Anomalous quartic $WW\gamma\gamma$ and $ZZ\gamma\gamma$ couplings in $\gamma$-induced processes

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Contents:

- $WW$ production cross section at the LHC
- Quartic anomalous couplings
- ATLAS/CMS Forward Physics projects

Work in collaboration with E. Chapon, O. Kepka
**Study of the process**:  $pp \rightarrow ppWW$

**Clean process**: $W$ in central detector and nothing else, intact protons in final state which can be detected far away from interaction point

**Exclusive production of $W$ pairs via photon exchange**: QED process, cross section perfectly known

**Two steps**: SM observation of $WW$ events, anomalous coupling study (NB: new anomalous couplings predicted by beyond standard model theories) at high luminosities at LHC

$\sigma_{WW} = 95.6$ fb, $\sigma_{WW}(W > 1 TeV) = 5.9$ fb

**Rich $\gamma \gamma$ physics at LHC**
**WW production at the LHC**

- **Signal:** We focus on leptonic signals decays of \( WW \) and \( ZZ \), the protons are tagged in the forward proton detectors; fast simulation of the ATLAS detector (ATLFast++)

- **Backgrounds considered:**
  - **Non diffractive \( WW \) production:** large energy flow in forward region, removed by requesting tagged protons
  - **Two photon dileptons:** back-to-back leptons, small cross section for high \( p_T \) leptons

  \[
  p \rightarrow \gamma \rightarrow l \bar{l} \rightarrow p
  \]

  - **Lepton production via double pomeron exchange:** activity in the forward region due to pomeron remnants, removed by \( E_T \) cut
  - **\( WW \) via double pomeron exchange:** removed by cut on high diffractive mass
Forward Physics Monte Carlo (FPMC)

• **FPMC (Forward Physics Monte Carlo):** implementation of all diffractive/photon induced processes

• **List of processes**
  – two-photon exchange
  – single diffraction
  – double pomeron exchange
  – central exclusive production

• **Inclusive diffraction:** Use of diffractive PDFs measured at HERA, with a survival probability of 0.03 applied for LHC

• **Survival probability for photon exchange events:** 0.9

• **Central exclusive production:** Higgs, jets... for Khoze Martin Ryskin or Dechambre Cudell models as an example; diphoton exclusive production being implemented

• **FPMC manual** (see M. Boonekamp, A. Dechambre, O. Kepka, V. Juranek, C. Royon, R. Staszewski, M. Rangel, ArXiv:1102.2531), code to be public soon

• **Output of FPMC generator interfaced with the fast simulation of the ATLAS detector in the standalone ATLFast++ package**
Strategy to measure the $\gamma\gamma \rightarrow WW$ SM cross section

- Require both $W$s to decay leptonically (as a starting point to avoid jet background) with $p_T$ of leading (2nd leading) lepton above 25, 10 GeV
- Require both protons in the ATLAS Forward Proton (AFP) detector
- $E_T > 20$ GeV, natural for $W$ decays (get rid of dilepton background produced by photon exchange)
- $\Delta\Phi$ between leading leptons allows to remove dilepton background
Measuring the $\gamma\gamma \rightarrow WW$ SM cross section

Number of events for 30 fb$^{-1}$ after successive cuts

<table>
<thead>
<tr>
<th>cut / process</th>
<th>$\gamma\gamma \rightarrow ll$</th>
<th>DPE$\rightarrow ll$</th>
<th>DPE$\rightarrow WW$</th>
<th>$\gamma\gamma \rightarrow WW$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p_T^{lep1,2} &gt; 10$ GeV</td>
<td>50620</td>
<td>17931</td>
<td>8.8</td>
<td>95</td>
</tr>
<tr>
<td>$0.0015 &lt; \xi &lt; 0.15$</td>
<td>21059</td>
<td>11487</td>
<td>5.9</td>
<td>89</td>
</tr>
<tr>
<td>$E_T &gt; 20$ GeV</td>
<td>14.9</td>
<td>33</td>
<td>4.7</td>
<td>78</td>
</tr>
<tr>
<td>$W &gt; 160$ GeV</td>
<td>9.2</td>
<td>33</td>
<td>4.7</td>
<td>78</td>
</tr>
<tr>
<td>$\Delta\phi &lt; 2.7$</td>
<td>0</td>
<td>14</td>
<td>3.8</td>
<td>61</td>
</tr>
<tr>
<td>$p_T^{lep} &gt; 25$ GeV</td>
<td>0</td>
<td>7.5</td>
<td>3.5</td>
<td>58</td>
</tr>
<tr>
<td>$W &lt; 500$</td>
<td>0</td>
<td>1.0</td>
<td>0.67</td>
<td>51</td>
</tr>
</tbody>
</table>

5 $\sigma$ discovery possible after 5 fb$^{-1}$ (pure leptonic decays of $W$s)
Measuring the $\gamma\gamma \rightarrow WW$ SM cross section: semi-leptonic decays

- Consider both leptonic and semileptonic decays of $W$s
- Fast generator level study: For a luminosity of $200 \text{ pb}^{-1}$, observation of 5.6 $W$ pair events for a background less than 0.4, which leads to a signal of $8\sigma$

<table>
<thead>
<tr>
<th>$\xi_{\text{max}}$</th>
<th>signal (fb)</th>
<th>background (fb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.05</td>
<td>13.8</td>
<td>0.16</td>
</tr>
<tr>
<td>0.10</td>
<td>24.0</td>
<td>1.0</td>
</tr>
<tr>
<td>0.15</td>
<td>28.3</td>
<td>2.2</td>
</tr>
</tbody>
</table>

- Study needs to be redone considering the simulation of all backgrounds: especially when one of the quarks radiates a $W$ boson, which is being implemented in FPMC
Quartic anomalous gauge couplings

- Quartic gauge anomalous $WW\gamma\gamma$ and $ZZ\gamma\gamma$ couplings parametrised by $a_0^W$, $a_0^Z$, $a_C^W$, $a_C^Z$

\[
\mathcal{L}_6^0 \sim -\frac{e^2}{8} \frac{a_0^W}{\Lambda^2} F_{\mu\nu} F^{\mu\nu} W^{+\alpha} W^{-\alpha} - \frac{e^2}{16 \cos^2(\theta_W)} \frac{a_0^Z}{\Lambda^2} F_{\mu\nu} F^{\mu\nu} Z^{\alpha} Z^{-\alpha}
\]

\[
\mathcal{L}_6^C \sim -\frac{e^2}{16} \frac{a_C^W}{\Lambda^2} F_{\mu\alpha} F^{\mu\beta} (W^{+\alpha} W^{-\beta} + W^{-\alpha} W^{+\beta})
\]

\[\sim \frac{e^2}{16 \cos^2(\theta_W)} \frac{a_C^Z}{\Lambda^2} F_{\mu\alpha} F^{\mu\beta} Z^{\alpha} Z^{\beta}\]

- Anomalous parameters equal to 0 for SM
- Non zero anomalous couplings motivated by Higgsless and extradimension models (under study: Christophe Grojean et al.)
- Best limits from LEP, OPAL (Phys. Rev. D 70 (2004) 032005) of the order of 0.02-0.04, for instance $-0.02 < a_0^W < 0.02 \text{ GeV}^{-2}$
- Allows to probe the values predicted by Higgsless/extradimension models (C. Grojean, J. Wells et al.)
- Dimension 6 operators $\rightarrow$ violation of unitarity at high energies
Quartic anomalous gauge couplings: form factors

- Unitarity bounds can be computed (Eboli, Gonzales-Garcia, Lietti, Novaes):

\[
4 \left( \frac{\alpha s}{16} \right)^2 \left( 1 - \frac{4M_W^2}{s} \right)^{1/2} \left( 3 - \frac{s}{M_W^2} + \frac{s^2}{4M_W^4} \right) \leq 1
\]

where \( a = a_0/\Lambda^2 \)

- Introducing form factors to avoid quadratical divergences of scattering amplitudes due to anomalous couplings in conventional way:

\[
a_0^W/\Lambda^2 \rightarrow \frac{a_0^W/\Lambda^2}{(1+W\gamma\gamma/\Lambda_{cutoff})^2} \quad \text{with} \quad \Lambda_{cutoff} \sim 2 \text{ TeV}, \text{ scale of new physics}
\]

- For \( a_0^W \sim 10^{-6} \text{ GeV}^{-2} \), no violation of unitarity
**Strategy to select quartic anomalous gauge couplings events**

- $p_T$ of the leading lepton: request high $p_T$ lepton to remove background
- Missing $E_T$ distribution: natural to be requested for $W$ pair production
- Diffractive mass computed using the forward proton detectors $\sqrt{\xi_1\xi_2 S}$: request high mass objects to be produced
- $\Delta\Phi$ between both leptons: avoid back-to-back leptons
Quartic anomalous gauge couplings

Distribution of the leading lepton $p_T$ after all cuts (proton tagged, $E_T$, diffractive mass, $\Delta \Phi$) except the cut on leading lepton $p_T$

![Graph showing distribution of leading lepton $p_T$.]
# Quartic anomalous gauge couplings

## Background events for 30 fb$^{-1}$

<table>
<thead>
<tr>
<th>cut / process</th>
<th>$\gamma\gamma \rightarrow ll$</th>
<th>$\gamma\gamma \rightarrow WW$</th>
<th>DPE$\rightarrow ll$</th>
<th>DPE$\rightarrow WW$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p_T^{lep1,2} &gt; 10$ GeV</td>
<td>50619</td>
<td>99</td>
<td>18464</td>
<td>8.8</td>
</tr>
<tr>
<td>$0.0015 &lt; \xi &lt; 0.15$</td>
<td>21058</td>
<td>89</td>
<td>11712</td>
<td>6.0</td>
</tr>
<tr>
<td>$E_T &gt; 20$ GeV</td>
<td>14.9</td>
<td>77</td>
<td>36</td>
<td>4.7</td>
</tr>
<tr>
<td>$W &gt; 800$ GeV</td>
<td>0.42</td>
<td>3.2</td>
<td>16</td>
<td>2.5</td>
</tr>
<tr>
<td>$M_{ll} \not\in (80, 100)$</td>
<td>0.42</td>
<td>3.2</td>
<td>13</td>
<td>2.5</td>
</tr>
<tr>
<td>$\Delta \phi &lt; 3.13$</td>
<td>0.10</td>
<td>3.2</td>
<td>12</td>
<td>2.5</td>
</tr>
<tr>
<td>$p_T^{lep1} &gt; 160$ GeV</td>
<td>0</td>
<td>0.69</td>
<td>0.20</td>
<td>0.024</td>
</tr>
</tbody>
</table>

## Signal events for 30 fb$^{-1}$

<table>
<thead>
<tr>
<th>cut / couplings (with f.f.)</th>
<th>$a_0^W/\Lambda^2$</th>
<th>$= 5.4 \cdot 10^{-6}$</th>
<th>$a_C^W/\Lambda^2$</th>
<th>$= 20 \cdot 10^{-6}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p_T^{lep1,2} &gt; 10$ GeV</td>
<td>202</td>
<td>200</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$0.0015 &lt; \xi &lt; 0.15$</td>
<td>116</td>
<td>119</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$E_T &gt; 20$ GeV</td>
<td>104</td>
<td>107</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$W &gt; 800$ GeV</td>
<td>24</td>
<td>23</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$M_{ll} \not\in (80, 100)$</td>
<td>24</td>
<td>23</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\Delta \phi &lt; 3.13$</td>
<td>24</td>
<td>22</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$p_T^{lep1} &gt; 160$ GeV</td>
<td>17</td>
<td>16</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Quartic anomalous gauge couplings

- **Strategy for \( ZZ \) events similar:** Request either three leptons or two leptons of the same sign, protons tagged in forward detectors, \( p_T \) of leading leptons greater than 160 GeV
- **Number of events for 30 fb\(^{-1} \)** for the different couplings
- **5\( \sigma \) discovery contours for two different luminosities 30 and 200 fb\(^{-1} \)**
- **Present LEP limits can be improved by up to four orders of magnitude**
Reach at LHC
Reach at high luminosity on quartic anomalous coupling

<table>
<thead>
<tr>
<th>Couplings</th>
<th>OPAL limits [GeV$^{-2}$]</th>
<th>Sensitivity @ $\mathcal{L} = 30$ (200) fb$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a^W_0 / \Lambda^2$</td>
<td>[-0.020, 0.020]</td>
<td>$5.4 \ 10^{-6}$ $(2.7 \ 10^{-6})$ $2.6 \ 10^{-6}$ $(1.4 \ 10^{-6})$</td>
</tr>
<tr>
<td>$a^W_C / \Lambda^2$</td>
<td>[-0.052, 0.037]</td>
<td>$2.0 \ 10^{-5}$ $(9.6 \ 10^{-6})$ $9.4 \ 10^{-6}$ $(5.2 \ 10^{-6})$</td>
</tr>
<tr>
<td>$a^Z_0 / \Lambda^2$</td>
<td>[-0.007, 0.023]</td>
<td>$1.4 \ 10^{-5}$ $(5.5 \ 10^{-6})$ $6.4 \ 10^{-6}$ $(2.5 \ 10^{-6})$</td>
</tr>
<tr>
<td>$a^Z_C / \Lambda^2$</td>
<td>[-0.029, 0.029]</td>
<td>$5.2 \ 10^{-5}$ $(2.0 \ 10^{-5})$ $2.4 \ 10^{-5}$ $(9.2 \ 10^{-6})$</td>
</tr>
</tbody>
</table>

- Improvement of LEP sensitivity by more than 4 orders of magnitude with 30/200 fb$^{-1}$ at LHC!!!
- Reaches the values predicted by Higgsless/extradimension models
- Without AFP: these values cannot be reached, only gain of two orders of magnitude by studying $pp \rightarrow l^\pm \nu \gamma \gamma$, see ArXiv 0907.5299
ATLAS and CMS Forward detector projects

- **what is needed?** Tag the protons intact after interaction, good proton position and good timing measurements (use Si pixel and picosecond quartz/gas detectors)
- **ATLAS**: Detectors at 220 and 420 m (220 m only by 2013-14)
- **CMS**: Detectors at 240 and 420 m
Both detectors at 420 and 220 m needed to have a good coverage of acceptance; 220 m detectors give the high mass acceptance needed for anomalous coupling studies (NB: acceptance slightly smaller in CMS than in ATLAS).
Conclusion

• ATLAS and CMS project to install additional forward proton detectors

• Observation of QED $WW$ production at the LHC: easy once forward detectors installed

• Quartic gauge anomalous coupling studies: Easy analysis (2 $W$ or $Z$ decaying in leptons); semi-leptonic decay studies in progress

• Improvement of LEP (OPAL) sensitivity by four orders of magnitude with $\sim 30$-$200$ fb$^{-1}$: allows to probe extradim/higgsless models with an unprecedented precision, looks impossible without forward detectors

• Project under evaluation in ATLAS (AFP)/CMS: in ATLAS, technical proposal submitted to ATLAS