Heavy vectors in Higgsless models

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Experiments provide unambiguous indications that the SM gauge group is spontaneously broken \([SU(2)_L \times U(1)_Y \rightarrow U(1)_Q]\)

One elementary \(SU(2)_L\) scalar doublet with \(\phi^4\) potential is the most economical & simple choice

\[
L_{\text{Higgs}}(\phi, A^I, \psi^i) = D_\mu \phi^+ D^\mu \phi + \mu^2 \phi^+ \phi - \lambda (\phi^+ \phi)^2 + Y^{ij} \psi^i_L \psi^j_R
\]

not the only allowed possibility

So far only the ground state of this Lagrangian has been tested with good accuracy

\(<\phi>=246\text{GeV} \leftrightarrow m_W, m_Z\)

Some dynamical sensitivity to the Higgs mechanisms is obtained from EWPO

Indirect indication of a light \(m_H\)
Do we need a fundamental Higgs field?

- EWPO indicate:
  - a spontaneous breaking of $SU(2)_L \times U(1)_Y$
  - the breaking mechanism must respect, to a good accuracy, the custodial symmetry $[m_Z^2/m_W^2 \approx 1 + (g'/g)^2]$

- General formulation of the symmetry breaking mechanism in absence of a fundamental Higgs (or for large Higgs masses) in terms of a Chiral Lagrangian:

  $$\mathcal{L}_\chi^{(2)} = \frac{v^2}{4} \text{Tr}(D_\mu U^\dagger D_\mu U)$$

  $$U \to g_R U \ g_L^+ = e^{im\sqrt{2}}$$

  3 Goldstones of the SM

- Global: $SU(2)_L \times SU(2)_R \times U(1)_{B-L} \rightarrow SU(2)_{L+R} \times U(1)_{B-L}$

- Local: $SU(2)_L \times U(1)_Y \rightarrow U(1)_Q$

  $$D_\mu U = -ig'B_\mu U + ig U W_\mu$$
EW Chiral Lagrangian

\[ \mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{gauge}}(A^i, \psi^i) + \mathcal{L}_{\text{Yukawa}}(U, \psi^i) + \frac{v^2}{4} \text{Tr}(D_\mu U^\dagger D^\mu U) \]

contains all the degrees of freedom we have directly probed in experiments

naive cut-off dictated by the convergence of EW loops: \( \Lambda_{\text{NDA}} = 4\pi v \approx 3 \text{ TeV} \)

perfectly describes particle physics up to 3 TeV, beyond the tree level, with only two drawbacks

(point toward the existence of new degrees of freedom below the naive cut-off):

Violation of unitarity in \( W_L W_L \rightarrow W_L W_L \) scattering (tree-level amplitude violates unitarity for \( s \approx 1 \text{ TeV} \))

Bad fit to S and T

\[ \text{SM Higgs mass [GeV]} \]

3000
Introducing heavy vectors

A natural alternative to Higgs-type mechanisms in curing the problem of unitarity in $WW \to WW$ scattering is represented by heavy vector fields.

Expected in many non-SUSY scenarios:
- techni-rho in technicolor,
- massive gauge bosons in 5-dimensional theories, hidden gauge-models.

Difficult task is to cure at the same time unitarity and EWPO can be analysed in general terms constructing an appropriate effective chiral Lagrangian with the heavy vectors as new explicit d.o.f.

$$\mathcal{L}_\chi = \frac{v^2}{4} \text{Tr}(D_\mu U^\dagger D^\mu U) + \mathcal{L}_{\text{kin}}(R, U, A_i; m_R) + \mathcal{L}_{\text{int}}(R, U, A_i; G_R)$$
Consider an effective theory based on the following two main assumptions:

- The (new) dynamics that breaks the SM EW symmetry is invariant under the global symmetry $\text{SU}(2)_L \times \text{SU}(2)_R$ and under the discrete parity $P: \text{SU}(2)_L \leftrightarrow \text{SU}(2)_R$

- One vector $(V)$, or one vector + one axial-vector $(V+A)$, both belonging to the adjoint representation of $\text{SU}(2)_L+\text{SU}(2)_R$ (triplets), are the only light fields below a cut-off $\Lambda = 2-3$ TeV

- Effective Lagrangian expansion based on ordering of operators according to the standard derivative (momentum) expansion
Unitarizing $W_L W_L$ scattering

- No tree-level violation of unitarity for $G_V^2 = v^2/3$
- The unitarity constraint is almost insensitive to the value $m_V$

$M = \frac{s}{v^2} - \frac{G_V^2}{v^4} \left[ 3s + m_V^2 \left( \frac{s-u}{t-m_V^2} + \frac{s-t}{u-m_V^2} \right) \right]$
The leading contributions to S & T generated by the exchange of single heavy fields

\[ \Delta \hat{S} = g^2 \left( \frac{F_V^2}{4m_V^2} - \frac{F_A^2}{4m_A^2} \right) \]

\[ \Delta \hat{T} = \frac{3\pi\alpha}{c_W^2} \left[ \frac{F_A^2}{4m_A^2} + \left( \frac{F_V - 2G_V}{2m_V} \right)^2 \right] \frac{\Lambda^2}{16\pi^2v^2} + \ldots \]

- O(1) factor [\( \Lambda \) replaced by some heavy mass]

Two natural ways to accommodate the bounds:
- Both V and A light, almost degenerate
- Only V light, with small F_V

EWPO & unitarity can be accommodated for specific choices of the free parameters

Main conclusion:
We need at least one relatively light vector field
Producing the heavy vectors at the LHC

Main properties of vector fields

- Leading decay mode: 2 longitudinal SM gauge bosons
  \[ \Gamma_{V^+} \approx \Gamma_{WZ}^V = \frac{G_{V}^2 m_V^3}{48\pi v^4} \left[ 1 + O(g^2 \epsilon^2) \right] , \quad 5 \text{ GeV} \quad [m_V = 0.5 \text{ TeV}] \]
  \[ \Gamma_{V^0} \approx \Gamma_{WW}^V = \Gamma_{WZ}^V \left[ 1 + O(g^2 \epsilon^2) \right] \]
- Narrow widths!
- ZZ channel forbidden

Coupling to SM fermions highly suppressed

- \[ Br(V^0 \to q\bar{q}) \approx 3 Br(V^0 \to \ell^+\ell^-) \approx \frac{6F_{V}^2 m_W^4}{G_{V}^2 m_V^4} \]
  \[ 1.6\% \quad [m_V = 0.5 \text{ TeV}, F_V = 2G_V] \]
  \[ 0.1\% \quad [m_V = 1.0 \text{ TeV}, F_V = 2G_V] \]

Leading decay modes of axial fields can be to a vector and SM g. b.
Producing the heavy vectors at the LHC

The most general signature of Higgsless models is the appearance of the vector state in WW scattering $[\text{pp} \rightarrow V + jj \text{ (WW fusion)} \rightarrow WW(WZ) + jj]$.

Model-independent link with the unitarity problem.

Belyaev [0711.1919]
Producing the heavy vectors at the LHC

The most general signature of Higgsless models is the appearance of the vector state in WW scattering $[\, pp \rightarrow V + jj \, (WW \, fusion) \rightarrow WW(WZ) + jj \, ]$

A difficult analysis, which requires high statistics.

Resonant cross section including
- leptonic BR’s $(l=e,\mu)$ $[\, \varepsilon_{\text{lept}} = 21\% \times 6.7\% = 1.5\% \, ]$
- $p_T(jets) > 30$ GeV
- standard VBF jet cuts $[\Delta \eta > 4, M_{jj} > 1\text{TeV} \, \varepsilon_{\text{VBF}} < 30\% \, ]$
Producing the heavy vectors at the LHC

A potentially cleaner signal (if the resonances are not too heavy) is the Drell-Yan production of the resonances and subsequent decay into $l^+l^-$, 2 and 3 SM heavy gauge bosons.

Link to the contribution of the heavy vectors to EPWO
Producing the heavy vectors at the LHC

Given the narrow widths, for low masses the signals are quite large.

<table>
<thead>
<tr>
<th>$\sigma(pp \rightarrow V^+ \rightarrow X)_{\sqrt{s}=14 \text{ TeV}}$</th>
<th>$\sigma(pp \rightarrow V^+ \rightarrow X)_{\sqrt{s}=10 \text{ TeV}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M = 500 \text{ GeV}$</td>
<td>11 pb</td>
</tr>
<tr>
<td>$1.2 \text{ pb}$</td>
<td>0.7 pb</td>
</tr>
<tr>
<td>$6.7 \text{ pb}$</td>
<td>$0.13 \text{ pb}$</td>
</tr>
</tbody>
</table>

However....

The leading decay modes (2W, 3W) have low efficiencies.

The $l^+l^-$ case is suppressed by the small Br($R\rightarrow l^+l^-$).
Signal of heavy vectors at the Tevatron?

- The $l^+l^-$ state of the art is the analysis of the $e^+e^-$ final state in $p$-pbar collisions published by CDF.

- Using their data as normalization for the SM events (takes into account all the relevant exp. efficiencies!), we have produced an exclusion plot in the $F_V-m_V$ plane.

- Two main assumptions:
  - $G_V$ fixed by unitarity
  - $m_A >> m_V$
Signal of heavy vectors at the Tevatron?

The $l^+l^-$ state of the art is the analysis of the $e^+e^-$ final state in $p$-$p\bar{p}$ collisions published by CDF.

If, on the other hand, the excess at higher mass will become significant, we can hope to see a clear signal at the LHC (even with 1-2 fb$^{-1}$).

Not huge peaks as with a sequential $Z'$, but they should be clearly visible.
Signals for heavy vectors at the LHC

- Two SM gauge boson final states
- Some illustrative examples
  - $[WZ] \ Br_{Z\text{lept}} \times Br_{W\text{lept}} = 1.5\%$
  - $F_V = 2\text{GeV}$
  - $F_A = F_V$
  - $G_V$ fixed by unitarity

[Warning: the configurations of free params. are realistic, but maximize the signal...]
Signals for heavy vectors at the LHC

- Three SM gauge boson final states
- Some illustrative examples
  - $[WWZ] \, \text{Br}_{\text{lept}} \times \text{Br}_{\text{lept}} \times \text{Br}_{\text{had}} = 0.9 \%$
  - $F_V = 2G_V$
  - $F_A = F_V$  
  - $G_V$ fixed by unitarity
  - $g_A = 1/2$

In the WWZ final state it is also worth to look at the WZ invariant-mass distribution
Conclusions

- Heavy vector fields, which replace the Higgs boson in maintaining perturbative unitarity up to LHC energies, are naturally expected in a wide class of Higgsless models.

- The most general signature of these models is the appearance of the lightest vector state in $WW$ scattering (model-independent link with the unitarity problem).

- The Drell-Yan production of the new states is subject to larger uncertainties.

- For light $m_{V(A)}$ we could expect visible signals (even with low statistics), and the information could help to clarify the role of the heavy vectors in EWPO.

- The results in the $e^+e^-$ channel from Tevatron are already providing a significant information.

- The 2 and 3 SM gauge boson final states seems to be quite promising and would deserve a more realistic study.
Backup Slides
EWPO in the SM

Some dynamical sensitivity to the Higgs mechanisms is obtained from EWPO

Indirect indication of a light $m_H$ under the hypothesis of a heavy cut-off for the SM as effective theory

(\leftrightarrow \text{fine tuning in the Higgs mass term})

$$T = \frac{\Pi_{33}(0) - \Pi_{WW}(0)}{m_W^2}$$

$$S = \left. \frac{g}{g'} \frac{d\Pi_{30}(q^2)}{dq^2} \right|_{q^2=0}$$
Heavy vectors in the EW Chiral Lagrangian

With heavy spin-1 fields, there is a peculiar problem related to the possible mixing of the heavy states and the Goldstone bosons.

Describing the heavy states in terms of Lorentz vectors \((V_\mu \& A_\mu)\), we have a possible mass-mixing of \(O(p)\) [→ tedious redefinition of the fields ]

\[ V_\mu \rightarrow V_\mu + \beta [\pi, \partial_\mu \pi], \quad A_\mu \rightarrow A_\mu + \alpha \partial_\mu \pi \]

This problem can be avoided describing the heavy spin-1 states by means of antisymmetric tensors \((R_{\mu\nu} = V_{\mu\nu}, A_{\mu\nu})\):

\[
\mathcal{L}_{\text{kin}}(R^{\mu\nu}) = -\frac{1}{2}\text{Tr}(\nabla_\mu R^{\mu\nu} \nabla^\sigma R_{\sigma\nu}) + \frac{1}{4}m_R^2 \text{Tr}(R^{\mu\nu} R_{\mu\nu})
\]

\[
\langle 0 | R^{\mu\nu} | R(p, \epsilon) \rangle = \frac{i}{m_R} [p_\mu \epsilon_\nu - p_\nu \epsilon_\mu]
\]

\[
\nabla_\mu R = \partial_\mu R + [\Gamma_\mu, R] \quad \Gamma_\mu = \frac{1}{2} [u^\dagger D_\mu u + u D_\mu u^\dagger], \quad u^2 = U
\]

Gasser & Leutwyler
[Annals Phys.158:142,1984]
Ecker et al.
Heavy vectors in the EW Chiral Lagrangian

In the antisymmetric formulation the couplings between heavy fields and Goldstone bosons start at $O(p^2)$.

$\Rightarrow$ integrating out the heavy fields we are automatically projected into the basis of the $O(p^4)$ chiral operators with light fields only.

In QCD case this procedure leads to a successful description of all the leading $O(p^4)$ light-field couplings.

$1 \leftrightarrow 1$ correspondence between lowest-order vector couplings [$O(p^2)$] and next-to-leading order Goldstone-boson couplings [$O(p^4)$].
Heavy vectors in the EW Chiral Lagrangian

The dynamics of the system below the cut-off is described by $3 + 2$ parameters: $(M_V, G_V, F_V) + (M_A, F_A)$.

- Naive dimensional analysis implies $F_{V(A)}, G_V = O(v)$

\[ [u_\mu = i u^\dagger D_\mu U u^\dagger] \]

\[ \mathcal{L}_{\text{int}} = \frac{i}{2\sqrt{2}} G_V \text{Tr}(V^{\mu\nu}[u_\mu, u_\nu]) \]

\[ + \frac{1}{2\sqrt{2}} F_V \text{Tr}(V^{\mu\nu}(u \hat{W}^{\mu\nu} u^\dagger + u^\dagger \hat{B}^{\mu\nu} u)) \]

\[ + \frac{1}{2\sqrt{2}} F_A \text{Tr}(A^{\mu\nu}(u \hat{W}^{\mu\nu} u^\dagger - u^\dagger \hat{B}^{\mu\nu} u)) \]

Specific UV completions of this effective theory correspond to specific choices of the free parameters.
EWPO with Resonances

- Tree-level positive contribution to $S$:
  - (worsens the agreement with EWPO)
- At 1-loop level potentially large (quadratically divergent) positive contribution to $T$
- One-loop breaking of the custodial symmetry due to $g' \neq 0$

$$\Delta S = g^2 \left( \frac{F_V^2}{4m_V^2} - \frac{F_A^2}{4m_A^2} \right)$$

$$\Delta T = \frac{3\pi\alpha}{e_W^2} \left[ \frac{F_A^2}{4m_A^2} + \left( \frac{F_V - 2G_V}{2m_V} \right)^2 \right] \frac{\Lambda^2}{16\pi^2v^2} + \ldots$$
Producing the heavy vectors at the LHC

Main properties of axial fields

- $O(m_A^3)$ widths only from $A \rightarrow VW$
  - [mediated by effective ops. with two heavy fields $A[\partial V, \partial U]$, not included in $L_{\text{int}}$]
  - potentially suppressed if $m_A \approx m_V$
  - $\Gamma_A^{V+W-} = \Gamma_A^{V-W+} = \Gamma_A^{V\rightarrow W+} = \Gamma_A^{V\rightarrow Z} \approx \Gamma_A^{VW}$
  - $\Gamma_A^{VW} = \frac{m_A^3}{48\pi v^2} (1 - r^2)^3 \left[ g_A^2 (1 + 2r^2) + g_V^2 \left( 1 + \frac{2}{r^2} \right) + 6g_A g_V \right]$

- $O(m_A)$ widths of the type $A \rightarrow$ longitudinal + transverse SM gauge bosons,
  - $\Gamma_A^{WW} = \frac{g^2 F_A^2 m_A}{192\pi v^2}$, $\Gamma_A^{WZ} = \frac{1}{2} \Gamma_A^{WW} \left[ 1 + \frac{(1 - 2s_W^2)^2}{c_W^2} \right]$, $\Gamma_A^{W \gamma} = 2s_W^2 \Gamma_A^{WW}$

- leading decay modes if $m_A \approx m_V$

- Decay widths to SM fermions identical to the vector case, with corresponding BR enhanced by the suppression of the total rate
Producing the heavy vectors at the LHC

A potentially clean signal (if the resonances are not too heavy) is the Drell-Yan production of the resonances and subsequent decay into $l^+l^-$, 2 and 3 SM heavy gauge bosons

easy to estimate (and simulate) normalizing the non-standard rate to SM Drell-Yan processes at the partonic level
Producing the heavy vectors at the LHC

E.g. for charged final states we define the form factor

\[ F_f^{R^+}(q^2) = \frac{\sigma(ud \to R^+ \to f)}{\sigma(ud \to \mu^+\nu)_{\text{SM}}} \]

\[
\frac{d}{dq^2} \sigma(pp \to R^+ \to f) = F_f^{R^+}(q^2) \frac{d}{dq^2} \sigma(pp \to \mu^+\nu)_{\text{SM}}
\]

As long as we can neglect interference effects (with SM or among different resonant contributions), the partonic resonant width is simply given by

\[
\sigma(q_i\bar{q}_j \to R \to f) = \frac{12\pi\Gamma_R^2 Br_{R_{\text{in}}} Br_R^f}{(q^2 - m_R^2)^2 + m_R^2 \Gamma_R^2} \left[ 1 + \mathcal{O}\left(\frac{q^2 - m_R^2}{m_R^2}\right) \right]
\]
Signal of heavy vectors at the Tevatron?

- The $l^+l^-$ state of the art is the analysis of the $e^+e^-$ final state in $p$-$p\overline{p}$ collisions published by CDF.

- The "2\sigma excess" can be fitted nicely by a light vector resonance:
  - $m_V \approx 246$ GeV
  - $F_V \approx 50$ GeV

- Predictions derived within the effective theory:
  - similar peak also in the $\mu^+\mu^-$ final state
  - axial state with $m_A \approx 1.3$ TeV to obtain a good EWPO fit

CDF [0810.2059]

Cata, Isidori & J.F.K [0905.0490]

excluded by CDF [0811.0053]
Early LHC Reach

At energies of 4TeV, 5TeV per beam

Reach in di-lepton channels statistics dominated!

Need $O(1fb^{-1})$ of data to surpass current Tevatron limits
Signals for heavy vectors at the LHC

- Two & three SM gauge boson final states

A detailed estimate of the realistic efficiency for the detection of the heavy vectors in these final states $[WZ, WW] + [WWW, WWZ, WZZ]$ has not been performed yet. So far we have analysed only the signal against the irreducible SM background = same e.w. final state.

Selecting leptonic decay is a high price to pay (in terms of efficiencies), but it should ensure a good rejection against non-irreducible backgrounds.

Some reference theoretical efficiencies:

- $[WZ] \ BrZ_{\text{lept}} \times BrW_{\text{lept}} = 1.5\%$
- $[WWZ] \ BrZ_{\text{lept}} \times BrW_{\text{lept}} \times BrW_{\text{had}} = 0.9\%$
- $[WZZ] \ BrZ_{\text{lept}} \times BrW_{\text{lept}} \times BrZ_{\text{had}} = 1\%$
- $[WZZ] \ (BrZ_{\text{lept}})^3 \times BrZ_{\text{had}} = 0.4\%$
- $[WWW] \ (BrW_{\text{lept}})^3 = 1\%$
Signals for heavy vectors at the LHC

- In the WWZ final state it is also worth to look at the WZ invariant-mass distribution.

- With high statistics (100 fb$^{-1}$), here we can hope to see a signal even without a light axial vector.