EFFECTIVE THEORIES FOR HIGGS PHYSICS

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Outline

- PART 1 - Life without a Higgs boson
- PART 2 - The role of the Higgs boson
- PART 3 - Effective Lagrangian for a Higgs doublet

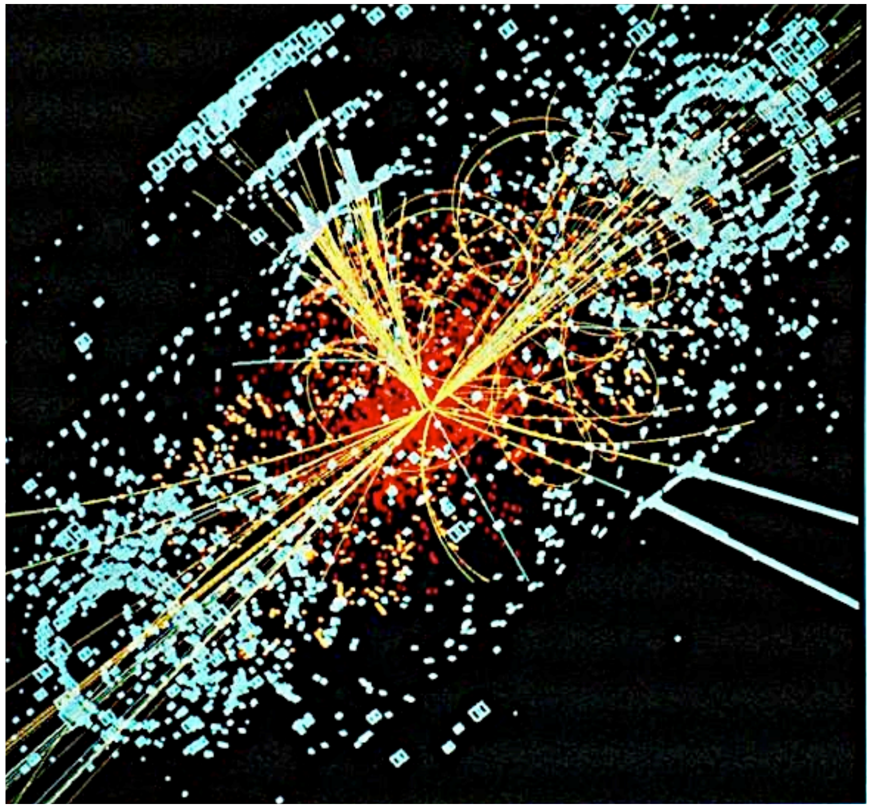
Part 1

Life without a Higgs boson

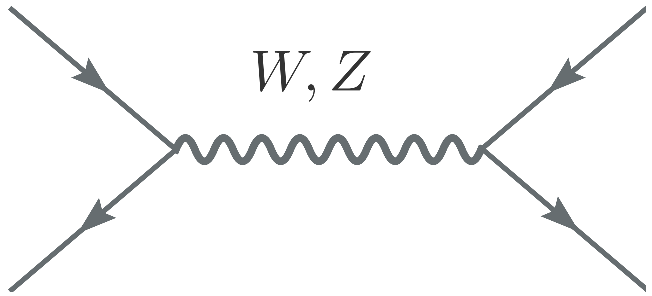
We have discovered a zoo of particles, yet simple rules govern their phenomenology:

- Interactions and decays obey selection rules: electromagnetic charge Q is always conserved
- Spectrum degeneracy: particles organized in multiples with same electromagnetic charge
- We feel a long-range force: electromagnetism

$U(1)_Q$ is a gauge (= local) symmetry and the photon is its carrier



In the spectrum of fundamental particles there are also massive spin-1 fields: $W^{\pm}$, Z^0



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W and Z are the gauge fields of a larger local $SU(2)_L x U(1)_Y$ invariance

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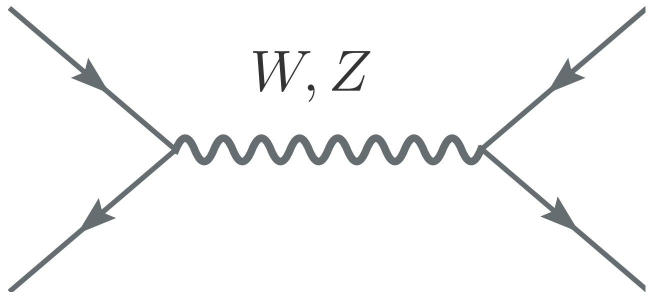

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Problems:

1. $SU(2)_L x U(1)_Y$ is not a symmetry of the particles' spectrum

2. W and Z are *massive*, and the EW force is *not* long-range

   What is the origin of the W,Z mass ?

<u>Solution:</u> The $SU(2)_L \times U(1)_Y$ *local* symmetry is spontaneously broken by the vacuum via the Brout-Englert-Higgs mechanism

The problems of the mass and of the missing NG bosons can solve each other:

- F. Englert, R. Brout, PRL 13 (1964) 321, "Broken symmetry and the mass of gauge vector bosons"

" it is precisely these singularities [of the NG bosons] which maintain the gauge invariance of the theory, despite the fact that the vector meson acquires a mass "

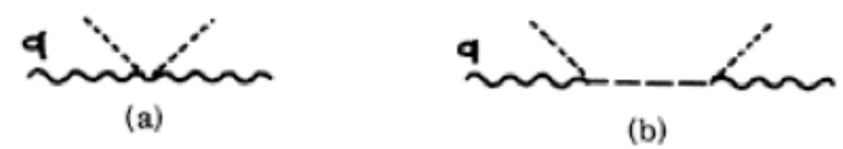


FIG. 1. Broken-symmetry diagram leading to a mass for the gauge field. Short-dashed line, $\langle\varphi_1\rangle$; long-dashed line, φ_2 propagator; wavy line, A_μ propagator. (a)$\to (2\pi)^4 ie^2 g_{\mu\nu}\langle\varphi_1\rangle^2$, (b)$\to -(2\pi)^4 ie^2(q_\mu q_\nu/q^2)\times\langle\varphi_1\rangle^2$.

- P. Higgs, Phys. Lett. 12 (1964) 132, "Broken symmetries, massless particles and gauge fields"

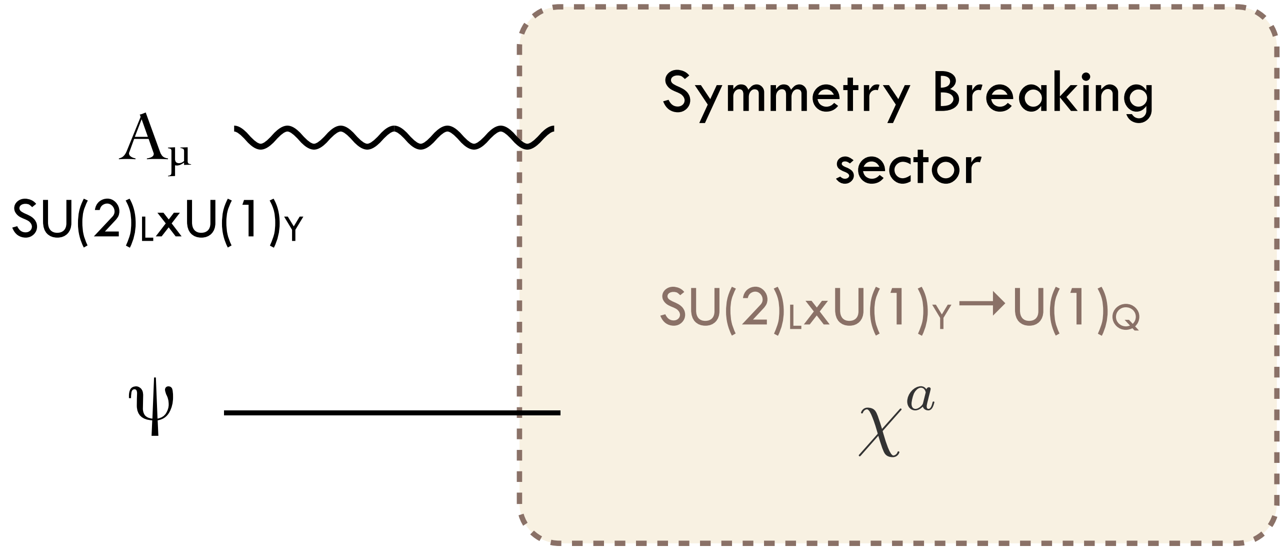
the choice of Coulomb gauge to quantize a gauge theory implies the existence of a time-like vector and thus invalidates Goldstone's theorem based on manifest Lorentz covariance

the group as coefficients. Now the structure of the Fourier transform of $i\langle[A_\mu'(x), \varphi_1(y)]\rangle$ must be given by eq. (3). Applying eq. (5) to this commutator gives us as the Fourier transform of $i\langle[f_\mu(x), \varphi_1(y)]\rangle$ the single term $[k^2 n_\mu - k_\mu(nk)]\rho(k^2, nk)$. We have thus exorcised both Goldstone's zero-mass bosons and the "spurion" state (at $k_\mu = 0$) proposed by Klein and Lee.

In a subsequent note it will be shown, by considering some classical field theories which dis-

Solution: The $SU(2)_L \times U(1)_Y$ *local* symmetry is spontaneously broken by the vacuum via the Englert-Brout-Higgs mechanism

The (massless) NG bosons from the spontaneous symmetry breaking are 'eaten' to form the longitudinal polarizations of the massive vector bosons



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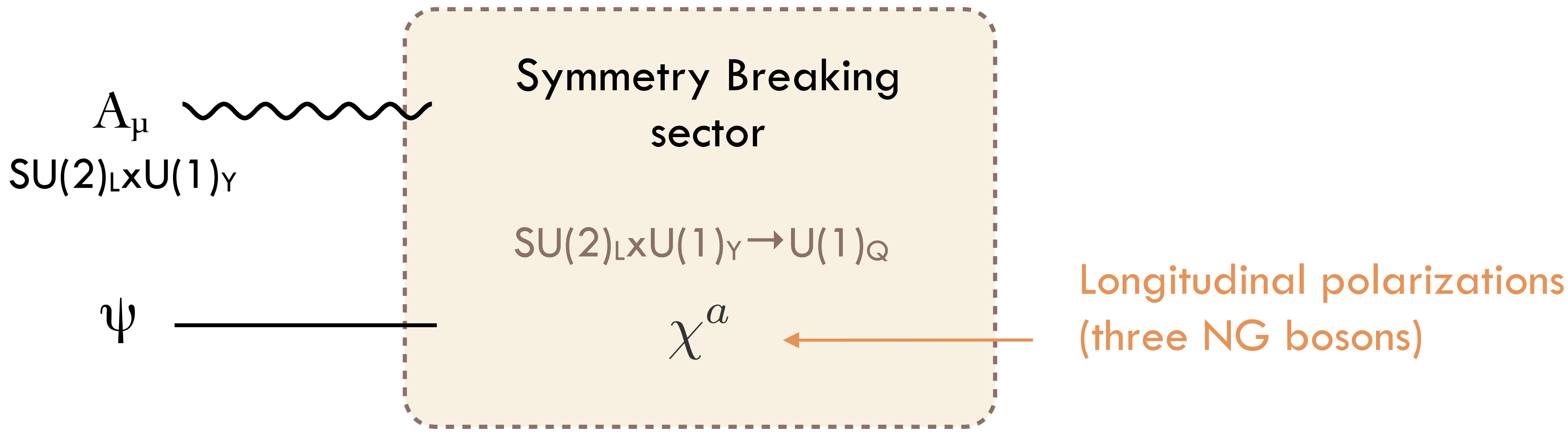

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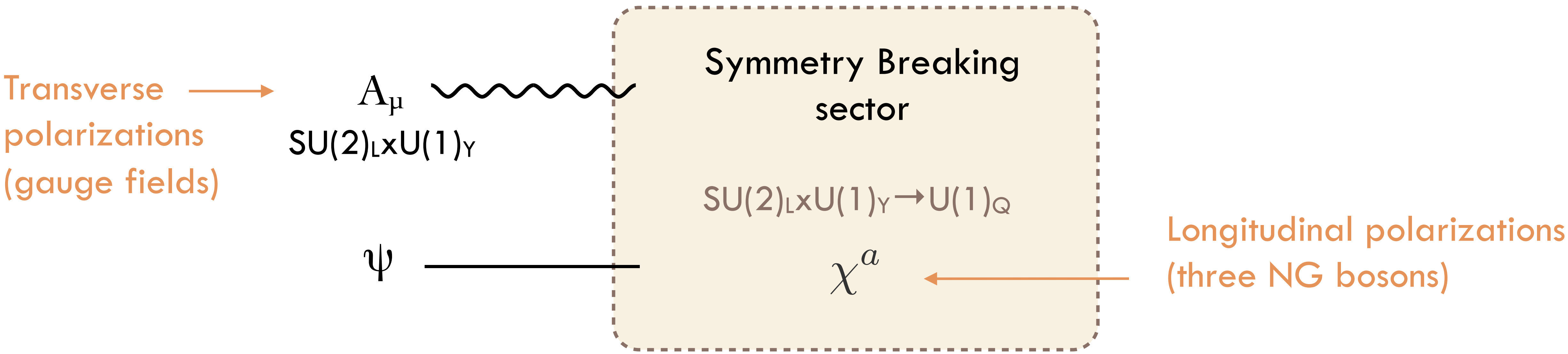

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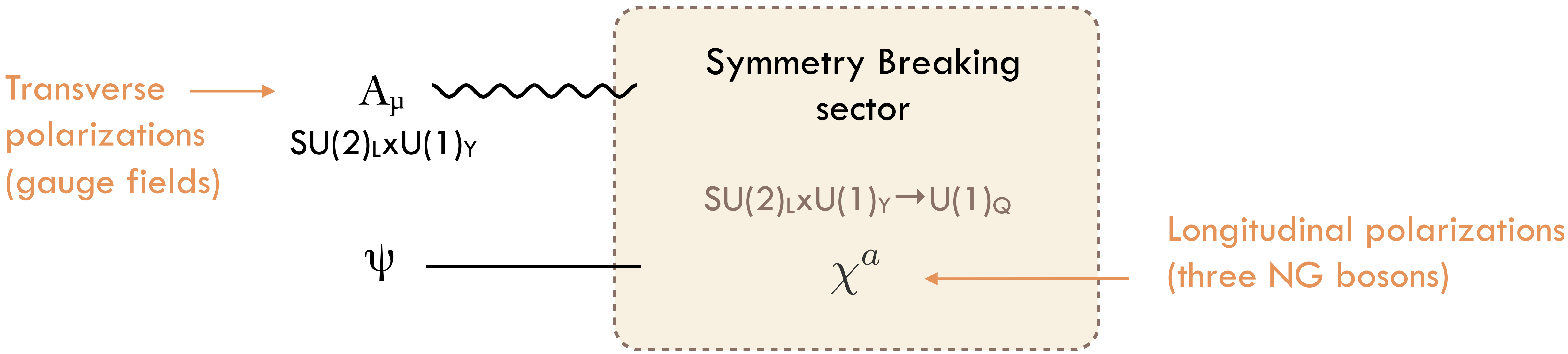
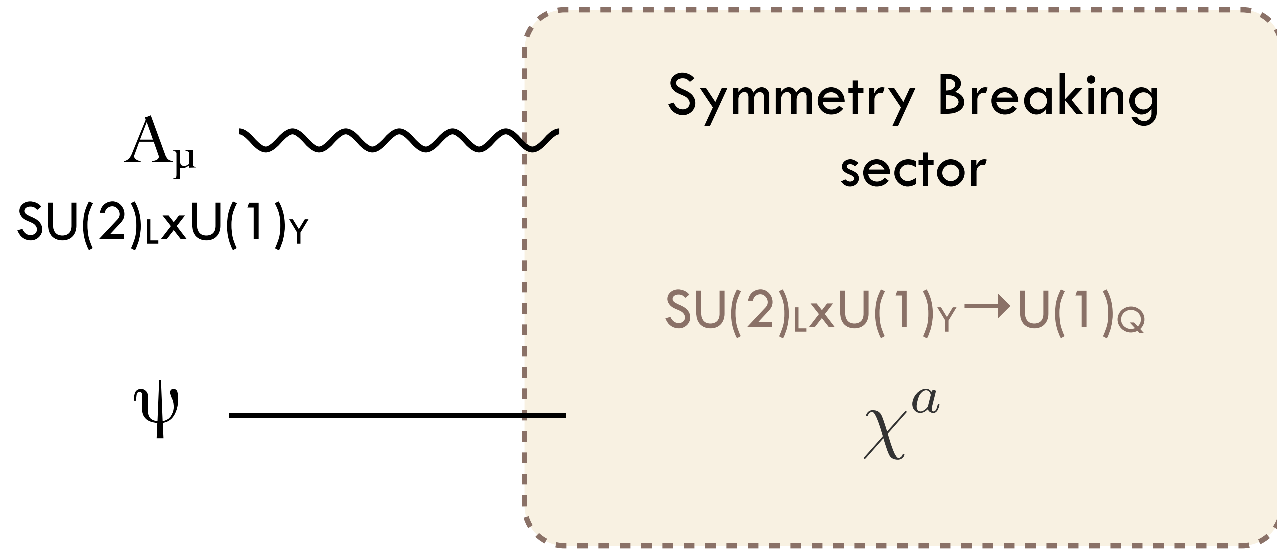


Englert and Higgs received the 2013 Nobel prize in Physics

" ... for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles "



The theory can be described by a manifestly gauge-invariant Lagrangian by including the NG fields:

$\Sigma(x) = \exp\left(i\sigma^a \chi^a(x)/v\right)$ $\quad a = 1, 2, 3$ (2x2 matrix)

$\Sigma \to U_L\, \Sigma\, U_Y^\dagger$

$SU(2)_L$ acts on the left $\quad U_L(x) = \exp(i\,\alpha_L^a(x)\sigma^a/2)$

$U(1)_Y$ acts on the right $\quad U_Y(x) = \exp(i\,\alpha_Y(x)\sigma^3/2)$

The vacuum $\langle\Sigma\rangle = 1$ spontaneously breaks $SU(2)_L\times U(1)_Y \to U(1)_Q$ $\quad$ ($Q = T_{3L} + Y$)

The $\chi^a(x)$ transform:

- non-linearly under SU(2)$_L$xU(1)$_Y$

ex: under SU(2)$_L$

$$\boxed{\begin{aligned}\hat{\chi}'^{\,a} &= \hat{\chi}^a\left(1+\frac{1}{2}\,\vec{\alpha}\cdot\hat{\chi}\,\cot\!\left(\frac{\chi}{v}\right)\right)+\frac{\alpha^a}{2}\cot\!\left(\frac{\chi}{v}\right)+O(\alpha^2)\\ \sin\left(\frac{\chi'}{v}\right) &= \sin\left(\frac{\chi}{v}\right)\left[1+\frac{1}{2}\,\vec{\alpha}\cdot\hat{\chi}\,\cot\!\left(\frac{\chi}{v}\right)\right]+O(\alpha^2)\end{aligned}}$$

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- linearly under the unbroken U(1)$_Q$ subgroup:

$$U_L = U_Y = \exp(i\alpha\,\sigma^3/2) \equiv U_Q$$

$$\Sigma' = U_Q\, e^{i\chi\cdot\sigma/v}\, U_Q^{-1} = e^{i\,U_Q(\chi\cdot\sigma)U_Q^{-1}/v}$$

$$\boxed{(\vec{\chi}'\cdot\vec{\sigma}) = U_Q\,(\vec{\chi}\cdot\vec{\sigma})\,U_Q^{-1}}$$

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Notice: the field Σ does transform linearly, but it is subject to the non-linear constraint $\Sigma^\dagger\Sigma = 1$

It is natural then to define the covariant derivative:

$$D_\mu \Sigma = \partial_\mu \Sigma - i g_2 \frac{\sigma^a}{2} W_\mu^a \Sigma + i g_1 \Sigma \frac{\sigma_3}{2} B_\mu$$

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There are *two* kinetic terms invariant under $SU(2)_L x U(1)_Y$ local transformations:

$$\mathcal{L}_{mass} = \frac{v^2}{4} \mathrm{Tr} \left[(D_\mu \Sigma)^\dagger \, (D^\mu \Sigma) \right] + \frac{a_T}{8} v^2 \, \mathrm{Tr} \big[\Sigma^\dagger D_\mu \Sigma \, \sigma^3 \big]^2$$

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in the unitary gauge $\chi(x) = 0$

$$M_W^2 = \frac{v^2}{4} g_2^2$$

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MUST BE SMALL

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if gauging is switched off the first term has a larger $SU(2)_L x SU(2)_R$ *global* symmetry:

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- The pattern of *global* non-linearly realized symmetry is $SU(2)_L x SU(2)_R \to SU(2)_V$

$\longrightarrow$ complete analogy with chiral symmetry in QCD

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- The pattern of *global* non-linearly realized symmetry is SU(2)$_L$xSU(2)$_R$→SU(2)$_V$

⟶ complete analogy with chiral symmetry in QCD

- The vacuum preserves a global SU(2)$_V$ 'custodial' symmetry (weak isospin)

⟶ physical states come in multiplets of SU(2)$_V$

⟶ the NG bosons χ^a form a triplet of SU(2)$_V$ $\Longleftrightarrow$ $M_W = M_Z$ for $g_1 = 0$

The Lagrangian $\mathcal{L}_{mass}$ gives an <u>effective</u> description valid below some cutoff scale:

$$\frac{v^2}{4}\mathrm{Tr}[(\partial_\mu\Sigma)^\dagger(\partial_\mu\Sigma)] = \frac{1}{2}\left(\partial_\mu\chi^a\right)^2 + \frac{1}{6v^2}\left[\left(\chi^a\partial_\mu\chi^a\right)^2 - \left(\chi^a\partial_\mu\chi^b\right)^2\right] + O(\chi^6)$$

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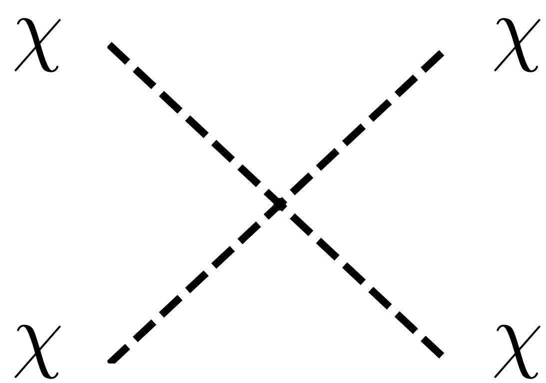

$$\boxed{A(s,t,u) = \frac{s}{v^2}}$$

$$\mathcal{A}\left(\chi^a\chi^b \to \chi^c\chi^d\right) = A(s,t,u)\delta^{ab}\delta^{cd} + A(t,s,u)\delta^{ac}\delta^{bd} + A(u,t,s)\delta^{ad}\delta^{bc}$$

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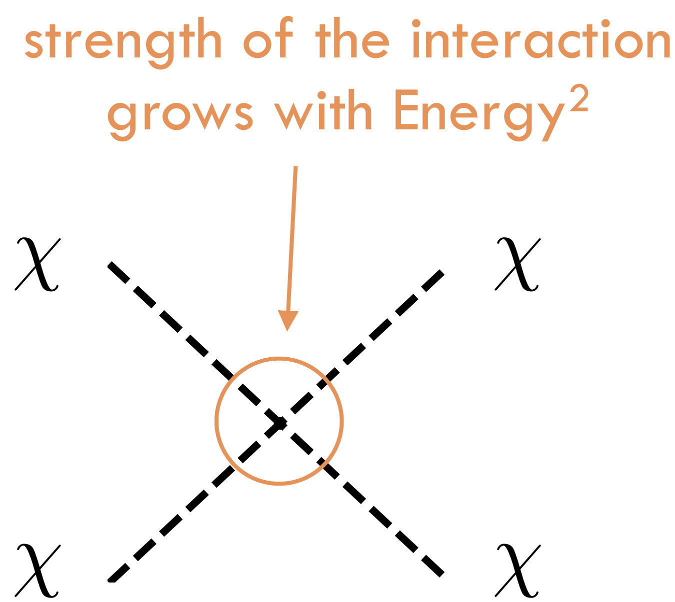

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In general:

$$\mathcal{A}(2 \to 2) = \text{coupling}^2 \quad \Rightarrow \quad \boxed{g(E) = \frac{E}{v}}$$

In absence of additional contributions to the scattering amplitude, the coupling strength becomes non-perturbative ($g(E) = 4\pi$) at energy scales $E \sim \Lambda_s = 4\pi v$

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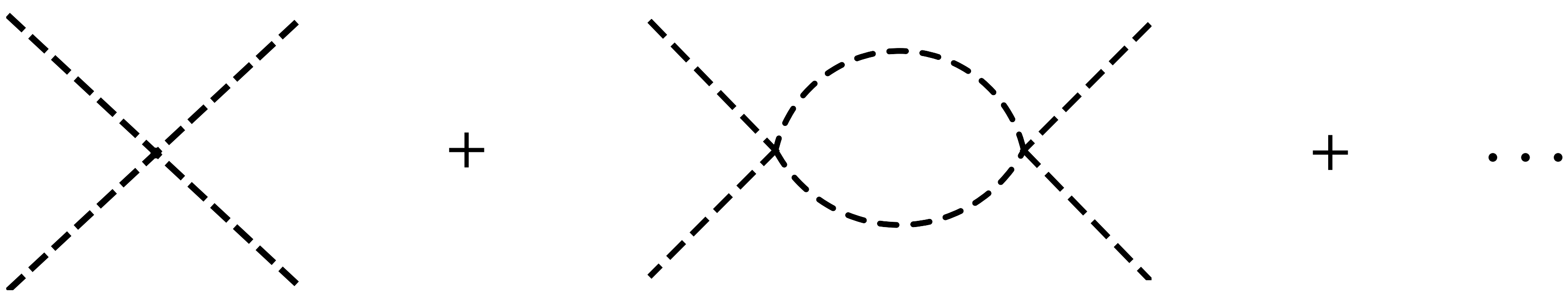
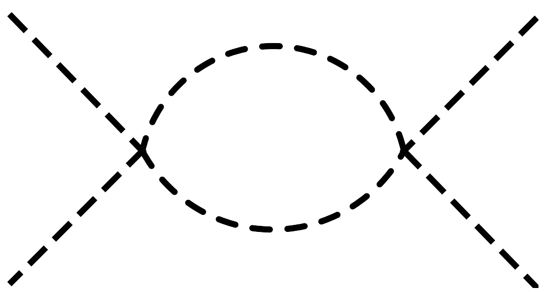


$$\frac{E^2}{v^2} = g(E)^2 \qquad\qquad \frac{1}{16\pi^2}\frac{E^4}{v^4} = g(E)^2 \left(\frac{g(E)^2}{16\pi^2}\right)$$

Loop diagrams are divergent and need to be renormalized

by higher-derivative operators



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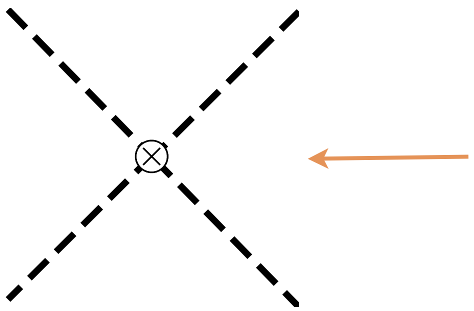

counterterm from 4-derivative operator. Ex:

$$\left(\mathrm{Tr}\left[\partial_\mu \Sigma^\dagger \partial^\mu \Sigma\right]\right)^2$$

$$\propto \frac{1}{16\pi^2}\frac{E^4}{v^4}\left(\frac{1}{\varepsilon} + finite\right)$$

$$\frac{E^4}{v^4}\left[c(\mu) + \frac{\gamma_c}{16\pi^2}\left(\frac{1}{\varepsilon} - \log\mu\right)\right]$$

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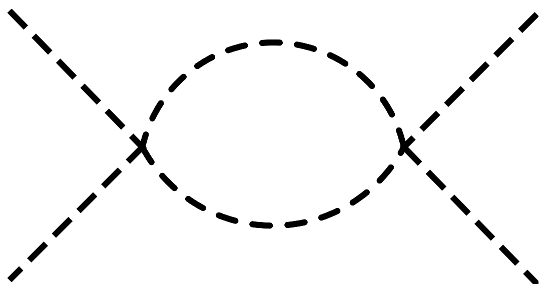

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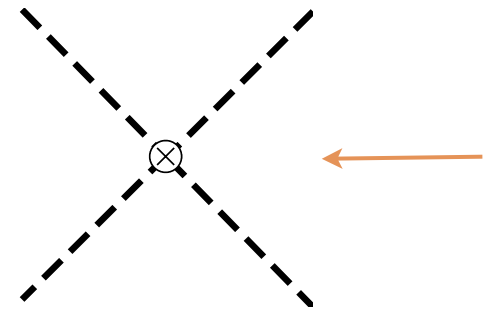

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$$\frac{d}{d\log\mu}c(\mu) = \frac{\gamma_c}{16\pi^2}$$

$$\boxed{c(\mu) = c(\Lambda) + \frac{\gamma_c}{16\pi^2}\log\left(\frac{\mu}{\Lambda}\right)}$$

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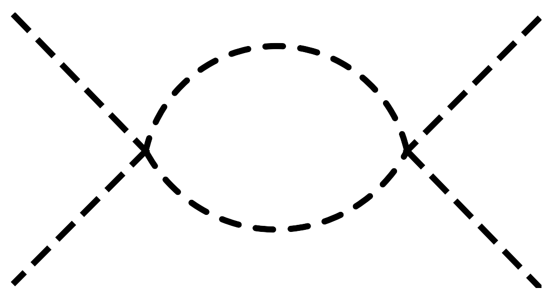

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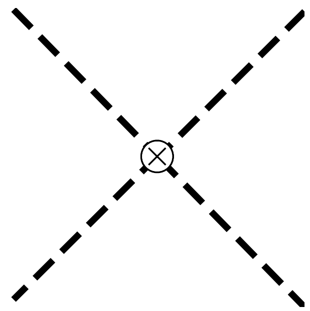

counterterm from
4-derivative
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$$\propto \frac{1}{16\pi^2}\frac{E^4}{v^4}\left(\frac{1}{\varepsilon} + finite\right)$$

$$\frac{E^4}{v^4}\left[c(\mu) + \frac{\gamma_c}{16\pi^2}\left(\frac{1}{\varepsilon} - \log\mu\right)\right]$$

$$\frac{d}{d\log\mu}c(\mu) = \frac{\gamma_c}{16\pi^2}$$

$$\boxed{c(\mu) = c(\Lambda) + \frac{\gamma_c}{16\pi^2}\log\left(\frac{\mu}{\Lambda}\right)}$$

Operators are additively renormalized

1-loop $O(p^2)$ $\longrightarrow$ $O(p^4)$

1-loop $O(p^4)$ $\longrightarrow$ $O(p^6)$
2-loops $O(p^2)$

$\vdots$ $\vdots$

The Lagrangian of NG bosons is thus “non-renormalizable” and should be thought of as a derivative expansion

$$\mathcal{L} = \mathcal{L}^{(2)} + \mathcal{L}^{(4)} + \mathcal{L}^{(6)} + \dots$$

$$\mathcal{L}^{(2)} = \frac{v^2}{4}\mathrm{Tr}[(D_\mu\Sigma)^\dagger(D^\mu\Sigma)]$$

$$\mathcal{L}^{(4)} = c_1\,\mathrm{Tr}\big[(D_\mu\Sigma^\dagger D^\mu\Sigma)^2\big] + c_2\,\mathrm{Tr}\big[(D_\mu\Sigma^\dagger D_\nu\Sigma)^2\big]$$

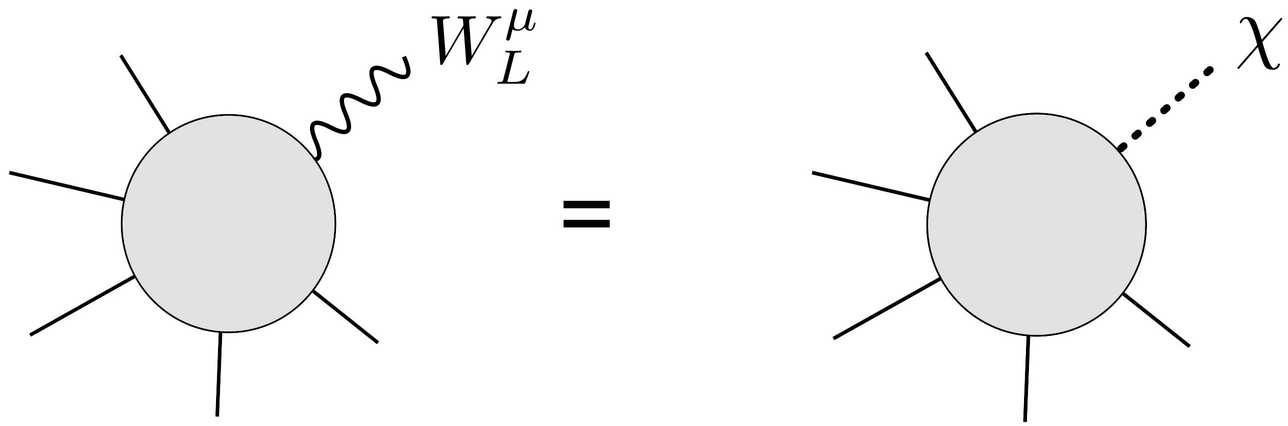
$$\vdots$$

Expansion parameters:

– (E/Λ) controlling the derivative expansion

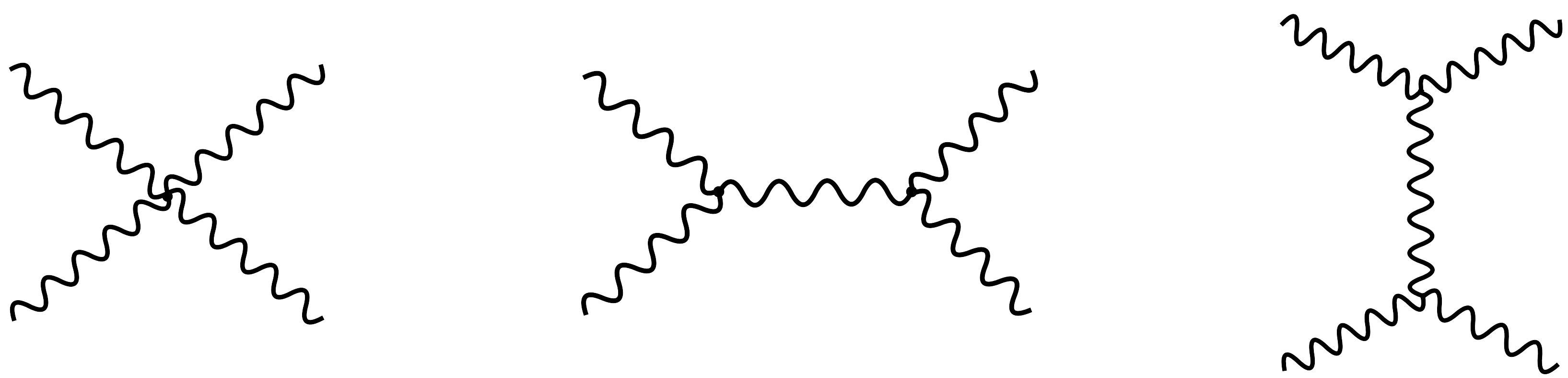
– $(\alpha/4\pi)$ weak gauging expansion parameter

The Equivalence Theorem



$$\left(1 + O\left(\frac{M_W^2}{E^2}\right)\right)$$

relates the scattering of NG bosons to that of longitudinal vector bosons $V_L V_L \to V_L V_L$ ($V = W, Z$) at high energies $E \gg m_W$



$$\mathcal{A}(W_L^+ W_L^- \to W_L^+ W_L^-) = \mathcal{A}(\chi^+ \chi^- \to \chi^+ \chi^-) \left(1 + O\left(\frac{M_W^2}{E^2}\right)\right) = \frac{g_2^2}{4 m_W^2}(s+t) + \dots$$

The evidence for a spontaneously-broken $SU(2)_L x U(1)_Y$ gauge symmetry is founded on the following facts:

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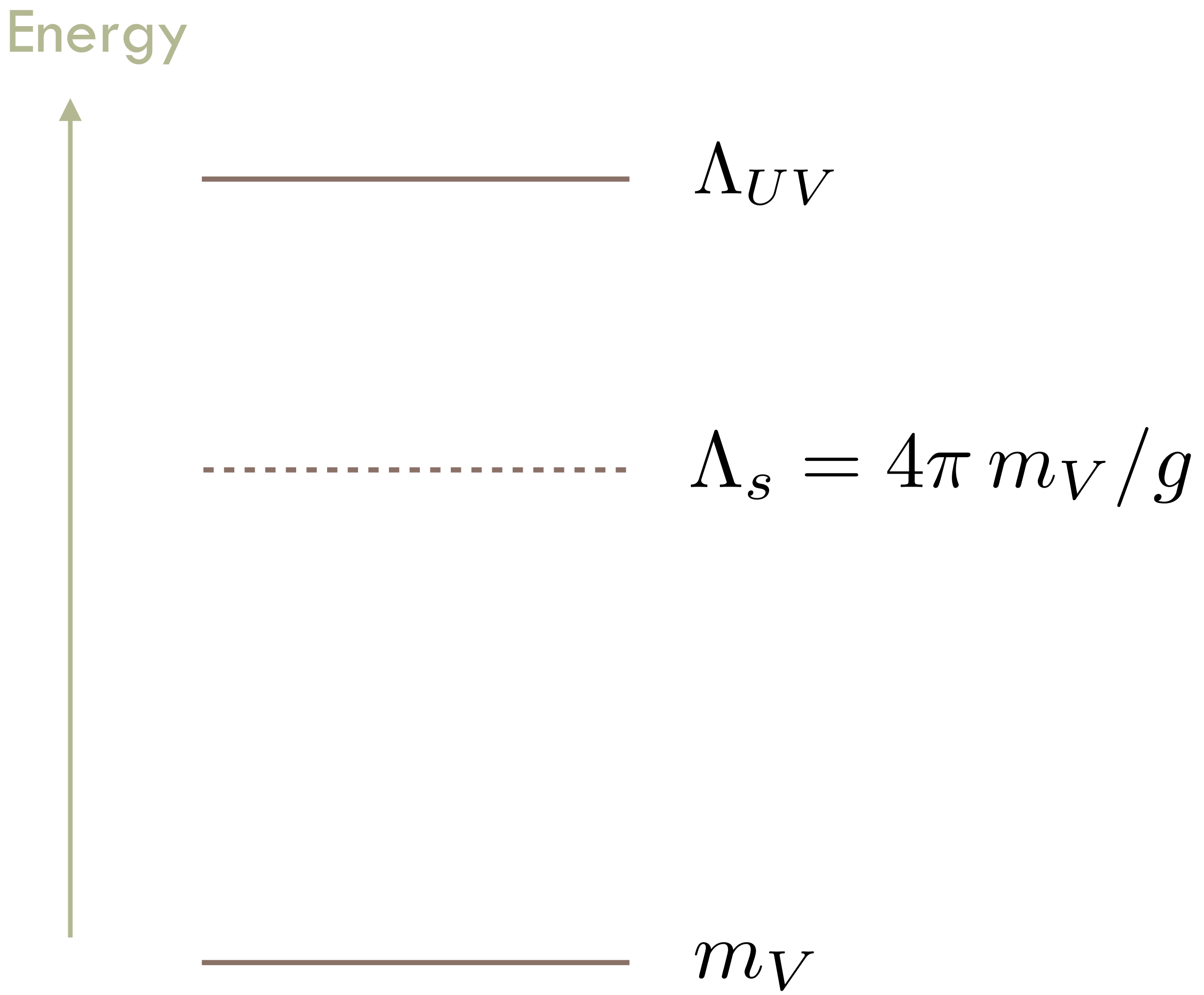
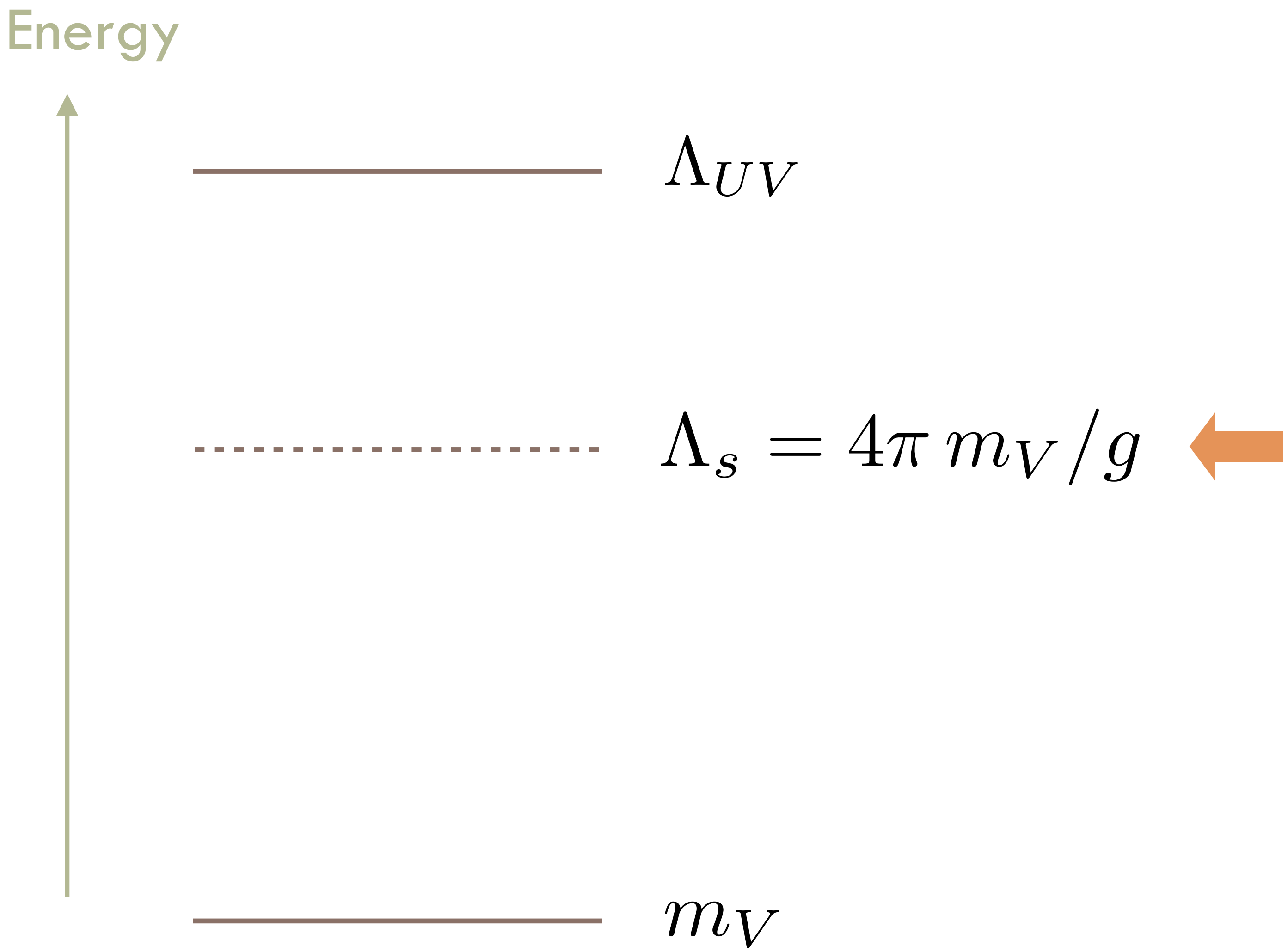
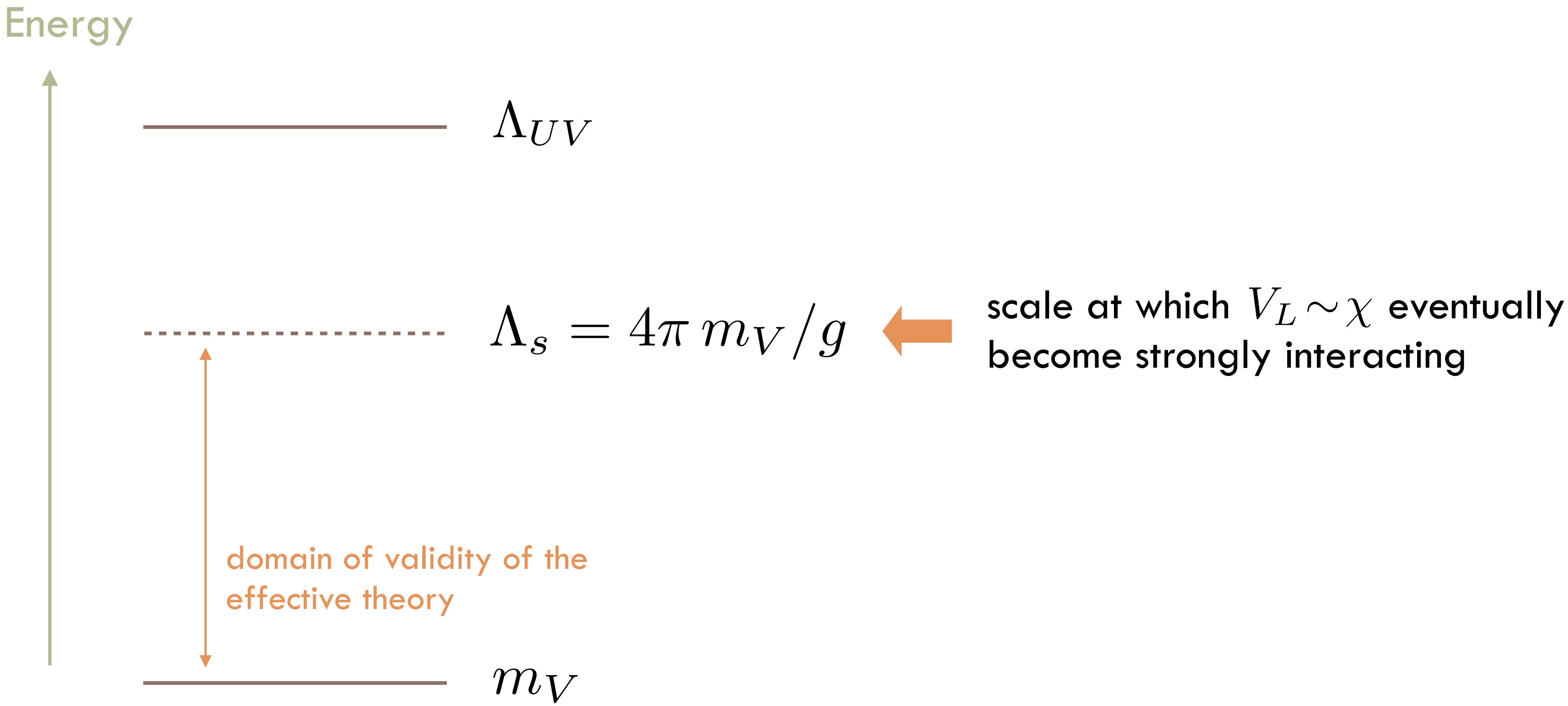
[3] the *transverse* W_μ^T, Z_μ^T are elementary up to energies $E \gg 4\pi\, m_V/g$


Energy
Λ_{UV}
$\Lambda_s = 4\pi\, m_V / g$
m_V



scale at which $V_L \sim \chi$ eventually become strongly interacting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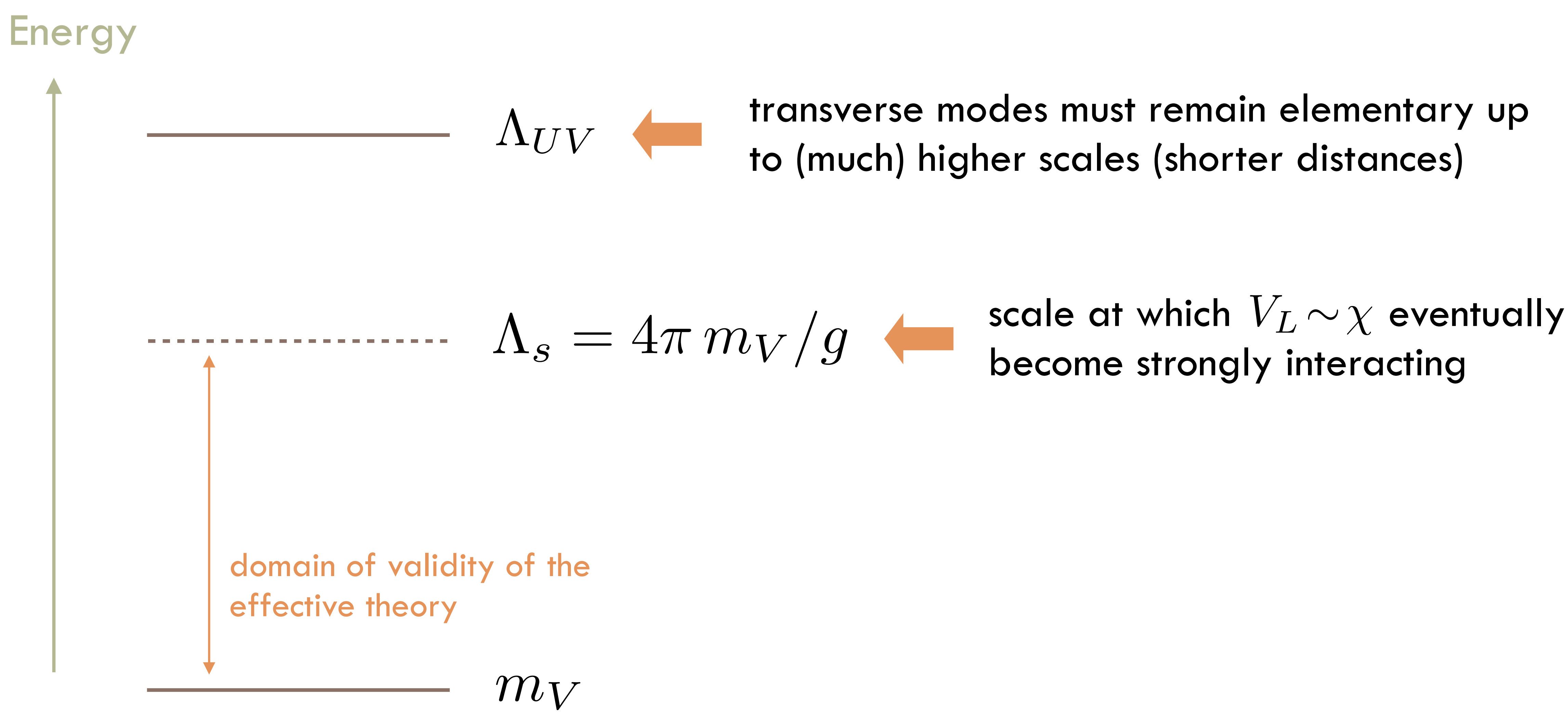
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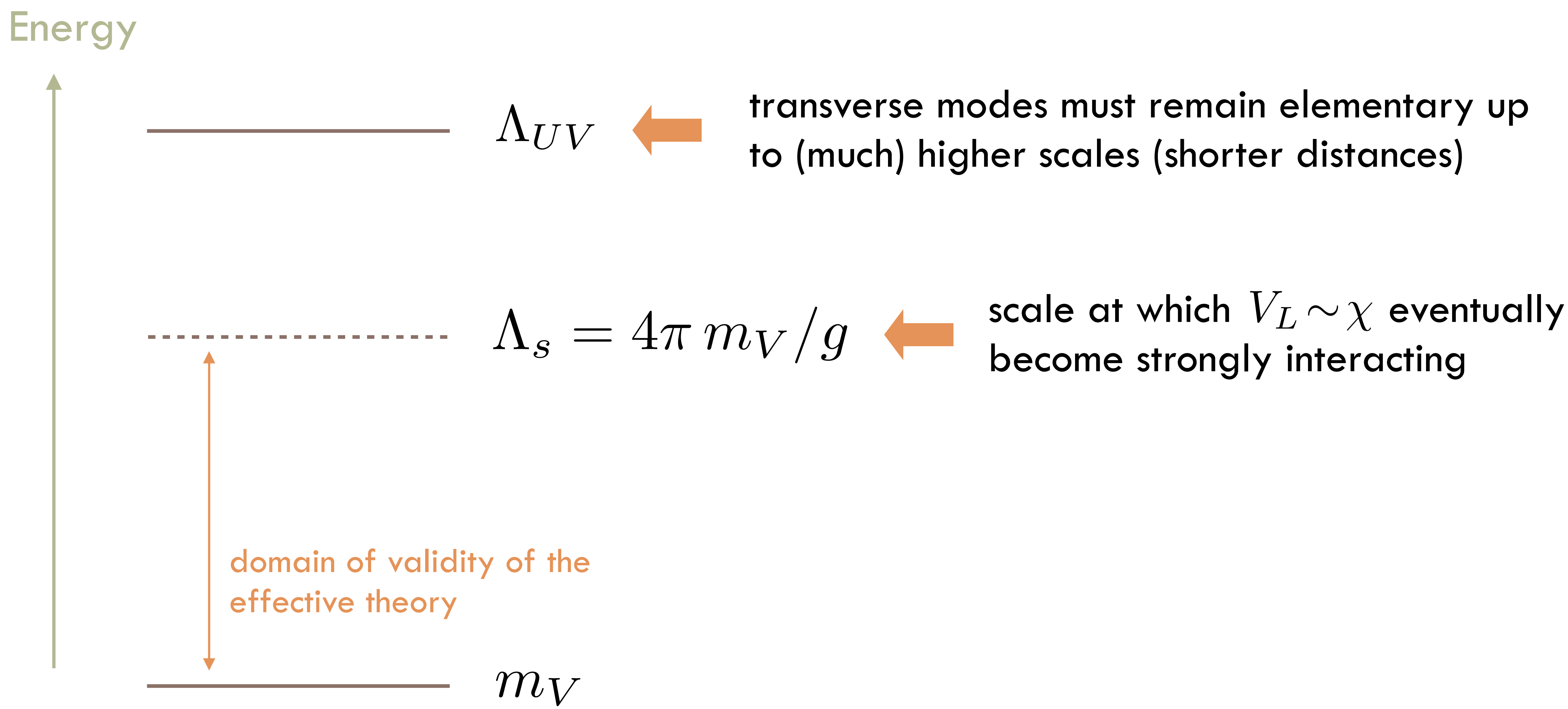
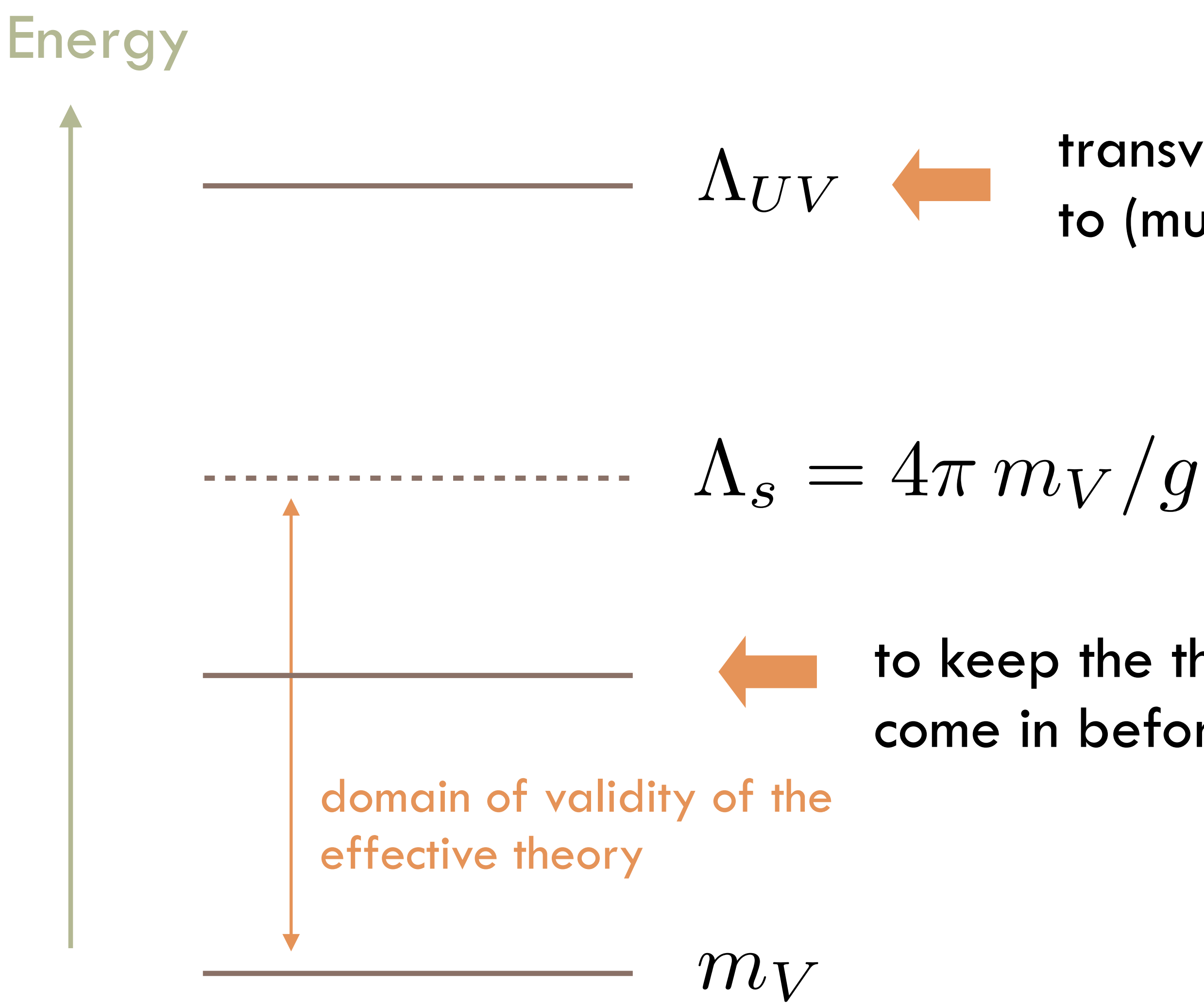


NOTICE:

the longitudinal polarizations need ***not*** be elementary

(i.e. they can be composites of some new dynamics)



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scale at which $V_L \sim \chi$ eventually become strongly interacting

to keep the theory perturbative new particles must come in before Λ_s to regulate the scattering amplitudes

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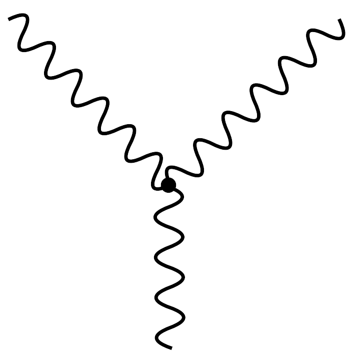
Elementary nature of W,Z tested at LEP, Tevatron and LHC through Triple Gauge Couplings (TGC)

Suppose an anomalous coupling is measured which can be parametrized by the operator

$$\frac{g_2\, c_{W3}}{m_W^2}\, \epsilon^{abc}\, W^a_{\mu\nu} W^b_{\nu\rho} W^c_{\rho\mu}$$



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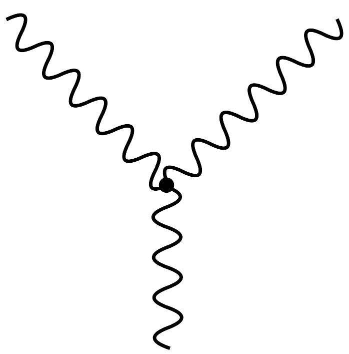

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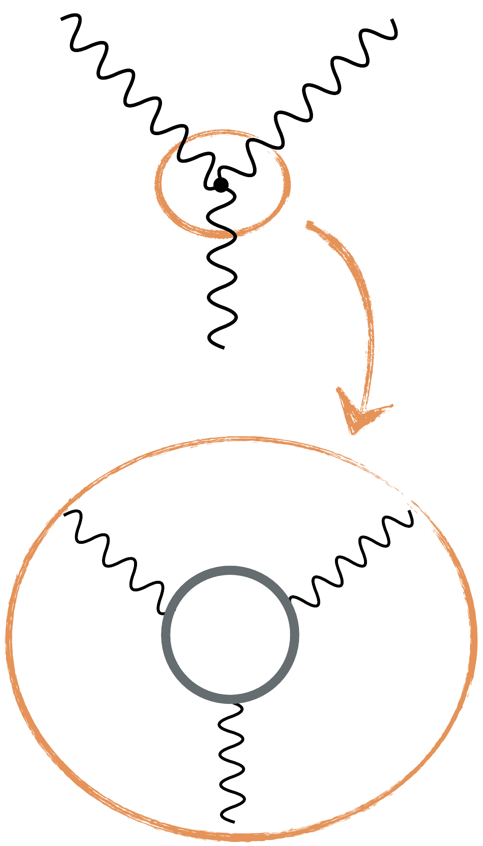

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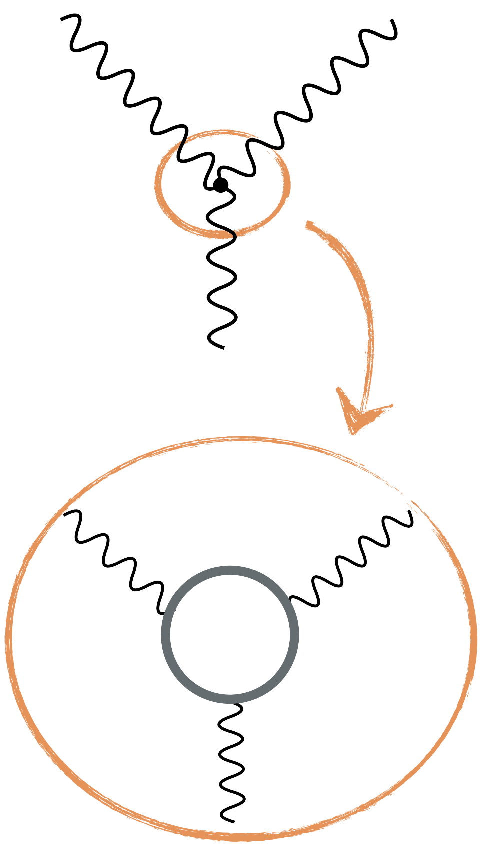

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$$m_* = \frac{m_W}{\sqrt{c_{W3}}} \times \frac{g}{4\pi}$$ if new physics arises at the 1-loop level

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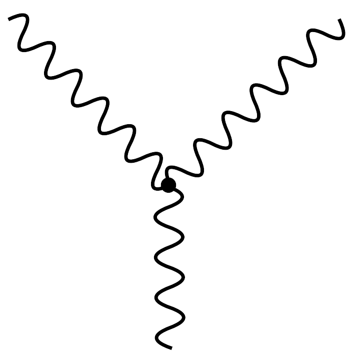

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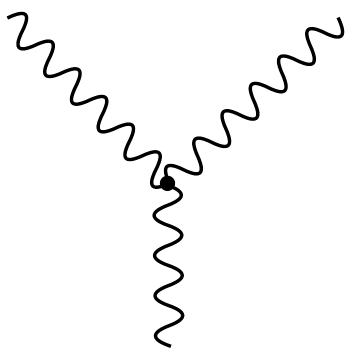

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$$E \sim m_W \sqrt{\frac{4\pi}{c_{W3}\, g}} \equiv \Lambda_S$$

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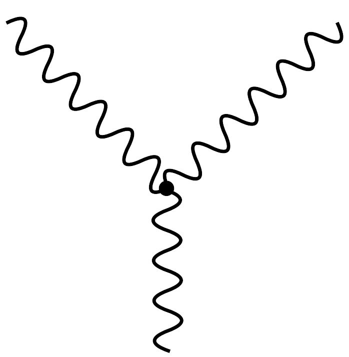

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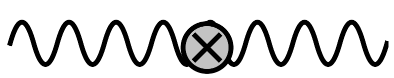
LEP, Tevatron and LHC set limits on the anomalous TGC of order $c_i < 10^{-2}$

$$\boxed{\Lambda_S \gtrsim 4\,\mathrm{TeV}}$$

Strong bounds on `structure` scale m_* come also from modifications to the vector propagator

Ex: S-parameter $a_S\,\mathrm{Tr}\left[W_{\mu\nu}\,\Sigma\,\sigma^3 B_{\mu\nu}\,\Sigma^\dagger\right] \supset \gamma_{\mu\nu} Z_{\mu\nu}$ (Z-photon mixing)



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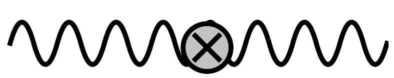

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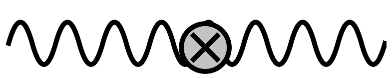

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LEP

$$\frac{g_2}{g_1}\, a_S(m_Z) = \frac{m_W^2}{m_*^2} \lesssim 2\times 10^{-3}$$

$$\boxed{m_* \gtrsim 1.8\,\mathrm{TeV}}$$

A counter-example: the ρ in QCD

- Could the ρ be the *gauge field* of a larger spontaneously-broken global symmetry $SU(2)_L \times SU(2)_H \times SU(2)_R \rightarrow SU(2)_V$?

Sakurai, *Currents and Mesons*, 1969
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ρ_μ

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3 NG bosons remain in the spectrum = the pions

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- There is no separation of scales

scale at which ρ^L becomes strongly interacting

$\Lambda_s = 4\pi\, m_\rho / g_{\rho\pi\pi} = 1.6\,\mathrm{GeV}$

$4\pi f_\pi = 1.2\,\mathrm{GeV}$

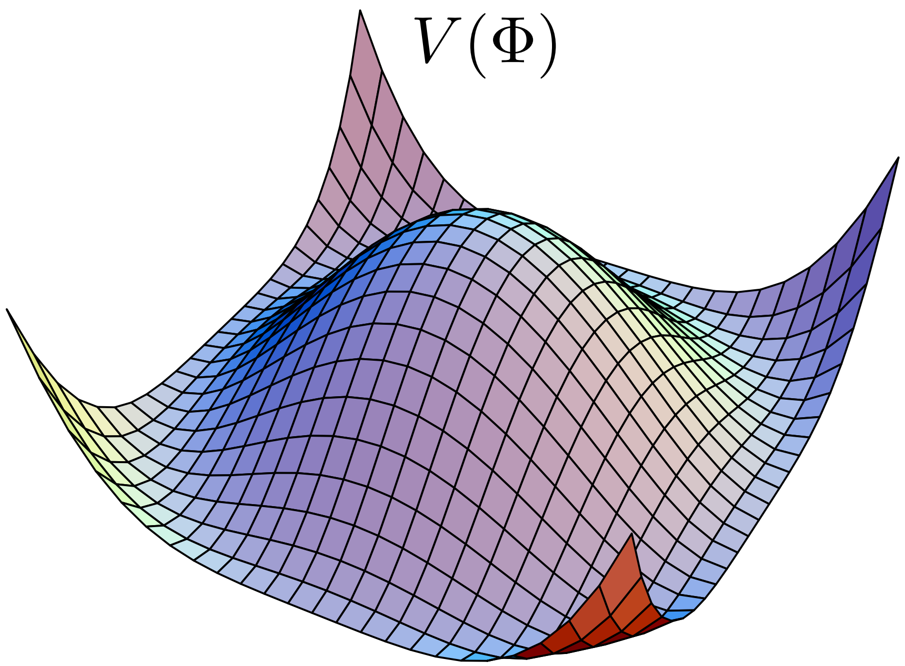
scale at which π's become strongly interacting

$m_\rho = 0.77\,\mathrm{GeV}$

Part 2

The role of the Higgs boson

What Higgs bosons are



E

EW condensate $\langle \Phi \rangle = v$

W, Z, h

QCD condensate $\langle \bar{q} q \rangle = \Lambda^3_{QCD}$

p, n

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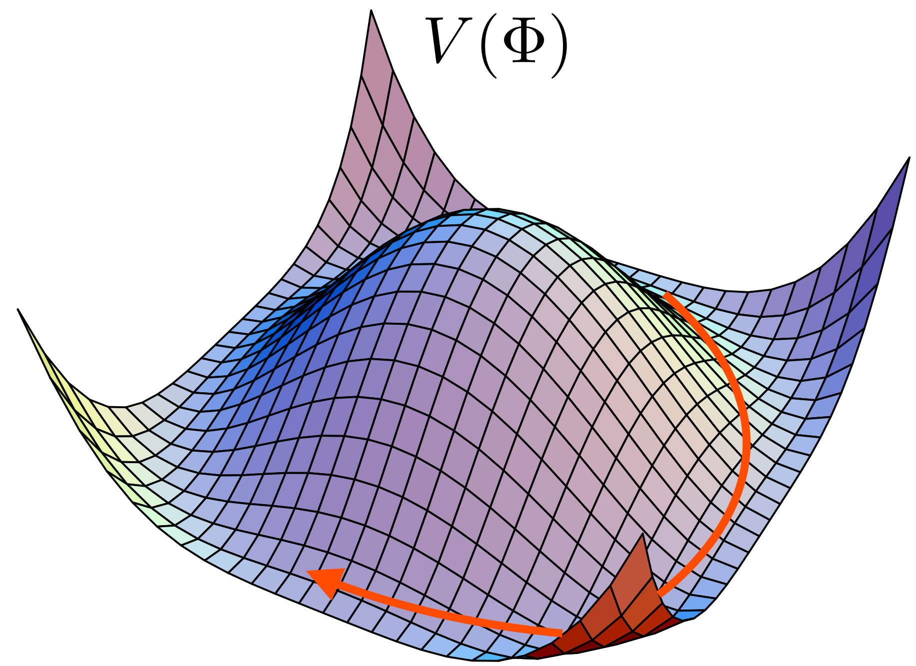

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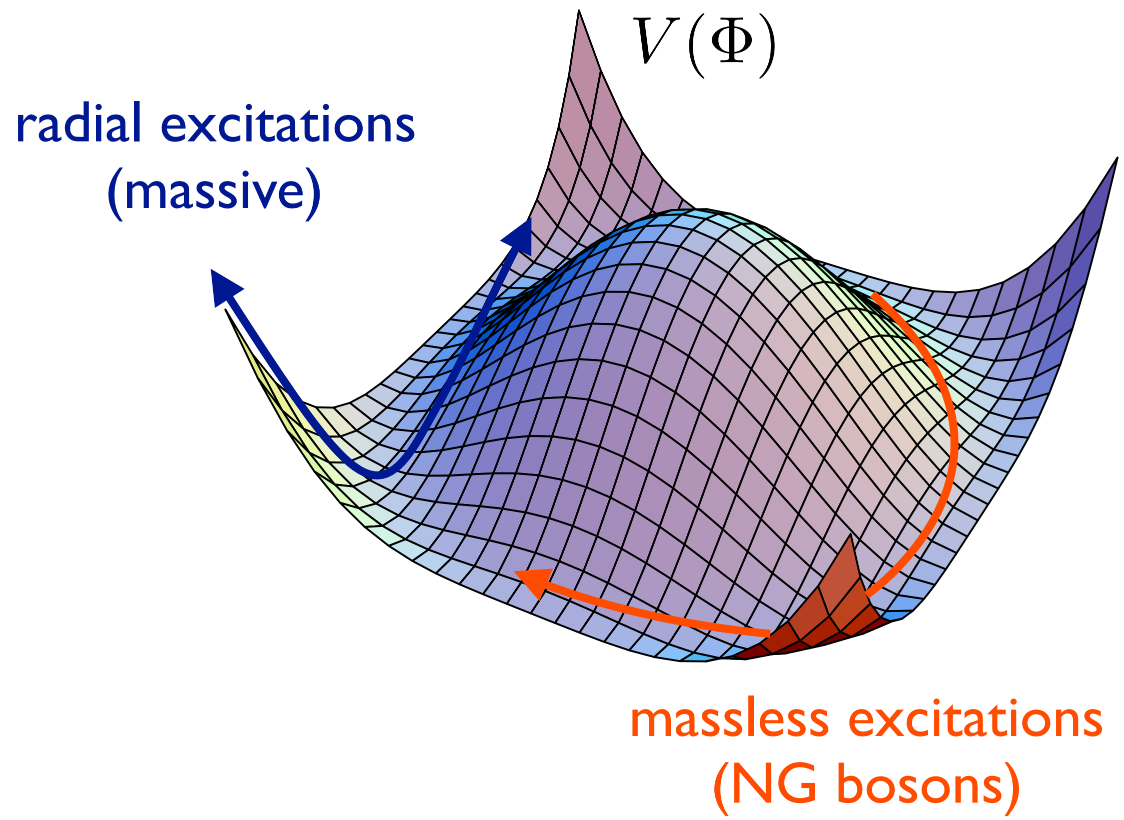
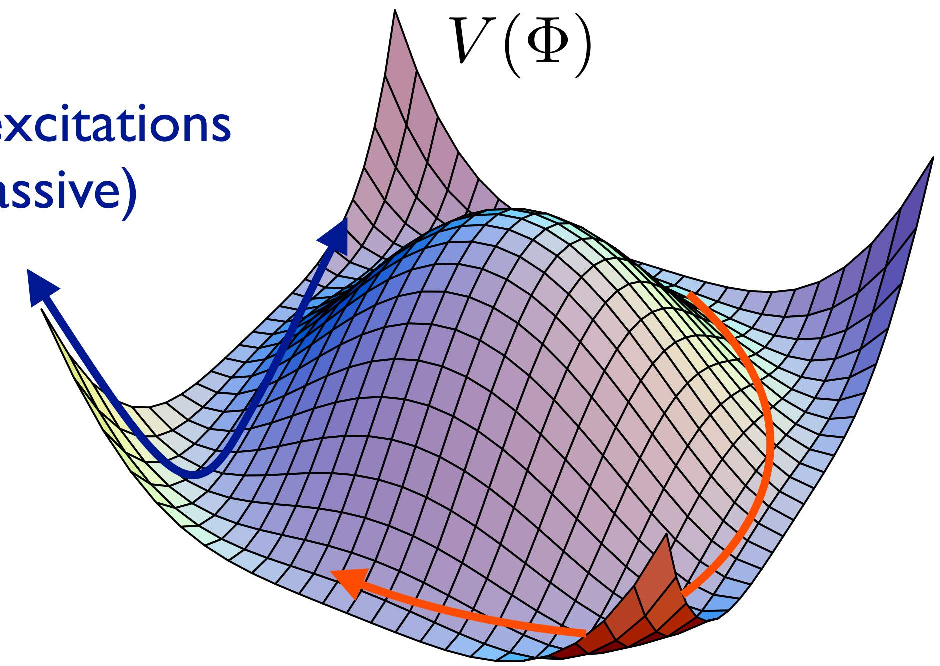


What Higgs bosons are

Higgs bosons → radial excitations (massive)



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Demystifying the Higgs boson

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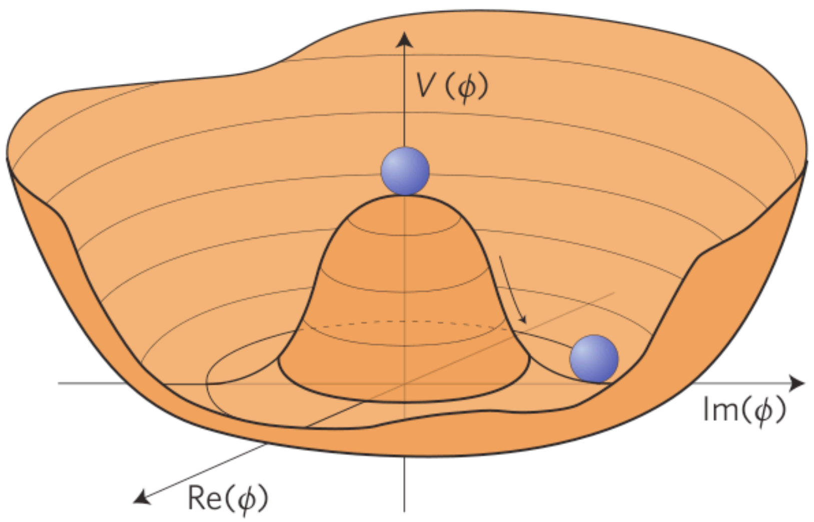
False: One has to distinguish between the vacuum and the quantum excitation around it

Particles can have mass even in absence of a light Higgs boson (Technicolor)

The Higgs model predicts: $\lambda_\psi = \frac{m_\psi}{v}$



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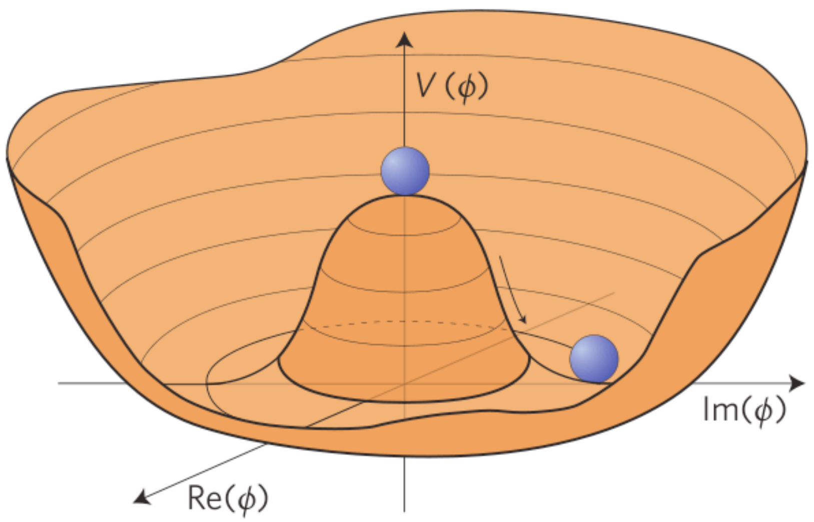

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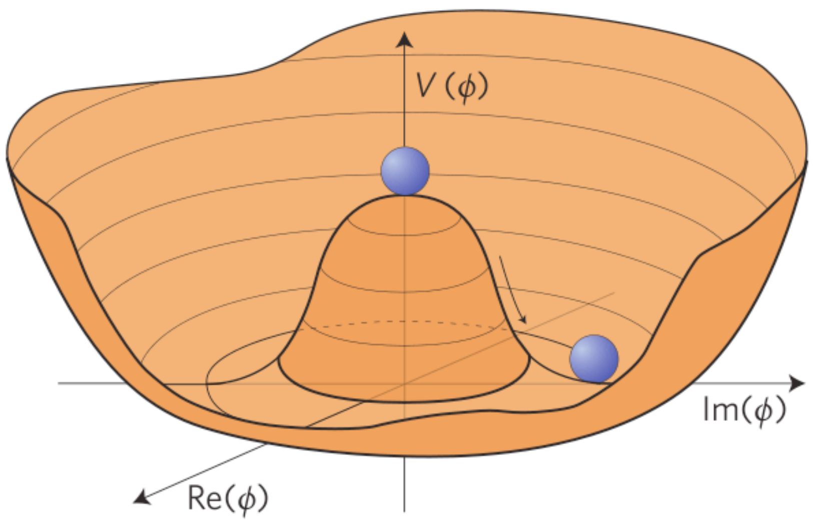

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False: The bulk of the mass of the proton and neutron comes from the QCD dynamics

$$m_P \sim \Lambda_{QCD} \gg m_q$$

Non-linear effective Lagrangian with a light Higgs

- Assumption: *h(x)* is a scalar (spin-0) field, singlet of the custodial SU(2)$_V$

$$\mathcal{L} = \frac{v^2}{4}\,\mathrm{Tr}\Big[(D_\mu\Sigma)^\dagger\,(D^\mu\Sigma)\Big]\left(1 + 2\,c_V\,\frac{h}{v} + c_{2V}\,\frac{h^2}{v^2} + \cdots\right)$$

$$-\frac{v}{\sqrt{2}}\lambda^u_{ij}\,(\bar{u}^{(i)}_L\;\bar{d}^{(i)}_L)\Sigma\begin{pmatrix} u^{(j)}_R \\ 0 \end{pmatrix}\left(1 + c_u\,\frac{h}{v} + \ldots\right) + h.c.$$

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$$V(h) = \frac{1}{2}m_h^2\,h^2 + \frac{1}{6}c_3\left(\frac{3m_h^2}{v}\right)h^3 + \frac{1}{24}c_4\left(\frac{3m_h^2}{2}\right)h^4 + \ldots$$

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c_V, c_{2V}, $c_{u,d}$, $c_{3,4}$ are free parameters

$c_{u,d}$ assumed to be flavor universal to avoid large FCNCs

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Example of possible (arbitrary) assumption:

Partial UV completion (PUVC)

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

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

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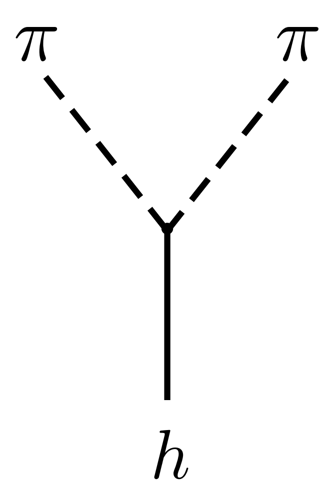

$$\sim c_V \frac{E^2}{v} = E \cdot \left(\frac{c_V E}{v} \right)$$

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 boson is of the same order as that of the NG bosons

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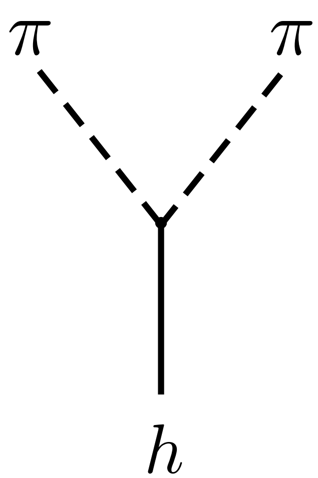
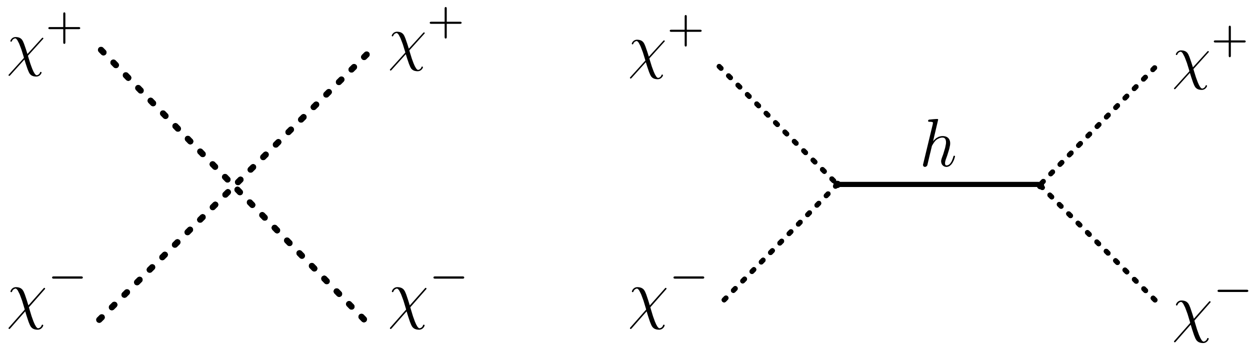


$$\sim c_V \frac{E^2}{v} = E \cdot \underbrace{\left(\frac{c_V E}{v}\right)}_{= g(E)}$$

$$g(\Lambda) \sim g_* \equiv \frac{\Lambda}{v} \quad \longrightarrow \quad \boxed{c_V = O(1)}$$

The Higgs boson can moderate the energy growth of scattering amplitudes:



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$$\simeq \frac{s}{v^2}(1 - c_V^2) + (s \leftrightarrow t)$$

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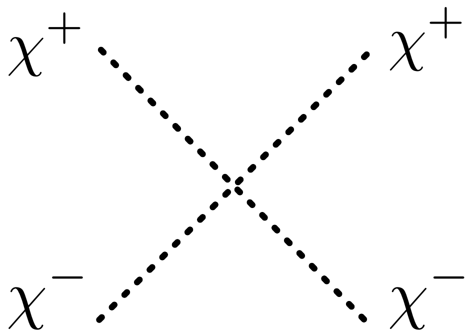

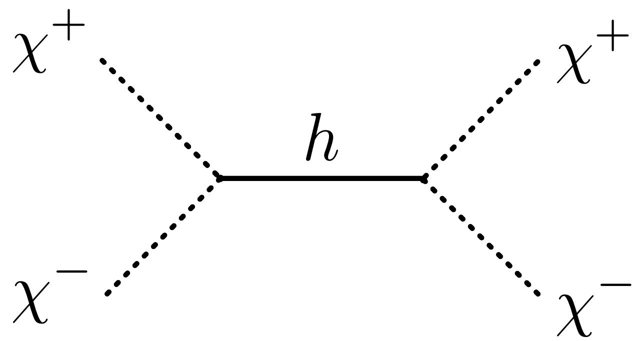

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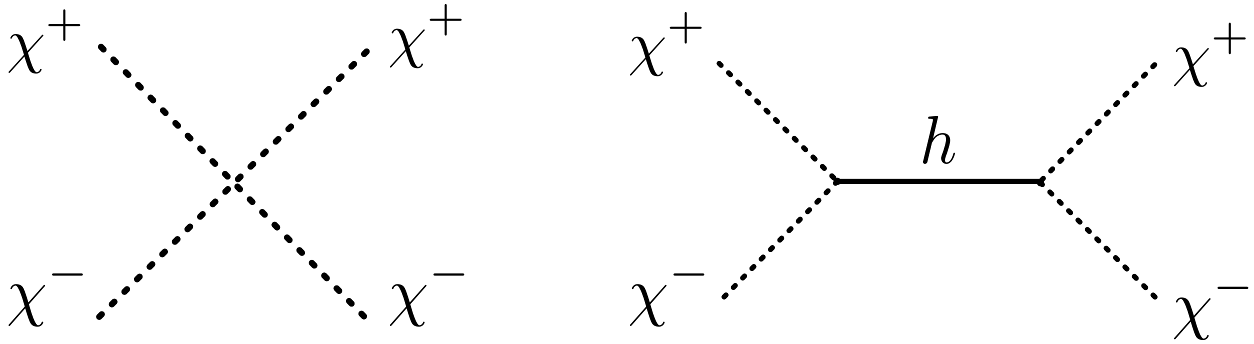

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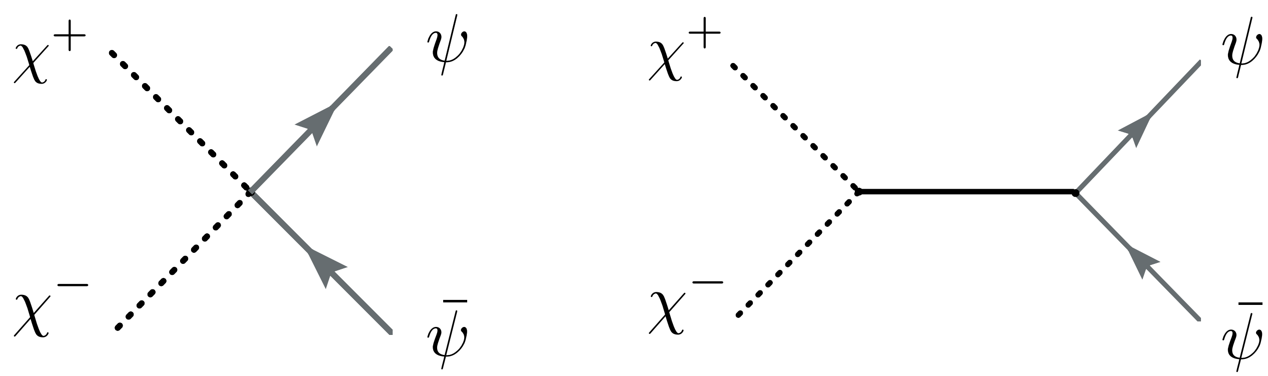

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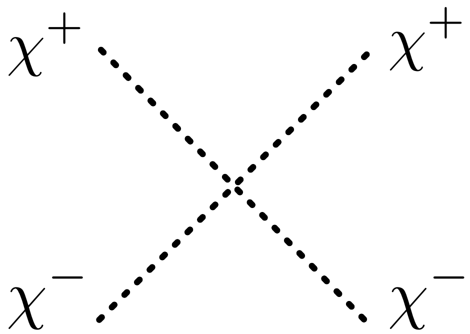

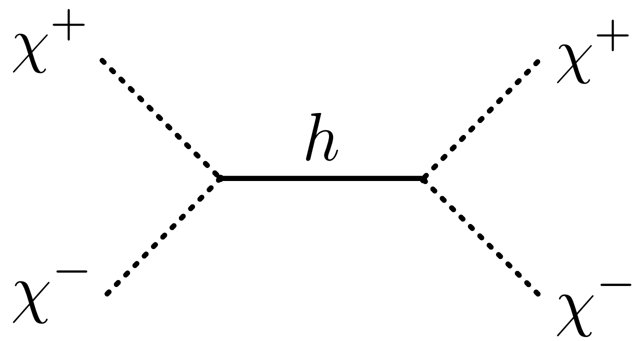

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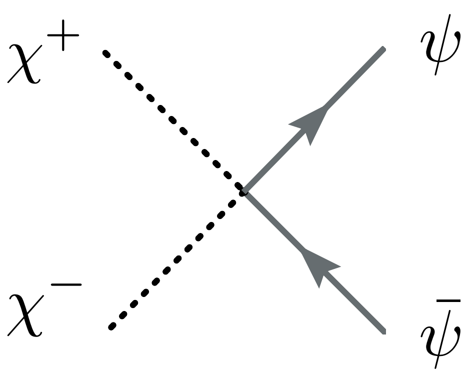

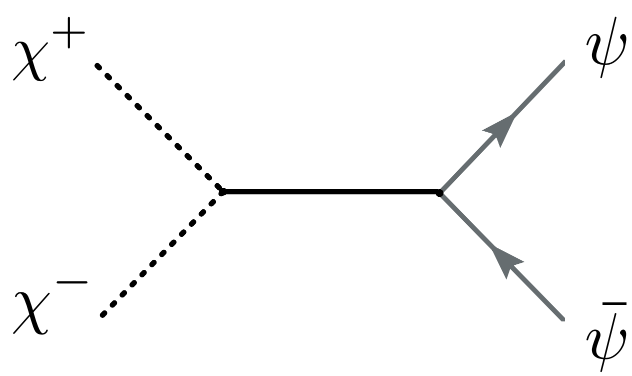

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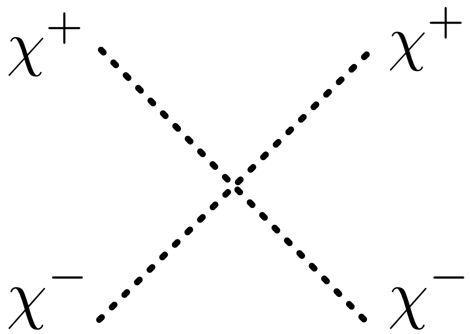

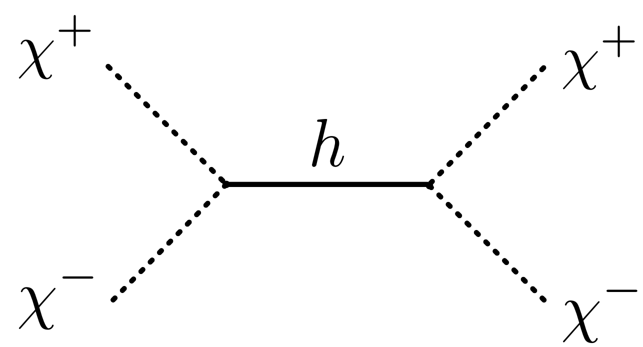

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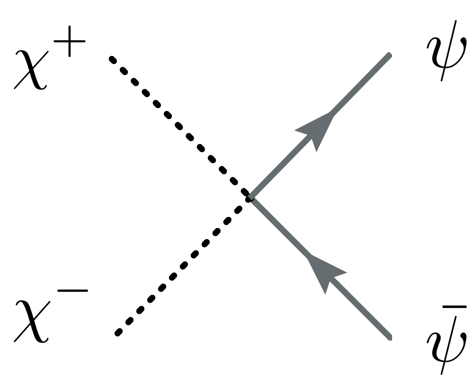

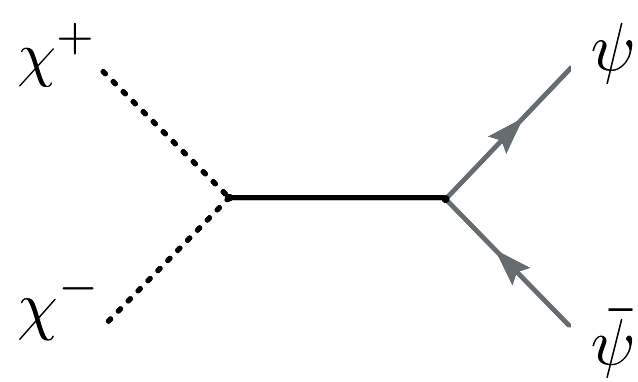

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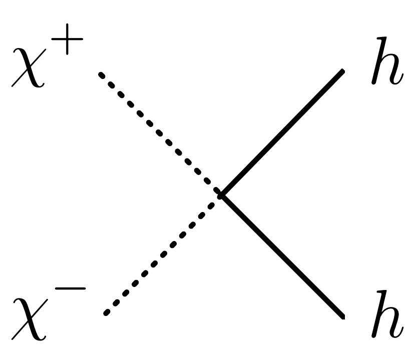

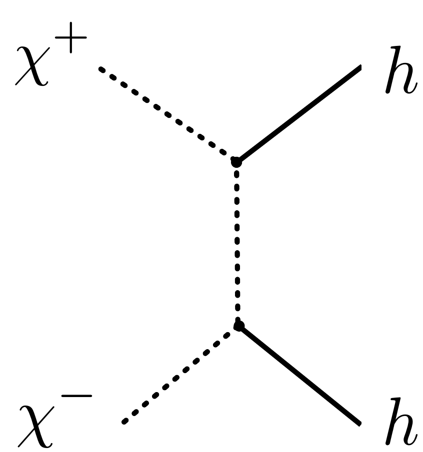

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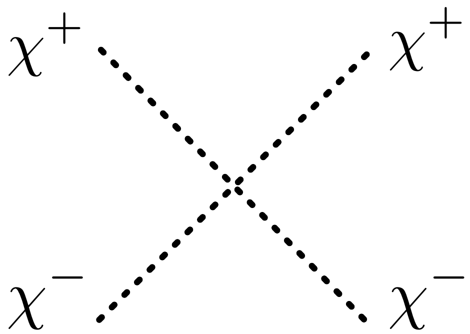

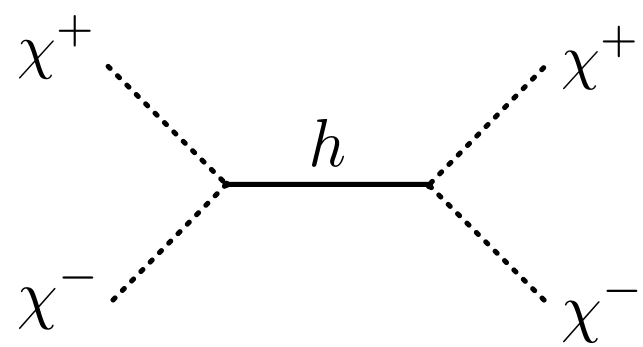

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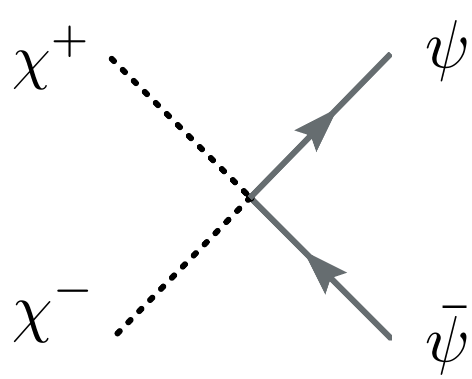

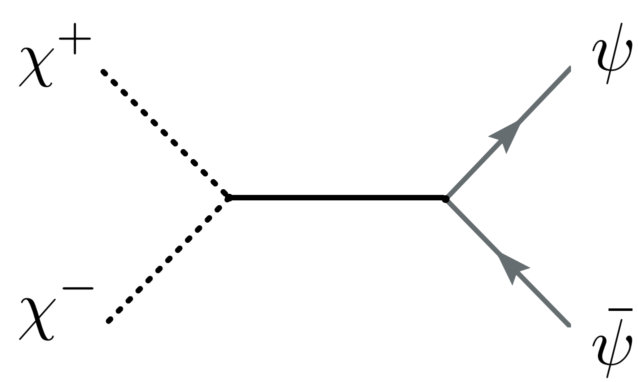

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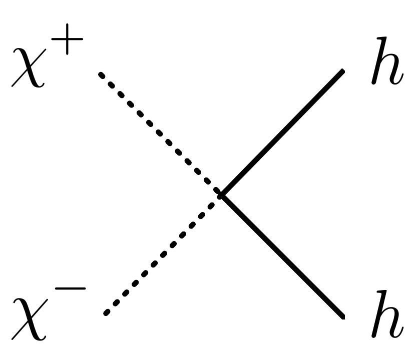

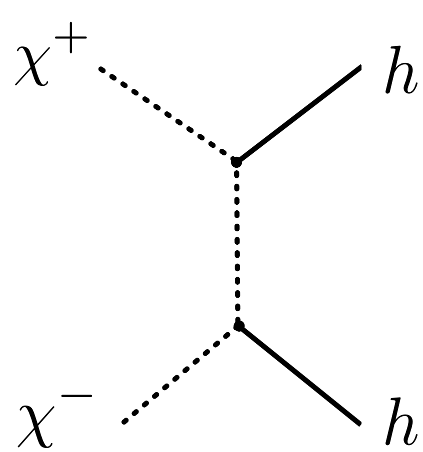

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The choice $\boxed{\begin{array}{c} c_V = c_{2V} = c_{u,d} = c_{3,4} = 1 \\ \text{(vanishing higher-order terms)} \end{array}}$ defines the Higgs Model

- if the scalar *h* is sufficiently *light* and *narrow*, $m_h \ll \sqrt{8\pi}v = 1.2\,\mathrm{TeV}$, *all* scattering amplitudes stay perturbative up to arbitrary energies

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- in terms of H the theory is manifestly renormalizable

$$\mathcal{L} = |\partial_\mu H|^2 - V(H^\dagger H) - \lambda^u_{ij}\, \bar{q}_L^{(i)} H^c u_R^{(j)} - \lambda^d_{ij}\, \bar{q}_L^{(i)} H d_R^{(j)} + h.c.$$

$$V(H^\dagger H) = \lambda_4 \left(H^\dagger H - v^2\right)^2 \qquad\qquad m_h^2 = \lambda_4\, v^2$$

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- there is an unbroken SO(3) custodial symmetry:

$$H = \begin{pmatrix} w_1 + i\, w_2 \\ w_3 + i\, w_4 \end{pmatrix} \qquad H^\dagger H = \sum_i (w_i)^2$$

$V(H^\dagger H)$ is SO(4)~SU(2)$_L$xSU(2)$_R$ invariant

$\langle H^\dagger H \rangle = v^2$ breaks SO(4)→SO(3)

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defines the Higgs Model

- First theory of this kind (an abelian SO(2) model) was constructed by P. Higgs

P. Higgs, PRL 13 (1964) 508, “Broken symmetries and the masses of gauge bosons”

P. Higgs pointed out the existence of a *massive* scalar (the Higgs boson) in addition to the eaten NG boson

about the “vacuum” solution $\varphi_1(x) = 0$, $\varphi_2(x) = \varphi_0$:

$$\partial^\mu\{\partial_\mu(\Delta\varphi_1) - e\varphi_0 A_\mu\} = 0, \tag{2a}$$

$$\{\partial^2 - 4\varphi_0^2 V''(\varphi_0^2)\}(\Delta\varphi_2) = 0, \tag{2b}$$

$$\partial_\nu F^{\mu\nu} = e\varphi_0\{\partial^\mu(\Delta\varphi_1) - e\varphi_0 A_\mu\}. \tag{2c}$$

Equation (2b) describes waves whose quanta have (bare) mass $2\varphi_0\{V''(\varphi_0^2)\}^{1/2}$; Eqs. (2a) and (2c) may be transformed, by the introduction of new variables

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- the Higgs boson is *elementary*:

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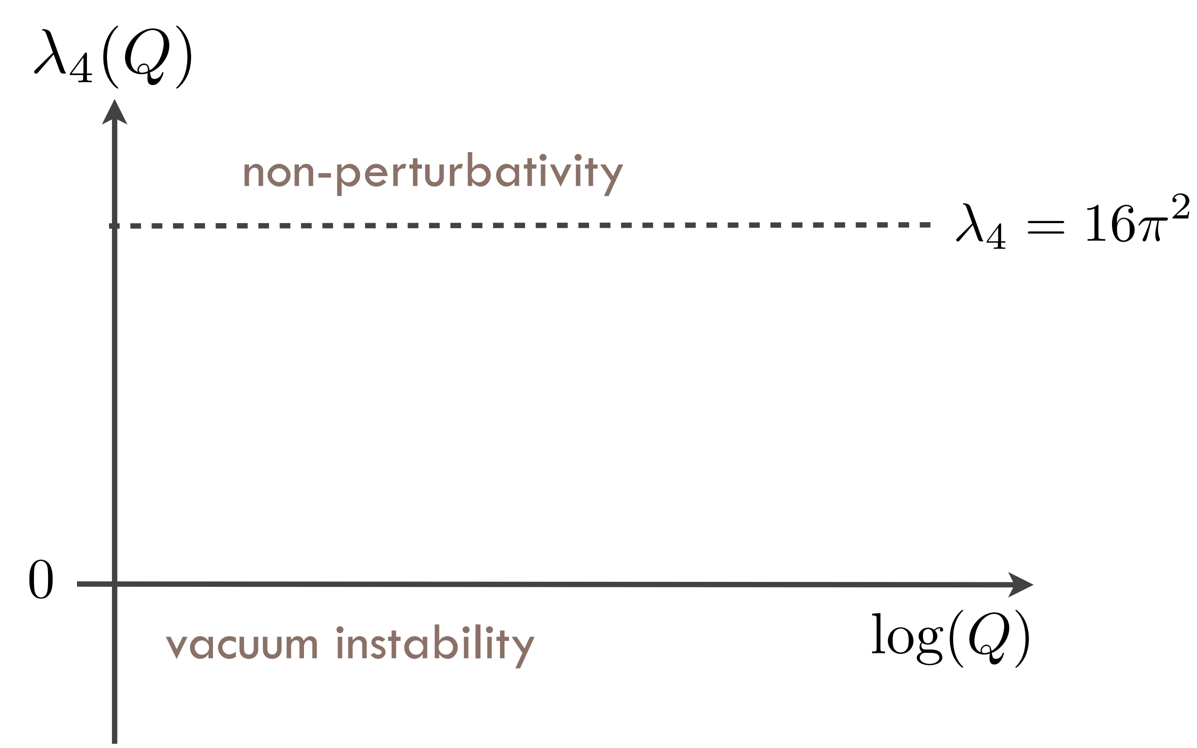

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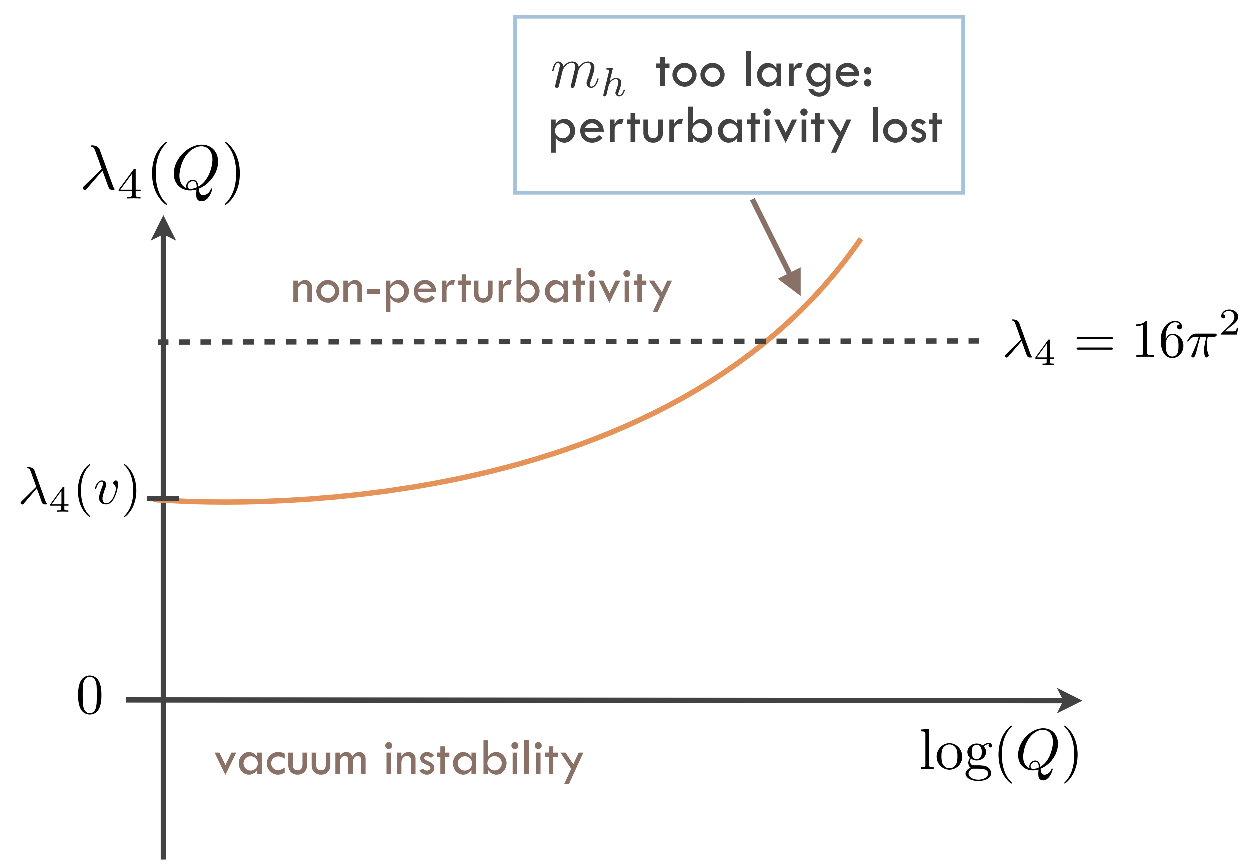

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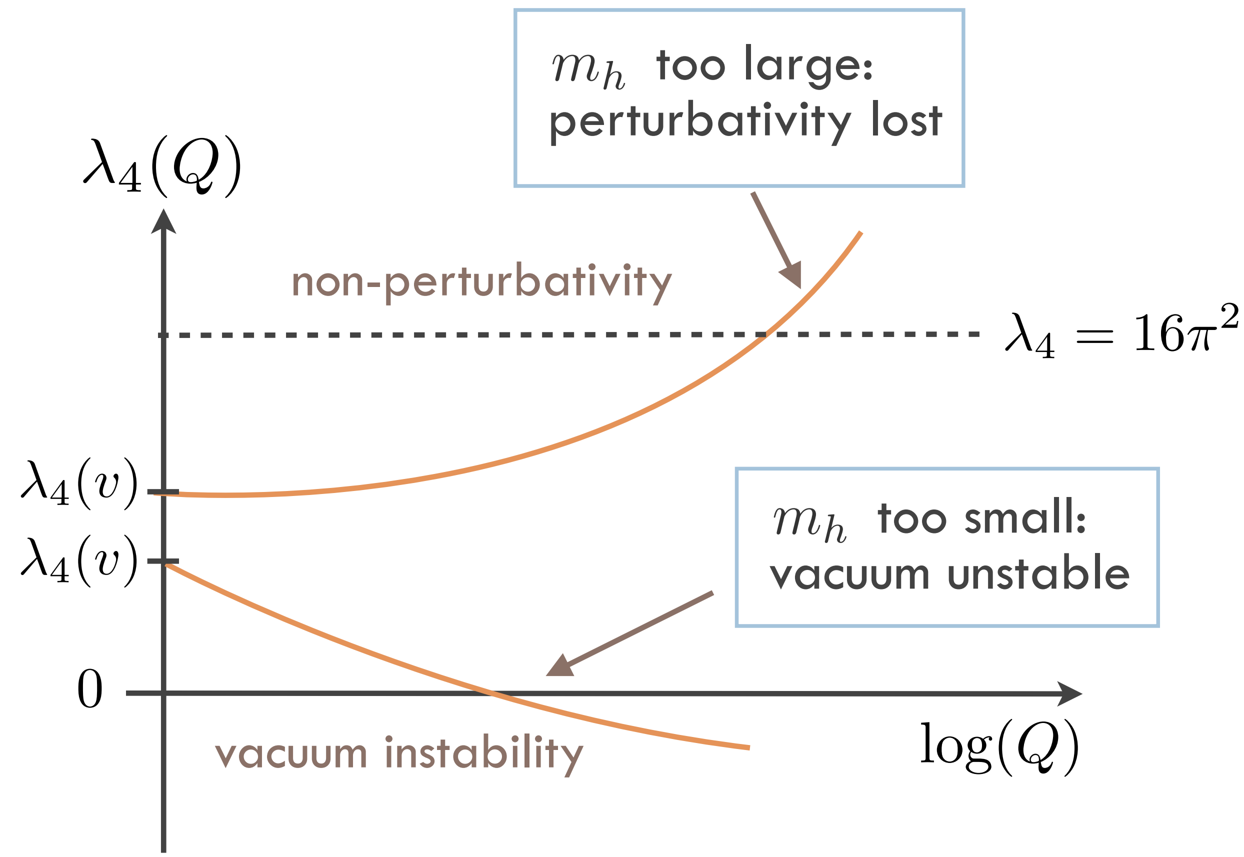

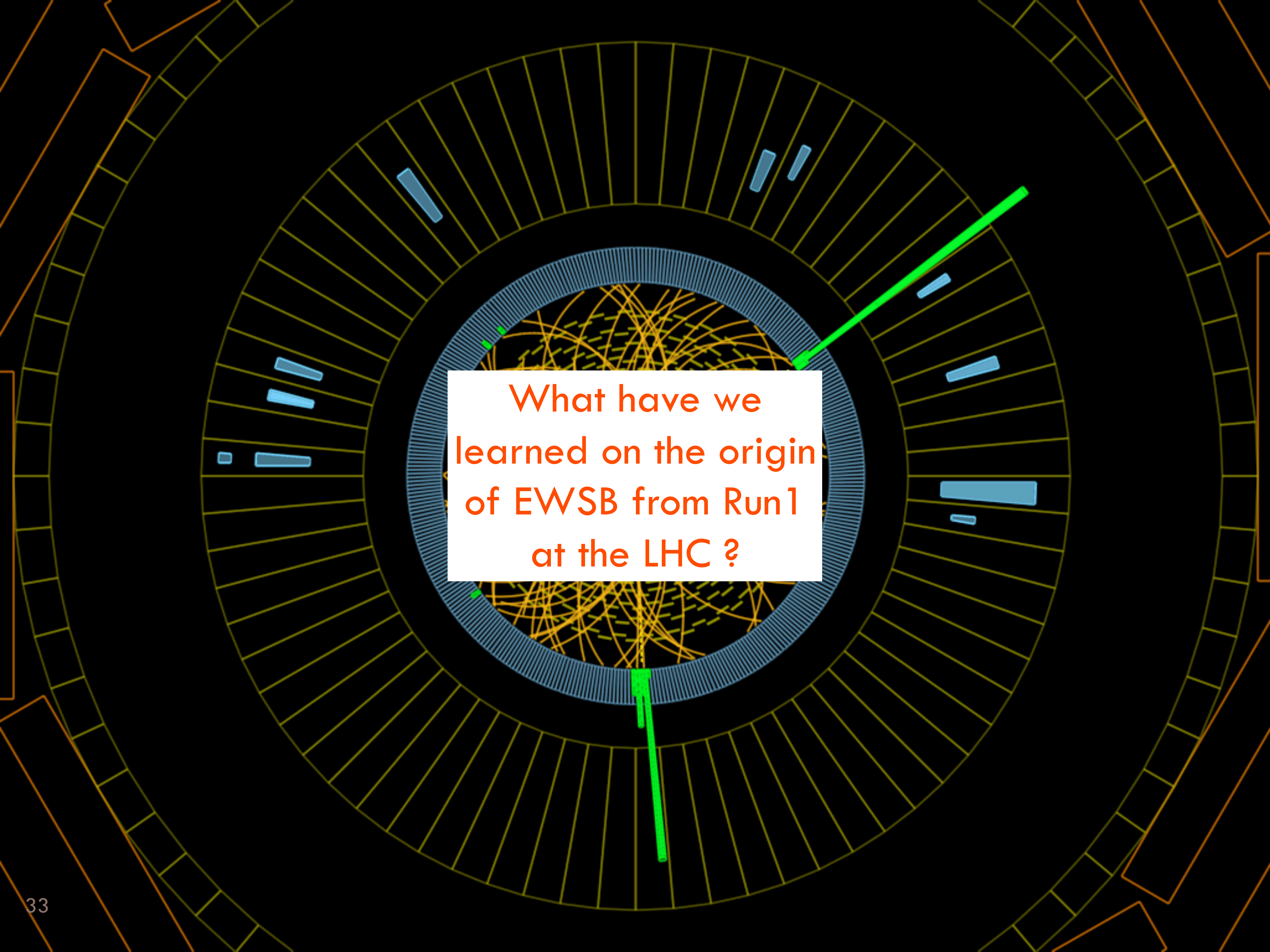

What have we learned on the origin of EWSB from Run1 at the LHC ?

Theoretical Questions

- How far in energy can we extrapolate our theory ?

  Do fundamental interactions among particles stay weak or do they get strong at high energy ?

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  Do fundamental interactions among particles stay weak or do they get strong at high energy ?

- Is the newly-discovered Higgs boson elementary or *composite* ?

  Are the Yukawa couplings and Higgs self-coupling new *fundamental* interactions, beyond the gauge paradigm ?

Higgs couplings must be proportional to masses for the Higgs to moderate the energy growth of scattering amplitudes

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Clear experimental evidence for

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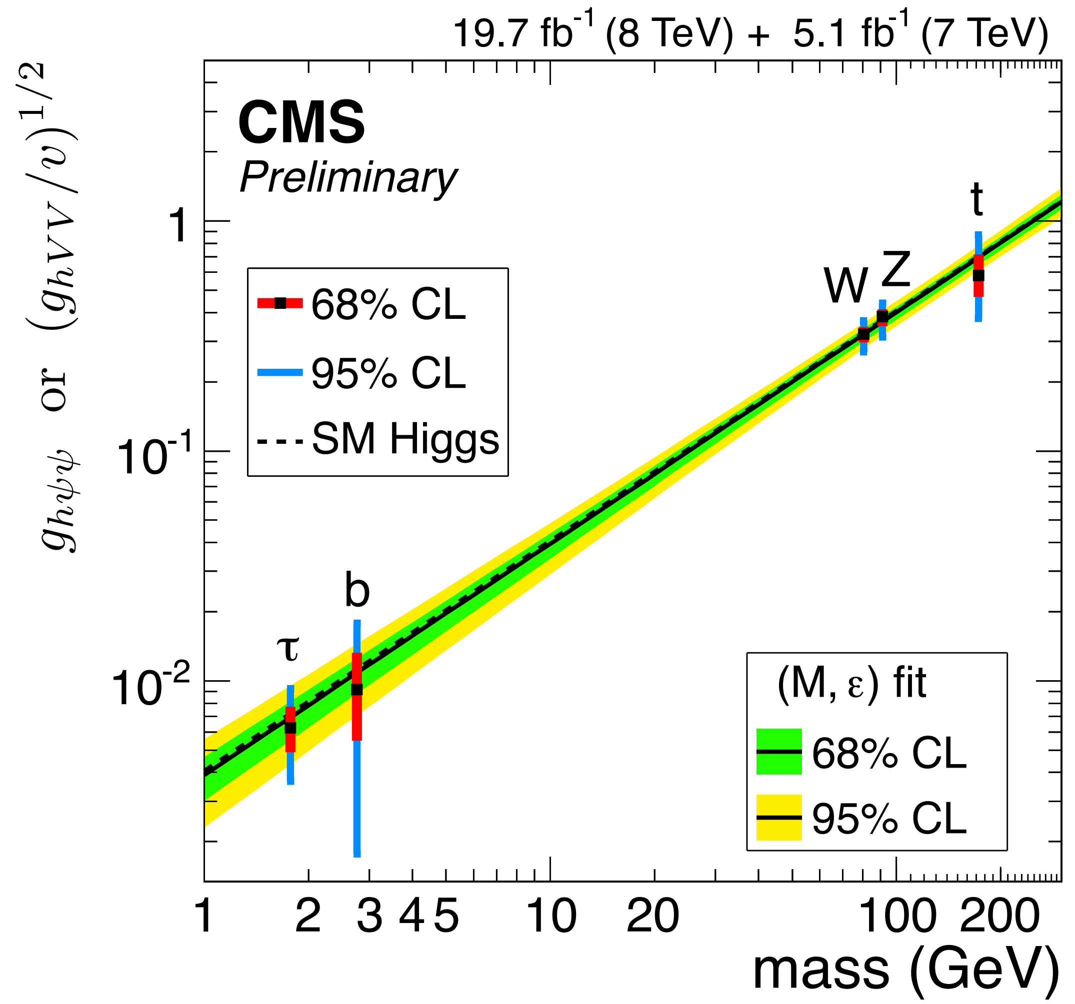

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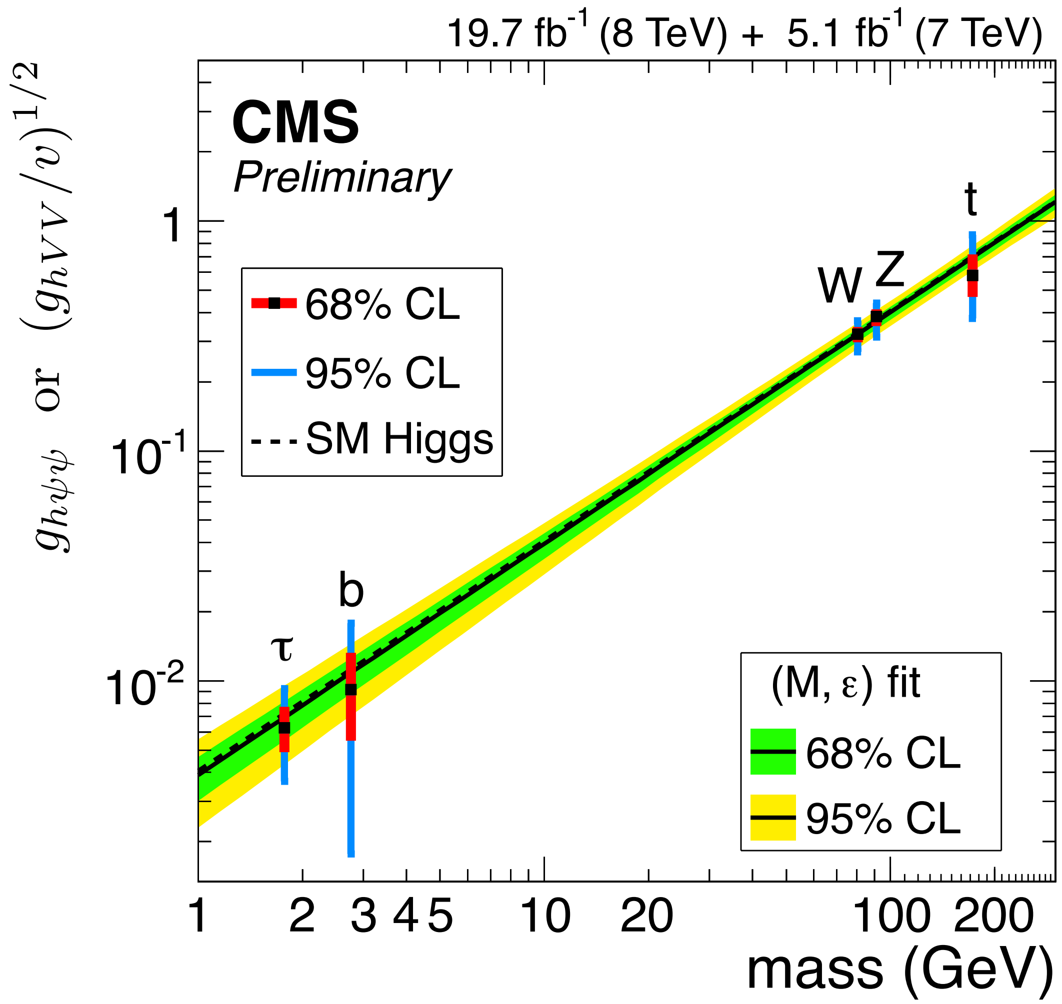

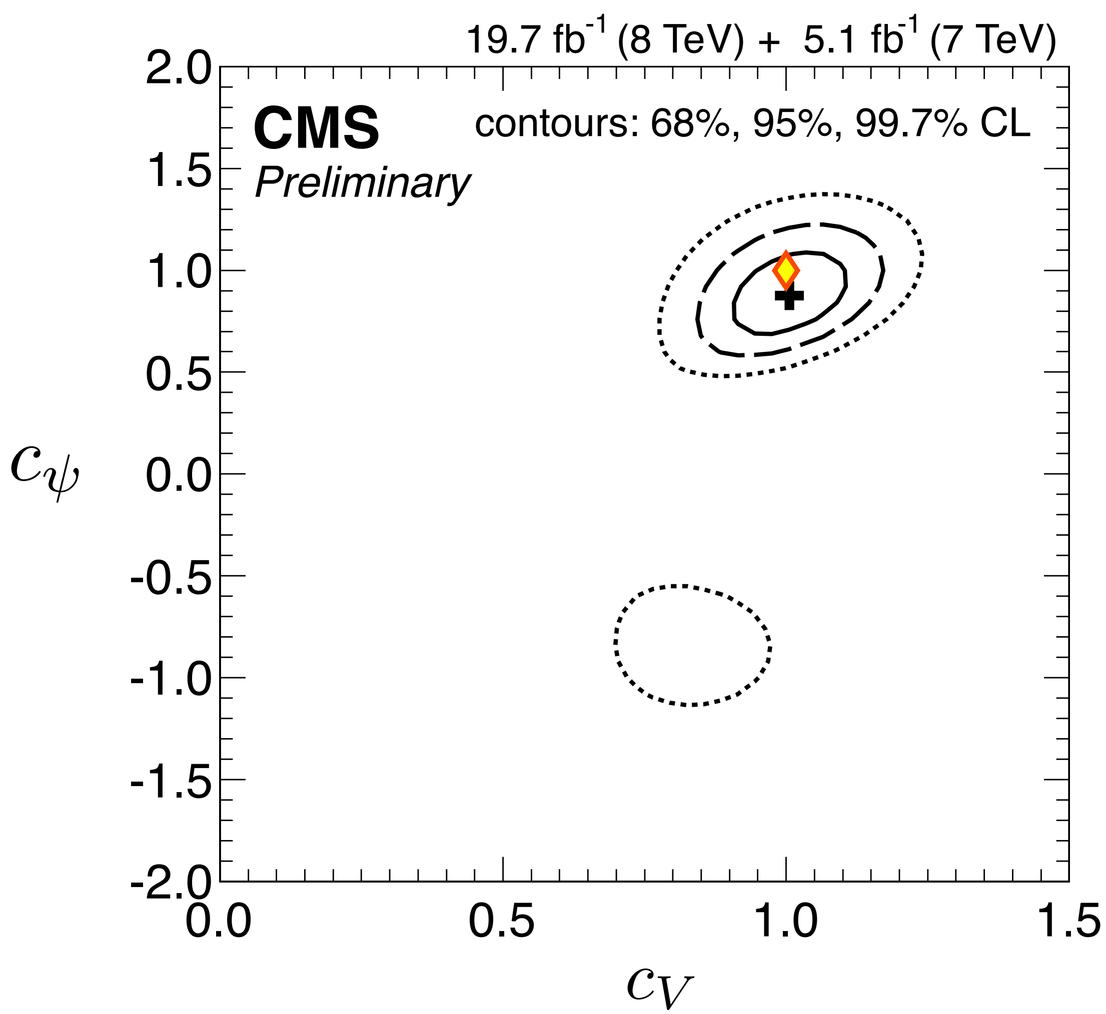

Data also indicate

$$c = 1 + \delta c$$

$$|\delta c| \lesssim 0.2 - 0.3$$

How far can can we extrapolate our theory

M_{Pl}

$4\pi v/\sqrt{\delta c_i} \simeq 5.5\,\mathrm{TeV}$

m_h

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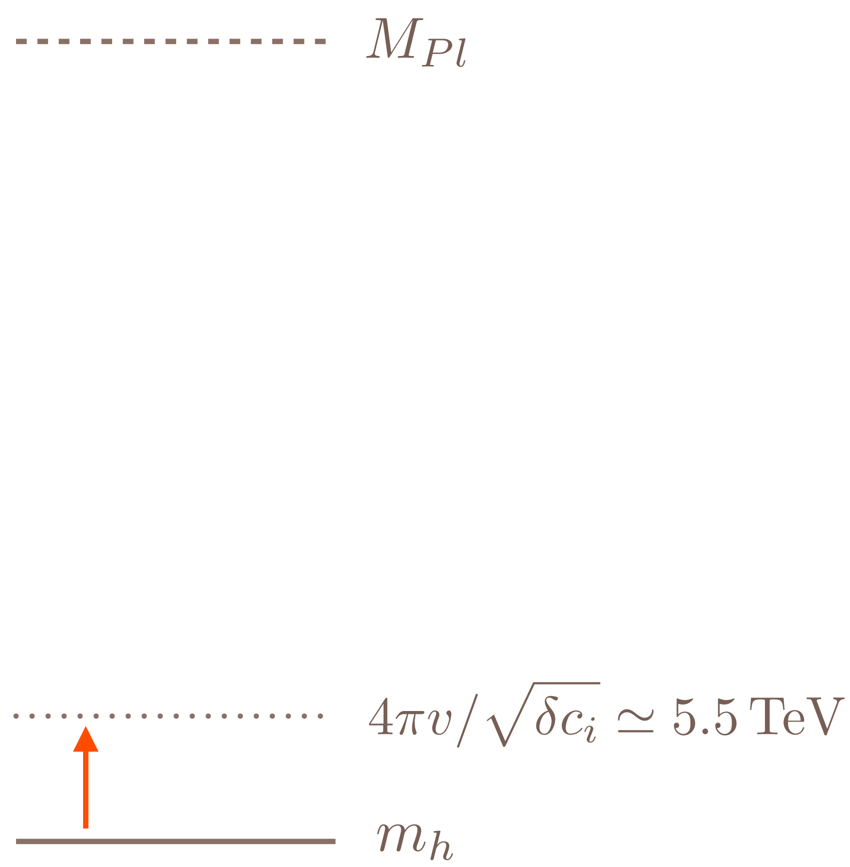

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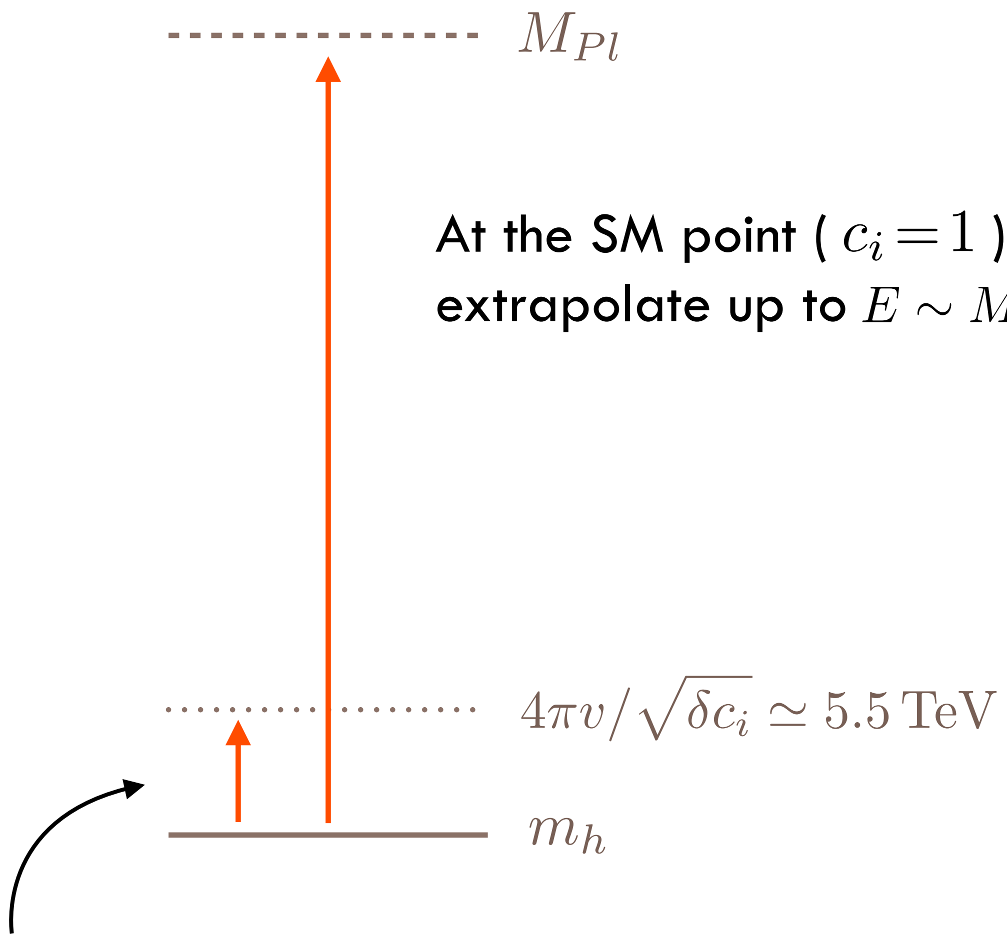

At the SM point ($c_i = 1$) we can extrapolate up to $E \sim M_{Pl}$

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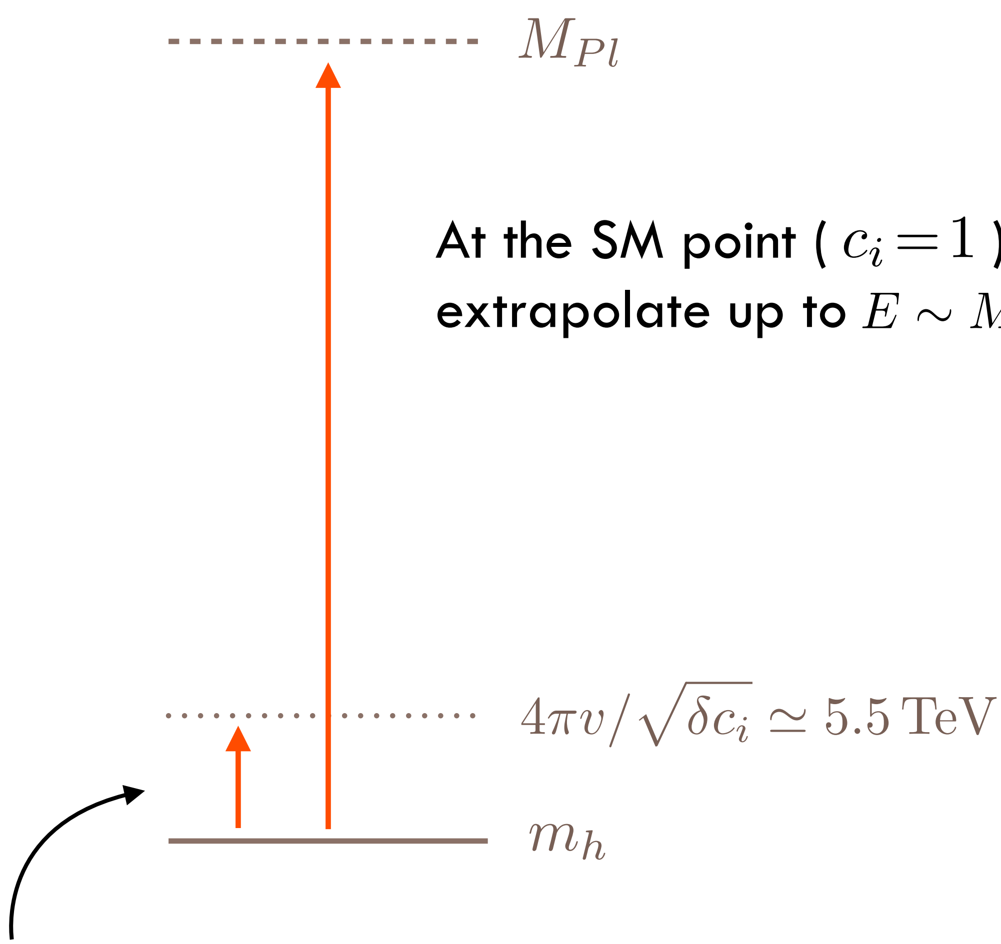

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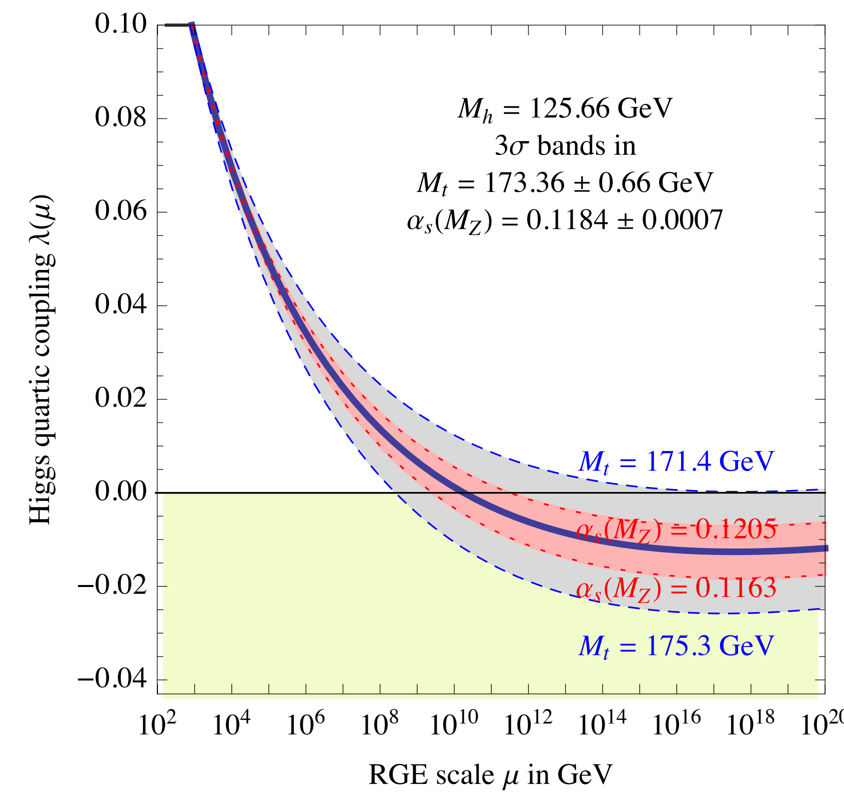
Residual $\log E$ dependence of Higgs trilinear coupling

$$\frac{d\lambda_4}{d\log Q} = \frac{3}{2\pi^2}\,\lambda_4^2 - \frac{3}{8\pi^2}\,y_t^4$$

For $m_h = 125\,\mathrm{GeV}$ $\Longrightarrow$ λ_4 remains weak



from: G. Degrassi et al. JHEP 1208 (2012) 098

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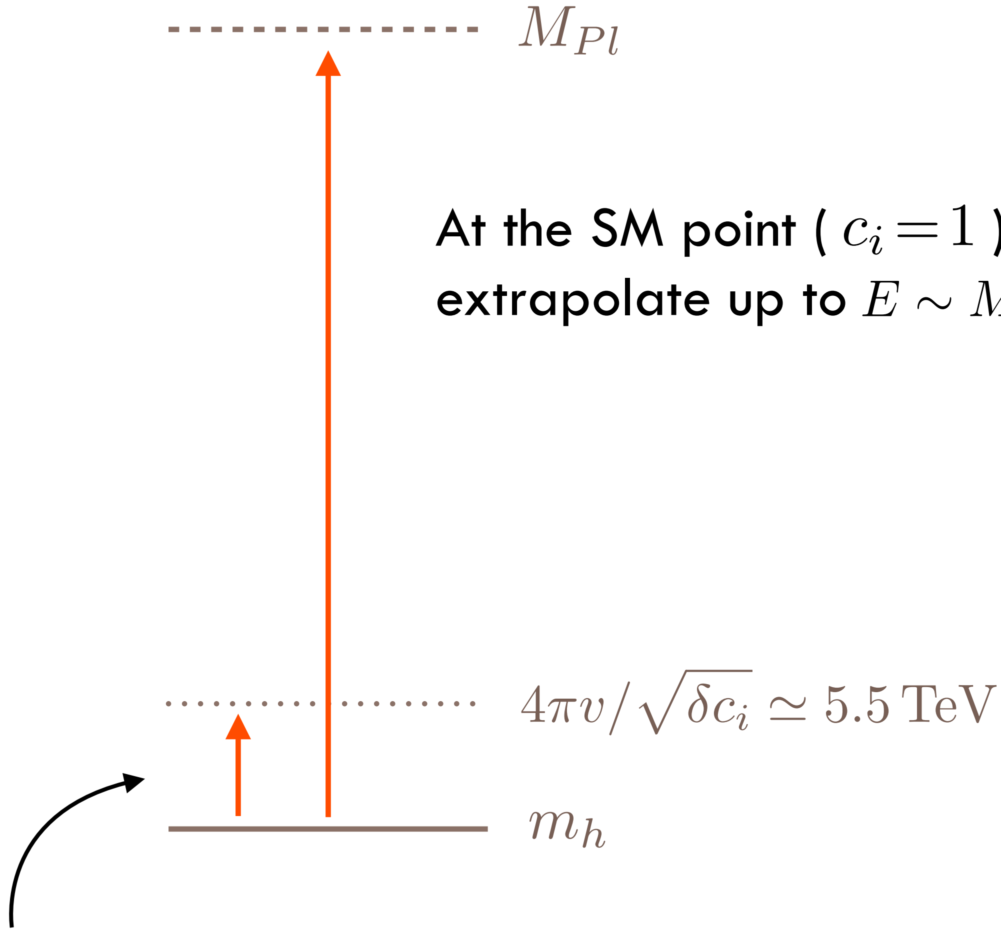

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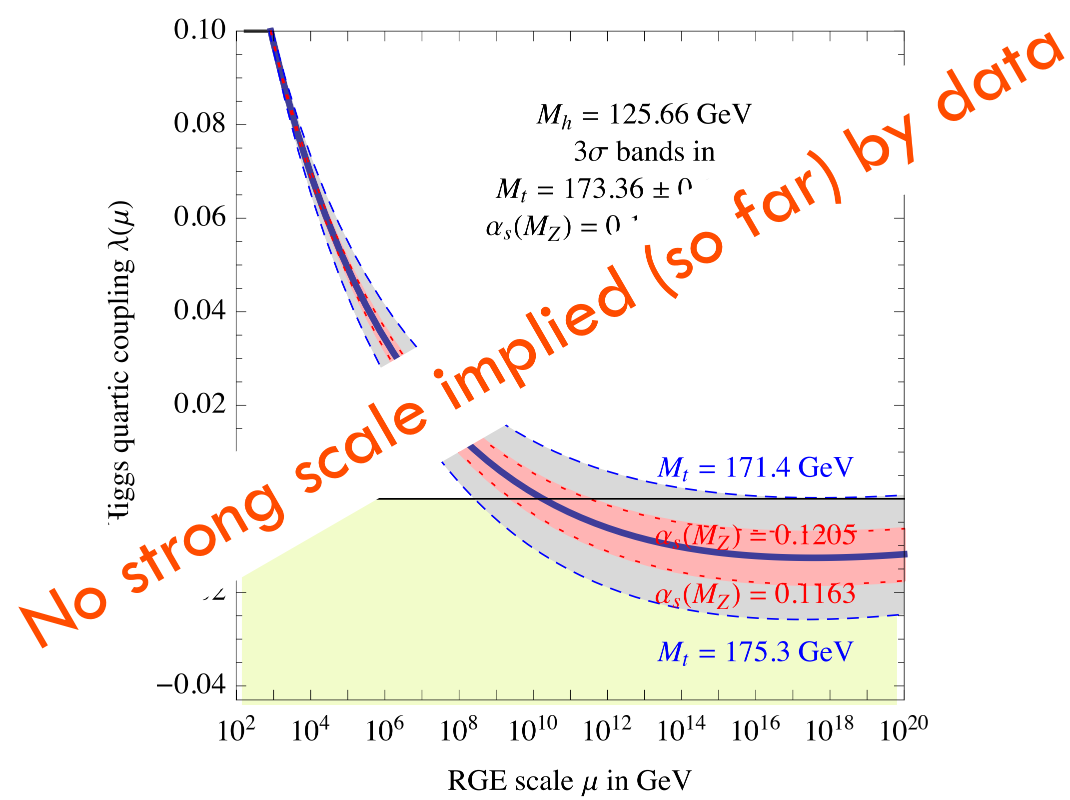

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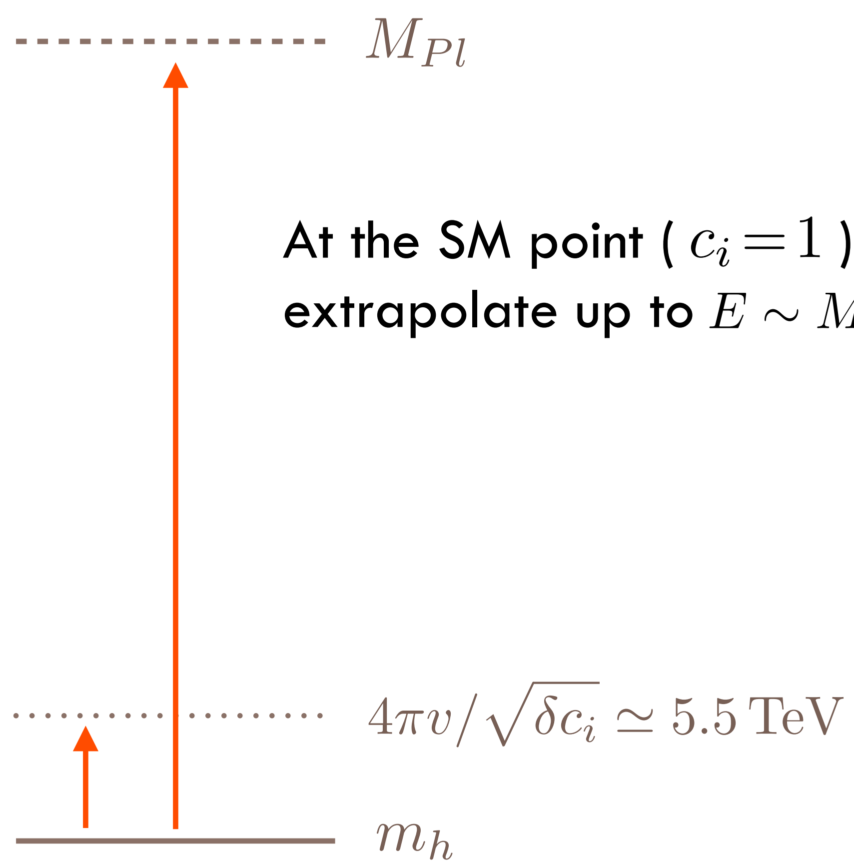

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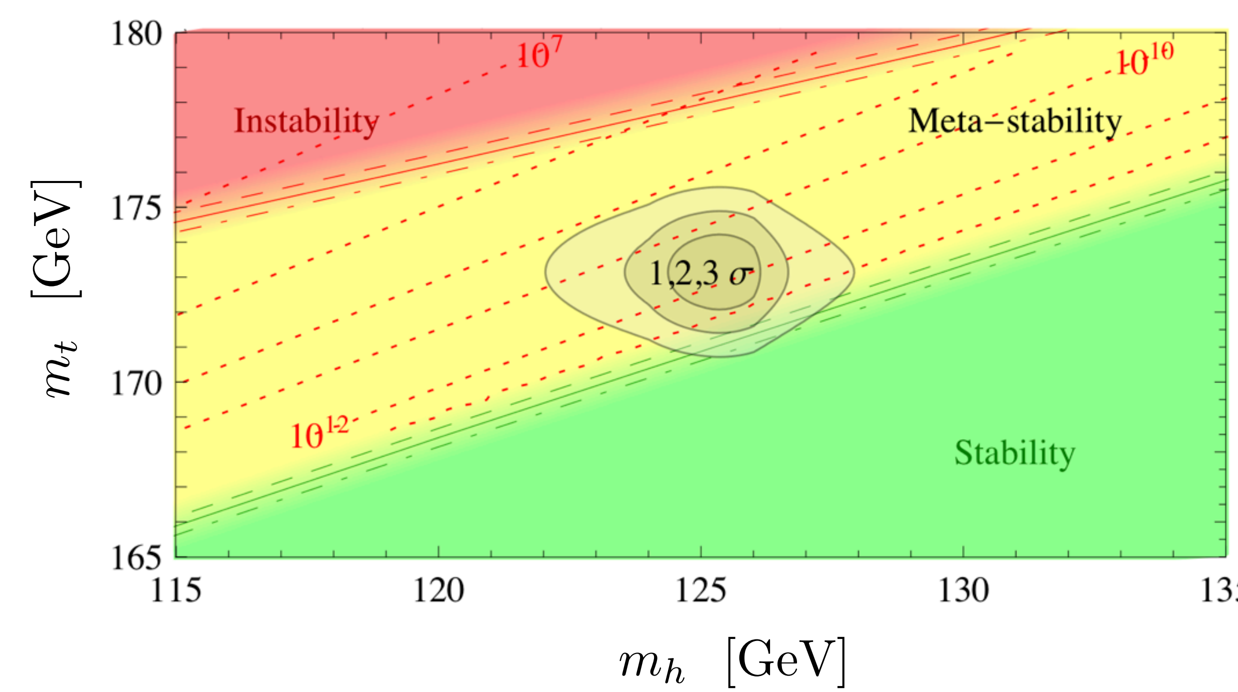

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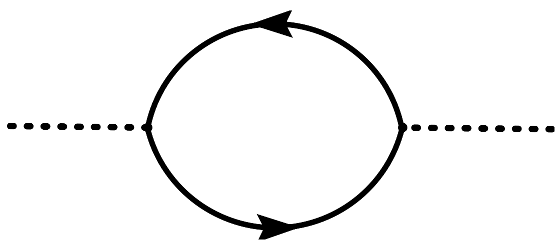
The puzzle of Higgs lightness (aka the Hierarchy Problem)

Q: *If the Higgs boson is elementary, why it is so much lighter than the cutoff scale ?*



$$\delta m_h^2 = \left[6\, y_t^2 - \frac{3}{4} \left(3\, g_2^2 + g_1^2 \right) - 6\, \lambda_4 \right] \frac{\Lambda^2}{8\pi^2}$$

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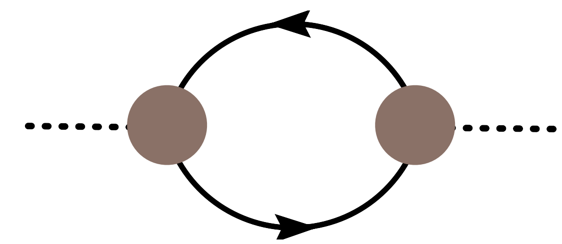

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A #1: Compositeness

The Higgs boson is a composite of a new strong dynamics at the TeV (i.e. cutoff is low)

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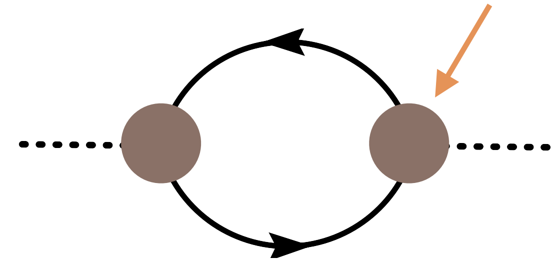
form factor
$F(q^2/\Lambda^2_{comp})$



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$$\boxed{\Lambda \approx \Lambda_{comp}}$$

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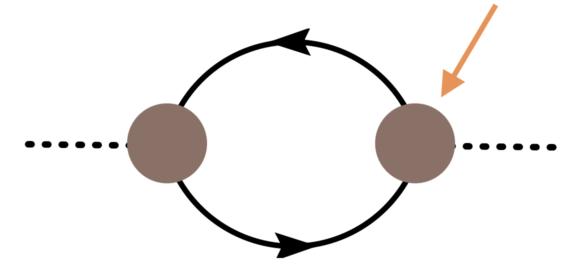

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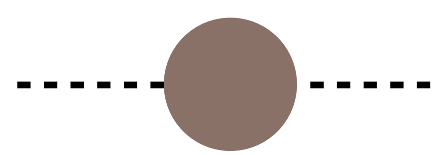
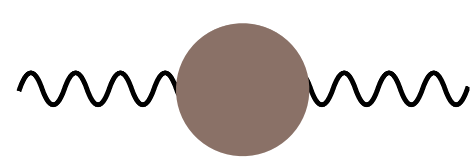
Problem: from loops of pure composites



$$m_h \approx \Lambda_{comp}$$

EWPT require



$$\Lambda_{comp} \gtrsim \text{a few TeV}$$

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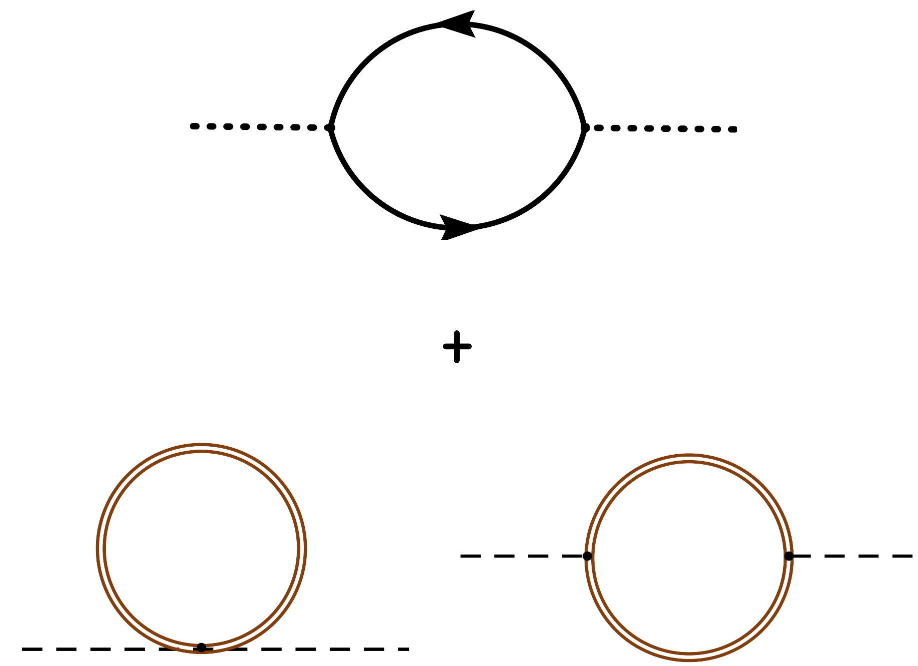

A #2: Symmetry protection

A symmetry protects the Higgs mass term, new particles Φ cancel the SM loops

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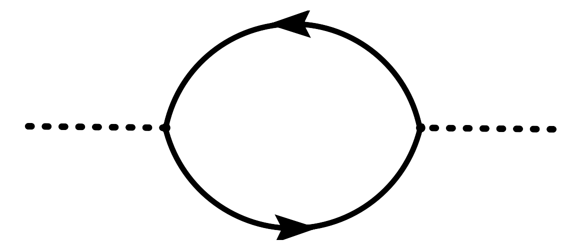

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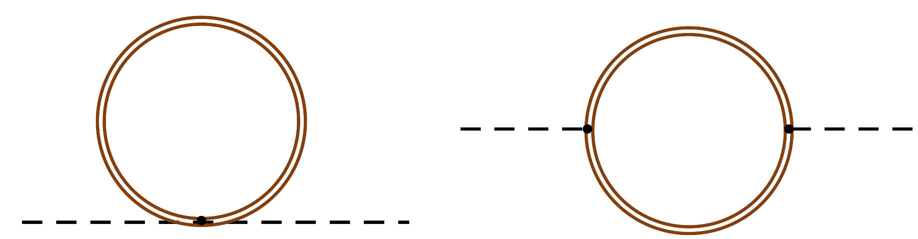

A #2: Symmetry protection

A symmetry protects the Higgs mass term, new particles Φ cancel the SM loops

Known examples:

Supersymmetry — top partners = stops

Global symmetry — top partners = vector-like fermions

(Higgs is a Nambu-Goldstone boson)

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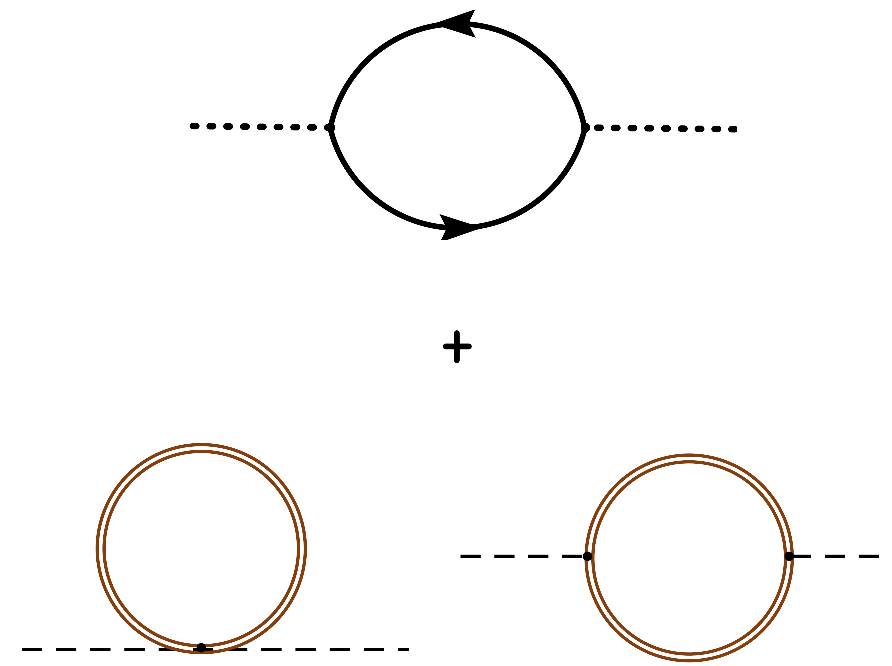

A #2: Symmetry protection

A symmetry protects the Higgs mass term, new particles Φ cancel the SM loops

Notice: the protecting symmetry must be broken in a *soft* way

$$\boxed{\Lambda \approx m_\Phi}$$

Supersymmetry	Only A-terms and soft masses
Global symmetry	Collective breaking
(Higgs is a Nambu-Goldstone boson)	(Little Higgs theories)

The puzzle of Higgs lightness (aka the Hierarchy Problem)

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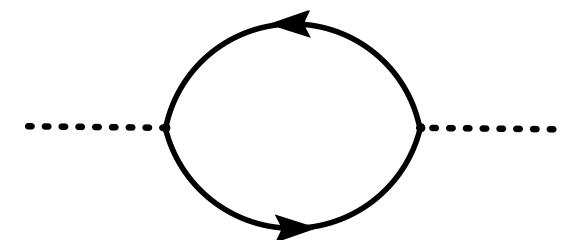
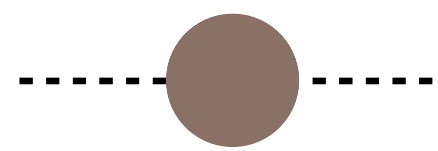


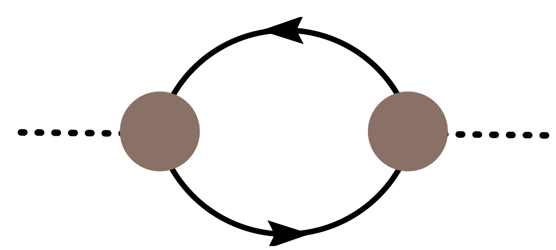
A #3: Higgs as a composite NG boson (combines #1 and #2)

Loops of pure composites vanish due to NG symmetry



= 0

NG symmetry broken by elementary-composite couplings:



$$m_h^2 \sim \frac{\lambda^2}{16\pi^2}\,\Lambda^2_{comp}$$

$$\lambda \ll 4\pi$$

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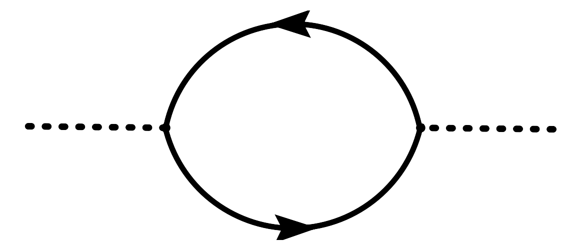

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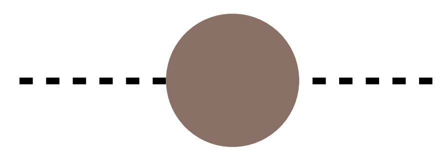

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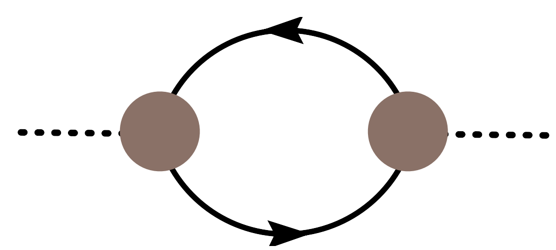
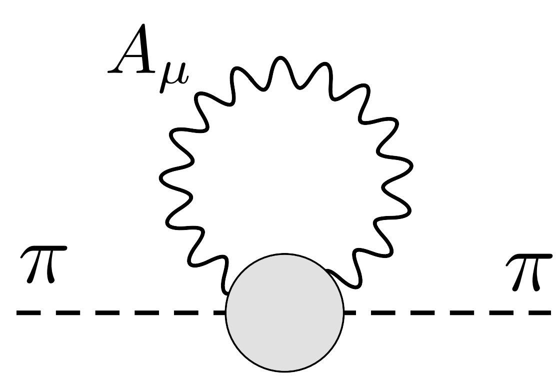


$$m_h^2 \sim \frac{\lambda^2}{16\pi^2}\,\Lambda^2_{comp}$$

$$\lambda \ll 4\pi$$

Known example: the EM mass of the pion



$$\Delta m_\pi^2 \approx 3\,\frac{\alpha_{em}}{4\pi}\,m_\rho^2$$

Part 3

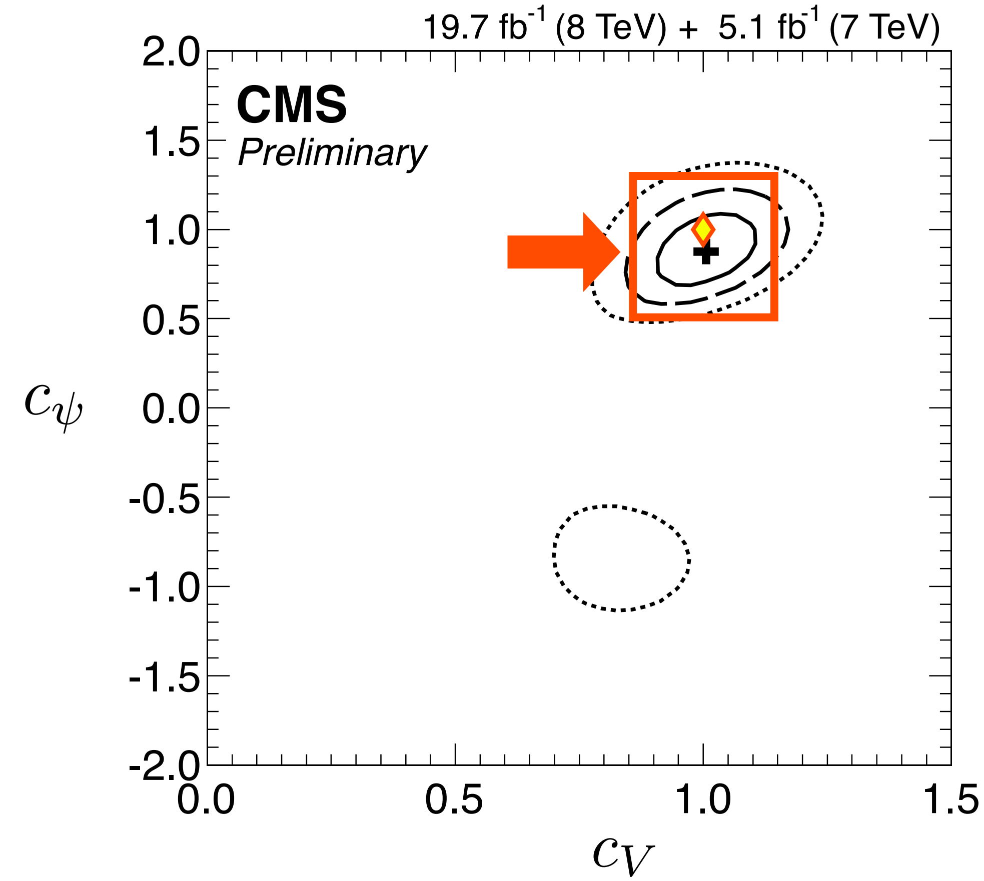
Effective Lagrangian for a Higgs doublet

How to live near the SM point

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 <u>gap</u> between the NP scale m_* and m_h



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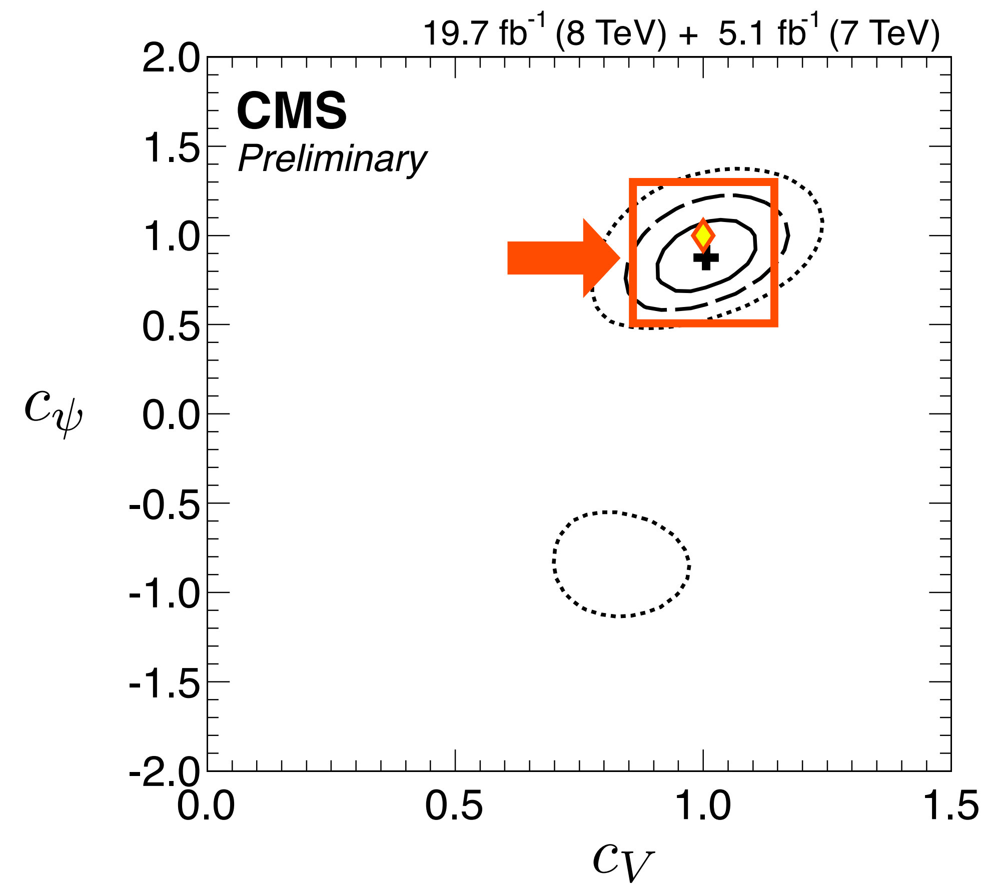
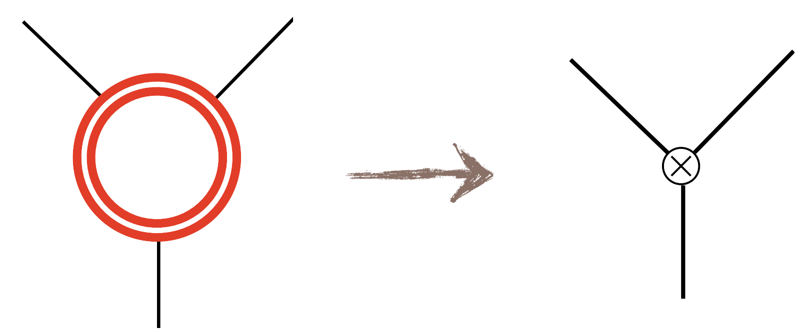


- At energies $E \ll m_*$, NP effects are well approximated by local operators

$$\mathcal{L} = \sum_i \bar{c}_i\, O_i(x)$$



Operators “generated” at m_* with coefficients

$$\bar{c}_i(m_*) \sim \left(\frac{1}{m_*}\right)^{d[O]-4}$$

Effective Lagrangian for a Higgs doublet

- Operators can be classified according to their dimension

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_i \bar{c}_i O_i \equiv \mathcal{L}_{SM} + \Delta\mathcal{L}^{(6)} + \Delta\mathcal{L}^{(8)} + \dots$$

Effective Lagrangian for a Higgs doublet

- Operators can be classified according to their dimension

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_i \bar{c}_i O_i \equiv \mathcal{L}_{SM} + \boxed{\Delta\mathcal{L}^{(6)}} + \Delta\mathcal{L}^{(8)} + \ldots$$

Leading effects from dim-6 operators

59 independent operators for 1 SM family

Buchmuller and Wyler NPB 268 (1986) 621

⋮

Grzadkowski et al. JHEP 1010 (2010) 085

For a review see:
RC, Ghezzi, Grojean, Muhlleitner, Spira JHEP 1307 (2013) 035

Effective Lagrangian for a Higgs doublet

$$\Delta\mathcal{L}^{(6)} = \Delta\mathcal{L}_{SILH} + \Delta\mathcal{L}_{cc} + \Delta\mathcal{L}_{dipole} + \Delta\mathcal{L}_{V} + +\Delta\mathcal{L}_{4\psi}$$

Effective Lagrangian for a Higgs doublet

$$\Delta\mathcal{L}^{(6)} = \boxed{\Delta\mathcal{L}_{SILH}} + \Delta\mathcal{L}_{cc} + \Delta\mathcal{L}_{dipole} + \Delta\mathcal{L}_{V} + +\Delta\mathcal{L}_{4\psi}$$

16 operators

(12 CP even, 4 CP odd)

Optimal basis to test light composite Higgs

Giudice, Grojean, Pomarol, Rattazzi JHEP 0706 (2007) 045

$$\begin{aligned}
\Delta\mathcal{L}_{SILH} = & \frac{\bar{c}_H}{2v^2}\,\partial^\mu\left(H^\dagger H\right)\partial_\mu\left(H^\dagger H\right) + \frac{\bar{c}_T}{2v^2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right)\left(H^\dagger \overleftrightarrow{D}_\mu H\right) - \frac{\bar{c}_6\,\lambda}{v^2}\left(H^\dagger H\right)^3 \\
& + \left(\frac{\bar{c}_u}{v^2}\,y_u\,H^\dagger H\,\bar{q}_L H^c u_R + \frac{\bar{c}_d}{v^2}\,y_d\,H^\dagger H\,\bar{q}_L H d_R + \frac{\bar{c}_l}{v^2}\,y_l\,H^\dagger H\,\bar{L}_L H l_R + h.c.\right) \\
& + \frac{i\bar{c}_W\,g}{2m_W^2}\left(H^\dagger\sigma^i \overleftrightarrow{D^\mu} H\right)\left(D^\nu W_{\mu\nu}\right)^i + \frac{i\bar{c}_B\,g'}{2m_W^2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right)\left(\partial^\nu B_{\mu\nu}\right) \\
& + \frac{i\bar{c}_{HW}\,g}{m_W^2}\,(D^\mu H)^\dagger\sigma^i(D^\nu H)W^i_{\mu\nu} + \frac{i\bar{c}_{HB}\,g'}{m_W^2}\,(D^\mu H)^\dagger(D^\nu H)B_{\mu\nu} \\
& + \frac{\bar{c}_\gamma\,{g'}^2}{m_W^2}\,H^\dagger H B_{\mu\nu}B^{\mu\nu} + \frac{\bar{c}_g\,g_S^2}{m_W^2}\,H^\dagger H G^a_{\mu\nu}G^{a\mu\nu} \\
& + \frac{i\tilde{c}_{HW}\,g}{m_W^2}\,(D^\mu H)^\dagger\sigma^i(D^\nu H)\tilde{W}^i_{\mu\nu} + \frac{i\tilde{c}_{HB}\,g'}{m_W^2}\,(D^\mu H)^\dagger(D^\nu H)\tilde{B}_{\mu\nu} \\
& + \frac{\tilde{c}_\gamma\,{g'}^2}{m_W^2}\,H^\dagger H B_{\mu\nu}\tilde{B}^{\mu\nu} + \frac{\tilde{c}_g\,g_S^2}{m_W^2}\,H^\dagger H G^a_{\mu\nu}\tilde{G}^{a\mu\nu}
\end{aligned}$$

Effective Lagrangian for a Higgs doublet

$$\Delta\mathcal{L}^{(6)} = \Delta\mathcal{L}_{SILH} + \boxed{\Delta\mathcal{L}_{cc}} + \Delta\mathcal{L}_{dipole} + \Delta\mathcal{L}_{V} + +\Delta\mathcal{L}_{4\psi}$$

6 current-current operators

$$\begin{aligned}\Delta\mathcal{L}_{cc} = {} & \frac{i\bar{c}_{Hq}}{v^2}\left(\bar{q}_L\gamma^\mu q_L\right)\left(H^\dagger \overleftrightarrow{D}_\mu H\right) + \frac{i\bar{c}'_{Hq}}{v^2}\left(\bar{q}_L\gamma^\mu\sigma^i q_L\right)\left(H^\dagger\sigma^i \overleftrightarrow{D}_\mu H\right) \\ & + \frac{i\bar{c}_{Hu}}{v^2}\left(\bar{u}_R\gamma^\mu u_R\right)\left(H^\dagger \overleftrightarrow{D}_\mu H\right) + \frac{i\bar{c}_{Hd}}{v^2}\left(\bar{d}_R\gamma^\mu d_R\right)\left(H^\dagger \overleftrightarrow{D}_\mu H\right) \\ & + \left(\frac{i\bar{c}_{Hud}}{v^2}\left(\bar{u}_R\gamma^\mu d_R\right)\left(H^{c\,\dagger} \overleftrightarrow{D}_\mu H\right) + h.c.\right) \\ & + \frac{i\bar{c}_{HL}}{v^2}\left(\bar{L}_L\gamma^\mu L_L\right)\left(H^\dagger \overleftrightarrow{D}_\mu H\right)\end{aligned}$$

Effective Lagrangian for a Higgs doublet

$$\Delta\mathcal{L}^{(6)} = \Delta\mathcal{L}_{SILH} + \Delta\mathcal{L}_{cc} + \boxed{\Delta\mathcal{L}_{dipole}} + \Delta\mathcal{L}_{V} + +\Delta\mathcal{L}_{4\psi}$$

8 dipole operators

$$\begin{aligned}\Delta\mathcal{L}_{dipole} = & \frac{\bar{c}_{uB}\, g'}{m_W^2}\, y_u\, \bar{q}_L H^c \sigma^{\mu\nu} u_R\, B_{\mu\nu} + \frac{\bar{c}_{uW}\, g}{m_W^2}\, y_u\, \bar{q}_L \sigma^i H^c \sigma^{\mu\nu} u_R\, W^i_{\mu\nu} + \frac{\bar{c}_{uG}\, g_S}{m_W^2}\, y_u\, \bar{q}_L H^c \sigma^{\mu\nu} \lambda^a u_R\, G^a_{\mu\nu} \\ & + \frac{\bar{c}_{dB}\, g'}{m_W^2}\, y_d\, \bar{q}_L H \sigma^{\mu\nu} d_R\, B_{\mu\nu} + \frac{\bar{c}_{dW}\, g}{m_W^2}\, y_d\, \bar{q}_L \sigma^i H \sigma^{\mu\nu} d_R\, W^i_{\mu\nu} + \frac{\bar{c}_{dG}\, g_S}{m_W^2}\, y_d\, \bar{q}_L H \sigma^{\mu\nu} \lambda^a d_R\, G^a_{\mu\nu} \\ & + \frac{\bar{c}_{lB}\, g'}{m_W^2}\, y_l\, \bar{L}_L H \sigma^{\mu\nu} l_R\, B_{\mu\nu} + \frac{\bar{c}_{lW}\, g}{m_W^2}\, y_l\, \bar{L}_L \sigma^i H \sigma^{\mu\nu} l_R\, W^i_{\mu\nu} + h.c.\end{aligned}$$

Effective Lagrangian for a Higgs doublet

$$\Delta\mathcal{L}^{(6)} = \Delta\mathcal{L}_{SILH} + \Delta\mathcal{L}_{cc} + \Delta\mathcal{L}_{dipole} + \boxed{\Delta\mathcal{L}_V} + +\Delta\mathcal{L}_{4\psi}$$

7 operators built with gauge fields only

(5 CP even, 2 CP odd)

$$\boxed{\begin{aligned}\Delta\mathcal{L}_V = &\frac{\bar{c}_{2W}}{m_W^2}\left(D^\mu W_{\mu\nu}\right)^i\left(D_\rho W^{\rho\nu}\right)^i + \frac{\bar{c}_{2B}}{m_W^2}\left(\partial^\mu B_{\mu\nu}\right)\left(\partial_\rho B^{\rho\nu}\right) + \frac{\bar{c}_{2G}}{m_W^2}\left(D^\mu G_{\mu\nu}\right)^a\left(D_\rho G^{\rho\nu}\right)^a \\ &+ \frac{\bar{c}_{3W}\, g^3}{m_W^2}\,\epsilon^{ijk}W_\mu^{i\,\nu}W_\nu^{j\,\rho}W_\rho^{k\,\mu} + \frac{\bar{c}_{3G}\, g_S^3}{m_W^2}\, f^{abc}G_\mu^{a\,\nu}G_\nu^{b\,\rho}G_\rho^{c\,\mu} \\ &+ \frac{\tilde{c}_{3W}\, g^3}{m_W^2}\,\epsilon^{ijk}W_\mu^{i\,\nu}W_\nu^{j\,\rho}\tilde{W}_\rho^{k\,\mu} + \frac{\tilde{c}_{3G}\, g_S^3}{m_W^2}\, f^{abc}G_\mu^{a\,\nu}G_\nu^{b\,\rho}\tilde{G}_\rho^{c\,\mu}\end{aligned}}$$

Effective Lagrangian for a Higgs doublet

$$\Delta\mathcal{L}^{(6)} = \Delta\mathcal{L}_{SILH} + \Delta\mathcal{L}_{cc} + \Delta\mathcal{L}_{dipole} + \boxed{\Delta\mathcal{L}_V} + + \boxed{\Delta\mathcal{L}_{4\psi}}$$

22 four-fermion operators

7 operators built with gauge fields only

(5 CP even, 2 CP odd)

$$\boxed{\begin{aligned}\Delta\mathcal{L}_V = {} & \frac{\bar{c}_{2W}}{m_W^2}\left(D^\mu W_{\mu\nu}\right)^i\left(D_\rho W^{\rho\nu}\right)^i + \frac{\bar{c}_{2B}}{m_W^2}\left(\partial^\mu B_{\mu\nu}\right)\left(\partial_\rho B^{\rho\nu}\right) + \frac{\bar{c}_{2G}}{m_W^2}\left(D^\mu G_{\mu\nu}\right)^a\left(D_\rho G^{\rho\nu}\right)^a \\ & + \frac{\bar{c}_{3W}\, g^3}{m_W^2}\,\epsilon^{ijk} W_\mu^{i\,\nu} W_\nu^{j\,\rho} W_\rho^{k\,\mu} + \frac{\bar{c}_{3G}\, g_S^3}{m_W^2}\, f^{abc} G_\mu^{a\,\nu} G_\nu^{b\,\rho} G_\rho^{c\,\mu} \\ & + \frac{\tilde{c}_{3W}\, g^3}{m_W^2}\,\epsilon^{ijk} W_\mu^{i\,\nu} W_\nu^{j\,\rho} \tilde{W}_\rho^{k\,\mu} + \frac{\tilde{c}_{3G}\, g_S^3}{m_W^2}\, f^{abc} G_\mu^{a\,\nu} G_\nu^{b\,\rho} \tilde{G}_\rho^{c\,\mu}\end{aligned}}$$

Estimating the coefficients at m_*

SILH power counting

Giudice et al. JHEP 0706 (2007) 045

- each extra (covariant) derivative costs a factor $\dfrac{1}{m_*}$
- each extra power of H(x) costs a factor $\dfrac{g_*}{m_*} \equiv \dfrac{1}{f}$

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- each extra (covariant) derivative costs a factor $\dfrac{1}{m_*}$
- each extra power of H(x) costs a factor $\dfrac{g_*}{m_*} \equiv \dfrac{1}{f}$

For a strongly-interacting light Higgs (SILH): $\dfrac{1}{f} \gg \dfrac{1}{m_*}$

Example:

$$O_H = \frac{1}{2v^2}\,\partial^\mu(H^\dagger H)\,\partial_\mu(H^\dagger H)$$

$$O_\psi = \frac{y_\psi}{v^2}\,(H^\dagger H)\bar{\psi}H\psi + h.c.$$

$$\bar{c}_H, \bar{c}_\psi \sim O\left(\frac{v^2}{f^2}\right)$$

$$c_V = 1 - \bar{c}_H/2$$

$$c_\psi = 1 - (\bar{c}_H/2 + \bar{c}_\psi)$$

Estimating the coefficients at m_*

$$\bar{c}_H, \bar{c}_T, \bar{c}_6, \bar{c}_\psi \sim O\left(\frac{v^2}{f^2}\right), \quad \bar{c}_W, \bar{c}_B \sim O\left(\frac{m_W^2}{m_*^2}\right), \quad \bar{c}_{HW}, \bar{c}_{HB}, \bar{c}_\gamma, \bar{c}_g \sim O\left(\frac{m_W^2}{16\pi^2 f^2}\right)$$

$$\bar{c}_{H\psi}, \bar{c}'_{H\psi} \sim O\left(\frac{\lambda_\psi^2}{g_*^2}\frac{v^2}{f^2}\right), \quad \bar{c}_{Hud} \sim O\left(\frac{\lambda_u \lambda_d}{g_*^2}\frac{v^2}{f^2}\right), \quad \bar{c}_{\psi W}, \bar{c}_{\psi B}, \bar{c}_{\psi G} \sim O\left(\frac{m_W^2}{16\pi^2 f^2}\right)$$

Estimating the coefficients at m_*

$$\bar{c}_H, \bar{c}_T, \bar{c}_6, \bar{c}_\psi \sim O\left(\frac{v^2}{f^2}\right), \quad \bar{c}_W, \bar{c}_B \sim O\left(\frac{m_W^2}{m_*^2}\right), \quad \bar{c}_{HW}, \bar{c}_{HB}, \bar{c}_\gamma, \bar{c}_g \sim O\left(\frac{m_W^2}{16\pi^2 f^2}\right)$$

$$\bar{c}_{H\psi}, \bar{c}'_{H\psi} \sim O\left(\frac{\lambda_\psi^2}{g_*^2}\frac{v^2}{f^2}\right), \quad \bar{c}_{Hud} \sim O\left(\frac{\lambda_u \lambda_d}{g_*^2}\frac{v^2}{f^2}\right), \quad \bar{c}_{\psi W}, \bar{c}_{\psi B}, \bar{c}_{\psi G} \sim O\left(\frac{m_W^2}{16\pi^2 f^2}\right)$$

Extra symmetry protections might be at work in the UV theory

- Ex: in the MSSM $g_* \sim g$

  R-parity $\Rightarrow$ $\bar{c}_W, \bar{c}_B \sim \frac{m_W^2}{m_*^2} \times \frac{g^2}{16\pi^2}$

- Ex: if the Higgs is a pNGB

  Goldstone symmetry $\Rightarrow$ $\bar{c}_\gamma, \bar{c}_g \sim \frac{m_W^2}{16\pi^2 f^2} \times \frac{g_{\not{G}}^2}{g_*^2}$

Strong-coupling vs form-factor effects

$$
\begin{aligned}
\Delta\mathcal{L}_{SILH} = {} & \frac{\bar{c}_H}{2v^2}\,\partial^\mu\big(H^\dagger H\big)\,\partial_\mu\big(H^\dagger H\big) + \frac{\bar{c}_T}{2v^2}\,\Big(H^\dagger \overleftrightarrow{D^\mu} H\Big)\Big(H^\dagger \overleftrightarrow{D}_\mu H\Big) - \frac{\bar{c}_6\,\lambda}{v^2}\,\big(H^\dagger H\big)^3 \\
& + \Big(\frac{\bar{c}_u}{v^2}\,y_u\,H^\dagger H\,\bar{q}_L H^c u_R + \frac{\bar{c}_d}{v^2}\,y_d\,H^\dagger H\,\bar{q}_L H d_R + \frac{\bar{c}_l}{v^2}\,y_l\,H^\dagger H\,\bar{L}_L H l_R + h.c.\Big) \\
& + \frac{i\bar{c}_W\,g}{2m_W^2}\,\Big(H^\dagger\sigma^i \overleftrightarrow{D^\mu} H\Big)\,(D^\nu W_{\mu\nu})^i + \frac{i\bar{c}_B\,g'}{2m_W^2}\,\Big(H^\dagger \overleftrightarrow{D^\mu} H\Big)\,(\partial^\nu B_{\mu\nu}) \\
& + \frac{i\bar{c}_{HW}\,g}{m_W^2}\,(D^\mu H)^\dagger\sigma^i(D^\nu H)W^i_{\mu\nu} + \frac{i\bar{c}_{HB}\,g'}{m_W^2}\,(D^\mu H)^\dagger(D^\nu H)B_{\mu\nu} \\
& + \frac{\bar{c}_\gamma\,{g'}^2}{m_W^2}\,H^\dagger H B_{\mu\nu}B^{\mu\nu} + \frac{\bar{c}_g\,g_S^2}{m_W^2}\,H^\dagger H G^a_{\mu\nu}G^{a\mu\nu}\,,
\end{aligned}
$$

Strong-coupling vs form-factor effects

$$
\begin{aligned}
\Delta\mathcal{L}_{SILH} = \; & \boxed{\begin{aligned} & \frac{\bar{c}_H}{2v^2}\,\partial^\mu\left(H^\dagger H\right)\partial_\mu\left(H^\dagger H\right) + \frac{\bar{c}_T}{2v^2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right)\left(H^\dagger \overleftrightarrow{D}_\mu H\right) - \frac{\bar{c}_6\,\lambda}{v^2}\left(H^\dagger H\right)^3 \\
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\end{aligned}
$$

Parametrize corrections to tree-level Higgs couplings:

$$\boxed{\frac{\Delta c}{c_{SM}} = O\left(\frac{v^2}{f^2}\right)}$$

Probe Higgs interaction strength

Strong-coupling vs form-factor effects

only this operator formally breaks custodial symmetry

$$\Delta\mathcal{L}_{SILH} = \frac{\bar{c}_H}{2v^2}\,\partial^\mu\left(H^\dagger H\right)\partial_\mu\left(H^\dagger H\right) + \frac{\bar{c}_T}{2v^2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right)\left(H^\dagger \overleftrightarrow{D}_\mu H\right) - \frac{\bar{c}_6\,\lambda}{v^2}\left(H^\dagger H\right)^3$$
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Strong-coupling vs form-factor effects

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Probe Higgs interaction strength

Strong-coupling vs form-factor effects

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Probe Higgs interaction strength

If Higgs is PNGB, *hγγ, hgg* protected by shift symmetry:

$$\boxed{\frac{\delta\Gamma}{\Gamma_{SM}} = O\left(\frac{v^2}{f^2}\times\frac{g_{SM}^2}{g_*^2}\right)}$$

Form factor effect

Strong-coupling vs form-factor effects

$$\Delta\mathcal{L}_{SILH} = \frac{\bar{c}_H}{2v^2}\,\partial^\mu\left(H^\dagger H\right)\partial_\mu\left(H^\dagger H\right) + \frac{\bar{c}_T}{2v^2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right)\left(H^\dagger \overleftrightarrow{D}_\mu H\right) - \frac{\bar{c}_6\,\lambda}{v^2}\left(H^\dagger H\right)^3$$

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Modify *h→WW, ZZ* (total rates and differential distributions):

$$\boxed{\frac{\delta\Gamma}{\Gamma_{SM}} = O\left(\frac{m_W^2}{m_*^2}\right) + O\left(\frac{m_W^2}{16\pi^2 f^2}\right)}$$

Strong-coupling vs form-factor effects

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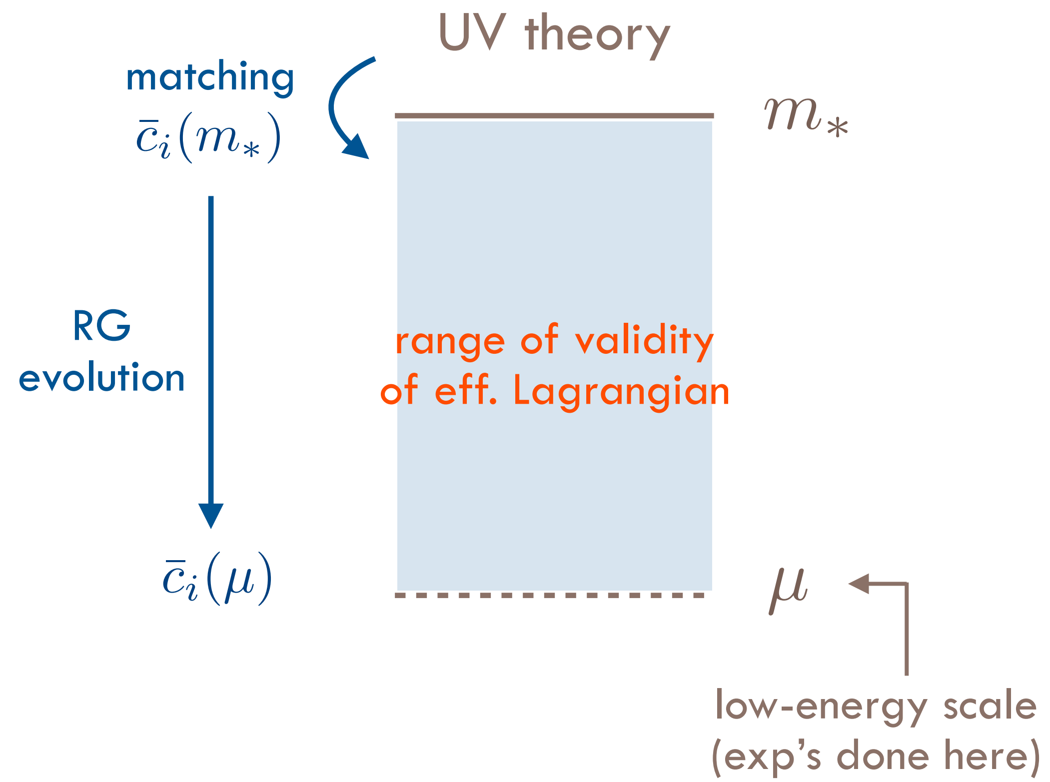
Probe NP scale (form factor)

RG evolution of coefficients

- Loops of *light* (SM) particles induce the RG flow (and mixing) of the coefficients $\bar{c}_i$

$$\bar{c}_i(\mu) = \left(\delta_{ij} + \gamma_{ij}^{(0)} \frac{\alpha_{SM}(\mu)}{4\pi} \log \frac{\mu}{m_*}\right) \bar{c}_j(m_*)$$

Elias-Miró et al. JHEP 1308 (2013) 033; JHEP 1311 (2013) 066
Jenkins et al. JHEP 1310 (2013) 087; JHEP 1401 (2014) 035
Alonso et al. JHEP 1404 (2014) 159



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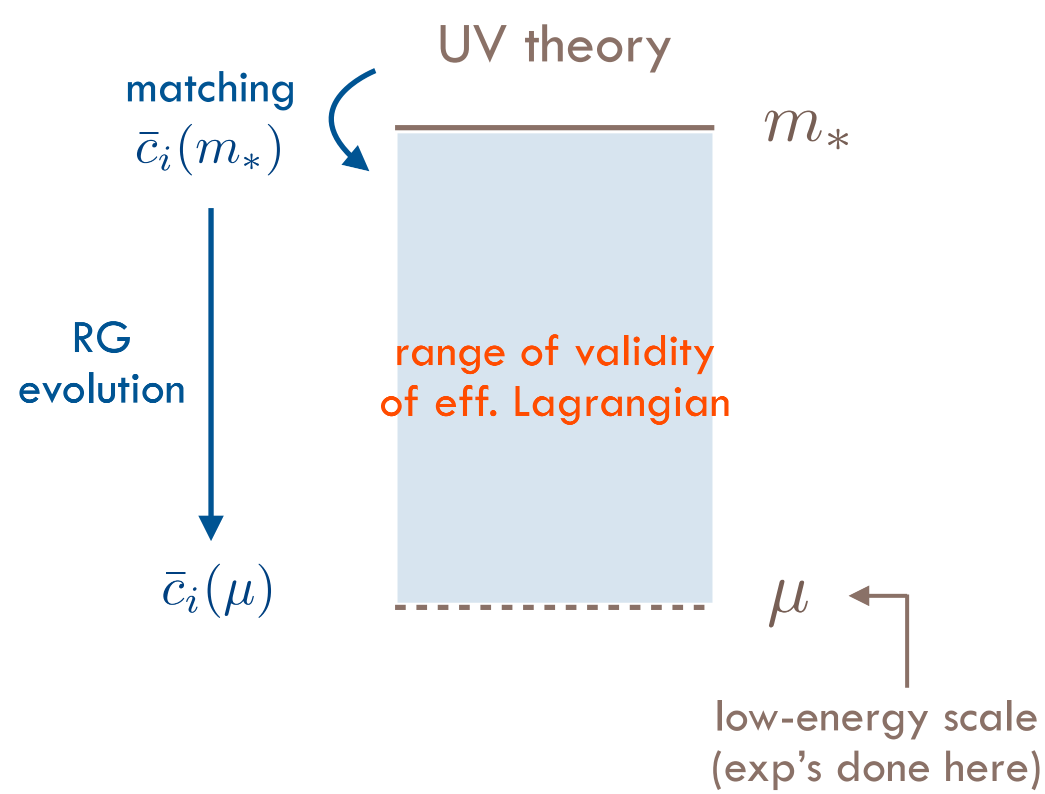

- By dimensional analysis: 1-loop RG come from diagrams with 1 insertion of a dim-6 operator

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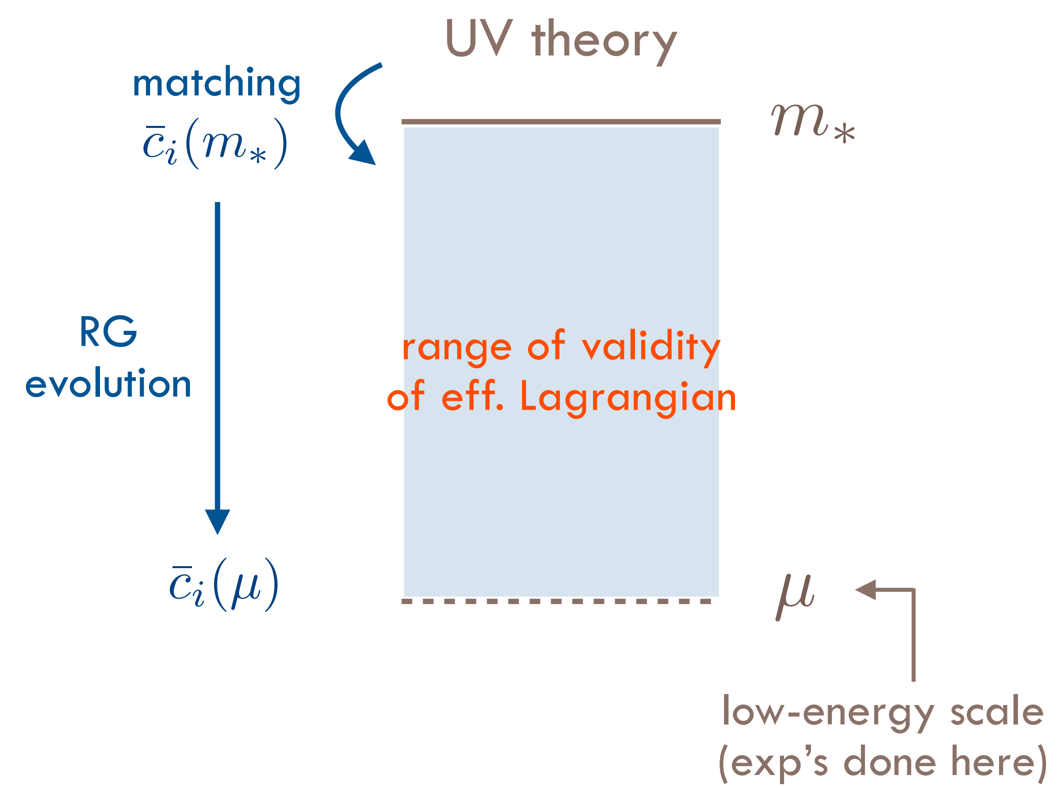


- By dimensional analysis: 1-loop RG come from diagrams with 1 insertion of a dim-6 operator

- dim-6 operators can mix with dim-6 and dim-4 (through m_H insertions) operators

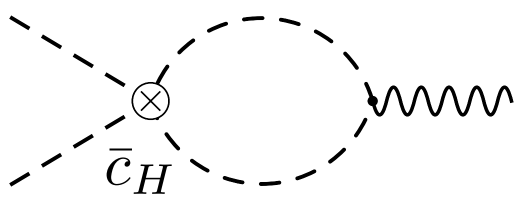
RG evolution of coefficients

- In case of strong dynamics, leading effects come from loops of composite particles (i.e. Higgs, top quarks, ...)

Examples:

1. Running of $\bar{c}_{W+B}$

$$O_{W+B} = \frac{ig}{2m_W^2} D^\nu W^i_{\mu\nu} (H^\dagger \sigma^i \overleftrightarrow{D^\mu} H) + \frac{ig'}{2m_W^2} \partial^\nu B_{\mu\nu} (H^\dagger \overleftrightarrow{D^\mu} H)$$



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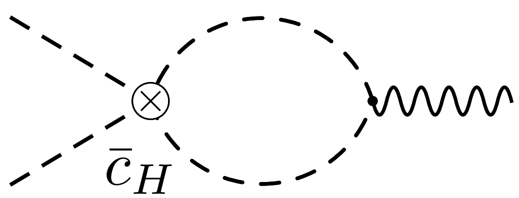

$O\left(\frac{\alpha}{4\pi} \times \log\right)$ short-distance (local) correction

$+$

$O\left(\frac{\alpha}{4\pi}\right)$ long-distance (threshold) correction

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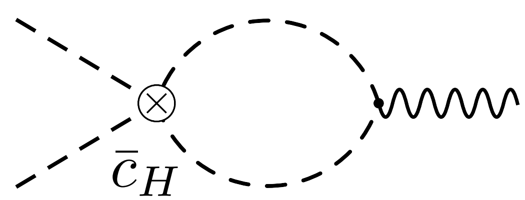

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$$\bar{c}_{W+B}(\mu) = \bar{c}_{W+B}(m_*) - \frac{1}{6}\,\frac{\alpha_2}{4\pi} \log\left(\frac{\mu}{m_*}\right) \bar{c}_H(m_*)$$

$$\boxed{\frac{\Delta \bar{c}_{W+B}}{\bar{c}_{W+B}} \sim \frac{g_*^2}{16\pi^2} \log\left(\frac{m_*}{\mu}\right)}$$

RG evolution of coefficients

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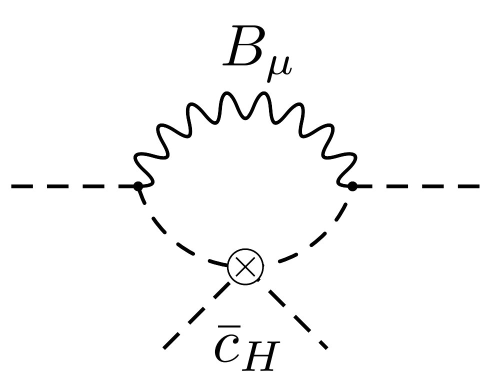
Examples:

2. Running of $\bar{c}_T$ $$O_T = \frac{1}{2v^2}\left|H^\dagger \overleftrightarrow{D_\nu} H\right|^2$$



$$\bar{c}_T(\mu) = \frac{3}{2}\tan^2\theta_W\,\frac{\alpha_2}{4\pi}\log\left(\frac{\mu}{M}\right)\bar{c}_H(m_*)$$

RG evolution of coefficients

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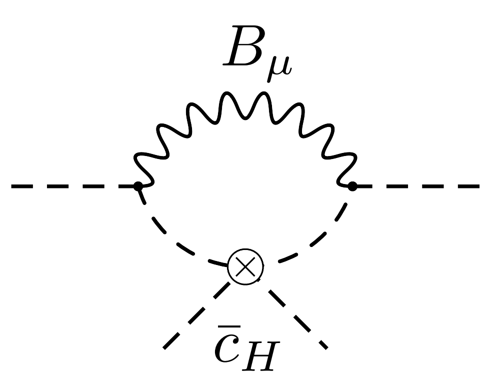

$$\bar{c}_T(\mu) = \frac{3}{2}\tan^2\theta_W \frac{\alpha_2}{4\pi}\log\left(\frac{\mu}{M}\right)\bar{c}_H(m_*)$$

$$\bar{c}_T(m_Z) \sim \frac{v^2}{f^2} \times \frac{g'^2}{16\pi^2}\log\left(\frac{m_*}{m_Z}\right)$$

Small but leading effect since $\bar{c}_T(m_*) = 0$ due to custodial invariance

Q: Which operators are constrained by Higgs searches only ?

In total: 59 dim-6 operators

17+4 involve the Higgs

8+3 affect Higgs physics only

Elias-Miro, Espinosa, Masso, Pomarol
JHEP 1311 (2013) 066

Pomarol, Riva JHEP 01 (2014) 151

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All other operators already constrained by:

See:

Pomarol, Riva JHEP 01 (2014) 151

RC, Ghezzi, Grojean, Muhlleitner, Spira JHEP 07 (2013) 035

and references therein

EW observables at LEP1	stronger
Electric dipole moments (EDMs)	
$b \to s\gamma$	
Triple gauge couplings (TGC)	
$e^+e^- \to f\bar{f}$ at LEP2	
CKM unitarity by KLOE and β-decay	
$t\bar{t}$, top decays	
Muon, electron (g-2)	weaker

Operators that affect Higgs physics only

Elias-Miro, Espinosa, Masso, Pomarol
JHEP 1311 (2013) 066

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$$O_H = (\partial_\mu |H|^2)^2$$

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shift $h\psi\psi$

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$$O_{BB} = g'^2 |H|^2 B_{\mu\nu} B^{\mu\nu}$$

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

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

affect $h \to \gamma\gamma$, $h \to Z\gamma$, $gg \to h$

modify inclusive rates and differential distributions (constrained by fit to Higgs couplings)

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

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

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

shift $h\psi\psi$

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

$$+ \text{ other 3 CP odd}$$

Operators that affect Higgs physics only

Elias-Miro, Espinosa, Masso, Pomarol
JHEP 1311 (2013) 066

Pomarol, Riva JHEP 01 (2014) 151

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$gg \to hh$ yet un-probed

$+$ other 3 CP odd

Conclusions

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  The smaller δc_i, the higher the scale to which we can extrapolate the theory

- Current data do not show any sign of a strong coupling scale:

  - Higgs couplings are close to their SM values: $\delta c_i \lesssim 20 - 30\%$

  - $m_h = 125\,\mathrm{GeV}$ is in the range in which λ_4 remains perturbative and the vacuum is (meta)stable

Conclusions

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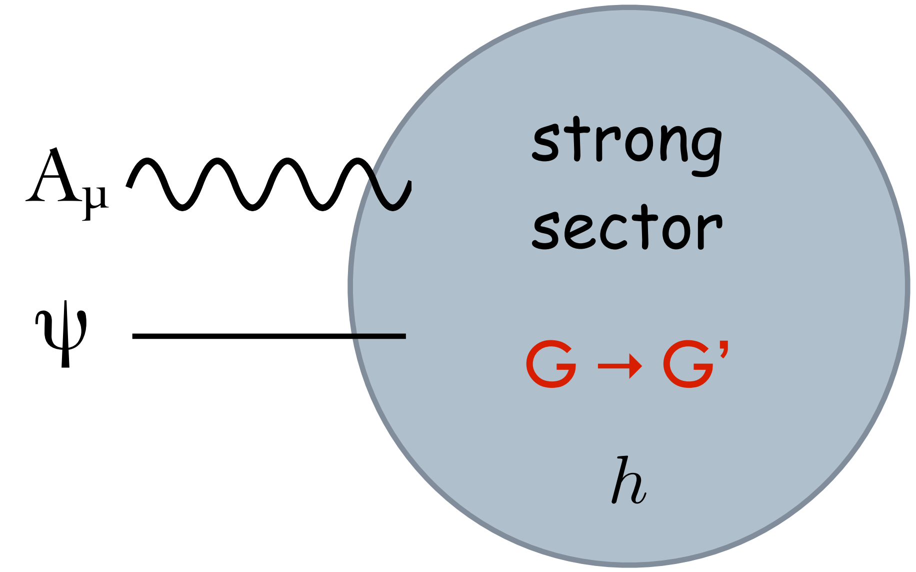
  - many directions already closed by past experiments

- One must always check that *any* effective Lagrangian is used within its range of validity

Extra slides

The Higgs as a composite pseudo-NG boson

[Georgi & Kaplan, `80]



- The Higgs doublet H is the NG boson associated to the global symmetry G → G' of a new strong dynamics

Minimal example (with custodial symmetry):

$SO(5) \to SO(4) \sim SU(2)_L \times SU(2)_R$

four real NG bosons:

$\mathbf{4}$ of $SO(4)$ = real $(2,2)$ of $SU(2)_L \times SU(2)_R$

= complex $\mathbf{2}$ of $SU(2)_L$

Agashe, RC, Pomarol, NPB 719 (2005) 165

RC, DaRold, Pomarol, PRD 75 (2007) 055014; Carena, Ponton, Santiago, Wagner, PRD 76 (2007) 035006; Hosotani, Oda, Ohnuma, Sakamura, PRD 78 (2008) 096002; Hosotani, Tanaka, Uekusa, PRD 82 (2010) 115024; Redi, Gripaios, JHEP 1008:116 (2010); Hosotani, Noda, Uekusa, Prog. Theor. Phys 123 (2010) 123; Panico, Safari, Serone, JHEP 1102:103 (2011)

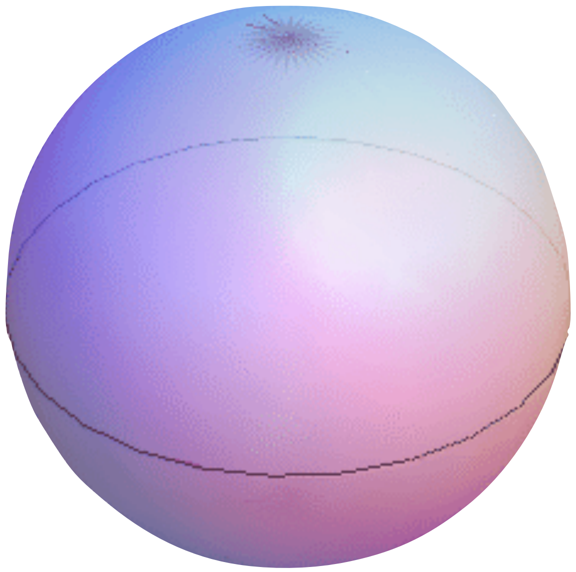
At high energies SO(4) is *linearly* realized

$$\mathcal{L} = \frac{f^2}{2}(D_\mu \phi)^T (D^\mu \phi)$$

$$\phi^T \phi = 1$$

$$\frac{SO(5)}{SO(4)} = S^4$$

vacuum manifold
is the 4-sphere



$$\phi = e^{i\pi^{\hat{a}} T^{\hat{a}}/f} \begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 1 \end{pmatrix} = \begin{pmatrix} \sin(\pi/f) \times \begin{pmatrix} \hat{\pi}^1 \\ \hat{\pi}^2 \\ \hat{\pi}^3 \\ \hat{\pi}^4 \end{pmatrix} \\ \cos(\pi/f) \end{pmatrix}$$

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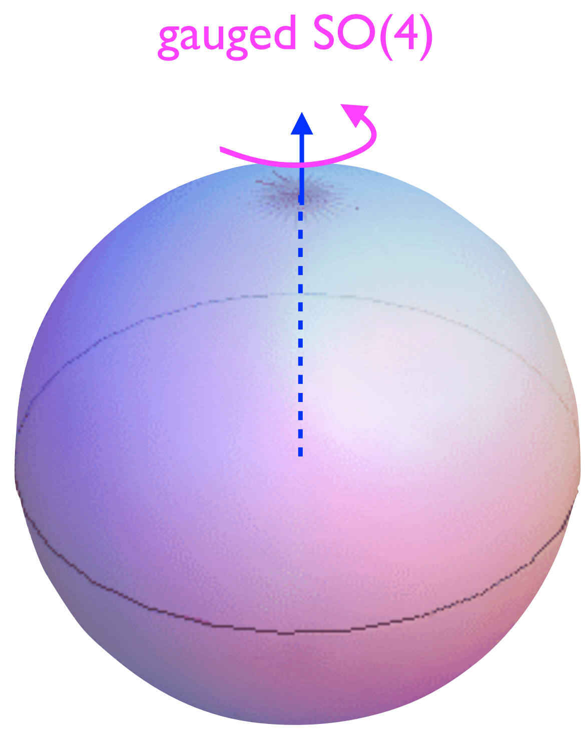

gauged SO(4)

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At tree level, gauged
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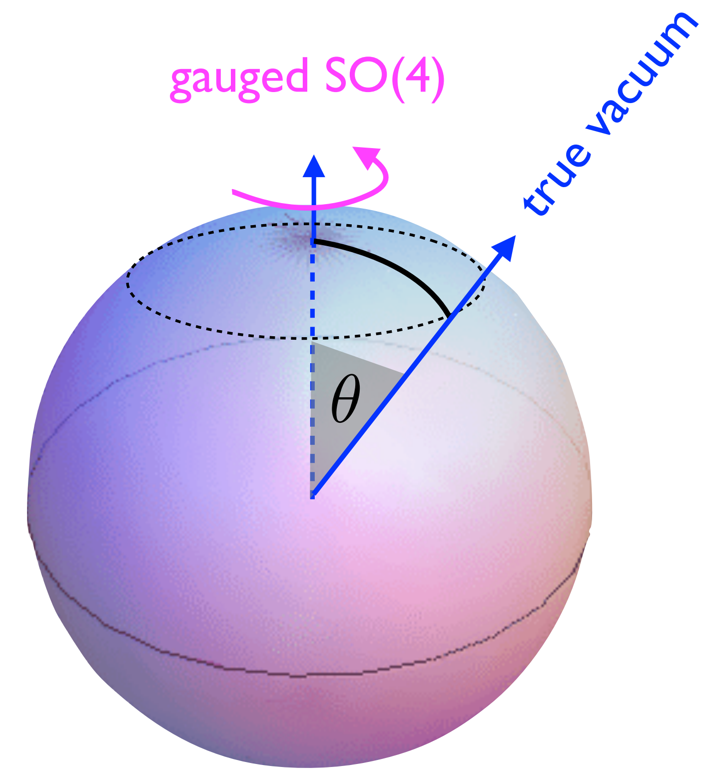

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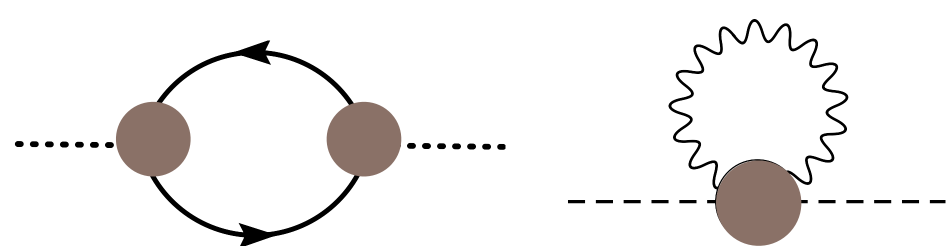

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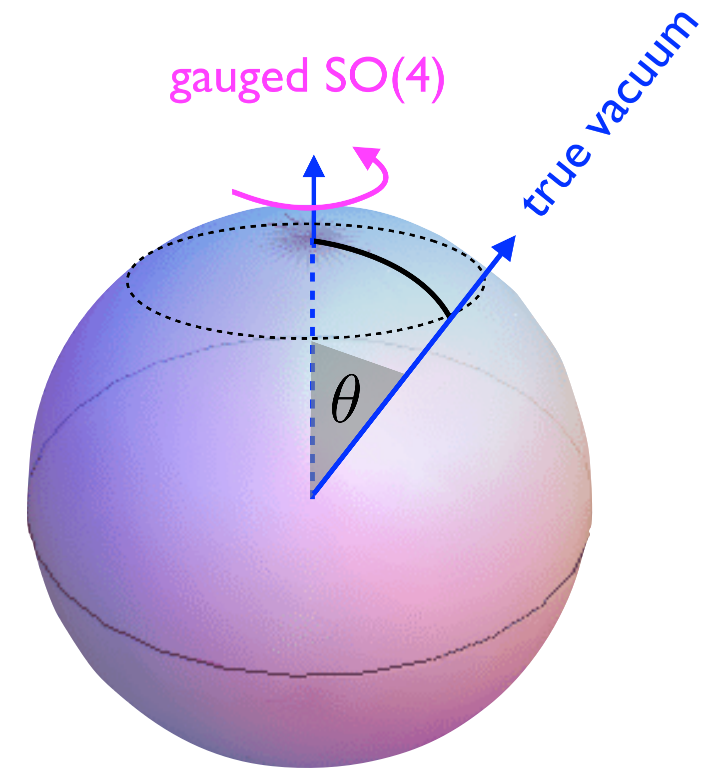

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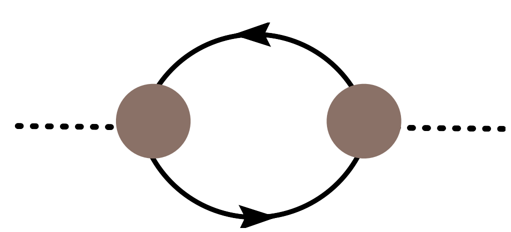

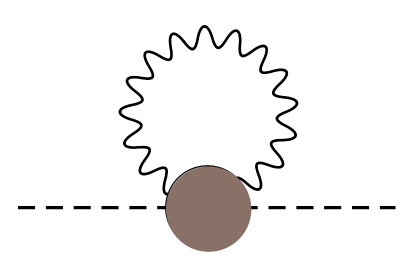

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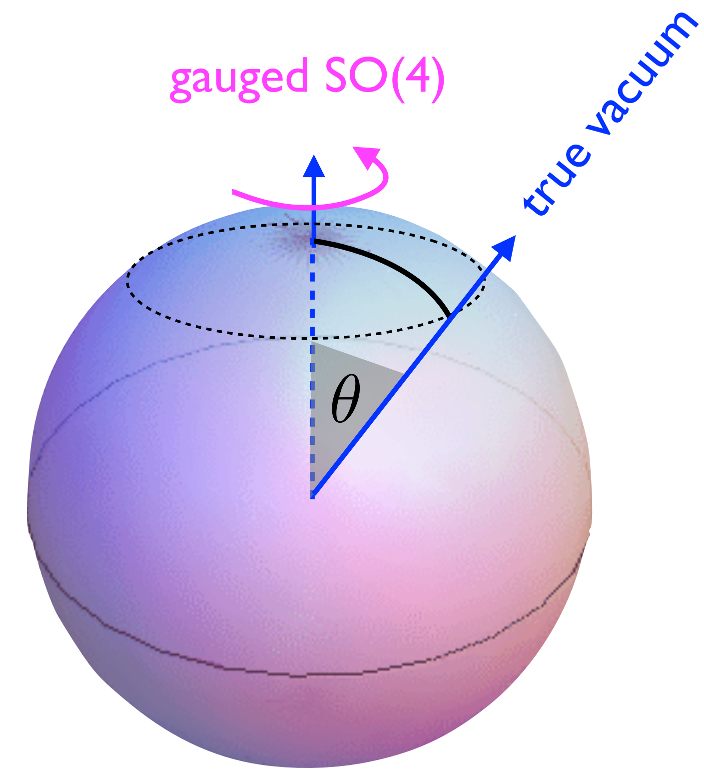

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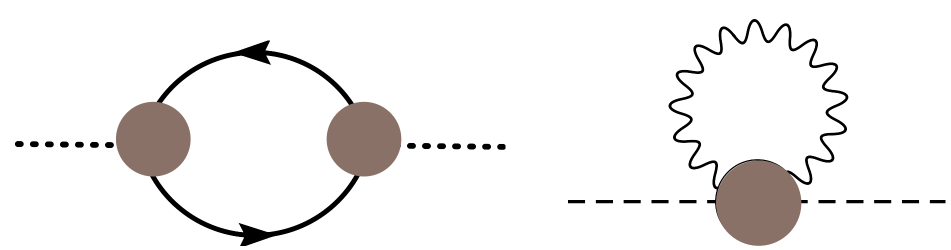

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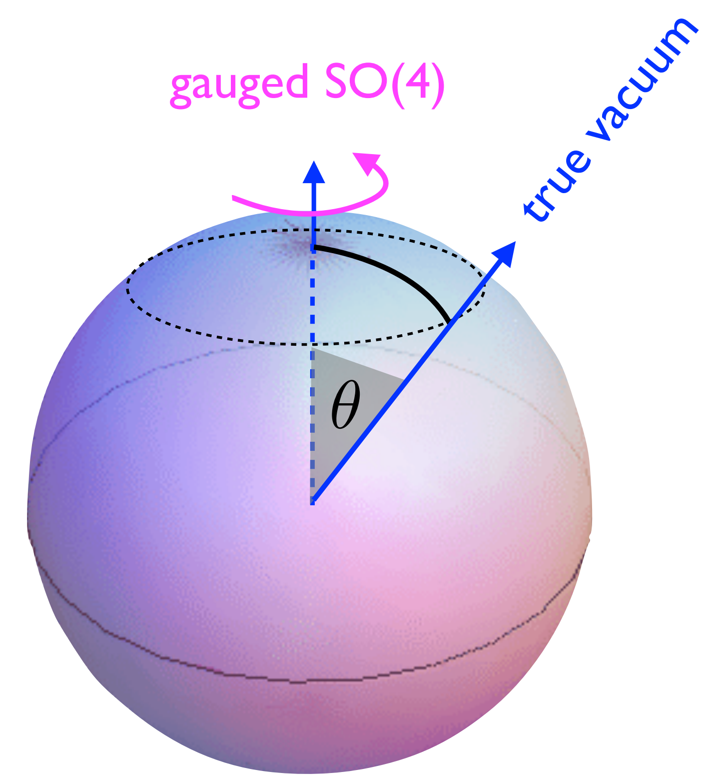

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VACUUM
MISALIGNMENT

The angle θ measures the degree of
misalignment between the gauged SO(4)
and the SO(4)' preserved in the true vacuum

$$\mathcal{L} = \frac{f^2}{2}(D_\mu \phi)^T (D^\mu \phi)$$

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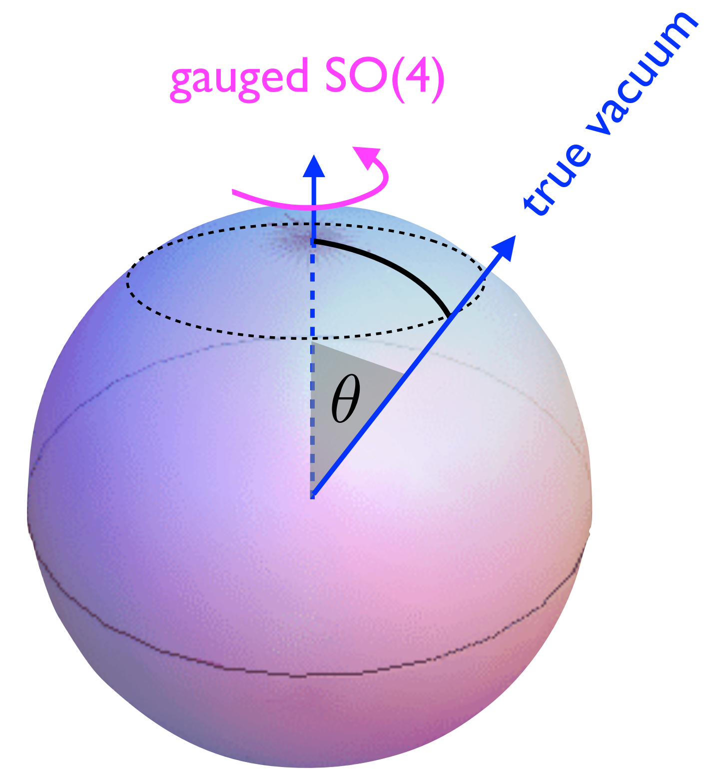
vacuum manifold is the 4-sphere



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A TWO-STEP SYMMETRY BREAKING:

$$\mathrm{SO(5)} \xrightarrow{f} \mathrm{SO(4)} \xrightarrow{v} \mathrm{SO(3)}$$

composite doublet H

EWSB

$$\mathcal{L} = \frac{f^2}{2}(D_\mu\phi)^T(D^\mu\phi)$$

$$= \frac{1}{2}(\partial_\mu h)^2 + \frac{f^2}{2}\mathrm{Tr}\big[(D_\mu\Sigma)^\dagger(D^\mu\Sigma)\big]\sin^2\left(\theta + \frac{h(x)}{f}\right)$$

$$\Sigma = e^{i\sigma^i\chi^i(x)/v}$$

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$$\Rightarrow \quad m_W^2 = \frac{g^2 f^2}{4}\sin^2\theta \qquad \boxed{\xi = \left(\frac{v}{f}\right)^2 = \sin^2\theta}$$

$$m_\rho \sim 4\pi f = \frac{4\pi v}{\sqrt{\xi}}$$

decoupling limit: $\xi \to 0$, $v = \text{fixed}$

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Expanding along the vacuum:

$$\mathcal{L} = \frac{1}{2}(\partial_\mu h)^2 + \frac{v^2}{4}\mathrm{Tr}\left[\partial_\mu \Sigma^\dagger \partial^\mu \Sigma\right]\left(1 + 2\sqrt{1-\xi}\,\frac{h}{v} + (1-2\xi)\left(\frac{h}{v}\right)^2 + \dots\right)$$

$$\boxed{c_V = \sqrt{1-\xi}\,, \quad c_{2V} = (1-2\,\xi)}$$

Higgs couplings to gauge bosons fixed by the coset, and predicted in terms of 1 parameter (ξ)

Implementing the Effective Lagrangian into software tools

- MC event generators

At least two FeynRules models implementing the Higgs Effective Lagrangian:

"Higgs Effective Lagrangian"
Alloul, Fuks, Sanz arXiv:1310.5150
http://feynrules.irmp.ucl.ac.be/wiki/HEL

"Higgs Characterization Model"
P. Artoisenet et al. JHEP 1311 (2013) 043
http://feynrules.irmp.ucl.ac.be

- Higgs decay rates and BRs

eHDECAY [based on HDECAY v5.10]
RC, Ghezzi, Grojean, Muhlleitner, Spira arXiv:1403.3381
http://www-itp.particle.uni-karlsruhe.de/~maggie/eHDECAY

A closer look to eHDECAY

RC, Ghezzi, Grojean, Muhlleitner, Spira arXiv:1403.3381

$$\frac{\Gamma(\bar\psi\psi)}{\Gamma(\bar\psi\psi)_{SM}} \simeq 1 - \bar c_H - 2\,\bar c_\psi \,,$$

$$\frac{\Gamma(h\to W^{(*)}W^*)}{\Gamma(h\to W^{(*)}W^*)_{SM}} \simeq 1 - \bar c_H + 2.2\,\bar c_W + 3.7\,\bar c_{HW} \,,$$

$$\frac{\Gamma(h\to Z^{(*)}Z^*)}{\Gamma(h\to Z^{(*)}Z^*)_{SM}} \simeq 1 - \bar c_H + 2.0\,\left(\bar c_W + \tan^2\theta_W\,\bar c_B\right) + 3.0\,\left(\bar c_{HW} + \tan^2\theta_W\,\bar c_{HB}\right) - 0.26\,\bar c_\gamma \,,$$

$$\frac{\Gamma(h\to Z\gamma)}{\Gamma(h\to Z\gamma)_{SM}} \simeq 1 - \bar c_H + 0.12\,\bar c_t - 5\cdot 10^{-4}\,\bar c_c - 0.003\,\bar c_b - 9\cdot 10^{-5}\,\bar c_\tau + 4.2\,\bar c_W + 0.19\left(\bar c_{HW} - \bar c_{HB} + 8\,\bar c_\gamma \sin^2\theta_W\right)\frac{4\pi}{\sqrt{\alpha_2\alpha_{em}}} \,,$$

$$\frac{\Gamma(h\to\gamma\gamma)}{\Gamma(h\to\gamma\gamma)_{SM}} \simeq 1 - \bar c_H + 0.54\,\bar c_t - 0.003\,\bar c_c - 0.007\,\bar c_b - 0.007\,\bar c_\tau + 5.04\,\bar c_W - 0.54\,\bar c_\gamma\,\frac{4\pi}{\alpha_{em}} \,,$$

$$\frac{\Gamma(h\to gg)}{\Gamma(h\to gg)_{SM}} \simeq 1 - \bar c_H - 2.12\,\bar c_t + 0.024\,\bar c_c + 0.1\,\bar c_b + 22.2\,\bar c_g\,\frac{4\pi}{\alpha_2} \,.$$

$$\alpha_2 \equiv \frac{\sqrt{2}\,G_F m_W^2}{\pi}$$

$$\alpha_{em} \equiv \alpha_{em}(q^2 = 0)$$

A closer look to eHDECAY

RC, Ghezzi, Grojean, Muhlleitner, Spira arXiv:1403.3381

- Decay rates computed by making a multiple perturbative expansion in (E/Λ), (v/f), $(\alpha_{SM}/4\pi)$

- QCD (long-distance) corrections factorize and can be easily included

- EW corrections do not factorize and can be included at $O(\alpha_2/4\pi)$, i.e. neglecting $O[(\alpha_2/4\pi)(v^2/f^2)]$

$$\Gamma(\bar{\psi}\psi)\big|_{SILH} = \Gamma_0^{SM}(\bar{\psi}\psi)\left[1 - \bar{c}_H - 2\bar{c}_\psi + \frac{2}{|A_0^{SM}|^2}\mathrm{Re}\left(A_0^{*SM} A_{1,ew}^{SM}\right)\right]\left[1 + \delta_\psi\, \kappa^{QCD}\right]$$

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QCD corrections

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$O(v^2/f^2)$ corrections

EW corrections $O(\alpha_2/4\pi)$

QCD corrections

Part 4

Validity of the EFT description

- So far Higgs searches have focussed on single-Higgs on-shell production and decay

→ gives information on on-shell couplings at a fixed scale $Q = m_h$

On shell:

$$\frac{\delta c}{c} \sim O\left(\frac{m_h^2}{m_*^2}\right) \text{ or } O\left(\frac{g_*^2}{g_{SM}^2} \times \frac{m_h^2}{m_*^2} = \frac{v^2}{f^2}\right) < 1$$

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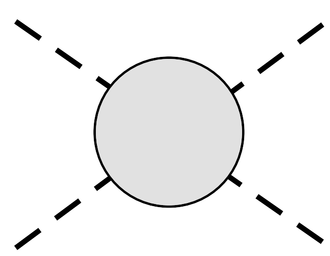
- Next frontier: measure 2→2 scattering processes to probe *directly* the strength of SSB dynamics at energies $E \gg m_h$



$$\sim g(E)^2$$

Validity of the EFT description

Inspired by:
R. Rattazzi, talk at "BSM physics opportunities at 100TeV", Cern 2014

In general:

$$A = g_{SM}^2 \times \left(1 + O\left(\frac{v^2}{f^2}\right)\right) + O\left(\frac{g_*^2 E^2}{m_*^2}\right) + \ldots$$

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Validity of the EFT description

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R. Rattazzi, talk at "BSM physics opportunities at 100TeV", Cern 2014

In general:

$$A = \underbrace{g_{SM}^2}_{= A_{SM}} \times \left(1 + O\left(\frac{v^2}{f^2}\right)\right) + \underbrace{O\left(\frac{g_*^2 E^2}{m_*^2}\right)}_{\equiv g(E)^2} + \dots$$

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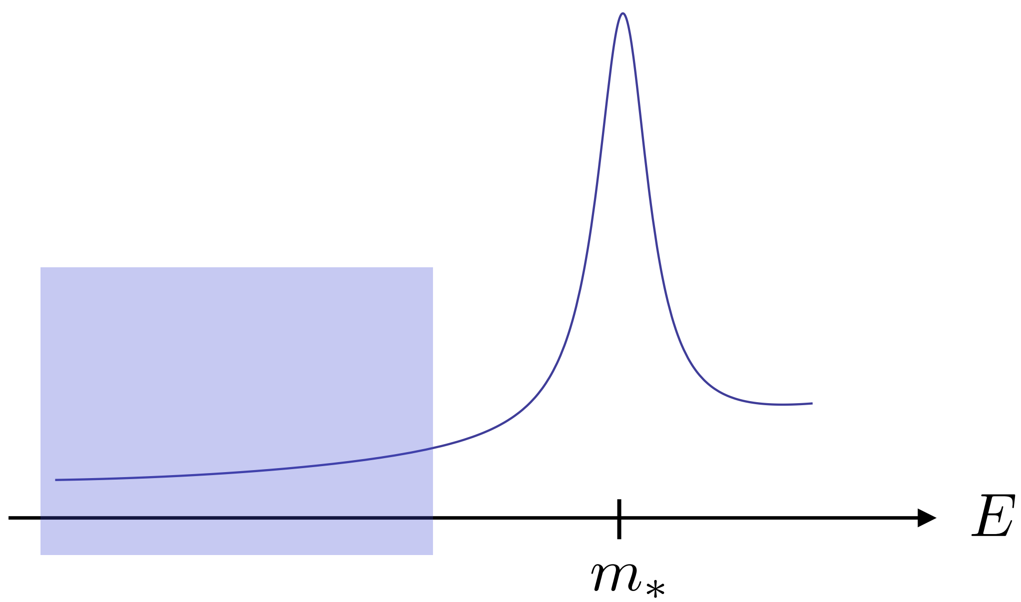
Interesting coupling range: $g_{SM} < g(E) < g_* \lesssim 4\pi$

Interesting energy window: $g_{SM}\, f < E < m_*$



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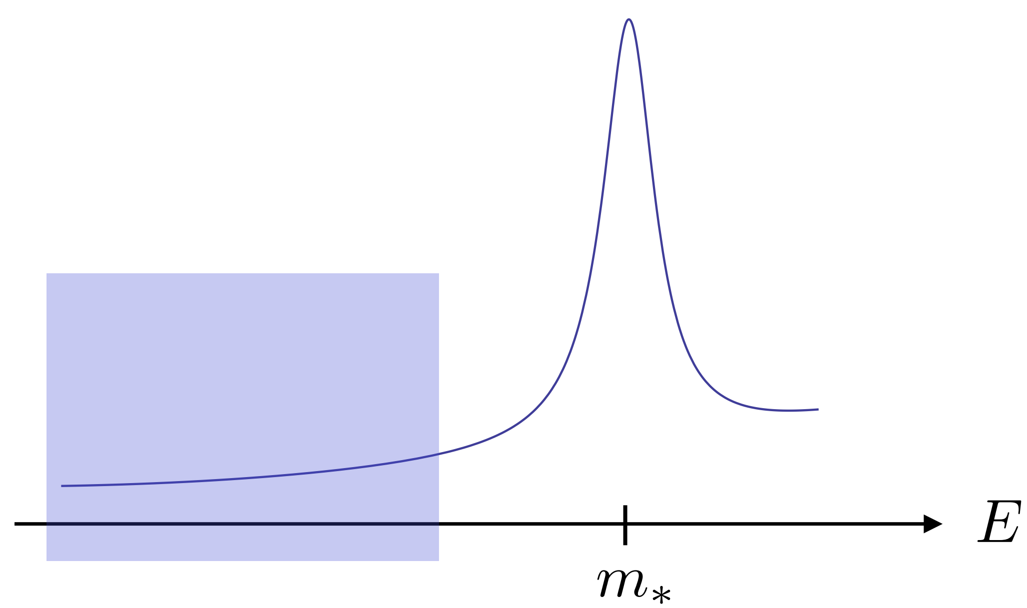

Thus: $\dfrac{\delta A}{A_{SM}} \sim \dfrac{g(E)^2}{g_{SM}^2}$ can be > 1 if NP dynamics is *strongly coupled* ($g_* > g_{SM}$)

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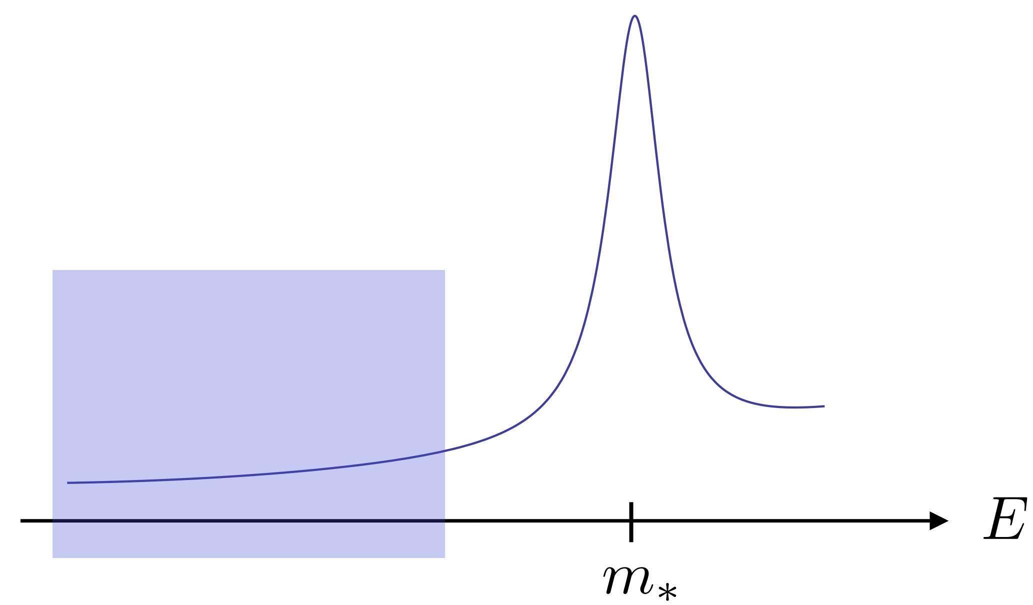


For:

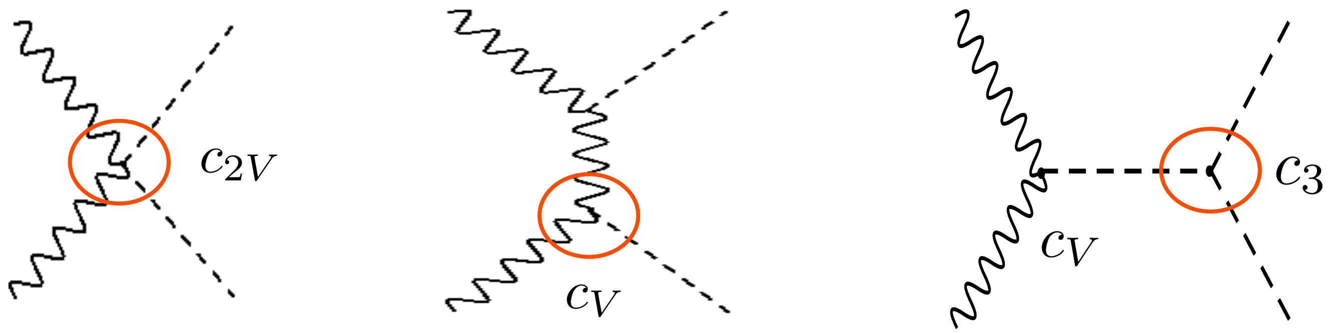
$\bar{f} =$ best sensitivity on f

$\bar{E} =$ largest energy probed

$\Rightarrow$ $\boxed{g_{min} \equiv \frac{\bar{E}}{\bar{f}} < g_* \leq 4\pi}$

Parameter space under scrutiny *within* the validity of EFT

Example #1: Double Higgs production via VBF ($V_L V_L \to hh$)



$$c_V = 1 - \frac{\bar{c}_H}{2}$$

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$$c_3 = 1 - \frac{3}{2}\bar{c}_H + \bar{c}_6$$

$$A = c_V^2 \frac{m_h^2}{v^2} \left(1 + O(\delta_2, \delta_3)\right) - c_V^2 \frac{\hat{s}}{v^2} \delta_2 + \ldots$$

$$\delta_2 \equiv 1 - c_{2V}/c_V^2$$

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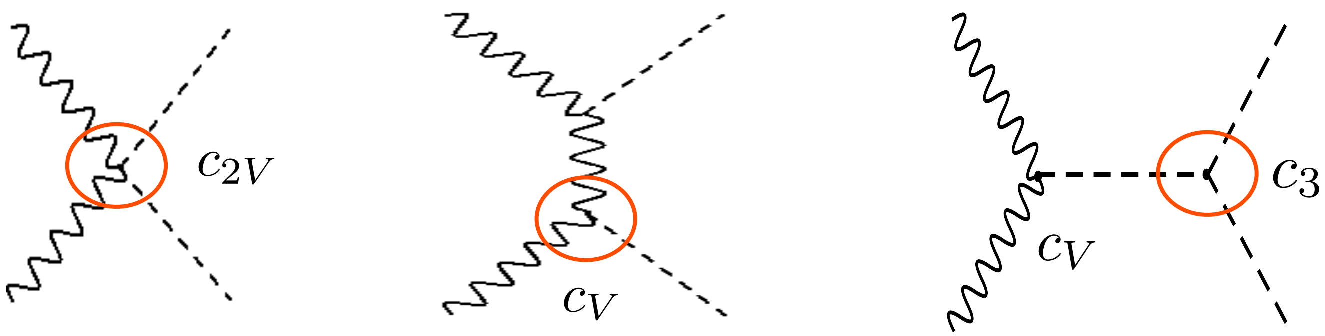

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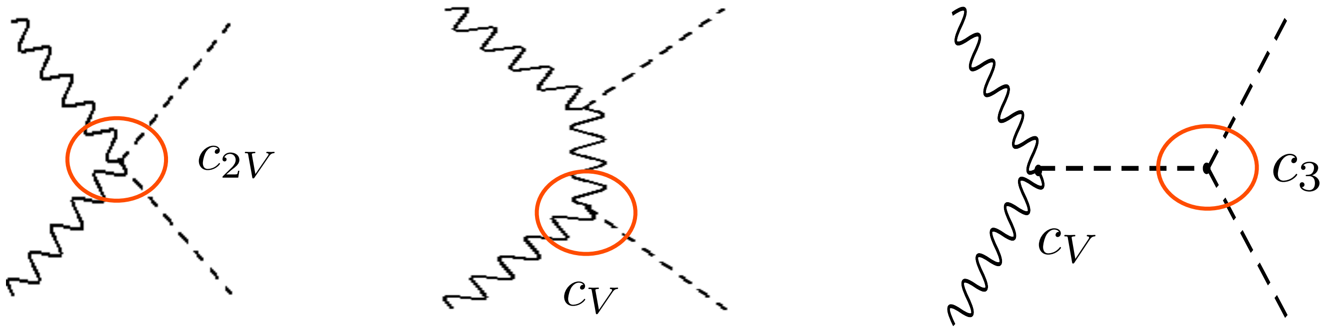

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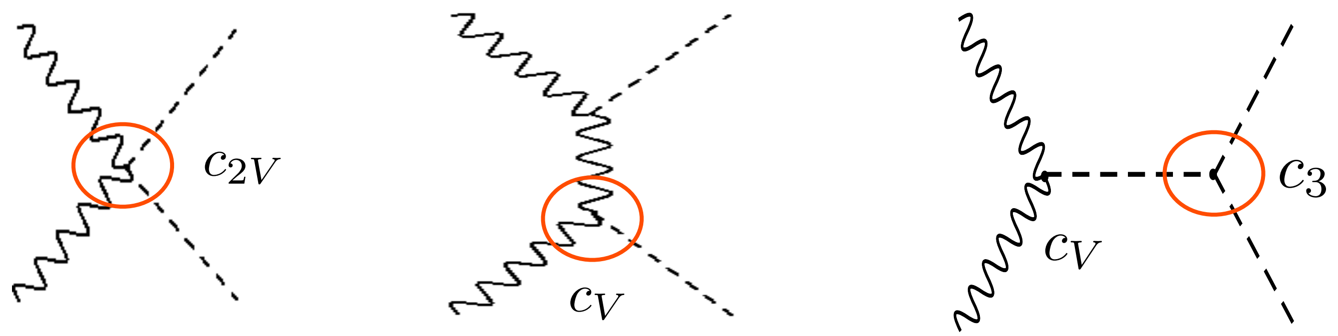

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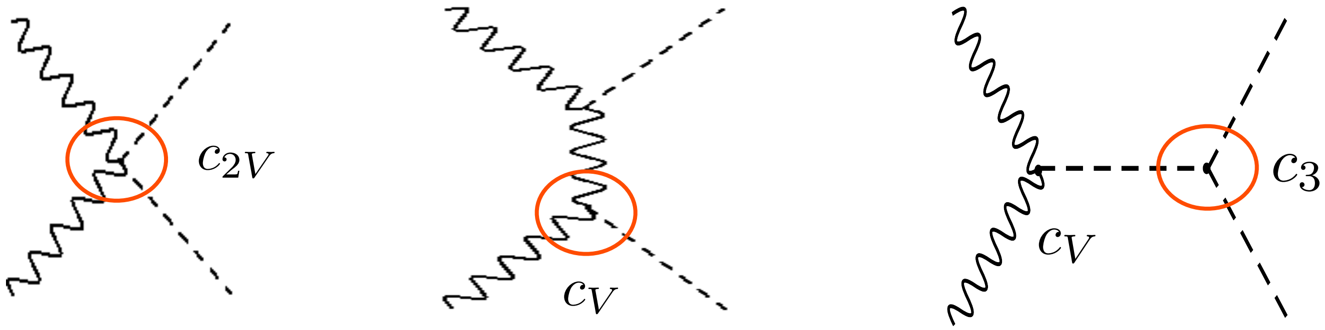

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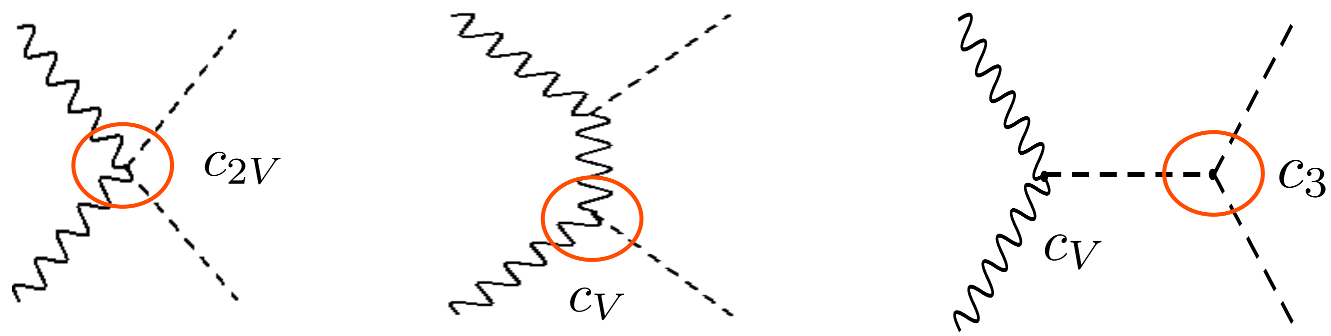

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$= A_{SM}$

$= g(E)^2 \sim \dfrac{E^2}{f^2}$

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If best sensitivity $(\delta_2)_{min}$ comes from events with invariant mass $m(hh) \sim \bar E$:

$$\boxed{\sqrt{(\delta_2)_{min}}\,\frac{\bar E}{v} = g_{min} < g_* \lesssim 4\pi}$$

Example #1: Double Higgs production via VBF ($V_L V_L \to hh$)

pp colliders $pp \to hh\, jj \to 4b\, jj$

	$(\delta_3)_{min}$	$(\delta_2)_{min}$	$\bar{E}$	g_{min}
$14\,\text{TeV}, \quad L = 300\,\text{fb}^{-1}$	$8-9$	0.35	$1.5\,\text{TeV}$	3.6
$14\,\text{TeV}, \quad L = 3\,\text{ab}^{-1}$	$5-8$	0.2	$1.5\,\text{TeV}$	2.7
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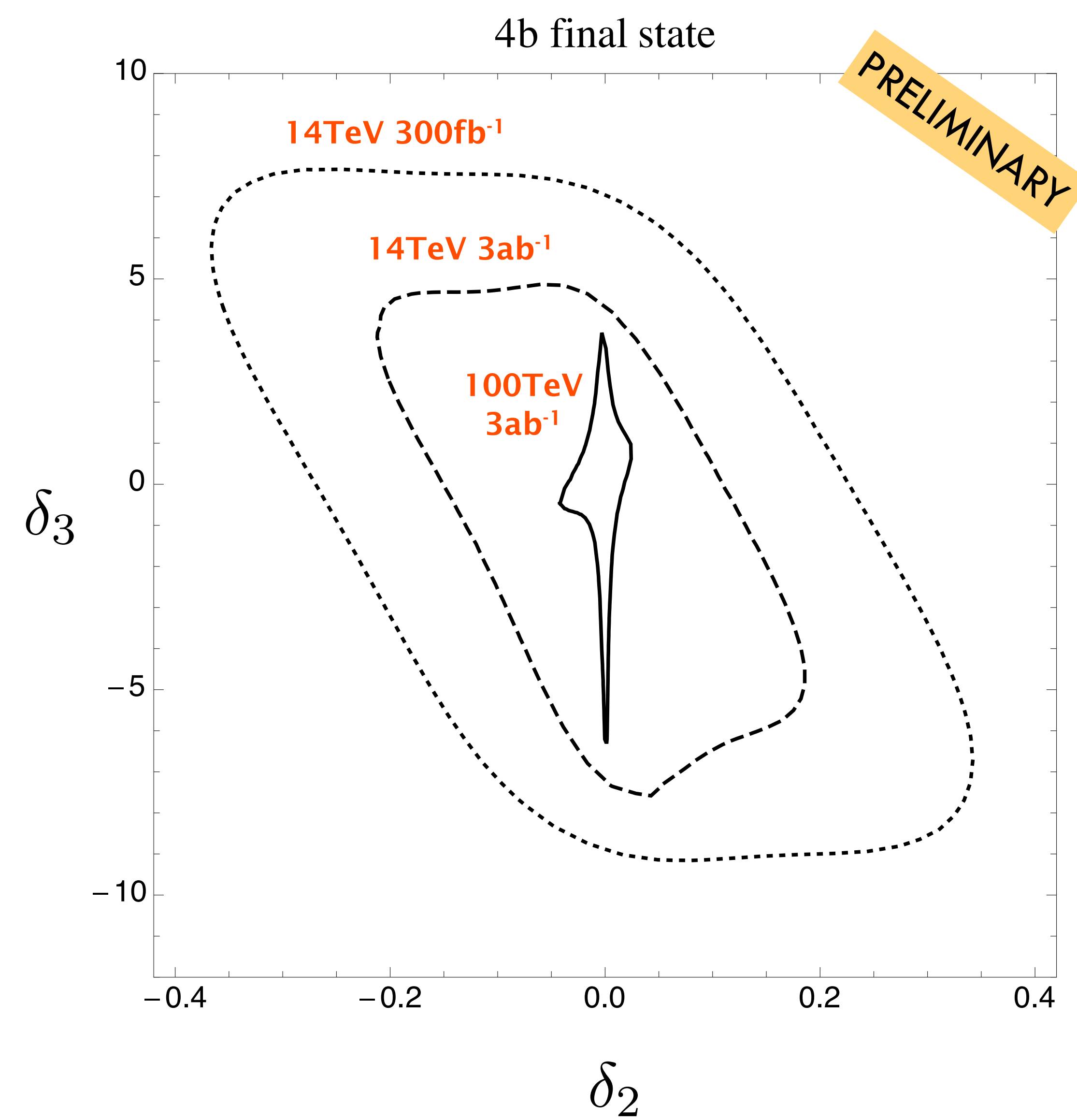
work in progress with O. Bondu, A. Massironi, J. Rojo



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CLIC $e^+e^- \to hh\,\nu\bar{\nu} \to 4b\,\nu\bar{\nu}$

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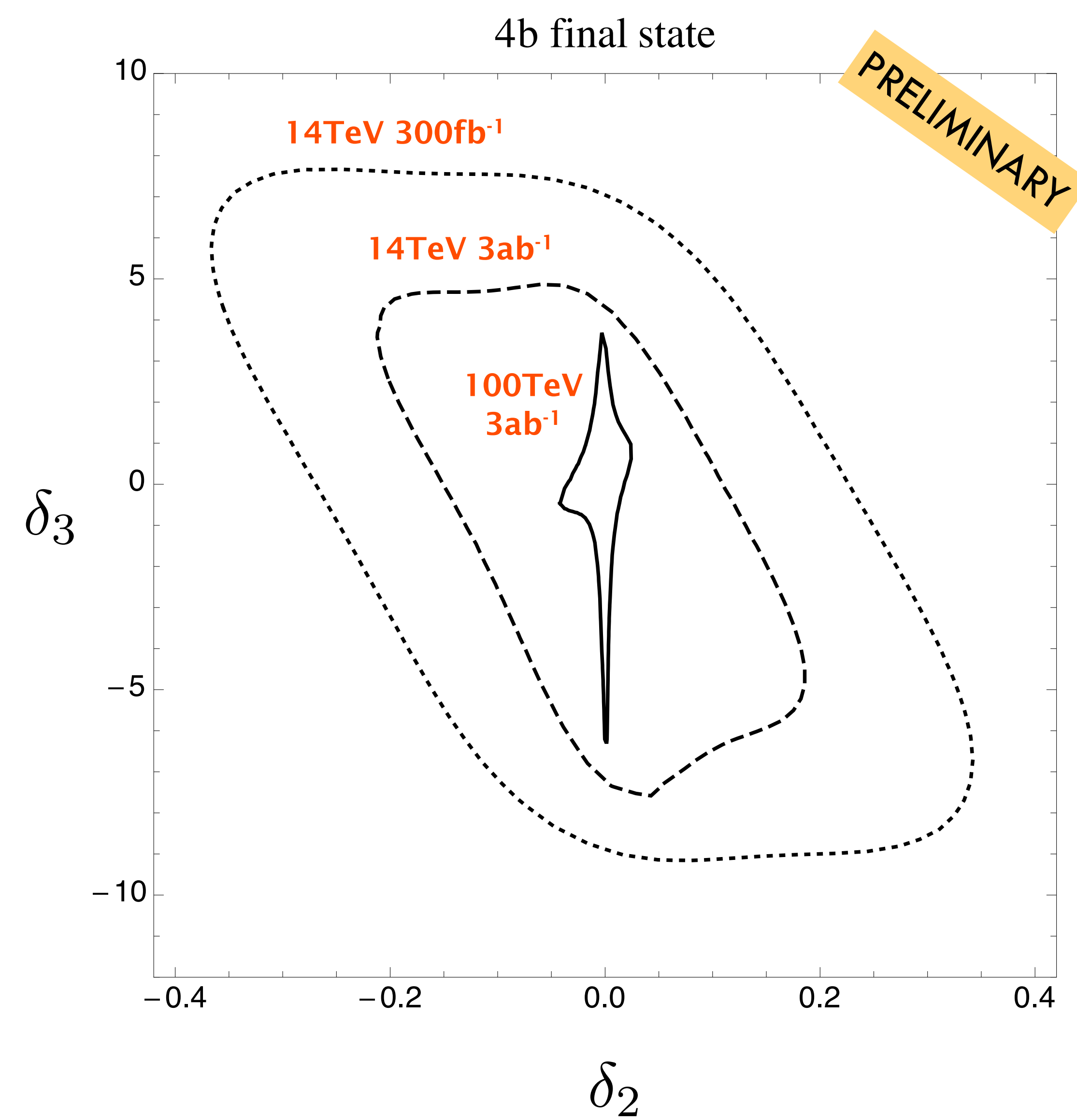
RC, Grojean, Pappadopulo, Rattazzi, Thamm JHEP 1402 (2014) 006



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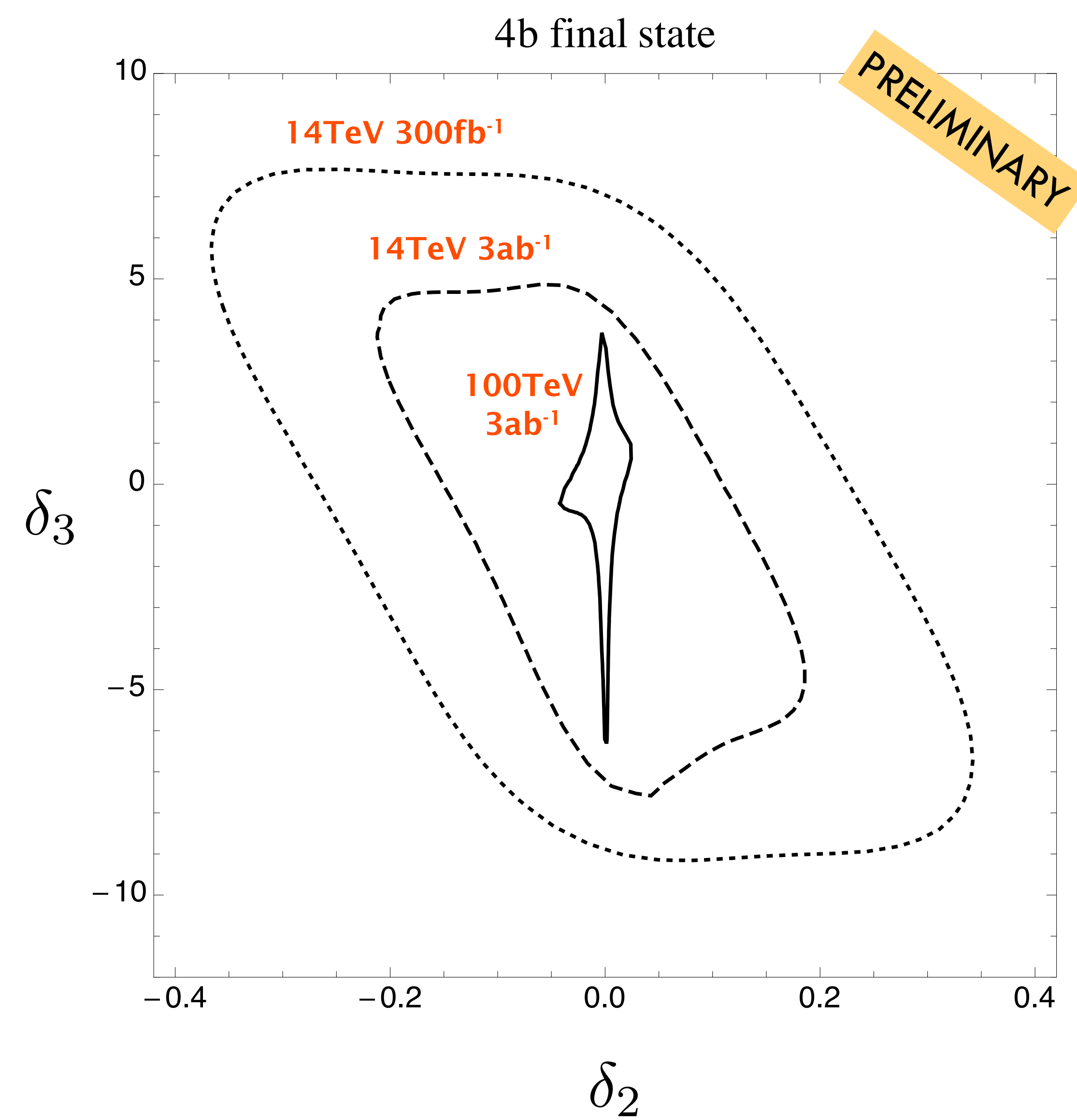

EFT better justified at high-precision machines (such as e+e- colliders)

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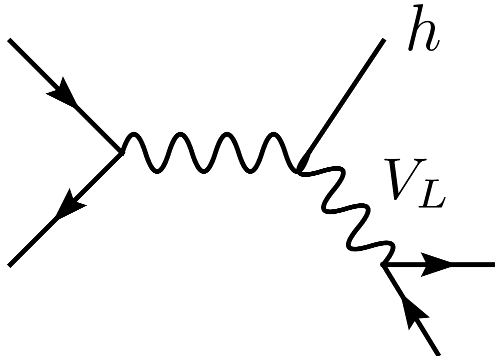
$$A = g^2 + O\left(g^2 \frac{E^2}{m_W^2}\, \bar{c}_{i=HB,(W-B)}\right) + O\left(g^2 \frac{E^2}{m_W^2}\, \bar{c}_{H\psi}\right)$$



$$O_W = \frac{ig}{2m_W^2}\left(H^\dagger \sigma^i \overleftrightarrow{D^\mu} H\right)(D^\nu W_{\mu\nu})^i$$

$$O_B = \frac{ig'}{2m_W^2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right)\partial^\nu B_{\mu\nu}$$

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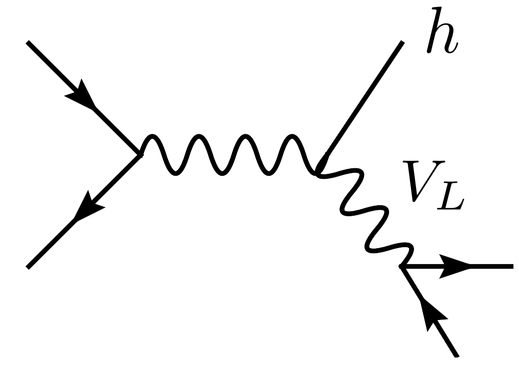

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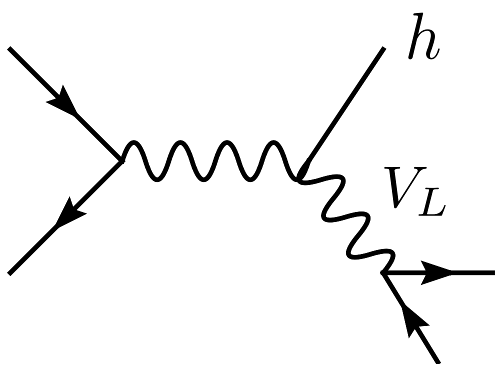
$$= O\left(g^2 \frac{E^2}{m_*^2}\right) \qquad = O\left(\lambda^2 \frac{E^2}{m_*^2}\right)$$



must have

$\delta A / A_{SM} < 1$

for EFT to be valid

Riva et al.
arXiv:1406.7320

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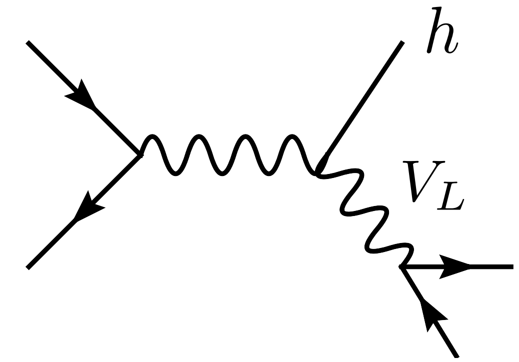

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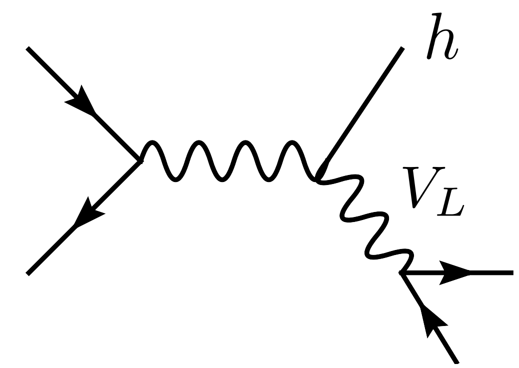

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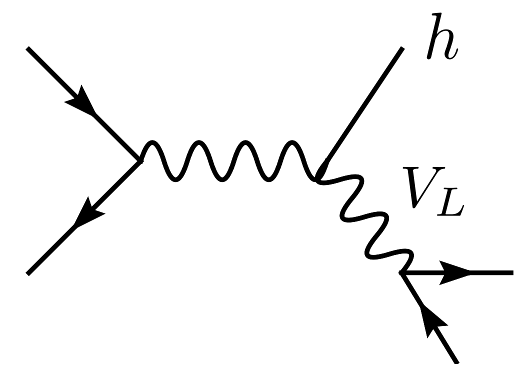

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→ $O_{HB}, (O_W - O_B)$ constrained by TGC

$$O_{H\psi} = \frac{i}{v^2}(\bar{\psi}\gamma^\mu\psi)(H^\dagger \overleftrightarrow{D}_\mu H)$$

→ constrained by Z-pole data at LEP1

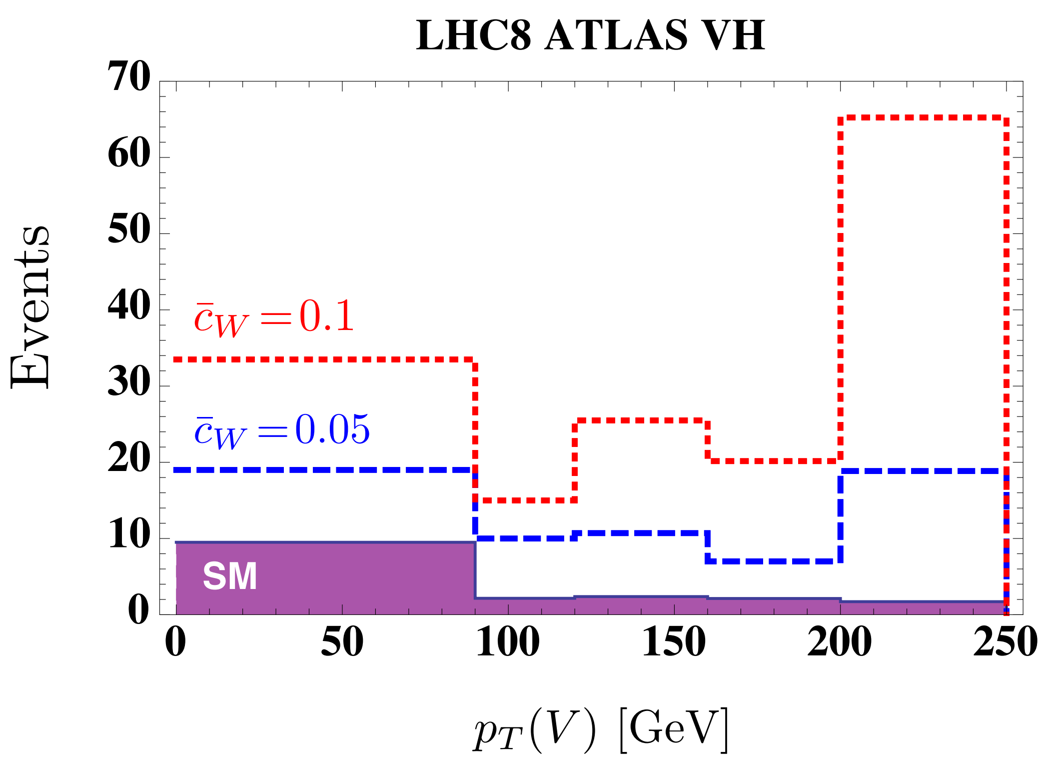
Example #2: Higgs associated production ($q\bar{q} \to V_L h$)

Experimental searches not yet sensitive to SM Higgs signal

ATLAS-CONF-2013-079
CMS PAS-HIG-13-012
D0, PRL 109 (2012) 121802

EFT <u>not</u> valid when setting limits on $\bar{c}_{HB}, (\bar{c}_W - \bar{c}_B)$

Riva et al. arXiv:1406.7320



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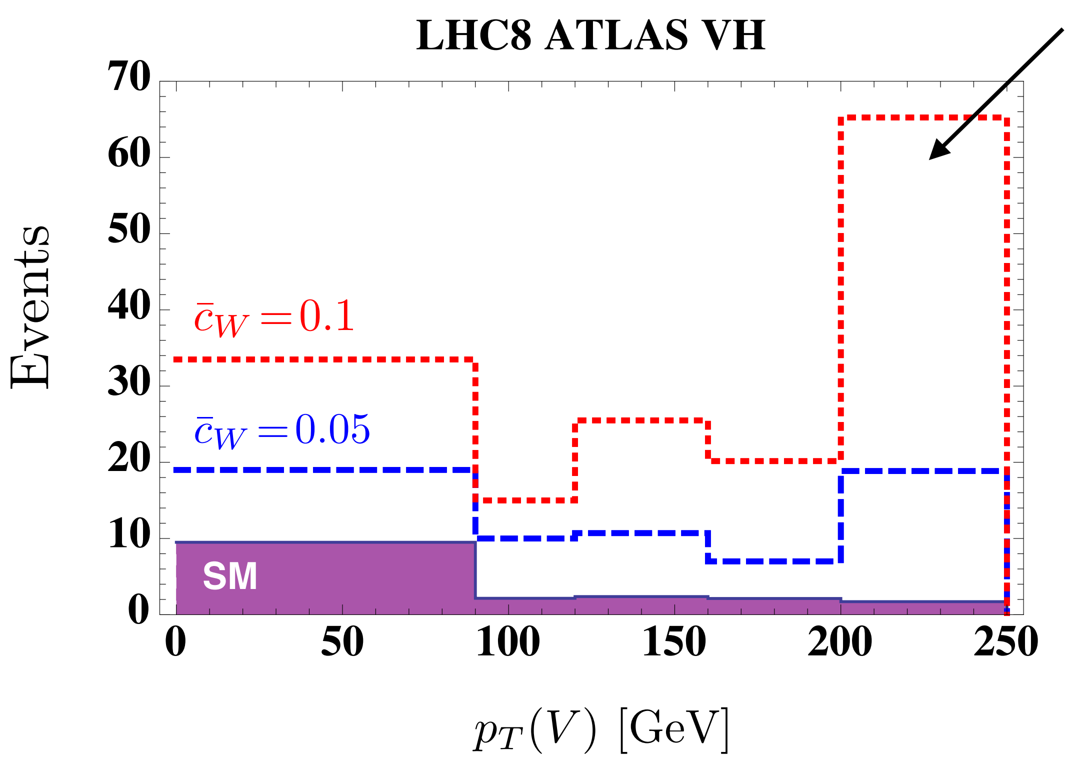
sensitivity comes from last bin where EFT breaks down



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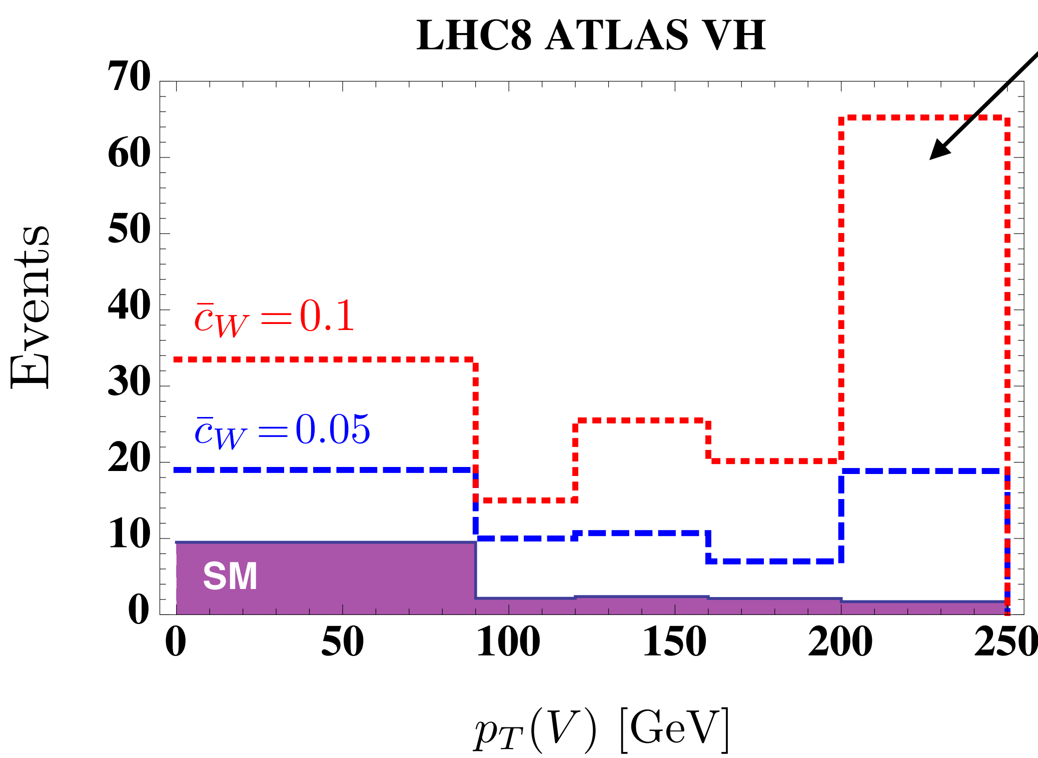
Compare with LEP2 (TGCs):

✓ strongest bounds
✓ EFT valid

EFT not valid when setting limits on $\bar{c}_{HB}, (\bar{c}_W - \bar{c}_B)$

Riva et al. arXiv:1406.7320

sensitivity comes from last bin where EFT breaks down



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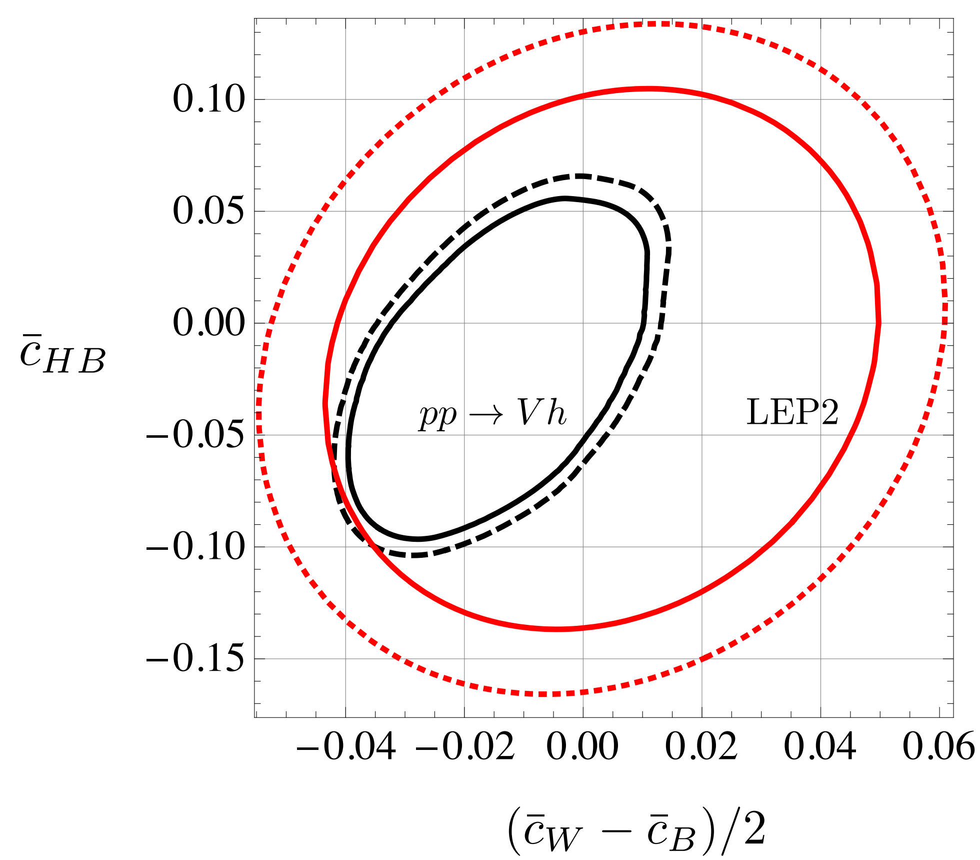
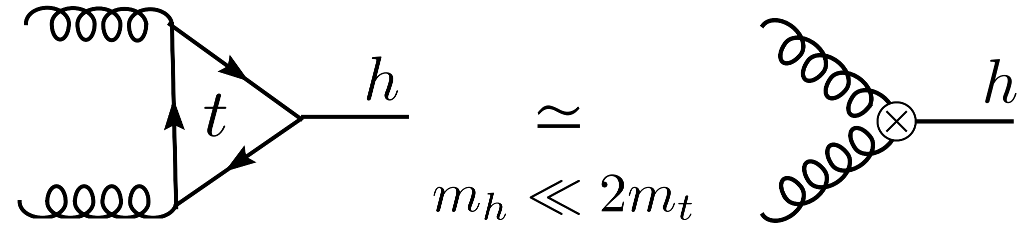


from: Riva et al. arXiv:1406.7320

from: Ellis et al. arXiv:1404.3667

Example #3: Telling the top loop from a point

On-shell single-Higgs cannot distinguish
the top loop from a point-like interaction:



$$A(gg \to h) = A_{SM} \left(1 - \underbrace{\bar{c}_u}_{O(v^2/f^2)} + \underbrace{12 \left(\frac{4\pi}{\alpha_2} \right) \bar{c}_g}_{O\left(\frac{\lambda^2}{y_t^2} \frac{m_t^2}{m_*^2} \right)} \right) + \ldots$$

$$O_u = \frac{y_u}{v^2} H^\dagger H \, \bar{q}_L H^c u_R$$

$$O_g = \frac{g_S^2}{m_W^2} H^\dagger H G^a_{\mu\nu} G^{a\mu\nu}$$

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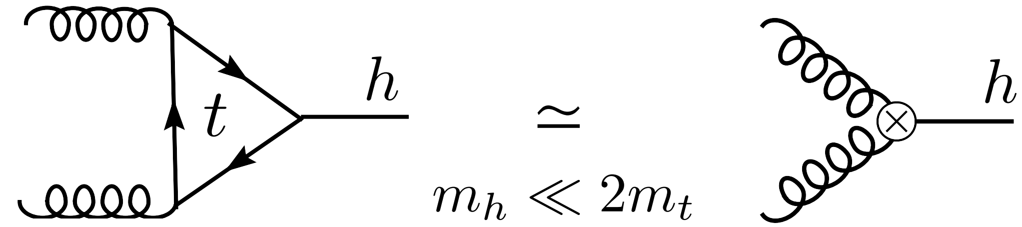

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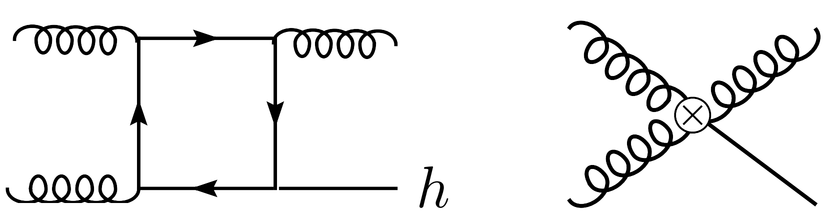
An extra hard jet can probe the top loop and break the degeneracy:

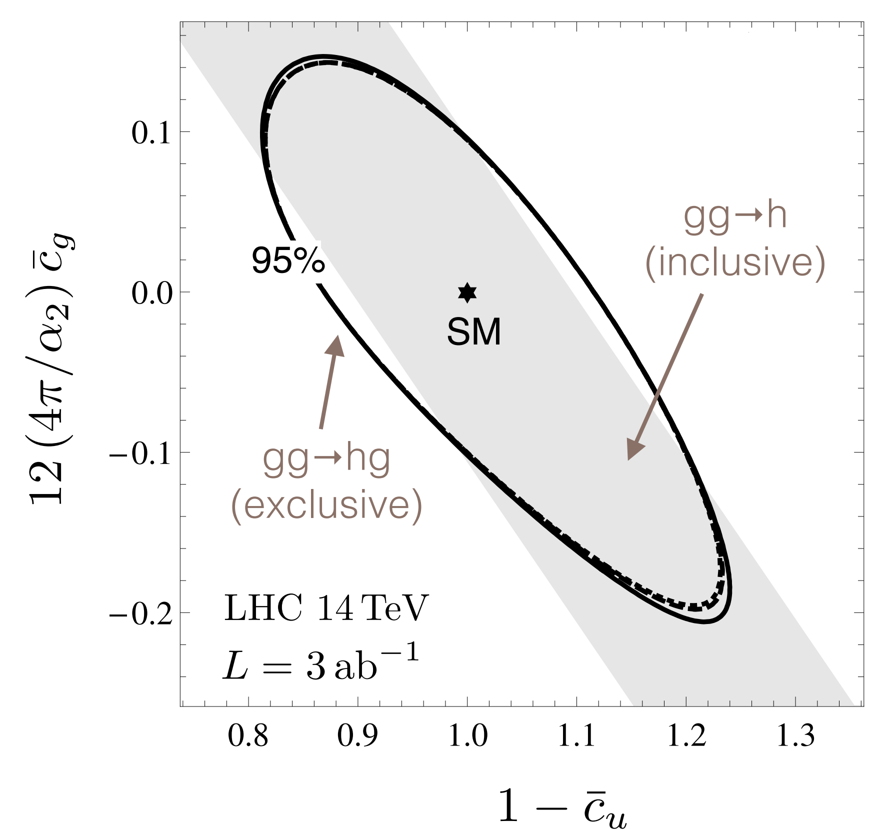
Banfi et al. arXiv:1308.4771
Azatov, Paul arXiv:1309.5273
Grojean et al. arXiv:1312.3317
Schlaffer et al. arXiv:1405.4295



$$A(gg \to gh) = A_{SM}\left(1 - \bar{c}_u + \underbrace{12\left(\frac{4\pi}{\alpha_2}\right)\bar{c}_g \times f\left(\frac{p_T}{m_t}\right)}_{O\left(\frac{\lambda^2}{y_t^2}\frac{E^2}{m_*^2}\right)}\right) + \dots$$

for $p_T \gg m_t$

from Grojean et al. arXiv:1312.3317



Example #3: Telling the top loop from a point

For the effective theory to be valid one needs:

$$12\left(\frac{4\pi}{\alpha_2}\right)\bar{c}_g \times \frac{p_T^2}{m_t^2} \approx \frac{\lambda^2}{y_t^2}\,\frac{E^2}{m_*^2} < \frac{\lambda^2}{y_t^2}$$

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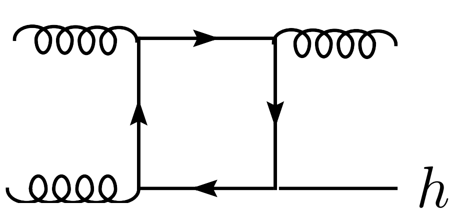

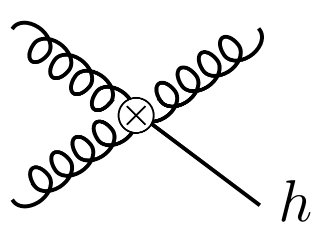

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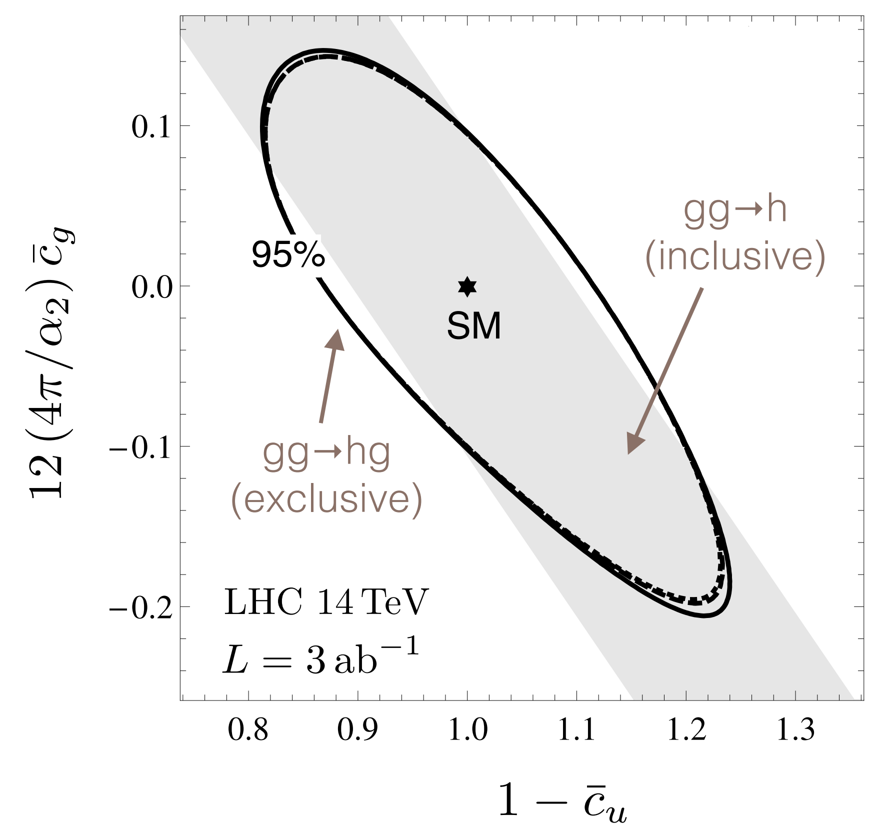

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For a cut $p_T > 650\,\mathrm{GeV}$
(as done in arXiv:1312.3317)

$$3 < \frac{\lambda^2}{y_t^2}$$

$$\boxed{1.7\,y_t \lesssim \lambda < g_* < 4\pi}$$

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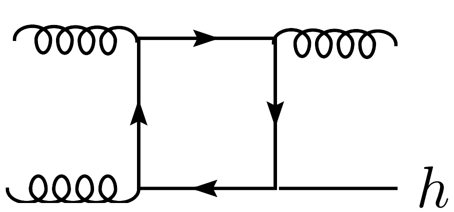

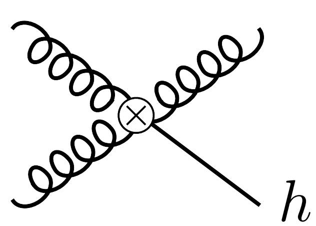

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