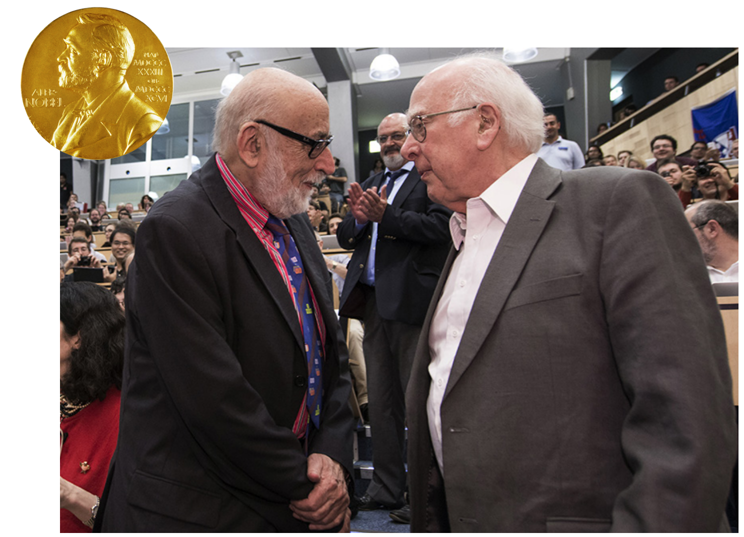
Overview of future directions of particle physics

LianTao Wang
Univ. of Chicago

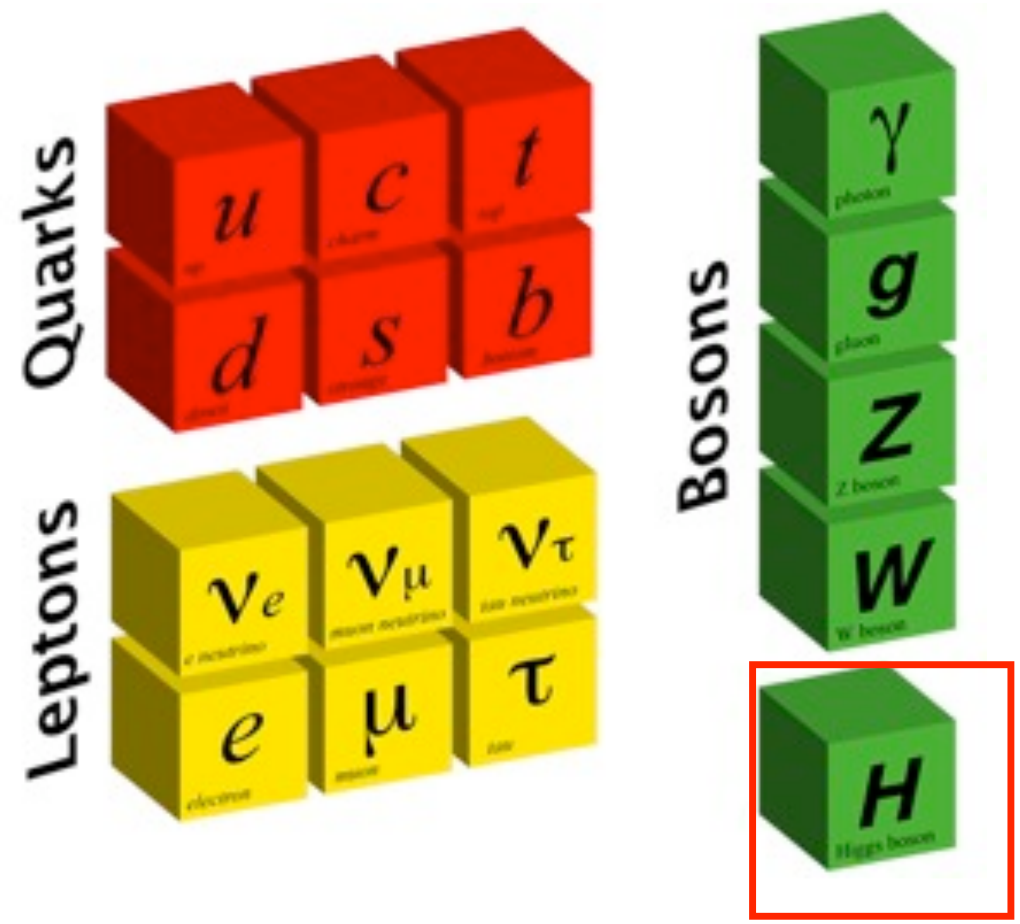
19th WIN Conference. July 2, Sun Yat-sen University, Zhuhai.

Where we are

It has been 10 years.



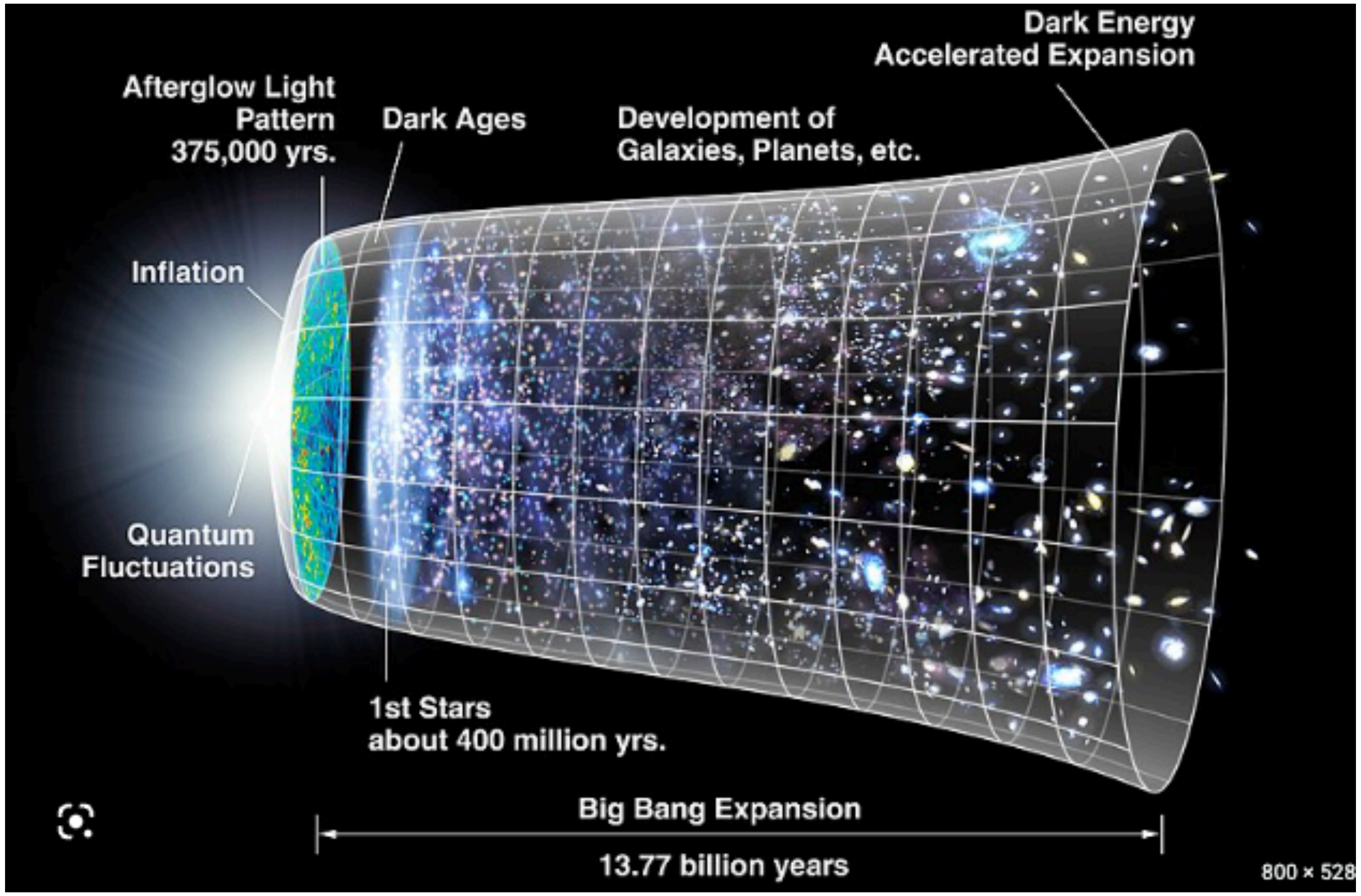
The Standard Model.

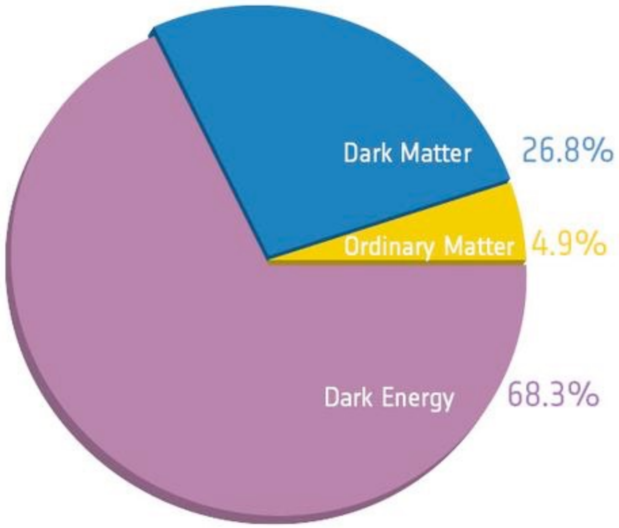


1961–1968

Very successful. Many experimental tests. No cracks yet.

Cosmos





A standard model of cosmology.

More than a century ago

Albert A. Michelson, 1899

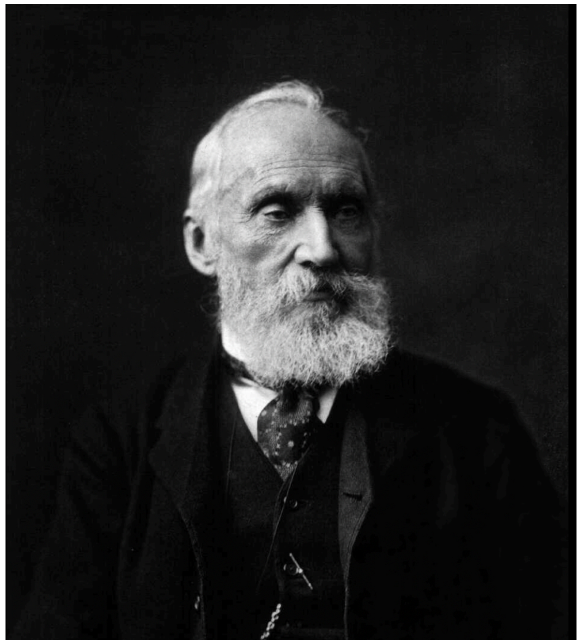
The more important fundamental laws and facts of physical science have all been discovered, and **these are now so firmly established that the possibility of their ever being supplanted in consequence of new discoveries is exceedingly remote.**

Are we in a similar situation?

More than a century ago

Albert A. Michelson, 1899

The more important fundamental laws and facts of physical science have all been discovered, and **these are now so firmly established that the possibility of their ever being supplanted in consequence of new discoveries is exceedingly remote.**



Lord Kelvin, 1900 "Two clouds"

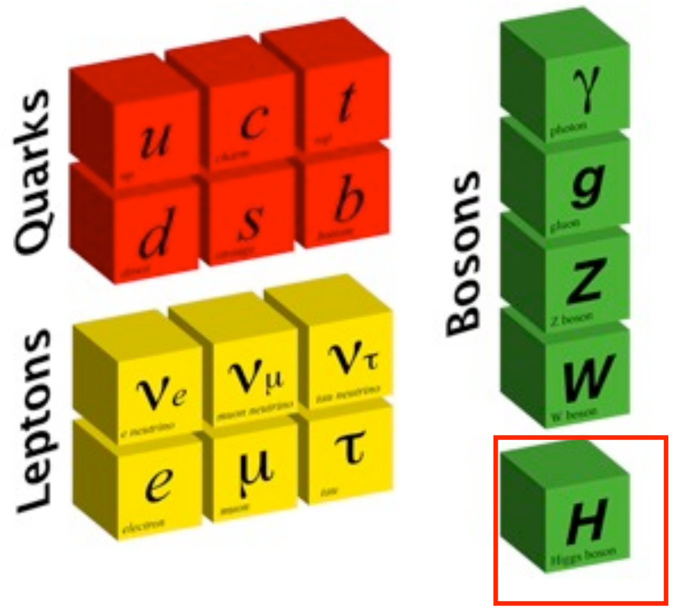
Light propagation, ether (Michelson-Morley)

Maxwell-Boltzmann, equipartition, specific heat

We have many clouds

Open questions in the Standard Model

Very nice, but it looks like chemistry to me.



Hierarchy, nautralness

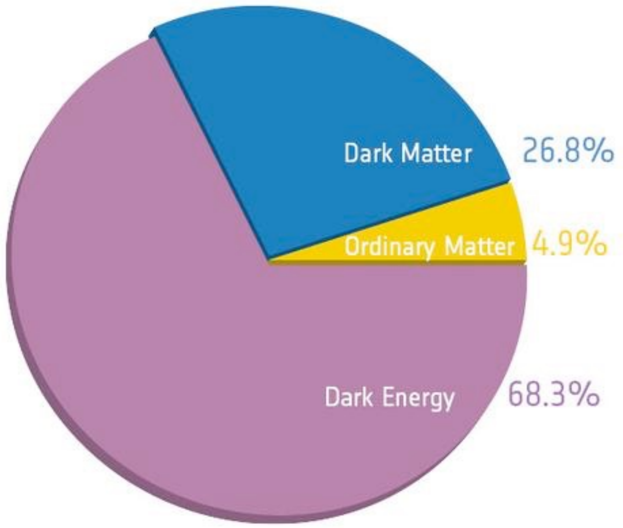
Flavor structure

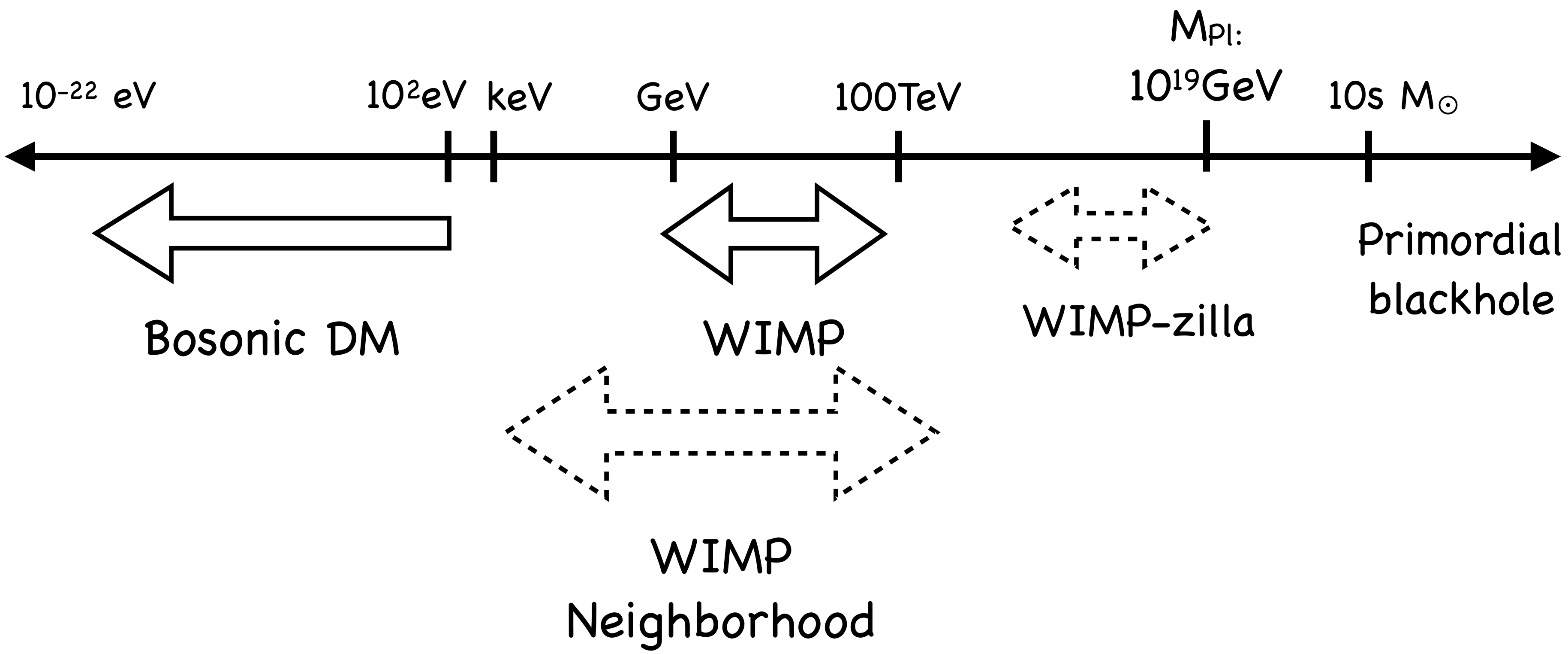
CP violation

Unification ...

Basically, what gives us the Standard Model?

Dark world

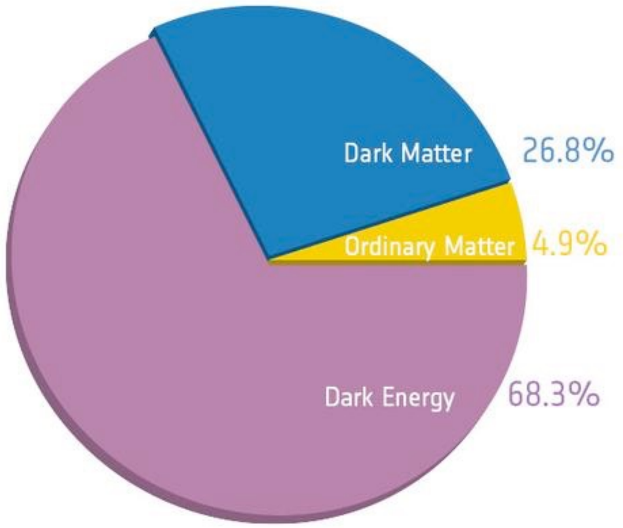


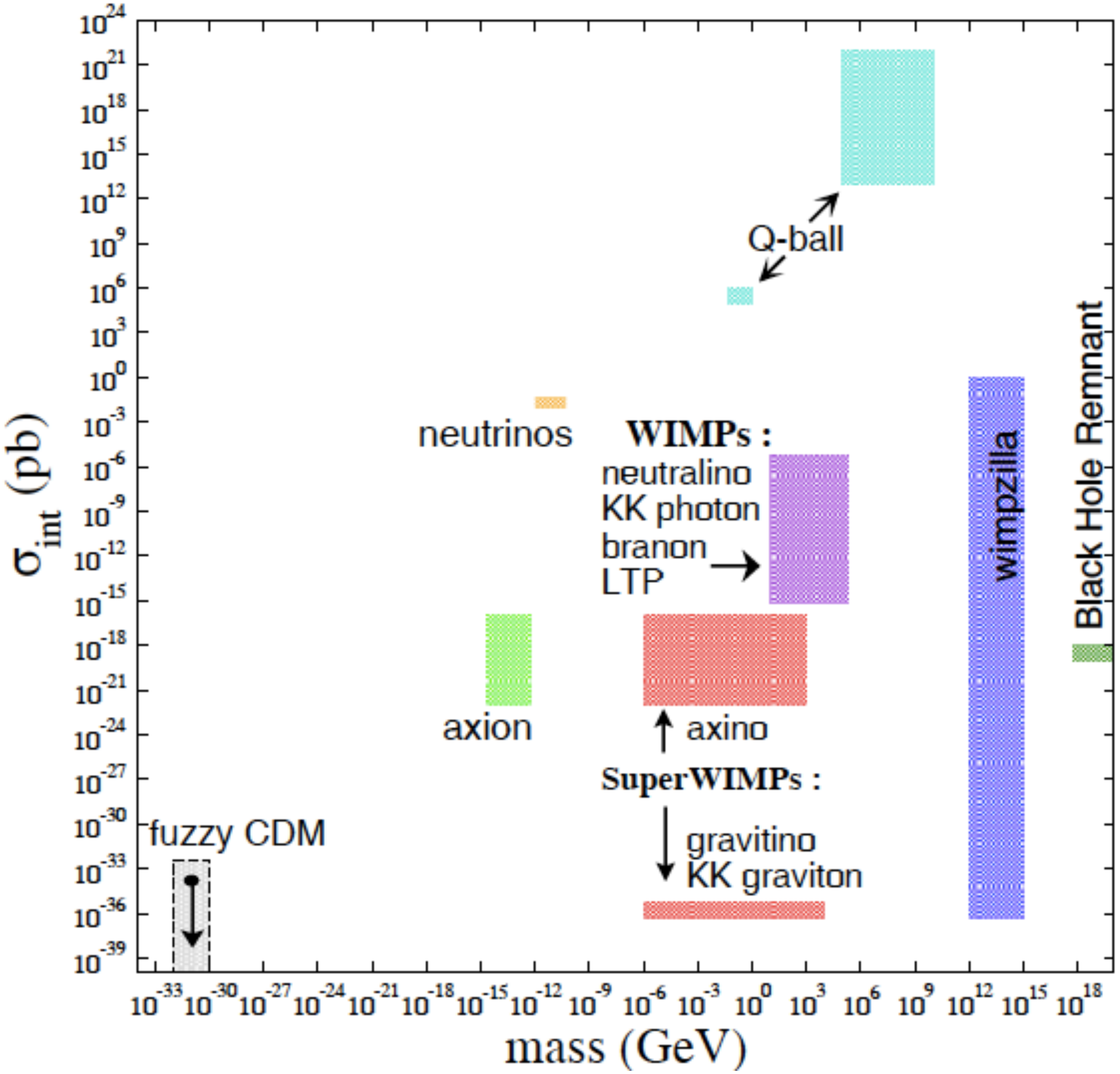


None of above?

In this case, we can't even start to look for them.

Dark world

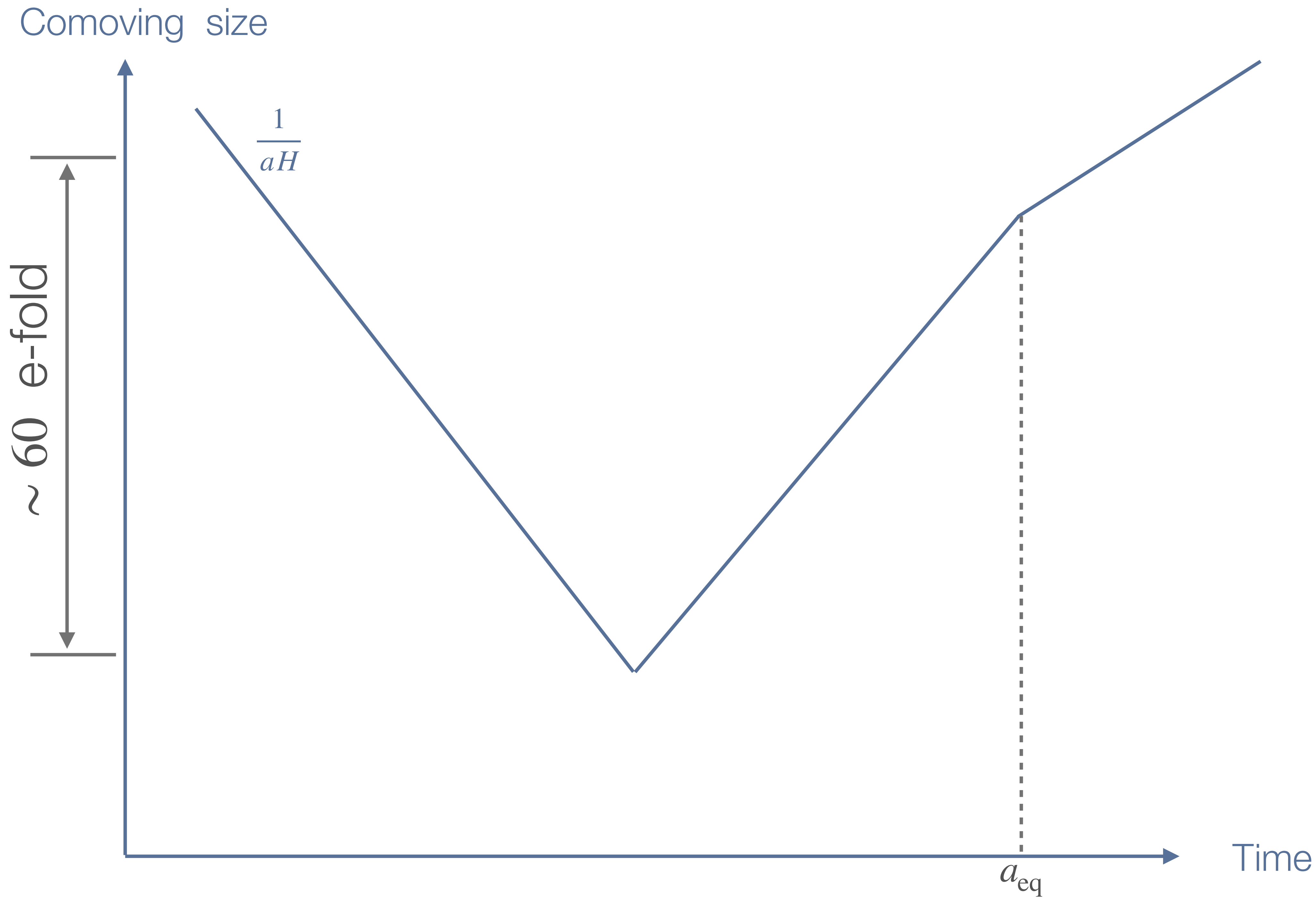




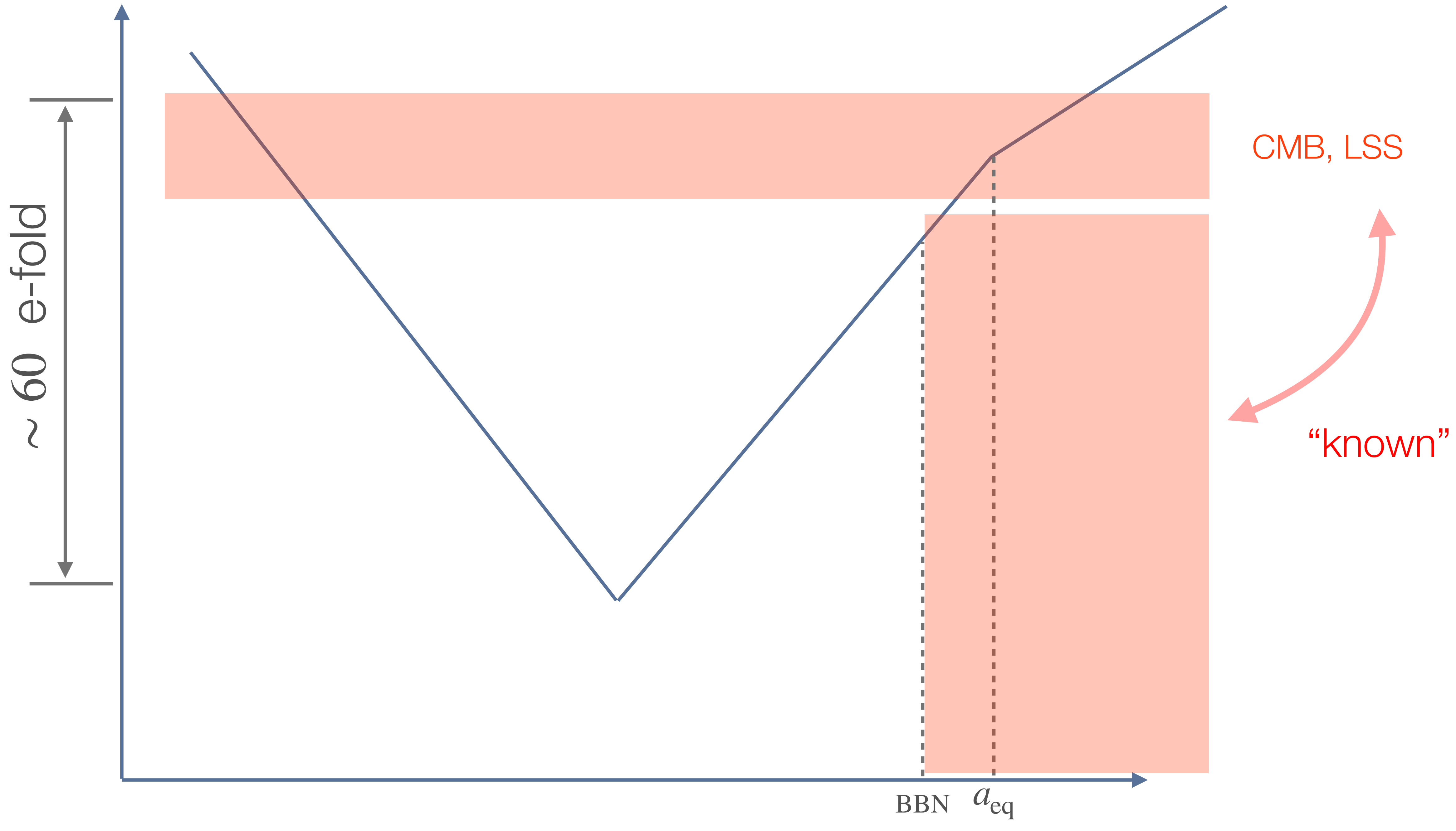
Vast gaps!

Need more lampposts.

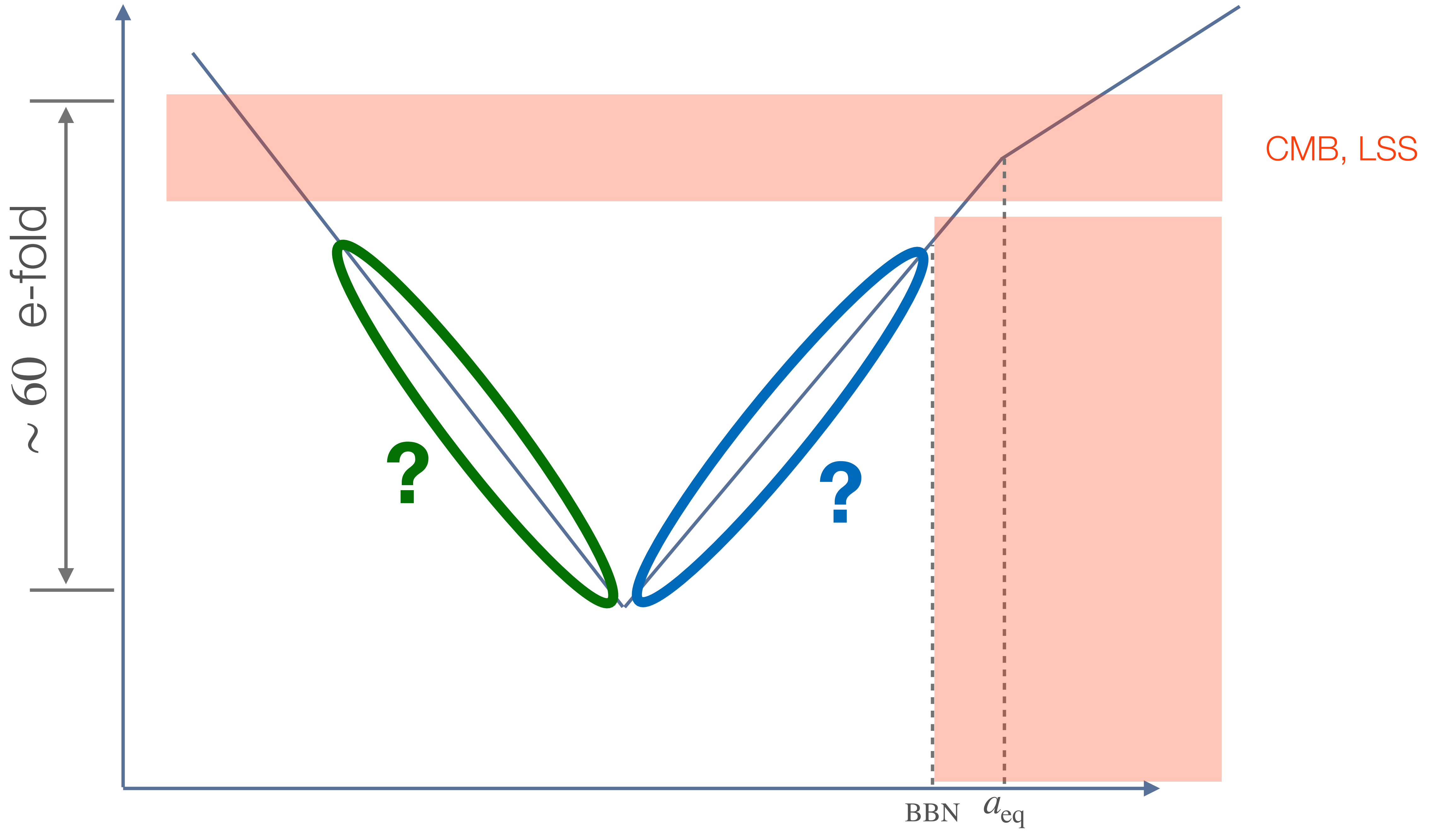
Early universe



Early universe



Early universe



What is the future?

Where will be the next breakthrough?

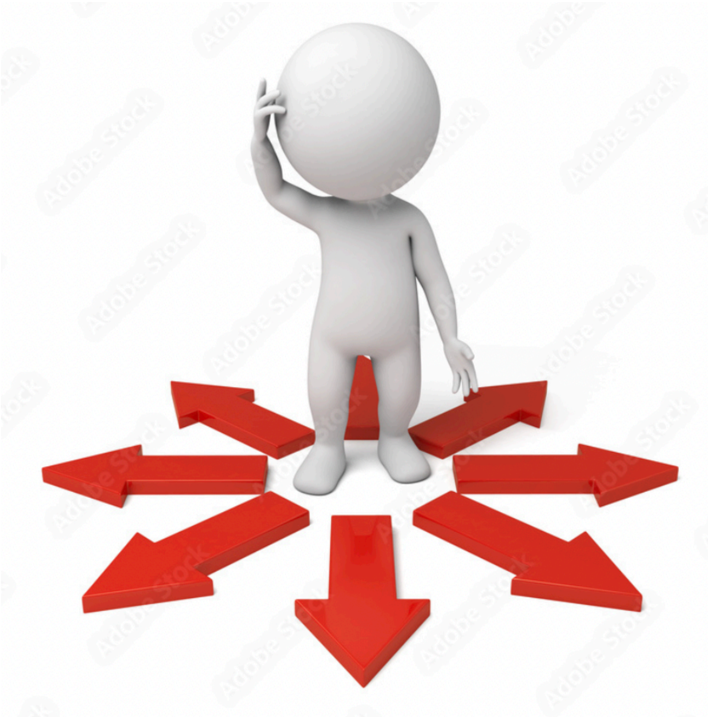
What is the future?

Where will be the next breakthrough?

Of course, I don't know.

What is the future?

Where will be the next breakthrough?



Of course, I don't know.

I will focus on:
Future experimental probes, and what we can learn from them

The experimental probes

Energy frontier
HL-LHC, Future colliders

Cosmological observations
CMB, LSS, Gravitational wave

Table top exp, fixed target, …
Intensity frontier

The experimental probes

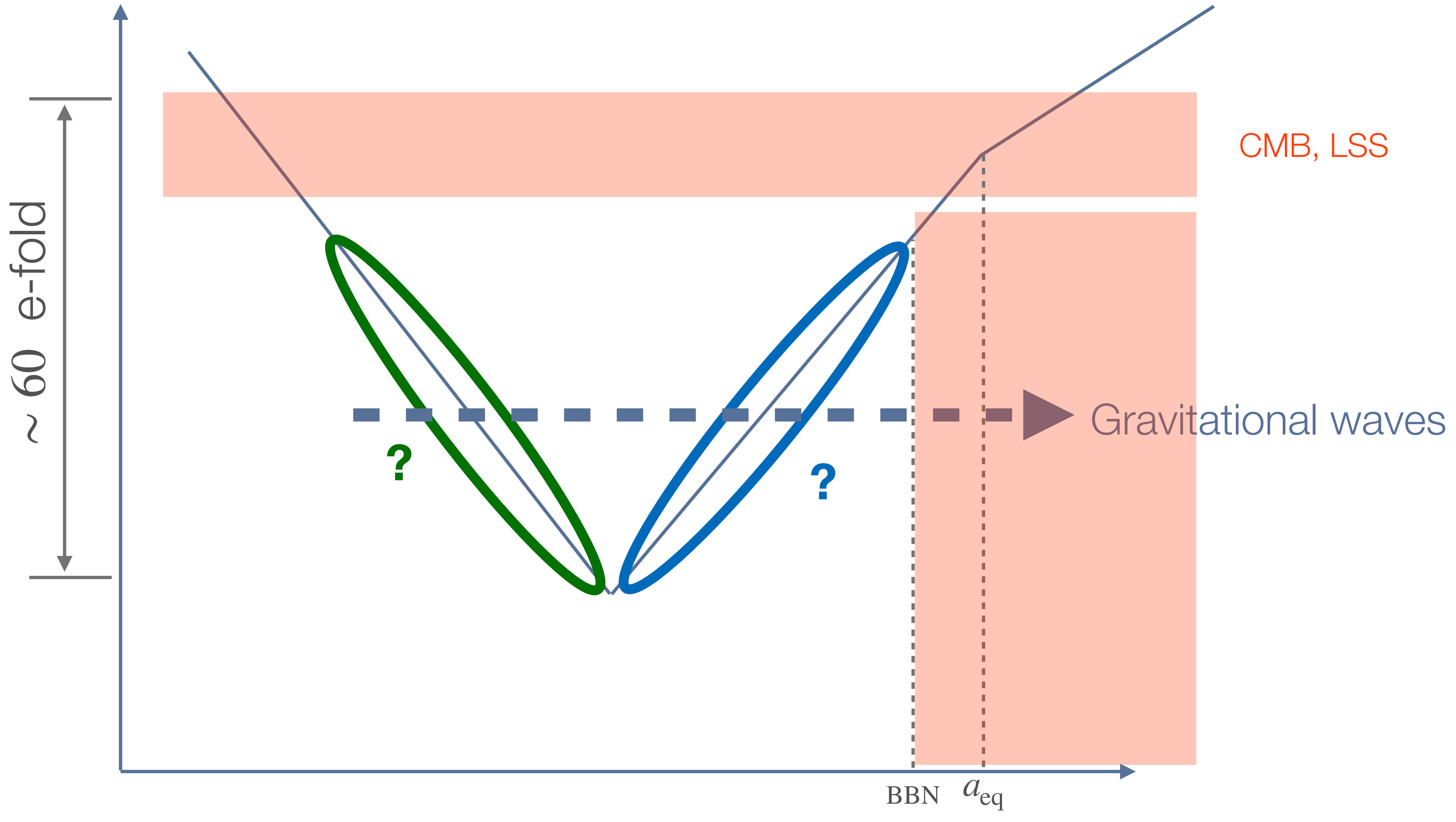
Energy frontier
HL-LHC, Future colliders

Cosmological observations
CMB, LSS, Gravitational wave

Very briefly

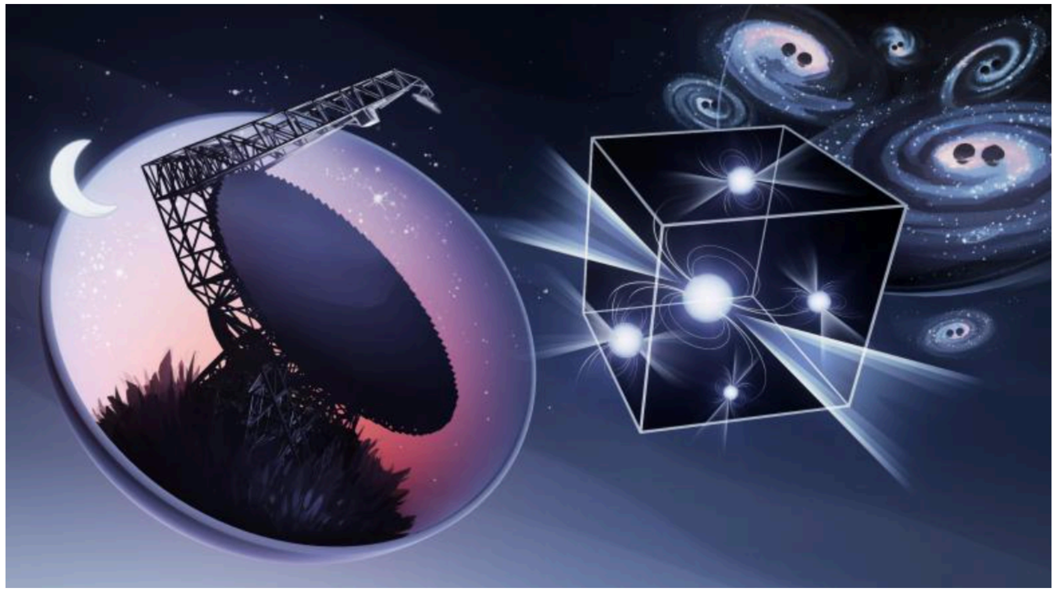
Table top exp, fixed target, …
Intensity frontier

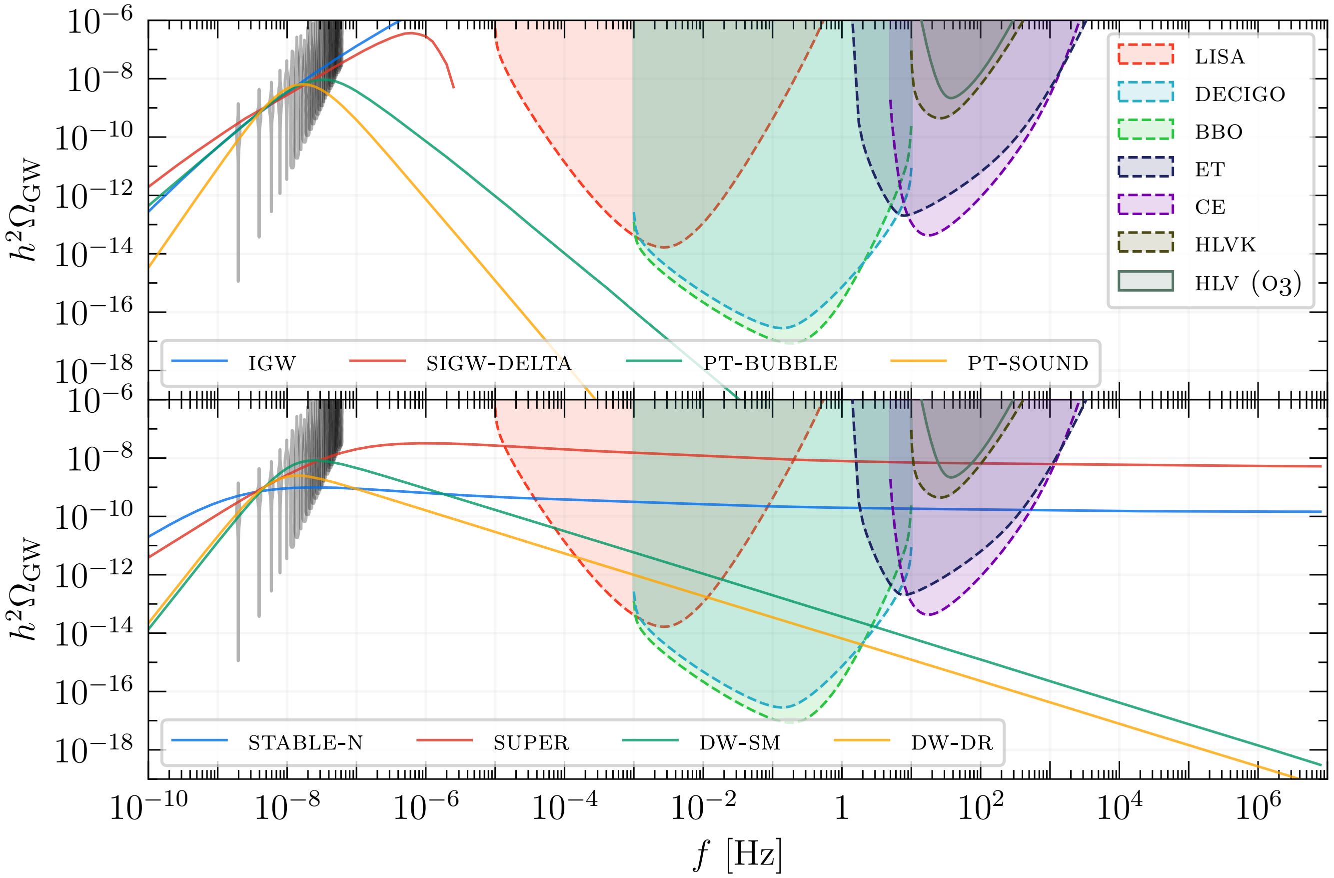
Early universe



Exciting news!

NANOGrav, June 29, 2023

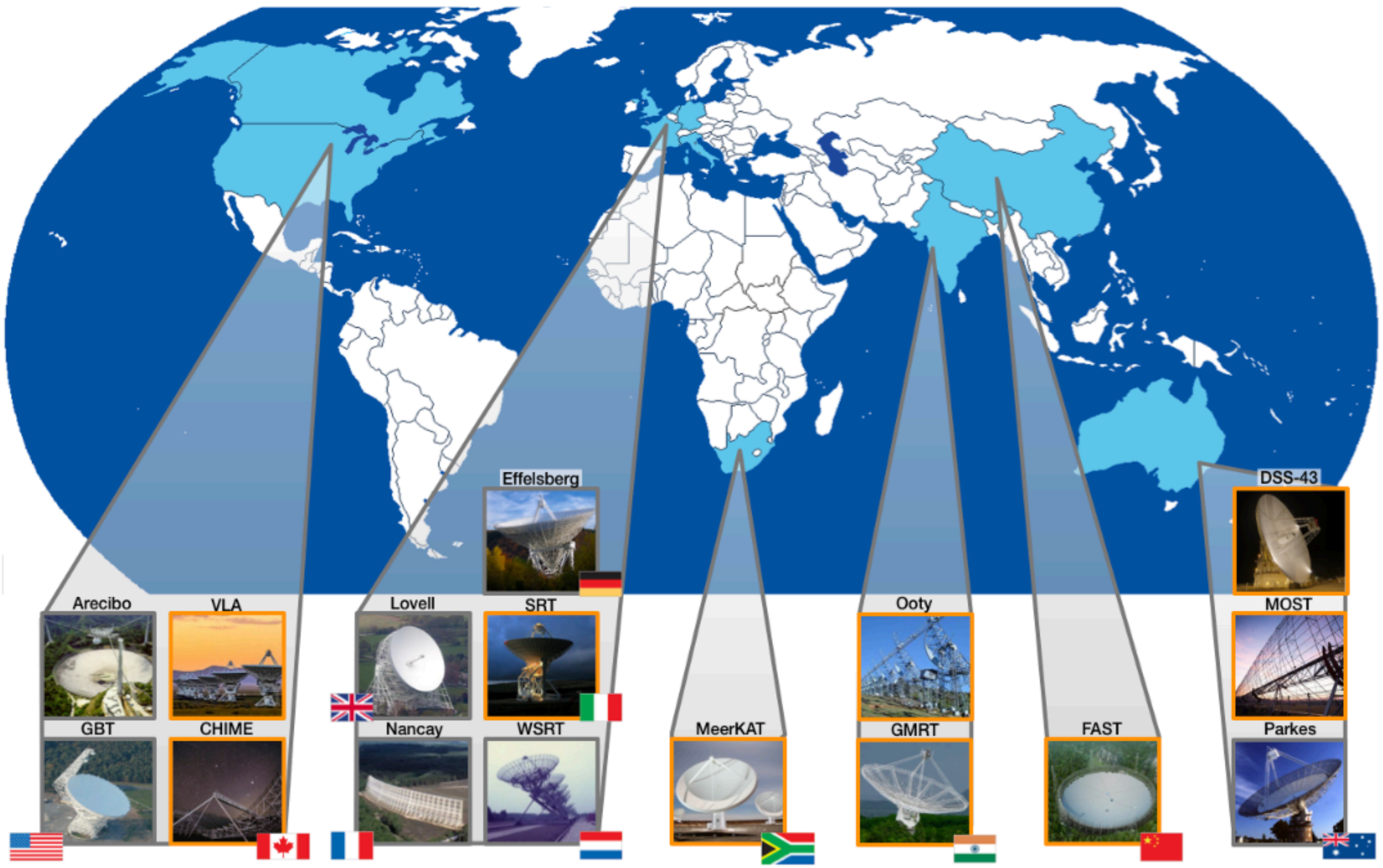




Likely the beginning of a new era!

Could be the first of observation of primordial GW!

More data to come!



The experimental probes

Energy frontier
HL-LHC, Future colliders

Rest of the talk

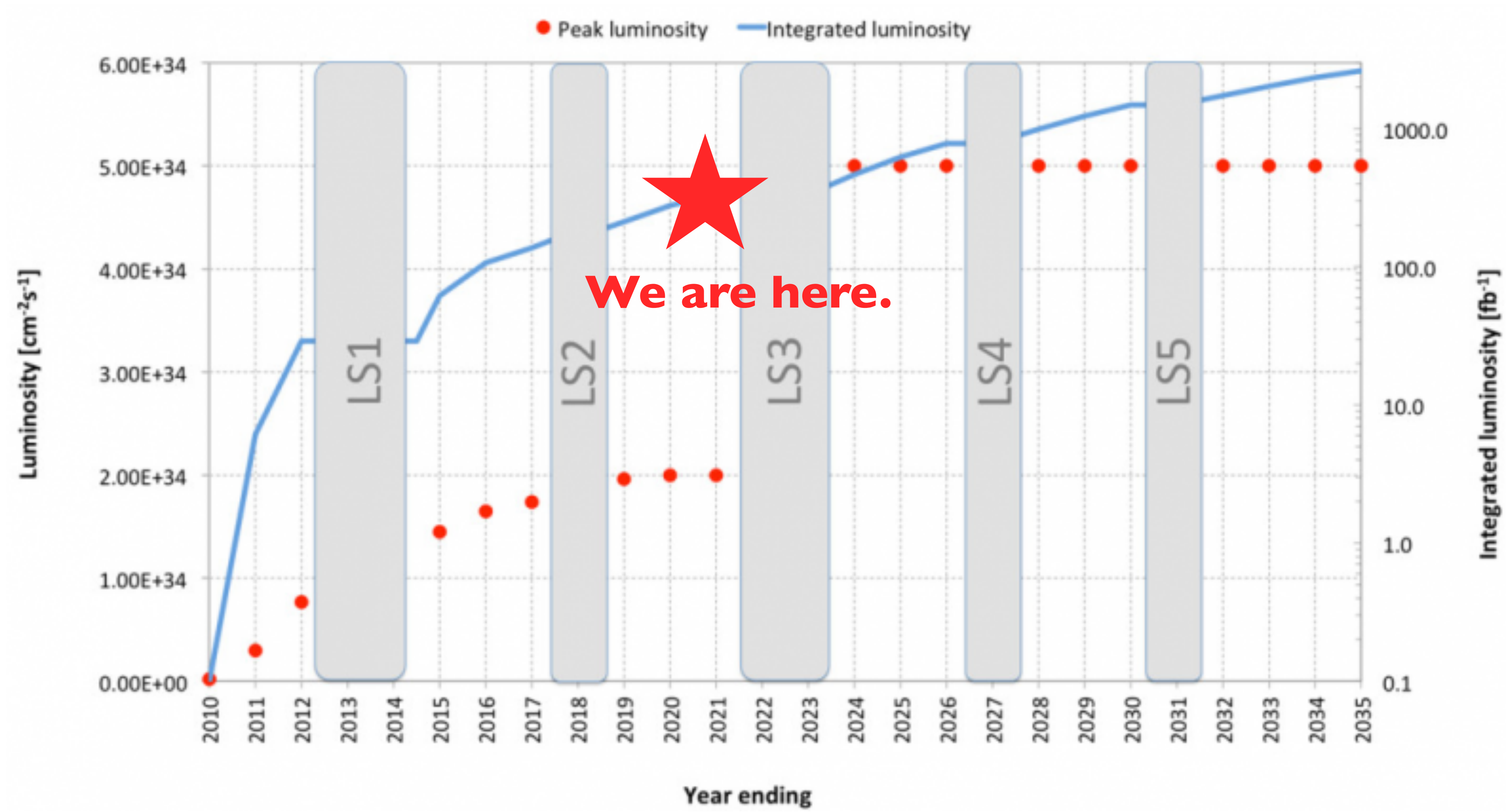
Cosmological observations
CMB, LSS, Gravitational wave

Table top exp, fixed target, …
Intensity frontier

Current Energy frontier:
HL-LHC

HL-LHC

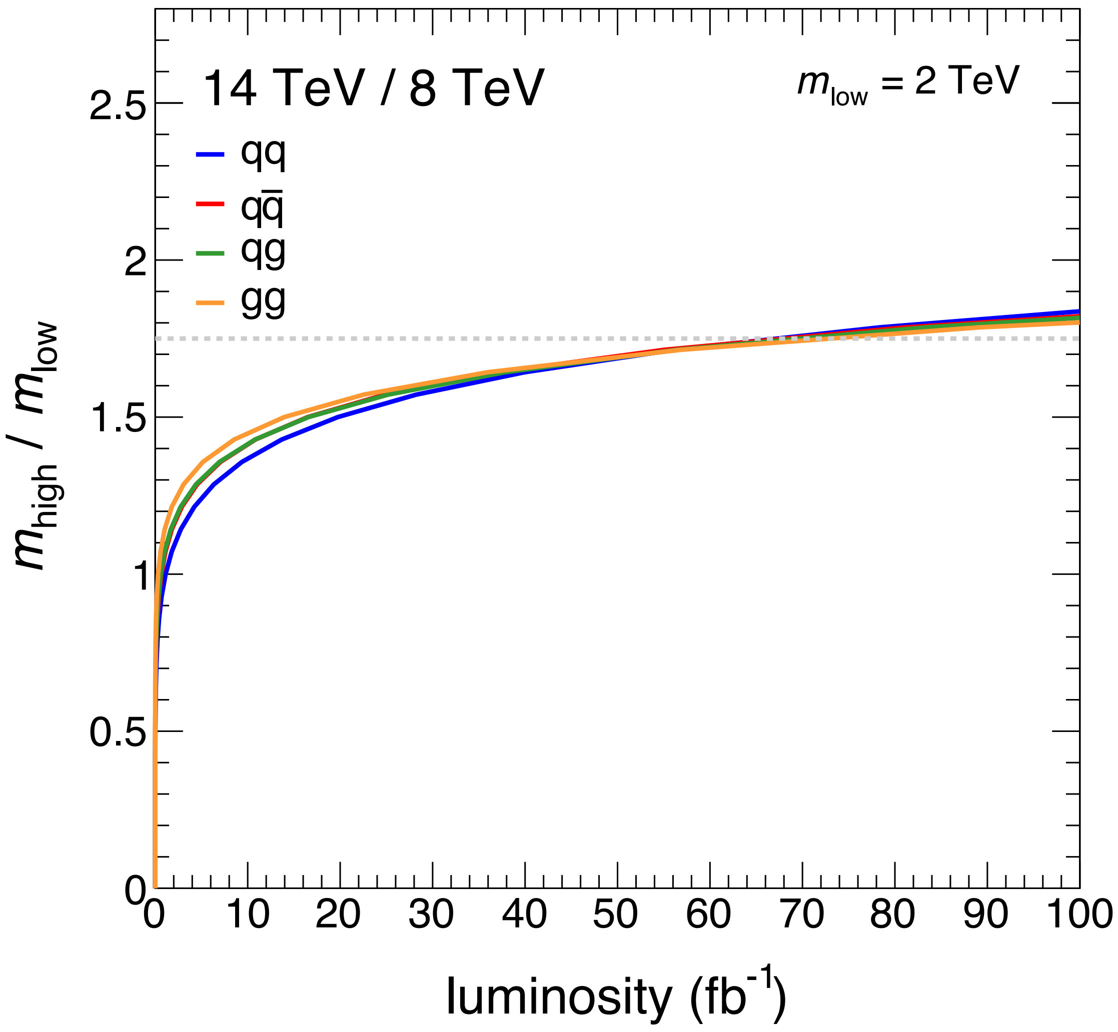
Still, 10 times more data to come.



The question: what will this data tell us?

As data accumulates

8 TeV limit on colored NP, about 2 TeV



Progress on direct search will become slower, harder

Two directions

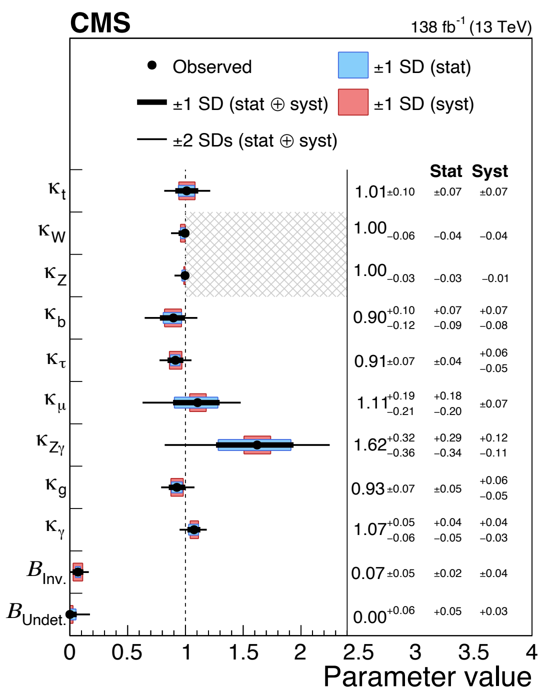
A lot of data

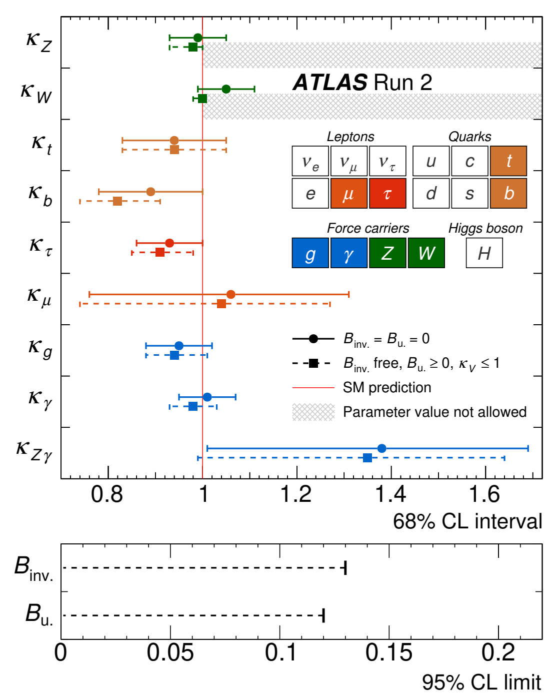
Precision

Exotica
(Very) rare phenomena

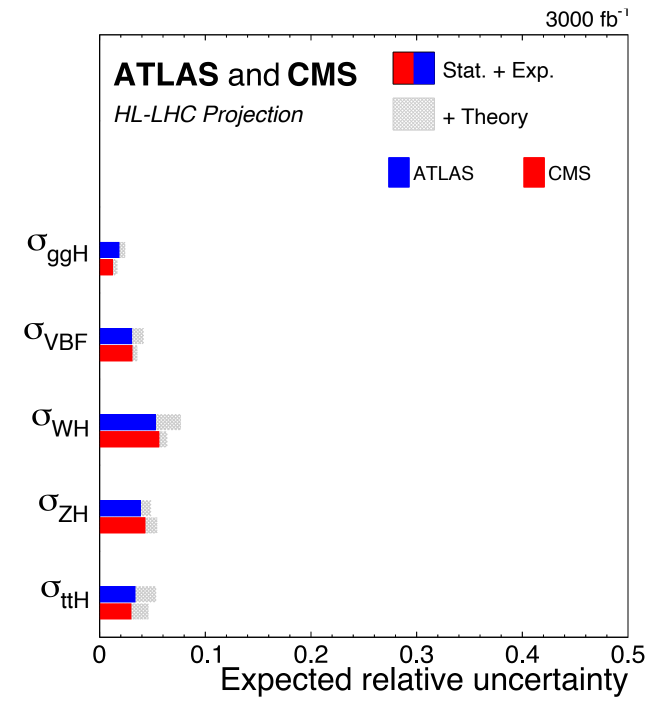
Precision: Higgs

Higgs coupling other SM particles:





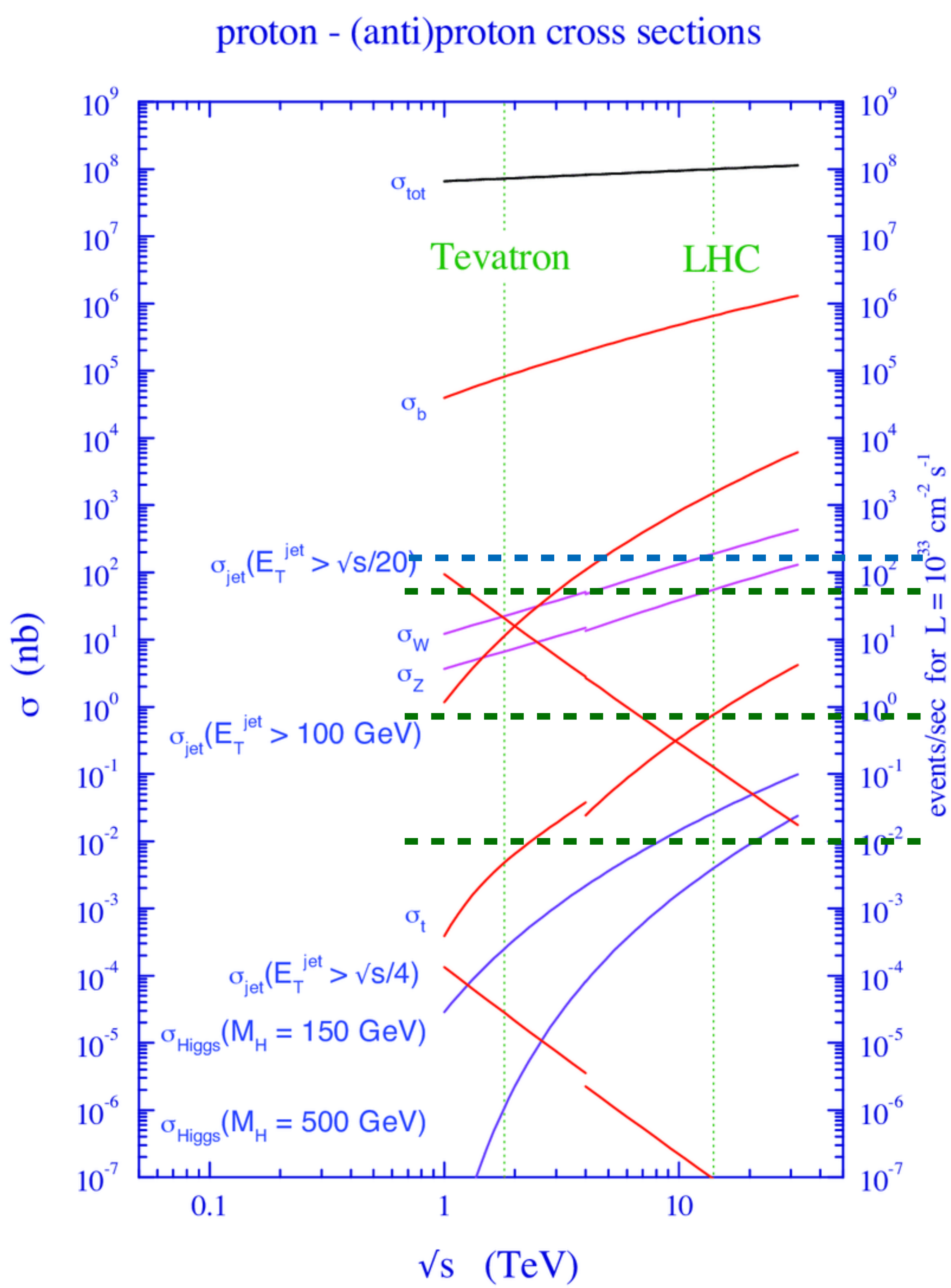
Eventually at the LHC



Higgs couplings. Presently, known to about 10%

1- a few %

HL-LHC as particle factories



> 10^{11} W and Zs

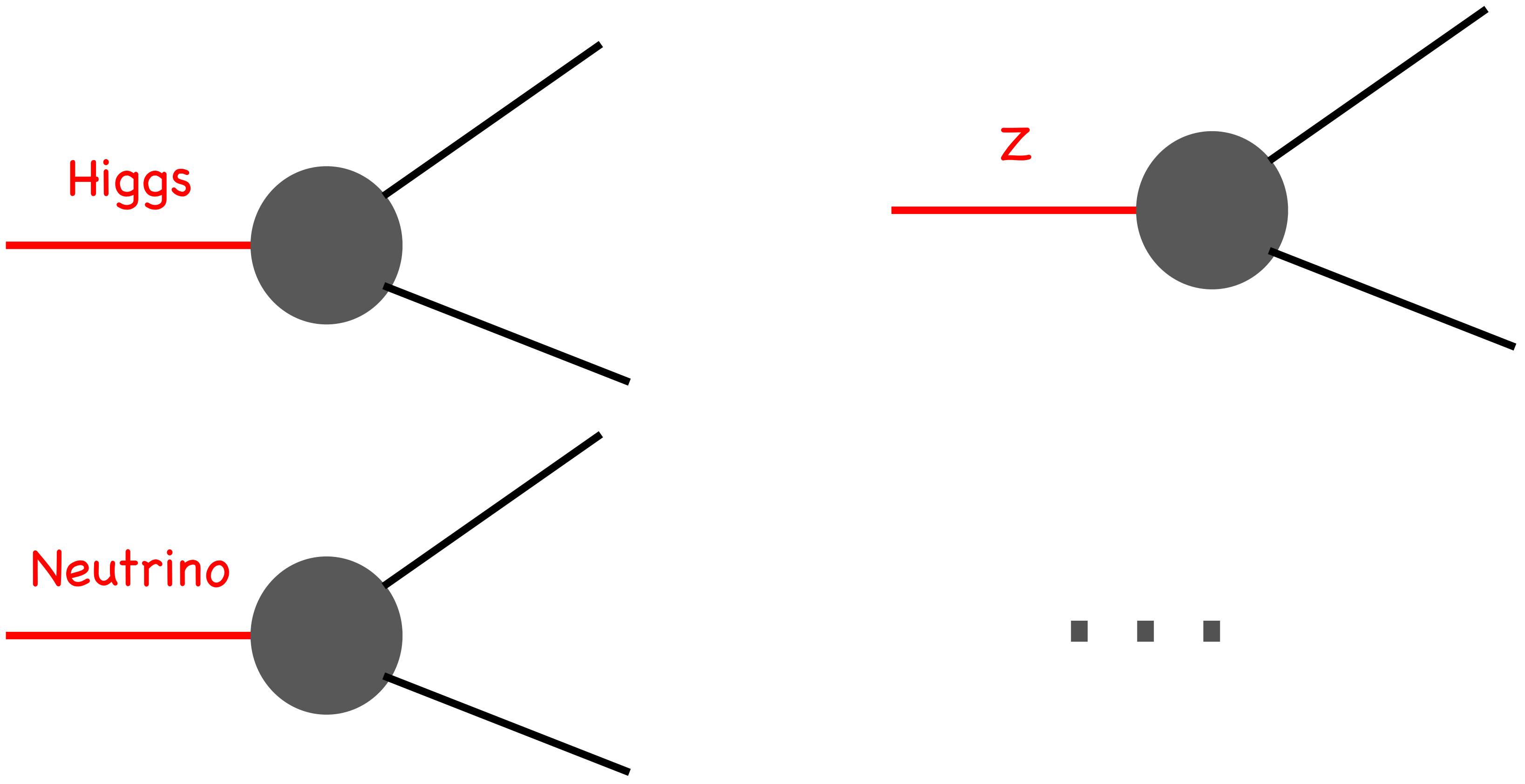
> 10^9 tops

> 10^8 Higgses

Expect a lot of progress in rare decay searches!

The portals

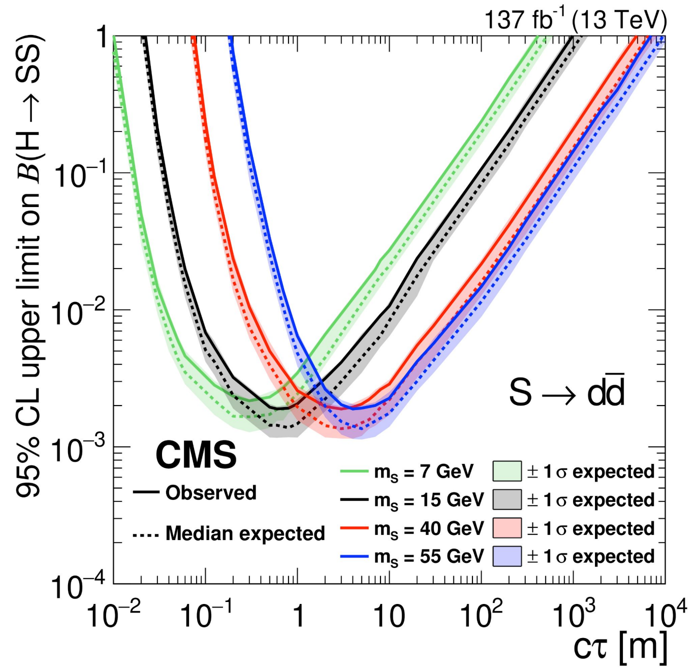
- (SM) particle with small couplings to dark matter/dark sector.

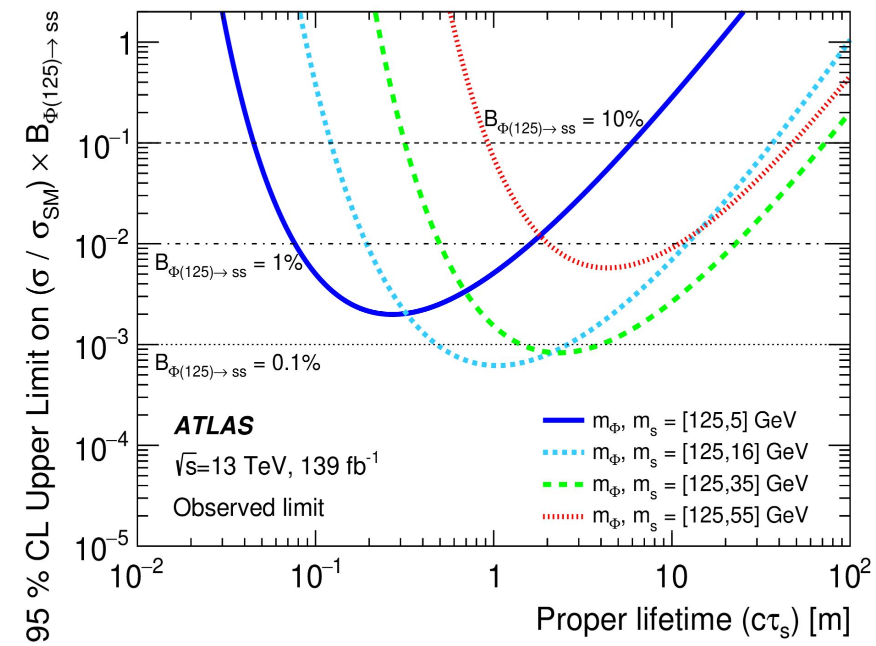


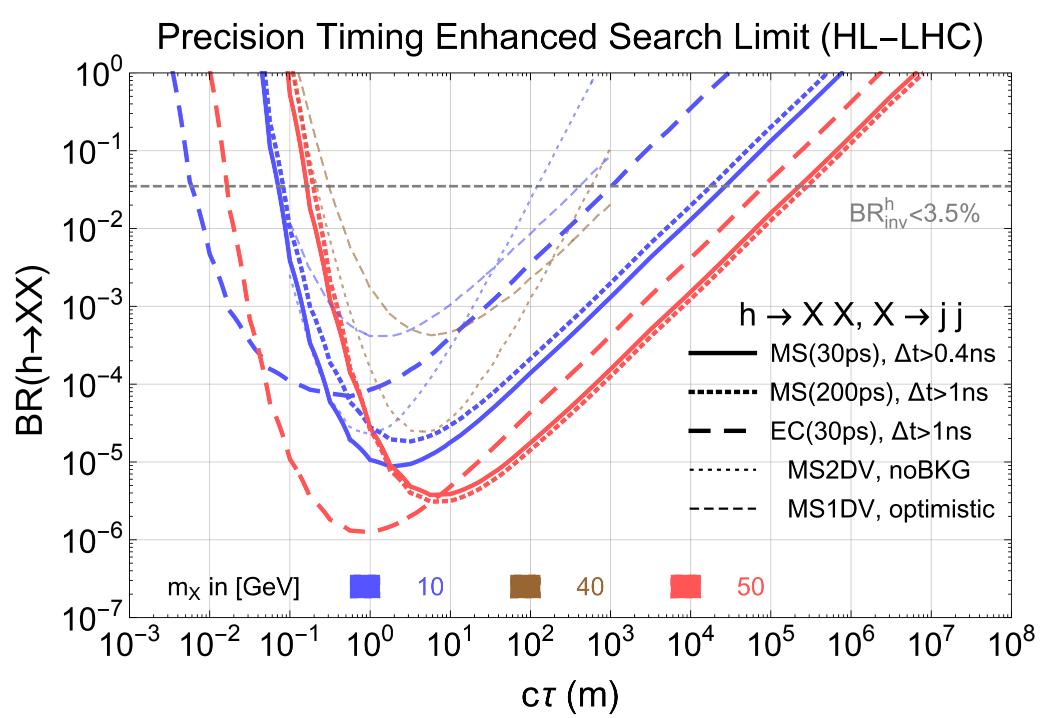
Example: Higgs portal long lived particles

$h \to XX$

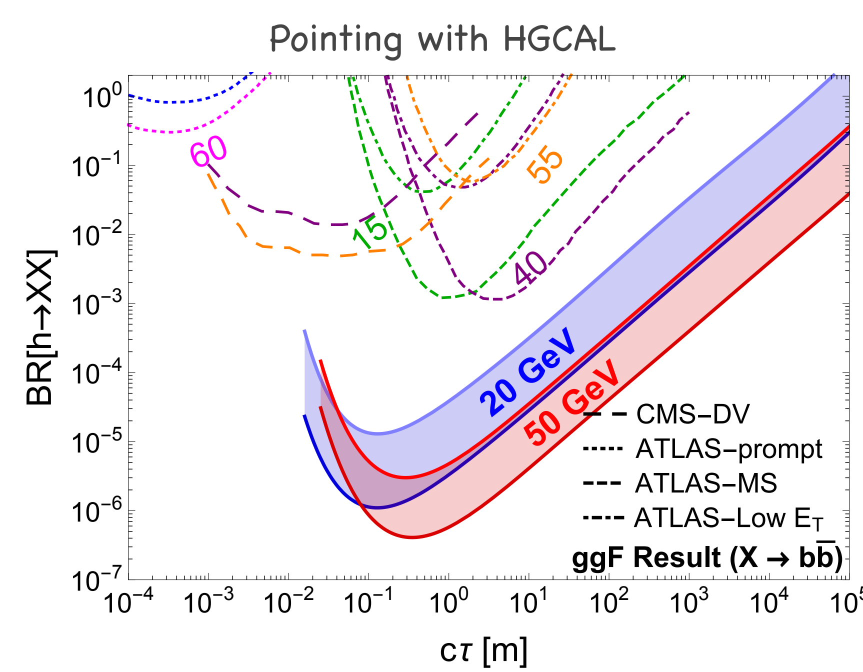
X: LLP







J. Liu, Z. Liu and LTW, 1805.05957



J. Liu, Z. Liu, X. Wang and LTW, 2005.10836

Potential to do better, BR(h→XX) < 10^{-5}

More ideas?

Any new directions for the HL-LHC?

They really need HELP!

Beyond the LHC:
What should the next step?

2014 P5: Higgs as a new tool for discovery

In summary, **the EF supports a fast start for construction of an e^+e^- Higgs factory (linear or circular), and a significant R&D program for multi-TeV colliders (hadron and muon). The realization of a Higgs factory will require an immediate, vigorous and targeted detector R&D program, while the study towards multi-TeV colliders will need significant and long-term investments in a broad spectrum of R&D programs for accelerators and detectors.** These projects have the potential to be transformative as they will push the boundaries of our knowledge by testing the limits of the SM, and indirectly or directly discovering new physics beyond the SM.

- 2021-2022 Snowmass EF report

For more details: Snowmass reports European strategy update

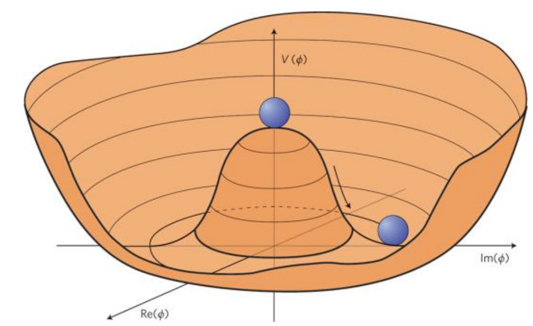
Why focusing on Higgs?

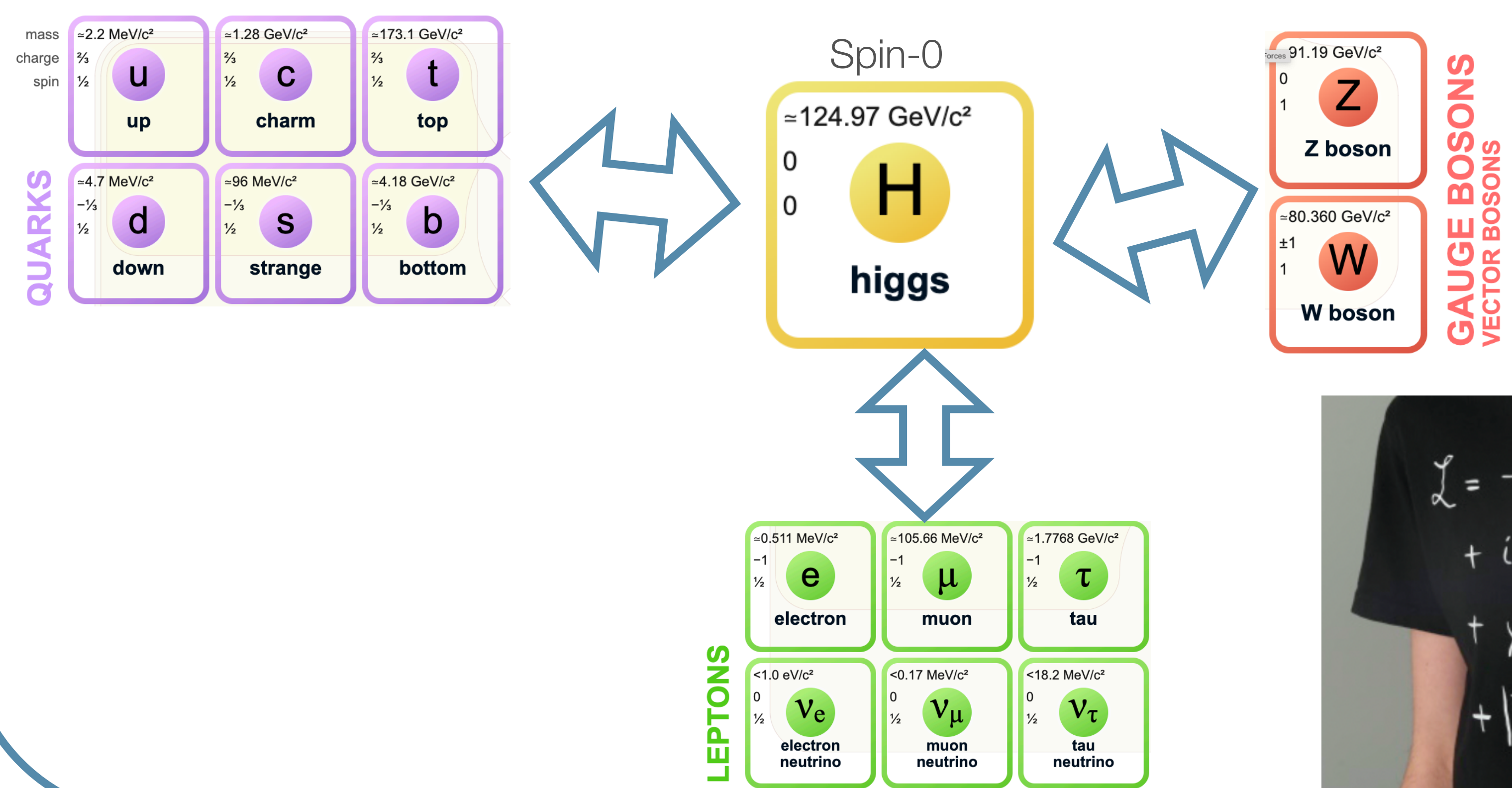
Higgs is simple.

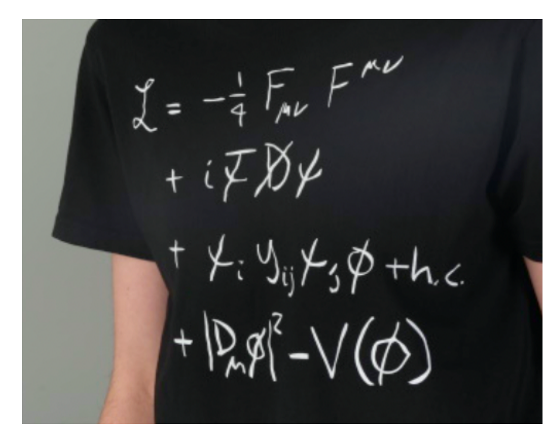
A simple “Mexican hat” potential.

⇒ Electroweak symmetry breaking

⇒ gives masses of SM particles







Why focusing on Higgs?

Yet, Higgs is confusing.

Sure, the math is simple.
It does not give us clues for a deeper understanding.

Different from other SM particles:
gauge boson (gauge symmetry), fermion (chiral symmetry)

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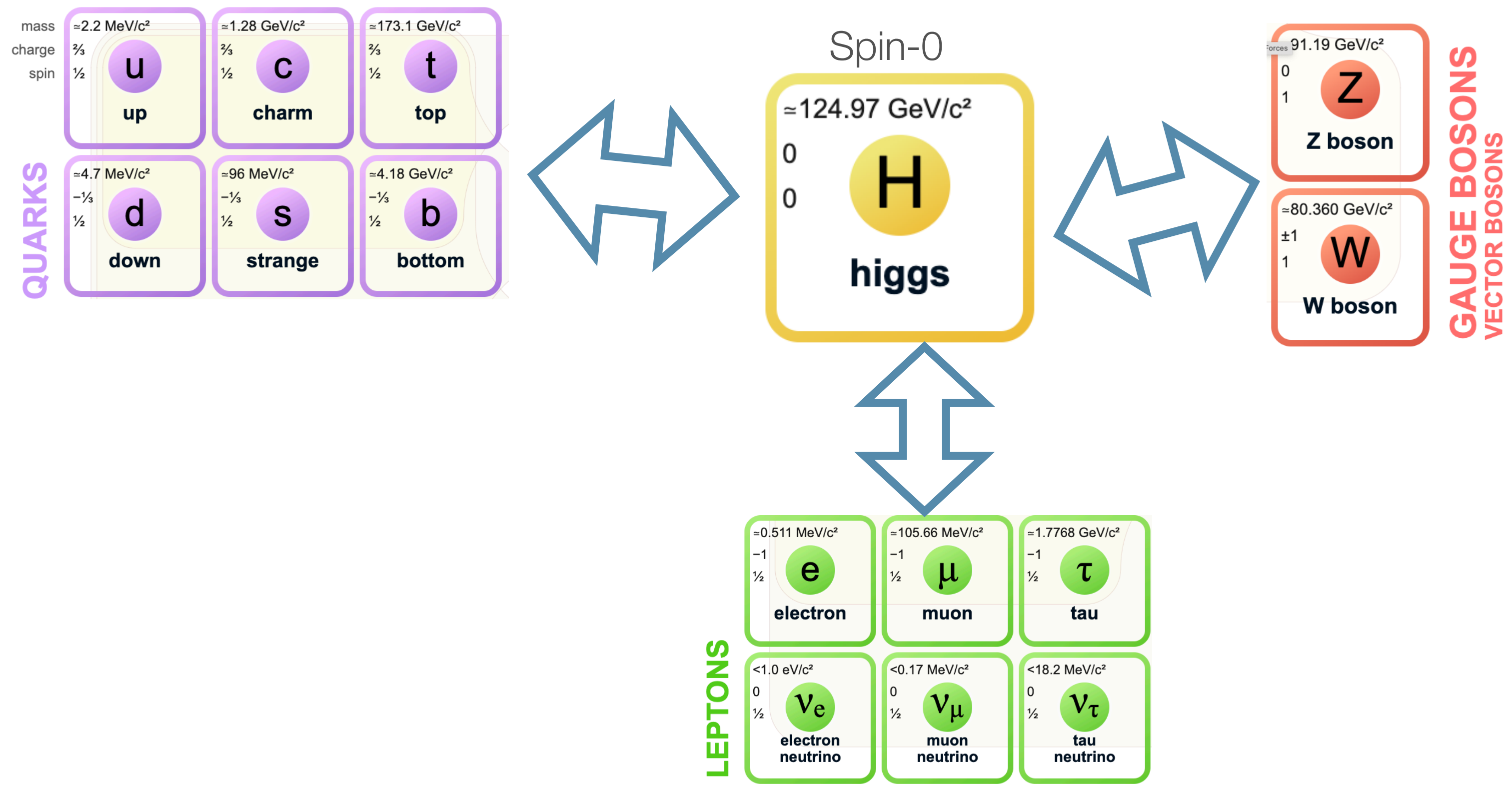
Different from other SM particles:
gauge boson (gauge symmetry), fermion (chiral symmetry)

Maybe not as simple as it seems?

Is it elementary (like electron) or composite (like proton or pion)?

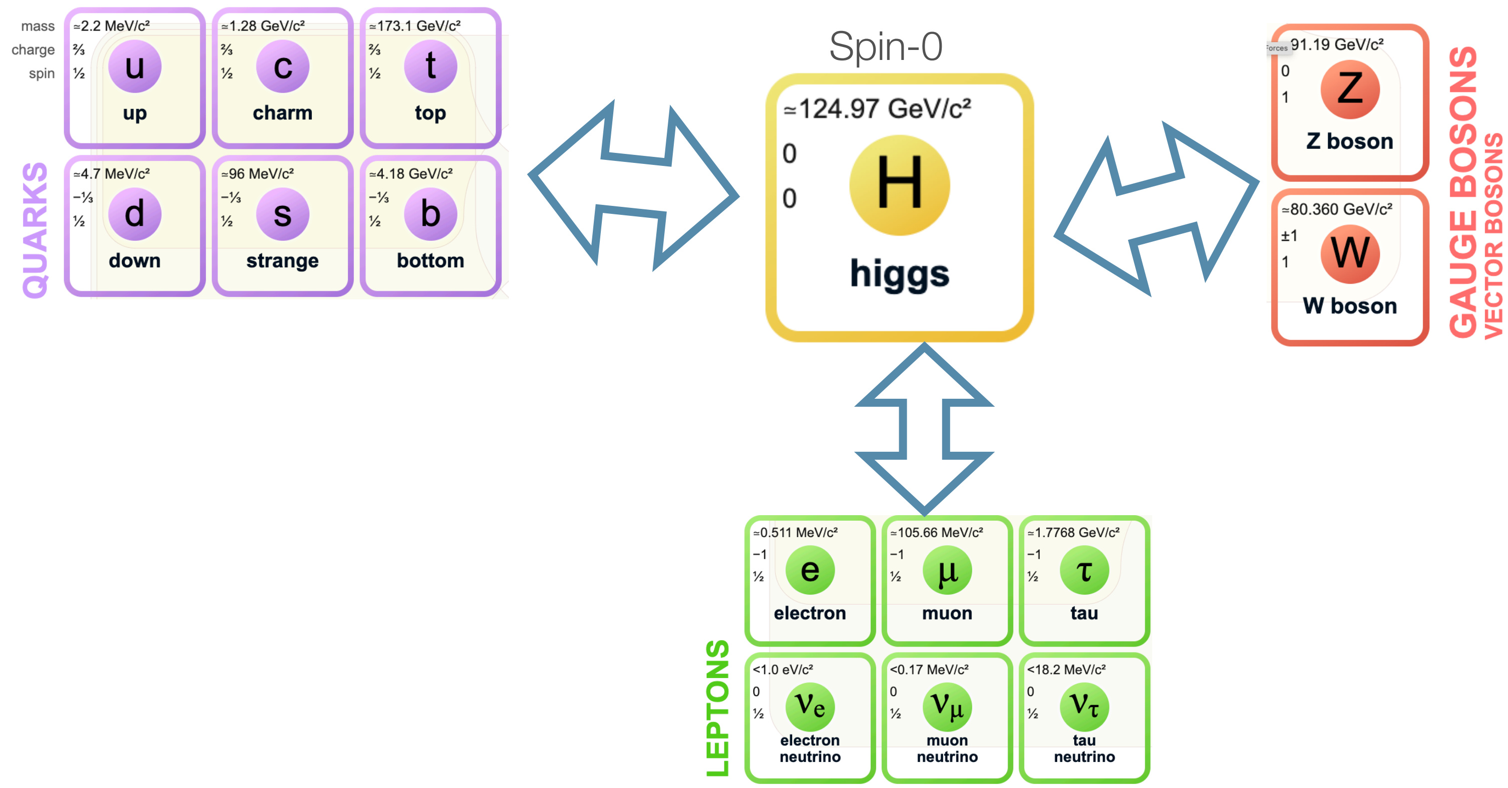
Is the Higgs the only spin-0 particle, or there are similar ones?

What sets the masses?



Higgs mechanism sets the masses of the SM particles

What sets the masses?

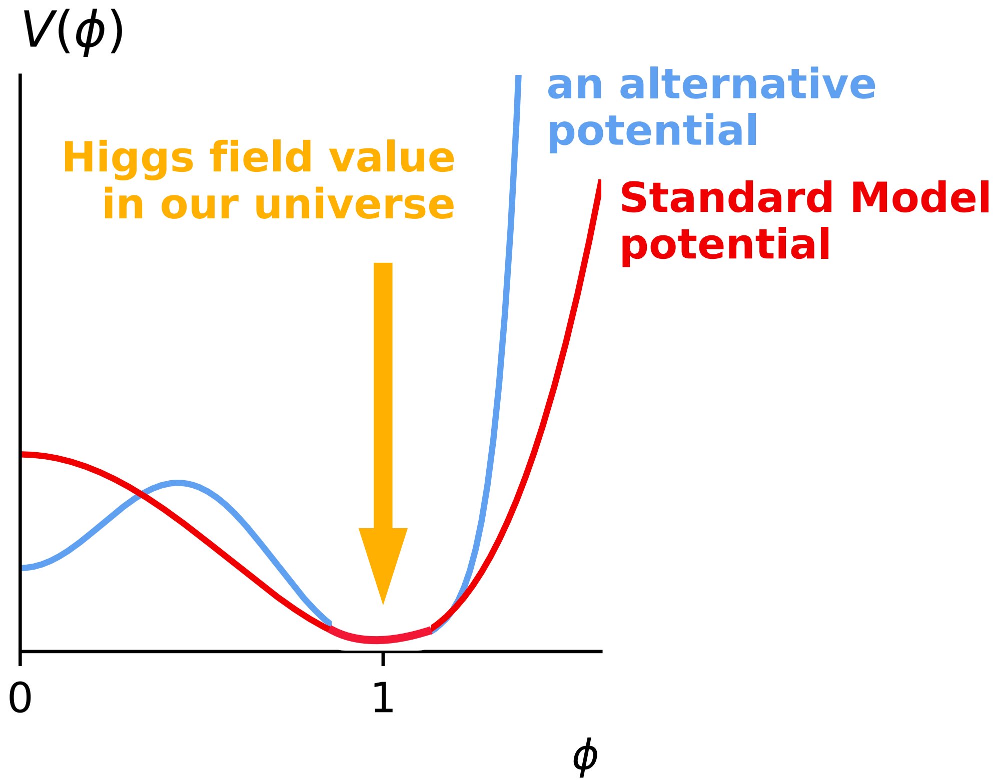


Higgs mechanism sets the masses of the SM particles

However, we can't explain how this mass scale is set.
Why is it around 100 GeV?

What do we know?

Higgs potential?



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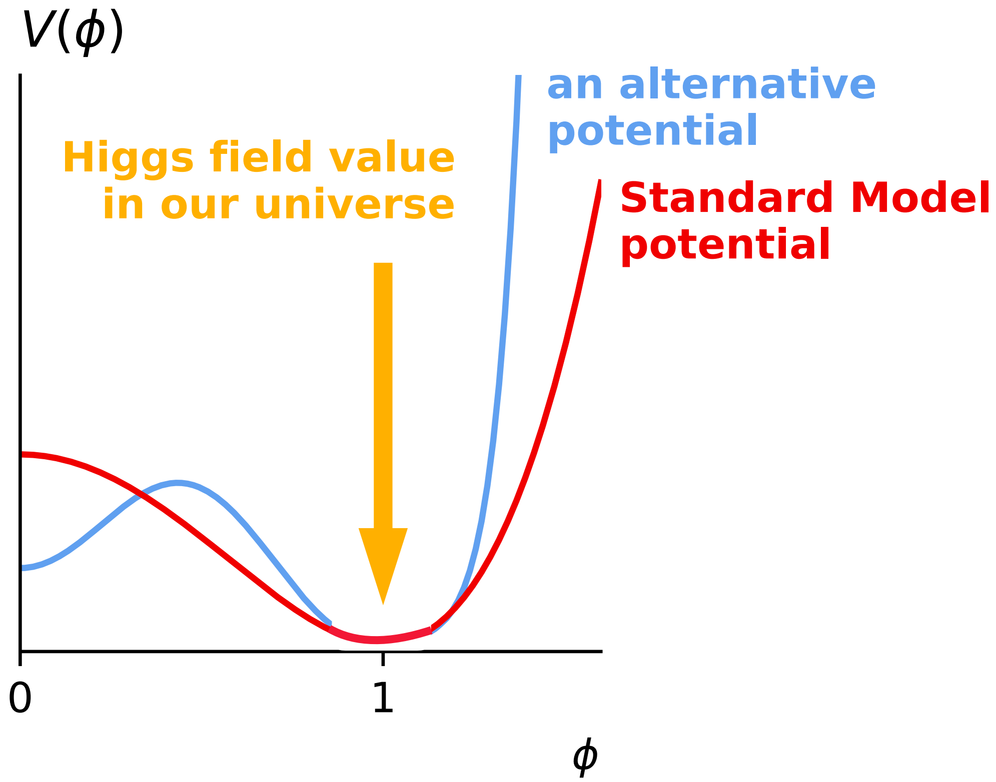
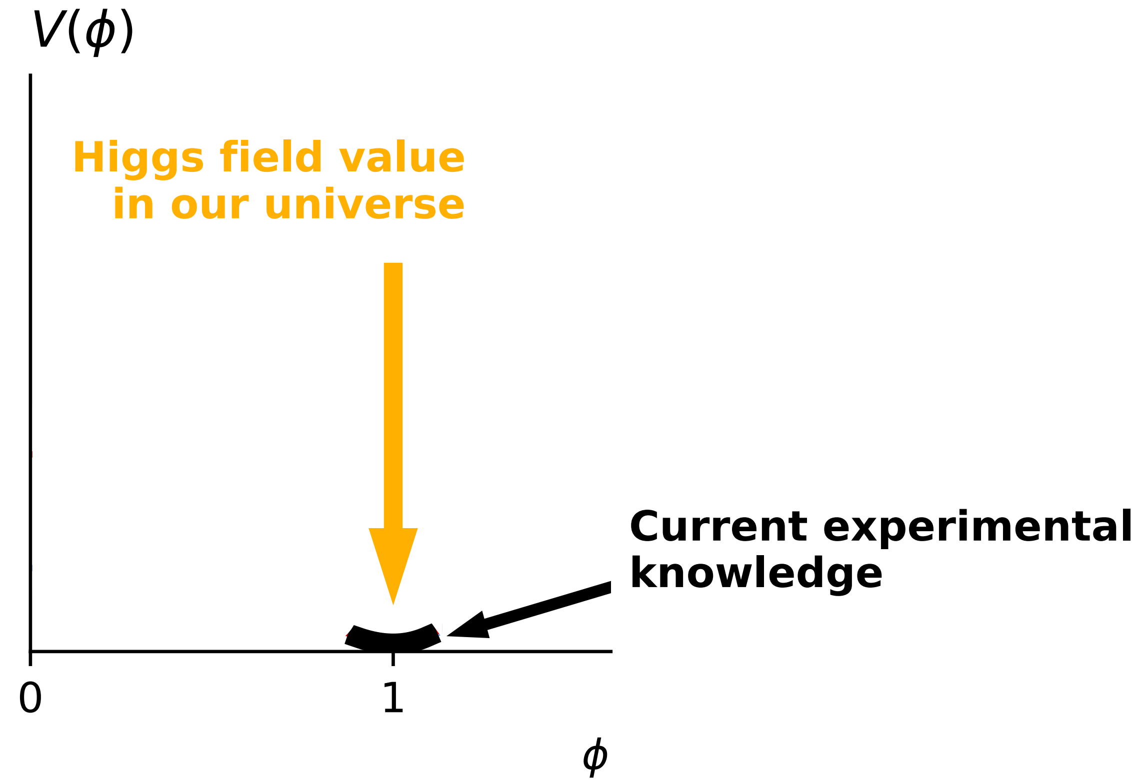


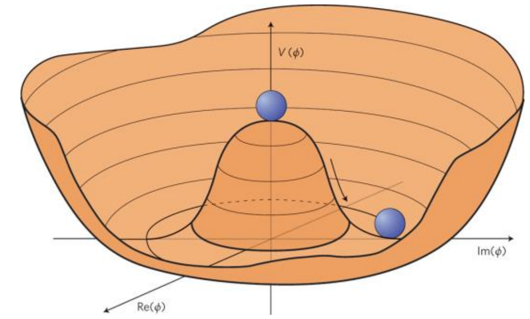


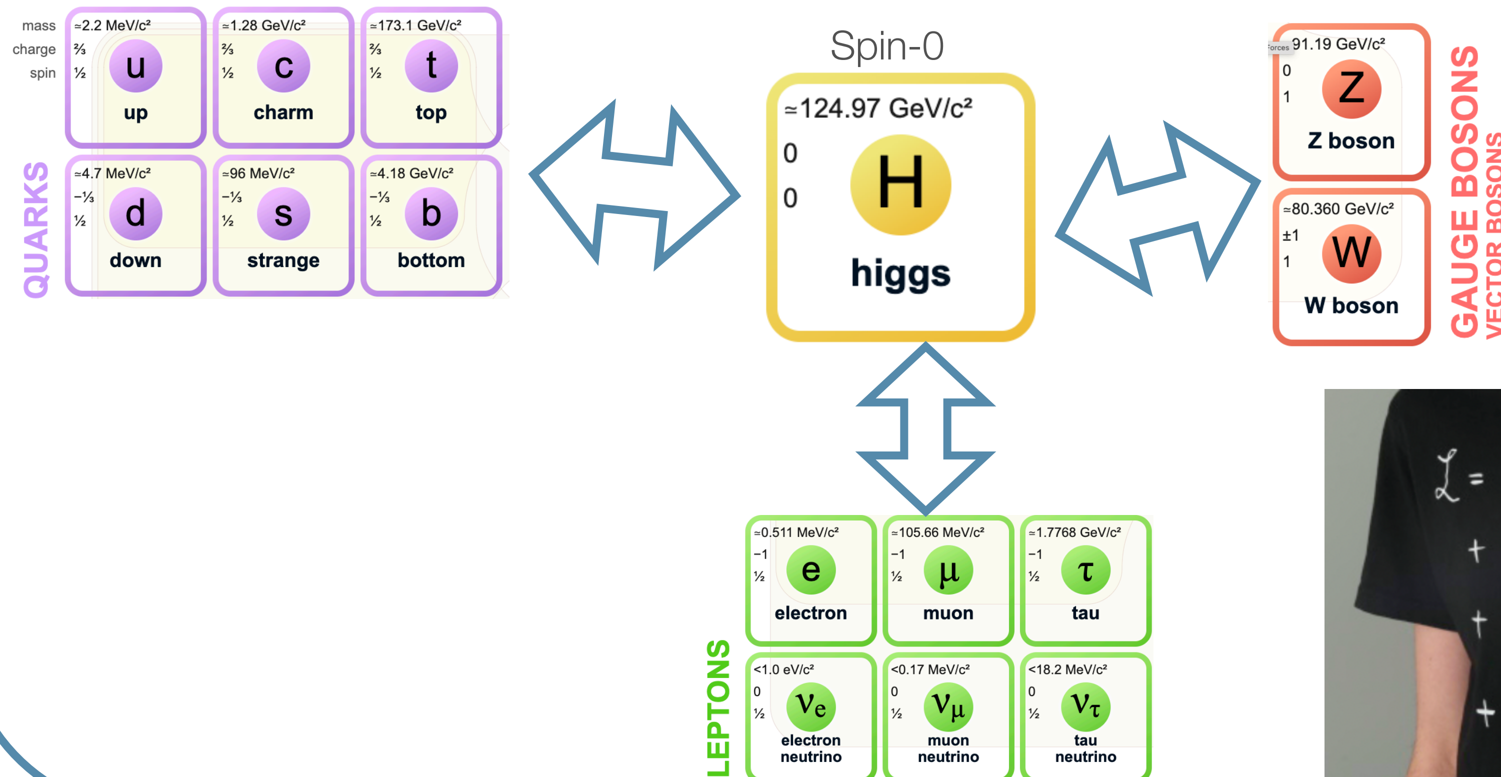
HL-LHC will make some progress.
But it won't clarify the picture.

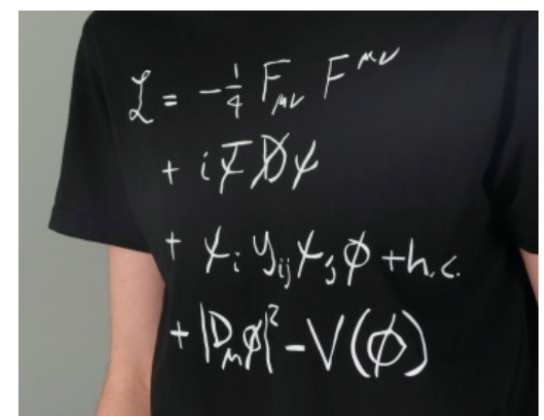
A simple “Mexican hat” potential.

⇒ Electroweak symmetry breaking

⇒ gives masses of SM particles



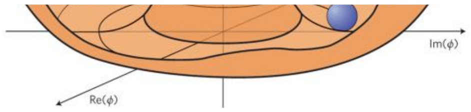


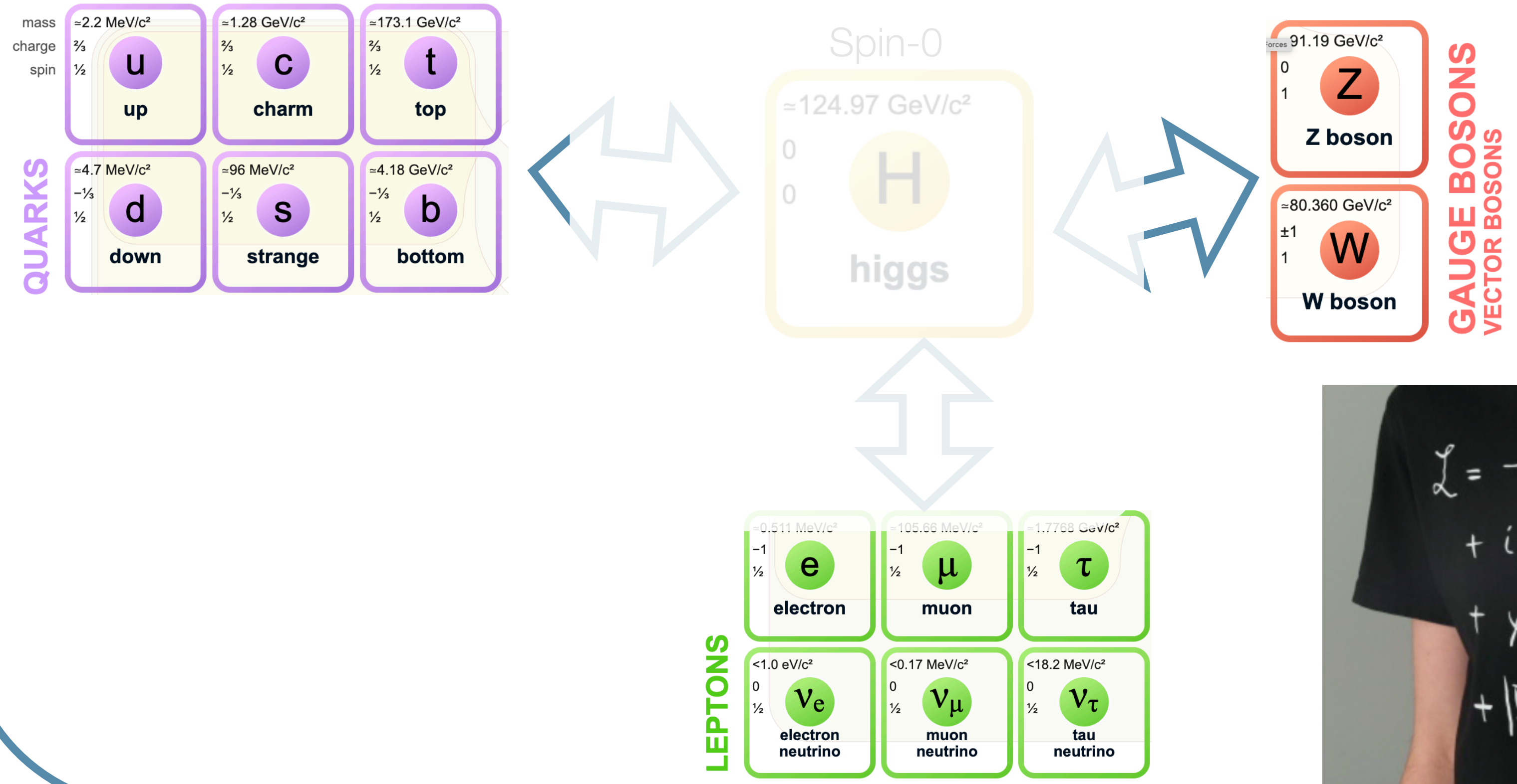


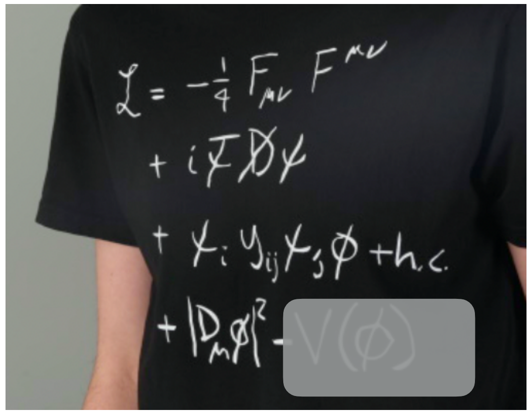
A simple "Mexican hat" potential ??

⇒ Electroweak symmetry breaking

⇒ gives masses of SM particles

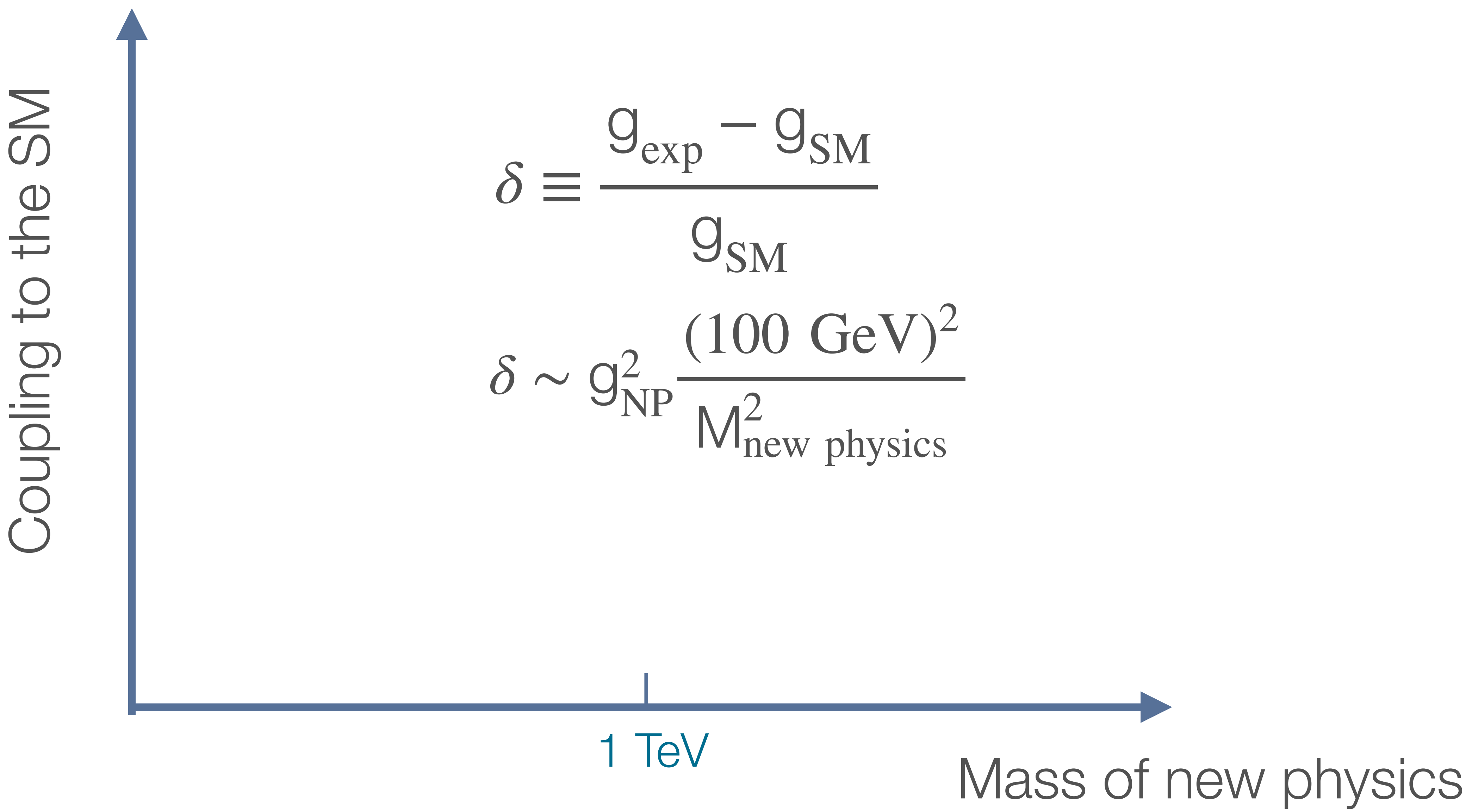






We need to know better!

Our target



$$\delta \equiv \frac{g_{exp} - g_{SM}}{g_{SM}}$$

$$\delta \sim g_{NP}^2 \frac{(100\ \mathrm{GeV})^2}{M_{\mathrm{new\ physics}}^2}$$

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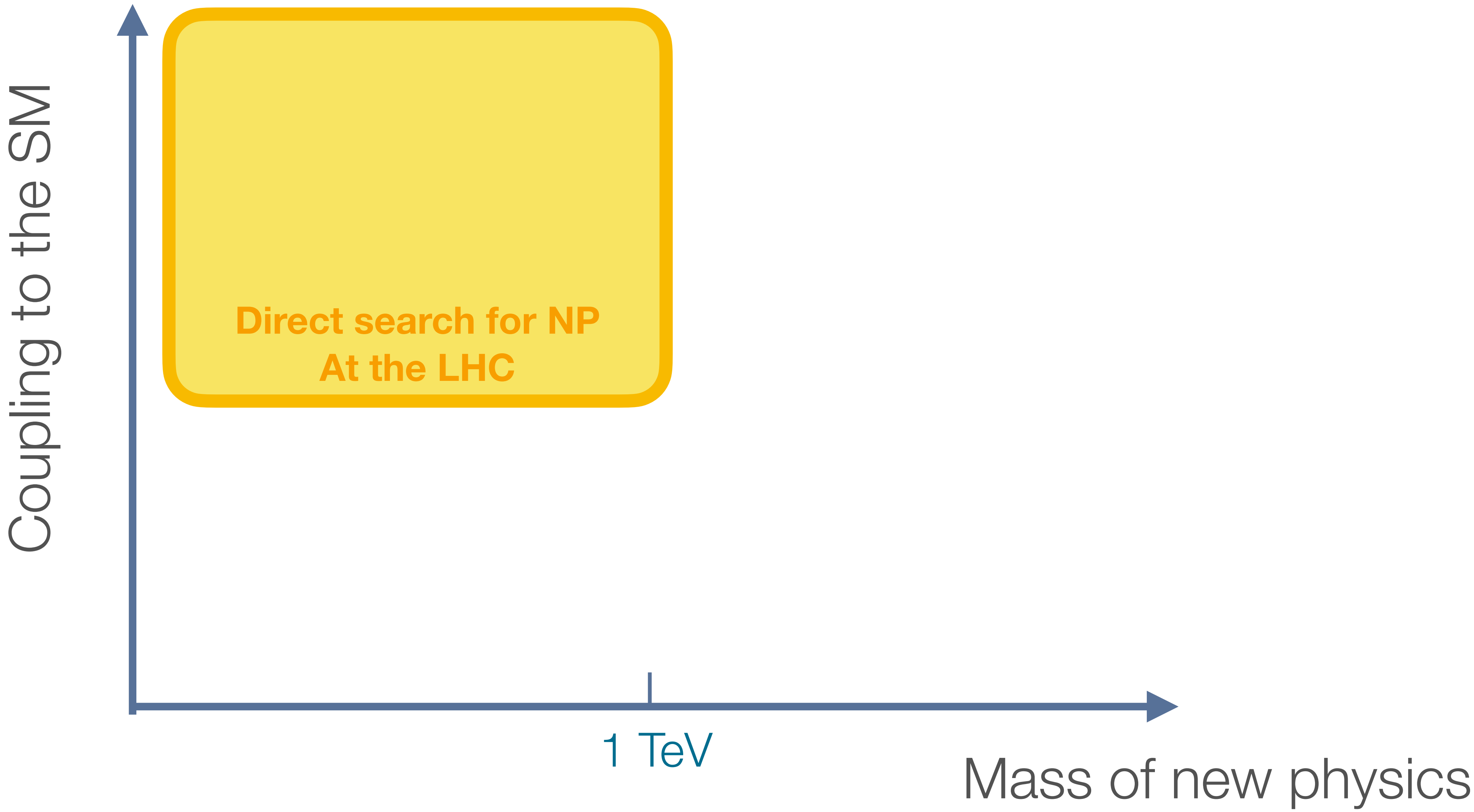

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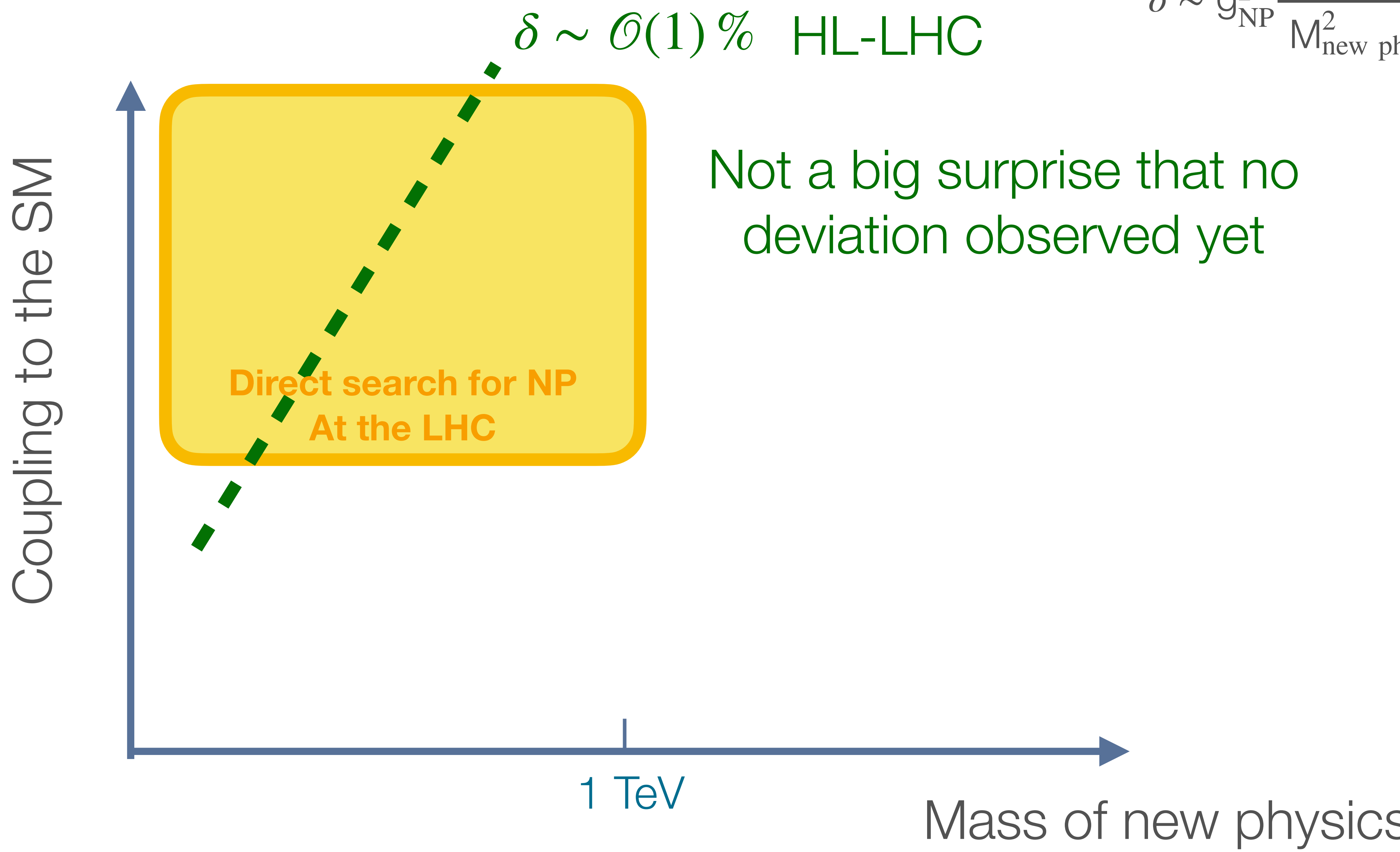

Not a big surprise that no deviation observed yet

Our target

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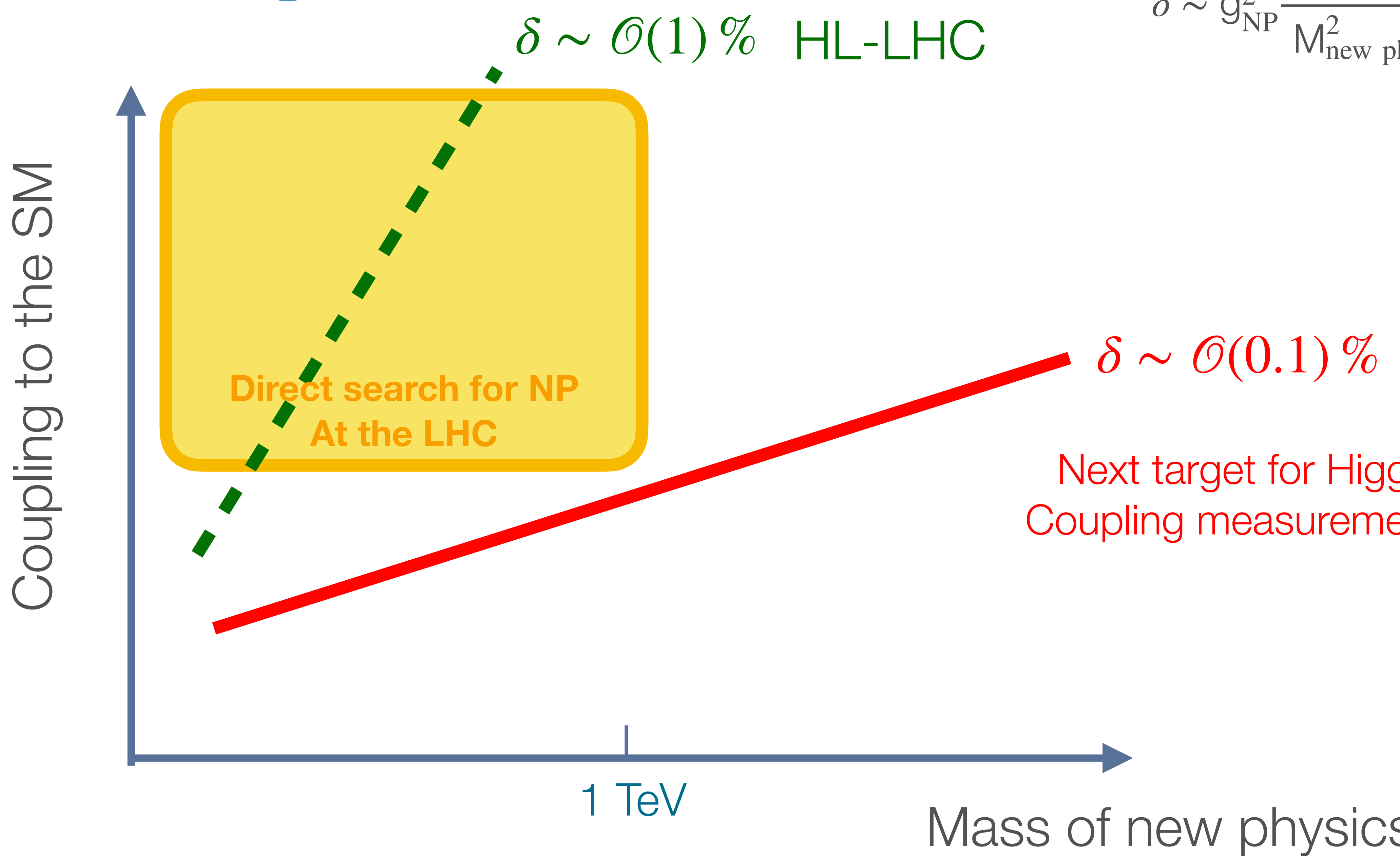
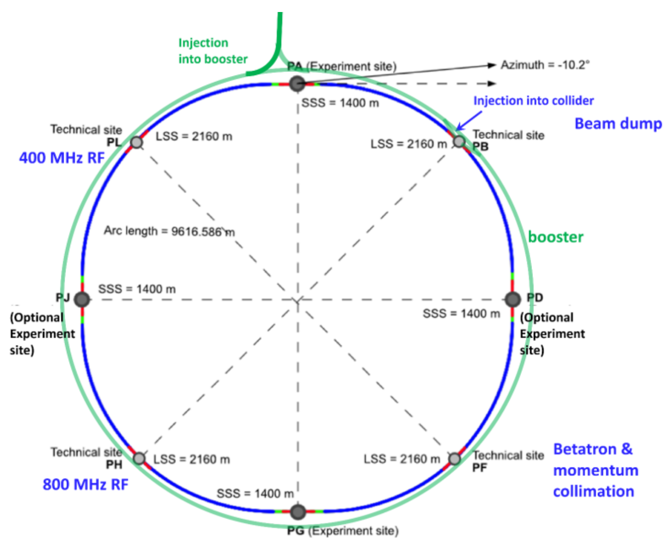
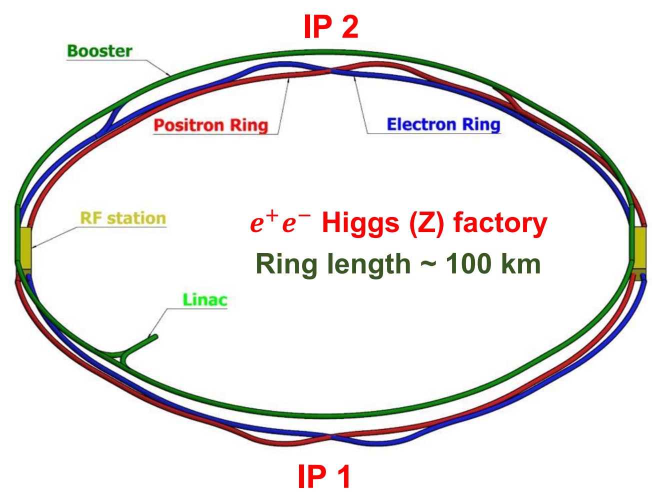


Higgs factories (e^+e^-)

Circular



FCC-ee

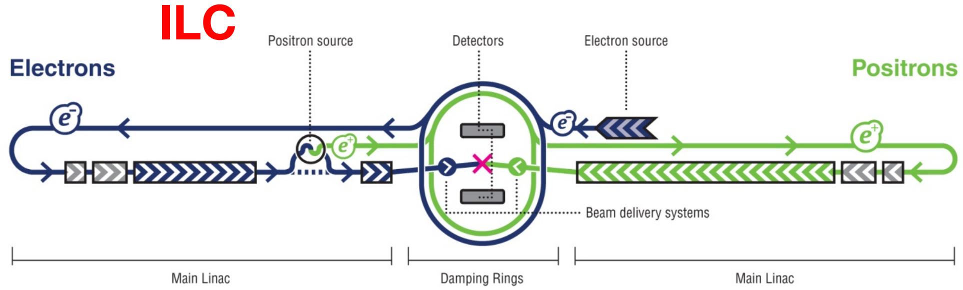


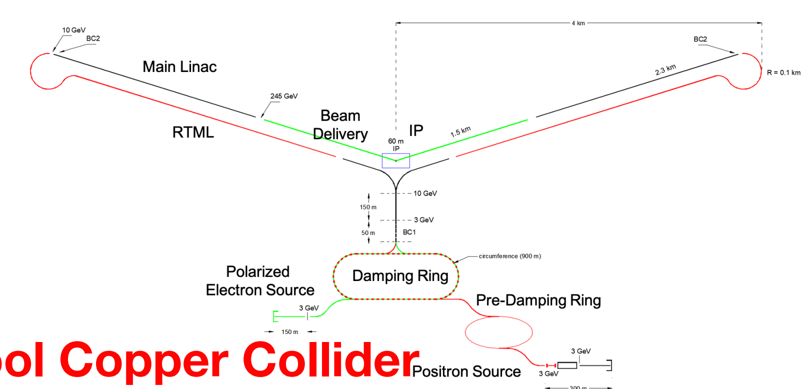
CEPC

+…

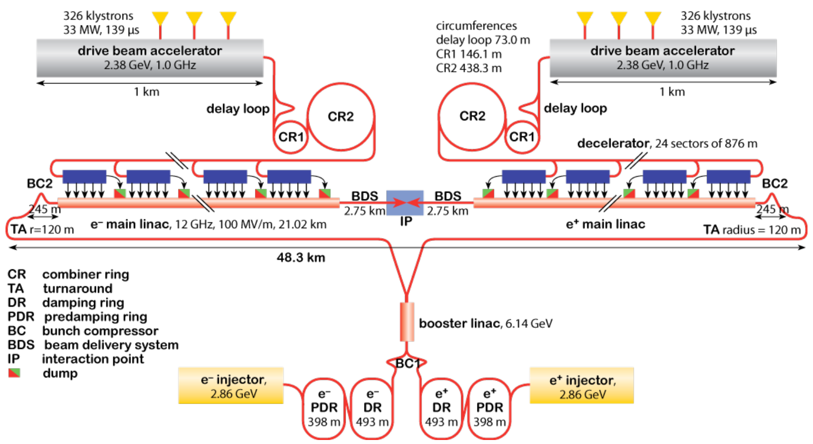
Linear

ILC



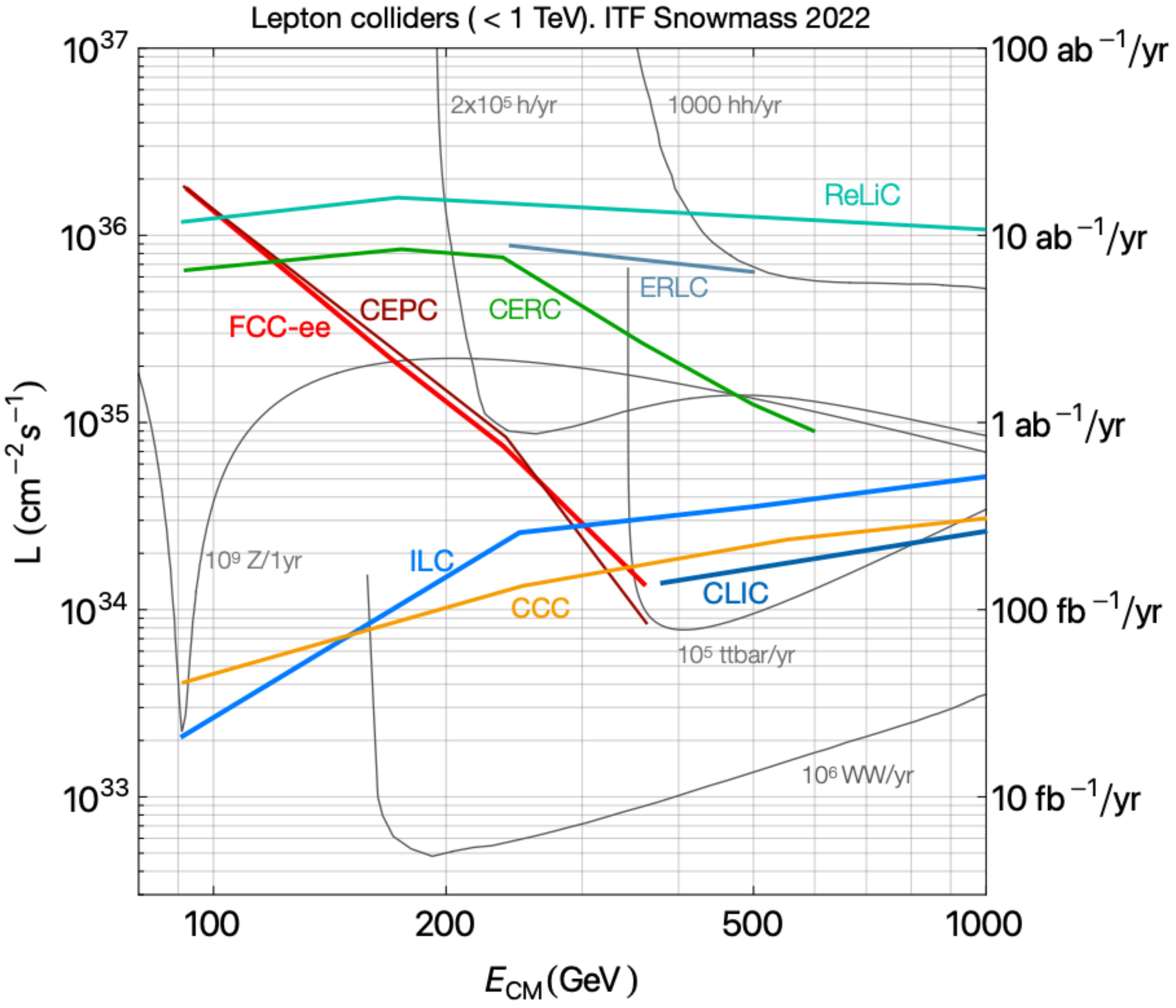


C^3 Cool Copper Collider



CLIC

Physics output



Main physics output:

10^6 Higgses

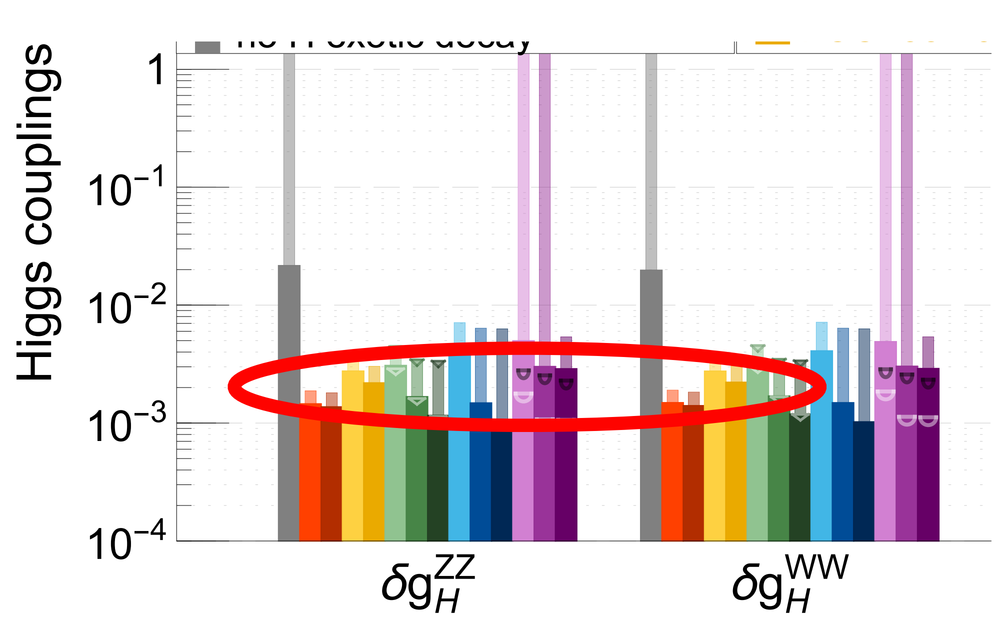
10^9 -10^{12} Zs

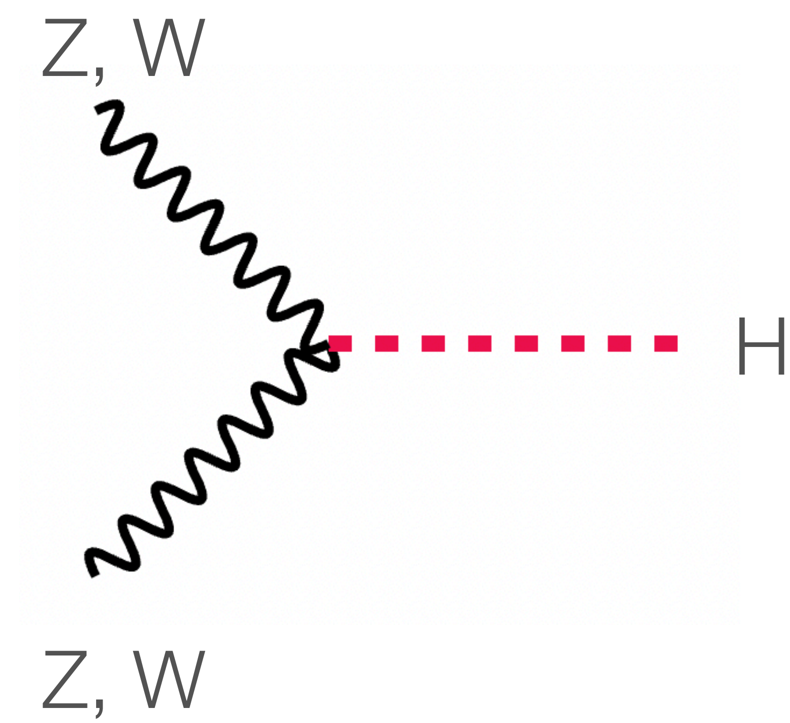
10^6 WW

10^5 ttbar

Central theme: the electroweak scale

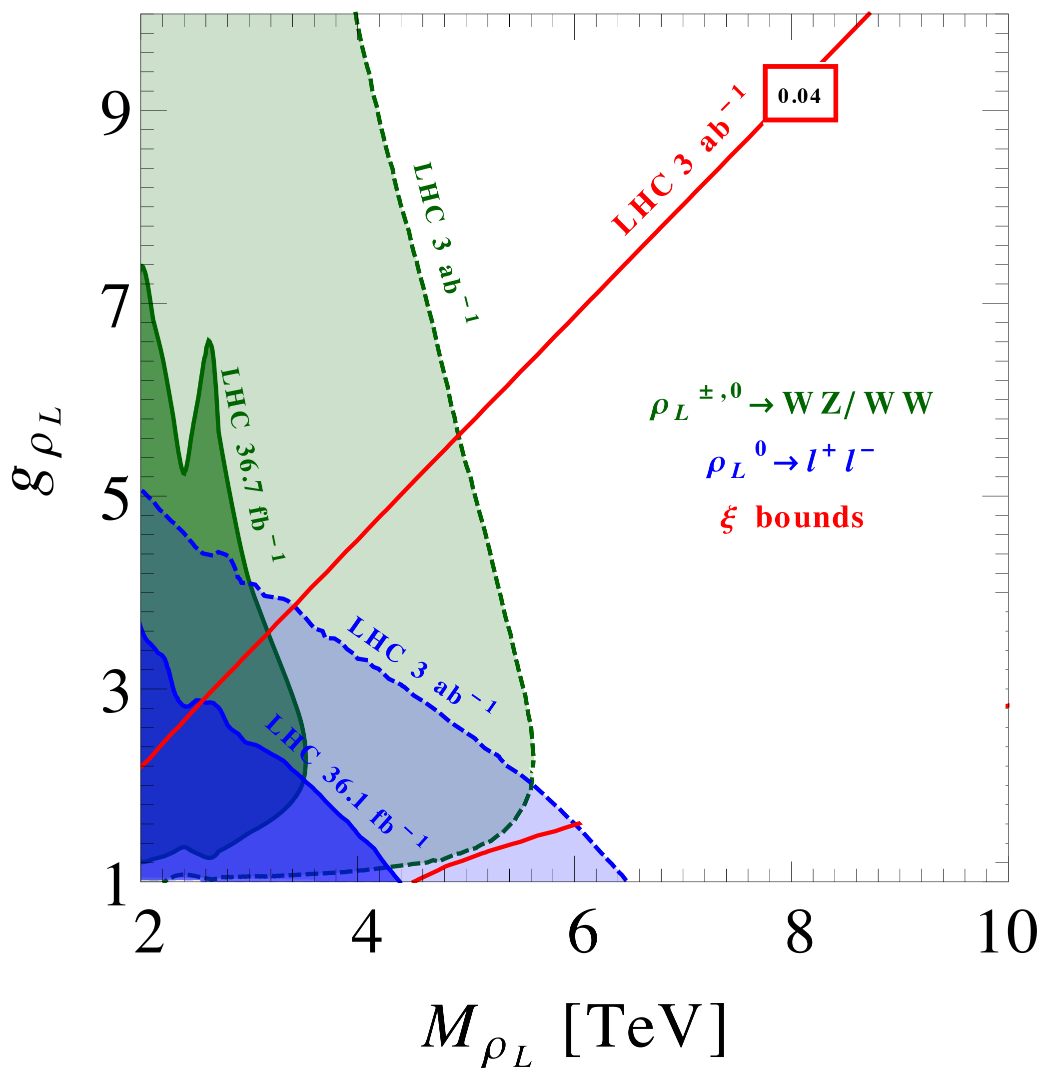
The Higgs measurements





Measuring crucial Higgs coupling up to 10^{-3}

Is the Higgs composite?



Perhaps the Higgs is similar to the pion?

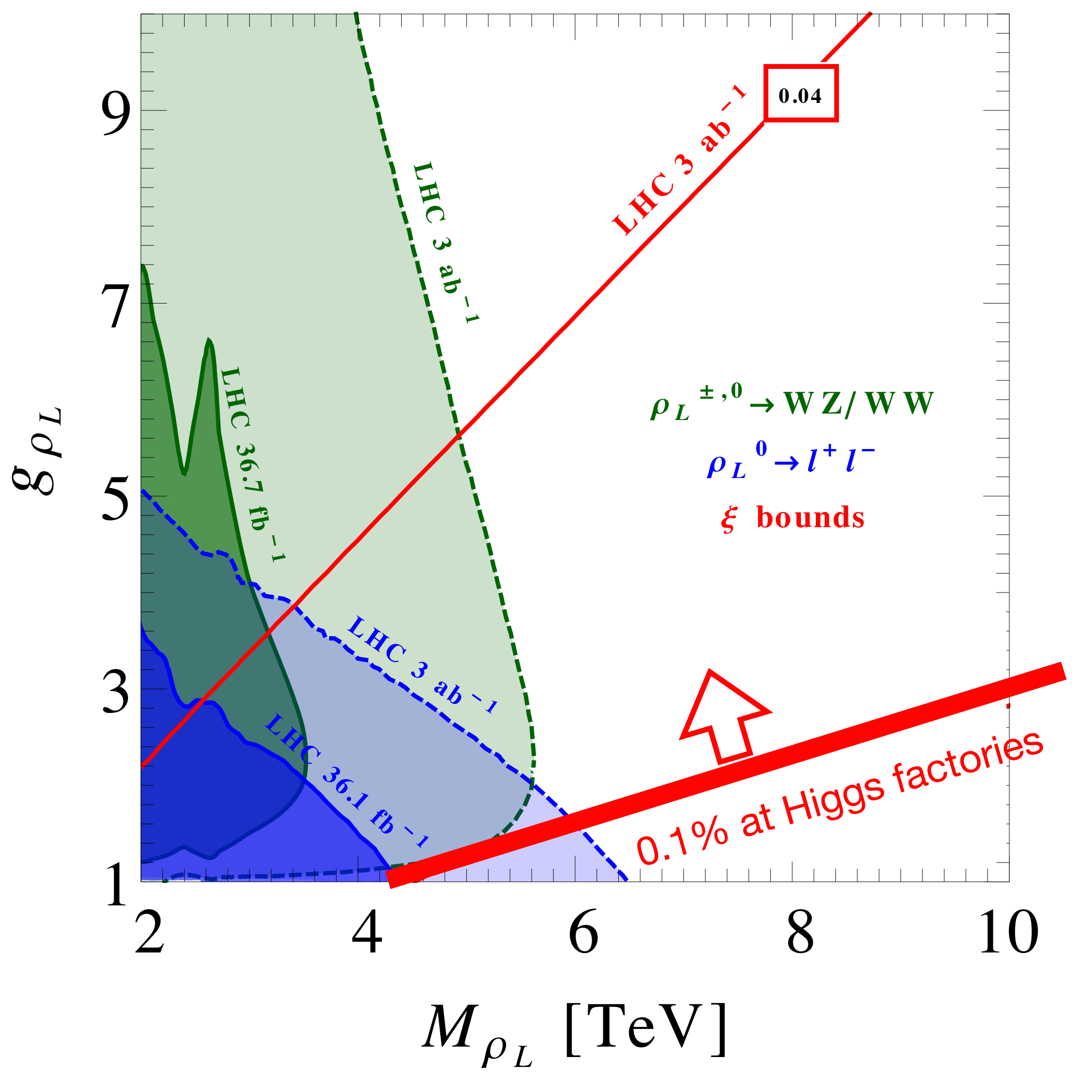
- Would make it naturally light, since it is not elementary.
- If so, will be other composite resonances

Direct search for composite resonances

Higgs coupling measurements

Composite ≠ elementary
Predicting different couplings

Is the Higgs composite?



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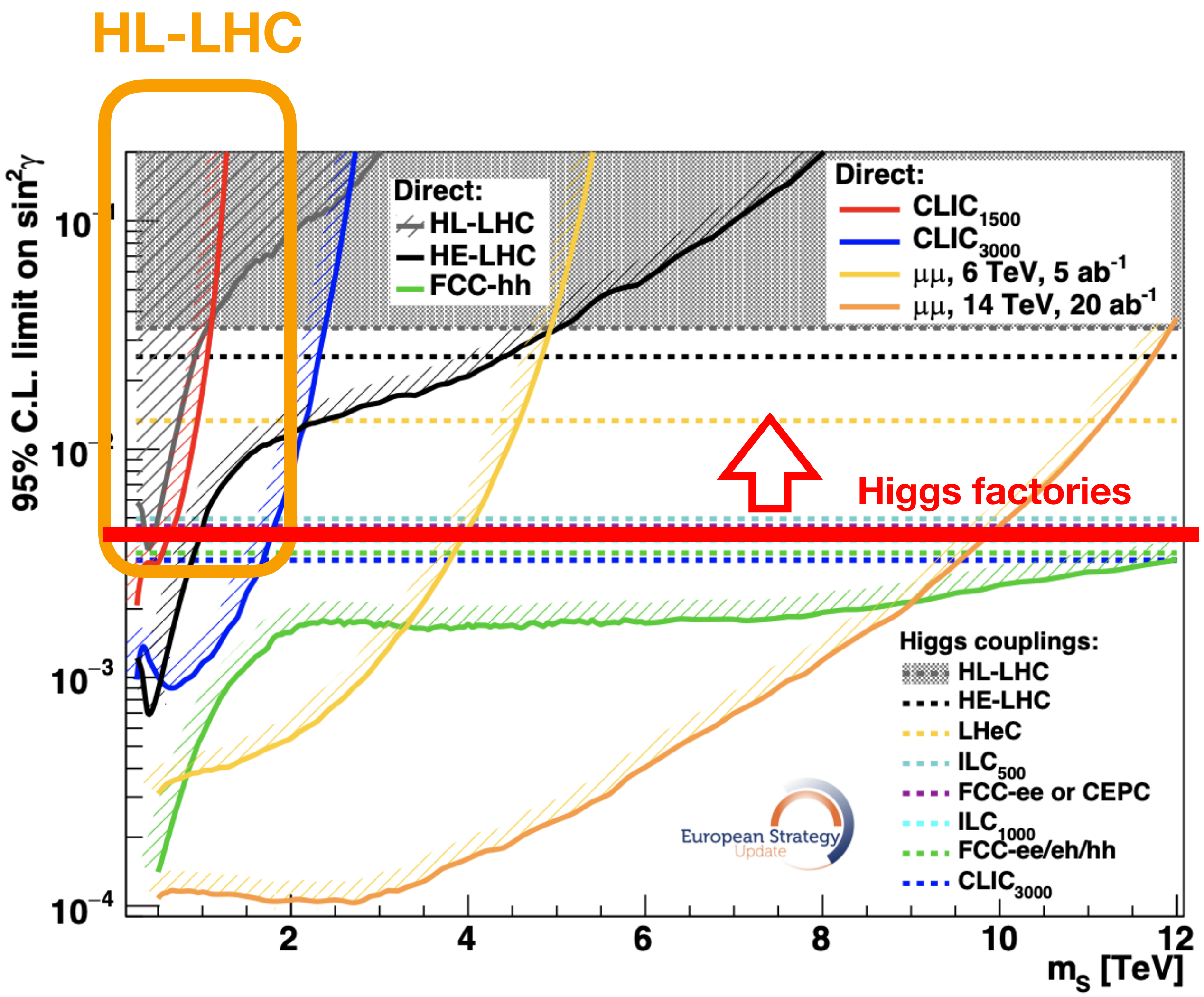
Direct search for composite resonances

Higgs coupling measurements

Composite ≠ elementary

Predicting different couplings

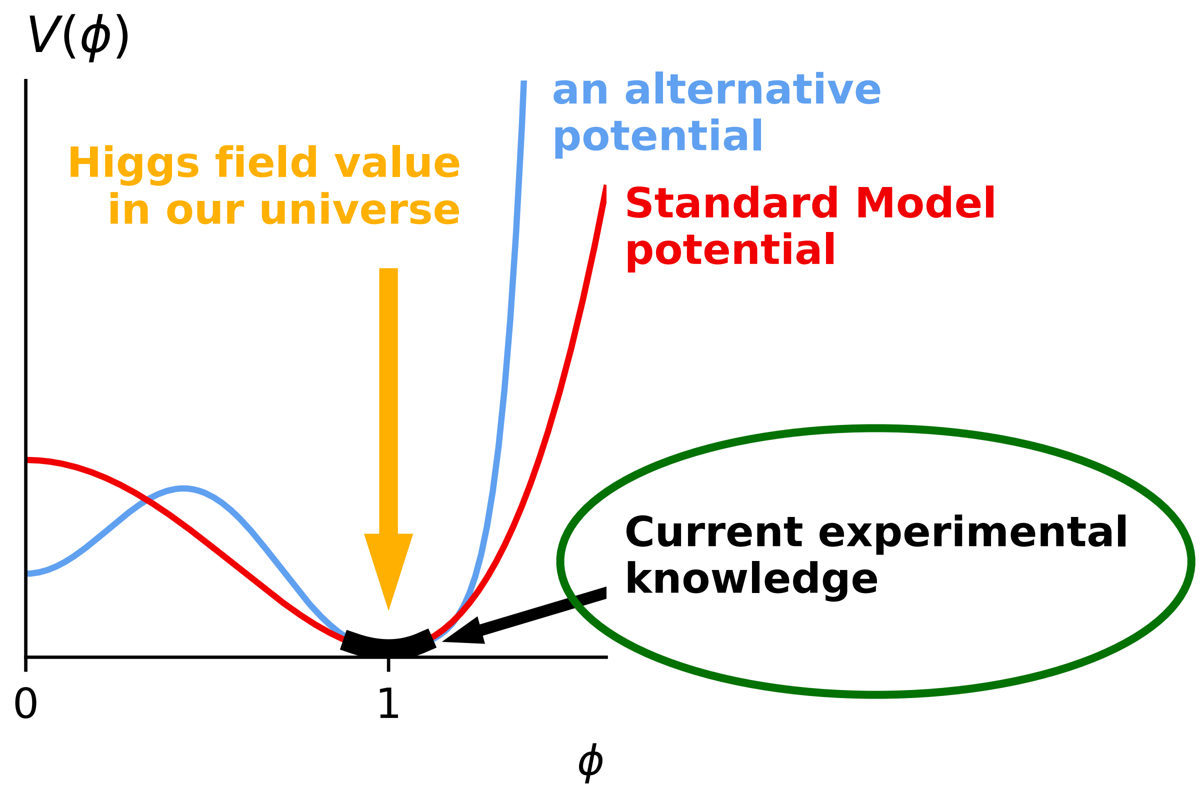
Is the Higgs boson alone?



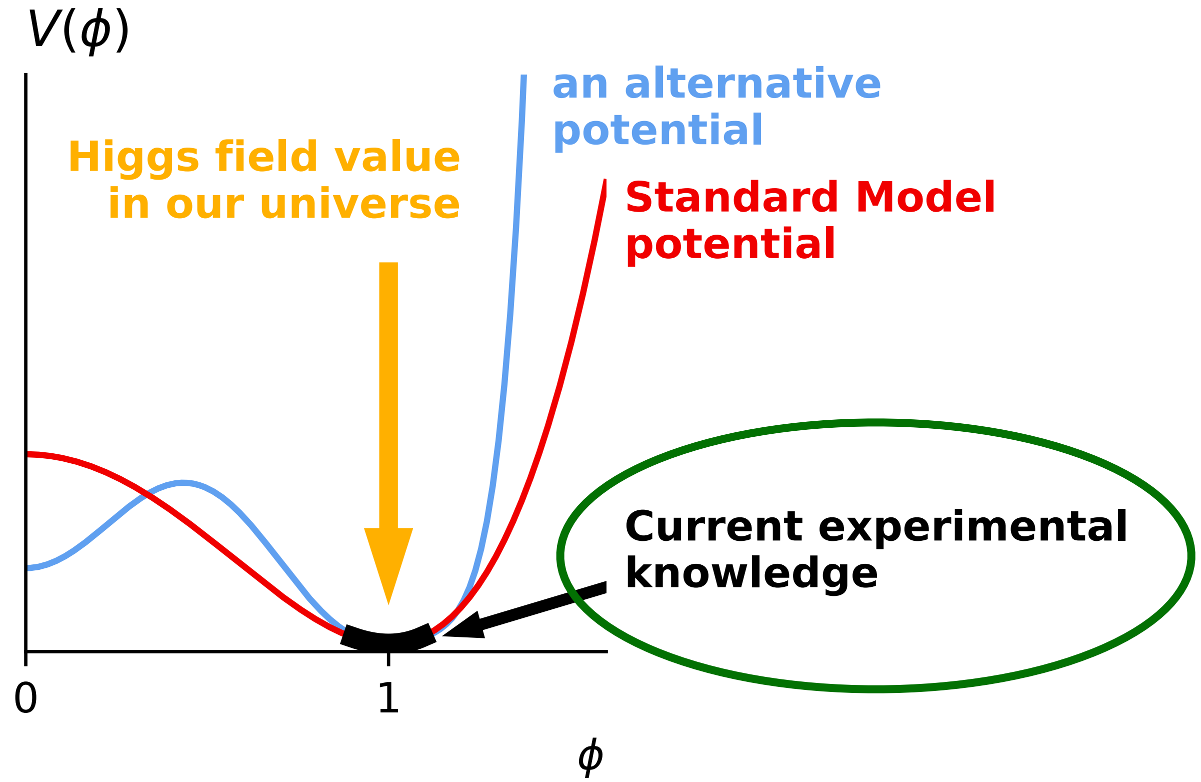
Maybe Higgs boson has some partners?

Will change Higgs behavior by interacting with it.

Simplest example:
Higgs coupling to one other spin-0 boson

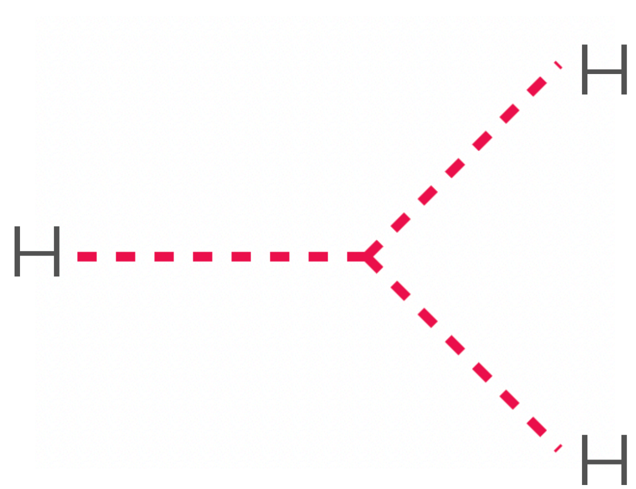


Need to go beyond this

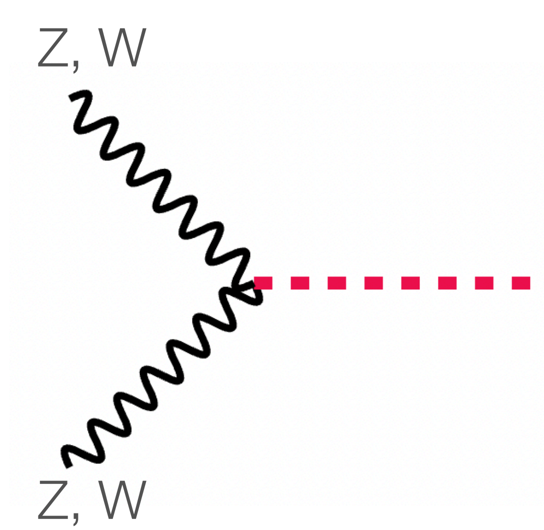


Need to go beyond this

1. Self-coupling



2. New physics in the alternative scenario often induce changes in other Higgs coupling, such as hZ



EFT expectation

If there is a modification of the self-coupling from new physics, which can be parameterized by the operator

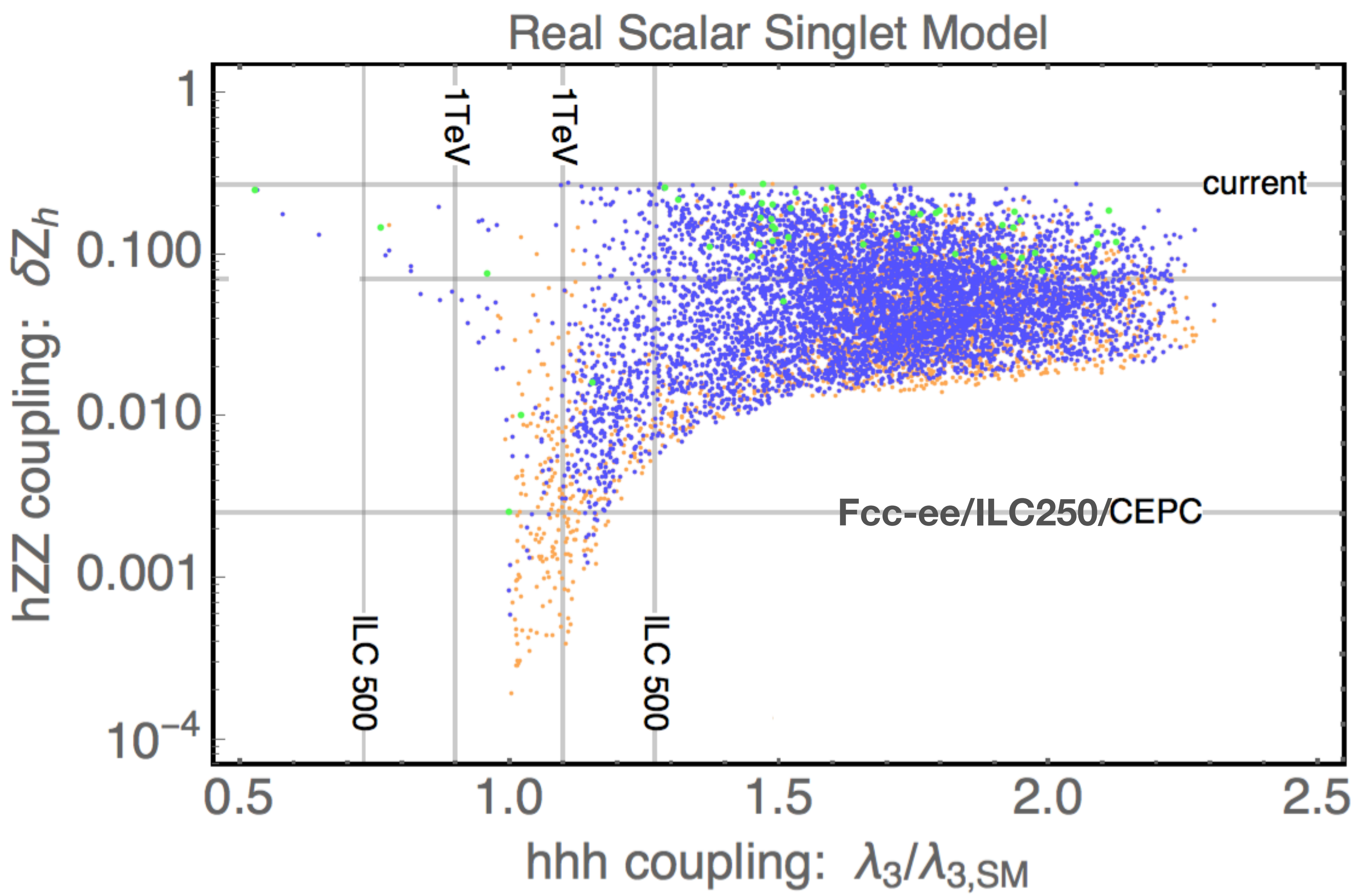
$$\frac{H^6}{\Lambda^2}$$

We should expect other effect of such NP, e.g.

$$\frac{(\partial(HH^\dagger))^2}{\Lambda^2} \to \delta_{Zh} \sim \frac{v^2}{\Lambda^2}$$

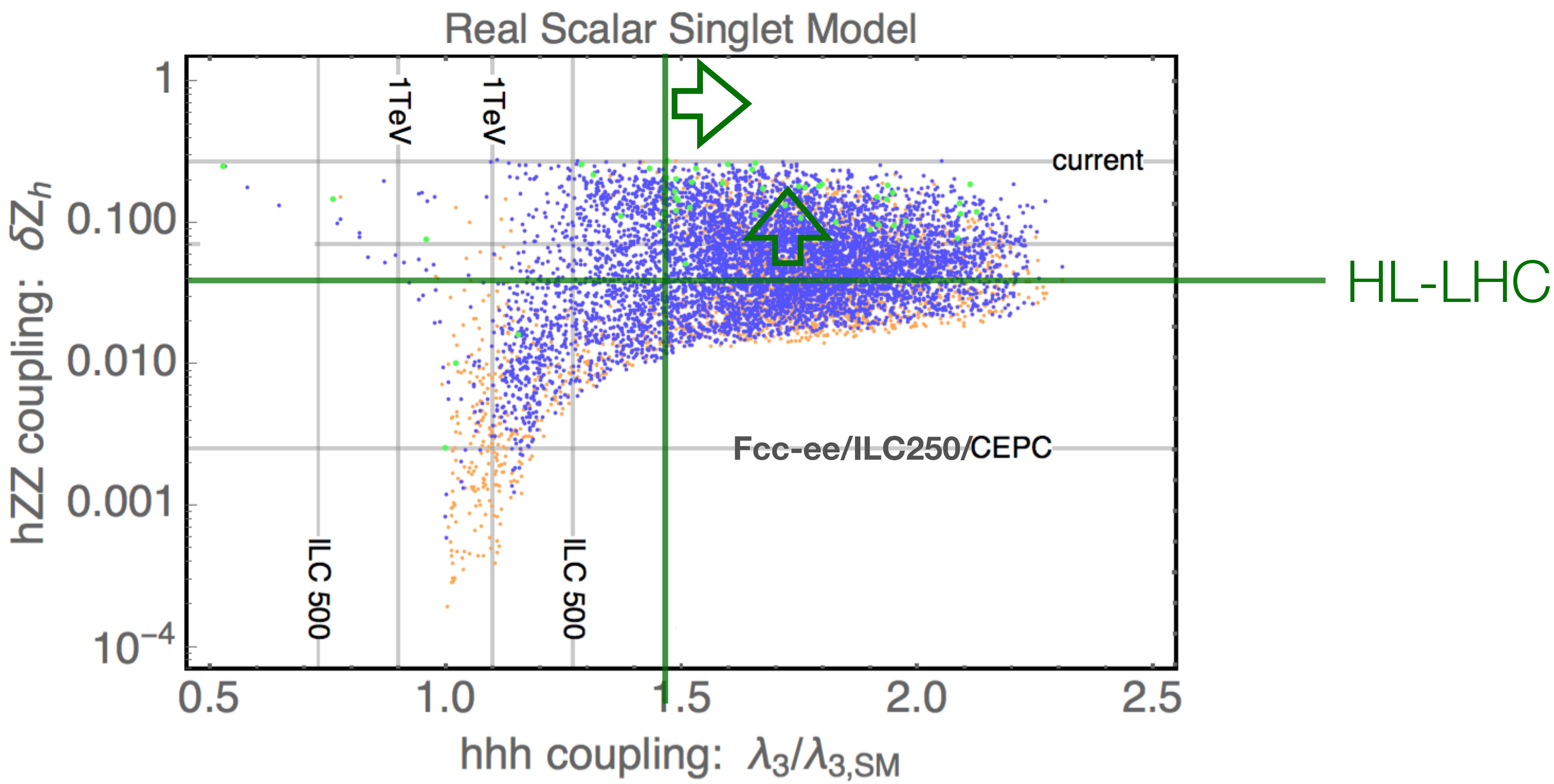
Self-coupling measurement, typically harder, may not be the discovery channel.

EW phase transition



A typical (simplest) model, Higgs mixes with a singlet

EW phase transition



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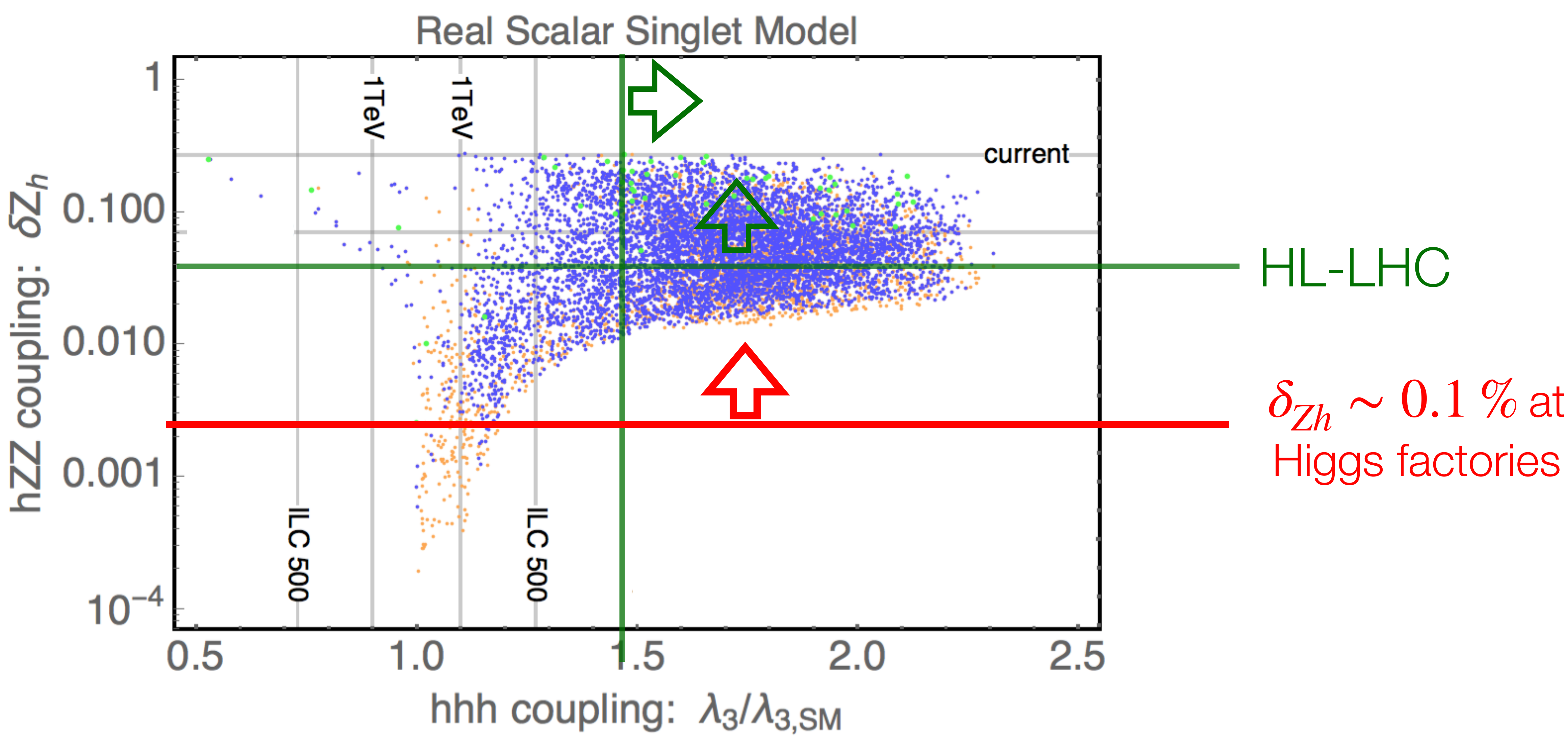
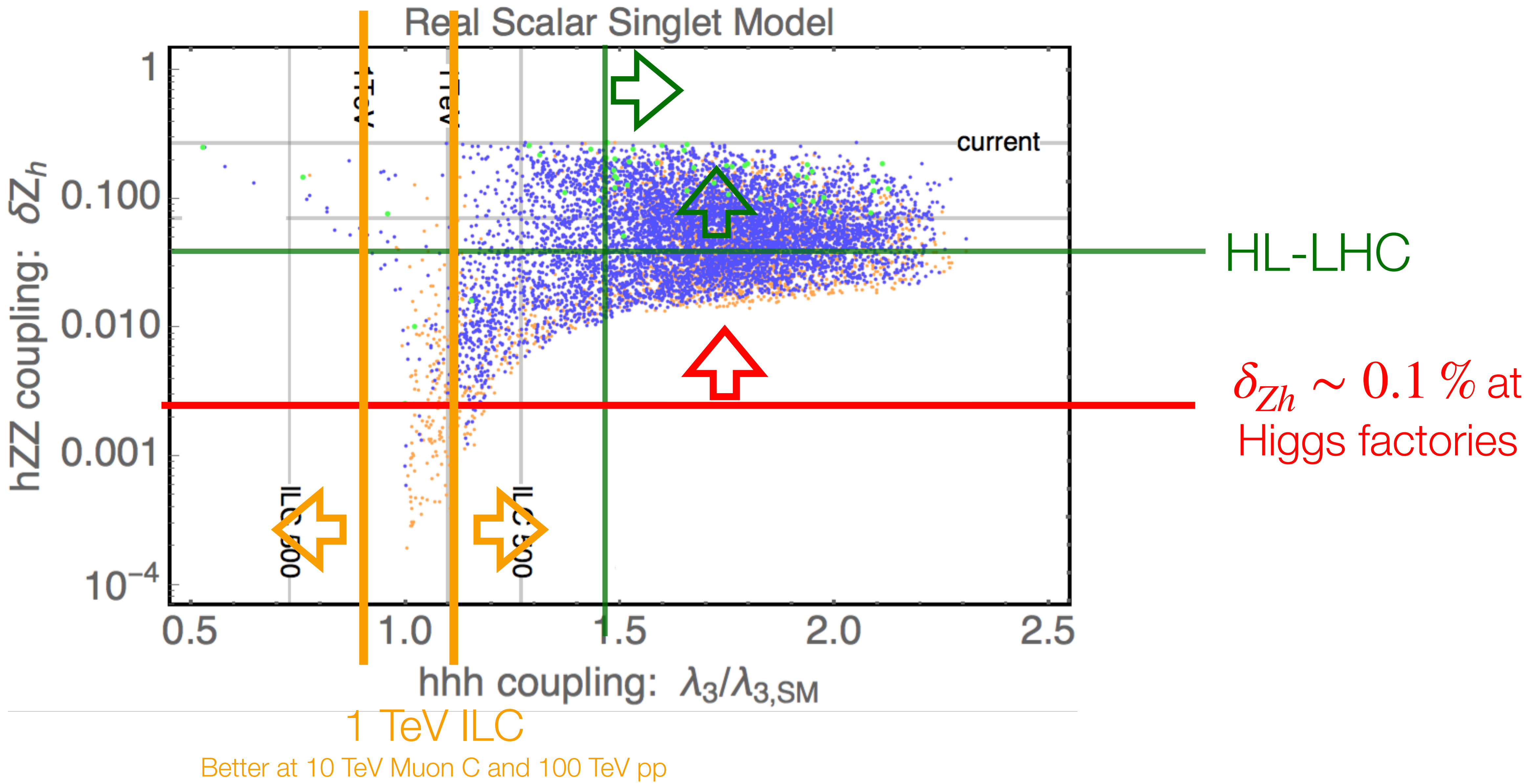
EW phase transition



A typical (simplest) model, Higgs mixes with a singlet

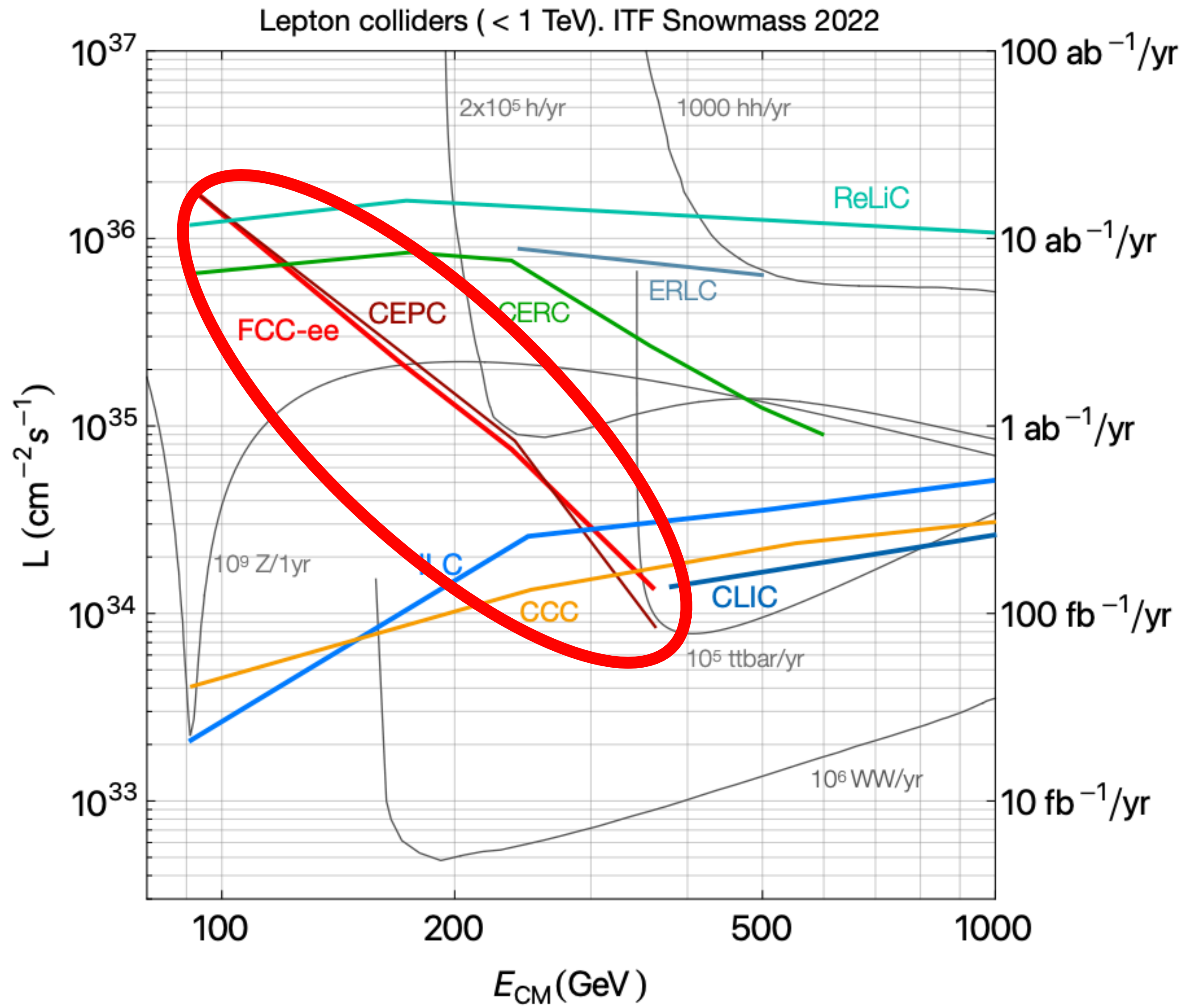
EW phase transition



A typical (simplest) model, Higgs mixes with a singlet

Comments on options

Circular



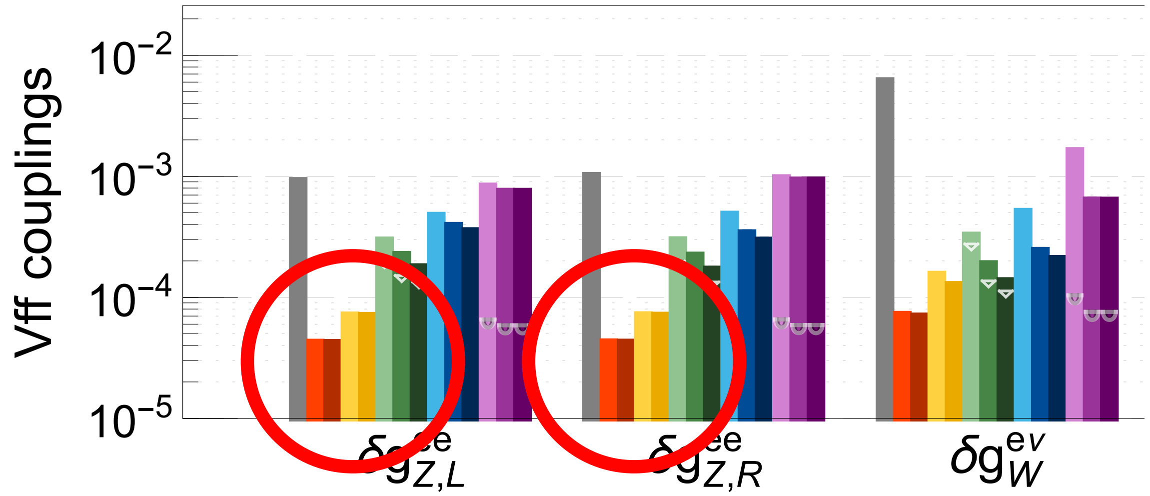
Higher luminosity.
⇒ more Higgs bosons!

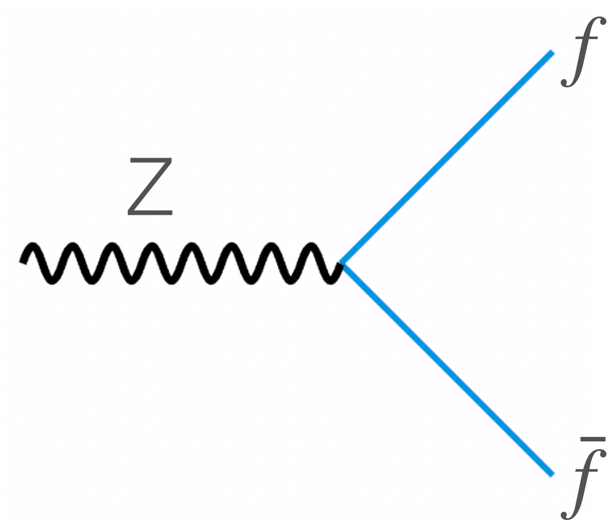
More W (10^6), Z (10^{12})

With more W, Zs

CircularHiggs factories:
10^{12} Zs 10^{6} WW

In comparison:
LEP has 10^{7} Zs

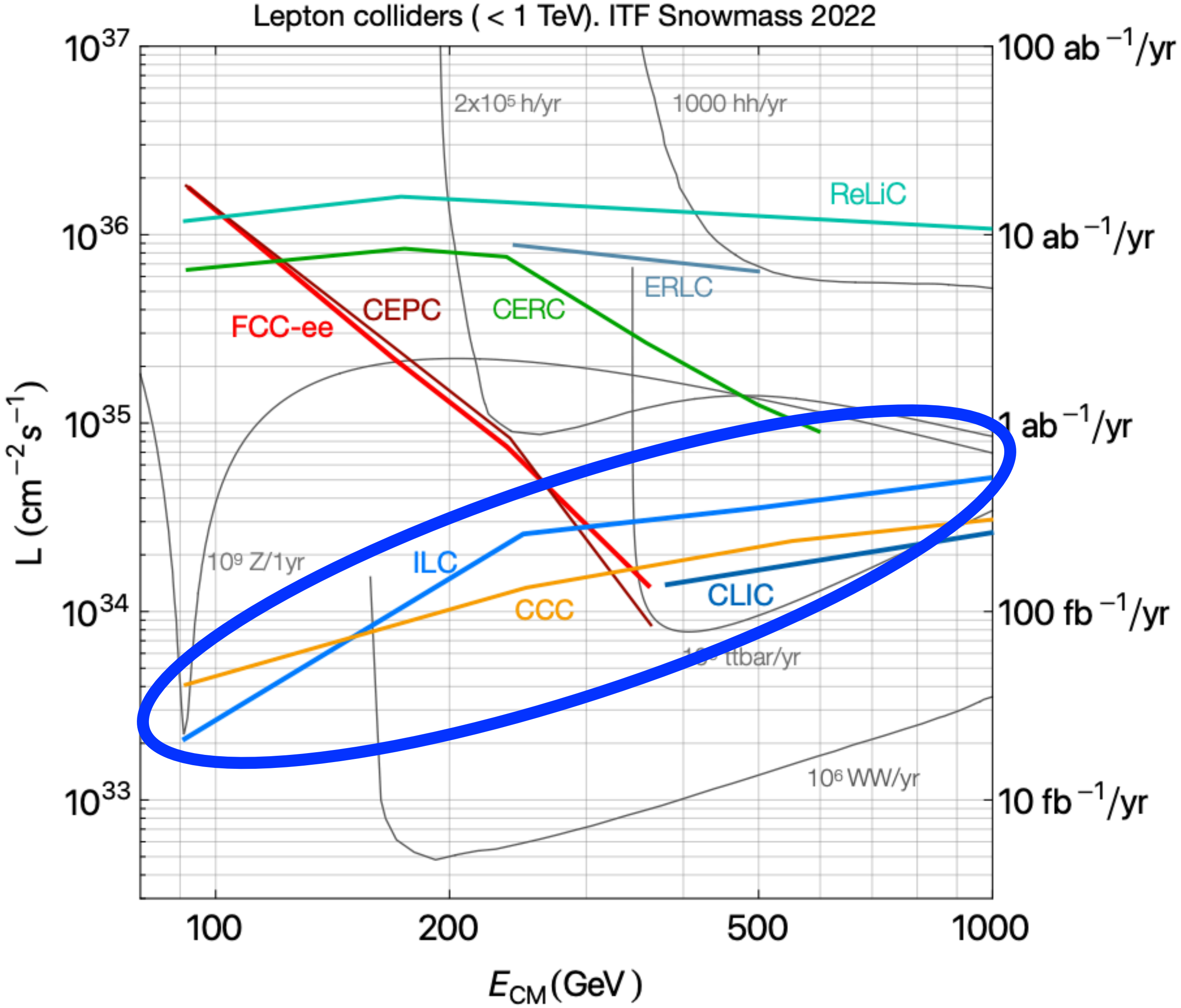




Precision on electroweak couplings: $10^{-3} \Rightarrow 10^{-4}$

Search for NP in exotic Z decays (more later)

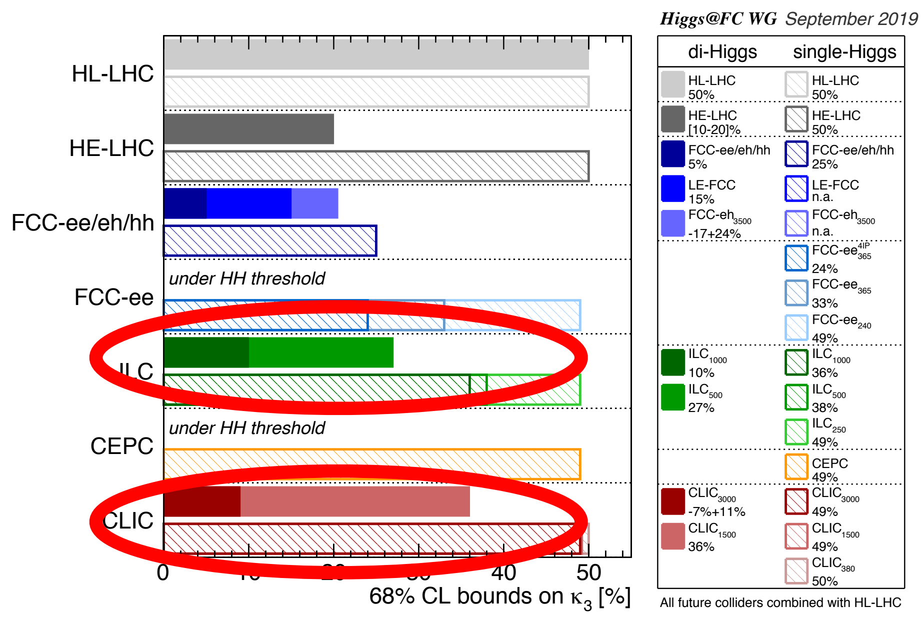
Linear

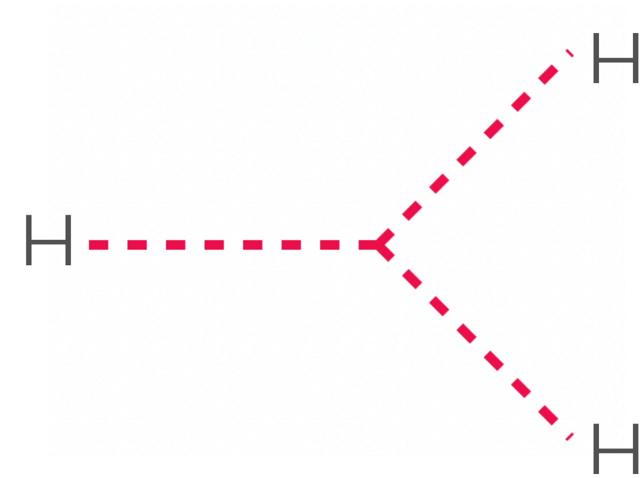


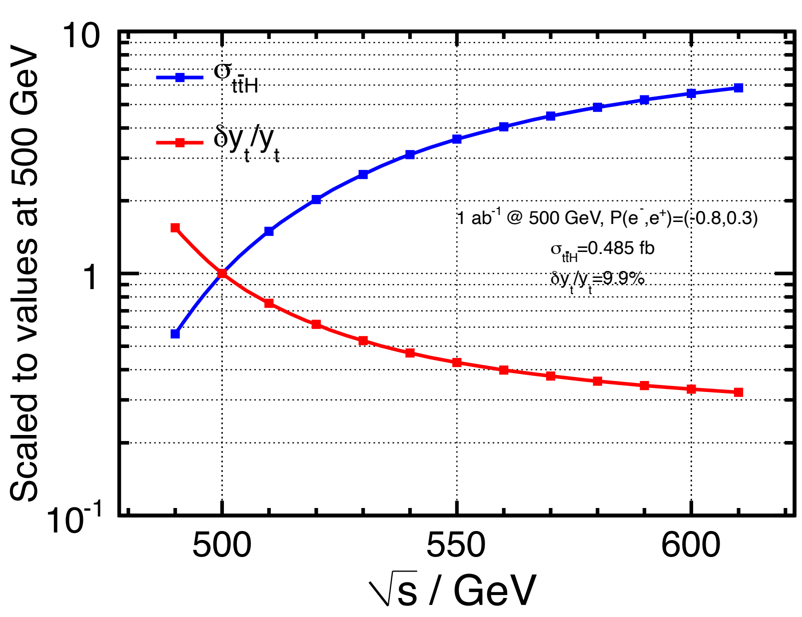
Longitudinal polarization.
Better at resolving certain signals

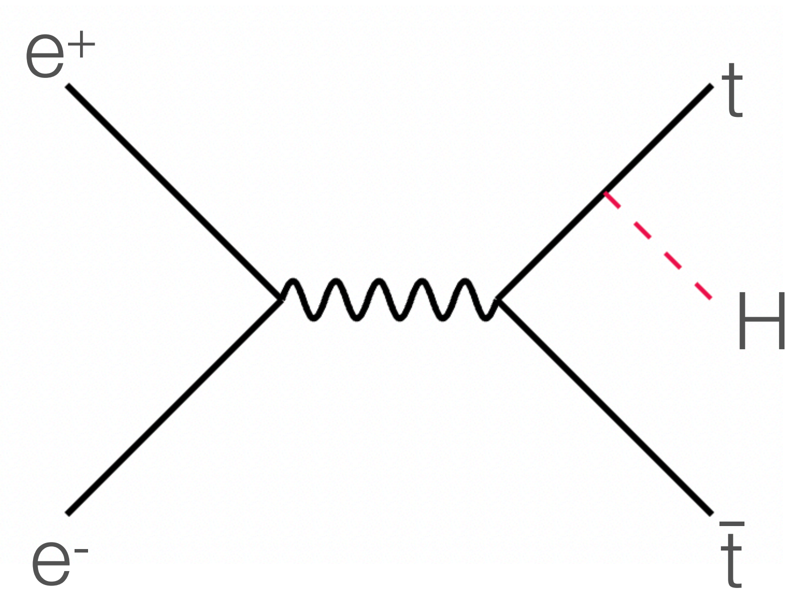
Can go to higher energies

At higher energies









Two excellent options!

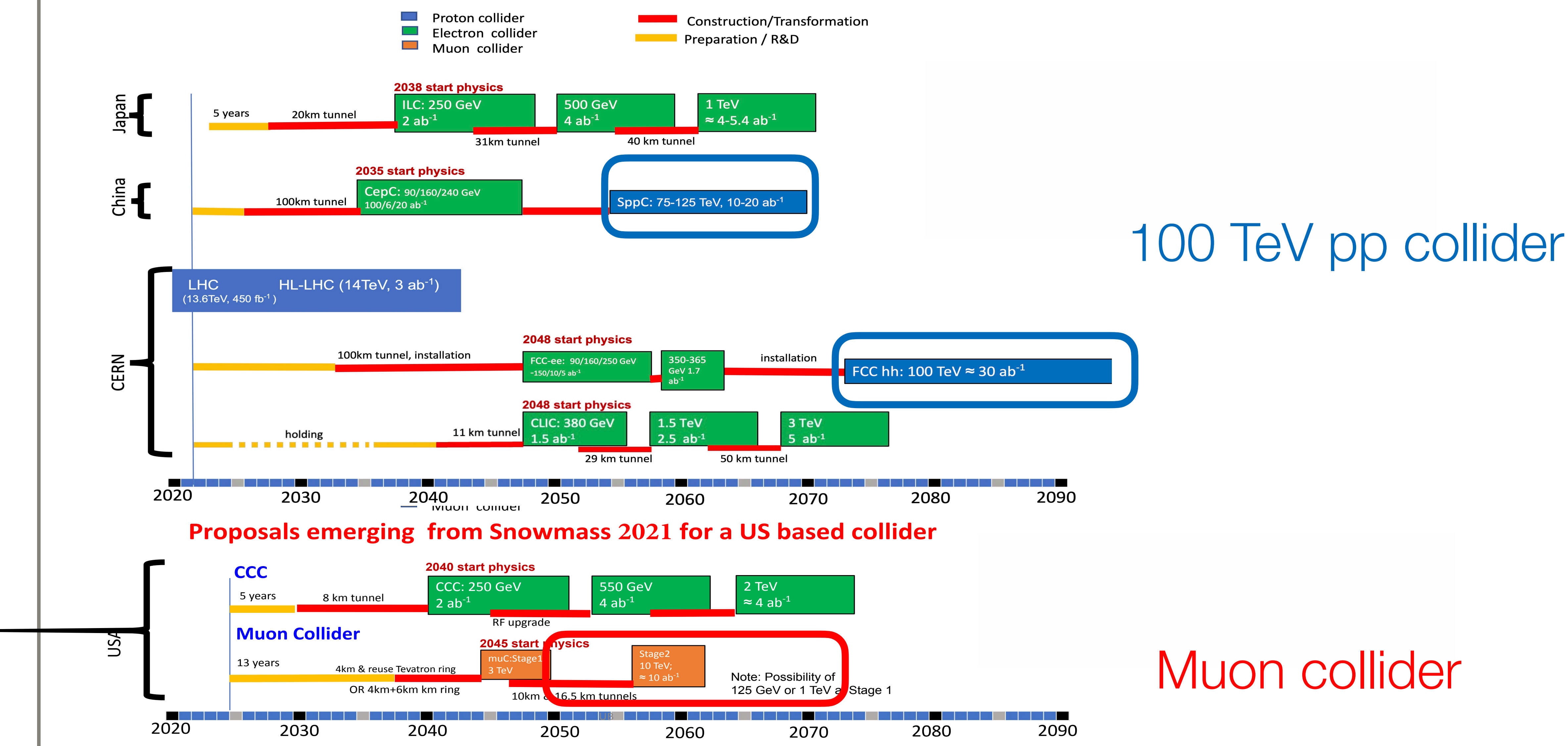
Great performances for Higgs measurements.

Different in additional physics program and prospects

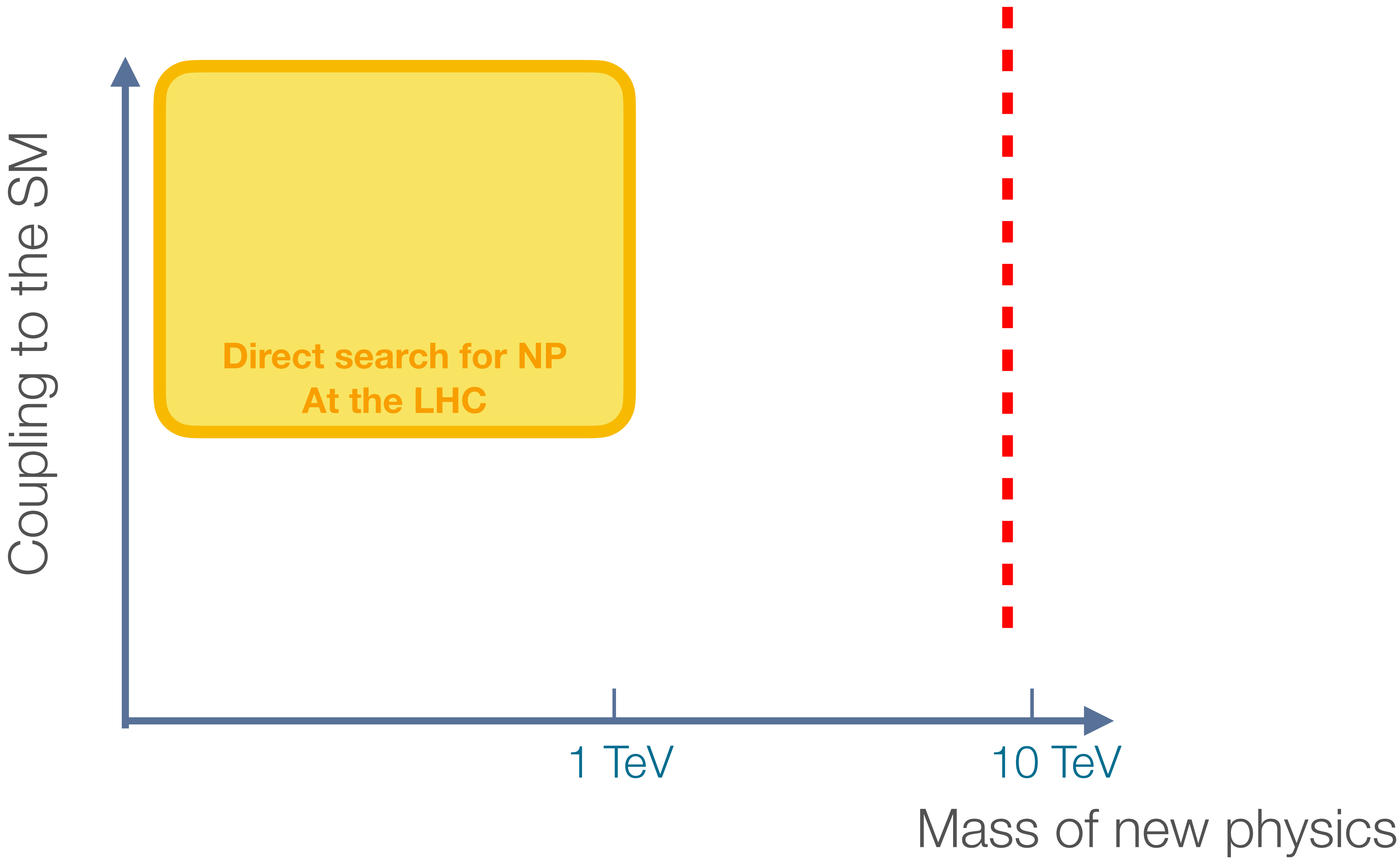
Beyond the LHC:

Next energy frontier $\sim$10 TeV.
How should we get there?

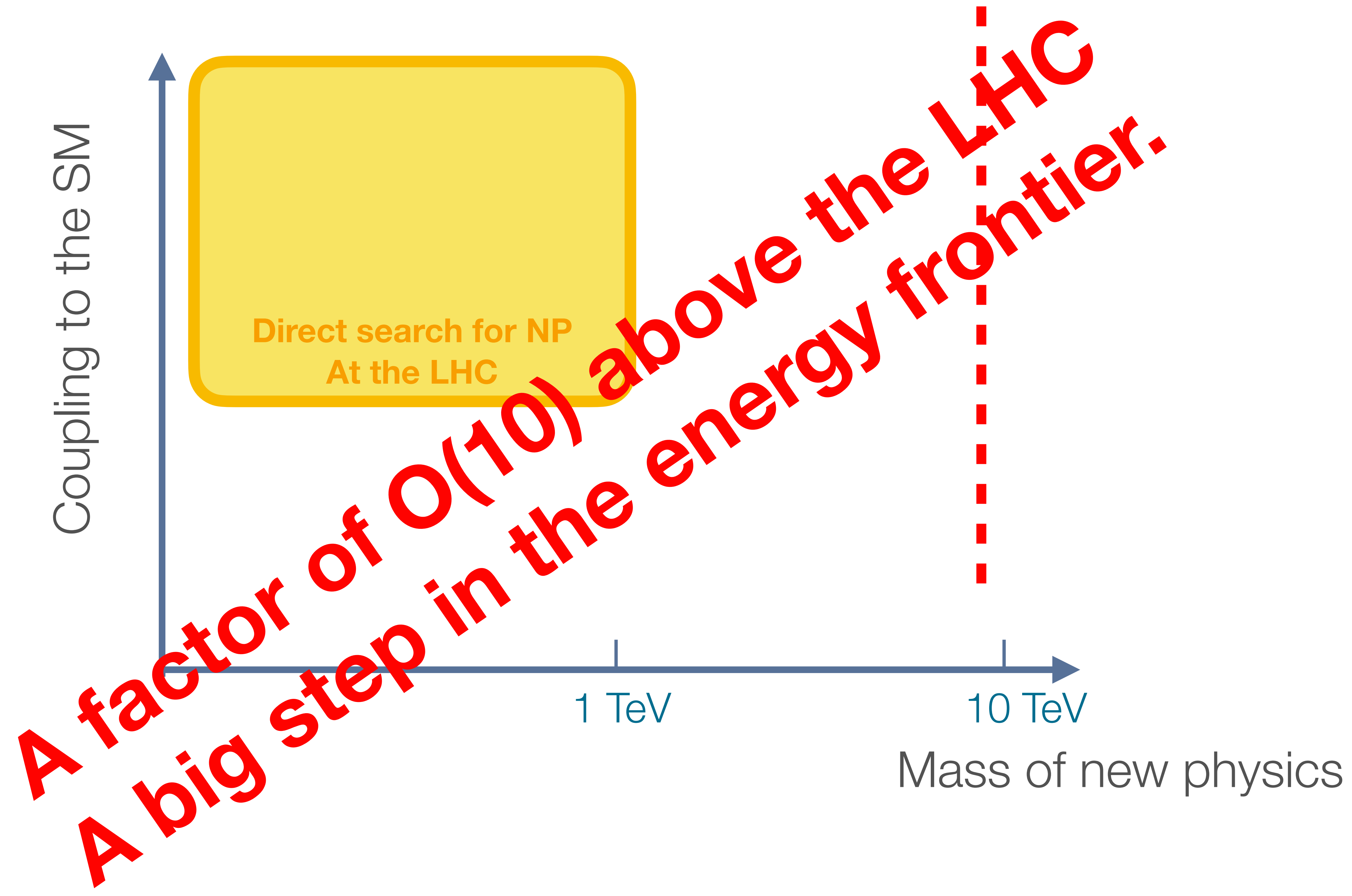
Energy frontier machines:



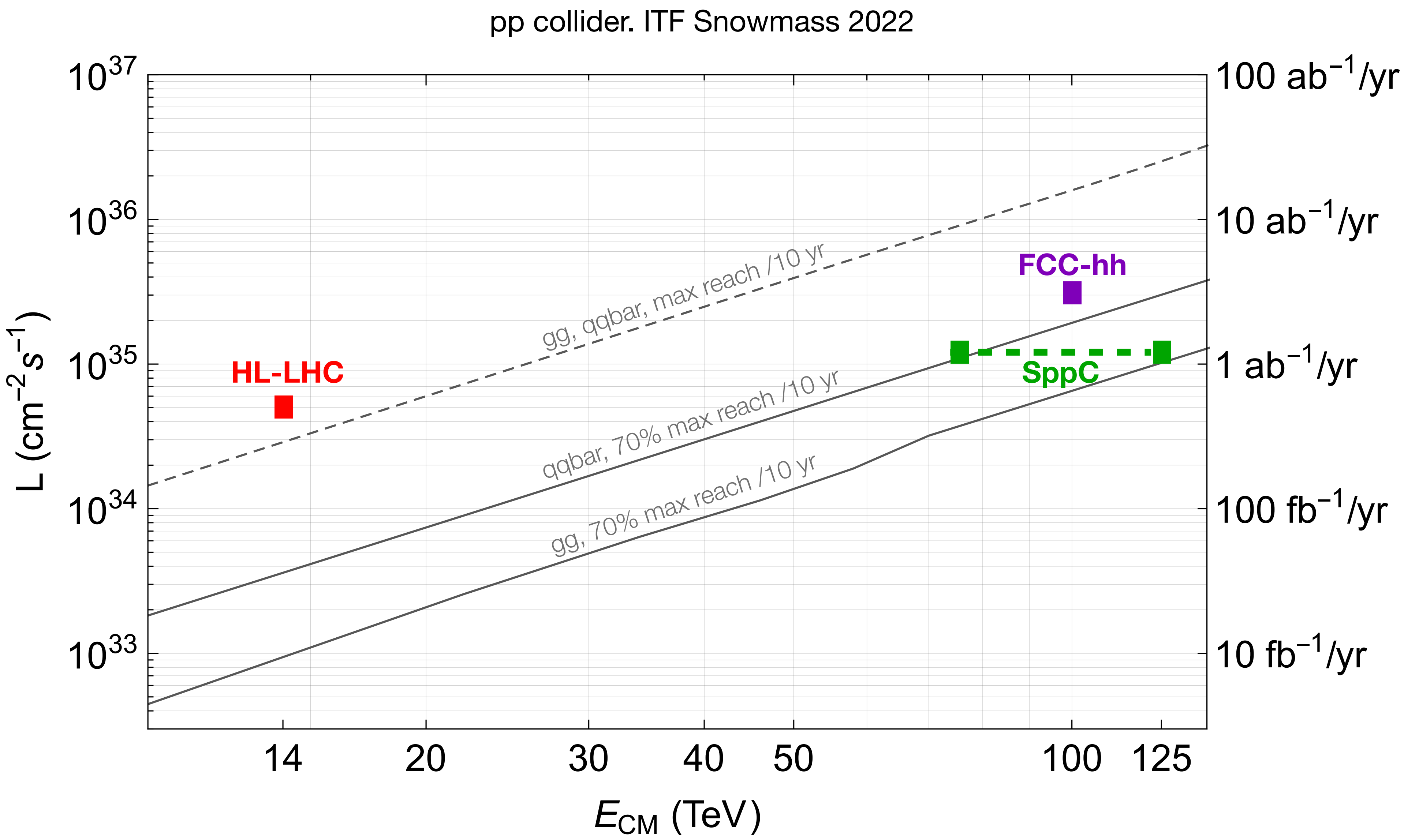
Physics case



Physics case



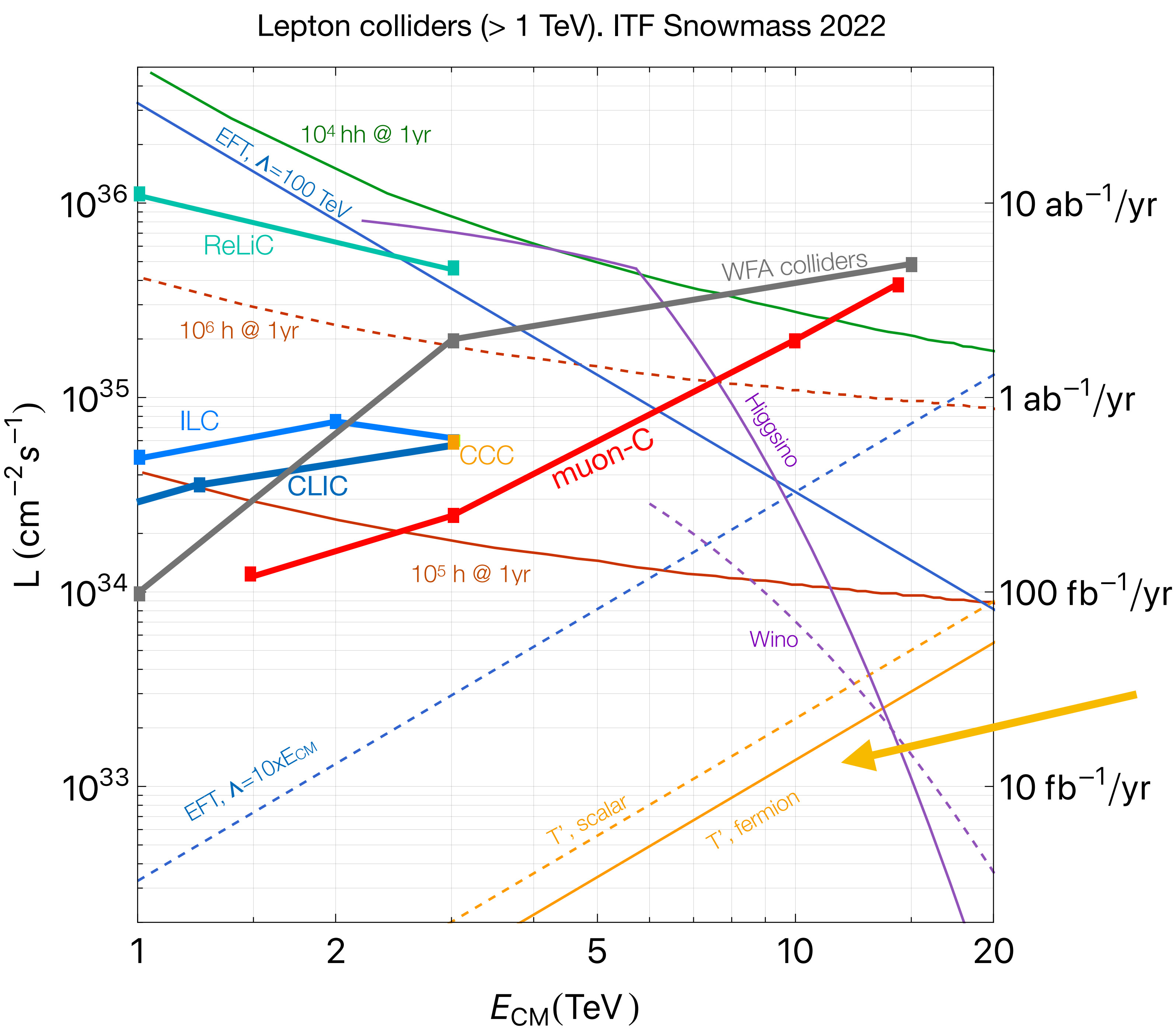
High energy pp



Max reach gain a factor of $\frac{E_{CM}}{E_{LHC}}$

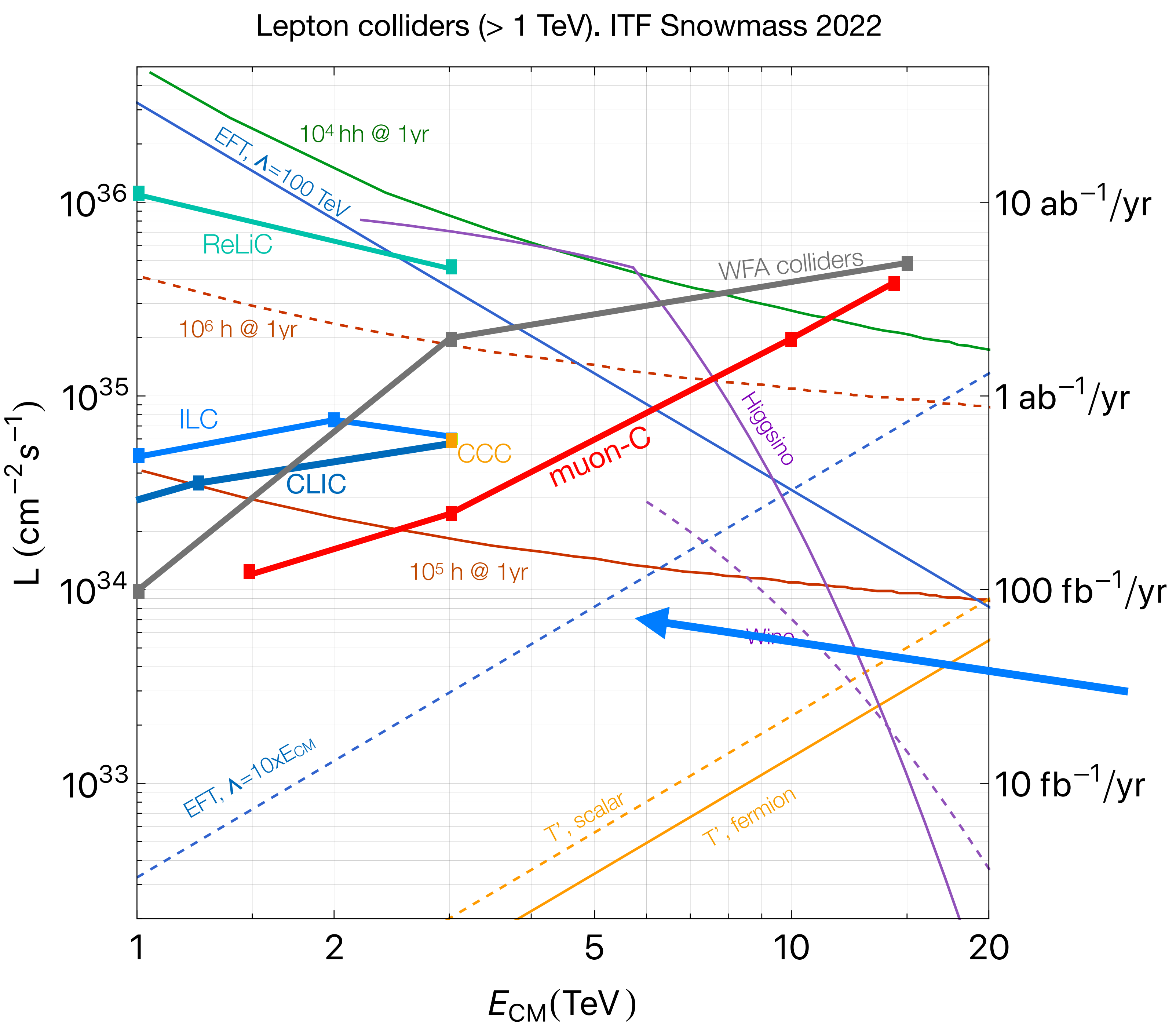
Big gain with modest luminosity.

Muon collider



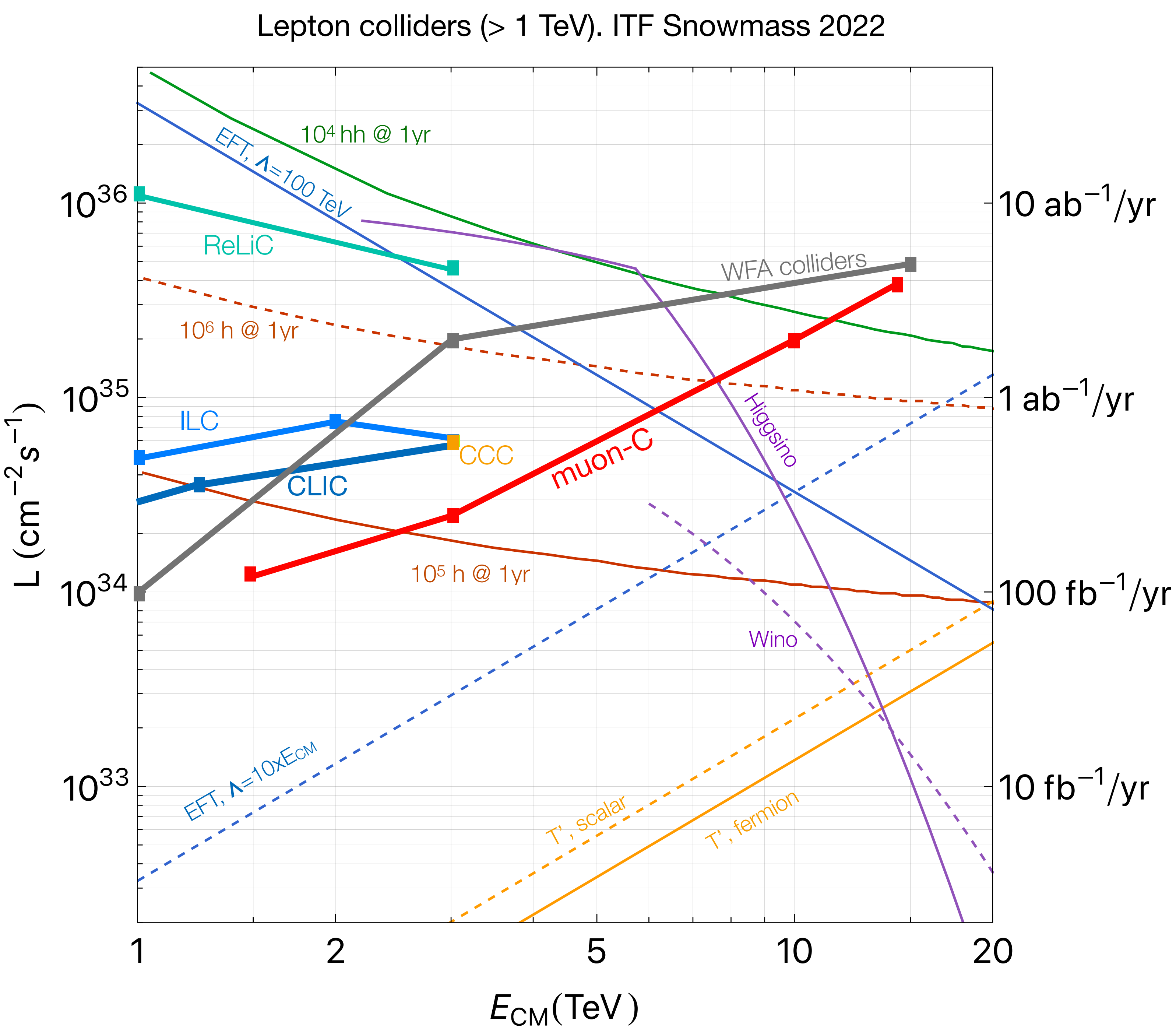
For generic new physics, such as top partner, the reach would be ≈ 0.5 E_{CM}, with very low luminosity requirement.

Muon collider



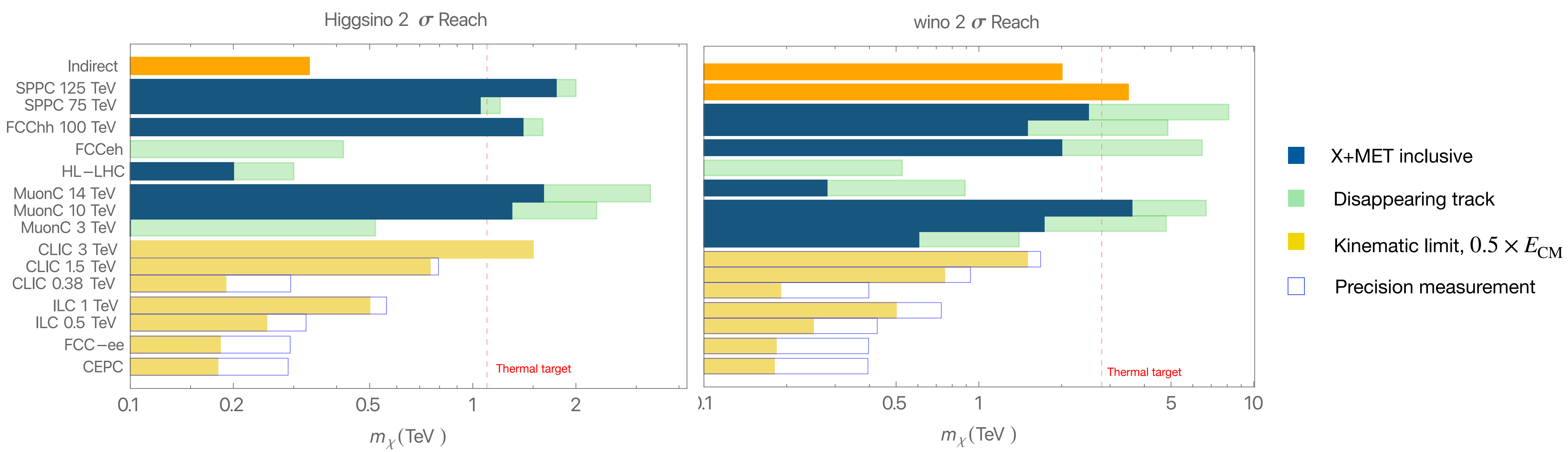
Indirectly probing much beyond E_{CM}

Muon collider



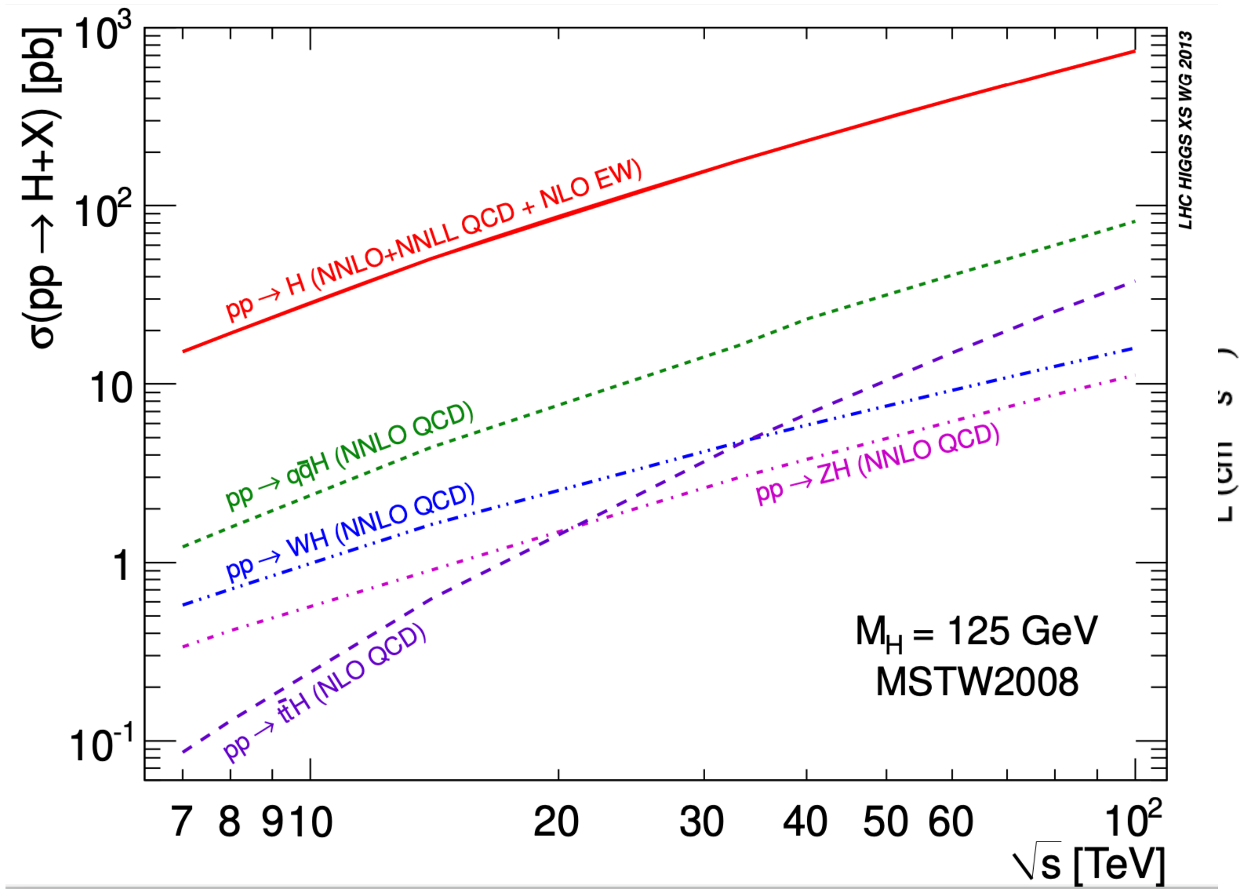
Similar for other lepton colliders.

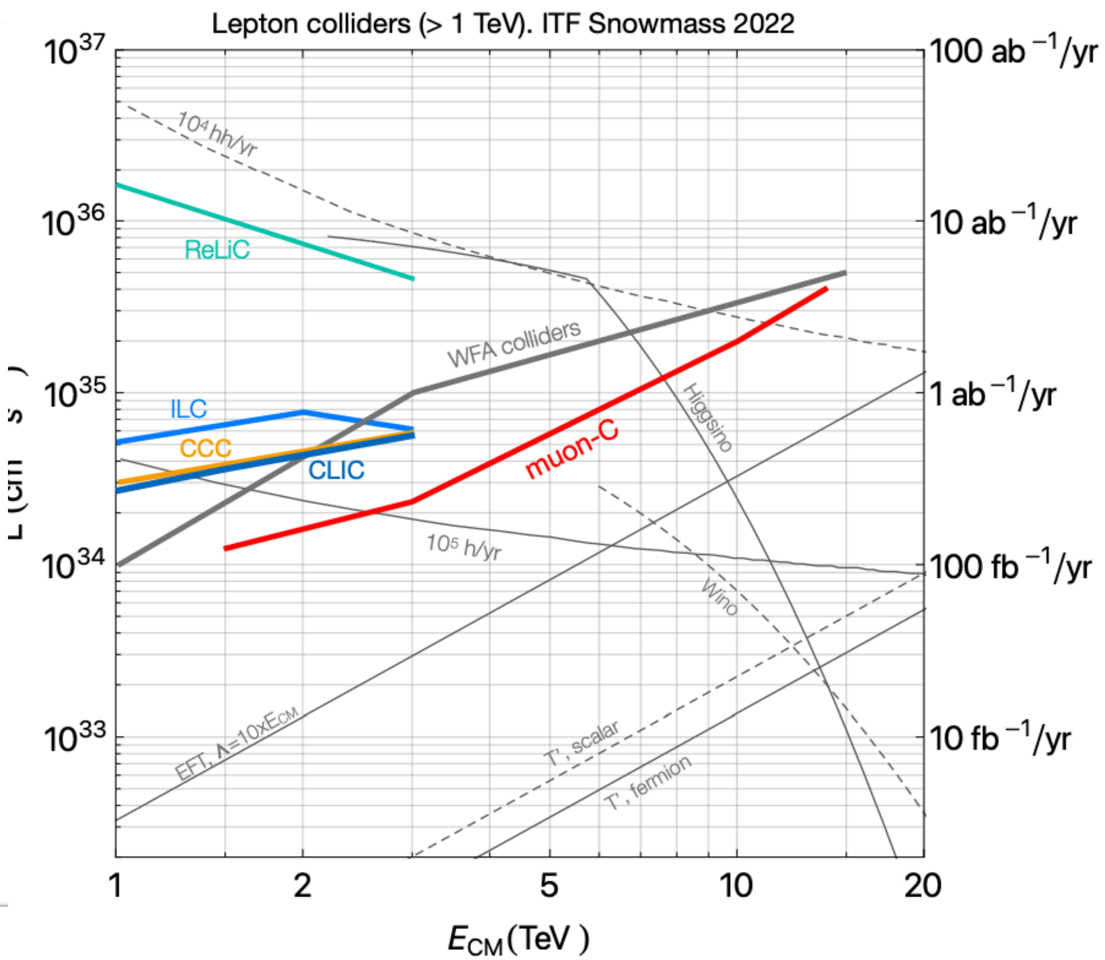
WIMP dark matter



Testing of these simplest WIMP models.
Requires 100 TeV pp or 10 TeV muon collider

As Higgs factories





Hadron collider @ 100 TeV: 10^{10} Higgses

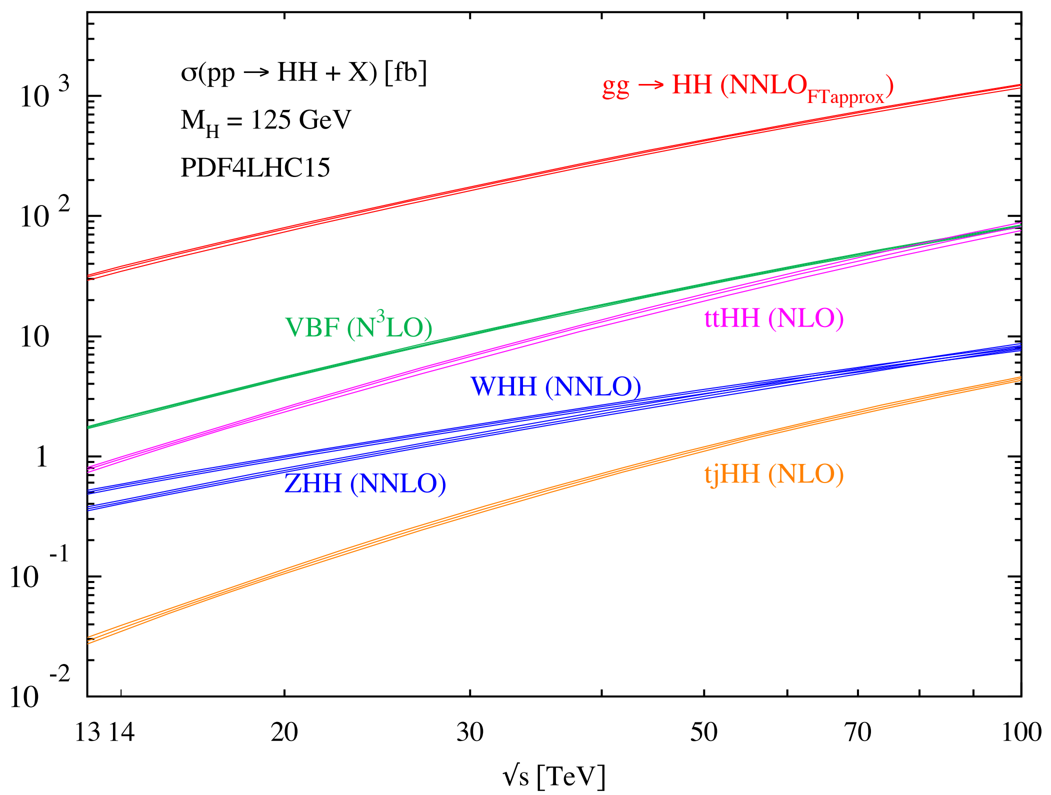
Muon collider @ 10 TeV: 10^{7} Higgses

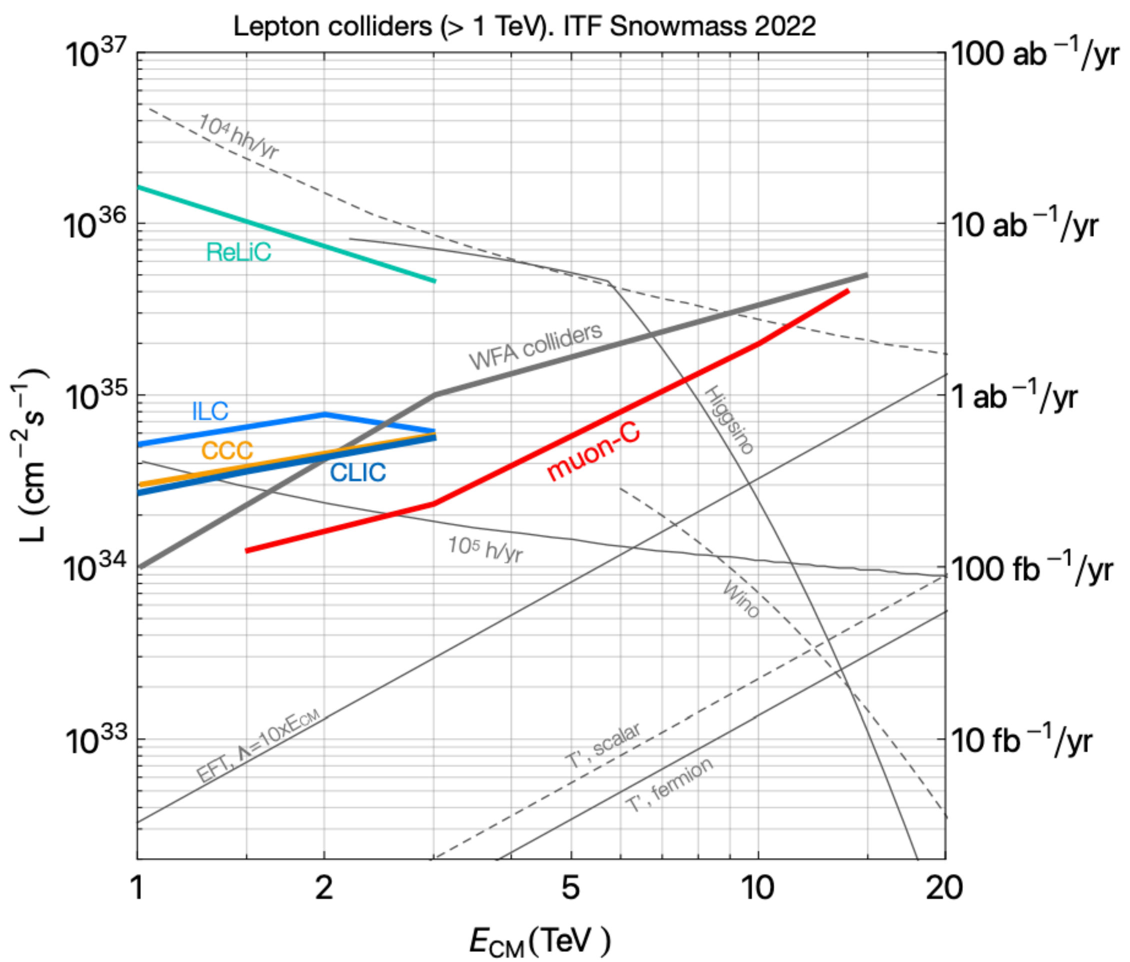
Performance

κ-0 fit	HL-LHC	LHeC	HE-LHC S2	HE-LHC S2′	ILC 250	ILC 500	ILC 1000	CLIC 380	CLIC 1500	CLIC 3000	CEPC	FCC-ee 240	FCC-ee 365	FCC-ee/eh/hh	$\mu^+\mu^-$ **10000**
κ_W	1.7	0.75	1.4	0.98	1.8	0.29	0.24	0.86	0.16	0.11	1.3	1.3	0.43	0.14	0.11
κ_Z	1.5	1.2	1.3	0.9	0.29	0.23	0.22	0.5	0.26	0.23	0.14	0.20	0.17	0.12	0.35
κ_g	2.3	3.6	1.9	1.2	2.3	0.97	0.66	2.5	1.3	0.9	1.5	1.7	1.0	0.49	0.45
κ_γ	1.9	7.6	1.6	1.2	6.7	3.4	1.9	98$\star$	5.0	2.2	3.7	4.7	3.9	0.29	0.84
$\kappa_{Z\gamma}$	10.	–	5.7	3.8	99$\star$	86$\star$	85$\star$	120$\star$	15	6.9	8.2	81$\star$	75$\star$	0.69	5.5
κ_c	–	4.1	–	–	2.5	1.3	0.9	4.3	1.8	1.4	2.2	1.8	1.3	0.95	1.8
κ_t	3.3	–	2.8	1.7	–	6.9	1.6	–	–	2.7	–	–	–	1.0	1.4
κ_b	3.6	2.1	3.2	2.3	1.8	0.58	0.48	1.9	0.46	0.37	1.2	1.3	0.67	0.43	0.24
κ_μ	4.6	–	2.5	1.7	15	9.4	6.2	320$\star$	13	5.8	8.9	10	8.9	0.41	2.9
κ_τ	1.9	3.3	1.5	1.1	1.9	0.70	0.57	3.0	1.3	0.88	1.3	1.4	0.73	0.44	0.59

Di-Higgs

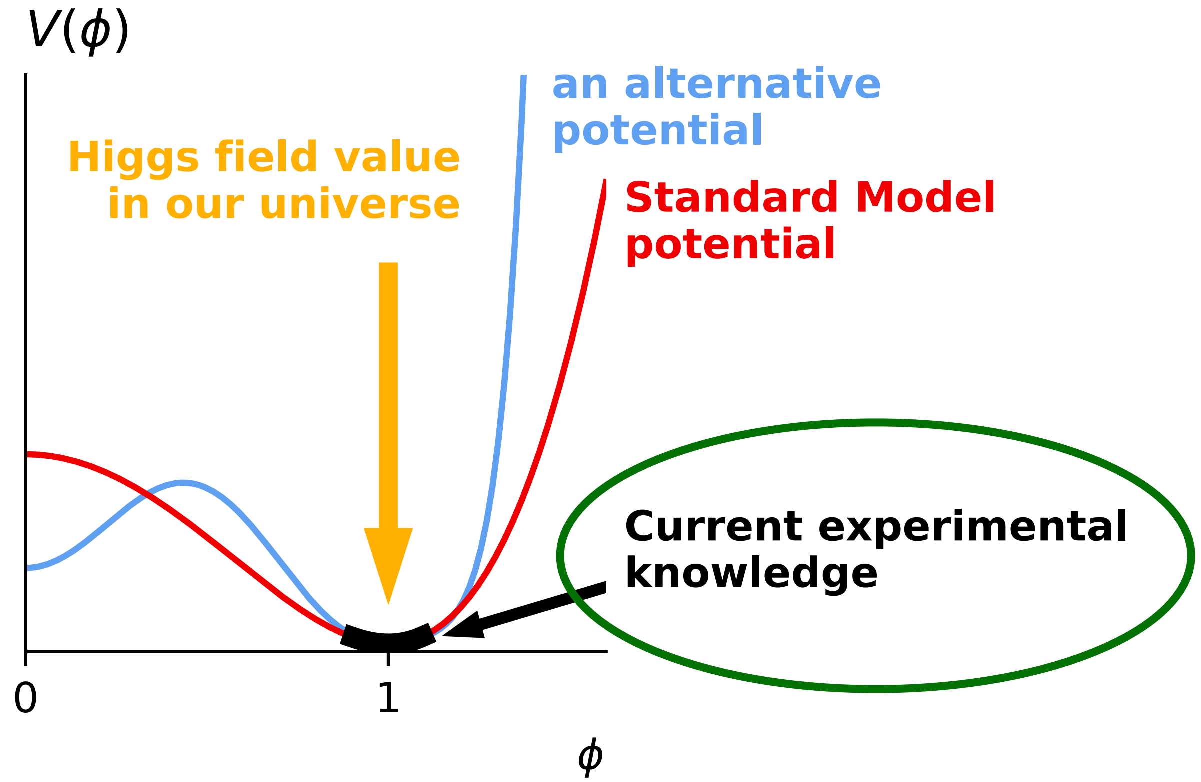
1910.00012





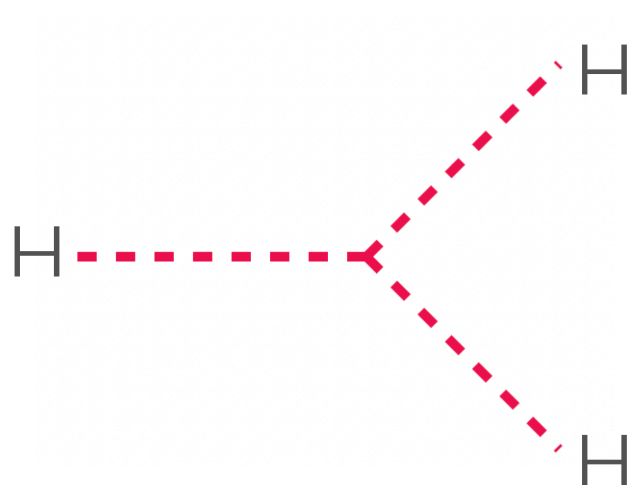
100 TeV pp, 40 times HL-LHC

Muon C @ 10 TeV: several x 10^4

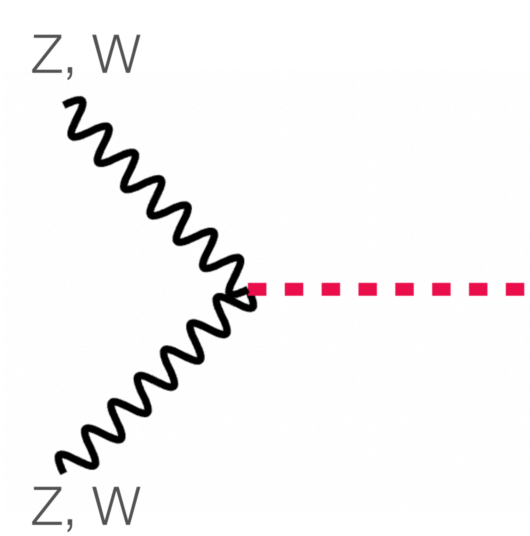


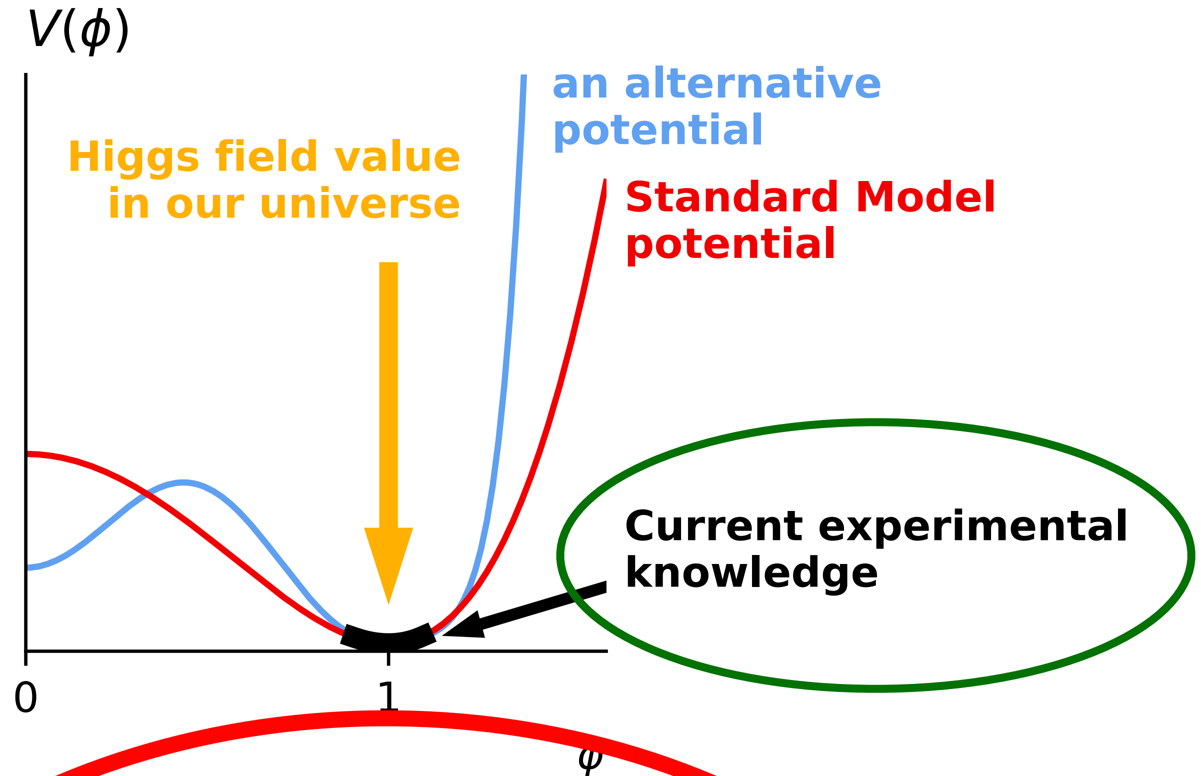
Need to go beyond this

1. Self-coupling



2. New physics in the alternative scenario often induce changes in other Higgs coupling, such as hZ





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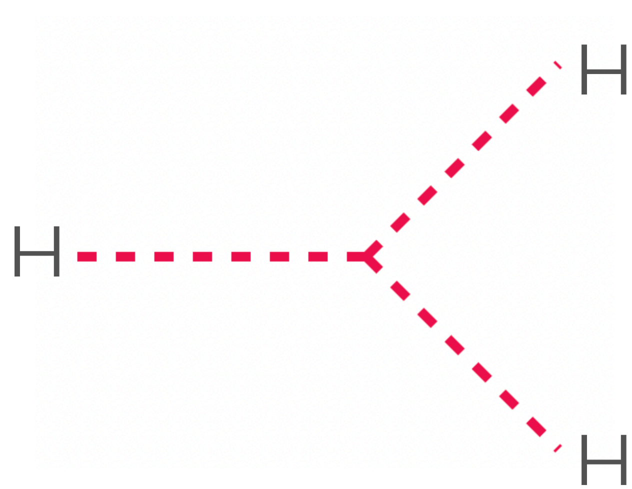

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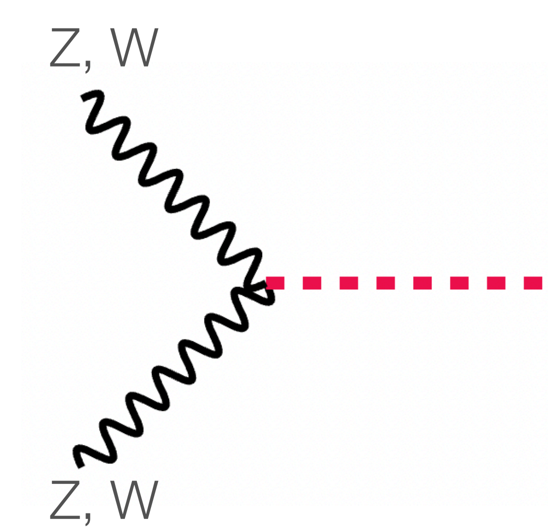
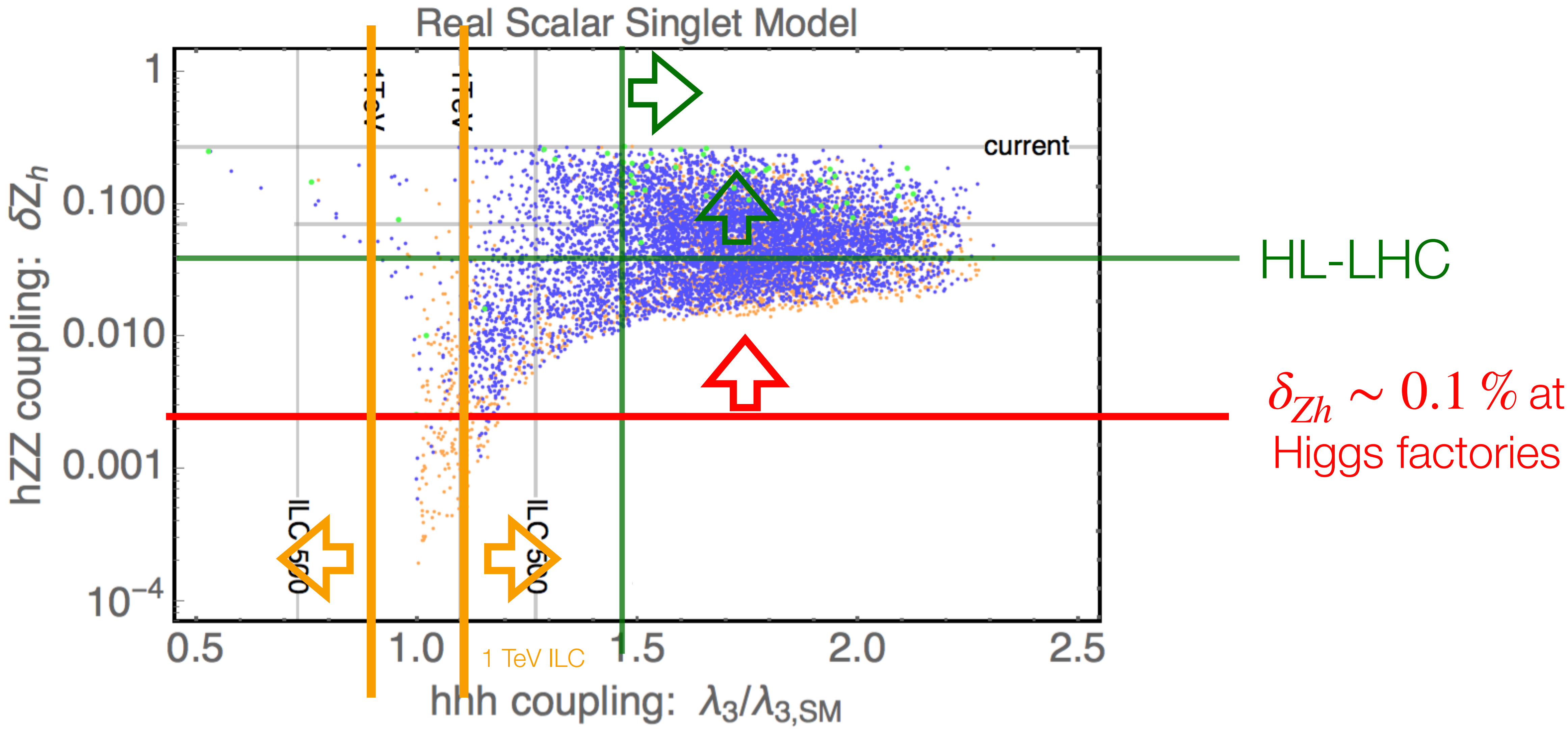
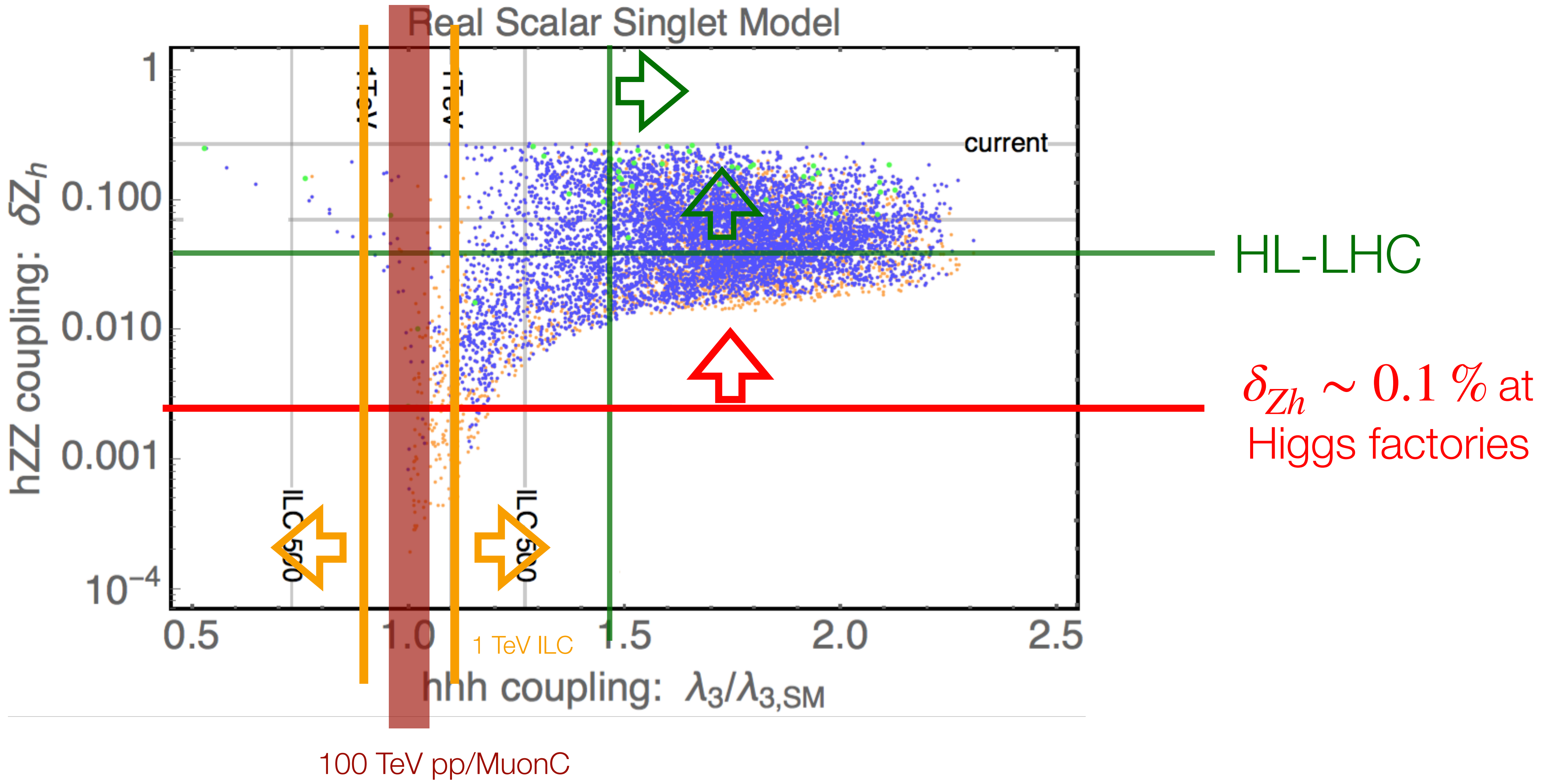


EW phase transition



A typical (simplest) model, Higgs mixes with a singlet

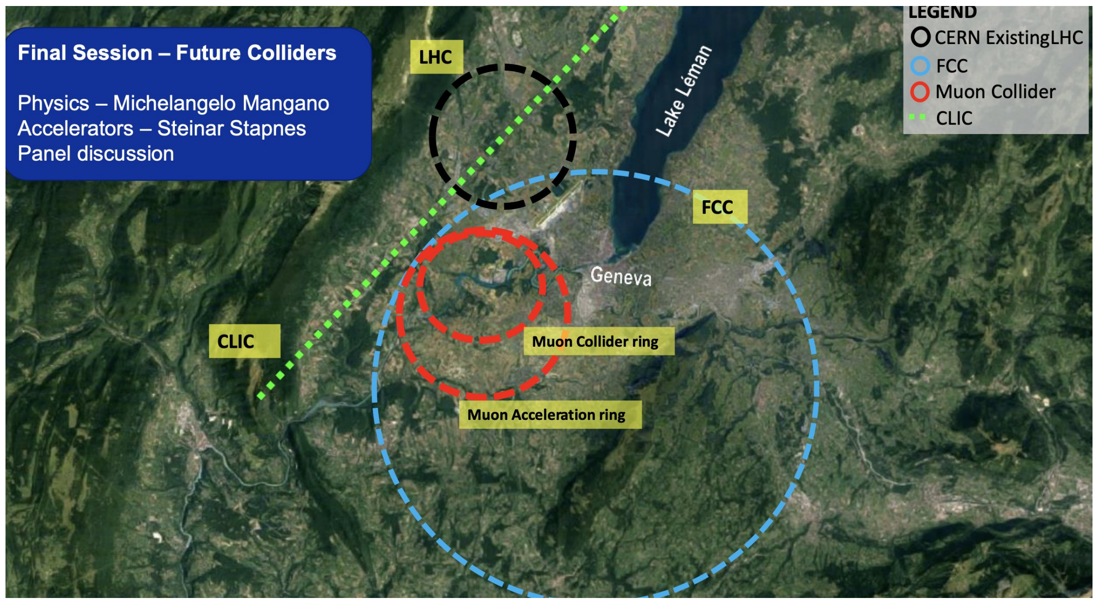
EW phase transition



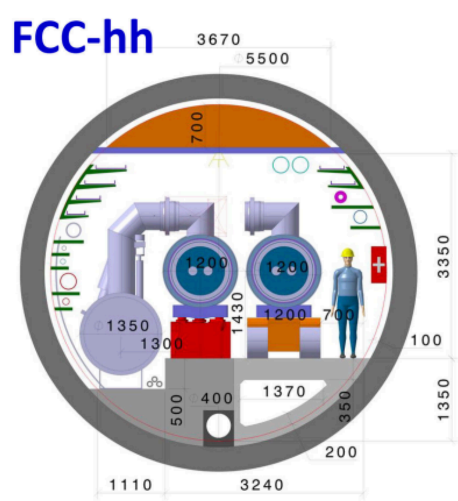
A typical (simplest) model, Higgs mixes with a singlet

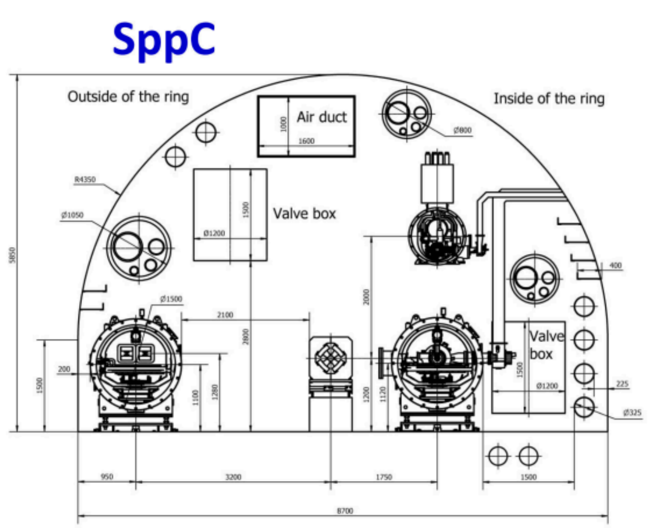
Comments on options

Hadron collider



Better for colored new physics.
Noisier collision environment.



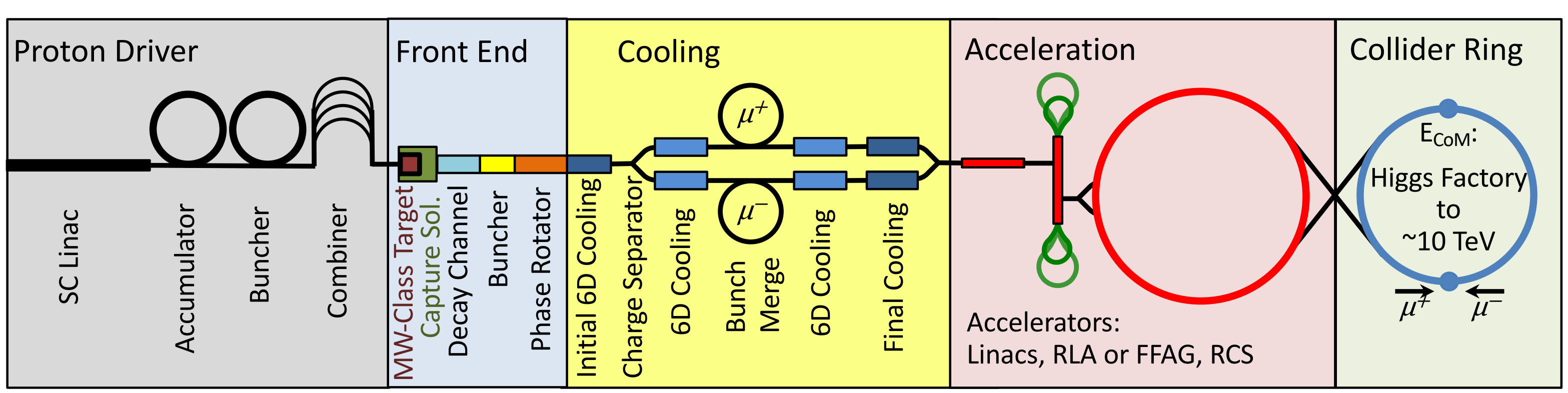


Have a lot of experience with pp.
Need a big ring, and new magnets.

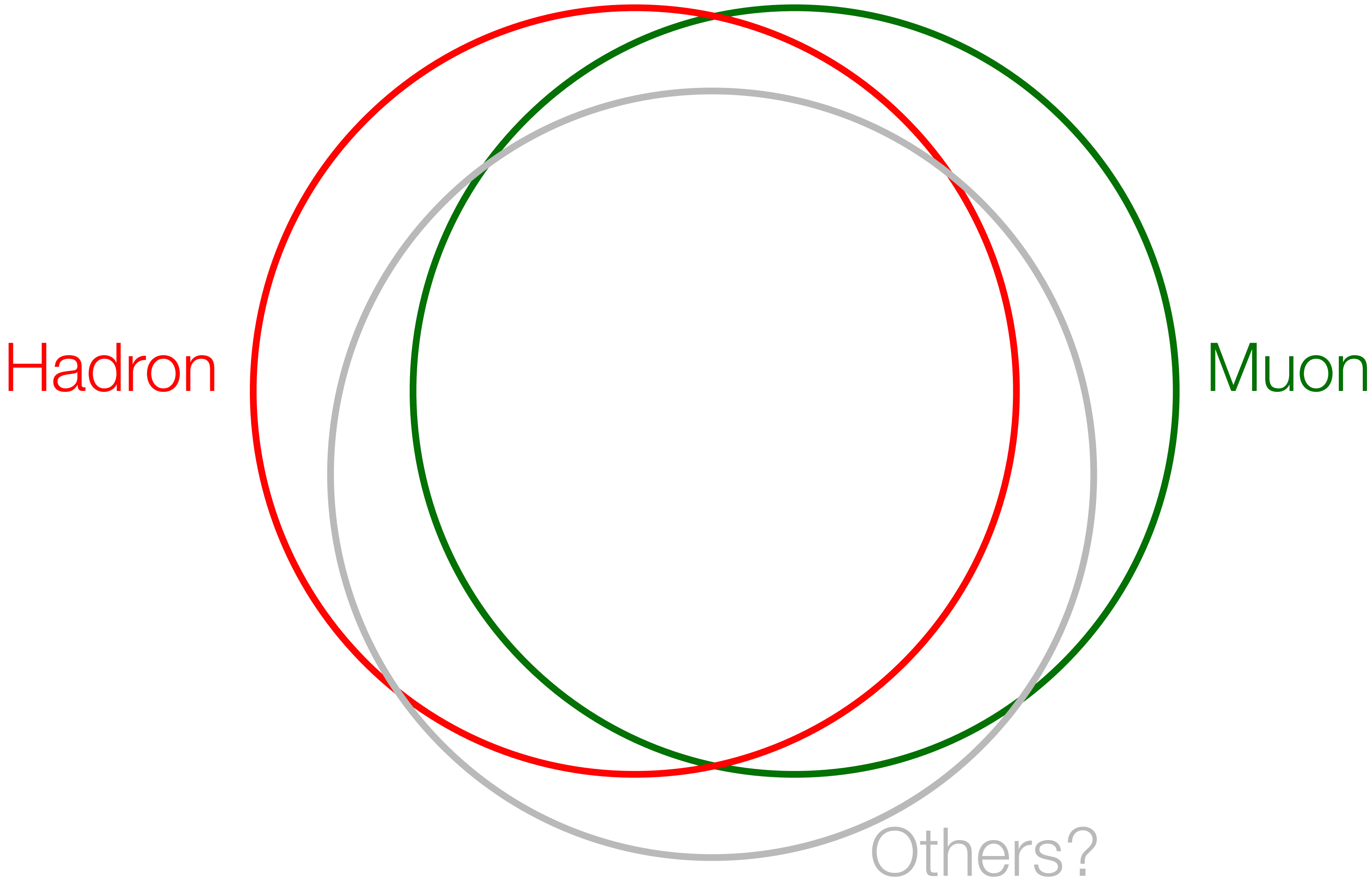
Muon collider

Cleaner (at least for high energy states).
More focus on electroweak processes

Don't know for sure we can make it yet.



Roads to 10 TeV



All exciting possibilities, we should study all of them!!

What energy is needed?

What energy is needed?

As high as possible. Of course, limited by tech knowhow and resource.

A good next step should be about 10 TeV.

Some physics benchmark, such as WIMP dark matter.
But mainly driven by other limitations.

Will we find new physics there?

Will we find new physics there?

We don’t know. However,

Will we find new physics there?

We don't know. However,

We will probe nature at much shorter distances, with the potential of answering big open questions.

Will we find new physics there?

We don't know. However,

We will probe nature at much shorter distances, with the potential of answering big open questions.

We will understand the working of the Standard Model in a new regime: with unbroken EW symmetry, qcd at 10xLHC…

An example for us

JWST

Big science project aiming at a better picture of how SM works under very different conditions.

An example for us

JWST

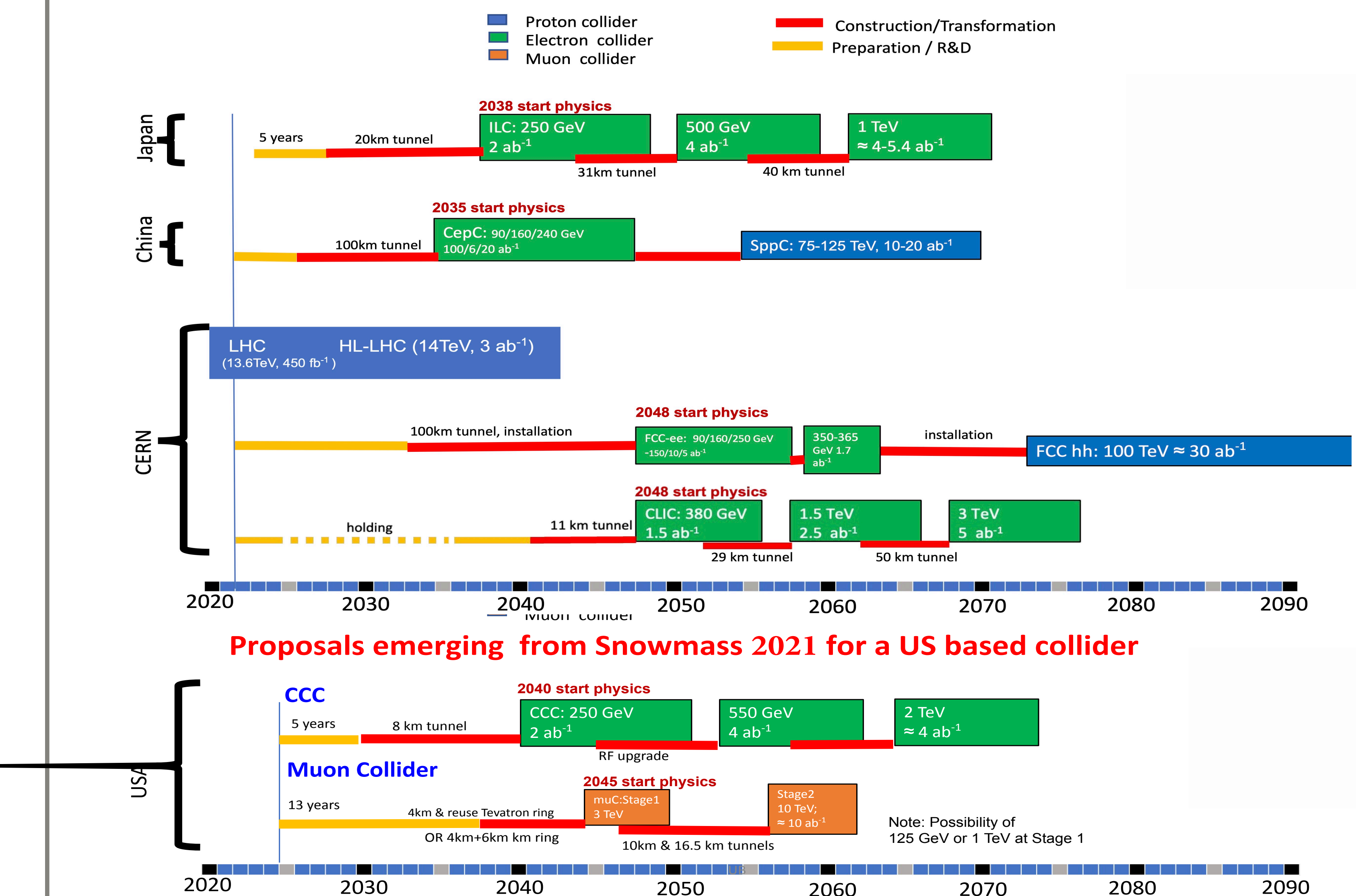
Probing the strange world at short distances should be at least as exciting!

My dream scenario

We get to a Higgs factory as soon as we can.

In the mean time, we (with a lot of R&D) to figure out the best way to get to higher energies (10 TeV).

With all these possibilities



+ more

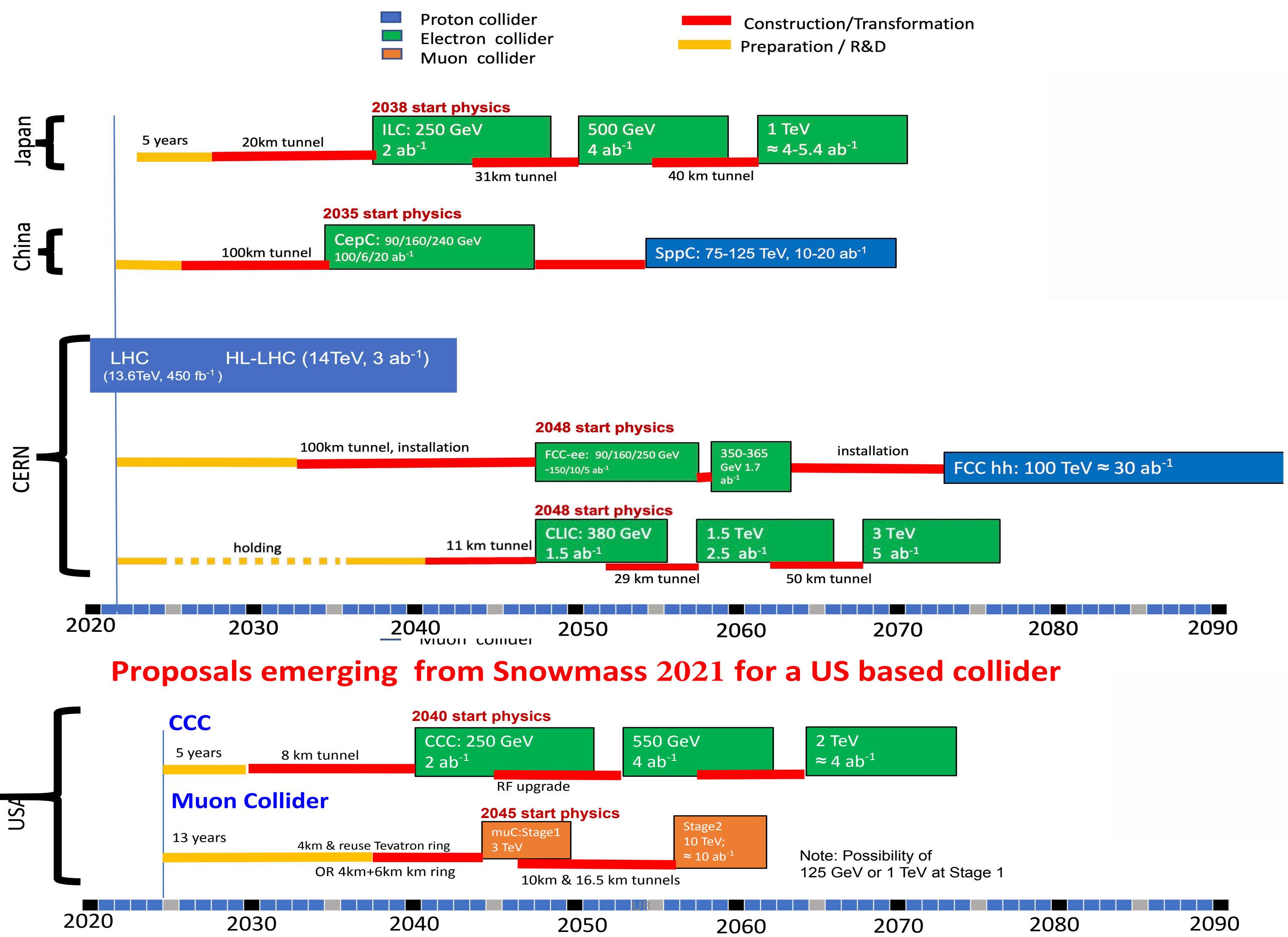
Let’s figure out a way to do something ASAP!

Extra

My dream scenario

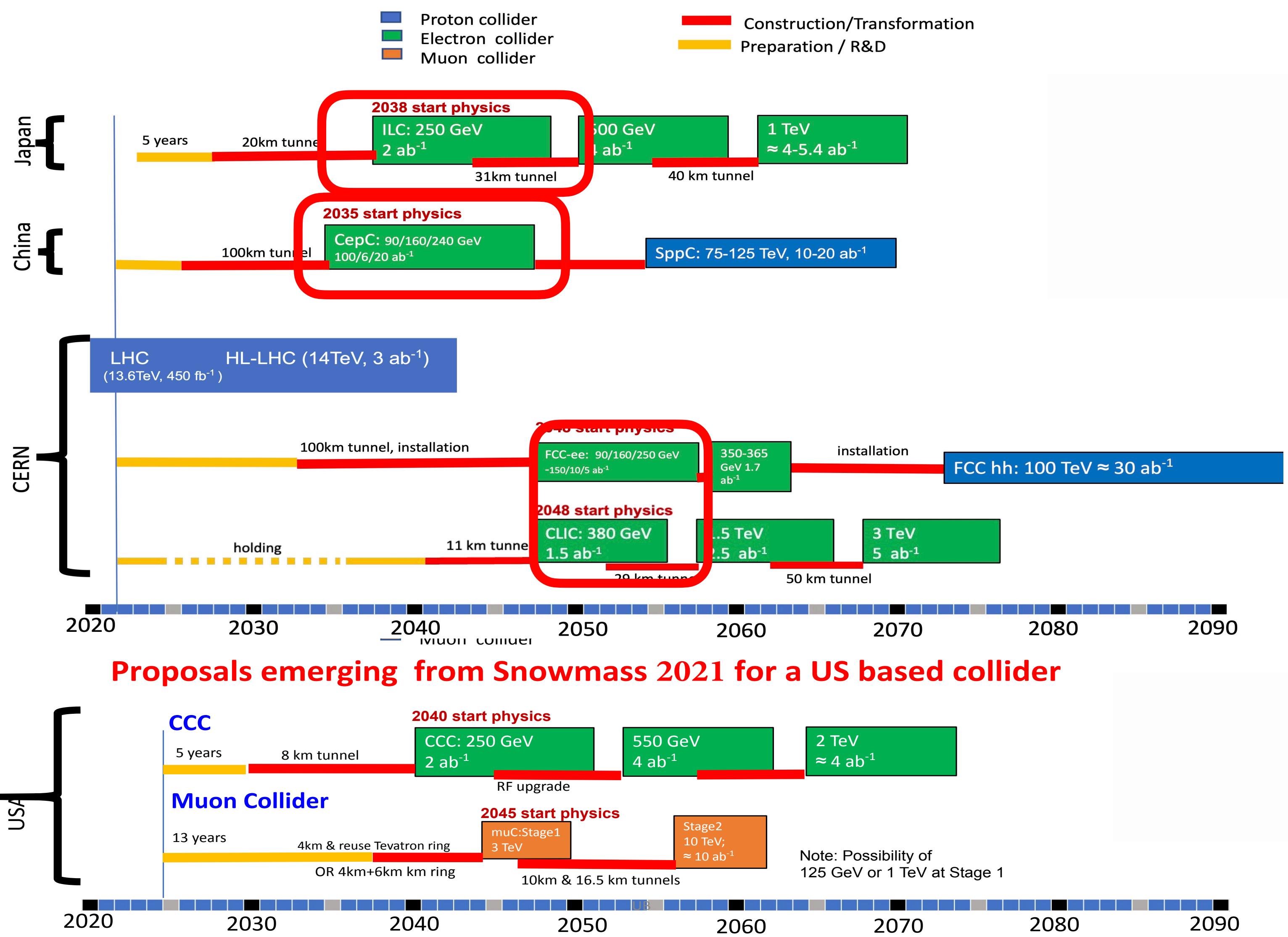
We get to a Higgs factory as soon as we can.

My dream scenario



Fastest way to get to a Higgs factory?

My dream scenario



“Shovel ready” options

+ maybe LEP 3?