The Higgs mechanism

$$\mathcal{L}_{SM} = \mathcal{L}_{YM} + \mathcal{L}_{Fermions} + \mathcal{L}_{Higgs} + \mathcal{L}_{Yukawa}$$

$\mathcal{L}_{YM}$ = pure YM

$\mathcal{L}_{Fermions}$ = kinetic terms for Fermions

Problem: * YM fields are massless
⇝ we observed massive Z and W
* Gauge symmetry forbids mass term for fermions

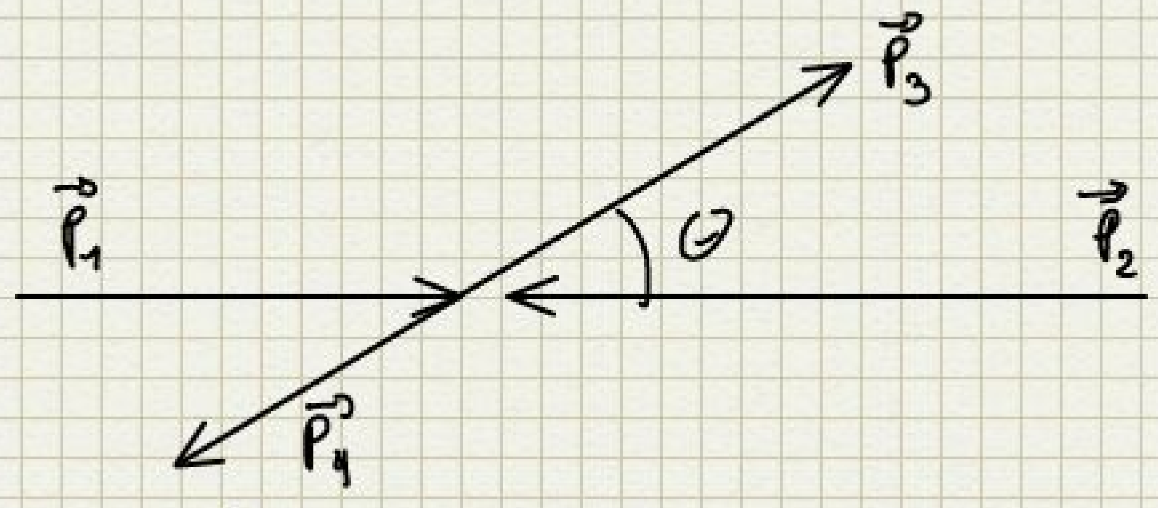
If we add mass term for W and Z "by hand" (= NLSM), then the theory violates unitarity.

<u>Example</u> $W_L W_L \to W_L W_L$

Can go to CoM frame of 1 and 2

$p_1 = (E, 0, 0, p)$ $\quad\quad$ $p_2\ (E, 0, 0, -p)$

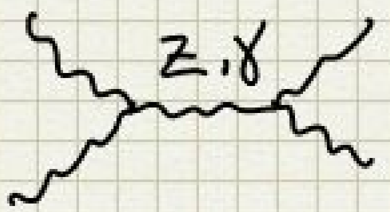
$p_3 = (E, 0, p\sin\theta, p\cos\theta)$ $\quad\quad$ $p_4\ (E, 0, -p\sin\theta, -p\cos\theta)$



$\varepsilon_L(p_1) = \frac{1}{M_W}(p, 0, 0, E)$ $\quad\quad$ $\varepsilon_L(p_2) = \frac{1}{M_W}(p, 0, 0, -E)$

$\varepsilon_L(p_3) = \frac{1}{M_W}(p, 0, E\sin\theta, E\cos\theta)$ $\quad$ $\varepsilon_L(p_4) = \frac{1}{M_W}(p, -E\sin\theta, E\cos$

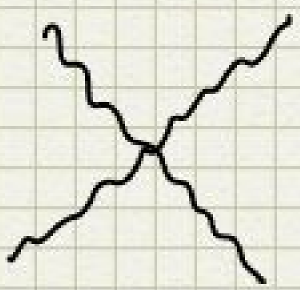
Contribution from 3-vertices :



$+ \dots$

$$\mathcal{M}_3 = g_w^2 \left\{ \frac{p^4}{M_W^4} \left(3 - 6\cos\theta - \cos^2\theta\right) + \frac{p^2}{M_W^2} \left(\frac{3}{2} - \frac{11}{2}\cos\theta - 2\cos^2\theta\right) \right]$$

Contribution from 4-vertex :



$$\mathcal{M}_4 = g_w^2 \left\{ - \frac{p^4}{M_W^4} \left(3 - 6\cos\theta - \cos^2\theta \right) + \frac{p^2}{M_W^2} \left(-4 + 6\cos\theta + 2\cos^2\theta \right) \right\}$$

$$\mathcal{M}_3 + \mathcal{M}_4 = 0 \cdot \frac{p^4}{M_W^2} + \frac{p^2}{2M_W^2} g_w^2 \left(1 + \cos\theta\right)$$

But $p^2 = E^2 - M_W^2 = \dfrac{s - 2M_W^2}{2M_W^2}$

$\rightsquigarrow$ Amplitudes grows with energy.

$\rightsquigarrow$ violates unitarity

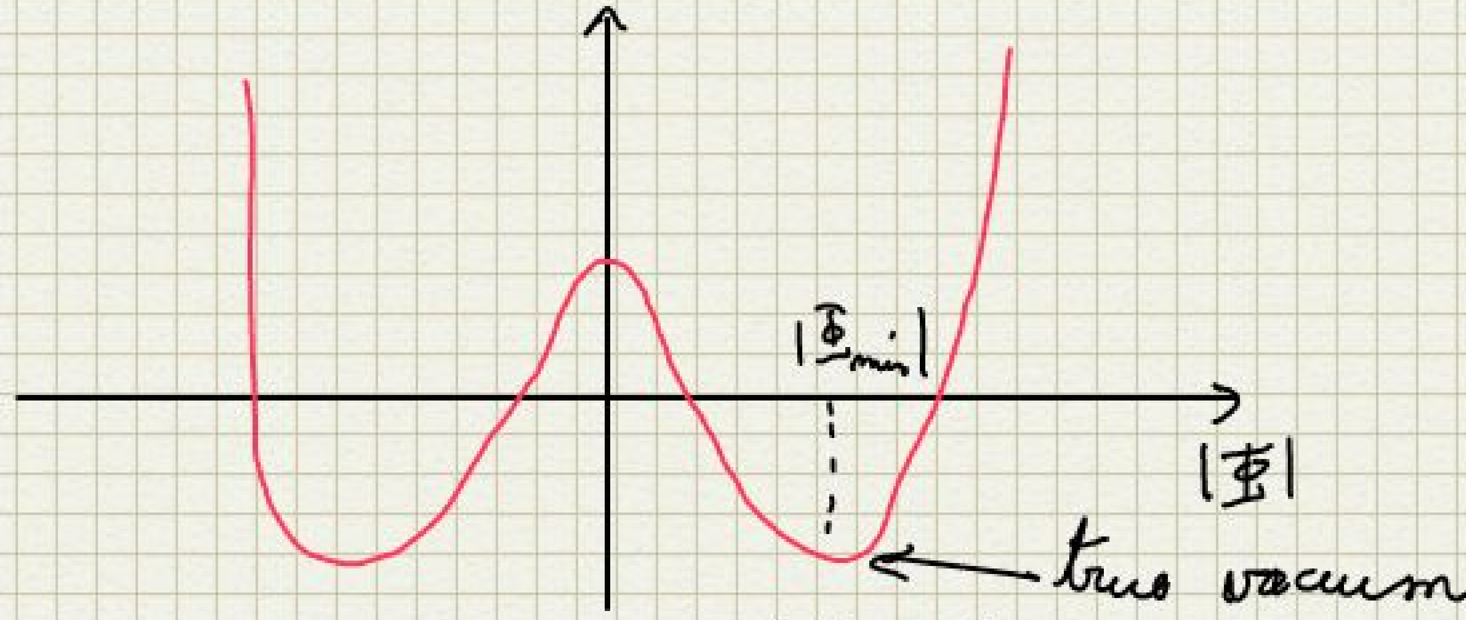
$$\mathcal{L}_{\text{Higgs}} = D_\mu \Phi^\dagger D^\mu \Phi - V(\Phi^\dagger \Phi) \qquad \Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$$

$$Y = 1/2$$

$$V(\Phi^\dagger\Phi) = -\mu^2 \Phi^\dagger\Phi + \frac{\lambda}{4}\left(\Phi^\dagger\Phi\right)^2 \quad , \lambda, \mu^2 > 0$$

$\rightsquigarrow$ Minimum of potential is not at $\Phi = 0$!

$$|\Phi_{min}| = \sqrt{\frac{2\mu^2}{\lambda}} \equiv \frac{v}{\sqrt{2}} > 0$$



We expand around the "true" vacuum

$$\Phi(x) = \underbrace{e^{-i\,T^a\theta^a(x)}}\begin{pmatrix} 0 \\ \frac{H+v}{\sqrt{2}} \end{pmatrix}$$

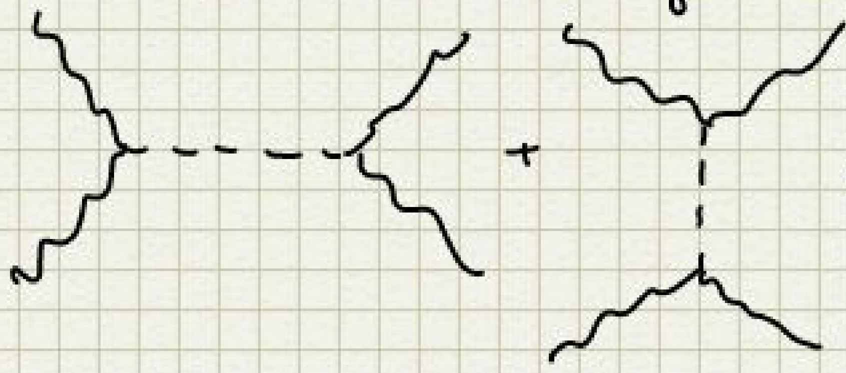
Choose gauge such as to rotate this factor away ("Unitary gauge")

⇝ Theory contains massive W and Z, and massless photon ($Q = Y + T_3$ is unbroken)

<u>N.B.:</u> Goldstone's theorem predicts 1 massless scalar per broken generator.

⇝ They are "eaten" by gauge boson, and reappear as longitudinal polarizations.

Back to unitarity :



$$= g_w^2 \left\{ \frac{p^2}{2M_W^2}\cancel{(1+\cos\theta)} - \frac{M_H^2}{4M_W^2}\left[\frac{s}{s-M_H^2} + \frac{t}{t-M_H^2}\right]\right\}$$

$$\rightsquigarrow \mathcal{M}_3 + \mathcal{M}_4 + \mathcal{M}_H = -\frac{g_W^2 M_H^2}{4 M_W^2}\left[\frac{s}{s-M_H^2} + \frac{t}{t-M_H^2}\right]$$

$$\longrightarrow c^{te} \text{ for } s \to \infty$$

N.B.: There are still issues with unitarity for large m_H. $\Rightarrow m_H \lesssim 1\,\text{TeV}$

Conclusion: We have a unitary theory of massive weak bosons.

Bonus: Fermion masses!

$$\mathcal{L}_{Yukawa} = \bar{u}_R Y_u Q_L \cdot \Phi^* + \bar{d}_R Y_d Q_L \Phi + \bar{e}_R Y_e L_L \Phi + h.c.$$

$\rightsquigarrow$ Higgs couples to mass.

- On July 4 2012, ATLAS and CMS announce the discovery of a resonance compatible with the SM Higgs
- 2013: Nobel prize to Englert and Higgs
- Today: Resonance <u>very much</u> compatible with SM Higgs.

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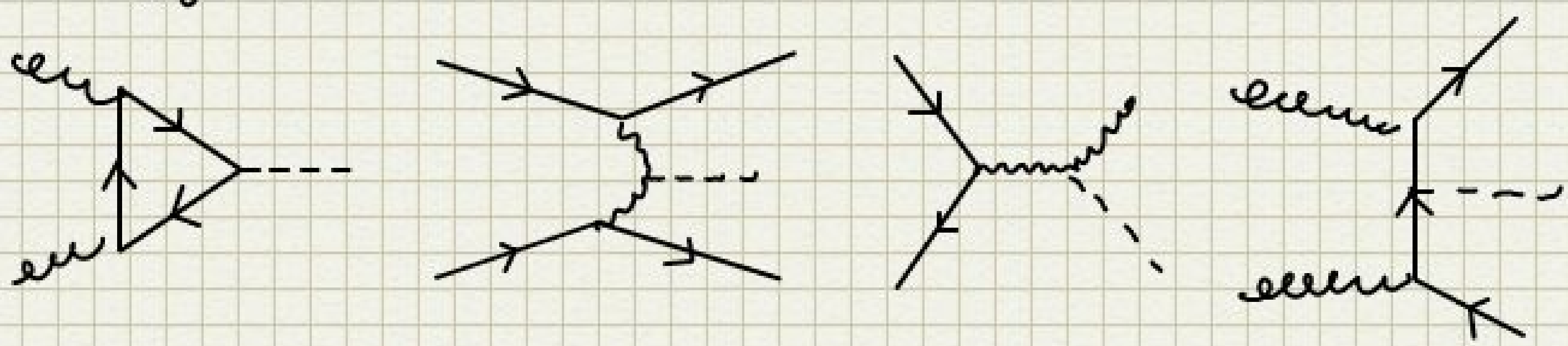
Higgs production at the LHC

LHC cross section ⟷ QCD factorisation

$$d\sigma(pp \to H+X) = \sum_{i,j} \int_0^1 dx_1\, dx_2\, f_i(x_1, \mu_F^2) f_j(x_2, \mu_F^2)\, d\hat{\sigma}_{ij}(i,j \to H+X)$$

There are 4 main production mechanisms at the LHC

ggF VBF HV $t\bar{t}H$



Questions

* Which of these channels dominates? and Why?
* What is the state of the art for each of them?
* How can we improve? Approximations? Tools?

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Reason :

* VH and VBF are EW processes @ LO
* ttH has a very large invariant mass

$$\hat{s} \geq m^2_{ttH} \geq 2m_t^2 + m_H^2$$

* ggF : enhanced by gluon flux.

Consider the integral over PDFs :
It can be written

$$d\sigma = \tau \sum_{i,j} \int_{\tau}^{1} \frac{dz}{z} \mathcal{L}_{ij}\left(\frac{\tau}{z}, \mu_F^2\right) \frac{d\hat{\sigma}_{ij}(z, \mu_F^2)}{z}$$

$$\tau = \frac{m_H^2}{S} \simeq 10^{-4} \text{ @ LHC}$$

$$z = \frac{m_H^2}{\hat{s}}$$

with parton luminosity

$$\mathcal{L}_{ij}\left(\frac{\tau}{z}\right) = \int_{\tau/z}^{1} \frac{dy}{y} f_i(y) f_j\left(\frac{\tau}{yz}\right)$$

N.B. : This is a convolution :

$$(f \otimes g)(z) = \int_0^1 dx\,dy\ f(x)\, g(y)\, \delta(z - xy)$$
$$= \int_z^1 \frac{dx}{x} f(x)\, g\left(\frac{z}{y}\right)$$

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