PROCEEDINGS OF SCIENCE

Soft QCD: the experimental perspective

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Experimental perspective about soft QCD from LHC experiments.

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1. Introduction

Soft interactions are characterized by low momentum transfers and can not be described using perturbative QCD, but effective field theories and phenomenological models are exploited. A variety of experimental observables can help shedding light on soft QCD processes, and providing constrains to existing models. This (not exhaustive) contribution will focus on some of the most recent and relevant results from the LHC experiments aimed at characterizing soft QCD studying different observables throughout all the phases of hadronic collisions.

2. Diffractive events

Diffractive processes are characterized by large rapidity gaps in the distributions of final state particles. Diffractive events were studied by the CMS experiment in p-Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 8.16$ TeV by identifying a large rapidity gap $\Delta\eta_F$, in the forward rapidity region [1]. Forward rapidity gap spectra allow the study of both pomeron-lead and pomeron-proton topologies. Ultra-peripheral photoproduction processes, that can mimic the diffractive event selection, contribute in particular to the pomeron-proton topology (since the photon flux is enhanced by a factor $\mathrm{Z}^2_{\mathrm{Pb}}$ for the Pb nucleus relative to the proton). Experimental results, unfolded at hadron level, are compared to the predictions from three different event generators: EPOS-LHC [2] , HIJING v2.1 [3] and QGSJET-II [4] . These event generators do not include the contribution from photoproduction. As shown in Fig. 1 (left) they all tend to underestimate the measured cross sections. For the pomeron-proton (plus photon-proton) topology the discrepancy becomes larger for higher $\Delta\eta_F$ values, suggesting that events with larger rapidity gaps include a strong contribution from photon-proton events. This measurement, performed for the first time at LHC energies, may be also helpful in improving the modelling for cosmic-air shower simulations.

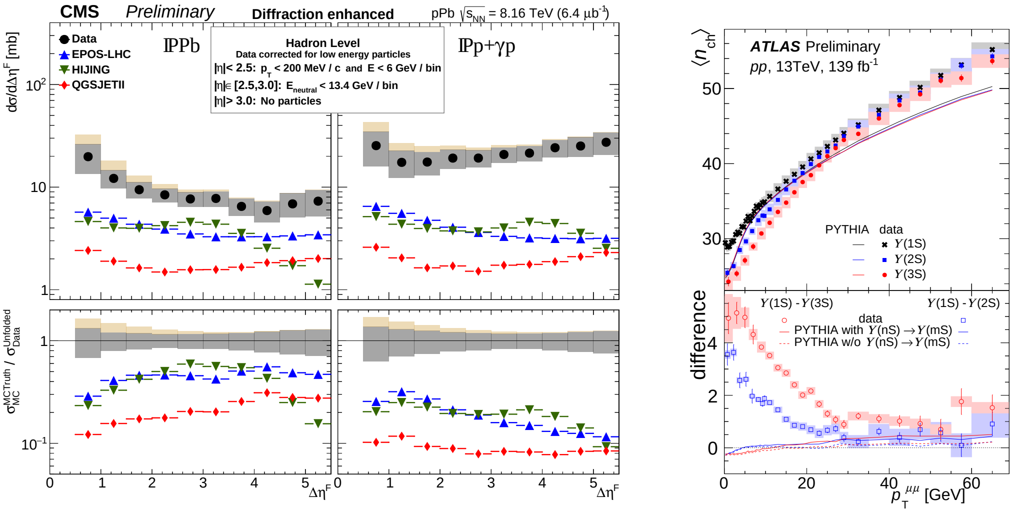

Figure 1: Left: $\frac{d\sigma}{d\Delta\eta^F}$ unfolded spectra compared to event generator predictions for pomeron-lead (left) and pomeron-proton (right) topologies. Right: average number of charged particles with $0.5 < p_T < 10$ GeV/c and $|\eta| < 2.5$ in events with Υ(nS) mesons (top) and difference relative to the excited and ground state (bottom).

3. Underlying event

The Underlying Event (UE) consists of products coming from soft processes, such as Multiple Parton Interactions (MPI) and beam remnants. In UE analyses, event by event, the particle produced at midrapidity with the highest p_{T}, the so called leading particle, is selected. Then three topological regions are defined, based on the azimuthal angle relative to the leading particle (emitted at $\phi = 0$): the toward ($|\phi| < 60°$) and the away ($|\phi| > 120°$) regions, dominated by the fragmentation from the hard scattering, and the transverse region ($60° < |\phi| < 120°$), dominated by the UE. The transverse region includes residual products from the hard scattering, namely Initial State Radiation (ISR) and Final State Radiation (FSR). ALICE studied the UE in pp and p–Pb collisions at the same center of mass energy [5]. As well known, in pp collisions, the charged particle multiplicity in the transverse region as a function of the leading particle transverse momentum, $p_{\mathrm{T}}^{\mathrm{leading}}$, saturates for $p_{\mathrm{T}} \geq 5$ GeV/c. Models used for comparison, PYTHIA 8.244 (Angantyr)[6] and EPOS LHC, are able to reproduce the plateau value measured in pp collisions, but underestimate the value reached in p–Pb collisions. ATLAS characterized the multiplicity in the UE, using as leading particle a Υ(nS) meson [7]. The average charged particle distribution in the transverse region as a function of the transverse momentum of the decay dimuon pair, $p_{\mathrm{T}}^{\mu\mu}$, shows significant differences between the ground state and the two excited states at low $p_{\mathrm{T}}^{\mu\mu}$ values, as shown in Fig. 1 (right). The measurement is not reproduced by PYTHIA predictions, even including an enhanced scheme for Color Reconnection (CR).

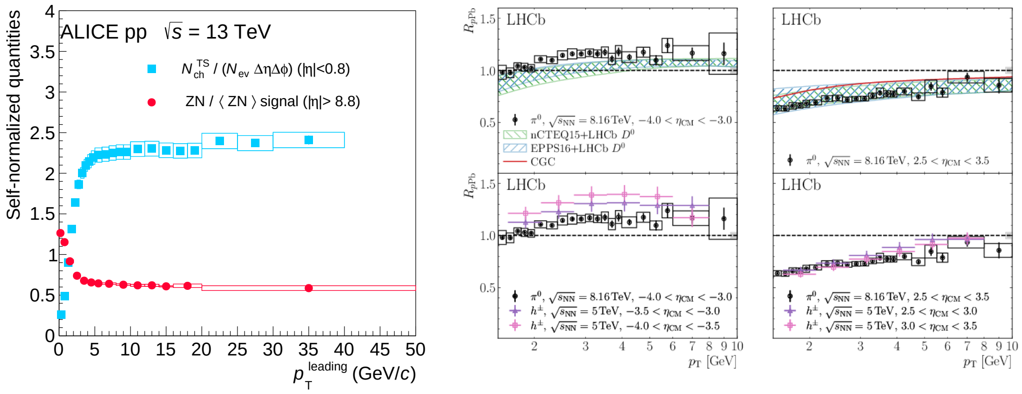

Figure 2: Left: self-normalised ZN signal (red circles) and number density N_{ch} (azure squares) distributions in the transverse region as a function of $p_{\mathrm{T}}^{\mathrm{leading}}$ in $|\eta| < 0.8$. Right: π^0 nuclear modification factor in the (left) backward and (right) forward η regions. The results are compared to theoretical predictions (top) and to charged-particle data (bottom).

ALICE has studied the correlation between the energy measured in the neutron Zero Degree Calorimeters (ZN), a proxy for the beam remnants, and the charged particle multiplicity at midrapidity, that is related to the number of MPI, in pp collisions at $\sqrt{s} = 13$ TeV [8]. Models including impact parameter dependence of MPI, such as different implementations of PYTHIA, predict that the zero-degree energy decreases for increasing number of MPI in the collision. ALICE observes indeed a decreasing ZN energy with increasing charged particle multiplicity at midrapidity. The measurement of the energy carried by the beam remnants at forward rapidities as a function of leading particle p_{T} at midrapidity is complementary to the UE measurements. Similarly to the transverse multiplicity at midrapidity, the ZN energy saturates as a function of leading particle transverse momentum, and this saturation occurs at the same $p_{\mathrm{T}}^{\mathrm{leading}}$ scale, around 5 GeV/c, for both observables, as shown in Fig. 2 (left).

4. Double Parton Scattering

Two partonic interactions occurring in the same collisions are the simplest case of MPI that can be studied. Assuming that the two scatterings are uncorrelated, one can fully factorize the cross sections for Double Parton Scattering (DPS) and use the formula: $\sigma_{\mathrm{A,B}}^{\mathrm{DPS}} = \frac{m}{2}\frac{\sigma_{\mathrm{A}}\sigma_{\mathrm{B}}}{\sigma_{\mathrm{eff}}}$, where m=1 (2) for identical (different) processes. The effective cross section, σ_{eff} parametrizes the transverse distribution of partons inside the colliding hadrons and their overlap in the collision, and is the parameter used to quantify DPS processes in models. Experimentally, observables that are sensitive to DPS processes are studied, exploiting the distinctive features relative to Single Parton Scattering (SPS). CMS published the first results about DPS in Z boson plus jets events channel [9]. Results clearly indicate that MPI modelling is crucial to be able to describe the measurements. Another analysis studies the 4 jets channel [10], comparing the azimuth angular difference between harder and softer jet pairs (that is the observable less sensitive to the parton shower implementation) to different classes of model predictions. This observable is then used to extract σ_{eff}, whose values show a large model dependence. In general, models including NLO matrix elements, allows for a larger DPS contribution and lead therefore to smaller values of σ_{eff}.

5. Minimum Bias event

The MB event is largely dominated by soft particle production and its characterization is therefore crucial. LHCb has performed a very precise measurement of the double differential cross section of inclusive forward production of prompt charged particles [11], separately for positive and negative charged particles. None of the model used for comparison is able to reproduce the measured cross section over the whole p_{T} interval. The ratio of positive to negative cross sections increases at high p_{T}, as expected from charge conservation, and none of the model used for comparison is able to describe the experimental results. LHCb has also studied the production of neutral pions in p-Pb collisions $\sqrt{s_{\mathrm{NN}}} = 8.16$ TeV, measuring the nuclear modification factor at backward ($10^{-3} < x < 10^{-1}$) and forward ($10^{-6} < x < 10^{-4}$) rapidities [12]. A suppression of π^0 production in the forward region, consistent with modified PDF but larger than Color Glass Condensate calculations, is observed, while in the backward region data show an enhancement in π^0 production relative to pp collisions, larger than what predicted by models considering modified PDF, as shown in Fig. 1 (right). This measurement puts severe constraints for nuclear PDF and saturation models in the low-x region.

6. Strangeness production

The evidence that strange particle production is enhanced not only in the deconfined medium produced in heavy ion collisions, but also in high multiplicity pp events at LHC energies, put a lot of interest in studying strangeness production in pp collisions. CMS measured the asymmetry in strange hadron production in p–Pb collision, by performing the ratio between strange particle distributions in the Pb-going and in the p-going directions in different rapidity intervals [13]. Larger asymmetry are observed at forward rapidities, consistently with expectations from nuclear shadowing. However, the asymmetry values measured for strange hadrons is larger than those measured for charged hadrons in the center of mass rapidity interval 1.3<$|y_{CM}|$<1.8. Even a model including collective effects like EPOS-LHC fails to describe the results. ALICE studied the strangeness production related to the production of a high-$p_{\rm T}$ particle in pp collisions to understand whether the production could be different in regions dominated by hard or soft particle production. However ,a similar evolution is measured in the region toward and in the region transverse to the primary hard scattering. ALICE also studied the strangeness enhancement as a function of the effective energy, namely the energy available at midrapidity for particle production, experimentally estimated as the center of mass energy minus the beam remnant energy measured at zero degrees. The ratio of strange over charged particle is found to increase with effective energy even when the multiplicity is fixed. This indicates that the final state multiplicity is not the only driving variable in the strangeness enhancement mechanism and that also initial stages of the collisions play a role.

7. Hadronization

Studying the hadronization phase, the universality of fragmentation and quark coalescence mechanisms can be addressed. LHCb studied the b quark hadronization, measuring the production rate of B^0_s mesons relative to B^0 mesons in pp collisions at $\sqrt{s}$ = 13 TeV [14]. An increase at high multiplicity and low $p_{\rm T}$ is observed, in qualitative agreement with expectations from coalescence as an additional hadronization mechanism. However, no enhancement is measured as a function of the number of tracks in the backward region indicating a possible dependence on the local particle density. This result suggests a possible breaking of b quark factorisation going from electron-positron to hadronic collisions. ALICE studied the ratio of Λ_c^+ to D_0 production to investigate the hadronization of c quarks and test the universality of fragmentation functions [15]. All the models that parametrize fragmentation from electron-positron data significantly underestimate the measured ratio and do not reproduce the observed $p_{\rm T}$ dependence, as shown in Fig. 3 (right), unless modifications and new effects are not considered, as an example, enhanced Color Reconnection mechanisms. These results give a strong indication that the hadronization mechanisms in pp collisions are very different from those occurring in e^+-e^- collisions.

8. Conclusions

“Conclusions” is not an appropriate word to use when talking about soft QCD, as there are a lot of open issues and several experimental results that we still have to correctly interpret and fully understand. On one side we clearly need to work on further improvement of existing theoretical models, on the other side we have ahead of us a challenging and exciting opportunity to perform even more precise and differential measurements in LHC Run-3. In both cases the aim is the same: a better understanding of soft processes in hadronic interactions.

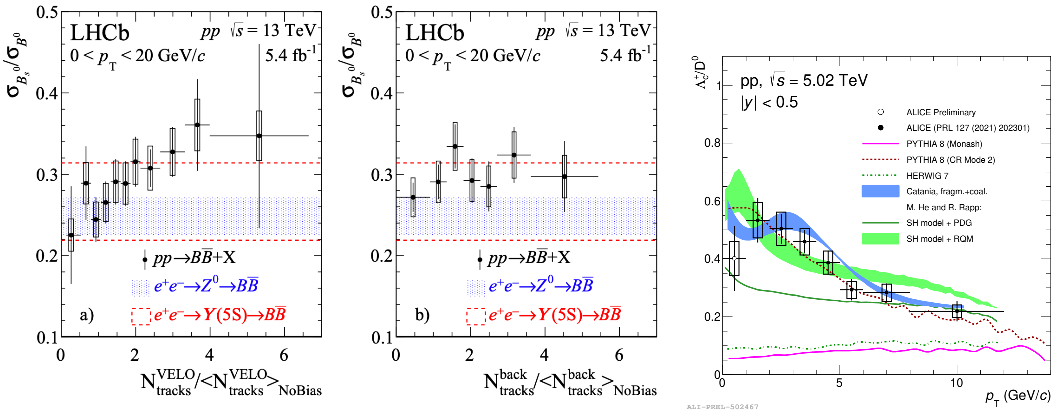

Figure 3: Left: ratio of cross sections $\sigma_{B_s^0}/\sigma_{B^0}$ versus the normalized multiplicity of a) all LHCb VELO tracks, and b) backward VELO tracks. Right: ratio Λ_c^+/D_0 as a function of p_T measured in pp collisions at $\sqrt{s}$ = 5.02 TeV compared with theoretical predictions.

References

[1] CMS Collaboration, “First measurement of the forward rapidity gap distribution in pPb collisions at $\sqrt{s_{NN}}$ = 8.16 TeV”. CMS-PAN-HIN-19-019

[2] T. Pierog, “Hadronic Interactions and Air Showers: Where Do We Stand?”, EPJ Web Conf. 208 (2019) 02002. doi:10.1051/epjconf/201920802002

[3] X.-N. Wang and M. Gyulassy, “HIJING: A Monte Carlo model for multiple jet production in pp, pA and AA collisions”, Phys. Rev. D 44 (1991) 3501. doi:10.1103/PhysRevD.44.3501

[4] S. Ostapchenko, “Monte Carlo treatment of hadronic interactions in enhanced Pomeron scheme: I. QGSJET-II model”, Phys. Rev. D 83 (2011) 014018. doi:10.1103/PhysRevD.83.014018

[5] ALICE Collaboration, “Underlying-event properties in pp and p–Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV”,arXiv:2204.10389

[6] C. Bierlich, et al., “The Angantyr model for Heavy-Ion Collisions in PYTHIA8”, JHEP 10 no. 134, (2018). arXiv:1806.10820

[7] ATLAS Collaboration, “Correlation of ϒ meson production with the underlying event in pp collisions measured by the ATLAS experiment”, ATLAS-CONF-2022-023

[8] ALICE Collaboration, “Study of very forward energy and its correlation with particle production at midrapidity in pp and p-Pb collisions at the LHC”, JHEP 08 (2022) 086. doi:10.1007/JHEP08(2022)086

[9] CMS Collabration, “Study of Z boson plus jets events using variables sensitive to double-parton scattering in pp collisions at 13 TeV”, J. High Energ. Phys. 2021, 176 (2021). doi:10.1007/JHEP10(2021)176

[10] CMS Collaboration, “Measurement of double-parton scattering in inclusive production of four jets with low transverse momentum in proton-proton collisions at $\sqrt{s}$ = 13 TeV”, J. High Energ. Phys. 2022, 177 (2022). doi:10.1007/JHEP01(2022)177

[11] LHCb Collaboration, “Measurement of prompt charged-particle production in pp collisions at $\sqrt{s}$ = 13 TeV”, J. High Energ. Phys. 2022, 166 (2022). doi:10.1007/JHEP01(2022)166

[12] LHCb Collaboration, “Nuclear modification factor of neutral pions in the forward and backward regions in pPb collisions”. arxiv:2204.10608

[13] CMS Collaboration, “Strange hadron production in pp and p–Pb collisions at $\sqrt{s_{\mathrm{NN}}}$ = 5.02 TeV”. doi:10.1103/PhysRevC.101.064906

[14] LHCb Collaboration,“Evidence for modification of b quark hadronization in high-multiplicity pp collisions at $\sqrt{s}$ = 13 TeV”. arxiv.org:2204.13042

[15] ALICE Collaboration, “Λ_c^+ production and baryon-to-meson ratios in pp and p–Pb collisions at $\sqrt{s_{\mathrm{NN}}}$ = 5.02 TeV”. doi:10.1103/PhysRevLett.127.202301