Akademie věd České republiky

Teze disertace
k získání vědeckého titulu “doktor věd”
ve skupině věd **Fyzikálně-matematické vědy**

High Energy Soft QCD and Diffraction

název disertace

Komise pro obhajoby doktorských disertací v oboru **Jaderná, subjaderná a matematická fyzika**

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Místo a datum Praha, Únor 2021

Chapter 1

Introduction

Soft Quantum Chromodynamics (QCD) physics is a domain of particle physics which is characterized by a low momentum transfer, typically a low transverse momentum, p_{T}. It is usually used to describe that part of the scattering which dominates at soft scales and where perturbative QCD cannot be applied. One example of a process which is entirely governed by soft QCD physics is hadronization (or fragmentation). Since there is no uniform description of the phenomena that occur at low p_{T}, there is a variety of models trying to explain them through comparisons with extracted data. There exists a wealth of LEP (Large Electron Positron collider at CERN) and LHC (Large Hadron Collider at CERN) measurements that probe the soft QCD phenomena. They occur in interactions investigated in measurements of inclusive total cross sections, inclusive and identified particle spectra, underlying event or particle correlations – here it is interesting to note surprising similarities, observed in recent years, between results from all three collision system at LHC: pp, pPb and $PbPb$ collisions. Models used to describe such measurements are based on multi-parton interactions, color reconnections, hadronization and hydrodynamical laws or gluon saturation in the proton.

Diffractive processes, the main focus of this text, belong to the class of forward physics processes, the latter ones defined very simply by presence of at least one particle in the final state emitted in the forward direction with respect to the beam (colliding) particle. How much forward is a matter of discussion - at LHC for example, central detectors usually cover the region of $|y| < 2.5$–3.0, where y is rapidity of produced particle, and hence forward usually means $|y| > 2.5$–3.0 Albeit very simply defined, forward physics is a class of processes of diverse final states and great potentials in testing precise predictions of Standard Model (SM) of particle physics as well as in searching for signals coming from beyond Standard Model (BSM) realm - which is one of the main goals of the physics program at the LHC and future colliders.

An important subset of forward physics processes are those in which a large interval of rapidity (typically at least 4 units) is devoid of any hadronic activity. Such an interval is called Large Rapidity Gap (LRG). It can be spoiled by additional proton–proton interactions; the probability of no such additional interactions is called 'soft survival probability' and is denoted by S^2. The most frequent case of processes with LRG is elastic scattering where the central detector is entirely empty and beam particles (for example protons, very often used at LHC) are detected in special forward proton detectors (FPD). Other processes with LRG and large cross sections are those where one or both incoming protons is transformed (or dissociate) into a set of two or more final state particles with mass $M \ll \sqrt{s}$ ($\sqrt{s}$ is proton–proton centre-of-mass energy) and proton quantum number. All these processes show characteristics similar to those observed in optics patterns that one obtains when a beam of light is diffracted on an obstacle. Thanks to this analogy, in high-energy physics, the corresponding processes are usually called diffractive. The classic example is the elastic scattering of hadrons on nuclei (see e.g. [1]), which manifests an angular distribution with a series of minima and maxima, analogous to the diffraction of light on a black disk. Diffraction dissociation can be considered as a quantum mechanical process caused by the fact that different components of the incoming hadron wave function have different probabilities for interaction with a target [2, 3]. This feature allows us to probe the transverse size of the interaction region. Note that besides being of a fundamental interest in their own right for understanding the high energy behaviour of the QCD amplitude, there are several reasons why it is important to study soft and diffractive processes. Firstly, soft interactions unavoidably give an underlying component to rare hard-scale events, from which we hope to extract

signals for New Physics. Secondly, we should be able to estimate the probability that rapidity gaps, which occur in hard-scale diffractive events, survive rescattering effects, that is, survive the population of the gaps by the secondary particles from the underlying event. Particles are also emitted very forward in interactions of cosmic rays with atmosphere. Models trying to describe such interactions are thus currently constrained by results from LHC - another reason to pursue the forward physics program at colliders. At LHC energies diffractive processes constitute up to 40% of the total (pp) cross section, σ_{tot}. And this is yet another reason why it pays off to study diffractive processes at LHC: an understanding of diffractive processes is very important for evaluation of pile-up backgrounds in high-luminosity pp collisions, which have a direct impact on various experimental measurements. Pile-up corresponds to soft independent interactions in the same bunch crossing whose number rises with increasing instantaneous luminosity.
Experimentally, diffractive processes are selected using two distinct features:

1. large rapidity gaps (typically at least $\Delta\eta > 4$) and/or
2. one or both incoming particles stay intact after collision and are registered by dedicated FPDs placed a few hundred meters from the interaction point. The momentum loss of the initial particle, ξ, is typically smaller than 0.15.

Thus, in the case of proton-proton collisions, diffractive events include elastic $pp \to pp$ scattering, $pp \to p \oplus X$ (Single Dissociation, SD), $pp \to X \oplus Y$ (Double Dissociation, DD) and $pp \to p \oplus X \oplus p$ (Central Diffraction, CD) processes, where the $\oplus$ sign denotes a LRG. Typically at the LHC the integrated cross sections of diffractive dissociation, σ_{SD}, σ_{DD}, are of the order of 5–10 mb depending on the gap size. The CD processes then occur by an order of magnitude less frequently. The central diffraction is a pivotal topic of this thesis and therefore it will be elaborated more compared to other processes. In CD processes both scattered protons stay intact, are detected in FPDs, and are accompanied by large rapidity gaps. They can be divided into four categories according to which particles collide or induce the hard scattering: either gluon-gluon (both from Pomerons), i.e. QCD exclusive production (so called central exclusive production, CEP), or photon-photon (both from protons), i.e. QED exclusive production, or inclusive Pomeron-Pomeron (so called Double Pomeron Exchange, DPE) or photon-Pomeron (both from protons), so called diffractive photoproduction.

1.0.1 Central exclusive processes

The process is defined as $pp \to p \oplus X \oplus p$ where all of the energy lost by the protons during the interaction (a few per cent) goes into the production of the central system, X. The final state therefore consists of a centrally produced system (e.g. dijet, heavy particle or Higgs boson) coming from a hard subprocess, two very forward protons and no other activity. One can thus put constraints on the Higgs sector of Minimal Supersymmetric SM (MSSM) and other popular BSM scenarios (see Ref. [A2] for references).

CEP is especially attractive for three reasons: firstly, if the outgoing protons remain intact and scatter through small angles then, to a very good approximation, the primary di-gluon system obeys a $J_z = 0$, $\mathcal{C}$-even, $\mathcal{P}$-even selection rule [4, 5]. Here J_z is the projection of the total angular momentum along the proton beam axis. This therefore allows a clean determination of the quantum numbers of any observed resonance. Thus, in principle, only a few such events are necessary to determine the quantum numbers, since the mere observation of the process establishes that the exchanged object is in the 0^{++} state. Secondly, from precise measurements of the proton momentum losses, ξ_1 and ξ_2, and from the fact that the process is exclusive, the mass of the central system can be measured much more precisely than from the central detector, by the so-called missing mass method [6], $M^2 = \xi_1 \xi_2 s$ which is independent of the decay mode. Thirdly in CEP the signal-to-background (S/B) ratios turn out to be close to unity, if the contribution from pile-up is not considered. This advantageous S/B ratio is due to the combination of the $J_z = 0$ selection rule, the potentially excellent mass resolution, and the simplicity of the event signature in the central detector.

1.0.2 Photon-induced processes

Photon–initiated (PI) particle production is a key ingredient in the LHC physics programme, playing a role in precision predictions for inclusive electroweak particle production, probes of BSM physics, SM physics in the diffractive sector, and in ultraperipheral heavy ion collisions (see Refs. [A3, B1] for references).

A unique feature of the PI channel in proton–proton collisions is that the colour singlet photon exchange naturally leads to exclusive events, where the photons are emitted elastically from the protons, which then remain intact. More generally, even if the initial–state photon is emitted inelastically, there is no colour flow as a result, and there is still a possibility for semi–exclusive events with rapidity gaps in the final–state between the proton dissociation system(s) and the centrally produced object ([B1]).

1.0.3 Fragmentation functions

The fragmentation function, $D_a^h(x, Q^2)$, is defined as the probability that parton a, which is produced at short distance, of order $1/Q$, fragments into hadron, h, carrying the fraction x of the momentum of a. In the experimental analysis reported in this thesis, the momentum fraction is defined as $x_{\mathrm{E}} = E_h/E_{\mathrm{j}et}$, where E_h is the energy of the hadron h and $E_{\mathrm{j}et}$ is the energy of the jet to which it is assigned.

The thesis is organized roughly in the same way as usual experiments are organized in time: first we learn about interesting processes and we desire to measure them. Then we use some tools to learn more about these processes and prepare some to extract useful information from real data. Finally we build detectors that are able to measure them. So in the first part, we will be discussing physics motivation for measuring interesting diffractive processes, for example searching for Dark Matter in exclusive processes, for which detecting diffractively scattered protons by dedicated forward detectors is indispensable, so the above motivation provides also arguments to install such special detectors; in the second part, we will mention some of the tools that can be used to analyse data collected by the above detectors, and the third part is devoted to a brief description of some of experimental analyses that were inspired by the motivational works above on one side, and that profited from the data collected by the special devices placed in the forward direction of the main detector on the other side.

Chapter 2

Physics motivations

In the first part of the thesis, devoted to physics motivation for measuring several diffractive processes and for installing forward proton detectors, we will briefly outline the matters and summarize main conclusions. In Section 2.1 we commence by two articles about exclusively produced Higgs boson, the core of the physics case for the FP420 project, one is chronologically the oldest and best cited work of those presented in this thesis, the other is a review. In Sections 2.2 and 2.3, we discuss two feasibility studies for using forward proton detectors at very high luminosities, even for High Luminosity phase of LHC (HL-LHC), namely searching for the Dark Matter candidates and for the exclusive $t\bar{t}$ signal. We close this Chapter by commenting on a motivational analysis of how to access the Wigner function at RHIC (Relativistic Heavy Ion Collider in Brookhaven National Laboratory) and LHC in Section 2.4.

2.1 Central Exclusive production of Higgs boson

The exclusive production of Higgs boson was a flagship topic of the project FP420 (see e.g. the title of the main document, "The FP420 R&D Project: Higgs and New Physics with forward protons at the LHC" [7]) whose main goal was to install detectors at 420 m from the interaction point of ATLAS and CMS experiments to detect diffractively scattered protons. The central exclusive production received a great deal of attention over the last two decades from theorists as well as experimentalists, see references in Ref. [A2].

The $b\bar{b}$, $WW^{(*)}$ and $\tau\tau$ decay modes were studied in detail and are documented in literature (see the full list in Ref. [A2]). Most of them are co-authored by the author of this thesis. It was the $b\bar{b}$ mode that was studied in greatest detail - thanks to advantages enumerated in Introduction and also thanks to the most favourable prospects for this decay mode in enhancing the production cross section in MSSM. The author of the thesis was asked to review results of existing studies (see Ref. [A2]). They can be summarized in the following way.

Although studies of properties of the Higgs boson with mass close to 125.5 GeV discovered by the ATLAS [8] and CMS [9] (see for example a global analysis in Ref. [10]) suggest that the Higgs boson is compatible with the Standard Model, there is still room for models of New Physics, e.g. at lower or higher masses than 125.5 GeV, and the CEP of the Higgs boson still represents a powerful tool to complement the standard strategies at LHC. A striking feature of this channel is that it provides valuable additional information on the spin and the coupling structure of Higgs candidates at the LHC. We emphasize that the $J_z = 0$, $\mathcal{C}$-even, $\mathcal{P}$-even selection rule of the CEP process enables us to estimate very precisely (and event-by-event) the quantum numbers of any resonance produced via CEP.

Signal selection and background rejection cuts are based on requiring a match between measurements in the central detector and FPD within assumed subdetector resolutions. In addition, pile-up backgrounds are suppressed by using Time-of-Flight (ToF) detectors, a natural part of FPD whose use necessitates protons to be tagged on both sides from the interaction point. The significances for the CEP Higgs boson decaying into $b\bar{b}$, WW or $\tau\tau$ pairs in SM are moderate but $3\,\sigma$ can be reached if the analysis tools, ToF measurement resolution or L1 trigger strategies are improved. Ways to improve those significances are discussed in Ref. [A2]. For example we can surely expect improvements in the gluon-jet/b-jet mis-identification probability $P_{g/b}$. In the original analyses a conservative approach has been followed by taking the maximum of two values available at that time in ATLAS and CMS. Meanwhile new developments were reported in reducing the light-quark-b mis-identification probabilities in ATLAS [11] and CMS [12]. Other possibilities to improve the significances in searching for the SM Higgs in CEP are a possible sub-10 ps resolution or finer granularity of timing detectors, the use of multivariate techniques or a further fine-tuning or optimization of the signal selection and background rejection cuts, thanks to the fact that the mass of the SM-like Higgs boson is already known with a relatively high precision. The known Higgs boson mass can also greatly facilitate proposals for a dedicated L1 trigger to efficiently save events with the CEP $H \to b\bar{b}$ candidates ([13]).

Further development after publication

Studying properties of Higgs bosons produced exclusively with a mass around 125 GeV would require building FPDs in the region 420 m from the interaction point. Such a possibility is still being discussed by ATLAS, CMS and TOTEM collaborations (see e.g. Ref. [14]). In principle equipping that region of the LHC beam pipe (so called "cold region") by Roman Pots or Hamburg Beampipe devices was thoroughly discussed in the framework of the FP420 collaboration, see Ref. [7] and Section 4.2. The constraints coming from experimental data exclude the heavy Higgs boson mass region below 400 GeV, although in special MSSM scenarios, for example Mh125 alignment scenario [15], masses lower than 400 GeV would still be possible, but for "fine-tuned" points rather than larger areas. Other extreme scenarios that are still possible are represented by the M_H^{125} scenario [15], in which the light CP-even Higgs is lighter than 125 GeV, and the discovered Higgs boson corresponds to the heavy CP-even MSSM Higgs boson. The development of the M_H^{125} scenario was triggered by the observation of a local excess of 3σ at about 96 GeV in the diphoton final state, based on the CMS Run 2 data [16]. First Run 2 results from ATLAS with 80 fb^{-1} in the $\gamma\gamma$ final state (see e.g. Ref [17]) or full Run 2 ATLAS results in the $\tau^+\tau^-$ final state [18] turned out to be weaker, but a full Run 2 analysis of the CMS data is still awaited.

2.2 Searches for Dark Matter at LHC in the forward proton mode

One of the main goals of the physics program at the LHC and future colliders is the search for signals from beyond Standard Model physics. A possibility that has received significant recent attention in the context of the LHC and future collider searches is the electroweak pair production of R-parity conserving states in compressed mass scenarios of supersymmetry (SUSY). That is, where the mass difference between the heavier state (e.g. the chargino, $\widetilde{\chi}^{\pm}$, or slepton, $\tilde{l}(g)$) and the Lightest SUSY Particle $\widetilde{\chi}_1^0$ (representing a Dark Matter (DM) particle candidate) is small, see references in Ref. [A3].

The potential to search for these comparatively light charged SUSY particles via photon-initiated production in hadron collisions has been widely discussed over the past decades [19–23]. One clear benefit is its production model independence, in sharp contrast to many other reactions. That is, the production cross sections are directly predicted in terms of the electric charges of the relevant states.

The experimental signature for the CEP of electroweakinos is then the presence of two very forward protons that are detected in the FPD and two leptons from the slepton $\tilde{l}(g) \to l + \widetilde{\chi}^0$ decay whose production vertex is indistinguishable from the primary vertex measured in the central detector. The well-defined initial state and presence of the tagged outgoing protons provides a unique handle, completely absent in the inclusive case, that is able to greatly increase the discovery potential.

In Ref. [A3] we studied in detail the LHC prospects for searching for such exclusive slepton pair produced in compressed mass scenarios at $\sqrt{s} = 14$ TeV. We performed for the first time a systematic analysis of various challenges and sources of backgrounds that such studies must deal with. In particular, as well as the irreducible exclusive WW background, we also consider the reducible backgrounds from semi-exclusive lepton pair production, where a proton produced in the initial proton dissociation registers in the FPDs, and the pile-up background where two soft inelastic events coincide with an inelastic lepton pair production event.

We have developed an experimental procedure basing on two pillars, both being represented by know-how acquired by ATLAS and CMS experiments in related published analyses of rather similar data. The first pillar is built on experience with handling very soft leptons, the second makes use of exclusivity requirements, both in the presence of high pile-up. To account for most of effects occurring during passages of particles through large volumes of detector material and for combinatorial effects from the presence of high pile-up, we have used the fast simulation program DELPHES [24]. Although we have advantageously generated only in the phase space necessary for a reliable analysis of all backgrounds, still extremely large samples had to be created, especially those of non-diffractive dijets with pile-up, which put immense demands on the computational power and time. One of powerful exclusivity cuts is the so called z-vertex veto requiring no additional charged particles and vertices in a close vicinity of the primary vertex, except those corresponding to the two signal leptons. The efficiency of such a cut as a function of the amount of pile-up events per bunch crossing was found to be in a good agreement with that published in the above experimental analyses, a prerequisite for any reliable feasibility study. Yet, a very challenging task emerged, namely to tame the pile-up background, higher by many orders of magnitude than the signal. We have found that requiring that the lepton pair lie in the signal $m_{ll} < 40$ GeV region, combined with further judicially chosen cuts on the lepton momenta leads to significant reductions in the background. The pile-up backgrounds are strongly reduced by the use of ToF subdetectors in the FPDs, as well as the aforementioned lepton cuts and a further cut on the proton transverse momentum. These also help to reduce the semi-exclusive backgrounds considerably. Introducing the proton p_T cut as well as requiring large rapidity gaps searched for relying on knowledge of the z-vertex veto efficiency are considered to be novelties in the field.

In summary, we observe that in total 2–3 signal events for an integrated luminosity of 300 fb^{-1}, corresponding roughly to $\langle\mu\rangle = 50$ ($\langle\mu\rangle$ = average number of pile-up interactions per bunch crossing), can be expected, with a $S/B \sim 1$. Experimentally, the signal yield can be doubled by taking all di-lepton masses into account. This would, however, not only increase the background but also the average di-lepton mass itself and hence limit the possibility of estimating the unknown mass of the DM particle by measuring the central system mass via the FPDs. Another way to increase the signal yield would be to increase the lepton reconstruction efficiencies. The background contamination, in turn, could be lowered by rejecting events with a displaced vertex which can be done by restricting track longitudinal, z_0, and transverse, d_0, impact parameters to some small values, or by a cut on the so called pseudo-proper lifetime. Furthermore, both ATLAS and CMS are upgrading their trackers to cover the additional region $2.4 < |\eta| < 4$. Both are also considering adding timing detectors in these forward areas with resolution of about 30 ps [25, 26]. By getting this timing information we acquire another ToF rejection factor in addition to that shown in table 6 of Ref. [A3].

Further development after publication

As described in Chapter 3, `SuperChic 4` [B1], the version to which the author of this thesis contributed significantly, correctly accounts for particle decay distribution from dissociation system and for the kinematically dependent survival probability S^2. This gave us a precise tool to re-evaluate the background from semi-exclusive lepton pair production, described above. The contamination by this type of background is found to be about three times smaller than originally estimated in Ref. [A3] by approximative means.

This study earned attention, among others, of colleagues from the ATLAS collaboration who are interested in measuring this process using the AFP detector (described in Section 4.2) both in Run 3 and in HL-LHC. This process, together with searching for New Physics in the top–anti-top pair production (described in Section 2.3) and potentially also in the Higgs boson production, become currently a core of the physics motivation for pursuing the exclusive physics using AFP at very large luminosities. The author of this thesis was offered to co-supervise a PhD thesis whose topic is searching for BSM signal in two channels: $t\bar{t}$ pair, and low-p_T sleptons (decaying to neutralinos, candidates for DM) using AFP to tag forward protons. The PhD student is going to develop and validate a L1 trigger for the DM search which will be based on two soft leptons fulfilling topological cuts developed in the discussed phenomenology study [A3]. For the HL-LHC phase where pile-up conditions will be harsher than for Run 3, more experimental handles will be needed to be developed such as timing information in the central detector, 2-dimensional cuts or making use of missing E_T value which is low in the signal process and evades so far measuring capabilities of the ATLAS detector which concentrates on inclusive processes where missing E_T is usually much larger.

2.3 Top quark pair production in the exclusive processes at LHC

The precise mass determination via FPDs – similarly as for Higgs boson, see Ref. [A1] – is also attractive in the case of the top quark. High precision of the mass measurements of the top quark as well as of the Higgs boson is claimed to allow to discriminate between stability, metastability or criticality of the electroweak vacuum (see e.g. [27]). Prospects for a top quark mass measurement using FPDs were studied in Ref. [A4] together with LHC prospects for measurements of the $t\bar{t}$ pair produced exclusively in photon-photon or semi-exclusively in photon-Pomeron and Pomeron-Pomeron processes using protons tagged in FPDs on both sides of the interaction point. These processes are also interesting from the point of view of constraining models used in BSM physics. Focusing on the semi-leptonic channel, $t\bar{t} \to jjbl\nu_l\bar{b}$ ($j(b)$ representing un-tagged (b-tagged) jet), making use of the exclusive nature of the final state, together with the use of timing information provided by FPDs, relevant exclusive and inclusive backgrounds are studied in detail. We analyzed four luminosity scenarios, going from zero pile-up up to $\langle\mu\rangle$ of 50 with corresponding assumed integral luminosities of up to 300 fb^{-1}. With the help of DELPHES fast simulation program [24], the main effects of detector acceptance and resolutions as well as the effect of pile-up background were included in the analysis procedure.

Good prospects for observing the semi-exclusive signal over a mixture of inclusive and combinatorial backgrounds are achieved for all luminosity scenarios, although a good separation between the two are observed for rather low amounts of pile-up, typically lower than $\langle\mu\rangle$ of 50. Statistical significances evaluated from estimated numbers of signal and background events are around 3 for the highest luminosity scenario $(\langle\mu\rangle, \mathcal{L}[\text{fb}^{-1}]) = (50, 300)$, about 6 for the (10,30) and 11 for the (5,10) scenarios. From a simple statistical analysis, we find that these significances are still not sufficient for a determination of the top quark mass that would be competitive with inclusive methods. Much higher statistics would be needed with the current experimental procedure or more sophisticated procedures to suppress the dominant background have to be developed.

Compared to the DM searches with FPDs, described in the previous Section, the initial particles are photons as well but topology and mass of the final state are entirely different: while for the dilepton system the mass is very low and topology is such that the central detector "sees" rather empty events (if pile-up is not considered), for the $t\bar{t}$ system the mass is more than 30 times higher and events are much denser. The more massive the central system and the emptier or the more exclusive topology of the final state, the more powerful handles one has in the fight with backgrounds. It is not then surprising that relative signal event yields and background contaminations are not too different between the two analyses, although final states differ considerably.

Further development after publication

After demonstrating good prospects for observing the $t\bar{t}$ system produced semi-exclusively at relatively high pile-up in Ref. [A4], the same team of authors accepted the challenge and started to look into the pure exclusive interaction, namely if the $t\bar{t}$ pair produced in photon-photon collisions could be separated from huge pile-up backgrounds or one would have to stay at low pile-up and expect only a handful of signal events. The main reason to tackle this (purely QED) interaction is that prospects to test some of BSM models are more promising than for the other two interactions. The main handle to suppress the Pomeron-induced backgrounds is p_T of forward protons which is expected to be on average smaller for those that emit photons.

With another team, we are developing an experimental procedure to detect top quark(s) in the so called inclusive photoproduction, i.e. photon-proton interaction. Since this is a process with singly-tagged proton in FPD, ToF detectors cannot be utilized hence only data with relatively low amounts of pile-up can be collected. The remaining pile-up contamination should be reducible by requiring the central system mass (or ξ) to match with measurements in a single FPD.

None of the above discussed processes have so far been measured at LHC, so measuring them for the first time would be exciting in their own right. But this would also promise to hold interesting information about diffractive properties of the interaction (for example values of the soft survival factor which are process- as well as kinematically-dependent) or can serve to search for New Physics.

2.4 Accessing the gluon Wigner distribution in ultraperipheral pA collisions

The so-called Wigner distribution is sometimes called "mother distribution" because it provides maximally detailed information about quantum systems. In the case of hadron structure, the Wigner distribution, or its Fourier transform, the generalized transverse momentum dependent distribution (GTMD), provides a multidimensional partonic imaging of the nucleon. When integrated over the impact factor (or transverse momentum), the Wigner function reduces to a transverse momentum dependent distribution, TMD, (or generalized parton distribution, GPD) and when integrated further, one arrives at parton density function (PDF), most commonly used in theory predictions.

In this study [A5] we tried to be self-contained in that we have not only discussed theoretical aspects but we also provided ideas on how possible measurements could be done, and investigated which existing data samples could be used. This study proposes to constrain the gluon Wigner distribution in the nucleon by studying the exclusive diffractive dijet production process in ultraperipheral proton-nucleus collisions (UPCs) at RHIC and the LHC. Compared to the previous proposal in Ref. [28] to study the same observable in lepton-nucleon scattering, the use of UPCs has a few advantages: not only is the cross section larger, but the extraction of the Wigner distribution from the data also becomes simpler, including its elliptic angular dependence. We compute the corresponding cross section and evaluate the coefficients using models which include the gluon saturation effects.

We demonstrate that both components (the ϕ-dependent and ϕ-independent) of the gluon Wigner distribution may be extracted from these data. The special role here is played by the elliptic component of the Wigner (or the corresponding GTMD) function providing the $\cos 2\phi$ dependence on the angle ϕ between the total and relative transverse momenta of the two jets going back-to-back. The former momentum (actually both) can of course be measured in the central detector but since it is equal to the p_T of the scattered proton, FPD can measure it by measuring the value of the t variable ($t \approx p_T^2$) which is usually done more precisely and with smaller systematic uncertainties than in the central detector. This is a nice example of a two-fold use of FPD: it can be utilized to tag protons and to measure its p_T. While the former tags event candidates for an exclusive process (thereby reduces combinatorial background), the latter measures the vectorial sum of two jets more precisely than in the central detector.

The angular dependence of the Wigner function was recently shown [29, 30] to be a complementary way to describe an elliptic flow in pA collisions and it is of interest how this mechanism should be combined with the "standard" collective mechanism of elliptic flow generation in quark-gluon plasma.

As mentioned above, this study also aims to encourage experimentalists to look in more detail to see if the Wigner function could be measured at the RHIC, LHC and EIC (future Electron Ion Collider to be built in Brookhaven National Laboratory). We tried to provide first experimental ideas but more work would be needed before making conclusions. It is encouraging that data which could be used for such studies exist. There are samples of pA data at both, the LHC and RHIC, where forward protons were tagged by FPDs. The RHIC environment seems to be more suitable to look at saturation effects that are expected to be visible at $p_T <$ 10 GeV, while the LHC data promise to provide more accurate measurements of protons and jets.

Results of this study were included in some collective works, for example in prospects for measurements of quarkonia at HL-LHC [31] or among new opportunities at the photon energy frontier in the framework of the 2021 Snowmass Summer Study [32]. There are also first experimental results inspired by the work [A5]: in the CMS analysis [33] the second moment of the angular distribution, $\langle \cos 2\phi \rangle$, was measured as a function of the momentum sum of the two jets.

Chapter 3

Tools

The second part of the thesis describes two papers whose topics, interesting and worth pursuing in their own right, may be considered as tools to analyze experimental or artificial (Monte Carlo) data. In Section 3.1 a new version of the `SuperChic` MC program is commented and in Section 3.2 we briefly discuss performance of the time-of-flight detector. These two tools represent a tiny fraction of plethora of tools used nowadays in modern experimental or phenomenological analyses. MC event generators seem to belong to the most frequently used tools because of their traditional role in estimating for example backgrounds, efficiencies, acceptances and resolutions of variables used in experimental analyses. These days, all these characteristics are witnessed to be directly estimated more and more frequently from real data but where the role of MC event generators seems to stay unshakable is their ability to be a platform serving to put our ideas/theories about how the microscopic world functions, and to test them straight away.

From the viewpoint of other big tasks in the data processing, the exploitation of the ToF detector and ToF method is rather narrow. But such a device is indispensable when trying to extract information about exclusive processes usually buried deep in an enormous pile-up background present at high-energy large hadron colliders at high luminosities.

3.1 Development of a Monte Carlo event generator as a tool to study photon-photon interactions

In Ref. [B1], a new `SuperChic 4` Monte Carlo implementation of photon–initiated production in proton–proton collisions, considering as a first example the case of lepton pair production, has been described. `SuperChic` is a dedicated MC event generator widely used in experimental analyses dealing with photon-induced processes at hadron colliders. At LHC, it was for example used to assess signal event yields as well as irreducible backgrounds in measurements of semi-exclusive dileptons with tagged protons in AFP [C4] or in TOTEM [34]. Without tagged protons, `SuperChic` served in measurements of semi-exclusive dileptons [35, 36], W bosons [37] and photons [38–40]. The results with exclusive photons in the final state established first observations of the so-called light-by-light scattering at LHC and served also to searches for axion-like particles (as candidates of Dark Matter).

`SuperChic` was also the main MC event generator used to estimate signal event yields as well as relevant irreducible backgrounds in the phenomenology feasibility study of Dark Matter searches at LHC in events with exclusively produced sleptons which decay to soft leptons [A3], discussed in Section 2.2.

It is based on the structure function calculation of the underlying process, and takes a complete account of the various contributing channels, including the case where a rapidity gap veto is imposed. We carefully treat the contributions where either (single dissociation), both (double dissociation) or neither (elastic) proton interacts inelastically and dissociates, and interface our results to `Pythia` for showering and hadronization. The particle decay distribution from dissociation system, as well the survival probability for no additional proton–proton interactions depending on the event kinematics and the specific channel (elastic or inelastic), are both fully accounted for; these are essential for comparing to data where a rapidity gap veto is applied. `SuperChic 4` is the first generator of its kind to take account of all of these features, which are essential when providing results for semi–exclusive PI production, in a way that the individual elastic, SD and DD components can be included individually or in combination. As such we believe it will have multiple applications for LHC physics. We also present detailed results for the impact of the veto requirement on the differential cross section, compare to and find good agreement with ATLAS 7 TeV data on semi–exclusive production [35], and provide a new precise evaluation of the background from semi–exclusive lepton pair production to SUSY particle production in compressed mass scenarios [A3], described and discussed in Section 2.2.

Further development after publication

Predictions of `SuperChic 4` were compared with results of the ATLAS measurement of the dilepton pair produced exclusively with a help of AFP [C4] reported in Section 4.5. They were found in a good agreement with measured cross sections for both, the e^+e^- and $\mu^+\mu^-$ channels, the only measured quantities corrected for detector effects.

3.2 Performance studies of Time-of-Flight detectors at LHC

Exclusive processes are characterized by low cross sections, the price to be paid for the very clean final state and relatively low irreducible backgrounds. If signal production cross sections are at a level of femtobarns or lower, the integrated luminosity has to be hundreds of inverse femtobarns. If such an amount of data is to be collected in a reasonable time period, instantaneous luminosities reach $10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ and more (at HL-LHC period), giving rise to tens or hundreds of pile-up interactions per bunch crossing, representing a dominant source of background. Stringent exclusivity cuts need to be applied, among which the time-of-flight (ToF) procedure belongs to powerful tools to suppress such a combinatorial source of background.

In Ref. [B2] performance studies have been performed with the aim to investigate how ToF detector, which is a natural part of AFP and CT-PPS (described in Section 4.2), can help to suppress the pile-up backgrounds. A developed toy model provides a generic double-tag probability for the signal and all relevant backgrounds stemming from pile-up interactions, as a function of the time and spatial resolutions of the ToF device and the amount of pile-up per bunch crossing, in the ranges of σ_t of 10–30 ps, σ_x of 0–5 mm and $\langle\mu\rangle$ of up to 200. This double-tag probability is to be in an ideal case scaled by selection efficiencies for the signal or rejection efficiencies for backgrounds for each process under study.

The effect of the time resolution is observed to be rather negligible for the CD signal and more-or-less linearly increasing with increasing σ_t for pile-up backgrounds. The effect of the granularity is in general more pronounced for the signal as well as backgrounds and, as expected, while it decreases for the signal, it increases for the backgrounds with increasing σ_x. For both these effects, it holds that as the amount of pile-up interactions grows, the effect gets stronger.

A very important consistency check has been carried out as a part of this study, namely it was shown that the fake double-tag probability as a function of pile-up amount and its reduction after making use of the ToF device follow very precisely those evaluated by an independent program whose results were shown for example in Refs. [A3, A4] and summarized in Ref. [A2] (where the rate of fake double-tagged events is parameterized by a simple combinatorial formula, see Eq. (1)).

In this context, it is also useful to note that the ToF suppression factors improve after applying an additional cut on proton p_T, the effect found in the search for Dark Matter with AFP [A3], see Section 2.2. For example the $p_T < 0.35$ GeV improves the ToF suppression by a factor of 2. Since an average proton p_T for photon-induced processes is smaller than for Pomeron-induced processes, a cut of this sort is usually applied to suppress Pomeron backgrounds in the case of a signal corresponding to the photon-induced process. Consequently, by applying this proton p_T cut we advantageously improve on two fronts. However, if the signal is a Pomeron-induced process, applying such a cut would lead to improvements in the ToF suppression but might entail losses in the statistical significance, so one would have to carefully study an optimal cut value of p_T.

Further development after publication

The results such as for example number of protons seen by FPD as a function of the amount of pile-up events per bunch crossing or how the ToF device is able to distinguish them at the same bunch crossing depending on its time and spatial resolutions, are naturally very important for all analyses dealing with exclusive processes of low cross sections — those to be measured at HL-LHC in particular. The conclusion that the current granularity would be insufficient for HL-LHC conditions belongs to messages one should take away. In general, the results seem to form a basis for building the physics case for keeping the AFP detector during the HL-LHC phase where pile-up numbers may reach values of a few hundreds.

Chapter 4

Experimental analyses

In this chapter we are briefly describing and commenting on some of experimental analyses the author of this thesis worked on either as the only analyzer (the fragmentation functions in Section 4.1) or as a member of a 3-body editorial board (the ALFA analysis in Section 4.4) or a member of small analysis teams (the dijet analysis in Section 4.3 and the AFP analysis in Section 4.5).

The analysis of fragmentation functions, touching the domain of genuine soft physics, was performed during the fellowship stay at CERN in the OPAL experiment. The other three deal with diffraction measured by the ATLAS experiment and differ in what is used as the main detector and techniques to select samples enhanced in diffractive signal and in how much pile-up they have to tackle with: the analysis in Section 4.3 searches for large rapidity gaps in the ATLAS detector, in Section 4.4 the ALFA spectrometer far from the main ATLAS detector serves as a diffraction tagger, both analyses using data with negligible amounts of pile-up, or finally the AFP spectrometer, also located far from the ATLAS detector and using data with large pile-up in Section 4.5. Acceptances of the ALFA and AFP devices are rather limited, however, by detecting forward protons, we suppress non-diffractive backgrounds significantly.

4.1 Quark and Gluon jet fragmentation functions using LEP data

The measurements of quark and gluon jet fragmentation functions at $\sqrt{s} = 91.2$ GeV and $\sqrt{s} = 183$–209 GeV were published in Ref. [C1]. The data were collected with the OPAL detector at the LEP e^+e^- collider at CERN. The fragmentation functions are extracted from three-jet $q\bar{q}g$ events that are selected by applying a jet finder. Different jet finders result in different assignments of particles to jets: thus jets defined using a jet finding algorithm are called *biased.* In contrast, quark and gluon jets used in theoretical calculations are usually defined as inclusive hemispheres of back-to-back $q\bar{q}$ and gg final states, respectively. The hemisphere definition yields a so-called *unbiased* jet because the jet properties do not depend on the choice of a jet finder. Measurements of unbiased quark jets have been performed at many scales (e.g. [41]). Direct measurements of unbiased gluon jets are, however, so far available only from the CLEO [42] and OPAL [43] experiments. The OPAL experiment has also measured properties of unbiased gluon jets indirectly [44].

We measured seven types of fragmentation functions: those from biased as well as unbiased flavour inclusive, udsc and b jets, and from biased gluon jets. While the two types of flavour inclusive jets have been measured many times, data on the other types of fragmentation functions are still rather scarce. The measured fragmentation function is defined here as the total number of charged particles, N_p, in bins of x_{E} and scale Q normalized to the number of jets, $N_{\mathrm{j}et}(Q)$, in the bin of Q:

$$\frac{1}{N_{\mathrm{j}et}(Q)} \frac{\mathrm{d}N_p(x_{\mathrm{E}}, Q)}{\mathrm{d}x_{\mathrm{E}}} \tag{4.1.1}$$

To measure the scale dependence, it is necessary to specify a scale relevant to the process under study. For inclusive hadronic events, the scale is $\sqrt{s}$. For jets in three-jet events, neither $\sqrt{s}$ nor $E_{\mathrm{j}et}$ is considered to be an appropriate choice of the scale [45]. QCD coherence suggests [46] that the event topology should also be taken into account. Similarly to previous studies, the transverse momentum-like scale, $Q_{\mathrm{j}et} = E_{\mathrm{j}et} \sin(\vartheta/2)$, is used where ϑ is the angle between the jet with $E_{\mathrm{j}et}$ and the closest other jet.

The quark biased jet data from LEP1 cover the region $Q_{jet} = 4$–42 GeV, while those from LEP2 cover the region $Q_{jet} = 30$–105 GeV. The udsc jet results above 45.6 GeV, the gluon jet results above 30 GeV (except for the g_{incl} jets), and the b jet results at all scales except 45.6 GeV represented the first LEP measurements.

A good correspondence found between the results from biased and unbiased jets suggests that Q_{jet} is an appropriate choice of scale in three-jet events with a general topology. The MC study presented in Ref. [C1], however, demonstrates that the bias introduced in the gluon jet identification is not negligible for $x_{\mathrm{E}} > 0.6$. The scaling violation seen in the data is positive for low x_{E} and negative for high x_{E}. It is more pronounced in the gluon jets than in the quark jets.

As suggested above, this was rather an elaborate and lengthy work. However, compared to most of LEP publications, the paper is rather comprehensive and contains several dedicated studies, each probably sufficient for an individual publication (e.g. comparison of biased and unbiased jets or choice of the proper hard scale - both are also considered to be assets of this study). This publication is also regularly cited in the Review of Particle Physics by Particle Data Group.

4.2 History and Status of Forward Proton Detectors at LHC

The ATLAS experiment [47] has two devices to detect forward protons: ALFA [48] and AFP [49, 50]. While the ALFA detector serves mainly to detect elastically deflected protons in the vertical direction from the beam center and operates only in special low luminosity runs, AFP detects diffractively scattered protons that are seen in the horizontal direction from the beam center and operates at any luminosity. The purpose of the diffraction-focused near-beam detectors is to measure intact protons arising at small angles, giving access to a wide range of diffractive processes. Dedicated FPDs discussed in this thesis are a part of both the ATLAS and CMS experiments. The AFP (ATLAS Forward Proton) [49, 50] and CT-PPS (CMS-Totem Precision Proton Spectrometer) [51] detectors were installed at around 220 m from the interaction point and their designs are similar. They use 3D-Silicon trackers to precisely measure ξ and either quartz bars, gas detector or diamond sensors to measure the time-of-flight (ToF) of the deflected protons between the interaction point and the timing detectors. The ToF determines the interaction point in the beam direction if (and only if) the protons detected at opposite sides of the interaction point came from the same interaction, thus reducing pile-up background. Both AFP and CT-PPS house the detectors in Roman pots as a means of moving them very close to the beams, as in Totem experiment and ALFA. Both AFP and CT-PPS were installed during the Run II and collected data whenever it was possible, i.e. with high as well as low amounts of pile-up. Since Roman Pots move very close to the beams of protons the danger of deteriorating conditions around the beams is non-negligible, therefore they are generally operated by the LHC machine crew which also decides when they can be inserted or need to be retracted.

The AFP spectrometer consists of four tracking units located along the beampipe at $z = \pm 205$ m and ± 217 m, referred to as Near and Far stations, respectively. Each station houses a silicon tracker comprising four planes of edgeless silicon pixel sensors. The sensors have 336×80 pixels with area $50 \times 250\ \mu\text{m}^2$. The direction normal to each sensor is tilted 14° relative to the beam to improve hit efficiency and x-position resolution, resulting in an overall spatial resolution of $\sigma_x = 6\ \mu$m. Movable Roman Pots insert the tracker along the x-direction in the beampipe.

4.3 Measurement of jets with large rapidity gaps without forward proton detectors

Diffractive dissociation (e.g. $pp \to pX$) contributes a large fraction of the total inelastic cross section at the LHC. The inclusive process has been studied using the earliest LHC data in samples of events in which a large gap is identified in the rapidity distribution of final-state hadrons [52, 53]. In the absence of hard scales, the understanding of these data is based on phenomenological methods rather than the established theory of the strong interaction, perturbative QCD.

A subset of diffractive dissociation events in which hadronic jets are produced as components of the dissociation system, X, was first observed at the SPS, a phenomenon which has since been studied extensively at HERA and the Tevatron. The jet transverse momentum provides a natural hard scale for perturbative QCD calculations, making the process sensitive to the underlying parton dynamics of diffraction and colour-singlet exchange. A model [54] in which the hard scattering is factorized from a colourless component of the proton with its own partonic content (diffractive parton distribution functions, dPDFs), corresponding to the older concept of a Pomeron [55], has been successful in describing diffractive deep inelastic scattering ($ep \to eXp$) at HERA. The success of the factorizable approach breaks down when dPDFs from ep scattering are applied to hard diffractive cross sections in photoproduction or at hadron colliders. Tevatron data [56] show a suppression of the measured cross section by a factor of typically 10 relative to predictions. A similar rapidity-gap survival probability, S^2, was suggested by the first results from the LHC [57]. This factorization breaking is usually attributed to secondary scattering from beam remnants, also referred to as absorptive corrections. Understanding these effects more deeply is an important step towards a complete model of diffractive processes at hadronic colliders.

In this paper [C2], the measurement of the cross section for dijet production in association with forward rapidity gaps is reported, based on 6.8 nb^{-1} low pile-up 7 TeV pp collision data taken at the LHC in 2010. The data are characterized according to the size of the forward rapidity gap (starting at the edge of calorimeter at $|\eta| = 5$), $\Delta\eta^{\mathrm{F}}$, and $\tilde{\xi}$, the fractional proton momentum loss. The ATLAS technique for finding large rapidity gaps, first introduced in Ref. [52], is developed further and applied to events in which a pair of high transverse momentum (p_{T}) jets is identified. The results are interpreted through comparisons with Monte Carlo models which incorporate dPDF-based predictions with no modelling of multiple scattering. Comparisons between the measurements and the predictions thus provide estimates of the rapidity-gap survival probability applicable to single dissociation processes at LHC energies. Non-diffractive Monte Carlo models are capable of describing the data over a wide kinematic range. However, a diffractive component is also required for a more complete description of the data, particularly when both large $\Delta\eta^{\mathrm{F}}$and small $\tilde{\xi}$ are required.

The rapidity-gap survival probability is estimated by comparing the measured cross section for events with both large $\Delta\eta^{\mathrm{F}}$ and small $\tilde{\xi}$ with the leading-order `Pomwig` Monte Carlo model of the diffractive contribution, derived from dPDFs extracted in deep inelastic *ep* scattering. This determination is limited by the uncertainties associated with the non-diffractive and double-dissociation contributions, the result being $S^2 = 0.16 \pm 0.04$ (stat.) $\pm\, 0.08$ (exp. syst.).

This analysis represented a series of challenges and although most of analysis work was done by two PhD students it took more than 3 years to get it published in the journal. One of the challenges was rather modest data statistics available. Since both key observables, namely $\Delta\eta^{\mathrm{F}}$ and jet p_{T} are steeply falling functions, and since the diffractive contribution is largest at he large size of $\Delta\eta^{\mathrm{F}}$, it was necessary to build and validate an event generation filter that selects events with large $\Delta\eta^{\mathrm{F}}$ in several bins of jet p_{T} but conserves proper weights with which to scale individual events to restore the original gap distribution. Much time was also spent on establishing jet trigger efficiencies and fitting them precisely so as to get cross section measurements reliable. Furthermore a big effort was then put to studying the lowest possible thresholds for p_T of charged and neutral particles (or tracks and clusters in detector). The reason being that the higher one goes with particle p_T, the higher efficiency and lower uncertainty are reached for the measured objects, but the more artificial gaps one creates. And vice-versa, the lower one goes with p_T, the more and more one gets influenced by the detector noise. So one has to carefully choose an optimum p_T of all measured objects and study the effect of varying the threshold up and down around the optimum value.

4.4 Measurements of single diffraction using the ALFA forward proton spectrometer at ATLAS

In this analysis of the LHC data collected by the ATLAS experiment, signal Single-Diffractive (SD) events are selected relying on tagging the intact proton in the ALFA spectrometer on either side. SD process in proton-proton collisions, $pp \to pX$, is characterized by an intact proton which is deflected under a very small angle with respect to the incoming proton, accompanied by a large rapidity gap, a region devoid of hadronic activity, and a central system X, originating from dissociation of the other proton. A non-negligible background comes from processes where both protons stay intact (Central Diffraction). When overlaid with a proton from an unrelated event, Double Diffractive and Non-Diffractive processes have to be considered as well. All details of this analysis can be found in Ref. [C3].

This measurement makes use of the sensitivity of the inner tracking detector (ID) and the minimum bias trigger scintillators (MBTS) to the components of the dissociating system X, and of the ALFA forward proton spectrometer to measure properties of the intact forward protons. The sample used in this analysis was taken during a special run where the luminosity was kept very low, such that the mean number of inelastic interactions per bunch crossing ('pile-up') is smaller than 0.08, allowing rapidity gaps to be identified and suppressing random coincidences between protons in ALFA and unrelated activity in the central detector.

The cross section measurement is performed differentially in t, which is determined from the p_T^2 of the scattered proton, as reconstructed using ALFA. The cross section is also measured differentially in $\Delta\eta$, the size of the region in which no primary charged particles are produced with $p_T > 200$ MeV, starting at the edge of tracker at $|\eta| = 2.5$ on the same side of the interaction point as the proton tag and extending towards the X system. The measurement is also performed as a function of ξ, determined via $\xi = M_X^2/s$ by using the charged particles reconstructed in the ID to obtain the mass of the diffractive system X, M_X. The variable ξ can also be reconstructed using the proton in ALFA via $\xi = 1 - E'_p/E_p$, where E'_p and E_p are the scattered proton energy and the beam energy, respectively.

After applying all selection cuts in the fiducial region, the overlay background (coincidences of a signal in ALFA with an uncorrelated signal in the ID) and CD background forms 25%, resp. 8.5% of the measured cross section.

The cross section measured in the fiducial region $-4.0 < \log_{10}\xi < -1.6$ and $0.016 < |t| < 0.43$ GeV^2 is 1.59 ± 0.03(stat.) $\pm\, 0.13$(syst.) mb. This measurement was extrapolated to the full t range integrating over $-4.0 < \log_{10}\xi < -1.6$ and then further extrapolated to the full t and ξ ranges (although an extrapolation to the full ξ range is not well defined) and both `Pythia 8` tunes, A2 and A3, as well as `Herwig 7` predictions overshoot the data by a factor between 2 and 3.

The asset of this measurement lies in the fact that there are no previously published LHC results in which the pure SD differential cross section in t is measured. There are numerous such measurements for elastic events (see e.g. the Chapter High Energy Soft QCD and Diffraction in the recent Review of Particle Physics by the Particle Data Group [58]) but there the experimental procedure is significantly different from these SD measurements: thanks to the unique topology, i.e. empty central detector and only protons in the ALFA detector on opposite sides from the interaction point (in the ideal case going back-to-back in the azimuthal angle but in real conditions, going up on one side and down on the other side) and relatively high cross section, backgrounds are different and generally the precision is significantly better for the elastic events. The measurement reported in this Section of course serves to improving the modeling of other measured data by MC event generators as well as by theory analytical calculations (see e.g. comparisons of KMR group predictions to this and other recent data in Ref. [59]).

4.5 Measurements of semi-exclusive dileptons using the AFP forward proton spectrometer at ATLAS

Electromagnetic fields accompanying colliding protons are intensive enough to produce lepton pairs via photon fusion, $\gamma\gamma \to l^+l^-$, where l denotes electron or muon [35, 36, 60, 61]. This process occurs in a wide range of astrophysical phenomena such as cosmic gamma rays and neutron stars. Measurements of $\gamma\gamma \to l^+l^-$ at the LHC provide a unique laboratory probe of these natural phenomena and are fundamental tests of quantum electrodynamics (e.g. Ref. [62]). The CMS and TOTEM collaborations reported proton-tagged dielectron (dimuon) production with 2.6σ (4.3σ) significance [34], but no cross-sections were measured. Previous measurements of $\gamma\gamma \to l^+l^-$ by the ATLAS experiment were performed without proton-tagging [35, 36]. The article reported in this Section [C4] extends the previous analyses in both aspects, by measuring cross sections (11.0±2.6(stat)±1.2(syst) fb for e^+e^- and 7.2±1.6(stat)±0.9(syst) fb for $\mu^+\mu^-$) and also in association with forward protons tagged by AFP. The latter helps to reduce non-diffractive backgrounds considerably. `SuperChic 4` ([B1]) predictions 12.2±0.9 fb and 10.4±0.7 fb, respectively, show a decent agreement.

Very first ATLAS results making use of AFP were published in 2017 in the form of a Public Note [63]. The work in Ref. [C4], a first journal publication about data utilizing the whole AFP detector, is extremely important for the AFP project as it demonstrates that the AFP detector can routinely be used and detect forward protons at high luminosities thereby enabling access to kinematics of initial photons, so far evading in inclusive collisions where protons break up. It is considered to be a first milestone on the road to further analyses with AFP data, by setting standards and procedures in analyses dealing with forward protons to be detected in the harsh pile-up environment. The publication was preceded by big efforts to understand well performance of the AFP detector in terms of acceptance, efficiencies, resolutions and global and local alignments. The author of this thesis has been responsible for the global alignment using Beam Position Monitors. Another example of complexity is the estimate of the pile-up contamination in the data after applying the z-vertex veto (explained in Section 2.2) by mixing events from Monte Carlo and real data samples (so called data-driven techniques).

Chapter 5

RESUME

This thesis represents rather an experimentalist's view on two classes of processes, soft QCD and diffractive, that ultimately are intimately connected with each other. It focuses on hard-scale diffractive processes and on exclusive or semi-exclusive in particular, with only one specific measurement of a soft QCD phenomenon, namely the fragmentation functions of quark and gluons, nevertheless as mentioned, soft processes are tenacious companions of hard-scale processes. That is the reason why they have to always be treated with care especially when studying difference between signal and background topologies and production rates. At LHC, the bulk of pile-up events and effects stemming from them are prominent representants of soft QCD processes and, thanks to their huge cross sections, especially of why it is extremely important to model them correctly.

The main body of the thesis, namely the description or rather commentary of the author's contribution to the field of soft QCD and diffraction at high energies, is split in three parts. The first one is devoted to phenomenology works focusing on exclusive or semi-exclusive processes, Pomeron-induced or photon-induced ones, to be measured in proton-proton or in heavy-ion collisions. In all of them, dedicated forward proton detectors are necessary, having to be equipped with time-of-flight detectors in most of cases, that are necessary to suppress pile-up backgrounds. None of the proposed processes have so far been measured at LHC.

Results presented in the above-mentioned works and briefly described in this thesis are realistic in the sense that generally none of the relevant backgrounds have been neglected and all relevant detector effects have been included. In most of cases, the results are encouraging on their own so they may challenge to perform measurements (the cases of Dark Matter and top quark pair are pursued in ATLAS, exclusive Higgs is currently being discussed) or they encourage to further studies. They thus serve as physics motivation in the domain of forward and diffraction physics at LHC and also as a motivation to equip or maintain the forward region of the main LHC detectors with the forward proton devices together with fast timing detectors.

The second part describes two of plethora of tools being used nowadays in analyzing real and artificial data at high-energy colliders, two which the author recently helped to develop in collaboration with their main developers. One is a dedicated Monte Carlo event generator `SuperChic 4` which is broadly used to model exclusive and semi-exclusive processes with various final states accessible at LHC, RHIC and future colliders. The version 4 provides elastic as well as inelastic channels for the dilepton production with a correct account of decays of proton dissociation system and the survival probability for no additional proton–proton interactions. The other contribution is related to time-of-flight detectors which are indispensable when measuring exclusive processes of tiny cross sections thanks to their capabilities to suppress combinatorial effects of accompanying pile-up events. The presented dependencies of suppressions on time and spatial resolutions, and on the amount of pile-up suggest that in order for forward proton detectors to be useful at HL-LHC, their timing detectors need to improve the granularity and possibly the time resolution. Such studies have a potential to motivate to working on upgrades of such devices at LHC.

The third part is dealing with experimental analyses whose analysis teams the author was a member of. While the analysis of quark and gluon fragmentation functions is about a genuine soft QCD process, it is investigated as a function of a hard scale provided by jets used to identify light quarks, heavy quarks and gluons. Thanks to a wide interval of hard scale accessible, the scaling violations were observed for all types of measured fragmentation functions. The other three works analyzed ATLAS data with the aim to separate diffractive processes. Two of them worked with data samples from special runs of low contamination by pile-up which enables one to rely purely on existence of large rapidity gaps. One of them used only central detector to search for them, the other used the ALFA proton spectrometer to tag protons in addition. Both report about measurements of Single-Diffraction, one inclusively, the other with two jets in the final state. The last analysis complements the two above by using data with large pile-up amounts and AFP as the proton tagger, and yet extracting a signal by several orders of magnitude less frequent than the two aforementioned – the semi-exclusive production of a lepton pair. It demonstrates a good understanding of the AFP device and techniques to suppress pile-up backgrounds without using time-of-flight detectors whereby establishing standards for upcoming ATLAS analyses which will be based on information about forward protons detected by AFP. Albeit probed at hard scales, the diffractive analyses above measured also the soft survival probability. This demonstrates the aforementioned interconnection.

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