Diffractive production of a W boson in association with a charm quark

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1. Introduction

Protons contain quarks and gluons. There are six types of quarks, known as flavors: up (u), down (d), charm (c), strange (s), top (t), and bottom (b). Proton is composed of two up and one down quark (referred to as valence quarks), while the contribution from other quarks to proton content (usually referred to as sea quarks) are perturbatively generated from gluon splitting. When two protons collide, a few types of interaction can occur:

- **Elastic scattering**: The energy of two protons is conserved, and they are scattered by small angles via t-channel exchange of a colorless object ($pp \to pp$).
- **Diffractive single/double dissociation**: Protons interact diffractively (t-channel exchange of a colorless object), where one or two protons break apart (dissociate) into a high mass system ($pp \to pN$ or $pp \to NN$).
- **Central diffraction**: Protons interact diffractively, and a fraction of their momentum is transferred to form a new central system of particles X ($pp \to pXp$).
- **Central semi-diffraction**: One proton interacts diffractively (emitting a colorless object) while the other proton dissociates due to the emission of a quark or a gluon, resulting in one intact proton in the final state. Particles emitted from dissociated and diffractive protons interact, forming a new central system of particles X ($pp \to pX$).
- **Non-diffractive scattering**: During the proton-proton collisions, quarks or gluons from the proton interact to form a new system X ($pp \to X$).

In non-diffractive proton-proton interactions, at high energies, quarks and gluons can be considered as point-like constituents of the proton, commonly called partons, contributing to the interaction. Parton distribution functions (PDFs) give the probability of finding partons (quarks and gluons) in a hadron. PDFs can be expressed as a function of the fraction of the proton's momentum (denoted by x) carried by the parton and determined from experimental data on proton-proton scattering. At high energies, it is convenient to consider partons emitted collinearly to the initial proton momentum so that the target can be seen as a stream of partons, each carrying a fraction x of the longitudinal momentum of the proton. The cross-section to produce state X in proton-proton collision ($pp \to X$) is defined as:

$$\sigma_X = \int_{x_1} \int_{x_2} \Sigma_i \Sigma_j f_i(x_1) f_j(x_2) \hat{\sigma}(ij \to X) \quad (1)$$

Where $f_k(x)$ is the PDF for parton of type k to be found in with momentum fraction x inside a proton, and $\hat{\sigma}(ij \to X)$ is a cross-section of the process initiated by pair of partons $ij \to X$ at the center of mass energy of $\hat{s} = \sqrt{sx_i x_j}$.

On the other hand, in diffractive interactions, the interaction occurs via the exchange of pomerons. A Regge trajectory - a family of particles - was postulated in 1961 to explain the slowly rising cross-section of hadronic collisions at high energies. It was assumed that the pomeron could be seen in elastic hadron-hadron scattering as a simple Regge pole. Like for protons, the pomeron distribution function can be defined as the probability of finding a parton (a quark or a gluon) in the pomeron, and for central semi-diffractive interactions (where one proton interacts diffractively) the cross-section to produce state X will be given as follows:

$$\sigma_X = \int_{\xi} \int_t f_{\mathbb{P}}(\xi, t) \int_x \int_{\beta} \Sigma_i \Sigma_j f_i(x) f_j^D(\beta) \hat{\sigma}(ij \to X) \quad (2)$$

Where $f_{\mathbb{P}}(\xi, t)$ is the pomeron flux, expressed as a function of proton momentum loss ξ and squared energy transfer t, $f_k(x)$ is the PDF for parton k to be found in a proton with momentum fraction x, $f_k^D(\beta)$ is the diffractive-PDF for parton k to be found in a pomeron with momentum fraction β, and $\hat{\sigma}(ij \to X)$ is a cross-section of the process initiated by pair of partons $ij \to X$ at the center of mass energy of $\hat{s} = \sqrt{sx\beta\xi}$.

The strange quark content of proton ($f_s(x)$) can be determined in the measurement of associated production of the W boson and a charm quark (a.k.a “W+c”). The project aimed to study the feasibility of measuring the diffractive-PDF of a strange quark ($f_s^D(\beta)$) via the diffractive production of a W boson in association with a charm quark. The partonic structure of a nucleon is best probed in scattering processes like Deep Inelastic Scattering (DIS) of leptons like electrons off nucleons, where the lepton acts as a probe that transfers a four-momentum of modulus q to the nucleon in the collision. The W bosons can be identified by their leptonic decay into a muon or a decay to an electron and a neutrino. A typical diagram of a central semi-diffractive production of a vector boson (V) is associated with a quark (q) where the pomeron or a proton emits the incoming quark is depicted in figure 1.

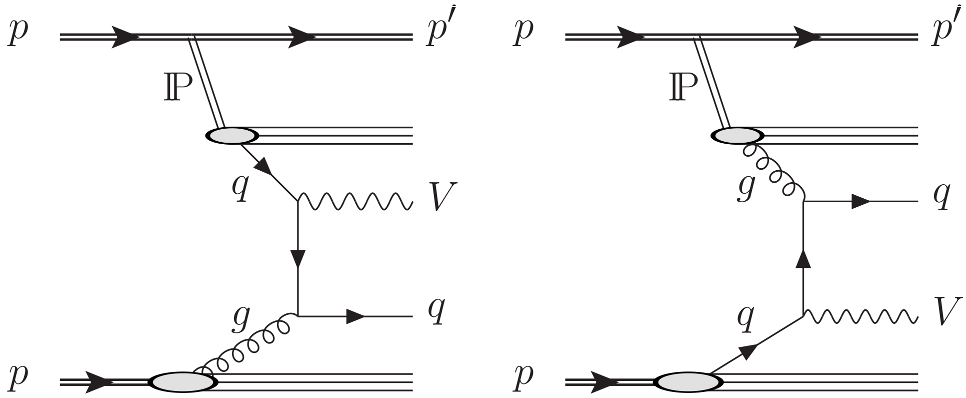


Fig. 1: Central semi-diffractive production of a W boson with a quark. Where the incoming quark can be produced from a diffractive proton (left) or a non-diffractive proton (right).

The instantaneous luminosity and the integrated luminosity are useful values to characterize the performance of a particle accelerator. In particular, all collider experiments aim to maximize their integrated luminosities, as the higher the integrated luminosity, the more data is available to analyze. In scattering theory, instantaneous luminosity (L) is related to the production rate of particles (R) and the cross-section (σ):

$$R = L \times \sigma \tag{3}$$

The integrated luminosity ($\int L$ dt) is related to the total number of produced events (N) and the cross-section (σ):

$$N = \int L \times \sigma \, \mathrm{dt} \tag{4}$$

The strange quark content of the proton can be probed through the measurement of the production cross-section of a W boson and a charm quark in diffractive proton-proton collisions.

2. Analysis strategy

We initiated an analysis of central semi-diffractive W+c production[1], aiming to use the CMS data recorded in November 2017, which was characterized by a relatively low number of pileup interactions. The analysis strategy is to select a clean sample of W+c events, using the same technique as in the measurement of the inclusive (non-diffractive) production cross-section of a W boson in association with a charm quark [1] and filter the diffractive component by tagging the intact proton.

The production rate of W+c events depends on the strange quark content of the proton. The leading diagrams of inclusive production of W + charm quark are shown in figure 2.

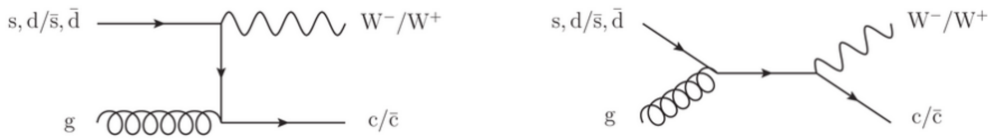


Fig. 2: Leading order diagrams for the associated production of a W boson and a charm quark. The figure is taken from [1].

The W+c selection is based on the charge asymmetry between the W boson and the c quark in the signal events. Contrary to background events with the same fraction of symmetric and asymmetric events. By subtracting charge symmetric from charge asymmetric processes, one can obtain a clean sample of W+c events as shown in figure 3.

In our analysis, we simulated diffractive and non-diffractive production of W+jets using Pythia8 event generator [2]. The production cross-section of the simulated samples is shown in Table 1.

[1]In the text, we will name central semi-diffractive production of W+c as a *single diffractive W+c production*

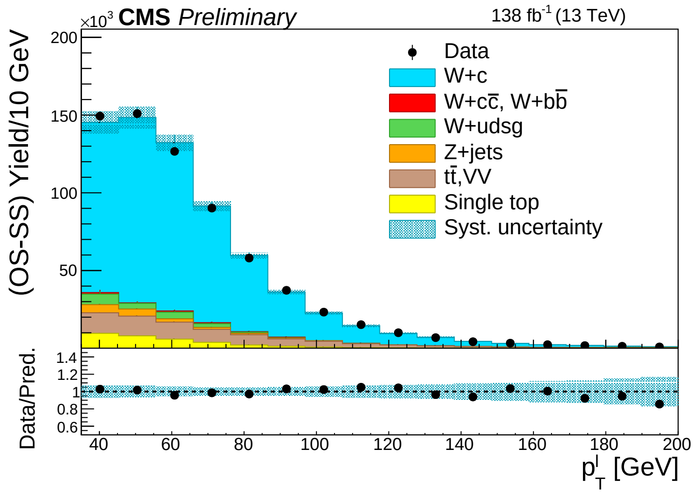


Fig. 3: Distribution of the p_T of the lepton from the W decay after subtracting contribution from the same-sign events. The figure is taken from [1].

Production type	W+quark	W + quark or gluon
Single diffractive	0.195 pb	0.252 pb
non-diffractive	25.88 pb	34.45 pb

Table 1: Cross-section obtained using Pythia8 MC event generator for single diffractive and non-diffractive production processes.

The diffractive component comprises 0.74% of the inclusive cross-section. During the LHC Run 2 (with 138 fb^{-1} of integrated luminosity collected by the CMS experiment) 3.5M W+jet events are expected to be produced[2]. Since we are interested in studying W+c events, we needed to extract the fraction that contains charm quark from the simulated samples. Particle type was stored as integers corresponding to a different type of particles and follows the Monte-Carlo Particle DataGroup ID numbering scheme[3].

The flavor composition in W+jet events for diffractive and non-diffractive processes is shown in figure 4.

One can note that we have slightly more diffractive than non-diffractive W+c events due to the

[2] The number of expected events is computed using equation 4.

[3] https://pdg.lbl.gov/2007/reviews/montecarlorpp.pdf

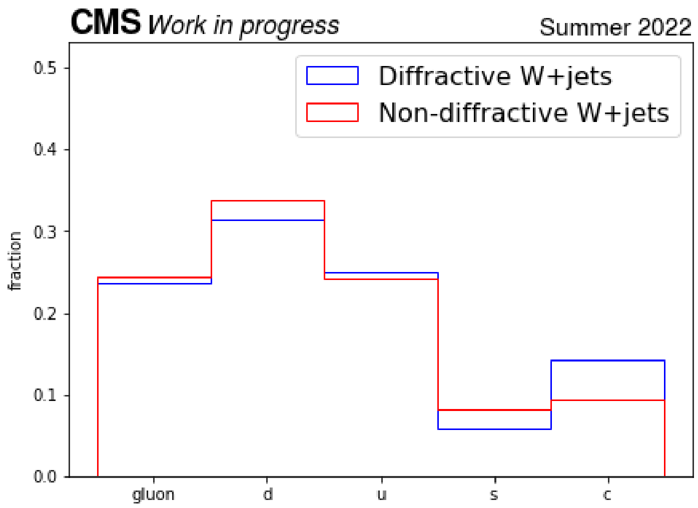


Fig. 4: Flavour composition in diffractive (blue) and non-diffractive (red) production of W+jets computed from Pythia8.3 event generator at the Leading Order.

differences between the parton distribution functions. The number of expected events for the full LHC Run 2 luminosity was computed to be ~5000 diffractive and ~44500 non-diffractive W+c events, whereas, for W(lep)+c case (multiplying by the branching ratio of W boson decay to lepton and a neutrino), we expect to produce 1630 diffractive and ~14400 non-diffractive events. Due to high pileup rates (~50 interactions per bunch crossing), the proton tagging technique is inefficient for selecting single diffractive events. Thus the aim is to use the tagging technique on low-pileup data, like the dataset collected in November 2017, which corresponds to the integrated luminosity of 200 pb^{-1} and ~3 average number of interactions per bunch crossing. We expect to produce ~2 diffractive and ~20 non-diffractive, leptonic W+c events for this low pileup dataset.

The expected event yields are low to measure the diffractive component using the available low pileup data. Therefore we focused on developing a strategy to enhance diffractive selection compared to non-diffractive, which can be applied in the future low pileup runs at the LHC. One way to proceed is to tag events with the forward proton. We computed the probabilities to select background and signal events. We used a new CMS subdetector - the Precision Proton Spectrometer (PPS) [3] - that allows us to tag diffractive events by measuring scattered protons with a momentum loss (ξ) in a range of ξ ϵ(0.03,0.15), where proton momentum loss is defined by:

$$\xi = 1 - |p_Z^{proton}|/E_{\text{beam}} \tag{5}$$

Where E_{beam} is the beam energy, and p_Z^{proton} is the longitudinal momentum of the outgoing proton. The ξ distribution of the diffractive proton in single-diffractive W+c events is shown in figure 5.

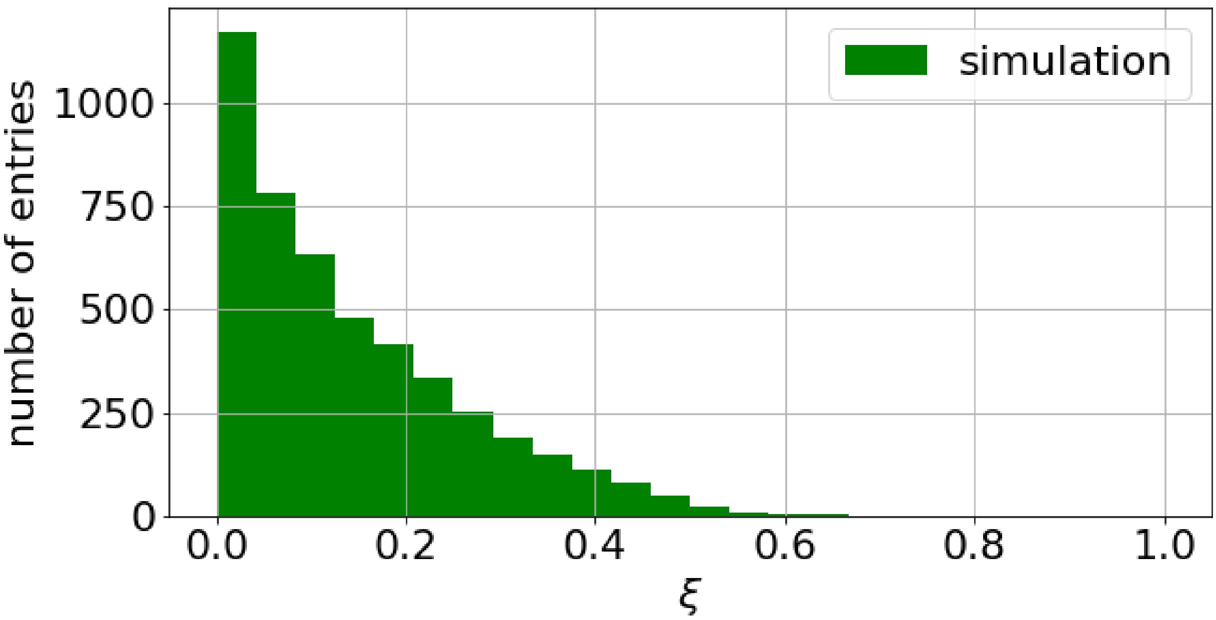


Fig. 5: Proton momentum loss (ξ) for signal events.

The fraction of signal events with a proton in the PPS acceptance was found to be 0.42. During a single bunch-crossing, multiple collisions occur, and a fraction of the collision produces soft diffractive events. To suppress background (non-diffractive) contributions, we exploited a strategy based on the asymmetry between the direction of the forward proton and the W+c final state to enhance the selection of the diffractive component.

For example, figure 6 shows the asymmetry for ξ values between 0.01 and 0.02 (outside the PPS acceptance).

We studied the event selection within the PPS acceptance where this asymmetry is pronounced, and the results are reported in the next section.

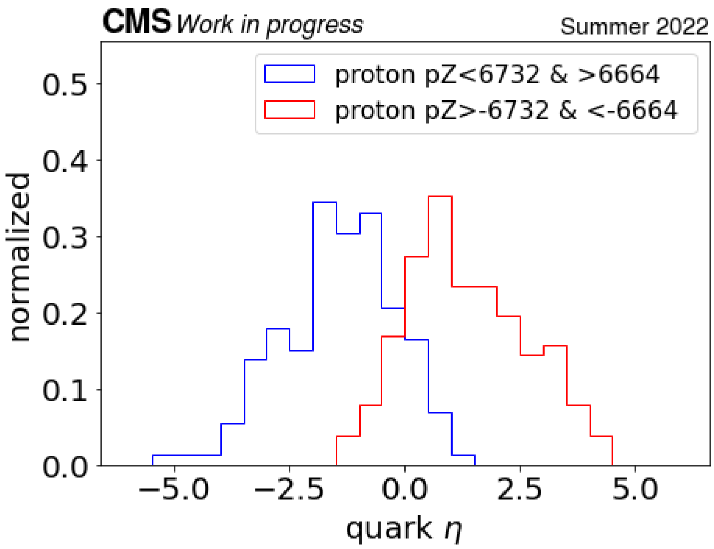


Fig. 6: Distribution of quark pseudorapidity in single diffractive W+c events with a proton in the negative (red) or positive (blue) direction.

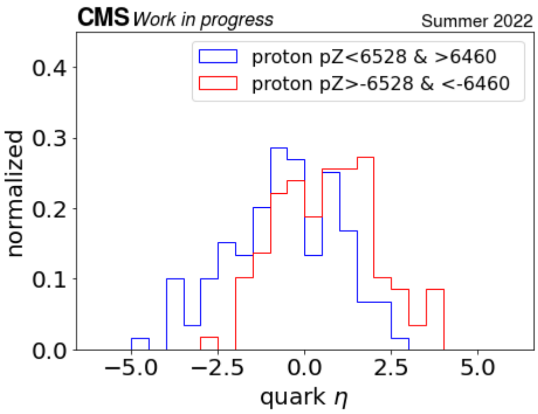
3. Results

During the analysis, we found that asymmetry between events with positive proton P_z and events with negative proton P_z exists for a small value of ξ as well as for a large value of ξ. Moreover, we observed that the window of ξ has to be narrow to enhance the asymmetry. Otherwise, asymmetry will vanish as one starts to widen the window.

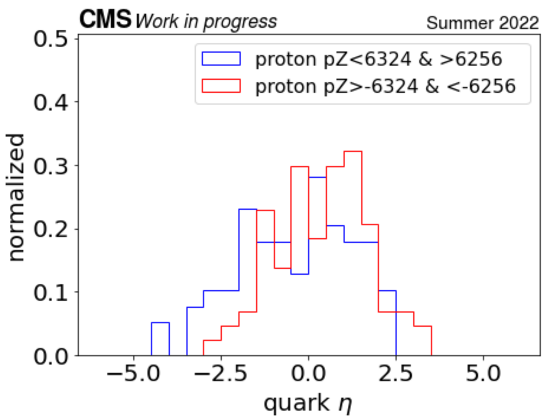
Figure 7 shows that as we increase the value of ξ, the asymmetry reduces until ξ reaches high values, and for ξ between 0.10 and 0.11, no asymmetry is seen. After that, as we increase ξ, asymmetry starts to be seen again but inverted. A distinct and clear correlation can be seen if ξ is considered to increase more, such as between 0.14 and 0.15 (Figure 7d).

In each case, the ξ window was considered very small. The difference between maximum ξ and minimum ξ was 0.01. No good asymmetry is observed for a larger ξ window. For example, figure 8 shows that the asymmetry was almost gone when we took ξ between 0.08 and 0.15.

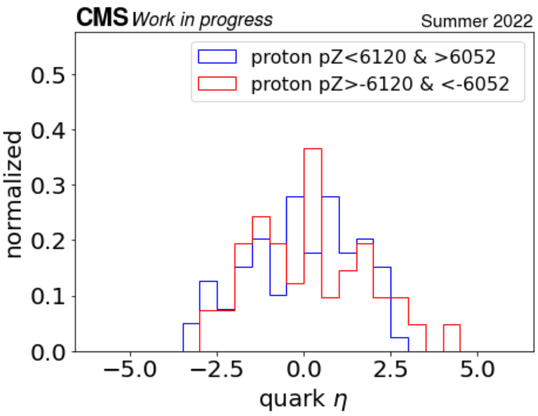
The correlation between the direction of the tagged proton and the rapidity of the W+jet has different nature between small and high ξ values. For smaller values of ξ, the W+jet events with forward protons have negative rapidity. While for large values of ξ, the events with forward proton (proton in a positive direction) have the rapidity distribution that tends to be shifted to the positive



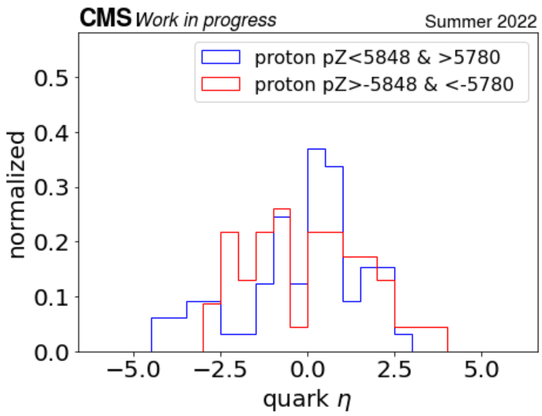
(a) $\xi \in (0.04, 0.05)$



(b) $\xi \in (0.07, 0.08)$



(c) $\xi \in (0.10, 0.11)$



(d) $\xi \in (0.14, 0.15)$

Fig. 7: Distribution of quark pseudorapidity in single diffractive W+c events with a proton in the negative (red) or positive (blue) direction for different ranges of measured proton momentum loss (ξ).

values.

Note: we also studied the effect of the quark p_T on the asymmetry, but no change was observed in the distributions.

4. Conclusion

We studied the correlation between the rapidity of the centrally produced particles and the direction of the proton, in single diffractive events, as a function of proton momentum loss (ξ). We found that the correlation exists within a small window of ξ and is more pronounced for large and small ξ values. The correlations are due to the kinematic constraint of the centrally

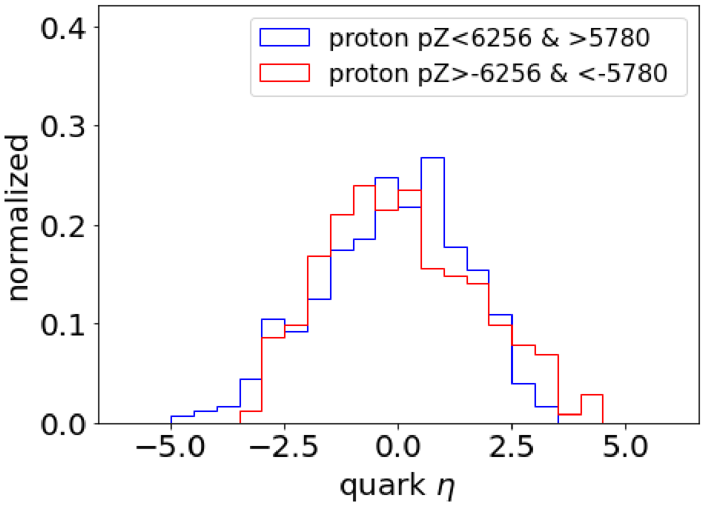


Fig. 8: Distribution of quark pseudorapidity in single diffractive W+c events with a proton in the negative (red) or positive (blue) direction for ξ between 0.08 and 0.15.

produced system of particles. When a diffractive proton transfers relatively small momentum (which corresponds to a low measured ξ), most of the energy to the central system is transferred from the non-diffractive proton resulting in a boost of the central system in the direction of the non-diffractive proton. When ξ grows, less asymmetry between the proton direction and rapidity of the central system is observed. The nature of asymmetry gets reversed as ξ goes from low to high values. For small values of the proton momentum loss ($\xi < 0.01$), in single diffractive processes, the central system (W+jet) rapidity opposes the direction of the intact proton. Contrary to high values of the momentum loss (typically above 0.15), the rapidity of w+jet is correlated to the direction of the intact proton. Proton momentum loss distribution follows rapidly drops toward high values of ξ (see Fig 5), resulting in large suppression of the cross-section. The expected cross section for single diffractive W+c with $\xi > 0.15$ is of the order of 14 fb. On the contrary, the low ξ range (for $\xi < 0.02$) shows evident asymmetry in the rapidity distribution. Yet, measuring such low values of ξ is challenging and requires further improvements of forward proton detectors.

References

[1] CMS Collaboration, “W+c differential cross-section at 13 TeV with full run2”, CMS-PAS-SMP-21-005. http://cds.cern.ch/record/2815162 .

[2] T. Sjöstrand, S. Ask, J. R. Christiansen, R. Corke, N. Desai, P. Ilten, S. Mrenna, S. Prestel, C. O. Rasmussen and P. Z. Skands, Comput. Phys. Commun. **191**, 159-177 (2015) doi:10.1016/j.cpc.2015.01.024 [arXiv:1410.3012 [hep-ph]].

[3] The CMS and TOTEM Collaborations, “CMS-TOTEM Precision Proton Spectrometer Technical Design Report”, CERN-LHCC-2014-021, TOTEM-TDR-003, CMS-TDR-13.