A Study of $W\gamma$ Events at the LHC

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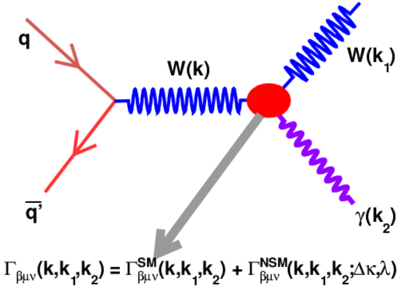
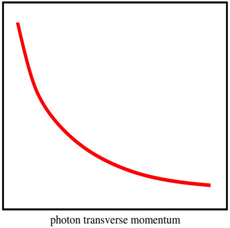
1. Introduction
   - Motivation
   - Essence of $W\gamma$ process
   - Previous studies at hadron colliders

Motivation

- Measurement of triple gauge boson couplings (TGC) $V_1V_2V_3$, and quartic gauge boson couplings (QGC) $V_1V_2V_3V_4$ where $V_{1,2,3} \equiv \gamma$, W or Z, is an important test of the gauge structure of the electroweak sector of the Standard Model.
- Any deviation of the gauge bosons' self-couplings from the Standard Model values may indicate the presence of new physics at as yet unprobed energy scales.
- The effects of such new physics, perhaps the compositeness of the weak bosons or presence of new particles in radiative loop corrections, will be parametrized by the anomalous couplings at the low energy.
- Of the different diboson productions, the rate of $W\gamma$ events will be reasonably high at the LHC, even at low energy running to merit an early study.
- In recent years, CDF and D0 has reported studies of WZ, ZZ, Wγ and Zγ processes. With the advent of LHC data it will be possible to place more stringent bounds on the anomalous couplings, or measure them if they exist.

What do we want to study?





- $\Delta\kappa = \kappa - 1$
- In SM: $\lambda = 0$, $\kappa = 1$ ($\Delta\kappa = 0$)
- Magnetic dipole moment :

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

- electric quadrupole moment :

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

Essence of $W\gamma$ process - I

- TGC Effective Lagrangian

$$\mathcal{L}_{WWV} = -i\epsilon\Big[W^{\dagger}_{\mu\nu}W^{\mu}V^{\nu} - W^{\dagger}_{\mu}V_{\nu}W^{\mu\nu} + \kappa_V W^{\dagger}W_{\mu}V^{\mu\nu} + \frac{\lambda_V}{M_W^2}W^{\dagger}_{\lambda\mu}W^{\mu}_{\nu}V^{\nu\lambda}\Big]$$

where $V = \gamma, Z$.

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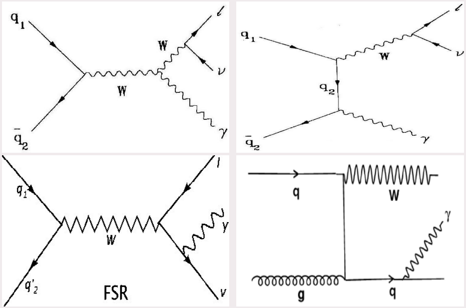
- Dipole moment $\sim 1/r^3$, and quad. mom. $\sim 1/r^4 \Longrightarrow$ can be probed with high energy.
- Unitarity violation avoided by using form factor:

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

- 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 as well.

Essence of $W\gamma$ process - II

$W\gamma$ production at tree level and *RAZ*



- $WW\gamma$ coupling involved only in the s-channel process.
- The photon transverse momentum is the most sensitive variable to anomalous $WW\gamma$ coupling $\Longrightarrow$ enhancement of rate at high values of p_T^γ.
- The **Quark-gluon Fusion** process contributes about 50% at the LHC and a jet veto is required to eliminate this type of events.
- The final state photon radiation from the lepton from W decay contributes to the "signal". This has to be eliminated by imposing cuts on the photon-lepton separation .

Radiation Amplitude Zero

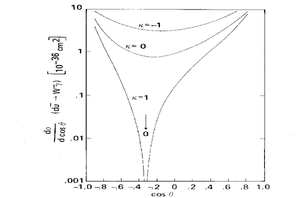


FIG. 2. The differential cross section for $d\bar{u}\to W^-\gamma$. θ is the angle between W^- and d, or between γ and $\bar{u}$, in the c.m. frame. $\sqrt{s}$ = 200 GeV and M_W = 85 GeV/c^2.

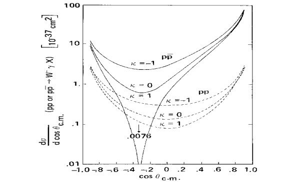
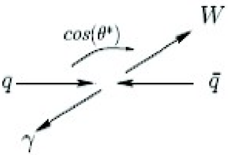


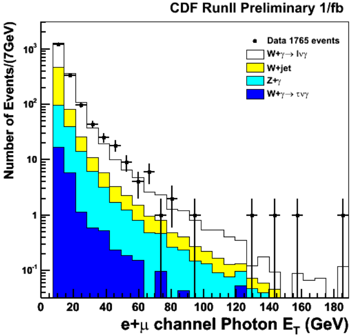
FIG. 3. The differential cross section for $pp\to W^-\gamma X$ and $p\bar{p}\to W^-\gamma X$, with a photon energy cut $E_\gamma > 30$ GeV. $\theta_{c.m.}$ is the angle between the W^- and the proton direction in the $W^-\gamma$ c.m. frame. $\sqrt{S}$ = 540 GeV and M_W = 85 GeV/c^2.

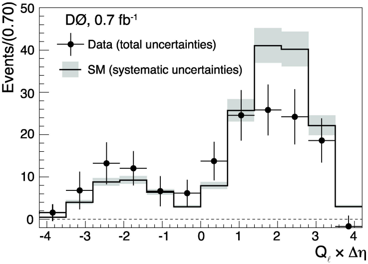
- PRL, 43, 11, 1979: Mikaelian, Samuel, Sahdev
- Zero amplitude at $cos\theta^* = 1/3$ for W^+ and $cos\theta^* = -1/3$ for W^-.



- If the *WW*γ vertex couplings depart from SM value, *RAZ* would disappear.
- Unfortunately, the higher order QCD corrections also decrease the sensitivity of measurement of the *RAZ in hadron colliders.*

Studies at the Tevatron





- CDF: $\sigma(W\gamma)$ x BR(W→leptonν)pb $=$ 18.03$\pm$0.65(stat.) $\pm$2.55(sys.)$\pm$1.05(lumi.)
- Theory: $\sigma(W\gamma)$ x BR(W→leptonν)pb $=$ 19.3$\pm$1.4.
- ($\Delta R_{l,\gamma} > 0.7$ and $E_T^{\gamma} > 7$GeV.)
- D0 detects *RAZ* manifested as the charge-signed rapidity difference between the lepton and the photon.

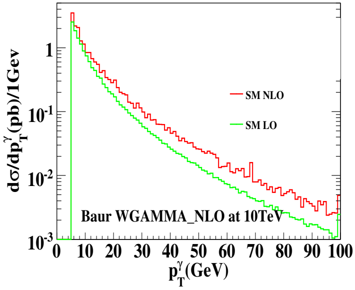
Event generator requirements

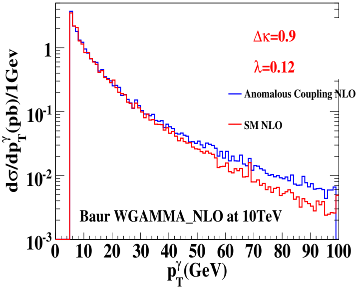
- Expect NLO QCD corrections to be significant at LHC energy; need an event generator which has such effects.
- Matrix element calculation preferred for hard emission calculations.
- Anomalous couplings should be incorporated.

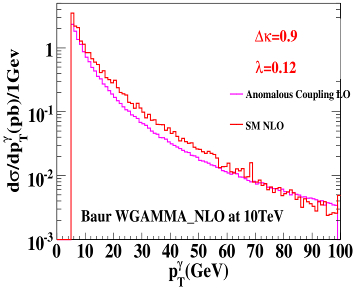
- We have chosen Baur's Monte Carlo generator package *WGAMMA_NLO* for $W\gamma$ events for our study

- U. Baur, T.Han, J. Ohnemus, Phys. Rev. D, Vol. **48**,11 (1993): QCD Corrections to hadronic $W\gamma$ production with nonstandard $WW\gamma$ couplings.

Effect of NLO and Anomalous Couplings







- Difficult to distinguish AGC_{LO} from SM_{NLO}.
- Even harder for smaller values of the anomalous coupling parameters.
- At LHC scale it is imperative to use NLO calculation for making these distinctions.

Analysis of Monte Carlo datasets

- We analysed Monte Carlo datasets from official production of the CMS.
- We analysed the signal ($W\gamma$) events and main backgrounds: W+jets, Z+jets, $t\bar{t}$+jets and also photon+jets and QCD events and devised a set of selection criteria for selecting signal while rejecting background events.
- We consider W's decaying through the muon mode.
- Events were selected using a single muon HLT and then a set of selection criteria were applied on the muon, the photon the missing transverse energy ($\not{E}_T$) and W-boson transverse mass.
- We use Standard Model couplings.
- LHC centre of mass energy of 10 TeV and 100 pb^{-1} of integrated luminosity are considered.

Samples used

Datasets	σ(pb)	lumi (pb^{-1}) (events)
Wγ	36.6	2856 (102806)
W+Jets	40000	176.4 (7055529)
Z+Jets	3700	313 (1158003)
$t\bar{t}$+Jets	317	2314 (733780)
γ+Jets ($H_T = 100 - 200$ GeV)	1.04e+05	8.262 (859288)
γ+Jets ($H_T = 40 - 100$ GeV)	3.96e+05	0.5173 (2048696)
Inclusive muons, $p_T^\mu > 15$ GeV	1.22e+04	50.7 (6171920)
QCD $p_T > 15$ GeV	1.46e+09	5.48e-5 (7986841)
QCD $p_T > 30$ GeV	1.09e+08	2.8e-3 (3105452)
QCD $p_T > 80$ GeV	1.93e+06	1.29 (2510991)
QCD $p_T > 170$ GeV	6.66e+04	55.6 (3699660)

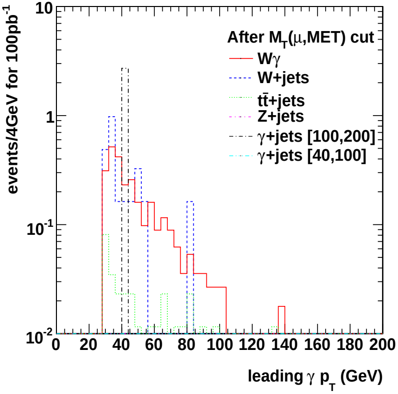
Selection Criteria used

Single isolated muon trigger used for selecting the events: HLT_IsoMu15.

PAT Object	Parameter	Criteria
Muon	normalised χ^2 of muon inner track	< 5
	number of valid track hits	> 12
	track impact parameter	< 0.2 mm
	Tracker Isolation	$< 0.09 \times p_T$
	leading p_T	$> 20.$ GeV
	$\|\eta\|$	< 2.4
	2^{nd} hardest muon	$< 10.$ GeV
Photon	hadronic energy/Electromagnetic energy	< 0.05
	$\sigma_{\eta\eta}$	< 0.01
	Tracker Isolation	< 5 GeV
	Ecal Isolation	$< 8 + 0.0073 \times p_T$
	Hcal Isolation	$< 5 + 0.002 \times p_T$
	leading p_T	$> 30.$ GeV
	$\|\eta\|$	< 2.4
	$\Delta R(\mu, \gamma)$	> 2.7
W reconstruction	$\not{E}_T$	$>$ 20 GeV
	W transverse mass	$>$ 50 GeV

The final photon transverse momentum spectrum

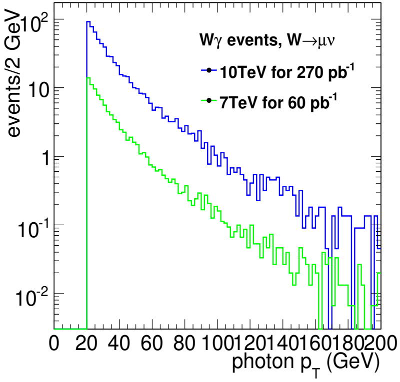
- After all the cuts, we have the final photon p_T spectrum with signal events distinguishable above the backgrounds. However, very low statistics at the high end of the p_T spectrum where the interesting phenomena might occur.
- No QCD events survive, mainly due to low statistics although we expect a sizable fraction of those in real data.
- We expect more contribution from QCD photons.
- An appreciable number of photon+jets events may also be seen with a muon from the jet passing quality and isolation criteria.



Summary

- $W\gamma$ events at the LHC can be studied with early data from the CMS detector.
- The measurement of the W and photon coupling will validate the electroweak gauge structure of the Standard Model or provide clues to new physics.
- Next-to-leading order effects are important at the LHC to understand anomalous couplings.
- The photon p_T spectrum is the most sensitive parameter to study for measuring anomalous couplings.
- We have devised a simple cut-based analysis to establish the signal over the background from the first few months' data from CMS.
- A study of systematic uncertainties, contributions from NLO, underlying events and pile-up etc before a numerical estimate of the cross-section of couplings can be made.

Photon spectrum with projected lumi for real data



- Within next year:
- 60 pb^{-1} luminosity at 7 TeV.
- 270 pb^{-1} luminosity at 8 to 10 TeV.

Relative selection efficiency for signal events

Gen. level σ (pb)	36.6	
Selection	**σ (pb)**	**Efficiency**
Trigger	6.13	0.17
Muon Quality	3.91	0.64
Muon Isolation	3.88	0.99
Muon kinematics	3.54	0.91
Muon veto	3.32	0.94
Photon ID	1.48	0.44
Photon Isolation	1.43	0.97
Photon kinematics	0.33	0.23
$\Delta R(\mu,\gamma)$ cut	0.21	0.62
$\not{E}_T$	0.15	0.71
M_T(W)	0.12	0.78
Total efficiency	3.12×10^{-3}	
Evts. for 100 pb^{-1}	12	

Relative selection efficiency for non-QCD backgrounds

	W+jets		Z+jets		$t\bar{t}$+jets	
Gen. level σ (pb)	40000		3700		317	
Selection	**σ (pb)**	**Efficiency**	**σ (pb)**	**Efficiency**	**σ (pb)**	**Efficiency**
Trigger	6008.73	0.15	861.04	0.23	44.68	0.14
Muon Quality	433.35	0.072	99.20	0.11	33.89	0.87
Muon Isolation	426.78	0.98	97.69	0.98	37.45	0.96
Muon kinematics	378.13	0.89	852.88	0.87	34.70	0.93
Muon veto	334.97	0.88	29.31	0.34	18.98	0.55
Photon Quality	21.82	0.065	2.72	0.092	0.36	0.018
Photon Isolation	12.11	0.56	1.87	0.69	0.12	0.34
Photon kinematics	0.60	0.05	0.58	0.31	0.05	0.44
$\Delta R(\mu,\gamma)$ cut	0.23	0.38	0.50	0.85	0.02	0.31
$\not{E}_T$ cut	0.13	0.54	0.04	0.09	0.016	0.98
M_T(W)	0.10	0.84	0	-	0.013	0.80
Total efficiency	2.5×10^{-6}		-		4.1×10^{-5}	
Evts. for 100 pb^{-1}	10		0		1.3	