QCD and Electroweak Measurements in the Forward Region at LHCb

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Results on the measurement of the W and Z cross-sections are presented using final state leptons having pseudo-rapidities between 2 and 4.5. The W measurement is performed in the channel $W \rightarrow \mu\nu$ while for the Z, all charged lepton final states have been used. Below the Z peak, di-muons allow the Drell-Yan cross-section to be measured down to a mass of 5 GeV. Di-muon events are also used to identify and measure the cross-sections for the exclusive production of $J/\psi, \psi'$ and $\chi_c$ mesons.

1 Forward Physics at the LHC

The LHCb experiment on the LHC collider is fully instrumented with tracking detectors, calorimetry and particle identification in the forward region between pseudorapidities, $\eta$, of 2 and 4.5. Although primarily designed for the study of $b$-quarks, the forward reach allows several interesting electroweak and QCD measurements to be made in a region which is complementary to ATLAS, CMS and ALICE. We report here on cross-section results for the production of vector bosons which decay to leptons and the central exclusive production of vector mesons. These measurements are facilitated by a unique feature of LHCb; the ability to trigger on low transverse momentum ($p_T$) muons and electrons down to 0.5 GeV/c.

The cross-section, $\sigma$ for two protons to produce a particle, $X$, expressed as a function of the invariant mass of the partonic interaction, $Q$ is

$$\sigma_X(Q^2) = \sum_{a,b} \int_0^1 dx_1 dx_2 f_a(x_1, Q^2) f_b(x_2, Q^2) \hat{\sigma}_{ab \rightarrow X}(x_1, x_2, Q^2)$$  \hspace{1cm} (1)$$

where $\hat{\sigma}$ is the partonic cross-section and the parton density function, $f_q(x, Q^2)$, describes the probability that the proton contains a parton $q$ with momentum fraction $x = Q \exp(\pm y)/\sqrt{s}$, where $y$ is rapidity and $\sqrt{s}$ is the centre-of-mass of the collision.
2 Drell-Yan production

Measurements of the W and Z cross-sections constitute important tests of the Standard Model. In addition, since $\hat{\sigma}$ is known to a precision of about 1% at NNLO, they constrain the parton density functions; for W and Z boson inside LHCb, the partons involved have $x \approx 10^{-1}$ and $x \approx 10^{-4}$.

Z bosons are selected by requiring two muons or two electrons with $p_T$ above 20 GeV/c, pseudorapidities between 2 and 4.5, and invariant mass between 60 and 120 GeV/$c^2$. Backgrounds are negligible in the di-muon channel and about 2% in the di-electron channel. The invariant mass distributions of the di-lepton pairs are shown in the upper plots in Figure 1. The broader peak in the di-electron channel is due to the electromagnetic calorimeter which is designed to saturate at high energies. Z bosons decaying to tau leptons have also been identified in the $\tau\tau \rightarrow \mu\mu\nu\mu$ and $\tau\tau \rightarrow \mu\nu\mu\nu$ final states; the invariant mass distributions for the charged leptons is shown in the lower plots in Figure 1.

Drell-Yan production of $\gamma^*/Z \rightarrow \mu\mu$ below the Z peak suffer from increasing backgrounds from semi-leptonic heavy flavor decays and muon mis-identification as the invariant mass of the di-muon system decreases. A template fit to the energy in a cone around the muons allows the signal purity to be determined. The measurement is performed down to di-muon invariant masses of 5 GeV/$c^2$, where the signal purity is estimated to be 7%. Such mass scales are of particular interest because they probe $x$ values down to $8 \times 10^{-6}$, where the gluon PDF has not previously been measured. Unfortunately an extraction of the PDF from the measurement will be difficult because the partonic cross-section has large theoretical uncertainties at such low $Q^2$ values.

W bosons are selected in the channel $W \rightarrow \mu\nu$ by requiring a single muon with $p_T$ above 20 GeV/c that is isolated and consistent with the collinear interaction point, having an impact parameter below 40 $\mu$m. A sample purity of about 80% is determined from a template fit to the $p_T$ spectra in bins of $\eta$ with the major backgrounds coming from pions which have been

\[ \text{We require that both the charged and neutral summed transverse energies in an eta-phi cone around the muon are less than 2 GeV.} \]
mis-identified as muons, and $Z \rightarrow \mu\mu$ events where one muon goes outside the LHCb acceptance.

The efficiencies for triggering, reconstructing and identifying the leptons is found from a ‘tag and probe’ technique using di-leptons from $J/\psi, \Upsilon$ and $Z$ events. The selection efficiencies are found using data wherever possible, e.g. the isolation requirement for the W analysis is evaluated using muons in $Z \rightarrow \mu\mu$ events. When efficiencies are determined from the simulation, this is calibrated using data control samples.

The cross-sections are derived from the number of selected events by multiplying by the sample purity, dividing by the efficiency and luminosity, and correcting for final state radiation. The upper left plot in Figure 2 summarizes the $Z$ results in each of the final states and compares them to theory predictions evaluated with various parton distribution functions. The right plot shows the W charge asymmetry in bins of lepton pseudorapidity compared to different PDF sets. The lower plot shows the Drell-Yan cross-section differentially as a function of di-muon invariant mass defined in the kinematic region where both muons have $p_T > 3$ GeV/c with $2 < \eta < 4.5$.

3 Central exclusive production with di-muon final states

Di-muon final states can also be produced by other mechanisms. One of the most dramatic signatures at a hadron collider is an event containing two muons and no other tracks. This can occur through the QED di-photon process or vector meson production by photo-production (to create $J/\psi$ or $\psi'$ mesons) or double pomeron exchange (producing $\chi_c$ mesons decaying to $J/\psi\gamma$).

In the fully instrumented range of the LHCb detector, the absence of additional tracks ensures a rapidity gap of at least 2 units. However, the VELO microstrip detector extends from about 25cm upstream of the interaction point to about 75cm downstream giving coverage in the backwards region, approximately $-4 < \eta < -1.5$. This provides an additional rapidity gap of over 2 units.

Exclusive $J/\psi, \psi'$ candidates are selected requiring no other activity in LHCb apart from...
two muons with invariant masses consistent with the mesons, while \( \chi_C \) candidates require one additional photon. Figure 3 shows the invariant mass spectra obtained. The principal backgrounds come from non-exclusive production of the mesons where one or both protons break up, but the remnants go outside the active area of LHCb. The only method to estimate this background is through the \( p_T \) of the reconstructed meson; non-exclusive events on average will have a higher \( p_T \) due to momentum conservation. A template fit is made with the signal shape coming from the SuperChic simulation\(^6\) and the background shape taken from data using known non-exclusive events (those with extra observed tracks). The purity of the \( J/\psi \) and \( \psi' \) samples is estimated to be 70% while for the \( \chi_C \), it is 40%.

The cross-sections for \( J/\psi \) and \( \psi' \) with both muons in the region \( 2 < \eta < 4.5 \) are measured to be 474 ± 103 pb and 12.2 ± 3.2 pb respectively in broad agreement with several theoretical predictions\(^7\). These results are also consistent with \( J/\psi \) photoproduction results from HERA\(^8\).

The cross-sections for \( \chi_0, \chi_1, \chi_2 \) are measured to be 9.3±4.5, 16.4±7.1, 28.0±12.3 pb respectively. The rates for \( \chi_0, \chi_1 \) agree with the theoretical predications but we measure a slightly higher \( \chi_2 \) contribution, albeit with a large uncertainty.

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**References**

2. LHCb Collaboration, CERN-LHCb-CONF-2012-011
3. LHCb Collaboration, CERN-LHCb-CONF-2011-041
4. LHCb Collaboration, CERN-LHCb-CONF-2012-013
5. LHCb Collaboration, CERN-LHCb-CONF-2011-022