X[*]-Factories and Beyond

* where X = Higgs, Z, W (and maybe top)

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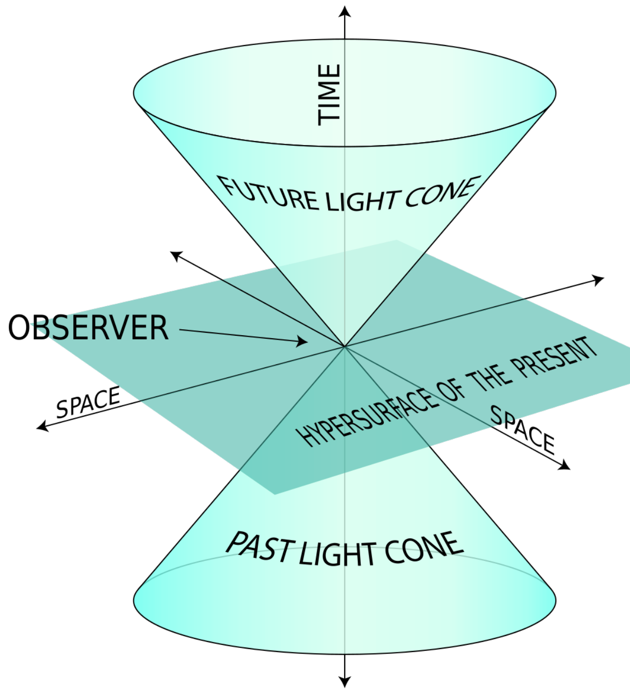
Disclaimer:

This is not a strategy talk, nor a projects comparison.

It is my answer to the question in the assigned title:

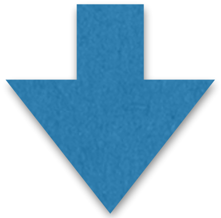
"Why are these projects interesting?"

The BIG achievements of Particle Physics



We discovered a satisfactory notion of **causality**
From Special Relativity

Understood that **particles do not have a position:**
Detectors have $\longrightarrow$ **Field** Observables $\mathcal{O}(t, \vec{x})$

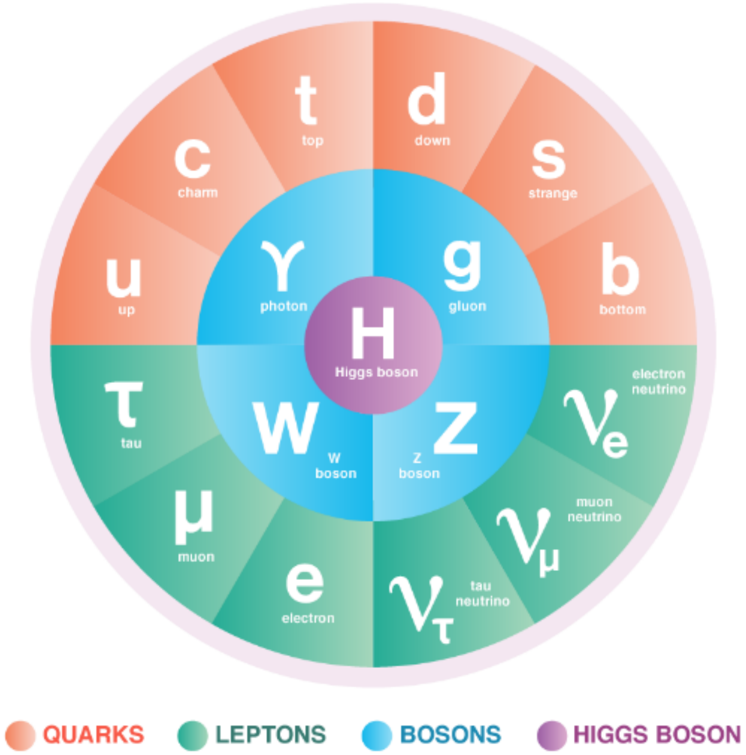


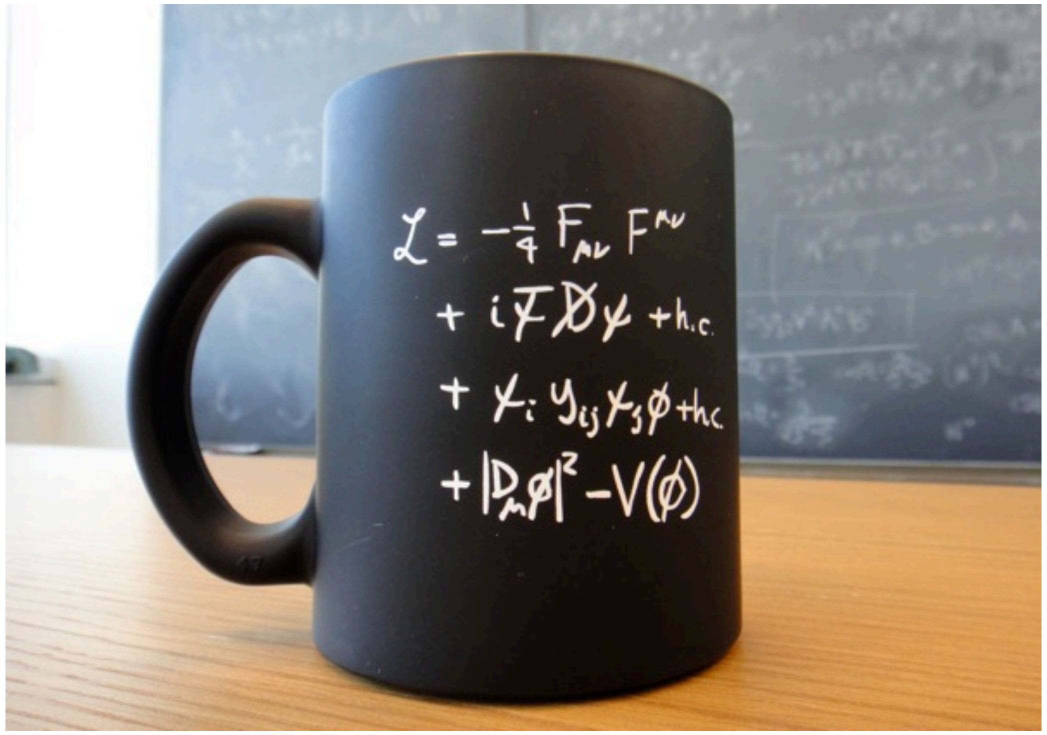
Microcausality Principle and QFT

Incorporates and **supersedes** both QM and SR

The BIG achievements of Particle Physics

We worked out **one single theory** that accounts for (almost) **all phenomena** that ever or will ever occur in the Universe!!





This monumental achievement of mankind is:

The Standard Model

It would definitely deserve a better name

The BIG achievements of Particle Physics

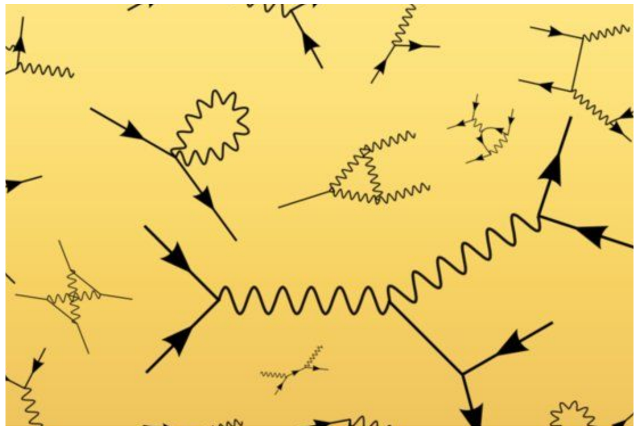
We worked out **one single theory** that accounts for (almost) **all phenomena** that ever or will ever occur in the Universe!!

This theory is close to accomplish the Particle Physics dream.

But we are not yet there

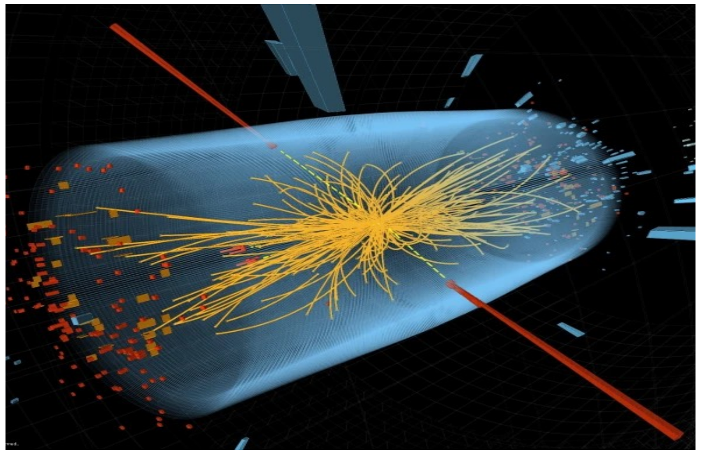
The Standard Model is not enough

Built by a **practical implementation** of QFT principles
Surely not the final one, as it **fails with Gravity**
A new theory breakthrough is waiting for us



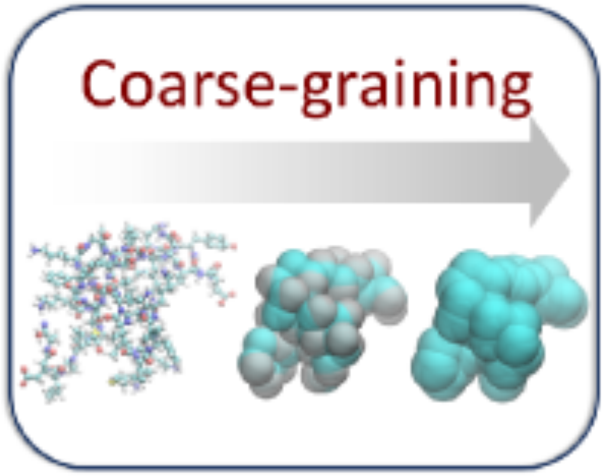
Its particle/field content is merely **dictated by experiments**
New experiments are needed to tell if there are more particles
And we believe there are: for instance dark matter

Creating heavy particle requires energy: $E = m\,c^2$



“Practical QFT” does not explain why only some type of interactions are observed.
The **Wilsonian explanation** is **disproven** if the Higgs boson is a **fundamental particle** as in the SM:

We must check if it truly is fundamental



We need energy

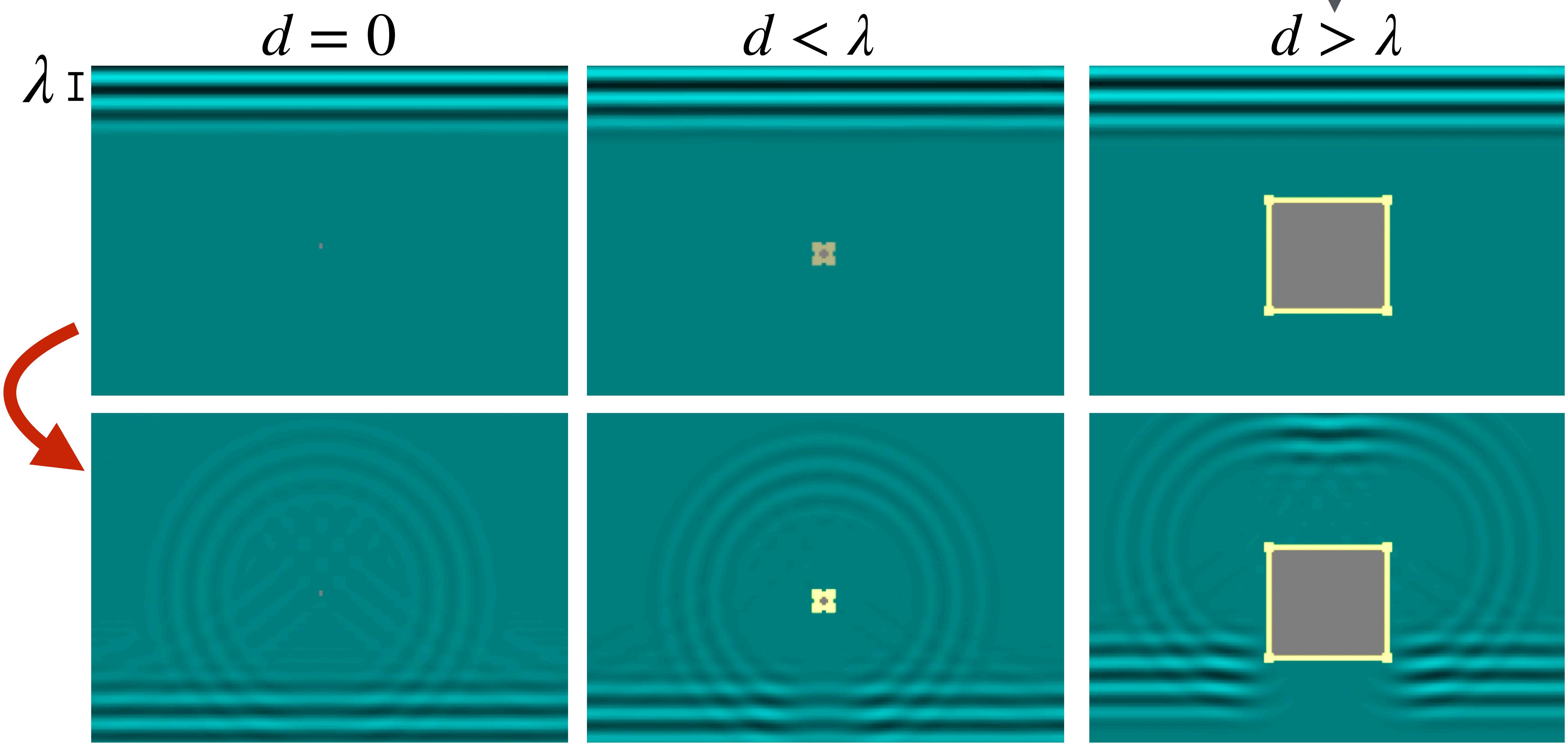
What's **inside?**

We need large energy in order to probe short distances:

$d =$ the length scale we want to resolve

$\lambda = 1/E =$ the wavelength of the wave we use

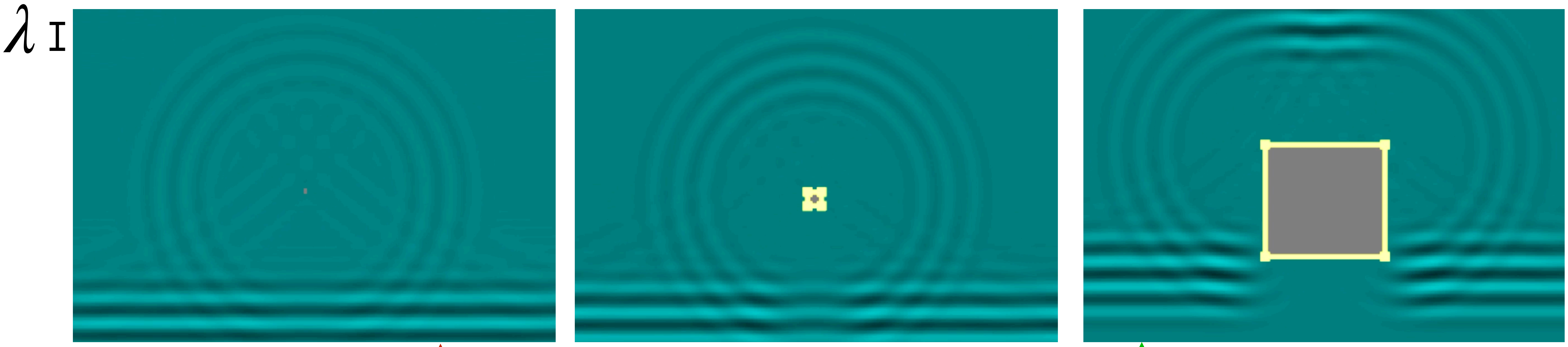
Detecting "d" requires: $\lambda < d$



We need **precision** as well

If you look **precisely** enough, **this** is different from **that**

$d = 0$ $d < \lambda$ $d > \lambda$



If instead you are **blind**, **this** will be the same as **that**

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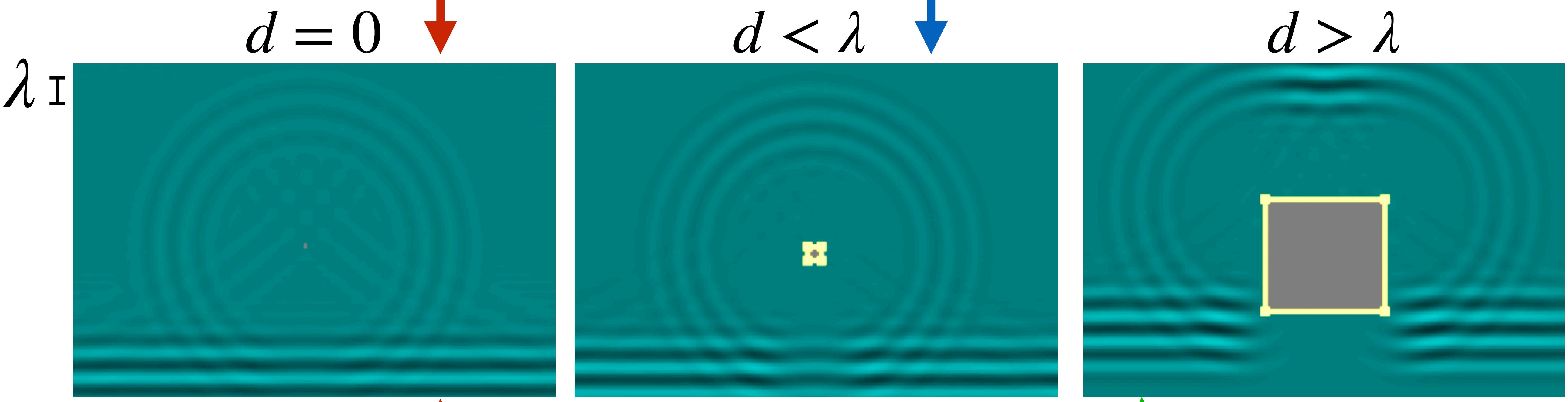

If instead you are **blind**, **this** will be the same as **that**

We can build a $\lambda \sim 1/(100\,\mathrm{GeV})$ **very precise** e^+e^- “microscope”

This is the first reason for doing that

Precision for precision's sake?

Two answers:

Precision for precision's sake?

Two answers:

#1: Why Not?

Precision for precision's sake?

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Hubble Telescope

James Webb Telescope

Precision for precision’s sake?

Two answers:

#1: Why Not?

The **Science** that goes in getting precise measurements and precise SM predictions **is a physics driver**.

Precision for precision's sake?

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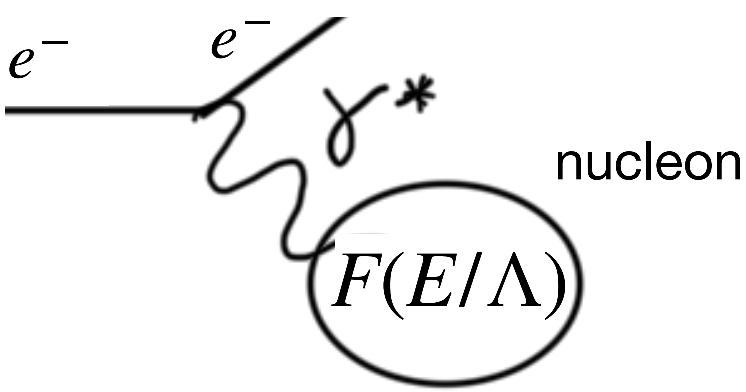
#2: Discovery Opportunities

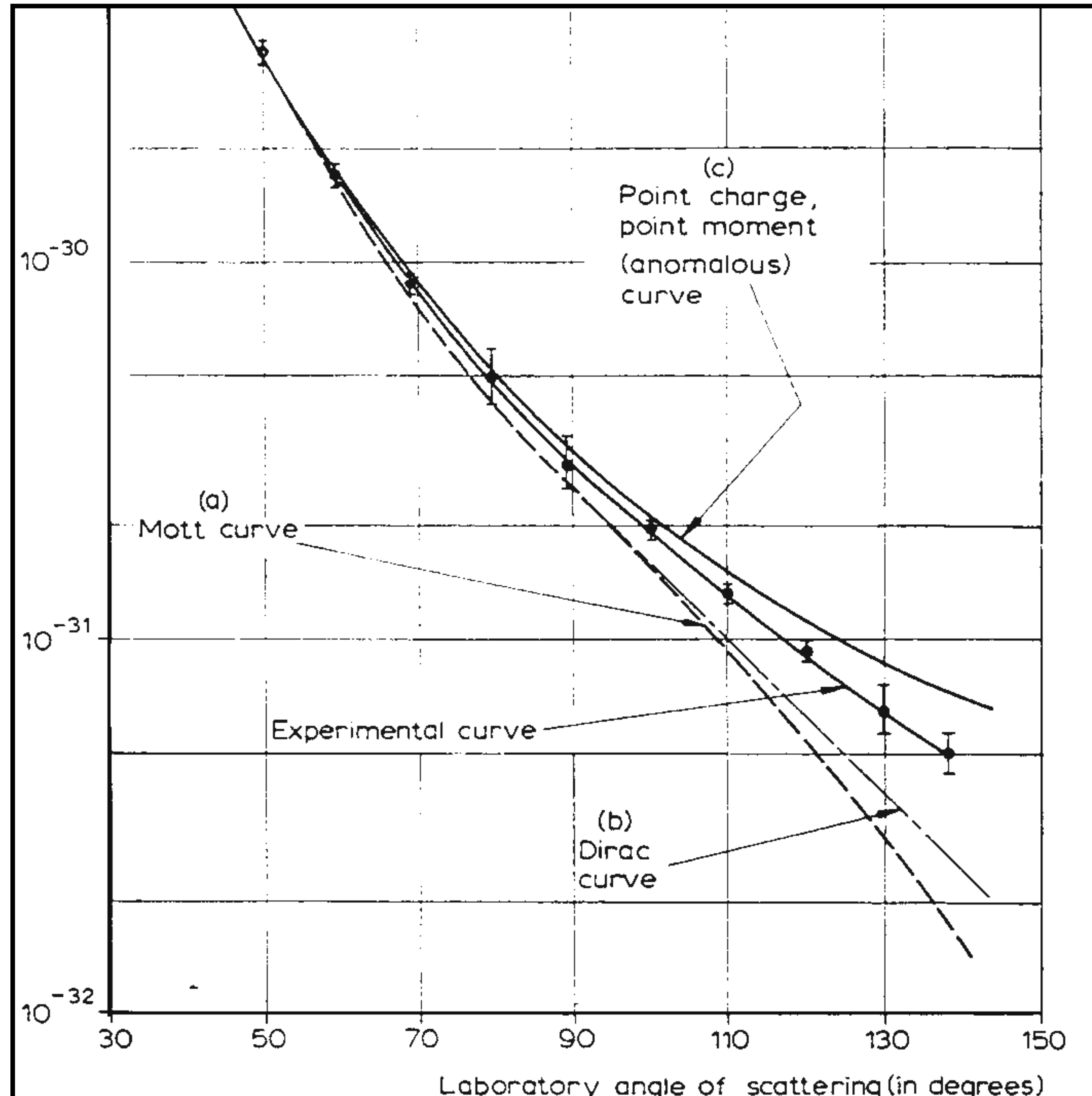
Many past breakthroughs from precision.

Precision for precision's sake?

Example: nucleon compositeness

- ⟶ Truly revolutionary, not anticipated
- ⟶ Comparing precise measurements with "SM" point-like nucleon predictions
- ⟶ Fully **conclusive** and **direct** proof of finite nucleon radius





Precision for precision's sake?

Two answers:

#1: Why Not?

The **Science** that goes in getting precise measurements
and precise SM predictions **is a physics driver**.

#2: Discovery Opportunities

Many past breakthroughs from precision.
Many **future** opportunities.

The Higgs physics case

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The Higgs is revolutionary!

One more direct experimental confirmation of the Practical QFT implementation of QFT principles (and indirectly of the principles).

The **first manifestation of** a new class of theories: **massive gauge theories**

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Higgs is not a superconductor
There is no Higgs “medium”

Spin-one relativistic particles and their high-energy description are as unique of hep as it sounds

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A special m.g.t.: perturbatively **extends to high, untested, energies**

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A special m.g.t.: perturbatively **extends to high, untested, energies**

Testing new SM predictions is a prime target

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Could be the first **elementary scalar**.
Disproves Wilsonian explanation of QFT emergent as EFT.

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We must check!!

Higgs physics opportunities

BSM coupled to Higgs

⟶ Extended H sector is **possible** in general, **expected** in CH, **needed** in SUSY
⟶ New Higgses could be DM, could make EWPT be first order
⟶ **Generic** expectation is modified Higgs couplings:

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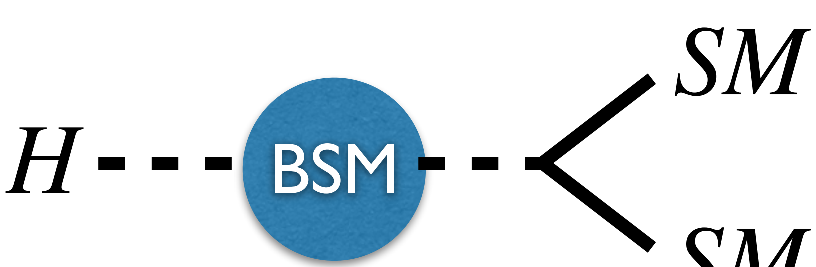


BSM with order-one tree-level coupling

$$\frac{\delta g_H}{g_H^{SM}} \sim \frac{m_H^2}{m_{BSM}^2} = 0.1\% \cdot \left(\frac{3\,\text{TeV}}{m_{BSM}}\right)^2$$

HL-LHC cannot probe this physics, not even at 1 TeV

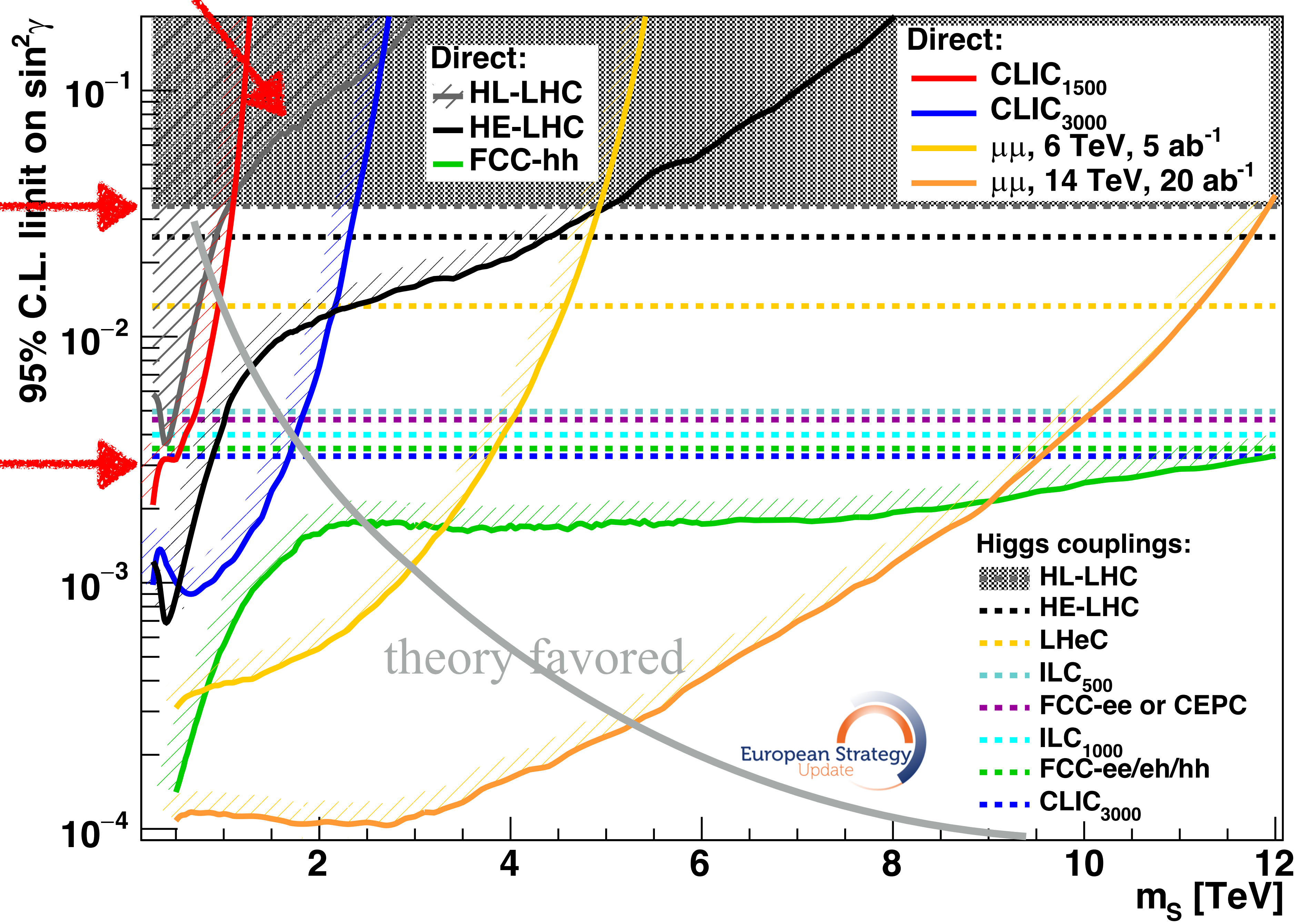
Higgs physics opportunities

resonance search @HL-LHC

H couplings @HL-LHC
Percent level

H couplings @X-Factory
Per mille level

Higgs Singlet Benchmark
[from 2020 ESPPU PBB]



Higgs physics opportunities

Composite Nambu-Goldstone Higgs

$\longrightarrow$ A structured framework where H is pNGB of new strong sector

$\longrightarrow$ **Explains** why H is light. **Accounts** for SM-like H provided ξ is small:

Electroweak symmetry breaking scale $\longrightarrow v^2$

Goldstone symmetry breaking scale $\longrightarrow f^2$

$$\frac{v^2}{f^2} = \xi \ll 1$$

$\longrightarrow$ Modified Higgs couplings:

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$$\frac{\delta g_H}{g_H^{SM}} \sim \xi$$

$\xi \sim 10^{-1}, 10^{-2}$ could be coincidence: Wilson ✅

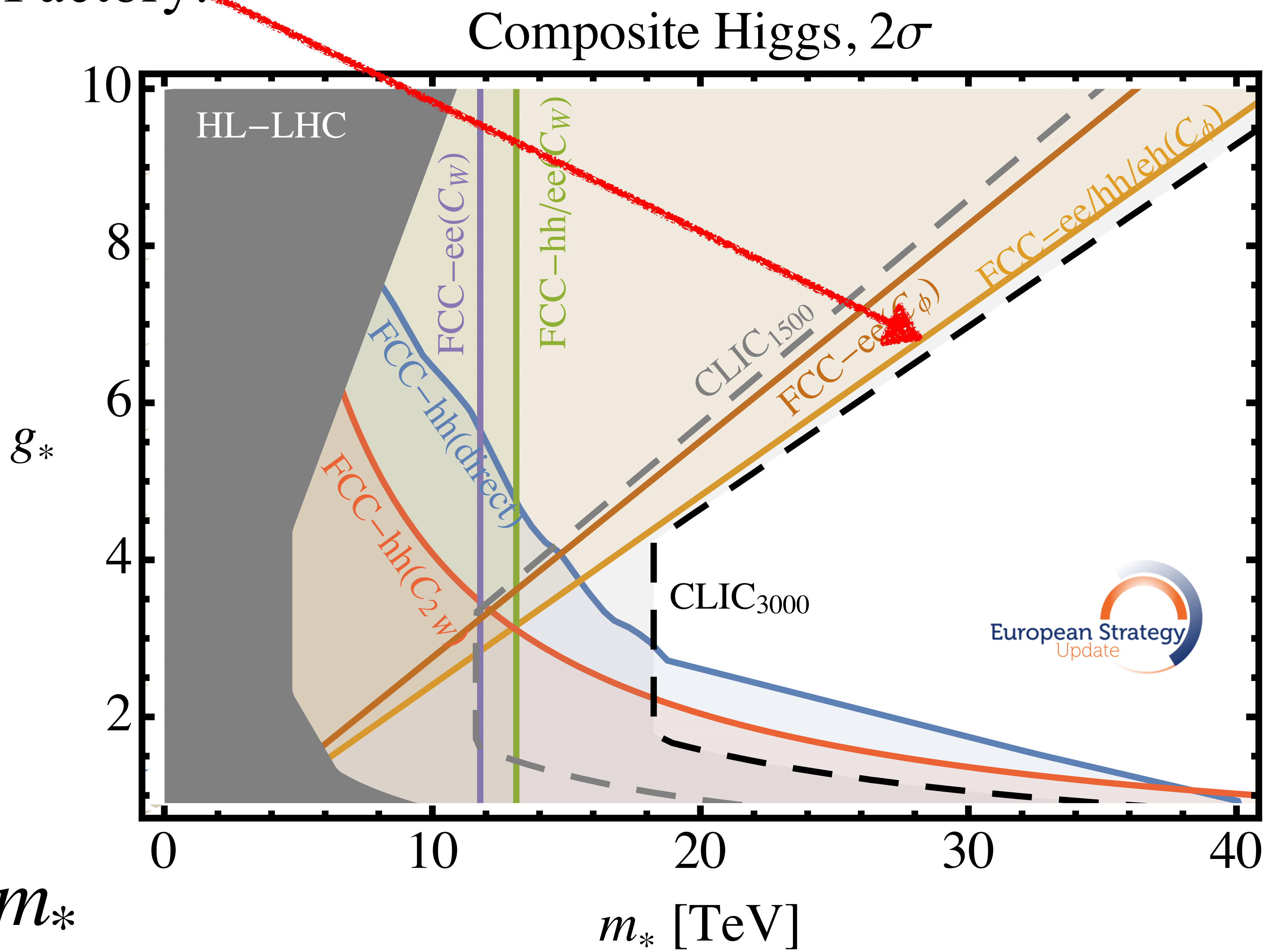
Smaller ξ is hard to believe: Wilson ❌

Higgs physics opportunities

H couplings @X-Factory:

$$\xi \sim 10^{-3}$$

$$g_* = \frac{m_*}{f}$$



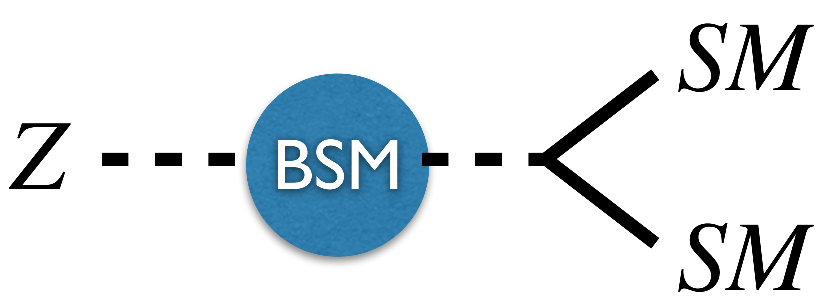
$$r_H = 1/m_*$$

EW physics opportunities

10^{12} Z bosons enable, statistically, 10^{-6} precision on couplings

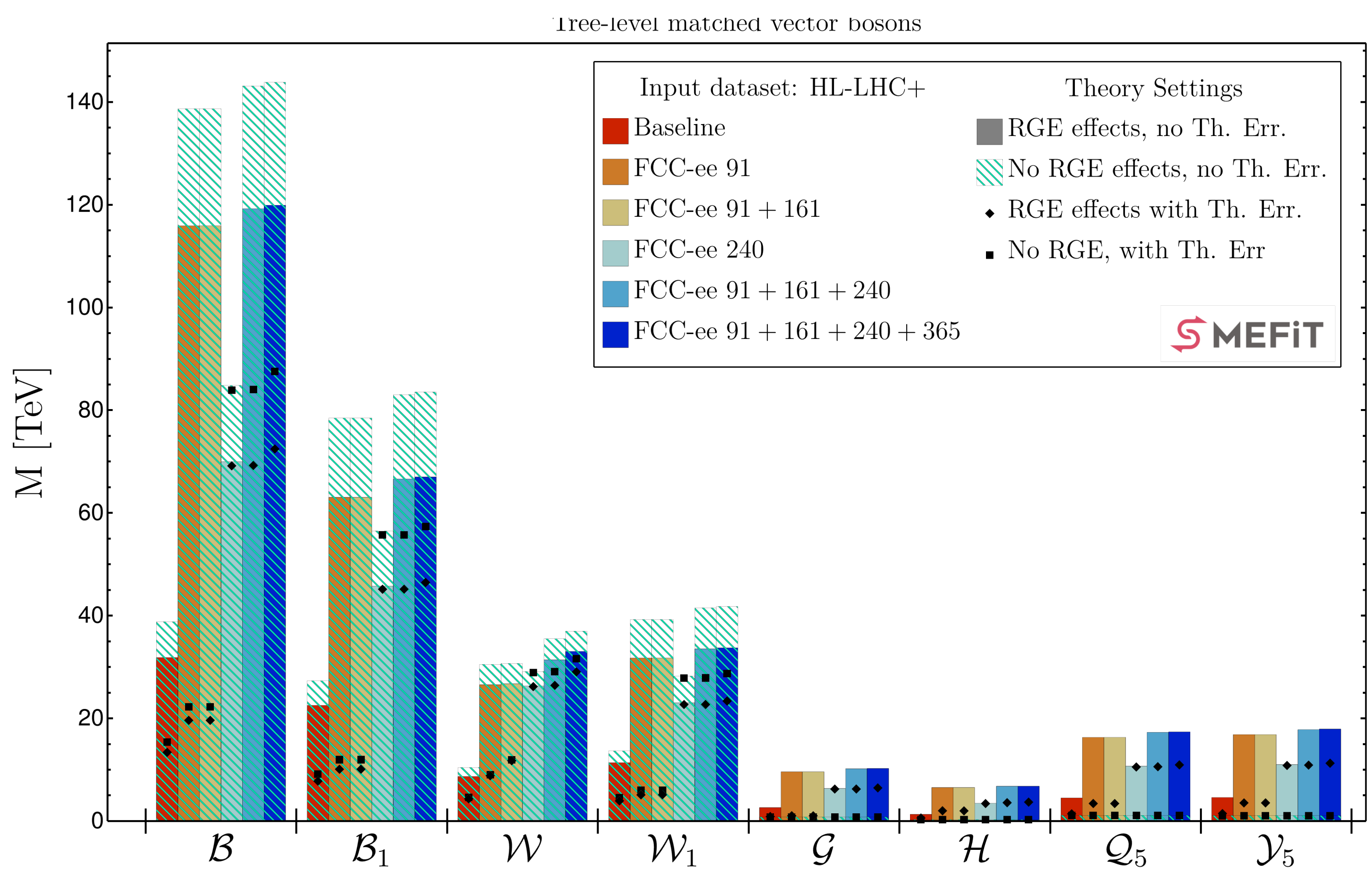
$\rightarrow$ Unlikely to get to 10^{-6}, but current is 10^{-3}: we will surely improve

$\rightarrow$ **Experimental** and **Theoretical** accuracy will be limiting factor.
Great challenge is great opportunity!



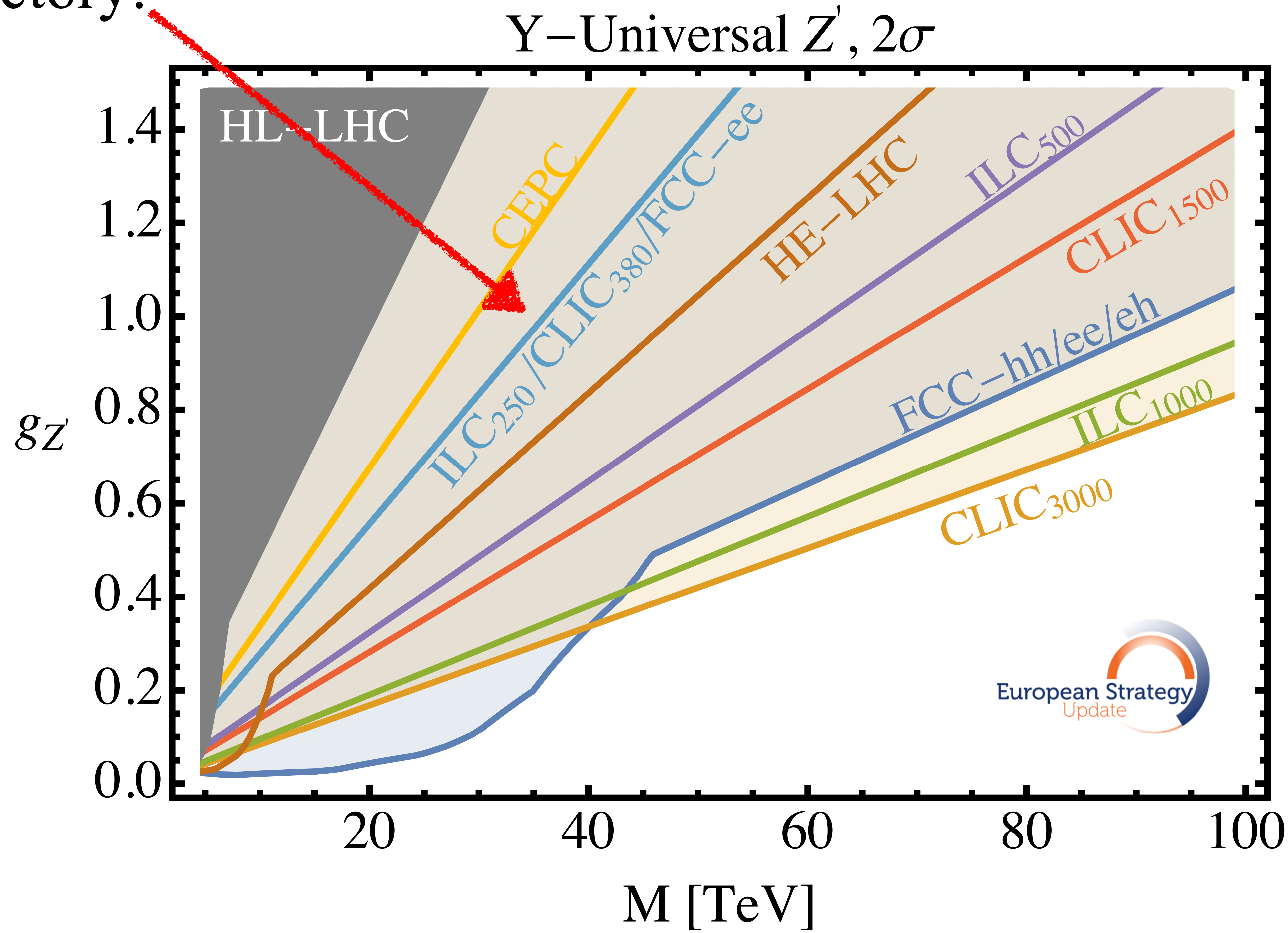
BSM with order-one tree-level coupling

$$\frac{\delta g_Z}{g_Z^{SM}} \sim \frac{m_Z^2}{m_{BSM}^2} = 10^{-6} \cdot \left(\frac{100\ \text{TeV}}{m_{BSM}}\right)^2$$



EW physics opportunities

EW @X-Factory:



EW physics opportunities

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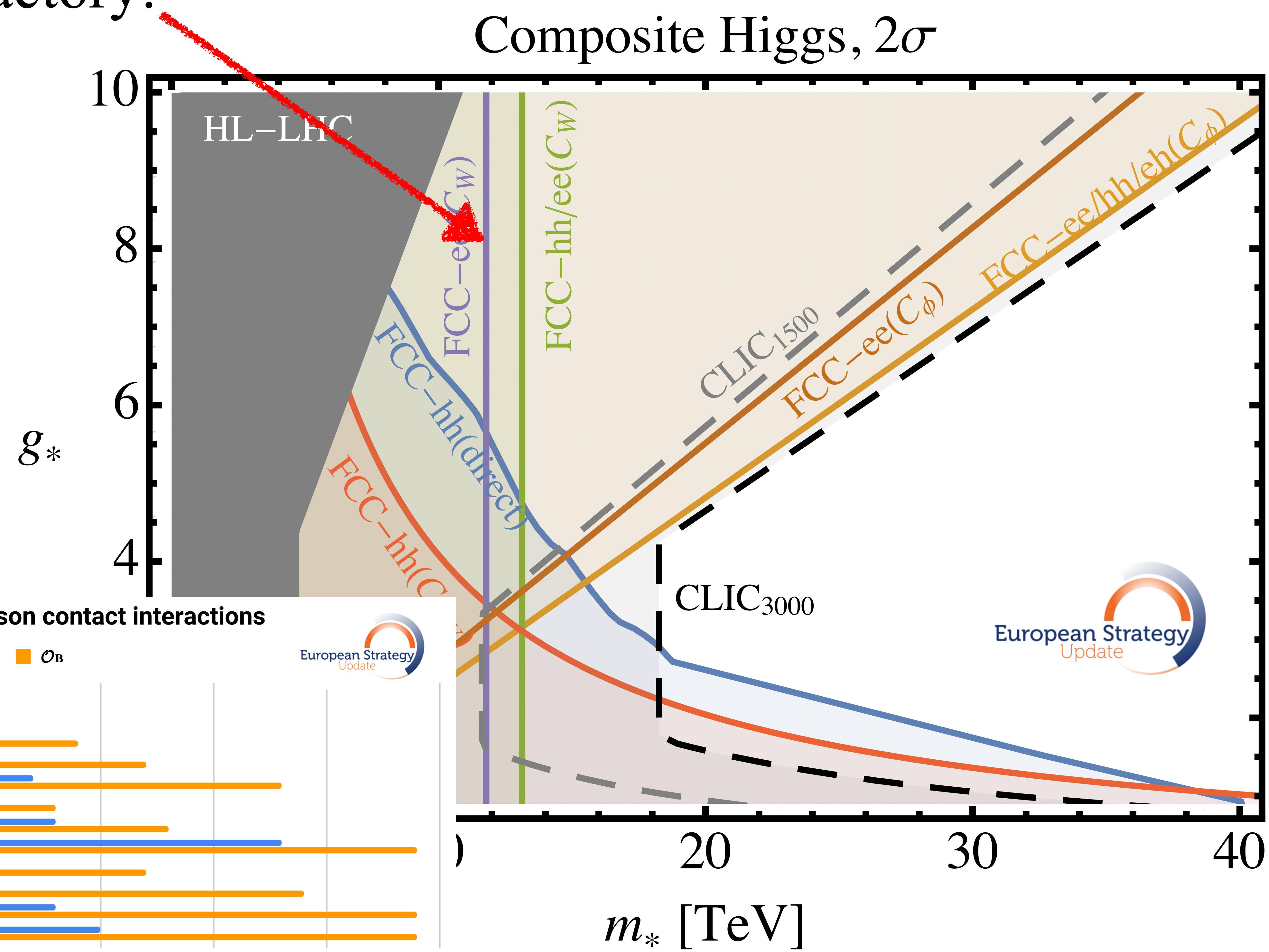
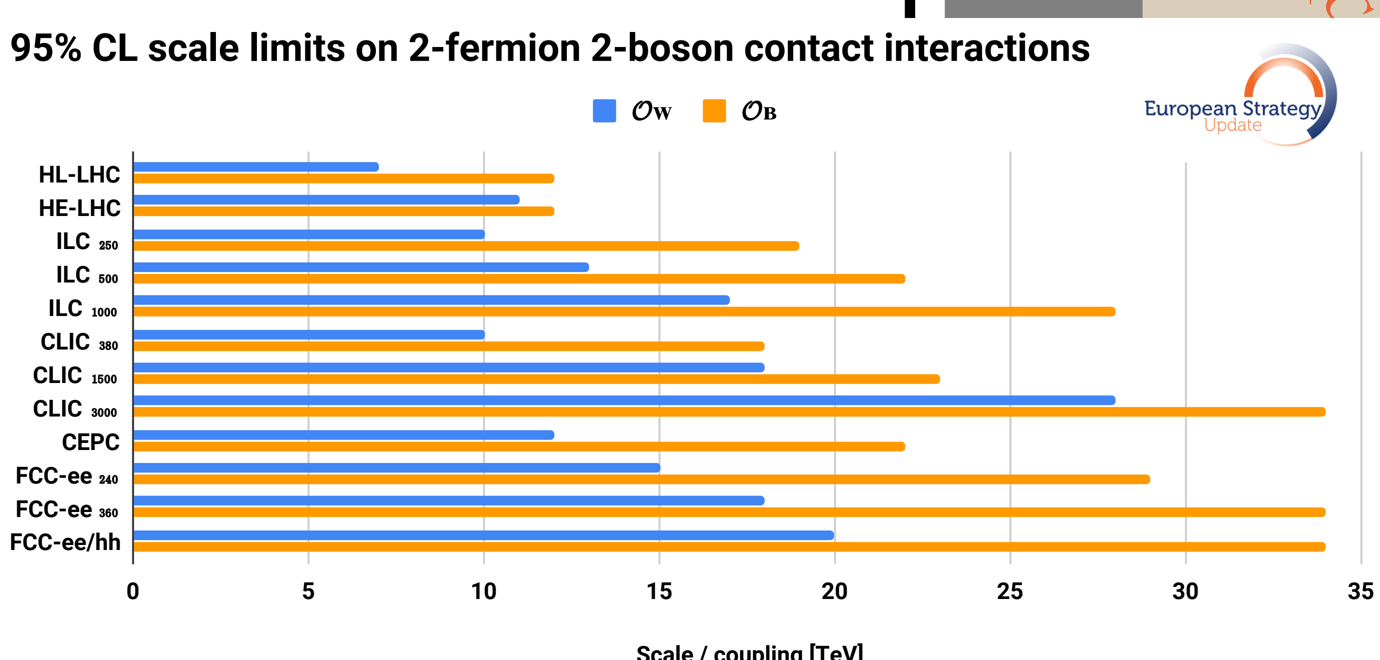
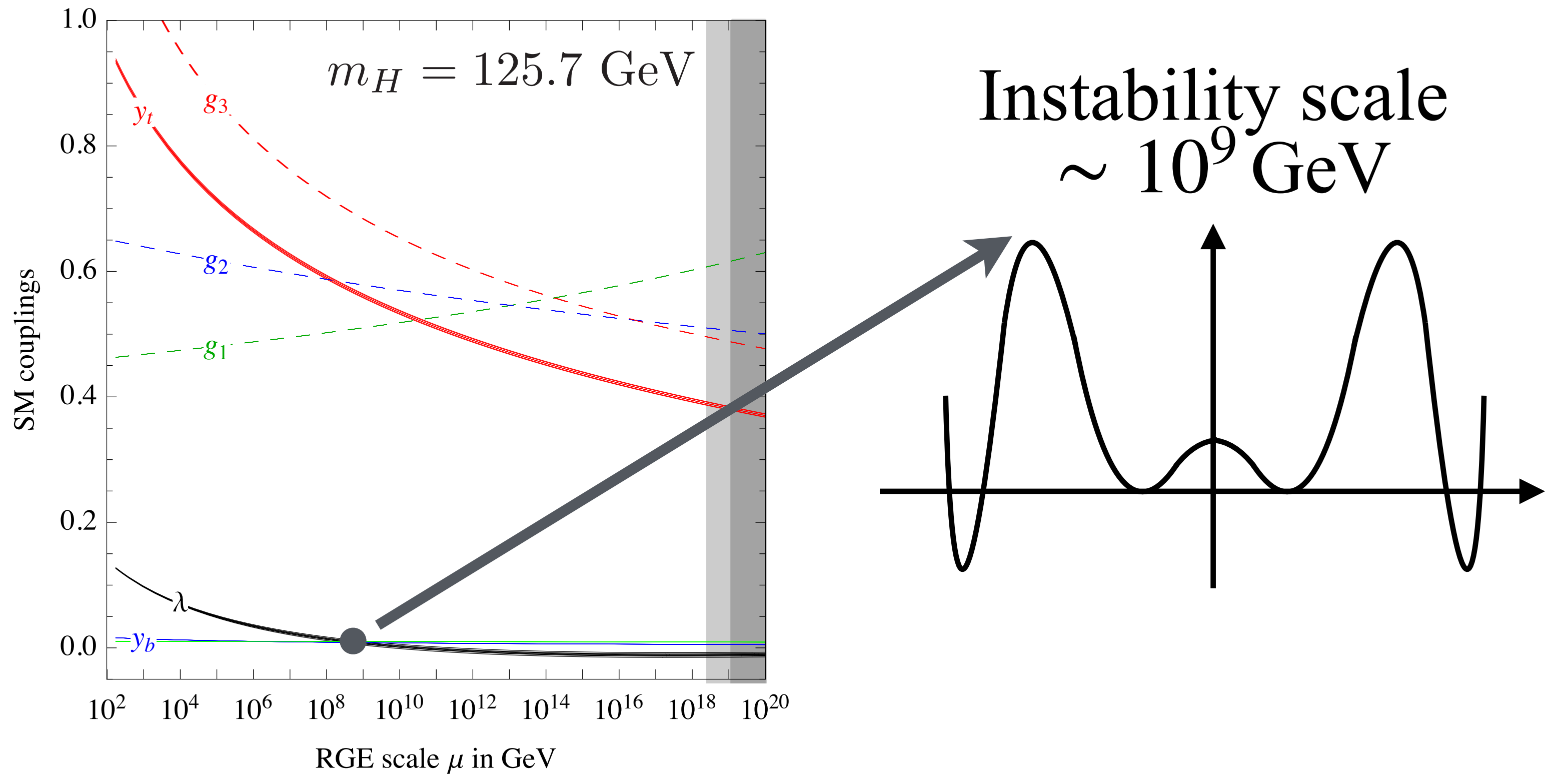
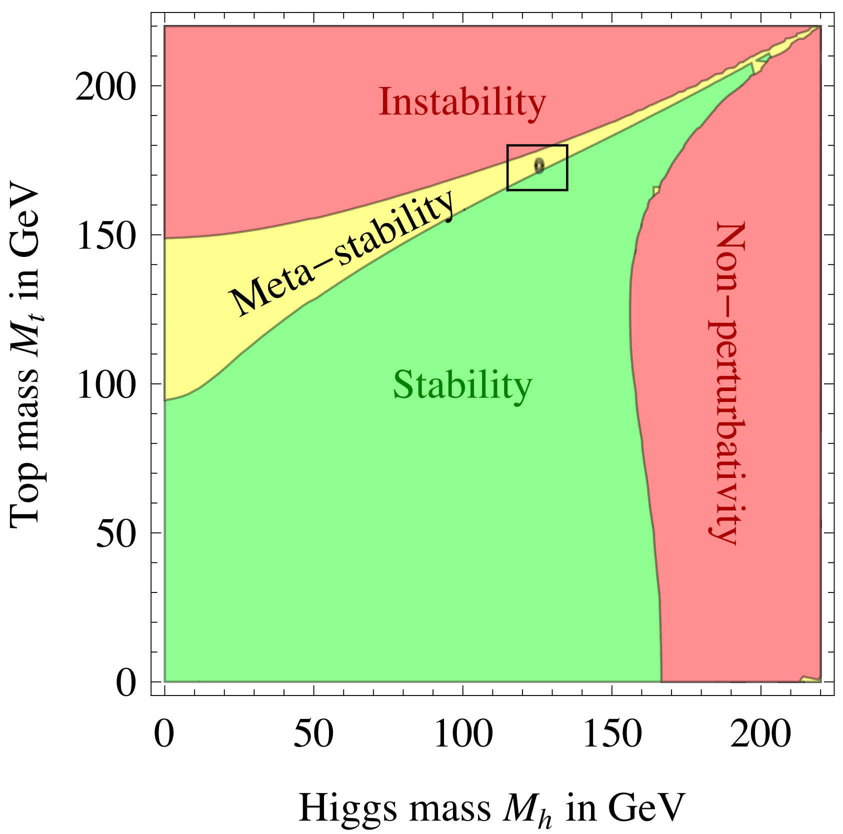




Top threshold

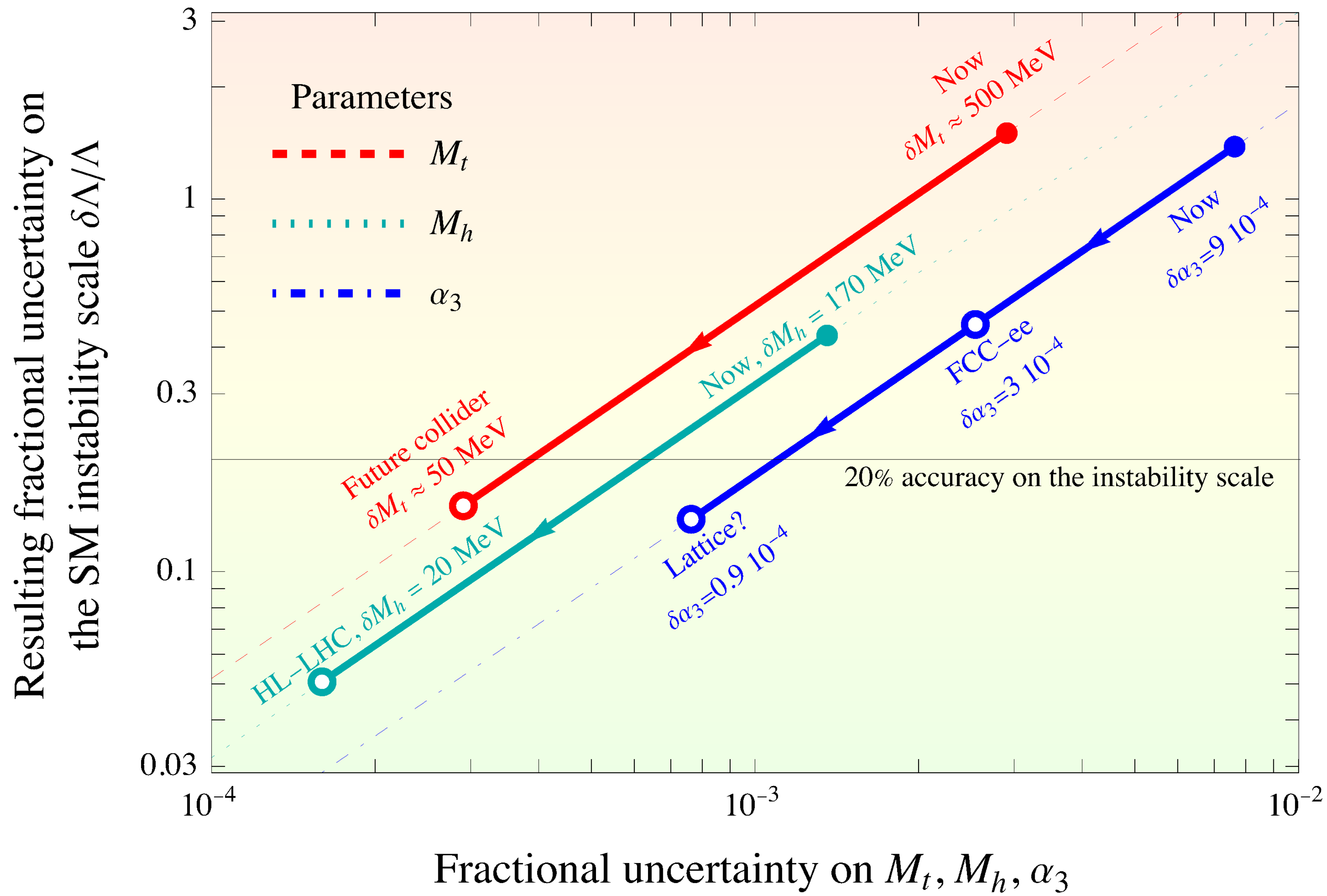
The SM Higgs potential seems to have a second minimum





To be sure that this really happens, and to measure the scale, we need more precision in α_S, m_H and m_t.

Top threshold



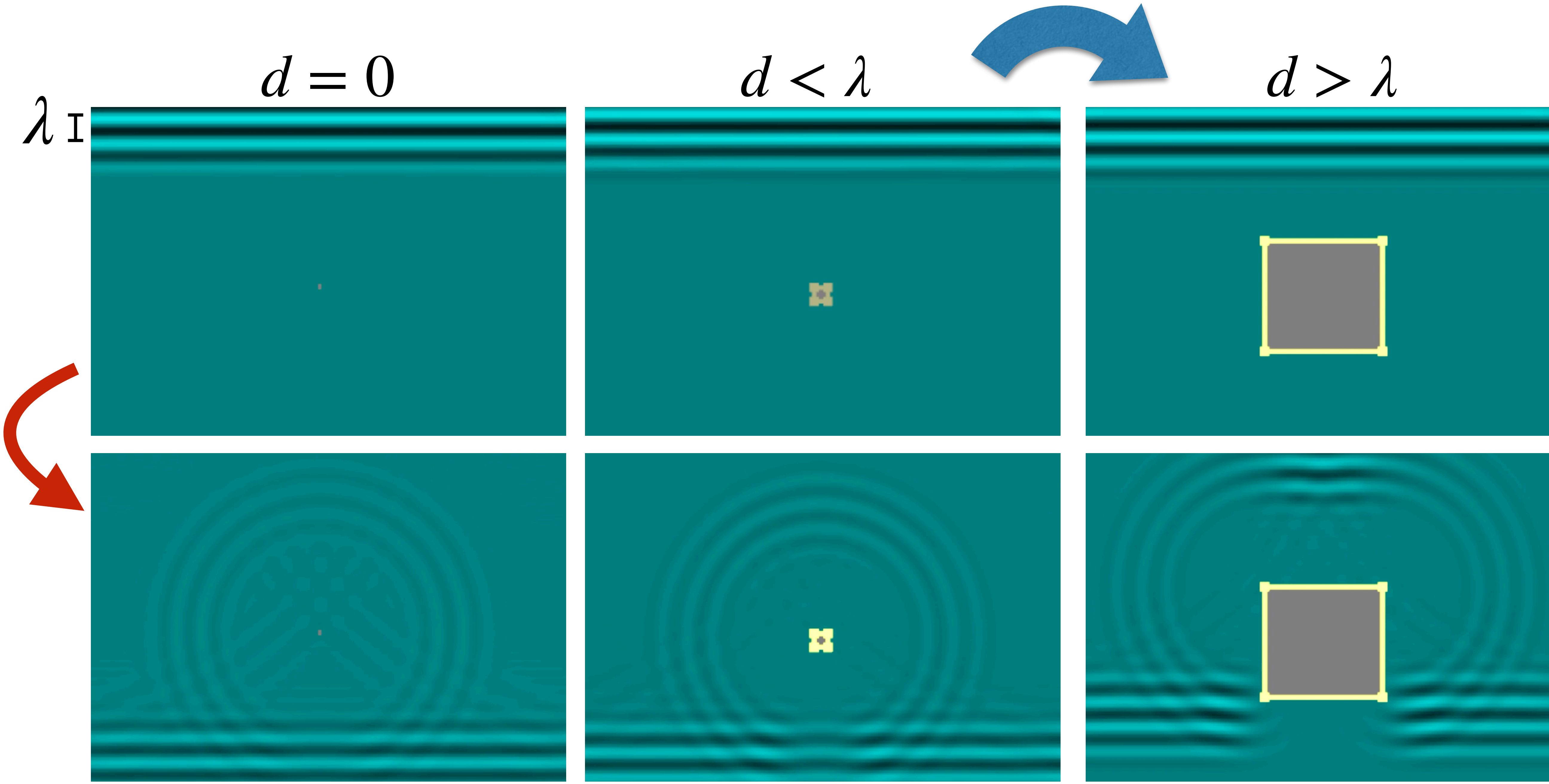
To be sure that this really happens, and to measure the scale, we need more precision in α_S, m_H and m_t.

Precise enough top mass requires **top threshold scan**

Beyond X-Factories

We need more Energy!

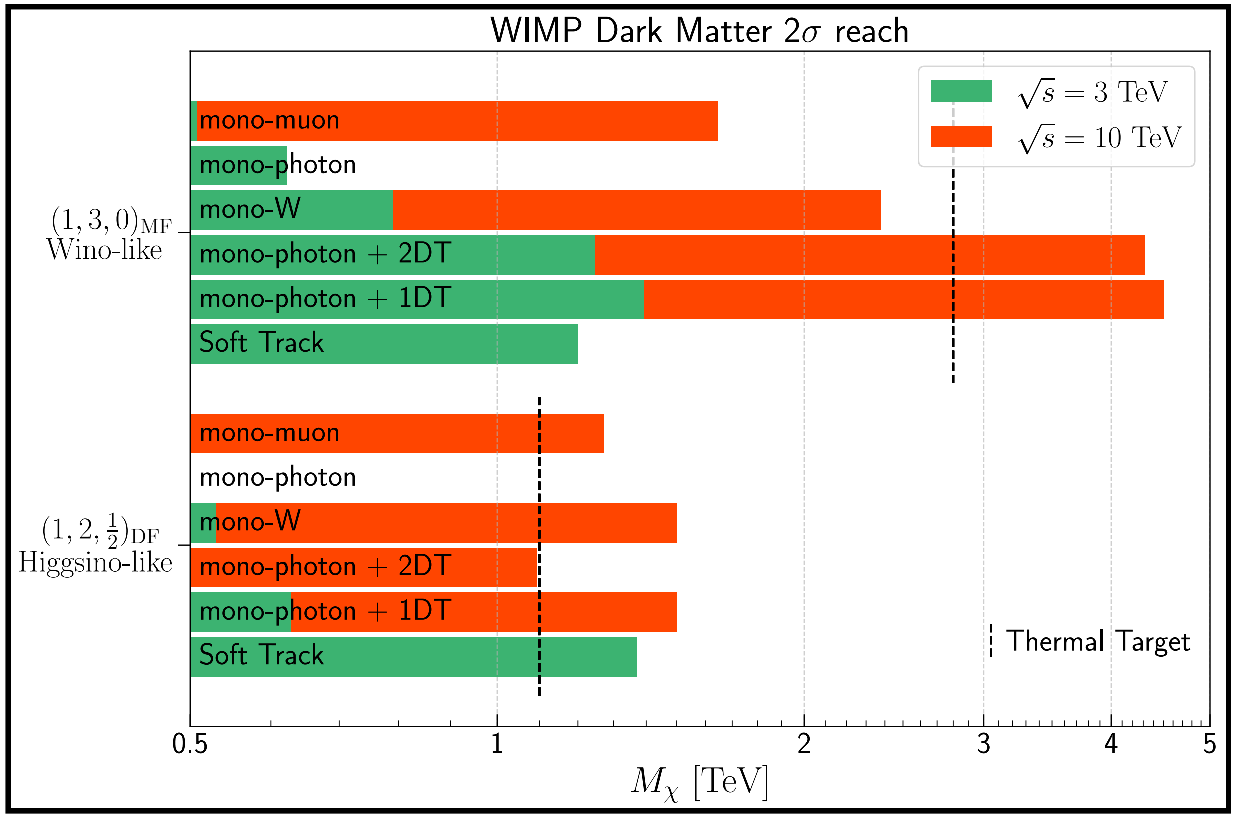
A 10 TeV pCM collider

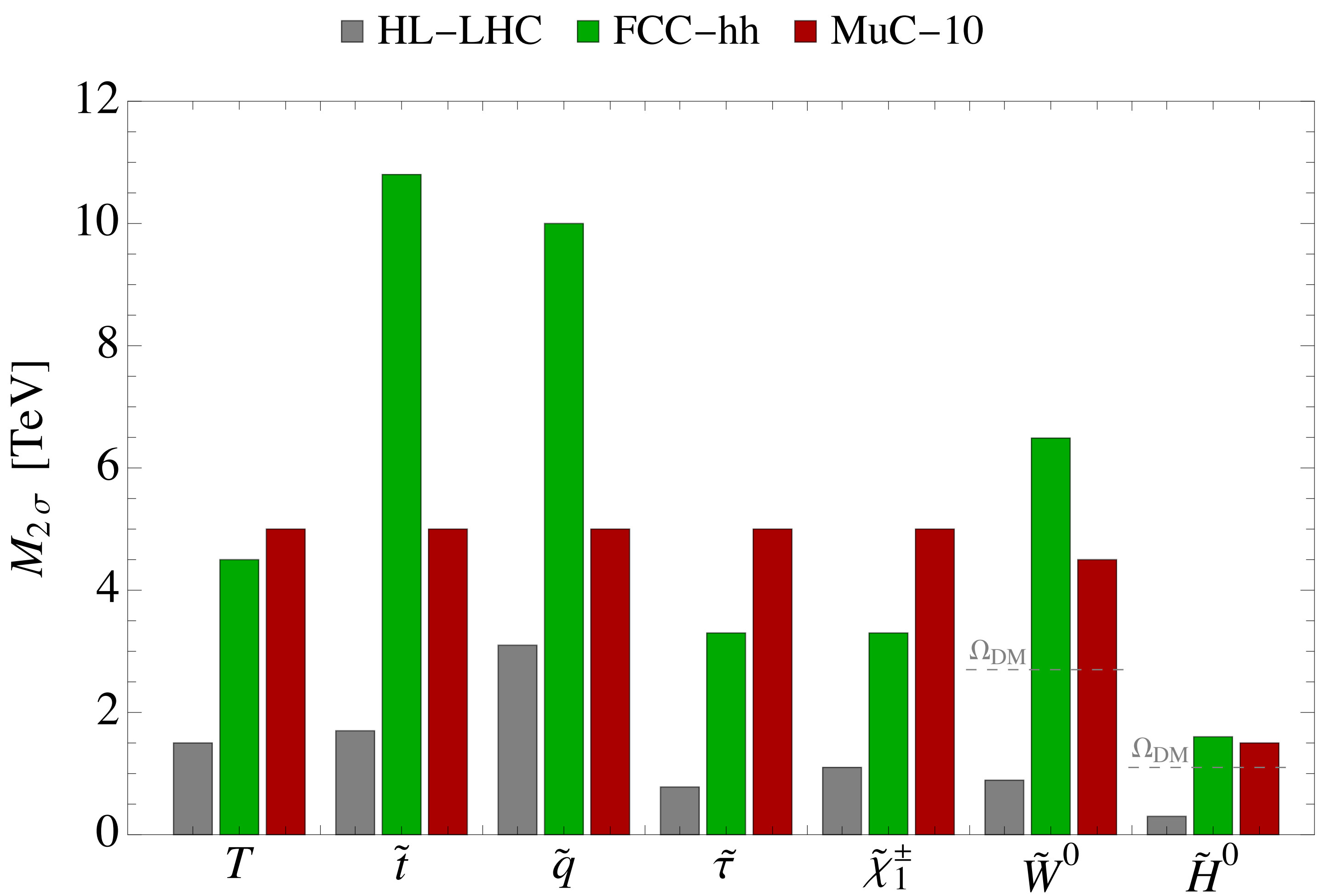


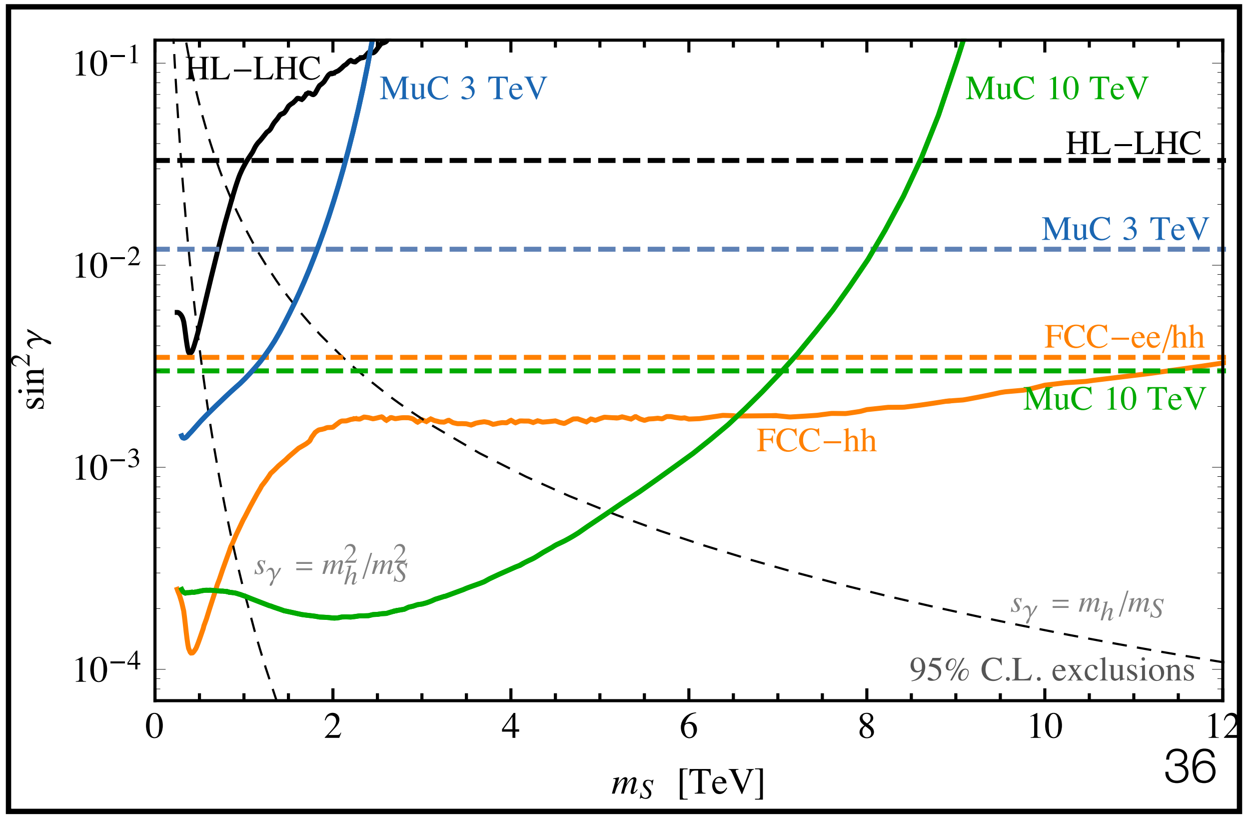
Search for heavy particles

Needs:

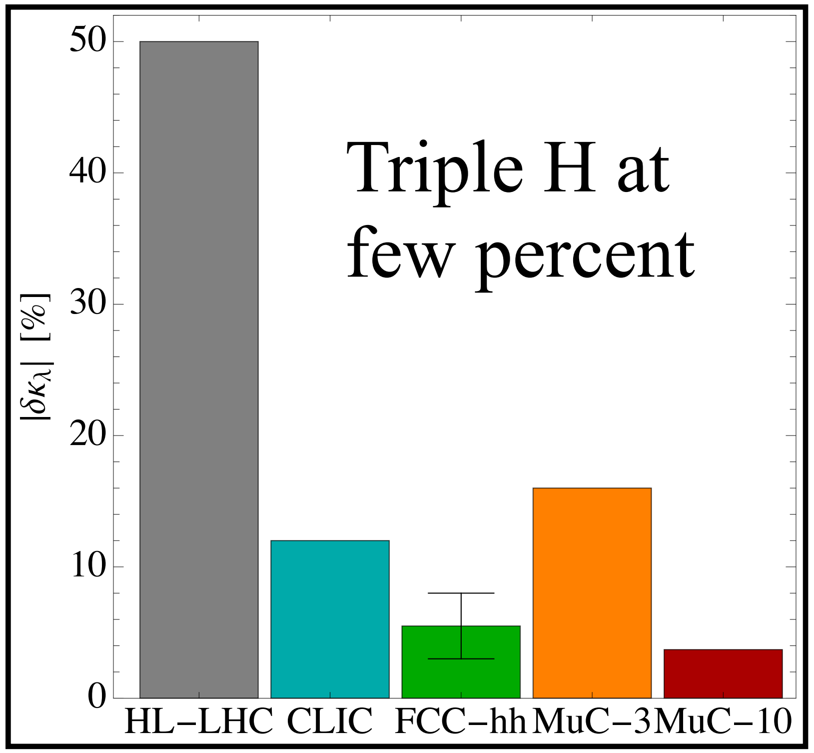
- Broad coverage of > 1 TeV masses.
- Specific targets like WIMP.
- React to SM tensions @X-Factory.

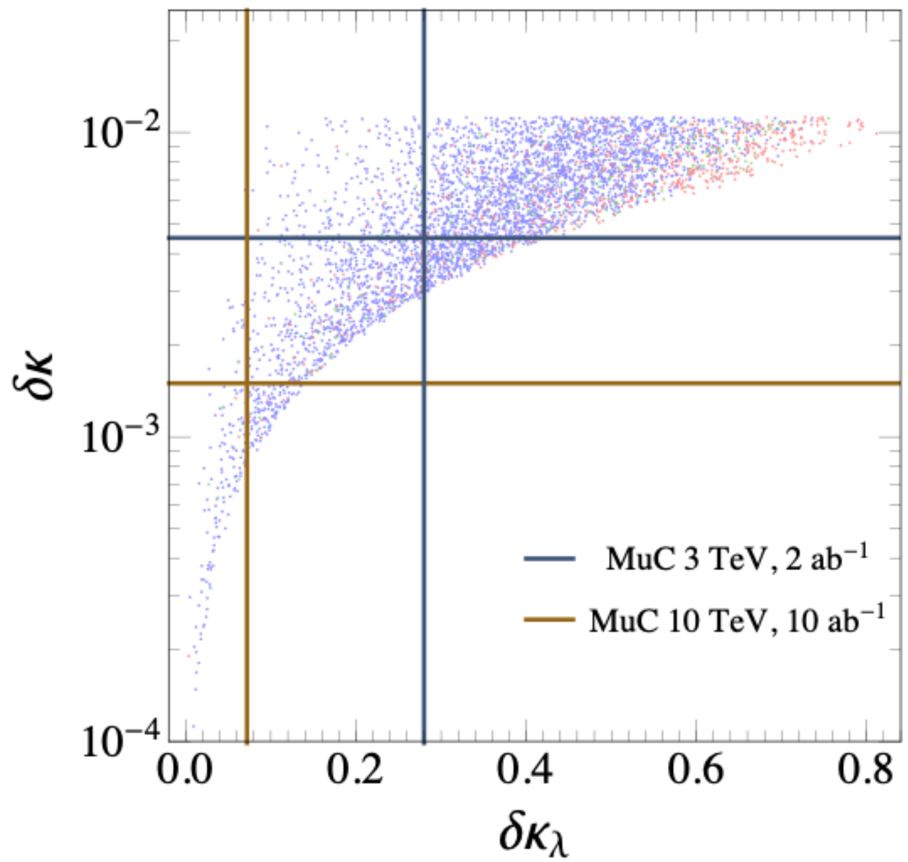






Complete the Higgs measurement program





MuC complementary on 1-H

	HL-LHC	HL-LHC +10 TeV	HL-LHC +10 TeV + ee
κ_W	1.7	0.1	0.1
κ_Z	1.5	0.2	0.1
κ_g	2.3	0.5	0.5
κ_γ	1.9	0.7	0.7
$\kappa_{Z\gamma}$	10	5.2	3.9
κ_c	-	1.9	0.9
κ_b	3.6	0.4	0.4
κ_μ	4.6	2.4	2.2
κ_τ	1.9	0.5	0.3

FCC-hh for rare H decays

observable	**param**	**stat.**	**stat. + syst.**
$\mu = \sigma(\mathrm{H}) \times \mathcal{B}(\mathrm{H} \to \gamma\gamma)$	$\delta\mu$	0.1%	1.4%
$\mu = \sigma(\mathrm{H}) \times \mathcal{B}(\mathrm{H} \to \mu\mu)$	$\delta\mu$	0.4%	1.2%
$\mu = \sigma(\mathrm{H}) \times \mathcal{B}(\mathrm{H} \to \ell\ell\ell\ell)$	$\delta\mu$	0.2%	1.8%
$\mu = \sigma(\mathrm{H}) \times \mathcal{B}(\mathrm{H} \to \gamma\ell\ell)$	$\delta\mu$	1.1%	1.7%
$\mu = \sigma(\mathrm{ttH})\, \mathcal{B}(\mathrm{H} \to \gamma\gamma)$	$\delta\mu$	0.4%	2.2%
$\mathrm{R} = \mathcal{B}(\mathrm{H} \to \mu\mu)/\mathcal{B}(\mathrm{H} \to \mu\mu\mu\mu)$	$\delta\mathrm{R}/\mathrm{R}$	0.5%	1.3%
$\mathrm{R} = \mathcal{B}(\mathrm{H} \to \gamma\gamma)/\mathcal{B}(\mathrm{H} \to \mathrm{ee}\mu\mu)$	$\delta\mathrm{R}/\mathrm{R}$	0.5%	0.8%
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$\mathrm{R} = \mathcal{B}(\mathrm{H} \to \mu\mu\gamma)/\mathcal{B}(\mathrm{H} \to \mu\mu\mu\mu)$	$\delta\mathrm{R}/\mathrm{R}$	1.6%	2.0%
$\mathrm{R} = \sigma(\mathrm{ttH})\, \mathcal{B}(\mathrm{H} \to \mathrm{b\bar{b}})/\sigma(\mathrm{ttZ})\, \mathcal{B}(\mathrm{Z} \to \mathrm{b\bar{b}})$	$\delta\mathrm{R}/\mathrm{R}$	1.2%	2.0%
$\mathrm{R} = \sigma(\mathrm{VBF-H}))\, \mathcal{B}(\mathrm{H} \to \mathrm{e}\mu\nu\nu)/\sigma(\mathrm{VBS-WW}))\, \mathcal{B}(\mathrm{WW} \to \mathrm{e}\mu\nu\nu)$	$\delta\mathrm{R}/\mathrm{R}$	1.9%	2.0%
$\mathcal{B}(\mathrm{H} \to \mathrm{invisible})$	$\mathcal{B}$@95%CL	1.2×10^{-4}	2.6×10^{-4}
$\sigma(\mathrm{HH})$	$\delta\kappa_\lambda$	3.5%	5.2%

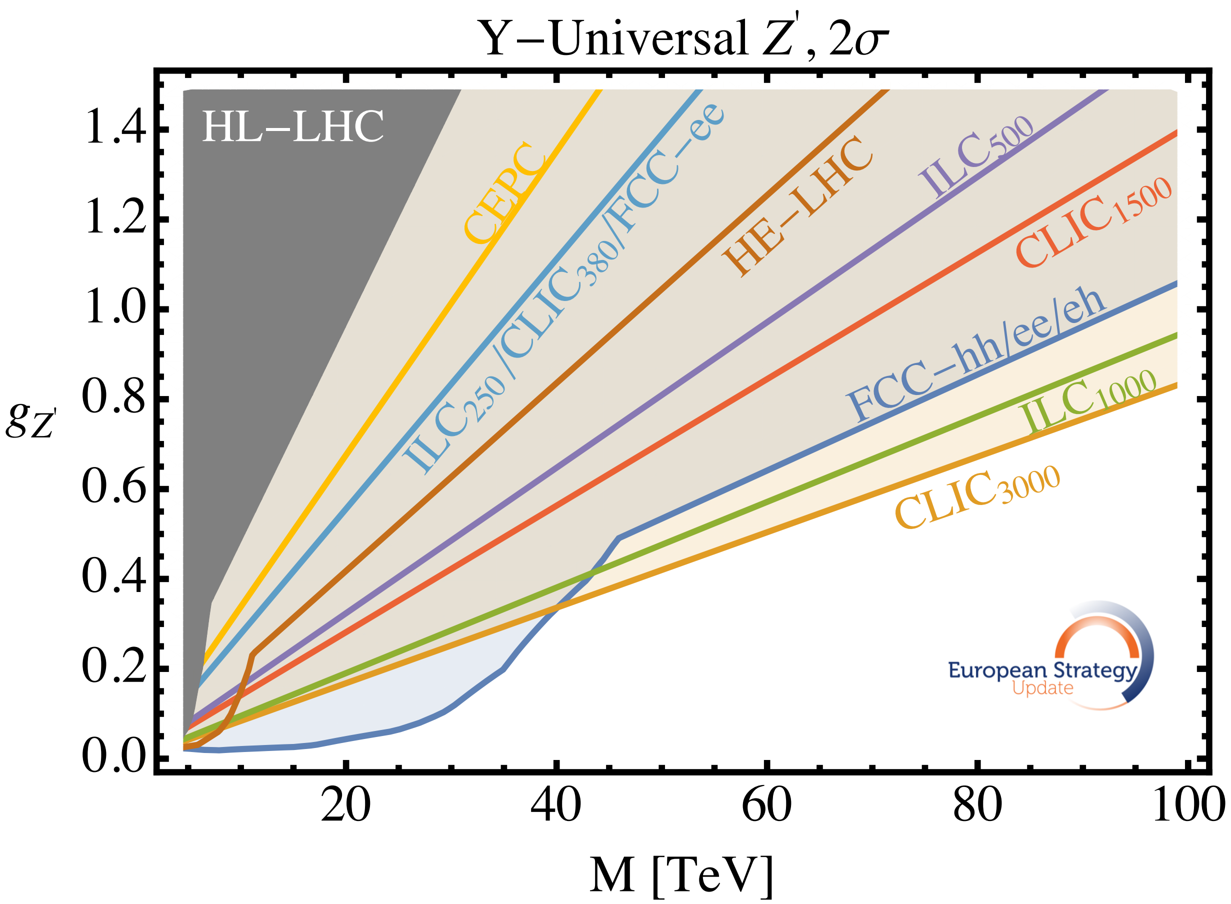
Precision from energy

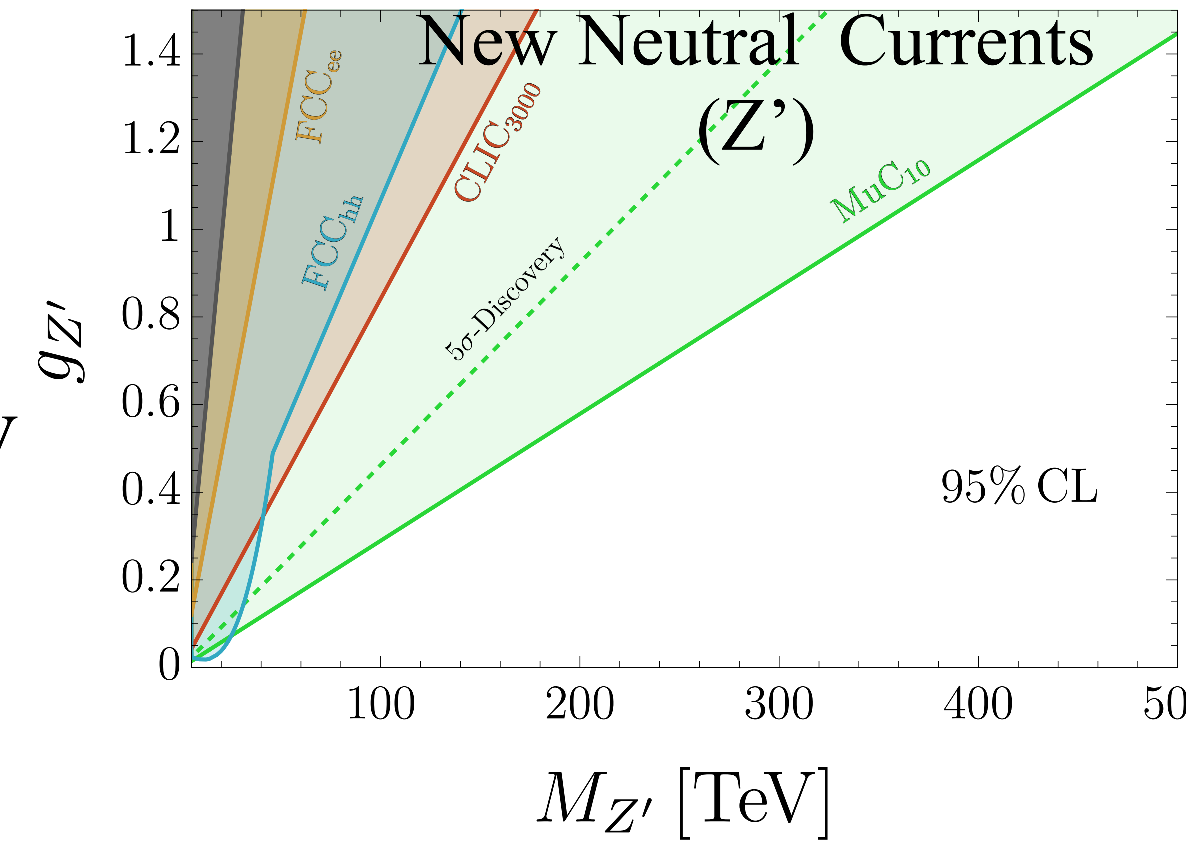
Higher-energy observables are more sensitive to heavy physics:

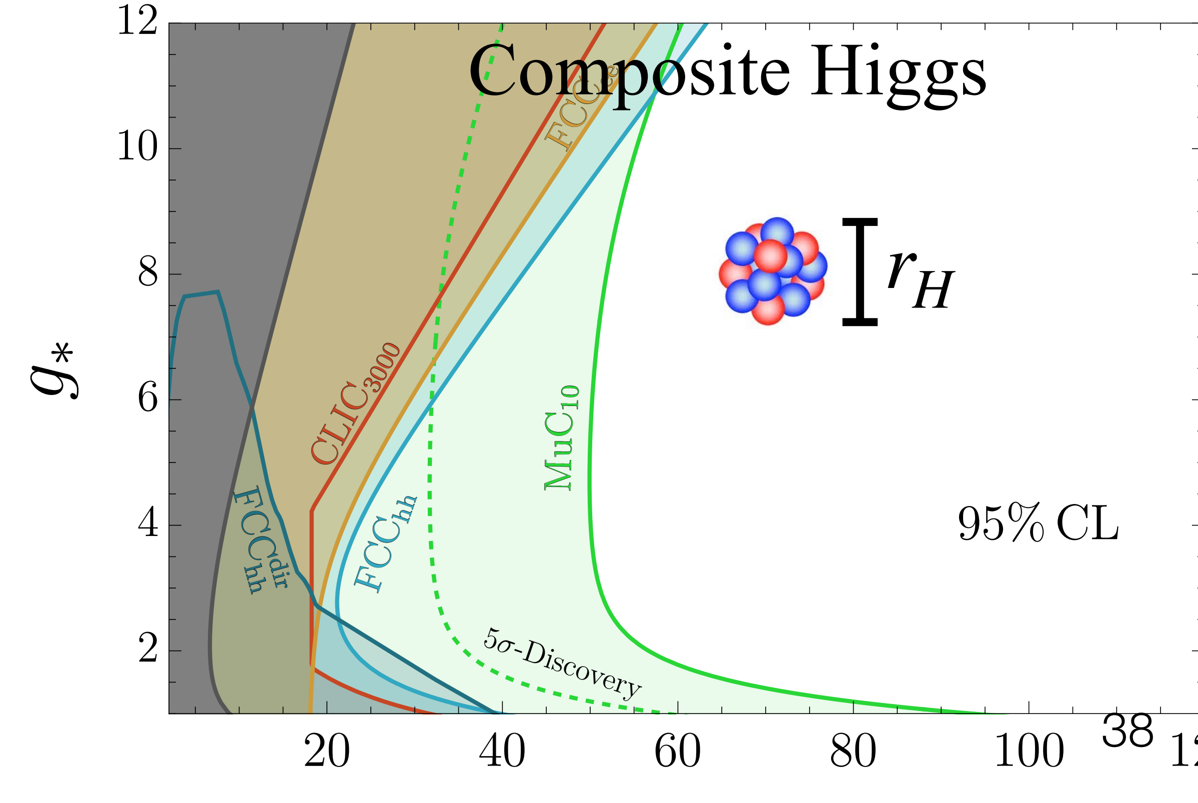
$$\frac{\Delta\sigma(E)}{\sigma_{\rm SM}(E)} \propto \frac{E^2}{\Lambda^2_{\rm BSM}} \overset{\Lambda_{\rm BSM}\,=\,100\ \text{TeV}}{=}$$

→ $\mathbf{10^{-6}}$ at EW.

→ $\mathbf{10^{-2}}$ at 10 TeV







Conclusions

X-Factory opens new era of **precision** in EW+H sector

- There are also particle discovery opportunities. From, e.g., 10^{12} Z decays
- For precision, details matter! The degree of success depends on these details.
- Precision is a physics driver as well as a tool.
  Work now on **Experiment**, **Theory** and **Detector** challenges/opportunity

Beyond X-Factories, we need **energy**

- Linear colliders can go to higher energy
- A big tunnel can host 100 TeV pp
- Muon collider feasibility would be game-changer
- We cannot decide it, but we can draw a path towards 10 TeV pCM
- **We must invest** on very high energy collider technologies

CEPC = ❤️