PROCEEDINGS OF SCIENCE

Study of soft QCD phenomena and double parton interactions with ATLAS

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Despite the success of perturbative QCD predictions in the high-energy regime, QCD itself remains mysterious at its nominal non-perturbative QCD 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 processes, as well as correlations in hadronization processes. This talk summarizes recent results from ATLAS, based on Run 2 LHC data samples: the first ATLAS observation of double parton scattering in leptonic decays of WW events, the measurement of strange particle production in the framework of underlying event, and the first combined measurement of parameters of helical QCD string in proton-proton and heavy ion collisions.

ATL-PHYS-PROC-2025-112
20 November 2025

The European Physical Society Conference on High Energy Physics (EPS-HEP2025)
7-11 July 2025
Marseille, France

*Speaker

 ISSN 1824-8039 . Published by SISSA Medialab.

PoS(EPS-HEP2025)252

1. Observation of double parton scattering in same-sign W boson pair production

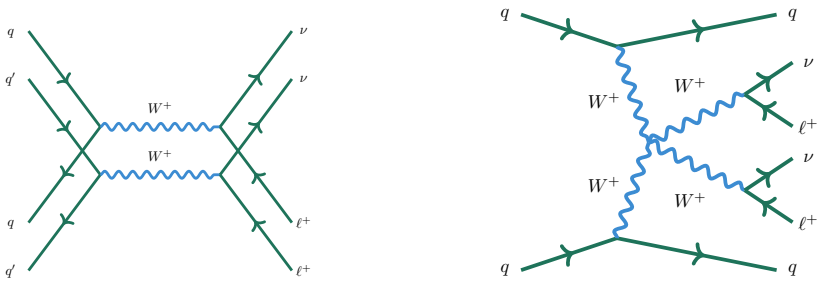

Figure 1: Representative Feynman diagrams of W+W+ process produced via DPS (left) and SPS (right).

The first ATLAS [1] measurement of double-parton scattering (DPS) in the production of same-sign W boson pairs is presented in Ref. [2]. Event configurations with two same-sign leptons (electrons or muons) accompanied with up to 1 jet are selected. Figure 1 shows the Feynman diagrams corresponding to the DPS signal and the single parton scattering (SPS) background process.

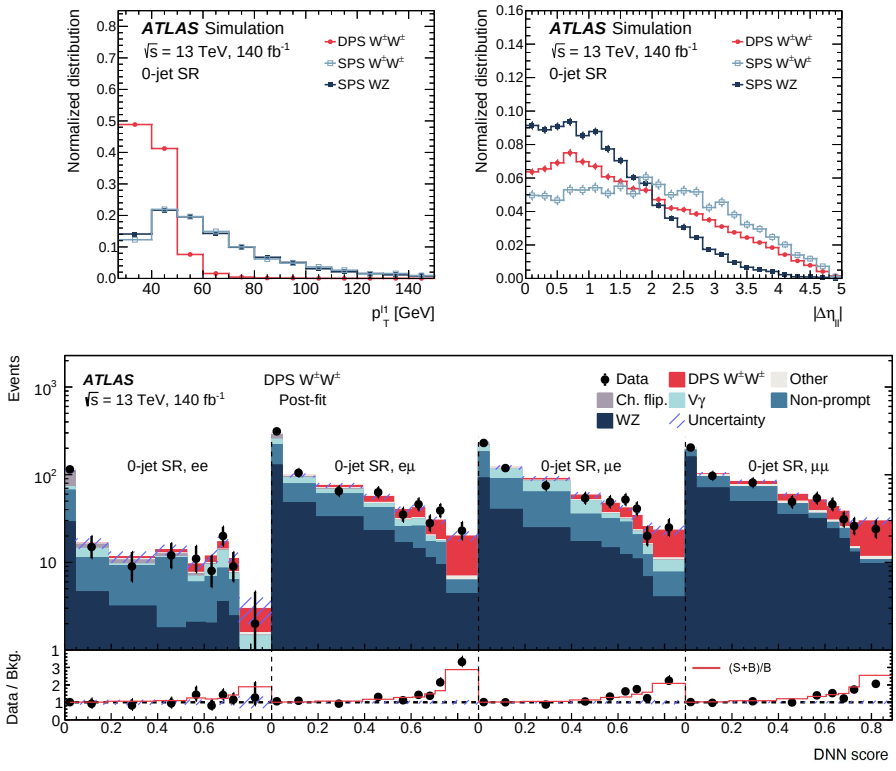

Figure 2: Top: Distributions of $p_{\mathrm{T}}^{\mathrm{ll}}$ and $|\Delta\eta^{\mathrm{ll}}|$ in the SR 0-jet category for the DPS $\mathrm{W^{\pm}W^{\pm}}$, SPS $\mathrm{W^{\pm}W^{\pm}}$, and WZ processes. Bottom: Distributions of the DNN scores in the SR for each four dilepton final states in the 0-jet category. Source: Ref. [2].

A set of kinematical observables discriminating between DPS and SPS signal is used to train deep neural network (DNN). The contribution from the leading SM background, WZ/γ^* production, is evaluated with help of simulated events normalized to the data in a signal-depleted control region. Two of discriminating observables and the DNN scores resulting from the application of the algorithm on the data are shown in Figure 2. Post-fit distributions of the mass of the di-lepton system as well as the azimuthal angle difference of leptons are visible in Figure 3. The best fit normalization allows for the extraction of the fiducial cross-section for DPS production $\sigma \cdot \mathcal{BR}(WW) = 4.59 \pm 0.64$ fb, with a significance of 8.8 standard deviations above the background. The corresponding double parton effective cross section is $\sigma_{\text{eff}} = 10.6 \pm 1.8$ mb. The precision is dominated by statistical uncertainties.

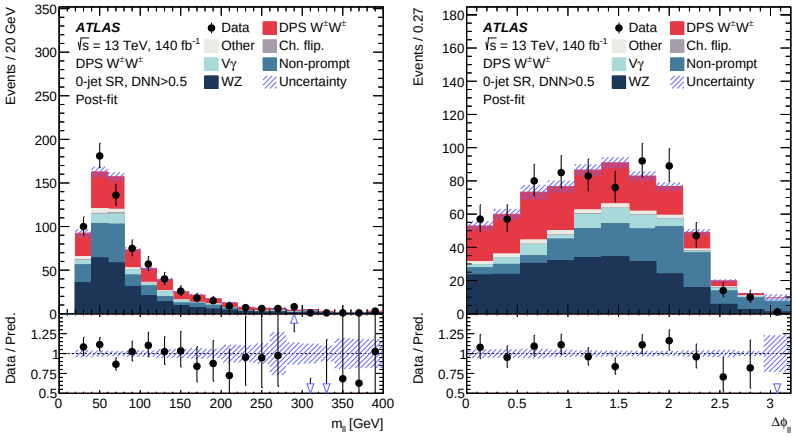

Figure 3: Post-fit distributions of m_{ll} (left), and $\Delta\Phi^{ll}$ in the 0-jet category in a region with the signal DNN score greater than 0.5. Source: Ref. [2].

2. Underlying event studies with strange hadrons

A measurement of the production of K^0_S and Λ baryons in pp collisions is published in Ref. [3]. The hadrons are reconstructed via the identification of the displaced two-particle vertices corresponding to the decay modes $K^0_S \to \pi^+\pi^-$, $\Lambda \to \pi^- p$ and $\bar{\Lambda} \to \pi^+ \bar{p}$. The measurement is using the underlying event framework defined with respect to the orientation of the leading jet (10 GeV $< p_T <$ 40 GeV) in the transverse plane as indicated in Figure 4. Towards, away, and transverse regions are defined, with the latter expected to be particularly sensitive to the underlying event activity. The measurement is done in each region, as a function of the transverse momenta of the leading jet, or the charged particle yield. Figure 5 shows a selection of results for K^0_S (top panels) and $\Lambda + \bar{\Lambda}$ (middle panels), comparing the measured data with predictions of Pythia and Epos in 'towards' and 'transverse' regions. Strange

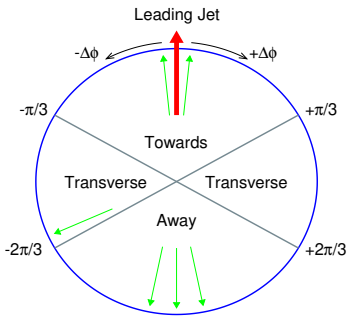

Figure 4: Definition of the underlying-event regions relative to the leading jet.

particle yields are normalized to the number of prompt charged particles. None of the models or tunes describe the data accurately, in particular for the soft leading jets. The bottom panel of Figure 5 shows the relative production of Λ baryons with respect to K^0_S, as a function of the prompt charged particle multiplicity. The dependence observed in the data is weaker than the model expectation.

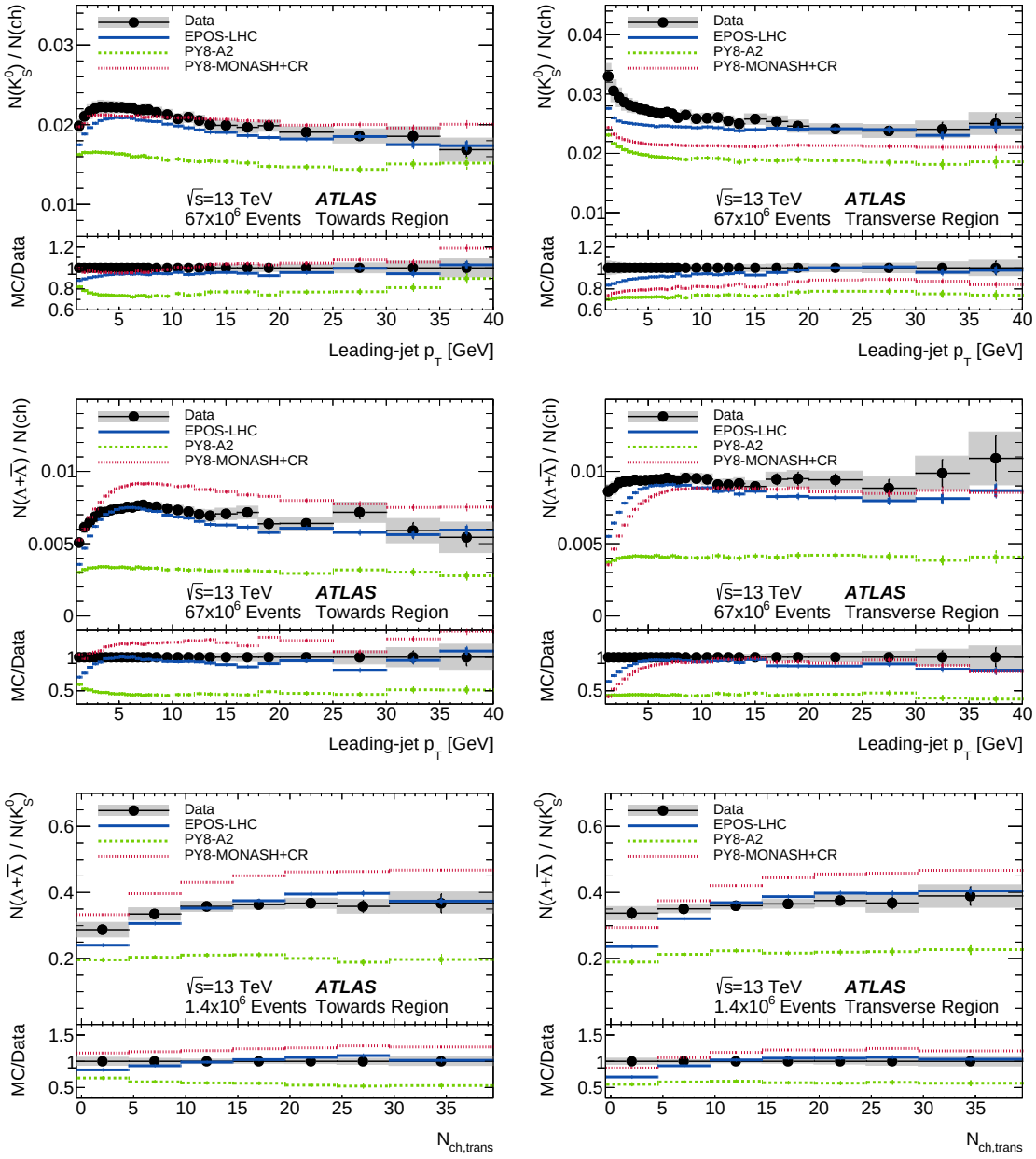

Figure 5: Top: measured K^0_S production in the 'towards'(left) and 'transverse'(right) regions, normalized to the number of prompt charged particles. Middle: Λ+$\bar{\Lambda}$ production in the 'towards'(left) and 'transverse'(right) regions, normalized to the number of prompt charged particles. Bottom: relative production rate of $\Lambda + \bar{\Lambda}$ with respect to K^0_S, as a function of prompt charged-particle multiplicity, in the 'towards' and 'transverse' regions. Source: Ref. [3].

3. Study of ordered hadron chains in proton–proton, proton–lead and lead–lead collisions

A study of correlations between color-adjacent hadrons, accessible via the difference between like-sign and opposite-sign hadron pairs, is presented in Ref. [4]. The analysis finds a significant excess of mass-minimized, charge-ordered hadron triplets consistent with the signature of a helical QCD string undergoing quantized fragmentation into a chain of three ground state pions. This three-particle signal is shown to generate the excess of like-sign charged particle pairs commonly attributed to the Bose-Einstein effect, as well as an enhancement of the low-p_{T} particle yields (Figure 6). The signals in 1-, 2- and 3-particle spectra are studied on various data samples collected by ATLAS. All results are consistent with the observations outlined above, demonstrating the universality of the hadronization. Even though correlations between various data signatures are established in a model independent way, and can be presented as such without referencing the model, the good qualitative agreement between data and model predictions allows the analysis to step further and to extract the parameters of the helical QCD string from the data. To that purpose, the charge-combination dependent resonant shape of particle correlations within the signal triplet chains is associated with the model predictions for the momentum difference between colour-adjacent pions with rank difference 1 and 2 (rank refers to the ordering sequence of prompt hadrons along the colour flow). A fit of the threshold mass of the quantized pion triplet allows for the evaluation of the two parameters describing quantized helical QCD string, the energy scale κR and the quantized phase $\Delta\Phi$. A very good agreement is found between measurements of pp samples collected at different collision energies

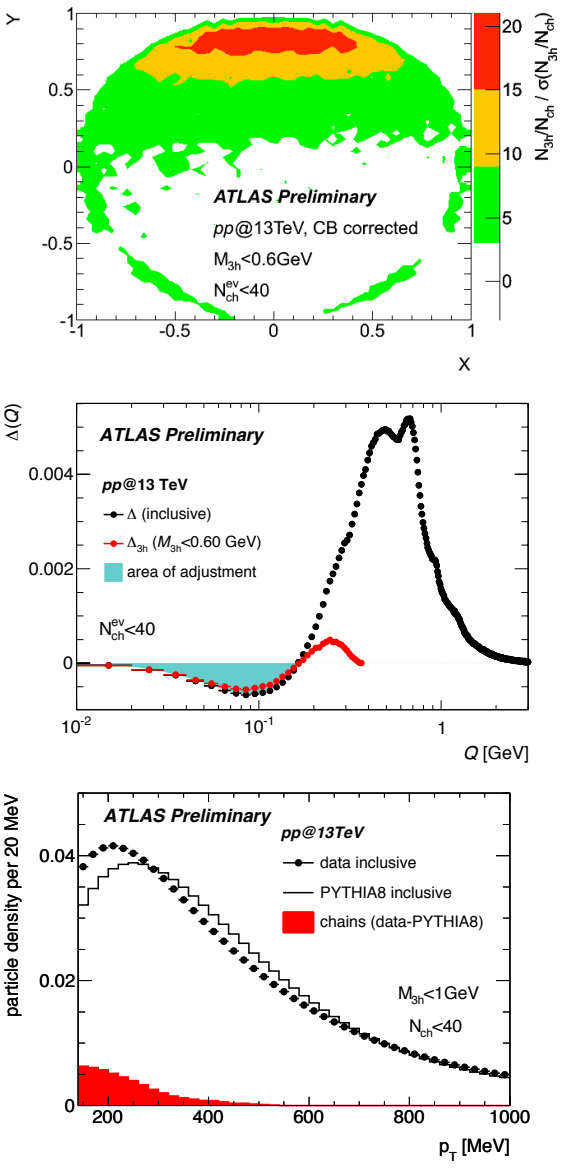

Figure 6: Top panel: Significance of the excess of mass-minimized, charge-ordered hadron triplets (chains), which is shown to be the source of the excess of like-sign pairs commonly attributed to the Bose-Einstein interference (indicated by colored area in the middle panel), while also contributing to the enhancement of the low-p_{T} single particle inclusive spectra (bottom panel). Source: Ref. [4].

and the heavy ion samples (Figure 7). The combined pp and heavy ion data yield the most precise measurement of the quantized helix phase to date, 2.819±0.014 rad, while the precision of the measured energy scale, 68.5±2.2 MeV, is comparable with the uncertainty obtained from the fit of light hadron spectra, see references in Ref. [4].

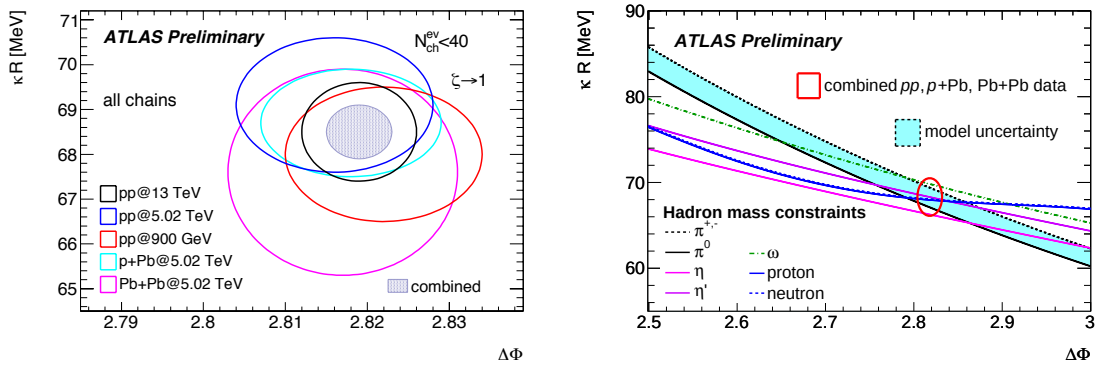

Figure 7: Left: Parameters of the helical QCD string measured in a variety of ATLAS datasets. Right: Combined measurement of string parameters using particle correlations (this analysis) compared with the constraints derived from hadron masses. Source: Ref. [4].

4. Conclusions

A selection of recent and novel measurements of hadron production dynamics and multiple parton scattering has been presented. All measurements are based on LHC Run 2 data collected by the ATLAS Collaboration.

Acknowledment

The work was supported by a grant agreement LM2023040, Ministry of Education, Youth, and Sports, Czech Republic.

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