Looking at the photoproduction of massive gauge bosons at the LHeC

Magno V. T. Machado

Instituto de Fisica - GFPAE Group
UFRGS, Porto Alegre. Brazil

Outline

- Motivation
- Photoproduction of massive gauge bosons in the SM: $W^\pm, Z (\gamma^*)$
- Present some estimates for future LHeC
- Beyond SM: anomalous coupling $WWW\gamma$
- Conclusions

Refs.:
Motivation

- LHeC: It will open a new kinematic window - $\gamma p$ CM energy can reach up to 1.4 TeV ($\sqrt{s} \gg 200$ GeV @ HERA) - small-$x$ physics and many other physics studies
- W and Z production @ LHC: important tests of SM and beyond
- W, Z photoproduction: cleaner than in pp collisions
- Despite of great successes of SM, the non abelian self-couplings of $W$, $Z$ and photon remains poorly measured up to now
- In this contribution, we also investigate the $WW\gamma$ coupling.
Main goal

- Study photoproduction of massive gauge bosons at future LHeC energies.
- Present estimates of production cross sections and number of events, $W^+ W^-$ asymmetries...
  - in SM
  - beyond SM... W photoproduction
  $\Rightarrow$ Investigating anomalous form factors in $WW\gamma$ vertex
Photoproduction of $W^\pm$ bosons in SM

- The cross section for the subprocess $\gamma q_i \rightarrow Wq_j$ is composed of the direct and resolved-photon production, $\hat{\sigma} = \hat{\sigma}_{dir} + \hat{\sigma}_{res}$.

- The direct part of the cross section then reads

$$\sigma_{dir}(\gamma p \rightarrow W^\pm X) = \int_{x_p^m}^{1} dx_p \sum_{q, \bar{q}} f_{q/p}(x_p, Q^2) \hat{\sigma}_W(\hat{s}),$$

- $f_{q/p}$ are the proton PDFs, $x_p^m = M_W^2/s$ and $\hat{s} = x_p s$.

- Here, C and P parity conserving effective Lagrangian for two charged $W$-boson and one photon interactions.

- The motivation is to use the $W$ photoproduction cross section as a test of the $WWW\gamma$ vertex.

- Two dimensionless parameters, $\kappa$ and $\lambda$, related to the magnetic dipole and electric quadrupole moments, $\mu_W = \frac{e}{2m_W}(1 + \kappa + \lambda)$ and $Q_W = -\frac{e}{m_W^2}(\kappa - \lambda)$. [In SM: $\kappa = 1$ and $\lambda = 0$].
Photoproduction of $W^\pm$ bosons in SM

The direct-photon contribution reads:

$$\hat{\sigma}_W = \sigma_0 \left\{ |V_{q_i q_j}|^2 \left( (|e_q| - 1)^2 (1 - 2\hat{z} + 2\hat{z}^2) \log\left(\frac{\hat{s} - M_W^2}{\Lambda^2}\right) \right. \right.$$

$$- \left[ (1 - 2\hat{z} + 2\hat{z}^2) - 2|e_q|(1 + \kappa + 2\hat{z}^2) + \frac{(1 - \kappa)^2}{4\hat{z}} \right) \right.$$

$$- \left( \frac{(1 + \kappa)^2}{4} \right) \log \hat{z} + \left[ (2\kappa + \frac{(1 - \kappa)^2}{16}) \right. \right.$$

$$+ \left( \frac{1}{2} + \frac{3(1 + |e_q|^2)}{2} \right) \hat{z} + (1 + \kappa)|e_q| - \frac{(1 - \kappa)^2}{16}$$

$$+ \frac{|e_q|^2}{2} \left( 1 - \hat{z} \right) - \frac{\lambda^2}{4\hat{z}^2} \left( \hat{z}^2 - 2\hat{z} \log \hat{z} - 1 \right)$$

$$+ \frac{\lambda}{16\hat{z}} \left( 2\kappa + \lambda - 2 \right) \left[ (\hat{z} - 1)(\hat{z} - 9) + 4(\hat{z} + 1) \log \hat{z} \right] \right\},$$
Photoproduction of $W^\pm$ bosons in SM

- Notation in previous slide:
  \[ \sigma_0 = \frac{\alpha G_F M_W^2}{\sqrt{2}\hat{s}}, \quad \hat{z} = \frac{M_W^2}{\hat{s}}. \]

- $\Lambda^2$ is the cutoff scale in order to regularize the $\hat{u}$-pole of the collinear singularity for massless quarks.

- The quantity $V_{ij}$ is the Cabibbo-Kobayashi-Maskawa (CKM) matrix and $e_q$ is the quark charge.

- In numerics, we use PDG values for electroweak parameters.

- In addition, $Q^2 = m_W^2$ and CTEQ (proton) + GRV (photon).
Photoproduction of $W^{\pm}$ bosons

- The resolved-photon part of the cross section can be calculated using the usual electroweak formula for the $q_i\bar{q}_j \rightarrow W^{\pm}$ fusion process, $\hat{\sigma}(q_i\bar{q}_j \rightarrow W) = \frac{\sqrt{2}\pi}{3} G_F m_W^2 |V_{ij}|^2 \delta(x_i x_j s \gamma_p - m_W^2)$.

$$\sigma_{\text{res}}(\gamma p \rightarrow W^{\pm} X) = \frac{\pi \sqrt{2}}{3 s} G_F m_W^2 |V_{ij}|^2 \int_{x_{\gamma}}^{1} \frac{dx_{\gamma}}{x_{\gamma}} \times \sum_{q_i, q_j} f_{q_i/p}(\frac{m_W^2}{x_S}, Q_p) \left[ f_{q_j/\gamma}(x_{\gamma}, Q_{\gamma}^2) - \tilde{f}_{q_j/\gamma}(x_{\gamma}, Q_{\gamma}^2) \right],$$

- In order to avoid double counting on the leading logarithmic level, one subtracts the pointlike part of the photon structure function (photon splitting at large $x$),

$$\tilde{f}_{q/\gamma}(x, Q_{\gamma}^2) = \frac{3\alpha e_q^2}{2\pi} [x^2 + (1 - x)^2] \log(Q_{\gamma}^2/\Lambda^2).$$
Photoproduction of $Z$ bosons

- Similar calculation can be done for the $Z$ boson photoproduction.
- Here, we focus on the SM prediction.
- The direct part of the $Z$-photoproduction cross section then reads

$$\sigma_{\text{dir}}(\gamma p \rightarrow Z^0 X) = \int_{x_p^m}^{1} dx_p \sum_{q,\bar{q}} f_{q/p}(x_p, Q^2) \hat{\sigma}_Z(\hat{s}),$$

- $f_{q/p}$ are the proton PDFs and $x_p^m = m_Z^2/s$.
- The direct-photon contribution reads as:

$$\hat{\sigma}_Z = \frac{\alpha G_F M_Z^2}{\sqrt{2} \hat{s}} g_q^2 e_q^2 \left[ (1 - 2\hat{z} + 2\hat{z}^2) \log \left( \frac{\hat{s} - M_Z^2}{\Lambda^2} \right) \right.$$  

$$+ \frac{1}{2} (1 + 2\hat{z} - 3\hat{z}^2) \right],$$

- $\hat{z} = M_Z^2/\hat{s}$ and $g_q^2 = \frac{1}{2} (1 - 4|e_e| x_W + 8e_q^2 x_W^2)$, with $x_W = 0.23$. 

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Photoproduction of $Z$ bosons

The resolved-photon part of the cross section stands for the subprocess $q\bar{q} \rightarrow Z^0$, and it is written as

$$\sigma_{res}(\gamma p \rightarrow Z^0 X) = \frac{\pi \sqrt{2}}{3 s} G_F m_W^2 g_{q}^2 \int_{x_m^{\gamma}}^{1} \frac{dx_{\gamma}}{x_{\gamma}} \times \sum_{q} \tilde{f}_{q/p} \left( \frac{m_Z^2}{x_s}, Q_p \right) \left[ f_{q/\gamma}(x_{\gamma}, Q_{\gamma}^2) - \tilde{f}_{q/\gamma}(x_{\gamma}, Q_{\gamma}^2) \right].$$
Results: energy dependence

![Graph showing cross sections for the production of massive W± and Z⁰ gauge bosons as a function of the CM energy.]

**Figure**: Cross sections for the production of massive $W^\pm$ and $Z^0$ gauge bosons as a function of the CM energy.

- The dependence is like $\sigma_V \propto W^{1.3}_{\gamma p}$, with SM coupling.
Results: number of events at LHeC

- Photon-proton total cross sections times branching ratio of $W \rightarrow \mu \nu$ and also for the $Z^0$ boson with a corresponding branching ratio of $Z^0 \rightarrow \mu^+ \mu^-$ (SM).

- The number of events

$$N_{\text{ev}} = \sigma(ep \rightarrow V + X) \text{BR}(V \rightarrow \mu \nu/\mu^+ \mu^-) L_{\text{int}}.$$ 

- At this point we consider the acceptance in the leptonic channel as 100%.

- The photoproduction cross section is calculated by convoluting the Weizsäcker-Williams spectrum

$$f_{\gamma/e}(y) = \frac{\alpha}{2\pi} \left[ \frac{1 + (1 - y)^2}{y} \log \frac{Q_{\text{max}}^2}{Q_{\text{min}}^2} - 2m_e^2 y \left( \frac{1}{Q_{\text{min}}} - \frac{1}{Q_{\text{max}}} \right) \right]$$

- Here, $Q_{\text{min}}^2 = m_e^2 y/(1 - y)$ and we impose a cut of $Q_{\text{max}}^2 = 0.01$. 
Results: number of events at LHeC

Table: The photon-proton cross sections times branching ratios
\( \sigma(\gamma p \rightarrow W^{\pm}X) \times BR(W^{\pm} \rightarrow \mu\nu) \) and \( \sigma(\gamma p \rightarrow Z^{0}X) \times BR(Z^{0} \rightarrow \mu^{+}\mu^{-}) \) in units of pb. The number of events \( N_{ev} \) is also presented at an integrated luminosity 10 fb\(^{-1}\).

<table>
<thead>
<tr>
<th>( V )</th>
<th>( \sigma(\gamma p \rightarrow V X) \times BR )</th>
<th>( N_{ev} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( W^{+} )</td>
<td>24</td>
<td>( 1.2 \times 10^{4} )</td>
</tr>
<tr>
<td>( W^{-} )</td>
<td>24</td>
<td>( 1.2 \times 10^{4} )</td>
</tr>
<tr>
<td>( Z^{0} )</td>
<td>2.1</td>
<td>( 1.1 \times 10^{3} )</td>
</tr>
</tbody>
</table>
Investigating physics beyond SM

- Certain properties of the $W$ bosons, such as $\mu_W$ and $Q_W$, play a role in the interaction vertex $WW\gamma$. They can be written in terms of parameters $\kappa$, $\lambda$ values for those parameters at tree level\(^1\).
- In $W$ photoproduction one has a unique scenario to test it.

\[
\Gamma_{\mu\nu\rho}(p_1, p_2, p_3) = \frac{e}{g_{\mu\nu}} \left( p_1 - p_2 - \frac{\lambda}{M_W^2} \left[ (p_2 \cdot p_3) p_1 - (p_1 \cdot p_3) p_2 \right] \right)_\rho \\
+ g_{\mu\rho} \left( \kappa p_3 - p_1 + \frac{\lambda}{M_W^2} \left[ (p_2 \cdot p_3) p_1 - (p_1 \cdot p_2) p_3 \right] \right)_\nu \\
+ g_{\nu\rho} \left( p_2 - \kappa p_3 - \frac{\lambda}{M_W^2} \left[ (p_1 \cdot p_3) p_2 - (p_1 \cdot p_2) p_3 \right] \right)_\mu \\
+ \frac{\lambda}{M_W^2} \left( p_{2\mu} p_{3\nu} p_{1\rho} - p_{3\mu} p_{1\nu} p_{2\rho} \right)
\]

Anomalous coupling

- In the photoproduction of $W^\pm$ bosons, the direct contribution $\sigma_{dir}$ involves the generalized $WW\gamma$ vertex.

**Table:** The number of muon plus neutrino events coming from the $W^+$ decay for distinct choices for the parameters $\kappa$ and $\lambda$ presented at an integrated luminosity of 10 fb$^{-1}$.

<table>
<thead>
<tr>
<th>$\kappa$</th>
<th>$\lambda$</th>
<th>$\sigma(\gamma p \to W^+ X) \times BR$ [pb]</th>
<th>$N_{ev}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>16</td>
<td>$8 \times 10^3$</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>24</td>
<td>$1.2 \times 10^4$</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
<td>44</td>
<td>$2.2 \times 10^4$</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>61</td>
<td>$3.1 \times 10^4$</td>
</tr>
<tr>
<td>1</td>
<td>2</td>
<td>172</td>
<td>$8.5 \times 10^4$</td>
</tr>
</tbody>
</table>
Results on the ratios @ LHeC

- In order to get rid of normalization uncertainties, one can take the ratios $\sigma_W^+/\sigma_Z$ to test the $WW\gamma$ vertex.
- To do this we propose the study of the following observable:

$$R_{W/Z}(\kappa, \lambda; \sqrt{s}) = \frac{\sigma_{W^+} + \sigma_{W^-}}{\sigma_Z}$$
Results on the ratios @ LHeC

- Another observable that could be studied is the $W^+ W^-$ asymmetry: $A(\kappa, \lambda; \sqrt{s}) = \frac{\sigma_{W^+} - \sigma_{W^-}}{\sigma_{W^+} + \sigma_{W^-}}$.

- sensitivity with the $\kappa$ and $\lambda$: SM X new physics...

- $W^+ W^-$ asymmetry depends strongly on the $\kappa$ and $\lambda$ parameters
Conclusions

- In this work in progress, we study the massive gauge photoproduction @ LHeC.
- Extended $\gamma p$ energy ($E_{CM} \simeq 1.3\ TeV$) will allow to go beyond HERA studies, including small-$x$, $\gamma$ and proton structure.
- New kinematic window to confirm SM and/or discover new physics.
- We present estimates of $W^\pm$, $Z$ photoproduction @ LHeC.
- Possibility to test non-abelian self-couplings of $W$, $Z$ and $\gamma$, and access new physics. Here we investigate the sensitivity with the anomalous form factors, $\kappa$ and $\lambda$, in some ratios and asymmetries which could be measured.
- This 'little extension' of LHC (ep machine) could provide many new insights of SM physics and beyond.