LHCb Studies of W and Z boson production in the forward region

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Presented here are studies of W and Z boson production in the forward region at LHCb.
The trigger, reconstruction and offline selection are described.

1 Motivation

The cross-section for the production of W and Z bosons at the LHC is given by the product of the $q\bar{q}$ hard-scattering cross-section and the parton distribution functions of the colliding protons [?]

$$\sigma_{pp \rightarrow X} = \int dx_1 dx_2 \hat{\sigma}_{q\bar{q} \rightarrow X} \sum_q [f_{q/p_1}(x_1, Q^2) f_{\bar{q}/p_2}(x_2, Q^2) + (q \leftrightarrow \bar{q})]$$

Here $\hat{\sigma}_{q\bar{q} \rightarrow X}$, is the hard-scattering cross-section, Q^2 is the energy scale at which the process takes place. $f_{q(\bar{q})/p_{1(2)}}(x_{1(2)}, Q^2)$ is the probability that the fraction $x_{1(2)}$ of the proton's momentum is found in the proton $p_{1(2)}$. These probabilities are given by the proton's parton distribution function (PDF). For W and Z production, $\hat{\sigma}_{q\bar{q} \rightarrow W/Z}$ is known to 1% at NNLO approximation [?]. The main uncertainty on the cross-section is due to the uncertainty on the PDFs.

The Large Hadron Collider beauty experiment (LHCb) [?] is a forward reaching spectrometer located at the LHC. It is fully instrumented in the pseudorapidity range $1.9 \leq \eta \leq 4.9$ compared with $|\eta| \leq 2.5$ for ATLAS and CMS. LHCb can therefore provide common measurements for $\eta \leq 2.5$ as well as unique measurements for $2.5 \leq \eta \leq 4.9$.

At central rapidities, the colliding partons will generally both be from the sea ($x_1 \approx x_2 \approx 0.005$). However in the forward region, W and Z bosons will predominantly be produced from a valence-sea quark collision where $x_1 \gg x_2$. LHCb will be able to probe high x values ($0.04 < x < 0.76$) which can cross-check measurements from previous experiments, and low x values ($4.2 \times 10^{-5} < x < 8.5 \times 10^{-4}$) which have not been measured directly and whose predictions rely on DGLAP evolution [?]. The uncertainty on the cross-section, $\sigma_{pp \rightarrow X}$, due to the PDFs varies from 2% at lower rapidities, where we can provide a precise test of the Standard Model, to 10% at high rapidities, where we can help to constrain the PDFs [?].

Taking the ratio of the cross-sections, many uncertainties will cancel. The following have been proposed [?].

$$R_{+-} = \frac{\sigma(W^+)}{\sigma(W^-)}, \quad R_{W/Z} = \frac{\sigma(W^+)}{\sigma(Z)}, \quad A_{+-} = \frac{\sigma(W^+) - \sigma(W^-)}{\sigma(W^+) + \sigma(W^-)}$$

R_{+-} will be sensitive to the ratio of the PDFs of the u and d valence quarks. Many PDF uncertainties will cancel in the $R_{W/Z}$ measurement allowing the Standard Model to be tested to better than 1%. A_{+-} is sensitive to the difference between the u and d valence quark distributions.

Samples of Ws and Zs containing muons in the final state will be accumulated at LHCb. LHCb can reconstruct and trigger on muons with a transverse momentum with respect to the beam axis, p_t , > 1 GeV^a. The trigger at LHCb has two levels [?]. Level 0 (L0) is a hardware trigger and the High Level Trigger (HLT) is a software trigger. The L0 streams of interest for W and Z collection are the single muon stream and the dimuon stream. The HLT has exclusive selections for each of the decay channels.

2 W Measurements at LHCb.

The W cross-section can be obtained given a sample of $W \rightarrow \mu\nu_\mu$ events by

$$\sigma_W = \frac{N_{signal} - N_{back}}{\epsilon_{total} \cdot \int \mathcal{L} dt \cdot BR(W \rightarrow \mu\nu_\mu)}$$

Here N_{signal} and N_{back} are the number of signal and background events respectively, ϵ_{total} is the efficiency of the measurement, $\int \mathcal{L} dt$ is the integrated luminosity and $BR(W \rightarrow \mu\nu_\mu)$ is the branching ratio for the W to decay to a muon. The total efficiency can be expressed as the product of the geometric acceptance, the reconstruction efficiency, the trigger efficiency and the offline selection efficiency.

The detector acceptance, is the fraction of events in 4π which have a muon inside LHCb and is calculated to be 0.26. The reconstruction efficiency is defined as the fraction of these events where the muon is fully reconstructed. Using the full detector simulation, this was found to be 0.84 ± 0.01 with most of the inefficiency due to problems with reconstruction at the edges of the acceptance.

L0 will accept the highest p_t muons in the event with a $p_t > 1.1$ GeV. The HLT will accept events where the muon p_t is greater than 20 GeV. This high cut is necessary to reduce the rate of minimum bias events passing the trigger. The L0

Figure 1: Effective cross-section in LHCb as a function of transverse momentum of muons reconstructed in LHCb originating from a W.

Figure 2: Effective cross-section for events reconstructed at LHCb as a function of transverse momentum asymmetry.

^aall units are assuming that $c = 1$.

efficiency (0.94 ± 0.01) is the fraction of events of fully reconstructed events which pass L0 . The HLT efficiency (0.79 ± 0.01) is the fraction these which also pass the HLT. The inefficiency here is due to the hard cut which is placed on the muon's transverse momentum.

To select the $W \rightarrow \mu\nu_\mu$ events offline, two characteristics of the decay are used. The first is the muon's transverse momentum. The spectrum is peaked at a transverse momentum of half the W mass, as shown in Figure ??.

The second characteristic is the transverse momentum asymmetry (A_{p_t}), which is defined as

$$A_{p_t} = \frac{p_{t_\mu} - p_{t_{rest}}}{p_{t_\mu} + p_{t_{rest}}}$$

where p_{t_μ} is the transverse momentum of the signal muon and $p_{t_{rest}}$ is the summed transverse momentum of all other charged tracks in the event. Figure ?? shows this for $W \rightarrow \mu\nu_\mu$ events. This is peaked towards +1, implying that most of the transverse momentum is carried by the muon in the event. Since the cross-section for W production is high at the LHC, the main factor in deciding the cuts for the offline selection is the purity of the signal rather than the selection efficiency.

The backgrounds for this decay will be events where there are muons identified which do not originate from W. A Z boson decaying to two muons where one falls inside the detector acceptance can mimic a W decay. The main QCD background will be from $b\bar{b} \rightarrow \mu X$ decays. Another background will be minimum bias events where a kaon or a pion is misidentified as a muon.

Figure ?? shows the A_{p_t} distributions for the signal and backgrounds. For the $b\bar{b} \rightarrow \mu X$ and the hadron misidentification backgrounds, the muon will generally not be isolated as is the case for $W \rightarrow \mu\nu_\mu$ events. This makes A_{p_t} a good discriminating factor for signal isolation.

To reduce the background it was required that $A_{p_t} > 0.85$. Figure ?? shows the effect of this cut on the p_t distribution of the signal and background. To further reduce the background a cut of $p_{t_\mu} > 30$ GeV was made. This gives an additional offline selection efficiency of 0.35 ± 0.01 and a purity of 0.90 ± 0.01 , where the dominant background is from the irreducible Z contribution.

Figure 3: Signal and Background transverse momentum asymmetry distributions. Each background is scaled by a factor as given in the legend. The position of the A_{p_t} cut for the offline selection is highlighted.

Figure 4: p_t distribution of signal and backgrounds after requiring $A_{p_t} > 0.85$. Highlighted is the position of the p_t cut for offline selection

3 Z Measurements at LHCb

The decay channel studied for the Z cross-section measurement is $Z \rightarrow \mu\mu$. The detector acceptance for having two muons in LHCb is 0.14 ± 0.01 . The muon reconstruction efficiency is 0.86 ± 0.01 , the inefficiencies being due to difficulties in reconstructing muons close to the edges of the fiducial volume.

The L0 trigger for dimuons requires that the sum of the p_t of the two muons is greater than 1.5 GeV. To pass HLT it is required that each muon has a $p_t > 10$ GeV and dimuon mass > 50 GeV.

$Z \rightarrow \mu\mu$ events will typically have two high transverse momentum muons of opposite charge and coming from the primary vertex. The invariant mass of the two muons will be close to the Z mass (~ 91 GeV). Recent studies of the trigger efficiency yield a 98% (93%) efficiency for L0 (HLT).

The background processes for this decay have been described in detail in [?] and consist of electroweak backgrounds ($Z \rightarrow \tau\tau \rightarrow \mu\mu$, $Z \rightarrow b\bar{b} \rightarrow \mu\mu$ etc.), QCD backgrounds ($b\bar{b} \rightarrow \mu\mu$, $c\bar{c} \rightarrow \mu\mu$ etc.) and backgrounds due to pions or kaons being misidentified as muons. To isolate the signal from the background, the following kinematic cuts were used. The dimuon invariant mass must be in the range $71 \text{ GeV} < M_{\mu\mu} < 111 \text{ GeV}$. The higher p_t muon must have a $p_t > 20$ GeV. The lower p_t muon must have a $p_t > 15$ GeV. Both muons must have a significance of the impact parameter with respect to the primary vertex of less than 5. Both muons must have less than 50 GeV of hadronic energy in the hadron calorimeter associated to their track.

Figure ?? shows the invariant mass distribution of the signal and background events

before and after these cuts. These cuts will give a offline selection efficiency of 0.91 ± 0.01 and a purity of 0.97 ± 0.03 .

Figure 5: Dimuon invariant mass distributions for signal and background after trigger and reconstruction (left) and with the additional offline cuts(right).

4 Conclusion

With 100 pb^{-1} of data it is expected that about 76,000 W^+ , 39,000 W^- and 21,000 Z will be selected by the LHCb experiment. This will allow cross-section measurements with a statistical uncertainty of better than 1%. The total uncertainty in this measurement will be dominated by systematic uncertainties largely due to the uncertainty on the luminosity. $R_{W/Z}$ will be measured to better than 1% allowing a sensitive test of the Standard Model. R_{+-} and A_{+-} will also be measured to this level allowing a better determination of the PDFs for valence u and d quarks.

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