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Single diffractive Drell-Yan and vector bosons production at the LHC

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Introduction

The exclusive diffractive production of particles in hadron-hadron scattering at high energies is one of the basic tools for both experimental and theoretical studies of the small-x and nonperturbative QCD physics. The characteristic feature of diffractive processes at high energies is the presence of a large rapidity gap between the remnants of the beam and target.

The understanding of the mechanisms of inelastic diffraction came with the pioneering works of Glauber [1], Feinberg and Pomeranchuk [2], Good and Walker [3]. If the incoming plane wave contains components interacting differently with the target, the outgoing wave will have a different composition, i.e. besides elastic scattering a new *diffractive* state will be created resulting in a new combination of the Fock components (for a detailed review on QCD diffraction, see Ref. [4]). Among the most important examples, the leading twist diffractive Drell-Yan (DDY) and vector boson production processes are of a special interest since they provide a clean experimental signature for the QCD factorisation breaking effects where soft and hard interactions interplay with each other [5–7], thus, opening up an access to soft QCD physics.

The main difficulty in the formulation of a theoretical QCD-based framework for diffractive scattering arises from the fact that it is essentially contaminated by soft and non-perturbative interactions. For example, diffractive deep-inelastic scattering (DIS), $\gamma^* p \to Xp$, although it is a higher twist process, is dominated by soft interactions [8]. Within the dipole approach [9] such a process looks like elastic scattering of $\bar{q}q$ dipoles of different sizes, and of higher Fock states containing more partons. Although formally the process $\gamma^* \to X$ is an off-diagonal diffraction, it does not vanish in the limit of unitarity saturation, the so called black disc limit. This happens because the photon distribution functions and hadronic wave functions are not orthogonal.

In hadronic diffraction the situation is different and even more complicated. It is well-known that the cross section of diffractive production of the W boson in $p\bar{p}$ collisions was found in the CDF experiment [10, 11] to be six times smaller than was predicted relying on factorization and HERA data [12]. The phenomenological models based on assumptions of the diffractive factorisation and universality of diffractive parton distributions, which are widely discussed in the literature (see e.g. Refs. [13, 14]), predict a significant increase of the ratio of the diffractive to inclusive gauge bosons production cross sections with energy. These predictions are supposed to be tested soon at the LHC. The diffractive QCD factorisation in hadron collisions is, however, severely broken by an interplay of hard and soft fluctuations and by the absorptive corrections as was recently advocated in Refs. [6, 7], and this "Yellow" paper is devoted to study of these important effects which may alter the results of diffractive factorisation based approaches.

The processes under discussion – diffractive Abelian radiation of vector (Z, $W^{\pm}$) bosons – correspond to off-diagonal diffraction. The respective observables vanish in the black-disc limit, and may be strongly suppressed by the absorptive corrections even being far from the unitarity bound. These corrections, also known as the survival probability of rapidity gaps, are related to soft initial- and final-state interactions. Usually the survival probability is introduced into the diffractive cross section in a probabilistic way and is estimated in simplified models such as eikonal, quasi-eikonal, two-channel approximations, etc.

Within the light-cone color dipole approach [9] a diffractive process is considered as a result of elastic scattering of $\bar{q}q$ dipoles of different sizes emerging in incident Fock states before and after the hard scattering. Within the dipole formulation, the study of the diffractive Drell-Yan reaction performed in Ref. [5] has revealed importance of soft interactions with the partons spectators, which contributes on the same footing as hard perturbative ones, and strongly violate QCD factorization.

One of the advantages of the dipole approach is the possibility to calculate directly (although in a process-dependent way) the full diffractive amplitude, which contains all the absorption corrections by employing the phenomenological universal dipole cross section (or dipole elastic amplitudes) fitted to data. Remarkably enough, the soft gap survival amplitude can be explicitly singled out as a factor from the diffractive amplitude being a superposition of dipole scatterings at different transverse separations.

Consider another very important source of the diffractive factorisation breaking. The diffractive Abelian γ, Z, $W^{\pm}$ radiation by a quark in quark-proton scattering in well-known to vanish in the forward direction i.e. at zero momentum transfer to the target [15]. In the case of proton-proton collisions, however, the directions of propagation of the proton and its quarks do not coincide leading to a nonvanishing diffractive Abelian radiation in forward pp scattering. Moreover, interaction with the spectator partons opens new possibilities for diffractive scattering, namely the color exchange in interaction of one projectile parton, can be compensated (neutralized) by interaction of another projectile parton. It was found in Refs. [5–7] that this contribution strongly dominates the forward diffractive Abelian radiation cross section. This mechanism leads to a dramatic violation of diffractive QCD factorisation is a result of a strong interplay between the soft and hard interactions, which considerably affects the corresponding observables. In this "Yellow" paper, we briefly discuss the corresponding effects whereas more details can be found in Refs. [6, 7].

Diffractive Abelian radiation: Regge vs dipole approach

Consider first the forward single diffractive Drell-Yan (DDY) and vector bosons production $G = \gamma$, Z, $W^{\pm}$ in pp collisions which is characterized by a relatively small momentum transfer between the colliding protons. In particular, one of the protons, e.g. p_1, radiates a hard virtual gauge G^* boson with $k^2 = M^2 \gg m_p^2$ and hadronizes into a hadronic system X both moving in forward direction and separated by a large rapidity gap from the second proton p_2, which remains intact. In the DDY case,

$$p_1 + p_2 \to X + (gap) + p_2\,, \qquad X = \gamma^*(l^+l^-) + Y\,. \tag{0.1}$$

Both the di-lepton and X, the debris of p_1, stay in the forward fragmentation region. In this case, the virtual photon is predominantly emitted by the valence quarks of the proton p_1.

In some of the previous studies [13, 16] of the single diffractive Drell-Yan reaction the analysis was made within the phenomenological Pomeron-Pomeron and γ-Pomeron fusion mechanisms using the Ingelman-Shlein approach [17] based on Regge (QCD) factorization. This led to specific features of the differential cross sections similar to those in diffractive DIS process, e.g., a slow increase of the diffractive-to-inclusive DY cross sections ratio with c.m.s. energy $\sqrt{s}$, its practical independence on the hard scale, the invariant mass of the lepton pair squared, M^2 [13].

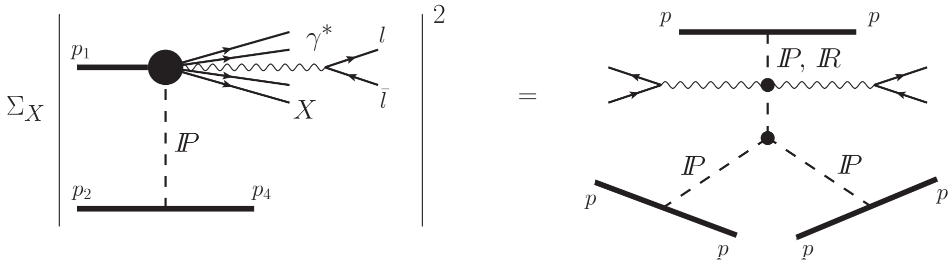

FIG. 1: The cross section of the diffractive DY process summed over all excitation channels at fixed effective mass M_X (left panel) corresponding to the Mueller graph in Regge picture (right panel).

One can derive a Regge behavior of the diffractive cross section of heavy photon production in terms of the usual light-cone variables,

$$x_{\gamma 1} = \frac{p_\gamma^+}{p_1^+}; \qquad x_{\gamma 2} = \frac{p_\gamma^-}{p_2^-}, \tag{0.2}$$

so that $x_{\gamma 1}x_{\gamma 2} = (M^2 + k_T^2)/s$ and $x_{\gamma 1} - x_{\gamma 2} = x_{\gamma F}$, where M, k_T and $x_{\gamma F}$ are the invariant mass, transverse momentum and Feynman x_F variable of the heavy photon (di-lepton).

In the limit of small $x_{\gamma 1} \to 0$ and large $z_p \equiv p_4^+/p_2^+ \to 1$ the diffractive DY cross section is given by the Mueller graph shown in Fig. 1. In this case, the end-point behavior is dictated by the following general result

$$\left.\frac{d\sigma}{dz_p dx_{\gamma 1} dt}\right|_{t\to 0} \propto \frac{1}{(1-z_p)^{2\alpha_{I\!P}(t)-1} x_{\gamma 1}^{\varepsilon}}\,, \tag{0.3}$$

where $\alpha_{I\!P}(t)$ is the Pomeron trajectory corresponding to the t-channel exchange, and ε is equal to 1 or 1/2 for the Pomeron $I\!P$ or Reggeon $I\!R$ exchange corresponding to γ^* emission from sea or valence quarks, respectively. Thus, the diffractive Abelian radiation process $pp \to (X \to G^* + Y)p$ at large Feynman $x_F \to 1$ of the recoil proton, or small

$$\xi = 1 - x_F = \frac{M_X^2}{s} \ll 1, \tag{0.4}$$

is described by triple Regge graphs $I\!\!P I\!\!P I\!\!P$ and $I\!\!P I\!\!P I\!\!R$ as represented in Fig. 2, (aa) and (ab) respectively, were we also explicitly included radiation of a virtual gauge boson G^*. Examples of Feynman graphs corresponding to the above triple-Regge terms, are shown in

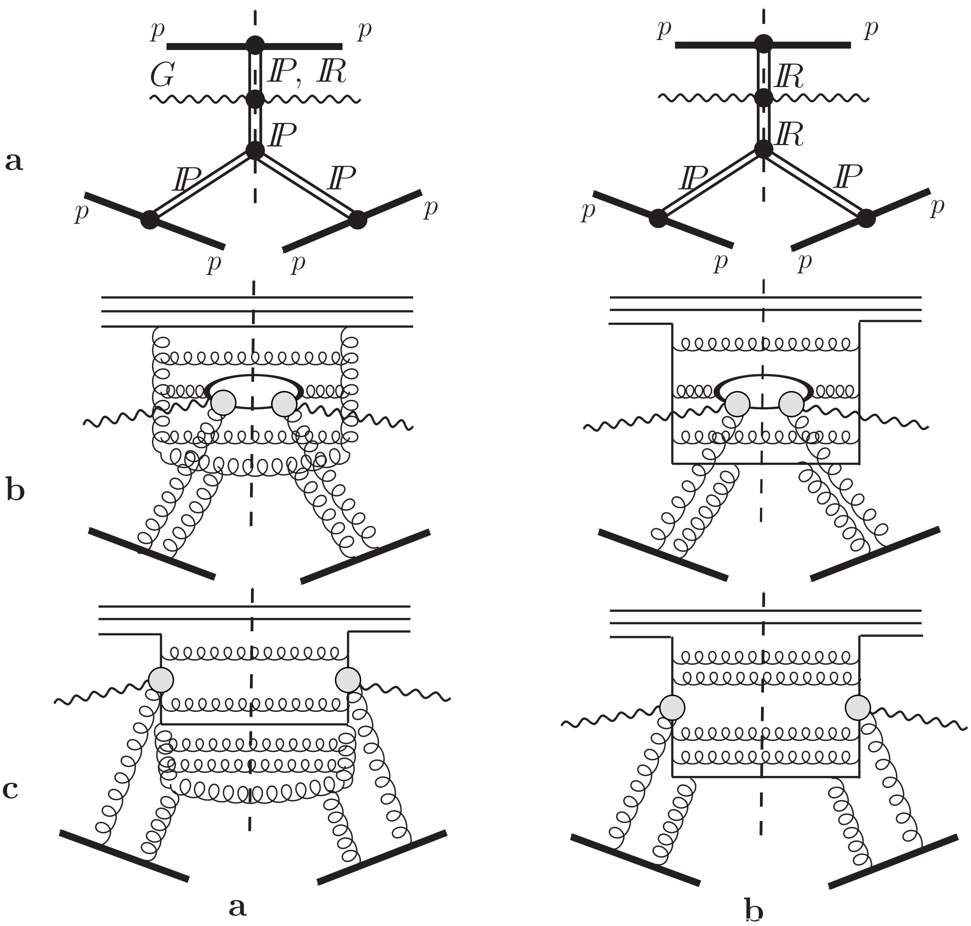

FIG. 2: *The upper row:* the triple-Regge graphs for the process $pp \to Xp$, where the diffractively produced state X contains a gauge boson. Examples of Feynman graphs corresponding to diffractive excitation of a large invariant mass, going along with radiation of a gauge boson are displayed in *the 2d and 3rd rows.* Curly and waving lines show gluons and the radiated gauge boson. The dashed line indicates the unitarity cut.

the second and third rows in Fig. 2. The graphs (ba) and (ca) illustrate the triple-Pomeron term in the diffraction cross section,

$$\frac{d\sigma^{I\!\!P I\!\!P I\!\!P}_{diff}}{d\xi dt} \propto \xi^{-\alpha_{I\!\!P}(0)-2\alpha'_{I\!\!P}(t)}, \qquad (0.5)$$

with the gauge boson radiated by either a sea, (ba), or a valence quark, (ca). The effective radiation amplitude $q+g \to q+G$ is depicted by open circles and is defined in Fig. 3. These Feynman graph interpret the triple-Pomeron term as a diffractive excitation of the incoming proton due to radiation of gluons with small fractional momentum. The proton can also dissociate via diffractive excitation of its valence quark skeleton, as is illustrated in Fig. 2

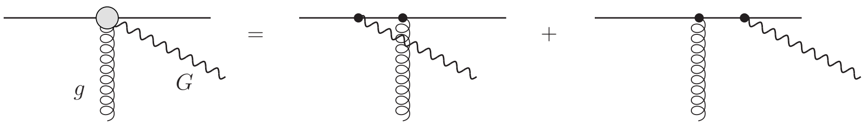

FIG. 3: The effective amplitude of gauge boson radiation by a projectile quark.

(bb) and (cb). The corresponding term in the diffraction cross section reads,

$$\frac{d\sigma^{I\!PI\!PI\!R}_{diff}}{d\xi dt} \propto \xi^{\alpha_{I\!R}(0)-\alpha_{I\!P}(0)-2\alpha'_{I\!P}(t)}\,, \tag{0.6}$$

Again, the gauge boson can be radiated either by a sea quark, (bb), or by the valence quark, (cb).

As an alternative to the Regge factorization based approach, the dipole description of the QCD diffraction, was presented in Refs. [9] (see also Ref. [18]). It is based on the fact that dipoles of different transverse size $r_\perp$ interact with different cross sections $\sigma(r_\perp)$, leading to the single inelastic diffractive scattering with a cross section, which in the forward limit is given by [9],

$$\left.\frac{\sigma_{sd}}{dp_\perp^2}\right|_{p_\perp=0} = \frac{\langle\sigma^2(r_\perp)\rangle - \langle\sigma(r_\perp)\rangle^2}{16\pi}, \tag{0.7}$$

where $p_\perp$ is the transverse momentum of the recoil proton, $\sigma(r_\perp)$ is the universal dipole-proton cross section, and operation $\langle\ldots\rangle$ means averaging over the dipole separation.

The color dipole description of inclusive Drell-Yan process was first introduced in Ref. [19] (see also Refs. [20, 21]) and treats the production of a heavy virtual photon via Bremsstrahlung mechanism rather than $\bar{q}q$ annihilation. The dipole approach applied to diffractive DY reaction in Refs. [5, 6] and later in diffractive vector boson production ([7]) has explictly demonstrated the diffractive factorisation breaking in diffractive Abelian radiation reactions. This effect manifest itself in specific features of observables like a significant damping of the cross section at high $\sqrt{s}$ compared to the inclusive production case. This is rather unusual, since a diffractive cross section, which is proportional to the dipole cross section squared, could be expected to rise with energy steeper than the total inclusive cross section, like it occurs in the diffractive DIS process. At the same time, the ratio of the DDY to DY cross sections was found in Ref. [5, 6] to rise with the hard scale, M^2. This is also in variance with diffraction in DIS, which is associated with the soft interactions [8].

Such striking signatures of the diffractive factorisation breaking are due to an interplay of soft and hard interactions in the corresponding diffractive amplitude. Namely, large and small size projectile fluctuations contribute to the diffractive Abelian radiation process on the same footing providing the leading twist nature of the process , whereas diffractive DIS dominated by soft fluctuations only is of the higher twist [5, 6].

It is worth emphasizing that the quark radiating the gauge boson cannot be a spectator, but must participate in the interaction. This is a straightforward consequence of the Good-Walker mechanism of diffraction [3]. As was mentioned above, the contribution of a given projectile Fock state to the diffraction amplitude is given by the difference of elastic amplitudes for the Fock states including or excluding the gauge boson,

$$\mathrm{Im}\, f^{(n)}_{diff} = \mathrm{Im}\, f^{(n+G)}_{el} - \mathrm{Im}\, f^{(n)}_{el}\,, \tag{0.8}$$

where n is the total number of partons in the Fock state; $f_{el}^{(n+G)}$ and $f_{el}^{(n)}$ are the elastic scattering amplitudes for the whole n-parton ensemble, which either contains the gauge boson or does not, respectively. Although the gauge boson does not participate in the interaction, the impact parameter of the quark radiating the boson gets shifted, and this is the only reason why the difference Eq. (0.8) is not zero. This also conveys that this quark must interact in order to retain the diffractive amplitude nonzero [5, 6]. For this reason in the graphs depicted in Fig. 2 the quark radiating G always takes part in the interaction with the target.

Notice that there is no one-to-one correspondence between diffraction in QCD and the triple-Regge phenomenology. In particular, there is no triple-Pomeron vertex localized in rapidity. The colorless "Pomeron" contains at least two t-channel gluons, which can couple to any pair of projectile partons. For instance in diffractive gluon radiation, which is the lowest order term in the triple-Pomeron graph, one of the t-channel gluons can couple to the radiated gluon, while another one couples to another parton at any rapidity, e.g. to a valence quark (see Fig. 3 in [15]). Apparently, such a contribution cannot be associated literally with either of the Regge graphs in Fig. 2. Nevertheless, this does not affect much the x_F- and energy dependencies provided by the triple-Regge graphs, because the gluon has spin one.

It is also worth mentioning that in Fig. 2 we presented only the lowest order graphs with two gluon exchange. The spectator partons in a multi-parton Fock component also can interact and contribute to the elastic amplitude of the whole parton ensemble. This gives rise to higher order terms, not shown explicitly in Fig. 2. They contribute to the diffractive amplitude Eq. (0.8) as a factor, which we define as the gap survival amplitude [7].

A. Diffractive Abelian radiation off a dipole and gap survival

The amplitude of diffractive gauge boson radiation by a quark-antiquark dipole does not vanish in forward direction, unlike the radiation by a single quark [5, 15]. This can be understood as follows. According to the general theory of diffraction [1–4], the off-diagonal diffractive channels are possible only if different Fock components of the projectile (eigenstates of interaction) interact with different elastic amplitudes. Clearly, the two Fock states consisting of just a quark and of a quark plus a gauge boson interact equally, if their elastic amplitudes are integrated over impact parameter. Indeed, when a quark fluctuates into a state $|qG\rangle$ containing the gauge boson G, with the transverse quark-boson separation $\vec{r}$, the quark gets a transverse shift $\Delta\vec{r} = \alpha\vec{r}$. The impact parameter integration gives the forward amplitude. Both Fock states $|q\rangle$ and $|qG\rangle$ interact with the target with the same total cross section, this is why a quark cannot radiate at zero momentum transfer and, hence, G is not produced diffractively in the forward direction. This is the general and model independent statement. The details of this general consideration can be found in Ref. [15] (Appendices A 1 and A 4). The same result is obtained calculating Feynman graphs in Appendix B 4 of the same paper. Unimportance of radiation between two interactions was also demonstrated by Stan Brodsky and Paul Hoyer in Ref. [22].

Note, in all these calculations one assumes that the coherence time of radiation considerably exceeds the time interval between the two interactions, what is fulfilled in our case, since we consider radiation at forward rapidities. The disappearance of both inelastic and diffractive forward Abelian radiation has a direct analogy in QED: if the electric charge gets no "kick", i.e. is not accelerated, no photon is radiated, provided that the radiation time considerably exceeds the duration time of interaction. This is dictated by the renown Landau-Pomeranchuk principle [23]: radiation depends on the strength of the accumulated kick, rather than on its structure, if the time scale of the kick is shorter than the radiation time. It is worth to notice that the non-Abelian QCD case is different: a quark can radiate gluons diffractively in the forward direction. This happens due to a possibility of interaction between the radiated gluon and the target. Such a process, in particular, becomes important in diffractive heavy flavor production [24].

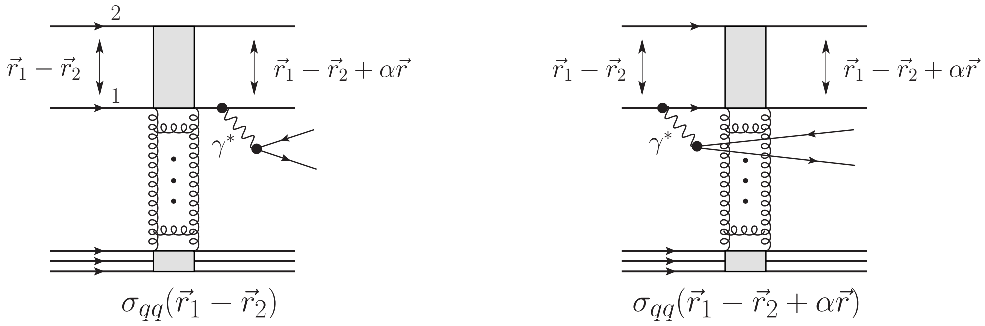

FIG. 4: Leading order contribution to the diffractive Drell-Yan in the dipole-target collision.

The situation changes if the gauge boson is radiated diffractively by a dipole as shown in Fig. 4. Then the quark dipoles with or without a gauge boson have different sizes and interact with the target differently. So the amplitude of the diffractive gauge boson radiation from the $q\bar{q}$ dipole is proportional to the difference between elastic amplitudes of the two Fock components, $|q\bar{q}\rangle$ and $|q\bar{q}G\rangle$ [5], i.e.

$$M^{diff}_{\bar{q}q}(\vec{b}, \vec{r}_p, \vec{r}, \alpha) \propto \Psi_{q\to G^*q}(\alpha, \vec{r}) \Big[2\mathrm{Im}\, f_{el}(\vec{b}, \vec{r}_p) - 2\mathrm{Im}\, f_{el}(\vec{b}, \vec{r}_p + \alpha\vec{r})\Big] \,, \tag{0.9}$$

where $\Psi_{q\to G^*q}$ is the light-cone wave function of $q \to G^*q$ fluctuation, $\vec{r}_p = \vec{r}_1 - \vec{r}_2$ is the transverse size of the $q\bar{q}$ dipole, α is the momentum fraction of the gauge boson G taken off the parent quark q and $r \sim 1/M$ is the hard scale. The partial elastic dipole-proton amplitude should be normalized to the dipole cross section, which is parameterized by the following simple ansatz [25],

$$\sigma_{\bar{q}q}(r_p, x) = \int d^2b\, 2\,\mathrm{Im} f_{el}(\vec{b}, \vec{r}_p) = \sigma_0(1 - e^{-r_p^2/R_0^2(x)}) \,, \tag{0.10}$$

where $\sigma_0 = 23.03\,\mathrm{mb}$; $R_0(x) = 0.4\,\mathrm{fm} \times (x/x_0)^{0.144}$ and $x_0 = 0.003$. This saturated form, although is oversimplified (compare with Ref. [26]), is rather successful in description of experimental HERA data with a reasonable accuracy. We rely on this parametrization in what follows, and the explicit forms of the amplitude $f_{el}(\vec{b}, \vec{r})$, can be found in Refs. [15, 27–29].

When applied to diffractive pp scattering the diffractive amplitude (0.9), thus, occurs to be sensitive to the large transverse separations between the projectile quarks in the incoming proton. Due to the internal transverse motion of the projectile valence quarks inside the incoming proton, which corresponds to finite large transverse separations between them, the forward photon radiation does not vanish [5, 7]. These large distances are controlled by a nonperturbative (hadron) scale r_p, such that the diffractive amplitude behaves as

$$M^{diff}_{\bar{q}q} \propto \vec{r} \cdot \vec{r}_p \,. \tag{0.11}$$

This means that even at a hard scale the Abelian radiation is sensitive to the hadron size due to a dramatic breakdown of diffractive factorization [30]. It was firstly found in Refs. [31, 32] that factorization for diffractive Drell-Yan reaction fails due to the presence of spectator partons in the Pomeron. In Refs. [5–7] it was demonstrated that factorization in diffractive Abelian radiation is thus even more broken due to presence of spectator partons in the colliding hadrons.

It is well-known that the absorptive corrections affect differently the diagonal and off-diagonal terms in the hadronic current [33], in opposite directions, leading to an additional source of the QCD factorisation breaking in processes with off-diagonal contributions only. Namely, the absorptive corrections enhance the diagonal terms at larger $\sqrt{s}$, whereas they strongly suppress the off-diagonal ones. In the diffractive DY process a new state, the heavy lepton pair, is produced, hence, the whole process is of entirely off-diagonal nature, whereas the diffractive DIS process contains both diagonal and off-diagonal contributions [4].

The amplitude Eq. (0.9) is the full expression, which includes by default the effect of absorption and does not need any extra survival probability factor [7]. This can be illustrated in a simple example of elastic dipole scattering off a potential. In this case, the dipole elastic amplitude has the eikonal form,

$$\mathrm{Im}\, f_{el}(\vec{b},\vec{r}_1-\vec{r}_2) = 1 - \exp\left[i\chi(\vec{r}_1) - i\chi(\vec{r}_2)\right], \tag{0.12}$$

where

$$\chi(b) = -\int\limits_{-\infty}^{\infty} dz\, V(\vec{b},z), \tag{0.13}$$

and $V(\vec{b},z)$ is the potential, which depends on the impact parameter and longitudinal coordinate, and is nearly imaginary at high energies. The difference between elastic amplitudes with a shifted quark position, which enters the diffractive amplitude, reads,

$$\mathrm{Im}\, f_{el}(\vec{b},\vec{r}_1-\vec{r}_2+\alpha\vec{r}) - \mathrm{Im}\, f_{el}(\vec{b},\vec{r}_1-\vec{r}_2) \simeq \exp\left[i\chi(\vec{r}_1) - i\chi(\vec{r}_2)\right]\, \exp\left[i\alpha\,\vec{r}\cdot\vec{\nabla}\chi(\vec{r}_1)\right]. \tag{0.14}$$

Here, the first factor $\exp\left[i\chi(\vec{r}_1)-i\chi(\vec{r}_2)\right]$ is exactly the survival probability amplitude, which vanishes in the black disc limit, as it should do. This proves that the diffractive amplitude Eq. (0.9) includes the effect of absorption. Note, usually the survival probability factor is introduced into the diffractive cross section probabilistically, while in Eq. (0.9) it is treated quantum-mechanically, at the amplitude level.

Data on diffraction show that diffractive gluon radiation is quite weak (due well known smallness of the triple-Pomeron coupling), and this can be explained assuming that gluons in the proton are located within small "spots" around the valence quarks with radius $r_0 \sim 0.3\,\mathrm{fm}$ [15, 34–36]. Therefore, the large distance between one valence quark and a satellite-gluon of the other quark is approximately equal (with 10% accuracy) to the quark-quark separation. Since a valence quark together with co-moving gluons is a color triplet, in our calculations the interaction amplitude of such an effective ("constituent") quark with the target is a coherent sum of the quark-target and gluon-target interaction amplitudes.

In addition to the soft gluons, which are present in the proton light-cone wave function at a soft scale, production of a heavy gauge boson certainly lead to an additional intensive hard gluon radiation. In other words, there might be many more spectator gluons in the quark which radiates the gauge boson. The transverse separation of those gluons is controlled by the DGLAP evolution. One can replace a bunch of gluons by dipoles [37] which transverse size r_d varies from $1/M_G$ up to r_0, and is distributed as dr_d/r_d [38]. Therefore the mean dipole size squared,

$$\langle r_d^2 \rangle = \frac{r_0^2}{\ln(r_0^2 M_G^2)}, \tag{0.15}$$

is about $\langle r_d^2 \rangle \approx 0.01\,\mathrm{fm}^2$, i.e. quite small. The cross section of such a dipole on a proton is also small, $\sigma_d = C(x)\,\langle r_d \rangle^2$, where according to Eq. (0.10) factor $C(x) = \sigma_0/R_0^2(x)$ rises with energy. Fixing $x = M_G^2/s$ and using the parameters fitted in Ref. [25] to DIS data from HERA we get at the Tevatron collider energy $\sigma_d \approx 0.9\,\mathrm{mb}$.

Presence of each such a dipole in the projectile light-cone wave function brings an extra suppression factor to the survival amplitude of a large rapidity gap,

$$S_d(s) = 1 - \,\mathrm{Im}\, f_d(b, r_d)\,. \tag{0.16}$$

We aimed here at a demonstration that the second term in (0.16) is negligibly small, so we rely on its simplified form (see more involved calculations in Ref. [39]),

$$\mathrm{Im}\, f_d(b, r_d) \approx \frac{\sigma_d}{4\pi B_d}\, e^{-b^2/2B_d}\,, \tag{0.17}$$

where B_d is the dipole-nucleons elastic slope, which was measured at $B_d \approx 6\,\mathrm{GeV}^{-2}$ in diffractive electro-production of ρ mesons at HERA [40]. We evaluate the absorptive correction (0.17) at the mean impact parameter $\langle b^2 \rangle = 2B_d$ and for the Tevatron energy $\sqrt{s} = 2\,\mathrm{TeV}$ arrive at the negligibly small value $\mathrm{Im}\, f_d(0, r_d) \approx 0.01$. However, the number of such dipole rises with hardness of the process,and may substantially enhance the magnitude of the absorptive corrections. The gap survival amplitude for n_d projectile dipoles reads,

$$S_d^{(n_d)} = \left[1 - \,\mathrm{Im}\, f_d(b, r_d)\right]^{n_d}. \tag{0.18}$$

The mean number of dipoles can be estimated in in the double-leading-log approximation to the DGLAP evolution formulated in impact parameters [38], the mean number of such dipoles is given by

$$\langle n_d \rangle = \sqrt{\frac{12}{\beta_0} \ln\left(\frac{1}{\alpha_s(M_G^2)}\right) \ln\left((1 - x_F)\frac{s}{s_0}\right)}\,. \tag{0.19}$$

Here the values of Bjorken x of the radiated gluons is restricted by the invariant mass of the diffractive excitation, $x > s_0/M_X^2 = s_0/(1 - x_F)s$. For the kinematics of experiments at the Tevatron collider (see next section), $1 - x_F < 0.1$, $\sqrt{s} = 2\,\mathrm{TeV}$, the number of radiated dipoles is not large, $\langle n_d \rangle \lesssim 6$. We conclude that the absorptive corrections Eq. (0.18) to the gap survival amplitude are rather weak, less than 5%, i.e. about 10% in the survival probability. This correction is certainly small compared to other theoretical uncertainties of our calculations. Notice that a similar correction due to radiation of soft gluons was found in Ref. [39] for the gap survival probability in leading neutron production in DIS. We conclude that the amplitude of survival of a large rapidity gap is controlled by the largest dipoles in the projectile hadron only, such that the first exponential factor in Eq. (0.14) provides a sufficiently good approximation to the gap survival amplitude.

The popular quasi-eikonal model for the so-called "enhanced" probability $\hat{S}_{enh}$ (see e.g. Refs. [41, 42]), frequently used to describe the factorisation breaking in diffractive processes, is not well justified in higher orders, whereas the color dipole approach considered here, correctly includes all diffraction excitations to all orders [4]. Such effects are included into the phenomenological parameterizations for the partial elastic dipole amplitude fitted to data. This allows to predict the diffractive gauge bosons production cross sections in terms of a single parameterization for the universal dipole cross section (or, equivalently, the elastic dipole amplitude) known independently from the soft hadron scattering data.

For more details on derivations of diffractive gauge boson production amplitudes and cross sections see Refs. [6, 7]. Now we turn to a discussion of numerical results for the most important observables.

I. NUMERICAL RESULTS

In Fig. 5 (for LHC energy $\sqrt{s} = 14$ TeV) we present the single diffractive cross sections for Z^0, γ^* (diffractive DY) and $W^\pm$ bosons production, differential in the di-lepton mass squared $d\sigma_{sd}/dM^2$ (left panels) and its longitudinal momentum fraction, $d\sigma_{sd}/dx_1$ (right panels). These plots do not reflect particular detector constraints – a thorough analysis including detector acceptances and cuts has to be done separately. The M^2 distributions here are integrated over the *ad hoc* interval of fractional boson momentum $0.3 < x_1 < 1$, corresponding to the forward rapidity region (at not extremely large masses). Then the mass distribution is integrated over the potentially interesting invariant mass interval $5 < M^2 < 10^5$ GeV^2, and can be easily converted into (pseudo)rapidity ones widely used in experimental studies, if necessary.

The M^2 distributions of the Z^0 and $W^\pm$ bosons clearly demonstrate their resonant behavior, and in the resonant region significantly exceed the corresponding diffractive Drell-Yan component; only for very low masses the γ^* contribution becomes important (left panels). For x_1 distribution, when integrated over low mass and resonant regions, diffractive W^+ and γ^* components become comparable to each other, both in shapes and values, whereas the W^- and, especially, Z-boson production cross section are noticeably lower (right panels). Quite naturally, the W^- cross section is (in analogy with the well-known inclusive $W^\pm$ production) smaller than the W^+ one due to differences in valence u- and d-quark densities

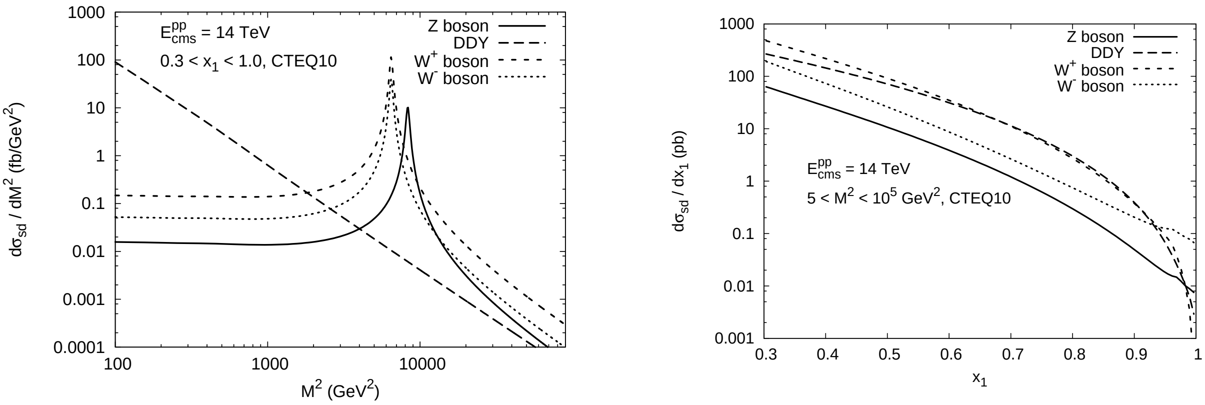

FIG. 5: Diffractive gauge boson production cross section as function of boson invariant mass squared M^2 (left panel) and boson fractional light-cone momentum x_1 (right panel) in pp collisions at the LHC energy $\sqrt{s} = 14$ TeV. Solid, long-dashed, dashed and dotted curves correspond to Z, γ^*, W^+ and W^- bosons, respectively. CTEQ10 PDF parametrization [43] is used here and below.

(dominating over sea quarks at large x_q) in the proton, the bosons couple to. So the precise measurement of differences in forward diffractive W^+ and W^- rates would allow to constrain quark content of the proton at large $x_q \equiv x_1/\alpha$.

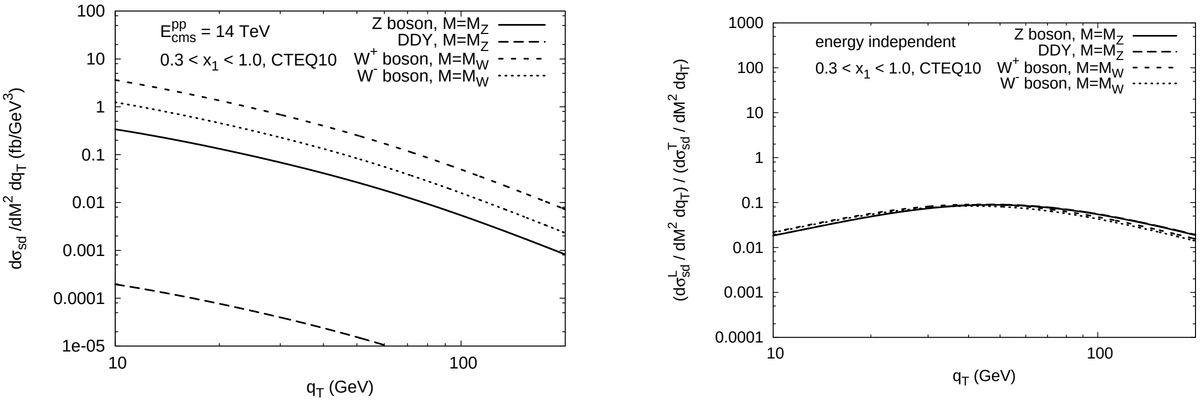

FIG. 6: The di-lepton transverse momentum $q_\perp$ distribution of the doubly-differential diffractive cross section at the LHC energy $\sqrt{s} = 14$ TeV at fixed di-lepton invariant mass is shown in the left panel. The longitudinal-to-transverse gauge bosons polarisations ratio as a function of the di-lepton $q_\perp$ is shown in the right panel. In both panels, the invariant mass is fixed as $M = M_Z$ in the Z^0, γ^* production case and as $M = M_W$ in the $W^\pm$ production case.

From the phenomenological point of view, the distribution of the forward diffractive cross section in the di-lepton transverse momentum $q_\perp$ could also be of major importance. In Fig. 6 (left panel) we show the di-lepton transverse momentum $q_\perp$ distribution of the doubly-differential diffractive cross section at the LHC energy $\sqrt{s} = 14$ TeV at the di-lepton invariant mass, fixed at a corresponding resonance value – the Z or W mass. The shapes turned out to be smooth and the same for different gauge bosons, and are different mostly in normalisation. In Fig. 6 (right panel) we show the $q_\perp$ dependence of the σ^L/σ^T ratio in the resonances. We notice that the ratio does not strongly vary for different bosons. It is peaked at about the half of the resonance mass, and uniformly decreases to smaller/larger $q_\perp$ values.

As one of the important observables, sensitive to the difference between u- and d-quark PDFs at large x, the $W^\pm$ charge asymmetry A_W is shown in Fig. 7 differentially as a function of the di-lepton invariant mass squared M^2 and integrated over $0.3 < x_1 < 1.0$ interval (left panel)

$$A_W(M^2) = \frac{d\sigma_{sd}^{W^+}/dM^2 - d\sigma_{sd}^{W^-}/dM^2}{d\sigma_{sd}^{W^+}/dM^2 + d\sigma_{sd}^{W^-}/dM^2}\,, \tag{1.1}$$

and as a function of the boson momentum fraction x_1 and integrated over $5 < M^2 < 10^5$ GeV^2 interval (right panel)

$$A_W(x_1) = \frac{d\sigma_{sd}^{W^+}/dx_1 - d\sigma_{sd}^{W^-}/dx_1}{d\sigma_{sd}^{W^+}/dx_1 + d\sigma_{sd}^{W^-}/dx_1}\,. \tag{1.2}$$

The ratio turns out to be independent on both the hard scale M^2 and the c.m. energy $\sqrt{s}$. One concludes that, due to different x-shapes of valence u, d quark PDFs, at smaller

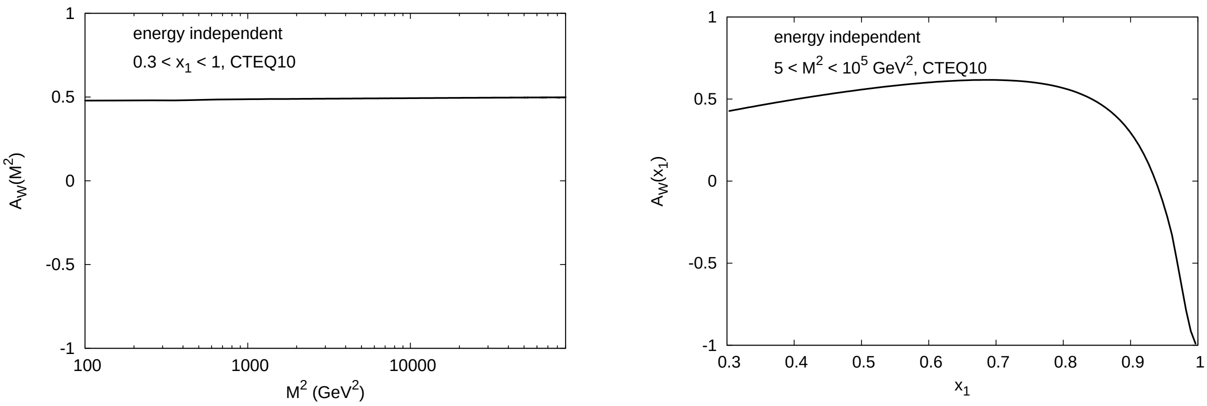

FIG. 7: Charge asymmetry in the single diffractive W^+ and W^- cross sections as a function of M^2, at fixed $x_1 = 0.5$ (left panel), and x_1, at fixed $M^2 = M_W^2$ (right panel). Solid lines correspond to the LHC energy $\sqrt{s} = 14$ TeV, dished lines – to the RHIC energy $\sqrt{s} = 500$ GeV.

$x_1 \lesssim 0.9$ the diffractive W^+ bosons' rate dominates over W^- one. However, at large $x_1 \to 1$ the W^- boson cross section becomes increasingly important and strongly dominates over the W^+ one.

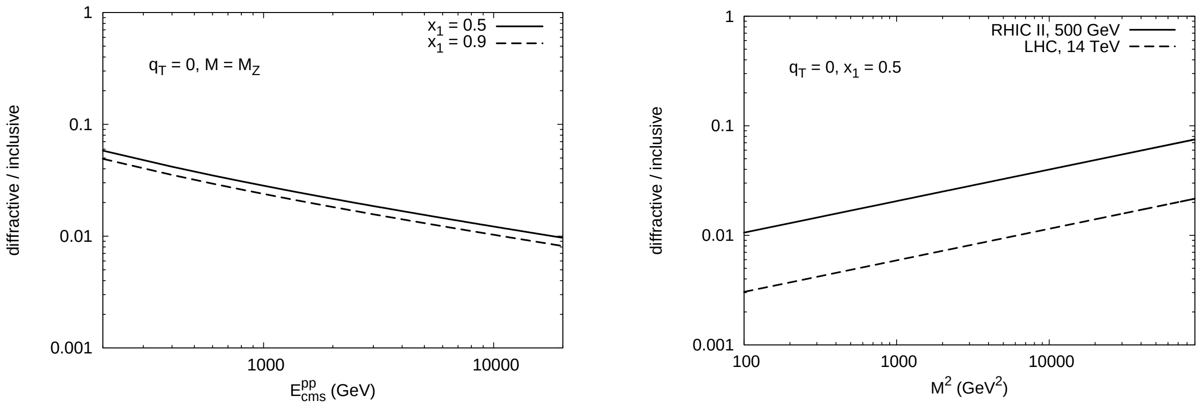

FIG. 8: The diffractive-to-inclusive ratio of the gauge bosons production cross sections in pp collisions as a function of the c.m. energy $\sqrt{s}$ (left panel) and the di-lepton invariant mass M^2 (right panel). It does not depend on the type of the gauge boson and quark PDFs.

An important feature of the diffractive-to-inclusive Abelian radiation cross sections ratio

$$R(M^2, x_1) = \frac{d\sigma_{sd}/dx_1 dM^2}{d\sigma_{incl}/dx_1 dM^2}\,, \tag{1.3}$$

which makes these predictions different from ones obtained in traditional diffractive QCD factorisation-based approaches (see e.g. Refs. [13, 14]), is their unusual energy and scale dependence demonstrated in Fig. 8. Notice that we stick to the case of small boson transverse momenta, $q_\perp \ll M$, where the main bulk of diffractive signals comes from. This ratio is independent of the type of the gauge boson, its polarisation, or quark PDFs. In this respect, it is the most convenient and model independent observable, which is sensitive only to the structure of the universal elastic dipole amplitude (or the dipole cross section), and can be used as an important probe for the QCD diffractive mechanism for forward diffractive reactions, essentially driven by the soft interaction dynamics. We see from Fig. 8 that the $\sigma_{sd}/\sigma_{incl}$ ratio decreases with energy, but increases with the hard scale, thus behaves opposite to what is expected in the diffractive factorisation-based approaches. Therefore, measurements of the single diffractive gauge boson production cross section, at least, at two different energies would provide important information about the interplay between soft and hard interactions in QCD, and its role in formation of diffractive excitations and color screening effects.

II. SUMMARY

The diffractive radiation of Abelian fields, γ, Z^0, $W^\pm$, expose unusual features, which make it very different from diffraction in DIS, and lead to a dramatic breakdown of QCD factorisation in diffraction.

The first, rather obvious source for violation of diffractive factorisation is related to absorptive corrections (called sometimes survival probability of large rapidity gaps). The absorptive corrections affect differently the diagonal and off-diagonal terms in the hadronic current [33], leading to an unavoidable breakdown of QCD factorisation in processes with off-diagonal contributions only. The latter is the case for diffractive Abelian radiation, whereas in the diffractive DIS contains both diagonal and off-diagonal contributions [4].

The second, more sophisticated reason to contradict diffractive factorisation is specific for Abelian radiation, namely, a quark cannot radiate in the forward direction (zero momentum transfer), where diffractive cross sections usually have a maximum. Forward diffraction becomes possible due to intrinsic transverse motion of quarks inside the proton by means of destructive interference between dipole scatterings with difference transverse sizes.

The third reason is due to the mechanism of Abelian radiation in the forward direction in *pp* collisions being related to participation of the spectator partons in the proton. Namely, the perturbative QCD interaction of a projectile quark is responsible for the hard process of a heavy boson radiation, while a soft interaction with the projectile spectator partons provides color neutralization, which is required for a diffractive (Pomeron exchange) process. Such an interplay of hard and soft dynamics is also specific for the processes under consideration, which makes it different from the diffractive DIS, dominated exclusively by soft interactions, and which also results in breakdown of diffractive factorisation. The above three reason together lead to rather unusual features of the leading-twist diffractive Abelian radiation w.r.t. its hard scale and energy dependence.

In this "Yellow" paper, we have presented the differential distributions (in transverse momentum, invariant mass and longitudinal momentum fraction) of the diffractive γ^*, Z^0 and $W^\pm$ bosons production at the LHC (14 TeV) energy, as well as the ratio of the boson longitudinal to transverse polarisation contributions. We have also shown the charge $W^\pm$ asymmetry, relevant for upcoming measurements at the LHC. The ratio diffractive to inclusive gauge bosons production cross sections does not depend on a particular type of the gauge boson, its polarisation state and quark PDFs, and depends only on properties of the universal dipole cross section and sensitive to the saturation scale at small x.

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