V-Gamma Production at LHC: NLO in Powheg Method

Dart-yin A. Soh

Academia Sinica Taiwan and Sun Yat-sen University
Supervised by Dr. P. Richardson & Prof. S.-C. Lee

September 23, 2010

Vector Boson-Photon Production at LHC

Testing Standard Model and Search for New Physics:

- $W/Z\gamma$: golden channel to test SM at LHC, we will have enough data to do significant analysis $\sim 1 fb^{-1}$ data for $W\gamma$ (early next year?).
- Anomalous $WW\gamma$ coupling: CP-conserving $\kappa, \lambda, \tilde{\kappa}$ and $\tilde{\lambda}$?
- Are there $ZZ\gamma$ or $Z\gamma\gamma$ couplings? Gauge symmetry breaking!
- Agree well with the standard model at Tevatron, and how about at LHC
- Learn to deal with photon at NLO.

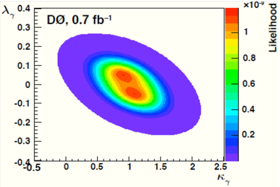
W γ production at DØ*:

Best points:

(-0.084, -0.05),
(+0.084, +0.05)

$$|\Delta\kappa| \leq 0.51$$

$$-0.12 \leq \lambda \leq 0.13$$



*Adam Lyon, ICHEP'08

NLO Matching ME with PS!

- LHC: high energy scale and high luminosity: we need more precise NLO calculations
- NLO ME (BHO genarator*): additional parton radiation + parton shower MC $\Rightarrow$ double counting and invalid in IR phase space region
- Soft gluon radiation cut δ_s and photon isolation cut δ_c for quark radiation to cancel the IR divergence

Methods to match NLO matrix element
with NLO parton shower:
Implement Powheg in Herwig++

* J.Ohnemus, Phys. Rev., D47, 940

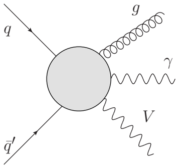
NLO Matrix Element in Catani-Seymour framework

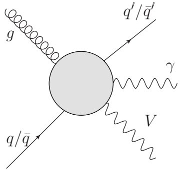
- The NLO cross-section for $V\gamma$ matrix element:

$$d\sigma^{\bar{B}} = d\sigma^{B}_{V\gamma} + d\sigma^{V}_{V\gamma} + d\sigma^{C}_{V\gamma,g} + d\sigma^{R}_{q\bar{q}\to V\gamma g} + d\sigma^{C}_{V\gamma,q} + \underline{d\sigma^{R}_{V\gamma(qg)_i} + d\sigma^{R}_{V(\gamma q)_f}} + d\sigma^{C,Brem}_{q\to\gamma}$$

- IR singularities: gluon soft and q/g collinear.We have *Catani-Seymour* subtraction framework to cancel divergences: Both $\int d\Phi_{n+1}[\sigma^{R}_{V(\gamma g)} - \sigma^{B} \otimes V_{dipole}]$ and $\int d\Phi^{B}[\sigma^{V}_{V\gamma} + \sigma^{C}_{V\gamma} + \sigma^{A}_{V\gamma}]$ are finite.
- Mapping from Φ^B to Φ_{n+1} associated to each dipole $\mathcal{D}(z,u)$ that defined for an IR singular region α_i: soft (z) and collinear (u).
- Multiply the weight factor with real radiation contribution in α_r to cancel IR singularities with dipole and for Powheg:

$$R^{\alpha_r}(\bar{\Phi}^B, z^{\alpha_r}, u^{\alpha_r}) = \frac{\mathcal{D}^{\alpha_r}(\bar{\Phi}^B, z, u)\cdot R(\Phi_{n+1})}{\sum_j \mathcal{D}^j}$$





PDF & Fragmentation Function Counterterm Remnants

- The dipole $\mathcal{D}^{\alpha_r}(\bar{\Phi}^B, z, u) \sim | \mathcal{M}^B(\bar{\Phi}^B) |^2 \cdot P_{ij}(z,u)/(2p_i \cdot p_j)$ has singularity in dimensional regularization ($\sim 1/\epsilon$)
- Consider dipoles $\mathcal{D}^{ag,b}$, $\mathcal{D}^{gq,\bar{q}}$, $\mathcal{D}^{a}_{\gamma q}$, $\mathcal{D}_{\gamma q,V}$ (and $\mathcal{D}^{a\gamma}_{q}$, $\mathcal{D}^{a\gamma}_{V}$?)
- After canceling the singularities the NLO PDF (and photon fragmentation function) remnants:
  - Gluon/quark PDF: standard, following C-S framework
  - Photon fragmentation function:

$$\int_{n+1} d\sigma^{A}_{\gamma q} + d\sigma^{C,FF}_{q\to\gamma}$$
$$= \int d[P_\gamma] \int_0^1 \frac{dz}{z^{2-2\epsilon}} \int d\Phi^{m-1}_{P_\gamma} \mid \mathcal{M}^B_{Vq}(p_V, P_\gamma/z) \mid^2 \frac{\alpha Q_c^2}{2\pi} [P_{q\gamma}(z) \ln(\frac{2P_\gamma \cdot \tilde{p}_V u_{lim}(z) z}{\mu_0^2(1-z)}) + z - 13.26]$$

where the non-perturbative photon fragmentation function fitted at ALEPH*:

$$D_{q\gamma}(z, \mu_{FS}) = \frac{\alpha Q_c^2}{2\pi} [P_{q\gamma}(z) \ln(\mu_{FS}^2/\mu_0^2) - P_{q\gamma}(z) \ln(1-z)^2 - 13.26]$$

* ALEPH Collaboration, Z. Phys., C69, 365

Gluon and Quark QCD Radiation in Matrix Element

- 8 diagrams for real matrix element of $d\sigma^{R}_{q\bar{q}\to V\gamma g}$ and $d\sigma^{R}_{q(\bar{q})g\to V\gamma q'(\bar{q}')}$ respectively, calculated numerically.
- Subtraction terms: initial emitter-initial spectator ($a, b = q, \bar{q}$) dipoles:

$$\mathcal{D}^{ag,b} = \frac{8\pi\alpha_S}{2k_a\cdot k_g}\frac{C_F}{x_{ga,b}}\cdot\frac{1+x^2_{ga,b}}{1-x_{ga,b}}\cdot\mid\mathcal{M}^B_{V\gamma}(\bar{\Phi}^B)\mid^2$$

$$\mathcal{D}^{gq,b} = \frac{8\pi\alpha_S}{2k_g\cdot k_q}\frac{T_R}{x_{qg,b}}\cdot[1-2x_{qg,b}(1-x_{qg,b})]\cdot\mid\mathcal{M}^B_{V\gamma}(\bar{\Phi}^B)\mid^2$$

- Calculation of these subtracted real terms is straight-wards:

$$\left(\frac{R^{ag,b}}{\mathcal{D}^{qg,\bar{q}}+\mathcal{D}^{\bar{q}g,q}}-1\right)\mathcal{D}^{ag,b} \qquad \left(\frac{R^{gq,b}}{\mathcal{D}^{gq,b}+\mathcal{D}^{a}_{\gamma q}+\mathcal{D}_{\gamma q,V}+\cdots}-1\right)\mathcal{D}^{gq,b}$$

- For $R^{gq,b}$ there is probability to produce soft photon that causes numerical instability, the region $E_\gamma \leq \texttt{cut.minKT}_\gamma \cosh(y_\gamma)$ should be cut out.

Powheg Method in Catani-Seymour framework

- NLO accuracy matching parton shower with matrix element
- Smooth IR region (low p_T) to high p_T region, no phase-space slicing, no double counting
- Generate hardest radiation in specific singular region $\alpha_r = (ag, b)$ or (gq, b) every time, by Powheg Sudakov form factor:

$$\Delta^{f_b}(\Phi^B, p_T) = \prod_{\alpha_r \in \{\alpha_r | f_b\}} exp\{\int \frac{[d\Phi_{rad} R^{\alpha_r}(\Phi_{n+1})\Theta(k_T(\Phi_{n+1}) - p_T)]_{\alpha_r}^{\bar{\Phi}_B^{\alpha_r} = \Phi^B}}{B^{f_b}(\Phi^B)}\}$$

- The cross-section of Powheg:

$$d\sigma = \sum_{f_b} d\Phi^B \bar{B}^{f_b}(\Phi^B)\{\Delta^{f_b}(\Phi^B, p_T^{\min}) + \sum_{\alpha_r} \frac{[d\Phi_{rad}\Theta(k_T - p_T^{\min})\Delta^{f_b}(\Phi^B, k_T) R(\Phi_{n+1})]_{\alpha_r}^{\bar{\Phi}_B^{\alpha_r} = \Phi^B}}{B^{f_b}(\Phi^B)}\}$$

Generate Radiation Events: Highest-pT-bid Method

- Highest-pT-bid method in Powheg:

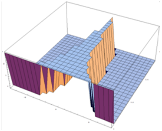
$$\left[\frac{R(\Phi_{n+1}^{\alpha_r})}{B^{f_b}(\Phi^B)}\Delta_{\alpha_r}^{f_b}(\Phi^B, k_T(\Phi_{n+1}))\right]^{\bar{\Phi}_B^{\alpha_r}=\Phi^B} d\Phi_{rad}^{\alpha_r}$$

  and choose the radiation in α_r with highest p_T.
- Veto technique: estimate the upper bounding function of $(R/B)_U$ according to dipoles $\mathcal{D}^{ag,b}$ and $\mathcal{D}^{gq,b}$ to generate k_T in MC numerical calculation.
- The prefactors for upper bounding function should be estimated suitable to have good efficiency.
- New constraint of radiation rapidity y rather than constant bounds $y_{\max}$, $y_{\min}$ is applied

$$\kappa_T^2 \geq \frac{(1-\bar{x}_a)^2}{4\bar{x}_a} \equiv \kappa_{T0}^2$$

$$\sqrt{\bar{x}_b}\,e^y \in \left(\frac{\kappa_{T0}}{\kappa_T} - \sqrt{\frac{\kappa_{T0}^2}{\kappa_T^2}-1},\ \frac{\kappa_{T0}}{\kappa_T} + \sqrt{\frac{\kappa_{T0}^2}{\kappa_T^2}-1}\right)$$

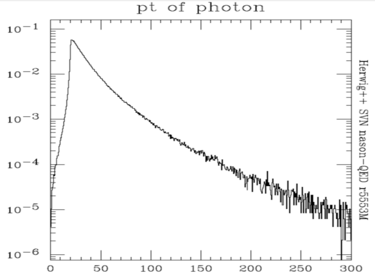
where $\kappa_T^2 = \frac{p_T^2}{\hat{s}}$

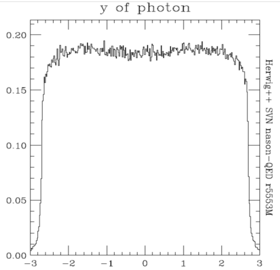


QED Quark Real Radiation

Two schemes to deal with the bremsstrahlung component:

- QED parton shower scheme: model γ fragmentation with QED shower
- Non-perturbative effect of the fragmentation may come from hadronization
- We don't have soft photon problem.
- Since we model $d\sigma^{Brem}_{Vjet}$ with QED Powheg shower, we cannot separate ME with PS to compare ME results with BHO generator.
- Try numerical result for $Z\gamma$ at $14TeV$ with cuts: $p_{T,\gamma} \geq 20GeV, \quad |\eta_\gamma| \leq 2.7$: Events number: $800,000$ Total Cross-section: $46.78(\pm 0.06)pb$

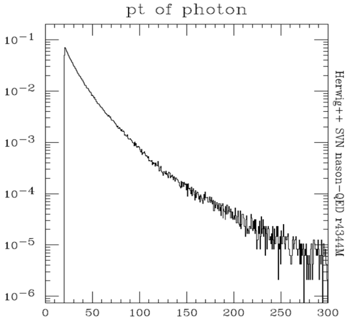


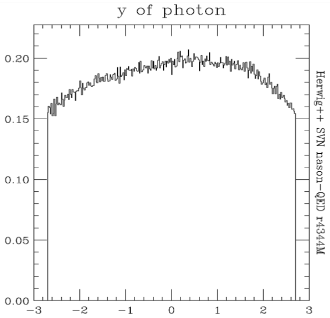


QED Quark Real Radiation

Two schemes to deal with the bremsstrahlung component:

- Photon fragmentation function scheme: photon FF fitted from experiment
- Non-perturbative effect is fitted into photon FF (as we see before)
- But we have soft photon problem.
- Due to soft photon divergence we have to separate $V\gamma$ events from $Vjet$
- Try numerical result for $Z\gamma$ at $14TeV$ with cuts: $p_{T,\gamma} \geq 20GeV, \quad |\eta_\gamma| \leq 2.7$, $z_{lim} = 0.5$ and $z_{cut} = 0.1$:
  Events number: 800,000   Total Cross-section: $43.93(\pm 0.02)pb$



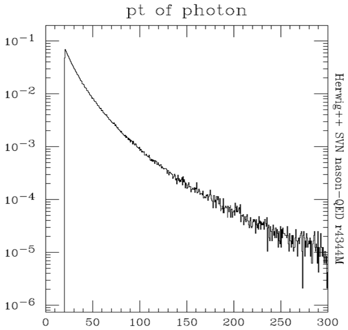


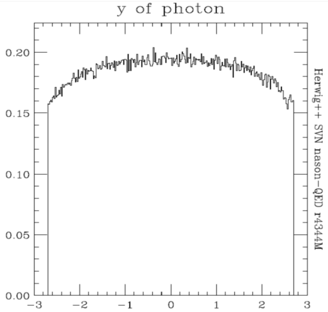
Compare with Leading Order

The LO (LO matrix element + shower MC) numerical result for $Z\gamma$ at $14\,TeV$ with cuts: $p_{T,\gamma} \geq 20GeV, \quad |\eta_\gamma| \leq 2.7$:

Events number: $800,000$ Total Cross-section: $34.84(\pm 0.02)pb$

The distribution of photon $p_{T,\gamma}$ and rapidity y_γ is





Photon Shower to Model Photon Fragmentation

- Inspired by Photon-jet and diphoton merging work*, in this scheme the non-perturbative effect of photon fragmentation comes from photon shower.
- Reminding the cross-section of our process:

$$d\sigma^{\bar{B}} = d\sigma^{B}_{V\gamma} + d\sigma^{V}_{V\gamma} + d\sigma^{C}_{V\gamma} + d\sigma^{R}_{q\bar{q}\to V\gamma g} + d\sigma^{R}_{V\gamma(qg)_i} + d\sigma^{R}_{V(\gamma q)_f} + d\sigma^{Brem}_{Vj}$$

$$d\sigma^{\bar{B}}_{V\gamma} \qquad d\sigma^{R}_{qg\to V\gamma q} \qquad d\sigma^{\bar{B}}_{V\,jet}$$

- We treat QCD and QED parton shower democratically and model fragmentation component by QED parton shower,

$$d\sigma = d\Phi_B \bar{B}_{V\gamma}[\Delta_{V\gamma}(\Phi_B, p_T^{min}) + \Delta_{V\gamma}(\Phi_B, k_T(\Phi_B, \Phi_R))\frac{R_{V\gamma g}(\Phi_B, \Phi_R) + R_{V\gamma(qg)_i}(\Phi_B, \Phi_R)}{B_{V\gamma}}]$$

$$+ d\Phi'_B B_{Vjet}[\Delta_{Vjet}(\Phi'_B, p_T^{min}) + \Delta_{Vjet}(\Phi'_B, k_T(\Phi'_B, \Phi'_R))\frac{R_{V(\gamma q)_f}(\Phi'_B, \Phi'_R)}{B_{Vjet}}]$$

* Hoche, *et al*, Phys. Rev. D 81, 034026

The Dipoles for QED Parton Shower Scheme

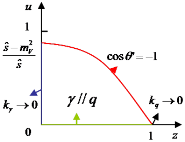
- Powheg QED shower to generate only one photon radiation and follow by QCD vetoed shower MC:

$$\Delta^{\alpha_r}_{Vjet}(\Phi'_B, k_T(\Phi'_B, \Phi'_{rad,\gamma})) = exp\{\int \frac{[d\Phi_{rad,\gamma} R^{\alpha_r}_{V(\gamma q)_f}(\Phi_{n+1})\Theta(k_T(\Phi_{n+1}) - p_T)]^{\bar{\Phi}'^{\alpha_r}_B = \Phi'^B}_{\alpha_r}}{B_{Vjet}(\Phi'_B)}\}$$

- Photon can be collinear with initial and final state quark: QED dipoles $\mathcal{D}^a_{q\gamma}$, $\mathcal{D}_{q\gamma,V}$, $\mathcal{D}^{a\gamma}_q$, $\mathcal{D}^{a\gamma}_V$. We don't need to consider: $\mathcal{D}^a_{W\gamma}$, $\mathcal{D}_{W\gamma,q}$ since the massive W doesn't lead to any singularity, and splitting function $P_{W\gamma}(z)$ is ill-define. These QED dipoles are similar with QCD dipoles: only have color charge products replaced to electric charge products $T_i \cdot T_j \to Q_i \cdot Q_j$.
- Kinematics mapping: photon radiation momentum is calculated in Breit frame of $a - q$ or $a - V$ except $\mathcal{D}_{W\gamma,q}$. It's a little complicated when massive V involves.

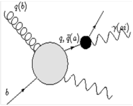
Photon Fragmentation Function Scheme: Identified Photon

- Photon fragmentation function $D_{q\gamma}(z, \mu_{FS})$ enters like PDF: treat photon as identified particle.
- We need dipoles $\mathcal{D}^{a(n)}_{\gamma q}$, $\mathcal{D}_{\gamma q,V}$ in this case. When we don't change $\bar{k}_g$ in the mapping, the two dipoles is the same except electric charge:



$$\mathcal{D}^{a(n)}_{\gamma q}(z) + \mathcal{D}_{\gamma q,V}(z) = \frac{8\pi\mu^{2\epsilon}\alpha}{2k_q \cdot k_\gamma}(Q_a \cdot Q_q \overset{Q_q^2}{//} - Q_V \cdot Q_q)\frac{1+(1-z)^2}{z} \mid M^B_{Vq} \mid^2$$

$$\Delta^{\gamma q}_{Vq}(\Phi_B, k_T(\Phi_B, \Phi_R))\left[\frac{\mathcal{D}_{\gamma q}}{\mathcal{D}_{\gamma q} + \mathcal{D}^{gq,b}} \frac{R(\Phi^{\gamma q}_{n+1})}{B_{V\gamma}}\right]$$



- The collinear limit is correct in integration of u but not soft photon limit $\Phi_{n+1}(z \to 0, u) \not\to \bar{\Phi}^B$.
- In Powheg the p_T and y and the constraints on them is quite complicated, and the upper bound of R/B is estimated more carefully.
- We can also use the unidentified photon dipole $\mathcal{D}^a_{q\gamma}$ that has correct soft photon limit. The collinear singularity is extracted by changing $\bar{\Phi}_{rad}$ variables to $\bar{y}, \bar{v}$ and exchange the integration order:

$$\bar{v}^{-1-\epsilon} = -\frac{\bar{v}_{cut}^{-\epsilon}}{\epsilon}\delta(\bar{v}) + \left(\frac{1}{\bar{v}}\right)_c - \epsilon\left(\frac{\ln \bar{v}}{\bar{v}}\right)_c + O(\epsilon^2) \qquad \left(\frac{1}{\bar{v}}\right)_c \to \int_0^1 \frac{f(\bar{v}) - f(0)\Theta(\bar{v}_{cut} - \bar{v})}{\bar{v}} d\bar{v}$$

Soft Photon Problem

- When photon fraction z (or $\bar{y}$)$\to 0$, we reach soft photon singularity related to photon virtual loop.
- But photon FF $D_{q\gamma}(z, \mu_{FS})$ is fitted down to the cutoff z_{lim} , and is insensitive to small fraction z.
- Inspired by *Wjet* QED correction*, we need to distinguish $V\gamma$ and *Vjet* events by imposing this cut, but real contribution $R_{\gamma q}$ in region $z \in (0, z_{lim})$ should be treated carefully so that no soft singularity.
- We can have two ways to do that:
    - Simply cut off $z \leq z_{lim}$, both in photon FF and subtracted real piece $R_{\gamma q}$.
    - Cut off the photon FF remnant, but in real piece extract the remained collinear and soft divergences. Need to study how they are canceled with photon loop.
- To extract the remained collinear and soft divergences in subtracted real piece $R_{\gamma q}$ we can use the similar technic of $\bar{v}^{-1-\epsilon}$:

$$\frac{1}{z^{1+2\epsilon}} = -\frac{z_{cut}^{-2\epsilon}}{2\epsilon}\delta(z) + (\frac{1}{z})_c - 2\epsilon(\frac{\ln z}{z})_c + \mathcal{O}(\epsilon^2)$$

- The trial numerical result we have is attained by throwing away these divergences that guarantee canceled with photon loop by KLN theorem.

* Denner, *et al*, JHEP08, 075

Outlook

- We have to study more carefully how the photon soft divergences should be handled.
- Compare the two scheme of photon fragmentation and see which is better.
- Compare with the previous WGamma MC tools and experimental data at LHC.
- Anomalous $WW\gamma$ couplings and beyond SM
- Complete the process with W/Z leptonic decay.