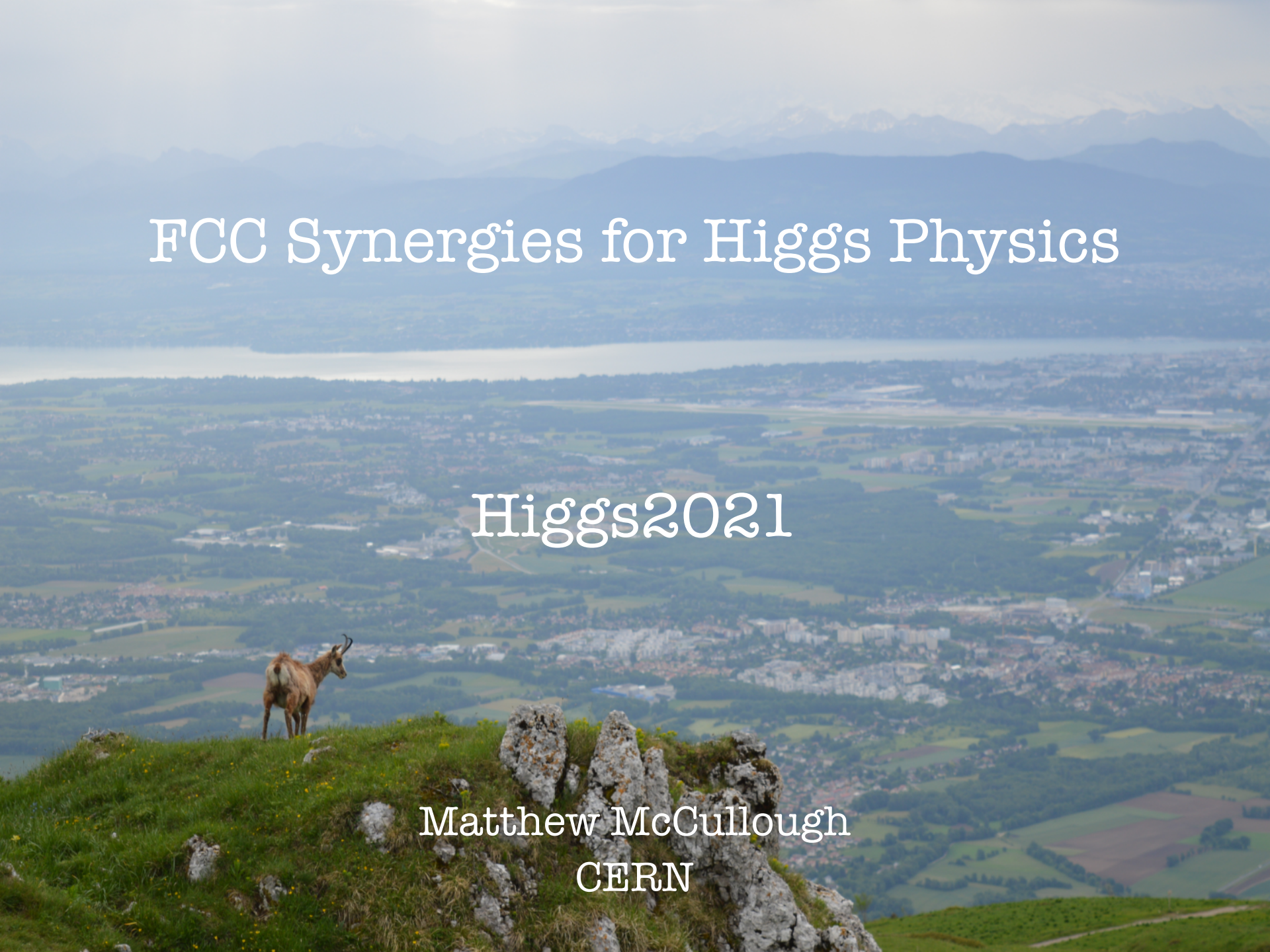


FCC Synergies for Higgs Physics

Higgs2021

Matthew McCullough
CERN

How well should we know Higgs properties?

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

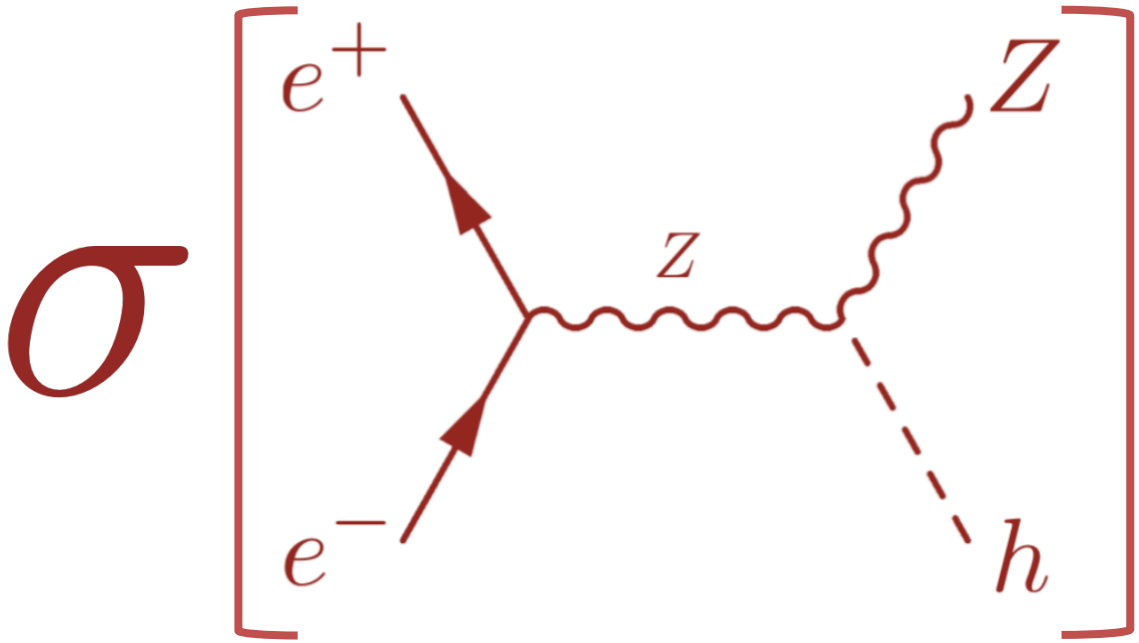
Better: Claiming to have discovered something requires around 20% precision, to claim 5σ.

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...

Higgs Factories

- Lepton colliders offer a unique measurement:



- An unambiguous measurement of the total cross section, and indirectly the Higgs width!
- This would be a boon to entire Higgs effort, as feeds into hadron-collider Higgs measurements to break redundancies and maximise impact.

Higgs Factories

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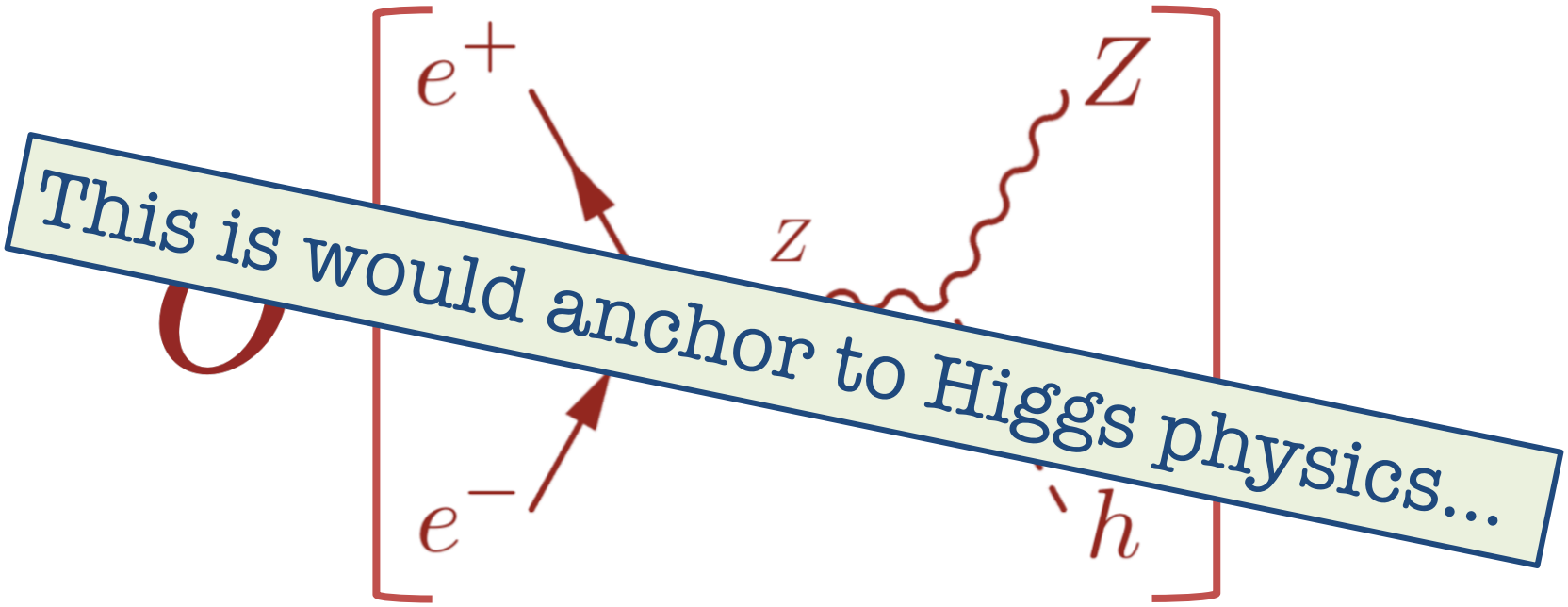


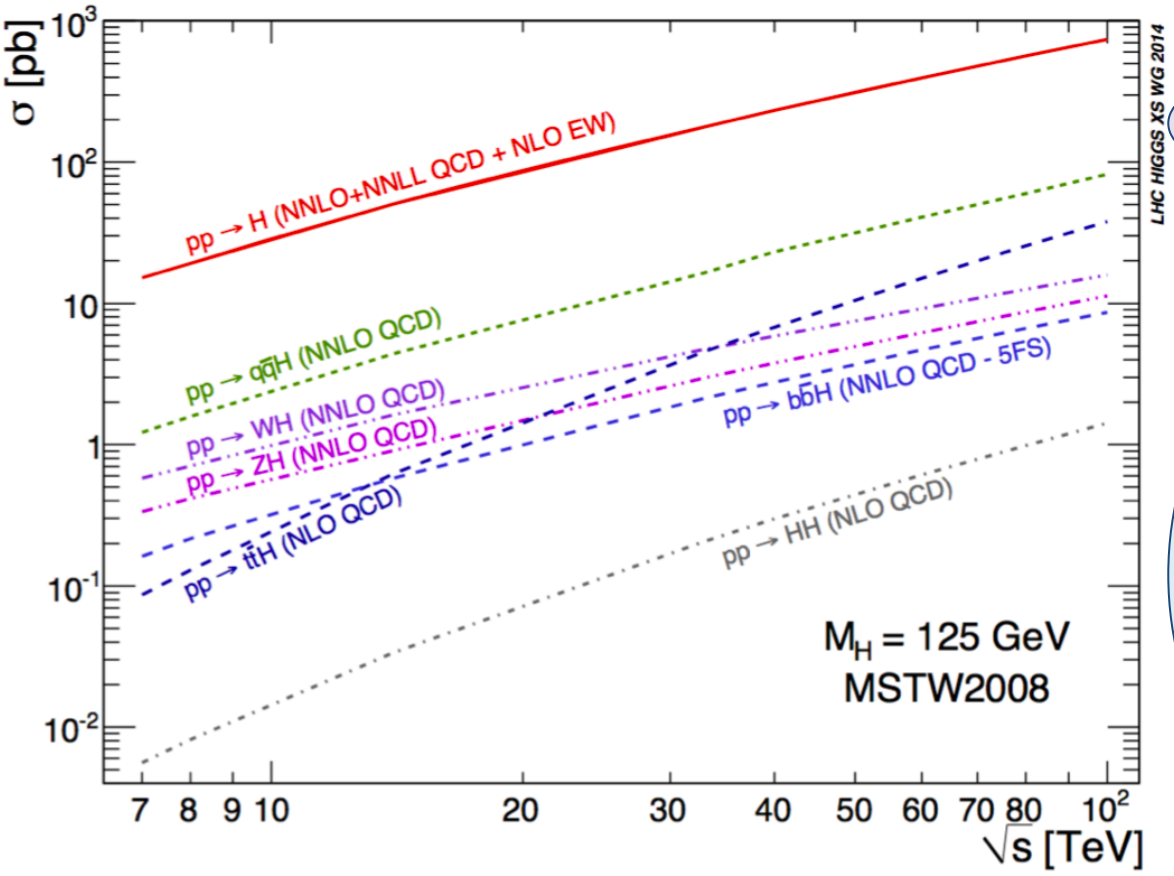
- An unambiguous measurement of the total cross section, and indirectly the Higgs width!
- This would be a boon to entire Higgs effort, as feeds into hadron-collider Higgs measurements to break redundancies and maximise impact.

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.

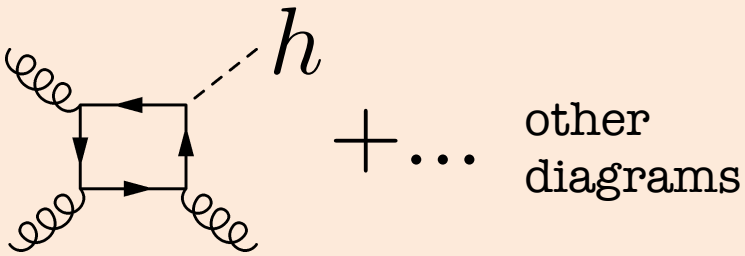
High energy also buys high precision. Not only for the Higgs, across the entire physics program.

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

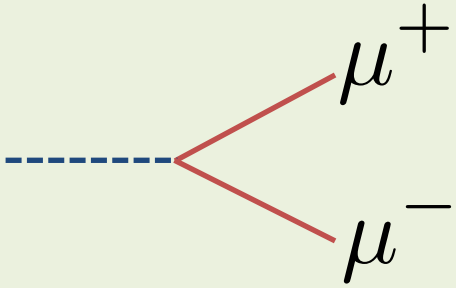


Would occur at Higgs p_T's as large as 7 TeV!

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.

How well should we know Higgs properties?

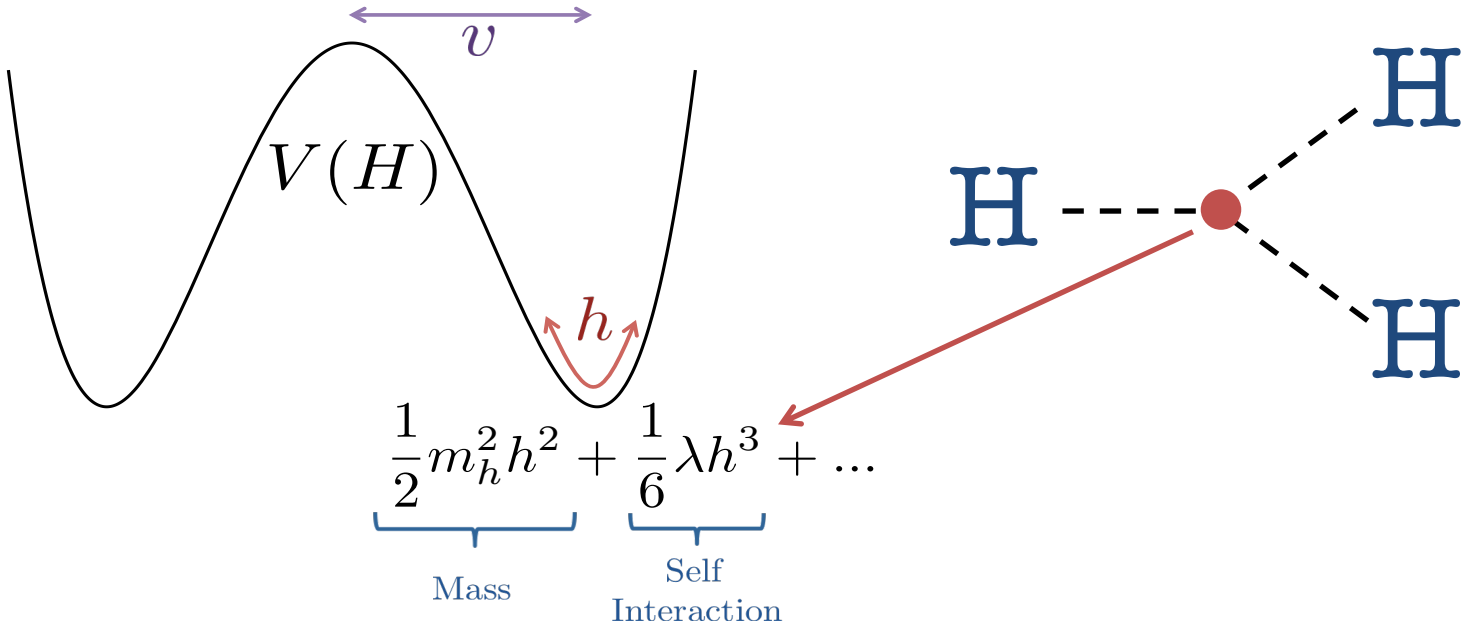
Future colliders can realise many life goals:

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...

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 Interaction

The interaction,

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

is very very special, since:

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

At one-loop we have:

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

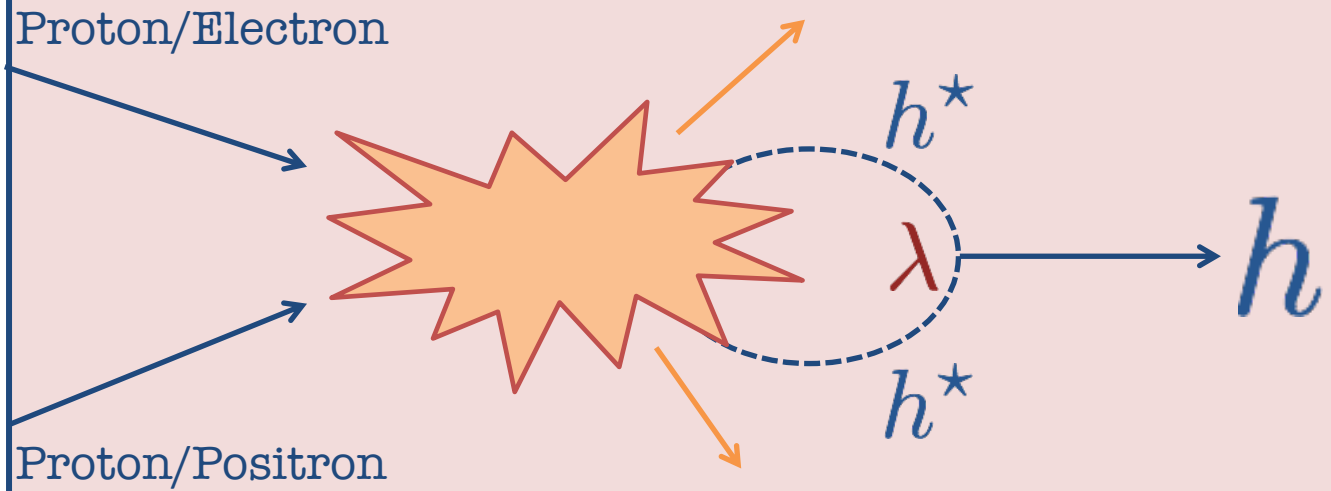
Thus, if any other coupling enters the game, coupling dimension is too large to match any other dim-6 operator!

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!

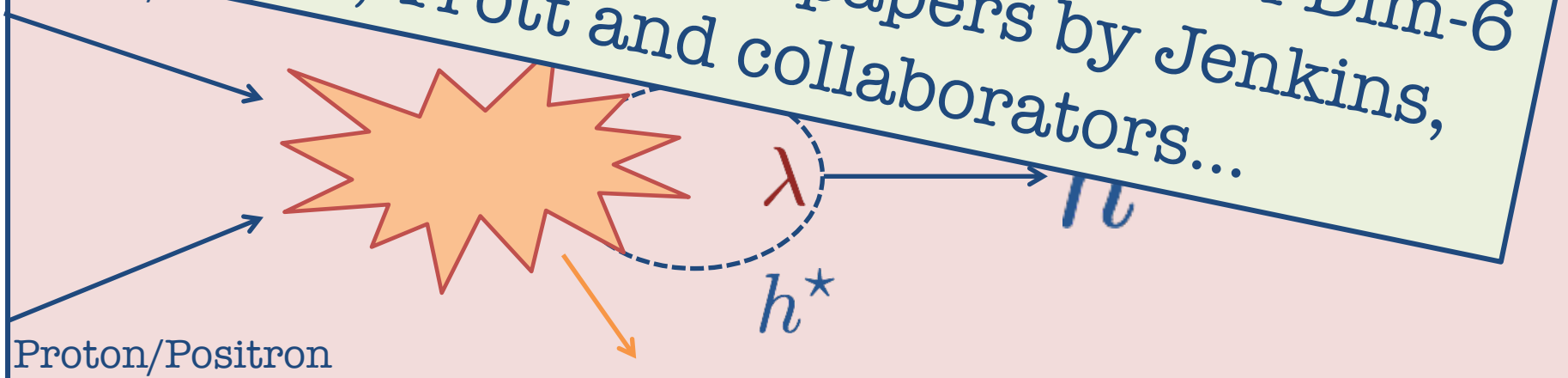
A Unique Operator

Observation:

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

...in-top in RG-space.

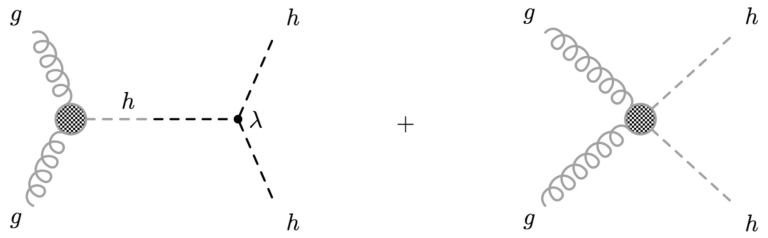
Can see where it lies in the space of Dim-6 operator RG space in papers by Jenkins, Manohar, Trott and collaborators...



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

A Unique Operator

At hadron colliders dominant production is via gluon fusion

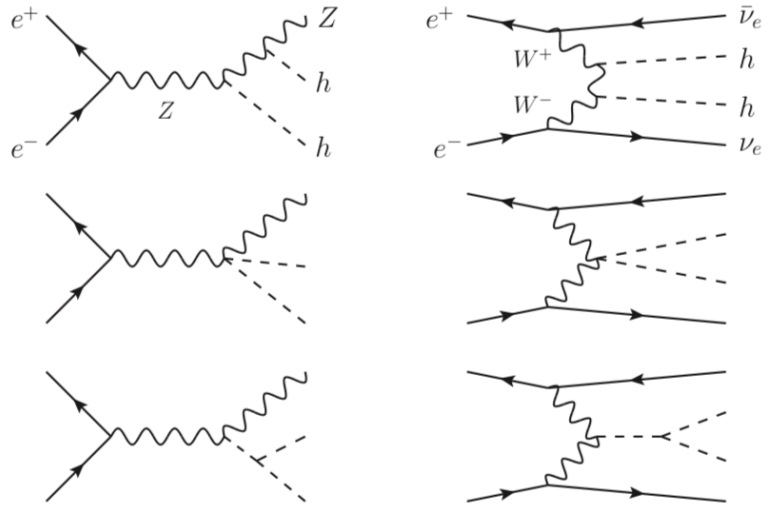


And most promising final state is

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

although a combination is better.

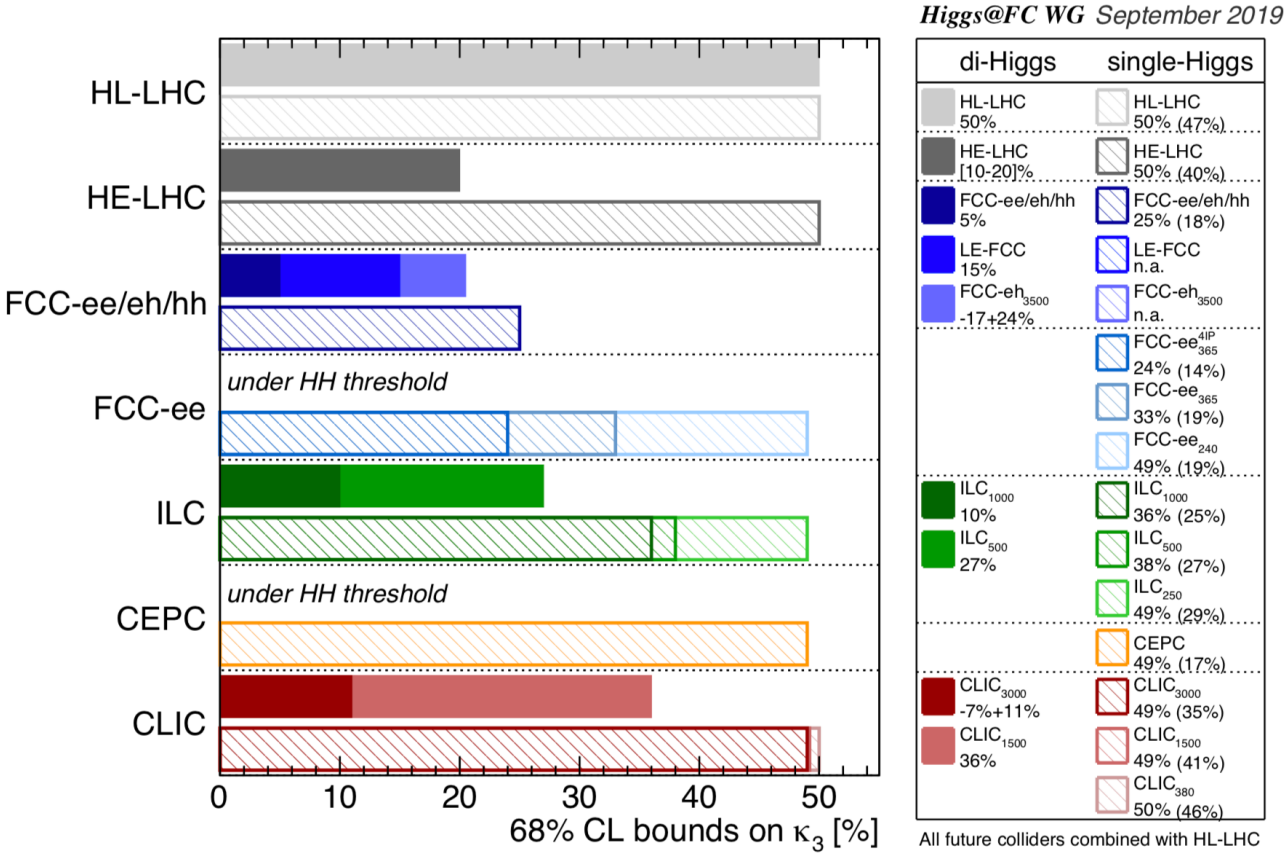
At lepton colliders a variety of pair production processes are possible.



A clean detector environment helps as well.

A Unique Operator

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

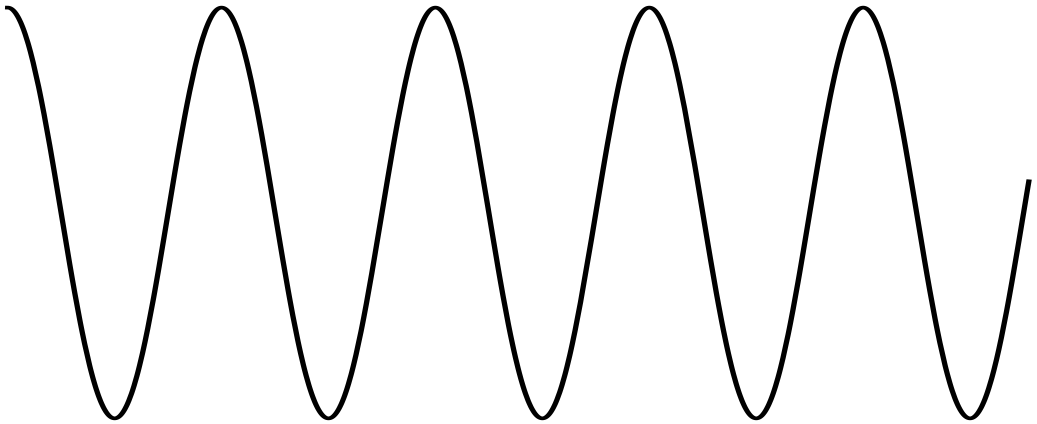


ECFA Higgs Working Group Report 1905.03764

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

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?

If the Higgs is made up of constituents

$$H = \overline{f} f \sim f$$

$$\xi \sim \frac{v^2}{f^2}$$

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

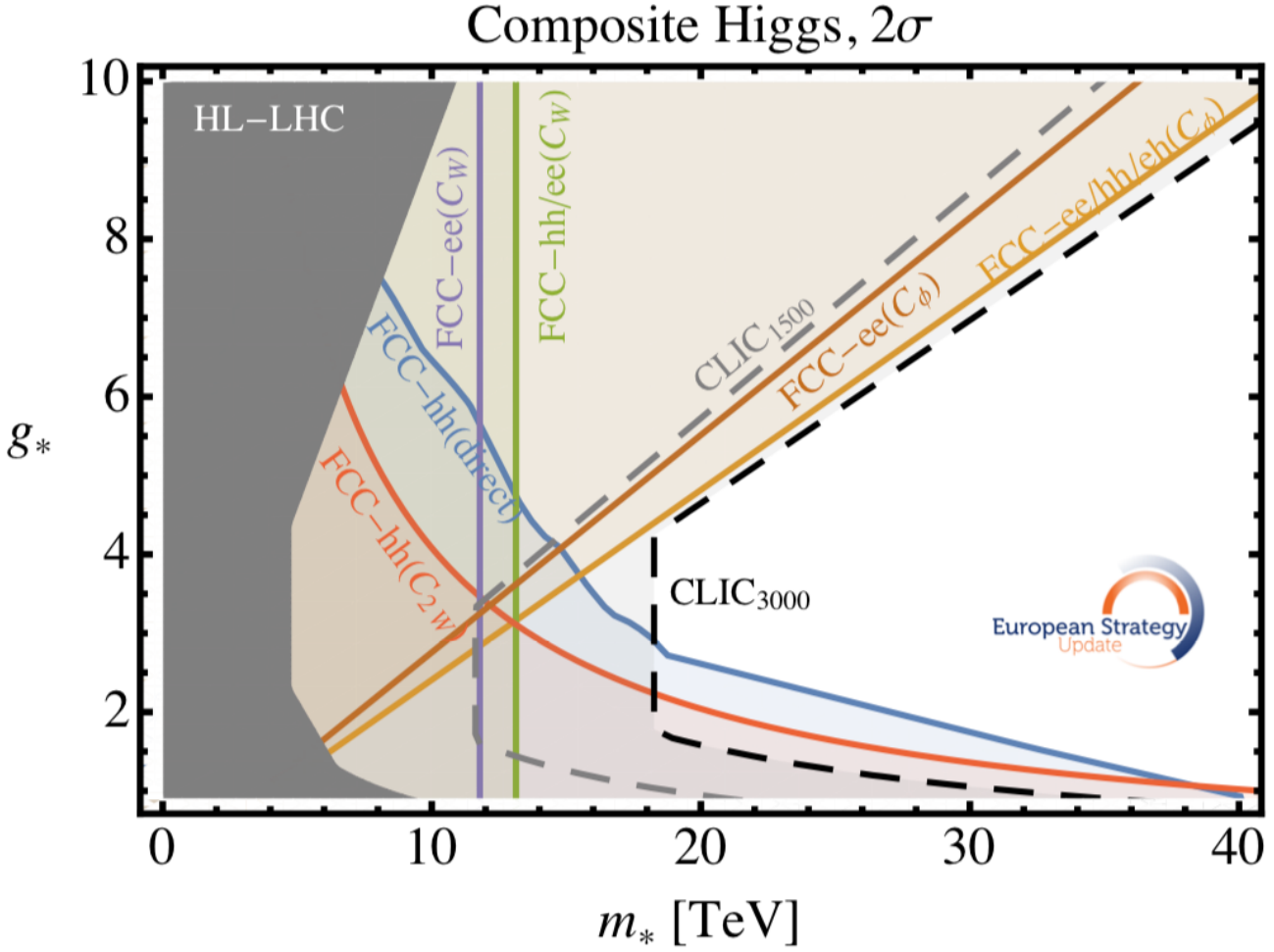
Such models can be thought of as realising the Higgs boson analogously to the pion in QCD.

$$\rho = \overline{f} f \sim \Lambda$$

Should also get other heavy resonances then!

Is the Higgs Fundamental?

Including direct searches for the associated composite-sector mesons



provides valuable complementary information.

Summary