CAN WE CALL *h125* THE "SM HIGGS" ?

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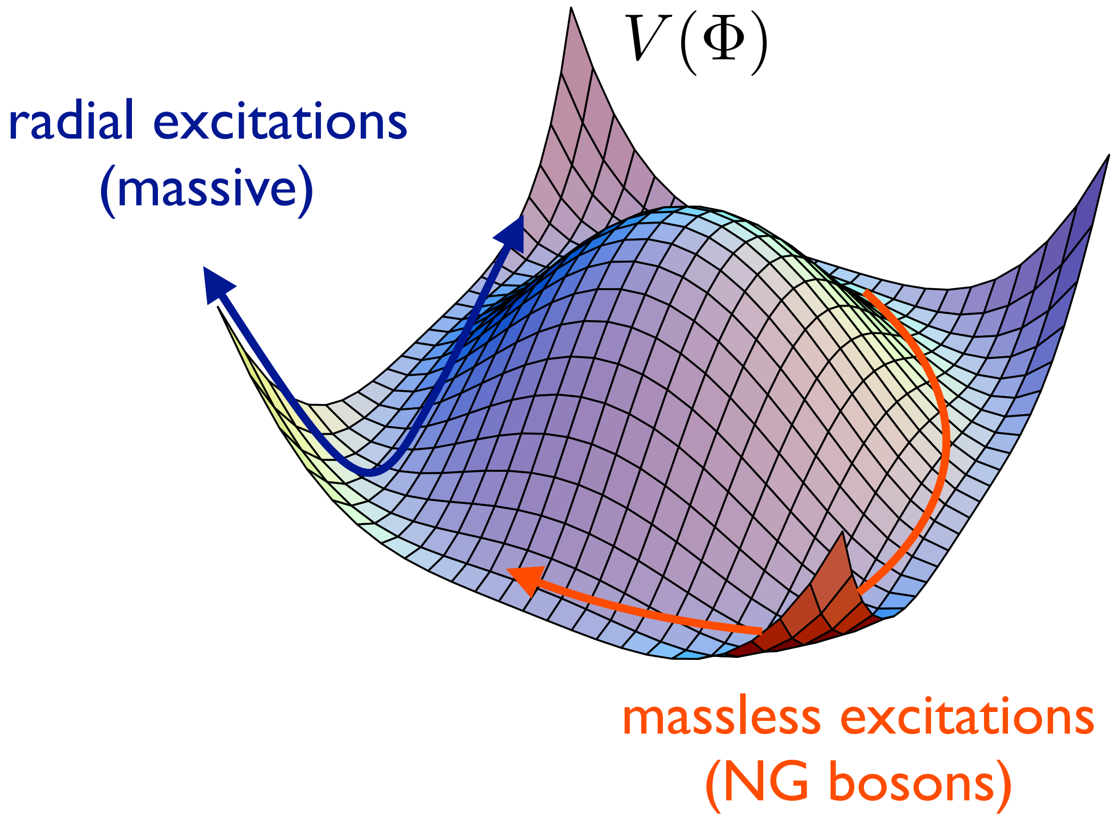
Les Rencontres de Physique de la Vallée d'Aoste, LaThuile 23 Feb-1 Mar 2014

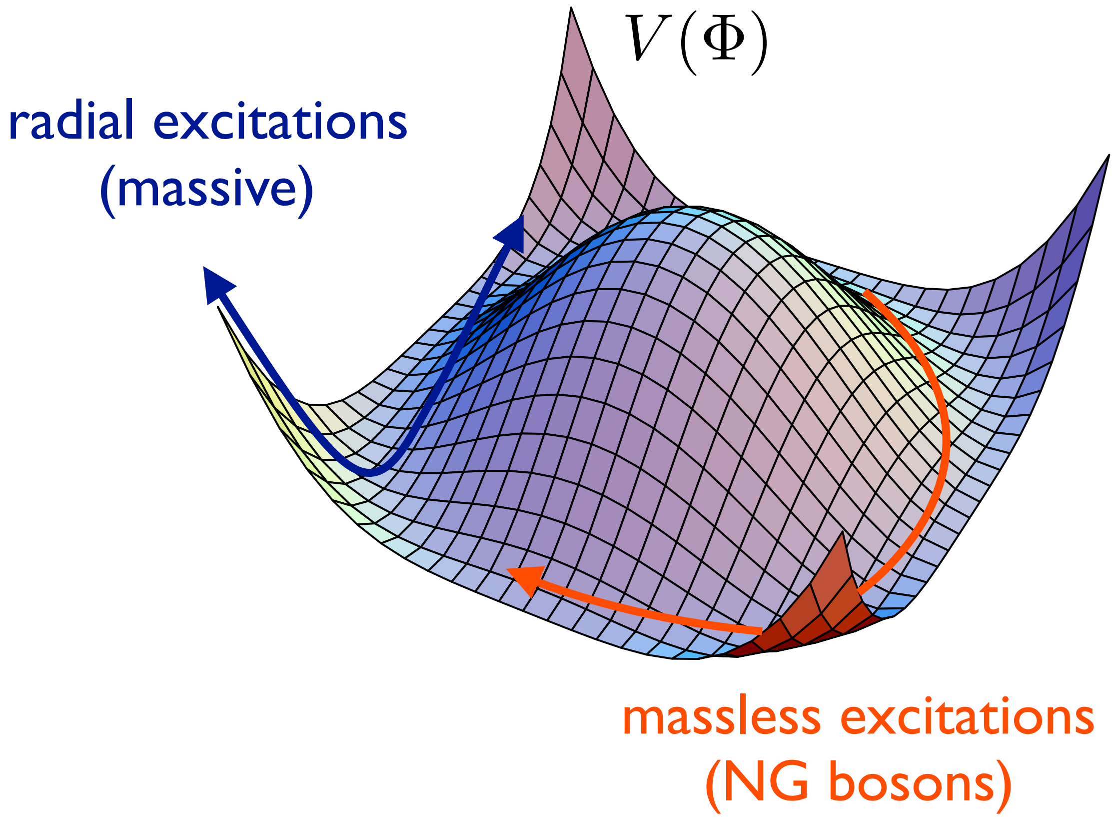
What the SM Higgs boson is



Higgs boson:

Excitation of the condensate with *tuned* couplings which maintains the theory perturbative up to very high energies

What the SM Higgs boson is

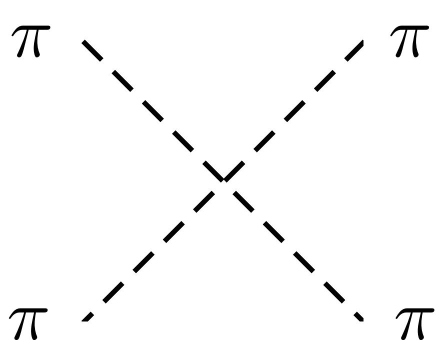


Higgs boson:

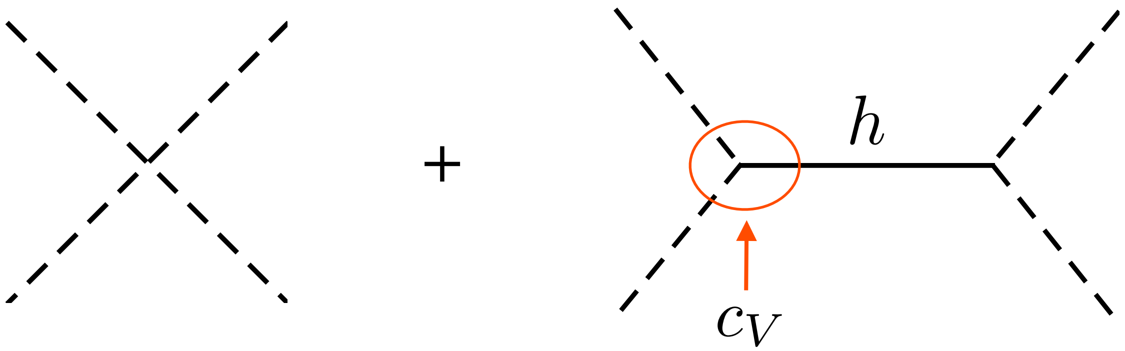
Excitation of the condensate with *tuned* couplings which maintains the theory perturbative up to very high energies

NG boson dynamics becomes strongly coupled at energies $E \sim 4\pi f$

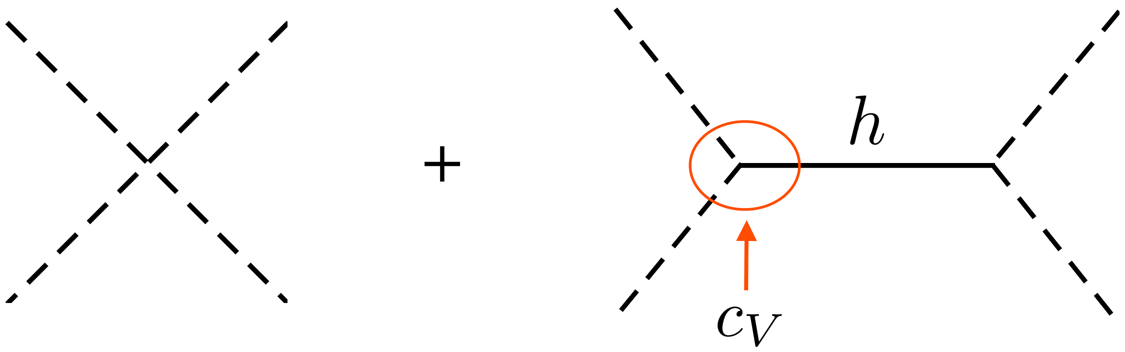
$$f^2 \left| \partial_\mu \, e^{i\pi/f} \right|^2 = (\partial\pi)^2 + \frac{(\pi\partial\pi)^2}{f^2} + \frac{\pi^2(\pi\partial\pi)^2}{f^4} + \dots$$



$$A(W_L W_L \to W_L W_L) = A(\pi\pi \to \pi\pi) \sim \frac{E^2}{v^2} \equiv g^2(E)$$



$$A \sim \frac{E^2}{v^2}(1 - c_V^2) - c_V^2\,\frac{m_h^2}{v^2}\,\frac{s}{s - m_h^2}$$



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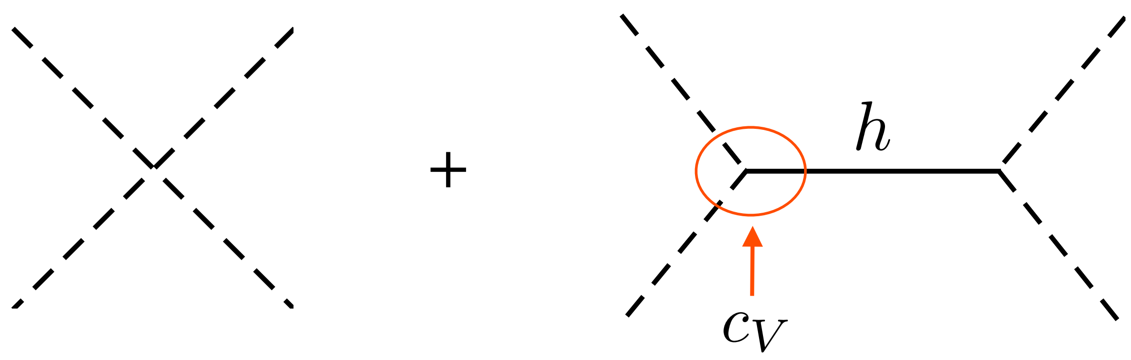
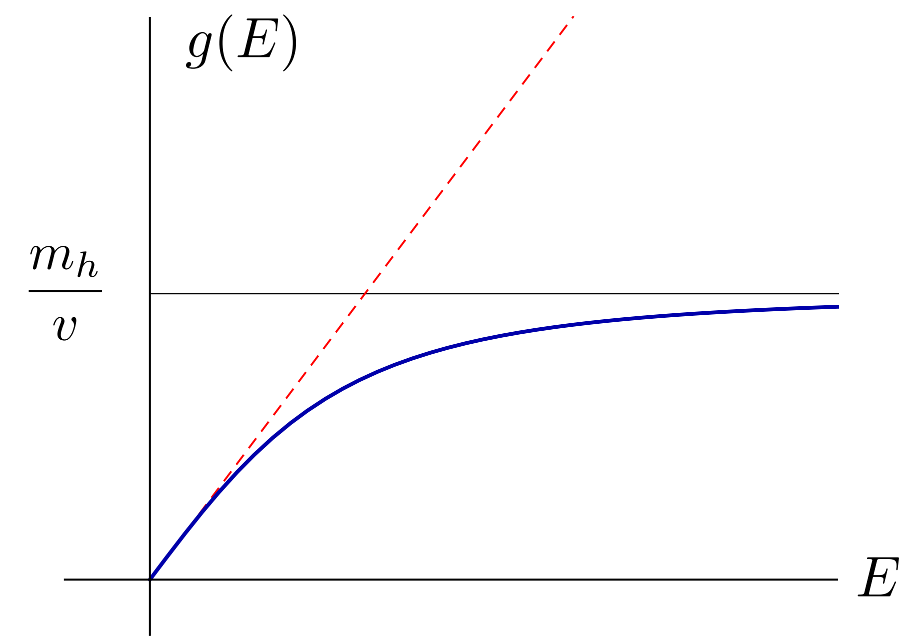
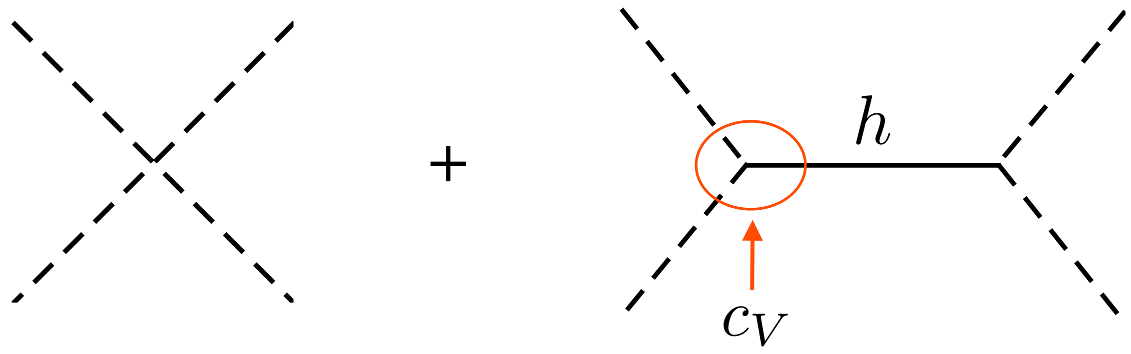
$= 0$



$$A \sim \underbrace{\frac{E^2}{v^2}(1 - c_V^2)}_{= 0} - c_V^2 \frac{m_h^2}{v^2} \frac{s}{s - m_h^2}$$

SM (elementary) Higgs: $c_V = 1$ weak →





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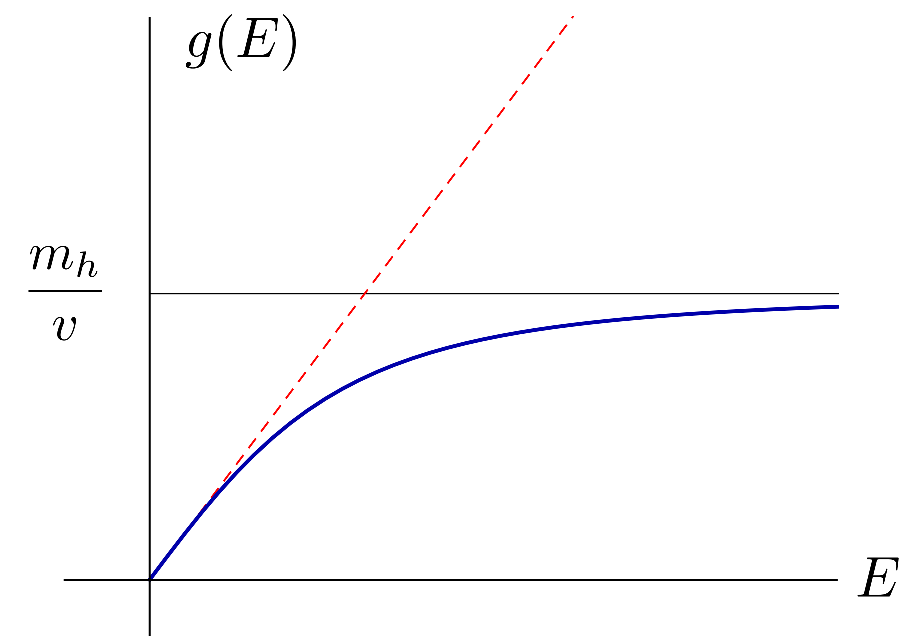

More than 1 (elementary) Higgs (ex: SUSY):

$$A \sim \underbrace{\frac{E^2}{v^2}\left(1 - \sum_i c_{Vi}^2\right)}_{=\,0} + \dots$$

- $\delta c_{Vi} \sim O(1)$ possible
- sum rule: $\sum_i c_{Vi}^2 = 1$

NG bosons of G/H transforms *non-linearly* under G

$$g = e^{i\alpha} \in G \qquad e^{i\pi/f} \to g \cdot e^{i\pi/f} \qquad \pi \to \pi + \alpha + O(\pi^2)$$

They transform linearly under H ➡ π form representations of H

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- actually: $\Delta\rho = 1 - \frac{m_W^2}{\cos^2\theta_W \, m_Z^2} \ll 1$ ⟶ W_L, Z_L form a *triplet* of a custodial SU(2)

$$G = SU(2)_L \times SU(1)_R \to SU(2) = H$$

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Theory stays perturbative to high energies if: $SU(2)_L \times U(1)_Y$ is restored (i.e. linearly realized) at $E \gg v$

⬇

the Higgs boson must form a doublet of $SU(2)_L \times U(1)_Y$ together with W_L, Z_L

$$H = e^{i\pi/v} \begin{pmatrix} 0 \\ v+h \end{pmatrix}$$

Can we call *h125* the “SM Higgs” ?

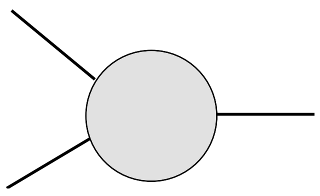
Question can be rephrased as follows:

Is *h125* part of a weak doublet which makes $SU(2)_L \times U(1)_Y$ linearly realized at high energies ?

Is the EWSB dynamics weak or strong ?

Two ways to test:

1. Measure Higgs couplings precisely and verify that they agree with SM prediction



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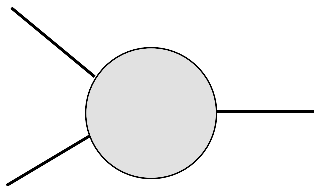
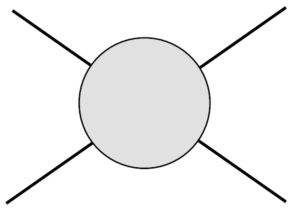


2. Directly access scattering amplitudes which grow with the energy



→ sensitive to new states (resonances) involved in unitarization

$$A(VV \to VV) \propto E^2 \qquad A(t\bar{t} \to hh/VV) \propto E\, m_t$$

$$A(VV \to hh) \propto E^2 \qquad A(tV \to tV) \propto E\, m_t$$

Two ways to test:

requires a model-independent parametrization of Higgs phenomenology (Effective Lagrangian)

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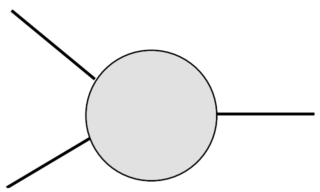

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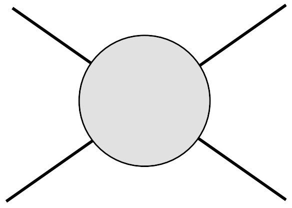

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Higgs Effective Lagrangian

* Start with building blocks of the $SU(2)_L \times U(1)_Y$ theory w/o Higgs boson

expansion parameter

NG bosons	$\dfrac{\partial}{\Lambda}$	(chiral expansion)
Gauge fields	$\dfrac{\alpha}{4\pi}$	
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Approximate symmetries:

1. Lepton and Baryon numbers (imposed)
2. Custodial symmetry (set global coset)
3. Flavor ?

Higgs Effective Lagrangian

* Add the light Higgs ($m_h \ll \Lambda$)

Operators built as series in $h(x)/v$

$$\mathcal{L} = \frac{v^2}{4}|D_\mu \Sigma|^2 \left(1 + 2c_V \frac{h}{v} + c_{2V}\frac{h^2}{v^2} + \dots\right)$$
$$+ m_\psi \bar{\psi}_L \Sigma \psi_R \left(1 + c_\psi \frac{h}{v} + \dots\right) + h.c.$$
$$+ \frac{1}{2}(\partial_\mu h)^2 - \frac{1}{2}m_h^2 h^2 \left(1 + c_3 \frac{h}{v} + \dots\right)$$
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$$\Sigma = e^{i\pi/v}$$

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NO power counting to estimate the new coefficients c_i
w/o making NEW ASSUMPTIONS

Example of possible (arbitrary) assumption:

Partial UV completion (PUVC)

at $E = \Lambda$ coupling strength of the Higgs is of the same order as that of the NG bosons

RC, Marzocca, Pappadopulo, Rattazzi JHEP 10 (2011) 081

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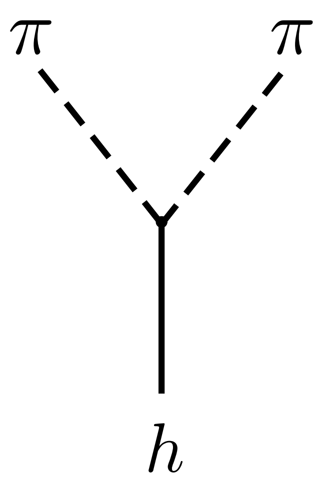

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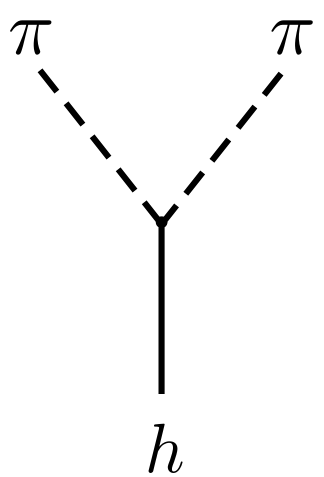

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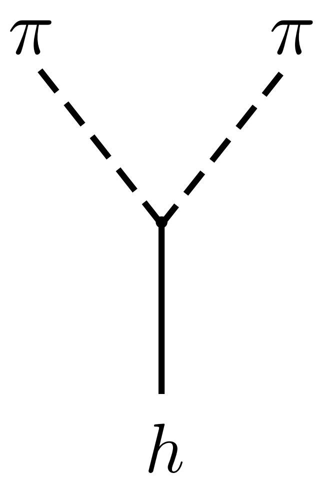

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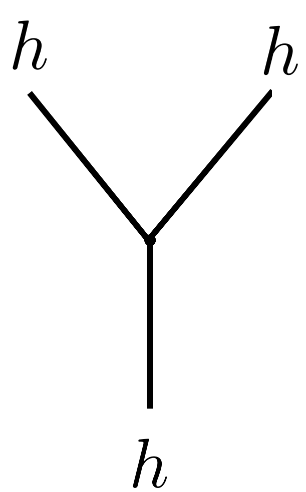

$$\sim \frac{m_h^2}{v} c_3 \equiv m_h \cdot g$$

$$g \sim g_* \equiv \frac{\Lambda}{v} \quad \Rightarrow \quad \boxed{c_3 \sim \frac{\Lambda}{m_h}}$$

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couplings c_i are arbitrary → *no* relation between terms with $n=0$ Higgs bosons and terms with $n>0$

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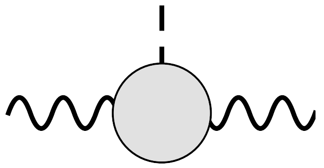
modifies q^2 spectrum in Higgs associated production $pp \to Vh$



$$\frac{d\sigma}{dq^2} \Big/ \left(\frac{d\sigma}{dq^2}\right)_{SM} = 1 + 2g^2 c'_W \left(1 + \frac{q^2}{m_V^2}\right)$$

Isidori, Trott JHEP 02 (2014) 082

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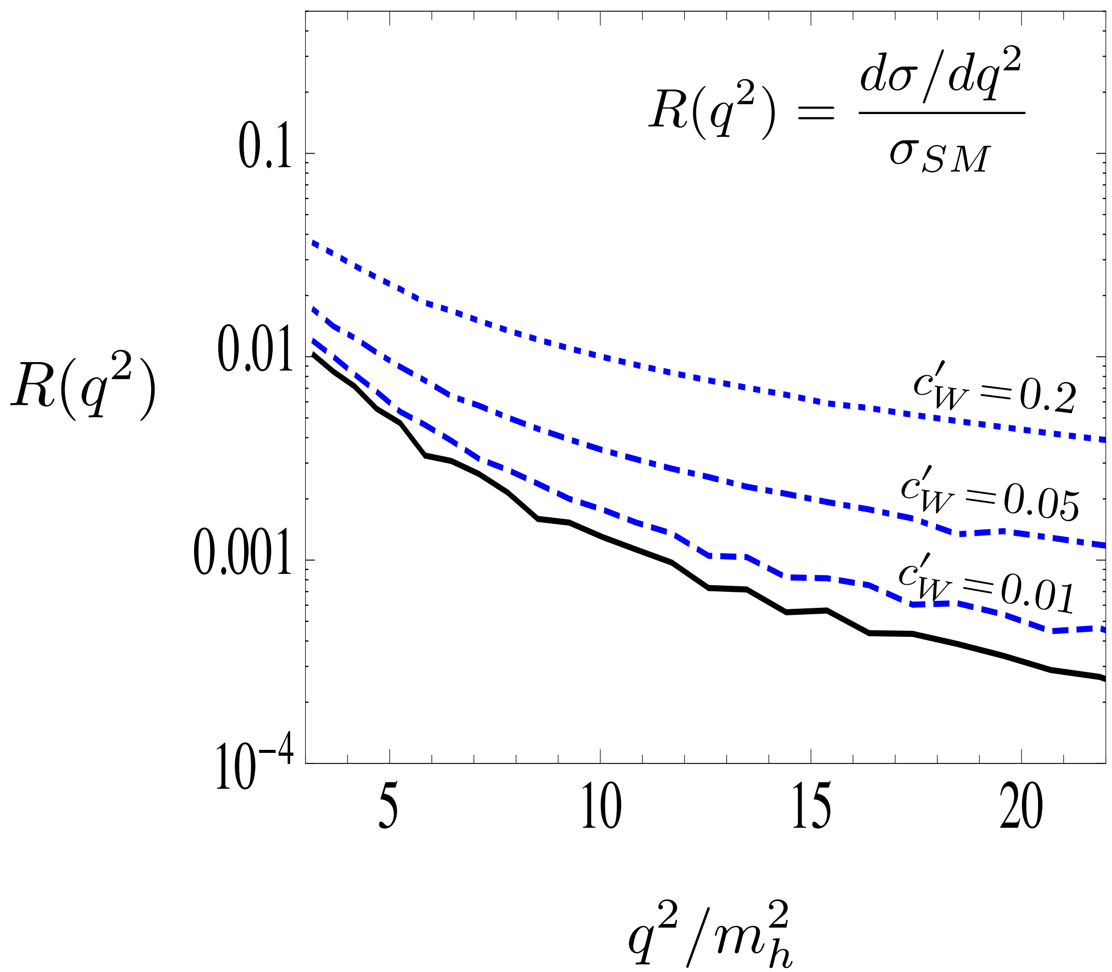

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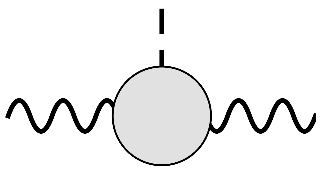

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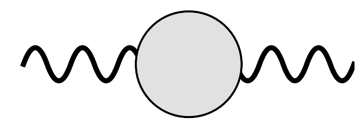

constrained by LEP

$$c_W \lesssim 1 \times 10^{-2}$$

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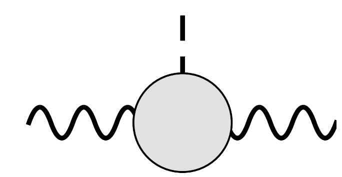

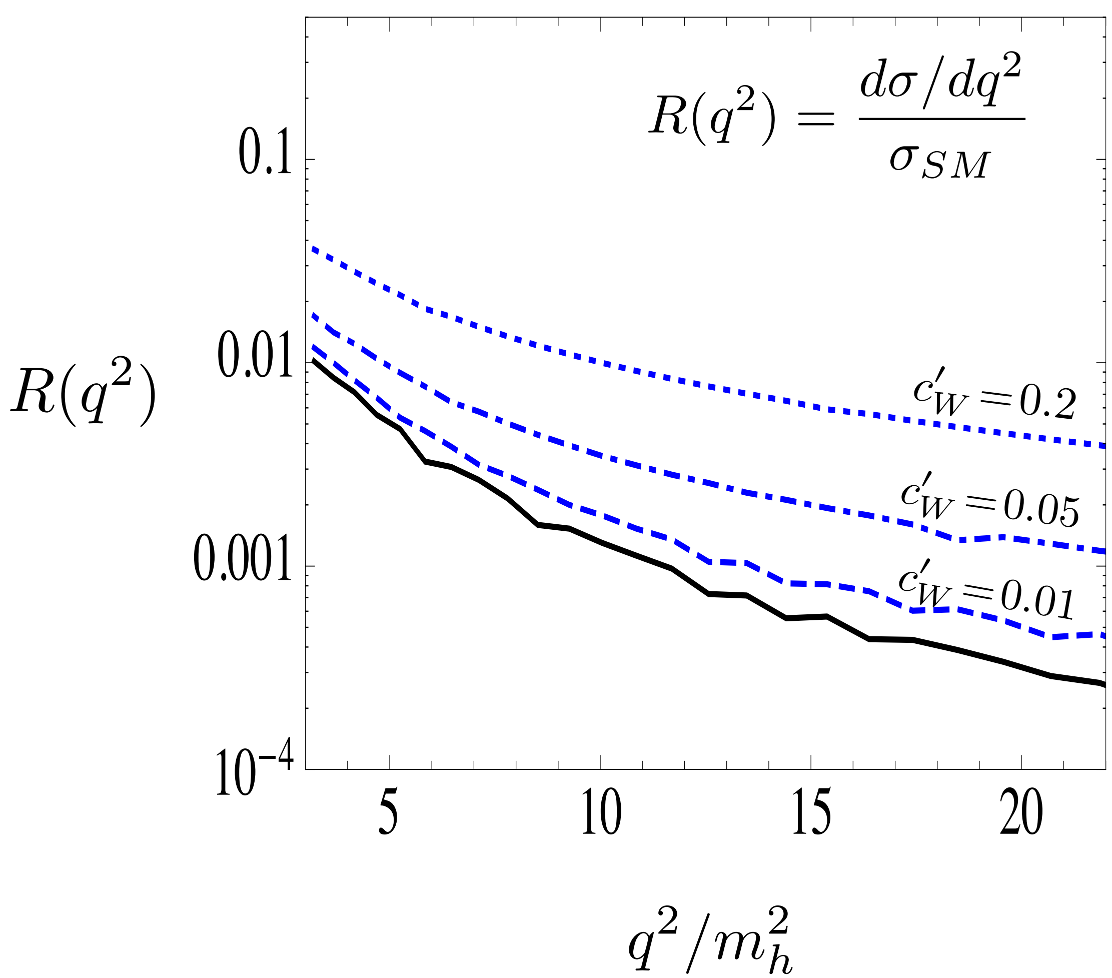

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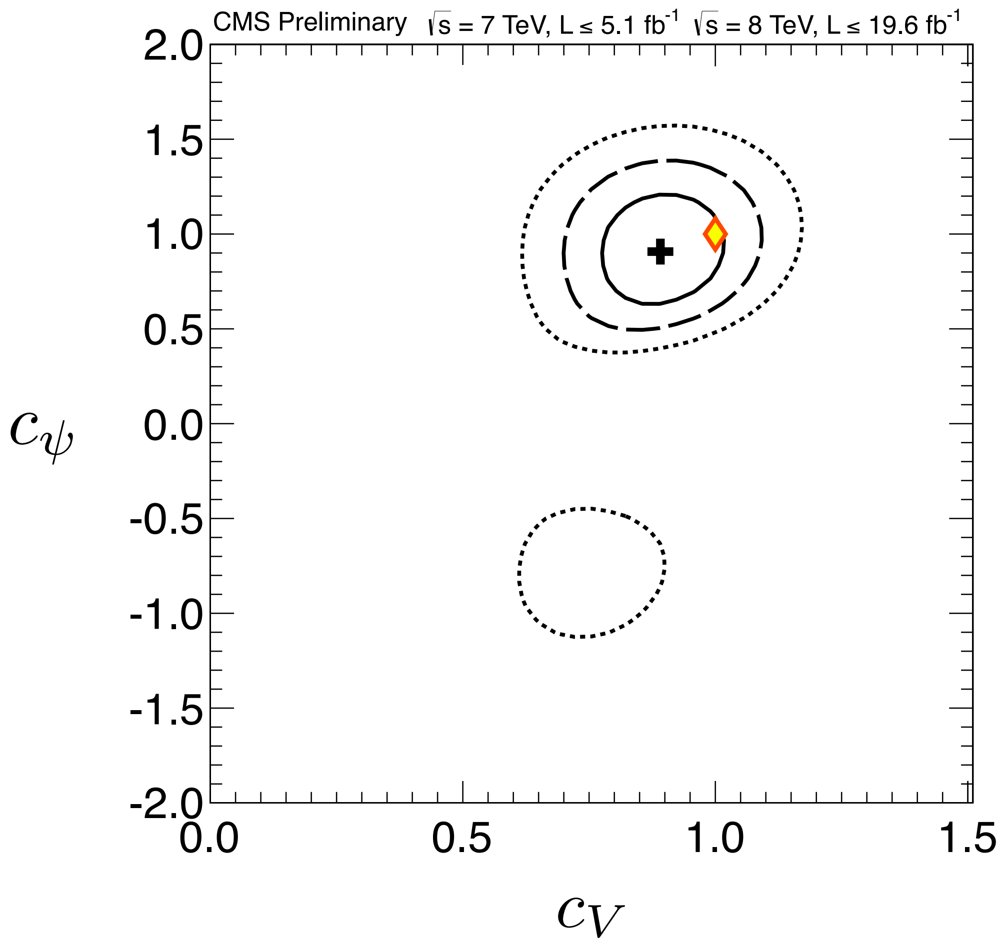
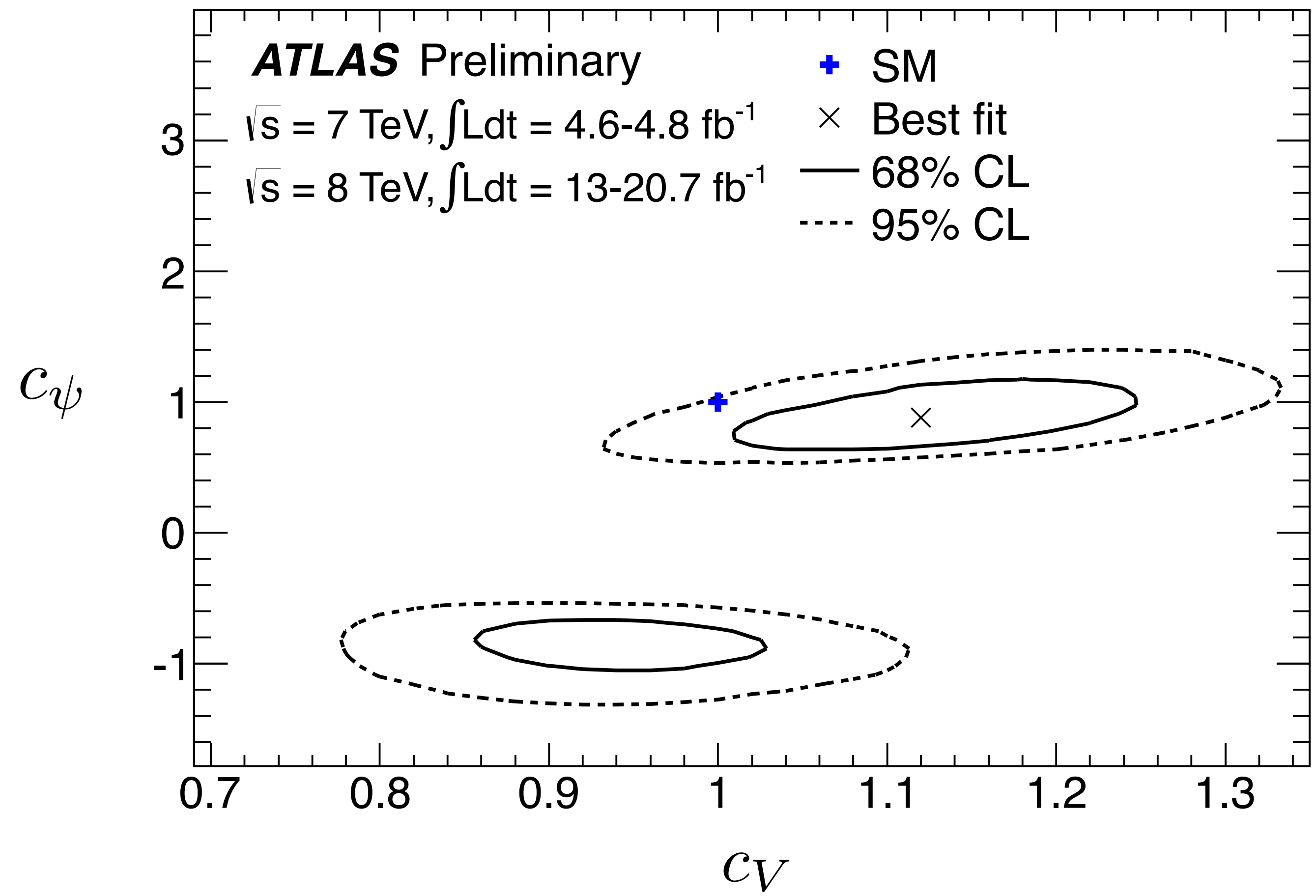
Current data indicate: $(c_i - 1) \ll 1$ Couplings close to SM point





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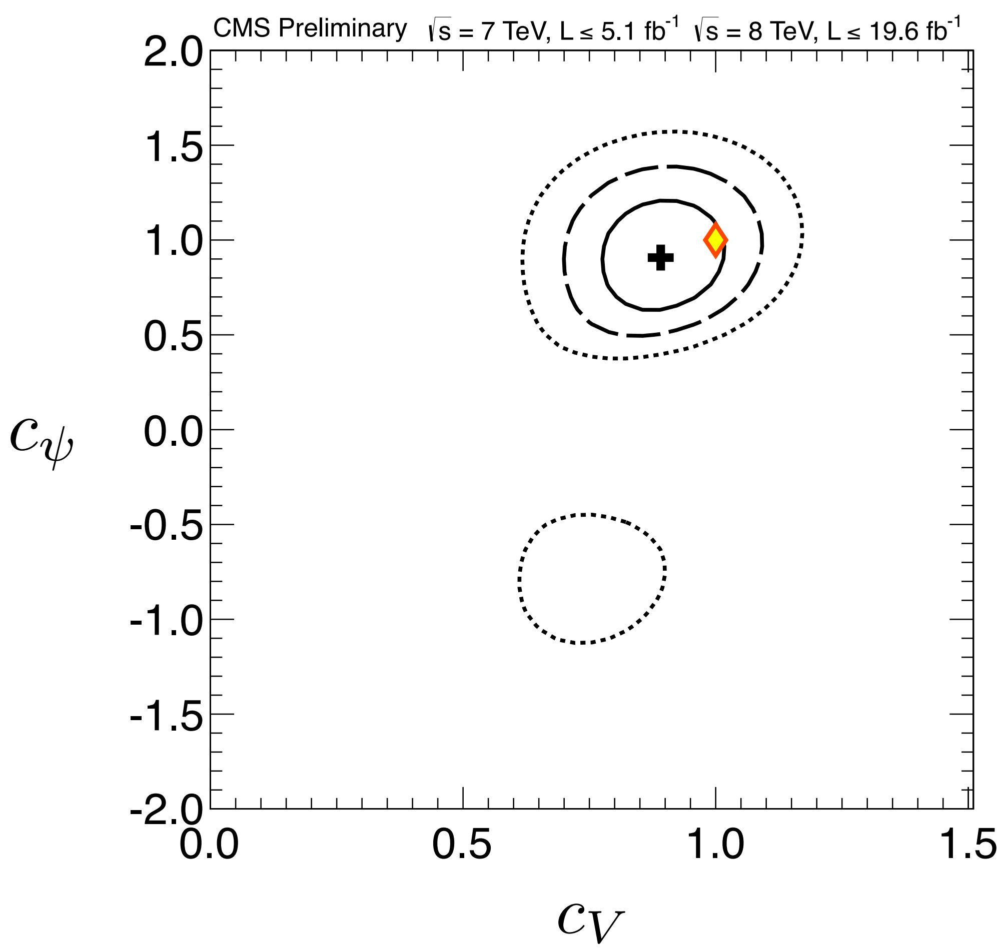

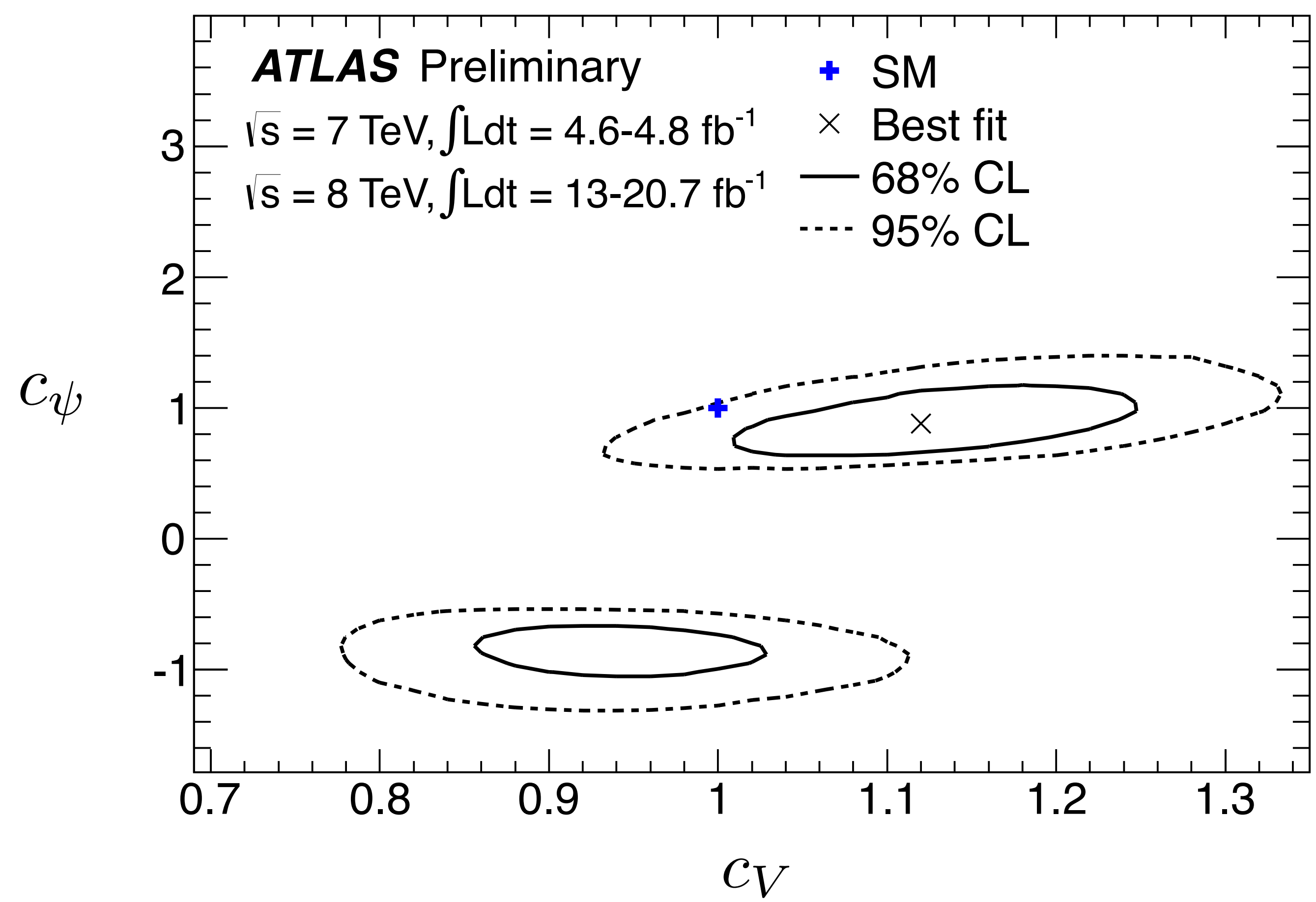

How to live near the SM:

1. The new boson is part of an $SU(2)_L$ doublet $H = e^{i\pi/v}\begin{pmatrix}0\\ v+h\end{pmatrix}$

2. There is a gap between the NP scale and m_h

Processes with 0, 1, 2, ... Higgses now *related*

Q: What is already constrained by experiments w/o Higgs ?

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All other operators probed
already by LEP + m_W + TGC

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$$O_{WW} = g^2 |H|^2 W_{\mu\nu} W^{\mu\nu}$$

$$O_{GG} = g_s^2 |H|^2 G_{\mu\nu} G^{\mu\nu}$$

$$O_{y_d} = y_d |H|^2 \bar{q}_L H d_R$$

$$O_{y_u} = y_u |H|^2 \bar{q}_L \tilde{H} u_R$$

$$O_{y_e} = y_e |H|^2 \bar{L}_L H e_R$$

$$O_6 = \lambda |H|^6$$

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Processes with 0, 1, 2, ... Higgses now *related*

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- Dimension-6 analysis of Higgs physics:

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  many directions closed by past experiments