Inclusive $W\gamma$ Production at the LHC
A Study of Monte Carlo Event Generators of Interest

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1 Introduction and Overview
   - Multiboson Studies at hadron colliders
   - What are we interested in measuring
   - Essence of $W\gamma$ process

2 Event Generation
   - Baur Monte Carlo
   - Generator level studies

3 Prospective studies while at Lund
   - Pythia-Baur_NLO Comparison
**Introduction**

- Measurement of triple gauge boson couplings (TGC) $V_1 V_2 V_3$, where $V_{1,2,3} \equiv \gamma, W$ or $Z$, is an important test of the gauge structure of the Standard Model (SM).

- The triple and quartic gauge couplings are among the least studied features of the Standard Model till date.

- The nature of the gauge boson couplings, eg. $WW\gamma$, $WWZ$ vertices are may be different in physics beyond the Standard Model. These could be due to compositeness of the $W,Z$ bosons or radiative loop corrections involving new particles.

- Anomalous structure of triple gauge vertices like $WWV$ ($V \equiv \gamma, Z$) were first studied in LEP.

- The di-boson production rate will be reasonably high at the LHC, even under low energy and low luminosity conditions.

- In recent years, CDF and D0 has reported studies of $WZ$, $ZZ$, $W\gamma$ and $Z\gamma$ processes. With the advent of LHC data the limits on anomalous couplings are expected to improve by order of magnitude.
Multiboson Studies at hadron colliders

Cross-sections of several Standard Model processes at the LHC, including diboson production

- Multiboson production at hadron collider:
  
  \[ q\bar{q}' \rightarrow W^* \rightarrow W\gamma \text{: } WW\gamma \text{ vertices} \]
  
  \[ q\bar{q}' \rightarrow W^* \rightarrow WZ \text{: } WWZ \text{ vertices} \]
  
  \[ q\bar{q} \rightarrow Z/\gamma^* \rightarrow WW \text{: } WW\gamma, WWZ \text{ vertices} \]
  
  \[ q\bar{q} \rightarrow Z/\gamma^* \rightarrow Z\gamma \text{: } ZZ\gamma, Z\gamma\gamma \text{ vertices} \]
  
  \[ q\bar{q} \rightarrow Z/\gamma^* \rightarrow ZZ \text{: } ZZ\gamma, ZZZ \text{ vertices} \]

- Leptonic (e, \( \mu \)) decay modes of \( W \) and \( Z \) provide the cleanest signatures in a hadron collider environment. Experimentally easy to identify and trigger; can be measured with high resolution as well.

- CMS experiment at the LHC has very good capabilities for electron, muon and photon detection.
What are we interested in measuring

- Measure the total and differential cross-section for the process
  \[ pp \rightarrow W\gamma X \text{ with } W \rightarrow \mu\nu_{\mu} \]

- We need to choose a parameter, the differential cross-section with respect to which is most sensitive to deviations from the Standard Model. Apriori, the photon transverse momentum, \( p_T^{\gamma} \) seems to be a good choice.

- Measure the radiation amplitude zero:
  - Zero amplitude at \( \cos \theta^* = 1/3 \) for \( W^+ \) and \( \cos \theta^* = -1/3 \) for \( W^- \).

- Measure the triple gauge boson coupling \( WW\gamma \) as parametrized by \( \lambda \) and \( \kappa \) which are related to the electric and magnetic dipole moments of the \( W \)-boson respectively.
Essence of $W\gamma$ process - I

- TGC Effective Lagrangian

$$\mathcal{L}_{WWV} = -i\epsilon \left[ W_{\mu\nu} \mathcal{V}_{\mu} V^\nu - W_{\mu}^\dagger V_{\nu} W_{\mu\nu}^\nu + \kappa V_{\mu} W_{\mu}^\dagger V^\mu \nu + \frac{\lambda V_{\nu}}{M_W^2} W_{\mu}^\dagger W_{\nu}^\lambda V^\nu \lambda \right]$$

where $V = \gamma, Z$.

- In SM: $\lambda_{V} = 0, \kappa_{V} = 1$

- Magnetic dipole moment:

$$\mu_W = \frac{e}{2M_W} (1 + \kappa + \lambda)$$

- Electric quadrupole moment:

$$Q_W = -\frac{e}{M_W^2} (\kappa - \lambda)$$

- Dipole moment $\sim 1/r^3$, and quad. mom. $\sim 1/r^4 \rightarrow$ can be probed with high energy.

- Unitarity violation avoided by using form factor:

$$\lambda(\hat{s}) \rightarrow \frac{\lambda(\hat{s})}{(1 + \hat{s}/\Lambda^2)^n}$$

- The Lagrangian contains terms respecting CP invariance only. CP-violating terms lead to additional two parameters $\tilde{\kappa}$ and $\tilde{\lambda}$. These terms are found to be small from measurement of neutron scattering cross-section in nuclear physics and are hence neglected here.
**Essence of $W\gamma$ process - II**

- **$W\gamma$ production at tree level and RAZ**
  
  ![Diagrams showing $W\gamma$ production]

- **RAZ** due to destructive interference among the processes shown.
- Related to Standard Model gauge structure; will not hold in BSM scenarios.

- Measurement of the cross-section at the LHC energy for $pp \rightarrow W\gamma X$ is one of the confirmatory tests of SM.
- $WW\gamma$ coupling involved only in the s-channel process.
- The last plot on the left shows the quark-gluon fusion diagram for production of a $W\gamma$ final state with a jet from the outgoing quark. Has large probability of occurrence at LHC energy. We use a jet veto on the final state to eliminate diagrams such as these.
- For probing RAZ, a promising variable is the charge-signed rapidity difference between the photon and the charged-lepton from W-decay: $Q^l \times |\eta^l - \eta^\gamma|$.
For understanding signal and background from collider data, Monte Carlo generated data have to be used.

We have chosen Baur’s Monte Carlo generator package for $W\gamma$ events for our study due to
- Matrix element calculation for the hard-scattering part.
- QCD Corrections available upto next-to-leading order.
- Anomalous couplings can be incorporated.

We use *Pythia* for showering and hadronization of Baur’s final state particles and for underlying events.
NLO QCD Diagrams included in Baur WGAMMA_NLO Monte Carlo
Generator level cuts on parameters and Plots

Gen Level Cuts

- $p_T(\gamma) > 5 \text{GeV}$
- $|\eta(\gamma)| < 10.0$
- $p_T(l) > 5 \text{GeV}$
- $|\eta(l)| < 10.0$
- $p_T(\nu) > 5 \text{GeV}$
- $p_T(\text{jets}) > 5 \text{GeV}$
- $|\eta(\text{jets})| < 10.0$
- $\Delta(R_{l\gamma}) > 0.05$
- $M_T(l\nu\gamma) > 10 \text{GeV}$

Lepton $p_T$ spectra

W $p_T$ Spectrum

Neutrino $p_T$ spectra

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Baur: Comparison of Factorization Scales

\( Q^2 = \frac{sH}{2} \)

\( Q^2 = sH \)

\( Q^2 = 2sH \)
One of the most important parameters in studying inclusive $W\gamma$ production at LHC is the photon $p_T$ spectrum.

Sources of photon could be the hard scattering process, namely the $W\gamma$ production process, as well as underlying events and other hard scattering in the same event.

We hope to gain some understanding of the different processes leading to the production of a final-state photon.

This would also lead us to investigating the interplay between the different sources of photons in a p-on-p collision at LHC energies.
Comparion of Pythia with Baur\_NLO matrix element generator
As a startup, we are comparing the output of Baur’s program, which is a matrix element generator, with Pythia, which is a parton shower generator.

Baur contains all QCD corrections to $O(\alpha_S)$.

We expect that the tree level calculation of Baur to match Pythia’s outcome when ISR s switched off.

We compare the effect of gluon radiation in Baur's program with the effect of ISR in Pythia.

We compare the $p_T$ spectrum of the photon and effects of gluon radiation/ISR on the $W\gamma$ system.
### Standard Model Parameters and Kinematic Cuts

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<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>PDF</td>
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<td>$M_{top}$</td>
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**Pythia Gen Level Cut:** CKIN(3) = 5.0 GeV

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Cut</th>
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<tbody>
<tr>
<td>$\gamma$ $p_T$</td>
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<tr>
<td>Charged lepton $p_T$</td>
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<tr>
<td>Photon rapidity</td>
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<tr>
<td>Jet $p_T$</td>
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</tr>
<tr>
<td>Jet rapidity</td>
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</tr>
<tr>
<td>$\Delta R(\gamma, \text{lepton})$</td>
<td>0.05</td>
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<td>Cluster($W, \gamma$) transverse mass</td>
<td>10.0 GeV</td>
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<tr>
<td>Fraction of hadronic energy in a cone around the photon</td>
<td>0.15</td>
</tr>
</tbody>
</table>
Baur WGAMMA:

\[ \frac{dN}{dp_T^\gamma} \text{ (pb)/2GeV} \]

- \( L = 200\text{pb}^{-1} \)
- Baur with final state radiation

Pythia6

\[ \frac{dN}{dp_T^\gamma} \text{ (pb)/2GeV} \]

- \( L = 200\text{pb}^{-1} \)
- Pythia \( W\gamma \) with ISR and MSTP(68)=3
- Pythia \( W\gamma \) with ISR MSTP(68)=2

- \( L = 200\text{pb}^{-1} \)
- Baur WGAMMA tree level

- \( L = 200\text{pb}^{-1} \)
- Pythia \( W\gamma \) no ISR
"K-factors" from Baur and Pythia

Baur WGAMMA

Pythia6

\[ \frac{p_T^{\gamma}}{p_T^{\gamma,\text{ISR}}} \]

\[ \text{MSTP}(68) = 3 \text{ (default value)} \]

\[ \text{MSTP}(68) = 2 \]
For process with a jet (gluon) in the final state, $p_T$ of the $W$ and the photon is not back-to-back and $p_T^W + p_T^\gamma$ will be opposite to the $p_T$ of the emitted jet.

On the left are the plots of the sum of the photon and $W$ $p_T$ for both Baur and Pythia.

We see that Baur gives a much harder $p_T$ spectrum for the emitted jet than Pythia, even when Pythia is configured such that the gluon from ISR has no upper limit on its $p_T$. 
Baur-Pythia Comparison contd....

- The distributions show the $p_T$ of the photon vs that of the $W$ in the three-body final state: i.e. when we have a gluon jet in the event.
- The distribution is asymmetric yet we do not have any apriori reason for this.
- Work in progress....
The other aspect of our study would be to try comparing Pythia6 generator with the new version of Pythia.

Pythia 8 also provides the opportunity to simulate multiple hard interactions. This should be interesting to study as well.

Further, we want to gain an understanding of the matching between a matrix element calculator, eg. Baur WGAMMA generator and a parton shower generator, eg. Pythia.