Physics with tagged protons at the LHC: understanding the Pomeron structure and anomalous coupling studies

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We describe different physics topics which can be performed at the LHC using tagged intact protons, namely a better understanding of the Pomeron structure in terms of quarks and gluons, and the search for quartic anomalous couplings.

1 Inclusive diffraction measurement at the LHC

In this section, we discuss potential measurements at the LHC that can constrain the Pomeron structure. The Pomeron structure in terms of quarks and gluons has been derived from QCD fits at HERA and at the Tevatron and it is possible to probe this structure and the QCD evolution at the LHC in a completely new kinematical domain.

1.1 Dijet production in double Pomeron exchanges processes

The high energy and luminosity at the LHC allow the exploration of a completely new kinematical domain. One can first probe if the Pomeron is universal between $ep$ and $pp$ colliders, or in other other words, if we are sensitive to the same object at HERA and the LHC. The different diagrams of the processes that can be studied at the LHC are namely double pomeron exchange (DPE) production of dijets, of $\gamma+\text{jet}$, sensitive respectively to the gluon and quark contents of the Pomeron, and the jet gap jet events. All diagrams were included in the FPMC\cite{1} generator that was used for this analysis.

The dijet production in DPE events at the LHC is sensitive to the gluon density in the Pomeron. In order to quantify how well we are sensitive to the Pomeron structure in terms of gluon density at the LHC, we display in Fig.\ref{fig:1}, left, the dijet cross section as a function of the dijet mass fraction $\beta$, assuming for instance the protons to be tagged in the AFP\cite{3} proton detectors at 210 m. The central black line displays the cross section value for the gluon density in the Pomeron measured at HERA including an additional survival probability of 0.03. The yellow band shows the effect of the 20% uncertainty on the gluon density taking into account the normalisation uncertainties. The dashed curves display how the dijet cross section at the LHC is sensitive to the gluon density distribution especially at high $\beta$. For this sake, we multiply the gluon density in the Pomeron from HERA by $(1 - \beta)\nu$ where $\nu$ varies between -1 and 1. When $\nu$ is equal to -1 (resp. 1), the gluon density is enhanced (resp, decreased) at high $\beta$. From Fig.\ref{fig:1} we notice that the dijet cross section is indeed sensitive to the gluon density in the Pomeron and we can definitely check if the Pomeron model from HERA and its structure
in terms of gluons is compatible between HERA and the LHC. This will be an important test of the Pomeron universality. This measurement can be performed for a luminosity as low as 10 pb$^{-1}$ since the cross section is very large (typically, one day at low luminosity without pile up at the LHC).

### 1.2 Sensitivity to the Pomeron structure in quarks using $\gamma+$jet events

Fig. 1, right, displays a possible observable at the LHC that can probe the quark content in the Pomeron, namely the $\gamma+$jet to the dijet cross section ratio [2] as a function of diffractive mass ($\sqrt{\xi_1 \xi_2 S}$) for different assumptions on the quark content of the Pomeron, $d/u$ varying between 0.25 and 4 in steps of 0.25. We notice that the cross section ratio varies by a factor 2.5 for different values of $u/d$. The aim of the diffractive mass distribution measurement is twofolds: is the Pomeron universal between HERA and the LHC and what is the quark content of the Pomeron? The QCD diffractive fits at HERA assumed that $u = d = s = \bar{u} = \bar{d} = \bar{s}$, since data were not sensitive to the difference between the different quark component in the Pomeron. The LHC data will allow us to determine for instance which value of $d/u$ is favoured by data. Let us assume that $d/u = 0.25$ is favoured. If this is the case, it will be needed to go back to the HERA QCD diffractive fits and check if the fit results at HERA can be modified to take into account this assumption. If the fits to HERA data lead to a large $\chi^2$, it would indicate that the Pomeron is not the same object at HERA and the LHC. On the other hand, if the HERA fits work under this new assumption, the quark content in the Pomeron will be further constrained. The advantage of measuring the cross section ratio as a function of diffractive mass is that most of the systematic uncertainties will cancel.

Soft color interaction models (SCI) is another model to explain diffraction at hadronic colliders [4]. In Fig. 1, right, we notice that the distribution of the $\gamma+$jet to dijet ratio as a function of the total diffractive mass distributions may allow to distinguish between the Herwig/DPE and Pythia/SCI models because the latter leads to a more flat dependence on the total diffractive mass, giving further insight into soft QCD.
1.3 Jet gap jet production in double Pomeron exchanges processes

In this process, both protons are intact after the interaction and detected in AFP at 210 m, two jets are measured in the ATLAS central detector and a gap devoid of any energy is present between the two jets [5]. This kind of event is important since it is sensitive to QCD resummation dynamics given by the BFKL [6, 7] evolution equation. This process has never been measured to date and will be one of the best methods to probe these resummation effects, benefitting from the fact that one can perform the measurement for jets separated by a large angle (there is no remnants which ‘pollute’ the event). As an example, the cross section ratio for events with gaps to events with or without gaps as a function of the leading jet $p_T$ is of the order of 20% which is much higher than the expectations for non-diffractive events. This is due to the fact that the survival probability of 0.03 at the LHC does need to be applied for diffractive events.

2 Exclusive $WW$ and $ZZ$ production

In the Standard Model (SM) of particle physics, the couplings of fermions and gauge bosons are constrained by the gauge symmetries of the Lagrangian. The measurement of $W$ and $Z$ boson pair productions via the exchange of two photons allows to provide directly stringent tests of one of the most important and least understood mechanism in particle physics, namely the electroweak symmetry breaking [8].

The parameterization of the quartic couplings based on [9] is adopted. The cuts to select quartic anomalous gauge coupling $WW$ events are the following, namely $0.0015 < \xi < 0.15$ for the tagged protons corresponding to the AFP detector at 210 and 420 m, $E_T > 20$ GeV, $\Delta \phi < 3.13$ between the two leptons. In addition, a cut on the $p_T$ of the leading lepton $p_T > 160$ GeV and on the diffractive mass $W > 800$ GeV are requested since anomalous coupling events appear at high mass. After these requirements, we expect about 0.7 background events for an expected signal of 17 events if the anomalous coupling is about four orders of magnitude lower than the present LEP limit [10] ($|\alpha_W^L/\Lambda^2| = 5.4 \times 10^{-6}$) for a luminosity of 30 fb$^{-1}$, and about two orders of magnitude better than the present CMS limits [11].

The search for quartic anomalous couplings between $\gamma$ and $W$ bosons was performed again after a full simulation of the ATLAS detector including pile up [3] assuming the protons to be tagged in AFP at 210 m only. Integrated luminosities of 40 and 300 fb$^{-1}$ with, respectively, 23 or 46 average pile-up events per beam crossing have been considered. In order to reduce the background, each $W$ is assumed to decay leptonically (note that the semi-leptonic case in under study). The full list of background processes used for the ATLAS measurement of Standard Model $WW$ cross-section was simulated, namely $t\bar{t}$, $WW$, $WZ$, $ZZ$, $W$+jets, Drell-Yan and single top events. In addition, the additional diffractive backgrounds were also simulated. Since only lepton decays of the $W$ bosons are considered, we require in addition less than 3 tracks associated to the primary vertex, which allows us to reject a large fraction of the non-diffractive backgrounds (e.g. $t\bar{t}$, diboson productions, $W$+jet, etc.) since they show much higher track multiplicities. Remaining Drell-Yan and QED backgrounds are suppressed by requiring the difference in azimuthal angle between the two leptons $\Delta \phi < 3.1$. After these requirements, a similar sensitivity with respect to fast simulation without pile up was obtained.

Of special interest will be also the search for anomalous quartic $\gamma\gamma\gamma\gamma$ anomalous couplings which is now being implemented in the FPMC generator. Let us notice that there is no present existing limit on such coupling and the sensitivity using the forward proton detectors is expected
to be similar as the one for $\gamma\gamma WW$ or $\gamma\gamma ZZ$ anomalous couplings. If discovered at the LHC, $\gamma\gamma\gamma\gamma$ quartic anomalous couplings might be related to the existence of extra-dimensions in the universe, which might lead to a reinterpretation of some experiments in atomic physics. As an example, the Aspect photon correlation experiments [12] might be interpreted via the existence of extra-dimensions. Photons could communicate through extra-dimensions and the deterministic interpretation of Einstein for these experiments might be true if such anomalous couplings exist. From the point of view of atomic physics, the results of the Aspect experiments would depend on the distance of the two photon sources.

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