W+jets production at LHC – *CompHEP*, *VECBOS* and *PYTHIA* comparison at the partonic level

Viacheslav Ilyin [1]
Skobeltsyn Institute of Nuclear Physics, Moscow State University, 119899 Moscow, Russia
Anna Skachkova [2]
Joint Institute for Nuclear Research, LPP, 141980 Dubna, Russia

Abstract

The W boson production recoiled by a hard jets at LHC is calculated at partonic level with the help of *CompHEP*, *VECBOS* and *PYTHIA* packages, and obtained results are cross checked. Main goal is to understand the accuracy of the corresponding calculations, in particular at very high transversal momenta. This task should be considered as a basis for the cross check of more complicated cases with W+Njets final states ($N = 2, 3, 4$) with hadronization of final states which study is crucial for understanding of the background, e.g. to the Higgs boson search and study of SUSY effects. All three packages have exact matrix elements of the subprocesses. Thus, one can normalize other calculation aspects, in particular the choice of QCD parameters, having in mind further analysis with hadronization of final states.

Reactions with W+jets production provide an important part of physical backgrounds to different standard and supersymmetrical processes at hadron colliders. We present detailed comparison of the rates at different transversal momenta calculated by *CompHEP* [1], *VECBOS* [2] and *PYTHIA* [3] packages.

Note that W production, associated with two jets, was calculated in [4] at TEVATRON energies with the help of *CompHEP* and *VECBOS*. Obtained results were compared, and reasonable agreement was found. In [5] *VECBOS* and *PYTHIA* were used for evaluation of W+Njets production ($N = 2, 3, 4$) at LHC, and serious underestimation of the rates was fixed for *PYTHIA*. For example, at moderate transversal momenta P_T=20 GeV the corresponding ratio *VECBOS*/*PYTHIA* was 1.5, and 2.5 at P_T = 200 GeV. This is not surprising because of the second jet in *PYTHIA* is simulated by the parton showering mechanism which is an approximation with *ad hoc* unknown applicability at high transversal momenta. However, *PYTHIA* is a standard tool for simulation of high energy collisions, used widely for LHC processes, for example in search for Higgs boson and SUSY effects. Here large transveral momenta of W boson and jets (up to 500-800 GeV) are of special interest.

We start our analysis from the W+1jet case. Here all three packages uses exact (LO QCD) matrix elements and one can normalise other calculation conditions. Among them the choice of QCD parameters (Q^2 scale of hard subprocess, the runing α_s normalization, the PDF set) plays the major role.

Let us give short characteristics of the software used in the calculations.

CompHEP is a package for automatic calculation of cross sections in leading order (LO) of perturbation theory for processes in the Standard Model and its extensions. Matrix elements are calculated symbolically for complete set of Feynman diagrams, and then integrated over the phase spase with the help of adaptive MC program VEGAS [6].

VECBOS is a package for evaluation of W+Njets cross sections (also Z plus up to 3 $jets$) at hadron colliders. It is based on the VEGAS integrator and exact (LO QCD) matrix elements for hard subprocesses. *VECBOS* was turned out to be an usefull tool for the Tevatron data analysis [9].

PYTHIA is a widely used Monte Carlo physical event generator.

We have used leading order CTEQ4l [7] parametrization for the parton distributions with $\Lambda^{(4)}_{QCD}$ =235 MeV (corresponds to $\Lambda^{(5)}_{QCD}$ =181 MeV) in *CompHEP* and *PYTHIA* (where we used the interface with PDFLIB [8]). Here the index at Λ_{QCD} parameter means the number of quark flavours. In the *VECBOS* code the CTEQ4l set is implemented with $\Lambda^{(4)}_{QCD}$ =300 MeV.

In all packages we used fixed strong coupling constant $\alpha_s(M_W)$=0.1345 (corresponds to the LO formula at $\Lambda^{(5)}_{QCD}$ =181 MeV).

[1]E-mail: ilyin@theory.npi.msu.su
[2]E-mail: askach@theory.npi.msu.su

The QCD scale Q^2 for hard subprocesses and for evolution of parton distributions was chosen equal to W boson mass in *CompHEP* and *VECBOS*. In *PYTHIA* this choice is not available. Thus we used default variant when Q^2 equals to average sum of the transversal masses squared for W and jet. We have corrected (MSTP(32)=2) this scale by the factor $K = 2M_W^2/(M_W^2 + 2p_T^0)$, where p_T^0 is the corresponding cut ($P_T > p_T^0$), to be closer to the fixed scale $Q^2 = M_W^2$.

Physical constants used are $sin\Theta_W$=0.473, M_W=80.3427 GeV, Γ_W=2.10526 GeV, α_{em}=1/127.9. Note that the value of the W width was obtained as a sum of all 2-body partial widths evaluated in electroweak LO.

VECBOS at CERN for the CMS experiment

Current version of *VECBOS* was copied on the CERN CMS disk space:

/afs/cern.ch/cms/physics/VECBOS

Here we placed also some commands and the code of the interface with *PYTHIA* for hadronization of partonic events generated by *VECBOS*. The *VECBOS* generator is created by the **VECBOS.make** command. All needed input parameters can be changed in the **INPUT.VECBOS** file. In particular the following PDF sets are available (all of them were implemented in original *VECBOS* code):

- 43 → CTEQ4l , $\Lambda^{(4)}_{QCD} = 300$ MeV
- 44 → CTEQ4m , $\Lambda^{(4)}_{QCD} = 300$ MeV
- 130 → CTEQ4m , $\Lambda^{(4)}_{QCD} = 215$ MeV
- 131 → CTEQ4m , $\Lambda^{(4)}_{QCD} = 255$ MeV
- 133 → CTEQ4m , $\Lambda^{(4)}_{QCD} = 348$ MeV
- 134 → CTEQ4m , $\Lambda^{(4)}_{QCD} = 401$ MeV

In order to start the *VECBOS* generator one has to use the **GetPev** command. A *VECBOS* calculation session finishes with placing:

– cross sections and histograms into the VECBOS.OUT file;

– partonic events into the file VECBOS.pev (in the *CompHEP* format).

$\Lambda^{N_f}_{QCD}$ in VECBOS

The strong coupling is evaluated in *VECBOS* through the well known LO formula

$$\alpha_s = \frac{12\pi}{(33-2N_f)\log(Q^2/\Lambda^2_{QCD})},$$

but without flavour matching: $\Lambda^{(4)}_{QCD}$ is used for any value of Q^2. More correct is to use $\Lambda^{(5)}_{QCD}$ when $Q > M_b$. This is a source for overestimation of the W+jet matrix element at the level of $3-4\%$ and (gradually) higher for W+Njets. Note, that $\Lambda^{(4)}_{QCD}$ for evaluation of α_s is taken from the PDF set used.

The CTEQ4l set implemented in the *VECBOS* code is normalized with $\Lambda^{(4)} = 300$ MeV rather than one has in standard CTEQ4l set[7], where $\Lambda^{(5)}_{QCD} = 181$ MeV is used (that corresponds to $\Lambda^{(4)}_{QCD} = 235$ MeV). This is the next source for overestimation of $(3-4\%)$ the matrix elements in *VECBOS*.

Of course, these two points of different using the Λ_{QCD} parameter in *VECBOS* affect also in the evaluation of parton distributions.

Thus, in our analysis we used two variants of the *VECBOS* code:

⋄ *VECBOS^d* – with CTEQ4l($\Lambda^{(4)}_{QCD} = 300$ MeV) and without flavour matching (original code);

⋄ *VECBOS^c* – with standard CTEQ4l($\Lambda^{(5)}_{QCD} = 181$ MeV) and α_s evaluated through the LO formula with $\Lambda^{(5)}_{QCD} = 181$ MeV.

W+jets **final states at the partonic level**

Several subprocesses contribute in the W+1jet final state at the partonic level, which we subdivided on two subsets (in correspondence with the *PYTHIA* subprocesses 16 and 31):
$f_i \bar{f}_j \to gW$, $f_i g \to f_j W$,
where f_i represents quarks and antiquarks of different flavours – u, d, c, s or b.
For the case of W+2jets the same two subprocesses contribute also but with an additional gluon in the final state, and some new channel appear:
$f_i \bar{f}_j \to f_k \bar{f}_l W$, $gg \to f_i \bar{f}_j W$, $\bar{f}_i \bar{f}_j \to \bar{f}_k \bar{f}_l W$ and $f_i f_j \to f_k f_l W$.
W boson was putted to decay in the $W \to \nu_e e$ channel.

In this paper we do the comparison at the partonic level. So, under the jet we understand the parton produced in the hard subprocess. For the jet we used a cut on pseudorapidity $|\eta| < 5$ covering all areas of the CMS detector (including the forward HCAL).
Then, we considered the five variants (denoted further as T1, ..., T5) of the cut on the transversal momentum: $P_T >$ 20, 50, 200, 400 and 800 GeV.
The resulting cross sections (MC error $\sim 0.7\%$) with percentage rates in terms of *CompHEP* results are presented in Tables 1 and 2 for W + jet case and in Table 3 for W + 2jets (MC error $\sim 1.2\%$).

Table 1: Partonic $pp \to W + jet$ cross sections [in nb] at different P_T cuts: *CompHEP vs PYTHIA*

Cut	*CompHEP*	*PYTHIA* 5.7
T1	4.926	4.978 (+1.1%)
T2	1.171	1,184 (+1.1%)
T3	$2.270 \cdot 10^{-2}$	$2.268 \cdot 10^{-2}$ (- 0.1%)
T4	$1.526 \cdot 10^{-3}$	$1.542 \cdot 10^{-3}$ (+1.1%)
T5	$6.620 \cdot 10^{-5}$	$6.416 \cdot 10^{-5}$ (- 3.1%)

Small difference between *CompHEP* and *PYTHIA* is caused by slightly different choice of the Q^2 scale – fixed in *CompHEP* ($Q^2 = M_W^2$), and $Q^2 = M_W^2(M_W^2 + (p_T)^2)/(M_W^2 + (p_T^0)^2)$ in *PYTHIA*.

Table 2: Partonic $pp \to W + jet$ cross sections [in nb] at different P_T cuts: *CompHEP vs VECBOS*

Cut	*CompHEP*	*VECBOS*^{c}	*VECBOS*^{d}
T1	4.926	4.812 (-2.3%)	5.019 (+1.9%)
T2	1.171	1.145 (-2.2%)	1.210 (+3.4%)
T3	$2.270 \cdot 10^{-1}$	$2.190 \cdot 10^{-1}$ (-3.6%)	$2.464 \cdot 10^{-1}$ (+8.5%)
T4	$1.526 \cdot 10^{-3}$	$1.498 \cdot 10^{-3}$ (-1.8%)	$1.732 \cdot 10^{-3}$ (+13.5%)
T5	$6.620 \cdot 10^{-5}$	$6.250 \cdot 10^{-5}$ (-5.9%)	$7.393 \cdot 10^{-5}$ (+11.7%)

Observed difference between *VECBOS*^{d} and *CompHEP/PYTHIA* at the level 10% at high transversal momenta is explained by the different uses of the Λ_{QCD} parameter discussed above.
Observed difference at the level $\sim 2\%$ between *CompHEP* and *VECBOS*^{c} is caused by the "scalar" treatment in *VECBOS* of the decay $W \to \nu_e e$, while in *CompHEP* this decay is treated in terms of "true" $2 \to 3$ Feynman diagrams with the Breit-Wigner form of the W propagator.
Some enlarged difference in $P_T > 800$ GeV case is caused by the effect of the finite W width implementation. Indeed, in *VECBOS* and *PYTHIA* the W width is implemented without spin correlations

(however with smearing the W mass in accordance with the Breit - Wigner distribution). This effect is enchanced at stronger P_T cut. We checked it in *CompHEP* using the exact $2 \to 3$ calculations with different values of the W width and comparing with the $(2 \to 2) \times$Br approximation. Note, that the latter approximation is in good correspondence with the "scalar" treatment of the W width in *VECBOS* and *PYTHIA*.

Table 3: Partonic $pp \to W + 2jets$ cross sections [in nb] at different P_T cuts: *COMPHEP vs VECBOS*

Cut	*CompHEP*	*VECBOS*^{c}	*VECBOS*^{d}
T1	1.888	1.477 (-21.8%)	2.224 (+17.8%)
T2	$2.670 \cdot 10^{-1}$	$2.075 \cdot 10^{-1}$ (-22.3%)	$3.204 \cdot 10^{-1}$ (+19.9%)
T3	$2.655 \cdot 10^{-3}$	$2.107 \cdot 10^{-3}$ (-20.6%)	$3.268 \cdot 10^{-1}$ (+23.1%)
T4	$1.134 \cdot 10^{-4}$	$8.983 \cdot 10^{-5}$ (-20.8%)	$1.406 \cdot 10^{-4}$ (+23.9%)
T5	$1.936 \cdot 10^{-6}$	$1.519 \cdot 10^{-6}$ (-21.6%)	$2.182 \cdot 10^{-5}$ (+12.7%)

Here the P_T cut means the P_T cut on jet and the P_T cut on W (${P_T}^{jet}$ cut = ${P_T}^{W}$ cut).

In the case of W+2jets one can see already not so good agreement between *CompHEP* and *VECBOS* results as it was in W+1jet case (the difference is about 20%). One can expect even larger differences in case of more jets.

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