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Probing low-x with Drell-Yan events at LHCb

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The prospects for reconstructing and selecting $q\bar{q} \to \gamma^*/Z \to \mu\mu$ events at LHCb are discussed. Due to the high rapidity coverage and low momentum trigger thresholds of the LHCb detector, these events will probe a unique kinematic region and have the potential to constrain the proton parton distribution functions (PDFs) down to Bjorken-x values of $10^{-6}$.

1 Introduction and motivation

LHCb [2], one of the four large experiments at the Large Hadron Collider (LHC), has been primarily designed and built to make measurements of CP-violating and rare decays in the b-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 rapidity of $1.9 < y < 4.9$. While a portion of this rapidity range ($1.9 < y < 2.5$) is also covered by the general purpose detectors ATLAS and CMS, the very forward region ($y > 2.5$) is unique to LHCb. Due to its forward geometry, LHCb will be capable of triggering on low transverse momentum ($P_T$) objects, where $P_T$ is defined with respect to the beam direction. Specifically, it will be able to trigger on dimuons with invariant masses greater than 2.5 GeV/c$^2$ and scalar summed transverse momenta larger than 1.5 GeV/c.

In addition to its main B physics programme, LHCb will be capable of making precision electroweak measurements at high rapidities. In particular, a measurement of the differential cross-section for the Drell-Yan process $q\bar{q} \to \gamma^*/Z \to \mu\mu$, which provides a distinctive and fully reconstructible final state, as a function of dimuon invariant mass and rapidity will enable the exploration of a large, previously unmeasured, kinematic region.

The main theoretical uncertainties on cross-section predictions for the Drell-Yan process at the LHC stem from the level of knowledge of the input proton PDFs. Figure 1(a) shows the kinematic region probed by events at LHCb in terms of the longitudinal fraction of the incoming proton’s momentum, $x$, carried by the interacting parton and the square of the four-momentum exchanged in the hard scatter, $Q^2$. For Drell-Yan production at LHCb, the momenta of the two interacting partons will be highly asymmetric. PDFs have been determined from fixed target data and to a lesser extent HERA data for the larger $x$ values and confirmed at higher $Q^2$ by W/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 [3] equations.

As shown in Figure 1(b), the percentage uncertainty on the Drell-Yan cross-section prediction at the LHC due to the uncertainty on the PDFs gets larger for smaller dimuon invariant masses and at higher rapidities [4]. By measuring the total and differential cross-section for this process for a variety of different invariant masses, sections of $x-Q^2$ space can be mapped out yielding large improvements to the PDFs. LHCb has a particular advantage

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over ATLAS and CMS in accessing the least understood regions due to its higher rapidity range and lower muon momentum trigger thresholds which will allow exploration down to \( Q^2 \approx 6.25 \text{ GeV}^2/c^4 \). LHCb will therefore have the unique ability to measure PDFs down to \( x \approx 10^{-6} \), below the smallest values accessible at HERA.

The following sections describe the results of simulation studies that suggest that LHCb will be able to trigger, reconstruct and select pure, high statistics samples of \( \gamma^* / Z \rightarrow \mu \mu \) events with dimuon masses down to 2.5 GeV/c^2 with relatively small amounts of data.

## 2 Measurements at the Z mass

Due to a distinctive final state that contains two high \( P_T \) muons, \( Z \rightarrow \mu \mu \) decays will be triggered, reconstructed and selected with high efficiency and purity at LHCb. As shown in Figure 2, using the full LHCb Monte-Carlo simulation we expect that the reconstruction efficiency for two muons inside the nominal LHCb acceptance from Z decays will be \( 86 \pm 1\% \) while the trigger efficiency for offline reconstructed \( Z \rightarrow \mu \mu \) decays will be \( 97 \pm 1\% \). A variety of background sources for these events have been studied: other electroweak processes such as \( Z \rightarrow \tau \tau \) where both taus decay to muons and neutrinos; heavy flavour production such as \( b \bar{b} \rightarrow \mu \mu + X \); and events where two hadrons are both mis-identified as muons. To deal with these backgrounds an offline selection has been developed [5] that has the following requirements: both muon candidates must traverse the entire muon system and have less than 50 GeV of associated hadronic energy; the dimuon invariant mass must be within 20 GeV/c^2 of the Z mass; the higher and lower transverse momentum muons must be greater than 20 GeV/c and 15 GeV/c respectively; the measured impact parameters of both muons with respect to the primary vertex must be consistent with both muons originating from the primary vertex. For \( Z \rightarrow \mu \mu \) events that are triggered and reconstructed at LHCb, these offline selection criteria will select \( 91 \pm 1\% \) of the signal events while reducing the background to \( 3 \pm 3\% \) of the signal level, where the dominant background contribution is

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**Figure 1:** (a) The kinematic range in \( x - Q^2 \) space probed at LHCb and the general purpose LHC detectors (GPDs). The regions covered by measurements at previous experiments are shown. (b) Percentage uncertainty on Drell-Yan cross-section predictions at the LHC due to the PDFs as a function of rapidity at the Z mass, 91 GeV/c^2, and two lower dimuon invariant masses, 8 GeV/c^2 and 24 GeV/c^2. The regions fully instrumented by LHCb and the GPDs are shown. From [4].
from mis-identified hadrons, a background source that can be well understood from real data or removed using tighter muon identification criteria.

Overall it is expected that $Z \rightarrow \mu \mu$ events will be triggered, reconstructed and selected at LHCb at a rate of $\sim 190$ evts/pb$^{-1}$ and that with just 50 pb$^{-1}$ of data a cross-section measurement inside the LHCb acceptance will be already limited by systematic uncertainties. Systematic uncertainties from a determination of the experimental efficiencies (trigger, reconstruction, muon-id etc.) using real data, and from theory (acceptance uncertainties due to higher order corrections, PDF uncertainties etc.), have been investigated and it is expected that with 50 pb$^{-1}$ of data they will constitute a $\sim 1\%$ uncertainty. For the luminosity determination, two methods have been studied: the reconstruction of the density distribution of the proton beams using beam-gas interactions inside the LHCb vertex detector [6], and a measurement of the event rate of the accurately predicted QED process $pp \rightarrow \mu + pp + \mu$ [5]. It is expected that the former method will be capable of determining the luminosity with a precision of $\sim 3\%$ with as little as 1 pb$^{-1}$ of data while the latter technique will ultimately reach a precision of $\sim 1\%$ with 1 fb$^{-1}$ of data. However, since the luminosity only affects the overall normalisation but not the shape of the differential distribution $d\sigma/dy$, even if a precise luminosity determination is lacking, constraints can still be placed on the PDFs. Since the percentage uncertainty on Z cross-section predictions inside the LHCb acceptance due to the PDFs is in the range 2-6% (see Figure 1(b)), a measurement of the Z cross-section using early data from LHCb will place constraints on the PDFs down to $x$ values of $4.8 \times 10^{-5}$ and up to $x$ values of 0.87.

3 Low invariant mass Drell-Yan production

As shown in Figure 2, LHCb will be capable of triggering and reconstructing Drell-Yan events with dimuon invariant masses as low as 2.5 GeV/c$^2$. The trigger efficiency will vary as a function of invariant mass, being flat at $\sim 95\%$ down to masses of 20 GeV/c$^2$ before falling off to $\sim 62\%$ for masses of 2.5 GeV/c$^2$, while the reconstruction efficiency for events with both muons inside the nominal LHCb acceptance is expected to be flat as a function of mass ($\sim 85\%$). The contamination due to background events from semi-leptonic heavy quark (HQ) decays and hadron mis-identification has been investigated. Since the event rate of these backgrounds is four orders of magnitude larger than the signal rate, the iso-
The expected experimental statistical precision, assuming a bin size of 0.1 in rapidity, is compared with the current theoretical uncertainties due to the PDFs in Figure 4(c).

![Image](image_url)

Figure 3: Asymmetry distributions, normalised in terms of effective cross-section, for signal and background events in the mass range 2.5 - 5 GeV/c² that are triggered, reconstructed and pass the off-line preselection. (a) \( A(P_{\mu 1}, P_{\text{cone}1}) \), (b) \( A(P_{\mu 1} + P_{\mu 2}, P_{\text{rest}}) \), (c) \( A(P_{\text{cone}1} + P_{\text{cone}2}, P_{\text{rest}}) \).

Purities of 95% can be achieved for the full mass range (2.5 - 60 GeV/c²) with corresponding selection efficiencies for signal events passing the preselection of between 30% in the mass range 2.5 - 5 GeV/c² and 90% in the range 20 - 60 GeV/c². Figure 4(b) shows the expected dimuon mass spectra for the signal and background events that are triggered, reconstructed and pass the off-line selection while Table 1 gives the expected event rate for four different mass regions. Again with as little as 50 pb⁻¹ of data a cross-section measurement inside the LHCb acceptance will be limited by systematic uncertainties for each mass range.

The expected experimental statistical precision, assuming a bin size of 0.1 in rapidity, is compared with the current theoretical uncertainties due to the PDFs in Figure 4(c).

![Image](image_url)

Table 1: Expected number of Drell-Yan events selected per pb⁻¹ of data.

<table>
<thead>
<tr>
<th>Mass range</th>
<th>Events/pb⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.5 - 5 GeV/c²</td>
<td>119.1 ± 1.0</td>
</tr>
<tr>
<td>5 - 10 GeV/c²</td>
<td>287.3 ± 1.6</td>
</tr>
<tr>
<td>10 - 20 GeV/c²</td>
<td>147.6 ± 0.9</td>
</tr>
<tr>
<td>20 - 60 GeV/c²*</td>
<td>49.7 ± 0.4</td>
</tr>
</tbody>
</table>

*Here we define the asymmetry between two variables, \( x \) and \( y \), to be \( A(x, y) = \frac{x - y}{x + y} \).
Figure 4: (a) Fisher discriminant distributions for signal and background events in the mass range 2.5 - 5 GeV/c² that are triggered, reconstructed and pass the off-line preselection. (b) Dimuon invariant mass spectra for triggered, reconstructed and off-line selected signal and background events. (c) Comparison between the percentage uncertainty on Drell-Yan cross-section predictions at the LHC due to the PDFs as a function of rapidity for two different dimuon invariant masses [4] and the expected experimental statistical precision using 10 pb⁻¹ and 100 pb⁻¹ of LHCb data.

With only 100 pb⁻¹ of data the statistical precision on each bin is expected to be 2 – 3%. While a detailed study of the systematic uncertainties has yet to be made, it seems likely that, using $Z$, $\Upsilon$ and $J/\psi$ events, the experimental efficiencies can be determined with uncertainties of < 5%. Since the percentage PDF uncertainty on cross-section predictions at high rapidities and small masses are expected to be O(100%), the proposed measurements will place substantial constraints on the PDFs down to $x$ values of $10^{-6}$ and $Q^2$ values of 6.25 GeV²/c⁴.

4 Conclusions

Due to the fact that it is fully instrumented in the forward region and has low muon momentum trigger thresholds, events at LHCb will explore a unique region in $x - Q^2$ space. The Drell-Yan process $q\bar{q} \rightarrow \gamma^*/Z \rightarrow \mu\mu$, having a simple, distinctive and fully reconstructable final state, provides an ideal laboratory for exploring this currently unmeasured region. LHCb will be capable of triggering, reconstructing and selecting high purity, high statistics samples of Drell-Yan events with masses as low as 2.5 GeV/c² and rapidities as high as $y = 4.9$. Such measurements will place valuable constraints on the proton PDFs down to $x$ values of $10^{-6}$ and explore a totally unknown, and important, kinematic region.

References

[1] Slides: http://indico.cern.ch/getFile.py/access?contribId=102&sessionId=26&resId=0&materialId=slides&confId=53294