# Higgs Physics in the SM and Beyond : 3° lecture

Today:
- . Equiv. Th. and WW scattering
- . higgs and UV completions
- . higgs couplings (matter, gauge, nucleons)
- . higgs ~~Ex~~ as a dilaton

$$\boxed{\text{GB's restore a larger symmetry of the theory}}$$

$$\underset{\substack{\uparrow \\ G\text{-sym}}}{\mathcal{L}_{int}} + \underset{\substack{\uparrow \\ \mathcal{H}\text{-symmetric} \\ \mathcal{H}\subset G}}{\mathcal{L}_{spectrum}} \Longleftrightarrow \underset{\substack{\uparrow \\ G\text{-symmetric with } G/\mathcal{H}}}{\mathcal{L}_{interactions + GB's}}$$

non-linearly realized: $U = e^{i\pi} \to U' = e^{i\pi'} = \underset{\cap\, G}{g}\, U\, \underset{\cap\, \mathcal{H}}{h^{-1}(\pi(x))}$

If the symmetry is local, GB's restore gauge invariance

$$\mathcal{L}_{\text{massive YM}} = -\frac{1}{4}F_{\mu\nu}^{\hat{a}\,2} + \frac{m^2}{2}A_\mu^{\hat{a}\,2} \longrightarrow \mathcal{L}_{\substack{\text{mass-YM} \\ + \\ \text{GB's}}} = -\frac{1}{4}F_{\mu\nu}^2 + \frac{1}{2}\left(\partial_\mu\pi^{\hat{a}} - mA_\mu^{\hat{a}} + \dots\right)^2$$

with $\begin{cases} A_\mu^{\hat{a}} \to A_\mu^{\hat{a}} + \partial_\mu \Omega^{\hat{a}} \\ \pi^{\hat{a}} \to \pi^{\hat{a}} + \Omega^{\hat{a}} \end{cases}$ restored

But why add GB's and pass from $\mathcal{H}$ ~~to~~ to $G \supset \mathcal{H}$ ? This question is particularly urgent for local symmetries where GB's can be gauged away and can't possibly carry new physical info.

↳ Intermediate steps are gauge dependent! Only the final result is gauge independent

It is often very useful to work in gauges where GB's are present. This is the case when looking at the UV behavior of massive YM.

Indeed, for Massive-YM

$$\mathcal{L}_{MYM} = -\frac{1}{4} F_{\mu\nu}^2 + \frac{1}{2}\left[\partial_\mu \pi^{\hat{a}} - m A_\mu^{\hat{a}} + O(\pi^2 \partial_\mu \pi)\right]^2$$

$$\Big\downarrow \; E \gg m$$

neglect $m$ compared to $\partial_\mu = E$

$$\mathcal{L}^{eff} = \underbrace{-\frac{1}{4} F_{\mu\nu}^2}_{\text{2 transverse modes}} + \frac{1}{2}\left[\underbrace{\partial_\mu \pi^{\hat{a}}}_{\text{1 scalar d.o.f.}} + O(\pi^2 \partial \pi)\right]^2 \quad = 3 \text{ d.o.f. in total } \underline{\text{ok}}$$

$\Rightarrow$ at high energy, $E \gg m$, the <u>$\pi$'s describe ~~the~~ the longitudinal modes</u>

This is nothing but the so called <u>Equivalence Theorem</u>


$=$


$$\left(1 + O\left(\frac{m^2}{E^2}\right)\right) \quad i^M$$

$\leftarrow$ accounts for the corrections from $m A_\mu$ to $\partial_\mu \pi$ term

Recap on <u>Polarizations</u> : massive spin-1 has <u>3 polarizations</u>

In the c.o.M. frame $K^\mu_{com} = (m, \vec{0})$ and 3 indep. polarizations are simply $\epsilon^\mu_{(1)} = (0,1,0,0)$, $\epsilon^\mu_{(2)} = (0,0,1,0)$, $\epsilon^\mu_{(3)} = (0,0,0,1)$ which have $\boxed{\epsilon^\mu_{(i)} \epsilon^\mu_{(j)} = -\delta_{ij}}$ and $\boxed{\epsilon^\mu_{(i)} K_\mu^{c.o.m} = 0}$

Now, boosting to a frame where $K^\mu = (E, 0, 0, K)$ the two conditions above are still respected by

$$\epsilon^\mu_{(1)} = (0,1,0,0) \qquad \epsilon^\mu_{(2)} = (0,0,1,0) \qquad \epsilon^\mu_{(3)} = (K, 0, 0, E)\frac{1}{m}$$

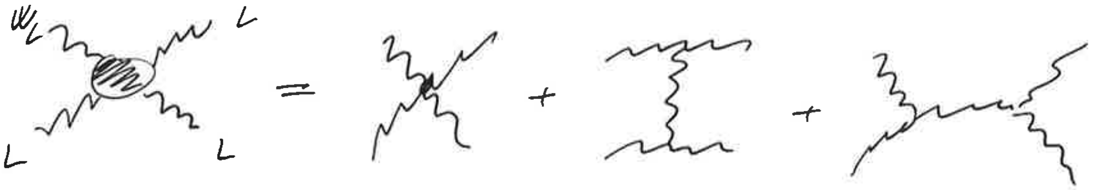
$\epsilon^\mu_{(3)}$ is said <u>longitudinal</u> and $\epsilon^\mu_{(3)} = \epsilon^\mu_L$ ; while the other are <u>transverse</u>

$$\boxed{\epsilon^\mu_L \xrightarrow[E \gg m]{} \frac{k^\mu}{m}}$$

the ~~y~~ longitudinal d.o.f. behaves at high energy like the derivative of a scalar field: $\langle 0 | i \frac{\partial \pi}{m} | \pi \rangle$

$\epsilon^\mu_L$ grow with $E$ and amplitudes with $W_L$ may blow up at some cutoff scale.

How $A(W_L W_L \to W_L W_L)$ behave in $E$?



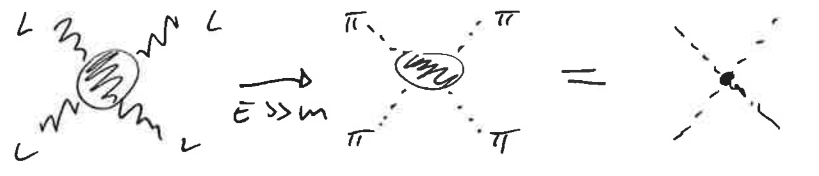
$+ (\ldots) \underset{\text{naively}}{\overset{E \gg m}{=}} g^2 \frac{E^4}{m^4}$

Both coupling and energy dependence are wrong because of an amazing cancellation among several diagrams — wrong!

$$\boxed{A(W_L W_L \to W_L W_L) \underset{E \gg m}{\sim} \frac{g^2 E^2}{m^2} = \frac{E^2}{V^2}}$$

it' $O(E^2)$ and doesn't depend on $g$ at all!

This cancellation and this $E$ and $g$ behavior at $E \gg m$ is way more transparent with the GB's:



$= \frac{E^2}{V^2}$

just one diagram! from $\mathcal{L} = \frac{1}{2}\left(\partial \pi + \frac{[\pi, \pi, \partial\pi]}{V^2} + \ldots\right)^2$

it gives the right $E$ and $g$ dependence.

The gauge coupling does not appear because $g$ is strength of transverse modes interactions. ~~A~~ We are instead scattering $W_L$, that is GB's and their coupling is $\frac{\partial}{v}$ (or ~~g~~ $g\frac{E}{m}$). $\longrightarrow$ Massive YM has a cutoff $\left(\frac{E = \Lambda}{V}\right) \leq 4\pi$

i.e. $\boxed{\Lambda \leq 4\pi V}$ (we could repeat the unitarity argument of 1st lecture)

Fermi theory $\longrightarrow$ Massive YM $\longrightarrow$ ? 

$E \ll m$ $\qquad$ $E \gtrsim m$ $\qquad$ $E \gg m$

what UV completes Massive-YM ?

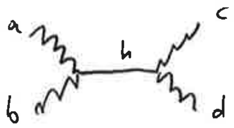
here is where the <u>Higgs Boson $h$</u> becomes important

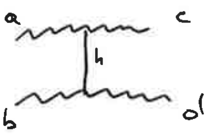
Adding just one extra d.o.f., a <u>scalar</u> $h$, that is <u>sufficiently light</u> and <u>properly coupled</u> provides the <u>simplest UV completion</u>

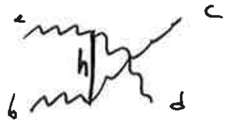
- $h$ must couple to $W_L$, i.e. to $\partial_\mu \pi$

Simplest possibility is to take <u>$h$ = singlet under $SO(3)$-custodial</u>

$$\Rightarrow \boxed{\frac{v^2}{4} Tr[D_\mu \Sigma^\dagger D_\mu \Sigma] \longrightarrow \frac{v^2}{4} Tr[D_\mu \Sigma^\dagger D_\mu \Sigma]\left(1 + 2\frac{a h}{v} + \frac{b h^2}{v^2} + \dots\right)}$$



+


+



$$\frac{a^2}{v^2}\,\frac{\delta^{ab}\delta^{cd}\,4(p_a\cdot p_b)(p^c p^d)}{s-m_h^2}, \quad \delta^{ac}\delta^{bd}\,\frac{4(p_a\cdot p_c)(p_b\cdot p_b)}{t-m_h^2}\,\frac{a^2}{v^2}, \quad \delta^{ad}\delta^{bc}\,\frac{4(p^a\cdot p^d)(p^b\cdot p^c)}{u-m_h^2}\,\frac{a^2}{v^2}$$

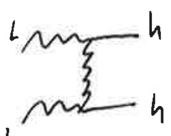
$$\downarrow E \gg m_W \qquad\qquad \downarrow E \gg m \qquad\qquad \downarrow E \gg m_W$$

$$\delta^{ab}\delta^{cd}\,\frac{s^2}{s-m_h^2}\,\frac{a^2}{v^2} \qquad \delta^{ac}\delta^{bd}\,\frac{t^2}{t-m_h^2}\,\frac{a^2}{v^2} \qquad \delta^{ad}\delta^{bc}\,\frac{u^2}{u-m_h^2}\,\frac{a^2}{v^2}$$

$$\Rightarrow \boxed{A(WW \to WW) \simeq \frac{E^2}{v^2}(1-a^2) \quad \text{for } s \gg m_h}$$

For $\boxed{a = 1}$ the amplitude does not grow

What about $A(W_L W_L \to hh)$ ?



+


$\sim \underline{\frac{E^2}{v^2}(a^2-b)}$

$\downarrow$ $E^2\frac{a^2}{v^2}$ $\qquad$ $\downarrow$ $-\frac{E^2 b}{v^2}$

does not grow for $\boxed{a^2 = b}$

These conditions, $a = 1$ and $a^2 = b$ are indeed satisfied by the Higgs Boson of the SM

$$H = e^{i\pi}\begin{pmatrix} 0 \\ \frac{v+h}{\sqrt{2}} \end{pmatrix} \longrightarrow \quad \underline{v \longrightarrow v + h = v\left(1+\frac{h}{v}\right)}$$

$$\mathrm{Tr}\left(D_\mu \Sigma^\dagger D_\mu \Sigma\right)\frac{v^2}{4} \longrightarrow \left(1+\frac{v}{h}\right)^2 v^2\, \mathrm{Tr}\left[D_\mu \Sigma^\dagger D_\mu \Sigma\right]$$

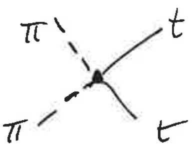
$$\hookrightarrow \underline{a = b = 1} \quad \underline{c = d = \ldots = 0}$$

The Higgs Boson provides a (the simplest) UV completion of massive YM such that $\boxed{3\,\pi\text{'s} + 1\,h}$ fit a linear realization of $\mathcal{G}$ at $E \gg m_W$. In other words, the non-linear sigma-model for $\Sigma$ has been extended to included a Higgs making it a linear sigma model. Remember that $\langle |H|^2 \rangle = \frac{(v+h)^2}{2}$.

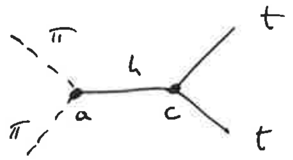
$3\pi + 1h = 1\,H$ doublet of $SU(2)_L \times U(1)_Y$

Analogous discussion hold for the coupling to matter fields

$$v\, \bar{Q}_L \Sigma \begin{pmatrix} y_t t_R \\ y_b b_R \end{pmatrix} \Longrightarrow$$




$+$




$$= \frac{m_t E}{v^2}(1 - ac)$$

$$\downarrow$$

$$v\left(1+\frac{c\,h}{v}\right)\bar{Q}_L \Sigma \begin{pmatrix} y_t t_R \\ y_b b_R \end{pmatrix} \qquad \frac{m_t E}{v^2} \qquad -\frac{m_t E}{v^2}(a \cdot c)$$

again $\underline{a = b = c\ 1}$ is the $\underline{\text{SM}}$ because $v \longrightarrow v + h = v\left(1+\frac{h}{v}\right)$ gives all Higgs couplings.

Of course, other UV-completions are possibles:

$W$'s are 3 of $SO_c(3)$: $\quad 3 \otimes 3 = \underset{\substack{\text{singlet}\\ I=0}}{1} \oplus \underset{\substack{\text{triplet}\\ I=1}}{3} \oplus \underset{\substack{\text{5-plet or weak isospin}\\ I=2}}{5}$

- $h$ is a custodial singlet $h = 1$

$$\boxed{\partial\pi^i \partial\pi^j \delta_{ij} \frac{h}{v} a}$$

I can certainly have more singlets $H = 1 \to \boxed{\partial\pi^i \partial\pi^j \delta_{ij} \frac{H}{v} b}$

$$(h \text{ exchange}) + (H \text{ exchange}) + (\text{crossing}) \underset{s \gg m_h^2, m_H^2}{=} \frac{s}{v^2}(1 - a^2 - b^2)$$

$\Rightarrow$ if $\underline{a^2 + b^2 = 1}$ the theory is also well behaved in the UV.

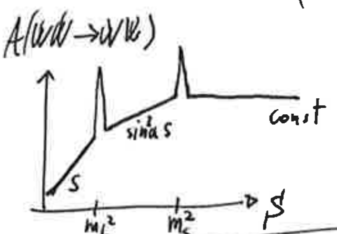
This automatically arise in weakly coupled model with more scalars.

Ex: extra singlet $m H^2 S$ $\xrightarrow{\text{after EWSB}}$ $\underline{m v h S}$ is a mass mixing term

$$\Rightarrow \begin{pmatrix} h \\ S \end{pmatrix} = \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} h^{ph} \\ S^{ph} \end{pmatrix}$$

and from $\frac{h}{v}\left(m_W^2 |W|^2 + \frac{m_Z^2 Z^2}{2}\right) \longrightarrow \left(\frac{h^{ph}}{v}\cos\alpha + \frac{S^{ph}}{v}\sin\alpha\right)\left(m_W^2|W|^2 + \frac{m_Z^2 Z_\mu^2}{2}\right)$

$|W|^2 \to (\partial\pi - m_W W)^2$, $\quad Z^2 \to (\partial\pi^0 - m_Z Z)^2$



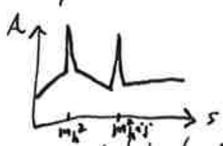

$$\Rightarrow \boxed{\begin{aligned} &a = \cos\alpha, \quad b = \sin\alpha \\ &a^2 + b^2 = 1 \end{aligned}}$$

- The 5 of $SO(3)$ is a symmetric traceless rep.

$\Rightarrow$ a scalar $h^{ab} = 5$ with $h^{aa} = 0$ can couple to $\partial\pi^a \partial\pi^b$ and enter the unitarization

$$\Rightarrow \partial\pi^i \partial\pi^j \left(a\delta^{ij}\frac{h}{v} + b\frac{h^{ij}}{v}\right) \Rightarrow (h \text{ exchange}) + (h^{ij} \text{ exchange}) + \text{crossing}$$

$$= \frac{s}{v^2}\left(1 - a^2 + \frac{5}{6}b^2\right)$$




This example shows that with $I = 2$ states $a > 1$ is allowed ~~...~~ in a UV completed Theory as long as $\boxed{a^2 - 5/6\, b^2 = 1}$ $\leftarrow$ Ex: Georgi-Machacek model has indeed $b = (1 - a^2)\frac{6}{5}$ with $a = \sqrt{8/3}$

• What about 3-plets $3 \in SO(3)$?

$3 \in SO(3)$ in $3 \otimes 3 = 1 \oplus 3 \oplus 5$
is anti-symmetric, $\epsilon^{ijk}\phi^k$ $\Rightarrow$ $\boxed{\partial_\mu \pi^i \partial_\mu \pi^j \epsilon^{ijk}\phi^k = 0 \text{ By Bose-sym.}}$

But for a spin-1 vector $\rho_\mu^k$, rather than a scalar $\phi^k$,
I'm able to write down a relevant coupling, namely

$$\left(\rho_\mu^k \, \epsilon^{kij} \partial_\mu \pi^i \pi^j\right) \cdot \left(\frac{m_\rho^2}{g_\rho v^2}\right)$$

growth is $s$ by the Longitudinal d.o.f.'s of $\rho_\mu$

$$= \frac{s}{v^2}\left[1 - \#\left(\frac{m_\rho^2}{g_\rho^2 v^2}\right) - a^2\right]$$

(# I think is 3/4 or so)
In extra D the sum of all KK modes kill $\sim s$ behavior

This may cure the $W_L W_L \to W_L W_L$ scattering but the theory wouldn't be unitary as it is since $\rho_L^\mu \rho_L^\mu \to \rho_L^\mu \rho_L^\mu$ also grows with $E^2$ (being a massive spin-1)

$\Rightarrow$ One can either Higgs-like states for the $\rho_\mu$ (making the theory weakly coupled)

or in fact, keep adding resonances of spin-1 ...

$\to$ $\boxed{\text{the theory is thus strongly coupled}}$ it gives tower or resonances

Notice that CCWZ automatically includes $\rho \cdot [\pi, \partial\pi]$ vertex

$$\begin{cases} \rho_\mu \to h \rho_\mu h^\dagger - i h \partial_\mu h^\dagger \\ E_\mu(\pi) \to h E_\mu h^\dagger - i h \partial_\mu h^\dagger \end{cases} \Rightarrow \boxed{\frac{\rho_{\mu\nu}^2}{4 g_\rho^2} + \frac{m_\rho^2 \mathrm{Tr}(\rho_\mu - E_\mu(\pi))^2}{2 g_\rho^2}}$$

where $E_\mu^k(\pi) \supset \frac{[\pi, \partial_\mu \pi]^k}{v^2} = \frac{\pi^i \partial_\mu \pi^j \epsilon^{ijk}}{v^2}$. We took $\rho_\mu$ has a gauge field since we want it below the cutoff (that is a good massless limit)

The mass-product gives: after normalizing $\rho_\mu$ $\boxed{\rho_\mu^k \epsilon^k \pi^i \partial_\mu \pi^j \epsilon^{ijk} \left(\frac{m_\rho^2}{g_\rho v^2}\right)}$

Let's come back to the $\boxed{\text{Higgs Couplings:}}$

- Higgs couples to masses: $\boxed{\left(m_W^2 |W_\mu|^2 + \frac{m_Z^2}{2} Z_\mu^2\right)\frac{h}{v}\, a + m_f \bar{f}_L f_R \frac{h}{v}\, c}$

with $a = c = 1$ in the SM

- The Higgs boson decays to the heaviest particle pair kinematically allowed

for $m_h \simeq 125$ GeV $\quad h \to b\bar{b}$ is the leading channel

(followed by $h \to W^* W$, $h \to \tau\tau$, $h \to gg, \dots$)

notice that $h \to b\bar{b}$ is controlled by $\boxed{y_b = \frac{m_b}{v}\sqrt{2} \simeq \frac{1}{40} \ll 1}$

$\Rightarrow$ any new particle pair the Higgs can decay into can significantly affect the BR, even for couplings $\sim 0.1$

- The Higgs width is thus very small: $\Gamma \lesssim 10^{-(4\div 5)} m_h$

$$\Gamma_{\text{estimate}} = \cancel{N_c\, y_b^2\, 2\pi}\; \underbrace{\underset{\uparrow\ \text{multeplicity}}{N_c}\ \underset{\uparrow\ \text{coupling}}{y_b^2}\ \underset{\uparrow\ \text{phase space}}{\frac{2\pi}{(4\pi)^2}}\ m_h} = \frac{N_c\, m_b^2\, m_h}{8\pi v^2}$$

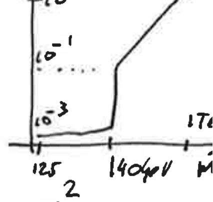
(just a factor of 4 off)

$m_h$: Higgs mass by Dim. analysis ($m_h \gg m_b$)

$\Gamma$ is thus a very good observable to look for new physics

e.g. $h \to$ invisible, even with $y \sim 0.1$ would be important

- For heavier higgs-like states the width isn't small




$h \to WW$ on-shell $\quad$ via Eq. Th. $\quad (\partial\pi)^2 \frac{h}{v} \Rightarrow$ coupling is $\frac{m_h^2}{v}$

$m_h \gg m_W$

Boost from longitudinal d.o.f.'s $\Rightarrow \Gamma_{h\to WW} \sim \left(\frac{m_h^2}{v}\right)^2 \frac{2\pi}{16\pi^2} \frac{1}{m_h} \sim \frac{m_h^3}{v^2}$ grows with $m_h^3$

Why does the Higgs Boson couple to masses ?

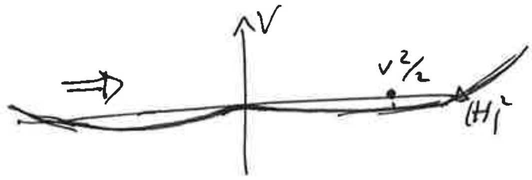
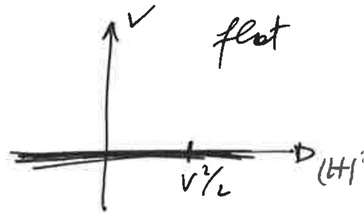
and how does it couple to $\gamma$ and gluons ?

• Let's take a look at the Higgs potential $V=\lambda\left(H^2-\frac{v^2}{2}\right)^2$

The famous mexican-hat potential

← mass$^2$ = $V''$(at minimum) $= \boxed{m_h^2 = 2\lambda v^2}$ $\Rightarrow \lambda = \frac{m_h^2}{2v^2} \simeq 0.13$

$\lambda$ is small, perturbative (smaller the electric charge)

$\Rightarrow$  very shallow potential $\approx$  flat

• The theory is well approximated by a $\boxed{\text{flat potential}}$ with a shift symmetry $h \to h + \text{const}$ broken spontaneously by the vev at its actual value when $\lambda$ is taken finite.

• This theory ~~…~~ has no mass dimension (except for $\Lambda_{QCD}$, see later) in the limit $\boxed{\lambda \to 0^+ \Rightarrow \langle H \rangle = v/\sqrt{2}}$ breaks also scale invariance spontaneously

• ~~…~~ Scale transf:

$$\begin{cases} x \to x' = e^{-\epsilon} x = (1-\epsilon)x + O(\epsilon^2) \\ \phi(x) \to \phi'(x') = e^{-\Delta\epsilon}\phi(e^{-\epsilon}x) \\ f_{L,R}(x) \to f'_{L,R}(x') = e^{-\Delta_{L,R}\epsilon} f_{L,R}(e^{-\epsilon x}) \end{cases}$$

$$S = \int \phi^4(x)\, d^4x \xrightarrow[\text{scale}]{} \int \phi^4(e^{-\epsilon}x)\, e^{-4\Delta\epsilon} d^4x = \int \phi^4(x')\, d^4x' \quad \text{for } \Delta = 1$$

~~Now, a higgs vev break scale transformations~~ ~~$v \to v e^{-\epsilon} = v(1-\epsilon) + \ldots$~~ ~~scale the vev~~

~~but since there is a flat direction the combined transformation~~

~~$h(x) \to \underbrace{e^{\epsilon} h(e^{-\epsilon x})}_{\text{scale tr.}} + \underbrace{\epsilon v}_{\text{shift sym.}}$~~ ~~leaves the vacuum invariant~~

Now, the Higgs vev break spontaneously scale transformations

$\langle H \rangle = \frac{v}{\sqrt{2}} \xrightarrow[\text{scale}]{} \frac{v}{\sqrt{2}} e^{-\epsilon}$ $\epsilon$ is the param. of scale tr.

just restore it by promoting $\epsilon$ to a field $\boxed{\epsilon \to -\frac{h}{v}}$
as usual for GB's

$$\frac{v}{\sqrt{2}} \longrightarrow \frac{v}{\sqrt{2}} e^{h/v} \simeq \frac{v+h}{\sqrt{2}} + \dots$$

usual replacement $\Rightarrow$ same coupling at linear level in h

scale transformation restored by:

$$\begin{cases} v \longrightarrow v e^{-\epsilon} \\ h \longrightarrow h(e^{-\epsilon} x) + v\epsilon \end{cases}$$

shifts non linearly

also spacetime changes because it's a space time sym.

$\Rightarrow$ The Higgs is the GB of scale transformation in the limit $\lambda \to 0^+$. Finite value of $\lambda$ give a potential and a mass

- Higgs is a weakly-coupled (fine-tuned) dilaton

- As all GB's couple to the matter current via the Goldberger-Treiman relation, $-\frac{\partial_\mu h}{v} D^\mu = +\frac{h}{v}\partial_\mu D^\mu$ dilation current

But $\partial_\mu D^\mu = T^\mu_\mu = \Sigma\, m_f \bar{f} f + 2m_W^2 \frac{(W)^2}{2} + \dots$
trace of energy momentum-tensor

Alternatively: $D^\mu_{conserv} = -v\,\partial_\mu h + D^\mu$ $\quad \partial_\mu D^\mu = 0 \Leftrightarrow \Box h = \frac{\partial_\mu D^\mu}{v}$

But from eq. of motion $\Box h = -V' = \Sigma$ masses

$m \propto v \underset{\text{add } h}{\Rightarrow} m\, e^{h/v} = m(1+\frac{h}{v}) \Rightarrow V' = m/v$ $\qquad m^2 \propto v^2 \longrightarrow m^2 e^{2h/v} = m^2(1+\frac{2h}{v})$

fermions $\qquad$ bosons $\qquad$ OK

$\Longrightarrow$ The Higgs boson couples to masses because it's the GB of scale invariance which is a good classical approximate symmetry broken spont.

- What about quantum effect? Loops?

- scale invariance is indeed broken by quantum effect, it's anomalous: trace anomaly $T^{\mu}_{\mu} = \partial_\mu D^\mu = \beta(g)\dfrac{\partial \mathcal{L}}{\partial g}$

$$= \frac{\beta(g)}{2g^3} F_{\mu\nu}^2$$

$\uparrow$ for $\mathcal{L} = -\frac{1}{4g^2}F_{\mu\nu}$

The Higgs will not couple to all of it $\longrightarrow$ but only to that part that arise from spont. break. (see below)

$\Longrightarrow \frac{h}{v}\partial_\mu D^\mu$ contain also a $\frac{h}{v}F_{\mu\nu}^2\beta$ term

Looking closer:
$$\frac{1}{g^2(\mu)} = \frac{1}{g^2(\Lambda_{UV})} - \frac{b^{UV}}{8\pi^2}\log\left(\frac{\Lambda_{UV}}{\mu}\right)^2 + \frac{b^{heavy}}{8\pi^2}\log\left(\frac{\Lambda_{UV}}{M_{heavy}}\right)^2$$

$UV \rightarrow$ all states

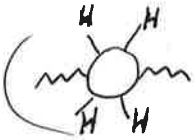
where $\boxed{\beta = \frac{-bg^3}{8\pi^2}}$

this one is from explicit breaking

this term is generated spontaneously

but if $M_{heavy} \propto v \Longrightarrow M_{heavy} \rightarrow M_{heavy}\, e^{h/v}$

$$\Longrightarrow \boxed{-\frac{1}{4g^2(\mu)}F_{\mu\nu}^2 \longrightarrow -\frac{F_{\mu\nu}^2}{4g^2(\mu)} + \frac{b^{heavy}}{16\pi^2}F_{\mu\nu}^2\frac{h}{v}}$$

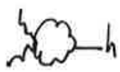


(loop in Higgs background)

Higgs coupling to massless gauge bosons: $\boxed{\frac{\beta^{heavy}}{2g^2}F_{\mu\nu}^2\frac{h}{v}}$ canonically normalized

heavy is w.r.t. momentum in the  $\Longrightarrow \boxed{M_{heavy} \text{ means} > \frac{m_h}{2}}$

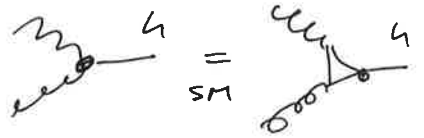
$\Longrightarrow$ h gluons only top contributions 

h photons top and W's  +  + 

(W contribution dominates $\frac{\Gamma}{\Gamma_{SM}} \simeq \left(1 + \frac{9}{7}(a-1) - \frac{2}{7}(c-1)\right)^2$)

Coupling to gluon fix the main production channel

Gluon fusion (GF)




$\leftarrow$ sensitive to $y_t$

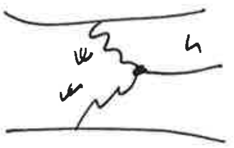
new physics can hide in the loop

for example, for a non standard Higgs with $\frac{h}{v} m_t \bar{t}_L t_R \longrightarrow c \frac{h}{v} m_t \bar{t}_L t_R$

$\sigma^{\text{production}}_{gg\to h} \longrightarrow c^2 \sigma^{\text{prod}}_{gg\to h}\big|_{SM}$ ($\sim 20\,pb$ for $7\,TeV$, $m_h \sim 125\,GeV$)

It's actually very important that we measure also

VBF




$\leftarrow$ ~~any~~ small but measured ($\sim \frac{1}{10}$ GF)

(becomes much more important at higher invariant masses because of the longitudinal boost)

sensitive to "a": $\frac{a h}{v} |W_\mu|^2$

Higgs coupling to photon: $BR(h \longrightarrow \gamma\gamma) \simeq$ few $\cdot 10^{-3}$

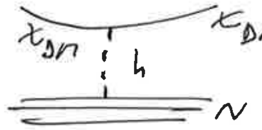
but it ~~[illegible]~~ has good mass resolution.

physics may hide here too

---

Higgs coupling to Nucleons

motivation: DM and Higgs portal: $\underline{H^2 \phi^2_{DM}}$




for direct detection!

what's the Higgs coupling to N? $\bar{N} N \frac{h}{v} m_N$? almost!

Anomaly matching:

$$\boxed{T^\mu_\mu = \underbrace{\frac{\beta^H}{2g} G^2_{\mu\nu}}_{\text{heavy q.+gluons}} + \underbrace{m_\ell \bar{q}_\ell q_\ell}_{\text{light q.}} = m_N \bar{N} N}$$

with $\beta \propto -(\underset{\substack{\uparrow\\ \text{gluons+heavy q.}}}{11} - \frac{2}{3} n_\ell)$ $\leftarrow$ light quarks

$\frac{h}{v} G^2_{\mu\nu} \frac{\beta^{\text{heavy}}}{2}$ $\Longrightarrow$ $\langle N | \frac{h}{v} G^2_{\mu\nu} \frac{\beta^{\text{heavy}}}{2} | N \rangle = m_N \langle N | \bar{N} N \frac{h}{v} | N \rangle \left(\frac{\beta^{\text{heavy}}}{\beta^H}\right)$

$\downarrow$ it picks just $2/3$

$= \left(\frac{2}{3} \Big/ 11 - 2\right) m_N \bar{N} N \frac{h}{v} = \left(\frac{2}{27}\right) m_N \bar{N} N \frac{h}{v}$