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Measurement of the production of a W boson in association with a charm quark at $\sqrt{s} = 13$ TeV with the ATLAS detector

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Summary. — The production of a W boson in association with a charm quark has been investigated since the Tevatron era, because of its connection with the strange quark PDF. This process is the most probable production from strange-gluon scattering, therefore the cross section gives direct information about strange distribution. At LHC, ATLAS and CMS have already performed a complete analysis of the Run-1 (2009–2013) and obtained interesting results about the contribution of strange quarks inside protons. In particular, the strange PDF is compared with the other light quarks up and down, which are expected to be in the same contribution as the strange quark. Results from analysis are mostly in agreement with theory, but still they need more investigation with higher statistics. ATLAS, in fact, is working to provide a new result after the Run-2 data (2015–2018). In this paper, a short overview of the published analyses is presented and some information on the ongoing one by ATLAS is given.

1. – Introduction

The motivation for studying the production of a W boson in association with a charm quark is the sensitivity to the strange quark PDF. W+c is, in fact, the main production of strange-gluon scattering and the cross section of the process gives information of s-quark distribution, as seen in the Feynman diagram in fig. 2. Strange quark, with the other two light quarks up and down, follows the $SU(3)$ approximate flavour asymmetry. Since their mass difference of about 100 MeV can be neglected, the contribution of the quarks should be mostly the same in the proton. However, in the past, a deep-inelastic scattering nucleon-neutrino experiment sited at Fermilab Tevatron found a strange suppression contribution compared with up and down quarks [1]. However, symmetric results have been obtained by ATLAS in 2012 [2] and 2017 [3]. The Run-1 ATLAS W+c analysis results are in agreement with symmetric strange distribution, as shown in fig. 1. The ATLAS analysis team is working on the Run-2 data analysis, *i.e.*, on data collection between 2015 and 2018 at $\sqrt{s} = 13$ TeV and 140.1 ± 1.2 fb^{-1}. In this paper, a short description of the analysis will be provided.

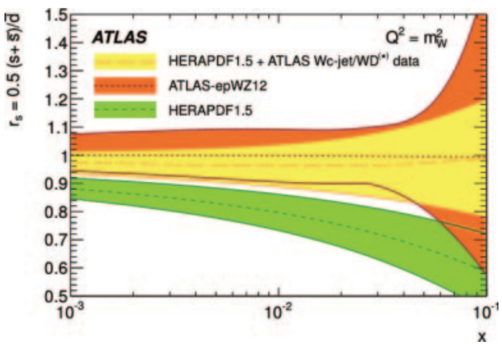

Fig. 1. – Ratio of strange-to-down sea-quark distributions $r_s = 0.5(s + \bar{s})/\bar{d}$ as a function of x as assumed in HERAPDF1.5 PDF compared to the ratio obtained from the fit including the ATLAS $W + c/WD^*$ data and the ratio obtained from ATLAS-epWZ12 [2]. The error band on the ATLAS $W + c/WD^*$ measurements represents total uncertainty. The r_s ratio is shown at $Q^2 = m_W^2$ [4].

2. – Analysis strategy

The analysis requires a W boson in association with a charm quark as a signal, but there are also different backgrounds that have the same reconstructed final state as the signal, and for those an analysis strategy is needed. The W boson is reconstructed through its lepton decay, with the muon and electron considered as leptons with $p_T >$ 27 GeV, while the charm quark is reconstructed through its semi-leptonic decay by charm-hadrons, where the soft muon of $p_T > 4$ GeV is used to tag the jet as originating from a charm quark (SMT algorithm). MET > 20 GeV and maximum 2 jets of $p_T > 30$ GeV are required. One of the Feynman diagrams of the process is shown in fig. 2. The charge correlation between W-lepton and c-soft muon is exploited: signal mostly has opposite sign (OS), while the backgrounds usually have no preferences in sign. A subtraction between opposite and same sign can significantly reduce the background. The most significant backgrounds are those which have larger contribution in the OS and cannot be eliminated by a simple subtraction. One is the multijet background, which comes from heavy flavour decays or jets and photons that can fake the electron or, with less

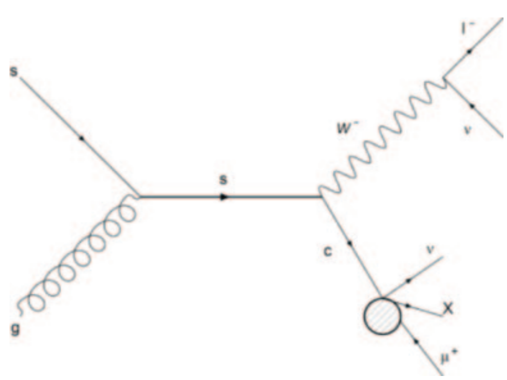

Fig. 2. – One of the possible Feynman diagrams for the signal production.

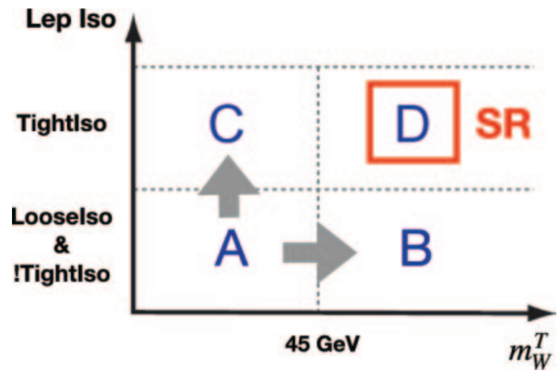

Fig. 3. – The figure shows a schematic representation of the ABCD regions, on the x-axis the m_W^T variable and on the y-axis the lepton cut isolation variable. The D region is the signal region, while A, B, C are the control regions.

probability, the muon from the W decay. Another one is the W boson associated with light quarks, W+light, that pass selections because jets originating from light-flavour quarks can be misidentified as originating from charm quarks. The signal, in the OS, after the selections, represents around 60% of the total. The main backgrounds are the W+light (13% for the electron and 16% for the muon), for the muon channel the Z (9%), which decays in double muons, top (5%), W+b (3–4%), single top (4%) and multijet (8% for the electron and 1.5% for the muon). Backgrounds can be estimated by the Monte Carlo simulation, but for these two other sources of background a data-driven estimation is preferred.

2·1. *Multijet estimation.* – In this analysis, the multijet is estimated by a data-driven method, namely the ABCD method. The name comes from the name of the four regions, one signal region, D, and three control regions A,C,B, used for the estimation. The regions are defined in agreement with different cuts on two uncorrelated variables, *i.e.*, the lepton isolation cut and the transverse mass of the W boson m_W^T. A schematic representation of the ABCD can be seen in fig. 3. If the two variables are supposed to be uncorrelated, then the ratio of the multijet between A and C must be the same as between B and D, hence the multijet in the signal region D can be obtained as

$$D = A(B/A)(C/A). \tag{1}$$

2·2. *W+light estimation.* – In order to estimate the W+light contribution, a 2D fit is considered. Since the fit is supposed to estimate also the signal shape, it needs several degrees of freedom. For this reason, the fit is split into two dimensions: one is the lepton pseudo-rapidity η and the other is the pseudo-continuous b tagging (PCBT) [5]. PCBT bins correspond to different requirements on the b-tagging algorithm discriminant distribution (DL1), ensuring a specific b-tagging efficiency ([100%,85%], [85%,77%],[77%,70%], [70%,60%], [60%,50%]). In this analysis, only two bins are considered, bin 0 = [100%,85%], and bin 1234 = [85%,0%]. The first bin is enriched with W+light sample, so the fit has a region where the contribution can be efficiently estimated.

2·3. *Simultaneous fit*. – The extraction of the signal from data should be background-independent, then a simultaneous fit signal and background is needed. The fit estimation goals are:

- multijet shape and asymmetry OS/SS, because the multijet shape has a preference contribution in opposite/same sign regions,
- W+light normalisation and asymmetry OS/SS,
- signal shape.

3. – Conclusions

The W+c analysis aims to increase the understanding of the internal structure of the proton, since production is connected with the strange quark PDF. For now, ATLAS has found results in agreement with strange quark symmetry compared to up and down light quarks. The analysis strategy is to select signal regions and control regions in order to estimate the background, in particular the multijet background with the ABCD method, and the signal with simultaneous fit. The next steps will be unfolding data with techniques already validated and extracting the unfolded signal for cross section estimation. The detector and experimental systematics will be taken into account, including the fit model uncertainty due to the background and signal estimation model.

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