NLO $V\gamma$ Production at LHC: Matched with Parton Shower in Powheg Method

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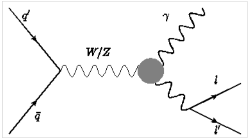
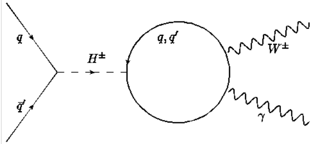
Vector Boson-Photon Production at LHC

Important Test of Standard Model & Searching for New Physics:

- LHC $p-p$ collisions: analyses of $36pb^{-1}$ collected data of 2010 $7TeV$ are published.
  $W\gamma$ and $Z\gamma$ by Atlas (1106.1592v1) and $W\gamma$ by CMS (1106.2889v1).
- Gauge symmetry breaking – physics beyond SM: Anomalous triangle gauge boson couplings
  - $WW\gamma$ anomalous couplings: CP-conserving κ, λ, and CP-violated $\tilde{\kappa}$, $\tilde{\lambda}$ in $W\gamma$ production?
  - Are there $ZZ\gamma$ or $Z\gamma\gamma$ couplings in $Z\gamma$ process?
- Charged Higgs decay to $W\gamma$ via loop? $Z'\gamma$ and $W'\gamma$ productions?

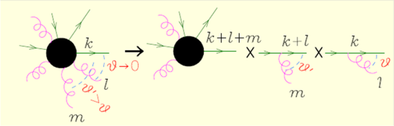


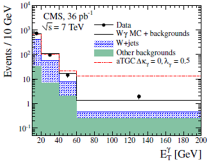


- Tevatron: good agreement with the standard model for $W\gamma$ in $D\emptyset$.
  Very loose constraint: $|\Delta\kappa| \leq 0.51$, $-0.12 \leq \lambda \leq 0.13$
- Looking forward more data collected at the LHC to give more precise measurements

Next-to-leading Order Parton Shower Predictions

- To measure anomalous coupling at LHC: more and more data accumulated at $7TeV$ and future at $14TeV$ enable more precise analysis studies and requires NLO theoretical predictions and multi-jet predictions
- NLO matrix element (BHO † & MCFM ††): higher $\mathcal{O}(\alpha_S)$ accuracy, better parton high-pT description and less scale dependence.
- Parton shower: model QCD from high scale to low scale, multi-jet inclusive observables for experiments
- ME+PS? double counting, accuracy violated, negative weighted events: LO mergings, NLO matchings and mergings





NLO matching methods:Powheg & MC@NLO

Implement $V\gamma$ Powheg in Herwig++

Nontrial problem: Photon Fragmentation   2 schemes proposed in $V\gamma$ & $\gamma\gamma$

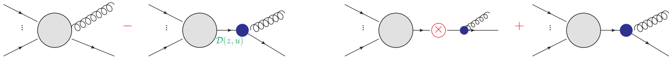
† Ohnemus, Baur and Han (1993)   †† Campbell, Ellis and Williams (JHEP07,018)

Hard Process at NLO: Catani-Seymour Subtraction

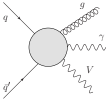
- The interesting electroweak physics in Hard Process ▶ s-channel related to the anomalous couplings.
- QCD NLO corrections: real g/q radiation, virtual loop and NLO PDF or bremsstrahlung IR effects for $V\gamma$ matrix element:

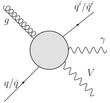
$$d\sigma^{\bar{B}} = d\sigma^{B}_{V\gamma} + d\sigma^{V}_{V\gamma} + d\sigma^{C,pdf}_{V\gamma,g} + d\sigma^{R}_{q\bar{q}\to V\gamma g} + d\sigma^{C,pdf}_{V\gamma,q} + \underline{d\sigma^{R}_{V\gamma(qg)_i} + d\sigma^{R}_{V(\gamma q)_f}} + d\sigma^{C,Brem}_{q\to\gamma}$$

- *Catani-Seymour* subtraction: cancel IR singularities without kinematic cuts.
- Factorize real ME as smooth dipole functions $\mathcal{D}(z,u)$, then $\int d\Phi_{n+1}[\sigma^{R}_{V(\gamma g)} - \sigma^{B}\otimes V_{dipole}]$ and $\int d\Phi^{B}[\sigma^{V}_{V\gamma} + \sigma^{C}_{V\gamma} + \sigma^{A}_{V\gamma}]$ is finite.



- Dimensional regularization: The dipoles are integrated over u, z to get ($\sim 1/\epsilon$) singularities analytically.





Long-range Physics: PDF & Fragmentation Function

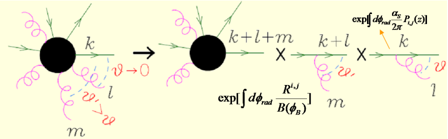
- IR singularities: dipoles $\mathcal{D}^{ag,b}$, $\mathcal{D}^{gq,\bar{q}}$, $\mathcal{D}^{a}_{\gamma q}$, $\mathcal{D}_{\gamma q,V}$ (and $\mathcal{D}^{a\gamma}_{q}$, $\mathcal{D}^{a\gamma}_{V}$?)
- Perturbative factorization theorem: collinear (and soft) logs in $\sigma^{V}_{V\gamma} + \sigma^{A}_{V\gamma}$ is absorbed into PDF or photon fragmentation function
- Non-perturbative long-term physics: remain finite PDF and photon FF are fitted from experiments.
  - Gluon or quark PDF: matrix element convolve with NLO PDFs.
  - Photon fragmentation function $D_{q\gamma}(z, \mu_{FS})$: new version, fitted from LEP. Only sensitive in $z > 0.7$.
    To attain a correct soft photon limit, a smoothing function $f_{FF}(z)$ is introduced (satisfy $f_{FF}(0.7) = 1$ and $f_{FF}(0) = 0$):

$$D_{q\gamma}(z, \mu_{FS}) = \frac{\alpha Q_c^2}{2\pi}[P_{q\gamma}(z) \ln \frac{\mu_{FS}^2}{2\bar{p}_\gamma \cdot \bar{p}_\gamma (1-z)^2} + f_{FF}(z) P_{q\gamma}(z) \ln \frac{2\bar{p}_\gamma \cdot \bar{p}_\gamma}{\mu_0^2} - 13.26]$$

Powheg Method to Match ME with PS

- NLO accuracy for ME+PS, at least leading-logarithm (LL) resummation of collinear/soft logs
- Smooth IR region to high p_T region, no phase-space slicing
- Always positive weights

Generate the hardest radiation by Powheg Sudakov form factor $\Delta(\Phi^B, p_T)$:



The cross-section of Powheg:

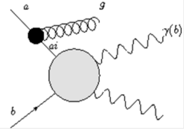
$$d\sigma = \sum_{f_b} d\Phi^B \bar{B}^{f_b}(\Phi^B)\{\Delta^{f_b}(\Phi^B, p_T^{\min}) + \sum_{\alpha_r} \frac{[d\Phi_{rad}\Theta(k_T - p_T^{\min})\Delta^{f_b}(\Phi^B, k_T)R(\Phi_{n+1})]_{\alpha_r}^{\bar{\Phi}_B^{\alpha_r}=\Phi^B}}{B^{f_b}(\Phi^B)}\}$$

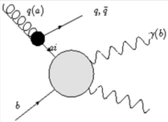
Small p_T: $R(\Phi_{n+1})/B(\Phi^B) \simeq \alpha_S(p_T) \cdot P_{i,j}(z)/2\pi$ as shower MC;

Large p_T: regains NLO ME: $d\sigma = \bar{B} \times R/B \simeq R[1 + \mathcal{O}(\alpha_S)]$

Gluon and Quark QCD Radiation

- The 8 diagrams for real (g or q) matrix element are calculated numerically.





- Quark-photon bremsstrahlung is non-trivial: QED quark-photon collinear and soft photon region in Quark real radiation.
- Truncated and veto parton shower should follow Powheg hardest emission to achieve Angular ordering
- Considering soft and collinear poles contribute to double logs term, when we change the strong coupling $\alpha_S(\mu_h^2)$ in the R/B ratio in the Powheg Sudakov form factor to be $A(\alpha_S(\mu_h^2))$, we can even guarantee next-to-leading logarithm for the QCD hardest emissions

$$\log \Delta(k_T) = -\int \frac{f_{a'} \mid \mathcal{M}^R(\alpha_S(k_T^2)) \mid^2}{z f_a \mid \mathcal{M}^B_{V\gamma} \mid^2} d\Phi_{rad} \rightarrow -\int_{p_T^2}^{Q^2} \frac{f_{a'} \mid \mathcal{M}^R(A(\alpha_S(k_T^2))) \mid^2}{z f_a \mid \mathcal{M}^B_{V\gamma} \mid^2} d\Phi_{rad}$$

when

$$A(\alpha_S(\mu_h^2)) = \alpha_S + \frac{\alpha_S^2}{2\pi}\left(\frac{67}{18} - \frac{\pi^2}{6}\right)C_A - \frac{5}{9}n_f \qquad \text{and} \qquad \mu_h^2 = k_T^2$$

Photon Shower to Model Photon Fragmentation

- 2 schemes to calculate photon fragmentation component in parton shower: QED Parton Shower Scheme and Photon Fragmentation Function Scheme
- Reminding the cross-section of our process:

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

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

- The non-perturbative effect of photon fragmentation can be either modeled by QED parton shower or measured from experiment.
- Soft photon region: suppressed by Powheg Sudakov probability or extracted and subtracted analytically.
- QED scheme: proved to work in γ-jet and diphoton merging. But it consumes much time to generate *Vjet* events.
- Fragmentation function scheme: pure Powheg correction to NLO matrix element, but a little tricky for the quark radiation from photon

QED Parton Shower Scheme

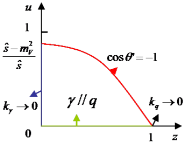
- Gluon and quark hardest emissions from initial state parton are apply on the $V\gamma$ events according to $\bar{B}_{V\gamma}$
- QED version of Powheg shower: generate only one photon emission:

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

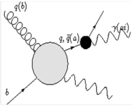
- Suppression functions to QED dipoles for the photon initial emission in Vg to suppress some incidental soft photon phase space points.
- Followed by QCD truncated and vetoed parton shower Monte Carlo.
- Since we model the fragmentation component $d\sigma^{Brem}_{Vjet}$ with QED Powheg shower, we cannot separate ME with PS, and compare our ME results with that in Baurs generator.

Photon Fragmentation Function Scheme

- Problem of soft photon limit $\Phi_{n+1}(z \to 0, u) \not\to \bar{\Phi}^B$ in dipole functions $\mathcal{D}_{\gamma q}^{a(n)}$, $\mathcal{D}_{\gamma q,V}$.



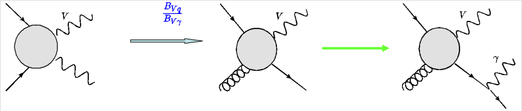
$$\Delta_{\gamma q}(\Phi_B, p_T^{min}) = \exp\Big[\int \frac{R_{V(\gamma q)_f}(\Phi_B, \Phi_R)}{B_{V\gamma}}\Big] \overset{k_T \to 0}{\not\Rightarrow} \exp\Big[\int \frac{\alpha P_{q\gamma}(z)}{2\pi}\Big]$$



- Extract the soft divergence and introduce smoothing function $f_{FF}(z)$, find it cancels with photon loop, guarantee by KLN theorem.
- Distinguish $V\gamma$ and *Vjet* events by imposing photon fraction cut $z \in (0, z_{lim})$
- Kinematic cut to separate $V\gamma$ events from *Vjet*: when $\delta R_{\gamma q} < 0.4$, $z = E_\gamma/(E_\gamma + E_q) > z_{lim}$
- Small fraction $z \leq z_{lim}$ region corresponds to *Vjet* events and soft limit is safe, so the cut is reasonable.
- p_T-ordering: the p_T and y and the constraints on them is quite complicated, and the upper bound of R/B is estimated more carefully.

Photon Fragmentation Function Scheme

- Gluon and quark hardest emissions from initial state parton are apply on the $V\gamma$ events according to $d\sigma_{\bar{B}}$
- When quark emission from photon is generated from bremsstrahlung contribution $d\sigma^{brem}_{Vjet}$, flavor structure of the hard process events have to be changes from $q\bar{q} \rightarrow V\gamma$ to $qg \rightarrow Vq$ in small p_T region



- To approximate this idea of particles reassignment, we can generate Vq hard process event according to $\bar{B}_{V\gamma} d\Phi_B \tilde{\Delta}_{QCD}(p_T^{\min})$ rather than $\bar{B}_{Vq} d\Phi_B$: a fake cross section weight!
- Then apply the photon emission from final state quark with the Sudakov $\Delta(R_{V\gamma q}/B_{V\gamma})$

$$d\sigma_{QED} = \bar{B}_{V\gamma} d\Phi_B \tilde{\Delta}_{QCD}(p_T^{\min})\{[d\Phi_{rad}\Theta(k_T - p_T^{\min})\Delta_{\gamma q}\frac{R_{\gamma q}}{B_{V\gamma}}] + [\Delta_{\gamma q}(p_T^{\min}) - 1]\} + \mathcal{O}(\alpha_S^2)$$

- It can be proved that this approximation tends to be quark final state real ME $d\sigma^R_{V(\gamma q)_f}$ in high photon p_T region, while in low p_T region it returns to the shower from $d\sigma^R_{Vq}$.
- But most of the Vq events won't be generated, just about twice of the real $V\gamma$ events.

NLO vs. LO at 14 TeV

We compare the $Z\gamma$ numerical results between LO with our NLO with and without Powheg shower (only for photon fragmentation scheme)
We find LO result is already consistent with that from CompHEP:
with PDF-cteq6l, Herwig++ LO: 33.9 pb, while CompHEP 33.86 pb .

- $Z\gamma$ with cuts: $p_{T,\gamma} \geq 20 GeV, \quad |\eta_\gamma| \leq 2.7$, $z_{lim} = 0.4$
- PDF sets: LO with MRST2004FFlo, while NLO with MRST2004FFnlo
- The photon isolation cuts: in the photon cone $\delta R_\gamma \leq 0.4$, require photon energy fraction $z_\gamma \equiv E_\gamma/(E_\gamma + E_h) \geq 0.4$

	Events number	X-section	Xsec of Z decay	K-factor
LO (Herwig++)	8,000,000	34.87 pb	1.172 pb	
NLO (Matrix Element)	800,000	51.92 pb	1.745 pb	1.49
LO of BHO	8,000,000		1.249 pb	
NLO of BHO	8,000,000		1.548 pb	1.32
QED shower scheme	~1,500,000	49.35 pb	1.658 pb	1.42
Frag. function scheme	~22,000	48.5 pb	1.630 pb	1.39

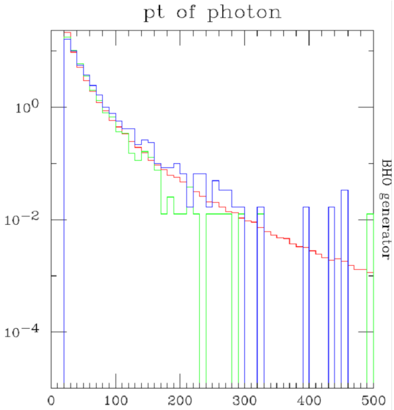
NLO vs. LO at 14 TeV

p_T distributions of small events number runs:

BHO (Baur's)

Photon fragmentation function scheme $\sim 6,000$

QED shower scheme $\sim 2,500$



Compare to Baur's,

QED scheme is higher in high

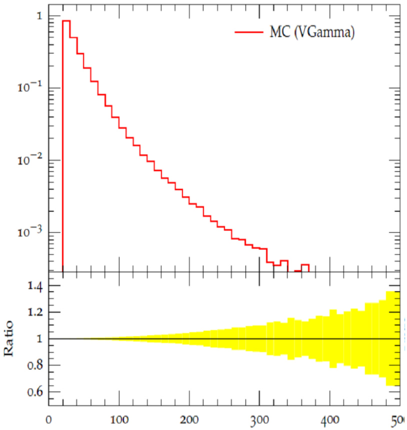
$p_T \in$ (100 GeV, 200GeV)

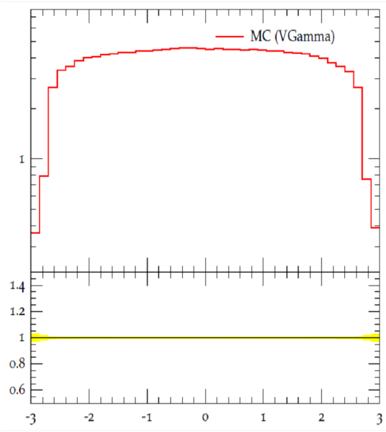
While fragmentation function scheme is lower.

Frag. Function Scheme is not so good compare to QED since we expect it higher from experimental data

QED shower scheme at 14 TeV

Photon transverse momentum p_T (in GeV) and rapidity y distributions of large events number run ($\sim 1,500,000$) of QED shower scheme





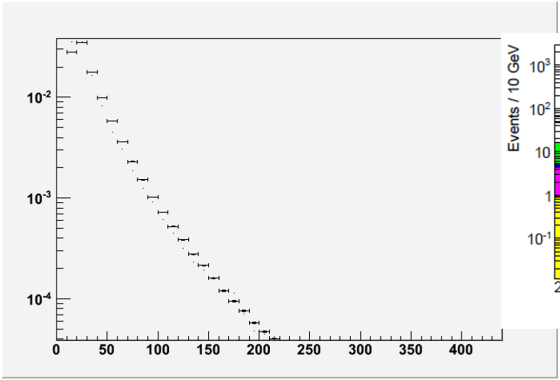
Compare with BHO Generator & data for $Z\gamma$ at $7TeV$

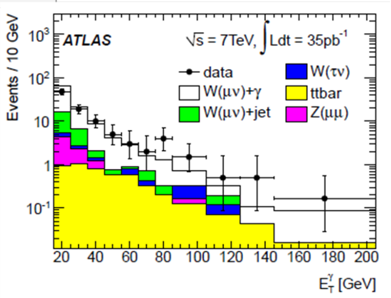
- Since in BHO NLO $V\gamma$ generator vector boson W/Z is treated with narrow width approximation via leptonic decay, we currently compare our results (QED shower scheme) with BHO by estimating our cross section with the $e+e-$ decay branch ratio (0.0336) of $Z-$boson at $7TeV$, and also compare with the 2010 $7TeV$ data from Atlas:
- We apply the photon transverse momentum and rapidity cuts: $p_{T,\gamma} \geq 15GeV, \quad |\eta_\gamma| \leq 2.7$
- And also photon isolation cuts: in the photon cone $\delta R_\gamma \leq 0.4$, require photon energy fraction $z_\gamma \equiv E_\gamma/(E_\gamma + E_h) \geq 0.4$ with h the hadronic particles
- QED shower scheme runs on the grid and get $\sim 4,100,000$ isolated event (with $\sim 6,300,000$ $V\gamma$ events and $\sim 4,300,000$ events pass the $p_{T,\gamma}$ and y_γ cuts.) The isolated cross section is $(31.89pb \pm 6.44pb) \times 0.0336 = 1.072pb \pm 0.216pb$
- While BHO $\sim 3,200,000$ events, cross section: $1.107pb$

Photon Transverse Momentum

We compare the photon p_T (in GeV) distributions and also with Atlas results:

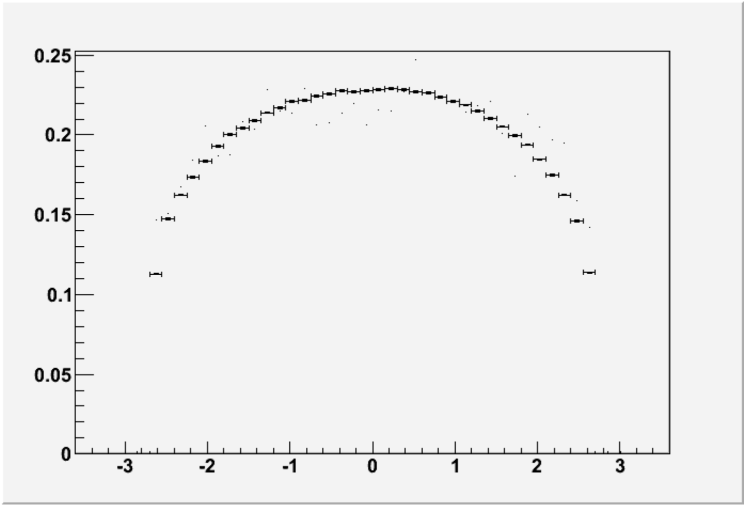
BHO: points; QED scheme: short lines





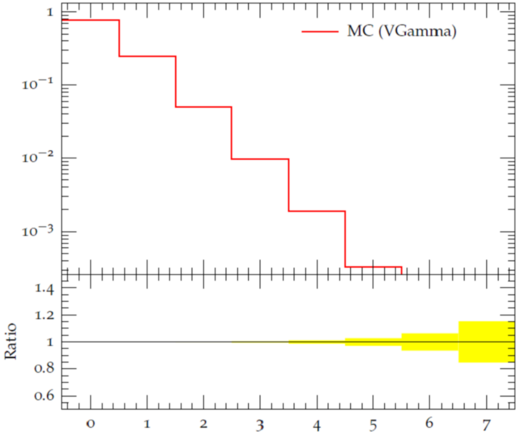
Photon Rapidity

We compare the photon y distributions : BHO: points; QED scheme: short lines



Jet Multiplicity

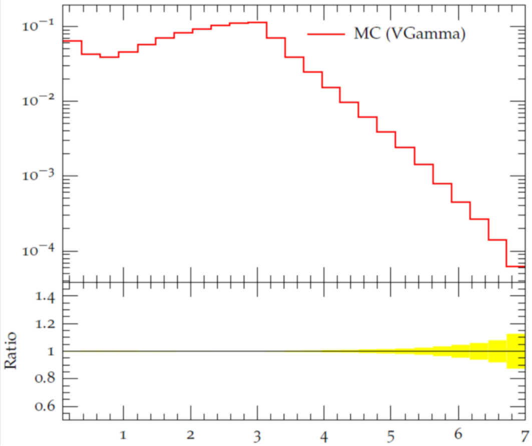
We plot the Jet Multiplicity distributions :



We also see the similar ”step shape” in the 2011 Atlas data.

dR between Photon and Leading Jet

We plot the *dR* between Photon and Leading Jet distributions :



Outlook

- The results QED shower scheme look quite reasonale.
- Further comparison between our results with BHO's and experimental data will be proposed.
- The similar results of $W\gamma$ will be given very soon.
- Anomalous $WW\gamma$ couplings and beyond SM
- Complete the process with W/Z leptonic decay.
- For the W/Z leptonic decay we will include the "FSR" (the contributions of photon radiation from the lepton) at NLO.