Prospects for indirect luminosity measurements at LHCb

Jonathan Anderson, Physik-Institut der Universität Zürich, Switzerland.
For the LHCb collaboration

Abstract

We summarise the prospects for indirect luminosity measurements at LHCb. Two candidate processes have been identified for such measurements: electroweak boson production and elastic dimuon production via two photon fusion. The cross-section for W and Z production at LHCb has been calculated at NNLO with an uncertainty of $\sim 4\%$, where the dominant theoretical error is due to the uncertainty on the parton distribution functions (PDFs). Using the first 16.5 pb^{-1} of data, a very clean sample of 833 Z bosons and a larger, but less clean, sample of W bosons have been recorded at LHCb. Using the currently available sample of W^+ (Z) events an integrated luminosity measurement with an uncertainty of $\sim$5% ($\sim$6%) could be made. Once 150 pb^{-1} of data has been collected a measurement using a high purity Z sample could be performed that would have an uncertainty of 4%. Cross-section predictions for elastic dimuon production via two photon fusion have been performed with an uncertainty of $< 1\%$. With the first 17.5 pb^{-1} of data, 250 candidate events of this type have been observed. While work is still ongoing to understand the purity and efficiency of this sample, the prospects for using this process to make a precision luminosity measurement at LHCb are promising.

INTRODUCTION

LHCb [1], one of the four large experiments at the Large Hadron Collider (LHC), has been designed for CP violation and rare decay studies in the heavy quark sector. Due to the $b\bar{b}$ production topology at the LHC, whereby both B hadrons are mostly produced in the same forward or backward cone, LHCb has been constructed as a forward single-arm spectrometer with an approximate coverage in terms of pseudorapidity of $1.9 < \eta < 4.9$. Since March 2010 the experiment has been successfully taking proton-proton collision data at a centre of mass energy of 7 TeV.

Knowledge of the integrated luminosity is necessary to make cross-section measurements and monitor running performance at colliding beam experiments. At LHCb the integrated luminosity will be determined both directly, by measuring the beam profiles and currents, and indirectly by measuring the production rates of processes that have cross-sections that are theoretically well known.

Two methods have been employed to measure the beam profiles at LHCb: the commonly used Van der Meer scan method [2], where the colliding beams are moved transversely across each other, and a recently proposed method [3] that utilises reconstructed beam-gas interaction vertices near the beams' crossing point to determine the beam shapes. Combining these techniques with measurements of the beam currents has allowed two luminosity measurements to be made. Both measurements give compatible results and have associated uncertainties of $\sim 10\%$. A more complete description of these measurements can be found elsewhere in these proceedings [4, 5].

The integrated luminosity can also be measured indirectly by recording the event rate of a process with a cross-section that can be accurately calculated from theory. The accuracy of a luminosity measurement using this method is usually limited by the theoretical uncertainty on the calculated cross-section. Two candidate processes have been identified for such measurements at LHCb: W and Z production which has been calculated at NNLO with an uncertainty of $\sim 4\%$, where the dominant theoretical error is due to the uncertainty on the PDFs, and elastic dimuon production via photon fusion which has a cross-section that has been calculated with a theoretical uncertainty of $< 1\%$ [6] but has a lower event rate.

This contribution summarises the progress that has been made towards indirect luminosity measurements at LHCb using electroweak boson production and elastic dimuon production via photon fusion.

PREDICTIONS FOR W AND Z PRODUCTION

Figure 1 shows the kinematic region probed by events at LHCb as a function of the longitudinal momentum fraction x carried by the interacting parton and Q^2, the square of the four momentum exchanged in the scattering process. For particle production processes at LHCb, the momenta of the two interacting partons will be highly asymmetric, meaning that events at LHCb will simultaneously probe a region at high-x and a currently unexplored region at very low-x. The main theoretical uncertainties on cross-section predictions for electroweak boson production at the LHC stem from the level of knowledge of the input proton PDFs. At high x they have been determined from fixed target and HERA data and confirmed at higher Q^2 by W and Z production at the Tevatron. For the smaller x values, the PDFs have been measured by HERA alone but at much lower Q^2 from where they must be evolved to higher energies using the DGLAP equations.

Figure 2(a) shows the percentage uncertainty on cross-section predictions for W and Z production at the LHC due to the uncertainty on the PDFs for the MSTW2007 PDF set. For boson rapidities between 2 and 4.5 the PDF uncertainty for Z and W^+ production is in the range 2 to 4%. The PDF uncertainty on W^- production, being dominated by

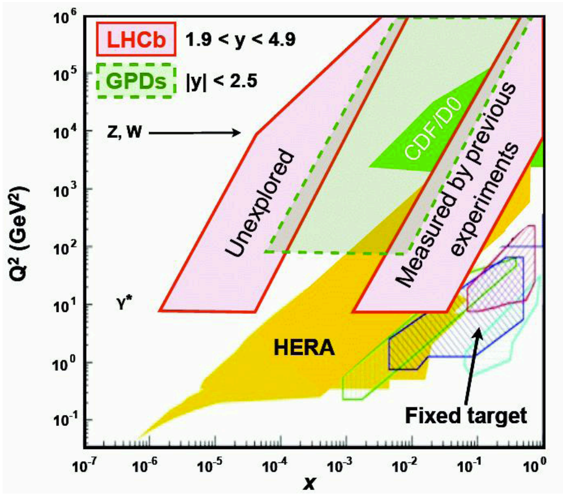

Figure 1: The kinematic region x-Q^2 probed by the LHCb experiment with electroweak boson production together with the region probed by a variety of previous experiments.

the valence down quark distribution at large rapidities, is larger and ranges between 3 and 10%. The compatibility of the results obtained using different PDF sets is illustrated in figure 2(b) which shows the fractional uncertainty on the $q\bar{q}$ luminosity as a function of $\sqrt{\hat{s}/s}$ for the MSTW2008, CTEQ6.6 and NNPDF2.0 PDF sets. It can be seen that in the region corresponding to W and Z production ($\sqrt{\hat{s}/s} \sim 10^{-2}$) all three sets give comparable results and suggest a PDF uncertainty of $\sim 4\%$.

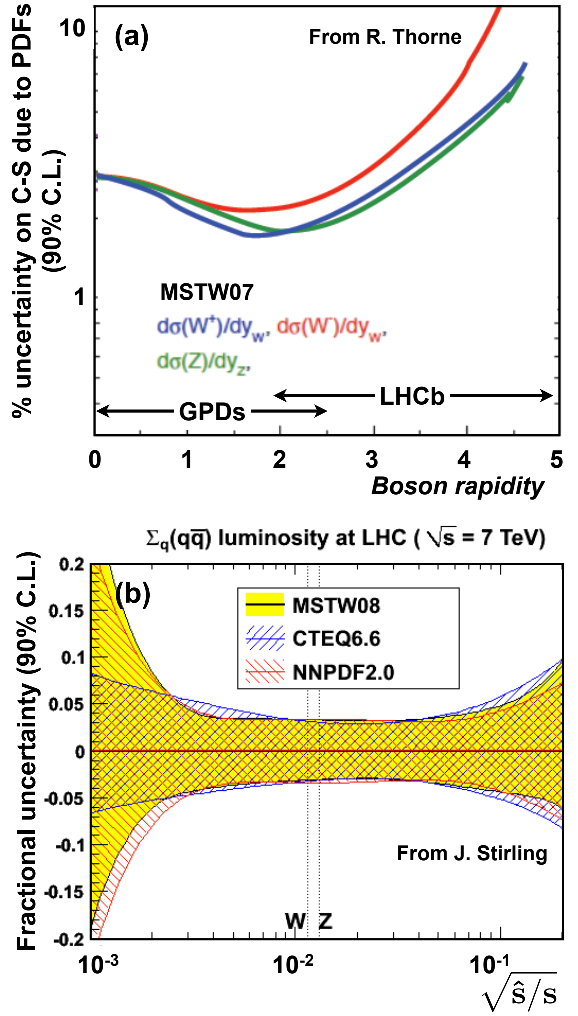

Figure 2: (a) Percentage uncertainty on cross-section predictions for W, Z and low mass Drell-Yan pairs at the LHC due to the PDFs as a function of rapidity. The regions fully instrumented by LHCb and the GPDs are shown (from [7]). (b) The fractional uncertainty on the $q\bar{q}$ luminosity as a function of $\sqrt{\hat{s}/s}$ for the MSTW2008, CTEQ6.6 and NNPDF2.0 PDF sets (From J. Stirling).

W AND Z MEASUREMENTS

Events containing Z or W bosons are initially selected at LHCb via a single muon trigger that requires the presence of at least one muon that has a transverse momentum (p_T) greater than 10 GeV/c.

Z candidate events are then selected offline by requiring two muons with $p_T > 20$ GeV/c and $2.0 < \eta < 4.5$, which combine to a mass between 81 and 101 GeV/c^2. To ensure a good track quality, cuts on the fractional momentum uncertainty and the χ^2 probability of the track are applied. No impact parameter or isolation cut is imposed. In total 833 Z candidates are selected using 16.5 pb^{-1} of data, their mass distribution is shown in figure 3. The background contribution in the selected mass region is very low and is estimated to be 1.2 ± 1.2 events, where the dominant contribution comes from events containing two semi-leptonic heavy quark decays. This background was estimated from data by selecting events with two muons with an impact parameter significance (IPS) greater than 5.

W candidate events are selected offline by requiring one muon with $p_T > 20$ GeV/c, $2.0 < \eta < 4.5$ and IPS < 2. In order to reduce a variety of QCD backgrounds, coming either from semi-leptonic heavy quark decays or hadron misidentification, further cuts are applied to three variables that are related to the other activity in the event: the invariant mass of the rest of the event ($M^{rest} < 20$ GeV/c^2), the transverse momentum of the vector sum of all other tracks in the event ($p_T^{rest} < 10$ GeV/c) and the transverse momentum of the vector sum of all other particles inside a cone $\Delta R = 0.5$ around the muon ($p_T^{cone} < 2$ GeV/c). In total 7624 (5732) W^+ (W^-) candidates are selected using 16.5 pb^{-1} of data. The selection efficiency has been determined from data using Z events with one of the muons removed from the event. Since the cuts on the impact parameter and the activity in the rest of the event are independent of the muon they have the same characteristic shape for W and Z bosons, a fact that has been confirmed using Monte-Carlo simulations. A selection efficiency of $55 \pm 1\%$ was measured. Since only one high p_T muon is required, the back-

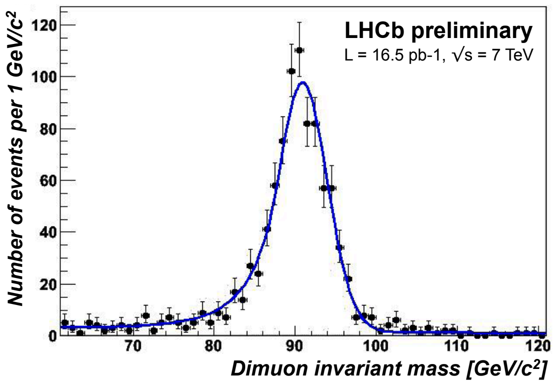

Figure 3: Invariant mass of the dimuon system.

ground contamination for the selected sample is considerably higher than for the offline selected Z sample. The contamination due to both electroweak processes (tauonic W and Z decays and muonic Z decays where only one of the muons is produced inside the LHCb acceptance) and QCD processes (semi-leptonic heavy quark decays and hadron mis-identification) have been determined by a fit to the muon transverse momentum distribution as shown in figure 4. The shapes for the p_T distributions for muons from electroweak processes are taken from simulation while the shape for the QCD background is taken from data by selecting a sample with a very small signal contribution.

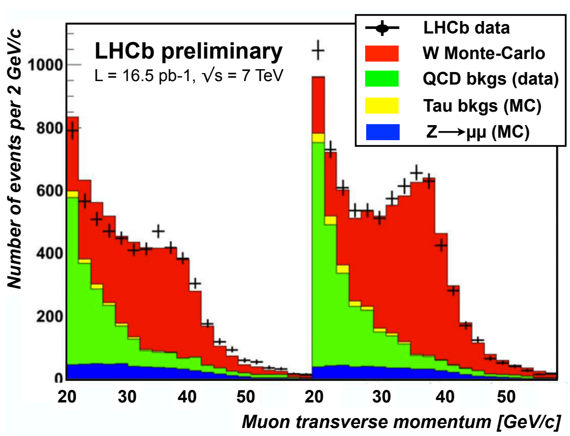

Figure 4: Distribution of the muon pT for negative(left) and positive (right) charged leptons. The data points are shown in black, the W contribution in red, the Z background in blue, the tau background in yellow and the QCD background in green.

The efficiencies for triggering, muon identification and track finding have all been estimated from data. The trigger efficiency has been determined using an offline selected Z sample. By requiring that one of the muons in the event caused the single muon line to fire the other muon can be used to determine the trigger efficiency. The single muon trigger efficiency is measured to be 80 $\pm$ 1%, exhibits no evidence for a charge bias and is found to be flat in muon ϕ, η and p_T. For Z events, where either muon can cause the trigger to fire, the efficiency is determined to be 96 $\pm$ 1%. The track finding and muon identification efficiencies are measured using a tag and probe method and an offline selected Z sample where the tag muon is required to have fired the single muon trigger line. The track finding and muon identification efficiencies for muons from W and Z events are found to be 92 $\pm$ 2% and 98 $\pm$ 1% respectively.

For muons with $2 < \eta_\mu < 4.5$, $p_T > 20$ GeV/c and Z boson masses between 81 and 101 GeV/c^2, the following preliminary results are obtained for the W and Z production cross-sections:

$$\sigma_Z = 74 \pm 2 \pm 3 \pm 7 \text{ pb}$$

$$\sigma_{W+} = 1007 \pm 48 \pm 33 \pm 101 \text{ pb}$$

$$\sigma_{W-} = 680 \pm 40 \pm 22 \pm 68 \text{ pb}$$

where the first error is statistical, the second systematic and the third comes from the luminosity determination. For the W measurements the statistical uncertainty also includes the uncertainty from the efficiency and purity estimation, however, the uncertainty due to the fit procedure is not included in the systematic uncertainty. The integrated luminosity was determined using the Van der Meer scan method and has a 10% uncertainty. These measured values are consistent with the NLO predictions from MCFM [8].

Currently, using the high purity sample of 833 Z events, the efficiencies that have been determined from data and the NNLO Z cross-section prediction, an indirect luminosity measurement could be made that would have an uncertainty of $\sim$6%. The precision is currently limited by the available statistics in two ways: firstly by the relatively large statistical uncertainty (3.5 %) and secondly, since the trigger, tracking and muon identification efficiencies are determined from data using an offline selected Z sample, a large systematic uncertainty on the determined reconstruction efficiency (3.5%). Once $\sim$150 pb^{-1} of data are collected the statistical and systematic uncertainties will be reduced to the 1% level and the uncertainty on a luminosity determination using the Z sample will be dominated by the PDF uncertainty of 4%. Using the currently available W^+ sample the luminosity could be determined with an uncertainty of $\sim$5%, though here the sample purity is lower and the systematics associated with the fit procedure that determines the purity has yet to be evaluated.

CROSS-SECTION PREDICTIONS FOR ELASTIC DIMUON PRODUCTION VIA PHOTON FUSION

Being primarily a QED process, the cross-section for elastic dimuon production via two photon fusion at the LHC has been calculated very precisely. The main features of the process can be illustrated within the Effective Photon Approximation. Here the cross-section can be calculated as a convolution of the direct cross-section of the two colliding photons that produce a muon pair and the fluxes of virtual photons surrounding the two colliding protons. For elastic events the virtual photon fluxes will be equal to

$$dn_{el} = \frac{\alpha}{\pi}\frac{d\omega}{\omega}\frac{\vec{q}_T d\vec{q}_T^2}{(\omega^2/\gamma^2 + \vec{q}_T^2)^2}\frac{G_E^2 - q^2/(2m_p G_M)^2}{1-(q/2m_p)^2} \quad (1)$$

where $q(\omega,\, \vec{q})$ is the four-momentum of the photon and m_p, G_E and G_M are the mass and electric and magnetic form factors of the proton respectively. The characteristic value of the the total transverse momentum of the dimuon pair produced in such elastic events is small ($\sim$ 10 MeV/c) and the cross-section can be calculated very accurately with an uncertainty of much less than 1%. However, there are two possible QCD contributions that can increase this uncertainty: strong interactions within the colliding protons that can cause one or both of the protons to dissociate during the photon emission, resulting in inelastic dimuon production via photon fusion, and rescattering contributions that are due to strong interactions between the colliding protons.

Due to uncertainties in the momentum distributions of the quarks within the proton and the collective excitations of these quarks, the matrix element describing inelastic vertices is not as well known as the matrix element for elastic vertices. This results in much higher uncertainties in the predicted cross-section for inelastic dimuon production via photon fusion ($\sim$ 20%). Fortunately, the characteristic dimuon pair p_T for inelastic production is higher ($\sim$ 250 MeV/c) enabling this contribution to be reduced by offline selection.

The rescattering corrections, which can be viewed as pomeron exchange between the colliding protons, can be either elastic or inelastic. It has been shown by Khoze et. al. [6] that the elastic rescattering contribution has the effect of modifying the phase of the matrix element but does not change the predicted cross-section, while the inelastic rescattering contribution effectively reduces the elastic cross-section and increases the inelastic cross-section. However, the calculations of Khoze et. al. have also shown that for events with small dimuon pair p_T ($\lesssim$ 100 MeV/c) these inelastic rescattering contributions are small ($\sim$ 0.2%).

MEASUREMENTS OF ELASTIC DIMUON PRODUCTION VIA PHOTON FUSION

The elastic production of dimuons via photon fusion is an exclusive process that leaves the interacting protons intact and deflected by a negligible amount. In the context of a hadron collider, therefore, these events are highly distinctive containing two muons and having no other activity.

At LHCb they are initially selected by a dedicated exclusive dimuon trigger line that requires the presence of two muons with a dimuon invariant mass greater than 1 GeV/c^2, a dimuon transverse momentum smaller than 900 MeV/c and a distance of closest approach between the muons smaller than 150 μm.

Candidate events are further isolated offline by exploiting the exclusivity of the events by requiring: no other tracks reconstructed in the vertex detector and less than five hits in the Scintillator Pad Detector (SPD) which is located before the calorimeters and covers the full acceptance of the experiment. In addition, since the trigger also accepts exclusive J/ψ and Υ events, produced via photon-pomeron fusion, and exclusive χ_c events, produced via pomeron-pomeron fusion, events that have an invariant mass near the J/ψ or Υ masses are rejected. In total 250 candidate events have been recorded in the first 17.5 pb^{-1} of data collected at LHCb. The dimuon invariant mass distribution of these events is shown in figure 5. The shape of the measured invariant mass distribution is in good agreement with the shape predicted by the LPAIR [9] Monte-Carlo generator. The expected background contamination in the selected sample is expected to be dominated by inelastic dimuon production via photon fusion and dimuons produced via pomeron fusion. These backgrounds have been investigated using Monte-Carlo samples produced using the LPAIR and Pomwig [10] generators respectively. While still under investigation, the overall purity of the sample is currently estimated to be above 95%. Data driven techniques to determine the trigger, tracking and muon identification efficiencies are currently being developed. In the future it is hoped that these efficiencies can be determined with uncertainties of O(1%), enabling a luminosity measurement with an uncertainty of $\sim$ 1% with 700 pb^{-1} of data.

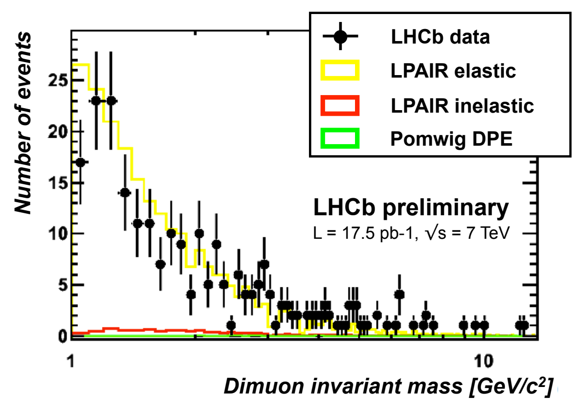

Figure 5: Invariant mass distribution for offline selected exclusive dimuon events at LHCb. The J/ψ and Υ mass regions have been excluded. The predicted distributions for signal and background are also shown.

CONCLUSIONS

Two candidate processes have been identified for indirect luminosity measurements at LHCb: electroweak boson production and elastic dimuon production via two photon fusion.

The cross-section for W and Z production at LHCb has been calculated at NNLO with an uncertainty of $\sim$ 4%, where the dominant theoretical error is due to the uncertainty on the parton distribution functions (PDFs). Using the first 16.5 pb^{-1} of data, a very clean sample of 833 Z bosons and a larger, but less clean, sample of W bosons have been recorded at LHCb. Using the currently available W^+ sample an integrated luminosity measurement could be made that would have an uncertainty of $\sim$5%. However, the systematic uncertainty associated with the fit procedure that is used to determine the sample purity has yet to be evaluated. Using the currently available Z sample would enable a luminosity determination with a $\sim$6% uncertainty. Here the measurement is currently limited by the available statistics. Ultimately, with 150 pb^{-1} of data, a measurement using a high purity Z sample would be limited by the current PDF uncertainties of 4%.

Cross-section predictions for elastic dimuon production via two photon fusion have been performed with an uncertainty of $< 1\%$. With the first 17.5 pb^{-1} of data, 250 candidate events of this type have been observed. The shape of the dimuon invariant mass distribution of these events is compatible with the shape predicted by the LPAIR generator. Work is still ongoing to understand the purity and efficiency of this sample. It is hoped that with 700 pb^{-1} of data, a luminosity measurement with an uncertainty of $\sim$ 1% will be possible using this process.

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