Studies of Soft QCD Phenomena with the ATLAS Detector at the LHC Collider

Presented at the 32nd International Symposium on Lepton Photon Interactions at High Energies, Madison, Wisconsin, USA, August 25-29, 2025

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15th December 2025

Despite the success of perturbative QCD predictions at high energy regime, QCD itself remains mysterious at its nominal scale. The LHC offers rich opportunities to probe the core of QCD related questions, by studying minimum bias events, double parton interactions, small-x and diffractive scattering, as well as correlations in hadronisation processes. This contribution summarises recent achievements on those topics from the ATLAS Collaboration at the LHC collider.

1 Introduction

Quantum Chromo-Dynamics (QCD) is our best theory to describe strong interactions since decades. But the non-perturbative nature of QCD at low energy (Soft QCD) prevents it from being predictive for various processes and observables. Limited knowledge of such processes results in systematics uncertainties which enter various measurements at cosmics rays, nuclear and particle physics experiments. Measurements of soft QCD phenomena help in reducing these uncertainties and provide inputs to improve strong interaction models.

At the CERN Large Hadron Collider (LHC) [1], the non-perturbative regime of QCD can be probed in diffractive interactions, underlying events, minimum bias (MB) events, hadronic jets and heavy-ion collisions (HI). Appropriately chosen observables and their correlations may give insight on parton shower and hadronisation details, which remain the most difficult processes to model.

In this contribution, a few measurements achieved by the ATLAS Collaboration [2] are discussed.

2 ATLAS Detector

The ATLAS Detector is described in [2]. Specific components which are relevant to presented results are briefly described below.

Twelve sectors of Minimum Bias Trigger Scintillators (MBTS) are located at distances from the interaction point (IP) of $z = \pm 3.56$ m and cover pseudorapidities η between 2.07 and 3.86. The twelve sectors are arranged in two radial rings separated at $\eta = 2.76$.

ATLAS is equipped with Roman pot stations named ALFA to detect diffracted protons or their remnants at very small angles. Roman pots are apparatus containing detectors, which can be moved inside the collider vacuum tube. ALFA has four stations located at $z = \pm 237$ m and ± 241 m from the interaction point. Each station has two vertical Roman pots on upper and lower sides of the vacuum tube. Each Roman pot contains a fiber tracker and a trigger scintillator. The active area dimensions of the trackers are of the order of ~ 1 cm.

3 Production of Same-Sign W Bosons Pairs in Double Parton Scattering

Double parton scattering (DPS) occurs when two parton — parton collisions occur in the same proton — proton collision. If the partons were independent, the cross-section of producing a final state A by the first parton collision and B by the second would be $\sigma_{AB}^{\mathrm{DPS}} = \sigma_A \times \frac{\sigma_B}{\sigma_{\mathrm{inel}}}$, where σ_A, σ_B and σ_{inel} are single parton cross-sections for final states A and B and the total inelastic cross-section, respectively. But partons are correlated, at least to satisfy statistics and conservation laws. Experimentally, this is accounted for by replacing σ_{inel} by σ_{eff}, called effective double parton cross-section: $\sigma_{AB}^{\mathrm{DPS}} = \frac{1}{1+\delta_{AB}} \frac{\sigma_A \, \sigma_B}{\sigma_{\mathrm{eff}}}$. If A and B are identical, and thus indistinguishable, the cross-section should be divided by 2, giving $\delta_{AB} = 1$, while it is zero otherwise. Partons are correlated in location, momentum, spin and colour. Momentum correlations are taken into account by introducing double parton distribution functions, where momentum

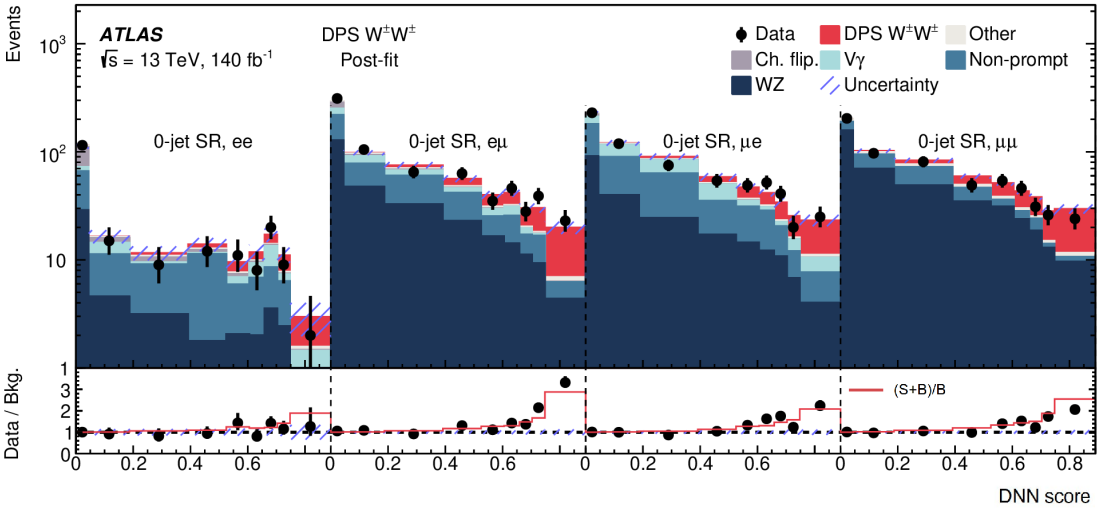

Figure 1: Distributions of the DNN scores in the SR for each four dilepton final states 0 jet category. The shaded area surrounding the expectation represents the total uncertainties in the predicted yields. The ratios of the observed yields to the total background predictions are shown by the points in the bottom panels. The solid line in the bottom panel represents the signal-to-background ratio (1+S/B) [6].

dependence of both interacting partons can be factorised thanks to the small Bjorken-x dominance of partonic cross-sections [3]. If in addition, spin and color correlations are taken into account [4], σ_{eff} measurement can be interpreted as a measurement of the transverse proton size [5].

Same-sign W pair production is an interesting final state in which to measure DPS. The background coming from such a production in single parton scattering can be easily rejected because it necessitates two additional partons in the final state. Only W decays into electrons and muons are considered. The main background is WZ production when the opposite sign lepton from the Z with respect to the one from the W is not properly reconstructed. The analysis has been carried on the full LHC proton — proton Run 2 data set at $\sqrt{s} = 13$ TeV , taken by ATLAS between 2013 and 2018 (140 fb^{-1}) [6]. Two same-sign leptons and missing transverse momentum are required. Single lepton triggers with a p_{T} threshold between 20 and 26 GeV are used. Figure 1 shows the result of signal and background fit of the score of a Monte-Carlo-trained Deep Neural Network (DNN) in the four signal regions with no additional jet. The background-only hypothesis is rejected with a significance of 8.8 σ. The fiducial cross-section is $\sigma^{\text{DPS}}_{W^{\pm}W^{\pm}} = 4.59 \pm 0.64$ fb, leading to an effective double-parton cross-section of $\sigma_{\text{eff}} = 10.6 \pm 1.8$ fb. This measurement is in agreement with older results from the S$\bar{\text{p}}$pS, Tevatron and LHC.

4 Strange Hadrons in Underlying Event

The underlying Event (UE) is the set of all possible processes which occur during the hard scatter that fired the trigger: initial and final state radiation, color reconnection, multiparton interactions (MPI) and

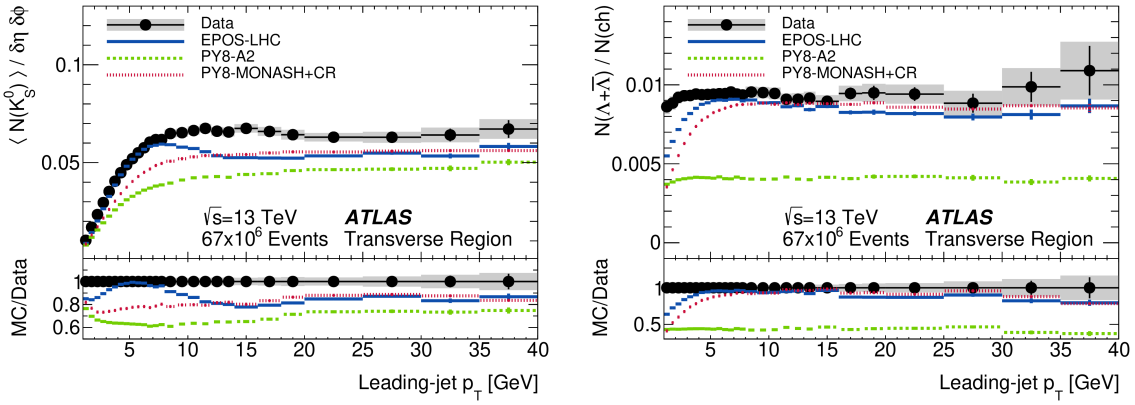

Figure 2: Per event and per unit (η, ϕ) normalised K^0_S yields (left) and per event and prompt charged particle normalised Λ and $\bar{\Lambda}$ yields (right), as a function of leading-jet p_{T} in the Transverse region. Error bars show the statistical error and the shaded bands show the total uncertainty [7].

beam remnants for diffractive scattering. QCD is non-perturbative at energy scales of these processes, so they are described by ad-hoc empirical models that need measurements to be compared and improved. To get rid of the hard scatter bias, ATLAS uses a minimum bias trigger, where the events are required to have at least one fired MBTS sector. To preserve the UE from pile-up, ATLAS recorded data during six special LHC fills which had only 29 colliding bunches (instead of the nominal more than 2,000) in June 2015, at $\sqrt{\mathrm{s}} = 13$ TeV . During those fills, the mean number of inelastic collisions μ was between 0.003 and 0.03 per bunch-crossing. ATLAS recorded 110×10^6 MB events.

Even MB events are biased by higher than average p_{T} particles which fired the MB trigger. The cone with an angular aperture of $2\pi/3$ around the direction of the highest p_{T} jet is defined as the Towards region. The back-to-back region is called Away. UE is considered to dominate in the region between the Towards and Away regions. This region is called Transverse.

The K^0_s and Λ particles are good probes to study UE: They are easy to produce because they are the lightest strange meson and strange baryon respectively, and easy to tag, thanks to their simple V^0 decay vertices $K^0_s \to \pi^+\pi^-$ and $\Lambda \to \pi^- p$ or $\bar{\Lambda} \to \pi^+ \bar{p}$. Typical decay lengths are 2.7 and 7.9 cm, respectively and ATLAS is able to reconstruct such V^0s.

Multiplicities of K^0_s and Λ are determined as a function of the p_{T} of leading-jets in the three regions [7]. Multiplicities are normalised by angle unit or by N_{ch}, the number of prompt charged particles in the considered region. Results of this analysis are compared to the prediction of two Pythia 8 [8] tunes and EPOS-LHC, an adaptation of EPOS [9], a model of hadronic interactions developed for extensive air shower simulation. The left plot of Figure 2 shows the angular normalised rate of K^0_s in Transverse region. The increase of the yield and its saturation above 10 GeV confirm the impact parameter modeling of MPI. The rates of Λ and $\bar{\Lambda}$ showed the same behavior. The Λ and $\bar{\Lambda}$ rate normalised by N_{ch} in Transverse region is shown on the right plot of Figure 2. The rate varies much less than the angular normalised one. Assuming that strange particle production in UE is dominated by MPI, this is an indication that MPI is independent from hadronisation details. In both measurements, EPOS is better than Pythia 8, but needs tuning in its modelling of hard processes.

Table 1: Exclusive pion-pair cross-section within the defined fiducial region for elastic and anti-elastic configurations, for the measurement and MC simulations. The statistical uncertainties of the MC simulations are negligible [10].

Exclusive $\pi^+\pi^-$ cross-section [μb]	
Elastic configuration	
Measurement	4.8 ± 1.0 (stat) $^{+0.3}_{-0.2}$ (syst) ± 0.1 (lumi) ± 0.1 (model)
GenEx $\times$ 0.22 (absorptive correction)	1.5
Dime	1.6
Anti-elastic configuration	
measurement	9 ± 6 (stat) $^{+1}_{-1}$ (syst) ± 1 (lumi) ± 1 (model)
GenEx $\times$ 0.22 (absorptive correction)	2
Dime	3

5 Exclusive Central $\pi^+\pi^-$ Production in Double Diffractive Events

Elastic and diffractive proton — proton scattering are dominated by low momentum transfer (smaller than $\sim$ 1 GeV) and can not be described by perturbative QCD. They are modelled as exchange of one or more pomerons, where a pomeron is a special Regge trajectory which carries no colour charge, and the protons or their remnants are scattered at very small angles, inside the LHC beam-pipe. Double diffraction events can be used to study pomeron properties. Each incident proton emits a pomeron and fires an ALFA station trigger. The products of the two-pomeron collision are detected in the central ATLAS detector.

The result shown here [10] concerns the simplest hadronic final state that can be produced, and the first exclusive double diffraction published by ATLAS: exclusive central production of $\pi^+\pi^-$ pairs. Special high betatronic function ($\beta = 90$ m) fills have been delivered during LHC Run 1 in 2011. ATLAS recorded 80 μb^{-1} with $\mu = 0.035$ at $\sqrt{s} = 7$ TeV . High β at the interaction point is necessary to have access to small angles in ALFA stations. In such a simple topology, event selection asks for minimal activity in central ATLAS, and momentum balance between the pions, measured in the ATLAS tracker, and the protons, measured in ALFA thanks to the knowledge of LHC optics. Table 1 shows the measured cross-section and simulation prediction for the two considered configurations: elastic when protons were scattered into two opposite vertical directions on each side of the IP and anti-elastic when protons are scattered on the same vertical direction. Large uncertainties prevent model tuning but this measurement shows the potential of double diffraction studies. New results are expected in the future.

6 Study of Ordered Hadron Chains

Correlations between final state hadrons is a tool to study hadronisation processes. During Run 1, ATLAS observed an unexpected excess of like-sign (LS) hadron pairs over opposite-sign (OS) pairs at low

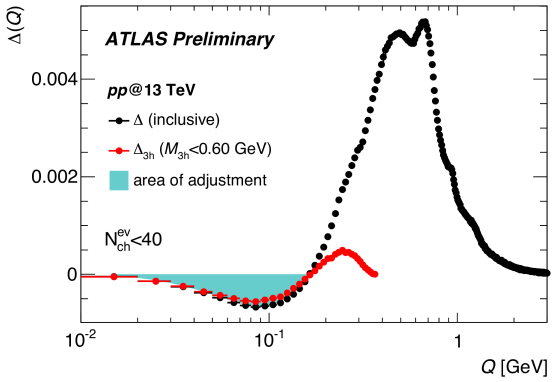

Figure 3: Comparison of the inclusive LS pair momentum difference (black) with LS pairs belonging to triplet chains with a total triplet mass smaller than 0.6 GeV (red). The colored area indicates the region where anomalous production of LS pair occurs [14].

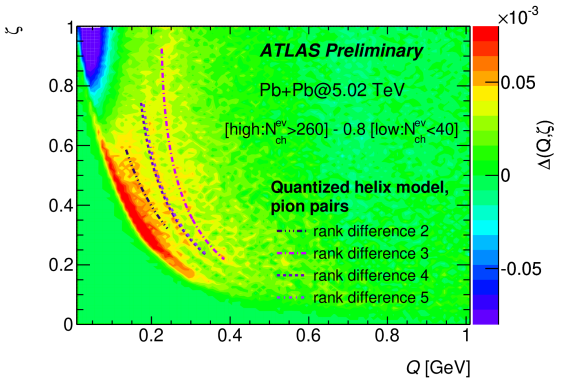

Figure 4: Strip pattern in the $Q\zeta$ plan for hadron pairs produced in 5.02 TeV lead —lead collisions(Color-scale) and predictions of the helical string model for different quantised azimuthal distances [14].

momentum difference [11]. This excess is interpreted as a manifestation of the bosonic nature of pions which represent the majority of produced hadrons. Another explanation is investigated: fragmentation of 3-D QCD helical string, which breaks at a regular $\Delta\phi$ intervals in azimuth [12]. This is in contrast with the QCD 1-D string of the Lund model [13]. The 3-D helical string model has been fitted with Run 1 data and successfully predicted momentum correlations between adjacent hadrons. New measurements using several sets of LHC Run 2 data recorded by ATLAS are summarised here [14]. The main set is 65.5 $\times$ 10^6 proton — proton MB events at $\sqrt{s} = 13$ TeV recorded at low luminosity LHC fills with $0.003 < \mu < 0.3$.

Figure 3 shows the normalised difference between the numbers of LS and OS pairs $N^{\mathrm{OS}} - N^{\mathrm{LS}}$ as a function of the momentum difference Q. An excess of LS pairs is observed at low momentum difference. To investigate the connection between this excess and the production of adjacent hadron chains, chains of adjacent triplets are studied. To select such chains, each prompt particle is paired with a prompt LS particle which minimises the momentum difference, then an OS particle is added that minimises the mass of the triplet. Pion mass is assigned to all particles. Adjacent hadrons are supposed to originate from two consecutive string breakdowns. The correlation between the LS pair of the triplets is shown in red on Figure 3. The triplets selection reproduces the excess of inclusive pairs, providing a strong indication in favour of helical string model.

More distant hadrons have been studied with a lead — lead collision sample at $\sqrt{s} = 5.02$ TeV . Figure 4 shows a strip pattern in the (Q, ζ) plane, where ζ is the LS pair relative momentum: $\zeta = \mathrm{Min}(\frac{p_1}{p_2}, \frac{p_2}{p_1})$ and p_i are the momenta of the two paired particles. The strips are nicely reproduced by the helical string model, where rank is the quantised azimuthal distance between two breakdowns of the helical string.

7 Conclusion

The LHC provides excellent data to study the strong interaction in regimes where perturbative computation is not possible. In this proceeding, a selection of ATLAS measurements in this domain is shown, including double parton scattering, underlying event, hadronisation processes and diffraction. More measurements are expected with the LHC Run 3 data and the future HL-LHC, starting from 2030, with an upgraded ATLAS detector.

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