The plan

1. The Standard Model: the “indirect” informations
2. “Higgsless”
3. The Higgs boson as a PGB
4. Beyond mSUGRA

EWSB: “weak” or “strong”?

“weak”

a relatively light Higgs boson exists

perturbativity extended →high E (M_{GUT}, M_{Pl})

perhaps (probably) embedded in susy

gauge couplings (perhaps) unify

“strong”

EWSB related to new forces, new degrees of freedom or even new dimensions opening up in the TeVs

perturbativity lost in the multi-TeV range

high E extrapolation highly uncertain

A gauge invariant Higgsless SM
The ElectroWeak Chiral Lagrangian

In the SM: $H_{SM} = \Sigma \begin{pmatrix} 0 \\ v+h \end{pmatrix}$ $\Sigma = \exp i\frac{\pi\cdot\tau}{v}$

invariant under

$H_{SM} \Rightarrow U_L H_{SM}$ $U_L = \exp i\omega_L \cdot \tau/2$ $H_{SM} \Rightarrow \exp(i\omega_Y/2) H_{SM}$

Changing notation:

$\boxed{\Phi \equiv (v+h)\Sigma}$ $\Phi \Rightarrow U_L \Phi$ $\Phi \Rightarrow \Phi \exp(-i\omega_Y \tau_3/2)$

$D_\mu \Phi \equiv d_\mu \Phi - g\hat{W}_\mu \Phi + g'\Phi\hat{B}_\mu$ $\hat{W}_\mu \equiv -i/2\mathbf{W}_\mu \cdot \tau$ $\hat{B}_\mu \equiv -i/2 B_\mu \cdot \tau_3$

$H_{SM}^+ H_{SM} = \frac{1}{2} Tr(\Phi^+ \Phi)$ $|D_\mu H_{SM}|^2 = \frac{1}{2} Tr(D_\mu \Phi)^+ (D_\mu \Phi)$

$\Rightarrow$ Throw away h and even forget the doublet origin of Σ

$\Rightarrow$ EW Chiral Lagrangian

In the g'→0 limit

$SU(2)_L x SU(2)_R$ $\Sigma \Rightarrow U_L \Sigma U_R^+$

The EW chiral Lagrangian (continued)

An expansion in powers of derivatives and $V_\mu \equiv (D_\mu \Sigma)\Sigma^+$

$$\mathcal{L}_{EWCh} = \mathcal{L}_G + \mathcal{L}_Y + \mathcal{L}_{NL} + \Sigma_{i=0}^{10} \mathcal{L}_i$$

$$\mathcal{L}_G = \frac{1}{2} Tr[\hat{W}_{\mu\nu}\hat{W}_{\mu\nu} + \hat{B}_{\mu\nu}\hat{B}_{\mu\nu}] \qquad \mathcal{L}_{NL} = \frac{v^2}{4} Tr[(D_\mu\Sigma)^+ D_\mu\Sigma]$$

$$\mathcal{L}_Y = \lambda_1^{ij} \bar{Q}_L^i \Sigma Q_R^j + \lambda_2^{ij} \bar{Q}_L^i \Sigma \tau_3 Q_R^j + h.c.$$

$\Rightarrow$ $$\mathcal{L}_0 = a_0 \frac{v^2}{4} [Tr(TV_\mu)]^2$$

$\Rightarrow$ $$\mathcal{L}_1 = a_1 \frac{igg'}{2} B_{\mu\nu} Tr\left(T\hat{W}^{\mu\nu}\right)$$

$\Rightarrow$ $$\mathcal{L}_2 = a_2 \frac{ig'}{2} B_{\mu\nu} Tr(T[V^\mu, V^\nu])$$

$\Rightarrow$ $$\mathcal{L}_3 = a_3 g Tr\left(\hat{W}_{\mu\nu}[V^\mu, V^\nu]\right)$$

$\Rightarrow$ $$\mathcal{L}_4 = a_4 [Tr(V_\mu V_\nu)]^2$$

$\Rightarrow$ $$\mathcal{L}_5 = a_5 [Tr(V_\mu V^\mu)]^2$$

$\Rightarrow$ $$\mathcal{L}_6 = a_6 Tr(V_\mu V_\nu) Tr(TV^\mu) Tr(TV^\nu)$$

$\Rightarrow$ $$\mathcal{L}_7 = a_7 Tr(V_\mu V^\mu) [Tr(TV^\nu)]^2$$

$\Rightarrow$ $$\mathcal{L}_8 = a_8 \frac{g^2}{4} \left[Tr\left(T\hat{W}_{\mu\nu}\right)\right]^2$$

$T \equiv \Sigma \tau_3 \Sigma^+$

$\Rightarrow$ $$\mathcal{L}_9 = a_9 \frac{g}{2} Tr\left(T\hat{W}_{\mu\nu}\right) Tr(T[V^\mu, V^\nu])$$

$\Rightarrow$ $$\mathcal{L}_{10} = a_{10} [Tr(TV_\mu) Tr(TV_\nu])]^2$$

$\Rightarrow$ 2V-terms $\Rightarrow$ 3V-terms

$\Rightarrow$ 4V-terms

Some remarks on the EWChL

⇒ Its symmetries:

gauged $SU(2)_L x U(1)_Y$ exact (surprising?)

As $g',\ \lambda_2 \rightarrow 0$, global $SU(2)_L x SU(2)_R$ conserved by

$$\mathcal{L}_G + \mathcal{L}_Y + \mathcal{L}_{NL} + \Sigma_{i=1}^{5} \mathcal{L}_i$$

⇒ Without knowing the underlying dynamics, 11 unknown parameters $a_0,\ a_1, ...,\ a_{10}$

as opposed to a single one in the SM: the Higgs mass m_h

(v, g, g' are in common)

⇒ The SM as $m_h \rightarrow \infty$ is a particular $\mathcal{L}_{EWCh}$

At one loop, 4 a_i's diverge logarithmically

What is it known of the a_i 's experimentally?

(LEP; can LHC do better?)

V^2 - terms: $a_0, a_1, a_8 \Leftrightarrow T, S, U$ see plot and below

(in one-to-one correspondence)

V^3 - terms: a_2, a_3, a_9

Setting $a_9 = 0$ $a_2, a_3 \Leftrightarrow g_1^Z, k_\gamma$

From $e^+e^- \to W^+W^-$ at LEP2

$g_1^Z - 1 = -0.016^{+0.022}_{-0.019}$

$k_\gamma - 1 = -0.027^{+0.044}_{-0.045}$ (O(10^{-3}) in the SM)

LEPEWWG

V^4 - terms: $a_4, a_5, a_6, a_7, a_{10}$

Nothing known

◯ = $SU(2)_{L+R}$ conserving

A nearby strong interaction

$$A(W_L W_L) \approx \quad (E/v)^2 \quad - \quad (E/v)^2 \approx E^0$$

Gauge Higgs

Without a Higgs, perturbation theory saturated at $E \approx 4\pi v$

Obvious from the point of view of $\mathcal{L}_{EWCh}$

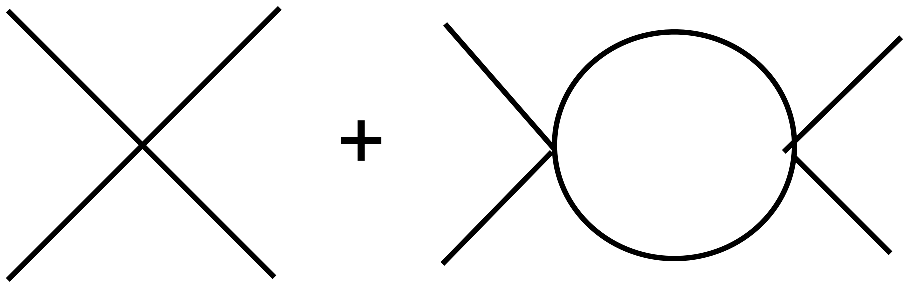
$$\Delta\mathcal{L}_{NL} = v^2/4 |(\partial_\mu + igA_\mu)e^{i\pi^a\tau^a/v}|^2$$

$$\approx g^2 v^2 A_\mu^2 + (\partial_\mu \pi)^2 + \frac{1}{v^2}\pi^2(\partial_\mu \pi)^2 + \ldots$$

$$\Rightarrow \Lambda_4 \sim 4\pi v \sim 4\pi \frac{M_W}{g}$$

Unless something happens below Λ_4

$$\approx g^2 v^2 A_\mu^2 + (\partial_\mu \pi)^2 + \frac{1}{v^2}\pi^2(\partial_\mu \pi)^2 + \ldots$$



$(E/v)^2$ $\qquad$ $(E/v)^2 \; (E/v)^2 \frac{1}{16\pi^2}$

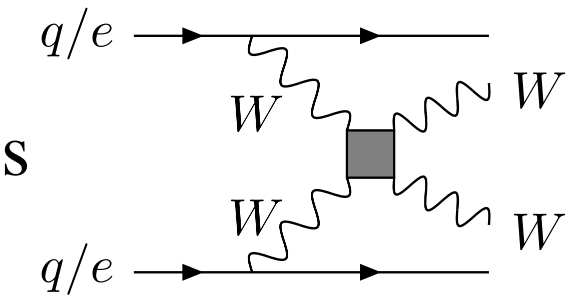
$$\Rightarrow \Lambda_4 \sim 4\pi v \sim 4\pi \frac{M_W}{g}$$

A better estimate gives $\Lambda_4 \sim \frac{4\pi v}{\sqrt{n_g}} \sim 1.2\ TeV$

Which problems without a Higgs boson?

1. Perturbation theory lost at $\sqrt{s} \approx 1.2\ TeV$

the central process



$I = 0, 2 \quad J$ even

$I = 1 \quad J$ odd

$$
\begin{aligned}
A(W^+W^- \to ZZ) &= A(s,t,u) \\
A(W^+W^- \to W^+W^-) &= A(s,t,u) + A(t,s,u) \\
A(ZZ \to ZZ) &= A(s,t,u) + A(t,s,u) + A(u,s,t) \\
A(W^-W^- \to W^-W^-) &= A(t,s,u) + A(u,s,t) \ .
\end{aligned}
$$

without the Higgs boson exchange

$$\mathcal{A} \approx \frac{s}{2v^2}$$

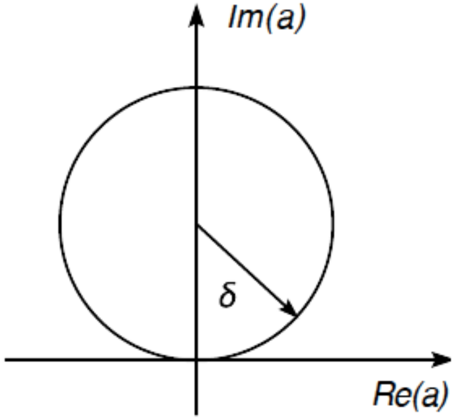
$$a_l = \frac{1}{32\pi}\int_{-1}^{+1} d\cos\theta\ \mathcal{A}(s,\theta)P_l(\cos\theta)$$

$$
\begin{aligned}
a_{00} &= +\frac{s}{16\pi v^2} \\
a_{11} &= +\frac{s}{96\pi v^2} \\
a_{20} &= -\frac{s}{32\pi v^2} \ .
\end{aligned}
$$

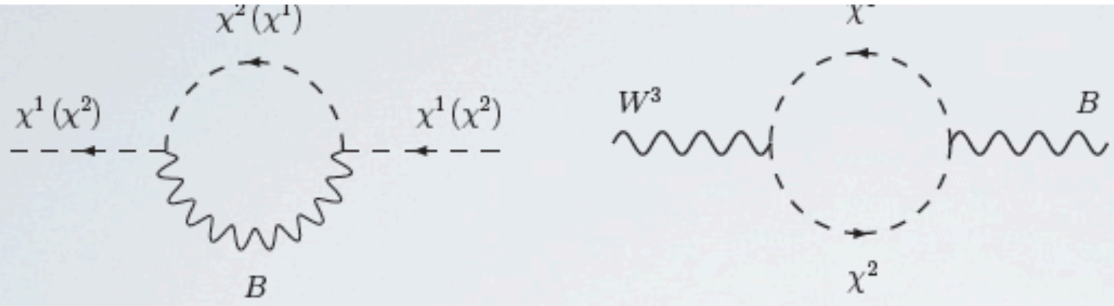
$$\mathcal{S} = \mathbf{1} + i\mathcal{A}$$

$$SS^+ = 1$$

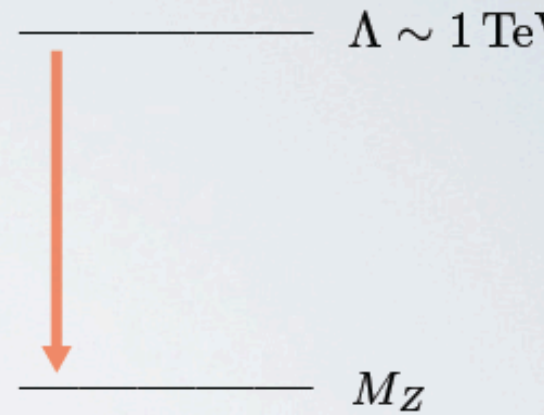
$$Im(a) = |a|^2 + |a^{in}|^2$$



2. EWPT problematic



$\pi^a \to \chi^a$

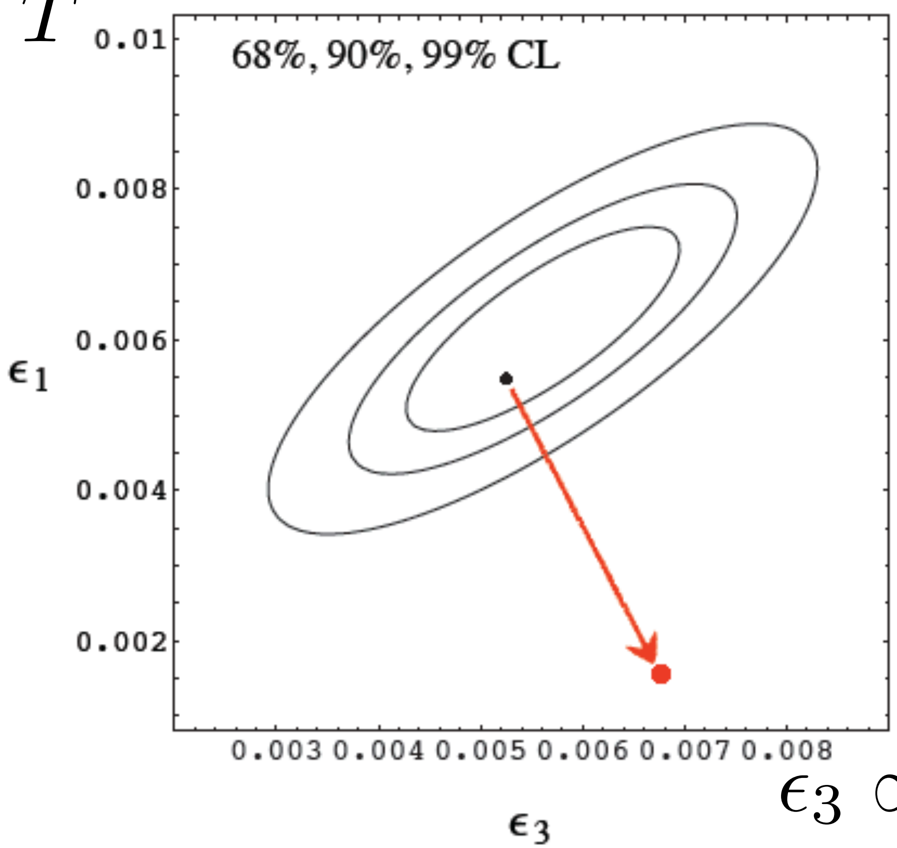


$$\Delta\epsilon_{1,3} = c_{1,3}\,\log\frac{\Lambda^2}{M_Z^2}$$

$$c_1 = -\frac{3}{16\pi^2}\,\frac{\alpha(M_Z)}{\cos^2\theta_W}$$

$$c_3 = +\frac{1}{12\pi}\,\frac{\alpha(M_Z)}{4\sin^2\theta}$$

$\epsilon_1 \propto T$



$\epsilon_3 \propto S$

An attempt to improve the situation

1. Keep SU(2)xU(1) gauge invariance but leave out the Higgs boson, while insisting on $SU(2)_L \times SU(2)_R \to SU(2)_{L+R}$ as relevant symmetry (except for $g' \neq 0$ and $m_t - m_b \neq 0$)

$$\mathcal{L} = \mathcal{L}^{SM}_{gauge} + \frac{v^2}{4} < (D_\mu U)^+ (D_\mu U) > + \frac{v}{\sqrt{2}} \bar{Q}_{Li} U Q_{Ri}$$

$$U(x) = e^{i\hat{\pi}(x)/v}, \qquad \hat{\pi}(x) = \tau^a \pi^a \qquad Q_{Ri} = \begin{pmatrix} \lambda^u_{ij} u_{Rj} \\ \lambda^d_{ij} d_{Rj} \end{pmatrix}$$

Consistent with all data so far, except the EWPT (although $\rho \approx 1$) and reliable only up to $\Lambda \approx 4\pi v$

2. Introduce new "composite" particles of mass <(<<)Λ consistently with 1 and see what happens:

scalars, fermions, vectors

Scalars: a "composite" Higgs boson

Contino et al

h = $SU(2)_{L+R}$- singlet   Why light? (PGB, h=A_5 ,...)

$$\mathcal{L} = \mathcal{L}^{SM}_{gauge} + \frac{1}{2}(\partial_\mu h)^2 - V(h) + \mathcal{L}^h_{SB} + \ldots$$

MFV

$$\mathcal{L}^h_{SB} = \frac{v^2}{4} < (D_\mu U)^+(D_\mu U) > (1 + 2a\frac{h}{v} + b\frac{h^2}{v^2}) + \frac{v}{\sqrt{2}}\bar{Q}_{Li}U(1 + c\frac{h}{v})Q_{Ri}$$

If (π_a, h) = linear SU(2)xU(1) multiplet: a=b=c=1

EWPT OK and consistency well above $4\pi v$ (if m_h small enough)

Too good not to be true!?!

Yet, if h found (by the usual means), hard to overestimate the importance of measuring a,b,c as well as possible

How?

h production and decays at the LHC, to some extent

WW→WW

WW→hh

but only for high luminosity

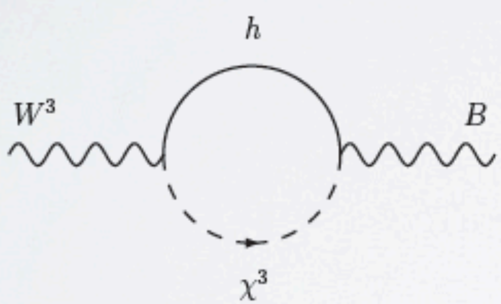
1. EWPT improved

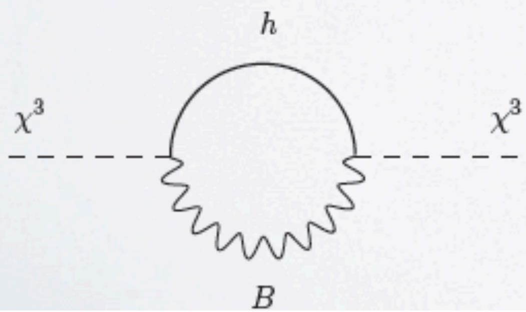
$$\mathcal{L} = \frac{v^2}{4} \mathrm{Tr}\left(D_\mu \Sigma^\dagger D^\mu \Sigma\right) \left(1 + 2a\frac{h}{v} + b\frac{h^2}{v^2} + \cdots\right) + V(h)$$

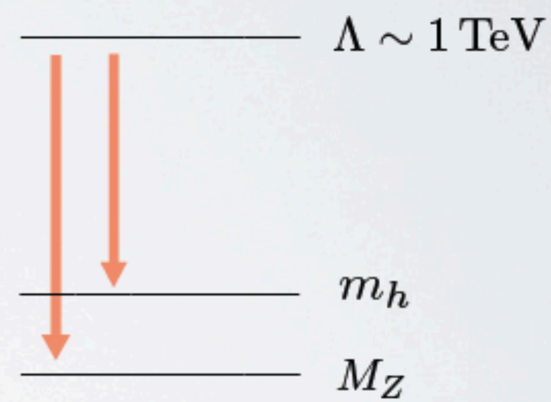
$$- \frac{v}{\sqrt{2}} \sum_{i,j} \left(u_L^{(i)}\ d_L^{(i)}\right) \Sigma \left(1 + c\frac{h}{v} + \cdots\right) \begin{pmatrix} \lambda^u_{ij}\, u_R^{(j)} \\ \lambda^d_{ij}\, d_R^{(j)} \end{pmatrix} + h.c.$$

a, b, c are free parameters

[for a SM Higgs: a=b=c=1]

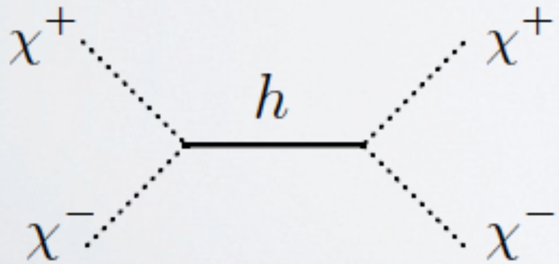






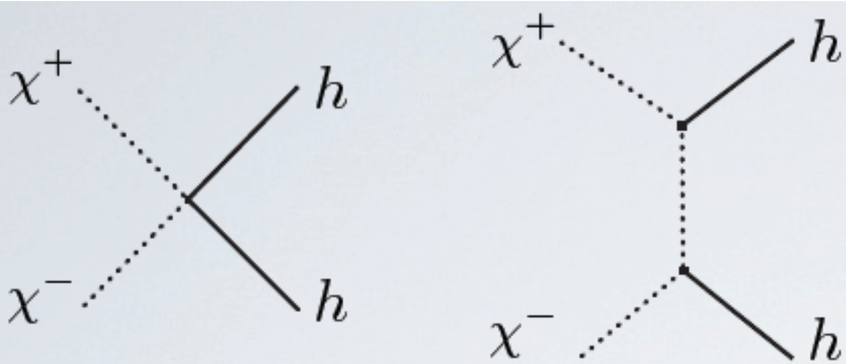
$$\Delta\epsilon_{1,3} = -c_{1,3}\ a^2 \log\frac{\Lambda^2}{m_h^2}$$

2. Perturbation theory valid up to higher energies



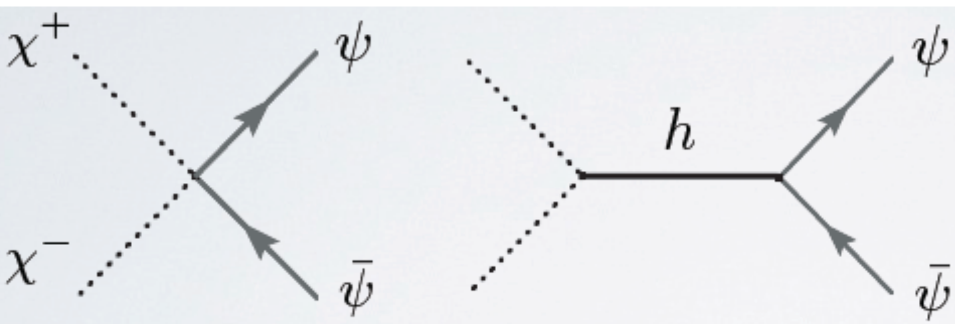
$$\mathcal{A}(\chi^+\chi^- \to \chi^+\chi^-) \simeq \frac{1}{v^2}\left[s - \frac{a^2 s^2}{s - m_h^2} + (s \leftrightarrow t)\right]$$

unitarity for: a=1



$$\mathcal{A}(\chi^+\chi^- \to hh) \simeq \frac{s}{v^2}(b - a^2)$$

unitarity for: a^2=b



$$\mathcal{A}(\chi^+\chi^- \to \psi\bar{\psi}) \simeq \frac{m_\psi \sqrt{s}}{v^2}(1 - ac)$$

unitarity for: a=c

Vectors: a "composite" ρ-like state

V^{μ}_{a} = a $SU(2)_{L+R}$ - triplet   Why light? (unitarity, EWPT?)

The formalism is there since always (CCWZ):

$$u \equiv \sqrt{U} \to g_R u h^\dagger = h u g_L^\dagger$$ under $SU(2)_L \times SU(2)_R$

$$V_\mu = \frac{1}{\sqrt{2}} \tau^a V^a_\mu, \;\; V^\mu \to h V^\mu h^\dagger$$

unlike a standard gauge boson!

two more covariant vectors made of π, W, B

$$\Gamma_\mu = \frac{1}{2}\Big[u^\dagger \left(\partial_\mu - iB_\mu\right) u + u \left(\partial_\mu - iW_\mu\right) u^\dagger\Big]$$

$$u_\mu = u_\mu^\dagger = i u^\dagger D_\mu U u^\dagger$$

E.g.:

$$\mathcal{L}^V_{\rm kin} = -\frac{1}{4}\left\langle \hat{V}^{\mu\nu}\hat{V}_{\mu\nu}\right\rangle + \frac{M_V^2}{2}\left\langle V^\mu V_\mu\right\rangle \;,$$

$$\hat{V}_{\mu\nu} = \nabla_\mu V_\nu - \nabla_\mu V = \partial_\mu V + [\Gamma_\mu, V]$$

The generic Lagrangian

$$\mathcal{L}^V = \mathcal{L}_{SB} + \mathcal{L}^V_{kin} + \mathcal{L}^V_{int}$$ + ...

$$\mathcal{L}^V_{int} = \mathcal{L}_{1\mathrm{V}} + \mathcal{L}_{2\mathrm{V}} + \mathcal{L}_{3\mathrm{V}}$$

parity assumed

$$\mathcal{L}_{1\mathrm{V}} = -\frac{i g_V}{2\sqrt{2}} \left\langle \hat{V}^{\mu\nu}[u_\mu, u_\nu] \right\rangle - \frac{f_V}{2\sqrt{2}} \left\langle \hat{V}^{\mu\nu}(u W^{\mu\nu} u^\dagger + u^\dagger B^{\mu\nu} u) \right\rangle$$

$$\mathcal{L}_{2\mathrm{V}} = g_1 \langle V_\mu V^\mu u^\alpha u_\alpha \rangle + g_2 \langle V_\mu u^\alpha V^\mu u_\alpha \rangle + g_3 \langle V_\mu V_\nu [u^\mu, u^\nu] \rangle + g_4 \langle V_\mu V_\nu \{u^\mu, u^\nu\} \rangle$$
$$+ g_5 \langle V_\mu \left(u^\mu V_\nu u^\nu + u^\nu V_\nu u^\mu\right) \rangle + i g_6 \langle V_\mu V_\nu (u W^{\mu\nu} u^\dagger + u^\dagger B^{\mu\nu} u) \rangle$$

$$\mathcal{L}_{3\mathrm{V}} = \frac{i g_K}{2\sqrt{2}} \left\langle \hat{V}_{\mu\nu} V^\mu V^\nu \right\rangle$$

9 parameters (an embarrassment)

but many processes as well: study

$$W_L W_L \to VV$$
$$\bar{q} q \to VV$$

in various charge configurations

NDA guess

$g_V\,,\ f_V \approx \frac{1}{4\pi}$

$g_{i=1,\ldots,6} \approx 1$

$g_K \approx 4\pi$

but $M_V < \Lambda$!

leave out direct coupling of V to SM fermions (top?)

V production and decays

Narrow ($\Gamma \approx M_V^3 < 40$ GeV at M < 1 TeV) and dominated by $V \to WW/Z$ ($l\bar{l}$ small but$\neq 0$ because of VZ kin. mixing)
($V \to t\bar{t}$?)

Single V-production by WW-fusion (g_V)
Single V or associated VW/Z production by DY (f_V)

pair-V production by WW-fusion (g_V, g_K, g_i)
pair-V production by DY (f_V, g_K, g_6)

leading to 2W/Z, 3W/Z, 4W/Z final states (+jj)
→ multi-leptons to be disantangled from the background