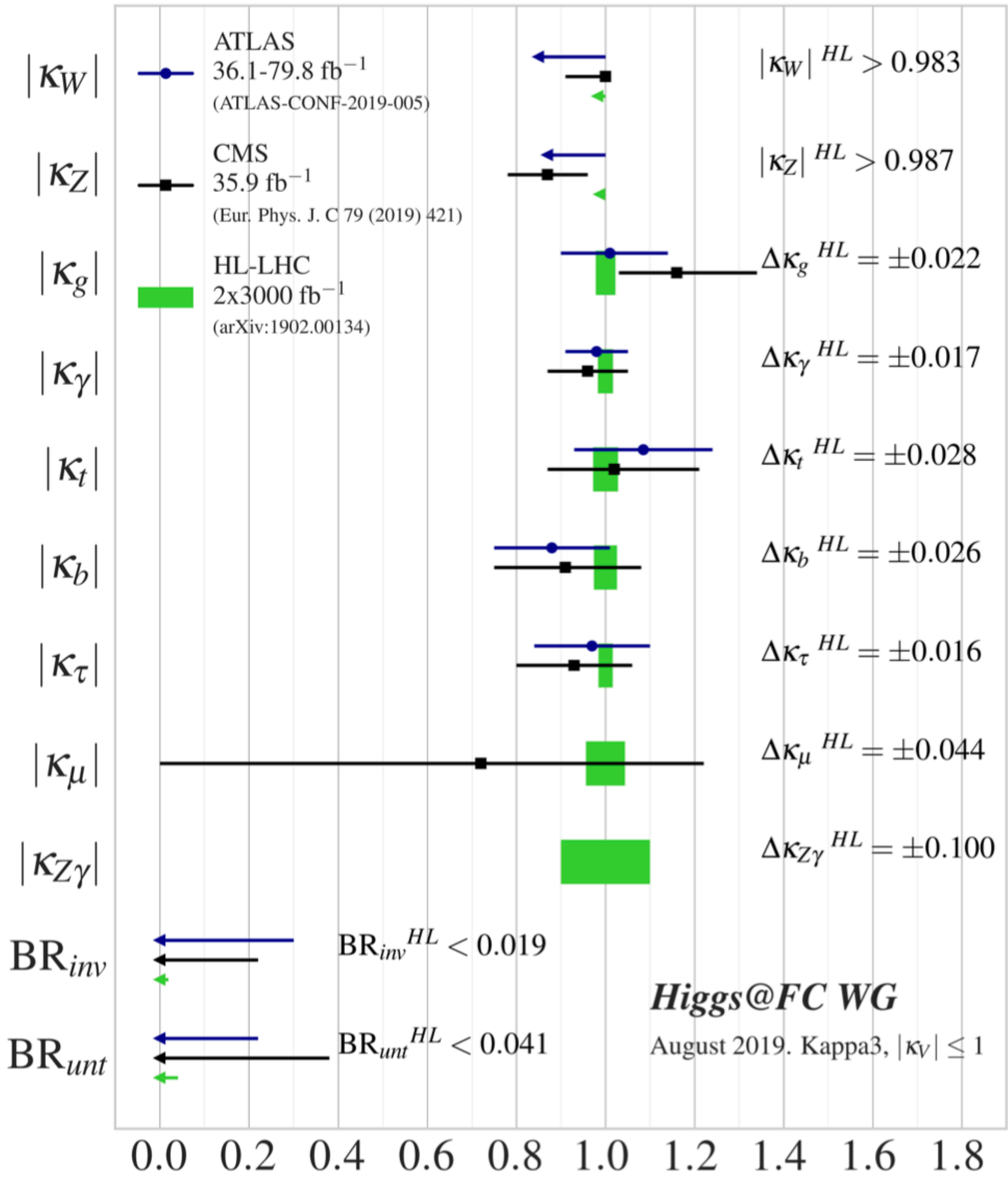
$$\kappa \sim \frac{v^2}{M_{NP}^2}$$

$$k \sim \mathcal{O}(\,\%\,) \implies M_{NP} \gtrsim \mathcal{O}(1)\,\text{TeV}$$

Lessons learned from the LHC so far



1 TeV



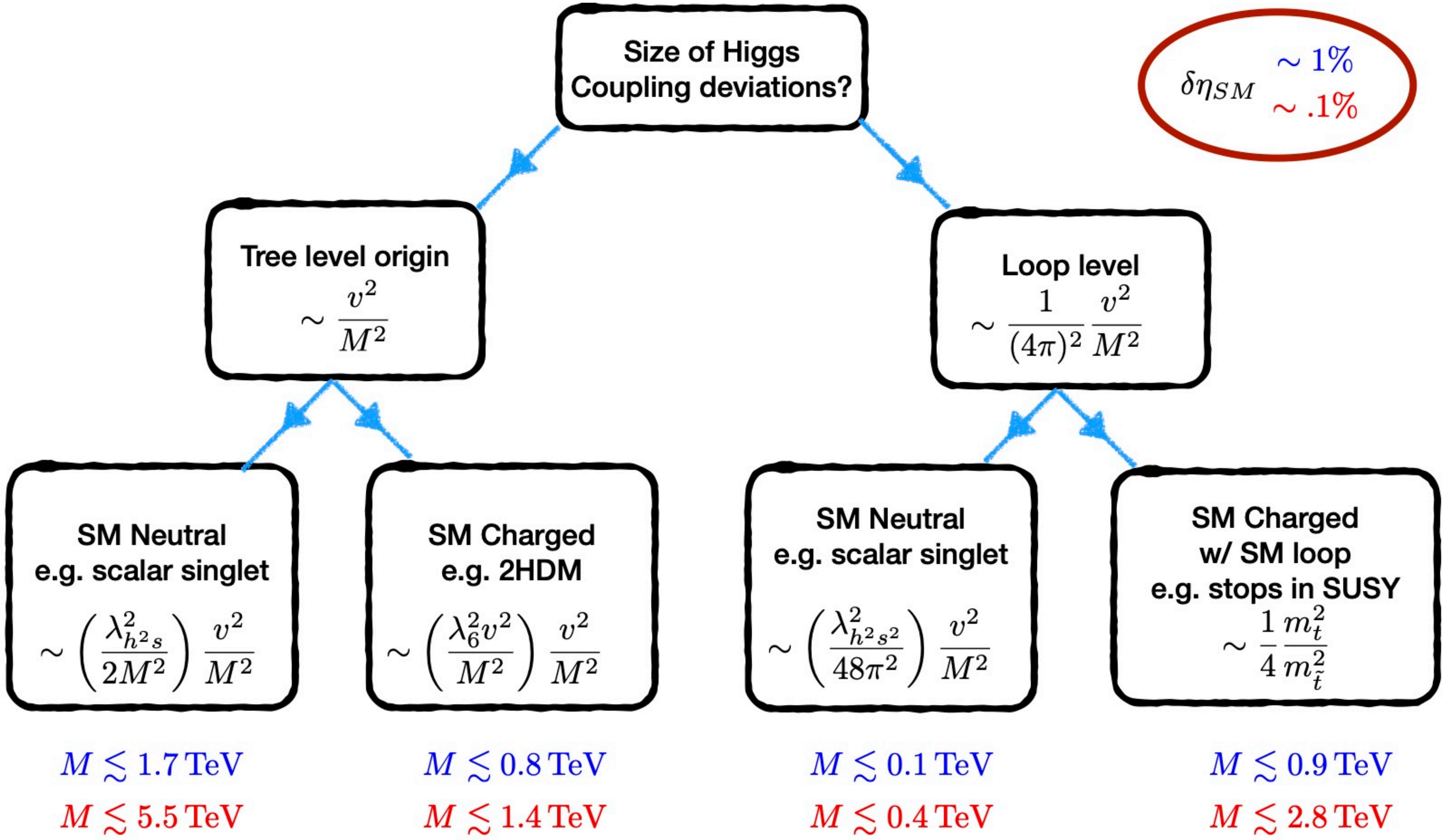
~1% tests on Higgs
Implies roughly the ~ TeV scale for NP which could cause such a deviation

There *could* still be new physics at LHC/HL-LHC… but we need to invest *NOW in R&D*

Data suggests generically there is a *gap* from EW scale to scale of New Physics

We need to be able to probe ≫1 TeV

This logic can be applied both ways to Higgs factories as well!



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

If we _see_ a deviation, we need to be able to at least reach greater than the few TeV scale

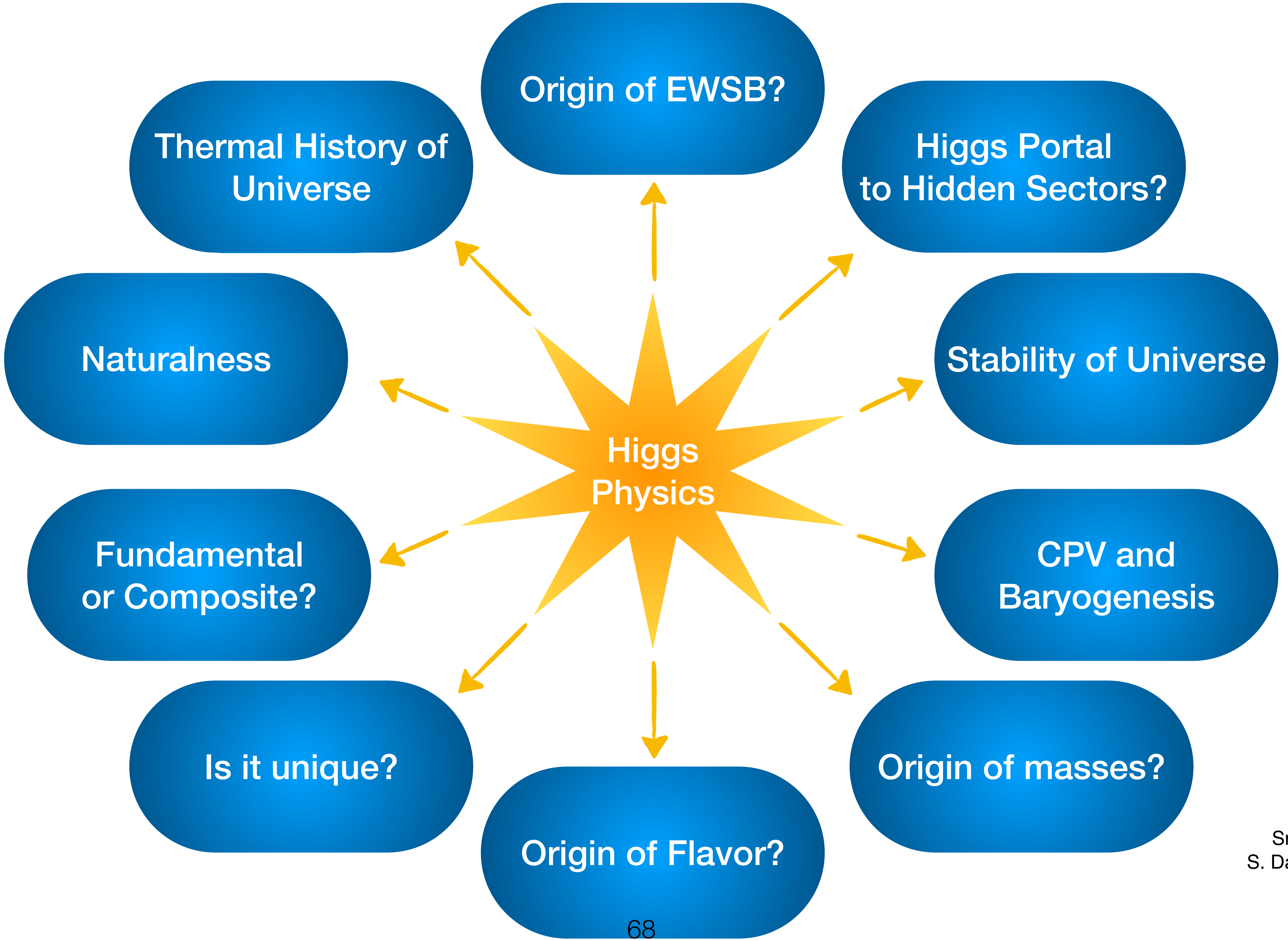
Whether 1% or .1% there are *no guarantees* that this precision is sufficient to break the SM, technology and cost driven

Need to be prepared to reach well beyond Higgs factories rather than *assume* they will set the scale

A 10 TeV muon collider would satisfy this!

Completing the SM

The Higgs is the most unique particle we've ever found and connected to so many questions about our universe



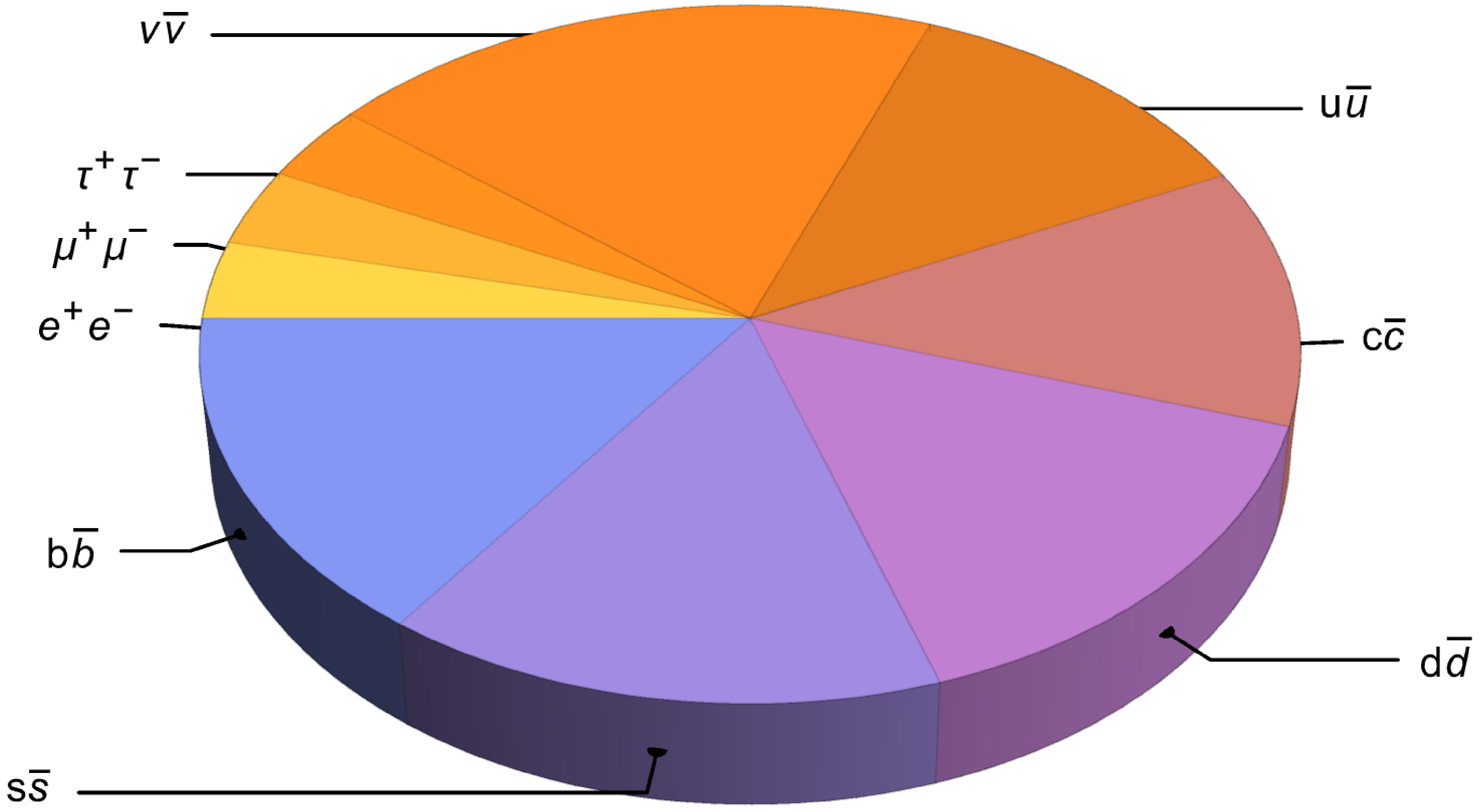
Snowmass EF Higgs Topical Report
S. Dawson, PM, I. Ojalvo, C. Vernieri et al
2209.07510

The SM Higgs is an *unprecedented* particle.

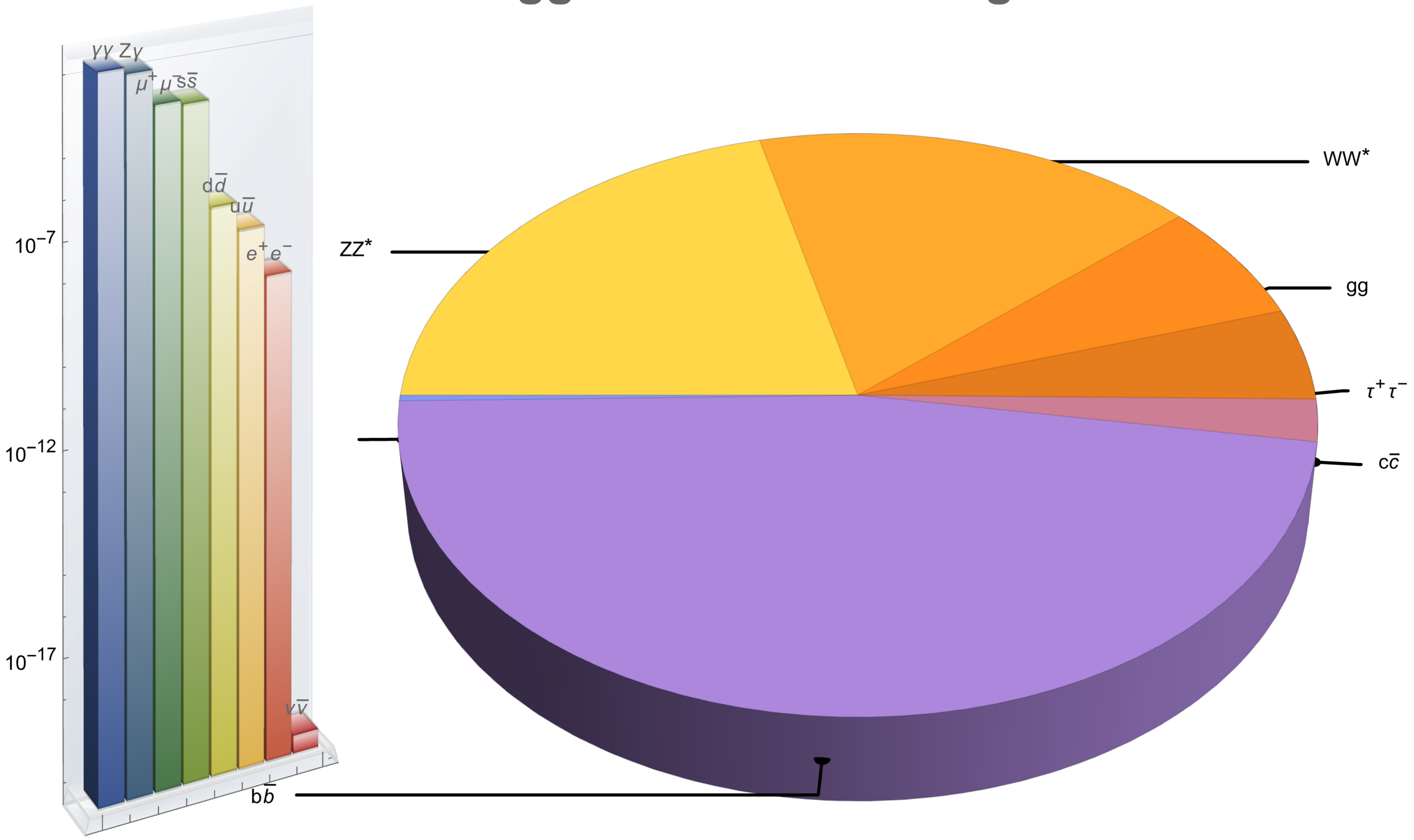
LEP was a Z boson factory and produced
~ 17 Million Z bosons

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!

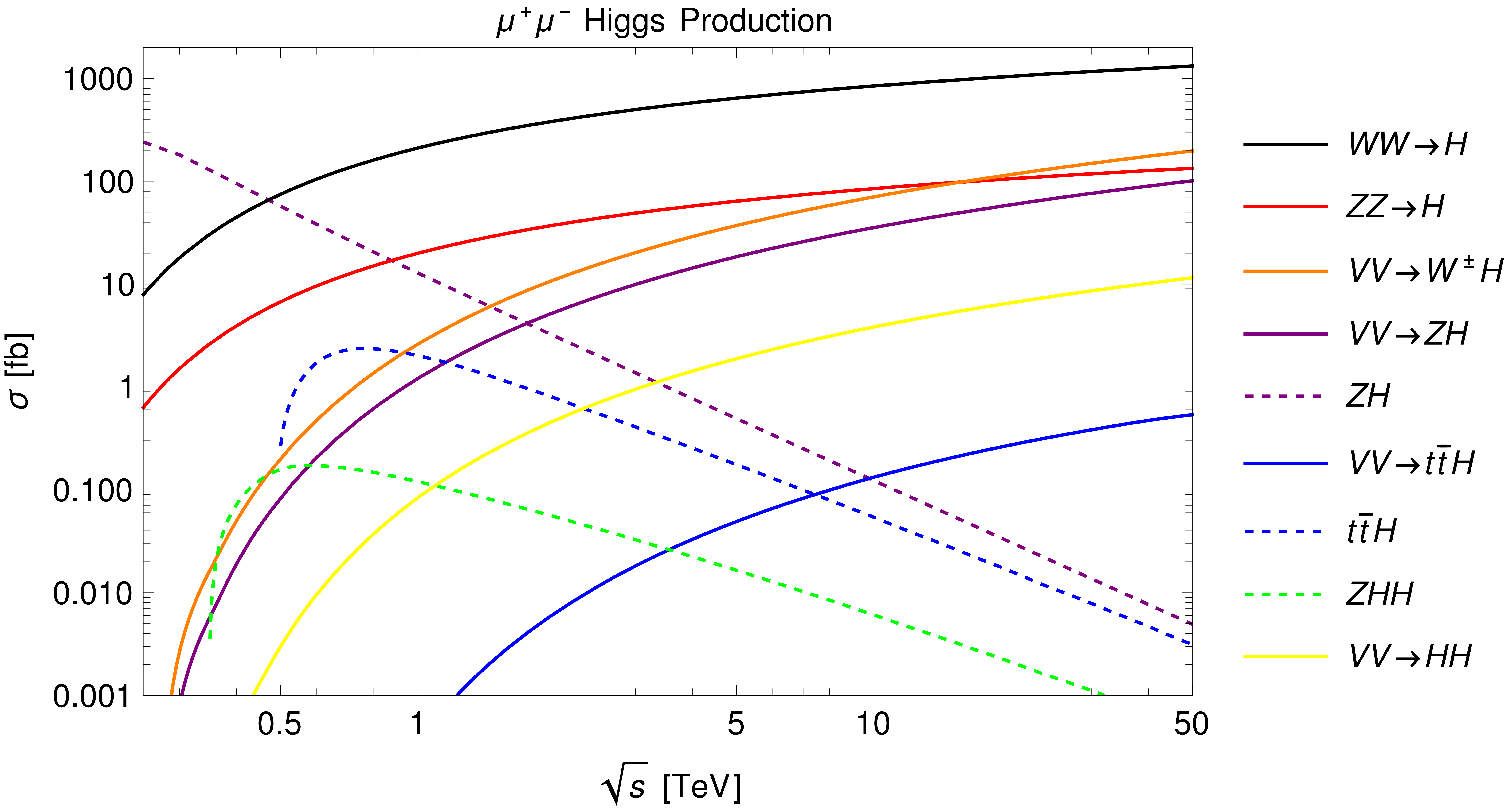
If we're ever to fully test the Higgs or Higgs potential we need a lot more than planned so far!

If we need more Higgs and Di-Higgs what do we do?

Hard to increase

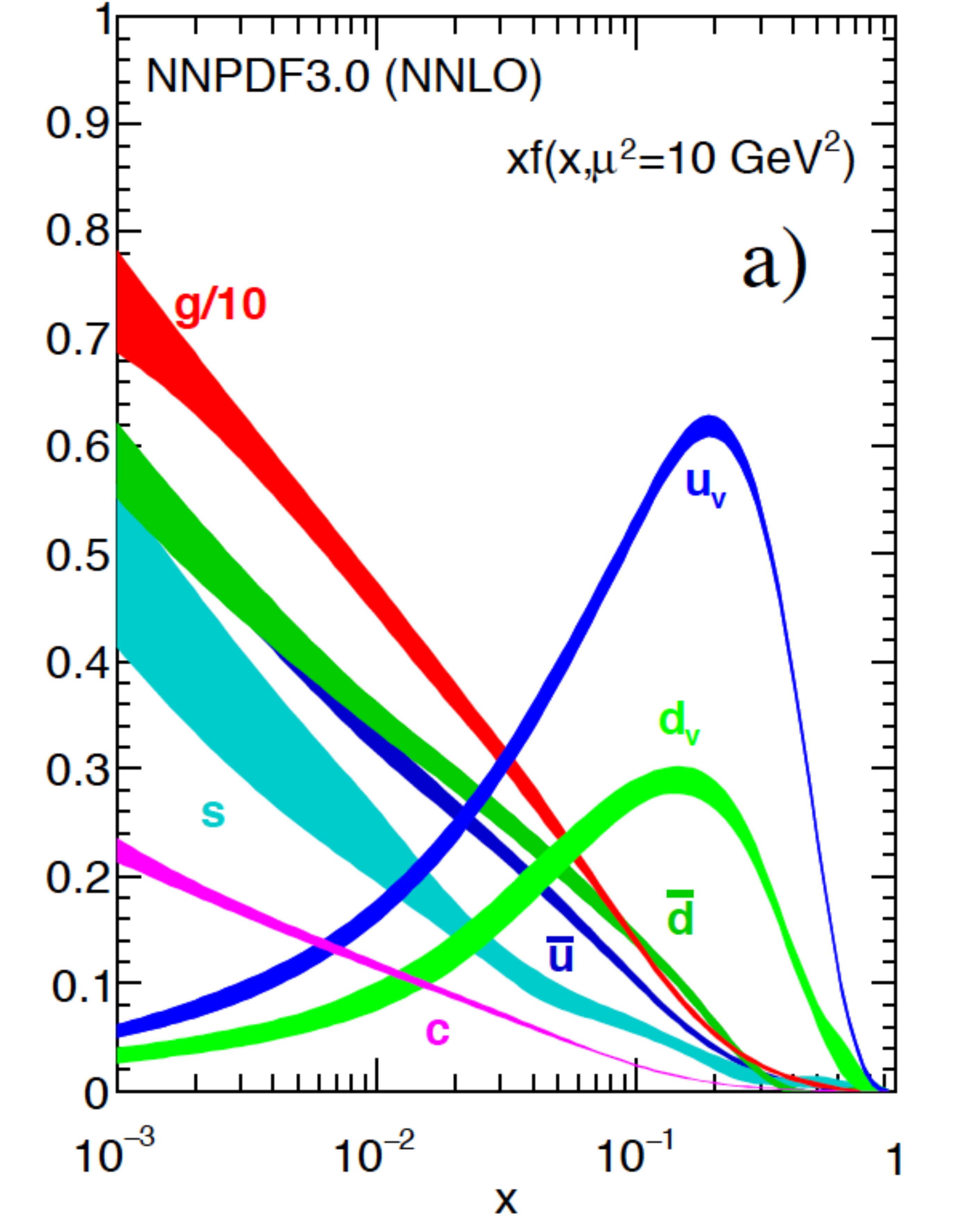
$$N_{ev} = \mathscr{L}\sigma$$

Lepton colliders *can* Increase this at high Energy

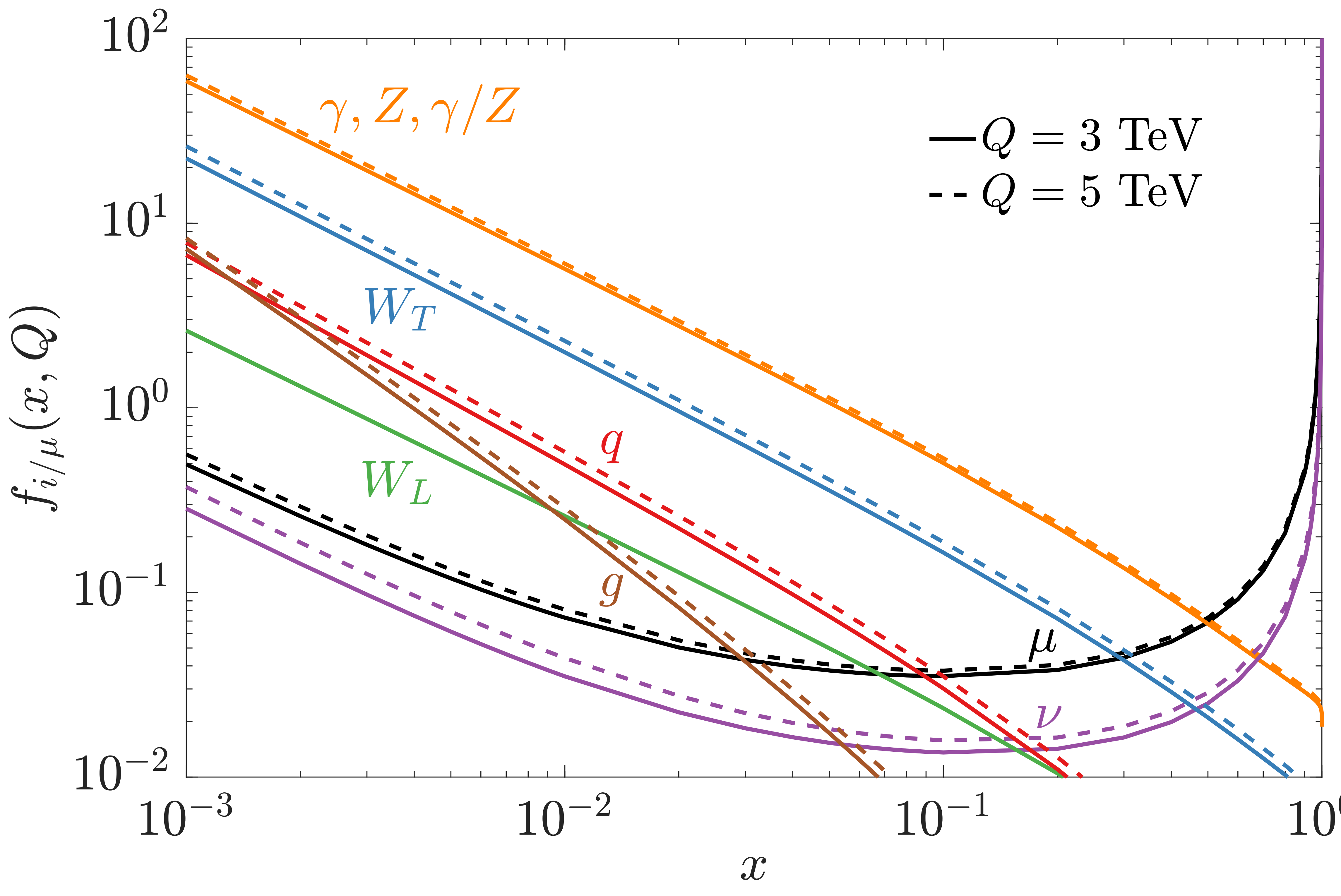


Similar concept to LHC/FCC-hh for why a muon collider can produce so many Higgs!

(See Dario's talk for more details)



Protons
valence peaks at x~.2
sea of quarks and gluons below

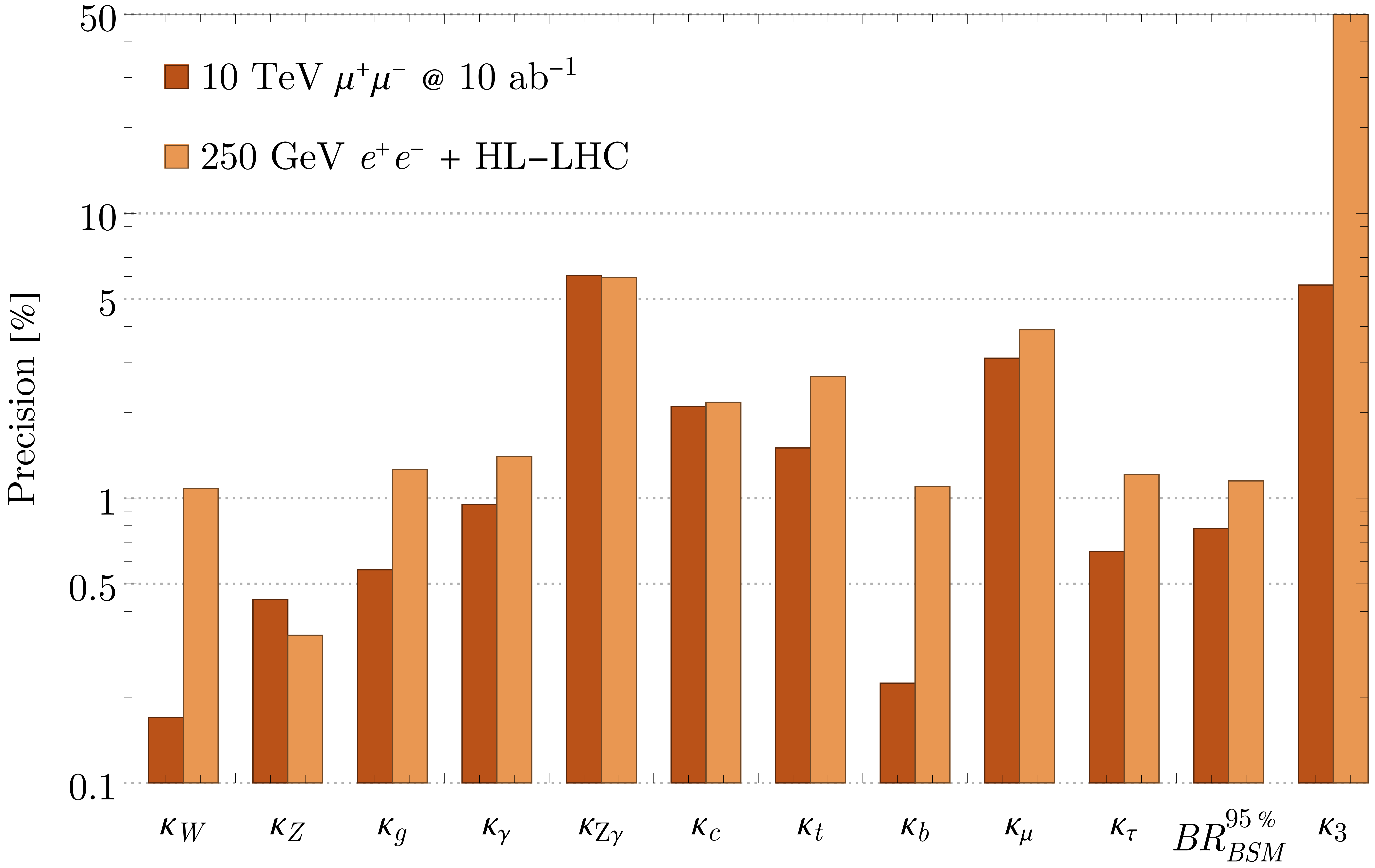


T.Han, Y.Ma, K. Xie
2007.14300

Muons
muons and neutrinos peak at x~1
EW + more sea

Both FCC-hh and μCol have a robust low-x (SM) program - not just absolute reach - but different backgrounds!

What does this get you?

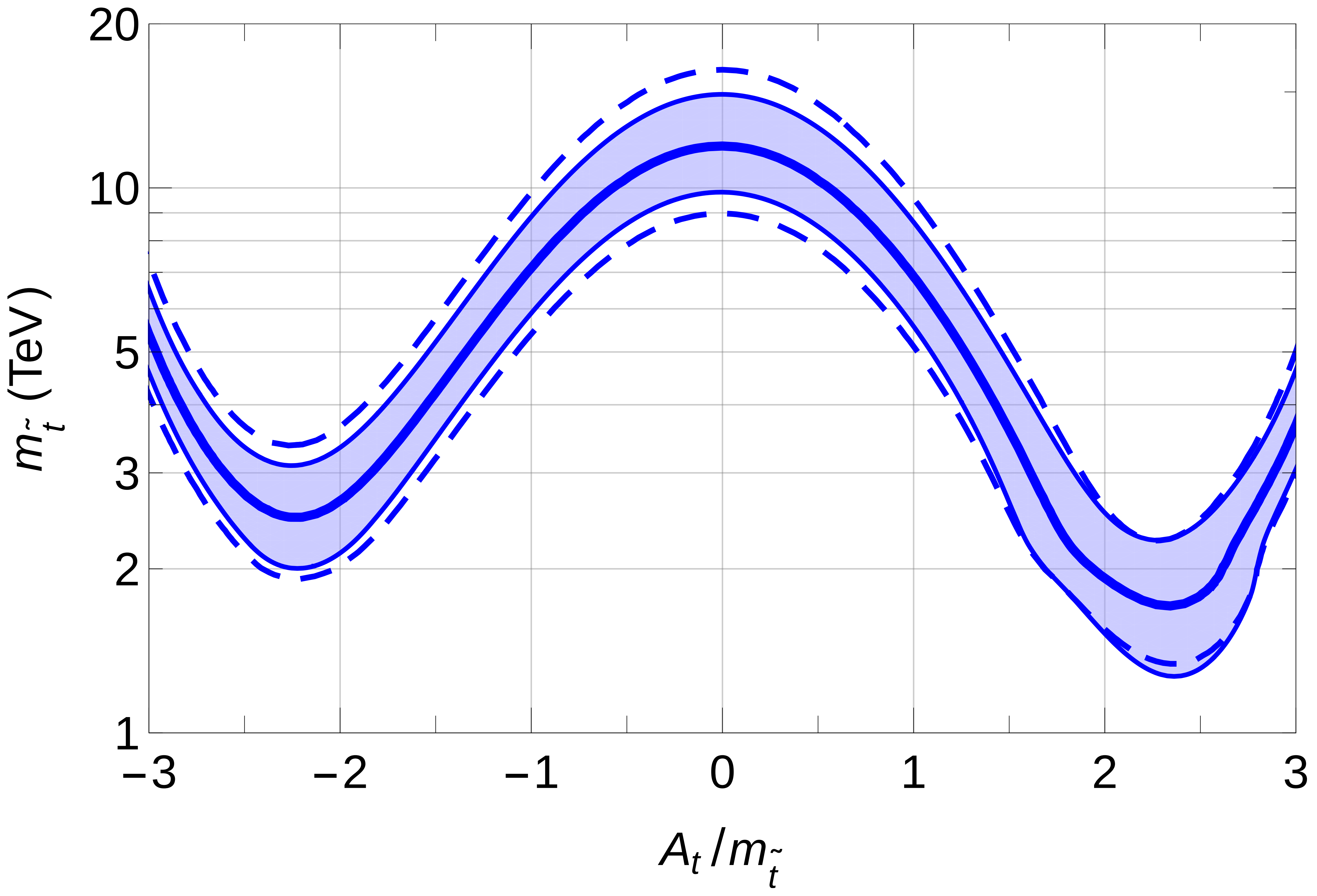


2308.02633 M.Forslund, PM

A 10 TeV muon collider wouldn’t complete the SM but it would be a next logical step beyond Higgs factories!

SUSY and the Higgs

Naturalness!



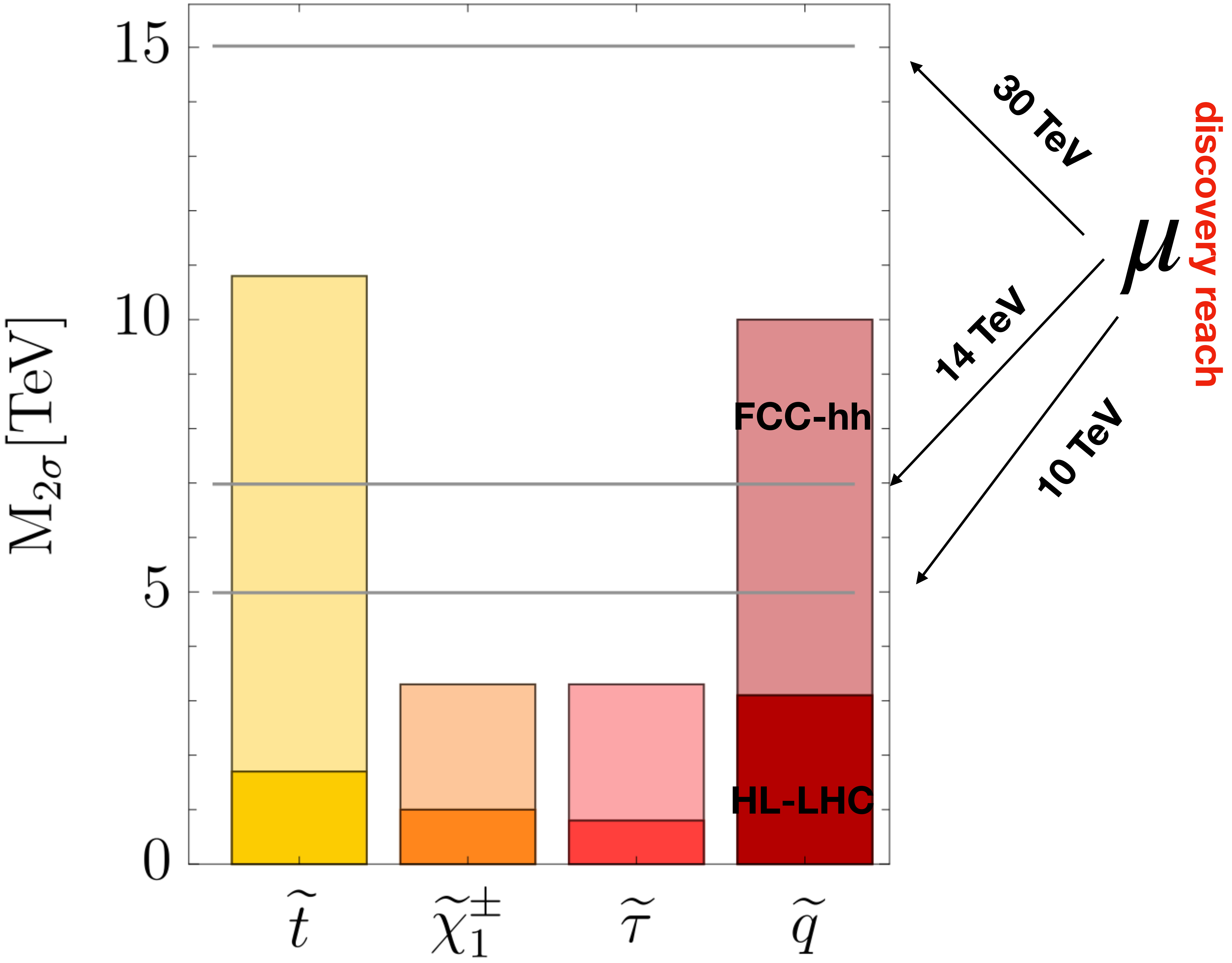
1504.05200 J.Vega, G.Villadoro

While some people got depressed about a lack of SUSY at LHC, if you *trusted* the theory the Higgs mass told you not to worry!

A natural theory should have *implications* for the actual Higgs mass, and the MSSM says the scale should be high for $m_h = 125$ GeV

I take QFT and spacetime symmetries very seriously!

Naturalness and Supersymmetry Example

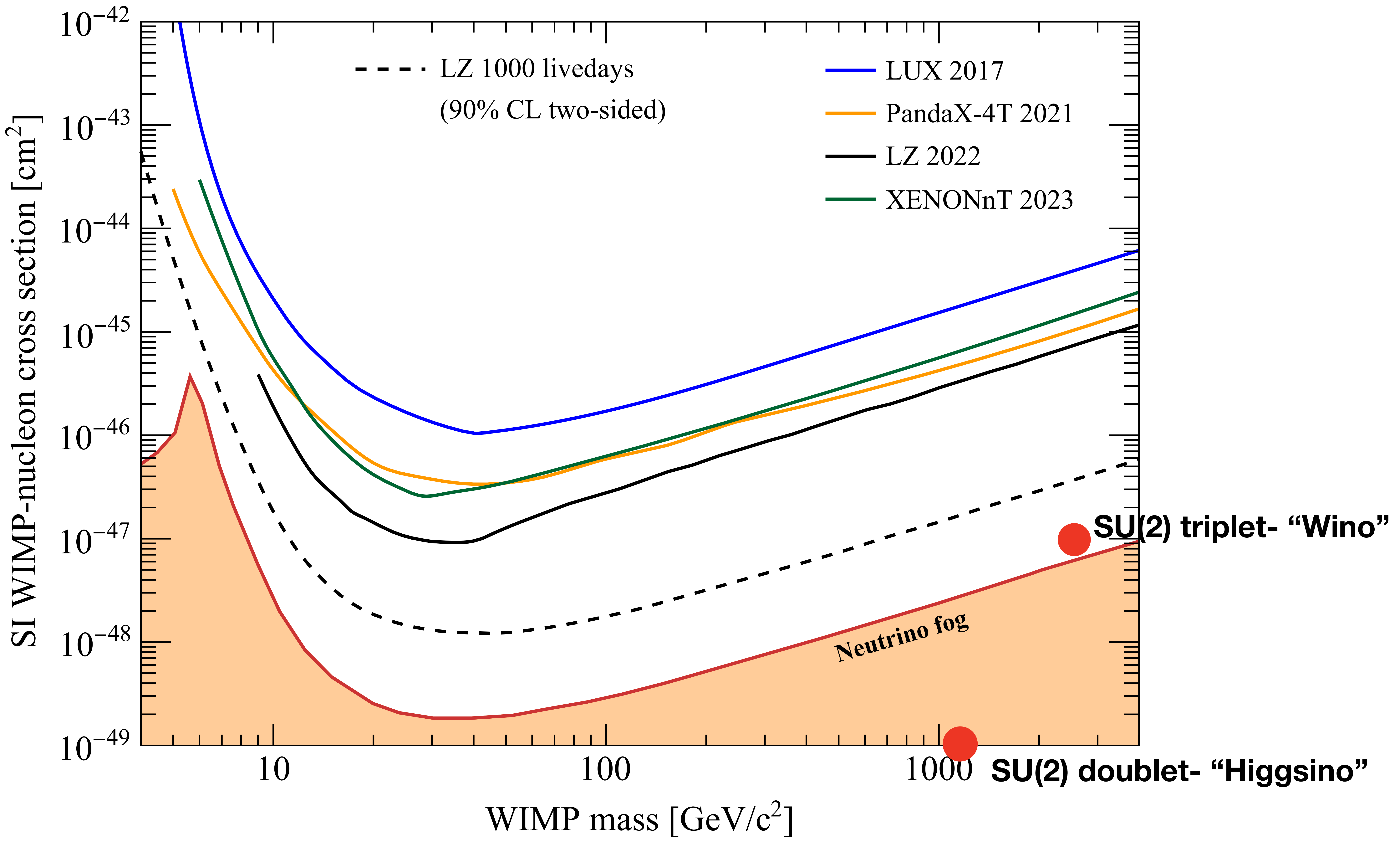


The Higgs at 125 GeV already suggested the SUSY scale was high, e.g. Stops ~ 10 TeV

FCC-hh is superior to 10 TeV muon collider for Stop Searches, given colored particle nature

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

The simplest models of WIMP DM still are untested directly!

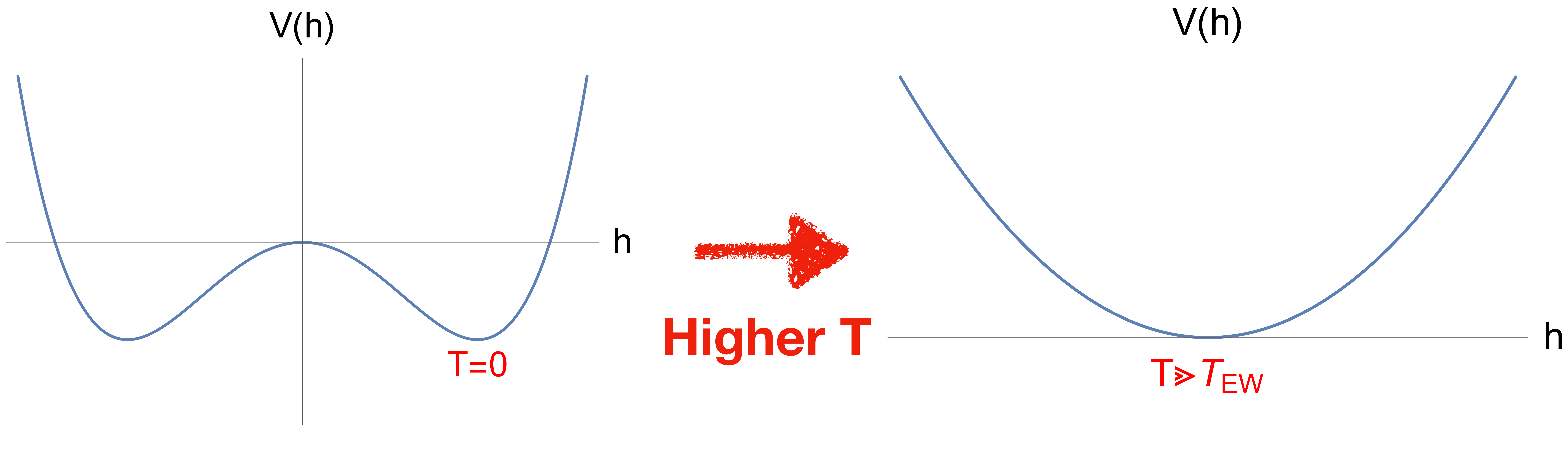


Testing the simplest WIMPs

A 10 muon collider is extremely well suited for this!

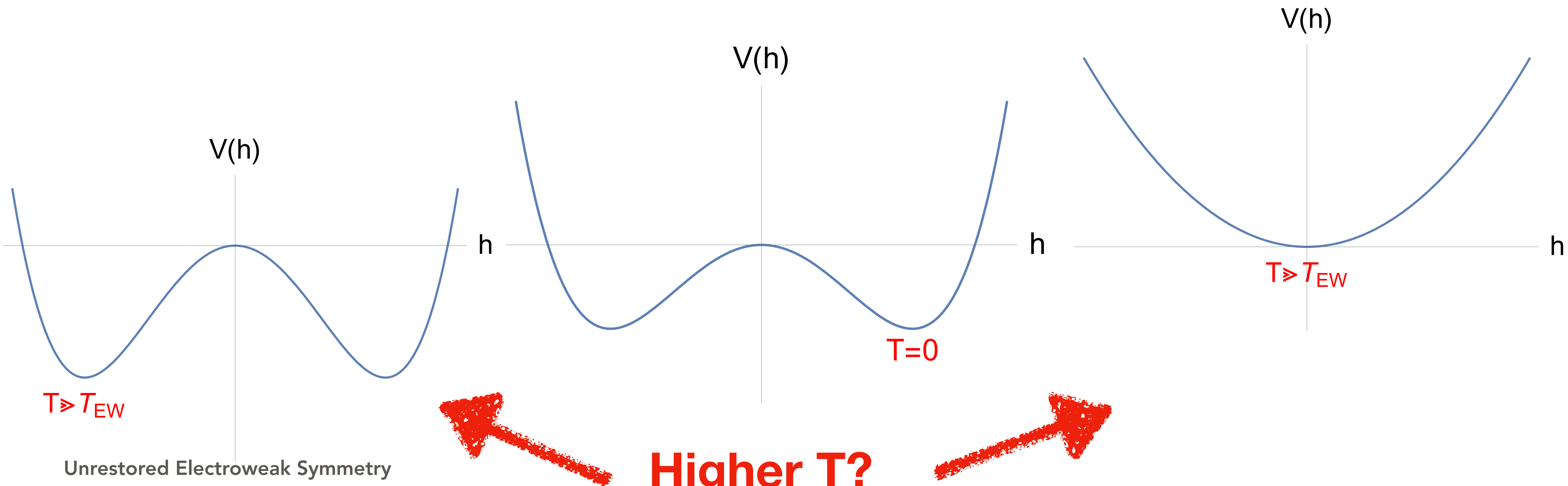
Testing the EWPT

Next era in SM history is the "Electroweak Phase Transition"



What is the phase diagram of the Electroweak Symmetry?

However, we don't know that there *was* symmetry restoration at temperatures ≫ EW scale!



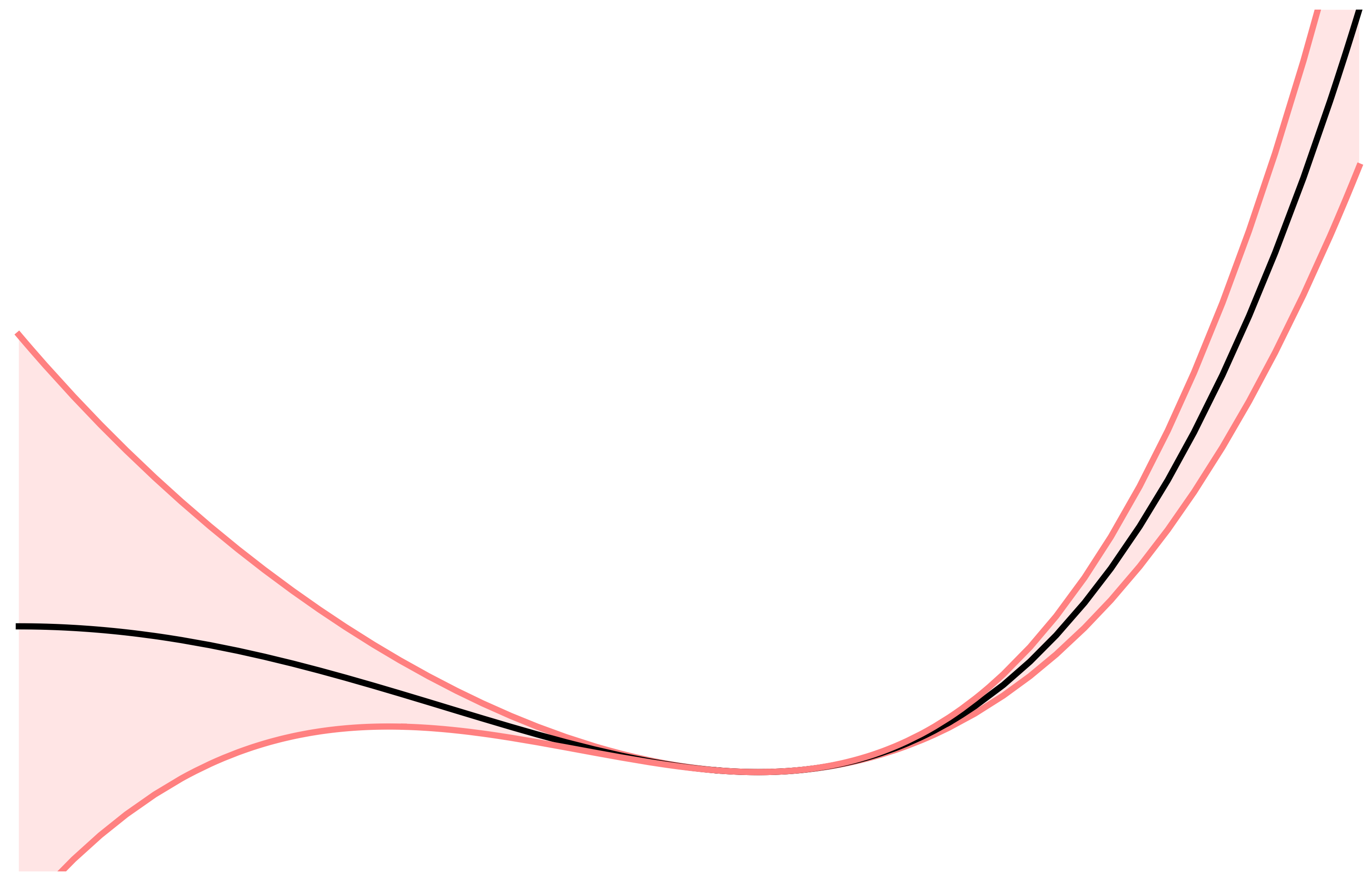
PM, H. Ramani
1807.07578

Even if it is restored we don’t know the order of the phase transition *experimentally*

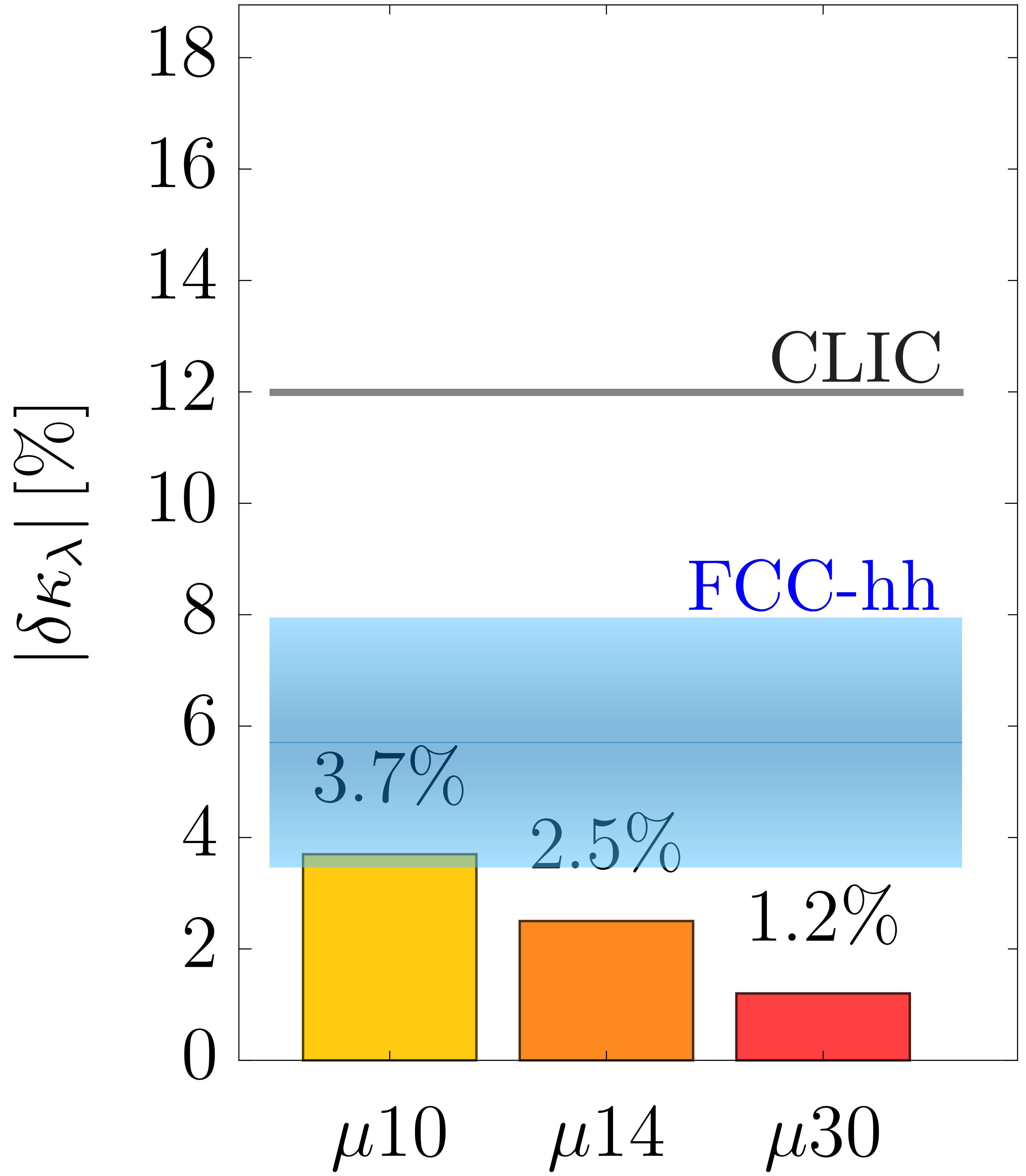
Proxy for understanding the early Universe are Higgs self interactions:

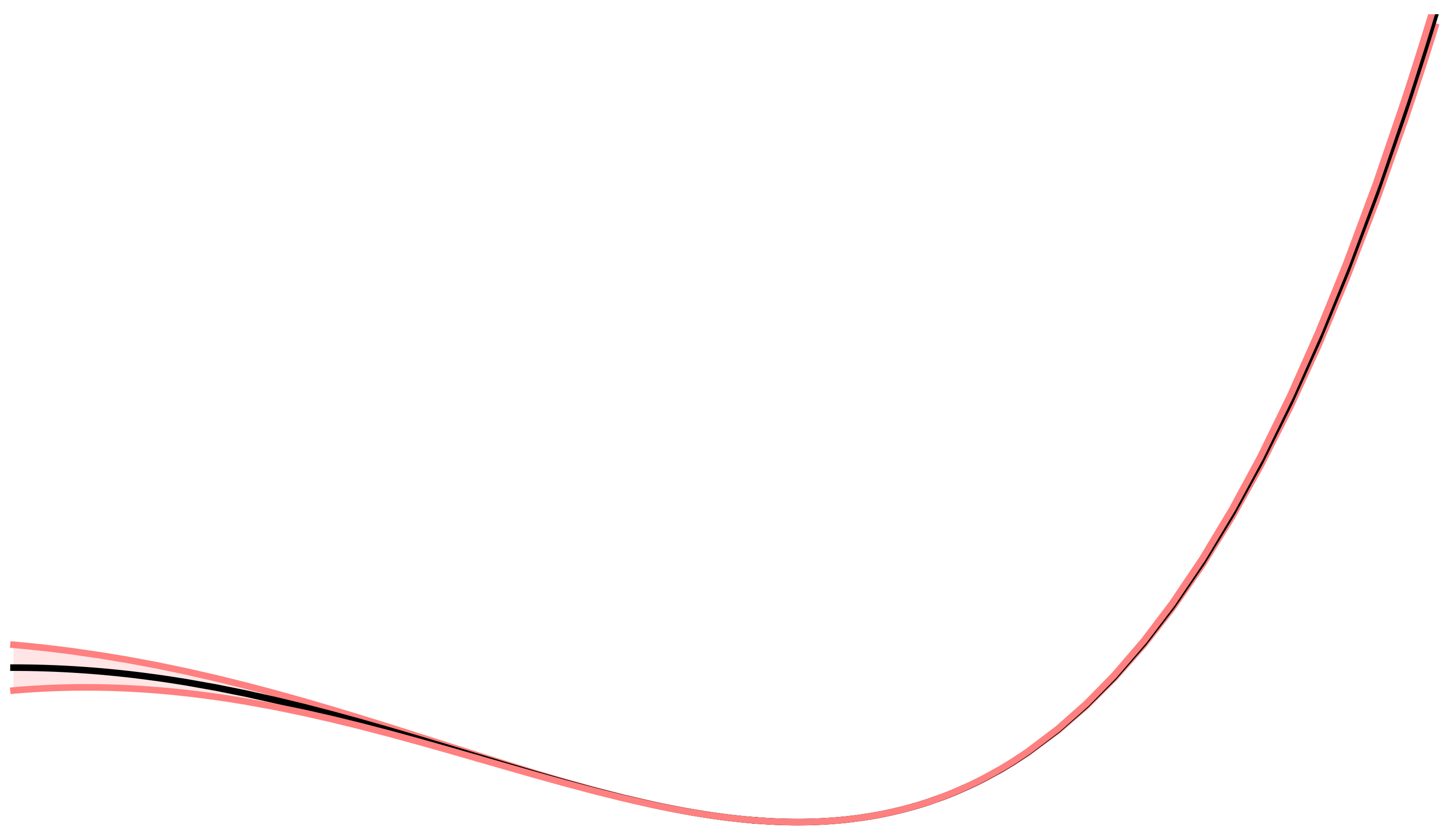
Probe the Higgs self interactions to *at least* $\lambda_3 \sim \mathcal{O}(1)\,\%$

High energy lets us finally improve on Higgs Potential



HL-LHC





10 TeV μCol

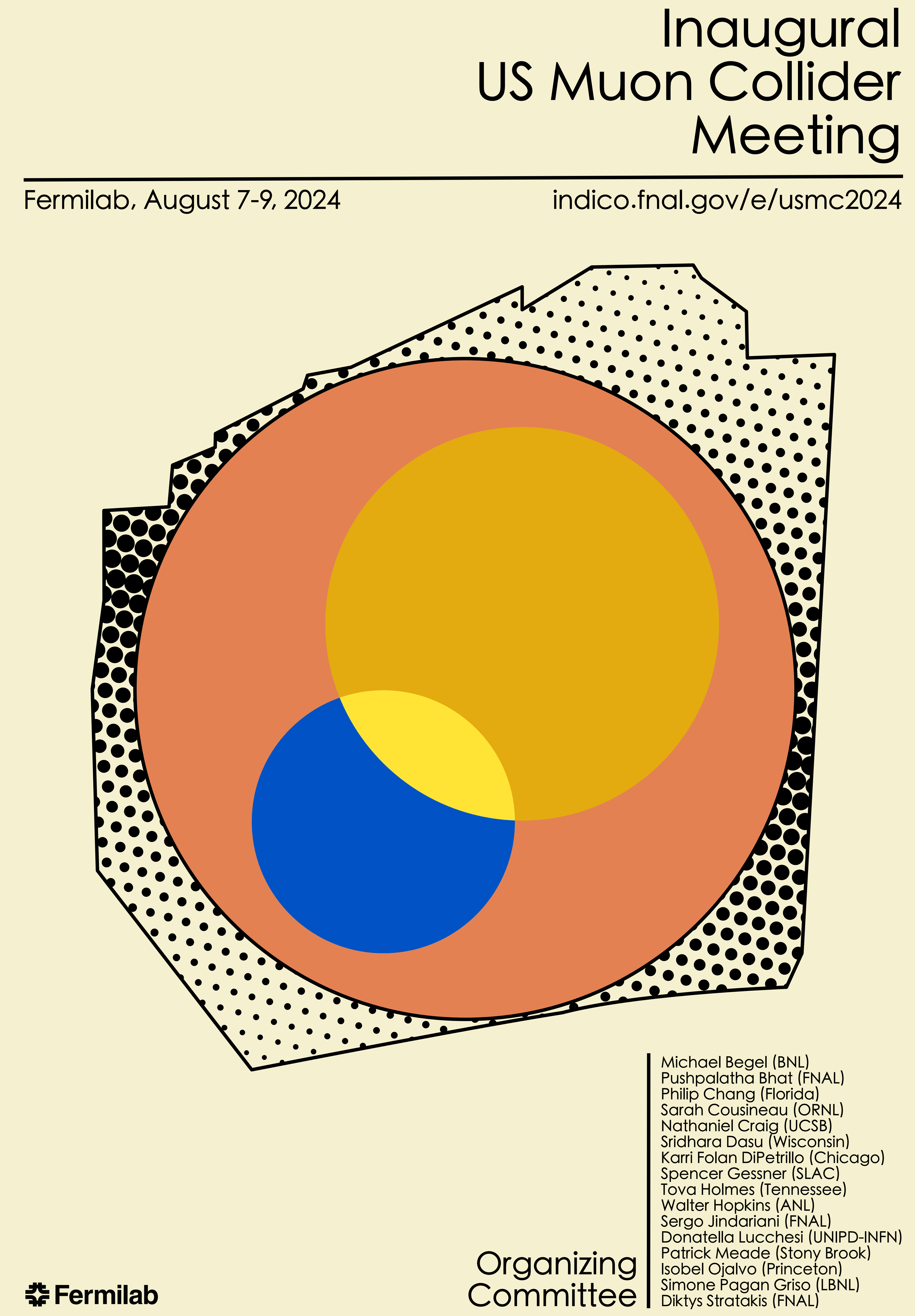
We can get to threshold for understanding if the EW phase transition is 1st order at the EW scale with a μCol

See other examples in Dario’s and Nadia’s talks for μCol and literature!

A leptonic vision for the future

Conclusions

- Circular and Linear Higgs Factories offer complementary physics cases and are far beyond just being “Higgs Factories”
- Getting to higher energy is *necessary* not optional!
    - Muon Colliders and WFA provide alternative routes to protons that change the energy OR precision paradigm
    - We must support R&D along all paths, e.g. instead of a first stage muon collider being potentially 20 years away it could have been 10 if accelerator R&D was better supported in the past
- If the world ended up with an FCC path at CERN and Muon Collider at Fermilab this would be amazing for physics and HEP in general, but let’s do the work to make sure we have options!



If you're in the US come join us as this *is* (IMCC) and *must continue to be* an international effort!

Or there is a nice GGI program next summer if you prefer Firenze…