Measurement of the distribution of $\phi_\eta^*$ in events containing dimuon pairs with masses between 30 and 500 GeV in 10.4 fb$^{-1}$ of $p\bar{p}$ collisions

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We present a measurement of the distribution of the variable $\phi_\eta^*$ in dimuon pairs with masses between 30 and 500 GeV, using the complete Run II data collected by the DØ detector at the Fermilab Tevatron proton-antiproton collider. The integrated luminosity corresponds to 10.4 fb$^{-1}$ at $\sqrt{s} = 1.96$ TeV. The variable $\phi_\eta^*$ probes the same physics as the $Z/\gamma^*$ boson transverse momentum, but is less sensitive to the effects of experimental resolution and efficiency. The data, having been corrected for detector effects, are presented in bins of dimuon mass and rapidity and compared to QCD predictions based on the resummation of multiple soft gluons.

1 Introduction

In hadron colliders Drell-Yan dilepton pair decays of $Z/\gamma^*$ may be produced with a non-zero momentum in the plane transverse to the beam direction, $p_T^\ell\ell$, due to recoils of gluons or quarks radiated from the incoming partons. The precise study of Drell-Yan $p_T^\ell\ell$ distribution provides an ideal ground for testing and improving initial state QCD radiation models because of the relatively low background and absence of color flow between initial state and final state. Understanding the performance of such models has important implications in $W$ mass measurement and Higgs production as well as new physics searches at hadron colliders.

In the low region of $p_T^\ell\ell$ spectrum, the precision is limited by uncertainties for correcting effects of experimental resolution and efficiency. An alternative variable $\phi_\eta^*$, with better experimental resolution and low susceptibility to detector effects, has been introduced to probe the low-$p_T^\ell\ell$ domain of $Z/\gamma^*$ production. The $\phi_\eta^*$ variable is defined as:

$$\phi_\eta^* \equiv \tan(\phi_{acop}/2) \sin\theta_\eta^*, \quad (1)$$

where $\phi_{acop}$ is the acoplanarity angle, given by: $\phi_{acop} = \pi - \Delta\phi^\ell\ell$, and $\Delta\phi^\ell\ell$ is azimuthal opening angle between the leptons.

Figure 1 presents a schematic diagram of relevant variables in the plane transverse to the beam direction. The variable $\theta_\eta^*$ is a measure of the scattering angle of the leptons with respect to the proton beam direction in the rest frame of the dilepton system. It is defined by:
\[
\cos(\theta^*_\eta) = \tanh \left( [(\eta^- - \eta^+) / 2] \right), \text{ where } \eta^- \text{ and } \eta^+ \text{ are the pseudorapidities of the negatively and positively charged lepton, respectively. Thus } \phi^*_\eta \text{ depends exclusively on the track directions of the two leptons, which is experimentally better measured than quantities relying on the momenta of the leptons, such as } p_T^\ell. \text{ It is highly correlated with } p_T^\ell/m_{ul}, \text{ where } m_{ul} \text{ is the invariant mass of the dilepton pair.}
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In this proceeding we present a short description of the updated measurements in the dimuon final state of the normalized \( \phi^*_\eta \) distribution, \((1/\sigma) \times (d\sigma/d\phi^*_\eta)\), in bins of dimuon rapidity, \(|y|\), in \( p\bar{p} \) collisions at \( \sqrt{s} = 1.96 \text{ TeV} \). In addition to the measurements updated for \( 70 < m_{\ell\ell} < 110 \text{ GeV} \) to the complete \( 10.4 \text{ fb}^{-1} \) data set collected by the D0 detector, we extend the measurements to “off-peak” samples of dimuon events and consider ranges of \( m_{\ell\ell} \) between 30 and 500 GeV. These are the first measurements at any collider of the \( \phi^*_\eta \) distributions away from the \( Z \) peak.

2 Event selection and analysis mythology

Simulation samples are used to model Drell-Yan dimuon signal and background processes from \( Z/\gamma^* \rightarrow \tau^- \tau^+ \), \( W \rightarrow t\bar{t} \) (jets), and \( WW \rightarrow t\bar{t}t\bar{t} \). Background from multijet events is estimated using data-driven techniques. Candidate dimuon events are required to pass the single-muon trigger and required to be matched to a pair of oppositely-charged particle tracks reconstructed in the central tracking detectors with momentum transverse to the beam direction of \( p_T > 15 \text{ GeV} \) and \(|\eta| < 2\). Candidate muons are required to pass identification and isolation criteria to reject misidentified hadrons or in-flight decay of hadrons. Contamination from cosmic ray muons is eliminated by requirements on the primary vertex impact parameters, times-of-flight and rejecting events in which the two muon candidates are back to back in \( \eta \).

In the off-peak region, additional selection criteria are imposed to select well-measured Drell-Yan dimuon events with acceptable levels of background. An important source of background in all the off-peak samples of dimuon events arises from Drell-Yan dimuon events that originate close to the \( Z \) peak, but are reconstructed with a value of \( m_{\ell\ell} \) away from the \( Z \) peak due to final state photon radiation (FSR) or the mis-measurement of the \( p_T \) of one of the muon candidates. Optimized cuts based on the momentum balance of the two leptons have been developed in the off-peak region to reject such migration background in \( m_{\ell\ell} \).

For \( 70 < m_{\ell\ell} < 110 \text{ GeV} \) a total of 645k dimuon events is selected with a total background fraction of 0.2%, mainly arising from multijet background. A total of 74k dimuon events is selected for \( 30 < m_{\ell\ell} < 60 \text{ GeV} \), where the selection criteria are relaxed to requiring \( p_T > 10 \text{ GeV} \) for both muons, with one muon required to satisfy \( p_T > 15 \text{ GeV} \) to increase selection efficiency in this low-mass region and to reduce any bias on the distribution of \( \phi^*_\eta \). After event selection in the low-mass region, \( Z/\gamma^* \rightarrow \tau^- \tau^+ \) accounts for 5% of the total background and the fraction of migration in \( m_{\ell\ell} \) is 1.3%, with the remaining background amount to 1.8% mainly from multijet background. For the mass ranges \( 160 < m_{\ell\ell} < 300 \text{ GeV} \) and \( 300 < m_{\ell\ell} < 500 \text{ GeV} \), respectively, the numbers of selected events are 1744 and 207, and the fractions of the selected event samples arising from migration background are 24% and 44%, respectively.

3 Differential cross-section measurement and systematic uncertainties

The observed \( \phi^*_\eta \) distributions are corrected for background, and for experimental efficiency and resolution. When evaluating the correction factors, the same kinematic selection criteria on \( m_{\ell\ell} \) and muon \( p_T \) and pseudorapidity used in data is applied at the MC particle level as
specified above. For this purpose, MC particle level muons are defined after QED final state radiation, which mimics the measurement of muon momentum in the tracking detector. Since the experimental resolution in $\phi_\eta$ is narrower than the chosen bin widths, simple bin-by-bin corrections of the $\phi_\eta$ distribution are sufficient.

In almost all $\phi_\eta$ bins the total systematic uncertainty is substantially smaller than the statistical uncertainty. Dominant systematic uncertainties arise from variations of the muon identification and trigger efficiencies at the detector module boundaries throughout the dimuon mass spectrum of interest. Modeling of $Z/\gamma^* \rightarrow \tau^- \tau^+$ background is the main systematic uncertainty in the below Z peak region and uncertainties due to migration in $m_{\ell\ell}$ is the largest in the above Z peak region.

4 Comparison to QCD predictions

The corrected dimuon data are compared to the predictions from ResBos$^{5,6}$ and from a calculation$^7$ with QCD corrections at the next-to-leading-order (NLO) and next-to-next-to-leading-log (NNLL) accuracy.

Figure 2 shows for $70 < m_{\ell\ell} < 110$ GeV the ratio of the corrected $\phi_\eta$ distributions to the ResBos predictions. In addition to the dimuon data from the present analysis, the dielectron data from Ref.$^2$ are shown. Given that the experimental acceptance corrections are very different between dimuon and dielectron channels, this consistency represents a powerful cross check of the corrected distributions.

Figure 3 shows for $30 < m_{\ell\ell} < 60$ GeV the ratio of the corrected $\phi_\eta$ distributions to the NNLL+NLO predictions of Ref.$^7,8$. The prediction describes the corrected data well within the assigned theoretical uncertainties.

Figure 4 shows for $160 < m_{\ell\ell} < 300$ GeV and and $300 < m_{\ell\ell} < 500$ GeV the ratio of the corrected $\phi_\eta$ distributions to the ResBos predictions. Within the fairly large statistical uncertainties, the predictions are in reasonable agreement with the corrected data.

5 Conclusion

Using 10.4 fb$^{-1}$ of $p\bar{p}$ collisions we have measured the normalized $\phi_\eta$ distribution, $(1/\sigma) \times (d\sigma/d\phi_\eta)$, in two bins of dimuon rapidity and in four bins of dimuon mass. Relative to the results presented in Ref.$^2$, these measurements in the dimuon channel represent an extension to the full D0 data set and also to regions of dimuon mass away from the Z peak. The data are reasonably well
Figure 3 – Ratio of the corrected distributions of $(1/\sigma) \times (da/d\phi^\prime)$ to the NNLL+NLO predictions of Ref.\textsuperscript{7,8} for $30 < m_{\ell\ell} < 60$ GeV: (a) $|y| < 1$ and (b) $1 < |y| < 2$. Statistical and systematic uncertainties are combined in quadrature. The yellow band around the NNLL+NLO prediction represents the uncertainty due to variations in the QCD scales.

Figure 4 – Ratio of the corrected distributions of $(1/\sigma) \times (da/d\phi^\prime)$ to ResBos for (a) $160 < m_{\ell\ell} < 300$ GeV and (b) $300 < m_{\ell\ell} < 500$ GeV. Statistical and systematic uncertainties are combined in quadrature. The yellow band around the ResBos prediction represents the quadrature sum of uncertainty due to PDFs, QCD scales and non-perturbative parameter $a_s$.

described within the theoretical uncertainties by the ResBos predictions and by the predictions at NNLL+NLO accuracy of Ref.\textsuperscript{7,8}.

References

8. L. Tomlinson, private communication.