Heavy Vector Searches at the LHC

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in collaboration with D. Pappadopulo, R. Torre and A. Wulzer
based on arXiv:1402.4431 and work in progress
Heavy Vector Resonances

- heavy vectors among the most motivated direct searches
- since they appear in many NP models

<table>
<thead>
<tr>
<th></th>
<th>$SU(3)_C$</th>
<th>$SU(2)_L$</th>
<th>$U(1)_Y$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B_{\mu}$</td>
<td>1</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>$B_{1\mu}$</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>$L_{\mu}$</td>
<td>1</td>
<td>2</td>
<td>$-3/2$</td>
</tr>
<tr>
<td>$W_{\mu}$</td>
<td>1</td>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td>$W_{1\mu}$</td>
<td>1</td>
<td>3</td>
<td>1</td>
</tr>
</tbody>
</table>

[del Aguila, de Blas, Perez-Victoria, arXiv:1005.3998]

- various colourless vectors

- simplified model approach

- weakly coupled models
  - $Z'$ models,
  - sequential $W'$, …

- strongly coupled models
  - Composite Higgs models

- singlets (work in progress)
- no coupling to quarks
- studied here!
- no coupling to fermions
Simplified Lagrangian can be matched to explicit models

Simplified Lagrangian parameters $c$ fixed in terms of explicit model parameters $p$

Limit on $\sigma \times BR$

Translate limits into bounds on simplified model parameters
The simplified Lagrangian can be matched to explicit models. Parameters $c$ in the simplified model are fixed in terms of explicit model parameters $p$. This allows for the translation of limits into bounds on the simplified model parameters. The bounds are extremely general and can be easily used in everyone’s favorite model.

Bridge
Phenomenological Lagrangian

\[ \mathcal{L}_V = -\frac{1}{4} D_\mu V_\nu^a D^{\mu \nu} V^a a + \frac{m_V^2}{2} V_\mu^a V^a \mu \]

\[ + ig V c_H V_\mu^a H^\dagger \tau^a D^\mu H + \frac{g^2}{g_V} c_F V_\mu^a J_F^{\mu a} \]

\[ + \frac{g V}{2} c_{VVV} \epsilon_{abc} V_\mu^a V_\nu^b D^{\mu \nu} V^c + g^2 c_{VVH} V_\mu^a V^a \mu H^\dagger H - \frac{g}{2} c_{VWW} \epsilon_{abc} W^{\mu \nu} V_\mu^a V_\nu^b V^c \]

Coupling to SM Vectors

\[ V_\mu \sim g_V c_H \]

\[ W_L, Z_L, h \]

Coupling to SM fermions

\[ J_F^{\mu a} = \sum_f \bar{f}_L \gamma^\mu \tau^a f_L \]

\[ c_F V \cdot J_F \rightarrow c_V \mu \cdot J_1 + c_q V \cdot J_1 + c_3 V \cdot J_3 \]

\[ \sim \frac{g^2}{g_V} c_F \]

\[ f \]

\[ \bar{f} \]
Phenomenological Lagrangian

\[
\mathcal{L}_V = -\frac{1}{4} D_{[\mu} V^a_{\nu]} D^{[\mu} V_{\nu]} a + \frac{m^2}{2} V^a_{\mu} V^{\mu a} V = (V^+, V^-, V^0)
\]

\[
+ i g_V c_H V^a_{\mu} H^\dagger a \tau^{a \mu} H + \frac{g^2}{g_V} c_F V^a_{\mu} J^{\mu a}_F
\]

\[
+ \frac{g_V}{2} c_{VVV} \epsilon_{abc} V^a_{\mu} V^b_{\nu} D^{[\mu} V_{\nu]} c + g_V^2 c_{VVH} H V^a_{\mu} V^{\mu a} H^\dagger H - \frac{g}{2} c_{VW} \epsilon_{a} W^\mu \nu a V^b_{\mu} V^c_{\nu}
\]

- Couplings among vectors
- do not contribute to V decays
- do not contribute to single production
- only effects through (usually small) VW mixing
- irrelevant for phenomenology
- only need \((c_H, c_F)\)
\[
\mathcal{L}_V = -\frac{1}{4} D[\mu V^a_\nu] D[^\mu V^\nu] a + \frac{m^2_V}{2} V^a_\mu V^\mu a \\
+ i g_V c_H V^a_\mu H^\dagger \tau^a D H + \frac{g^2}{g_V} c_F V^a_\mu J^\mu_F a \\
+ \frac{g_V}{2} c_{VVV} \epsilon_{abc} V^a_\mu V^b_\nu D[^\mu V^\nu] c + g^2_{VHH} c_{VVV} V^a_\mu V^\mu a H^\dagger H - \frac{g}{2} c_{VVW} \epsilon_{abc} W^{\mu \nu} V^a_\mu V^b_\nu V^c_\nu
\]

**Weakly coupled model**

\( g_V \) typical strength of V interactions

\( g_V \sim g \sim 1 \)

\( c_i \) dimensionless coefficients

\( c_H \sim -g^2/g_V^2 \) and \( c_F \sim 1 \)

**Strongly coupled model**

\( 1 \leq g_V \leq 4\pi \)

\( c_H \sim c_F \sim 1 \)
Production rates

- DY and VBF production

\[ \sigma_{DY} = \sum_{i,j \in p} \frac{\Gamma_{V \rightarrow ij}}{M_V} \frac{4\pi^2}{3} \frac{dL_{ij}}{d\hat{s}} \]

\[ \sigma_{VBF} = \sum_{i,j \in p} \frac{\Gamma_{V \rightarrow W_L i W_L j}}{M_V} \frac{48\pi^2}{d\hat{s}} \frac{dL_{W_L i W_L j}}{d\hat{s}} \]

- can compute production rates analytically
- easily rescale to different points in parameter space

quark initial state

vector boson initial state
Decay widths

- relevant decay channels: di-lepton, di-quark, di-boson

\[ \Gamma_{V \pm \to f \bar{f}'} \simeq 2 \Gamma_{V_0 \to f \bar{f}} \simeq N_c[f] \left( \frac{g^2 c_F}{g_V} \right)^2 \frac{M_V}{96\pi}, \]

\[ \Gamma_{V_0 \to W_L^+ W_L^-} \simeq \Gamma_{V_\pm \to W_L^\pm Z_L} \simeq \frac{g_V^2 c_H^2 M_V}{192\pi} \left[ 1 + \mathcal{O}(\zeta^2) \right] \]

\[ \Gamma_{V_0 \to Z_L h} \simeq \Gamma_{V_\pm \to W_L^\pm h} \simeq \frac{g_V^2 c_H^2 M_V}{192\pi} \left[ 1 + \mathcal{O}(\zeta^2) \right] \]

Weakly coupled model

\[ g_V c_H \simeq g^2 c_F / g_V \simeq g^2 / g_V \]

![Graph for Model A](image)

Strongly coupled model

\[ g_V c_H \simeq -g_V, \quad g^2 c_F / g_V \simeq g^2 / g_V \]

![Graph for Model B](image)
**LHC bounds**

**Weakly coupled model**
- theoretically excluded
- exclusions up to 1.5 TeV

**Strongly coupled model**
- di-lepton most stringent
- di-boson searches < 1-2 TeV

- excluded for masses < 1.5 TeV
- unconstrained for larger $g_V$
- di-boson most stringent
- in excluded region $G_F$, $m_Z$ not reproduced
Heavy Vector Resonances

- many searches at 8 and 13 TeV
• experimental limits converted into \((c_H, c_F)\) plane

• \(l\nu\) dominates
• EWPT not competitive
• only \(-1 \lesssim c_F \lesssim 1\) allowed

• EWPT become comparable
• di-bosons more and more relevant
• strongly coupled model evades bounds from direct searches

[References: Pappadopulo, Thamm, Torre, Wulzer, arXiv:1402.4431]
Limits on parameter space

- **ATLAS:**
  - $W'$ to $WZ$
  
- **ATLAS:**
  - $V'$ to $HV$ to $(bb)(lep lep)$

- **CMS:**
  - $Z'$ to $HZ$ to $(tau tau)(qq)$

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yellow: CMS $l^+\nu$ analysis

dark blue: CMS $WZ \rightarrow 3l\nu$

light blue: CMS $WZ \rightarrow jj$

black: bounds from EWPT
**Combination of searches**

- simplified model makes combination of searches easy

\[ V^0 \in (1,3)_1 \quad V^+ \in (1,3)_1 \]

<table>
<thead>
<tr>
<th>Channel</th>
<th>Final states</th>
</tr>
</thead>
<tbody>
<tr>
<td>( ll )</td>
<td>( l\ell q\ell )</td>
</tr>
<tr>
<td>( lv )</td>
<td>( l\ell l\ell , l\ell q\ell , qqq )</td>
</tr>
<tr>
<td>( l\nu_R )</td>
<td>( l\nu l\nu l\nu , uu )</td>
</tr>
<tr>
<td>( jj )</td>
<td>( \gamma\ell )</td>
</tr>
<tr>
<td>( tb )</td>
<td>( { bb, \pi\pi, \gamma\gamma } \otimes { bb, \pi\pi, \gamma\gamma } )</td>
</tr>
<tr>
<td>( tt )</td>
<td>( { bb, \pi\pi, \gamma\gamma } \otimes { bb, \pi\pi, \gamma\gamma } )</td>
</tr>
<tr>
<td>( WW )</td>
<td>( { bb, \pi\pi, \gamma\gamma } \otimes { bb, \pi\pi, \gamma\gamma } )</td>
</tr>
<tr>
<td>( ZZ )</td>
<td>( { bb, \pi\pi, \gamma\gamma } \otimes { bb, \pi\pi, \gamma\gamma } )</td>
</tr>
<tr>
<td>( Zh )</td>
<td>( { bb, \pi\pi, \gamma\gamma } \otimes { bb, \pi\pi, \gamma\gamma } )</td>
</tr>
<tr>
<td>( WZ )</td>
<td>( { bb, \pi\pi, \gamma\gamma } \otimes { bb, \pi\pi, \gamma\gamma } )</td>
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<tr>
<td>( Wh )</td>
<td>( { bb, \pi\pi, \gamma\gamma } \otimes { bb, \pi\pi, \gamma\gamma } )</td>
</tr>
<tr>
<td>( W\gamma )</td>
<td>( { bb, \pi\pi, \gamma\gamma } \otimes { bb, \pi\pi, \gamma\gamma } )</td>
</tr>
<tr>
<td>( hh )</td>
<td>( { bb, \pi\pi, \gamma\gamma } \otimes { bb, \pi\pi, \gamma\gamma } )</td>
</tr>
</tbody>
</table>
Limit setting
• want limits on $\sigma \times BR$ since model-independent can be easily reinterpreted
• but depends on details of analysis (assumed total width of resonance)
• discuss two (well known, but often forgotten) effects
• example: di-lepton invariant mass distribution

2 TeV resonance

3.5 TeV resonance
1. Interference with SM background

- depends on S/B ratio
- dashed green: signal + background with no interference
- green shaded region: constructive and destructive interference
- can be large effect
- interference vanishes exactly at $\hat{s} = M_V^2$, is odd around this point
- $[M_V - \Gamma, M_V + \Gamma]$ less sensitive

\[
\hat{s}_1(\hat{s}) \propto \frac{\hat{s} - M_V^2}{(\hat{s} - M_V^2)^2 + M_V^2 \Gamma^2}
\]

[Accomando, Becciolini, Balyaev, Moretti, Shepherd, arXiv:1304.6700]
[Accomando, Becciolini, de Curtis, Dominici, Fedeli, Shepherd, arXiv:1110.0713]
1. Interference with SM background

- parameterize interference as
  \[
  \left( y, 1 - \frac{\sigma_{\text{Full}}(y)}{\sigma_{BW}} \right)
  \]
  within mass window, deviation is < 10%

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[Accomando, Becciolini, Balyaev, Moretti, Shepherd, arXiv:1304.6700 ]
[Accomando, Becciolini, de Curtis, Dominici, Fedeli, Shepherd, arXiv:1110.0713]
2. Distortion from BW

- due to steep fall of parton luminosities at large energies
- total BW cross section

\[
\frac{d\sigma_S}{dM^2_{l^+l^-}} = \sum_{i,j} \frac{4\pi}{3} \frac{\Gamma_{V \rightarrow q_i q_j} \Gamma_{V \rightarrow l^+l^-}}{(M^2_{l^+l^-} - M_V^2)^2 + M_V^2 \Gamma^2} M^2_{l^+l^-} \frac{dL_{ij}}{d\hat{s}} \bigg|_{\hat{s}=M^2_V} \sim \frac{dL_{ij}}{d\hat{s}} \bigg|_{\hat{s}=M^2_V}
\]

- in peak region only  \( M_{l^+l^-} - M_V \sim \Gamma \)

\[
\frac{d\sigma_S}{dM^2_{l^+l^-}} = \sigma \times BR_{V \rightarrow l^+l^-} \times BW(M^2_{l^+l^-}; M_V, \Gamma)
\]
2. Distortion from BW

- Assumption depends on variation of parton luminosities
  \[ \frac{M_{l^+l^-}^2}{M_V^2} \frac{dL_{ij}}{d\hat{s}} \left|_{\hat{s}=M_{l^+l^-}^2} \right. \approx \frac{dL_{ij}}{d\hat{s}} \left|_{\hat{s}=M_V^2} \right. \]

- Agreement better for small width
- Parton luminosities decrease faster at larger masses
- However, in peak region deviation < 10%
**Limit setting**

**Conclusion**

- only limits set on peak region give model independent bounds (give bounds on $\sigma \times BR$ for each mass and width)
- searches sensitive to the tail only valid in the assumed model, not reusable
Conclusions

- model independent strategy to study heavy spin-1 triplets

- extremely useful to present results in terms of simplified model parameters allows easy reinterpretation

- limits should be set on $\sigma \times BR$ by focusing on the on-shell region