Checking formalism for central exclusive production in the first LHC runs

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Abstract

We discuss how the early LHC data runs can provide crucial tests of the formalism used to predict the cross sections of central exclusive production.

1   Introduction

The physics potential of forward proton tagging at the LHC has attracted much attention in the last years, for instance, [1–5]. The combined detection of both outgoing protons and the centrally produced system gives access to a unique rich programme of studies in QCD, electroweak and BSM physics. Importantly, these measurements will provide valuable information on the Higgs sector of MSSM and other popular BSM scenarios, see [6–9].
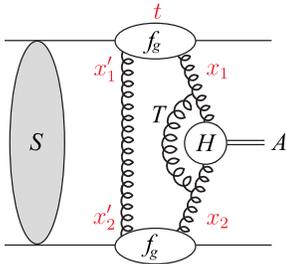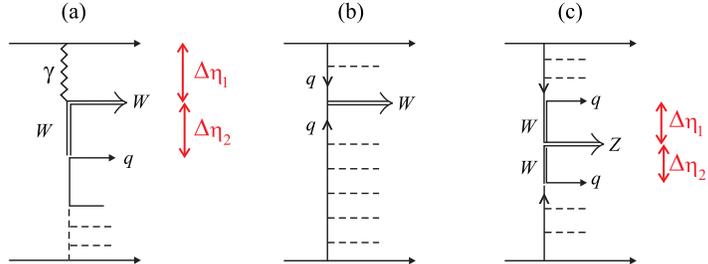

Fig. 1: A symbolic diagram for the CEP of a system A.

Fig. 2: (a) W production with 2 gaps, (b) Inclusive W production, (c) Z production with 2 gaps.

The theoretical formalism [10–12] for the description of a central exclusive production (CEP) process contains quite distinct parts, shown symbolically in Fig. 1. We first have to calculate the $gg \to A$ subprocess, H, convoluted with the gluon distributions f_g. Next, we must account for the QCD corrections which reflect the absence of additional radiation in the hard subprocess – that is, for the Sudakov factor T. Finally, we must enter soft physics to calculate the survival probability S^2 of the rapidity gaps (RG) .

The uncertainties of the CEP predictions are potentially not small. Therefore, it is important to perform checks using processes that will be accessible in the first LHC runs [13]. We first

consider measurements which do not rely on proton tagging and can be performed through the detection of RG.

The main uncertainties of the CEP predictions are associated with

(i) the probability S^2 that additional secondaries will not populate the gaps;

(ii) the probability to find the appropriate gluons, that are given by generalized, unintegrated distributions $f_g(x, x', Q_t^2)$;

(iii) the higher order QCD corrections to the hard subprocess, in particular, the Sudakov suppression;

(iv) the so-called semi-enhanced absorptive corrections (see [14, 15]) and other effects, which may violate the soft-hard factorization.

2 Gap survival factor S^2

Usually, the gap survival is calculated within a multichannel eikonal approach [16]. The probability S^2 of elastic pp rescattering, shown symbolically by S in Fig. 1 can be evaluated in a model independent way once the elastic cross section $d\sigma_{\mathrm{el}}/dt$ is measured at the LHC. However, there may be excited states between the blob S and the amplitude on the r.h.s of Fig. 1. The presence of such states enlarges absorption. To check experimentally the role of this effect, we need a process with a bare cross section that can be reliably calculated. Good candidates are the production of W or Z bosons with RGs [13]. In the case of 'W+gaps' production the main contribution comes from the diagram of Fig. 2(a) [17]. One gap, $\Delta\eta_1$, is associated with photon exchange, while the other, $\Delta\eta_2$, is associated with the W. In the early LHC data runs the ratio (W+gaps/W inclusive) will be measured first. This measurement is a useful check of the models for soft rescattering [13].

A good way to study the low impact parameter (b_t) region is to observe Z boson production via WW fusion, see Fig. 2(c). Here, both gaps originate from W-exchange, and the corresponding b_t region is similar to that for exclusive Higgs production. The expected Z+gaps cross section is of the order of 0.2 pb, and S^2=0.3 for $\Delta\eta_{1,2} > 3$ and for quark jets with $E_T > 50$ GeV [18].

3 Generalized, unintegrated gluon distribution f_g

The cross section for the CEP of a system A essentially has the form [10]

$$\sigma(pp \to p+A+p) \simeq \frac{S^2}{B^2} \left| \frac{\pi}{8} \int \frac{dQ_t^2}{Q_t^4} \, f_g(x_1, x_1', Q_t^2, \mu^2) f_g(x_2, x_2', Q_t^2, \mu^2) \right|^2 \hat{\sigma}(gg \to A). \quad (1)$$

Here the factor $1/B^2$ arises from the integration over the proton transverse momentum. Also, f_g denotes the generalized, unintegrated gluon distribution. In our case the distribution f_g can be obtained from the conventional gluon distribution, g, known from the global parton analyses. The main uncertainty here comes from the lack of knowledge of the integrated gluon distribution
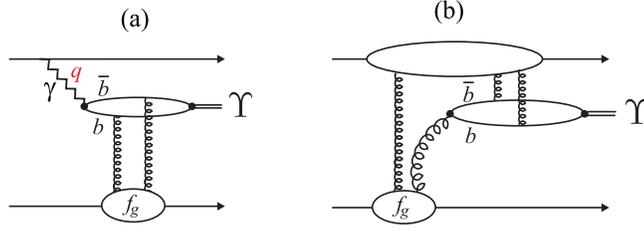
Fig. 3: Exclusive Υ production via (a) photon exchange, and (b) via odderon exchange.

$g(x, Q_t^2)$ at low x and small scales. For example, taking $Q_t^2 = 4 \, \text{GeV}^2$ we find [13] $xg = (3 - 3.8)$ for $x = 10^{-2}$ and $xg = (3.4 - 4.5)$ for $x = 10^{-3}$. These are big uncertainties bearing in mind that the CEP cross section depends on $(xg)^4$. To reduce the uncertainty associated with f_g we can measure exclusive Υ production. The process is shown in Fig. 3(a). The cross section for $\gamma p \to \Upsilon p$ is given in terms of the same unintegrated gluon distribution f_g that occurs in Fig. 1. There may be competition between production via photon exchange, Fig. 3(a), and via odderon exchange, see Fig. 3(b). A lowest-order calculation (e.g. [19]) indicates that the odderon process (b) may be comparable to the photon-initiated process (a). If the upper proton is tagged, it will be straightforward to separate the two mechanisms.

4   Three-jet events as a probe of the Sudakov factor

The search for the exclusive dijets at the Tevatron, $p\bar{p} \to p + jj + \bar{p}$, is performed [20] by plotting the cross section in terms of the variable $R_{jj} = M_{jj}/M_A$, where M_A is the mass of the whole central system. However, the R_{jj} distribution is smeared out by QCD radiation, hadronization, the jet algorithm and other experimental effects [20,21]. To weaken the smearing it was proposed in Ref. [21] to study the dijets in terms of a variable $R_j = 2E_T (\cosh \eta^*)/M_A$, where only the transverse energy and the rapidity η of the jet with the *largest E_T* enter. Here $\eta^* = \eta - y_A$, where y_A is the rapidity of the central system. Clearly, the largest E_T jet is less affected by the smearing. As shown in [13], it is sufficient to consider the emission of a third jet, when we take all three jets to lie in a specified rapidity interval $\delta\eta$. The cross section $d\sigma/dR_j$, as a function of R_j, for the production of a pair of high E_T dijets accompanied by a third jet is discussed in [13, 21]. It is shown that the measurements of the exclusive two- and three-jet cross sections *as a function of E_T* of the highest jet allow a detailed check of the Sudakov physics; with much more information coming from the $\delta\eta$ dependence study. A clear way to observe the Sudakov suppression is just to measure the E_T dependence of exclusive dijet production. On dimensional grounds we would expect $d\sigma/dE_T^2 \propto 1/E_T^4$. This behaviour is modified by the gluon anomalous dimension and by a stronger Sudakov suppression with increasing E_T. Already the existing CDF dijet data [20] exclude predictions which omit the Sudakov effect.
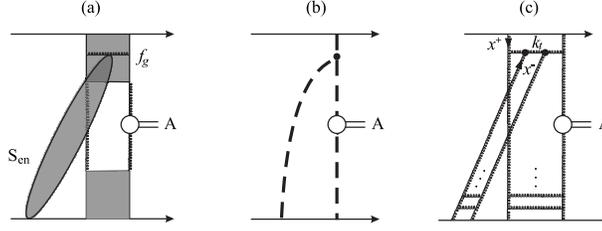
Fig. 4: (a) A typical enhanced diagram, where the shaded boxes denote f_g, and the soft rescattering is on an intermediate parton, giving rise to a survival factor $S_{\rm en}$; (b) and (c) are the Reggeon and QCD representations, respectively.

5 Soft-hard factorization: enhanced absorptive effects

The soft-hard factorization implied by Fig. 1 could be violated by the so-called enhanced Reggeon diagrams, see Fig. 4(a). The contribution of the first Pomeron loop, Fig. 4(b) was calculated in pQCD in Ref. [15]. A typical diagram is shown in Fig. 4(c). For LHC energies it was found that such effect may be numerically large. The reason is that the gluon density grows at low x and, for low k_t partons, approaches the saturation limit. However, as discussed in [13], the enhanced diagram should affect mainly the very beginning of the QCD evolution – the region that cannot be described perturbatively and which, in [11, 12], is already included phenomenologically.

Experimentally, we can study the role of semi-enhanced absorption by measuring the ratio R of diffractive event rate for W (or Υ or dijet) as compared to the inclusive process [13]. That is

$$R \;=\; \frac{\text{no. of } (A + \text{gap}) \text{ events}}{\text{no. of (inclusive } A) \text{ events}} \;=\; \frac{a^{\rm diff}(x_{I\!\!P}, \beta, \mu^2)}{a^{\rm incl}(x = \beta x_{I\!\!P}, \mu^2)} \, \langle S^2 S_{\rm en}^2 \rangle_{\text{over } b_t}, \qquad (2)$$

where $a^{\rm incl}$ and $a^{\rm diff}$ are the parton densities determined from the global analyses of inclusive and diffractive DIS data, respectively. We can measure a double distribution $d^2\sigma^{\rm diff}/dx_{I\!\!P} dy_A$, and form the ratio R using the inclusive cross section, $d\sigma^{\rm incl}/dy_A$. If we neglect the enhanced absorption, it is quite straightforward to calculate the ratio R of (2). The results for a dijet case are shown by the dashed curves in Fig. 5 as a function of the rapidity y_A of the dijet system. The enhanced rescattering reduce the ratios and lead to steeper y_A distributions, as illustrated by the continuous curves. Perhaps the most informative probe of $S_{\rm en}^2$ is to observe the ratio R for dijet production in the region $E_T \sim 15 - 30$ GeV. For example, for $E_T \sim 15$ GeV we expect $S_{\rm en}^2 \sim$ 0.25, 0.4 and 0.8 at $y_A = -2, \ 0$ and 2 respectively.

6 Conclusion

The addition of forward proton detectors to LHC experiments will add unique capabilities to the existing LHC experimental programme. For certain BSM scenarios, the tagged-proton mode may even be the discovery channel. There is also a rich QCD, electroweak, and more exotic physics, menu.
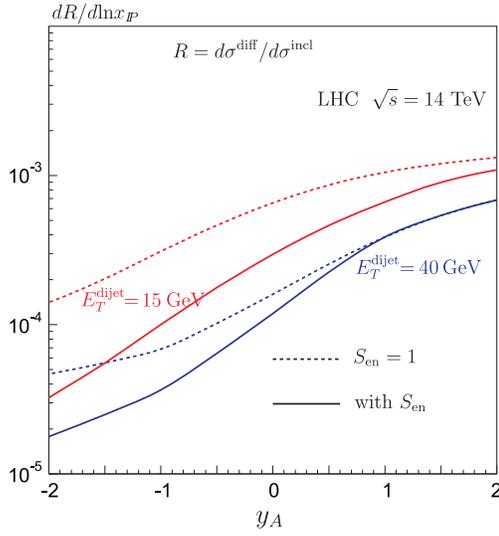
Fig. 5: The predictions of the ratio R of (2) for the production of a pair of high E_T jets.
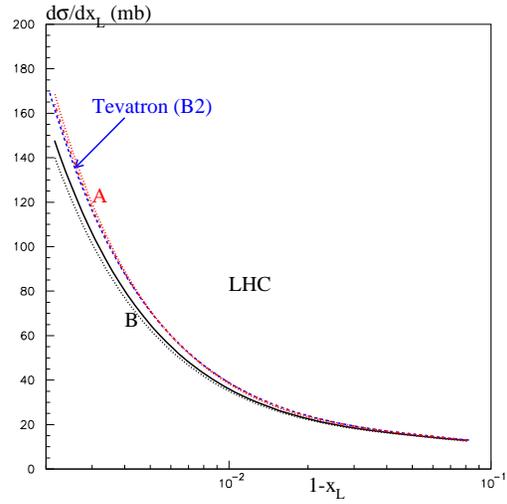
Fig. 6: The cross section $d\sigma_{\mathrm{SD}}/dx_L$ for single dissociation integrated over t at the LHC energy.

The uncertainties in the prediction of the CEP processes are potentially not small. Therefore, it is crucial to perform checks of the theoretical formalism using reactions that will be experimentally accessible in the first LHC runs [13].

Most of the measurements discussed above can be performed, without detecting the protons, by taking advantage of the relatively low luminosity in the early LHC runs. When the forward proton detectors are operating much more can be done. First, it is possible to measure directly the cross section $d^2\sigma_{\mathrm{SD}}/dt dM_X^2$ for single diffractive dissociation and also the cross section $d^2\sigma_{\mathrm{DPE}}/dy_1 dy_2$ for soft central diffractive production. These measurements will strongly constrain the models used to describe diffractive processes and the effects of soft rescattering. The recent predictions can be found in [12]. For illustration we show in Fig. 6 the expectation for $d\sigma_{\mathrm{SD}}/dx_L$, see for details [12]. Next, a study of the transverse momentum distributions of both of the tagged protons, and the correlations between their momenta, is able to scan the proton optical density [17, 22].

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