A comparison of Event generators for $W\gamma$ production at the LHC and a Matching scheme for Baur WGAMMA_NLO and PYTHIA

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Abstract

We present here a comparative study of PYTHIA monte carlo event generator and a matrix element calculation by Baur et. al. for $W + \gamma$ production at proton-proton collision at the LHC. Baur’s calculation is at NLO containing all diagrams up to $O(\alpha_S)$ whereas PYTHIA contains diagrams only for the tree level process $pp \rightarrow W\gamma$. We study how a NLO calculation makes a difference to the $W + \gamma$ production mechanism at the LHC and what differences arise due to the use of parton shower modelling of the photon as well as the QCD radiation w.r.t. that from an exact matrix element calculation. Finally we describe in detail a scheme, proposed by T. Sjöstrand, for combining the hard interaction part as obtained from the NLO package with PYTHIA parton shower for the evolution of the whole event.
1 Introduction

We study the production of inclusive $W + \gamma$ events at the LHC using the CMS detector. With early data, we are particularly interested in obtaining the photon $p_T$ spectrum from such events. We report here a comparison of the kinematic properties of the final state particles in proton-proton collision producing a W-boson and a photon along with other particles, in particular the photons and the jets as obtainable from PYTHIA [2] Monte Carlo generator and a software package developed by Baur et. al. [3]. As explained later in this note, an attempt has been made to integrate the matrix element level calculation of Baur with the PYTHIA generator (version 8210) taking into account the fact that Baur’s package is a next-to-leading order calculation and issues like double counting and negative weights for events.

Though the Electroweak (EWK) theory of the Standard Model (SM) has been tested to a remarkable precision in previous and current accelerators, the couplings among the vector bosons or the triple gauge couplings are mostly untested. Even, during the early phase of LHC data-taking, with limited statistics, the measurement of cross-sections of various di-boson productions will be interesting. With higher luminosity, the couplings will be determined eventually with better precision than that at present. Among all the di-boson processes, $W\gamma$ production rate is the highest and a preliminary study of $W \rightarrow \mu\nu + \gamma$ channel at the monte carlo event generator level is presented here.

The most general Lorentz and electromagnetic gauge-invariant CP-conserving Lagrangian for the $WW\gamma$ vertex can be written as follows:

\[ \mathcal{L}_{WW\gamma} = -ie \left[ W^+_{\mu\nu} A^\nu - W^\dagger_{\mu\nu} A_{\nu} W^{\mu\nu} + \kappa W^{\dagger}_\mu W_{\mu} F^{\mu\nu} + \frac{\lambda}{M_W^2} W^\dagger_{\mu\nu} W_{\mu} F^{\mu\nu} \right] \]  

(1)

where $A^\mu$ and $W^\mu$ are the photon and $W^-\text{-fields}$ respectively, $W_{\mu\nu} = \partial_\mu W_\nu - \partial_\nu W_\mu$ and $F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$. The variables $\kappa$ and $\lambda$ are related to the magnetic dipole moment $\mu_W$ and the electric quadrupole moment $Q_W$ of the $W$-boson:

\[ \mu_W = \frac{e}{2M_W}(1 + \kappa + \lambda), \quad Q_W = -\frac{e}{M_W}(\kappa - \lambda) \]

The experimental measurements of neutron electric dipole moment restrict the CP-violating $WW\gamma$ coupling terms $\kappa$ and $\lambda$ to $|\kappa|,|\lambda| \lesssim 10^{-3}[6]$. Hence the CP-violating vertex couplings are neglected at present.

The vertex term in equation [1] contains both the SM and the non-Standard Model (NSM) contributions, the latter being expressible in terms of $\Delta \kappa = \kappa - 1$ and $\lambda$, both of which are zero in the SM.

The differential cross-section for $q_1\bar{q}_2 \rightarrow W^-\gamma$ is given by

\[ \frac{d\sigma}{dt}(q_1\bar{q}_2 \rightarrow W^-\gamma) = \frac{\alpha}{s^{\frac{1}{2}}} \frac{M_W^2 G_F}{\sqrt{2}} g_{12}^2 \left[ (Q_1 + \frac{1}{1 + t/u})^2 \left( \frac{t^2 + u^2 + 2sM_W^2}{tu} \right) \right. \\
\left. + \left( \Delta \kappa \right) (Q_1 + \frac{1}{1 + t/u}) \frac{t - u}{t + u} \right. \\
\left. + \frac{\Delta \kappa^2}{2(t + u)^2} \left( tu + (t^2 + u^2) \frac{s}{4M_W^2} \right) \right] \]

(2)

where $s, t$ and $u$ are the Mandelstam variables, $g_{12} = \cos \theta_C$ for $q_1\bar{q}_2 = d\bar{u}$ and $s\bar{c}$ and $g_{12} = \sin \theta_C$ for $q_1\bar{q}_2 = s\bar{u}$ and $d\bar{c}$. $Q_1 e$ is the charge of the quark $q_1$ and $Q_2 = Q_1 + 1$. This expression does not include the factor $\lambda$ which only occurs for non-SM WW\gamma vertex factors. The differential cross-section can also be expressed as

\[ \frac{d\sigma}{d\cos \theta^*}(d\bar{u} \rightarrow W^-\gamma) = \frac{1}{2}(s - M_W^2) \frac{d\sigma}{dt}(d\bar{u} \rightarrow W^-\gamma) \]  

(3)

where $\theta^*$ is the angle between the $W^-$ and $d$-quark or equivalently between the $\gamma$ and $u$-quark in the centre of mass frame of the system.

A special feature of the gauge theory is manifested in this distribution due to the value of $\kappa = 1$ in SM. Notably, the differential cross-section $d\sigma(q_1\bar{q}_2 \rightarrow W\gamma)/d\cos \theta^*$ vanishes at a particular angle $\theta^* = \cos \theta^* = -1/3$. This phenomenon, the radiation amplitude zero (RAZ), is possible only for SM values of $\kappa (= 1)$ and $\lambda (= 0)$. This
feature can be attributed to the expression \( [Q_1 + 1/(1 + t/u)]^2 \) which vanishes for \( t^*/u^* = -(1 + 1/Q_1) \), or in other words, for \( \cos \theta^* = -(1 + 2Q_1) \) corresponding to the charge of the quark \( Q_1 = -1/3 \).

The zero occurs due to destructive interference of radiation patterns in gauge theory tree level amplitudes for the emission of massless gauge bosons [4]. Any anomalous moment resulting in different values of the coupling, would destroy the occurrence of the zero. Consequently the precise measurement of the radiation amplitude zero would serve to establish the Standard Model and also to search for Beyond Standard Model (BSM) physics. The hadro-production provides model-independent, direct measurements of the triple boson vertices (ref. [1]). The anomalous couplings can be tested in such a situation by measuring the production rate at high value of photon transverse momentum. The D0 experiment has recently reported a study of the radiation amplitude decay at the Tevatron [5]. In the present study, we deal only with the Standard Model parameters, i.e. \( \Delta \kappa = \lambda = 0 \).

2 \( W + \gamma \) Production at \( pp \) Collisions

In a hadron collider, the Born level graphs producing \( W\gamma \) events are shown in Fig.s 1a and 1b. Also the crossed diagram for fig 1a, corresponding to the \( u \)-channel process, is present. These interfere to give rise to the RAZ feature of Standard Model \( W\gamma \) production. If we look at the \( W \) decay mode with \( W \) decaying leptonically, the photon may also be produced from the charged lepton bremsstrahlung (fig. 1c). This produces identical final state in the detector as those from Fig.s 1a and 1b.

In addition to the Born level, there exist higher order diagrams involving QCD loops and real particle emission. Some higher order diagrams involving real QCD emission or loop corrections are shown in Fig.s 2a – 2c. The contribution of the higher order diagrams to the total production of \( W + \gamma \) is expected to be significant at the LHC.

The quark-gluon fusion process \( qq \rightarrow W\gamma X \) makes a significant contribution to the inclusive \( W\gamma \) production at the LHC due to the large quark-gluon luminosity at LHC energies and causes considerable enhancement at high photon transverse momentum \( p_T^\gamma \). Further, NLO QCD corrections spoil the special feature of radiation amplitude zero as well as the sensitivity towards anomalous couplings.

Thus the \( W\gamma \) production at the LHC is likely to be accompanied by a large transverse momentum jet. However, an appropriate jet veto should be able to reject a good fraction of such events. Additionally, there are electroweak corrections as well, and we do not take them into account at the moment because of their smallness in comparison to QCD corrections.
3 Generator Level Study

We use PYTHIA, which is a general purpose parton-shower generator and Baur’s package which henceforth shall be referred to as WGAMMA_NLO and which is a dedicated matrix element generator for simulating the signal: \( pp \to W\gamma X \). We compare the various features of these generators with different combinations of parameters with the objectives of

- understanding the physics process of \( W + \gamma \) production in hadron colliders
- trying to estimate the topology of the event from detector point of view so as to optimize analysis of collider data
- trying to set realistic kinematic cuts and choose relevant parameter sets so as to generate events for detector simulation

WGAMMA_NLO contains all diagrams up to \( \mathcal{O}(\alpha_S) \) except Fig. 1c. WGAMMA_NLO neglects the W-mass altogether and puts it to zero to simplify calculations at NLO. In such an approximation the photon bremsstrahlung diagram is not required for maintaining gauge invariance of the whole calculation.

The Baur calculation also includes a middle stage between Born and NLO, called LO, wherein the resolved Born + 1 jet topologies have been removed from the NLO cross section, leaving only topologies of the Born types, but with NLO-corrected cross sections. This classification thus depends on the jet resolution parameters used in the calculation.

On the other hand PYTHIA calculates \( W + \gamma \) at Born level with \( \Delta \kappa = 0 \) and uses a narrow-width approximation for the W boson. Fig. 1c is included in PYTHIA through the simulation of final state radiation (FSR). Pythia does not explicitly include NLO, but does add the topologies in the parton-shower approximation. This includes both the real corrections of fig. 2a and fig. 2b up to a leading logarithmic accuracy and the virtual corrections of fig 2c via the Sudakov form factor.

3.1 Reproducing Baur’s results

We start by trying to reproduce the results from Baur’s paper[3] for Tevatron Run I energy of 1.8 TeV. We keep the parameter values identical to that in the paper as given in Table 1.

With these parameters (selection criteria) we plot below the photon transverse momentum spectra (\( p_T^\gamma \)) for Born level, leading order (LO) and next-to-leading order (NLO) and the k-factor, which is defined as the ratio of next-to-leading order to the Born level calculation, as a function of the photon \( p_T \) are displayed in Fig. 3.

The photon \( p_T \) spectra are in good agreement with that in Baur’s paper and the k-factor as obtained is the accepted one for the Tevatron energy.
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Cut</th>
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</thead>
<tbody>
<tr>
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</tr>
<tr>
<td>Charged lepton $p_T$</td>
<td>20 GeV</td>
</tr>
<tr>
<td>Neutrino $p_T$</td>
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</tr>
<tr>
<td>Jet $p_T$</td>
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</tr>
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<tr>
<td>Collinear divergence parameter</td>
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</tr>
<tr>
<td>Fraction of hadronic energy in a cone around the photon</td>
<td>0.15</td>
</tr>
</tbody>
</table>

Table 1: Generator level cuts for Baur WGamma for comparing Baur’s result presented in [3].

Figure 3: Photon $p_T$ from WGAMMA_NLO at $\sqrt{s} = 1.8$ TeV and the k-factor, as defined in the text.
### Table 2: Generator level cuts for WGAMMA_NLO as used for generating LHC events at 10 TeV.

<table>
<thead>
<tr>
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<tr>
<td>Soft divergence parameter</td>
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<td>Collinear divergence parameter</td>
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</tr>
<tr>
<td>Fraction of hadronic energy in a cone around the photon</td>
<td>0.15</td>
</tr>
</tbody>
</table>

### Figure 4: Photon $p_T$ from WGAMMA_NLO at LHC centre of mass energy, 10 TeV and the k-factor at that energy.

3.2 **WGAMMA_NLO and PYTHIA**

#### 3.2.1 k-factor from WGAMMA_NLO

Since WGAMMA_NLO provides a NLO calculation and the NLO effects are expected to be quite pronounced at the LHC, we would like to consider NLO calculations in our experimental study and hence in the simulated data samples. For this, we compare the effects of NLO over and above the tree-level diagrams for $W + \gamma$. We now plot the $p_T^\gamma$ spectrum at LHC energy of $\sqrt{s} = 10$ TeV as obtained from WGAMMA_NLO. Certain cuts from Table[1] are modified as in Table[2]. Also, the Baur k-factor at Tevatron energy is shown in fig. 3b.

Using these cuts, we get the $p_T^\gamma$ spectrum and the k-factor as in Fig. [4].

#### 3.2.2 WGAMMA_NLO and PYTHIA 6 matrix element and PYTHIA 6 parton showers

WGAMMA_NLO , as we noted previously is a NLO calculation. On the other hand, PYTHIA contains matrix element calculation at tree level for certain $2 \rightarrow 2$ processes as well as parton showers to simulate higher order real and virtual corrections which are of leading log accuracy.

We wish to compare the kinematic distributions of final state photons from the above-mentioned two generators for the $W + \gamma$ process. For PYTHIA , the choices are as follows:

- Generate $W + \gamma$ events from the $2 \rightarrow 2$ process in PYTHIA (MSUB(20) = 1) (as in eqn. 2 with $\Delta \kappa = 0$).
Figure 5: $p_T^\gamma$ from WGAMMA_NLO, PYTHIA ME (with and without ISR turned on) and PYTHIA ISR parton shower for inclusive W production (left) and the $p_T^\gamma$ spectrum from PYTHIA $W + \gamma$ matrix element calculation without PS compared to WGAMMA_NLO Born (tree) level calculation (right). This gives an idea about the difference between a full matrix element calculation with diagrams Fig. 1b and Fig. 1a and the crossed diagram as in Baur and calculation with only one diagram, Fig. 1a and its crossed diagram as in PYTHIA.

We can then add the ISR emissions by parton showers.

- We can also start from the inclusive W production, $q\bar{q} \rightarrow W$, and then let the ISR shower mechanism provide both the photon emissions and other QCD radiation. This is less efficient computationally, since most of the events will not contain a photon within the detector’s fiducial volume that survives the trigger cuts, but this may be a useful framework for studies of the fake-photon background in W events.

Figure 5a compares the WGAMMA_NLO Born level (tree) calculation with the PYTHIA matrix element calculation of $pp \rightarrow W\gamma$ with the initial state radiation (ISR) from the parton showers (PS) switched off (MSTP(61) = 0). This is the basic level of comparison which can be made between PYTHIA and WGAMMA_NLO.

Figure 5b shows the photon $p_T^\gamma$ from WGAMMA_NLO with leading order (Born level with all one loop corrections) as well as WGAMMA_NLO with next-to-leading order (full $O(\alpha_S)$) calculation with a final state parton and compares the distributions from PYTHIA 6 parton shower ISR photons. We see that the parton shower methodology overestimates the number of photons compared to the actual matrix element calculation. This could be attributed to the fact that the parton shower resums all higher order corrections as well, whereas the matrix element calculations are exact only till the order to which they are calculated.

For an understanding of the PYTHIA parton shower mechanism, we choose to study two effects:

1. how it modifies the photon transverse momentum $p_T^\gamma$ in an inclusive $W\gamma$ process compared to the process $pp \rightarrow W\gamma$ with ISR switched off (MSTP(61) = 0);
2. how the ISR the $W\gamma$ system.

We plot the ratio of $p_T^\gamma$ from $pp \rightarrow W\gamma$ without ISR and with ISR in Fig. 6a. The parton shower calculation resum QCD radiations up to all orders in $\alpha_S$ with logarithmic accuracy. In effect, this ratio reveals the corrections due the higher order diagrams which can be viewed as an overall "k-factor". Previously we noted in Fig. 5b that the parton shower overestimates the photon emission cross-section. Yet we find that the PYTHIA "k-factor" in Fig. 6a is appreciably lower and has a more flat distribution compared to the WGAMMA_NLO k-factor, shown in Fig. 4b. Two reasons may be forwarded for this attribute. One, we see from Fig. 5a that the PYTHIA estimated photon transverse momentum spectrum is harder than that from WGAMMA_NLO Born level. A second reason may be that although PYTHIA parton shower overestimates the photon emission cross-section it is not so in case of QCD radiation. These two reasons and their interplay may explain the lower higher order correction from PYTHIA parton shower compared to the WGAMMA_NLO NLO correction to the Born level process.
Figure 6: The ratio of $p_T^\gamma$ spectrum from PYTHIA matrix element without and with ISR from PS. This gives an effective "k-factor" for the PYTHIA PS which is supposed to take into account higher order emission diagrams for the process (left) and plot of the transverse momentum of the $W\gamma$ system (right). This gives the amount of boost received by the $W\gamma$ from QCD ISR. Also shown on the same canvas are the corresponding plots for WGAMMA_NLO Born level, LO and NLO. Predictably for WGAMMA_NLO Born and LO, this quantity peaks at the origin since there are no QCD radiation present.

### 3.3 PYTHIA 6 vs. PYTHIA 8

For our future requirement, we made a comparison of PYTHIA 6 and the new PYTHIA 8 which is written in object-oriented programming style using C++. We compare the photons from $W\gamma$ matrix element in PYTHIA 6 with that of PYTHIA 8 (Fig. 7a) and ISR photons from parton shower in PYTHIA 8 with that in PYTHIA 6 (Fig. 7b).

Figure 7: Comparison of matrix element photon $p_T$ from PYTHIA 6 and PYTHIA 8 and comparison of parton shower photons from PYTHIA 6 and PYTHIA 8.

The comparison, though good is not perfect owing to the different default renormalization and factorization scales used by PYTHIA 6 and 8. With the settings of PYTHIA 8 renormalization and factorization scales changed to PYTHIA 6’s default values, we obtain a perfect match of the matrix element $W\gamma$ calculation from the two generators. This is plotted in Fig. 8.
Figure 8: Comparison of matrix element photon $p_T$ from PYTHIA 6 and PYTHIA 8 and comparison of parton shower photons from PYTHIA 6 and PYTHIA 8.

Figure 9: Comparing photon $p_T$ from PYTHIA $W \gamma$ matrix element, from ISR shower and both ISR and a second hard interaction producing a photon in the same event.

3.3.1 PYTHIA 8 with a 2\textsuperscript{nd} hard interaction (Multiparton Interaction)

Finally, we also investigated multiple parton-parton scattering in a single proton-proton collision where we can have more than one hard interaction. This is entirely possible at the LHC and the impact on the distribution of the photon’s transverse momentum due to multiple interaction was considered. This is a new feature of PYTHIA 8 and did not exist in the old Fortran version of PYTHIA 6. We switched on the $W$ production process in PYTHIA 8 and with it the production of a parton and a photon ($qg \rightarrow q\gamma$, $q\bar{q} \rightarrow q\gamma$, $gg \rightarrow g\gamma$, $q\bar{q} \rightarrow \gamma\gamma$, $gg \rightarrow \gamma\gamma$) in the same event (PYTHIA 8 switch PartonLevel:MI = on). Here the hard process producing the photon is different form the $W$’s yet they arise from the same proton pair colliding. It turned out that such events were of little significance as their numbers were small compared to the actual $W+\gamma$ events and so we may disregard them. Figure 9a shows the photon $p_T$ from full NLO calculation of WGAMMA_NLO, from PYTHIA 8 ISR (corrected for overestimation of photon spectrum w.r.t. to matrix element calculation, as was discussed in section 3.2.2), from PYTHIA 8 ISR plus a 2nd hard interaction producing a photon as well as from PYTHIA 8 FSR photons.

We also looked at the jet $p_T$ spectrum in WGAMMA_NLO arising from quarks and from gluons. This is shown in Fig. 10a. The quark and gluon jets are produced with roughly the same frequency and the quark jets are slightly dominating on the higher side of $p_T$ spectrum.
4 Matching

The hard scattering part of hadronic interactions involving a few final state particles are best described by a matrix element calculation which is exact up to a fixed order in $\alpha_S$. Besides this hard scattering there are numerous softer interactions between the parton of the incoming hadrons which give rise to myriads of softer particles. The parton shower approach is best suited for this regime of QCD interactions involving many soft particles. Furthermore, what one sees in the detector are not quarks and gluons but colour-singlet hadrons which requires an algorithm to group coloured partons from QCD interactions in hadrons. This requires a hadronisation scheme.

The parton shower approach is complementary to the matrix element approach and one would always like to combine the two for a complete event simulation. Ideally, we would like to have WGAMMA_NLO take care of the hard scattering part of an interaction producing a $W$, a photon and sometimes a high energy parton and then pass over the information to PYTHIA which would then simulate softer interactions (also called underlying events) and hadronize the products.

There are two problems encountered in this approach: first, some events from WGAMMA_NLO are produced with 'negative weights' and second, there is 'double counting’. Below are a short description of each of these problems followed by the solution:

In a matrix element calculation, every event comes associated with a weight factor. The weight of an event indicates the frequency of the occurrence of an event with such a configuration of particle energies and momenta in an interaction. Since WGAMMA_NLO is a NLO matrix element calculator there are some events which acquire negative weights as some events in NLO occur via the production of very short-lived unobservable particles of non-physical mass. These are called virtual particles. The momentum associated with virtual particles can be anything and so every possible momentum value has to be integrated over. The procedure can introduce a negative weight for a fraction of such a set of events.

As a solution, we select events from WGAMMA_NLO based on the probability of their occurrence and reassign the weights of all particles to unity. Events with higher weights are more likely to be selected and those with lower weights are more likely to be rejected, thus conserving the total probability of seeing the whole collection of events.

For the 'double counting’ problem, let us consider the following: WGAMMA_NLO produces event containing a $W$ and a photon (2-body events) and occasionally a $W$, a photon and a parton (3-body events) because it is a NLO generator. Once the set of WGAMMA_NLO events are passed on to PYTHIA for parton showering and hadronization, it may so happen that for some WGAMMA_NLO events with only a $W$ and a photon the parton shower added by PYTHIA is of high enough energy. This event is then reclassified as 3-body event. This is a problem because the number of 2-body or 3-body events are not supposed to change by the action of the parton shower mechanism, which only takes care of soft interactions. This problem is called double-counting because we are actually counting a particular 3-body event twice, once when produced with WGAMMA_NLO and again as a spurious 3-body event after a PYTHIA parton shower has been added to an original 2-body WGAMMA_NLO event. The way out is called matching which is supposed to preserve the count of 2-body and 3-body events at
lowest order separately when the WGAMMA_NLO output is processed by PYTHIA. At a higher order this can still change.

The matching scheme was tested and the effects of different parameters like the transverse momentum components of the W decay products, the photon and the parton were compared before and after the matching. We did not observe any significant change in any of the parameters apart from those of the partons’ before and after matching as they are supposed to be left intact by the matching procedure. For the partons, we observed that while the total number of events with hard partons are conserved, there were also many more events with low energy partons which were the 2-body events with parton showers from PYTHIA.

4.1 The matching algorithm

1. WGAMMA_NLO produces 3-body final states (µ, ν and γ) and 4-body final state (µ, ν, γ and jet (q or g)).
2. The 4-body events lack a Sudakov form factor (the probability of no emission which take into account the effect of virtual loops) which requires the following:
   - Project onto a 3-body, by assuming that the outgoing parton can be emitted from either incoming partons (flavours permitting), with relative weights by splitting kernels and parton densities. So we assume that the 4-body state never had a parton emitted and all the kinematics are recalculated based on that. This gives the projected 3-body event.
   - Shower the resultant 3-body, compare $p_{T}^{\text{shower}}$ at the first ISR branching with the $p_{T}^{\text{parton}}$ in original 4-body.
     - If $p_{T}^{\text{shower}} > p_{T}^{\text{parton}}$ then the event is reclassified to 3-body; move to step 3 below.
     - If $p_{T}^{\text{shower}} < p_{T}^{\text{parton}}$ then the original 4-body event is now showered and $p_{T}^{\text{shower}}$ is compared with $p_{T}^{\text{parton}}$.
       - If $p_{T}^{\text{shower}} > p_{T}^{\text{parton}}$ then go back one step.
       - Continue with rest of shower to give a complete event.
3. Shower the 3-body events; compare $p_{T}^{\text{shower}}$ with $p_{T}^{\text{separate}}$ after first ISR branching. $p_{T}^{\text{separate}}$ can be considered to be the boundary between the ME calculation’s regime and that of the parton shower’s.
4. If $p_{T}^{\text{shower}} > p_{T}^{\text{separate}}$ then stop any further shower evolution and go back one step.
5. Continue with the rest of the shower.

4.2 Matching results

According to the above-mentioned algorithm, we first project a 4-body state on to a 3-body state and try to determine the Sudakov form factor for the QCD emission which is originally from the matrix element calculation. Figure(11a) shows the jet $p_{T}$ from events after the “Sudakov correction”, i.e., the jet $p_{T}$ from those 4-body events which were retained as 4-body events after they had passed the test that the first ISR emission from the corresponding projected 3-body events are softer than the matrix element generated parton.

As a second step to the parton matching scheme, the events are showered and the first ISR $p_{T}$ is plotted in fig 11b. Since according to our algorithm, we are clearly demarcating a $p_{T}$ region above which matrix element calculation is valid and below which is the parton shower regime (at 5 GeV for the present study) we see that the first ISR emission from 3-body events are always confined to below 5 GeV. But this is not so in the case where the parton showering is only required to be softer than the matrix element parton. Hence for 4-body events, we get a long tail for events with highly energetic matrix element parton.

Fig. 11a depicts the jet $p_{T}$ after the matching is performed. This is the parton’s $p_{T}$ from WGAMMA_NLO for those events which belong to the region of phase-space where the matrix element calculation is considered valid and for 3-body events, this is the first ISR parton’s $p_{T}$.

Looking at Fig. 12 we see all jets from WGAMMA_NLO (in red) and from PYTHIA (in green) after the matching has been performed. The relative softness of the jet $p_{T}$ spectrum from PYTHIA after the matching has been done is because we now have several more events which are of 3-body type and for which the leading jet comes from the parton shower and not from the matrix element.

The matching scheme is rather simplistic and is suitable for this particular event topology which contains only one jet. The advantage is that it does not require any modification of the matrix element calculation of WGAMMA_NLO for the Sudakov form factor for emission.
Figure 11: Jets after Sudakov correction and matching (left) and from 3 and 4-body events after 1st ISR emission.

Figure 12: Final jets: Comparison with original jets from WGAMMA_NLO ME
Our matching prescription is surely not perfect; whereas we expect a smooth transition from the domain of matrix element to the parton shower, we see a kink below 5 GeV in the boundary of the parton transverse momentum distribution where the parton shower takes over from matrix elements. Furthermore, it seems at present that the WGAMMA_NLO generator, adapted for producing events with unit weights, produces events with partons energy going all the way down to zero, although we can explicitly configure WGAMMA_NLO to produce parton emissions above a certain energy only. This feature remains to be investigated and was not looked into at depth during the tenure of the studentship. We have demonstrated a proof-of-principle matching scheme for WGAMMA_NLO and PYTHIA and further details like looking that the parton spectrum and cuts on the parton (jet definition) has to be optimized.

5 Summary

The preparation for data analysis of high energy physics experiments involve the use of monte carlo techniques to simulate generation of events one wishes to study and aslo simulation of detector equipment and interactions of the produced particles in the detector. As a preparation for studying the production of $W + \gamma$ events at LHC proton-proton collision using the CMS detector, we wish to accurately model the production mechanism of $W + \gamma$ at the LHC. In this note, we have made a comparison of a well-established general purpose event generator, PYTHIA with the dedicated WGAMMA_NLO generator. PYTHIA has been found wanting on several issues regarding $W + \gamma$ production mechanism and WGAMMA_NLO too has been found to lack the total description of a realistic hadron collision scenario leading to $W + \gamma$ production. The most effective strategy, thus would be to combine the two event generators to the best of our advantage and in the later section of this note, we have outlined a home-brewed apporach to this combination, the so called “Matching strategy”. Given the individual performance of WGAMMA_NLO and PYTHIA , a successful implementation of the matching strategy will pave the way for event generation taking into account aspects of all physics involved, at various scales, in hadronic production of $W + \gamma$ at the LHC.

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