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

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Abstract

We revisit diffractive and exclusive $W^{\pm}X$ production at hadron colliders in different models for soft colour 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 colour reconnection models. Our detailed analysis of the latter models at LHC energies shows, however, that they give similar results as pomeron models for very leading protons and central $W^{\pm}X$ production, including a vanishing $W^{\pm}$ charge asymmetry. We demonstrate that soft colour 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 hadronisation models. Such sensitivity also concerns the differential distributions in proton momentum and $W^{\pm}$ transverse momentum which opens possibilities to discriminate between different colour 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 back-bone 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 non-perturbative QCD dynamics and, thereby, providing a tool to explore this unsolved sector of QCD.

Considering as low scales as $\mu_{\text{soft}} \sim \Lambda_{\text{QCD}}$, individual gluons are not resolved and one should rather consider collective gluon fields, such as modeled by colour string-fields in the Lund hadronisation model [2], or even hadron-like objects, such as 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 colour 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 Colour Interaction (SCI) model [5] and has later been developed in various ways such as the Generalized Area Law (GAL) model [6] making the probability for colour 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 LHC, where the Higgs boson mass might be reconstructed from a measurement of the leading proton momenta [9, 10]. The estimated cross-section is, however, 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]. 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 anti-protons [16]. Compared to measurements based on rapidity gaps, this has the advantage of 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 [17, 18] due to a quite 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 factorisation breaking in diffractive Drell-Yan and W, Z production [19] enhances the interest for this kind of processes.

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 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 [18] on W charge asymmetry in the latter case.

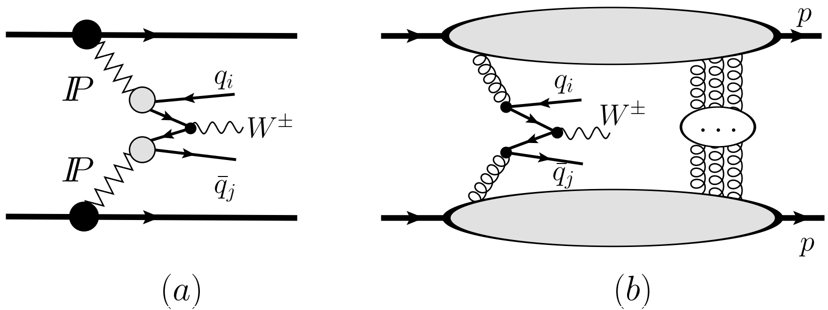

Figure 1. The exclusive diffractive process $pp \to p[W^\pm X]p$, with central $W^\pm + 2$ jets separated from the final protons, based on (a) double pomeron exchange in Regge approach and (b) soft colour exchange in QCD.

II. COLOUR 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. Fig. 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 [20], and different models of diffraction can then be tested.

On general grounds, the requirement of a leading proton (or anti-proton) in the final state, which is more or less unscathed, means that the momentum transfer 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 $1 - z \sim M_{\mathrm{WX}}/\sqrt{s} \ll 1$ (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.

In the Regge approach, this type of processes are described in terms of single or double pomeron exchange (DPE), Fig. 1a, using a factorisation into a pomeron flux and parton density functions (PDF) in the pomeron. Such diffractive PDF's 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 PDF's are not universally applicable for other diffractive processes. For example, 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 observed at the Tevatron [21]. Although this problem can be cured by introducing an overall renormalisation through a soft rapidity gap survival factor depending on the cms 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 colour topologies of the confining string-fields, giving different hadronic final states after hadronisation. In particular, a rapidity range without a string-field results in an event with a corresponding rapidity gap.

The Soft Colour Interaction (SCI) model [5] is based on the exchange of soft gluons, below the conventional cut-off $Q_0 \sim 1$ GeV for perturbative QCD. The momentum exchange does then not significantly change the momenta of emerging partons, but the exchange of colour does change the colour structure of the emerging parton system, resulting in a modified string-field topology and thereby affecting the resulting distribution of final state hadrons. In effect, the SCI model introduces a probability, given by a parameter $P_{\rm SCI}$, for the exchange of a colour octet between any pair of partons (including beam and target spectators) emerging from the perturbative QCD treatment of the event in the Monte Carlo event generators Lepto [22] for deep inelastic lepton-nucleon scattering or Pythia [23] for hadron-hadron scattering. As a result, a modified string topology is obtained before the conventional Lund hadronisation model [2] is applied. In spite of its simplicity and with a single value of the only new parameter $P_{\rm SCI}$, 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 [24, 25]. The model has also been applied for predicting diffractive Higgs production at the LHC [26]. In the following we will be using the canonical value $P_{\rm SCI} = 0.5$.

In the same spirit as the original SCI model, but with a different mechanism for non-perturbative colour rearrangements, the Generalized Area Law (GAL) model has been developed in [6]. The GAL model was a first attempt to make the colour reconnection probability dynamical instead of static as in the SCI model. In short it employs the difference in generalized string area for two different string configurations to weight the reconnection probability, $P_{\rm GAL} = P_0\,[1 - \exp(-b\Delta A)]$, 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 $\Delta A = A^{\rm old} - A^{\rm new}$ 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 [27]. Both the SCI and GAL models have recently been adapted to Pythia 6.4 [28].

Although formulated in terms of interactions or rearrangements of strings, the GAL model describes the transition from a parton state with a given colour configuration at the scale Q_0 to a set of strings at the soft scale $\mu_{\rm soft} \sim \Lambda_{\rm QCD}$. The SCI model, on the other hand, is formulated in terms of exchange of gluons, although softer than the factorized dominating hard partonic interactions, they may have scales anywhere in the range from such a factorisation scale down to the hadronisation scale, $\mu_{\rm soft} \sim \Lambda_{\rm QCD}$. Even if considering a factorisation scale as low as the perturbative QCD cut-off $Q_0 \sim 1$ GeV, this range is not small in the logarithmic measure applicable in QCD. Therefore, significant soft colour exchanges are to be expected — the problem is how to properly describe them. A theoretical QCD-basis for SCI-like models has been proposed in [29] and developed into a dynamical colour exchange model later in [30].

The common feature of the various colour reconnection models is that the hard production process of the $[W^\pm X]$ system is described using standard collinear factorisation. Given the requirement of leading protons, the momentum fractions of the initiating partons will be $x_1 \sim x_2 \sim M_{\rm WX}/\sqrt{s} \ll 1$ for the $W^\pm X$ system at central rapidity $y \sim 0$. Such small-x, processes are expected to be dominated by gluons, e.g. $gg \to Wq\bar{q}$, due to the large gluon density. 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 $M_{\rm WX}$. In this case, one or even both protons will predominantly be destroyed by the interaction, giving a reduced contribution to the process of interest.

As illustrated in Fig. 1b, the colour octet charge of the gluon initiating the hard subprocess can be compensated by additional gluon exchanges resulting in an overall colour singlet exchange. Provided that all these gluons have small transverse momenta, the proton can remain in a coherent state with only some loss of longitudinal momentum. In accordance with the uncertainty relation, the time and space ordering of these exchanges cannot be specified better than the inverse of the momentum transfer scale. When this is soft, colour exchange is possible before the coherence of the proton is destroyed. When it stays intact one has the leading proton characteristic for diffractive scattering. When it does not stay intact, it may emerge as an excited small mass state. In case the gluon exchange does not constitute a singlet exchange, a colour charged proton remnant will emerge and hadronise, which may still produce a leading proton, but then at a lower fraction of the initial beam momentum.

This scenario is compatible with the exchanged gluons as parts of the bound state proton and given by standard parameterisations of the gluon density $g(x, Q_0^2)$, giving a large probability for gluons with small longitudinal momentum fraction x. Moreover, with the conventional gluon $p_\perp$-distribution at Q_0 given by a Gaussian distribution of width $\sim \Lambda_{\rm QCD}$ (often referred to as intrinsic $p_\perp$), one naturally obtains the experimentally observed distribution e^{-bt}, with $b \sim 1/2\Lambda_{\rm QCD}^2$, of the momentum transfer squared $t \sim -p_\perp^2/z$ to the final proton.

To summarize, the common key feature of diffractive-like events generated by colour reconnection models, is the dominance of a gluon-initiated hard parton process augmented by additional softer colour octet exchanges, resulting in a t-channel exchange which is colour 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 [18].

For diffraction and leading protons more generally, the most essential issue is how the proton remnant is treated. Conventional Monte Carlo event generators employ hadronisation models based on colour 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, a colour octet uud remnant is conventionally "split" into a quark and a diquark with triplet and anti-triplet colour charges and separate four-vectors, which is called a "cluster" in the following. This split occurs even if the above soft colour exchanges restore the remnant to a colour singlet. In this case the valence quark and diquark have to be recombined during hadronisation to form a hadron or a small-mass system which further decays, and the details of these splitting and recombination procedures affect the spectrum of diffractive-like leading protons. A proper treatment of diffraction may motivate a changed Monte Carlo procedure where the proton's uud remnant is kept as a single object during the coherence time and only split if it emerges, after colour exchanges, in a colour octet state.

When the proton remnant is not in a colour singlet state after colour reconnections, hadronisation can still produce a spectrum of leading protons, extending to large fractions z of the beam momentum.

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 [23], with basic hard subprocess $q\bar{q} \to W$. An implementation of the SCI and GAL model [28] for the colour exchanges before hadronisation with the standard Lund

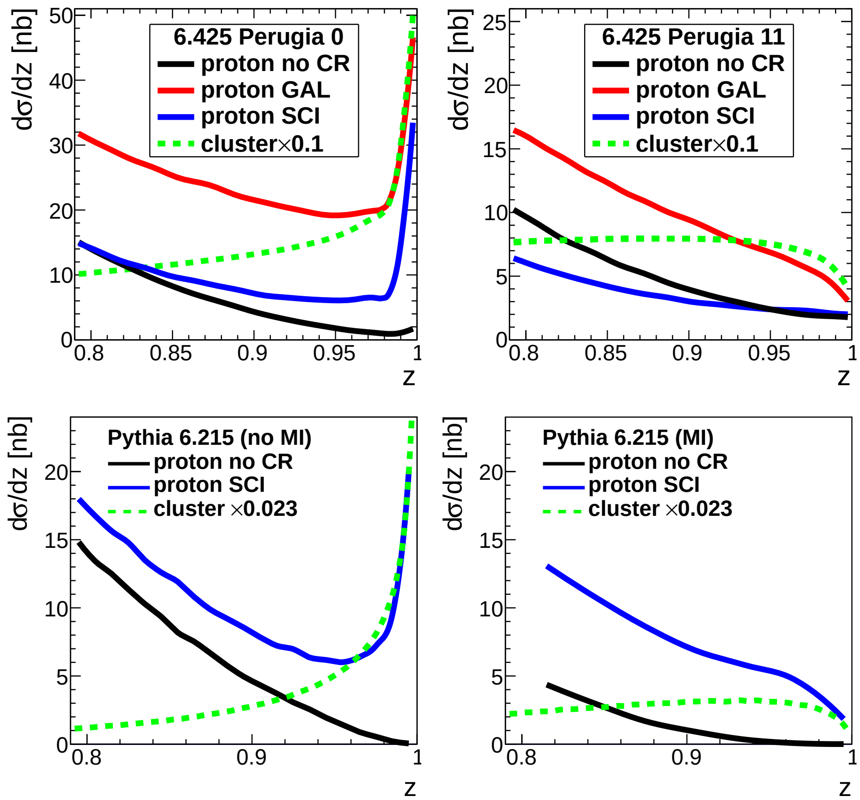

Figure 2. Distribution in momentum fraction $z = |p_z|/p_{\rm beam}$ of the single leading proton in $pp \to p[W^\pm X]$ events at $\sqrt{s} = 14$ TeV obtained from different versions and tunes of Pythia without colour reconnections and with GAL and SCI models. Leading clusters with $m_{cl} < 1.5$ GeV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

model [2] is used for generating the diffractive events. However, details in the Monte-Carlo modeling such as the multi-parton 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 baseline we use Pythia version 6.425 with the Perugia 0 tune [31], 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 colour 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 colour exchange mechanism (SCI or GAL) can turn these clusters into colour singlet states, giving rise to leading protons after hadronisation. At the same time the actual amount of leading protons will depend on the hadronisation 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. Fig. 2 top-left clearly shows the two contributions to the proton spectrum which are the diffractive-like peak from beam protons staying intact after an overall colour singlet exchange, and the tail of the hadronisation spectrum. We note that the shape of the cluster spectrum resembles the proton spectrum in the peak region. We also note that although the normalisation 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 corner of Fig. 2 there is no "diffractive peak" even at parton level and, hence, also not at 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. Not only is it doubtful to what extent one can properly define dipole radiation from such a system but, in addition, this effectively means that the non-perturbative remnant is radiating perturbative partons in contradiction with the leading proton coherence condition.

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 at difference to the new Pythia version where they are intertwined. More specifically the latter means that there is a common Sudakov form factor for both intitial 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 precisely these events contribute to the diffractive sample.

The bottom row of Fig. 2 shows the result 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 hadronisation, which makes it impossible to single out the "diffractive" component.

This implementation of multiple interactions was also used in [18] in the study of the W charge asymmetry in the SCI model together with a lower cut on the forward protons of $z^{cut} = 0.85$. Based on Fig. 2 bottom-right we note that the resulting event sample contains large contributions from the quark-induced subprocesses, instead of only charge-symmetric gluon-induced ones, and thereby a non-negligible source for the W asymmetry from such a non-diffractive 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. "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 colour exchange models can only be done in the peak region of $z \to 1$ up to hadronisation corrections discussed above.

It should be noted that the diquark fragmentation tail clearly seen in Fig. 2 is inherent

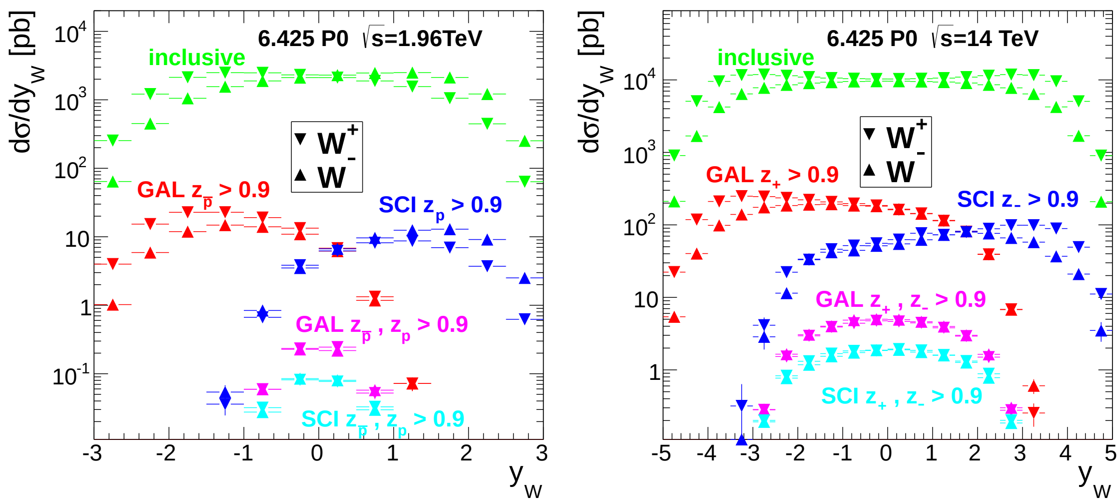

Figure 3. The distribution in rapidity of inclusive $W^{\pm}$ production compared to the results when requiring single or double leading protons in the GAL and SCI models for the Tevatron (left) and LHC (right) energies, respectively. In the Tevatron case $z_{\bar{p}}$ (z_p) denotes the fractional momentum 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.

to all hadronisation models and is always there irrespectively of whether one employs a colour reconnection model or not. It is also clear from the figure that for large $z \to 1$, the leading proton spectra obtained with colour reconnection models follow 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 them 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 from the combination of the valence diquark and a sea quark with the right quantum numbers. In this case, the coherence of the proton can clearly not be retained and, therefore, this should not be considered as part of the diffractive sample. It is, therefore, not completely clear where one should draw the line between diffractive and non-diffractive contributions. This is a natural consequence of the colour 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 antiproton for the Tevatron), where a leading proton is operationally defined as having $z > 0.9$. Fig. 3 shows the resulting distributions obtained by using GAL and SCI models comparing also 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 for having 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 two 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 [16]. 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 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 inclusive is about 3 % with the GAL model (again including a factor two to take into account both sides) 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 both when requiring single and double leading protons. In addition, whereas for the single leading (anti)protons there is an asymmetry between W^+ and W^- very similar to the inclusive one, in the case of double leading protons any charge asymmetry is much smaller than the inclusive one. It should be clear that there is an additional uncertainty in these results due to the extrapolation of both the colour reconnection and hadronisation 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 $W^{\pm}$'s 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 seen clearly 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 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 cms 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. 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 enhances the cross-section for small p_T compared to the inclusive one, which is natural given the way 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 imply increased combinatorics for soft colour exchanges

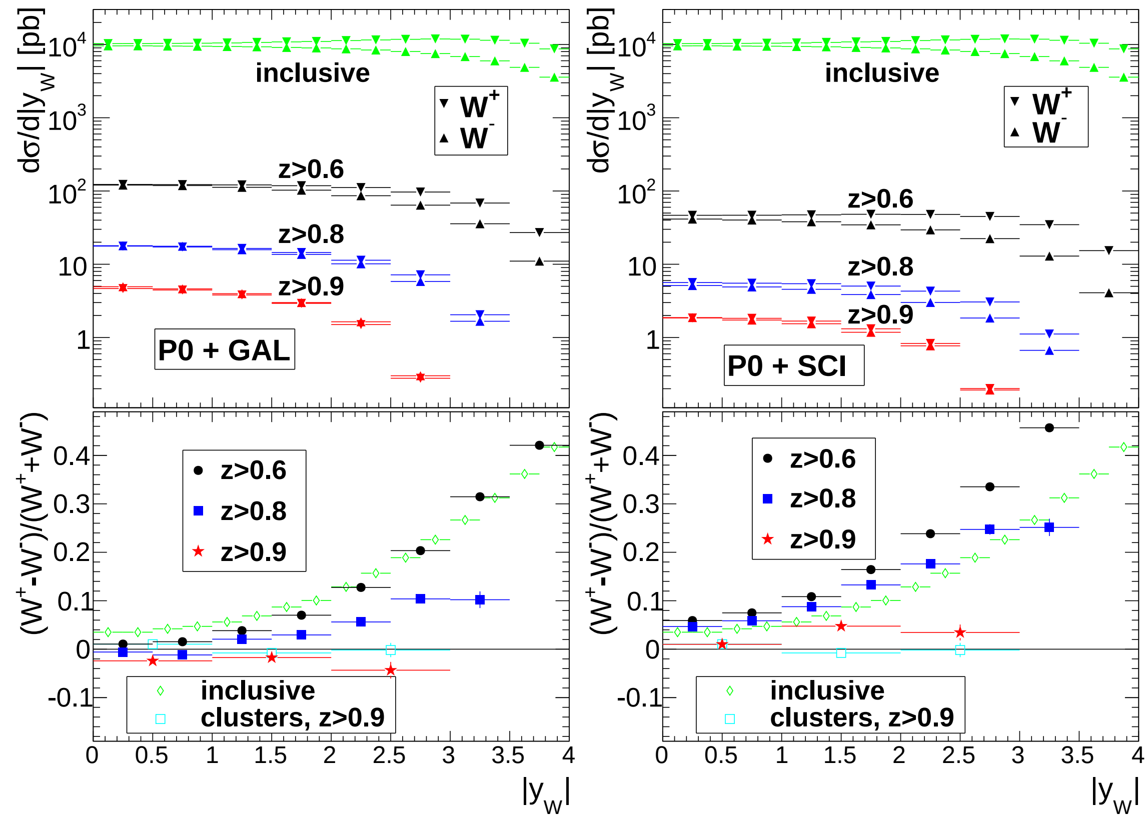

Figure 4. The differential cross sections in rapidity y_W (top) and the corresponding charge asymmetries (bottom) for the GAL (left) and SCI (right) models. The curves correspond to the double leading protons, unless stated otherwise, obtained with Pythia 6.425 using the Perugia 0 (P0) tune model.

that in turn reduces the probability for the proton remnant to emerge as a colour singlet. Turning to the charge asymmetry, it is again clearly visible for the inclusive production, although mostly as an overall difference in the normalization for W^+ and W^- respectively. The effects of requiring more and more leading protons can also be clearly seen giving essentially no or little asymmetry for $z > 0.9$ in both models. The remaining asymmetry is of the order a few percent and is the result of hadronisation effects, which again can be seen comparing to the asymmetry for clusters and is thus well within an overall uncertainty of the diffractive Monte Carlo modeling.

In addition to looking at the kinematics of the $W^{\pm}$'s produced and the associated asymmetries, it is 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 requiring a leading proton also on the negative side (z_-) with 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 to 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. Thus in order to obtain a selection of diffractive events one has to apply also a cut on the rapidity of the W-bosons in addition to the cuts

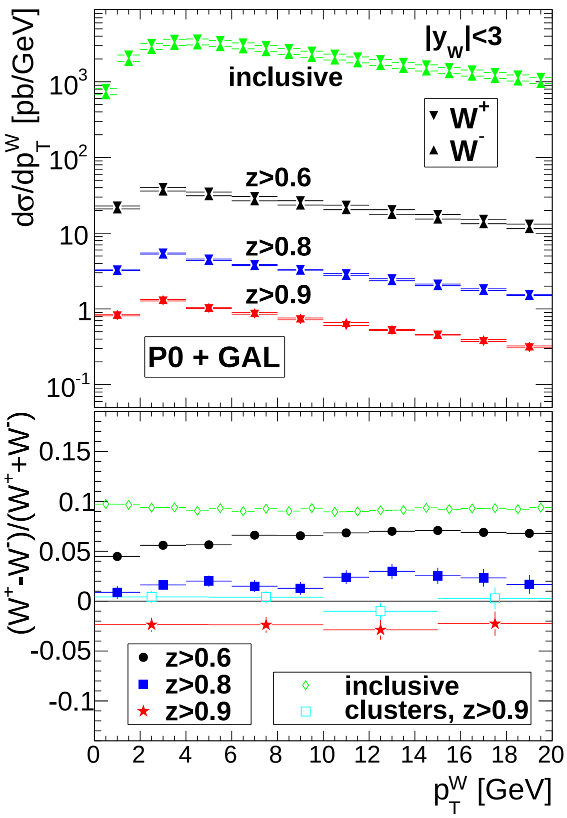

Figure 5. The differential cross sections in transverse momentum p_T^W (top) and the corresponding charge asymmetries (bottom) for the GAL (left) and SCI (right) models. The curves correspond to the double leading protons, unless stated otherwise, obtained with Pythia 6.425 using the Perugia 0 (P0) tune.

on the leading protons. From the figure it is also clear that the "diffractive" peak for central W's is more pronounced in the SCI case than in the GAL one. Similarly to the single leading proton case, this is due to an increased production of leading protons for $z \gtrsim 0.6$ in the GAL model compared to the standard Perugia 0 tune, whereas for 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 general grounds, namely, the charge asymmetry vanishes or, at least, becomes very small in the asymptotic

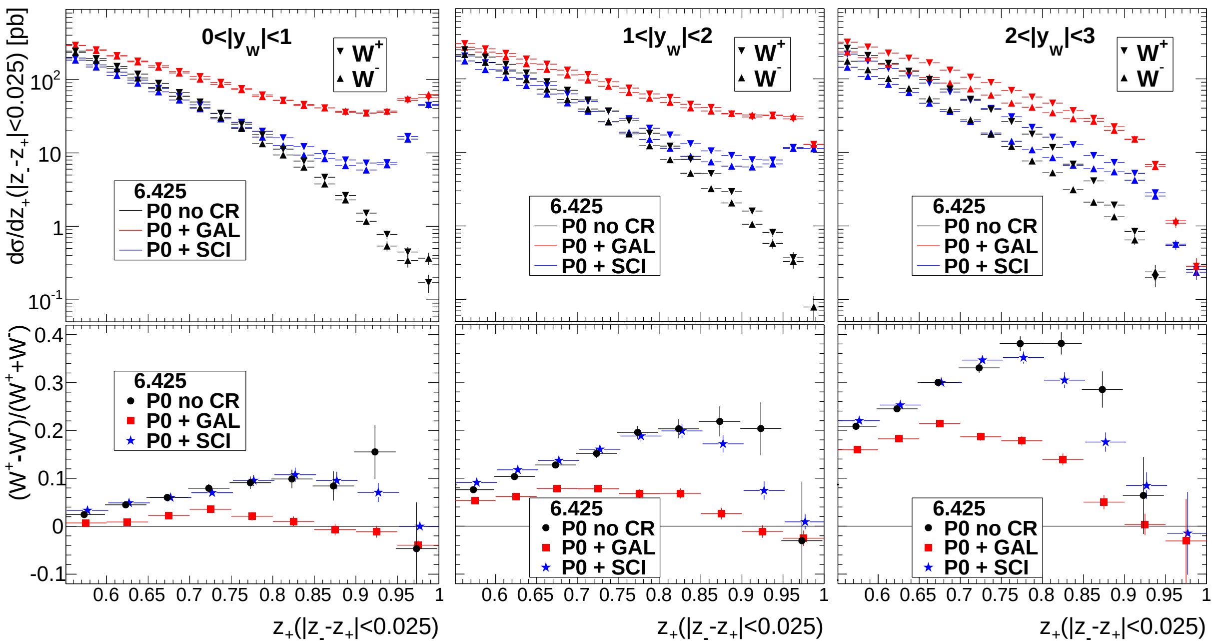

Figure 6. The differential cross sections in the longitudinal momentum fraction of the leading proton moving in the positive direction z_+ (with simultaneous requirement on the z fraction of the second leading proton moving in the negative direction z_- as $|z_- - z_+| < 0.025$), (top) and the corresponding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

case $z \to 1$. Before coming to the conclusions we now want to discuss the question of the origin of the asymmetry reported recently in [18], where the earlier 6.215 version of Pythia was used. Given the results obtained above with Pythia version 6.425 and the general arguments why there should be no electric charge transfer in the t-channel in the limit $z \to 1$, 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 [18] 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 with the results obtained with Pythia 6.425 there are two things that stand out. On the one hand the cross-sections when requiring double leading protons are much smaller when using the old Pythia version and the asymmetries are much larger. At the same time, in the limit $z \to 1$ it is still the case that the asymmetries goes away. However, looking at the double leading proton momentum fraction it is clear that even for central W's there is not really any diffractive-like peak in this case.

The explanation of this apparently contradicting result has to do with details of the Monte Carlo setup used in [18]. It has long been known [32] 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

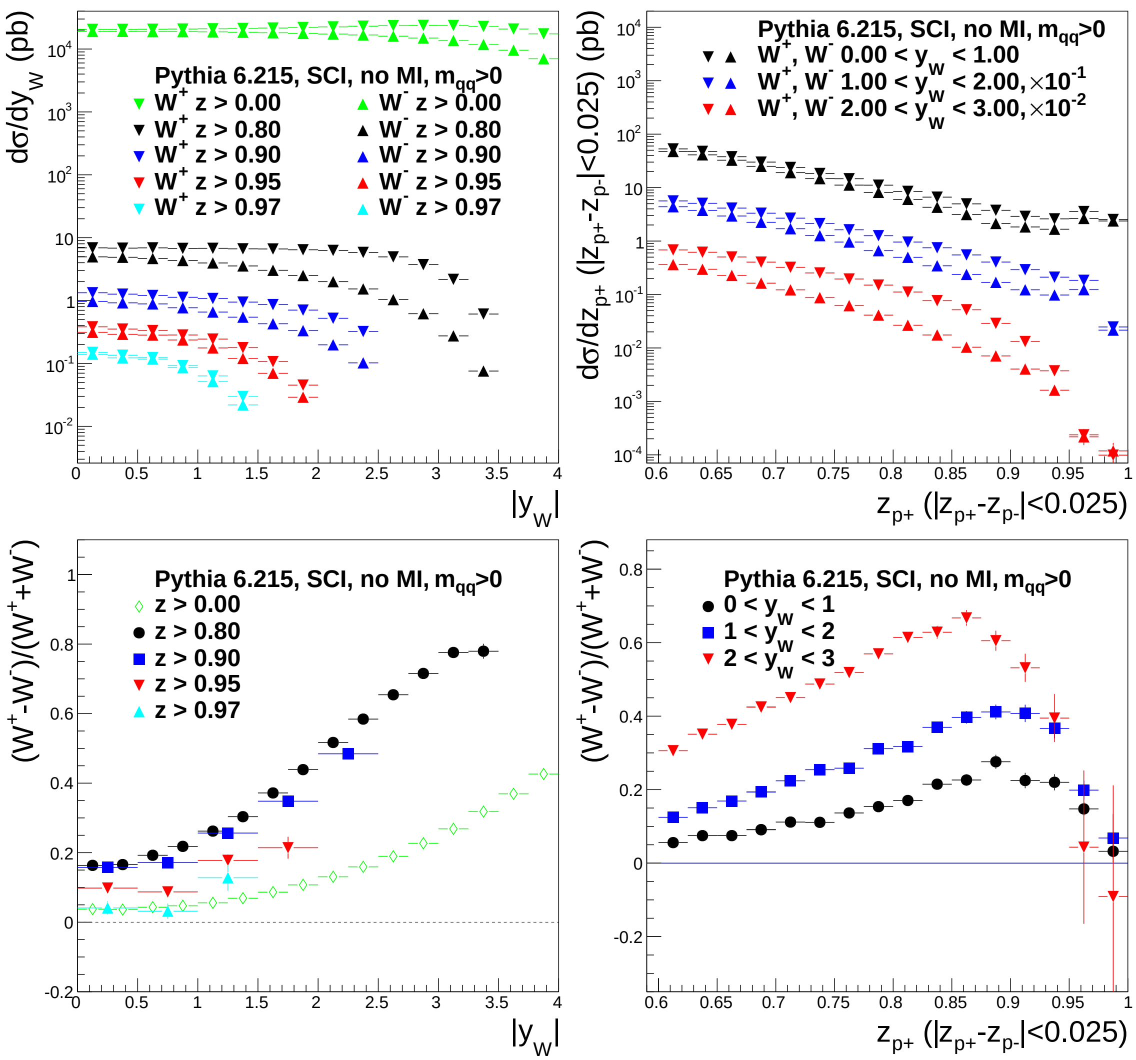

Figure 7. Diffractive W production cross sections and W charge asymmetry when requiring both leading protons in earlier 6.215 version of PYTHIA with default settings but no multiple interactions. Left: $d\sigma/dy_W$ for different cuts on $\min(z^+, z^-)$ of leading protons. Right: $d\sigma/dz_+$ of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

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 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 flavour 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

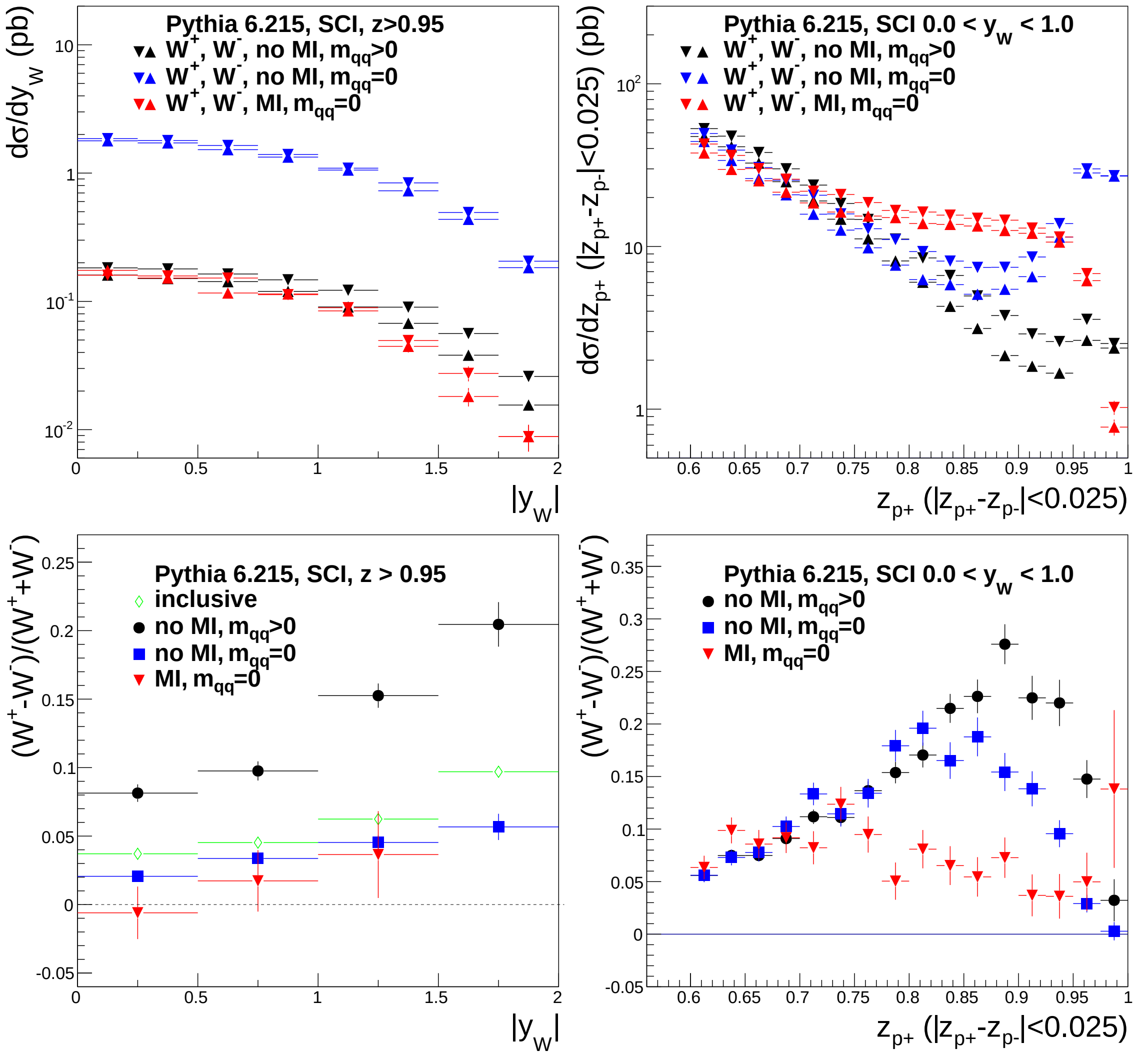

Figure 8. Comparison of the results for the cross-sections (top) and corresponding charge asymmetries (bottom) as functions of the W rapidity for $z > 0.95$ (left) and the momentum fraction z for central rapidities $|y_W| < 1$ (right) comparing different choices of the diquark masses used in the remnant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

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 colour 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 sensitivity to other ingredients in the Monte Carlo, 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.

Looking at the spectra of both single as well as double leading protons we see clear diffractive-like peaks for both the SCI and GAL models. We have, however, shown that these peaks are sensitive to other details of the Monte Carlo such as the amount of parton showering, the implementation of multiple interactions, and the constituent quark and diquark masses. Thus, in order to use these models to make predictions for diffractive-like phenomena one has to take also these effects into account.

A focus of our paper has been on the issue of any possible W charge asymmetry in diffractive $W^{\pm}X$ production with double leading protons at the LHC. On general grounds, requiring two leading protons there is no charge exchange in the t-channel, and thus no charge asymmetry should exist. This is true for diffractive-like events where the leading proton is produced from the incoming beam with only a small momentum transfer. As we have shown, in the Monte Carlo there are also other mechanisms, most importantly diquark fragmentation, which may contribute more or less to the amount of leading protons depending on how these are defined. Based on our results we find that in both the SCI and GAL models the diffractive-like protons starts to be significant when the outgoing proton carries a fractional momentum z of the beam energy which is larger than ~ 0.9 and only for $z \gtrsim 0.95$ do they dominate the spectrum. In addition, for double leading protons, the diffractive-like peak is only visible for centrally produced $W^{\pm}$ with rapidity $|y_W| \lesssim 1$.

Looking at W's produced centrally and with double leading protons each having $z > 0.9$ we find that the charge asymmetry, present when looking inclusively, goes away at the percent level in agreement with the general expectations. Even so there are details that differ between the two colour reconnection models. Fig. 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 non-diffractive 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 [18] 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.

A major strength of the colour 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 colour field. The SCI model has recently been developed into a proper QCD-based model [30] for diffractive deep inelastic scattering that does describe the salient features of data from HERA. Since this model is derived from k_T factorisation at the amplitude level it is non-trivial to cast into a probabilistic Monte Carlo framework, but such an extension is under development [33] in order to facilitate more detailed comparisons with 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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