Future Collider Projects: A Theoretical Viewpoint

Annual Christmas Meeting

December 18th 2019

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My personal perspective, for all else consult this document:

arXiv.org > hep-ex > arXiv:1910.11775

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High Energy Physics – Experiment

Physics Briefing Book

European Strategy for Particle Physics Preparatory Group

(Submitted on 25 Oct 2019)

The European Particle Physics Strategy Update (EPPSU) process takes a bottom–up approach, whereby the community is first invited to submit proposals (also called inputs) for projects that it would like to see realised in the near–term, mid–term and longer–term future. National inputs as well as inputs from National Laboratories are also an important element of the process. All these inputs are then reviewed by the Physics Preparatory Group (PPG), whose role is to organize a Symposium around the submitted ideas and to prepare a community discussion on the importance and merits of the various proposals. The results of these discussions are then concisely summarised in this Briefing Book, prepared by the Conveners, assisted by Scientific Secretaries, and with further contributions provided by the Contributors listed on the title page. This constitutes the basis for the considerations of the European Strategy Group (ESG), consisting of scientific delegates from CERN Member States, Associate Member States, directors of major European laboratories, representatives of various European organizations as well as invitees from outside the European Community. The ESG has the mission to formulate the European Strategy Update for the consideration and approval of the CERN Council.

Scientific history is littered with empirical models, with some unexplained parameters, which were later superceded by some deeper, more microscopic structure.

These models tended to look like…

This...

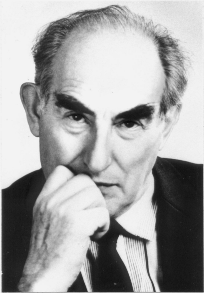
At low energies all we have of QCD is the pions

$$U = f_\pi e^{i\Pi/f_\pi}$$

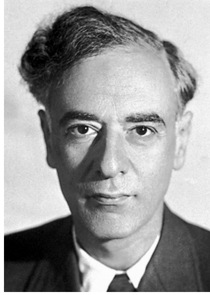
The phenomenological action

$$\mathcal{L} = \frac{1}{2}|D_\mu U|^2 - \mathrm{Tr}\left[\Sigma U + \mathrm{h.c.}\right] + \ldots$$

contains the parameters which fix the dynamics, but does not explain their origin.



This...



The G-L Theory of superconductivity involves a complex scalar field and the photon

$$\Phi \qquad\qquad A$$

The Free energy is

$$F = |(\nabla + 2ieA)\Phi|^2$$

$$+m^2(T)|\Phi|^2 + \lambda|\Phi|^4 + \ldots$$

Where the mass depends on the temperature.

and this...

The Higgs sector of the Standard Model involves the Higgs field and the gauge fields

$$H \qquad\qquad W_\mu^a$$

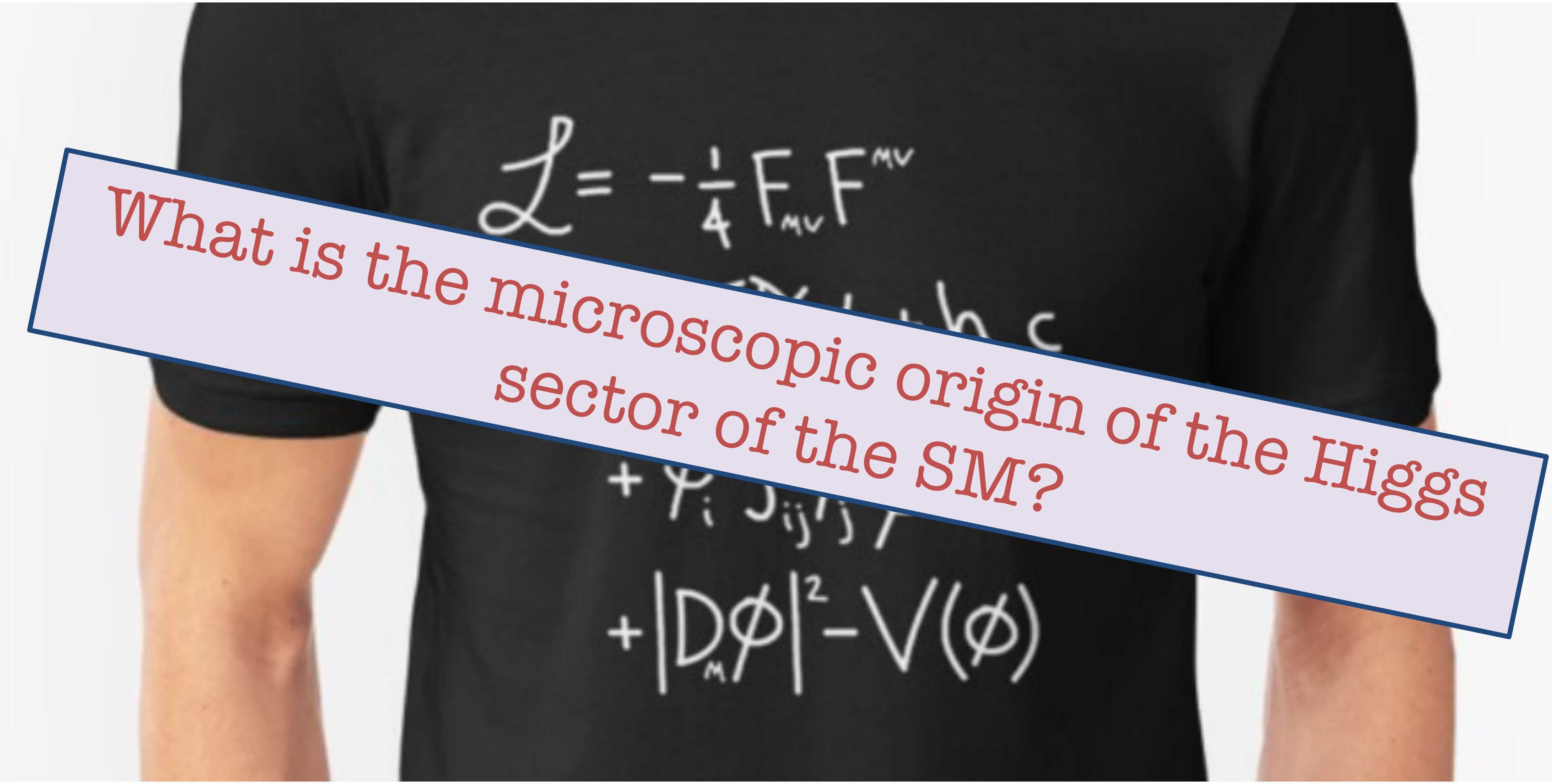
The Lagrangian for this theory is

$$\mathcal{L} = \left|(\partial_\mu + ig\sigma^a W_\mu^a)H\right|^2$$

$$+m^2(T)|H|^2 - \lambda(T)|H|^4 + \ldots$$

This is just the relativistic non-Abelian version of Ginzburg-Landau.

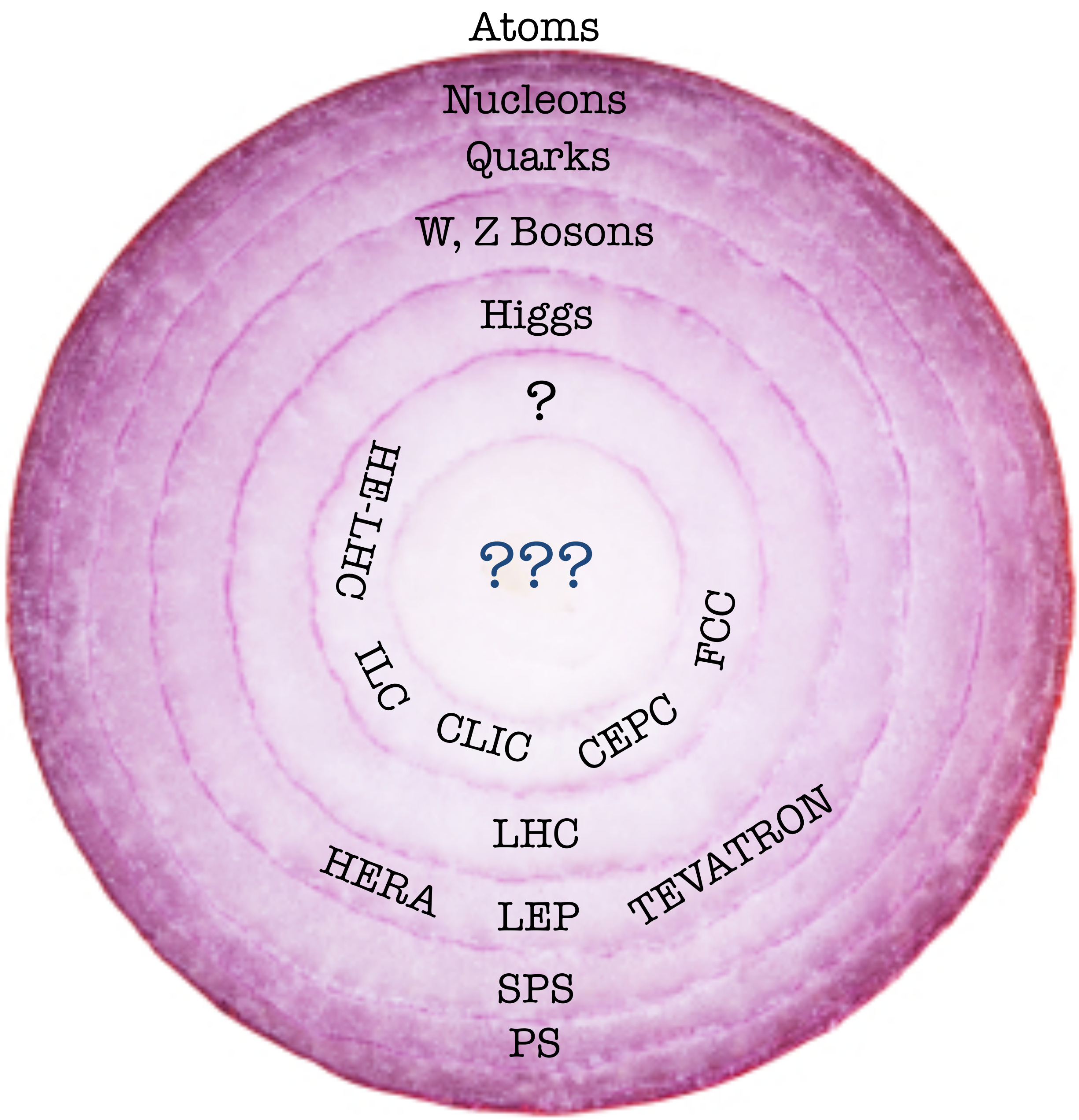
Perhaps you are proud of this Lagrangian? I think it's a bit of a mess. So many parameters, interactions. But most arbitrariness is linked to one, lonely, scalar field...



What is the microscopic origin of the Higgs sector of the SM?

If this is what the ultimate fundamental theory looks like then I'm going home...


Aren’t you talking about the hierarchy problem?



What is the next layer?

Where next?

Personal view. I can identify the protagonist

in the next chapter of particle physics.

How well should we know Higgs properties?

OK: Claiming to have a measurement of something requires around 50% precision, to claim 2σ.

Better: Claiming to have discovered something requires around 20% precision, to claim 5σ.

Life goals: Quantum corrections* are around a few percent in the Higgs sector, so to claim to have probed the quantum nature, which we should, then aim for a few percent.

* By quantum corrections, I mean an extra factor of ħ compared to leading result. Nothing to do with tree-versus-loop…

How well should we know Higgs properties?

Future colliders can realise many life goals:

kappa-0	HL-LHC	LHeC	HE-LHC		ILC			CLIC			CEPC	FCC-ee		FCC-ee/eh/hh
			S2	S2′	250	500	1000	380	15000	3000		240	365	
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
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
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
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
$\kappa_{Z\gamma}$ [%]	10.	–	5.7	3.8	99$\star$	86$\star$	85$\star$	120$\star$	15	6.9	8.2	81$\star$	75$\star$	0.69
κ_c [%]	–	4.1	–	–	2.5	1.3	0.9	4.3	1.8	1.4	2.2	1.8	1.3	0.95
κ_t [%]	3.3	–	2.8	1.7	–	6.9	1.6	–	–	2.7	–	–	–	1.0
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
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
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

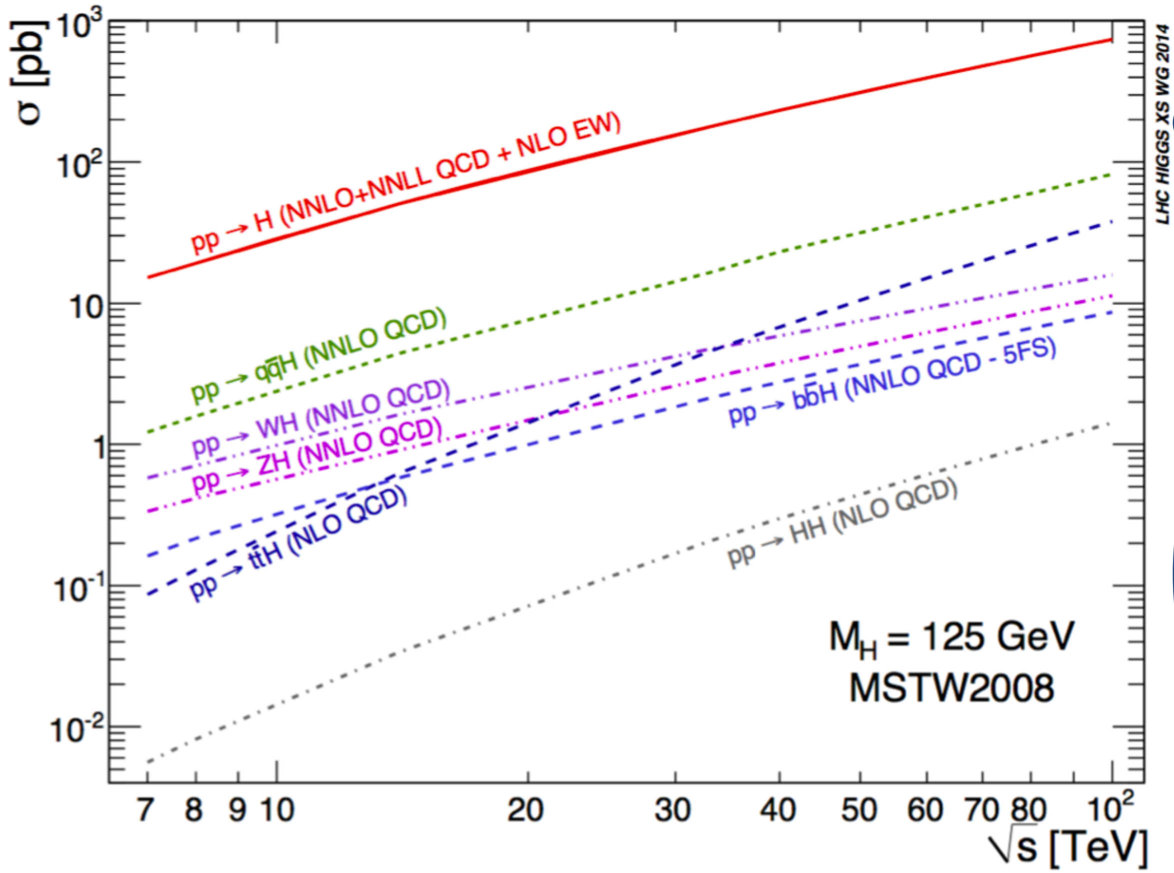
But we all know there is more to physics than Kappas...

FCC-hh at Higgs Intensity Frontier

High precision in dominant production modes.

Differential distributions.

Rare, associated, production modes



Rare/ exotic decays.

For exotic signatures can take full advantage of cross section if background is small. E.g. displaced vertices.

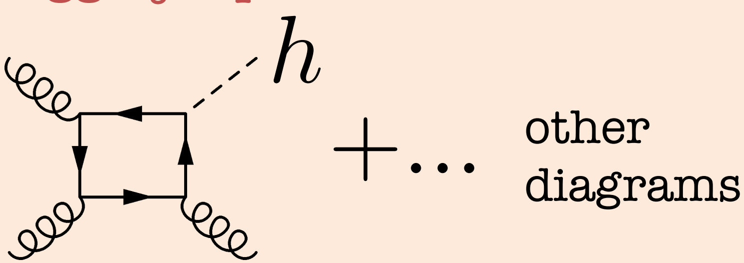
High energy also buys high precision. Not only for the Higgs, across the entire physics program.

FCC-hh at Higgs Intensity Frontier

At FCC-hh **TEN BILLION** Higgs bosons produced. Allowing to study extremely rare behaviour.

Higgs Production

Higgs+jet production

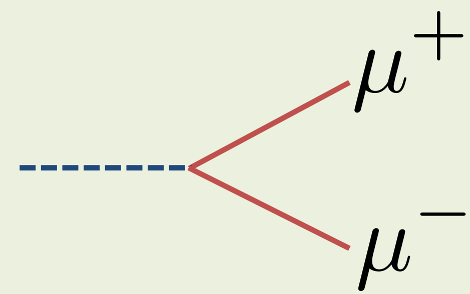


Would occur at Higgs p_T's as large as 7 TeV!

This is 56 times the mass, in other words, speed of 0.9998c.

Higgs Decays

Higgs coupling to muons



Would be measured to 0.4% essentially due to large statistical sample.

For systematic exploration we go beyond Kappas, to EFT.

Organizing the Unknown

To understand the origin and nature of the Higgs boson, we need to study how it behaves.

$$\mathcal{O}_T = \frac{c_T}{2M^2}(H^\dagger \overleftrightarrow{D}^\mu H)^2 \qquad \mathcal{O}_W = \frac{ig\, c_W}{2M^2}(H^\dagger \sigma^a \overleftrightarrow{D}^\mu H) D^\nu W^a_{\mu\nu} \qquad \mathcal{O}_{2B} = -\frac{c_{2B}}{4M^2}(\partial_\rho B_{\mu\nu})^2$$

$$\mathcal{O}_{2G} = -\frac{c_{2G}}{4M^2}(D_\rho G^a_{\mu\nu})^2 \qquad \mathcal{O}_\Box = \frac{c_\Box}{M^2}|\Box H|^2 \qquad \mathcal{O}_{WW} = \frac{g^2\, c_{WW}}{M^2}|H|^2 W^{a\,\mu\nu} W^a_{\mu\nu}$$

$$\mathcal{O}_B = \frac{ig'\, c_B}{2M^2}(H^\dagger \overleftrightarrow{D}^\mu H)\partial^\nu B_{\mu\nu} \qquad \mathcal{O}_6 = \frac{c_6}{M^2}|H|^6 \qquad \mathcal{O}_{GG} = \frac{g_s^2\, c_{GG}}{M^2}|H|^2 G^{a,\mu\nu} G^a_{\mu\nu}$$

$$\mathcal{O}_H = \frac{c_H}{2M^2}\left(\partial^\mu |H|^2\right)^2 \qquad \mathcal{O}_R = \frac{c_R}{M^2}|H|^2 |D^\mu H|^2$$

$$\mathcal{O}_{BB} = \frac{g'^2\, c_{BB}}{M^2}|H|^2 B^{\mu\nu} B_{\mu\nu}$$

$$\mathcal{O}_{2W} = -\frac{c_{2W}}{4M^2}(D_\rho W^a_{\mu\nu})^2 \qquad \mathcal{O}_{WB} = \frac{gg'\, c_{WB}}{M^2} H^\dagger \sigma^a H B^{\mu\nu} W^a_{\mu\nu}$$

Operators like those above capture leading effects of heavy physics beyond the standard model. Probing them could reveal origins.

Organizing the Unknown

Naïve dimensional analysis:

$$[H] = [A_\mu] = \frac{1}{LC} \quad , \quad [\psi] = \frac{1}{L^{3/2}C}$$

Fields carry not only dimension of inverse length, but also inverse coupling.

<u>Fermi Scale</u>

Interaction: $\mathcal{L} \sim \dfrac{\psi^4}{\Lambda^2}$

UV-completion

Dimension: $[\Lambda] = [G_F^{-1/2}] = \dfrac{[M_W]}{[g]}$

Coupling

Organizing the Unknown

Higgs Only

$[g_*^0]$

$\mathcal{O}_{\Box} = \frac{c_{\Box}}{M^2}|\Box H|^2$

$[g_*^2]$

$\mathcal{O}_H = \frac{c_H}{2M^2}\left(\partial^\mu |H|^2\right)^2$

$\mathcal{O}_T = \frac{c_T}{2M^2}(H^\dagger \overleftrightarrow{D}^\mu H)^2$

$\frac{c_R}{\ldots}|H|^2|D^\mu H|^2$

$[g_*^4]$

$\mathcal{O}_6 = \frac{c_6}{M^2}|H|^6$

$\mathcal{O}_{2G} = -\frac{c_{2G}}{4M^2}(D_\rho G^a_{\mu\nu})^2$

Any new physics interacting primarily with Higgs and gauge sectors matches, at leading order, to these operators.

Mixed

$\mathcal{O}_B = \frac{ig' c_B}{2M^2}(H^\dagger \overleftrightarrow{D}^\mu H)\partial^\nu B_{\mu\nu}$

$\mathcal{O}_W = \frac{ig\, c_W}{2M^2}(H^\dagger \sigma^a \overleftrightarrow{D}^\mu H)D^\nu W^a_{\mu\nu}$

$\mathcal{O}_{GG} = \frac{g_s^2 c_{GG}}{M^2}|H|^2 G^{a,\mu\nu}G^a_{\mu\nu}$

$\mathcal{O}_{WB} = \frac{gg' c_{WB}}{M^2}H^\dagger \sigma^a H B^{\mu\nu}W^a_{\mu\nu}$

$\mathcal{O}_{WW} = \frac{g^2 c_{WW}}{M^2}|H|^2 W^{a\,\mu\nu}W^a_{\mu\nu}$

$\mathcal{O}_{BB} = \frac{g'^2 c_{BB}}{M^2}|H|^2 B^{\mu\nu}B_{\mu\nu}$

Organizing the Unknown

Higgs Only

$[g_*^0]$

$$\mathcal{O}_{\Box} = \frac{c_{\Box}}{M^2}|\Box H|^2$$

$[g_*^2]$

$$\mathcal{O}_H = \frac{c_H}{2M^2}\left(\partial^\mu |H|^2\right)^2$$

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$$\mathcal{O}_R = \frac{c_R}{M^2}|H|^2|D^\mu H|^2$$

$[g_*^4]$

$$\mathcal{O}_6 = \frac{c_6}{M^2}|H|^6$$

Gauge Only

$$\mathcal{O}_{2G} = -\frac{c_{2G}}{4M^2}(D_\rho G^a_{\mu\nu})^2 \qquad \mathcal{O}_{2W} = -\frac{c_{2W}}{4M^2}(D_\rho W^a_{\mu\nu})^2 \qquad \mathcal{O}_{2B} = -\frac{c_{2B}}{4M^2}(\partial_\rho B_{\mu\nu})^2$$

Mixed

$$\mathcal{O}_B = \frac{ig' \, c_B}{2M^2}(H^\dagger \overleftrightarrow{D}^\mu H)\partial^\nu B_{\mu\nu}$$

$$\mathcal{O}_W = \frac{ig \, c_W}{2M^2}(H^\dagger \sigma^a \overleftrightarrow{D}^\mu H)D^\nu W^a_{\mu\nu}$$

$$\mathcal{O}_{GG} = \frac{g_s^2 \, c_{GG}}{M^2}|H|^2 G^{a,\mu\nu}G^a_{\mu\nu}$$

$$\mathcal{O}_{WB} = \frac{gg' \, c_{WB}}{M^2}H^\dagger \sigma^a H B^{\mu\nu}W^a_{\mu\nu}$$

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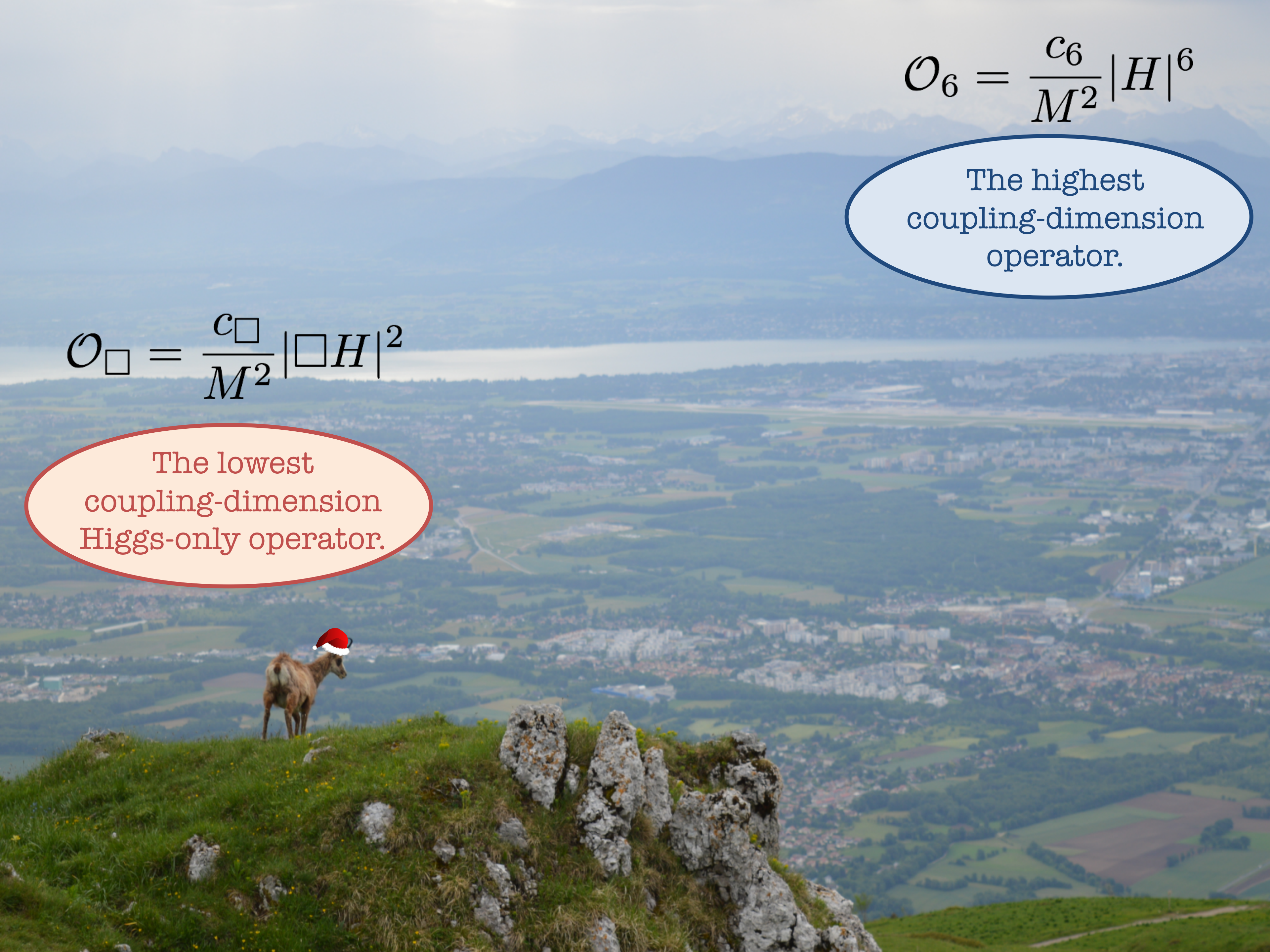
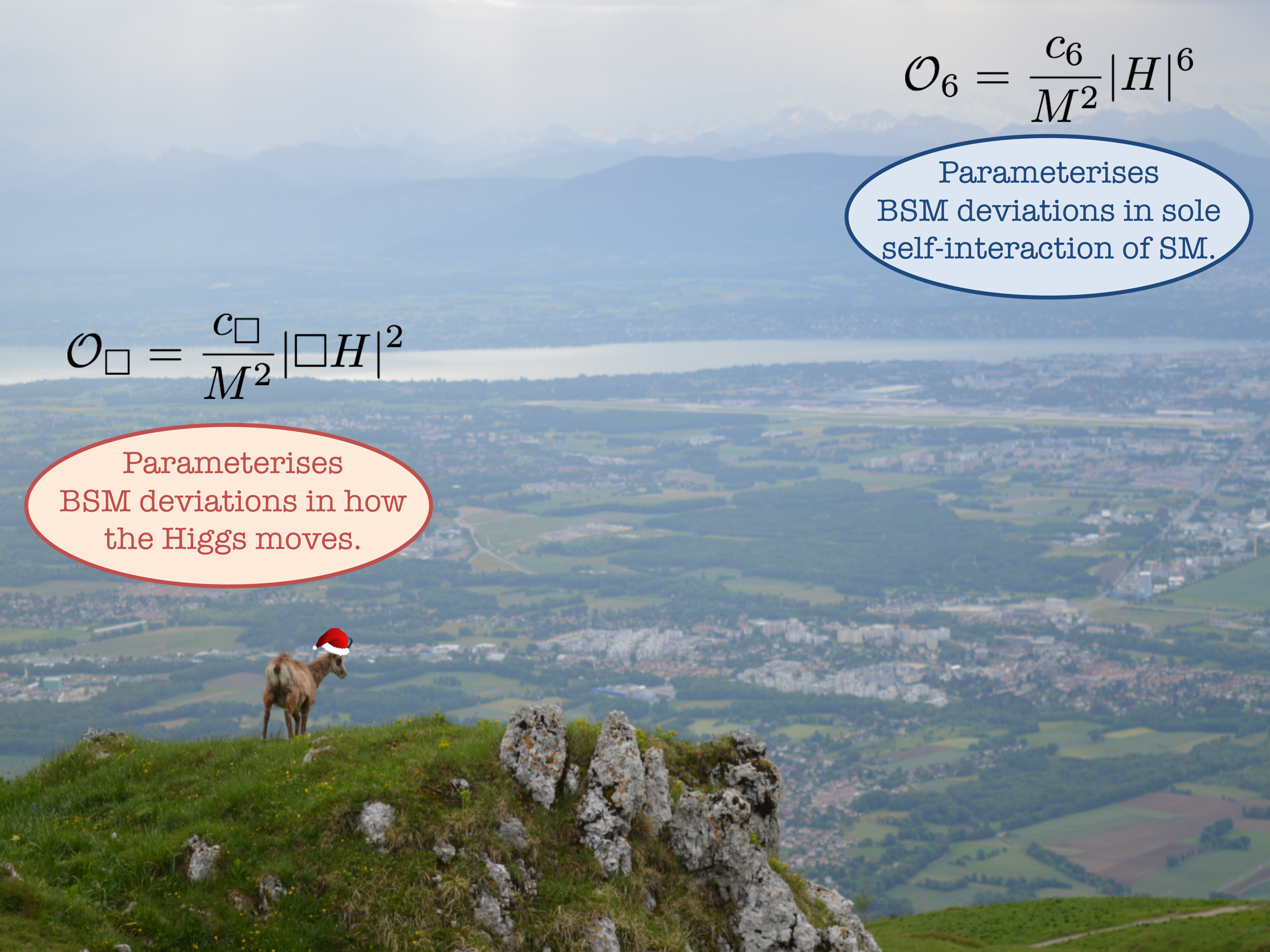


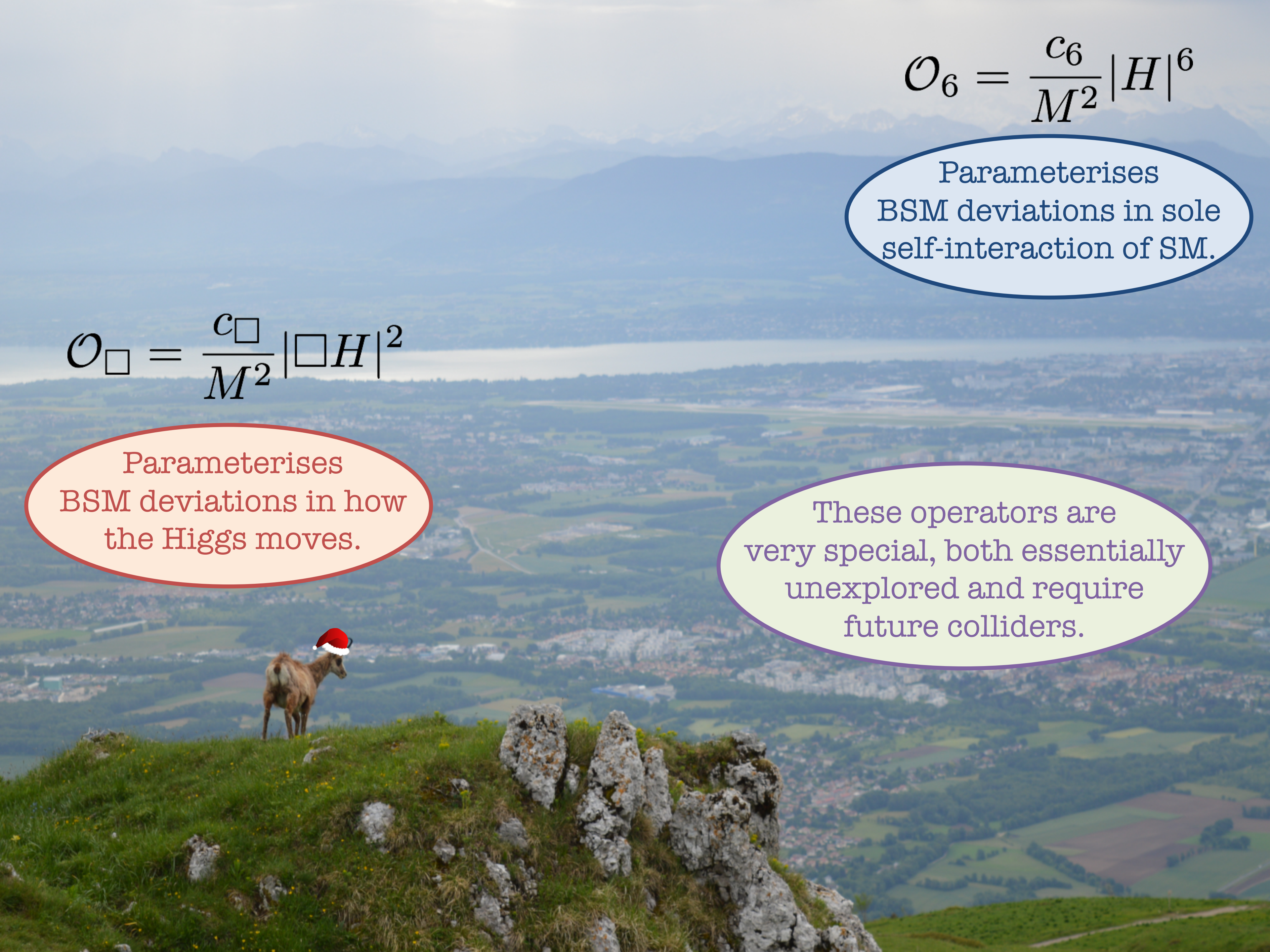
$$\mathcal{O}_6 = \frac{c_6}{M^2}|H|^6$$

The highest coupling-dimension operator.

$$\mathcal{O}_\Box = \frac{c_\Box}{M^2}|\Box H|^2$$

The lowest coupling-dimension Higgs-only operator.


$$\mathcal{O}_6 = \frac{c_6}{M^2}|H|^6$$
Parameterises BSM deviations in sole self-interaction of SM.
$$\mathcal{O}_\Box = \frac{c_\Box}{M^2}|\Box H|^2$$
Parameterises BSM deviations in how the Higgs moves.



$$\mathcal{O}_6 = \frac{c_6}{M^2}|H|^6$$
Parameterises BSM deviations in sole self-interaction of SM.
$$\mathcal{O}_\Box = \frac{c_\Box}{M^2}|\Box H|^2$$
Parameterises BSM deviations in how the Higgs moves.
These operators are very special, both essentially unexplored and require future colliders.

Context...

We got the symmetries: LEP.

$$\mathrm{SU}(2)_L \times \mathrm{U}(1)_Y \to \mathrm{U}(1)_{\mathrm{EM}}$$

Then we got the mechanism: LHC.

$$\langle H \rangle = v + h$$

Time to get the dynamics: Future facilities...

$$\mathcal{O}_{\Box} = \frac{c_{\Box}}{M^2} |\Box H|^2$$

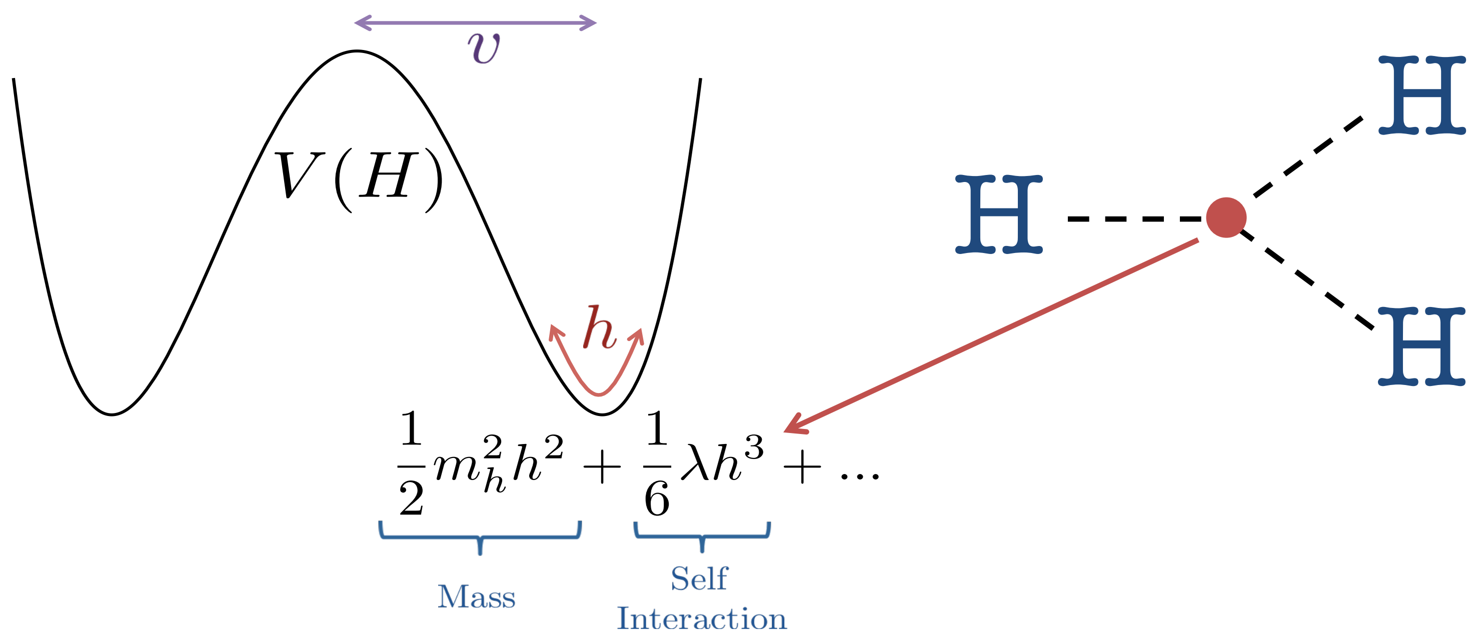
The lowest coupling-dimension Higgs-only operator.

$$\mathcal{O}_6 = \frac{c_6}{M^2} |H|^6$$

The highest coupling-dimension operator.

A Unique Operator

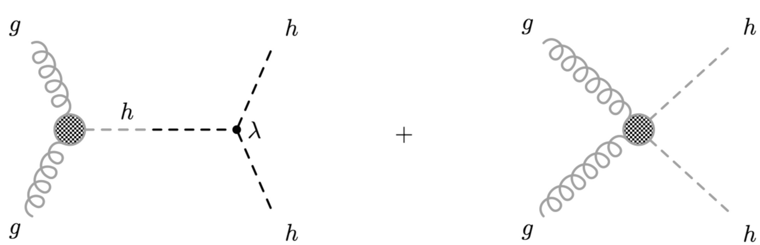
Measuring the Higgs self-coupling is the only way to probe the structure of the Higgs potential.



Discovering the Higgs was difficult enough, now we want to know how it interacts with itself...

A Unique Operator

At hadron colliders dominant production is via gluon fusion

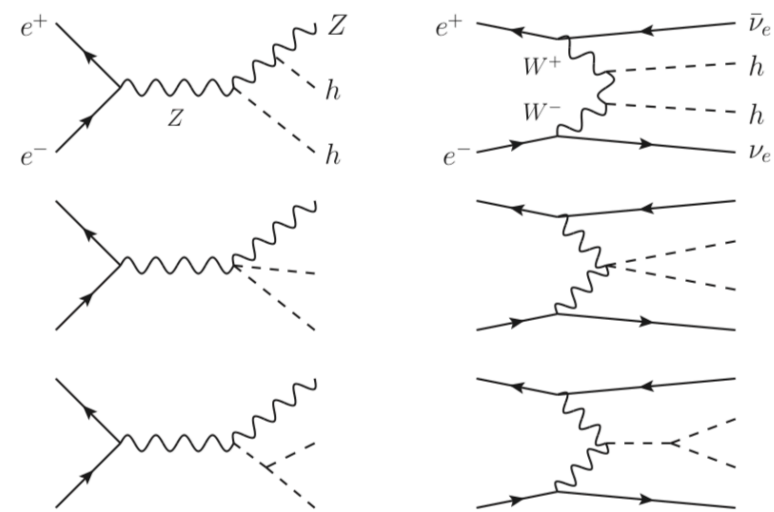


And most promising final state is

$$hh \to b\bar{b}\gamma\gamma$$

although a combination is better.

At lepton colliders a variety of pair production processes are possible.



A clean detector environment helps as well.

A Unique Operator

However,

$$\mathcal{O}_6 = \frac{c_6}{M^2}|H|^6$$

is also very very special, since:

$$[c_6] = C^4 \quad , \quad [\hbar] = C^{-2}$$

At one-loop we have:

$$[\hbar c_6] = C^2$$

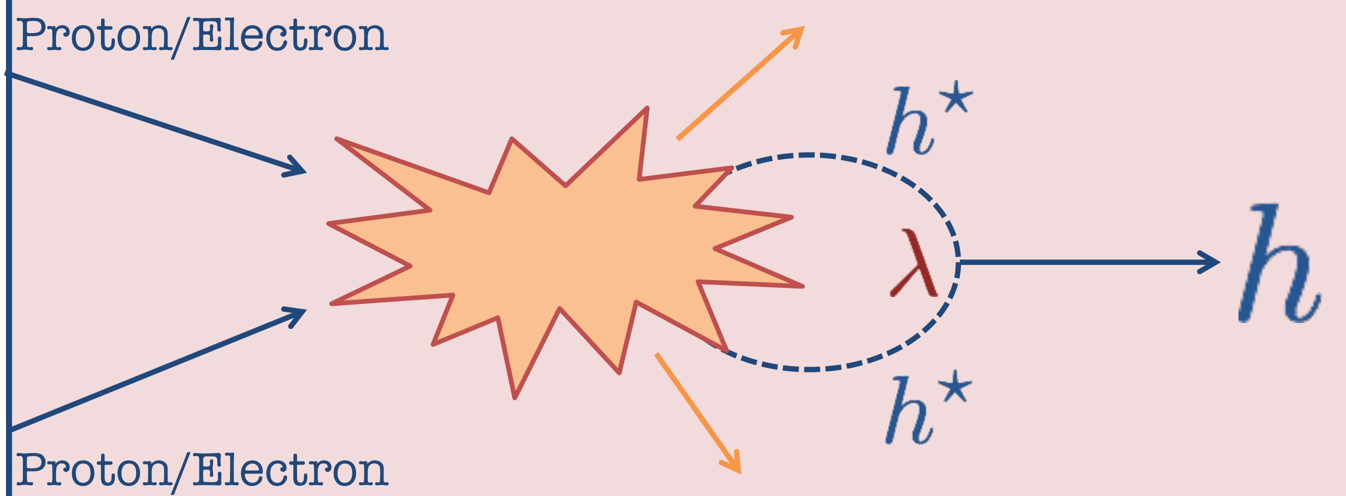
Thus, if any other coupling enters the game, coupling dimension is too large to match any other dim-6 operator!

A Unique Operator

Observation:

$$\mathcal{O}_6 \xrightarrow{\text{One-loop running}} \mathcal{O}_6$$

This operator is a mountain-top in RG-space.



Insert into any one-loop diagram and no dim-6 counterterms will be required, result always finite!

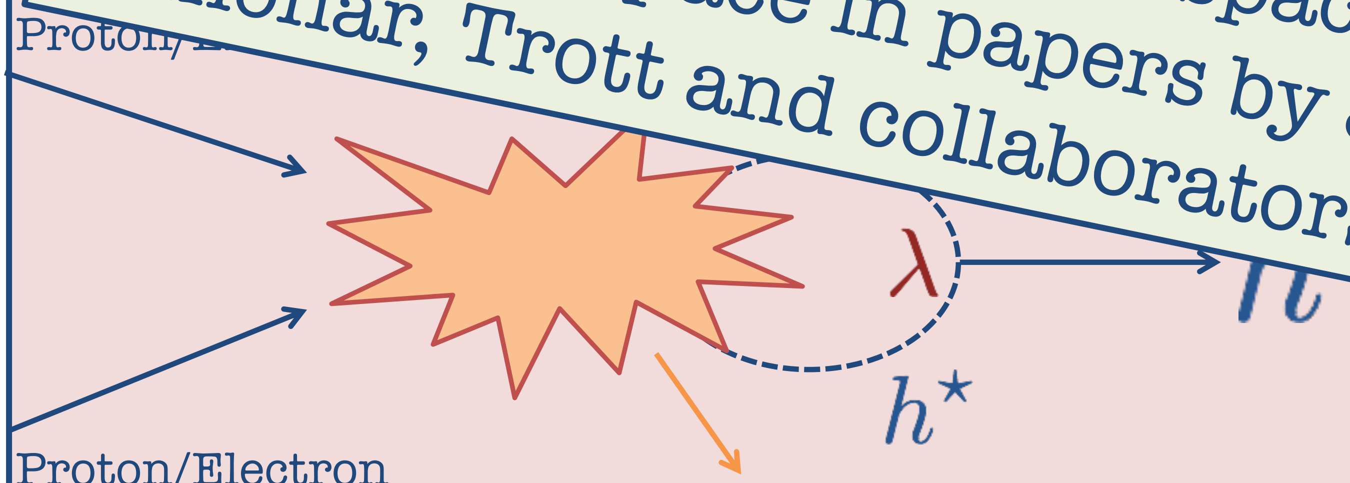
A Unique Operator

Observation:

$$\mathcal{O}_6 \xrightarrow{\text{One-loop running}} \mathcal{O}_6$$

ain-top in RG-space.

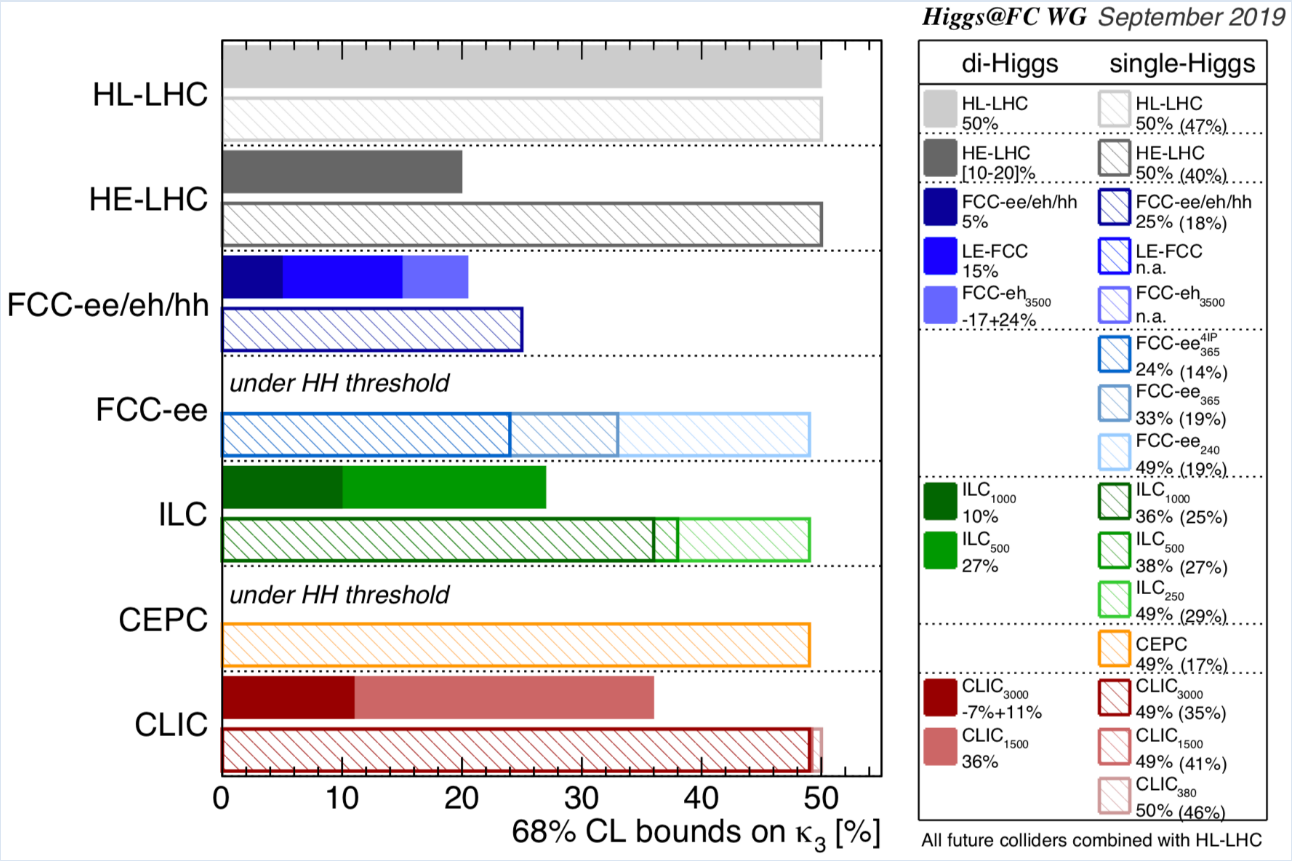
Can see where it lies in the space of Dim-6 operator RG space in papers by Jenkins, Manohar, Trott and collaborators...



Insert into any one-loop diagram and no dim-6 counterterms will be required, result always finite!

A Unique Operator

At high energies we can use Higgs pair production, at low energies quantum effects:



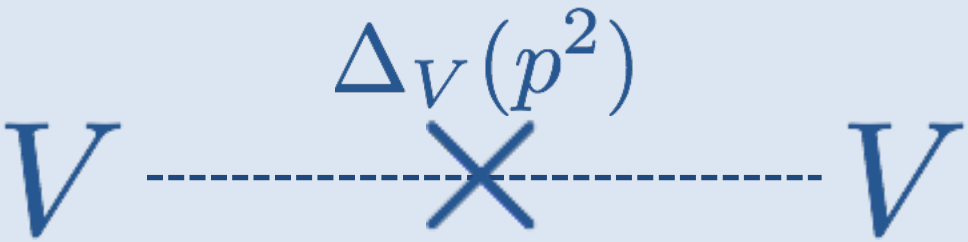
ECFA Higgs Working Group Report 1905.03764

This is the future of the Higgs self coupling (Higgs potential)…

Oblique Corrections

Oblique corrections have been a formidable toolkit in the effort to explore the electroweak sector.

- S-parameter
- T-parameter
- W-parameter
- Y-parameter



The latter two contribute to amplitudes in an “energy-growing” manner:

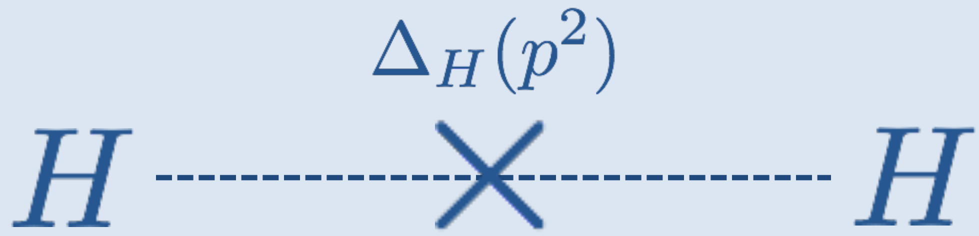
$$\Delta_W(p^2) \approx \frac{1}{p^2 - M_W^2} - \frac{\hat{W}}{M_W^2}$$

Making these oblique parameters an excellent target for hadron colliders…

Oblique Corrections

Makes sense to extend to the Higgs sector. Especially since the Higgs can easily interact with new states…

- H-parameter:



1903.07725

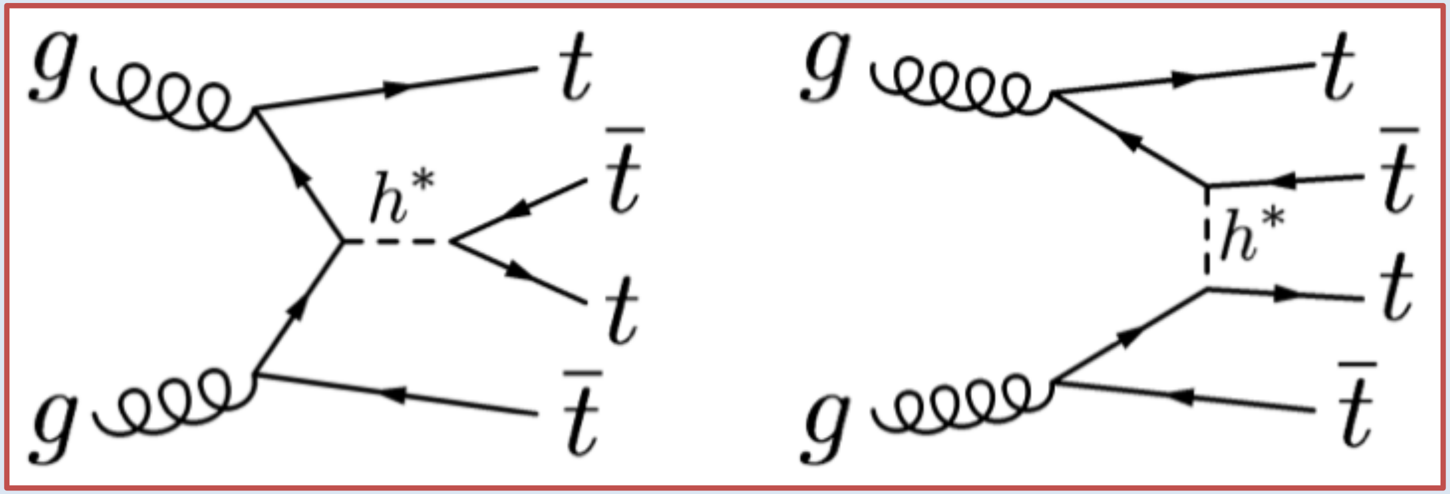
This also contributes to amplitudes in an "energy-growing" manner:

$$\Delta_H(p^2) \approx \frac{1}{p^2 - m_h^2} - \frac{\hat{H}}{m_h^2} + \dots$$

However, one needs to take the Higgs off-shell, which isn't easy…

Oblique Corrections

Most promising avenue to take this Higgs off-shell is through four-top production:

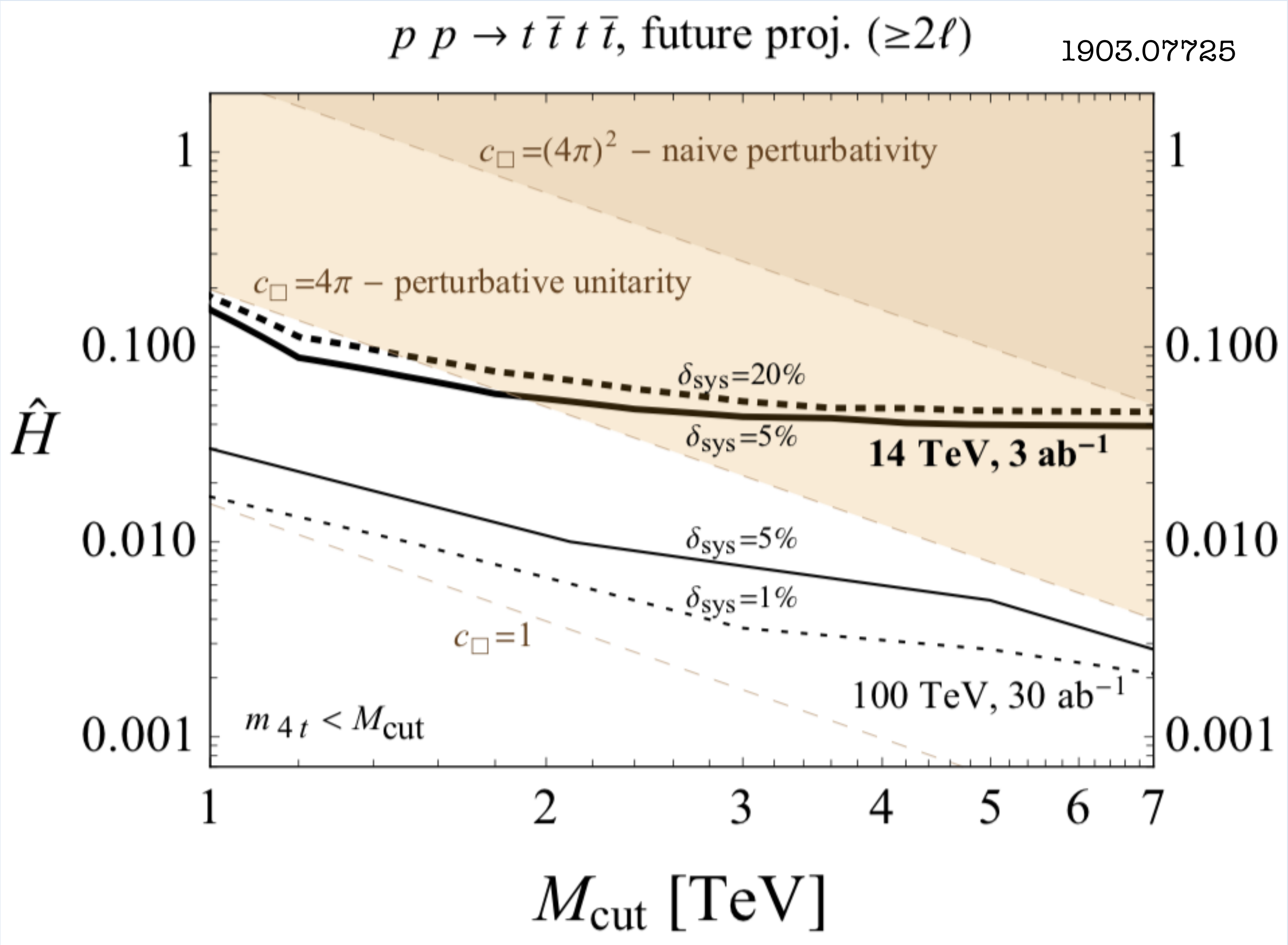


We may relate this Wilson coefficient to the scale of new physics as:

$$\frac{\hat{H}}{m_h^2} = \frac{c_\square}{M^2}$$

Oblique Corrections

Our estimate suggests the practical way to probe this special operator is with future colliders:



Let's not overlook the outlier operators...

Higgs Only

$[g_*^0]$

$$\mathcal{O}_\Box = \frac{c_\Box}{M^2}|\Box H|^2$$

$[g_*^2]$

$$\mathcal{O}_H = \frac{c_H}{2M^2}\left(\partial^\mu |H|^2\right)^2$$

$$\mathcal{O}_T = \frac{c_T}{2M^2}(H^\dagger \overleftrightarrow{D}^\mu H)^2$$

$$\mathcal{O}_R = \frac{c_R}{M^2}|H|^2|D^\mu H|^2$$

$[g_*^4]$

$$\mathcal{O}_6 = \frac{c_6}{M^2}|H|^6$$

which determine the dynamics of the Higgs, from how it moves to the shape of the Higgs potential.

Let's not overlook the outlier operators...

Higgs Only

$[g_*^0]$

$$\mathcal{O}_\Box = \frac{c_\Box}{M^2}|\Box H|^2$$

$[g_*^2]$

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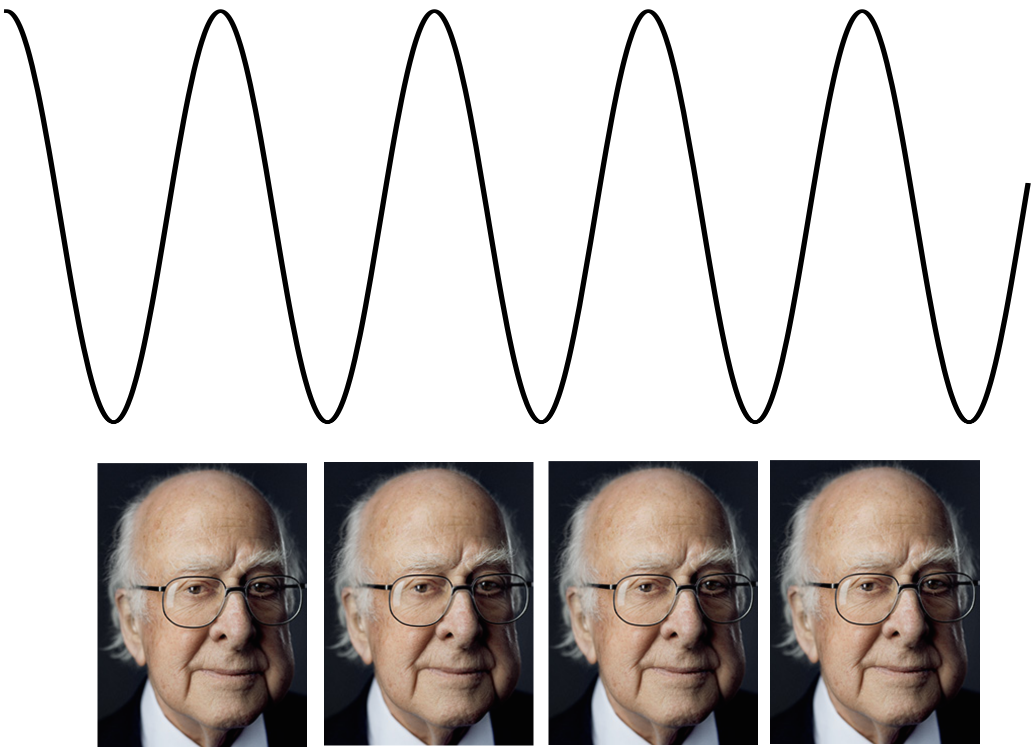
Probing the dynamics of the Higgs sector unequivocally requires a future collider.

Is the Higgs Fundamental?

- The Higgs boson has a size/wavelength. What's inside?



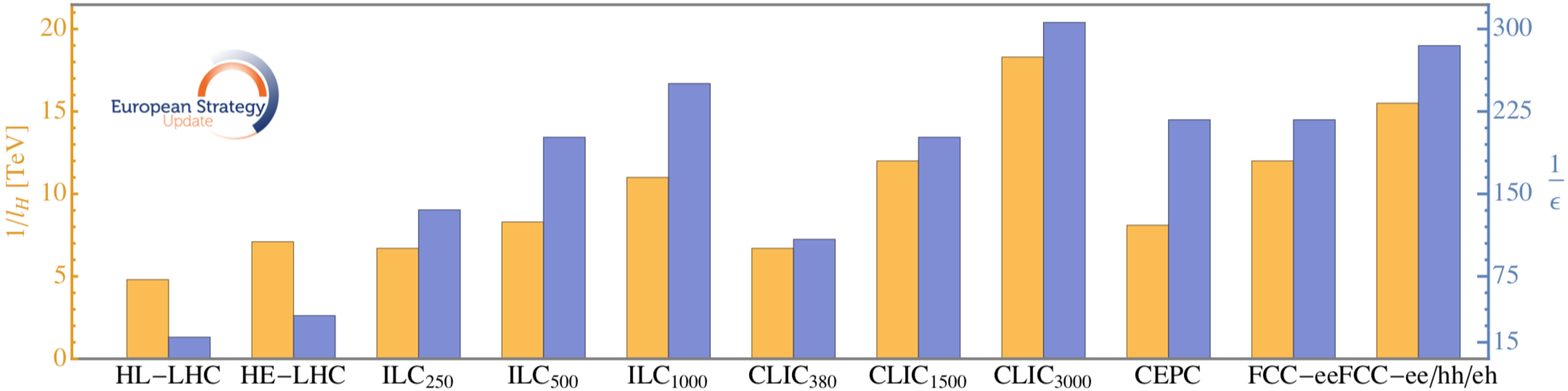
Precision measurements are different ways of probing the "compositeness of the Higgs".

$\lambda_h \approx 10^{-17}$ m

$\lambda_{10\ \mathrm{TeV}} \approx 10^{-19}$ m

Is the Higgs Fundamental?

- Future colliders offer unprecedented examination of the Higgs boson:



$$\lambda_h \approx 10^{-17}\ \mathrm{m}$$

$$\lambda_{10\ \mathrm{TeV}} \approx 10^{-19}\ \mathrm{m}$$

Is the Higgs Fundamental?

If the Higgs is made up of constituents

$$H = \bar{f} f \quad \Big| \sim f \qquad\qquad \xi \sim \frac{v^2}{f^2}$$

Could resolve some puzzles of the SM, providing the microscopic origin of Higgs, like QCD for pions.

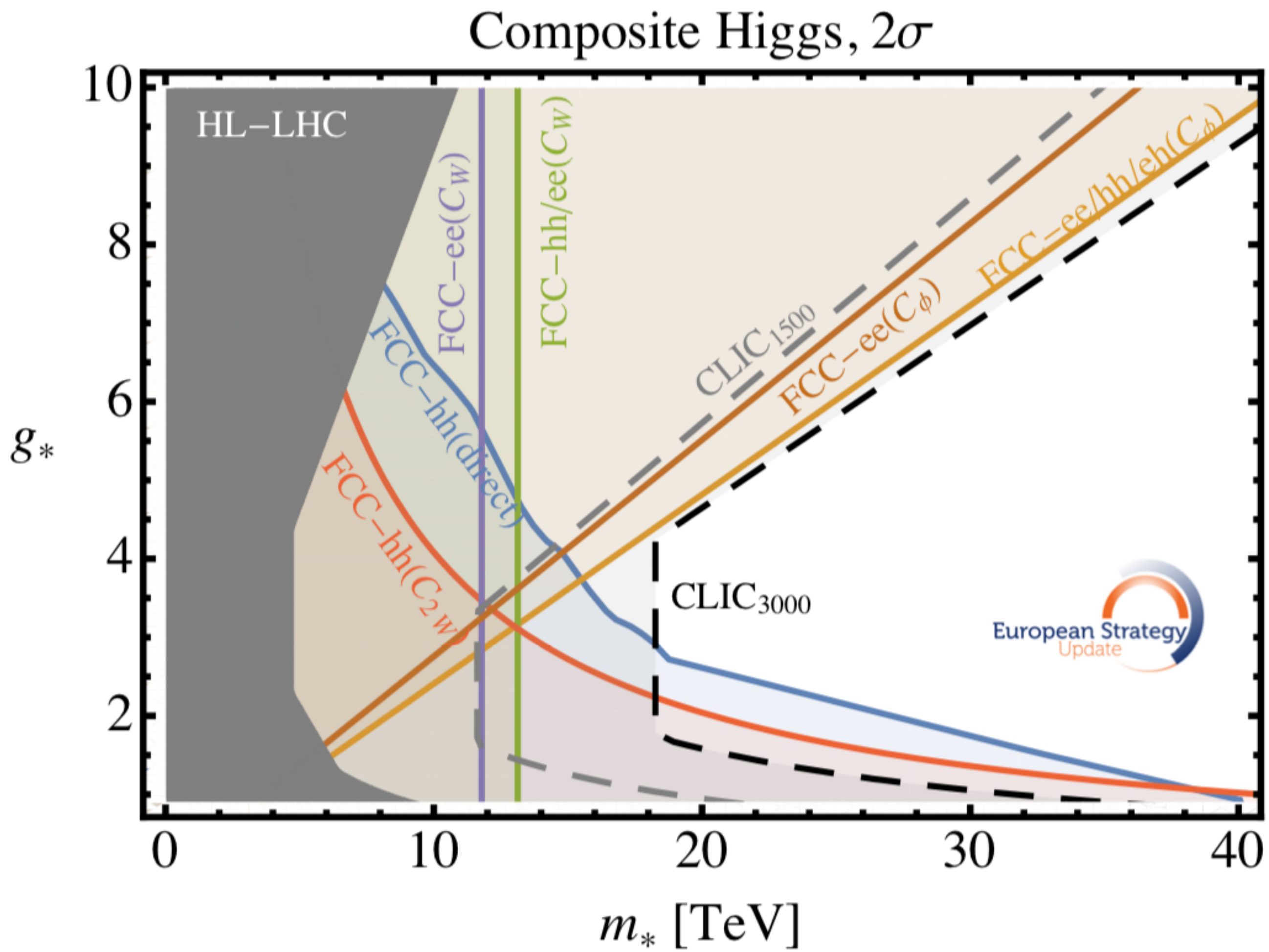
Such models can be thought of as realising the Higgs boson analogously to the pion in QCD.

$$\rho = \bar{f} f \quad \Big| \sim \Lambda$$

Should also get other heavy resonances then!

Is the Higgs Fundamental?

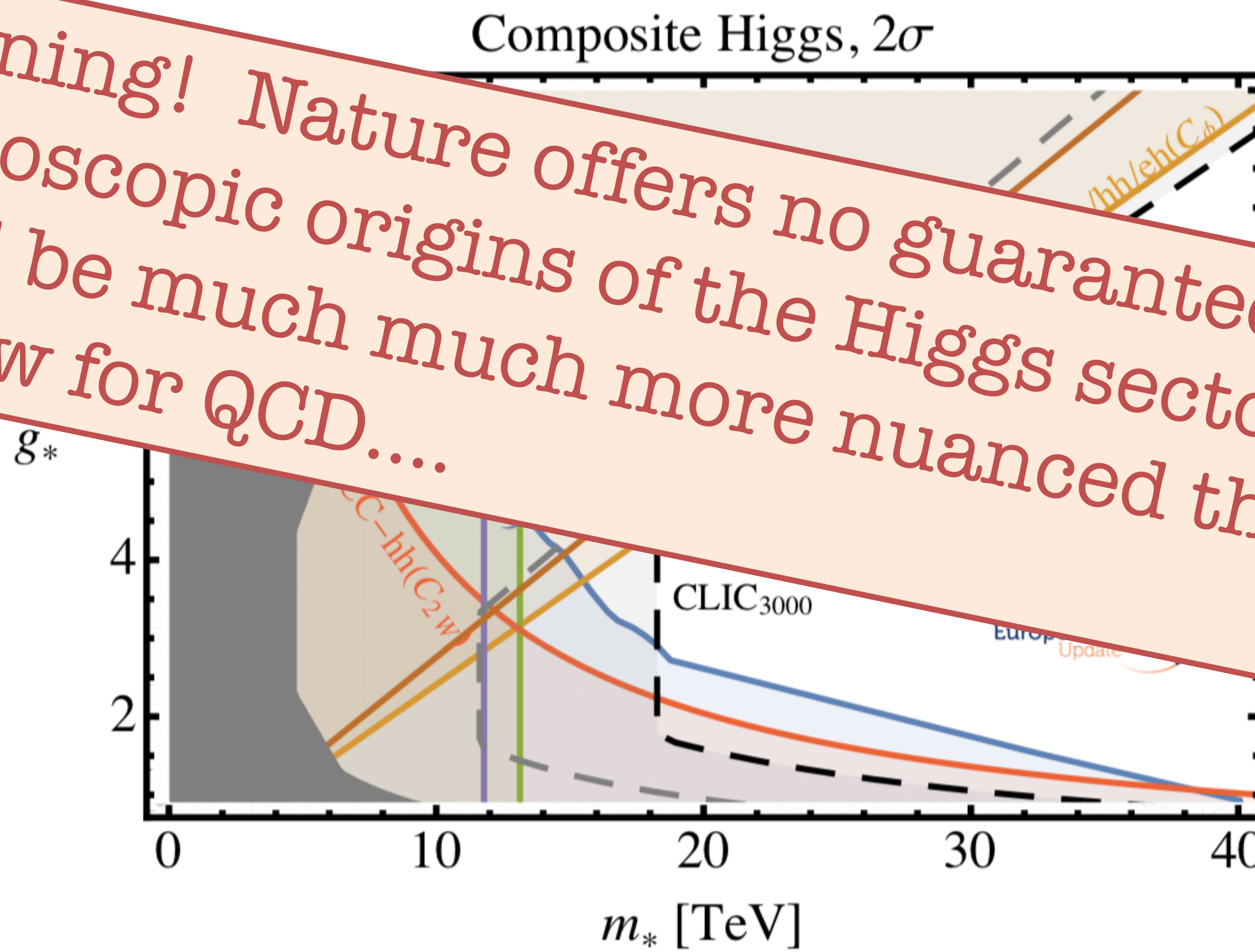
Including direct searches for the associated composite-sector mesons



provides valuable complementary information.

Is the Higgs Fundamental?

Including direct searches for the associated composite-sector mesons

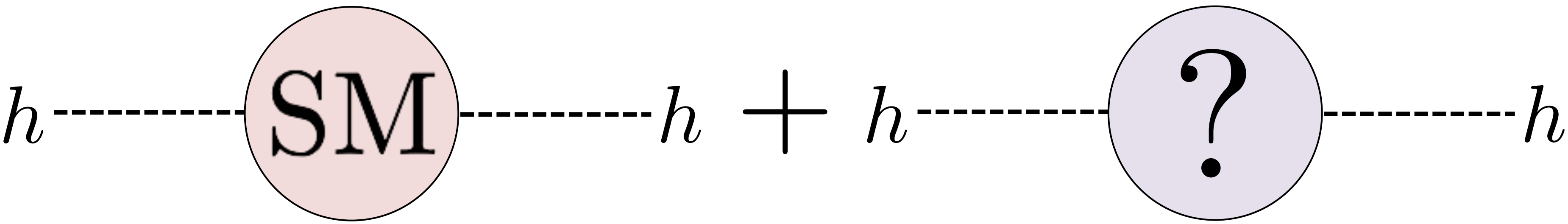


Warning! Nature offers no guarantees. Microscopic origins of the Higgs sector could be much much more nuanced than we saw for QCD….

provides valuable complementary information.

Neutral Naturalness

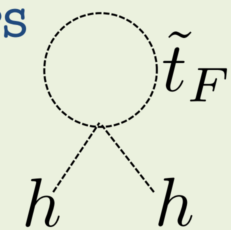
Could there be a hidden states which tame sensitivity to physics at the cutoff?



Much attention now to alternative ideas:

Folded SUSY hep-ph/0609152

Theory where EW-charged uncoloured scalars are top partners



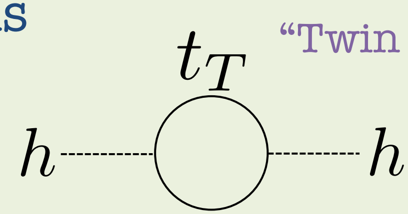
"Folded Stops"

...but they must be charged under new hidden QCD'.

Twin Higgs hep-ph/0506256

Theory where top partners are SM gauge neutral fermions

"Twin Tops"

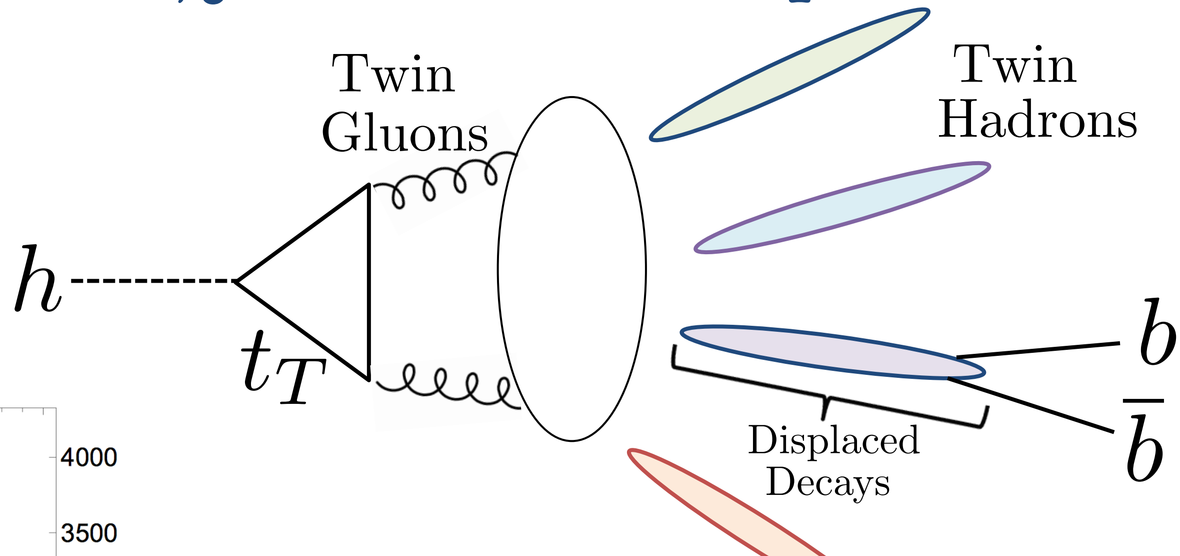


...but they must be charged under new hidden QCD'.

Neutral Naturalness

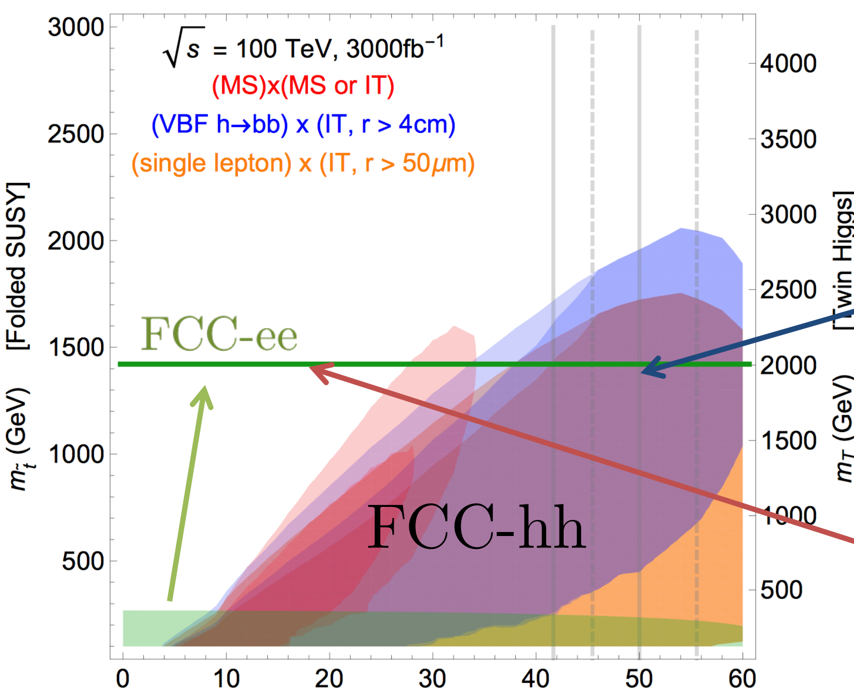
Naturalness not hidden, just look in new places...

New hidden sector introduces exotic Higgs decays:



FCC-hh can thoroughly probe larger Twin scales through displaced searches.

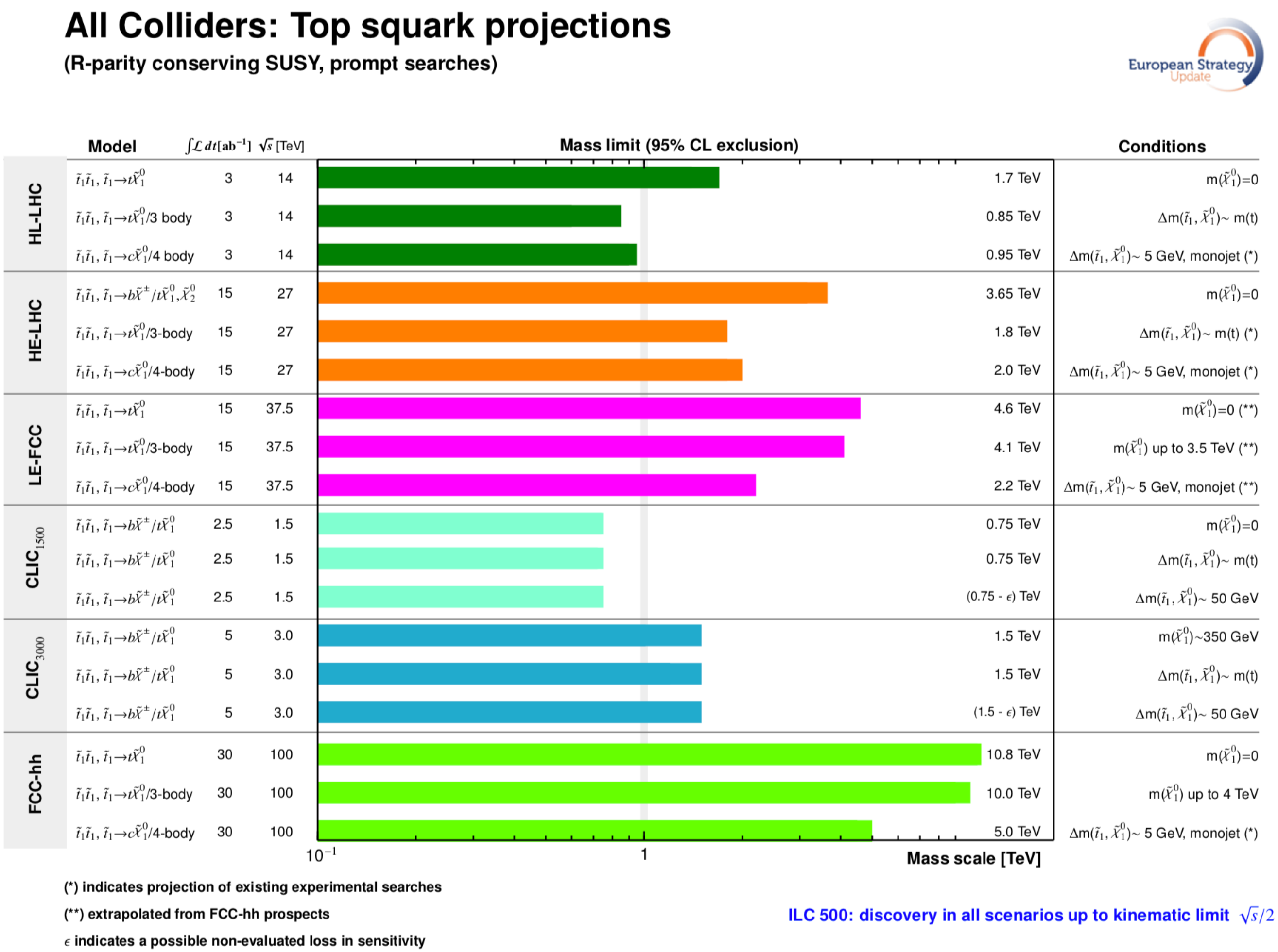
FCC-ee/CEPC has indirect access for top partners, including for low confinement scales.



Curtin, CV 1506.06141

Or fundamental to small scales?

Supersymmetry can stabilize the Higgs all the down to extremely short distances.



Stop!

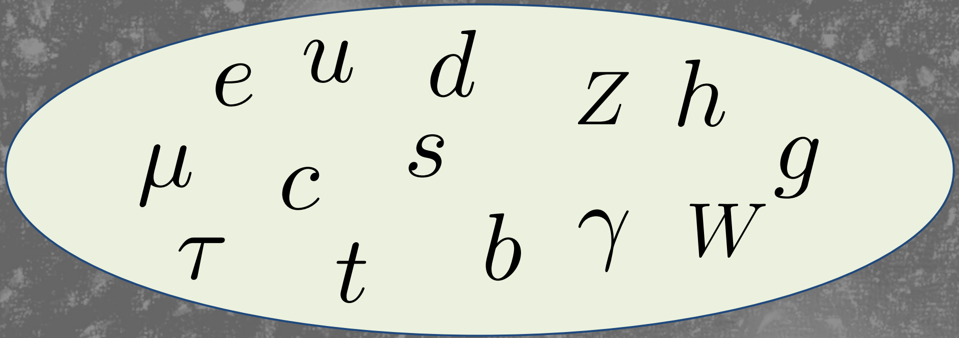
The stops are, arguably, the most most important players. But the heavier they are, the less effective they are.

Split SUSY?
Unification?
Neutralino DM?

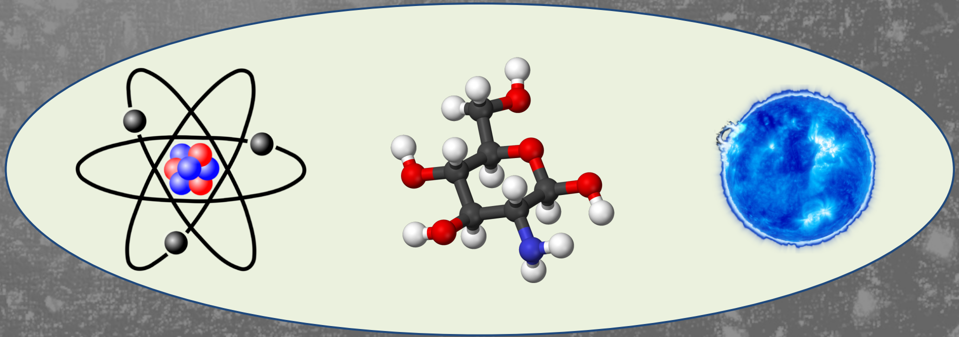
Your choice.

Where there is darkness, let there be light…

Only 18% of all matter in Universe is visible.



Within that 18% we observe extraordinary complexity.



The photon, despite not being matter itself, gave us our first tool to explore the visible sector.

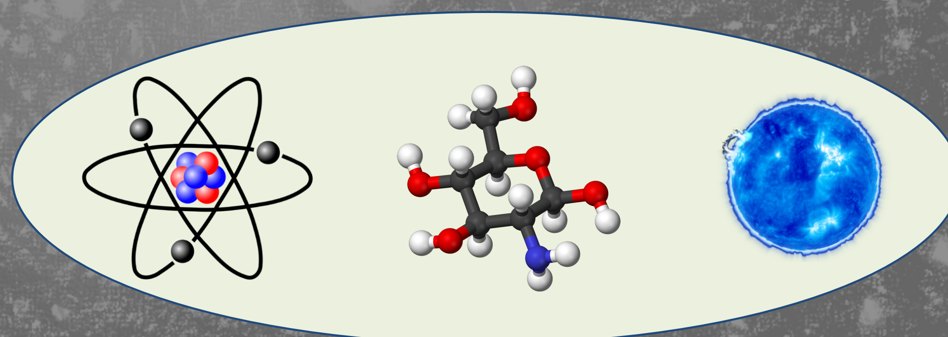
Only 18% of all matter in Universe is visible.

e u d Z h

μ c s g

τ t b γ W

Within that 18% we observe extraordinary complexity.



Similarly, it may be the light mediators, or other states, that open the window to the dark sector.

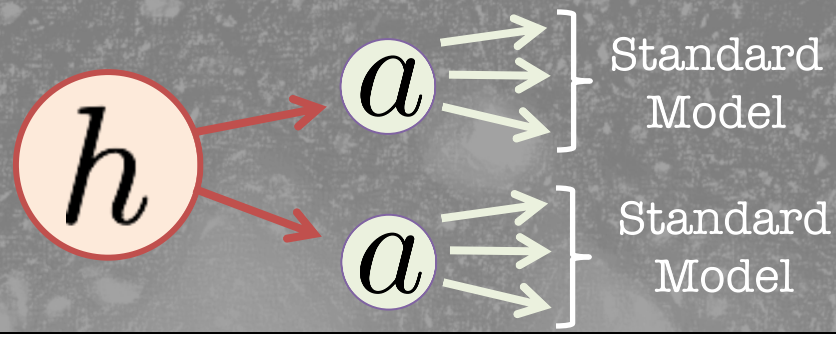
Darkened Windows

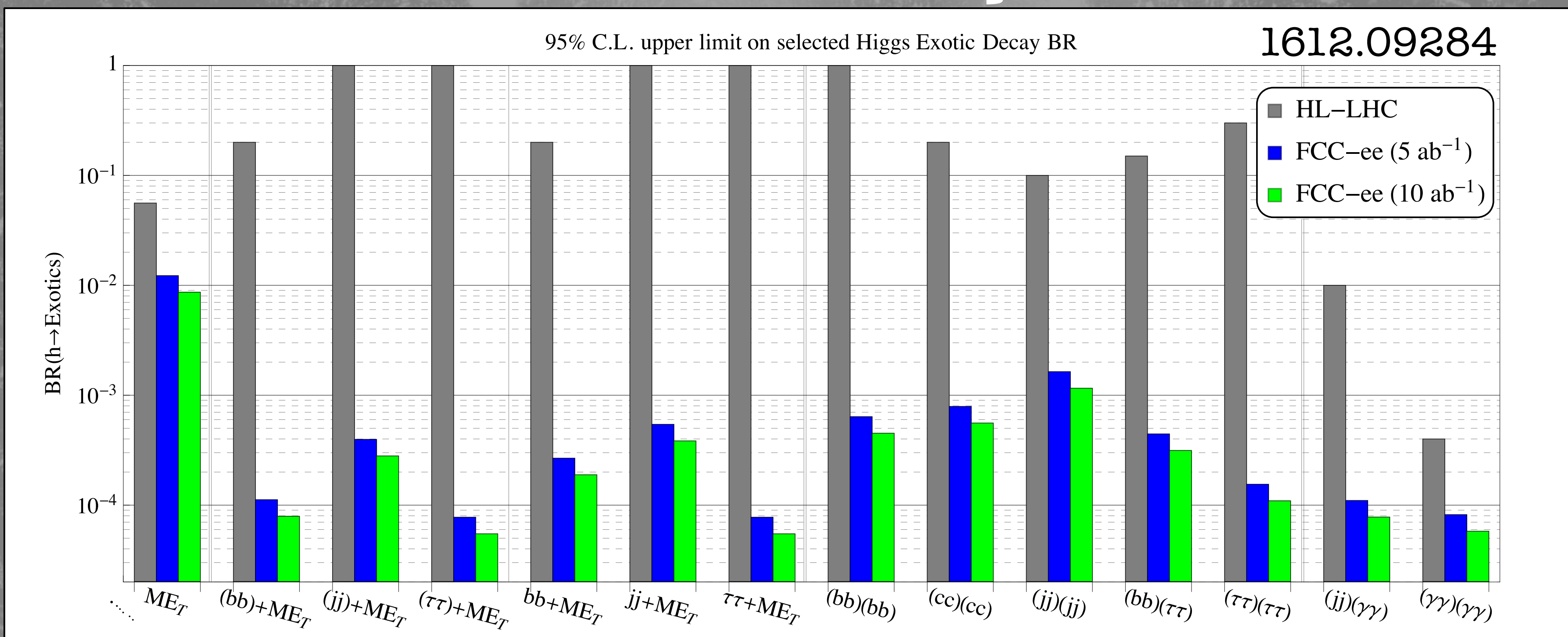
The standard model provides two examples of neutral bosons which can comfortably be light and have arbitrarily weak interactions:

Standard Model	Dark Sector
Z	Z'
π	a

Driving out the Darkness

The Higgs is totally different from other particles and could be our new window to the dark sector:





Driving out the Darkness

The … is totally different from other particles

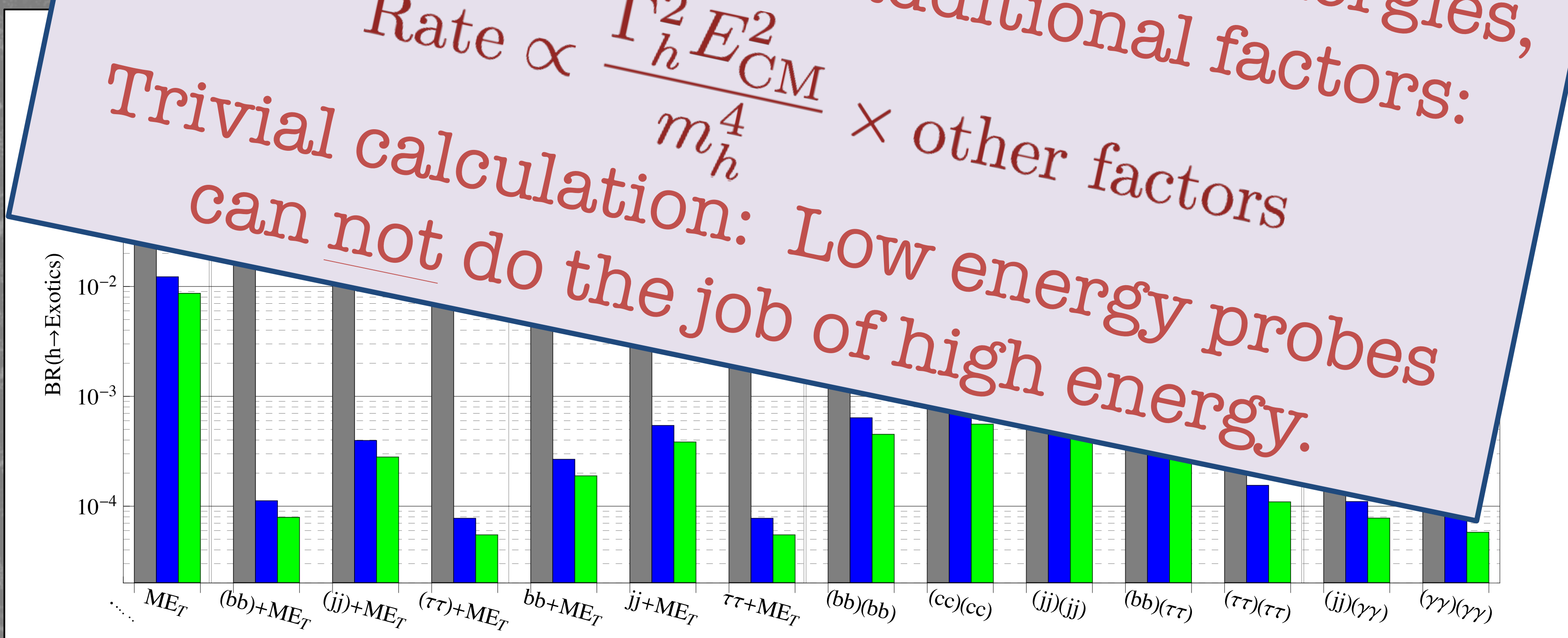
an… window to the dark sector:

Standard

The only way to search for such scenarios is with a Higgs boson. At lower energies, suppressed by tiny additional factors:

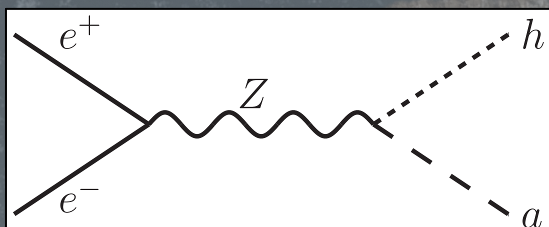
$$\text{Rate} \propto \frac{\Gamma_h^2 E_{\text{CM}}^2}{m_h^4} \times \text{other factors}$$

Trivial calculation: Low energy probes can not do the job of high energy.



Driving out the Darkness

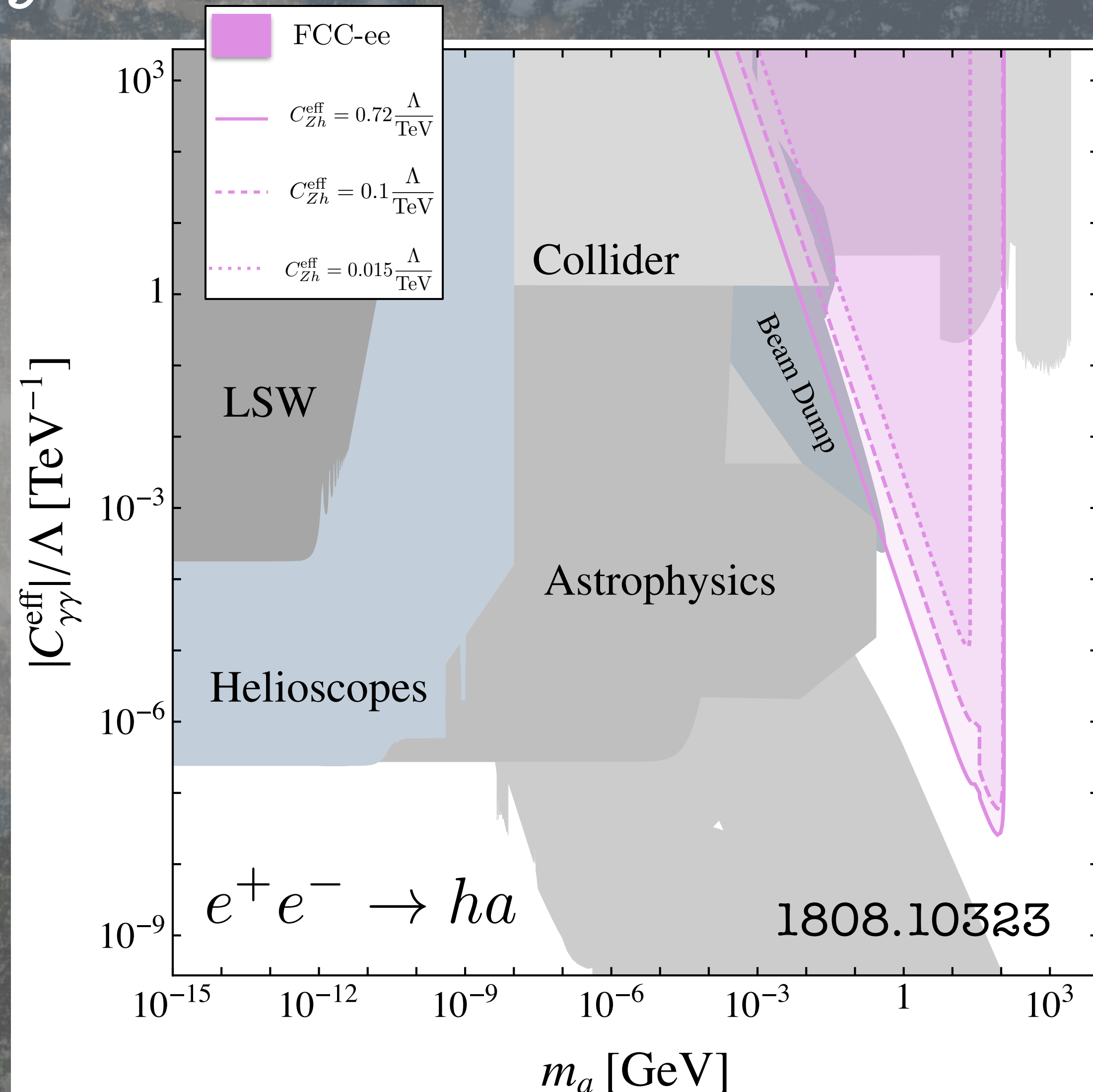
The Higgs can be a key player in production:



Followed by:

$$a \to \gamma\gamma$$

FCC-ee can probe extremely high scales through the Higgs.



Driving out the Darkness

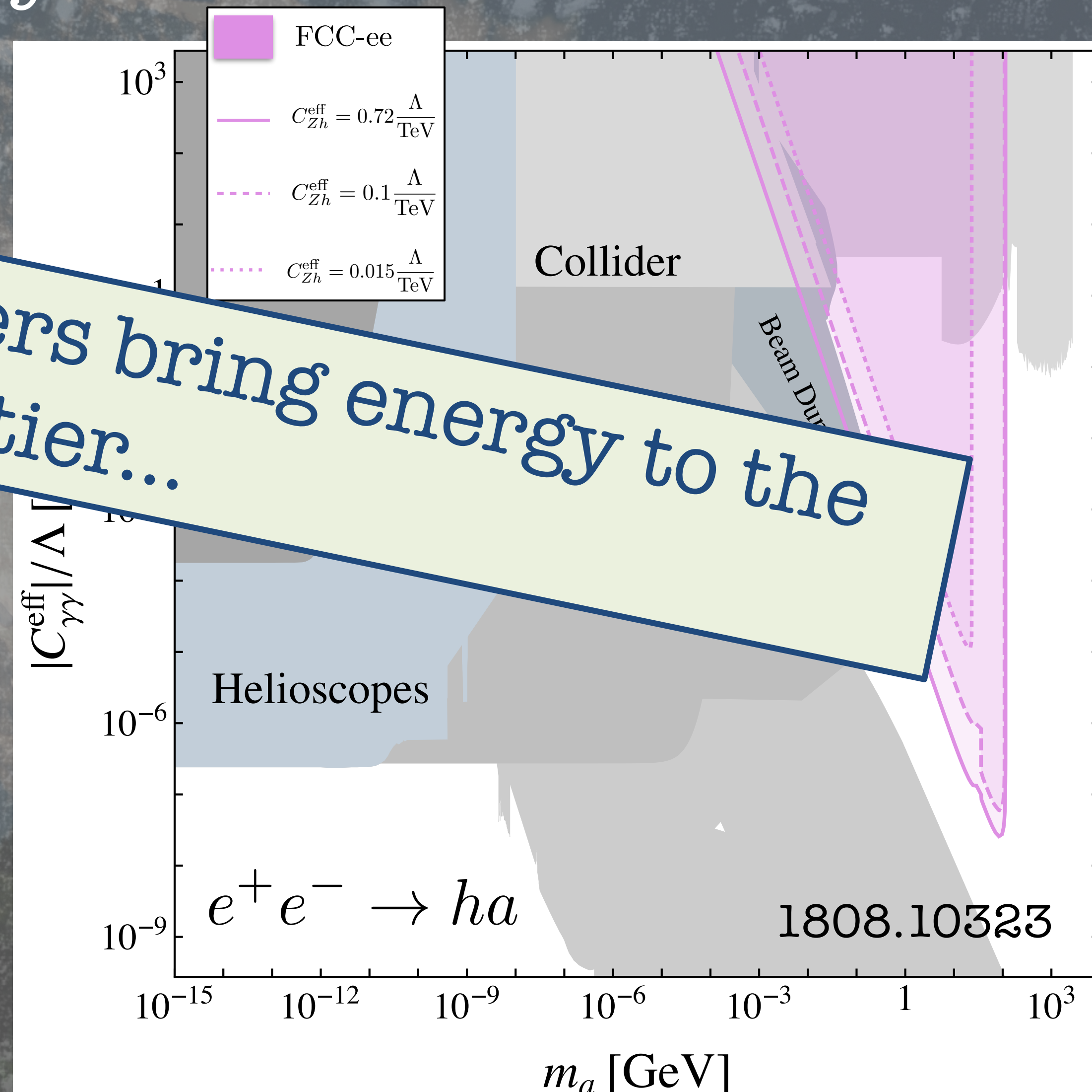
The Higgs can be a key player in production:

Followed by:

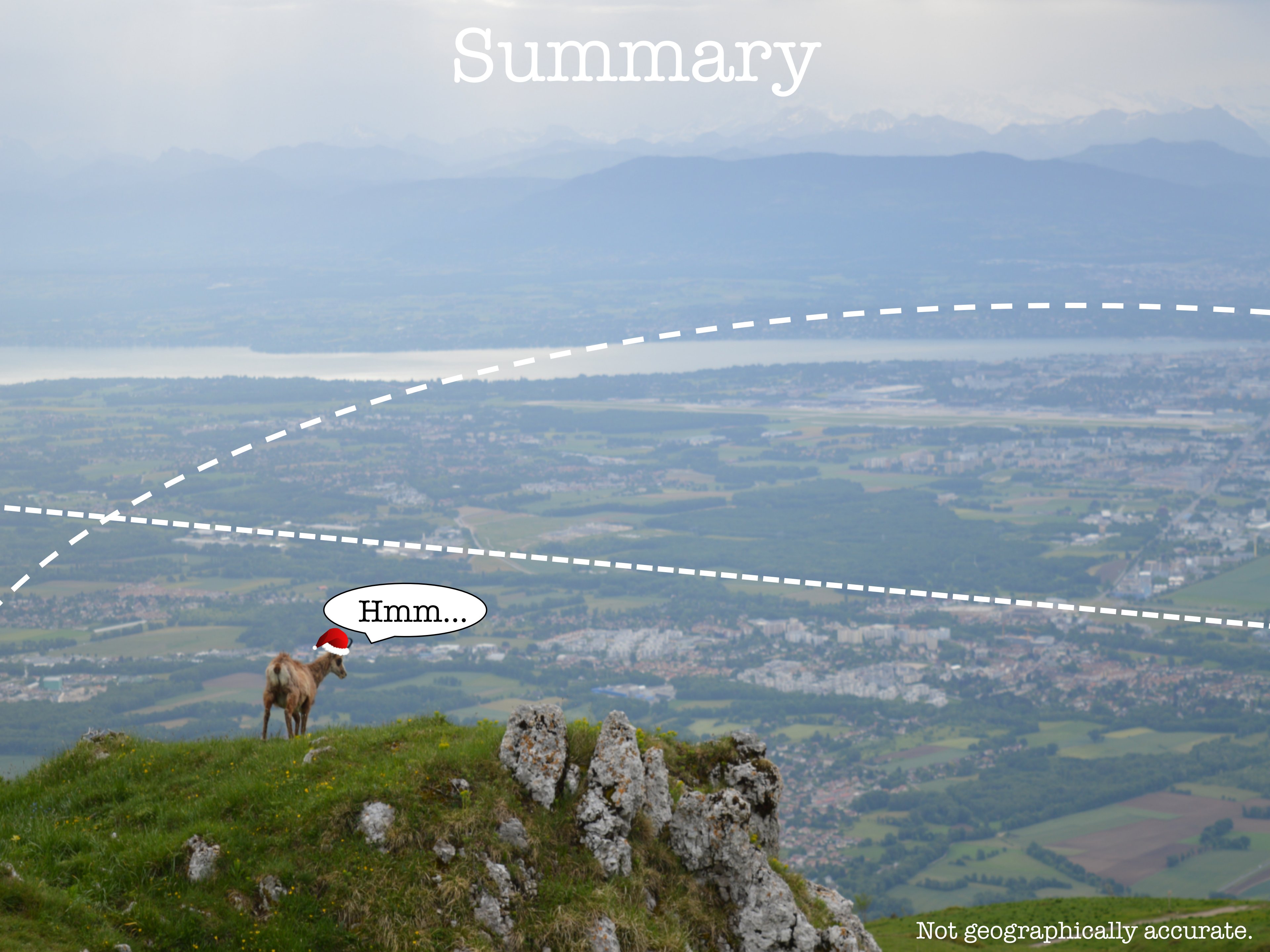
$$a \to \gamma\gamma$$

FCC-ee can probe extremely high scales through the Higgs.

Future colliders bring energy to the intensity frontier...



Summary

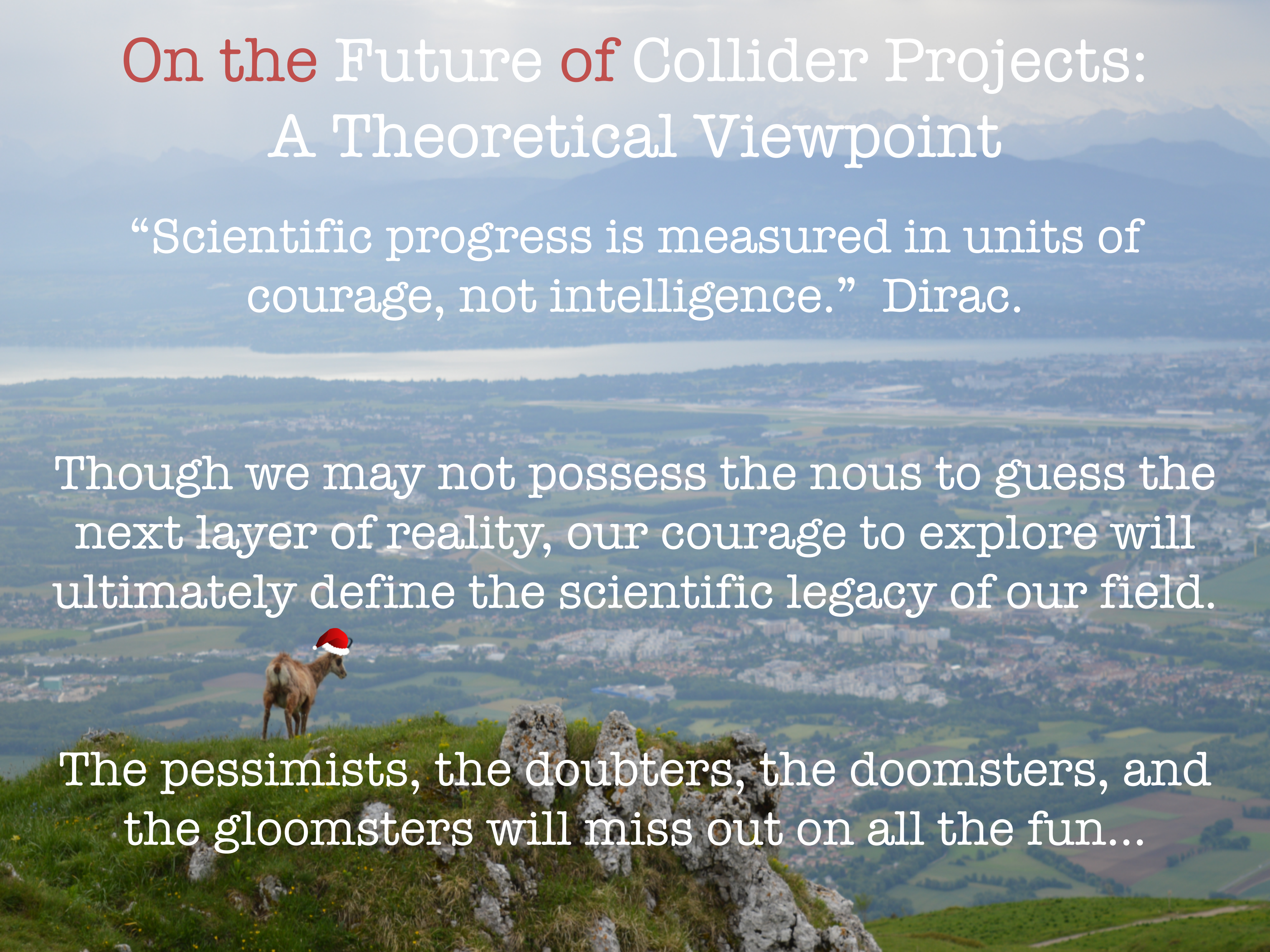


On the Future of Collider Projects: A Theoretical Viewpoint

"Scientific progress is measured in units of courage, not intelligence." Dirac.

Though we may not possess the nous to guess the next layer of reality, our courage to explore will ultimately define the scientific legacy of our field.

The pessimists, the doubters, the doomsters, and the gloomsters will miss out on all the fun…



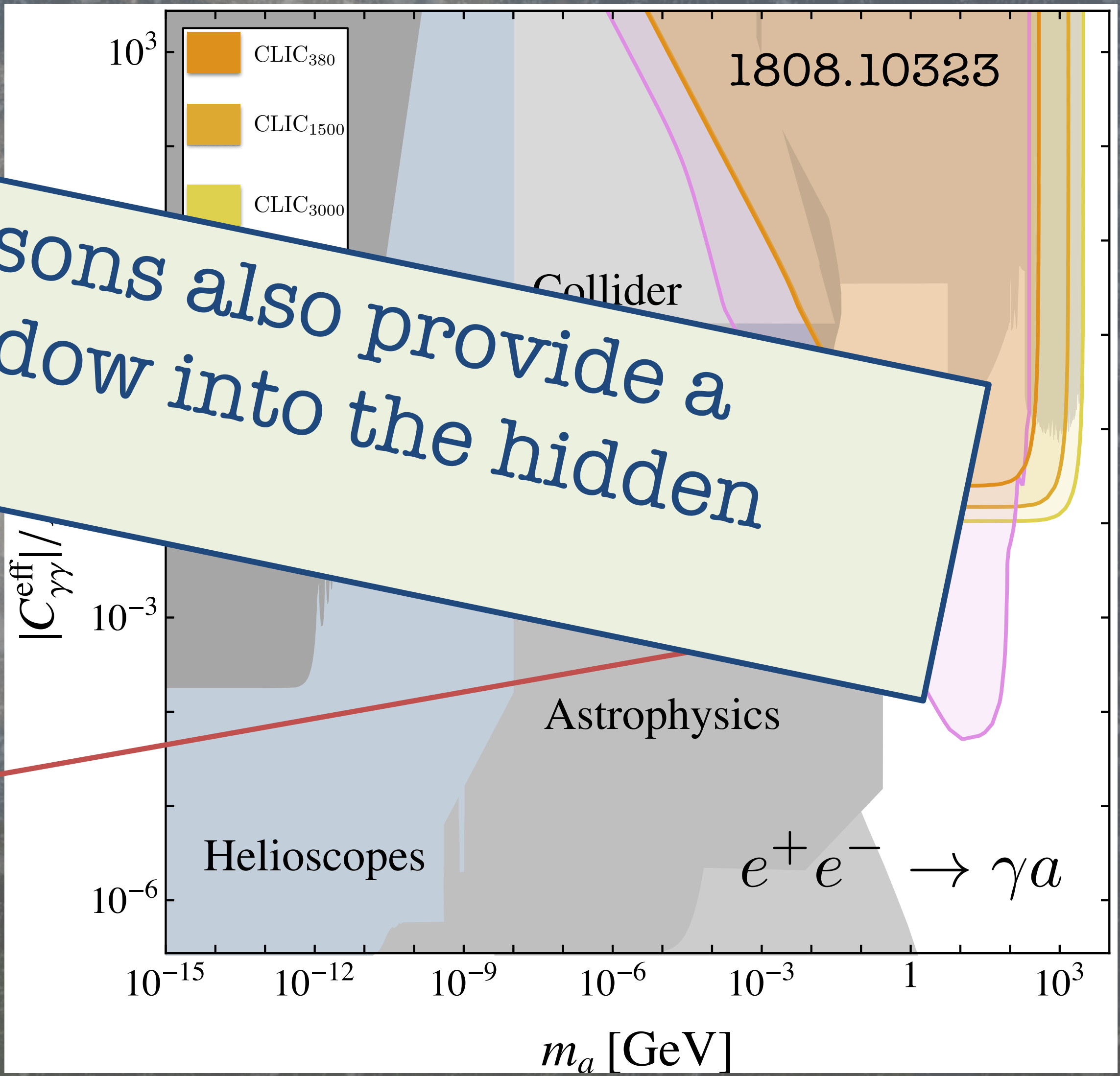
Driving out the Darkness

Key production channel:

Follow...

$$a \to \gamma\gamma$$

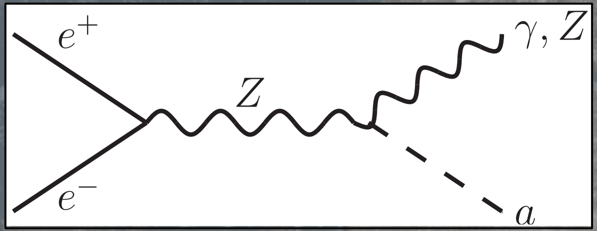
FCC-ee is an intensity frontier machine!!!



The other bosons also provide a potential window into the hidden sector...

Driving out the Darkness

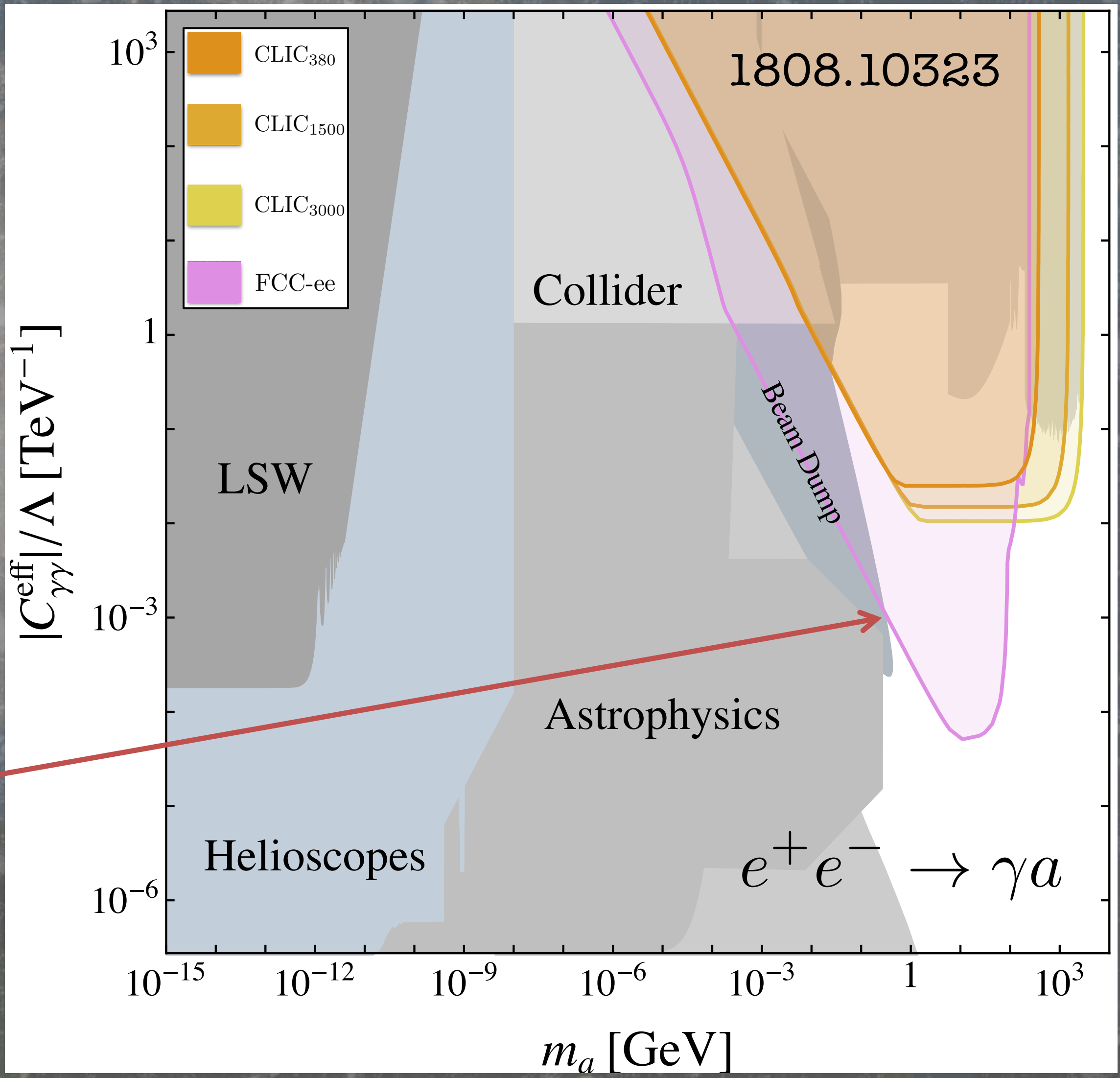
Key production channel:



Followed by:

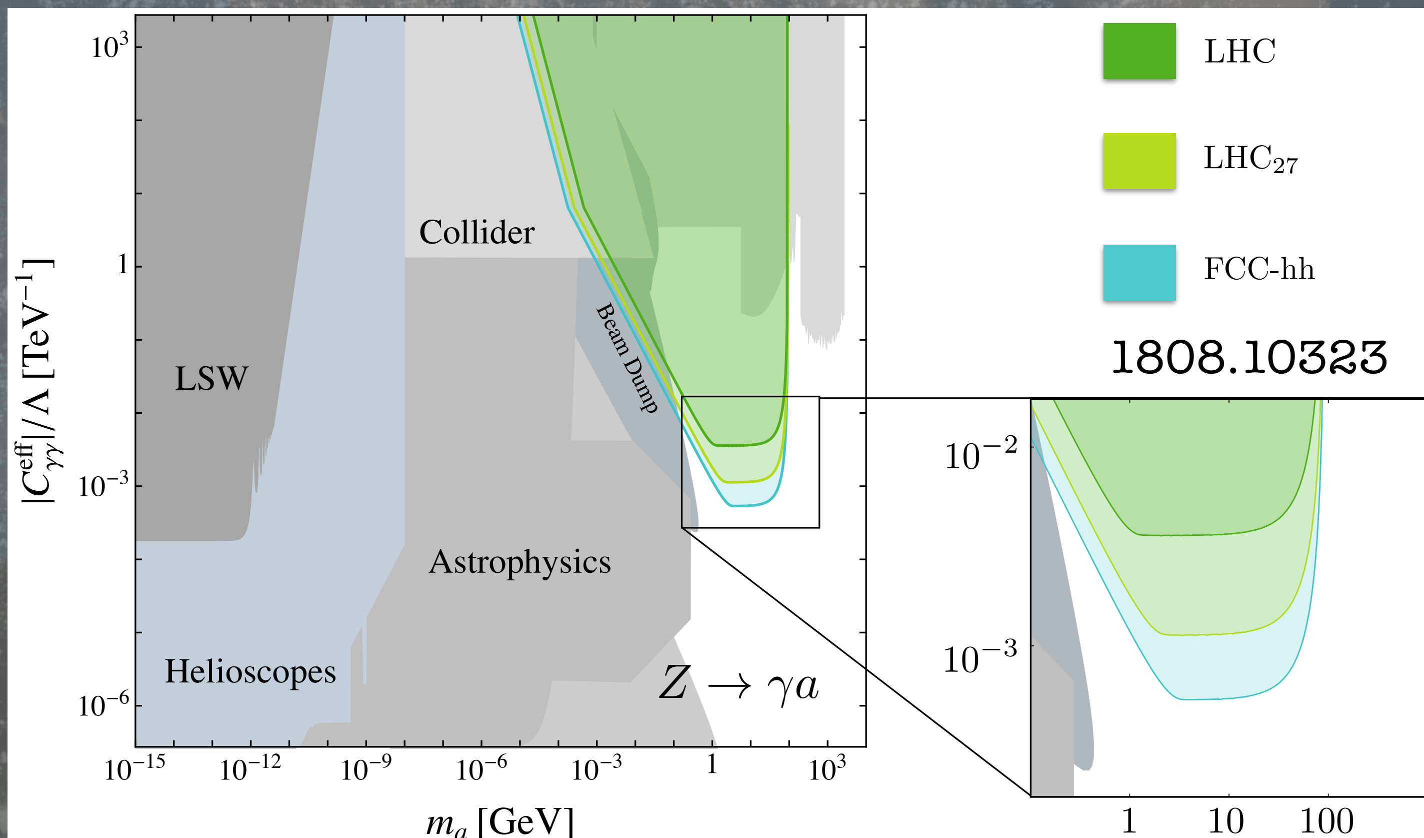
$$a \to \gamma\gamma$$

FCC-ee is an <u>intensity frontier</u> machine!!!



Driving out the Darkness

Future proton colliders can also reach intensity frontier levels:

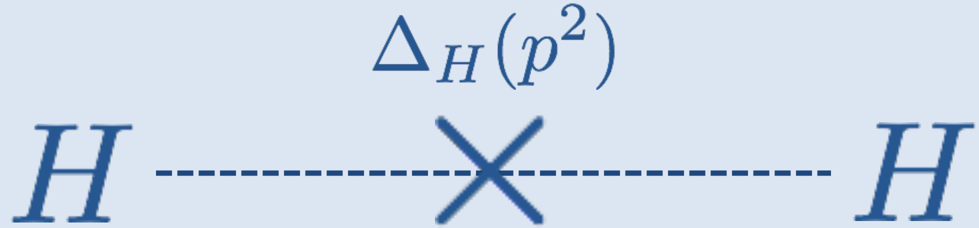


Again here searching for the decay: $a \to \gamma\gamma$

Oblique Corrections

Makes sense to extend to the Higgs sector. Especially since the Higgs can easily interact with new states…

- H-parameter:



One can also translate basis to one in which this is a four-fermion operator and some more involving the Higgs

$$\mathcal{O} \propto \frac{\lambda^2 \hat{H}}{m_h^2}(\overline{\psi}\psi)^2$$

If new physics model interacts primarily with Higgs, then original basis may be better for interpretation purposes.