Diffractive $W^{\pm}$ production at hadron colliders as a test of color singlet exchange mechanisms

Gunnar Ingelman,[1,*] Roman Pasechnik,[2,†] Johan Rathsman,[2,‡] and Dominik Werder[1,§]

[1]Department of Physics and Astronomy, Uppsala University, Box 516, SE-751 20 Uppsala, Sweden

[2]Department of Astronomy and Theoretical Physics, Lund University, Sölvegatan 14A, SE-223 62 Lund, Sweden

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We revisit diffractive and exclusive $W^{\pm}X$ production at hadron colliders in different models for soft color exchanges. The process $pp \to p[W^{\pm}X]p$, and in particular a $W^{\pm}$ charge asymmetry, has been suggested as a way to discriminate diffractive processes as being due to pomeron exchange in Regge phenomenology or QCD-based color reconnection models. Our detailed analysis of the latter models at LHC energies shows, however, that they give similar results as pomeron models for leading protons and central $W^{\pm}X$ production, including a vanishing $W^{\pm}$ charge asymmetry. We demonstrate that soft color exchange models provide a continuous transition from diffractive to inelastic processes and thereby include the intrinsic asymmetry of inelastic interactions while being at the same time sensitive to the underlying hadronization models. Such sensitivity also concerns the differential distributions in proton momentum and $W^{\pm}$ transverse momentum, which opens possibilities to discriminate between different color reconnection models.

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I. INTRODUCTION

Diffractive and exclusive processes in quantum chromodynamics (QCD) still remain a theoretically unsolved and intriguing chapter of the Standard Model of particle physics. Considerable progress has been made in recent years by focusing on diffractive hard-scattering processes [1], where a hard scale defines a partonic subprocess which can be calculated perturbatively and used as a well-defined backbone for the poorly understood soft processes that give rise to the characteristic features of diffraction in terms of a leading proton or a large gap in rapidity with no particle production. In such processes the dominating effect is thus caused by soft fluctuations of the gluonic field at large distances, making diffractive observables very sensitive to nonperturbative QCD dynamics and, therefore, providing a tool to explore this unsolved sector of QCD.

Considering scales as low as $\mu_{\mathrm{soft}} \sim \Lambda_{\mathrm{QCD}}$, individual gluons are not resolved and one should rather consider collective gluon fields, such as those modeled by color string fields in the Lund hadronization model [2], or even hadron-like objects, such as those modeled through pomeron exchange in the Regge approach [3,4]. This has led to different approaches to describe the soft dynamics of diffractive processes: on the one hand, models based on pomeron exchange using Regge phenomenology initially developed in the pre-QCD era and, on the other hand, models based on soft gluon exchange between hard-scattered partons and beam hadron remnants, which can modify the color topology between the emerging partons resulting in a different final state of hadrons, e.g., with rapidity gaps. The latter type of dynamics was first introduced in the soft color interaction (SCI) model [5] and was later developed in various ways such as the generalized area law (GAL) model [6], making the probability for color exchanges dynamical.

Many different diffractive hard-scattering processes have been observed experimentally and studied theoretically [7]. Much attention has been given to central exclusive processes [8], in particular the spectacular Higgs boson production process $pp \to pHp$ at the LHC, where the Higgs boson mass might be reconstructed from a measurement of the leading proton momenta [9,10]. However, the estimated cross section is small and has a substantial uncertainty due to its dependence on soft QCD dynamics [11].

On the experimental side, both the CDF and D0 collaborations at the Fermilab Tevatron have reported the measurement of several different diffractive processes [12–15]. There are also some first results from the CMS experiment at the LHC [16,17]. Of special interest here is the diffractive gauge boson production for which the CDF experiment recently reported results based on the forward spectrometer to detect leading antiprotons [18]. Compared to measurements based on rapidity gaps, this has the advantage of a much smaller dependence on the gap survival and gap acceptance factors, resulting in more stringent tests of diffractive models.

On the theoretical side, the diffractive production of gauge bosons has also received attention [19,20] due to a rather high sensitivity to the production mechanism and at the same time a large enough cross section to be experimentally observed and studied in detail. The intricate mechanism of QCD factorization breaking in diffractive Drell-Yan and W, Z production [21] enhances the interest for these kinds of processes.

*Gunnar.Ingelman@physics.uu.se
†Roman.Pasechnik@thep.lu.se
‡Johan.Rathsman@thep.lu.se
§Dominik.Werder@physics.uu.se

In this paper, spurred by these recent developments, we will revisit the SCI and GAL models for diffractive W production at hadron colliders. After a short recapitulation of the essence of these models we will compare them with the most recent data on leading antiprotons from the Tevatron and make predictions for double leading protons at the LHC. In particular, we will clarify the recent claim [20] on W charge asymmetry in the latter case.

II. COLOR-SINGLET EXCHANGE MODELS

The focus of the paper is on diffractive gauge boson production in hadron collisions. In particular, we will concentrate on the exclusive process $pp \to p[W^{\pm}X]p$ at the LHC with $\sqrt{s} = 14$ TeV, but we will also consider single diffractive W production such as $\bar{p}p \to \bar{p}[W^{\pm}X]$ at the Tevatron with $\sqrt{s} = 1.96$ TeV. Figure 1 illustrates the former for a typical parton-level subprocess where X is a pair of quark jets, as an example. This process will be measured in the near future by the ATLAS experiment using forward spectrometers [22], and different models of diffraction can then be tested.

On general grounds, the requirement of a leading proton (or antiproton) in the final state, which is more or less unscathed, means that the squared momentum transfer t should be soft, $\sqrt{|t|} \sim \Lambda_{\mathrm{QCD}}$, and that larger momentum transfers are exponentially suppressed. In addition, only a small fraction of the proton's longitudinal momentum may be lost, such that $1 - z \sim M_{WX}/\sqrt{s} \ll 1$ (for the $W^{\pm}X$ system at central rapidity $y \sim 0$) with $z = |p_z|/p_{\mathrm{beam}}$ being the momentum carried by the leading proton compared to the beam energy.[1]

In the Regge approach, these types of processes are described in terms of single or double pomeron exchange, Fig. 1(a), using a factorization into a pomeron flux and parton density functions (PDF) in the pomeron. Such diffractive PDFs have been fitted to diffractive deep inelastic scattering data from the H1 and ZEUS experiments at the ep collider HERA. In this way a consistent description of diffractive deep inelastic scattering can be obtained [7]. The problem is that these diffractive PDFs are not universally applicable for other diffractive processes. For example, by using them to calculate diffractive hard-scattering processes in $p\bar{p}$ collisions one obtains cross sections that are an order of magnitude larger than those observed at the Tevatron [24]. Although this problem can be cured by introducing an overall renormalization through

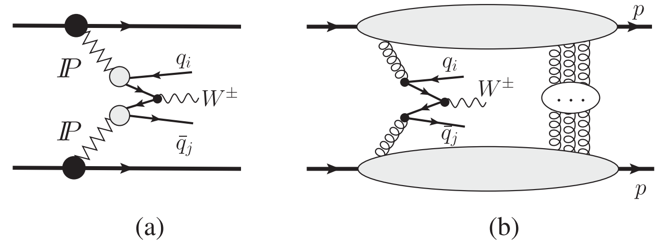

FIG. 1. The exclusive diffractive process $pp \to p[W^{\pm}X]p$, with central $W^{\pm} + 2$ jets separated from the final protons, based on (a) double pomeron exchange in the Regge approach and (b) soft color exchange in QCD.

a soft rapidity gap survival factor depending on the center-of-mass system (c.m.s.) energy, it represents an incompleteness of the double pomeron exchange model in general.

As an alternative to the pomeron approach, models have been developed where soft interactions result in different color topologies of the confining string fields, giving different hadronic final states after hadronization. In particular, a rapidity range without a string field results in an event with a corresponding rapidity gap.

The SCI model [5] is based on color-octet exchange below the conventional cutoff $Q_0 \sim 1$ GeV for perturbative QCD, but above the hadronization scale Λ_{QCD}, as illustrated in Fig. 1(b). This exchange does not significantly change the momenta of emerging partons, but it does change the color structure of the parton system, resulting in a modified string-field topology and thereby affecting the resulting distribution of final-state hadrons. In particular, it can result in an overall color-singlet exchange and leave the beam remnant in a color-singlet state before the hadronization scale is reached and the conventional Lund hadronization model [2] is applied. In effect, the SCI model introduces a probability, given by a parameter P_{SCI}, for the exchange of a color octet between any pair of partons—including beam spectators—emerging from the perturbative QCD treatment of the event in the Monte Carlo event generators LEPTO [25] for deep inelastic lepton-nucleon scattering or PYTHIA [26] for hadron-hadron scattering. In spite of its simplicity and with a single value of the only new parameter P_{SCI}, this provides a phenomenologically successful model that can account for a large variety of diffractive data, including the diffractive structure function at HERA [5], diffractive jets and quarkonia production at the Tevatron [27,28]. The model has also been applied for predicting diffractive Higgs production at the LHC [29]. In the following we will be using the canonical value $P_{\mathrm{SCI}} = 0.5$.

In the same spirit as the original SCI model, but with a different mechanism for nonperturbative color rearrangements, the GAL model has been developed in Ref. [6]. The GAL model was a first attempt to make the color reconnection probability dynamical, instead of static as in the SCI model. In short, it employs the difference in the

[1]The processes considered here have only a small squared momentum transfer via the effective color-singlet exchange. This implies that soft, nonperturbative QCD is essential to understand the dynamics of this exchange. In contrast, there are other processes with a large momentum transfer across a rapidity gap in between two balancing high-$p_{\perp}$ jets, where the observations can be described through a color-singlet gluon ladder in the Balitsky-Fadin-Kuraev-Lipatov formalism of perturbative QCD [23].

generalized string area for two different string configurations to weight the reconnection probability, $P_{\mathrm{GAL}} = P_0[1 - \exp(-b\Delta A)]$, where $P_0 \sim 0.1$ is the maximal reconnection probability of order $1/N_C^2$, b is the string parameter [PARJ(42) in PYTHIA], and the area difference is defined as $\Delta A = A^{\mathrm{old}} - A^{\mathrm{new}}$, with the area for a string piece between partons i and j being $A(p_i, p_j) = 2(p_i \cdot p_j - m_i \cdot m_j)$. We will use the standard value $P_0 = 0.1$. The model has been shown to give a good description of the diffractive structure function at HERA [6] as well as other characteristics of both the diffractive and inclusive final state [30]. Both the SCI and GAL models have recently been adapted to PYTHIA 6.4 [31].

Although formulated in terms of interactions or rearrangements of strings, the GAL model describes the transition from a parton state with a given color configuration at the scale Q_0 to a set of strings at the soft scale $\mu_{\mathrm{soft}} \sim \Lambda_{\mathrm{QCD}}$. The SCI model, on the other hand, is formulated in terms of explicit exchanges of color-octet charges; although softer than the factorized dominating hard partonic interactions, they may have scales anywhere in the range from such a factorization scale down to the hadronization scale, Λ_{QCD}. Even if considering a factorization scale as low as the perturbative QCD cutoff $Q_0 \sim 1$ GeV, this range is not small in the logarithmic measure applicable in QCD. Therefore, significant soft color exchanges are to be expected—the problem is how to properly describe them. A theoretical QCD basis for SCI-like models was proposed in Ref. [32] and later developed into a dynamical color exchange model in Ref. [33].

The common feature of these color reconnection models is the usage of the factorization of the hard subprocess from the soft processes, such that the hard processes are calculated in conventional perturbative QCD whereas new model elements are introduced for the soft processes, which presently cannot be treated with rigorous QCD theory. However, the clean case of diffractive deep inelastic scattering has been extensively studied at HERA and found to be leading twist, i.e., having the same dependence on the hard scale Q^2 as inclusive deep inelastic scattering. This indicates that the hard process, manifested at central rapidity of the event, is effectively factorized from the soft process between the initial and final protons at large rapidity. In accordance with this and illustrated in Fig. 1(b), the SCI and GAL models treat the gluon initiating the hard subprocess based on conventional collinear factorization as a probabilistic density function for a gluon with small transverse momentum and virtuality. The additional soft color-octet exchanges are similarly factorized in the model from the hard subprocess, although a theoretically well-defined factorization scheme is not available here. Altogether, these exchanges can result in an overall color-singlet exchange.

The fact that these models are phenomenologically very successful in describing data on several diffractive scattering processes, as well as a continuous transition to inclusive event samples, indicates that they effectively account for dominant aspects of a proper theoretical description, and may therefore guide theoretical developments concerning soft QCD.

Based on these models one may develop a physical interpretation. The large momentum transfer of the hard scattering subprocess implies that it takes place in a small spacetime region that is embedded in a color "background" field of the Fermi-sized, bound-state proton. The color-neutralizing soft exchanges with this background occur before any color charges are separated by more than the Fermi scale of $\sim\Lambda_{\mathrm{QCD}}$ where hadronization sets in. Based on the uncertainty relation, one cannot specify the spacetime ordering of the soft exchanges better than that given by their soft momentum scale μ_{soft}, discussed above. A proper quantum-mechanical treatment on the amplitude level with interferences can in a probabilistic Monte Carlo model only be effectively described. In the case of DIS however, the Feynman diagram-based calculation in Ref. [33] shows that summing such multiple gluon exchanges to all orders leads to exponentiation and an amplitude in analytic form, which is dominantly imaginary, as is characteristic for diffractive scattering. The longitudinal momentum fraction carried by the soft exchanges can be assumed to be very small, and their transverse momentum corresponds to a Fermi motion in the proton. Combining this with the gluon entering the hard subprocess, described by a gluon density $g(x, Q_0^2)$ dominantly at small x and the conventional Gaussian transverse Fermi motion, one naturally obtains leading protons with the experimentally observed distribution e^{-bt} ($b \sim 7$ GeV^{-2}) for the diffractive momentum transfer $t \sim -p_\perp^2/z$ by using $b \sim 1/2\Lambda_{\mathrm{QCD}}^2$.

Returning to the process under consideration, $pp \to p[W^{\pm}X]p$, we note that the requirement of leading protons implies that the momentum fractions of the initiating partons will be $x_1 \sim x_2 \sim M_{WX}/\sqrt{s} \ll 1$ for the $W^{\pm}X$ system at central rapidity $y \sim 0$. For such small x, gluon-initiated processes are expected to dominate due to the large gluon density, in our case giving $gg \to Wq\bar{q}$. The quark (sea or valence) content of the proton could become noticeable at larger x_1 or x_2, i.e., at larger rapidities or larger M_{WX}, but in this case one or even both remnants will predominantly not hadronize into leading protons.

In the framework of Monte Carlo event generators, the most essential issue for diffraction and leading protons is how the proton remnant is treated. Conventional generators employ hadronization models based on color-triplet string fields, most notably the Lund model [2]. Gluons are here represented by energy-momentum-carrying kinks on a string, but quarks, antiquarks and diquarks are triplet charges at the end of strings. Therefore, even if a gluon is resolved in the hard process, the color octet uud remnant is still split into triplet and antitriplet color charges to describe the color structure of the event for later hadronization, even though these color charges are not individually resolved. If the remnant turns out to be color neutral when the hadronization scale is reached, the details of how a hadronization model attempts to merge the individual triplet and antitriplet charges affect the spectrum of diffractive-like leading protons. One could consider a modified Monte Carlo treatment in which the *uud* remnant is kept as a single object until the hadronization scale is reached and then, after soft color exchanges, is split if it is not in a color-singlet state.

To summarize, the common key feature of diffractive-like events generated by color reconnection models is the dominance of a gluon-initiated hard parton process augmented by additional softer color-octet exchanges, resulting in a t-channel exchange which is color singlet and electrically neutral. Thus, the overall expectation is that no charge asymmetry between diffractive W^+X and W^-X production should appear, which is contrary to the claim in Ref. [20].

III. RESULTS

The following results are obtained by simulations of $pp \to W^{\pm}X$ events at the LHC energy $\sqrt{s} = 14$ TeV as well as $\bar{p}p \to W^{\pm}X$ events at the Tevatron energy $\sqrt{s} = 1.96$ TeV using PYTHIA [26], with basic hard subprocess $q\bar{q} \to W$. An implementation of the SCI and GAL models [31] for the color exchanges before hadronization with the standard Lund model [2] is used for generating the diffractive events. However, details of the Monte Carlo modeling, such as the multiparton interactions and the treatment of the proton remnants, are also crucial for the resulting leading proton spectrum, as we will demonstrate by comparing different versions and tunes of PYTHIA. As a baseline we use PYTHIA version 6.425 with the Perugia 0 tune [34], which mainly has been adjusted to data from the Tevatron. In the following we will start by exploring the single leading proton spectra at LHC energies. We will then turn to the rapidity distributions of the W's both at the Tevatron and the LHC. Finally, we will discuss the question of the W charge asymmetry.

A. Single leading protons

The basic features of the single leading proton spectrum in diffractive $W^{\pm}X$ production at 14 TeV are demonstrated in Fig. 2, showing the momentum distributions of protons and small mass clusters. The latter are required to have the same quark content as a proton and invariant masses $m_{cl} \leq 1.5$ GeV, but are not required to be in a color-singlet state. These cluster spectra have been scaled with a numerical factor such that they agree with the leading proton spectra for large z. The color-exchange mechanism (SCI or GAL) can turn these clusters into color-singlet states, giving rise to leading protons after hadronization. At the same time the actual amount of leading protons will depend on the hadronization mechanism used in the Monte Carlo. If the cluster mass is above the threshold for two-particle production $m_{cl} \gtrsim m_p + m_\pi$ it will likely give two particles that share the cluster momentum. This also means that the resulting leading proton spectrum will be sensitive to the masses assigned to the quarks and diquarks in the proton remnant, as will be made more clear below. The top left panel of Fig. 2 clearly shows the two contributions to the proton spectrum, which are the diffractive-like peak from beam protons staying intact after an overall color-singlet exchange and the tail of the usual hadronization spectrum. We note that the shape of the cluster spectrum resembles the proton spectrum in the peak region. We also note that although the normalization is somewhat different, the shapes of the leading proton spectra obtained with the SCI and GAL models are very similar.

However, the forward peak may be lost due to details in the Monte Carlo models. As an example, in the Perugia 11 tune shown in the top right panel of Fig. 2 there is no "diffractive peak" even at the parton level and, hence, also not at the hadron level. The reason for this is that in the Perugia 11 tune dipoles stretched between perturbative partons and the beam remnant are allowed to radiate in the forward direction, which effectively resolves the constituents of the proton remnant and treats them as pointlike charges.

For comparison, we add the results for the same observable from the older PYTHIA 6.215 using the old virtuality-ordered parton shower and underlying event model based on multiple interactions treated separately from the parton shower, which differs from the new PYTHIA version where they are intertwined. More specifically, the latter means that there is a common Sudakov form factor for both initial- and final-parton showering as well as the multiple interactions, instead of one for each. As a consequence, the exponentially suppressed tail of the distribution giving events with very low extra activity is different in the two versions, but it is precisely these events that contribute to the diffractive sample.

The bottom row of Fig. 2 shows the results of PYTHIA 6.215 with and without multiple interactions. Removing additional partons from the proton as is done by multiple interactions certainly reduces the momentum fraction left for the remnant, which may result in smearing out the "diffractive peak" and shifting it down to smaller momentum fractions. The resulting protons are now mixed with the contribution of protons coming from string hadronization, which makes it impossible to single out the "diffractive" component.

This implementation of multiple interactions was also used in Ref. [20] in the study of the W charge asymmetry in the SCI model together with a lower cut on the forward protons of $z^{\rm cut} = 0.85$. Based on the bottom right panel of Fig. 2, we note that the resulting event sample contains large contributions from the quark-induced subprocesses,

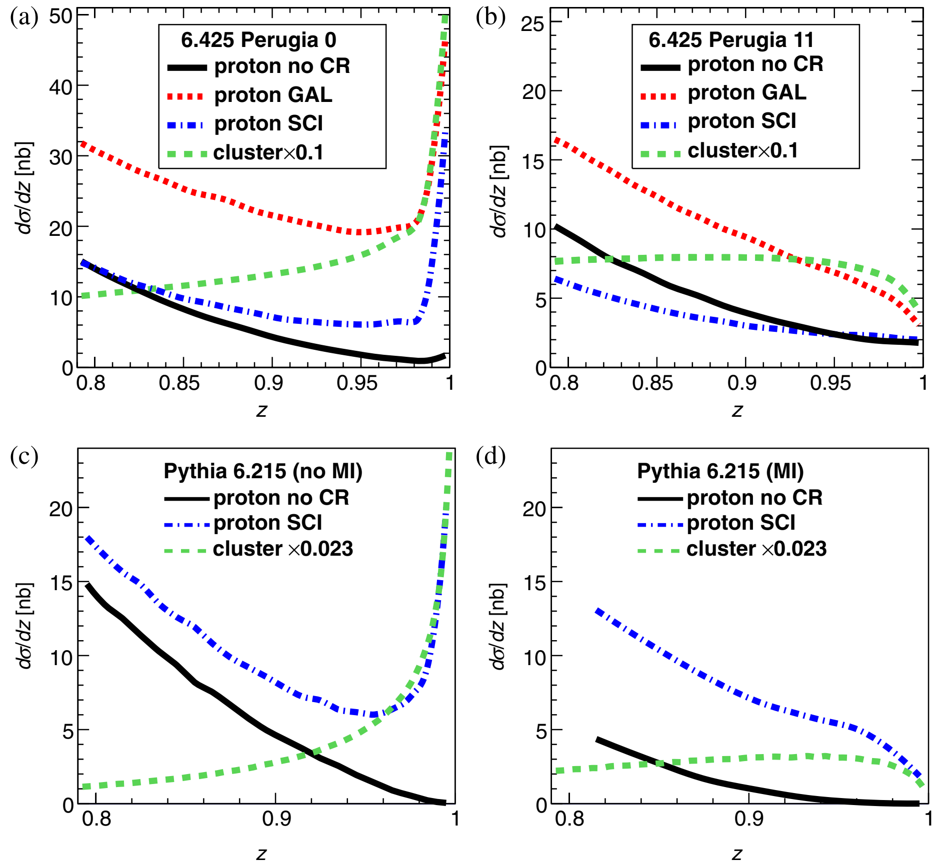

FIG. 2 (color online). Distribution in momentum fraction $z = |p_z|/p_{\mathrm{beam}}$ of the single leading proton in $pp \to p[W^{\pm}X]$ events at $\sqrt{s} = 14$ TeV obtained from different versions and tunes of PYTHIA without color reconnections and with GAL and SCI models. Leading clusters with $m_{cl} < 1.5$ GeV and proton flavor quantum numbers, but not necessarily color singlets, are scaled down to overlap with the diffractive proton peak at $z \to 1$.

instead of only charge-symmetric gluon-induced ones, and thereby a non-negligible source for the W asymmetry from such a nondiffractive sample has emerged, as will be made more clear below. In the Regge approach, this corresponds to contributions induced not only by pomeron exchange, but also by Reggeon exchanges in terms of meson trajectories. These are expected to introduce a charge asymmetry, since, e.g., a "meson" exchange of π^+ quantum numbers leaving a leading neutron is less suppressed than a π^- exchange, leaving a more massive forward Δ^{++}. Thus, comparing pomeron exchange alone with soft color exchange models can only be done in the peak region of $z \to 1$ up to hadronization corrections, as discussed above.

It should be noted that the diquark fragmentation tail clearly seen in Fig. 2 is inherent to all hadronization models and is always there irrespective of whether or not one employs a color reconnection model. It is also clear from the figure that for large $z \to 1$, the leading proton spectra obtained with color reconnection models follows the one from the leading clusters. It is thus natural to use the difference between the leading proton spectrum with reconnections and the one without as the genuine diffractive contribution. At the same time, this simple picture is complicated by the fact that such leading protons can also arise in the Monte Carlo model from the combination of the valence diquark and a sea quark with the right quantum numbers. It is therefore not completely clear where to draw the line between diffractive and nondiffractive contributions. This is a natural consequence of the color reconnection models having no sharp distinction between these two types of events but instead providing a smooth transition between diffractive and inclusive processes [5].

B. *W* charge asymmetries

Having established these properties of the single leading proton spectrum in the Monte Carlo model, which are of fundamental importance for any discussion of diffractive-like phenomena, we now turn to the W charge asymmetries in the case of single and double leading protons.

We start by showing the rapidity distributions of the produced W's when requiring single or double leading protons (or antiprotons for the Tevatron), where a leading

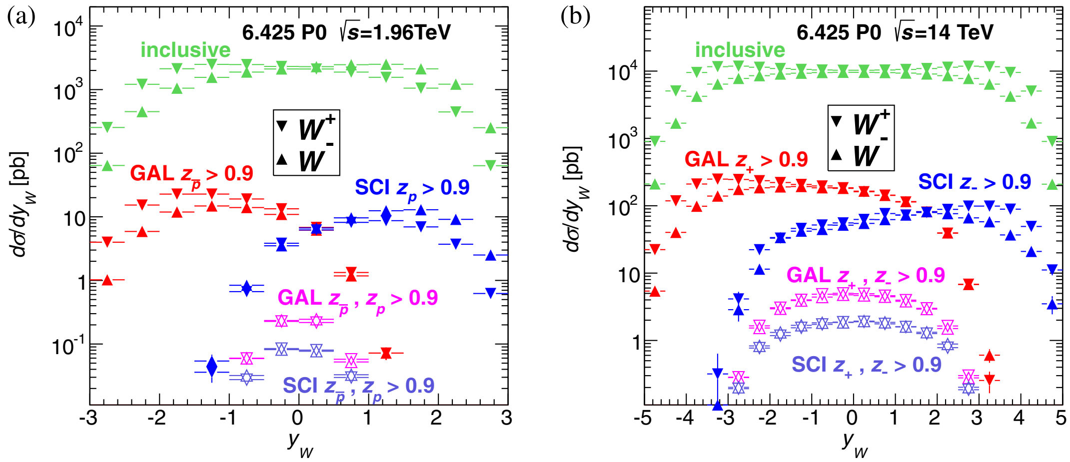

FIG. 3 (color online). The distribution in rapidity of inclusive $W^{\pm}$ production compared to the results when requiring single or double leading protons in the GAL and SCI models for the Tevatron (left) and LHC (right) energies, respectively. In the Tevatron case, $z_{\bar{p}}$ (z_p) denotes the fractional momentum of the leading antiproton (proton) compared to the beam energy, whereas for LHC z_+ (z_-) is the fractional momentum of the leading proton in the positive (negative) direction. The results have been obtained with PYTHIA 6.425 using the Perugia 0 (P0) tune.

proton is operationally defined as having $z > 0.9$. Figure 3 shows the resulting distributions obtained by using the GAL and SCI models while also comparing them to the inclusive rate. The left plot shows results for the Tevatron with the antiproton beam assumed to be along the positive z axis. As is clear from the figure, the ratio of the cross section with a single leading antiproton (illustrated for the GAL model) as well as a single leading proton (shown for the SCI model) to the inclusive one is close to 1% (taking into account a factor of 2 for the leading protons, the ratio is 1.0% for GAL and 0.5% for SCI), whereas the ratio of double leading to single leading rates is smaller and amounts to 0.3% for GAL and 0.2% for SCI. This can be compared with the recent results from the CDF experiment at the Tevatron [18]. They find that $(1.00 \pm 0.11)\%$ of the W's are produced with a single leading proton or antiproton with $0.90 < z < 0.97$ and $-1 < t < 0$ GeV^2 and that the fraction of double leading to single leading protons is less than 1.5%. Although the experimental measurements done at the Tevatron are not precisely for the same conditions, the results are very encouraging, and the overall agreement is as good as can be expected without having resorted to a retuning of the Monte Carlo model.

Going to LHC energies, as depicted in the right panel of Fig. 3, the ratio of single leading protons to the inclusive one is about 3% with the GAL model (again including a factor of 2 to take both sides into account), to be compared with 1% with the SCI model, and the ratio of double leading to single leading is 0.8% (0.9% for SCI). From the figure it is also clear that the higher energy at the LHC opens up a much larger W rapidity region when requiring both single and double leading protons. In addition, there is a $W^{\pm}$ charge asymmetry in the case of single leading (anti) protons, which is very similar to the inclusive case, but this asymmetry becomes much smaller for double leading protons. It should be clear that there is an additional uncertainty in these results due to the extrapolation of both the color reconnection and hadronization models to LHC energies. However, a detailed analysis of this uncertainty goes beyond the scope of the present paper.

In order to investigate the asymmetries in more detail, we start by considering the rapidity distributions of the $W^{\pm}$ and the corresponding asymmetries at LHC energies in Fig. 4 for different cuts on z of the leading protons on both sides, and for comparison the inclusive distributions without any z cut. As can be clearly seen from the figure, for both the GAL and SCI models the rates as well as the asymmetries are strongly dependent on the z cut. For not so strong cuts on z the asymmetry is close to the inclusive one, whereas for stronger cuts $z \gtrsim 0.9$ the asymmetry goes away at the percentage level. For the GAL model it even becomes slightly negative, although this may depend on tunable parameters. To show this we also include a curve with the asymmetries for double leading clusters with $z > 0.9$.

From the figure it is also clear that for the SCI model the asymmetries are generally larger than for the GAL model, except for $z \to 1$. The reason is that in the SCI model the leading protons with $z \lesssim 0.9$ are mainly produced from diquark fragmentation, as will become more clear below. Finally, we also see that harder cuts on z correspond to a more central production of the $W^{\pm}$, which is a simple kinematical consequence of requiring leading protons. For example, $z > 0.9$ means that the c.m.s. energy of the $W^{\pm}X$ system is less than $\sqrt{\hat{s}_{\max}} = 1.4$ TeV and thus the rapidity of the $W^{\pm}$ is limited to $|y_W| < \log \sqrt{\hat{s}_{\max}}/m_W = 2.86$.

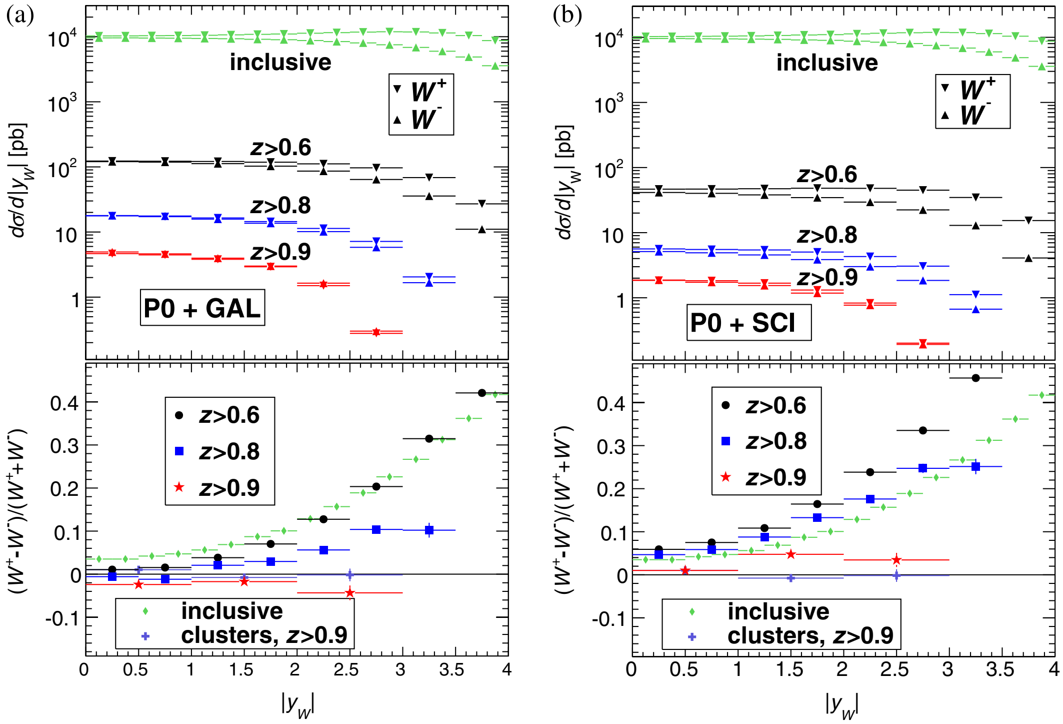

FIG. 4 (color online). The differential cross sections in rapidity y_W (top) and the corresponding charge asymmetries (bottom) for the GAL (left) and SCI (right) models. The curves correspond to the double leading protons, unless stated otherwise, obtained with PYTHIA 6.425 using the Perugia 0 (P0) tune model.

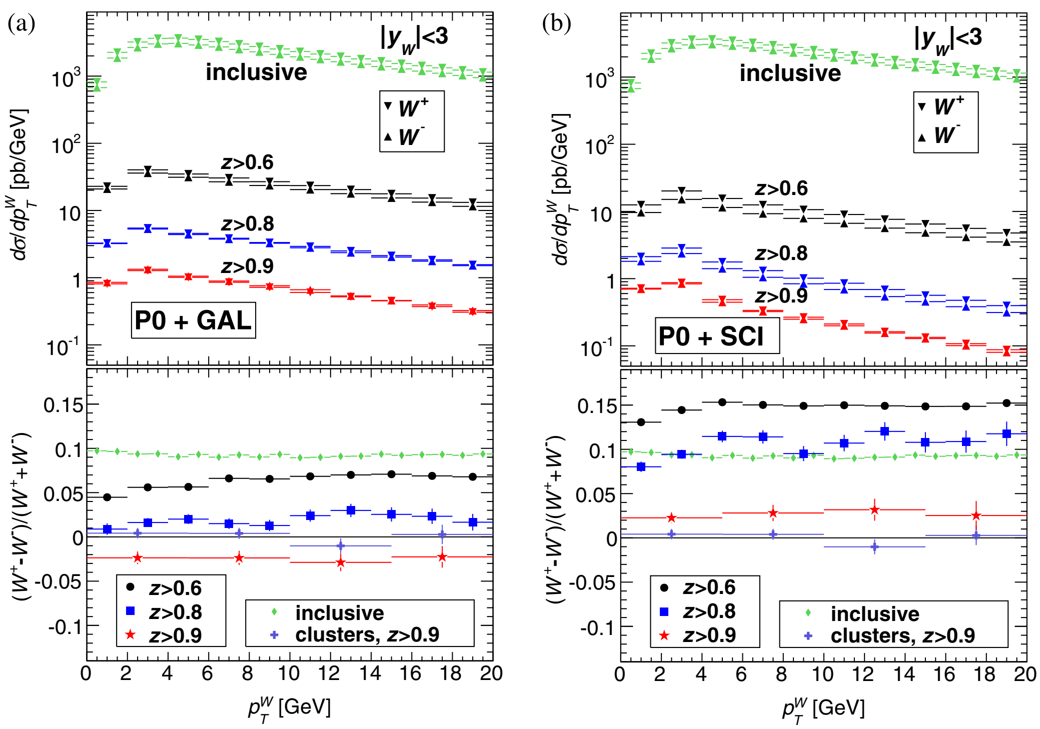

FIG. 5 (color online). The differential cross sections in transverse momentum p_T^W (top) and the corresponding charge asymmetries (bottom) for the GAL (left) and SCI (right) models. The curves correspond to the double leading protons, unless stated otherwise, obtained with PYTHIA 6.425 using the Perugia 0 (P0) tune.

Figure 5 shows the transverse-momentum (p_T) distribution for the $W^{\pm}$. We first note that for both the GAL and SCI models the requirement of double leading protons suppresses the cross section for large p_T more than for small p_T compared to the inclusive one, which is natural given the way that the reconnection models are constructed. We also see that the W p_T spectrum becomes slightly steeper at large p_T when requiring high-z protons from the SCI model, since the increased parton multiplicity in high-p_T events implies increased combinatorics for soft color exchanges that in turn reduces the probability for the proton remnant to emerge as a color singlet. The charge asymmetry is again clearly visible for inclusive production and is only weakly dependent on p_T. The requirement of more leading protons gives essentially no or little asymmetry for $z > 0.9$ in both models. The remaining asymmetry is of the order of a few percent and is the result of hadronization effects, which again can be seen by comparing it to the asymmetry for clusters and is thus well within an overall uncertainty of the diffractive Monte Carlo modeling.

It is also instructive to look at the spectra of leading protons on both sides simultaneously. In order to make the picture as clean as possible we show in Fig. 6 the spectrum of protons in the positive direction (z_+) when also requiring a leading proton on the negative side (z_-) with a similar momentum fraction $|z_- - z_+| < 0.025$. In addition, we show the results not only for the GAL and SCI models but also the results when neither of them is applied.

Similarly, in the case of single leading protons, the characteristic diffractive peak at $z \to 1$ can also be seen for the case with double leading protons in Fig. 6 (top row). However, it is visible at central W rapidities only. For more forward W bosons the peak disappears, essentially due to momentum conservation. The figure also shows that the "diffractive" peak for central W's is more pronounced in the case of SCI compared to GAL, and that—similar to the single leading proton case—GAL already gives an increased production of leading protons from $z \gtrsim 0.6$ compared to the standard Perugia 0 tune, whereas in the SCI model the additional double leading protons are only seen for $z \gtrsim 0.85$.

Turning to the charge asymmetries we first note that in the limit $z \to 1$ the valence quarks of the initial proton have to be part of the outgoing proton, so there is no way to obtain any W charge asymmetry in this case. Indeed, in Fig. 6 (bottom row) we see the vanishing asymmetry at large $z \to 1$ for both the GAL and SCI models. At the same time, since in the diquark fragmentation contribution both valence and sea quarks may initiate the production of a diffractive-like $W^{\pm}$, such a mechanism leads to a noticeable W charge asymmetry at moderate $z \lesssim 0.9$ (see Fig. 6, bottom row). From the figure it is also clear that the relative importance of this contribution is larger for the SCI model than for the GAL one, giving larger asymmetries in the former case. Finally, for larger W rapidities the asymmetry is larger, which is due to an increasing probability for a quark-initiated W production.

Having studied the W charge asymmetries in detail in both the GAL and SCI models it is thus clear that the Monte Carlo simulation affirms the statements made on

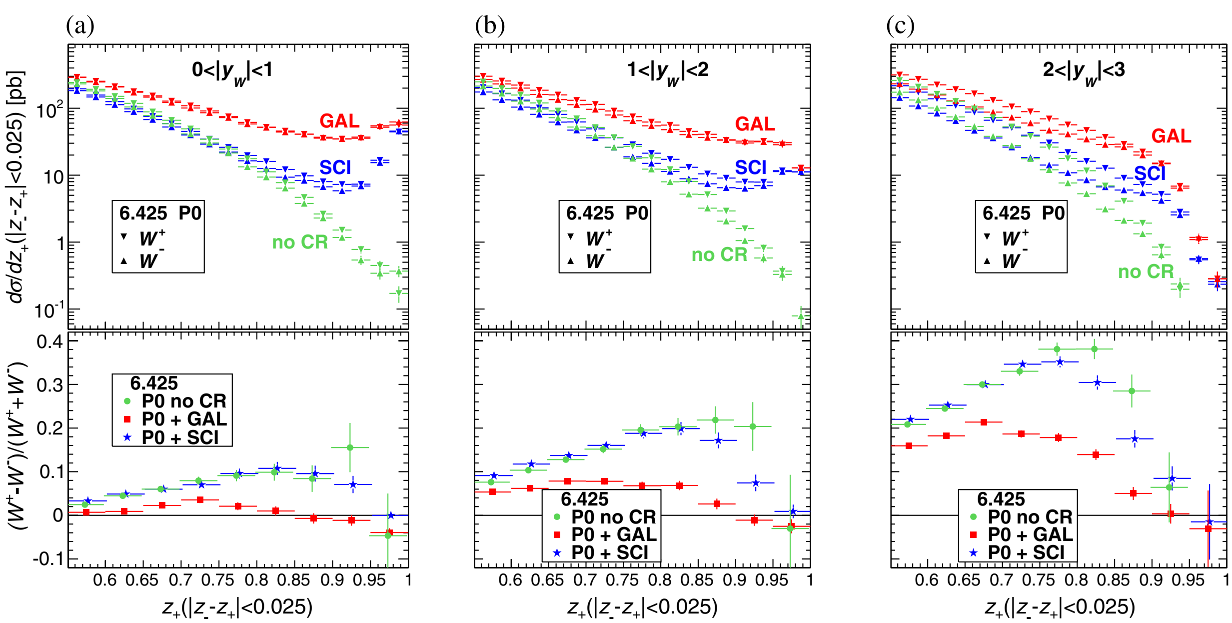

FIG. 6 (color online). The differential cross sections in the longitudinal momentum fraction of the leading proton moving in the positive direction z_+ (with simultaneous requirement on the z fraction of the second leading proton moving in the negative direction z_- as $|z_- - z_+| < 0.025$), (top) and the corresponding charge asymmetries (bottom) for different rapidity intervals as indicated.

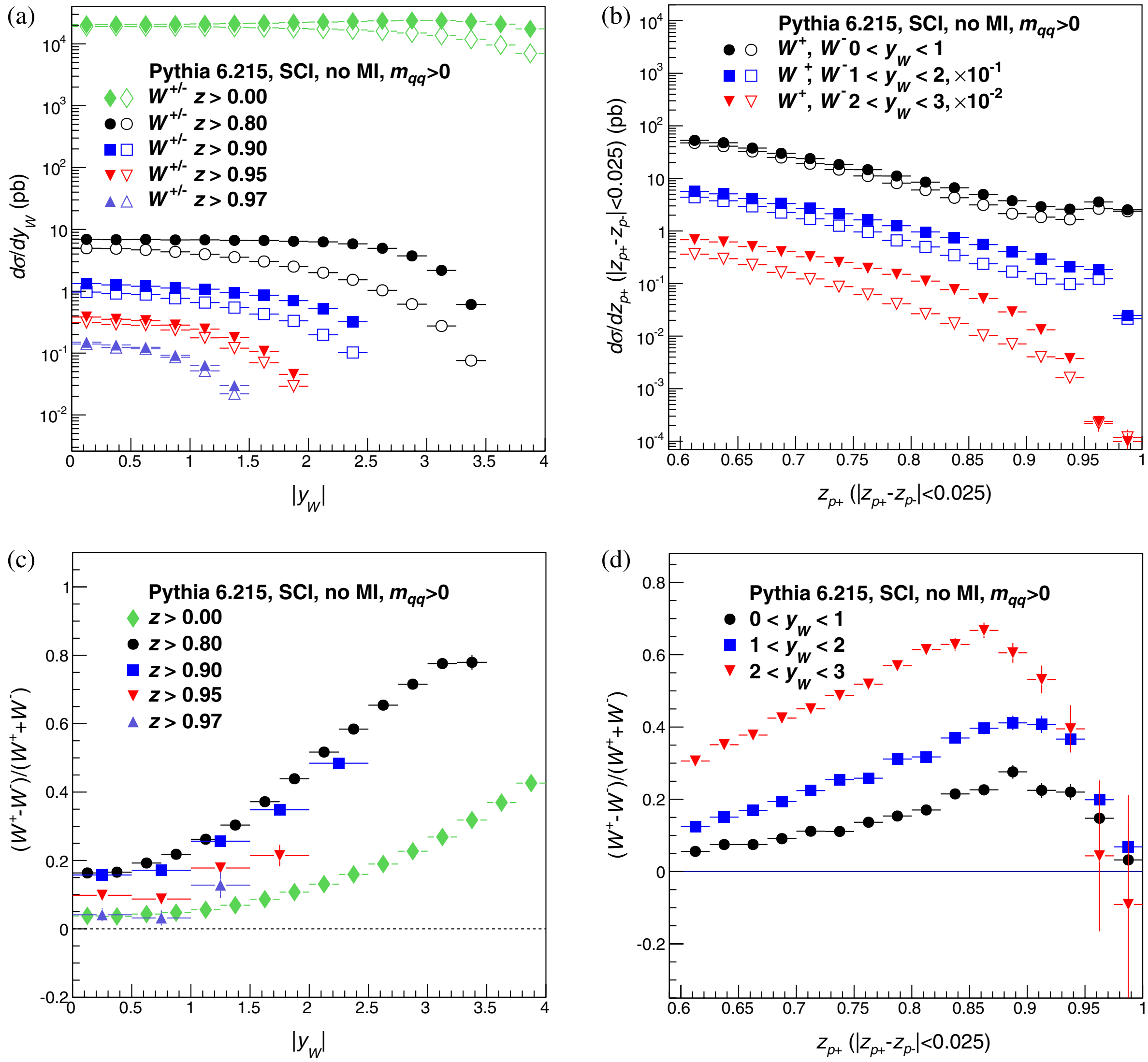

FIG. 7 (color online). Diffractive W-production cross sections and W charge asymmetry when requiring both leading protons in the earlier 6.215 version of PYTHIA with default settings but no multiple interactions. Left: $d\sigma/dy_W$ for different cuts on $\min(z^+, z^-)$ of leading protons. Right: $d\sigma/dz_+$ of the leading protons, requiring both protons to have similar z, for different bins in W rapidity.

general grounds, namely that the charge asymmetry vanishes or, at least, becomes very small in the asymptotic case $z \longrightarrow 1$. Before coming to the conclusions we now want to discuss the question of the origin of the asymmetry reported recently in Ref. [20], where the earlier 6.215 version of PYTHIA was used. Given the results obtained above with PYTHIA version 6.425 and the general arguments of why there should be no electric charge transfer in the t-channel in the limit $z \longrightarrow 1$, the observation of such an asymmetry may seem contradictory. In order to be able to resolve this apparent contradiction we have used the old 6.215 version of PYTHIA in the following. However, based on the observation made above that there was no "diffractive" peak in the single leading proton spectrum when running the Monte Carlo with the same settings as used by Ref. [20], we have turned off the multiple interactions.

We start by investigating the cross sections and corresponding asymmetries as functions of the W rapidity and the momentum fraction of the leading proton on the positive side when requiring a leading proton on the negative side with similar momentum, as displayed in Fig. 7. Comparing this with the results obtained with PYTHIA 6.425, there are two things that stand out. On the one hand, when requiring double leading protons, the cross sections are much smaller when using the old Pythia version and the asymmetries are much larger. At the same time, in the limit $z \longrightarrow 1$ it is still true that the asymmetries vanish. However, looking at the double leading proton momentum fraction it is clear that even for

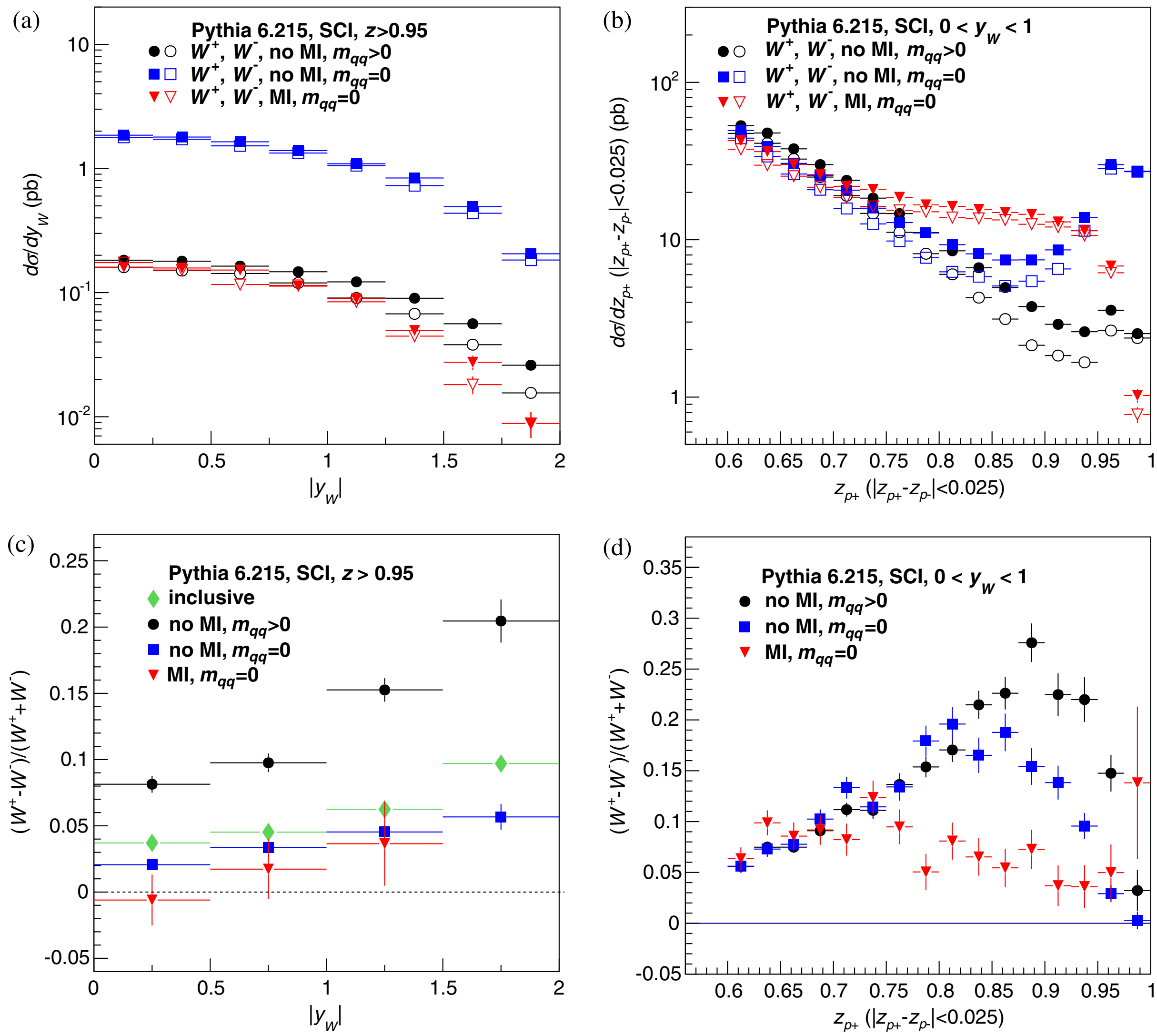

FIG. 8 (color online). Comparison of the results for the cross sections (top) and corresponding charge asymmetries (bottom) as functions of the W rapidity for $z > 0.95$ (left) and the momentum fraction z for central rapidities $|y_W| < 1$ (right), comparing different choices of the diquark masses used in the remnant treatment, as well as multiple interactions.

central W's there is not really any diffractive-like peak in this case.

The explanation of this apparently contradictory result has to do with the details of the Monte Carlo setup used in Ref. [20]. It has long been known [35] that the amount of leading protons depends crucially on the constituent masses assigned in the Monte Carlo to the valence quarks and diquarks in the proton remnant. The default values in the 6.215 version are $m = 0.33$ GeV for quarks and $m = 0.58(0.77)$ GeV for spin-0 (spin-1) diquarks. In addition, the partons in the proton remnant are given some transverse momentum. This means that the invariant mass of the quark-diquark system will in most cases be above the threshold for two-particle production, such as $p + \pi$. Then most clusters will give two particles instead of only one and hence very few high-z protons (cf. the cluster scaling factors in Fig. 2).

In the later version of PYTHIA (6.425), the kinematics of the remnant is calculated using massless four-vectors for the valence quarks and diquarks. This means that a much larger fraction of the clusters will have invariant masses that are small enough to give just one proton (or other baryon depending on the flavor and spin quantum numbers). To verify that this is indeed the explanation, we show in Fig. 8 the results obtained when setting the diquark masses to zero. (For clarity we only show the results for $z > 0.95$.) From the figure it is clear that this gives a substantial increase of the cross section and at the same time a decrease of the asymmetry. Looking at the distribution in fractional momentum z for centrally produced W's we see that with this setting there is a diffractive-like peak. For reference we also show the results obtained when including the multiple interactions. This decreases both the magnitude of the cross section and the asymmetries, but at the same time there is no diffractive peak, as demonstrated before.

IV. SUMMARY AND CONCLUSIONS

In this paper we have revisited the SCI and GAL color reconnection models for diffractive and exclusive $W^{\pm}X$ production at LHC ($\sqrt{s} = 14$ TeV) and Tevatron energies, when requiring both single and double leading protons (or antiprotons for the Tevatron). The requirement of a leading beam particle constitutes a much more stringent test of the models than just requiring a rapidity gap and also leads to a sensitivity to other ingredients in the Monte Carlo model, in particular the constituent quark and diquark masses. Even so, when applying the SCI and GAL models to the recent PYTHIA version 6.425 using the Perugia 0 tune, the resulting rates are in overall agreement with data from the CDF experiment. Thus the models can also be used to make predictions for the upcoming experiments at the LHC implying, however, that there is an extra systematic uncertainty related to the extrapolation from the Tevatron energy.

Despite the sensitivity of the probability for additional soft color exchanges, we have shown in this paper how the spectra of leading protons are also sensitive to other aspects in event generators, in particular the amount of parton showering, the implementation of multiple interactions and the constituent quark and diquark masses. Investigating diffractive physics in the context of soft color exchange models therefore provides a possible way to constrain these complex and partly uncertain aspects of the Monte Carlo treatment. Based on our results we find that in both the SCI and GAL models the diffractive-like protons start to be significant when the outgoing proton carries a fractional momentum z of the beam energy that is larger than ~ 0.9, and only for $z \gtrsim 0.95$ do they dominate the spectrum. For lower z, the spectrum is dominated by protons from diquark fragmentation. In addition, for double leading protons, the diffractive-like peak is only visible for centrally produced $W^{\pm}$ with rapidity $|y_W| \lesssim 1$.

A focus of our paper has been the issue of any possible W charge asymmetry in diffractive $W^{\pm}X$ production with double leading protons at the LHC, and we argue on general grounds that a charge asymmetry must be highly suppressed because there is no charge exchange in the t-channel in this kinematic limit. Looking at W's produced centrally and requiring double leading protons with $z > 0.9$ we find that the charge asymmetry vanishes at the percent level, in agreement with the general expectations. Even so, there are details that differ between the two color reconnection models. Figure 2 shows that both have the same shape of the diffractive peak, the main difference is that the underlying background level of the proton z spectrum is higher for the GAL model. This difference is also seen in Fig. 6. In addition, the charge asymmetry is smaller in the GAL model, going to zero around $z \sim 0.8$, whereas in the SCI model the asymmetry is close to or larger than the inclusive one for $z \lesssim 0.8$. Thus, in this nondiffractive region, the charge asymmetry and double leading proton spectrum can potentially be used to discriminate between the SCI and GAL models.

Finally, we have clarified that the charge asymmetry observed in Ref. [20] originates in the use of the older PYTHIA 6.215 multiple-interactions model, default constituent quark and diquark masses and a leading proton definition requiring the relaxed cut $z > 0.85$. As a consequence the fraction of diffractive-like protons is very small and instead the results are completely dominated by the diquark fragmentation contribution, making the result incompatible with a pomeron-based model, which does inherently only describe the diffractive part. On the other hand, for a cut of $z > 0.85$ a Regge-based model can not rely on pomeron exchange only but should also consider nonvacuum Reggeon exchanges, which may well introduce a charge asymmetry.

A major strength of the color exchange models, such as SCI and GAL, is that they describe both diffractive and inclusive events with a smooth transition in between. The GAL model is based on a string-field minimization property that may reveal important aspects of the soft QCD color field. The SCI model has recently been developed into a proper QCD-based model [33] for diffractive deep inelastic scattering that does describe the salient features of data from HERA. Since this model is derived from k_T factorization at the amplitude level it is nontrivial to cast into a probabilistic Monte Carlo framework, but such an extension is under development [36] in order to facilitate more detailed comparisons with the data. Models of the kind studied in detail in this paper will be tested by the expected LHC data on various diffractive processes, which should increase our understanding of soft QCD dynamics.

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