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Forward Physics Results from ATLAS and CMS

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We present recent forward and diffractive physics results from ATLAS and CMS experiments. Mainly, the physics results on diffraction, underlying event at forward rapidity and forward jets measurements are discussed. Also, using the combined CMS and TOTEM detectors, we show the first event candidate for central jets production with two leading protons detected in the TOTEM Roman Pot stations.

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Keywords: LHC, forward physics, soft QCD, rapidity gaps, forward jets

1. Introduction

Forward and diffractive physics cover a wide range of subjects, including low- x QCD, underlying event and multiple interactions characteristics, ultra-high-energy cosmic rays, and Higgs boson search in central exclusive production. New experimental opportunities and the large rapidity coverage of the ATLAS [1] and CMS [2] detectors in the forward region allow these measurements in yet unexplored regions. Many of these measurements of forward physics at the LHC have already been performed and they provide further testing of models in a unique kinematic regime. In this paper, we review some of the recent forward physics results from the ATLAS and CMS experiments.

2. Diffractive Dissociation

Diffractive events in pp collisions can be characterized by a region of the detector, in pseudorapidity space, devoid of any particle production, known as a pseudorapidity gap. The differential forward pseudorapidity gap cross section ($d\sigma/d\Delta\eta^F$) at $\sqrt{s} = 7$ TeV pp collisions is measured with the ATLAS detector at the LHC using minimum bias data sample [3]. The forward gap, $\Delta\eta^F$, is defined as the largest empty η interval from the edges of the detector ($\eta = \pm 4.9$), in which no final

state particles are produced above a transverse momentum threshold p_T . The p_T threshold is varied between 200 MeV and 800 MeV, and the results are given up to $\Delta\eta^F = 8$. The upper limit on the gap size is constrained by the high trigger efficiency requirement. In Fig.1, the differential cross section of the forward pseudorapidity gap size for all stable final state particles with $p_T > 200$ MeV and $|\eta| < 4.9$ is given with a comparison of PYTHIA8 tune 4C [4].

Figure 1: Differential cross section of the forward rapidity gap size $d\sigma/d\Delta\eta^F$ for particles with $p_T > 200$ MeV and $|\eta| < 4.9$ is compared with the prediction of PYTHIA8 tune 4C. The green band represents the total uncertainty on the measurement.

The observed diffractive plateau at large gap sizes corresponds to a mixture of the single-diffractive dissociation (SD) and double dissociation (DD) with $M_Y \lesssim 7$ GeV¹. The differential cross section of the forward rapidity gap size is also recently measured with the CMS detector [5], using the method originally proposed in [6]. A comparison of CMS measurement to the ATLAS measurement is given in Fig. 2. Both measurements agree within uncertainties and the CMS measurement extends the ATLAS result by 0.4 unit of gap size.

Figure 2: Differential cross section of the forward rapidity gap size $d\sigma/d\Delta\eta^F$ for particles with $p_T > 200$ MeV and $|\eta| < 4.7$, compared with ATLAS measurement [3] ($p_T > 200$ MeV and $|\eta| < 4.9$). The green band represents the total systematic uncertainty of the CMS measurement, while the ATLAS measurement is incorporated in the error bars of the ATLAS points.

CMS experiment have also measured SD and DD cross sections in pp collisions at $\sqrt{s} = 7$ TeV using the very forward calorimeter (CASTOR, $-6.6 < \eta < -5.2$) to separate SD and DD events [5]. The differential SD cross section is measured (in the region of $-5.5 < \log_{10} \xi_X < -2.5$) as a function of ξ which approximates to the fractional momentum loss of the scattered proton in SD events. The differential DD cross section is measured as a function of $\xi_X = M_X^2/s$ for $-5.5 < \log_{10} \xi_X < -2.5$ by detecting one of the two dissociated systems in the central detector and the other in the CASTOR calorimeter ($3.2 \lesssim M_Y \lesssim 12$ GeV, CASTOR acceptance). As a complementary measurement, the differential DD cross section is also measured as a function of the size of the central pseudorapidity gap², $\Delta\eta$, for $\Delta\eta >$

3 and $M_X, M_Y > 10$ GeV. The visible SD and DD cross sections in these regions are $4.27 \pm 0.04(\text{stat.})^{+0.65}_{-0.58}(\text{syst.})$ mb and $0.93 \pm 0.01(\text{stat.})^{+0.26}_{-0.22}(\text{syst.})$ mb, respectively. The differential SD and DD cross sections are given in Fig. 3 with the comparisons of PYTHIA8 tune 4C, PYTHIA6 tune Z2 and PYTHIA8-MBR [7]. The predictions of PYTHIA8-MBR is given for the two values of the ε parameter of the Pomeron trajectory. The SD cross section is described well by PYTHIA8-MBR ($\varepsilon = 0.08$ and 0.104) within uncertainties, while the DD data favor the smaller value of the ε . The PYTHIA8 and PYTHIA6 have a good description of the DD cross section but they overestimate the SD data at high $\log_{10} \xi$.

3. The Underlying Event at Forward Rapidity

The transverse energy flow in the pseudorapidity range $|\eta| < 4.8$ for minimum bias events and for events with central dijet system is measured with the ATLAS detector at $\sqrt{s} = 7$ TeV pp collisions [8]. In the dijet events, the measurements are made in the region transverse to the hard scatter. All the default MC tunes underestimate the measured activity at the largest pseudorapidities. Recently, the ATLAS experiment also measured the underlying event in jet events at $\sqrt{s} = 7$ TeV and extended the earlier measurements using the calorimeter jets in the full acceptance $|\eta| < 4.8$ and by separating the inclusive jet and exclusive dijet selections [9]. The observables in the full acceptance show larger deviations from MC predictions than in the central region.

A first measurement of underlying event activity at very forward pseudorapidity ($-6.6 < \eta < -5.2$) is performed with the CMS detector [10]. The hard-to-inclusive forward energy ratio, $dE/d\eta$, is measured as a function of the central jet transverse momentum at different center-of-mass energies, $\sqrt{s} = 0.9, 2.76$ and 7 TeV. The hard scale in an event is defined by the leading track jet with $p_T > 1$ GeV in $|\eta| < 2$. Also, the relative increase of the forward energy density as a function of center-of-mass energy is measured in inclusive events and in events with a central charged-particle jet with $p_T > 10$ GeV as presented in Fig. 4. All models fail to reproduce the dependence on the center-of-mass energy simultaneously for inclusive events and events with a hard scale.

¹ M_Y (M_X) is the diffractive mass of the Y (X) hadronic system in $pp \rightarrow XY$ double-dissociation process.

² Central pseudorapidity gap is defined as $\Delta\eta = \eta_{\max}^0 - \eta_{\min}^0$ where

$\eta_{\max}^0$ ($\eta_{\min}^0$) is the closest-to-zero η value of the particle reconstructed on the positive (negative) η -side of the central detector.

Figure 3: The SD (left) and DD (middle) cross sections as a function of ξ and DD (right) cross section as a function of $\Delta\eta$ compared to PYTHIA8-MBR, PYTHIA8 tune 4C and PYTHIA6 tune Z2. Error bars represent the total uncertainty on the measurement.

Figure 4: Energy density in $-6.6 < \eta < -5.2$ for inclusive events (left) and for events with a charged-particle jet with $p_T > 10$ GeV in $|\eta^{\text{jet}}| < 2$ (right) as a function of $\sqrt{s}$, normalized to the energy density at $\sqrt{s} = 2.76$ TeV. The grey band represents the total uncertainties.

4. Forward Jets

The inclusive jet double-differential cross-section is measured in pp collisions at $\sqrt{s} = 2.76$ TeV with the ATLAS detector [11]. The results are presented as a function of the jet transverse momentum in bins of rapidity of the jet as given in Fig. 5. Also, the ratio of the measured cross section at $\sqrt{s} = 2.76$ TeV to the one at $\sqrt{s} = 7$ TeV (earlier measurement from the ATLAS Collaboration) is calculated as a function of both transverse momentum and the dimensionless quantity $x_T = 2p_T/\sqrt{s}$, in bins of jet rapidity. The results are compared with the NLO pQCD prediction corrected for non-perturbative effects, and NLO MC simulations. In general, the predictions are in good agreement with the data. Particularly, in the forward region, the central value of the predictions describes the data well.

The azimuthal angle decorrelations of Mueller-Navelet jets (the most forward and backward jets in rapidity) are measured at $\sqrt{s} = 7$ TeV pp collisions with the CMS detector [12]. The measurements are performed for jets with $p_T > 35$ GeV and $|\eta| < 4.7$

Figure 5: Inclusive jet double-differential cross-section as a function of the jet p_T in bins of rapidity. For presentation, the cross-sections in each rapidity interval are multiplied by the factor indicated in the histogram legend.

allowing rapidity separation between Mueller-Navelet jets, Δy , up to 9.4 for the first time at the LHC. The azimuthal angle distributions between Mueller-Navelet jets, average cosines of the azimuthal angle, and the ratios of the cosines are measured. The measured ratios of the average cosines (C_2/C_1 and C_3/C_2), known as the most sensitive observable to the BFKL-effects [13], are given in Fig. 6 with the comparisons of the different MC predictions and analytical NLL BFKL calculations at the parton level. The NLL BFKL calculations, and the DGLAP-based MC generator PYTHIA6 with with angular ordering (AO) and multiple parton interactions (MPI), have a good description of the ratios. Herwig++ shows a satisfactory agreement with the data for all measured observables.

Figure 6: The ratios of average cosines $C2/C1$ (left) and $C3/C2$ (right) are compared to (top) PYTHIA6 Z2 with the different ordering of parton emissions and modified multiple parton interaction modeling, (bottom) SHERPA, CASCADE and analytical BFKL calculations performed at next-to-leading order.

5. High- p_T jets with two leading protons

The first CMS+TOTEM common data taking was performed in 2012, during the low-pileup and $\beta^* = 90$ m runs at $\sqrt{s} = 8$ TeV pp collisions. Each experiment took data separately with a bi-directional exchange of triggers, TOTEM Roman Pot (RP) & T2 to CMS and combined CMS dijets & lepton / γ trigger to TOTEM, and the events were synchronized offline. A preliminary analysis of central high- p_T jet production with two leading protons ($pp \rightarrow p + jets + p$) are performed using the CMS+TOTEM data [14, 15]. The non-elastic leading protons are detected as tracks in the TOTEM RP stations on both side of the CMS detector and the jets are reconstructed at CMS with $p_T > 20$ GeV in $|\eta| < 4.4$. In addition, the CMS Forward Shower Counter (FSC, $6 < |\eta| < 8$) are required to have no hits. An event candidate for central high- p_T jet production with two leading protons is presented in Fig. 7.

6. Summary

The forward detector components of the ATLAS and CMS experiments make it possible to perform precise measurements on diffractive processes, and provide a more complete picture of underlying event structure at a larger phase space. The measurements made so far

Figure 7: An event display of high- p_T jets with two leading protons detected in the TOTEM Roman Pot (RP) stations.

already lead to tune the underlying event models in the forward region. The forward data at higher center-of-mass energies and higher luminosities will give a better insight to parton evolution and saturation effects at low- x region.

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