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DIFFRACTIVE PHYSICS AT THE LHC

Diffractive processes possible to be measured at the LHC are listed and briefly discussed. This includes soft (elastic scattering, exclusive meson pair production, diffractive bremsstrahlung) and hard (single and double Pomeron exchange jets, γ + jet, W/Z, jet-gap-jet, exclusive jets) processes as well as Beyond Standard Model phenomena (anomalous gauge couplings, magnetic monopoles).

Keywords: LHC, AFP, ALFA, TOTEM, pomeron, diffraction, exclusive processes, beyond standard model.

1. Introduction

About a half of collisions at the LHC are of diffractive nature. In such events, a rapidity gap [1] between the centrally produced system and scattered protons is present. Due to the exchange of a colorless object – photon (electromagnetic) or Pomeron (strong interaction) – one or both outgoing protons may stay intact.

Studies of diffractive events are an important part of the physics program of the LHC experiments. The diffractive production could be recognized by the search for a rapidity gap in the forward direction or by the measurement of scattered protons. The first method is historically a standard one for the diffractive pattern recognition. It uses the usual detector infrastructure: *i.e.* tracker and forward calorimeters. Unfortunately, the rapidity gap may be destroyed by *e.g.* particles coming from the pile-up – parallel, independent collisions happening in the same bunch crossing. In addition, the gap may be outside the acceptance of a detector. In the second method, protons are directly measured. This solves the problems of gap recognition in the very forward region and a presence of a pile-up. However, since protons are scattered at small angles (few hundreds microradians), additional devices called “forward detectors” are needed to be installed.

At the LHC, the so-called Roman pot technology is used. In ATLAS [1], two systems of such detectors were installed: ALFA [2, 3] and AFP [4]. At the LHC interaction point 5, Roman pots are used by CMS [5] and TOTEM [6,7] groups. Since protons are scattered at small angles, there are several LHC elements (*i.e.*, magnets and collimators) between them and the IP which influence their trajectory. The settings of these elements, commonly called machine optics, determine the acceptance of forward detectors. The detailed description of the properties of optics sets used at the LHC can be found in [8].

In both experiments, a large community works on both phenomenological and experimental aspects of diffraction. In this paper, the diffractive processes possible to be measured will be briefly described.

2. Soft Diffraction

Collisions at hadron accelerators are dominated by soft processes. The absence of a hard scale in these events prevents one from using perturbation theory. Instead, in order to calculate the properties of the produced particles such as the energy or angular distributions, one has to use approximative methods.

The elastic scattering process has the simplest signature that can be imagined: two protons exchange their momentum and are scattered at small angles. At the LHC, the measurement of protons scattered elastically requires a special settings commonly named the high-β^* optics. Properties of the elastic scattering were measured by both ATLAS and TOTEM Collaborations for center-of-mass energies of 7 [9, 10], 8 [11, 12], and 13 TeV [13].

Another soft process is a diffractive bremsstrahlung. It is typically of electromagnetic nature. However, high-energy photons can be radiated in the elastic

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[1] A space in the rapidity devoid of particles.

proton-proton scattering as postulated in [14]. This idea was further extended in [15] by introducing the proton form-factor into the calculations and by considering other mechanisms such as a virtual photon re-scattering. The feasibility studies presented in [16] suggest that such measurement should be possible at the LHC. The requirements are high-β^* optics, proton measurement in ALFA/TOTEM and photon measurement in Zero Degree Calorimeter.

Last of the processes described in this section is the exclusive meson pair production, a 2 → 4 process in which two colliding protons result in two charged mesons and two scattered protons present in the final state. In the non-resonant pion pair production (also called continuum), a Pomeron is "emitted" from each proton resulting in four particles present in the final state: scattered protons and (central) pions [17]. The object exchanged in the t-channel is an off-shell pion. Exclusive pions can also be produced via resonances, *e.g.*, f_0 [18]. Although the dominant diagram of the exclusive pion pair continuum production is a Pomeron-induced one, the production of a photon-induced continuum is also possible. On the top of that, a resonant ρ^0 photo-production process may occur [19].

Recently, the models of elastic scattering, exclusive meson production, and diffractive bremsstrahlung were added to the GenEx Monte-Carlo generator [20–22].

3. Hard Diffraction

Hard diffractive events can be divided into the single diffractive and double Pomeron exchange classes. In the first case, one proton stays intact, whereas the other one dissociates. In the second case, both interacting protons "survive". In addition, the sub-case of the exclusive production can be considered – a processes in which all final-state particles can be measured by ATLAS and CMS/TOTEM detectors.

Depending on the momentum lost during the interaction, the emitting proton may remain intact and be detected by a forward proton detector. However, it may happen that the soft interactions between the protons or the proton and the final-state particles can destroy the diffractive signature. Such effect is called the gap survival probability. For the LHC energies, the gap survival is estimated to be of about 0.03–0.1 depending on the process [23].

From all hard events, the diffractive jets have the highest cross-section [2]. By studying the single diffractive and double Pomeron exchange jet productions, a Pomeron universality between *ep* and *pp* colliders can be probed. As was discussed in [24], the tagging of diffractive protons will allow the QCD evolution of gluon and quark densities in the Pomeron to be tested and compared to the ones extracted from the HERA measurements. Another interesting measurement is the estimation of the gap survival probability. A good experimental precision will allow for comparison to theoretical predictions and differential measurements of the dependence of the survival factor on, *e.g.*, the mass of the central system.

An interesting class of jet events is one with a rapidity gap is present between jets – the so-called jet-gap-jet production. In such events, an object exchanged in the t-channel is a color singlet and carries a large momentum transfer. When the gap size is sufficiently large, the perturbative QCD description of jet-gap-jet events is usually performed in terms of the Balitsky–Fadin–Kuraev–Lipatov (BFKL) model [27–29]. The jet-gap-jet topology can be produced also in the single diffractive and double Pomeron exchange processes. Properties of such events were never measured – the determination of the cross-section should enable the tests of the BFKL model [30].

Jets produced in the processes described above are typically of gluonic nature. In order to study the quark composition of a Pomeron, diffractive photon + + jet productions should be considered. In such cases, one Pomeron emits a gluon, whereas the other one delivers a quark. A measurement of the photon + jet production in the DPE mode can be used to test the Pomeron universality between HERA and LHC. Moreover, HERA was not sensitive to the difference between the quark components in a Pomeron. This means that the fits assumed the equal amounts of light quarks, $u = d = s = \bar{u} = \bar{d} = \bar{s}$. The LHC data should allow more precise measurements [25].

Another interesting process is the diffractive production of W and Z bosons. Similarly to $\gamma +$ jet, it is sensitive to the quark component, since many of the observed production modes can originate from a quark fusion. As was discussed in [26], by measuring the ratio of the W production cross-section to the Z one, the d/u and s/u quark density values in the

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[2] Depends on the jet transverse momentum.

Pomeron can be estimated. In addition, a study of the DPE W asymmetry can be performed [26]. Such measurement can be used to validate theoretical models.

The feasibility studies of all measurements described above in this section are described in Ref. [31].

Diffractive jets can be produced in the exclusive mode. Usually, it is assumed that one gluon is hard, whereas the other one is soft [32, 33]. The role of the soft gluon is to provide the color screening in order to keep the net color exchange between protons equal to zero. The exclusivity of the event is assured via the Sudakov form factor [34], which prohibits an additional radiation of gluons in higher orders of perturbative QCD. In [35], a discussion about the feasibility of such measurement in the case of the ATLAS detector and both tagged protons is held. A semiexclusive measurement, when one of the protons is tagged, is discussed in [36, 37].

4. Anomalous Couplings and Beyond Standard Model Physics

The presence of an intact proton can be used to search for a new phenomena. The Beyond Standard Model (BSM) processes are usually expected to be on a high mass, which makes them visible in forward detectors.

One example of the BSM physics is anomalous couplings: $\gamma\gamma WW$, $\gamma\gamma ZZ$, $\gamma\gamma\gamma\gamma$ or $WW\gamma$. As was shown in [38, 39], the possibility of the forward proton tagging provides a much cleaner experimental environment which improves the discovery potential. Authors expect that, with 30–300 fb^{-1}, the data collected with the ATLAS detector with information about scattered protons tagged in AFP should result in a gain in the sensitivity of about two orders of magnitude over a standard ATLAS analysis.

Finally, the presence of protons with a high energy loss and a lack of energy registered in the central detector might be a sign of a new physics, for example, magnetic monopoles [31].

5. Conclusions

The Large Hadron Collider gives possibility to study the properties of diffractive physics in a new kinematic domain. Diffractive events can be identified in all major LHC experiments using the rapidity gap recognition method. In addition, as ATLAS and CMS/TOTEM are equipped with the set of forward detectors, it is possible to use the proton tagging technique.

In this paper, a brief summary of the diffractive processes measurable at the LHC was done. Using special settings of the LHC – high-β^* optics – the processes of elastic scattering, exclusive meson pair production, and diffractive bremsstrahlung can be studied. Hard diffractive events, due to smaller cross-sections, should be measured with the standard LHC optics. The studies of properties of the diffractive di-jet, photon+jets, and the W/Z boson production processes should lead *i.a.* to the determination of a gap survival probability and a Pomeron structure. Studies of diffractive jet-gap-jet events should bring more insight into the description of the Pomeron, *i.a.* to verify predictions of the BFKL model. On the top of that, the measurement of the jet production in the exclusive (double proton tag) and semiexclusive (single tag) modes can be performed. Finally, the additional information about a scattered proton may improve the searches for a New Physics including such phenomena as anomalous gauge couplings or magnetic monopoles.

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ДИФРАКЦІЯ НА LHC

Резюме

Перераховано і коротко обговорено дифракційні процеси, які можна вимірювати на LHC. Список включає м’які (пружне розсіяння, ексклюзивне продукування мезонних пар, дифракційне гальмівне випромінювання) та жорсткі (струмені з обміном одного або двох померонів, фотон + струмінь, W/Z, струмінь-розрив-струмінь, ексклюзивні струмені) процеси, а також явища поза рамок Стандартної Моделі (аномальні калібрувальні зв’язки, магнітні монополі).