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

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Contents:

- $WW$ production cross section at the LHC
- Trilinear anomalous coupling
- Quartic anomalous couplings

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 low and high luminosities at LHC

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

Measuring the $\gamma\gamma \rightarrow WW$ SM cross section

- Forward detectors assumed for ATLAS/CMS experiments allowing to detect protons in the final state: $0.0015 < \xi < 0.15$ (proton fraction momentum carried by the photon)

- Signal and double pomeron exchange background cross section

- Clean signal: 2 $W$ decaying in central detector, and proton detected in forward detectors

- For a luminosity of 200 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>$\xi_{max}$</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>
Quartic anomalous gauge couplings

- Quartic gauge anomalous $WW\gamma\gamma$ and $ZZ\gamma\gamma$ couplings parametrised by $a_W, a_Z, a_W^C, a_Z^C$

\[ L_6^0 \sim -\frac{e^2}{8} \frac{a_W}{\Lambda^2} F_{\mu\nu} F^{\mu\nu} W^+ W^- - \frac{e^2}{16 \cos^2(\theta_W)} \frac{a_Z}{\Lambda^2} F_{\mu\nu} F^{\mu\nu} Z^\alpha Z^\alpha \]

\[ L_6^C \sim -\frac{e^2}{16} \frac{a_C^W}{\Lambda^2} F_{\mu\alpha} F_{\mu\beta} (W^+ W^- + W^- W^+) \]

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

- Anomalous parameters equal to 0 for SM

- Best limits from LEP, OPAL (Phys. Rev. D 70 (2004) 032005) of the order of 0.02-0.04, for instance $-0.02 < a_W < 0.02 \text{ GeV}^{-2}$

- Dimension 6 operators $\rightarrow$ violation of unitarity at high energies

- Introducing form factors in conventional way:

\[ \frac{a^W}{\Lambda^2} \rightarrow \frac{a^W/\Lambda^2}{(1 + W\gamma\gamma/\Lambda_{\text{cutoff}})^2} \text{ with } \Lambda_{\text{cutoff}} \sim 2 \text{ TeV, scale of new physics} \]
Anomalous $WW\gamma\gamma$ quadric gauge coupling

- High cross sections at LHC even for an anomalous coupling much smaller than LEP limits ($\sim 0.01$), given the expected luminosity ($\sim \text{fb}^{-1}$)
- **Strategy:** Look for $W$ pair events even at low luminosity at the beginning of the LHC ($10 \text{ pb}^{-1}$ at $\sqrt{S} = 10 \text{ TeV}$) and at higher luminosity when forward detectors to tag the protons are installed
Quartic anomalous coupling signal at low luminosity at LHC

- **Signal:** We focus on leptonic signals decays of $WW$ and $ZZ$ (typically at least two leptons and nothing else (no jet) in the detector): request two high $p_T$ leptons, exclusivity requirements

- **Backgrounds considered:**
  - Non diffractive $WW$ production: large energy flow in forward region, removed by “exclusivity cut”
  - Two photon dileptons: back-to-back leptons, small cross section for high $p_T$ leptons
  - Lepton production via double pomeron exchange (high mass): activity in the forward region due to pomeron remnants, removed by “exclusivity cut”
  - $WW$ via double pomeron exchange: Idem
  - Standard model $WW$ production via photon exchange: small cross section, removed partly by requesting a high $p_T$ lepton
Quartic anomalous coupling signal at low luminosity at LHC

- $P_T$ distribution of leading lepton (e or $\mu$): removes SM background with a cut $p_T > 160$ GeV
- Other backgrounds very small after cuts (all implemented in FPMC Monte Carlo)
Event distribution for 10 pb$^{-1}$

After cuts, no background, sensitivity comes mainly for $WW$ or $ZZ$ production cross section with anomalous coupling.

- signal - $a_W^0 = 1.75 \times 10^{-5}$ GeV$^{-2}$
- $\gamma\gamma \rightarrow ee$ or $\mu\mu$
- $\gamma\gamma \rightarrow WW$

All cuts:
- $p_T^{lep1,2} > 10$ GeV in acc.
- $n_{tracks} \leq 2$
  (removes DPE $\rightarrow ll$, DPE $\rightarrow WW$)
Reach at low luminosity

Reach at low luminosity on quartic anomalous coupling

<table>
<thead>
<tr>
<th>Coupling</th>
<th>OPAL limits</th>
<th>95% CL 10 pb(^{-1})</th>
<th>95% CL 100 pb(^{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td>( a_0^W )</td>
<td>0.020</td>
<td>8.1 (10^{-5})</td>
<td>2.5 (10^{-5})</td>
</tr>
<tr>
<td>( a_0^C )</td>
<td>0.037</td>
<td>4.5 (10^{-4})</td>
<td>1.4 (10^{-4})</td>
</tr>
<tr>
<td>( a_0^Z )</td>
<td>0.023</td>
<td>6.7 (10^{-3})</td>
<td>2.3 (10^{-4})</td>
</tr>
<tr>
<td>( a_C^Z )</td>
<td>0.029</td>
<td>2.7 (10^{-3})</td>
<td>8.0 (10^{-4})</td>
</tr>
</tbody>
</table>

- Improvement of LEP sensitivity by more than 2 orders of magnitude with 10 pb\(^{-1}\) at LHC!!
- NB: Effect of cutoff to avoid the violation of unitarity: reduces the sensitivity by a factor 4-5
Reach at high luminosity

- Exclusivity cut impossible because of pile up events
- Request protons tagged in forward detectors with $0.0015 < \xi < 0.15$

![Graph showingReach at high luminosity](image)

- Additional cuts to remove background: $p_T^{\text{leading lepton}} > 160$ GeV, $p_T^2/p_T^1 < 0.9$, proton missing mass $\sqrt{\xi_1\xi_2 S} > 800$ GeV, MET > 20 GeV

- Reach: (95% CL limits for different luminosities)

<table>
<thead>
<tr>
<th>Coupling</th>
<th>OPAL limits</th>
<th>(10 \text{ pb}^{-1})</th>
<th>(30 \text{ fb}^{-1})</th>
<th>(200 \text{ fb}^{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a_W^0$</td>
<td>0.020</td>
<td>$2.2 \times 10^{-5}$</td>
<td>$1.4 \times 10^{-6}$</td>
<td>$7.9 \times 10^{-7}$</td>
</tr>
<tr>
<td>$a_W^W$</td>
<td>0.037</td>
<td>$8.4 \times 10^{-5}$</td>
<td>$5.7 \times 10^{-6}$</td>
<td>$3.6 \times 10^{-6}$</td>
</tr>
</tbody>
</table>

Improvement by more than 3 orders of magnitude with respect to LEP!
Trilinear anomalous gauge couplings

- Lagrangian with trilinear gauge $WW\gamma$ anomalous couplings $\lambda\gamma$ and $\Delta\kappa\gamma$

\[ \mathcal{L} \sim (W_{\mu\nu}^\dagger W^\mu A^\nu - W_{\mu\nu} W_{\mu\nu}^\dagger A^\nu) + (1 + \Delta\kappa\gamma) W_{\mu}^\dagger W_{\nu} A^{\mu\nu} + \frac{\lambda\gamma}{M_W^2} W_{\rho\mu}^\dagger W_{\rho\nu} A^{\mu\rho} \]

- Present limits on trilinear gauge anomalous couplings:
  - From LEP: $-0.098 < \Delta\kappa\gamma < 0.101$; $-0.044 < \lambda\gamma < 0.047$ (Inconvenient: mixture of $\gamma$ and $Z$ exchanges in $e^+e^- \rightarrow WW$)
  - From Tevatron: $-0.51 < \Delta\kappa\gamma < 0.51$; $-0.12 < \lambda\gamma < 0.13$ (direct limits)
Anomalous $WW\gamma$ triple gauge coupling

Different behaviour of the cross section as a function of anomalous couplings

Measurement of $WW$ events at high luminosities at LHC, $2W$ events and protons tagged in forward detectors
**Reach on anomalous coupling**

- Reach on anomalous coupling at the LHC using a luminosity of 30 fb$^{-1}$
  - 5σ discovery: $-0.097 < \Delta \kappa^\gamma < 0.069$; $-0.047 < \lambda^\gamma < 0.038$
  - 95% CL limit: $-0.034 < \Delta \kappa^\gamma < 0.029$; $-0.033 < \lambda^\gamma < 0.026$, about 970 (resp. 65) events expected in the detector acceptance for $\Delta \kappa^\gamma$ (resp. $\lambda^\gamma$)

- Reach on anomalous coupling at the LHC using a luminosity of 200 fb$^{-1}$: 5σ discovery: $-0.033 < \Delta \kappa^\gamma < 0.029$; $-0.033 < \lambda^\gamma < 0.026$

- Best reach before ILC

![Graph showing SM and background expectations with Atlas data, SM, and $\lambda^\gamma = 0.05$ for $L = 200$ fb$^{-1}$](chart.png)
Conclusion

- **Observation of QED $WW$ production at the LHC:** easy even with low luminosity ($200 \text{ pb}^{-1}$) once forward detectors installed.

- **Quartic gauge anomalous coupling studies at low luminosities:** Easy analysis ($2W$ or $Z$ decaying in main detector and nothing else); Improvement of LEP (OPAL) sensitivity by two to three orders of magnitude with $\sim 10 \text{ pb}^{-1}$.

- **Quartic gauge anomalous coupling studies at high luminosities:** Requires forward detectors to be installed, further improvement on sensitivity of one order of magnitude.

- **Trilinear gauge anomalous coupling at high luminosity:** requires forward detectors, gain of a factor 30 compared to Tevatron sensitivity (direct limit), gain of a factor 5 with respect to LEP (indirect limits), best reach before ILC.

- **400 events expected for $200 \text{ fb}^{-1}$ for $WW$ events QED SM production with $W > 1 \text{ TeV}$:** sensitive to beyond standard model effects (SUSY, new strong dynamics at the TeV scale).