Vector Boson Scattering at 100 TeV pp Collider

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Fermilab / Duke University

100 TeV Workshop
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Questions from Snowmass 2013 Workshop

What do we gain from measurements of gauge couplings, trilinear (TGC) & quartic (QGC), in light of other precision electroweak data?

Do theories exist where we expect to naturally have SM-like precision measurements, but large deviations in the TGCs & QGCs?
What do we gain from measurements of gauge couplings, trilinear (TGC) & quartic (QGC), in light of other precision electroweak data?

**Answer:** A lot

Do theories exist where we expect to naturally have SM-like precision measurements, but large deviations in the TGCs & QGCs?
What do we gain from measurements of gauge couplings, trilinear (TGC) & quartic (QGC), in light of other precision electroweak data?

**Answer: A lot**

Do theories exist where we expect to naturally have SM-like precision measurements, but large deviations in the TGCs & QGCs?

**Answer: yes**
Spontaneous Symmetry Breaking of Gauge Symmetry

- The Higgs potential in the SM is a parameterization that respects certain rules of QFT

- Phase transition → vacuum state possesses non-trivial quantum numbers

- Dynamical origin of this phase transition is not known

- Broadly speaking, underlying dynamics may be
  - Weakly coupled (e.g. Supersymmetry)
  - Strongly coupled
A Toy Model for BSM extension

- Consider a term coupling the Higgs to a singlet scalar $S$: $f \phi \phi S$
- Via $S$ exchange, can mediate scattering process: $\phi \phi \rightarrow \phi \phi$

[Diagram showing $S$ exchange]

$[\Box - m_S^2]^{-1} \sim m_S^{-2}[1 + \Box / m_S^2]$

- For energies $<< m_S$, induces effective field theory operators:
  - Dimension-4: $(f / m_S)^2 (\phi \phi^\dagger)^2$
  - Dimension-6: $O_{\phi^d} = (f^2 / m_S^4) |\partial_\mu (\phi \phi^\dagger) \partial^\mu (\phi \phi^\dagger)|$
    - This is one of the operators predicted in strongly-interacting light Higgs models
  - Alternate mechanism to SUSY for ensuring light Higgs boson alters VBS compared to SM
A Toy Model for BSM extension

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- Via $S$ exchange, can mediate scattering process: $\phi \phi \rightarrow \phi \phi$
- For energies $\ll m_S$, induces effective field theory operators:
  - Dimension-4: $(f / m_S)^2 (\phi \phi^\dagger)^2$
  - Dimension-6: $O = (f^2 / m_S^4) \partial_\mu (\phi \phi^\dagger) \partial^\mu (\phi \phi^\dagger)$
  - Observing a deviation in gauge and Higgs couplings consistent with this model would immediately point to model parameter values for $f$ and $m_S$
Examples from Strongly Interacting Light Higgs models

Effective Field Theory Operators provide a general parameterization of new physics at a high mass scale

Especially useful to parameterize new strong dynamics

(see Low et al, JHEP 1004:126 (2010), Giudice et al, JHEP06, 045 (2007) and references therein)

\[ O_{WWW} = \text{Tr}[W_{\mu\nu}W^{\nu\rho}W^\mu_\rho] \]
\[ O_W = (D_\mu \Phi)^\dagger W^{\mu\nu} (D_\nu \Phi) \]
\[ O_B = (D_\mu \Phi)^\dagger B^{\mu\nu} (D_\nu \Phi), \]
\[ O_{\phi d} = \partial_\mu (\phi^\dagger \phi) \partial^\mu (\phi^\dagger \phi) \]
\[ O_{\phi W} = (\phi^\dagger \phi) \text{Tr}[W^{\mu\nu}W_{\mu\nu}] \]
\[ O_{\phi B} = (\phi^\dagger \phi) B^{\mu\nu} B_{\mu\nu} \]

Coupling modifications

<table>
<thead>
<tr>
<th></th>
<th>ZWW</th>
<th>AWW</th>
<th>HWW</th>
<th>HZZ</th>
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Gauge & Higgs couplings
Examples from Strongly Interacting Light Higgs models

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</tr>
<tr>
<td>$\mathcal{O}_W$</td>
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<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>$\mathcal{O}_B$</td>
<td>x</td>
<td>x</td>
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<td></td>
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<tr>
<td>$\mathcal{O}_{\phi d}$</td>
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<td>x</td>
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<td>$\mathcal{O}_{\phi W}$</td>
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<td>x</td>
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<tr>
<td>$\mathcal{O}_{\phi B}$</td>
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<td></td>
<td>x</td>
<td>x</td>
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</tbody>
</table>

Higgs couplings
Combined Fit to Higgs and Anomalous Gauge Couplings

- Illustrates the complementary of approaches to new physics via deviations of Higgs-to-gauge and gauge-gauge couplings
  - Combined fit provides significantly tighter constraints

\[ \propto (O_W + O_B) \]

Corbett et al.,
arXiv:1304.1151
Another Toy Model – for Dimension-8 Operators

- Consider the analogy with light-by-light scattering via electron loop

- Euler-Heisenberg effective lagrangian at low energies

\[ \mathcal{L} = \frac{1}{2} (E^2 - B^2) + \frac{2\alpha^2}{45m^4} \left[ (E^2 - B^2)^2 + 7 (E \cdot B)^2 \right] \]
Another Toy Model – for Dimension 8 Operators

- Consider the analogy with light-by-light scattering via electron loop

- Euler-Heisenberg effective lagrangian at low energies

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- Second term can be re-written in terms of

\[ F_{\mu\rho} F^{\mu\sigma} F^{\nu\rho} F^{\nu\sigma} \quad (F_{\mu\nu} F^{\mu\nu})^2 \]

Operator coefficients contain information on mass and coupling of new dynamical degrees of freedom
Another Analogy – Primakoff Production of $\pi^0$

- Primakoff production by photon interacting with strong nuclear EM field

- Therefore following operators can describe scalar resonance production in VBS

$$F_{\mu\rho} F^{\mu\sigma} F^{\nu\rho} F_{\nu\sigma} \quad (F_{\mu\nu} F^{\mu\nu})^2$$

Operator coefficients contain information on mass and coupling of new scalar resonance
Vector Boson Scattering

- This is a key process accessible for the first time at LHC

Vector Boson Scattering is intimately connected with EWSB

Provides a unique method of exploring the possibility of strong dynamics
Effective Field Theory Operators at Dimension-8

- All dimension-6 and dimension-8 operators involving SM boson fields have been catalogued

\[ \mathcal{L}_{\text{EFT}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{|c_i|}{\Lambda^2} \mathcal{O}_i + \sum_j \frac{f_j}{\Lambda^4} \mathcal{O}_j \]

- Examples of dimension-8 operators

\[ \mathcal{O}_{T,1} = \text{Tr} \left[ W_{\alpha\nu} W^{\mu\beta} \right] \times \text{Tr} \left[ W_{\mu\beta} W^{\alpha\nu} \right] \]
\[ \mathcal{O}_{T,8} = B_{\mu\nu} B^{\mu\nu} B_{\alpha\beta} B^{\alpha\beta} \]
\[ \mathcal{O}_{T,9} = B_{\alpha\mu} B^{\mu\beta} B_{\beta\nu} B^{\nu\alpha} \]

- Dimension-8 operators only affect vector boson scattering and triboson production

  - These processes open up a new and unique window on new dynamics in the EWSB sector
Effective Field Theory Operators

- All dimension-6 and dimension-8 operators have been catalogued

\[ \mathcal{L}_{\text{EFF}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{|c_i|}{\Lambda^2} \mathcal{O}_i + \sum_j \frac{f_j}{\Lambda^4} \mathcal{O}_j \]

- VBS processes have the potential for
  - measuring new physics parameterized by higher-dimension operators
  - Differentiating between different operators using
    - Direct measurement of energy-dependence
    - different channels

- Dimension-8 operators tested:

\[ \mathcal{O}_{S,0} = \left[ (D_\mu \Phi)^\dagger D_\nu \Phi \right] \times \left[ (D^\mu \Phi)^\dagger D^\nu \Phi \right] \]

\[ \mathcal{O}_{T,8} = B_{\mu\nu} B^{\mu\nu} B_{\alpha\beta} B^{\alpha\beta} \]

\[ \mathcal{O}_{T,9} = B_{\alpha\mu} B^{\mu\beta} B_{\beta\nu} B^{\nu\alpha} \]

\[ \mathcal{O}_{T,1} = \text{Tr} \left[ W_{\alpha\nu} W^{\mu\beta} \right] \times \text{Tr} \left[ W_{\mu\beta} W^{\alpha\nu} \right] \]
VBS Studies using Forward Tagged Jets

**ZZ → leptons**

Threshold of interest for dim-6 operator coefficient \(< v^2 \sim 16 \text{ TeV}^{-2}\)

\[ p_T^j > 50 \text{ GeV} \]
\[ m_{jj} > 1 \text{ TeV} \]

dim-8 operator coefficient implies sensitivity to strong dynamics at TeV-scale

**WZ → leptons**

Complementarity of VBS and Triboson production

Anomalous $Z\gamma\gamma$ production at high mass also very sensitive to "T" operators

$\int L\, dt = 3000 \text{ fb}^{-1}$
$\sqrt{s} = 14 \text{ TeV}$

Anomalous $Z\gamma\gamma$ production at high mass also very sensitive to "T" operators

$\Rightarrow$ Comparison of VBS and triboson production is another powerful capability for characterizing the new physics
VBS and Tribosons at 100 TeV \( pp \) Collider

<table>
<thead>
<tr>
<th>Parameter</th>
<th>( \sqrt{s} ) [TeV]</th>
<th>Luminosity [fb(^{-1})]</th>
<th>pileup</th>
<th>5( \sigma ) [TeV(^{-4})]</th>
<th>95% CL [TeV(^{-4})]</th>
</tr>
</thead>
<tbody>
<tr>
<td>( f_{T,1}/\Lambda^4 )</td>
<td>14</td>
<td>300</td>
<td>50</td>
<td>0.2 (0.4)</td>
<td>0.1 (0.2)</td>
</tr>
<tr>
<td>( f_{T,1}/\Lambda^4 )</td>
<td>14</td>
<td>3000</td>
<td>140</td>
<td>0.1 (0.2)</td>
<td>0.06 (0.1)</td>
</tr>
<tr>
<td>( f_{T,1}/\Lambda^4 )</td>
<td>14</td>
<td>3000</td>
<td>0</td>
<td>0.1 (0.2)</td>
<td>0.06 (0.1)</td>
</tr>
<tr>
<td>( f_{T,1}/\Lambda^4 )</td>
<td>100</td>
<td>1000</td>
<td>40</td>
<td>0.001 (0.001)</td>
<td>0.0004 (0.0004)</td>
</tr>
<tr>
<td>( f_{T,1}/\Lambda^4 )</td>
<td>100</td>
<td>3000</td>
<td>263</td>
<td>0.001 (0.001)</td>
<td>0.0008 (0.0008)</td>
</tr>
<tr>
<td>( f_{T,1}/\Lambda^4 )</td>
<td>100</td>
<td>3000</td>
<td>0</td>
<td>0.001 (0.001)</td>
<td>0.0008 (0.0008)</td>
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</tbody>
</table>

Table 1-25. In \( pp \to W^\pm W^\pm + 2j \to \ell\nu\ell\nu + 2j \) processes, 5\( \sigma \)-significance discovery values and 95\% CL limits are shown for coefficients the higher-dimension operator, \( f_{T,1}/\Lambda^4 \), for different machine scenarios without the UV cut and with the UV cut in parenthesis. Pileup refers to the number of \( pp \) interactions per crossing.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>dim.</th>
<th>Luminosity [fb(^{-1})]</th>
<th>14 TeV</th>
<th>33 TeV</th>
<th>100 TeV</th>
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<tr>
<td>( c_{WWW}/\Lambda^2 ) [TeV(^{-2})]</td>
<td>6</td>
<td>300</td>
<td>4.8 (8)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1000</td>
<td>-</td>
<td>-</td>
<td>1.3 (1.5)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3000</td>
<td>2.3 (2.5)</td>
<td>1.7 (2.0)</td>
<td>0.9 (1.0)</td>
</tr>
<tr>
<td>( f_{T,0}/\Lambda^4 ) [TeV(^{-4})]</td>
<td>8</td>
<td>300</td>
<td>1.2</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1000</td>
<td>-</td>
<td>-</td>
<td>0.004</td>
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<td>0.6</td>
<td>0.05</td>
<td>0.002</td>
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</table>

Table 1-26. In the \( pp \to WWW \to 3\ell + 3\nu \) process, the 5\( \sigma \)-significance discovery values are shown for the coefficients of higher order operators. The values in parentheses are obtained with the UV bound applied. \( pp \) colliders at \( \sqrt{s} = 14, 33 \) and 100 TeV are studied.
Conclusions

VBS and triboson production is dramatically more sensitive to new physics at higher beam energy.

Dimension-8 operators are probed much more strongly than Dimension-6 operators (due to stronger growth of amplitude with energy).

For dimension-8 operator coefficients of order $\sim 1$:
- HL-LHC probes energy scale $\Lambda \sim 1.6 \text{ TeV}$
- VLHC (100 TeV) probes $\Lambda \sim 6 \text{ TeV}$ (with $3 \text{ ab}^{-1}$)

High energy pp colliders probe dimension-8 operators much more sensitively than lepton colliders.
Complication with EFT Approach

EFT approach valid and results easy to interpret when $m_{\nu\nu} \ll \Lambda$

Safe to use at lepton colliders

Hadron colliders can probe $m_{\nu\nu} \sim \Lambda$

Observation of resonances more likely than EFT description?

To preserve generality offered by EFT operators, intermediate solution may be to preserve unitarity by imposing ad-hoc prescription:

eg. K-matrix unitarization (adds no parameters)

Agreement and implementation of some unitarization scheme would facilitate studies immensely

technical problem for K-matrix method in MADGRAPH
What do we gain from measurements of gauge couplings, trilinear (TGC) & quartic (QGC), in light of other precision electroweak data?

Answer: A lot, because heavy gauge bosons and Higgs boson are inextricably linked. Gauge couplings contain complementary and independent information to other electroweak measurements.

Do theories exist where we expect to naturally have SM-like precision measurements, but large deviations in the TGCs & QGCs?

Answer: yes, individual models eg. Littlest Higgs etc. predict specific values for coefficients of specific higher-dimension operators.

Observing a certain pattern of deviations in electroweak precision observables, Higgs and gauge boson processes can pick out certain models and associated mass scales.
THANK YOU

- Thanks to the Snowmass Energy Frontier Electroweak working group members

**Conveners: A. Kotwal and D. Wackeroth**


Electroweak Report posted at:


and arXiv:1310.6708
Backup
## Program of VBS and Triboson Measurements

<table>
<thead>
<tr>
<th>Parameter</th>
<th>dimension</th>
<th>channel</th>
<th>$\Lambda_{UV}$ [TeV]</th>
<th>$300 \text{ fb}^{-1}$</th>
<th>$3000 \text{ fb}^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$c_{\phi W}/\Lambda^2$</td>
<td>6</td>
<td>ZZ</td>
<td>1.9</td>
<td>34 TeV$^{-2}$</td>
<td>16 TeV$^{-2}$</td>
</tr>
<tr>
<td>$f_{S0}/\Lambda^4$</td>
<td>8</td>
<td>$W^+W^-$</td>
<td>2.0</td>
<td>10 TeV$^{-4}$</td>
<td>4.5 TeV$^{-4}$</td>
</tr>
<tr>
<td>$f_{T1}/\Lambda^4$</td>
<td>8</td>
<td>WZ</td>
<td>3.7</td>
<td>1.3 TeV$^{-4}$</td>
<td>0.6 TeV$^{-4}$</td>
</tr>
<tr>
<td>$f_{T8}/\Lambda^4$</td>
<td>8</td>
<td>Z$\gamma\gamma$</td>
<td>12</td>
<td>0.9 TeV$^{-4}$</td>
<td>0.4 TeV$^{-4}$</td>
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<tr>
<td>$f_{T9}/\Lambda^4$</td>
<td>8</td>
<td>Z$\gamma\gamma$</td>
<td>13</td>
<td>2.0 TeV$^{-4}$</td>
<td>0.7 TeV$^{-4}$</td>
</tr>
</tbody>
</table>

Table 5: $5\sigma$-significance discovery values and 95\% CL limits for coefficients of higher-dimension electroweak operators. $\Lambda_{UV}$ is the unitarity violation bound corresponding to the sensitivity with $3000 \text{ fb}^{-1}$ of integrated luminosity.

### Conclusions:

1) factor of 2-3 improvement in sensitivity with HL-LHC upgrade

2) single-channel sensitivities pushed into the TeV-scale if new dynamics is strongly-coupled to Higgs and vector bosons

3) a powerful method of probing models of strongly-interacting light Higgs

4) model-independent tests of BSM dynamics
Example Test of Unitarization by Higgs

<table>
<thead>
<tr>
<th>Parameter</th>
<th>dimension</th>
<th>channel</th>
<th>$\Lambda_{UV}$ [TeV]</th>
<th>$300$ fb$^{-1}$</th>
<th>$3000$ fb$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$c_{\phi d}/\Lambda^2$ at 14 TeV</td>
<td>6</td>
<td>WZ</td>
<td>1.9</td>
<td>29 TeV$^{-2}$</td>
<td>15 TeV$^{-2}$</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>17 TeV$^{-2}$</td>
<td>8.7 TeV$^{-2}$</td>
</tr>
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</table>

Conclusion:
We are not really testing unitarization by SM Higgs until operator $< 16$ TeV$^{-2}$

$$O_{\phi d} = \frac{c_{\phi d}}{M_S^2} \partial_\mu (\Phi^\dagger \Phi) \partial^\mu (\Phi^\dagger \Phi)$$
Example Test of Unitarization by Higgs

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Single-channel tests of unitarization achievable with HL-LHC
LHC and ILC Comparison for Anomalous Trilinear Gauge Couplings

- equivalent to dimension-6 operator coefficients

Figure 1-22. Comparison of $\Delta \kappa_\gamma$ and $\Delta \lambda_\gamma$ at different machines. For LHC and ILC three years of running are assumed (LHC: 300 fb$^{-1}$, ILC $\sqrt{s} = 500$ GeV: 500 fb$^{-1}$, ILC $\sqrt{s} = 800$ GeV: 1000 fb$^{-1}$). If available the results from multi-parameter fits have been used. Taken from Ref. [193, 194].

Generally, ILC probes dimension-6 operators, through diboson production, much better than LHC
Hadron vs Lepton Colliders

- ILC1000 vs LHC sensitivity to higher-dimension operators in VBS and multi-boson production:
  - ILC more sensitive to dimension-6 operators through diboson production (clean environment, sensitivity through interference with SM)
  - LHC more sensitive (by 1-2 orders of magnitude) to dimension-8 operators compared to ILC1000, as probed by VBS and triboson production
VBS Study using same-sign WW → leptons

Stronger SM interference for “S0” operator → different kinematic dependence