Heavy Vectors
at the LHC and Future Colliders

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Based on 1402.4431, 1502.01710, 2207.05091, 2404…
In collaboration with M. Baker, D. Pappadopulo, T. Martonhelyi, R. Torre, A. Wulzer
Outline

1. Theory motivation
2. Heavy vector triplets
3. Heavy vector singlets
4. Heavy vectors at future colliders
5. Conclusions
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1. Theory motivation
2. Heavy vector triplets
3. Heavy vector singlets
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Theory Motivation

Heavy vectors appear in many new physics models

Weakly coupled

$Z'$ models,
$W_R$ extensions, ...

Strongly coupled

$\rho_R$ in composite Higgs models

They have been studied and searched for extensively

Simplified model approach

• Captures features of weakly and strongly coupled explicit models

Simplified Lagrangian can be matched to explicit models

- bounds are extremely general
- can be easily used in everyone’s favourite model

**Theorey Motivation**

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

Translate limits into bounds on simplified model parameters

Limit on $\sigma \times BR$
Theory Motivation

Heavy vectors appear in many new physics models

- Weakly coupled
  - $Z'$ models,
  - $W_R$ extensions, ...

- Strongly coupled
  - $\rho_R$ in composite Higgs models

They have been studied and searched for extensively

Simplified model approach

- Captures features of weakly and strongly coupled explicit models
- Production via vector boson fusion had never been studied
- Updated LHC limits
- Compare projections for different future colliders
Theory Motivation

Various colourless vectors

<table>
<thead>
<tr>
<th></th>
<th>$SU(3)_C$</th>
<th>$SU(2)_L$</th>
<th>$U(1)_Y$</th>
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<tr>
<td>$B^0_\mu$</td>
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<td>$B^1_\mu$</td>
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<td>1</td>
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<td>$W^0_\mu$</td>
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</tr>
<tr>
<td>$W^1_\mu$</td>
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<td>1</td>
</tr>
</tbody>
</table>

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

Heavy vector singlets (HVS)
[Baker, Martonhelyi, Thamm, Torre: 2404…]

Heavy vector triplets (HVT)
[Pappadopulo, Thamm, Torre, Wulzer: 1402.4441]
[Baker, Martonhelyi, Thamm, Torre: 2207.05091]

No coupling to quarks

No coupling to fermions
Outline

1. Theory motivation
2. Heavy vector triplets
3. Heavy vector singlets
4. Heavy vectors at future colliders
5. Conclusions
1. Theory motivation

2. Heavy vector triplets
   - Simplified model Lagrangian
   - Drell-Yan and VBF production
   - Decay
   - Limits on simplified parameter space

3. Heavy vector singlets

4. Heavy vectors at future colliders

5. Conclusions
HVT - Simplified Model Lagrangian

Simplified Model for Heavy Vector Triplets

\[ \mathcal{L}_V = -\frac{1}{4} D_{\mu\nu} V^a D^{\mu\nu} V^a + \frac{m^2}{2} V^a V^a + i g_V c_H V^a \bar{H}^{\dagger a} \sigma^{\mu a} \mathcal{D}_\mu H \]

\[ + \frac{g^2}{g_V} c_F \bar{V}^a J^a \]

\[ + \frac{g_V}{2} c_{VVV} \epsilon_{abc} V^a \bar{V}^b D_{\mu\nu} V^c \]

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

\[ V = (V^+, V^-, V^0) \]

Coupling to SM vectors

\[ \sim g_V c_H \]

\[ V_\mu \]

\[ W_L, Z_L, h \]

Coupling to SM fermions

\[ J^{\mu a}_F = \sum_f \bar{f}_L \gamma^{\mu a} f_L \]

\[ f \]

\[ \sim \frac{c_F}{g_V} \]

\[ \bar{f} \]

\[ c_F V \cdot J_F \rightarrow c_1 V \cdot J_1 + c_q V \cdot J_q + c_3 V \cdot J_3 \]

[Pappadopulo, Thamm, Torre, Wulzer: 1402.4431]
HVT - Simplified Model Lagrangian

Simplified Model for Heavy Vector Triplets

\[ \mathcal{L}_V = -\frac{1}{4} D_{\mu V a} D^{\nu \mu V a} + \frac{m_{V a}^2}{2} V_{\mu}^a V_{\mu}^a + \frac{g^2}{g_{V}} c_F V_{\mu}^a J_{\mu}^a a \]

\[ \mathcal{L}_V = V = (V^+, V^-, V^0) \]

- Couplings among vectors
- Do not contribute to single production
- Do not contribute to V decays
- Only effect through (usually small) VW mixing

\[ \text{irrelevant for phenomenology} \quad \text{only need} \quad (c_H, c_F) \]

[Pappadopulo, Thamm, Torre, Wulzer: 1402.4431]
HVT - Simplified Model Lagrangian

Simplified Model for Heavy Vector Triplets

\[ \mathcal{L}_V = -\frac{1}{4} D_{[\mu} V^a_{\nu]} D^{[\mu} V^{\nu]} a + \frac{m_V^2}{2} V^a_{\mu} V^a_{\mu} + \frac{g^2}{g_V} c_F V^a_{\mu} J^a_{\mu} + \frac{g_V}{2} c_H V^a_{\mu} V^a_{\nu} D^{[\mu} V^{\nu]} c + \frac{g^2}{g_V} c_V V_H H V^a_{\mu} V^a_{\mu} H^\dagger H - \frac{g}{2} c_V V W \epsilon_{abc} W^\mu V^a_{\mu} V^b V^c \]

Weakly coupled model

\[ g_V \sim g \sim 1 \]

\[ c_H \sim -g^2 / g_V^2 \quad \text{and} \quad c_F \sim 1 \]

Strongly coupled model

\[ 1 < g_V \leq 4\pi \]

\[ c_H \sim c_F \sim 1 \]

[Paadopulo, Thamm, Torre, Wulzer: 1402.4431]
HVT - Production

Drell-Yan production

Vector boson fusion
Narrow width approximation: $\Gamma_{\text{tot}} \lesssim 0.15 \, M_V$

Production cross-section of narrow resonance:

$$\sigma(pp \to V + X) = \sum_{i,j \in p} \frac{\Gamma_{V \to ij}}{M_V} \frac{16\pi^2(2J + 1)C}{(2S_i + 1)(2S_j + 1)C_iC_j} \frac{dL_{ij}}{ds} \bigg|_{\hat{s} = M_V^2}$$

Drell-Yan

$$\text{DY} = \frac{4\pi^2}{3}$$

Vector boson fusion

$$\text{VBF} = 48\pi^2$$

Ratio

$$\frac{\text{VBF}}{\text{DY}} = 36$$
Narrow width approximation: $\Gamma_{\text{tot}} \lesssim 0.15 M_V$

Production cross-section of narrow resonance:

$$\sigma(pp \to V + X) = \sum_{i,j \in p} \frac{\Gamma_{V \to ij}}{M_V} \frac{16\pi^2(2J + 1)}{(2S_i + 1)(2S_j + 1)} \frac{C}{C_i C_j} \left. \frac{dL_{ij}}{d\hat{s}} \right|_{\hat{s} = M_V^2}$$
Narrow width approximation: $\Gamma_{\text{tot}} \lesssim 0.15 \, M_V$

Production cross-section of narrow resonance:

$$\sigma(pp \to V + X) = \sum_{i,j \in p} \frac{\Gamma_{V \to i_j}}{M_V} \left| \frac{16\pi^2(2J + 1)}{(2S_i + 1)(2S_j + 1)} \frac{C_i}{C_j} \frac{dL_{ij}}{ds} \right|_{s=M_V^2}$$

Partial widths

$$\Gamma_{V^\pm \to W_L^\pm Z_L} \simeq \Gamma_{V^0 \to W_L^+ W_L^-} \simeq \Gamma_{V^\pm \to W_{L\pm} h} \simeq \Gamma_{V^0 \to Z_L h} \simeq \frac{g_V^2 c_H^2 M_V}{192\pi}$$

$$\Gamma_{V^\pm \to q\bar{q}'} \simeq 2\Gamma_{V^0 \to q\bar{q}} \simeq \frac{g^2 M_V}{16\pi} \frac{g^2}{g_V^2} c_q$$

Ratio

$$\frac{\Gamma_{V^\pm \to W_L^\pm Z_L}}{\Gamma_{V^\pm \to q\bar{q}'}} \simeq \frac{1}{2} \frac{\Gamma_{V^0 \to W_L^+ W_L^-}}{\Gamma_{V^0 \to q\bar{q}}} = \frac{1}{12} \frac{g_V^4}{g^4} \frac{c_H^2}{c_q^2} \quad \frac{c_H}{c_q} \sim 3, \frac{c_q}{g_V} \lesssim 0.05$$
HVT - Production

Narrow width approximation: \( \Gamma_{\text{tot}} \lesssim 0.15 \, M_V \)

Production cross-section of narrow resonance:

\[
\sigma(pp \to V + X) = \sum_{i,j \in p} \frac{\Gamma_V \to i_j}{M_V} \frac{16\pi^2 (2J + 1)}{(2S_i + 1)(2S_j + 1)} \frac{C}{C_i C_j} \frac{dL_{ij}}{d\hat{s}} \bigg|_{\hat{s}=M_V^2}
\]

Partial widths

\[
\begin{align*}
\Gamma_{V^\pm \to W_L^\pm Z_L} &\simeq \Gamma_{V^0 \to W_L^+ W_L^-} \simeq \Gamma_{V^\pm \to W_L^\pm h} \simeq \Gamma_{V^0 \to Z_L h} \simeq \frac{g_V^2 c_H^2 M_V}{192\pi} \\
\Gamma_{V^\pm \to q\bar{q}'} &\simeq 2\Gamma_{V^0 \to q\bar{q}} \simeq \frac{g^2 M_V}{16\pi} \frac{g^2}{g_V^2} \left[ c_q^2 \left( 1 - c_H^2 \frac{g^2}{g_V^2} \zeta^4 \right) + 2c_q c_H \zeta^2 \left( 1 + \frac{g^2}{g_V^2} \zeta^2 \right) + c_H^2 \zeta^4 \right]
\end{align*}
\]

Putting everything together - Ratio for \( c_q = 0 \)

\[
\frac{\text{VBF}}{\text{DY}} \sim 0.4 \text{ at } 1 \text{ TeV} \\
\frac{\text{VBF}}{\text{DY}} \sim 3.2 \text{ at } 2 \text{ TeV}
\]
HVT - Production

Ratio of VBF to DY production cross-section

[Baker, Martonhelyi, Thamm, Torre: 2207.05091]
HVT - Decay

Branching ratios

Di-boson decay > di-jet decay
Di-jet generally irrelevant for VBF studies
Di-lepton and 3rd generation quarks enter with independent couplings

[Baker, Martonhelyi, Thamm, Torre: 2207.05091]
HVT - Limits on simplified parameter space

Benchmark parameter points

- VBF-DB (Di-Boson) Benchmark
  \[ g_V c_H = 4, \ c_\ell / g_V = 0, \ c_q / g_V = c_{q3} / g_V = 0 \]

- VBF-DL (Di-Lepton) Benchmark
  \[ g_V c_H = 3, \ c_\ell / g_V = -3, \ c_q / g_V = c_{q3} / g_V = 0 \]

[Baker, Martonhelyi, Thamm, Torre: 2207.05091]

VBF benchmark in CMS and ATLAS papers: \[ g_V = 1, \ c_H = 1, \ c_\ell = 0, \ c_q = c_{q3} = 0 \]

- Smaller production cross-section than VBF-DB
- \( c_q = 0 \) does not imply vanishing DY
HVT - Limits on simplified parameter space

Existing ATLAS and CMS searches considering DY and VBF production at $L = 140 \text{ fb}^{-1}$

<table>
<thead>
<tr>
<th>Channel</th>
<th>Reference</th>
</tr>
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<tbody>
<tr>
<td>$WZ \rightarrow \ell\nu\ell'\ell'$</td>
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<td>$WW, WZ \rightarrow \text{leptons hadrons}$</td>
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<td>$\ell\nu$</td>
<td>[50, 51]</td>
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<td>$\tau\nu$</td>
<td>[52]</td>
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</table>
Existing ATLAS and CMS searches considering DY and VBF production at $L = 140 \text{ fb}^{-1}$

Currently, similar limits but VBF more promising in the future
Existing ATLAS and CMS searches considering DY and VBF production at $L = 140 \text{ fb}^{-1}$

VBF outperforms DY at 1.5 TeV and is only sensitive probe at larger masses
HVT - Limits on simplified parameter space

Projections for HL-LHC at 14 TeV with 3 ab$^{-1}$

Significantly higher mass reach in VBF than DY

[Baker, Martonhelyi, Thamm, Torre: 2207.05091]
Ratio of VBF to DY production cross-section

Drell-Yan production

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HVT - Limits on simplified parameter space

Take experimental searches to put limits on simplified model parameter space
HVT - Limits on simplified parameter space

Take experimental searches to put limits on simplified model parameter space

yellow: CMS $\ell^+\nu$ analysis
dark blue: CMS $WZ \rightarrow 3\ell\ell$
light blue: CMS $WZ \rightarrow jj$
black: bounds from EWPT

ATLAS: $W'$ to $WZ$

CMS $Z'$ to $HZ$ to $\tau\tau$ (qq)

ATLAS: $V'$ to HV to (bb)(lep lep)

[Pappadopulo, Thamm, Torre, Wulzer, arXiv:1402.4431]
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1. Theory motivation
2. Heavy vector triplets
3. Heavy vector singlets
   • Simplified model Lagrangian
   • Drell-Yann production and decay
   • Limits on simplified parameter space
   • Matching onto explicit models
4. Heavy vectors at future colliders
5. Conclusions
HVS - Simplified Model Lagrangian

Simplified Model for Heavy Vector Singlets

\[ \mathcal{L}_{\mathcal{V}^+} = -\frac{1}{2} D_{[\mu} \mathcal{V}^+_{\nu]} D^{[\mu} \mathcal{V}^{-\nu]} + m_{\mathcal{V}^+}^2 \mathcal{V}^+_{\mu} \mathcal{V}^{-\mu} \]

\[ -i \frac{g_V}{\sqrt{2}} c_H^+ \mathcal{V}^+_{\mu} H^\dagger D^\mu D \tilde{H} + \frac{g_V}{\sqrt{2}} c_q^+ \mathcal{V}^+_{\mu} J_{q}^\mu + \text{h.c.} \]

\[ + 2g_V^2 c_{V VH}^0 \mathcal{V}^0_{\mu} \mathcal{V}^{-\mu} H^\dagger H + ig' c_{V VB}^+ \mathcal{V}^+_{\nu} \mathcal{V}^{-\nu} + \text{h.c.} \]

\[ \mathcal{L}_{\mathcal{V}^0} = -\frac{1}{4} \partial_{[\mu} \mathcal{V}^0_{\nu]} \partial^{[\mu} \mathcal{V}^0_{\nu]} + \frac{m_{\mathcal{V}^0}^2}{2} \mathcal{V}^0_{\mu} \mathcal{V}^0_{\mu} + \]

\[ + i \frac{g_V}{2} c_H^0 \mathcal{V}^0_{\mu} H^\dagger D^\mu D H + \sum_{\Psi=Q,L,U,D,E} \frac{g_V}{2} c_{\Psi}^0 \mathcal{V}^0_{\mu} J_{\Psi} + \]

\[ + g_V^2 c_{V VH}^0 \mathcal{V}^0_{\mu} \mathcal{V}^0_{\mu} H^\dagger H , \]

\[ \mathcal{L}_{\text{mix}} = ig_V c_{V VH}^+ D_{[\mu} \mathcal{V}^-_{\nu]} \mathcal{V}^0_{\mu} \mathcal{V}^+_{\nu} + \text{h.c.} + ig_V c_{V VH}^0 \partial_{[\mu} \mathcal{V}^0_{\nu]} \mathcal{V}^+_{\mu} \mathcal{V}^{-\nu} \]

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HVS - Simplified Model Lagrangian

Simplified Model for Heavy Vector Singlets

$$ \mathcal{L}_{\nu^+} = -\frac{1}{2} D_{[\mu} \nu^+ D^{[\mu} \nu^-] + m_{\nu^+}^2 \nu^+ \nu^- $$

$$ -i \frac{g V}{\sqrt{2}} c_H^+ \nu_\mu^+ H^\dagger \tilde{D}^\mu \tilde{H} + \frac{g V}{\sqrt{2}} c_q^+ \nu_\mu^+ J_q^\mu + \text{h.c.} $$

$$ + 2 g_V^2 c_{V VH}^+ \nu_\mu^+ \nu^- H^\dagger H + i g' c_{V VB}^+ B_{\mu \nu} \nu^+ \nu^- \nu $$

$$ J_q^\mu = \sum_{i=1}^{3} \bar{U}^i \gamma^\mu D^i $$

$$ \mathcal{L}_{\nu^0} = -\frac{1}{4} \partial_{[\mu} \nu^0 \partial^{[\mu} \nu^0 \nu] + \frac{m_{\nu^0}^2}{2} \nu^0 \nu^0 $$

$$ + i \frac{g V}{2} c_H^0 \nu_\mu^0 H^\dagger D^\mu H + \sum_{\Psi=Q,L,U,D,E} \frac{g V}{2} c_{\Psi}^0 \nu_\mu^0 J_{\Psi}^\mu $$

$$ + g_V^2 c_{V VH}^0 \nu_\mu^0 \nu^0 H^\dagger H $$

$$ J_{\Psi}^\mu = \sum_{i=1}^{3} \bar{\Psi}^i \gamma^\mu \Psi^i $$

Coupling to SM vectors

$V_\mu \sim g_V c_H^+ + g_V c_H^0$ for $W_L, Z_L, h$

Coupling to SM fermions

$V_\mu \sim g_V c_q^+ + g_V c_\Psi^0$ for $f, \bar{f}$
HVS - Simplified Model Lagrangian

Simplified Model for Heavy Vector Singlets

\[ \mathcal{L}_{\mathcal{V}^+} = -\frac{1}{2} D_{[\mu} \mathcal{V}^+_{\nu]} D^{\mu\nu} + m_{\mathcal{V}^+}^2 \mathcal{V}^+ \mathcal{V}^- - \frac{g_V}{\sqrt{2}} c_H^+ \mathcal{V}^+ H^\dagger D^{\mu} \mathcal{H} + \frac{g_V}{\sqrt{2}} c_q^+ \mathcal{V}^+ J^\mu_{q} + \text{h.c.} + 2g_V^2 c_{\mathcal{V}^+ \mathcal{V}^0} \mathcal{V}^- H^\dagger H + ig' c_{\mathcal{V}^+ \mathcal{V}^0} \mathcal{V}^+ \mathcal{V}^- \nu \]

\[ \mathcal{L}_{\mathcal{V}^0} = -\frac{1}{4} \partial_{[\mu} \mathcal{V}^0_{\nu]} \partial^{[\mu} \mathcal{V}^0_{\nu]} + \frac{m_{\mathcal{V}^0}^2}{2} \mathcal{V}^0 \mathcal{V}^{0\mu} + i \frac{g_V}{2} c_H^0 \mathcal{V}^0 H^\dagger D^\mu H + \sum_{\Psi=Q,L,U,D,E} \frac{g_V}{2} c_{\Psi}^0 \mathcal{V}^0 J^\mu_{\Psi} + g_V^2 c_{\mathcal{V}^+ \mathcal{V}^0} \mathcal{V}^0 H^\dagger H, \]

\[ \mathcal{L}_{\text{mix}} = ig_V c_{\mathcal{V}^+ \mathcal{V}^0} D_{[\mu} \mathcal{V}^+_{\nu]} \mathcal{V}^0 \mathcal{V}^{+\nu} + \text{h.c.} + ig_V c_{\mathcal{V}^+ \mathcal{V}^0} \partial_{[\mu} \mathcal{V}^0_{\nu]} \mathcal{V}^+ \mathcal{V}^{-\nu} \]

- irrelevant for phenomenology → only need \((c_H, c_F)\)
Simplified Model for Heavy Vector Singlets

\[ \mathcal{L}_{\nu^+} = -\frac{1}{2} D_{[\mu} \nu^{+} D_{\nu]}^{\mu} \nu^{-\mu} + m_{\nu^+}^2 \nu_{\mu}^+ \nu^{-\mu} \]

\[ -i \frac{g_V}{\sqrt{2}} c_H^+ \nu_{\mu}^+ H^{\tau\mu} \tilde{H} + \frac{g_V}{\sqrt{2}} c_q^+ \nu_{\mu}^+ J_{\mu}^q + \text{h.c.} \]

\[ + 2g_V^2 c_{VHH}^+ \nu_{\mu}^+ \nu^{-\mu} H^{\tau\mu} H + ig' c_{VBB}^+ \nu_{\mu}^+ \nu^{-\mu} \]

\[ \mathcal{L}_{\nu^0} = -\frac{1}{4} \partial_{[\mu} \nu_{\nu]}^0 \partial_{[\mu} \nu_{-\nu]}^0 + \frac{m_{\nu^0}^2}{2} \nu_{\mu}^0 \nu_{\mu}^0 \]

\[ + i \frac{g_V}{2} c_H^0 \nu_{\mu}^0 H^{\tau\mu} H + \sum_{\Psi=Q,L,U,D,E} \frac{g_V}{2} c_{V}^0 \nu_{\mu}^0 J_{\Psi}^\mu \]

\[ + g_V^2 c_{VHH}^0 \nu_{\mu}^0 \nu_{\mu}^0 H^{\tau\mu} H , \]

**Weakly coupled model**

\[ g_V \text{ typical strength of } V\text{ interactions} \]

\[ g_V \sim g \sim 1 \]

**Strongly coupled model**

\[ 1 < g_V \leq 4\pi \]

\[ c_i \text{ dimensionless coefficients} \]
HVS - Limits on simplified parameter space

Experimental searches

\[ c_X^+ = 1 \]

\[ c_X^0 = 1 \]

\( \sigma (pp \rightarrow V^+) \) [fb]

\( m_{V^+} \) [TeV]

\( \sigma (pp \rightarrow V^0) \) [fb]

\( m_{V^0} \) [TeV]

\( \sigma (pp \rightarrow V^+) \) [fb]

\( m_{V^+} \) [TeV]

\( \sigma (pp \rightarrow V^+) \) [fb]

\( v \rightarrow WZ \)
Experimental limits on simplified parameter space
HVS - Limits on simplified parameter space

Experimental limits on simplified parameter space

Simplified model works very well for the charged singlet

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HVS - Limits on simplified parameter space

Experimental limits on simplified parameter space

Simplified model for neutral singlets has many 7 parameters
For singlet production and decay they only enter in certain combinations

\[
\begin{align*}
(c_u^{\text{eff}})^2 &= (c_Q^0)^2 + (c_U^0)^2, \\
(c_d^{\text{eff}})^2 &= (c_Q^0)^2 + (c_D^0)^2, \\
(c_e^{\text{eff}})^2 &= (c_L^0)^2 + (c_E^0)^2, \\
c_n^{\text{eff}} &= c_L^0,
\end{align*}
\]

Reduce number of free parameters to 4
Also define

\[
\begin{align*}
\lambda_d &= \frac{c_d^{\text{eff}}}{c_u^{\text{eff}}}, & \lambda_e &= \frac{c_e^{\text{eff}}}{c_u^{\text{eff}}}, & \lambda_n &= \frac{c_n^{\text{eff}}}{c_u^{\text{eff}}},
\end{align*}
\]
HVS - Limits on simplified parameter space

Experimental limits on simplified parameter space

Orange: ATLAS $\ell^+\ell^-$
Blue: ATLAS $WW$
Black: bounds from EWPT

[Baker, Martonhelyi, Thamm, Torre: 2404…]
I. New $U(1)_X$ gauge extensions

Gauge group $SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_X$

Associated gauge boson is $V^0$ (often called $Z'$)

Matching fixes all parameters except $g_V, m_V^0$

<table>
<thead>
<tr>
<th>Model C</th>
<th>$U(1)_{B-x_L}$</th>
<th>$U(1)_R$</th>
<th>$U(1)_{q+nu}$</th>
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<td>$g_V$</td>
<td>$g_x$</td>
<td>$g_x$</td>
<td>$g_x$</td>
</tr>
<tr>
<td>$m_{V^0}$</td>
<td>$m_{V^0}$</td>
<td>$m_{V^0}$</td>
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<td>2/3</td>
</tr>
<tr>
<td>$c_U^0$</td>
<td>2/3</td>
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</tr>
<tr>
<td>$c_D^0$</td>
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<td>2/3</td>
<td>2(2-x)</td>
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<tr>
<td>$c_L^0$</td>
<td>-2x</td>
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<td>-2</td>
</tr>
<tr>
<td>$c_E^0$</td>
<td>-2x</td>
<td>2/3</td>
<td>-2(2+x)</td>
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<td>$c_H^0$</td>
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<td>$c_{VHH}$</td>
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<td>$4(x-1)^2/9$</td>
</tr>
</tbody>
</table>
1. New $U(1)_X$ gauge extensions

Gauge group $SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_X$
Associated gauge boson is $V^0$ (often called $Z'$)
Matching fixes all parameters except $g_V, m^0_V$
2. New non-abelian gauge extensions

Gauge group $SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_X$

Associated gauge bosons are $V^0, V^\pm$ (often called $W_R, X$)

Matching fixes all parameters except $g_V, m_V^0$
2. New non-abelian gauge extensions

Gauge group \( SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_X \)

Associated gauge bosons are \( V^0, V^\pm \) (often called \( W_R, X \))

Matching fixes all parameters except \( g_V, m_V^0 \)
3. Minimal composite Higgs model

Strongly coupled heavy sector at scale

- Spontaneous breaking of global symmetry
- Higgs arises as a pseudo-Nambu-Goldstone boson
- Above $\Lambda_S$ $H$ no longer elementary d.o.f. solves hierarchy problem
3. Minimal composite Higgs model

Global symmetry breaking pattern: $SO(5)/SO(4)$
Associated gauge bosons are $V^0$, $V^\pm$ (often called $\rho_R$)
Matching fixes all parameters except $g_V, m_V^0$
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1. Theory motivation
2. Heavy vector triplets
3. Heavy vector singlets
4. Heavy vectors at future colliders
5. Conclusions
Muon collider - 10 TeV

Production via

- Resonance production
- Radiative return
- Vector boson fusion
Muon collider - 10 TeV

\[ \text{VBF } \rho^0 \rightarrow W^+ W^- \]

\[ \rho^\pm W^\mp + \rho^0 Z \rightarrow W^+ W^- Z \]

\[ \rho^\pm W^\mp \rightarrow e^\pm \nu_e W^\pm \]

\[ \xi = 0.00256 \text{ [CEPC]} \]

\[ \xi = 0.0015 \]

\[ \xi = 0.0784 \text{ [HL-LHC]} \]

\[ g_\rho \]

\[ M_\rho \text{ [TeV]} \]

[Ref: Liu, Wang, Xie: 2312.09117]
HVT - Future Colliders

Muon collider - 10 TeV

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\[ \text{LHC} \]

\[ \text{HL-LHC} \]

\[ \text{ILC} \]

\[ \text{TLEP/CLIC} \]

\[ \text{FCC-10ab} \]

\[ \text{FCC-4ab} \]

\[ \text{TEPC} \]

\[ \text{HPC} \]

\[ \text{HPCAC} \]

[Thamm, Torre, Wulzer: 1502.01710]
Muon collider - 10 TeV

\[ \rho^0 \rightarrow W^+ W^- \]

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\[ M_\rho [\text{TeV}] \]

[Thamm, Torre, Wulzer: 1502.01710]
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Conclusions

• Simplified models are very versatile for vector triplets and singlets

• Vector boson fusion can be a dominant production mode

• Collider probes complementary to electroweak precision tests

• Future colliders can close the gap between them
Thank you!