Higgs Measurements at Future Circular Colliders

WIN2021

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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

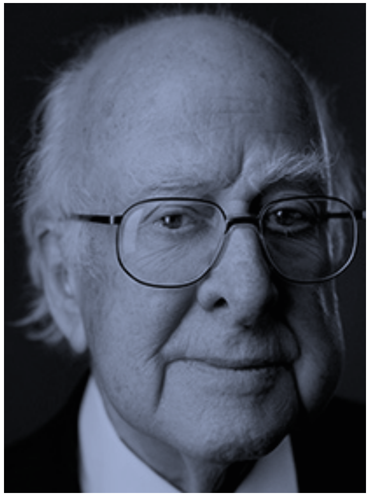
European Strategy for Particle Physics Preparatory Group

(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.

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 $\hbar$ 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⋆	5.0	2.2	3.7	4.7	3.9	0.29
$\kappa_{Z\gamma}$ [%]	10.	–	5.7	3.8	99⋆	86⋆	85⋆	120⋆	15	6.9	8.2	81⋆	75⋆	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⋆	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

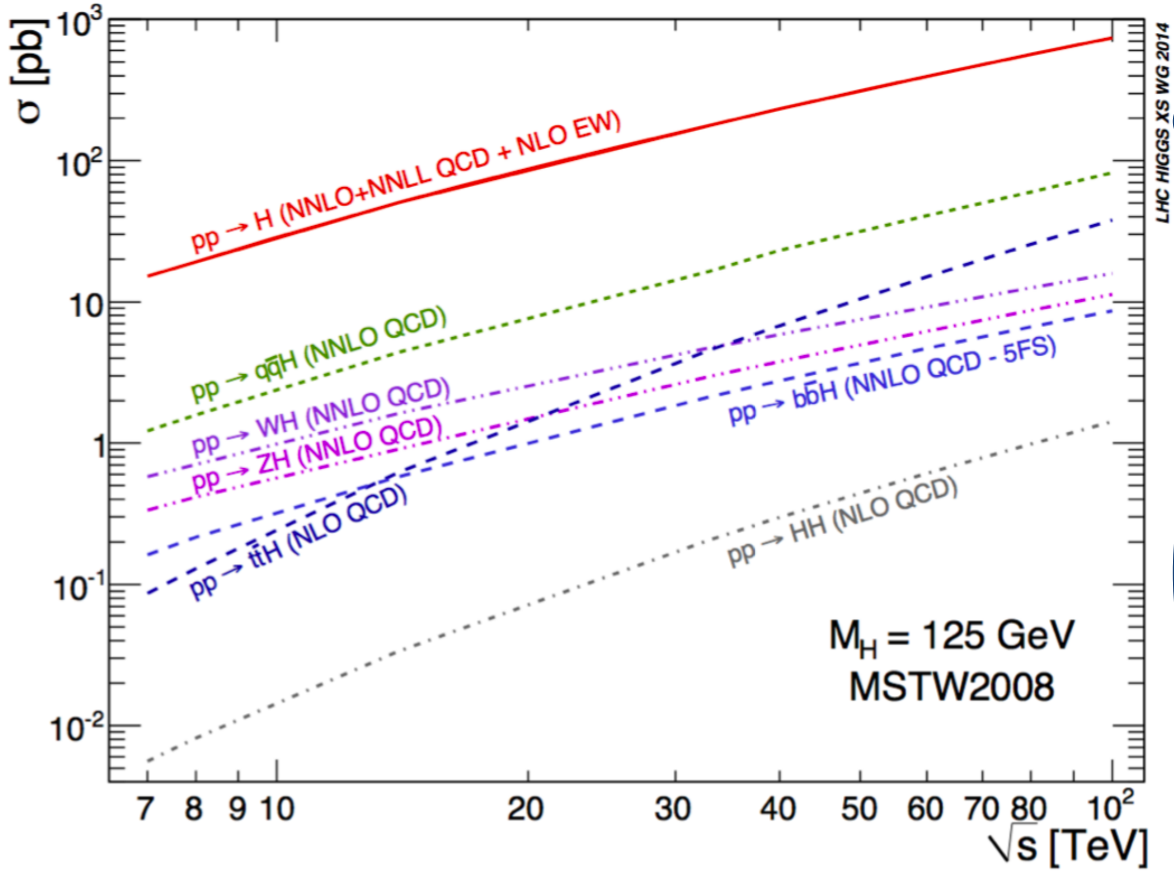
But we all know there is more to physics than Kappas...

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.

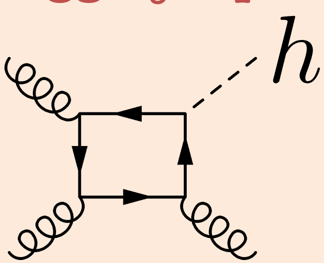
High energy also buys high precision. Not only for the Higgs, across the entire physics program.

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



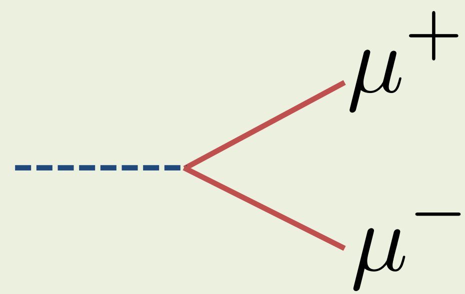
$+\ldots$ other diagrams

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.

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

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

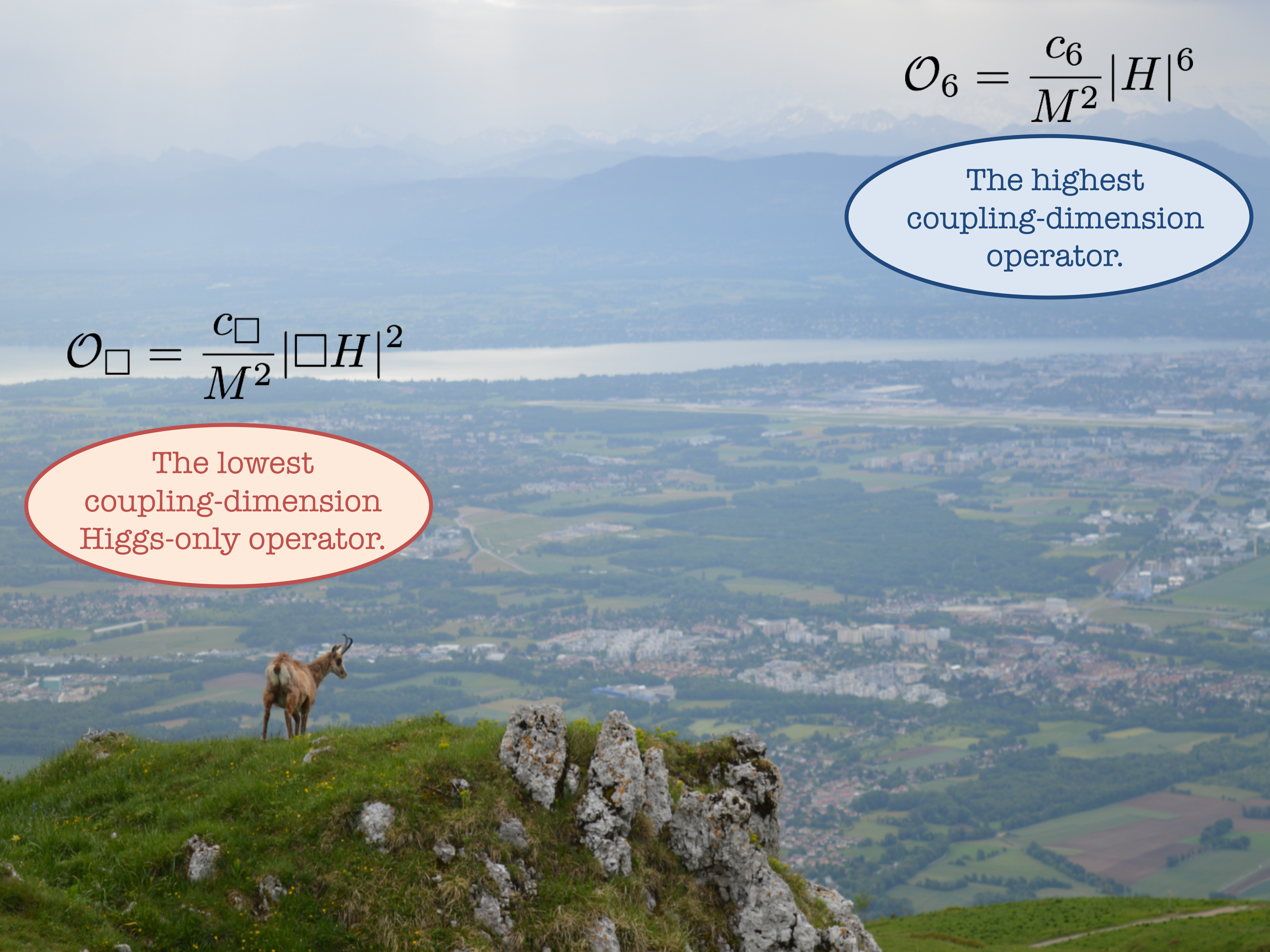
$$\mathcal{O}_B = \frac{ig'\, c_B}{2M^2}(H^\dagger \overleftrightarrow{D}^\mu H)\partial^\nu B_{\mu\nu} \qquad \mathcal{O}_6 = \frac{c_6}{M^2}|H|^6 \qquad \mathcal{O}_{GG} = \frac{g_s^2\, c_{GG}}{M^2}|H|^2 G^{a,\mu\nu} G^a_{\mu\nu}$$

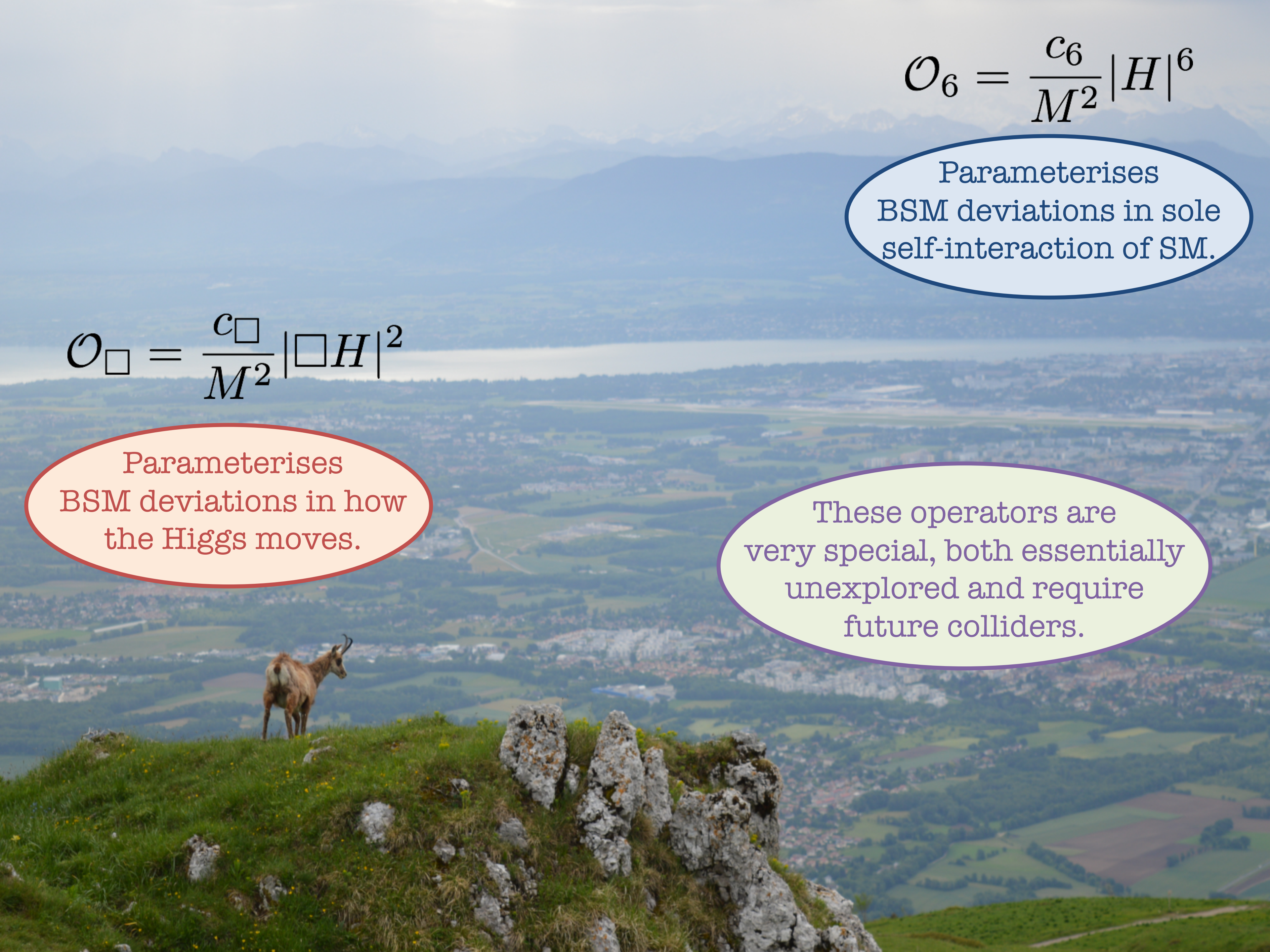
$$\mathcal{O}_H = \frac{c_H}{2M^2}\left(\partial^\mu |H|^2\right)^2 \qquad \mathcal{O}_R = \frac{c_R}{M^2}|H|^2 |D^\mu H|^2$$

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

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

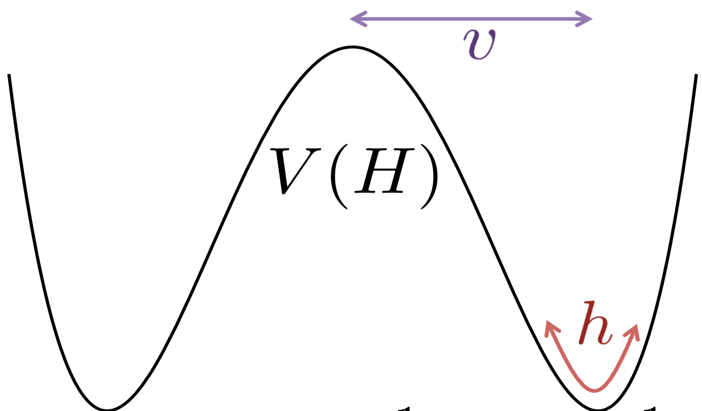
Operators like those above capture leading effects of heavy physics beyond the standard model. Probing them could reveal origins.

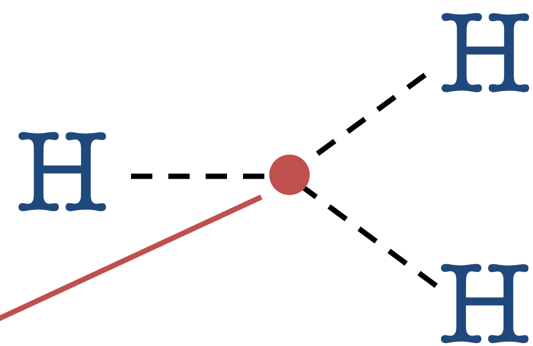

$\mathcal{O}_6 = \frac{c_6}{M^2}|H|^6$
The highest coupling-dimension operator.
$\mathcal{O}_{\Box} = \frac{c_{\Box}}{M^2}|\Box H|^2$
The lowest coupling-dimension Higgs-only operator.


$\mathcal{O}_6 = \frac{c_6}{M^2}|H|^6$
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.
These operators are very special, both essentially unexplored and require future colliders.

A Unique Operator

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



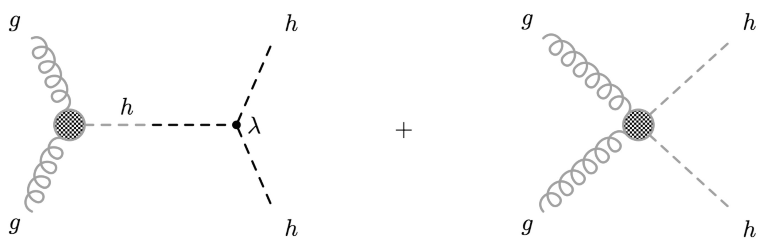


$$\underbrace{\frac{1}{2} m_h^2 h^2}_{\text{Mass}} + \underbrace{\frac{1}{6} \lambda h^3}_{\text{Self Interaction}} + \ldots$$

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

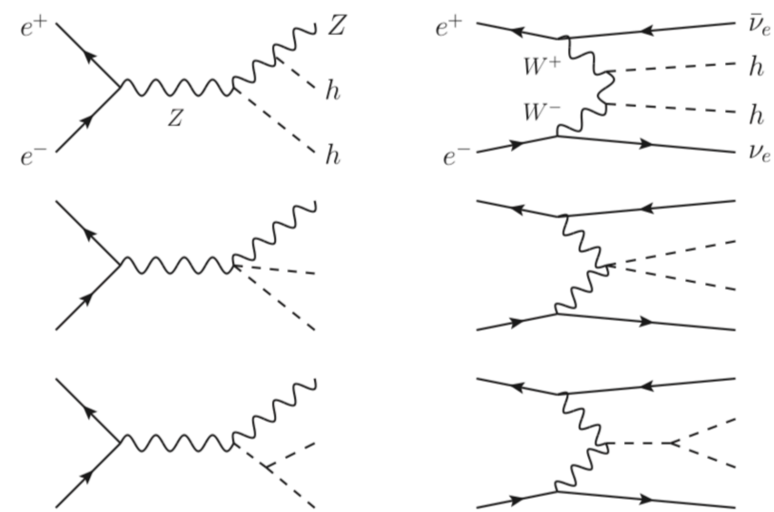


And most promising final state is

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

although a combination is better.

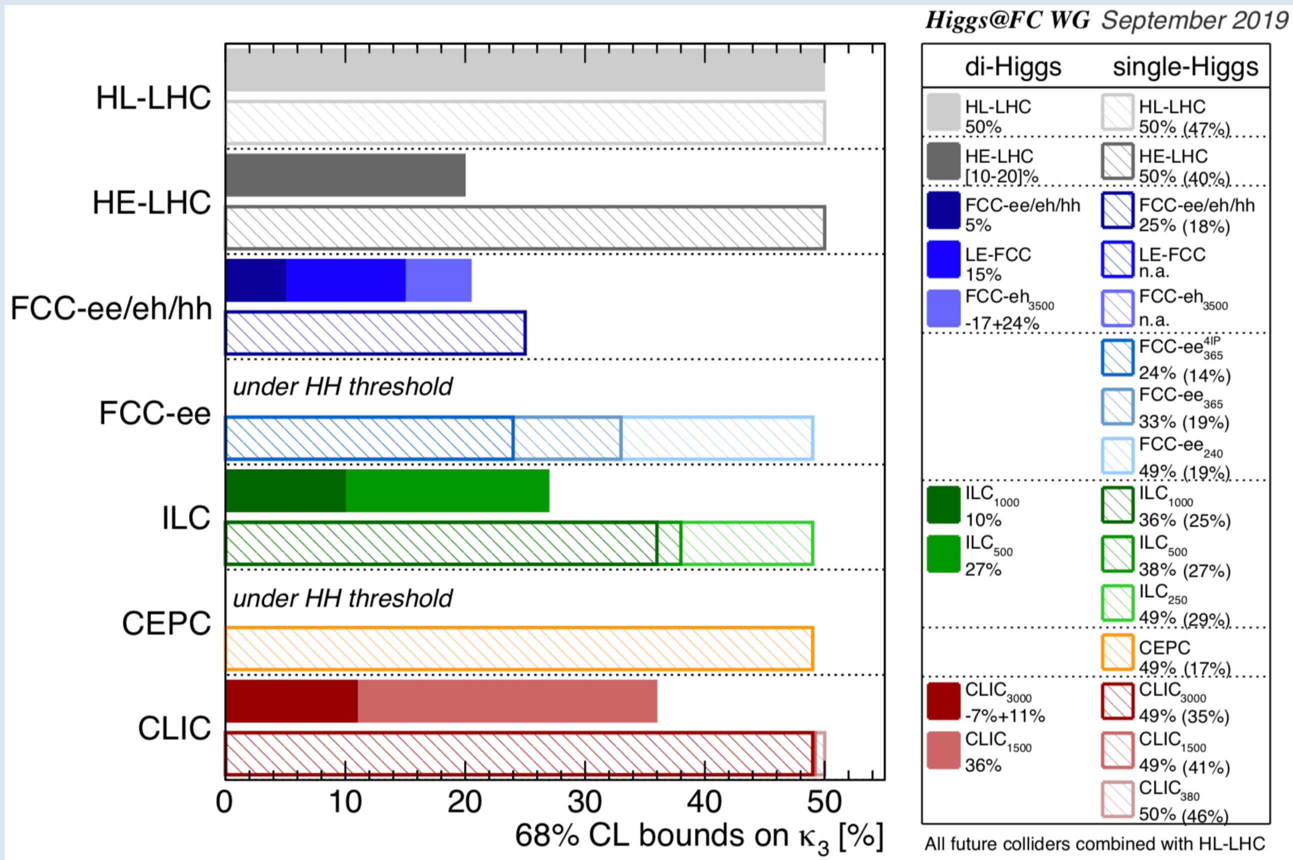
At lepton colliders a variety of pair production processes are possible.



A clean detector environment helps as well.

A Unique Operator

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



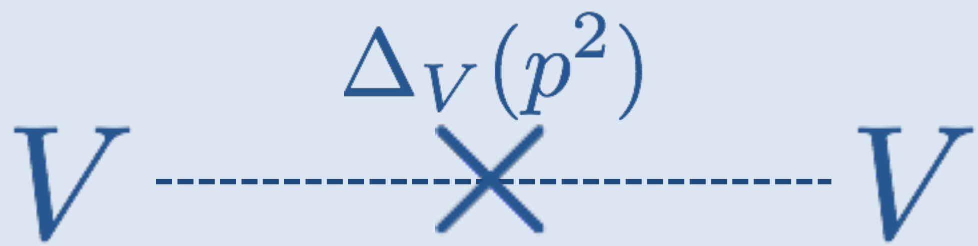
ECFA Higgs Working Group Report 1905.03764

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:

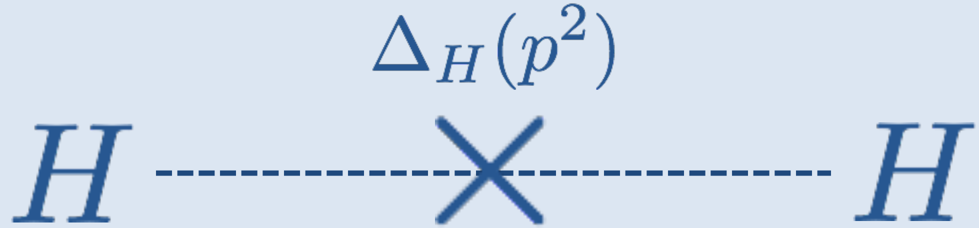
$$\Delta_W(p^2) \approx \frac{1}{p^2 - M_W^2} - \frac{\hat{W}}{M_W^2}$$

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

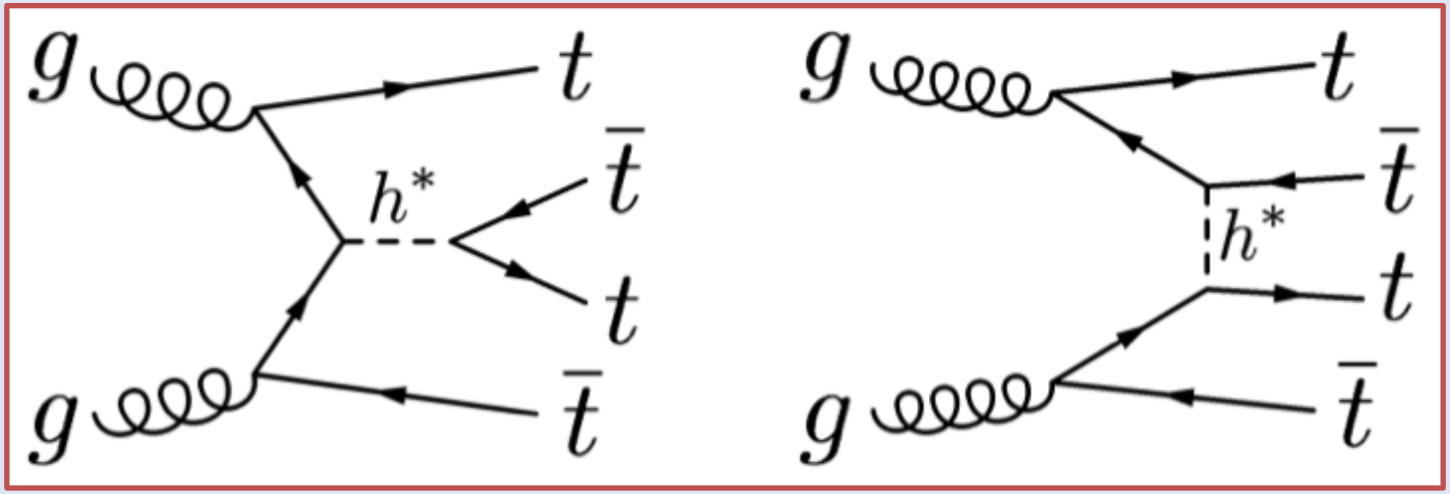
This also contributes to amplitudes in an "energy-growing" manner:

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

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:

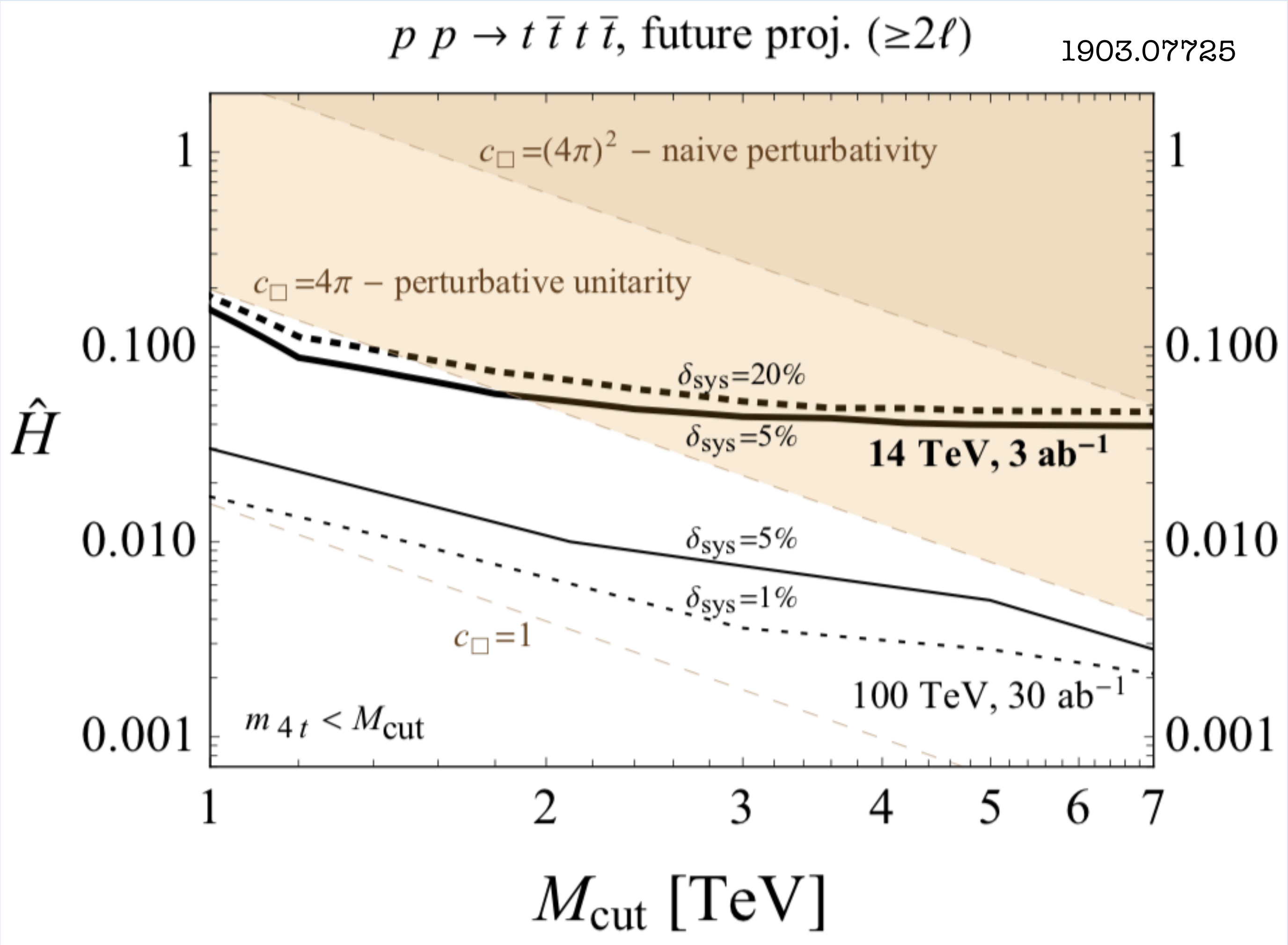


We may relate this Wilson coefficient to the scale of new physics as:

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

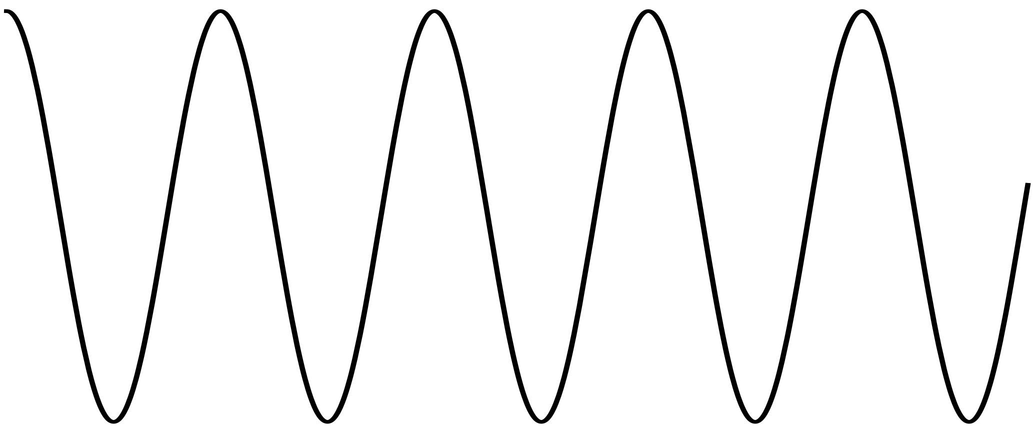
Oblique Corrections

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



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".

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

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

Is the Higgs Fundamental?

If the Higgs is made up of constituents

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

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

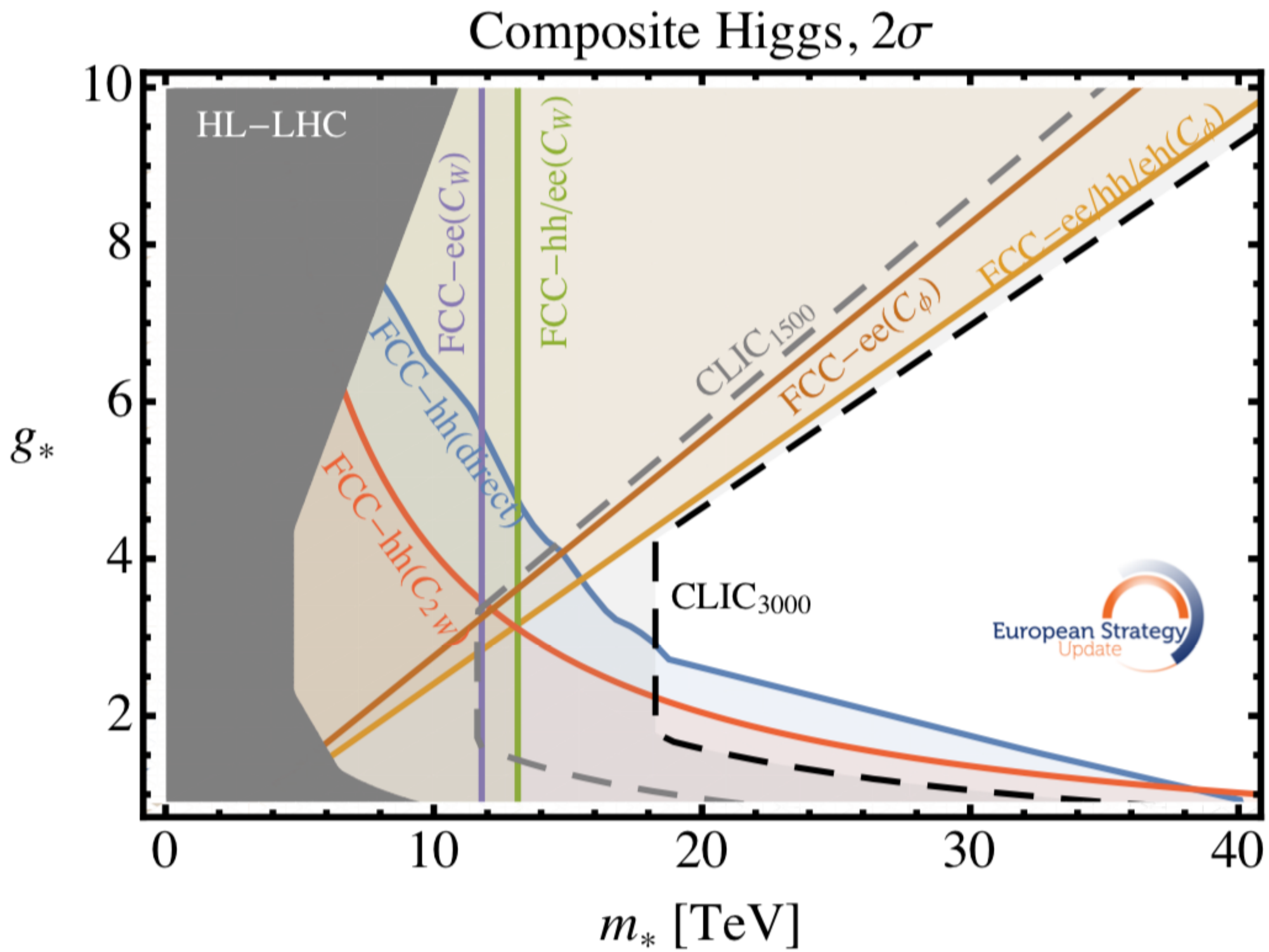
Such models can be thought of as realising the Higgs boson analogously to the pion in QCD.

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

Should also get other heavy resonances then!

Is the Higgs Fundamental?

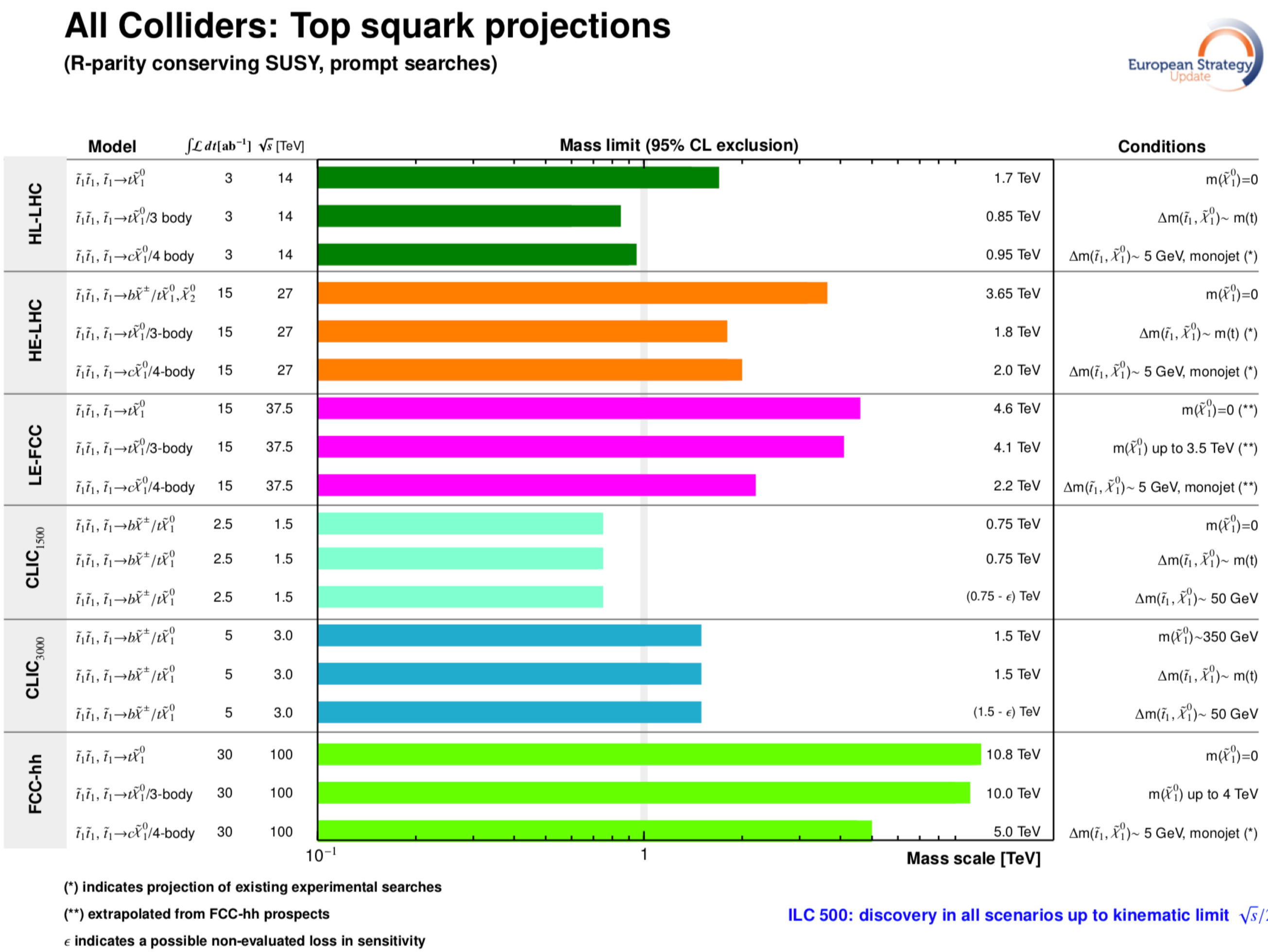
Including direct searches for the associated composite-sector mesons



provides valuable complementary information.

Or fundamental to small scales?

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

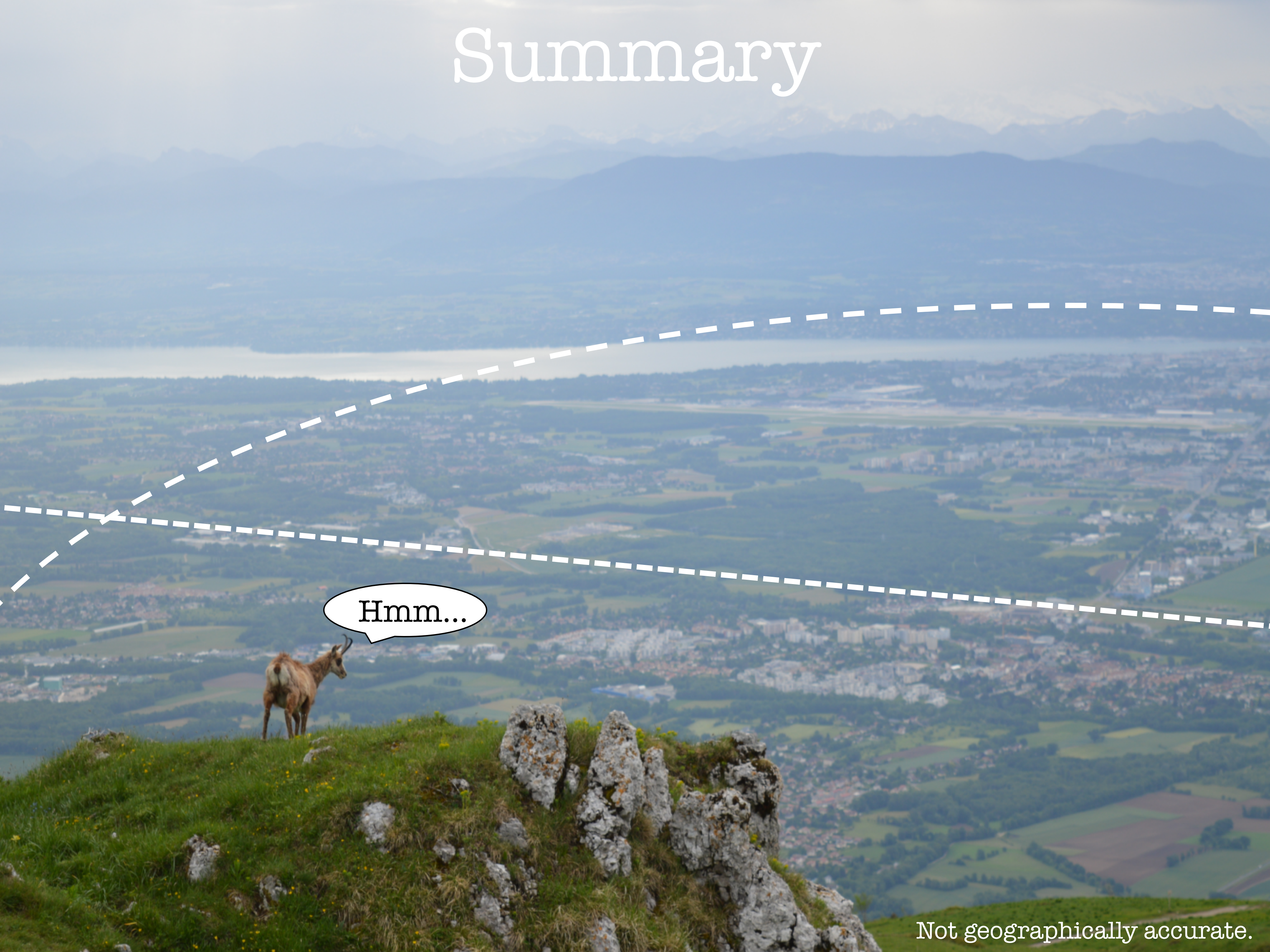


Stop!

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.


Summary
Hmm...
Not geographically accurate.