RAPIDITY CORRELATIONS IN $W\gamma$ PRODUCTION 
AT THE TEVATRON

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ABSTRACT

We study the correlation of photon and charged lepton pseudorapidities, $\eta(\gamma)$ and $\eta(\ell)$, $\ell = e, \mu$, in $p\bar{p} \rightarrow W^{\pm}\gamma + X \rightarrow \ell^{\pm}\bar{p}p\gamma + X$ at the Tevatron. In the Standard Model, the $\Delta\eta(\gamma, \ell) = \eta(\gamma) - \eta(\ell)$ differential cross section is found to exhibit a pronounced dip at $\Delta\eta(\gamma, \ell) \approx \mp 0.4$, which originates from the radiation zero present in $q\bar{q}' \rightarrow W\gamma$. The sensitivity of the $\Delta\eta(\gamma, \ell)$ distribution to higher order QCD corrections, non-standard $WW\gamma$ couplings, and the cuts imposed is explored. The $\Delta\eta(\gamma, \ell)$ distribution is compared with other quantities which are sensitive to the radiation zero.

1. Introduction

A pronounced feature of $W\gamma$ production in hadronic collisions is the so-called radiation zero which appears in the parton level subprocesses which contribute to lowest order in the Standard Model (SM) of electroweak interactions. For $u\bar{d} \rightarrow W^+\gamma$ ($d\bar{u} \rightarrow W^-\gamma$) all contributing helicity amplitudes vanish for $\cos \Theta^* = -1/3$ ($+1/3$), where $\Theta^*$ is the angle between the quark and the photon in the parton center of mass frame. In practice, however, this zero is difficult to observe. Structure function effects transform the zero into a dip. Higher order QCD corrections and finite $W$ width effects, together with photon radiation from the final state lepton line, tend to fill in the dip. Finally, the twofold ambiguity in the reconstructed parton center of mass frame which originates from the two possible solutions for the longitudinal momentum of the neutrino, $p_L(\nu)$, represents an additional com-

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plication in the extraction of the \( \cos \Theta^* \) or the corresponding rapidity distribution, \( d\sigma/dy^*(\gamma) \), which further dilutes the effect.

The effect of higher order QCD corrections can largely be compensated by imposing a jet veto \([3]\). Unwanted effects originating from the twofold ambiguity in \( p_L(\nu) \) can be avoided by considering quantities which reflect the radiation zero, but which do not require the reconstruction of the parton center of mass frame. Recently, the ratio of \( Z\gamma \) and \( W^\pm\gamma \) cross sections as a function of the minimum photon \( p_T \) has been demonstrated \([5]\) to be such a quantity. However, a sufficiently large sample of \( Z\gamma \) events is necessary to establish the increase of the cross section ratio with \( p_T^{\min}(\gamma) \) predicted by the SM. In addition one has to assume that there are no non-standard contributions to \( Z\gamma \) production, e.g. from anomalous \( ZZ\gamma \) or \( Z\gamma\gamma \) couplings \([6]\).

Here we consider correlations between the photon rapidity, \( \eta(\gamma) \), and the rapidity \( \eta(\ell) \) of the charged lepton, \( \ell = e, \mu \), originating from the \( W \) decay as tools to observe the radiation zero predicted by the SM for \( W\gamma \) production in hadronic collisions. We show that the double differential distribution \( d^2\sigma/d\eta(\gamma)d\eta(\ell) \) and the distribution of the difference of rapidities, \( \Delta\eta(\gamma,\ell) = \eta(\gamma) - \eta(\ell) \), clearly display the SM radiation zero. We also study the sensitivity of the \( \Delta\eta(\gamma,\ell) \) spectrum to higher order QCD corrections, non-standard \( WW\gamma \) couplings and the cuts imposed.

2. Photon Lepton Rapidity Correlations

In our analysis we shall focus entirely on the \( W^+\gamma \) channel. Results for \( W^-\gamma \) production can be obtained by exchanging the sign of the rapidities involved. The calculation of \( W\gamma \) production in the Born approximation and at \( O(\alpha_s) \) is performed using the results of Ref. \([7]\) and \([3]\), respectively. In the Born approximation, our calculation fully incorporates finite \( W \) width effects, together with photon bremsstrahlung from the final state charged lepton line. The NLO QCD calculation, on the other hand, treats the \( W \) boson in the narrow width approximation. In this approximation, diagrams in which the photon is radiated off the final state lepton line are not necessary to maintain electromagnetic gauge invariance. Imposing a large photon lepton separation cut, together with a cluster transverse mass cut, these diagrams can be ignored \([8]\).

The SM radiation zero leads to a pronounced dip in the photon rapidity distribution in the center of mass frame, \( d\sigma/dy^*(\gamma) \), at

\[
y^*(\gamma) = y_0 = -\frac{1}{2} \log 2 \approx -0.35.
\]

For \( u\bar{d} \rightarrow W^+\gamma \) the photon and the \( W \) are back to back in the center of mass frame. The corresponding rapidity distribution of the \( W \) in the parton center of mass frame, \( d\sigma/dy^*(W) \), thus exhibits a dip at \( y^*(W) = -y_0 \). In the double differential distribution of the rapidities in the laboratory frame, \( d^2\sigma/d\eta(\gamma)d\eta(W) \), one then expects a “valley” for rapidities satisfying the relation\(^\dagger\) \( \eta(\gamma) - y(W) \equiv y^*(\gamma) - y^*(W) = 2y_0 \).

\(^\dagger\) Differences of rapidities are invariant under boosts.
In the SM, the dominant $W^\pm$ helicity in $W\gamma$ production is $\lambda_W = \pm 1$, implying that the charged lepton will tend to be emitted in the direction of the parent $W$, thus reflecting most of its kinematic properties. The difference in rapidity, $\Delta y(W, \ell) = y(W) - \eta(\ell)$, between the $W$ boson and the charged lepton originating from the $W$ decay is rather small with an average $\Delta y(W, \ell)$ of 0.30. The double differential distribution $d^2\sigma/d\eta(\gamma)d\eta(\ell)$ for $p\bar{p} \to W^+\gamma \to \ell^+p_T\gamma$ is thus expected to display a valley for rapidities fulfilling the relation $\Delta \eta(\gamma, \ell) = \eta(\gamma) - \eta(\ell) \approx -0.4$. Figure 1 shows $d^2\sigma/d\eta(\gamma)d\eta(\ell^+)$ for $p\bar{p} \to \ell^+p_T\gamma$ in the Born approximation, together with the corresponding distribution for $p\bar{p} \to \ell^+\ell^-\gamma$. Here we have imposed a $p_T(\ell) > 5$ GeV, a $p_T(\gamma) > 20$ GeV and a $p_{T}(\ell) > 20$ GeV cut, together with cuts on the pseudorapidities of the photon and charged lepton of $|\eta(\gamma)| < 3$ and $|\eta(\ell)| < 3.5$. To select a phase space region where radiative $W$ ($Z$) decays are suppressed and $q\bar{q}' \to W\gamma$ ($q\bar{q} \to Z\gamma$) dominates, we have required in addition a large photon lepton separation cut of $\Delta R(\gamma, \ell) > 0.7$, a cluster transverse mass cut of $m_T(\ell\gamma; p_T) > 90$ GeV for $W^+\gamma$ production, and invariant mass cuts of $m(\ell^+\ell^-) > 70$ GeV and $m(\ell^+\ell^-\gamma) > 100$ GeV in the $Z\gamma$ case. For the parton distribution functions we use the MRSS0 parametrization [8]. The double differential cross section for $p\bar{p} \to \ell^+\ell^-\gamma$ is calculated using the results of Ref. [6].

Figure 1a exhibits a pronounced minimum at $\Delta \eta(\gamma, \ell) \approx -0.4$, as expected. Furthermore, the photon and lepton rapidities are seen to be strongly correlated, with most photons (leptons) having positive (negative) rapidities. Since the sign of the rapidities changes for $W^-\gamma$ production, this correlation may aid in determining
the charge of the electron in the DØ detector which does not have a central magnetic field. If the cluster transverse mass cut of \( m_T(\ell\gamma; \not{p}_T) > 90 \text{ GeV} \) is removed, radiative \( W \) decays dominate and the valley disappears. In contrast to the situation for \( p\bar{p} \rightarrow \ell^+\ell^-\gamma \), there is no sign of a valley, and no strong correlation between the rapidities in \( p\bar{p} \rightarrow \ell^+\ell^-\gamma \) (see Fig. 1b).

Since the valley is approximately 1.5 units in rapidity wide and occurs essentially in the diagonal of the \( \eta(\gamma), \eta(\ell) \) plane, it is completely obscured if one integrates over the full range of either the photon or the lepton rapidity. Only for sufficiently strong cuts, e.g. \( |\eta(\gamma)| < 1 \) or \( |\eta(\ell)| < 1 \), a slight dip can be observed in \( d\sigma/d\eta(\ell) \) (or \( d\sigma/d\eta(\gamma) \)) in the region around \( \eta(\ell) \approx 0.4 \) (\( \eta(\gamma) \approx -0.4 \)).

The double differential distribution \( d^2\sigma/d\eta(\gamma)d\eta(\ell) \) can only be mapped out if a sufficiently large number of events is available. For a relatively small event sample the distribution of the rapidity difference, \( d\sigma/d\Delta \eta(\gamma, \ell) \), is more useful. The \( \Delta \eta(\gamma, \ell) \) distribution for the cuts summarized above is shown in Fig. 2a (solid line). As anticipated, the distribution exhibits a strong dip at \( \Delta \eta(\gamma, \ell) \approx -0.4 \). In the region of the dip, most events originate from the high \( p_T(\gamma) \) region. This is illustrated by the dashed line in Fig. 2a, which shows the \( \Delta \eta(\gamma, \ell) \) distribution for \( p_T(\gamma) > 10 \text{ GeV} \) instead of \( p_T(\gamma) > 5 \text{ GeV} \). Around the minimum the result almost coincides with that obtained for the smaller photon \( p_T \) cut. Increasing the photon transverse momentum threshold, the dip becomes less pronounced. The dotted line in Fig. 2a, finally, displays the rapidity difference distribution with the \( \Delta R(\gamma, \ell) > 0.7 \) cut replaced by \( \Delta R(\gamma, \ell) > 0.3 \). Reducing the photon lepton isolation cut increases the contribution of the diagram where the photon is radiated off the final state lepton line. The final state bremsstrahlung contribution, which diverges in the collinear limit, destroys the SM radiation zero, and thus tends to fill in the dip.

The \( \Delta \eta(\gamma, \ell) \) distribution at next-to-leading order in QCD is shown in Fig. 2b. Besides the cuts described above, we also require the photon to be isolated from hadrons in the NLO calculation by imposing a cut on the total hadronic energy in a cone of size \( \Delta R = 0.7 \) about the direction of the photon of

\[
\sum_{\Delta R < 0.7} E_{\text{had}} < 0.15 E_{\gamma},
\]

where \( E_{\gamma} \) is the photon energy. This requirement strongly reduces photon bremsstrahlung from final state quarks and gluons.

NLO QCD corrections are seen to partially fill in the dip caused by the SM radiation zero (dashed line). While \( \mathcal{O}(\alpha_s) \) QCD corrections enhance the cross section by \( 30 - 40\% \) outside the dip region, they increase the rate by approximately a factor 2.5 at \( \Delta \eta(\gamma, \ell) \approx -0.4 \). This effect is predominantly caused by the \( 2 \rightarrow 3 \) processes \( qg \rightarrow W\gamma q' \) and \( q'g \rightarrow W\gamma q \) where no radiation zero is present in the helicity amplitudes. Imposing a jet veto, i.e. requiring that no jets with transverse momentum \( p_T(j) > 10 \text{ GeV} \) and rapidity \( |\eta(j)| < 2.5 \) are present in the event, the NLO \( \Delta \eta(\gamma, \ell) \) distribution (dotted line) is very similar to that obtained in the Born approximation (solid line).

In \( W\gamma \) production both the virtual \( W \) and the decaying onshell \( W \) couple
Figure 2: a) The rapidity difference distribution, $d\sigma/d\Delta\eta(\gamma, \ell)$, for $p\bar{p} \to W^{+}\gamma + X \to \ell^{+}\bar{p}_{T}\gamma + X$, $\ell = e, \mu$, in the Born approximation. The solid line shows the result obtained for the cuts described in the text. The dashed (dotted) curve displays the rapidity difference distribution if the $p_{T}(\gamma) > 5$ GeV ($\Delta R(\gamma, \ell) > 0.7$) cut is replaced by $p_{T}(\gamma) > 10$ GeV ($\Delta R(\gamma, \ell) > 0.3$), with all other cuts unchanged.

b) The $\Delta\eta(\gamma, \ell)$ distribution, including $O(\alpha_{s})$ QCD corrections, for the cuts described in the text. The solid and dashed lines represent the Born and the inclusive NLO result, respectively. The dotted line shows the NLO result obtained for the exclusive reaction $p\bar{p} \to W^{+}\gamma + 0$ jet, $W^{+} \to \ell^{+}\nu$.

to essentially massless fermions, which insures that effectively $\partial_{\mu}W^{\mu} = 0$. This condition together with Lorentz invariance, electromagnetic gauge invariance, and CP conservation, allows two free parameters, $\kappa$ and $\lambda$, in the $WW\gamma$ vertex. The most general vertex compatible with these conservation laws is described by the effective Lagrangian [10]

$$
\mathcal{L}_{WW\gamma} = -ie \left[ W_{\mu\nu}^{\dagger}W^{\mu\nu}A^{\nu} - W_{\mu}^{\dagger}A_{\nu}W^{\mu\nu} + \kappa W_{\mu}^{\dagger}W_{\nu} F^{\mu\nu} + \frac{\lambda}{M_{W}^{2}} W_{\mu\nu} W_{\nu} F^{\mu\nu} \right],
$$

where $A^{\mu}$ and $W^{\mu}$ are the photon and $W^{-}$ fields, respectively, $W_{\mu\nu} = \partial_{\mu}W_{\nu} - \partial_{\nu}W_{\mu}$, and $F_{\mu\nu} = \partial_{\mu}A_{\nu} - \partial_{\nu}A_{\mu}$. The variables $\kappa$ and $\lambda$ are related to the magnetic dipole moment, $\mu_{W}$, and the electric quadrupole moment, $Q_{W}$, of the $W$-boson:

$$
\mu_{W} = \frac{e}{2M_{W}} (1 + \kappa + \lambda), \quad Q_{W} = -\frac{e}{M_{W}^{2}} (\kappa - \lambda).
$$
At tree level in the SM, $\kappa = 1$ and $\lambda = 0$. The two $CP$ conserving couplings have recently been measured by the UA2 Collaboration in the process $p\bar{p} \rightarrow e^{\pm}\nu\gamma X$ at the CERN $p\bar{p}$ collider [11]:

$$\kappa = 1 + 2.6^{-2.2} \quad \text{(for } \lambda = 0), \quad \lambda = 0 + 1.7^{-1.8} \quad \text{(for } \kappa = 1), \quad (5)$$

at the 68.3% confidence level (CL). Although bounds on these couplings can also be extracted from low energy data and high precision measurements at the $Z$ pole, there are ambiguities and model dependencies in the results [12]. No rigorous bounds on $WW\gamma$ couplings can be obtained from LEP I data if correlations between different contributions to the anomalous couplings are fully taken into account.

Tree level unitarity uniquely restricts the $WW\gamma$ couplings to their SM gauge theory values at asymptotically high energies [13]. This implies that any deviation of $\kappa$ or $\lambda$ from the SM expectation has to be described by a form factor $a(M_{W\gamma}^2, p_W^2, p_\gamma^2)$, $a = (\Delta \kappa = \kappa - 1)$, $\lambda$ which vanishes at high energies. Consequently, the anomalous couplings are introduced via form factors

$$a(M_{W\gamma}^2, p_W^2 = M_W^2, p_\gamma^2 = 0) = \frac{a_0}{(1 + M_{W\gamma}^2/\Lambda^2)^n}, \quad (6)$$

where $a_0 = \Delta \kappa_0$, $\lambda_0$ are the form factor values at low energies and $\Lambda$ represents the scale at which new physics becomes important in the weak boson sector, e.g. due to a composite structure of the $W$-boson. For the numerical results presented here, we use a dipole form factor ($n = 2$) with a scale $\Lambda = 1$ TeV.

The sensitivity of the rapidity difference distribution in the Born approximation to non-standard $WW\gamma$ couplings is explored in Fig. 3. The solid line shows the SM result, whereas the dashed and dotted curves give the prediction for the current UA2 68% CL limits of $\Delta \kappa_0 = 2.6$ and $\lambda_0 = 1.7$, respectively. In presence of any anomalous contribution to the $WW\gamma$ vertex the radiation zero is eliminated and the dip in $d\sigma/d\Delta \eta(\gamma, \ell)$ is filled in at least partially. Most of the excess cross section for non-standard couplings originates in the high $p_T(\gamma)$ region [4], where events tend to be central in rapidity. Deviations from the SM $\Delta \eta(\gamma, \ell)$ distribution, therefore, mostly occur for small rapidity differences. In Fig. 3 we have also included the statistical errors expected in the SM case for an integrated luminosity of $\int L\,dt = 22$ pb$^{-1}$. This demonstrates that the rapidity difference distribution is sensitive to anomalous $WW\gamma$ couplings already with the current CDF and DØ data samples, in particular to $\lambda$. However, we do not expect $d\sigma/d\Delta \eta(\gamma, \ell)$ to be more sensitive to anomalous couplings than the photon transverse momentum distribution.

3. Conclusions

We have considered photon – lepton rapidity correlations as a tool to study the radiation zero predicted by the SM for $W\gamma$ production in hadronic collisions. In the SM, the dominant $W^\pm$ helicity in $W\gamma$ production is $\lambda_W = \pm 1$. Combined with the $V - A$ coupling of the charged lepton to the $W$, this implies that the lepton
Figure 3: The rapidity difference distribution, $d\sigma/d\Delta\eta(\gamma, \ell)$, for $p\bar{p} \rightarrow W^+\gamma + X \rightarrow \ell^+ p_T \gamma + X$, $\ell = e, \mu$, at the Tevatron in the Born approximation for anomalous $WW\gamma$ couplings. The curves are for the SM (solid), $\Delta\kappa_0 = 2.6$ (dashed), and $\lambda_0 = 1.7$ (dotted). Only one coupling is varied at a time. A dipole form factor with scale $\Lambda = 1$ TeV is assumed for non-standard $WW\gamma$ couplings. The cuts imposed are described in the text. The error bars indicate the expected statistical errors for an integrated luminosity of 22 pb$^{-1}$.

tends to be emitted in the direction of the parent $W$, thus reflecting most of its kinematic properties. As a result we found that the SM radiation zero leads to a pronounced valley in the double differential distribution, $d^2\sigma/d\eta(\gamma)d\eta(\ell)$, for $W^\pm\gamma$ production and rapidities fulfilling the relation $\Delta\eta(\gamma, \ell) = \eta(\gamma) - \eta(\ell) \approx \mp0.4$.

Equivalently to the double differential distribution, the rapidity difference distribution, $d\sigma/d\Delta\eta(\gamma, \ell)$, can be studied. Here the radiation zero is signaled by a dip located at $\Delta\eta(\gamma, \ell) \approx \mp0.4$. The details of the rapidity difference distribution are sensitive to the cuts imposed; increasing the photon $p_T$ threshold and reducing the photon lepton isolation cut tends to fill in the dip. A similar trend is observed for non-standard $WW\gamma$ couplings, and if NLO QCD corrections are taken into account. However, if the a jet veto is imposed, i.e. the exclusive $W\gamma + 0$ jet channel is considered, the NLO rapidity difference distribution is very similar to that obtained in the Born approximation.

Compared to $d\sigma/dy^*(\gamma)$, the rapidity difference distribution has the advantage of being independent of the twofold ambiguity in the reconstruction of the parton center of mass frame, which partially obscures the radiation zero in the
\(y^*(\gamma)\) distribution. In contrast to the \(Z\gamma\) to \(W^\pm\gamma\) cross section ratio which also reflects the radiation zero, the rapidity difference distribution does not depend on the \(Z\gamma\) cross section, and the validity of the SM for \(p\bar{p} \to Z\gamma\).

While the NLO QCD corrections to \(W\gamma + 0\) jet production are small at the Tevatron, this is not the case for realistic jet definitions at supercollider energies, due to the very much increased \(qg\) luminosity. For a jet defining \(p_T\) threshold of 30 GeV or larger, the dip is completely filled in at the SSC. Present studies \([4]\) suggest that it will be difficult to reconstruct jets at the SSC with a transverse momentum less than about 30 GeV. Given a sufficiently large integrated luminosity, experiments at the Tevatron studying photon – lepton rapidity correlations thus offer a unique chance to search for the SM radiation zero in hadronic \(W\gamma\) production.

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