How does the Higgs Move?

Higgs-Maxwell Meeting
Edinburgh

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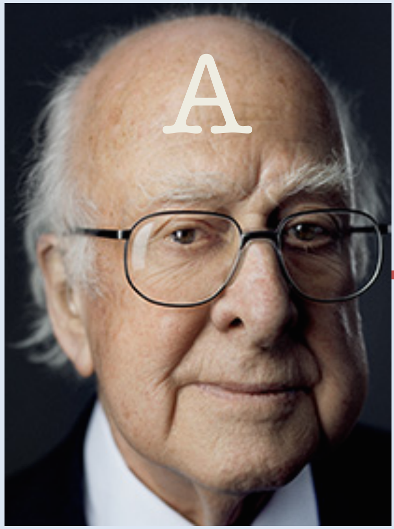
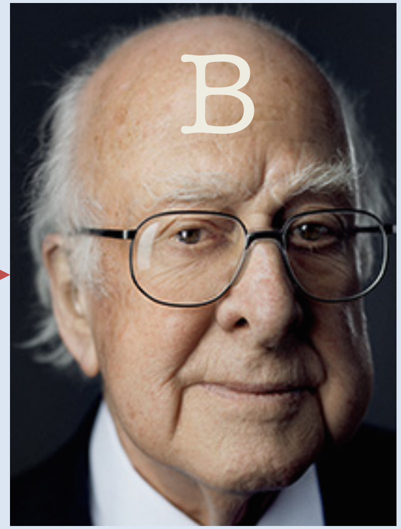
Cambridge
and/or
CERN

How Does the Higgs Move?

Surprisingly, we don't really know how the Higgs boson gets from:



to



This is especially true if it is only a very short distance.

Theoretical Perspective

Based on 1903.07725 with Gian Giudice, Admir Greljo.

How Does the Higgs Move?

We know, thanks to Källén-Lehmann, that the propagator is, in full generality:

$$\langle 0|T\{h(z)h(0)\}|0\rangle = i\int d^4p\, e^{-ipz}\int_0^\infty dq^2 \frac{\rho_h(q^2)}{p^2-q^2+i\epsilon}$$

This encodes information on correlations in the Higgs field between two space-time points. For a free field

$$\rho_h(q^2) = \delta(q^2-m_h^2)$$

and we have measured the position of the pole!

How Does the Higgs Move?

In the Standard Model we have interactions, thus:

$$\rho_h(q^2) = \rho_{\mathrm{SM}}(q^2)$$

The right hand side is at least calculable...

But we don't know all fields in nature, thus all we can say in full generality is that

$$\rho_h(q^2) = \rho_{\mathrm{SM}}(q^2) + \rho_X(q^2)$$

and

$$\rho_h(q^2) \geq 0 \quad .$$

How Does the Higgs Move?

Returning to the momentum-space propagator:

$$\Delta_h(p^2) = \int_0^\infty dq^2 \frac{\rho_h(q^2)}{p^2 - q^2 + i\epsilon}$$

The density of states is associated with the poles and branch cuts at the mass scale of new (multi)particle Hamiltonian eigenstates. Thus, if the BSM states are heavy

$$\rho_X(q^2 < M^2) = 0$$

We may make some general statements.

How Does the Higgs Move?

Expanding the propagator in small momenta we have:

$$\Delta_h(p^2) = \Delta_{\mathrm{SM}}(p^2) - \frac{1}{M^2}\sum_{n=1}^{\infty} c_n \left(\frac{p^2}{M^2}\right)^{n-1}$$

where

$$c_n = M^2 \int_0^1 dx\, \rho_X(M^2/x)\, x^{n-2} \ .$$

Some comments...

How Does the Higgs Move?

Staring at this we may make some observations:

$$c_n = M^2 \int_0^1 dx \, \rho_X(M^2/x) \, x^{n-2} \, .$$

a) From positivity of density of states

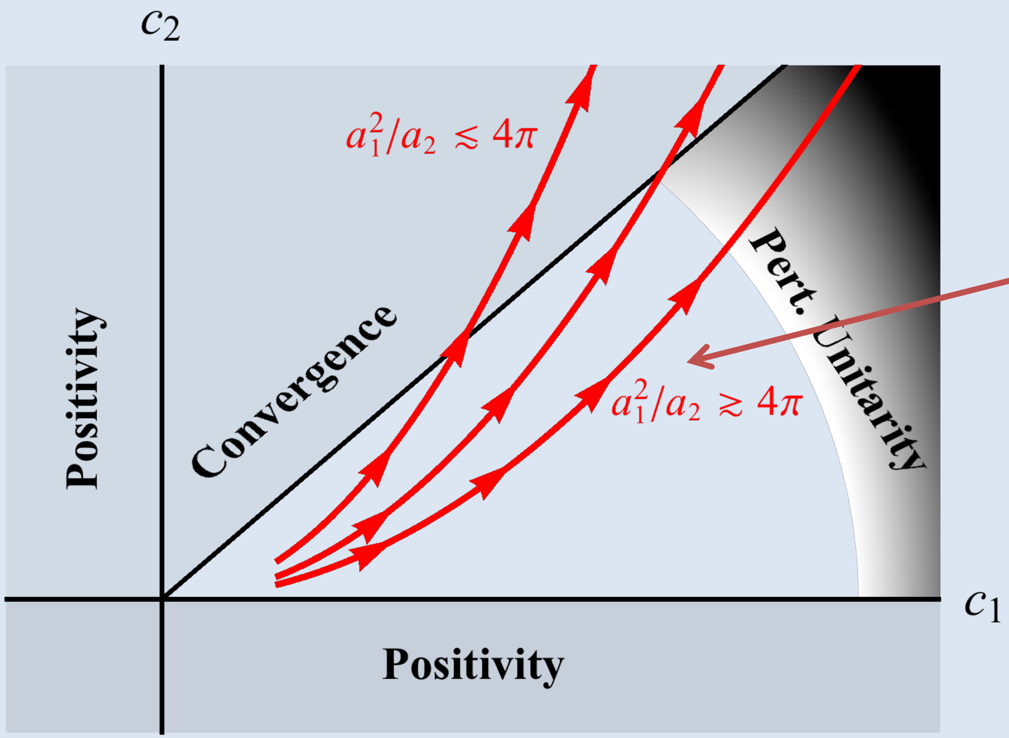
$$c_n \geqslant 0 \quad \forall n$$

b) From the integrand, we have a convergent series

$$c_n \geqslant c_{n+1} \quad \forall n$$

How Does the Higgs Move?

If one could measure leading and subleading Wilson coefficients in the momentum expansion

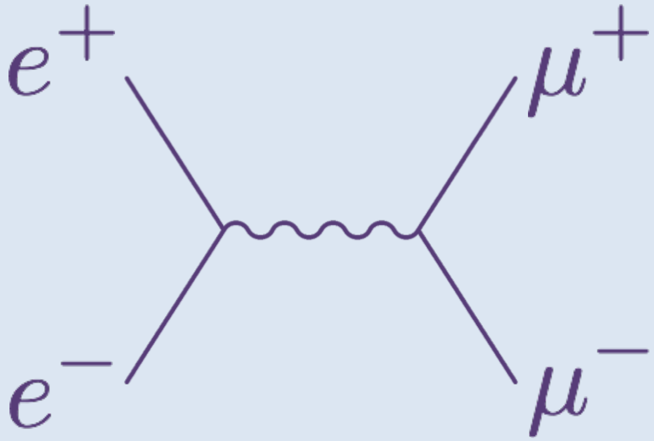


$$a_n = \frac{c_n}{M^{2n}}$$

it would be possible to extract constraints on the scale of UV-completion which are stronger than from Unitarity alone!

Convergence Applied (a posteriori)

Consider the front-back asymmetry in low energy (E < 45 GeV), PEP, PETRA, TRISTAN:



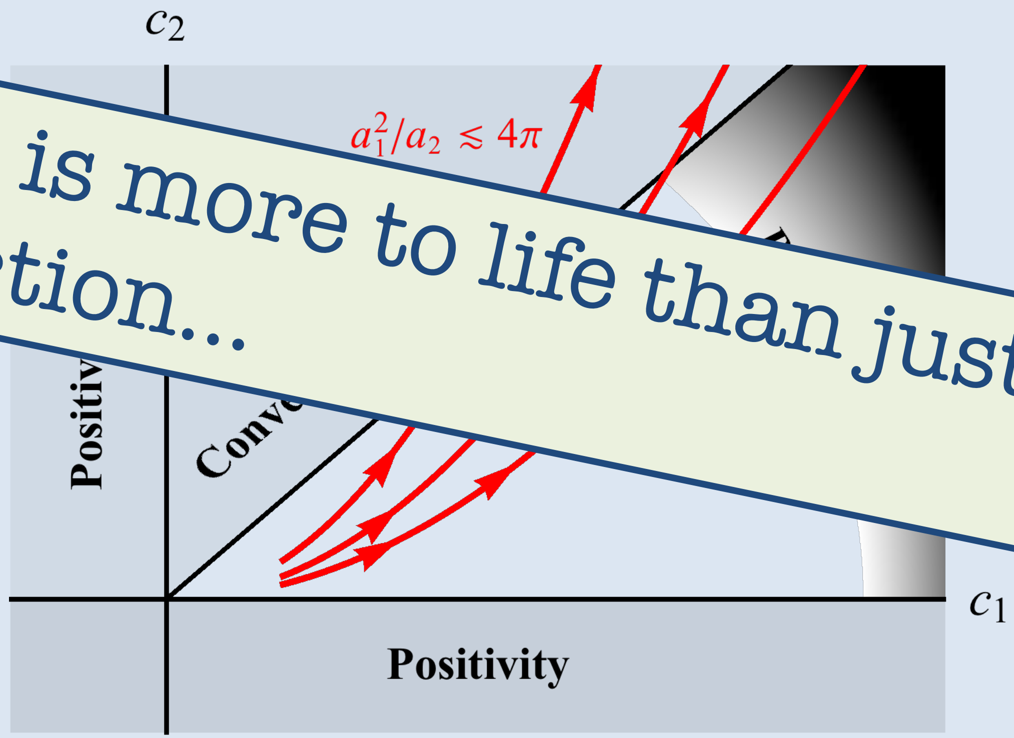
$$A_{FB}(s) = -\frac{3\,a_1\,s\,\left(1 + \frac{a_2}{a_1}\,s\right)}{8\,\pi\,\alpha^2}$$

With this precision data alone, had we not already discovered the Z-boson, could have bounded, at 90%, the mass much better than from Unitary:

$$m_Z \lesssim 170\ \ \mathrm{GeV}$$

How Does the Higgs Move?

If one could measure leading and subleading Wilson coefficients in the momentum expansion



But there is more to life than just the two-point function...

it would be possible to extract constraints on the scale of UV-completion which are stronger than from Unitarity alone!

Stating a Well-Posed Question

To consider the full suite of heavy new physics possibilities, we need to go to full(ish) EFT...

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

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

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

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

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

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

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

Organising Thoughts

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.

Fermi Scale

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

UV-completion

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

Coupling

Organising the UV

Higgs Only

$[g_*^0]$

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

$[g_*^2]$

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

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

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

$[g_*^4]$

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

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

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

Mixed

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

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

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Organising the UV

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$[\boldsymbol{g_*^4}]$

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

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

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

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

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

The lowest
coupling-dimension
Higgs-only operator.

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

Parameterises BSM deviations in how the Higgs moves.

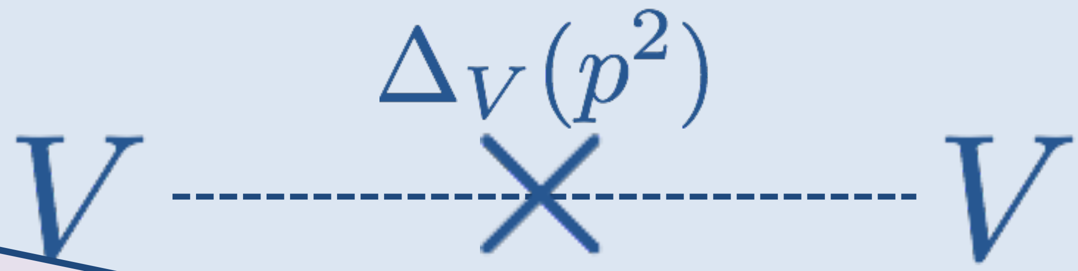
Phenomenological Perspective

Based on 1903.07725 with Gian Giudice, Admir Greljo.

Oblique Corrections

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

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



We've been here before...

The latter two contribute to amplitudes in … 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...

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

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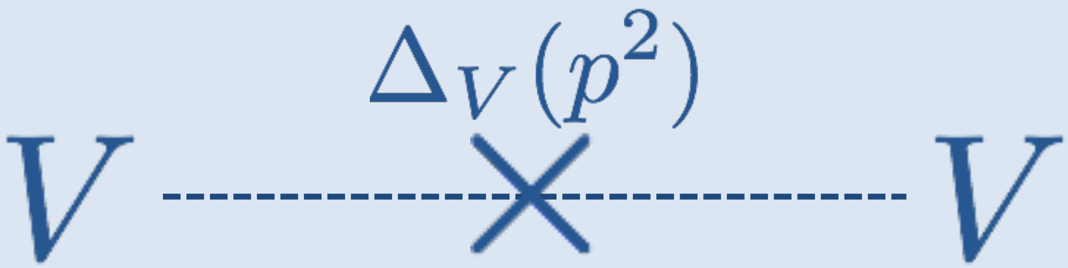


The latter two contribute to amplitudes in an "energy-growing" manner:

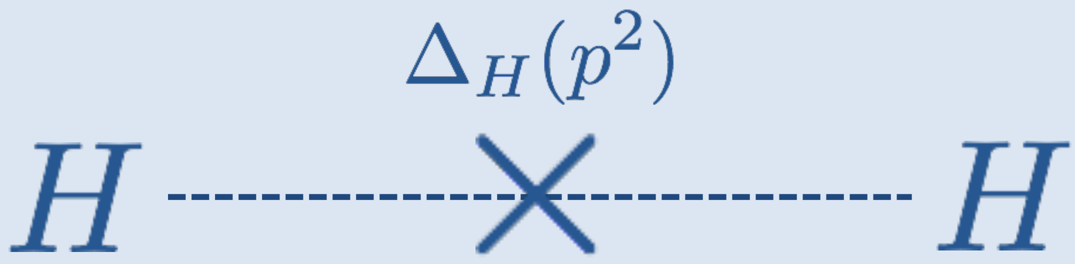
$$\Delta_W(p^2) \approx \frac{1}{p^2 - M_W^2} - \frac{\hat{W}}{M_W^2}$$

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:

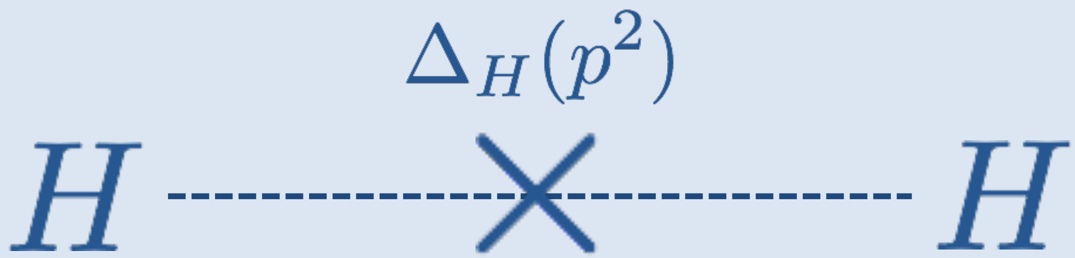
$$\Delta_H(p^2) \approx \frac{1}{p^2 - m_h^2} - \frac{\hat{H}}{m_h^2} + \ldots$$

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

Oblique Corrections

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

- H-parameter:



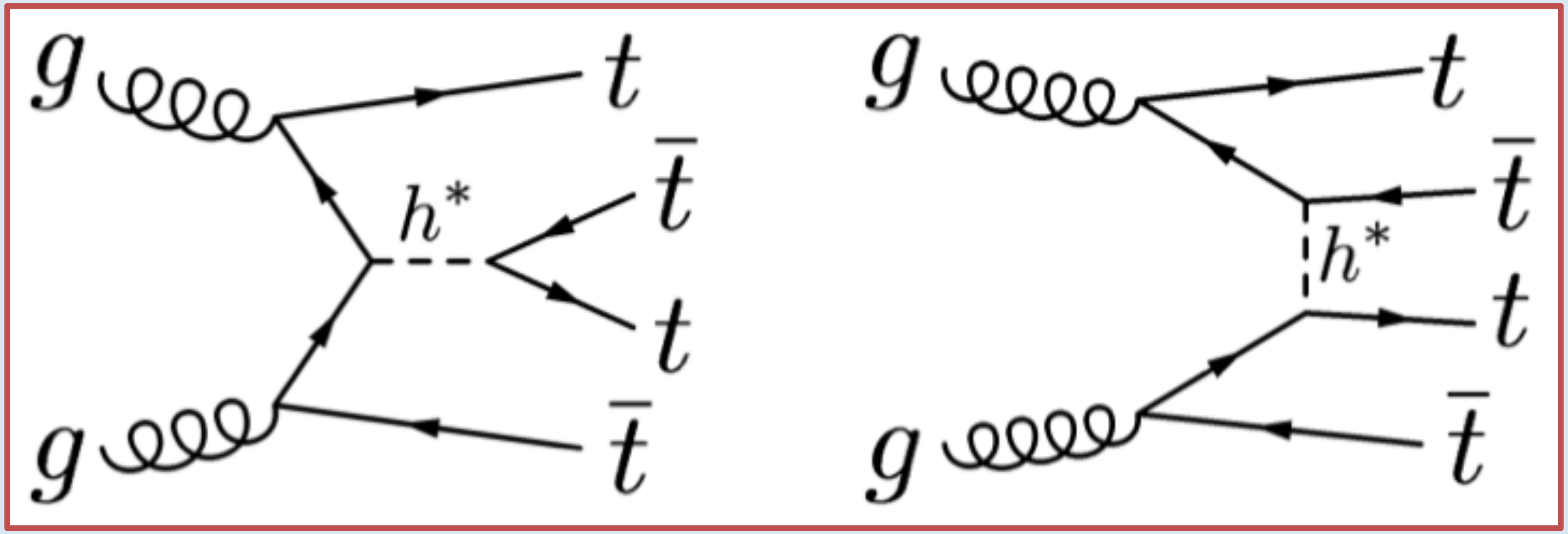
One can also translate basis to one in which this is a four-fermion operator and some more involving the Higgs

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

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

Oblique Corrections

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

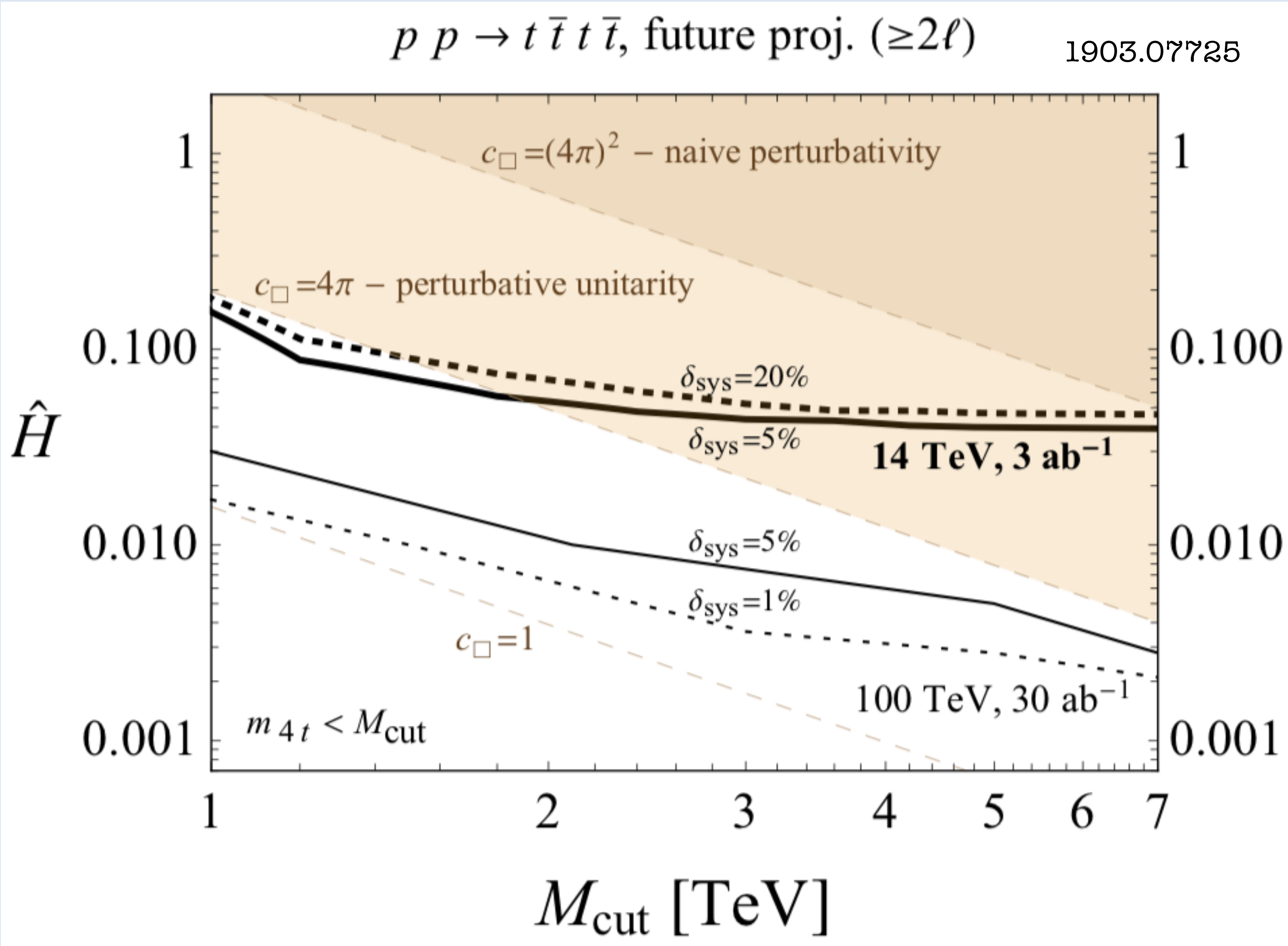


We may relate this Wilson coefficient to the scale of new physics as:

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

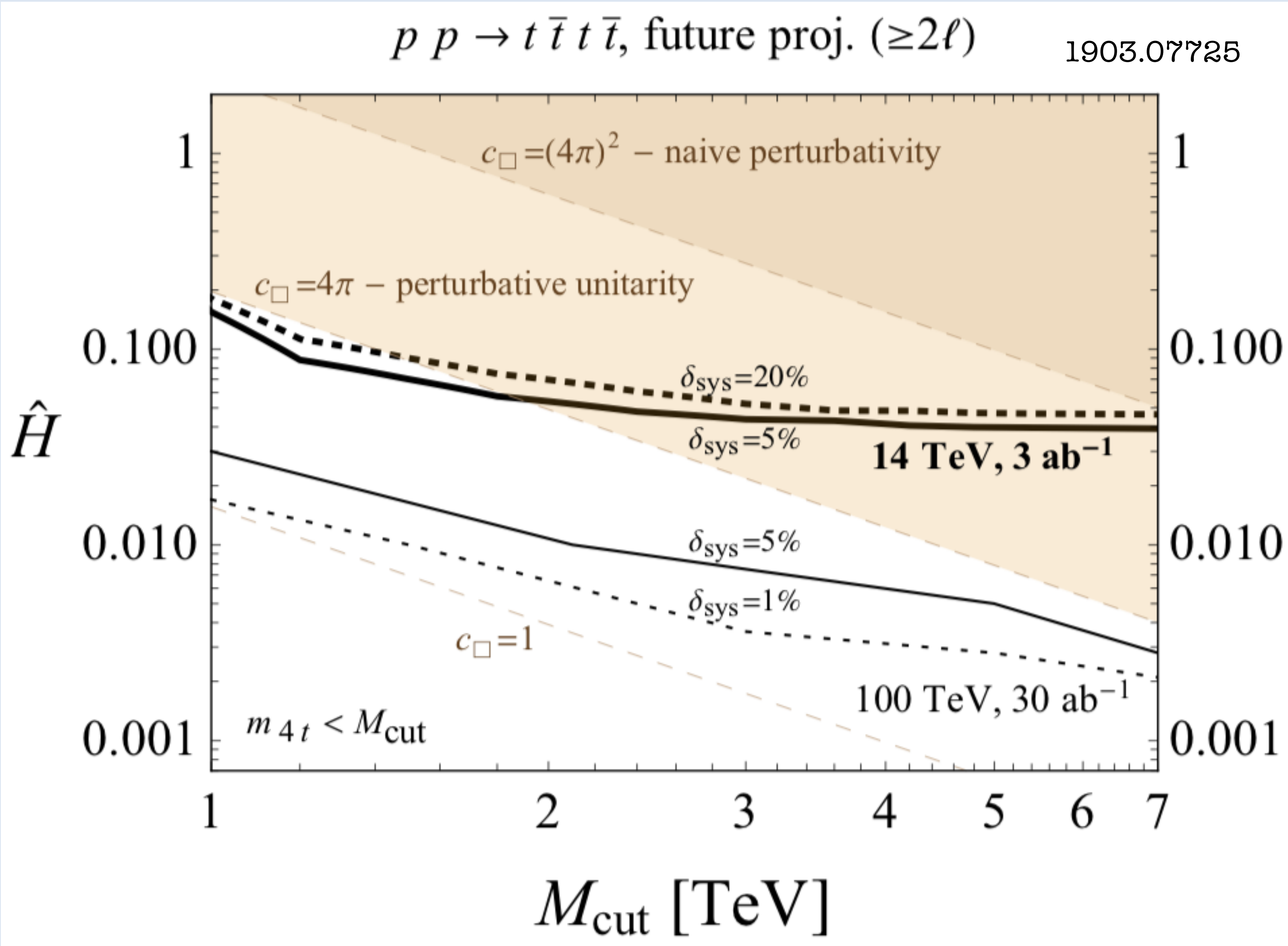
A Unique Operator

Our estimate suggests meaningful constraints are possible, but challenging at the HL-LHC:



A Unique Operator

Future proton colliders could do much much better:



A Unique Operator

CMS does better than our estimates:

Abstract

1908.06463

The standard model (SM) production of four top quarks ($\mathrm{t\bar{t}t\bar{t}}$) in proton-proton collision is studied by the CMS Collaboration. The data sample, collected during the 2016–2018 data taking of the LHC, corresponds to an integrated luminosity of 137 fb^{-1} at a center-of-mass energy of 13 TeV. The events are required to contain two same-sign charged leptons (electrons or muons) or at least three leptons, and jets. The observed and expected significances for the $\mathrm{t\bar{t}t\bar{t}}$ signal are respectively 2.6 and 2.7 standard deviations, and the $\mathrm{t\bar{t}t\bar{t}}$ cross section is measured to be $12.6^{+5.8}_{-5.2}$ fb. The results are used to constrain the Yukawa coupling of the top quark to the Higgs boson, y_{t}, yielding a limit of $|y_{\mathrm{t}}/y_{\mathrm{t}}^{\mathrm{SM}}| < 1.7$ at 95% confidence level, where $y_{\mathrm{t}}^{\mathrm{SM}}$ is the SM value of y_{t}. They are also used to constrain the oblique parameter of the Higgs boson in an effective field theory framework, $\hat{H} < 0.12$. Limits are set on the production of a heavy scalar or pseudoscalar boson in Type-II two-Higgs-doublet and simplified dark matter models, with exclusion limits reaching 350–470 GeV and 350–550 GeV for scalar and pseudoscalar bosons, respectively. Upper bounds are also set on couplings of the top quark to new light particles.

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

Parameterises
BSM deviations in how
the Higgs moves.

Thus far, at the LHC,
we haven't even begun to
understand how the
Higgs moves...

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

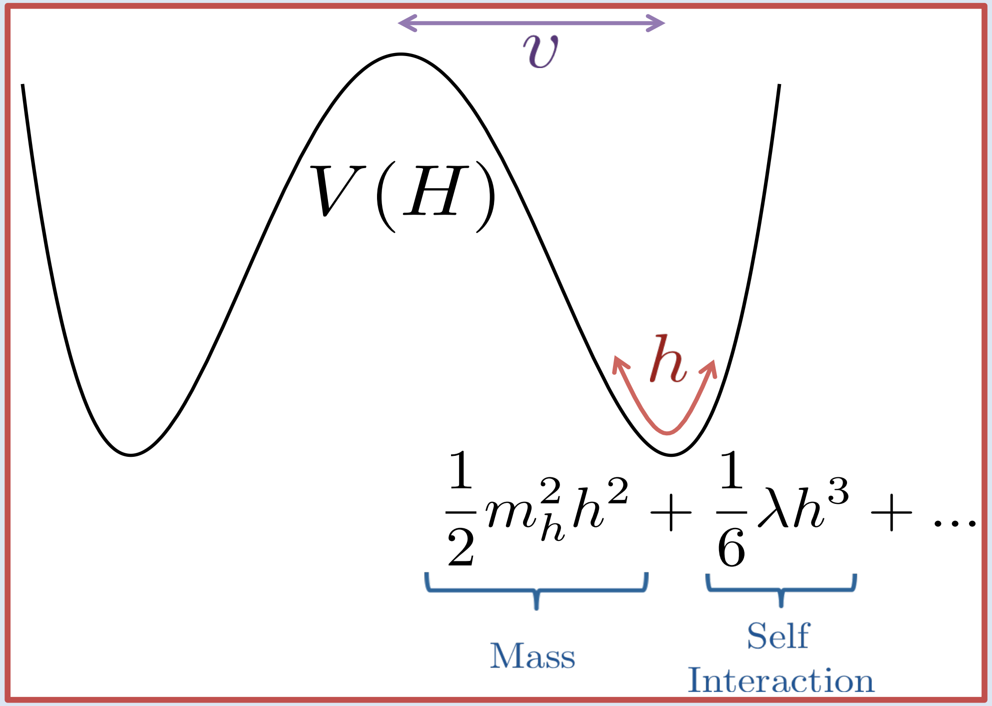
The highest coupling-dimension operator.

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

Parameterises
BSM deviations in sole
self-interaction of SM.

The Higgs Potential

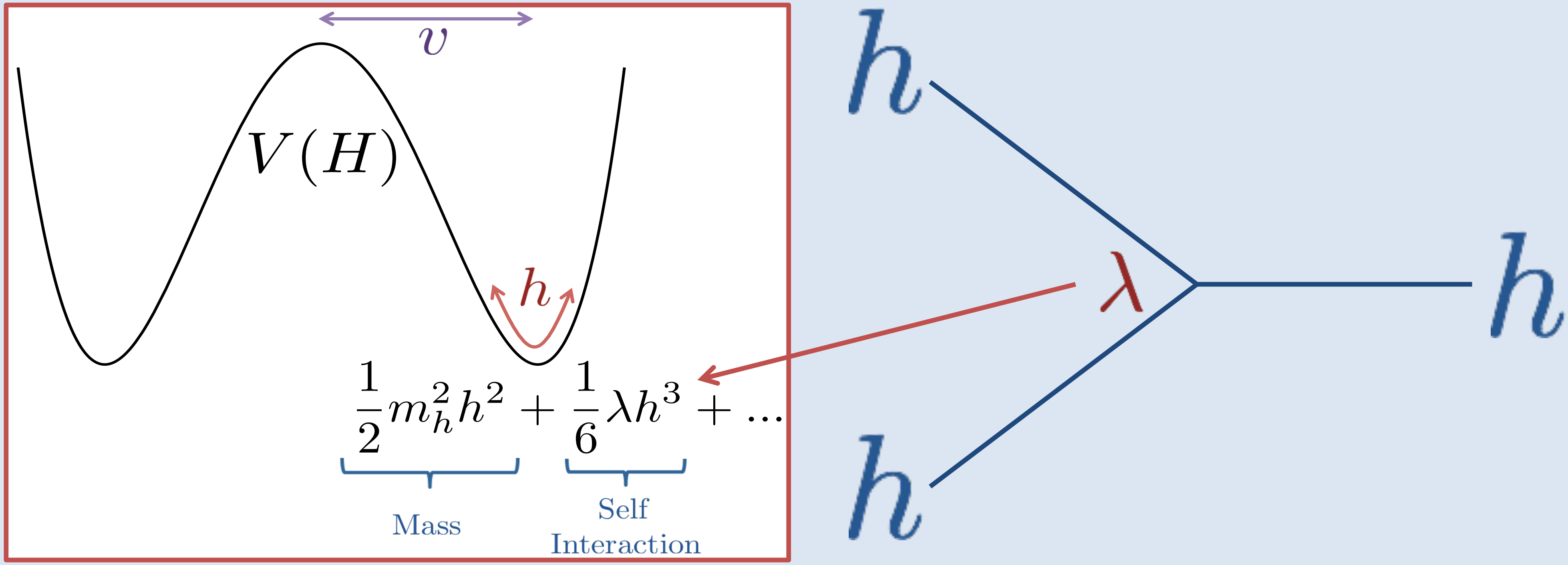
The potential energy in our Universe depends on the value of the Higgs field:



We can measure the form of this potential energy.

The Higgs Potential

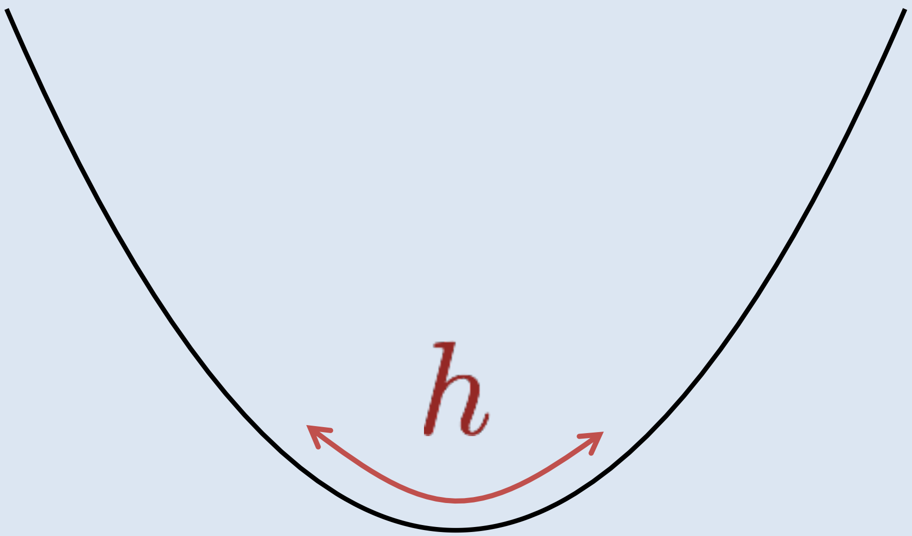
Measuring the Higgs self-coupling is the only way to measure the structure of the Higgs potential.

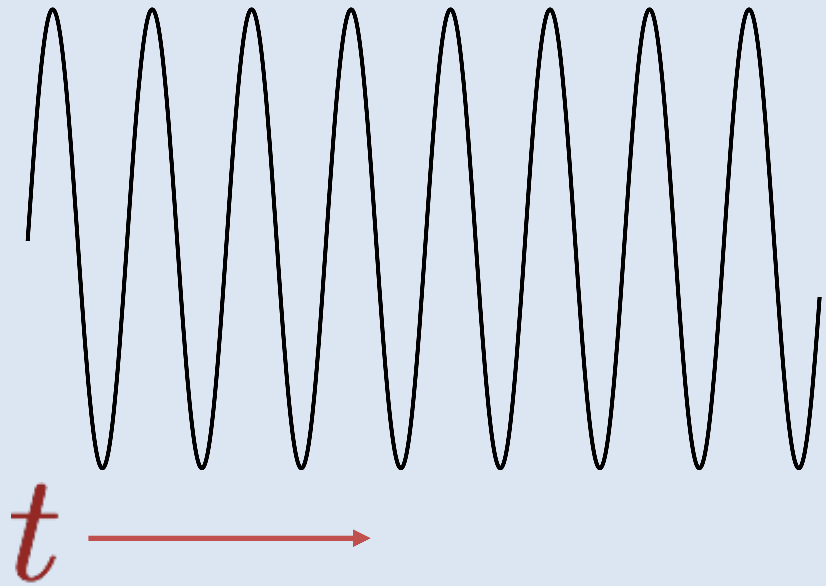


Discovering the Higgs was difficult enough, now we need to know how it interacts with itself!

The Higgs Potential

At leading order, the movement of the Higgs is that of a simple harmonic oscillator…

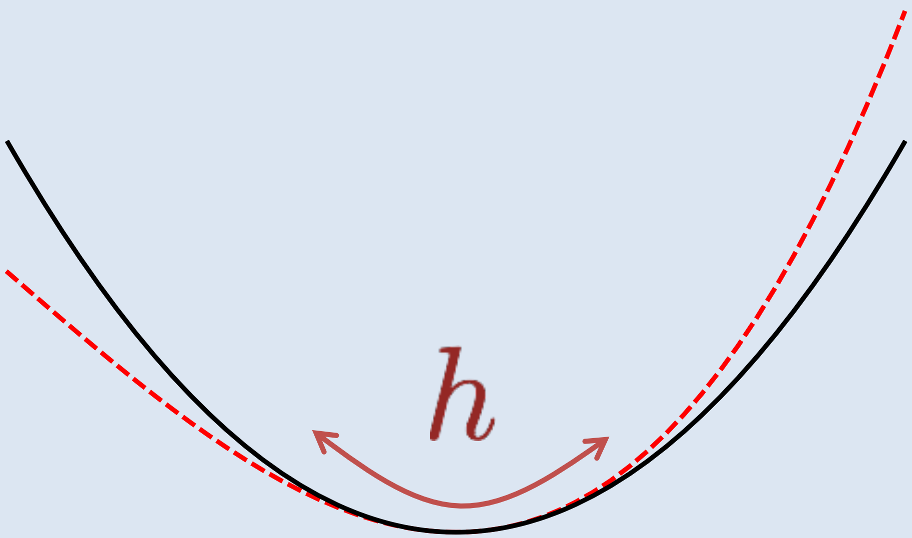


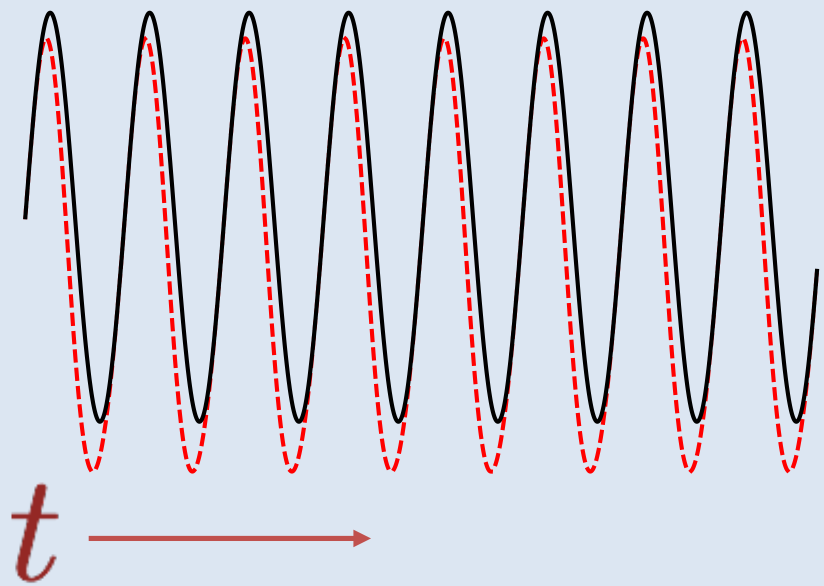


and by measuring the mass we have determined the oscillation frequency.

The Higgs Potential

However, once we include the Higgs self-interaction which is, as yet, undetermined...

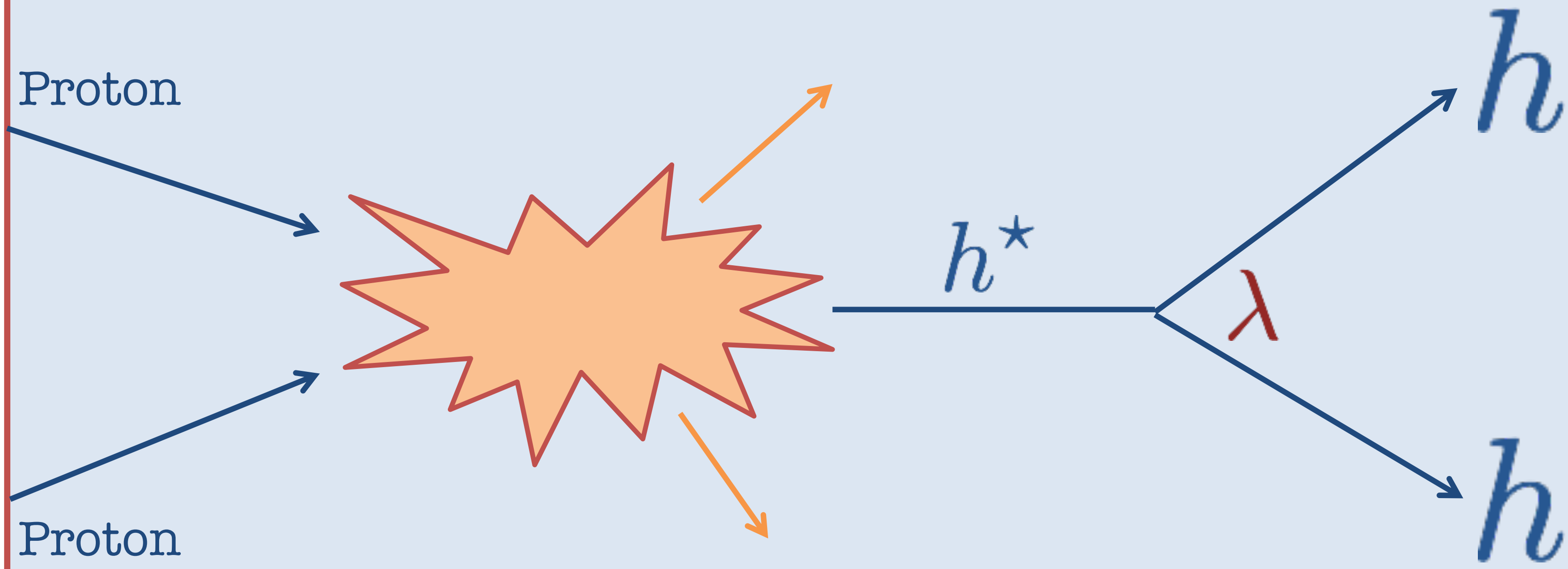




The movement of the Higgs about the local minimum of the potential is modified.

Scattering a Higgs

One way to investigate the Higgs self-interaction was to observe processes involving Higgs pair production:



And prospects for discovering this interaction at the LHC aren't very promising...

Theoretical Perspective

Based on Phys.Rev. D90 (2014) 015001.

Organising the UV

Higgs Only

$[g_*^0]$

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

$[g_*^2]$

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

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

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

$[g_*^4]$

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

Thinking about this stuff again...

Only

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

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

$$(\partial_\rho B_{\mu\nu})^2$$

Mixed

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

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A Unique Operator

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

is very very special, since:

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

At one-loop we have:

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

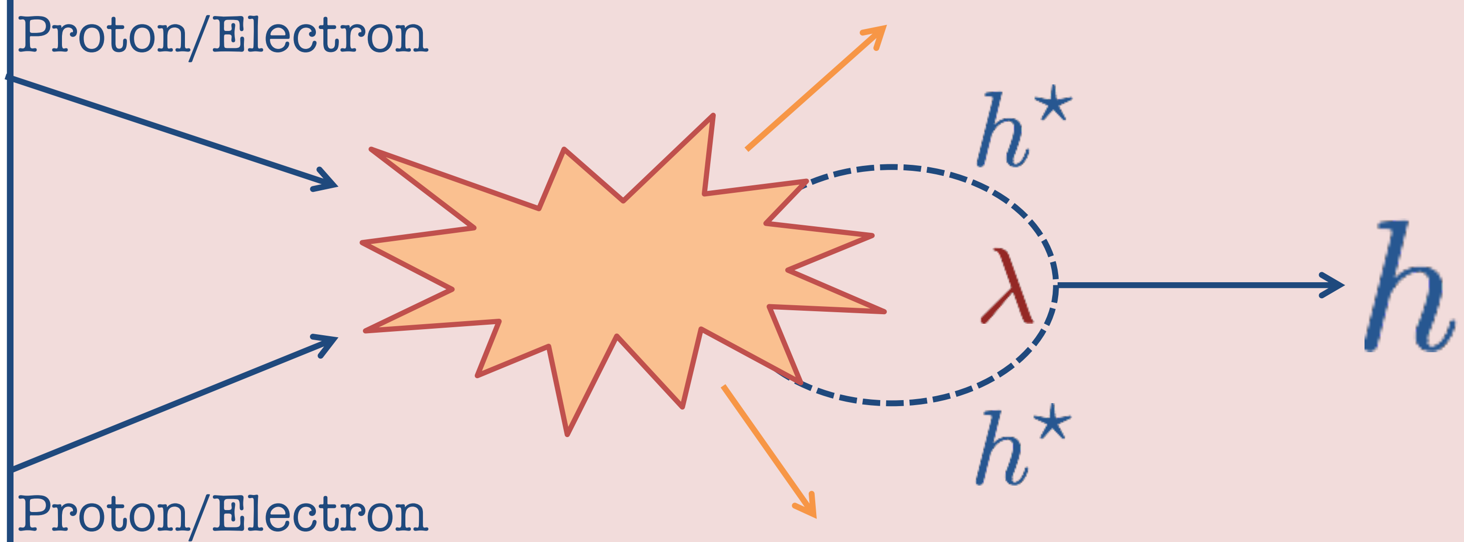
Thus, if <u>any</u> other coupling enters the game, coupling dimension is too large to match any other dim-6 operator!

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!

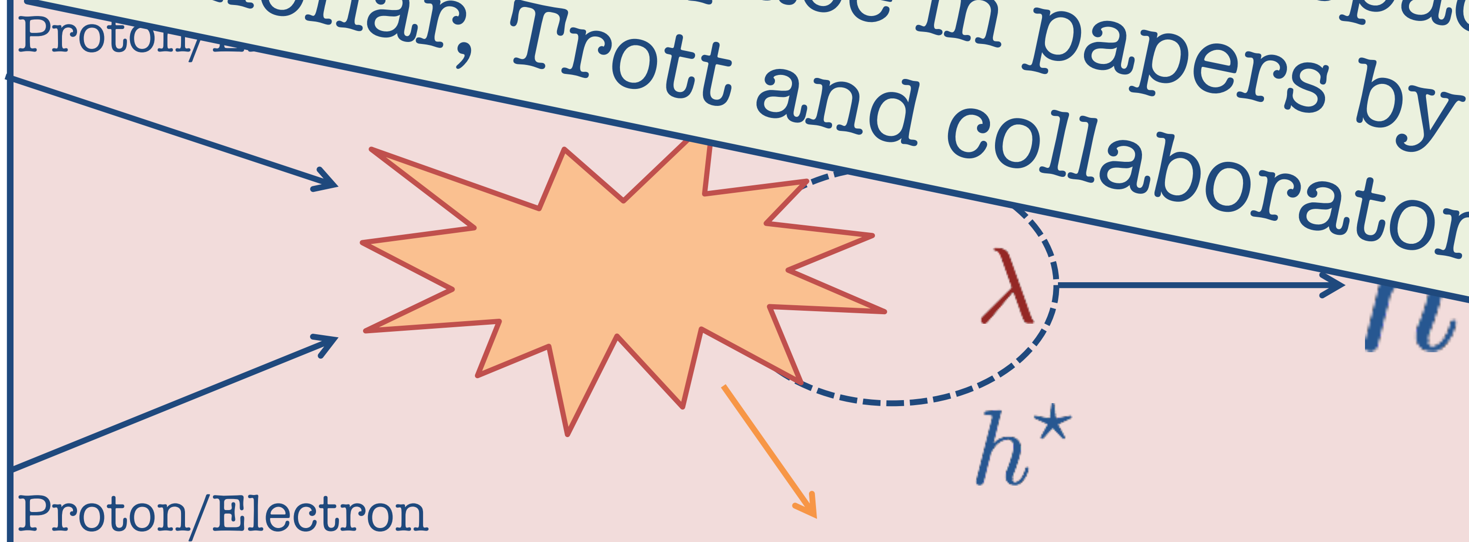
A Unique Operator

Observation:

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

...in-top in RG-space.

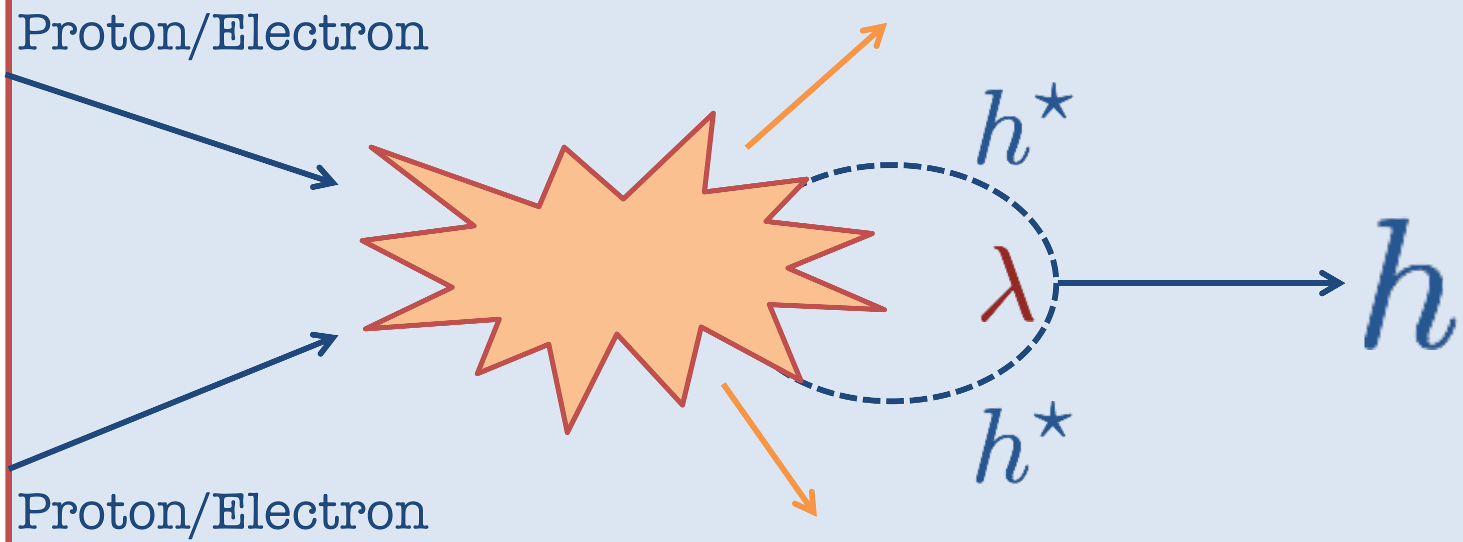
Can see where it lies in the space of Dim-6 operator RG space in papers by Jenkins, Manohar, Trott and collaborators...



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

Scattering a Higgs

The implication of this is that if you insert a modified trilinear vertex into a single-Higgs production one-loop diagram you will get a shift in the result which is free of logarithms.



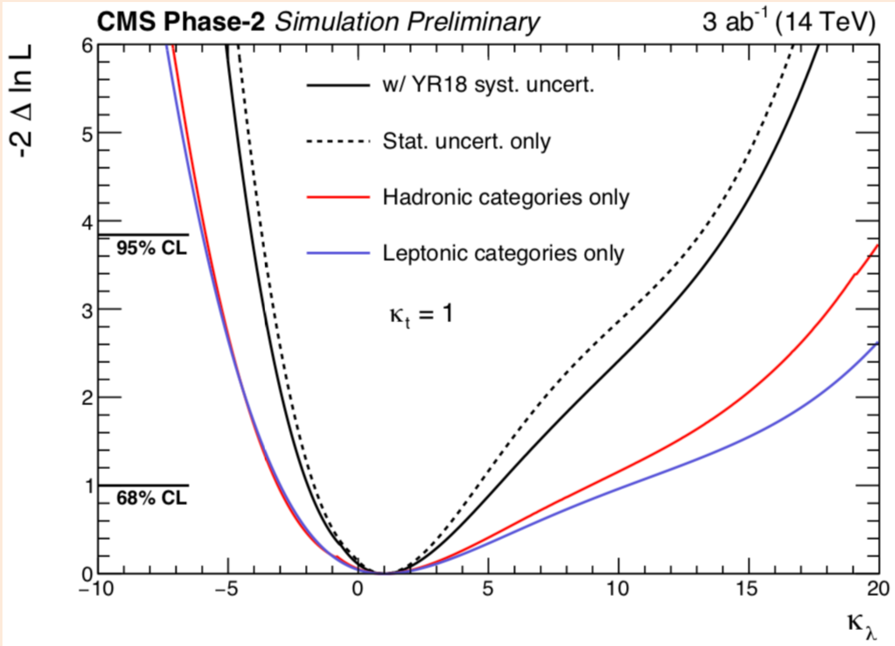
In other words, these modifications are finite and fully calculable within the IR EFT, without recourse to physics at the cutoff.

Phenomenological Perspective

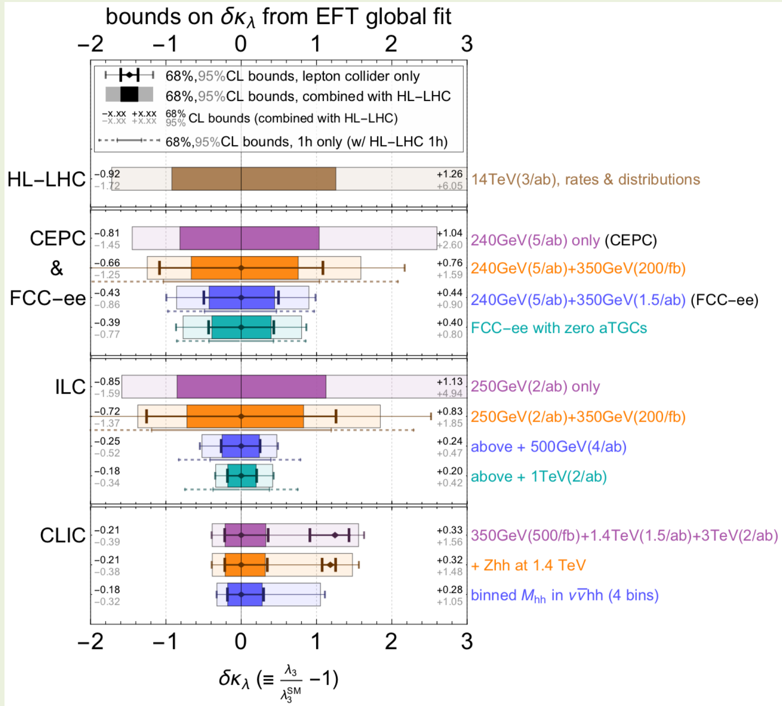
Scattering a Higgs

Has been studied for HL-LHC and the future...

Current LHC experiments:



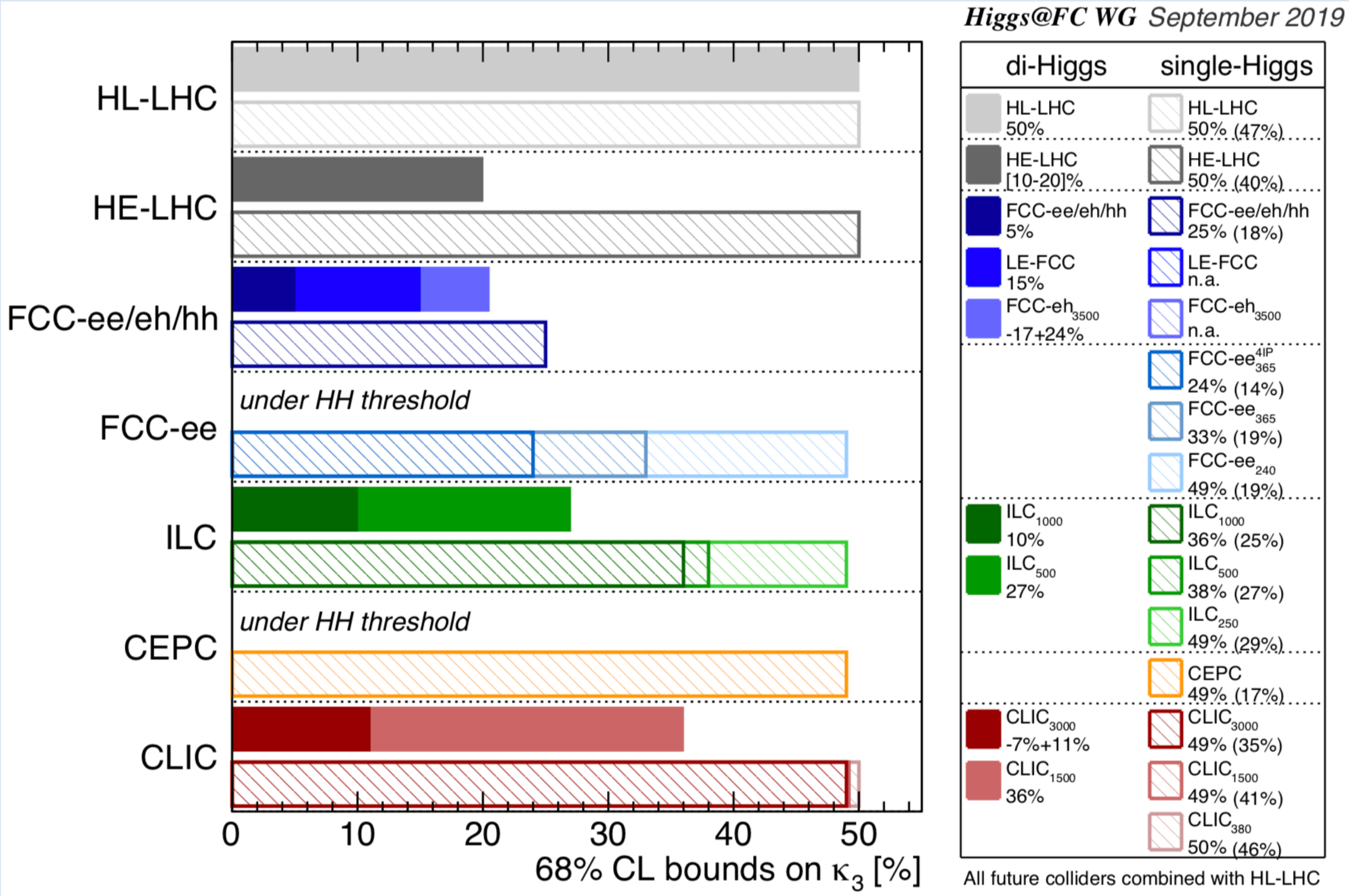
Future collider proposals:



Could form a useful tool for future efforts to understand the origins of the Higgs boson potential, and hence of particle masses etc.

A Unique Operator

Provides a calculable, complementary tool to explore the shape of the Higgs potential:



ECFA Higgs Working Group Report 1905.03764

We need to strive for a meaningful measurement of this incredibly important interaction…

For which precision should we strive?

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...

Wrapping Up

Let's not overlook the outlier operators...

Higgs Only

$[\boldsymbol{g_*^0}]$

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

$[\boldsymbol{g_*^2}]$

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

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

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

$[\boldsymbol{g_*^4}]$

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

which determine how the Higgs moves, whether from A to B, or as it oscillates in the Higgs potential.

In a similar sentiment to Michael's introduction, before we declare "The Higgs is SM-like" to our colleagues let's make sure we have the measurements to back the statement up…

Right now **no one** knows if the Higgs moves as the Standard Model predicts.