Vector Boson Scattering and Quartic Gauge Couplings at the LHC

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Particle Physics Seminar @ Brookhaven National Laboratory

June 19, 2014
Outline

1. Introduction & motivation
2. Vector boson scattering at the LHC
3. Anomalous quartic gauge couplings
4. Summary and outlook
The Standard Model of particle physics (SM)

- the SM is based on 3 fundamental symmetries being origin of interactions between matter particles & mediators of the interactions

\[ SU(3)_C \times SU(2)_L \times U(1)_Y \]

- the Lagrangian density \( \mathcal{L} \) must be invariant under these symmetries, fundamental principle: local gauge invariance \( \rightarrow \) conservation laws

- main ingredients of the SM:
  - forces: electromagnetism \((\gamma)\)
    weak interaction \((W^\pm, Z)\)
    strong interaction \((g)\)
  - matter: 6 quarks and 6 leptons
    in 3 generations
  - EWSB: spontaneous electroweak symmetry breaking via Brout-Englert-Higgs mechanism
The Standard Model of particle physics (SM)

- EW theory is non-Abelian
  - ⇒ EW gauge bosons carry weak charge
  - ⇒ their self-interactions should exist
- $\mathcal{L}_{WWWV}$ contains the **quartic gauge self-couplings (QGC)**

$$\mathcal{L}_{WWWV} = -\frac{g^2}{4} \left\{ [2W_\mu^+ W^- - (A_\mu \sin \theta_W - Z_\mu \cos \theta_W)^2]^2 
- [W_\mu^+ W^\nu_\nu + W^\nu_\nu W^-_\mu + (A_\mu \sin \theta_W - Z_\mu \cos \theta_W)(A_\nu \sin \theta_W - Z_\nu \cos \theta_W)]^2 \right\}$$

- no neutral gauge boson self-couplings in the SM
the heavy vector bosons $W^\pm$ and $Z$ acquire their **mass and longitudinal polarization state** through spontaneous EWSB

the mechanism responsible for EWSB must regulate $\sigma(V_L V_L \rightarrow V_L V_L)$ to restore unitarity above $\sim 1 - 2$ TeV

- cross section attenuated to a linear growth by the quartic gauge boson self-coupling
- a light SM Higgs boson exactly cancels increase for large $s$ (for $HWW$ coupling)

$\mathcal{A}(W_L W_L \rightarrow W_L W_L) \propto \frac{g_W^2}{v^2} \left[ -s - t + \frac{s^2}{s-m_H^2} + \frac{t^2}{t-m_H^2} \right]$}

unitarity preservation visible only in $VV$ scattering

$\Rightarrow VV$ scattering is the key process to experimentally probe the SM nature of EWSB!
Vector boson scattering and EWSB

- total cross sections as a function of the $m_{VV}$ center-of-mass energy:
  arXiv:0806.4145

\[ \sigma(VV \rightarrow VV), \text{ no Higgs} \]

\[ \sigma(VV \rightarrow VV) \text{ with } m_h = 120 \text{ GeV} \]
Processes with quartic gauge boson couplings

- no reaction is ever mediated by a QGC vertex alone
  (even a gauge-invariant definition of the QGC contribution is not possible!)
- two measurable classes of processes where a QGC vertex contributes:
  - triple gauge boson production, $VVV$
  - vector boson scattering (VBS) as $VVjj$
    or exclusive $VV(pp)$ final states
- what can we learn from QGC vertices?
  - observe the SM processes with QGC vertices
    - pre-LHC: attempted for $\gamma\gamma WW$ and $\gamma Z WW$
  - constrain anomalous quartic gauge couplings (aQGC)
    - loose limits by LEP and Tevatron
  - test EWSB and Higgs properties
    - access through $ZZWW$ and $WWW$ at large $\sqrt{s} = m_{VV} \gtrsim 1$ TeV
    - one of the core reasons, why LHC has been built!
Experimental tests of the EW theory at LEP

- SM confirmed at very high precision by the LEP experiments
- triple gauge boson couplings validated by $e^+e^- \rightarrow W^+W^-$ cross section measurements
- measured processes with QGC vertices at LEP:
  - e.g. $e^+e^- \rightarrow \nu\nu\gamma\gamma$ and $e^+e^- \rightarrow W^+W^-$
  - significant observation with small/negligible background
    → consistent with ISR/FSR processes
      (can be gauge-invariantly distinguished from processes containing QGC vertices)
      - DELPHI: http://arxiv.org/pdf/hep-ex/0311004v1
    → no “real” observation of any process including QGC vertices at LEP (nor at Tevatron)
**Large Hadron Collider (LHC) at CERN**

- **pp** collisions at $\sqrt{s} = 7/8$ TeV in 2011/2012
- Outstanding LHC performance:
  - delivered $\sim 6 \text{ fb}^{-1} @ 7$ TeV and $\sim 23 \text{ fb}^{-1} @ 8$ TeV
- Large rise in instantaneous luminosity from $2 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$ to $7.7 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$
- 50 ns bunch spacing and up to almost 40 interactions/bunch crossing
The multi-purpose detectors ATLAS & CMS

ATLAS

CMS

candidate $Z \rightarrow \mu\mu$ event with high pileup

length $\approx 25$ cm

large luminosity comes at the cost of high pileup (many $pp$ collisions overlaid)

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Vector boson scattering at the LHC
Vector boson scattering at the LHC

**$VV(pp)$ from “exclusive” $\gamma\gamma \rightarrow WW$**

- **first $VV \rightarrow VV$ analysis at LHC:**
  - $\gamma\gamma \rightarrow WW$

- CMS, $\sqrt{s} = 7$ TeV, $\mathcal{L} = 5$ fb$^{-1}$

- exclusive or quasi-exclusive $W^+ W^-$ production

$$pp \rightarrow p^(*) W^+ W^- p^(*) \rightarrow p^(*) e^+ \bar{\nu}\mu^- \nu p^(*)$$

in mixed flavour $e\mu$ channel

both very forward-scattered protons escape detection

- main event selection variables:
  - 2 high $p_T$ isolated opposite charge $\mu e$
  - 0 extra tracks from primary vertex
  - $m(\mu^\pm e^\mp) > 20$ GeV
  - $p_T(\mu^\pm e^\mp) > 30$ GeV
    - suppresses $\tau^+ \tau^-$ background from Drell-Yan and $\gamma\gamma$
  - $(p_T(\mu^\pm e^\mp) > 100$ GeV (for aQGC analysis))
Vector boson scattering at the LHC

$VV(pp) \text{ from } "exCLUSIVE" \gamma \gamma \rightarrow WW$

- remaining background very small
  - after $p_T(\mu^\pm e^{\mp}) > 30$ GeV:
    - diffractive $WW$ and $W^+jets$ production

- event yields:
  - expected background: $0.84 \pm 0.15$
  - expected signal: $2.2 \pm 0.4$
  - observed: 2 events

- cross sections:
  - predicted: $\sigma \times BR = 4.0 \pm 0.7$ fb
  - measured: $\sigma \times BR = 2.2^{+3.3}_{-2.0}$ fb ($\sim 1\sigma$)
  - upper limit: $\sigma < 10.6$ fb @ 95% C.L.
Vector boson scattering in $VVjj$ final states

- VBS: SM processes which have not been measured so far
- protons in LHC serve as source of vector boson beams

signature: diboson + 2 jets ($VVjj$)

- typically large $m_{jj}$
- jets well separated in $y$

$\sqrt{s} = m_{VV} \approx 300 - 800$ GeV
**VVjj production process classification**

### Pure Electroweak VVjj Production

\[ \mathcal{O}(\alpha_w^6) \]

- **VBS diagrams**
  - Not separable:
  - Separable:
    - Can be suppressed by VBS topology cuts

### "Strong" VVjj Production

\[ \mathcal{O}(\alpha_w^4\alpha_s^2) \]

- Gauge invariantly separable: can be suppressed by VBS topology cuts
VBS processes (heavy vector bosons only)

- leading order cross sections (Sherpa) at $\sqrt{s} = 8$ TeV:

<table>
<thead>
<tr>
<th>final state</th>
<th>$\sigma(VV jj - EW)$</th>
<th>$\sigma($strong $VV jj)$</th>
<th>$\sigma(EW)/\sigma($strong$)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W^{\pm}W^{\pm} jj$</td>
<td>19.5 fb</td>
<td>18.8 fb</td>
<td>$\sim 1:1$</td>
</tr>
<tr>
<td>$W^{\pm}W^{\mp} jj + ZZ jj$</td>
<td>93.7 fb</td>
<td>3192 fb</td>
<td>$\sim 1:35$</td>
</tr>
<tr>
<td>$WZ jj$</td>
<td>30.2 fb</td>
<td>687 fb</td>
<td>$\sim 1:20$</td>
</tr>
<tr>
<td>$ZZ jj$</td>
<td>1.5 fb</td>
<td>106 fb</td>
<td>$\sim 1:70^*$</td>
</tr>
</tbody>
</table>

* includes $\gamma^*$, would be also 1:20 – 1:30 with higher $m_{ll}$ cut

(generator cuts: $m_{ll} > 4$ GeV, $p_T^l > 5$ GeV, $p_T^j > 15$ GeV)

⇒ most promising measurable $VV jj$ final states in terms of VBS:

- same-sign $W^{\pm}W^{\pm} jj$
  → strong $W^{\pm}W^{\pm} jj$ contributions very small
    (no LO gluon-gluon initial state)

- $W^{\pm} Z jj$
  → clean channel due to 3-lepton final state
Same-sign $W^\pm W^\pm jj$ measurement

- $W^\pm W^\pm jj$-EW VBS (no s-channel diagrams):

- lowest order: $W^\pm W^\pm + 2$ jets, there is no SM inclusive $W^\pm W^\pm$!

- for EW+strong measurement (“inclusive signal phase space”)
  - look at $e^\pm e^\pm$, $e^\pm \mu^\pm$ and $\mu^\pm \mu^\pm$ channels
  - exactly 2 high $p_T$ same-sign leptons with $p_T > 25$ GeV
  - $E_{T\text{miss}} > 40$ GeV (from $W$ decays)
  - veto events containing $b$-jets
  - 2 hard, forward tagging jets with $p_T > 30$, GeV and large $m_{jj}$
    $\rightarrow$ cut on $m_{jj} > 500$ GeV

- for EW-only measurement (“VBS signal phase space”)
  - additional cut on $|\Delta y_{jj}| > 2.4$
Vector boson scattering at the LHC

$W^\pm W^\pm jj$ sample composition

- $W^\pm W^\pm jj$ EW (46%)
- $W^\pm W^\pm jj$ strong (5%)
  (SHERPA, normalized with POWHEG)

- prompt background (28%):
  - 3 or more prompt leptons
    - $WZ/\gamma^*+\text{jets}$ (SHERPA)
    - $ZZ+\text{jets}$ (SHERPA)
    - $t\bar{t} + W/Z$ (MADGRAPH+PYTHIA8)
    - $tZj$ (SHERPA)

- conversions (13%):
  - prompt photon conversion
    - $W\gamma$ (ALPGEN+HERWIG/JIMMY, SHERPA)
  - charge mis-ID due to bremsstrahlung with conversion (data driven)
    - $Z/\gamma^*+\text{jets}$
    - di-leptonic $t\bar{t}$ decays
    - $W^\pm W^\mp$

- other non-prompt background (8%): (data driven)
  - leptons from hadron decays in jets
    - $W+\text{jets}$
    - semi-leptonic $t\bar{t}$ decays
    - di-jet events
Electroweak $W^\pm W^\pm jj$ production

in inclusive region

( EW+ strong measurement)

invariant mass of the 2 tagging jets
(before $m_{jj}$ cut)

VBS signal region

( EW-only measurement)

$|\Delta y_{jj}|$ between the 2 tagging jets
(before $|\Delta y_{jj}|$ cut)
$W^\pm W^\pm$ system in the VBS signal region

lepton centrality $\zeta$

\[ \zeta = \min \left[ \min(\eta_{e1}, \eta_{e2}) - \min(\eta_{j1}, \eta_{j2}), \max(\eta_{j1}, \eta_{j2}) - \max(\eta_{e1}, \eta_{e2}) \right] \]

- both leptons within tagging jets (in $\eta$): $\zeta > 0$
- one or both leptons with larger $\eta$ than closest jet: $\zeta < 0$

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### $W^\pm W^\pm jj$ Event Yields

<table>
<thead>
<tr>
<th>Source</th>
<th>$e^\pm e^\pm$</th>
<th>$e^\pm \mu^\pm$</th>
<th>$\mu^\pm \mu^\pm$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prompt</td>
<td>$2.2 \pm 0.5$</td>
<td>$4.2 \pm 1.0$</td>
<td>$1.9 \pm 0.5$</td>
</tr>
<tr>
<td>Conversions</td>
<td>$2.1 \pm 0.5$</td>
<td>$1.9 \pm 0.7$</td>
<td>$-$</td>
</tr>
<tr>
<td>Other non-prompt</td>
<td>$0.50 \pm 0.26$</td>
<td>$1.5 \pm 0.6$</td>
<td>$0.34 \pm 0.19$</td>
</tr>
<tr>
<td>$W^\pm W^\pm jj$ Strong</td>
<td>$0.25 \pm 0.06$</td>
<td>$0.71 \pm 0.14$</td>
<td>$0.38 \pm 0.08$</td>
</tr>
<tr>
<td>$W^\pm W^\pm jj$ Electroweak</td>
<td>$2.55 \pm 0.25$</td>
<td>$7.3 \pm 0.6$</td>
<td>$4.0 \pm 0.4$</td>
</tr>
<tr>
<td>Total background</td>
<td>$5.0 \pm 0.9$</td>
<td>$8.3 \pm 1.6$</td>
<td>$2.6 \pm 0.5$</td>
</tr>
<tr>
<td>Total predicted</td>
<td>$7.6 \pm 1.0$</td>
<td>$15.6 \pm 2.0$</td>
<td>$6.6 \pm 0.8$</td>
</tr>
<tr>
<td>Data</td>
<td>$6$</td>
<td>$18$</td>
<td>$10$</td>
</tr>
</tbody>
</table>

- Interference between EW and strong $W^\pm W^\pm jj$ production: $\sim 7\%$
- Evaluated with SHERPA, included in EW $W^\pm W^\pm jj$ prediction
$W^\pm W^\pm jj$ candidate event

jets: $p_T^{j1} = 271$ GeV, $p_T^{j2} = 54$ GeV, $\eta^{j1} = 2.9$, $\eta^{j2} = -3.4$

muons: $p_T^{\mu1} = 180$ GeV, $p_T^{\mu2} = 38$ GeV, $\eta^{\mu1} = 1.4$, $\eta^{\mu2} = -1.3$

$E_T^{\text{miss}} = 75$ GeV

Run Number: 207490, Event Number: 33152138
Date: 2012-07-26 04:16:35 UTC
$W^\pm W^\pm jj$ production cross sections

- cross sections measured in two fiducial regions with different sensitivities to EW and strong $W^\pm W^\pm jj$ production mechanisms
  - extracted by fitting a likelihood function to the observed data

<table>
<thead>
<tr>
<th></th>
<th>measurement</th>
<th>theory prediction</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>inclusive signal region</strong> (EW+strong $W^\pm W^\pm jj$ production)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>cross section [fb]</td>
<td>$2.1 \pm 0.5$ (stat) $\pm 0.3$ (syst)</td>
<td>$1.52 \pm 0.11$</td>
</tr>
<tr>
<td>significance</td>
<td>$4.5 \sigma$</td>
<td>$3.4 \sigma$</td>
</tr>
<tr>
<td><strong>VBS signal region</strong> (EW $W^\pm W^\pm jj$ production)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>cross section [fb]</td>
<td>$1.3 \pm 0.4$ (stat) $\pm 0.2$ (syst)</td>
<td>$0.95 \pm 0.06$</td>
</tr>
<tr>
<td>significance</td>
<td>$3.6 \sigma$</td>
<td>$2.8 \sigma$</td>
</tr>
</tbody>
</table>

- **first evidence of a process containing a $VVVV$ vertex!**
Anomalous quartic gauge couplings
Look at physics beyond the SM

- the SM is assumed to be a low energy effect of new physics at scales beyond the current kinematic reach
- model independent approach, complementary to direct searches for new physics:
  - low energy effects from beyond SM physics can be parametrized by an effective Lagrangian (SM + higher-dimension operators):
    \[
    \mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum_{\text{dimension } d} \sum_{i} \frac{c_{i}^{(d)}}{\Lambda^{d-4}} O_{i}^{(d)}
    \]
    (valid only, if new physics out of direct LHC reach, \( s \ll \Lambda^2 \))
- new physics in EW sector modify gauge boson self-interactions
  - VBS could still be strong and differ from SM predictions
- genuine dimension 8 QGC operators with no effect on TGC:

<table>
<thead>
<tr>
<th></th>
<th>WWWW</th>
<th>WWZZ</th>
<th>ZZZZ</th>
<th>WWAZ</th>
<th>WWAA</th>
<th>ZZZA</th>
<th>ZZAA</th>
<th>ZAAA</th>
<th>AAAA</th>
</tr>
</thead>
<tbody>
<tr>
<td>(O_{S,0}, O_{S,1})</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(O_{M,0}, O_{M,1}, O_{M,6}, O_{M,7})</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(O_{M,2}, O_{M,3}, O_{M,4}, O_{M,5})</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(O_{T,0}, O_{T,1}, O_{T,2})</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>(O_{T,5}, O_{T,6}, O_{T,7})</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>(O_{T,8}, O_{T,9})</td>
<td>X</td>
<td></td>
<td></td>
<td>X</td>
<td></td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Look at physics beyond the SM

- Effective Field Theory description can be translated in EW chiral Lagrangian approach and vice versa arXiv:hep-ph/0606118
  → switch of operator basis, dependent on vertex

- relevant effective aQGC parametrizations (examples):

<table>
<thead>
<tr>
<th>dimension 4</th>
<th>dimension 6</th>
<th>dimension 8</th>
</tr>
</thead>
<tbody>
<tr>
<td>$WWW\bar{W}$, $WZZ\bar{Z}$</td>
<td>$WZ\gamma$, $W\gamma\gamma$</td>
<td>all $VVVVV$</td>
</tr>
<tr>
<td>EW chiral Lagrangian</td>
<td>non-linear representation</td>
<td>effective operators</td>
</tr>
<tr>
<td></td>
<td>$\alpha_4, \alpha_5$</td>
<td>linear representation</td>
</tr>
<tr>
<td></td>
<td>$a_0/\Lambda^2$, $a_c/\Lambda^2$</td>
<td>$f_{S,i}/\Lambda^4$, $f_{M,i}/\Lambda^4$, $f_{T,i}/\Lambda^4$</td>
</tr>
</tbody>
</table>

- example: $\alpha_4/5 \leftrightarrow \frac{f_{S,0}/1}{\Lambda^4}$ conversion arXiv:1309.7890, arXiv:1310.6708
  → $WWW\bar{W}$ vertex: $\alpha_4 = \frac{f_{S,0}}{\Lambda^4} \frac{v^4}{8}$ and $\alpha_4 + 2 \cdot \alpha_5 = \frac{f_{S,1}}{\Lambda^4} \frac{v^4}{8}$
Anomalous quartic gauge couplings

Unitarization

- with aQGCs unitarity may be violated even in the presence of a SM Higgs (effective parametrization always violates unitarity at some $m_{VV}$)

  ⇒ unitarization scheme needed!

  → all unitarization schemes are arbitrary and introduce model dependence!

- form factors (e.g. in VBFNLO arXiv:1205.4231)

  \[ F(s) = \left(1 + \hat{s}/\Lambda_{FF}^2\right)^{-n} \]

  → suppression of amplitude

  - additional arbitrary parameters: exponent $n$ and form factor scale $\Lambda_{FF}$
  - weakly motivated, but easy to implement
  - can be generally used for arbitrary anomalous operators
  - needs “fine tuning”

Feigl, Zeppenfeld, 2010

for $n = 2$ at $\Lambda_{FF} = 2$ TeV:
amplitude suppressed by a factor of 4
with aQGCs unitarity may be violated even in the presence of a SM Higgs (effective parametrization always violates unitarity at some \( m_{VV} \))

\[ \Rightarrow \] unitarization scheme needed!

\[ \rightarrow \] all unitarization schemes are arbitrary and introduce model dependence!

**K-matrix** method (**WHIZARD** arXiv:0806.4145)

- scattering amplitude \( A(s) \) projected on Argand circle
  \[ \rightarrow \] saturation of the amplitude

\[ A_K(s) \rightarrow \text{allows for probing the entire} \\
\text{kinematic phase space without} \\
\text{being unphysical} \]
Constraints on aQGCs from $\gamma\gamma \rightarrow WW$

- sensitive to $WW\gamma\gamma$ vertex
- additional cut at $p_T(\mu^{\pm}e^{\mp}) > 100$ GeV: 0 events left
- 1D and 2D limits (95% CL) on aQGC parameters $a_W^0/\Lambda^2$ and $a_W^c/\Lambda^2$:
  - $|a_W^0/\Lambda^2| < 0.00015$ GeV$^{-2}$
  - $|a_W^c/\Lambda^2| < 0.0005$ GeV$^{-2}$
- unitarization with form factor with $\Lambda_{FF} = 500$ GeV, $n = 2$
- un-unitarized limits (without form factor):
  - 30 – 40 times better, but dominated by $\sqrt{s}$ above unitarity
  - $\times100$ improvement wrt. D0
  - $\times3000$ improvement wrt. LEP
Anomalous quartic gauge couplings

- exclusion limits on $\alpha_4$ and $\alpha_5$ extracted from cross section in VBS phase space
- aQGC samples from WHIZARD+PYTHIA8 with K-matrix unitarization
- efficiency only weakly dependent on aQGC

1D 95% confidence intervals
expected:
$-0.10 < \alpha_4 < 0.12$
$-0.18 < \alpha_5 < 0.20$

observed:
$-0.14 < \alpha_4 < 0.16$
$-0.23 < \alpha_5 < 0.24$
(respective other $\alpha_i = 0$)

$\widehat{=}$ scale of new physics: $\Lambda > 500 – 650$ GeV
(rule of thumb: $\Lambda = \frac{v}{\sqrt{\alpha_i}}$ arXiv:1307.8170)
Summary and outlook

- exploring gauge boson self-interactions at the LHC in full swing
- first results on processes involving a $VVVV$ vertex
- cross sections for vector boson scattering processes:

<table>
<thead>
<tr>
<th></th>
<th>$\sigma(\gamma\gamma \rightarrow W^+W^-) \times BR$</th>
<th>$= 2.2^{+3.3}_{-2.0}$ fb</th>
<th>$\sim 1$ s.d.</th>
</tr>
</thead>
<tbody>
<tr>
<td>CMS</td>
<td>$\sigma(pp \rightarrow W^\pm W^\pm jj$-EW) $\times BR$</td>
<td>$= 1.3 \pm 0.4 \pm 0.2$ fb</td>
<td>$3.6$ s.d.</td>
</tr>
</tbody>
</table>

→ first evidence for a process containing vector boson scattering
→ first evidence for a process containing a $VVVV$ vertex!

- rough sensitivity scales $\Lambda$ from aQGC limits:

<table>
<thead>
<tr>
<th></th>
<th>CMS $\gamma\gamma \rightarrow W^+W^-$</th>
<th>ATLAS $W^\pm W^\pm \rightarrow W^\pm W^\pm$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>un-unitarized: 260 - 500 GeV</td>
<td>un-unitarized: not given</td>
</tr>
<tr>
<td></td>
<td>unitarized: 40 - 80 GeV</td>
<td>unitarized: 500 - 650 GeV</td>
</tr>
</tbody>
</table>

- further 8 TeV results expected
Outlook

- Higgs boson discovered, but still need to check whether this Higgs unitarizes the VBS process
  
  → need to explore VBS at higher energies, complementary to studying Higgs properties

- **LHC @ 13/14 TeV:**
  above $\sqrt{s} = m_{VV} \approx 1 - 2$ TeV it will become possible to experimentally probe the SM nature of EWSB by VBS measurements

- **beyond the LHC:**
  fully explore EWSB, probing in particular unitarization of $WW$ scattering at $m_{WW} \gg 1$ TeV, and explore dynamics well above EWSB
Backup
$W^±W^±jj$ production: event selection

- exactly 2 same-sign leptons, $p_T^\ell > 25$ GeV, $|\eta^\ell| < 2.5$
  - $e^± e^±, e^± \mu^±$ and $\mu^± \mu^±$ final states
- $m_{\ell\ell} > 20$ GeV
- veto events with any additional electron (muon) with $p_T > 7(6)$ GeV $\rightarrow$ reduces $WZ$ and $ZZ$
- $E_T^{\text{miss}} > 40$ GeV
  $\rightarrow$ reduces $Z+$jets with charge mis-identification
- $Z$-veto in $ee$ channel: $|m_{ee} - m_Z| > 10$ GeV
  $\rightarrow$ reduces $Z+$jets with charge mis-identification
- $\geq 2$ jets, $p_T^{\text{jet}} > 30$ GeV, $|\eta^{\text{jet}}| < 4.5$
- veto events containing b-jets
  $\rightarrow$ reduces $t\bar{t}$ events (lepton from b-decays)
- $m_{jj} > 500$ GeV (jets with largest $p_T$)
- VBS signal region: $|\Delta\eta_{jj}| > 2.4$
### Inclusive Signal Region

<table>
<thead>
<tr>
<th></th>
<th>$e^\pm e^\pm$</th>
<th>$e^\pm \mu^\pm$</th>
<th>$\mu^\pm \mu^\pm$</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W^\pm W^\mp jj$ Electroweak</td>
<td>$3.07 \pm 0.30$</td>
<td>$9.0 \pm 0.8$</td>
<td>$4.9 \pm 0.5$</td>
<td>$16.9 \pm 1.5$</td>
</tr>
<tr>
<td>$W^\pm W^\mp jj$ Strong</td>
<td>$0.89 \pm 0.15$</td>
<td>$2.5 \pm 0.4$</td>
<td>$1.42 \pm 0.23$</td>
<td>$4.8 \pm 0.8$</td>
</tr>
<tr>
<td>$WZ/\gamma^*,ZZ,tt+WW/Z$</td>
<td>$3.0 \pm 0.7$</td>
<td>$6.1 \pm 1.3$</td>
<td>$2.6 \pm 0.6$</td>
<td>$11.6 \pm 2.5$</td>
</tr>
<tr>
<td>$W+\gamma$</td>
<td>$1.1 \pm 0.6$</td>
<td>$1.6 \pm 0.8$</td>
<td>$-$</td>
<td>$2.7 \pm 1.2$</td>
</tr>
<tr>
<td>OS prompt leptons</td>
<td>$2.1 \pm 0.4$</td>
<td>$0.77 \pm 0.27$</td>
<td>$-$</td>
<td>$2.8 \pm 0.6$</td>
</tr>
<tr>
<td>Other non-prompt</td>
<td>$0.61 \pm 0.30$</td>
<td>$1.9 \pm 0.8$</td>
<td>$0.41 \pm 0.22$</td>
<td>$2.9 \pm 0.8$</td>
</tr>
<tr>
<td><strong>Total Predicted</strong></td>
<td><strong>$10.7 \pm 1.4$</strong></td>
<td><strong>$21.7 \pm 2.6$</strong></td>
<td><strong>$9.3 \pm 1.0$</strong></td>
<td><strong>$42 \pm 5$</strong></td>
</tr>
</tbody>
</table>

#### Data

|                      | 12 | 26 | 12 | 50 |

### VBS Signal Region

<table>
<thead>
<tr>
<th></th>
<th>$e^\pm e^\pm$</th>
<th>$e^\pm \mu^\pm$</th>
<th>$\mu^\pm \mu^\pm$</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W^\pm W^\mp jj$ Electroweak</td>
<td>$2.55 \pm 0.25$</td>
<td>$7.3 \pm 0.6$</td>
<td>$4.0 \pm 0.4$</td>
<td>$13.9 \pm 1.2$</td>
</tr>
<tr>
<td>$W^\pm W^\mp jj$ Strong</td>
<td>$0.25 \pm 0.06$</td>
<td>$0.71 \pm 0.14$</td>
<td>$0.38 \pm 0.08$</td>
<td>$1.34 \pm 0.26$</td>
</tr>
<tr>
<td>$WZ/\gamma^*,ZZ,tt+WW/Z$</td>
<td>$2.2 \pm 0.5$</td>
<td>$4.2 \pm 1.0$</td>
<td>$1.9 \pm 0.5$</td>
<td>$8.2 \pm 1.9$</td>
</tr>
<tr>
<td>$W+\gamma$</td>
<td>$0.7 \pm 0.4$</td>
<td>$1.3 \pm 0.7$</td>
<td>$-$</td>
<td>$2.0 \pm 1.0$</td>
</tr>
<tr>
<td>OS prompt leptons</td>
<td>$1.39 \pm 0.27$</td>
<td>$0.64 \pm 0.24$</td>
<td>$-$</td>
<td>$2.0 \pm 0.5$</td>
</tr>
<tr>
<td>Other non-prompt</td>
<td>$0.50 \pm 0.26$</td>
<td>$1.5 \pm 0.6$</td>
<td>$0.34 \pm 0.19$</td>
<td>$2.3 \pm 0.7$</td>
</tr>
<tr>
<td><strong>Total Predicted</strong></td>
<td><strong>$7.6 \pm 1.0$</strong></td>
<td><strong>$15.6 \pm 2.0$</strong></td>
<td><strong>$6.6 \pm 0.8$</strong></td>
<td><strong>$29.8 \pm 3.5$</strong></td>
</tr>
</tbody>
</table>

#### Data

|                      | 6  | 18 | 10 | 34 |
### $W^\pm W^\pm jj$ event yields

<table>
<thead>
<tr>
<th>Source</th>
<th>$e^\pm e^\pm$</th>
<th>$e^\pm \mu^\pm$</th>
<th>$\mu^\pm \mu^\pm$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prompt</td>
<td>3.0 ± 0.7</td>
<td>6.1 ± 1.3</td>
<td>2.6 ± 0.6</td>
</tr>
<tr>
<td>Conversions</td>
<td>3.2 ± 0.7</td>
<td>2.4 ± 0.8</td>
<td>−</td>
</tr>
<tr>
<td>Other non-prompt</td>
<td>0.61 ± 0.30</td>
<td>1.9 ± 0.8</td>
<td>0.41 ± 0.22</td>
</tr>
<tr>
<td>$W^\pm W^\pm jj$ Strong</td>
<td>0.89 ± 0.15</td>
<td>2.5 ± 0.4</td>
<td>1.42 ± 0.23</td>
</tr>
<tr>
<td>$W^\pm W^\pm jj$ Electroweak</td>
<td>3.07 ± 0.30</td>
<td>9.0 ± 0.8</td>
<td>4.9 ± 0.5</td>
</tr>
<tr>
<td>Total background</td>
<td>6.8 ± 1.2</td>
<td>10.3 ± 2.0</td>
<td>3.0 ± 0.6</td>
</tr>
<tr>
<td>Total predicted</td>
<td>10.7 ± 1.4</td>
<td>21.7 ± 2.6</td>
<td>9.3 ± 1.0</td>
</tr>
<tr>
<td>Data</td>
<td>12</td>
<td>26</td>
<td>12</td>
</tr>
</tbody>
</table>

- Interference between EW and strong $W^\pm W^\pm jj$ production: $\sim 12\%$
- Evaluated with Sherpa, included in EW $W^\pm W^\pm jj$ prediction.
### Systematic Uncertainties $ee/e\mu/\mu\mu$ (%) - VBS SR

<table>
<thead>
<tr>
<th>Background</th>
<th></th>
<th>Signal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jet uncertainties</td>
<td>13/15/15</td>
<td>Theory $W^\pm W^\pm jj$-ewk 6.0</td>
</tr>
<tr>
<td>Theory $WZ/\gamma^*$</td>
<td>4.5/5.4/7.8</td>
<td>Jet uncertainties 5.1</td>
</tr>
<tr>
<td>MC statistics</td>
<td>8.9/6.4/8.4</td>
<td>Luminosity 2.8</td>
</tr>
<tr>
<td>Fake rate</td>
<td>4.0/7.2/6.8</td>
<td>MC statistics 4.5/2.7/3.7</td>
</tr>
<tr>
<td>OS lepton bkg/</td>
<td>5.5/4.4/–</td>
<td>$E_T^{miss}$ reconstruction 1.1</td>
</tr>
<tr>
<td>Conversion rate</td>
<td></td>
<td>Lepton reconstruction 1.9/1.0/0.7</td>
</tr>
<tr>
<td>$E_T^{miss}$ reconstruction</td>
<td>2.9/3.2/1.4</td>
<td>b-tagging efficiency 0.6</td>
</tr>
<tr>
<td>Theory $W + \gamma$</td>
<td>3.1/2.6/–</td>
<td>trigger efficiency 0.1/0.3/0.5</td>
</tr>
<tr>
<td>Luminosity</td>
<td>1.7/2.1/2.4</td>
<td></td>
</tr>
<tr>
<td>Theory $W^\pm W^\pm jj$-strong</td>
<td>0.9/1.5/2.6</td>
<td></td>
</tr>
<tr>
<td>Lepton reconstruction</td>
<td>1.7/1.1/1.1</td>
<td></td>
</tr>
<tr>
<td>b-tagging efficiency</td>
<td>0.8/0.9/0.7</td>
<td></td>
</tr>
<tr>
<td>Trigger efficiency</td>
<td>0.1/0.2/0.7</td>
<td></td>
</tr>
</tbody>
</table>
$W^\pm W^\pm jj$ production – control regions

### Trilepton Control Region

- Prompt conversions ($ee$)
- Non-prompt conversions ($\gamma$, $W$, $Z$

#### Data/Expected

<table>
<thead>
<tr>
<th>$m_{jj}$ [GeV]</th>
<th>0</th>
<th>100</th>
<th>200</th>
<th>300</th>
<th>400</th>
<th>500</th>
<th>600</th>
<th>700</th>
</tr>
</thead>
<tbody>
<tr>
<td>Events/50 GeV</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Data/Expected</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>

**ATLAS**

- Data 2012
- Syst. Uncertainty
- $W^\pm W^\pm jj$ ewk+strong
- $WZ/\gamma^*$
- $ZZ\rightarrow 4l$
- Non-prompt leptons
- $t\bar{t}+W/Z$

#### Syst. Uncertainty

### Less than 1 Jet Control Region

- Prompt conversions ($\mu\mu$)
- Non-prompt leptons
- Other non-prompt leptons

#### Data/Expected

<table>
<thead>
<tr>
<th>$m_{jj}$ [GeV]</th>
<th>100</th>
<th>200</th>
<th>300</th>
<th>400</th>
<th>500</th>
<th>600</th>
<th>700</th>
</tr>
</thead>
<tbody>
<tr>
<td>Events/10 GeV</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Data/Expected</td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>

**ATLAS**

- Data 2012
- Syst. Uncertainty
- $W^\pm W^\pm jj$ ewk+strong
- OS prompt leptons
- $WZ/\gamma^*$, $ZZ$
- $W+\gamma$
- Other non-prompt leptons
- $t\bar{t}+W/Z$

#### Syst. Uncertainty

<table>
<thead>
<tr>
<th>Control Region</th>
<th>Trilepton</th>
<th>$\leq 1$ jet Control Region</th>
<th>$b$-tagged</th>
<th>Low $m_{jj}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e^\pm e^\pm$</td>
<td>36 ± 6</td>
<td>278 ± 28</td>
<td>40 ± 6</td>
<td>76 ± 9</td>
</tr>
<tr>
<td>Data</td>
<td>40</td>
<td>288</td>
<td>46</td>
<td>78</td>
</tr>
<tr>
<td>$e^\pm \mu^\pm$</td>
<td>110 ± 18</td>
<td>288 ± 42</td>
<td>75 ± 13</td>
<td>127 ± 16</td>
</tr>
<tr>
<td>Data</td>
<td>104</td>
<td>328</td>
<td>82</td>
<td>120</td>
</tr>
<tr>
<td>$\mu^\pm \mu^\pm$</td>
<td>60 ± 10</td>
<td>88 ± 14</td>
<td>25 ± 7</td>
<td>40 ± 6</td>
</tr>
<tr>
<td>Data</td>
<td>48</td>
<td>101</td>
<td>36</td>
<td>30</td>
</tr>
</tbody>
</table>
$W^\pm W^\pm jj$ production – control regions

$\bar{t}t$ / b-tag control region:
$\rightarrow$ other non-prompt ($b$-decays)

$m_{jj} < 500$ GeV control region:
$\rightarrow$ mix

<table>
<thead>
<tr>
<th>Control Region</th>
<th>Trilepton</th>
<th>$\leq 1$ jet</th>
<th>$b$-tagged</th>
<th>Low $m_{jj}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e^\pm e^\pm$</td>
<td>exp.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>data</td>
<td></td>
<td></td>
<td></td>
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<td>288</td>
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<td>78</td>
</tr>
<tr>
<td>$e^\pm \mu^\pm$</td>
<td>exp.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>data</td>
<td></td>
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<td></td>
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<tr>
<td></td>
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<td>120</td>
</tr>
<tr>
<td>$\mu^\pm \mu^\pm$</td>
<td>exp.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>data</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
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</tr>
<tr>
<td></td>
<td>48</td>
<td>101</td>
<td>36</td>
<td>30</td>
</tr>
</tbody>
</table>
$W^\pm Z j j$: experimental tasks

- $W^\pm Z$ ($+ n$ jets) can have any number of jets: $n = 0, 1, 2, 3, \ldots$
  - lowest order: $W^\pm Z + 0$ jets

- 3 high $p_T$, isolated leptons

- 1 opposite-sign lepton pair forming $Z$ within $81 \text{ GeV} < m_{\ell\ell} < 101 \text{ GeV}$

- residual lepton + $E_T^{\text{miss}}$ forming $W$

- results:
  - 1094 events observed
  - 277 background events expected (mainly $Z$+jets & fake leptons)
  - $\sigma_{\text{total}} = 20.3^{+0.8}_{-0.7}\text{(stat)}^{+1.2}_{-1.1}\text{(syst)}^{+0.7}_{-0.6}\text{(lumi)} \text{ pb}$
  - $\sigma_{\text{MCFM}} = 20.3 \pm 0.8 \text{ pb}$

- for $W^\pm Z$ VBS measurement: require additional 2 jets

\[ \sqrt{s} = 8 \text{ TeV}, 13 \text{ fb}^{-1} \]

ATLAS Preliminary
Modeling of anomalous quartic gauge couplings

EFT description can be translated in EW chiral Lagrangian approach for aTGC/aQGC and vice versa (switch of operator bases) arXiv:hep-ph/0606118

**EW chiral Lagrangian approach** (non-linear realization of the gauge symmetry)

- aQGC operators (dimension 4):
  \[
  \mathcal{L}_4 = \alpha_4 (\text{Tr}[V_\mu V_\nu])^2 \quad \mathcal{L}_5 = \alpha_5 (\text{Tr}[V_\mu V_\mu])^2
  \]

- \(V_\mu = \Sigma (D_\mu \Sigma)^\dagger\), \(\Sigma = e^{-i \frac{w}{v}}\), \(w\): goldstone scalar field triplett

- aQGC parametrizations: \(\alpha_4\) and \(\alpha_5\)

**EFT approach** (linear realization of gauge symmetry)

- operators (dimension 8):
  \[
  \mathcal{L}_{S,0} = \frac{f_{S,0}}{\Lambda^4} [(D_\mu \Phi)^\dagger D_\nu \Phi] \times [(D_\mu \Phi)^\dagger D_\nu \Phi] \\
  \mathcal{L}_{S,1} = \frac{f_{S,1}}{\Lambda^4} [(D_\mu \Phi)^\dagger D^\mu \Phi] \times [(D_\nu \Phi)^\dagger D^\nu \Phi]
  \]

- parametrizations: \(\frac{f_{S,0}}{\Lambda^4}\) and \(\frac{f_{S,1}}{\Lambda^4}\)
Unitarization schemes

K-matrix: saturation of amplitude to achieve unitarity
form factor: suppression of amplitude to get below unitarity bound

https://indico.desy.de/getFile.py/access?contribId=8&sessionId=2&resId=0&materialId=slides&confId=7512
Kinematic distributions, unitarized

- comparison of unitarization with K-matrix method (\textsc{Whizard}, \(\alpha_4/5\)) and form factors (\textsc{VBFNLO}, \(f_{S,0/1}\)) at generator level
- example process: \(pp \rightarrow qqe^+\nu e^+\nu\)

\[\Delta \phi (\text{leptons}) \text{ differential cross-section distribution:}\]

\[
\begin{align*}
\tilde{f}_{s0} &= \tilde{f}_{s1} = 0 \\
\tilde{f}_{s0} &= \tilde{f}_{s1} = -217.6 \\
\tilde{f}_{s0} &= \tilde{f}_{s1} = -435.2 \\
\tilde{f}_{s0} &= \tilde{f}_{s1} = -870.4 \\
\alpha_4 &= 0, \alpha_5 = 0 \\
\alpha_4 &= -0.1, \alpha_5 = 0 \\
\alpha_4 &= -0.2, \alpha_5 = 0 \\
\alpha_4 &= -0.4, \alpha_5 = 0
\end{align*}
\]

generator cuts:
- \(p_T^\ell > 10 \text{ GeV}, |\eta_\ell| < 5\)
- \(p_T^j > 20 \text{ GeV}, |\eta_j| < 5\)
- \(|\Delta R(jj)| > 0.4\)
- \(m_{jj} > 150 \text{ GeV}\)

aQGC parameter:
- \(\tilde{f}_{S,0} = \tilde{f}_{S,1} \approx 2176 \cdot \alpha_4\) (with \(\tilde{f}_{S,0/1} = f_{S,0/1}/\Lambda_4^4 \text{ TeV}^4\))
- \(\alpha_5 = 0\)
## Limits on aQGCs for $WW\gamma\gamma$

### July 2013

<table>
<thead>
<tr>
<th>Anomalous $WW\gamma\gamma$ Quartic Coupling limits @95% C.L.</th>
<th>Channel</th>
<th>Limits</th>
<th>$L$</th>
<th>$\sqrt{s}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a_0^W/\Lambda^2$ TeV$^{-2}$</td>
<td>$WW\gamma$</td>
<td>[- 15000, 15000]</td>
<td>0.43fb$^{-1}$</td>
<td>0.20 TeV</td>
</tr>
<tr>
<td></td>
<td>$\gamma\gamma \rightarrow WW$</td>
<td>[- 430, 430]</td>
<td>9.70fb$^{-1}$</td>
<td>1.96 TeV</td>
</tr>
<tr>
<td>$a_C^W/\Lambda^2$ TeV$^{-2}$</td>
<td>$WW\gamma$</td>
<td>[- 21, 20]</td>
<td>19.30fb$^{-1}$</td>
<td>8.0 TeV</td>
</tr>
<tr>
<td></td>
<td>$\gamma\gamma \rightarrow WW$</td>
<td>[- 4, 4]</td>
<td>5.05fb$^{-1}$</td>
<td>7.0 TeV</td>
</tr>
<tr>
<td>$f_{t,0}/\Lambda^4$ TeV$^{-4}$</td>
<td>$WW\gamma$</td>
<td>[- 48000, 26000]</td>
<td>0.43fb$^{-1}$</td>
<td>0.20 TeV</td>
</tr>
<tr>
<td></td>
<td>$\gamma\gamma \rightarrow WW$</td>
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<td>9.70fb$^{-1}$</td>
<td>1.96 TeV</td>
</tr>
<tr>
<td></td>
<td>$WW\gamma$</td>
<td>[- 34, 32]</td>
<td>19.30fb$^{-1}$</td>
<td>8.0 TeV</td>
</tr>
<tr>
<td></td>
<td>$\gamma\gamma \rightarrow WW$</td>
<td>[- 15, 15]</td>
<td>5.05fb$^{-1}$</td>
<td>7.0 TeV</td>
</tr>
<tr>
<td>$\nabla^2 f_{t,0}/\Lambda^4$ TeV$^{-4}$</td>
<td>$WW\gamma$</td>
<td>[- 25, 24]</td>
<td>19.30fb$^{-1}$</td>
<td>8.0 TeV</td>
</tr>
</tbody>
</table>

**LEP L3 limits**

**D0 limits**

**CMS $WW\gamma$ limits**

**CMS $\gamma\gamma \rightarrow WW$ limits**
Effective QGC in VBS

- non-linear realization of the gauge symmetry → chiral EW Lagrangian:

$$L_4 = \alpha_4 \frac{g^2}{2} \left\{ \left[ (W^+ W^+) (W^- W^-) + (W^+ W^-)^2 \right] + \frac{2}{c_w^2} (W^+ Z) (W^- Z) + \frac{1}{2c_w^4} (ZZ)^2 \right\}$$

$$L_5 = \alpha_4 \frac{g^2}{2} \left\{ (W^+ W^-)^2 + \frac{2}{c_w^2} (W^+ W^-) (ZZ) + \frac{1}{2c_w^4} (ZZ)^2 \right\}$$

- effective parametrization of physics beyond kinematic reach, e.g. resonances at new physics scale $\Lambda = \frac{v}{\sqrt{\alpha_i}}$
  - wide → continuum, narrow → particles

- $\alpha_i$ parametrize low-mass tail of these resonances, e.g. $\alpha_5 = g_\sigma^2 \left( \frac{v^2}{8M_\sigma^2} \right)$

<table>
<thead>
<tr>
<th></th>
<th>$J = 0$</th>
<th>$J = 1$</th>
<th>$J = 2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$I = 0$</td>
<td>$\sigma^0$ (Higgs)</td>
<td>$\omega^0$ ($\gamma'/Z'$)</td>
<td>$f^0$ (Graviton?)</td>
</tr>
<tr>
<td>$I = 1$</td>
<td>$\pi^\pm, \pi^0$ (2HDM?)</td>
<td>$\rho^\pm, \rho^0$ ($w'/Z'$)</td>
<td>$a^\pm, a^0$</td>
</tr>
<tr>
<td>$I = 2$</td>
<td>$\phi^{\pm\pm}, \phi^\pm, \phi^0$ (Higgs triplett?)</td>
<td>–</td>
<td>$t^{\pm\pm}, t^{\pm}, t^0$</td>
</tr>
</tbody>
</table>

- unitarization only guaranteed for explicitly included resonance(s) at unique values of the coupling $g$

- effective parametrization always violates unitarity at some $m_{VV}$
Resonances in VBS

Example with resonances, scalars ($\alpha_4$ and $\alpha_5 = 0$, no longer needed!)

→ cross sections (in nb) for $VV$ scattering in dependence of the centre-of-mass energy:

\[
\begin{align*}
\sigma(VV \rightarrow VV), & \text{ with 500 GeV scalar isoscalar} \\
\sigma(VV \rightarrow VV), & \text{ with 500 GeV scalar isotensor}
\end{align*}
\]
Prospects for VBS at $\sqrt{s} = 14$ TeV

- LHC @ 14 TeV $\rightarrow \sqrt{s} = m_{VV} \approx 1 - 2$ TeV
- signal chosen: anomalous VBS $ZZ$ tensor singlet resonance $f^0$
  - exactly four selected leptons: two opposite sign, same flavor pairs
  - hard benchmark, sensitivity higher for other resonances

<table>
<thead>
<tr>
<th>$m_{resonance}$</th>
<th>coupling</th>
<th>width</th>
<th>$300 \text{ fb}^{-1}$</th>
<th>$3000 \text{ fb}^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>500 GeV</td>
<td>$g = 1$</td>
<td>$\Gamma = 2$ GeV</td>
<td>2.4$\sigma$</td>
<td>7.5$\sigma$</td>
</tr>
<tr>
<td>1 TeV</td>
<td>$g = 1.75$</td>
<td>$\Gamma = 50$ GeV</td>
<td>1.7$\sigma$</td>
<td>5.5$\sigma$</td>
</tr>
<tr>
<td>1 TeV</td>
<td>$g = 2.5$</td>
<td>$\Gamma = 100$ GeV</td>
<td>3.0$\sigma$</td>
<td>9.4$\sigma$</td>
</tr>
</tbody>
</table>

![Graph showing SM VV, Diboson, Non-VV, and VBS signal](image)

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