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Measurements with QCD and Jets at the LHC

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In the light of the successful restart of the data-taking of the LHC experiments at the unprecedented energy in the center of mass $\sqrt{s} = 13$ TeV, we review the prospects for the second run of the LHC for measurements related to Quantum Chromodynamics (QCD) and jets in pp collisions. Recent results from the ATLAS, CMS, and LHCb collaborations lead the discussion on the open questions on soft production that the LHC experiments are called to address during the next few years of activities. The discussion is mainly focused on measurements related to the underlying event, to the production mechanism of jets, and to the associative production of jets and heavy flavours.

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1. Introduction

The nature of the strong interaction, described in the Standard Model (SM) by Quantum Chromodynamics (QCD), is unique among the fundamental interactions [1, 2]. At high energy, the asymptotic freedom of the partons constituting hadrons, allows to treat the interaction with perturbative models analogue to those used to describe the electroweak processes. At the other extreme, at low energy, *quark confinement* and *gluon self-interaction* require a non-perturbative approach which must rely either on advanced computational techniques, such as Lattice QCD, or on effective models. A large variety of effective theories and models was developed to describe different processes at the various energies that the experiments have explored, with perturbative and non-perturbative effects concurring to describe the hadronic interaction. Today, it is customary to implement effective models in Monte Carlo generators that, interfaced with the simulation of a detector response, can be directly compared to experimental data, to measure the free parameters and to test the validity of the underlying assumptions with different processes and regimes.

The quality of the effective models describing the soft interaction of protons in high-energy collisions is crucial to predict and model the background sources to searches for effects beyond the Standard Model. This is particularly true for jets, narrow cones of hadrons and other particles produced by the hadronization of a quark or gluon, which often appear in the predicted final states for decays of particles beyond the Standard Model.

Great advances were made in the last decades in the description of QCD processes, reaching an accuracy not rarely better than 10%. The measurements from the data collected at the LHC at an energy in the center of mass of the pp collisions of 7 and 8 TeV, have been used to test the effective models and to tune several Monte Carlo generators. Recent measurements of QCD processes from the second data taking of the LHC, at an increased center-of-mass energy $\sqrt{s}$ = 13 TeV, are being compared with the predictions without further tunings and the agreement is very encouraging when not satisfying.

On the other hand, the first data taking of the LHC has opened questions on QCD processes that can be addressed studying the data collected at $\sqrt{s}$ = 13 TeV. In this write-up we focus mainly on some of these questions describing the context in which they arose and discussing the opportunities for further investigation from the second Run of the LHC.

The remainder of this document is divided in five sections. Section 2 is related to the description of the underlying event where effects known in ion-ion collisions have been unexpectedly observed in high-multiplicity pp interactions. We devote Section 3 to jet measurements focusing on measurements that investigate and classify the parton originating a jet. In Section 4 we discuss the heavy flavour production measurements, that have displayed a surprising enhancement of the Υ production cross-section from $\sqrt{s} = 7$ to 8 TeV. Measurements of associative production are discussed in Section 5; the contribution to the associative production cross-section from *double parton scattering* is of particular interest because it was found reasonably described with a single parameter, named *effective cross-section* σ_{eff}, found consistent for a variety of very different processes, with unclear dependence on the energy in the center of mass. A summary concludes this write-up in Section 6.

2. The underlying event

Before focusing on rare objects and production mechanisms at the new energy $\sqrt{s} = 13$ TeV, it is useful to study the soft part of the proton-proton collision to ensure that the extrapolation of the quantities measured at 7 and 8 TeV describes properly the new data. The most basic quantity to test is the inelastic cross-section σ_{inel} of the pp collision. Due to the large value of σ_{inel} with respect to the rare processes the LHC is designed to study, the statistical uncertainty is negligible and the dominant sources of uncertainty are propagated from the integrated luminosity evaluation and the model-dependent extrapolation to geometrical regions outside the detector acceptance, as for example those in the forward region (high absolute pseudorapidity $|\eta|$). The measurements obtained by CMS [3],

$$\sigma_{\text{inel}}^{\text{CMS}} = 71.3 \pm 0.5(\text{exp}) \pm 2.1(\text{lum}) \pm 2.7(\text{extr}) \text{ mb}, \tag{2.1}$$

confirms the result published by ATLAS [4],

$$\sigma_{\text{inel}}^{\text{ATLAS}} = 73.1 \pm 0.9(\text{exp}) \pm 6.6(\text{lum}) \pm 3.8(\text{extr}) \text{ mb}, \tag{2.2}$$

which is compared to other experimental results and predictions in Figure 1, and found consistent within the uncertainties.

The kinematic distributions of charged particles generated in inelastic pp collisions were also investigated by both ATLAS [5] and CMS [6] drawing to the conclusion that models specialized in soft interactions described with Pomeron exchanges, such as EPOS-LHC [7], result in more accurate predictions. Conclusions are less in favour of generators based on diffractive models when studying the soft part of events where a hard scattering process occurs. Defining the leading track as the track with highest p_T and $\Delta\phi$ as the azimuthal angle relative to the leading track, three spatial regions are identified as depicted in Figure 2: toward for $|\delta\phi| < 60°$; transverse for $60° < |\delta\phi| < 120°$; and away for $|\delta\phi| > 120°$. The *charged track density* $\left\langle \frac{\text{d}N_{\text{ch}}^2}{\text{d}\eta \text{d}\phi} \right\rangle$ and the *energy density* $\left\langle \frac{\text{d}^2 \sum p_T}{\text{d}\eta \text{d}\phi} \right\rangle$ are measured both separately and averaged for $\delta\phi \in [60°, 120°]$ and $\delta\phi \in [-120°, -60°]$. The average distribution is then compared to predictions obtained from various MC generators, as shown in Figure 3, separately for ATLAS and CMS, taking as an example the charged track density. As anticipated, these studies indicate that the agreement between experimental distributions and the MC generators implementing LHC tunings of Pythia [8] such as Monash [9] are better than what reached with generators based on diffractive theories.

Studies of the track multiplicity as a function of the angle formed with the leading track were performed in gold-gold collisions already at RHIC by the STAR and PHENIX collaborations, observing for the first time a long-range rapidity correlation in ion-ion collisions at high multiplicity, named *ridge effect* [12]. The effect was later confirmed by the CMS experiment in lead-lead collisions [13]. The interpretation is still not unique, but there is consensus around the idea that the origin of the effect is related to collective mechanisms, possibly related to the formation of *quark gluon plasma*. Such an interpretation was challenged when CMS observed the formation of a ridge in proton-lead collisions [14]. The effect has been recently confirmed by LHCb, in the forward region [15]. A further challenge to the nuclear interpretation of the ridge effect came with the observation of a similar long-range pseudorapidity correlation by CMS in pp collisions at $\sqrt{s} = 8$

TeV [16], and more recently in pp collisions at $\sqrt{s} = 13$ TeV [17]. In the last work, the yield of the correlated production was measured as a function of the transverse momentum of the leading track and of the track multiplicity, as shown in Figure 4. The resulting dependence is roughly linear, definitely not consistent with the quadratic behaviour predicted for the initial state by Glasma [18].

To our knowledge, the ridge effect represents today the largest discrepancy between experimental data and predictions among the many measurements of the underlying event's soft component. Further theoretical investigation, and experimental characterization of the dependence of the yield of the ridge from other kinematical and geometrical quantities also exploiting the new datasets collected at the LHC will be of major interest in the next years.

3. Production and nature of jets

Measurements of hard jet production processes and the running of alpha strong are the main probes capable of providing strong constraints to perturbative QCD [19]. For that reason there is a lot of interest in extending the studies with data at $\sqrt{s} = 13$ TeV that are actually ongoing and to be public very soon. On the other hand, the softer part of the collision is not totally understood, for instance the jet production cross-section measurements. Jets are defined as sets of particles produced, within a limited region in space of η and ϕ (referred below as "cone"), because of the hadronization process of a quark or a gluon. The definition of jets require the anti-k_T clusterization algorithm, as vastly used in many analysis. It is also customary to indicate the geometrical parameter relative to the aperture of the cone as R.

While in good consistency with the theoretical predictions from Pythia and NLOJet++ [20, 21], the jet production cross-section measurements performed by ATLAS and CMS with pp collisions

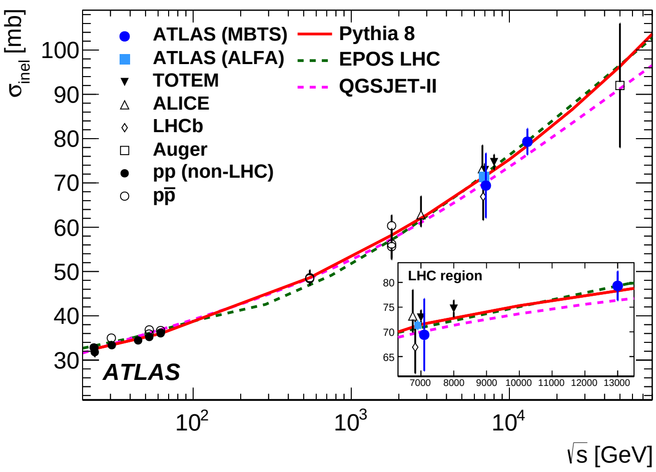

Figure 1: Comparison of the ATLAS measurement of the inelastic cross-section of pp collisions at 13 TeV with measurements from other experiments and with effective models implemented as MC generators. The Figure was published in Ref. [4], where the reader finds references for the measurements and predictions shown in the plot.

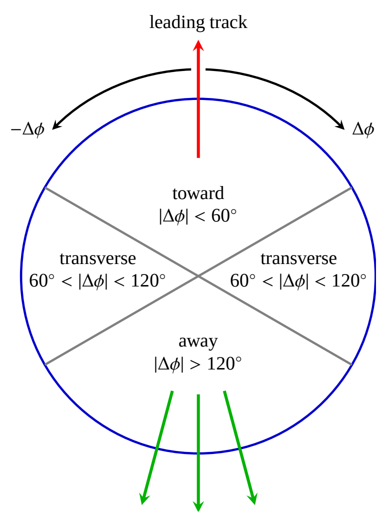

Figure 2: Azimuthal regions. The Figure was presented in Ref. [10].

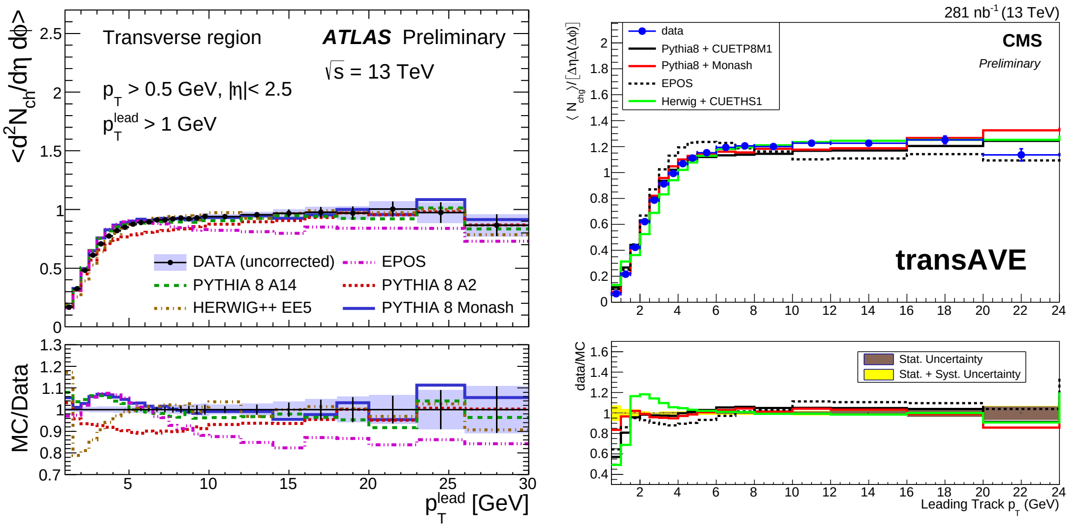

Figure 3: Example of comparison of the charged track density as measured by ATLAS (left) and CMS (right) with different models and tuning for MC generators. The ATLAS results are discussed in Ref. [10], those obtained by CMS is Ref. [11].

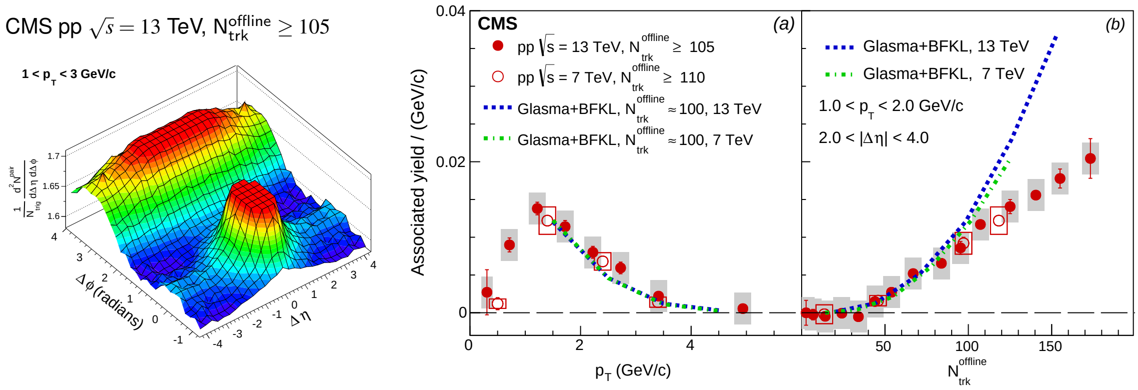

Figure 4: At left, an example of the long range pseudorapidity correlation arising at high track multiplicity. At right, the dependence of the associated yield, obtained fitting the ridge structure, as a function of the track multiplicity. The dashed lines superposed to the experimental data represent the predictions from Glasma [18]. Both Figures were published in Ref. [17].

at $\sqrt{s} = 13$ TeV reveal a systematic shift of the theoretical predictions with respect to the data which depends on the geometrical parameter R [22, 23]. This unexpected dependence is possibly due to the mismodelling of some soft effect out-of-the-cone assuming different relevance when variating the cone aperture.

3.1 Classification of the originating parton

In the next years, the physics measurements with jets will be able to profit of experimental techniques and observations that allows to distinguish the originating parton. Such an opportunity is obviously important in the determination of the properties of a hypothetically observed particle beyond the Standard Model. In this paragraph, two recent studies representative of the advances with jet-tagging are briefly discussed.

The ATLAS Collaboration has extracted the gluon-initiated jet constituent charged-particle multiplicity showing that it is higher than the corresponding quantity for quark-initiated jets [24]. The analysis strategy uses di-jet events and classifies the jet at highest pseudo-rapidity as *more-forward* and the jet at lower pseudo-rapidity as *more-central*. Taking from Pythia (using PDF CT10 [25]) the probabilities for a gluon jet to be classified as the *more-central* or *more-forward*, it is possible to compute the average multiplicity of gluon-jets and quark-jets from the measured average multiplicity of the *more-forward* and *more-central* jets. The result of this study, presented in bins of jet transverse momentum, and compared to predictions from Pythia and perturbative QCD, is shown in Figure 5.

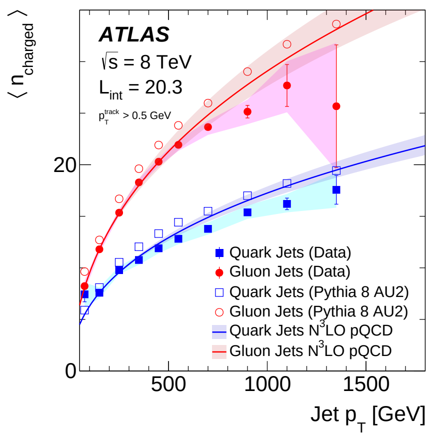

Figure 5: The p_T dependence of the average track-multiplicity for quark- and gluon-jets. The Figure was published in Ref. [24].

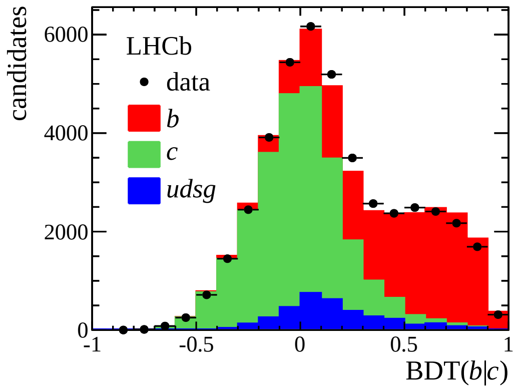

Figure 6: Fit of template distributions for the response of a classifier trained to distinguish *b*-jets from *c*-jets to a sample of jets produced in association with a *D* meson. The Figure was published in [26].

The distinction of the flavour of *beauty* or *charm* quarks resulting in a jet has been studied recently by the LHCb collaboration combining a Seconday Vertex (SV) tagger, pairing tracks geometrically close to each other, with two multivariate discriminants based on *Boosted Decision Trees* [27] trained to distinguish heavy quarks from light partons, and *b*-quarks from *c*-quarks, respectively [26]. The variables entering the multivariate analysis are related to the geometry of the jet and its kinematics. Among the input variables, those related to the distance between the primary and secondary vertices are particularly useful to discriminate between jets originated by *b* and *c* quarks, exploiting their different lifetimes.

The performance of the tagging algorithm, tested on real data studying the effect of jets produced in association with a *B* or *D* quark to enrich the fraction of jets originated from *b*- and *c*-quarks, is well reproduced by the simulation. The algorithm offers much better purity in the selection of jets originated by heavy flavours, with respect to the simpler alternative based on the separation of the leading track from the primary vertex. Figure 6 represents a fit of the template distributions for the classifier response as obtained from Simulation, to a sample of jets produced in association with a *D* meson.

4. Heavy Flavours and Quarkonia production

As for other QCD processes, the theoretical description of the heavy quark production mechanisms and their agreement with the experimental data has seen a significant improvement in the last years. Both in the *charm* and in the *beauty* sectors, the recent measurements at $\sqrt{s}$ = 13 TeV performed by the CMS, and LHCb collaborations are found in reasonable agreement with predictions [28, 29].

Also for charmonium production, the theoretical expectations were found in good agreement with the experimental data of the ATLAS, CMS, and LHCb collaborations [30, 31, 32].

Some questions, instead, were raised by the comparison of the bottomonium production cross-section in the forward region [33]. The measurements performed by the LHCb Collaboration at $\sqrt{s} = 7$ TeV and 8 TeV showed a 30% increase of production cross-section between the two energies. The production spectrum in transverse momentum and pseudrapidity is found in evident disagreement with the theorietical predictions [34, 35]. The increase in the production cross-section observed in bins of p_T and y is compared to the expectations in Figure 7.

The latest results of LHC data extended the Υ production cross-section measurement at the increased energy of $\sqrt{s}$ = 13 TeV. Each result at a different energy scale and precision can provide useful constraint on the process models. The latest measurement from CMS shows that the production cross-section scales linearly with the energy (Figure 8), as naively expected. The same behavior was also observed, for example, for the production of $c\bar{c}$ or b-hadrons [31]. Precise comparison with the expectations awaits for the update of the theoretical models [34].

The LHCb Collaboration is called to update the measurement of the production cross-section of the Υ state at the increased energy of $\sqrt{s}$ = 13 TeV, to complete the previous measurements with a point corresponding to the same p_T and y range.

5. Associative production

Interesting studies on the production measurement of heavy flavours, jet and electroweak bosons, focus on their associative production. In general, the production of two objects in the same pp (or $p\bar{p}$) collision can be due to:

- *Single Parton Scattering* (SPS), if the interaction between the two colliding hadrons is described through a unique interaction of two partons, gluons or quarks, with some process producing the two objects through a single interaction;
- *Double Parton Scattering* (DPS), if the interaction between the two colliding hadrons is described through the simultaneous interaction of two pairs of partons, each producing one of the two objects that we observe as associatively produced.

While the cross-section of SPS processes is somewhat unrelated to the production cross-section of the two single objects, because the production mechanisms, including the underlying Fenyman diagrams, are different, the associative production of two objects A and B due to DPS has a cross-section that is believed to be proportional to the product of the cross-section of the two processes producing separately A or B:

$$\sigma_{A+B} \propto \sigma_A \sigma_B. \tag{5.1}$$

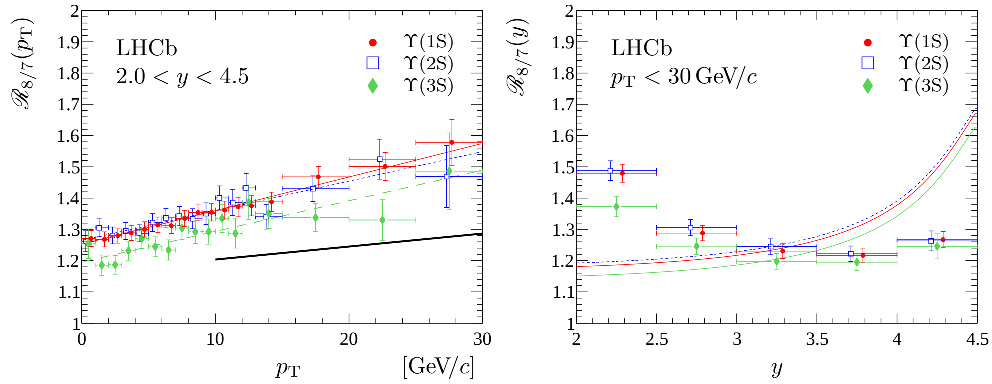

Figure 7: Comparison of the increase in the production cross-section of the Υ meson between $\sqrt{s} = 7$ and 8 TeV with the theoretical predictions. Predictions from Ref. [34] are represented as thick black line in the left plot. Predictions from Ref. [35] are represented as dashed lines in the right plot, separately for $\Upsilon(1S)$, $\Upsilon(2S)$ and $\Upsilon(3S)$. The Figures were published in Ref. [33].

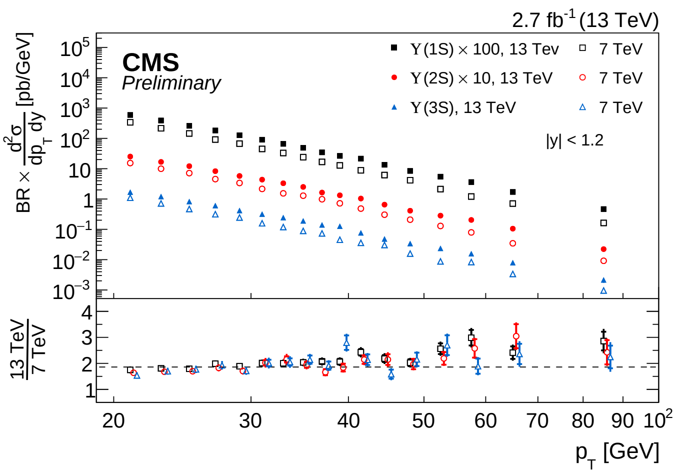

Figure 8: Measurement of the Υ production cross-section in pp collisions at $\sqrt{s}$ = 13 TeV performed by the CMS Collaborations. The Figure was published in Ref. [32].

The constant of proportionality of Equation 5.1 has the dimensions of an inverse cross-section and it is therefore indicated as $\frac{1}{\sigma_{\text{eff}}}$. Namely:

$$\sigma_{A+B} = \frac{m}{2} \frac{\sigma_A \sigma_B}{\sigma_{\text{eff}}}, \tag{5.2}$$

where m is a symmetrization parameter, equal to 1 in case of indistinguishable processes, 2 otherwise. The parameter σ_{eff} is improperly named *effective cross-section*.

The dependence of σ_{eff} on the exact process is matter of theoretical debate, but several experimental measurements of very different processes seem to indicate that such a dependence is not large [38].

Figure 9 reports a summary of several measurements of σ_{eff} in very different processes involving jets, heavy flavours, and electroweak objects. Measurements involving $W^{\pm}$ and Z^0 bosons are

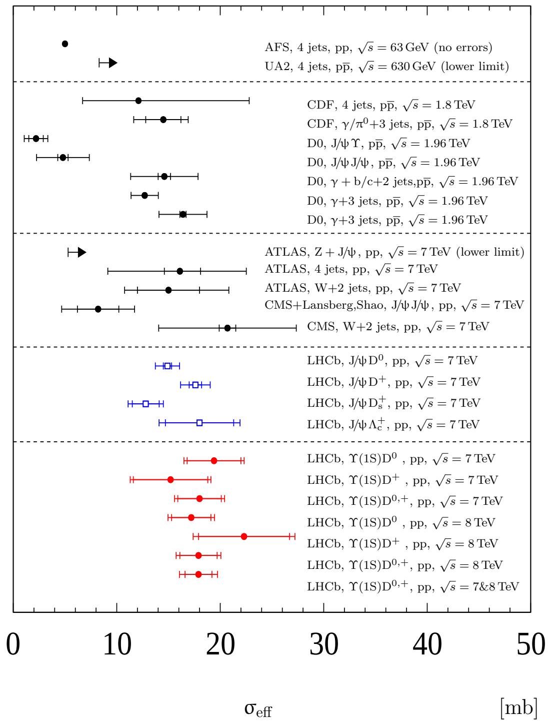

Figure 9: Summary of the σ_{eff} measurements in several processes and at different energies in the center of mass. The Figure was published in Ref. [36], whose references include those to the measurements summarized in the plot.

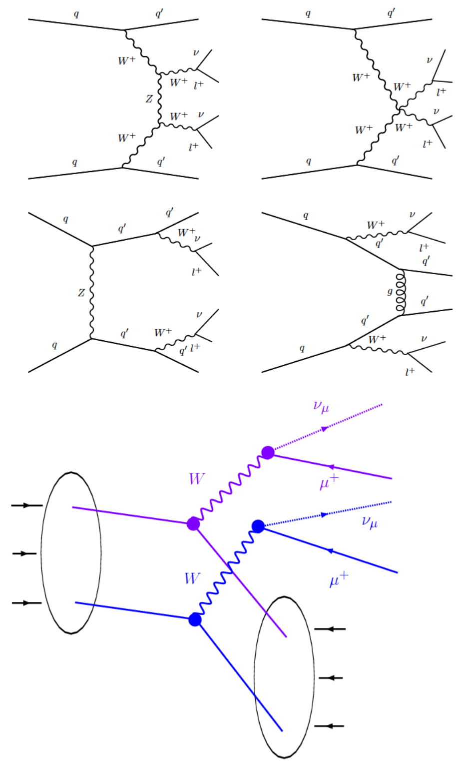

Figure 10: Typical diagrams describing the associative production of same-sign $W^\pm$ bosons through SPS (top) and DPS (bottom). The Figure was published in Ref. [37].

powerful means of investigation of DPS mechanisms, but are sometime limited in statistics when analysing 2012 data, only.

For example, CMS in a recent work, reports about the study of the associative production of same-sign $W^\pm$ bosons, using multivariate analysis techniques to identify DPS [37]. It is interesting to observe that the production cross-section of same-sign $W^\pm$ bosons, which is $\mathcal{O}(10^{-1}\,\text{pb})$, has contributions from SPS and DSP which are predicted to be comparable. Opposite-sign $W^\pm$ pairs, instead, are mainly produced through SPS, with a contribution from DPS expected to be at the percent level.

In the absence of strong evidence for the signal, an upper limit on the associative production cross-section through DPS and a lower limit on σ_{eff} are set at 95% of confidence level,

$$\sigma^{\text{DPS}}_{W^\pm W^\pm} < 1.12\,\text{pb}^{-1} \qquad \text{and} \qquad \sigma_{\text{eff}} > 5.91\,\text{mb}, \tag{5.3}$$

the latter is consistent with the order of magnitude for σ_{eff} reported by other measurements.

Profiting from 13TeV data samples, processes like the associative production of same-sign $W^\pm$ bosons, with enhanced contribution from DPS, will be further explored to shed light on the dependence of σ_{eff} from the process and from the energy in the center of mass.

6. Conclusive remarks

The last years have seen an incredible increase in the understanding and modelling of QCD processes. ATLAS, CMS, and LHCb measurements at 8 TeV show an agreement with simulation which is often better than 10%.

In this picture of reassuring understanding, a few disagreements of the collected data with theoretical models stimulate our curiosity and call for further investigations.

The observation of a dependence in the soft event structure, notably as long-range η correlations, on the multiplicity suggests that collective hadro-dynamic processes, usually employed to describe physics in heavy ion collisions, might take place in pp collisions as well. On the other hand it was shown that theoretical models developed for heavy ion collisions, fail to reproduce the observed behaviour in pp collisions.

Other measurements seem to indicate that the soft part of events where a hard process take place is not fully understood. For example, CMS reported about an unexpected dependence of the jet production cross-section on the geometrical parameter R defining the aperture of the cone in the anti-k_T factorization algorithm. Several studies on jet-tagging techniques will allow further studies at 13 TeV, investigating, for example, whether the soft part of the event behaves differently for different partons hadronizing into the jet.

Another open question which will need further investigation during the following years is related to the enhanced production cross-section of heavy flavours in the central rapidity bins of the LHCb acceptance. This behaviour which has been observed with great significance in the comparison of the Υ production measurements at 7 and 8 TeV, finds confirmation in other measurements from LHCb. Still, such an increase in the production cross-section at low rapidity does not seem to be confirmed by publications from ATLAS and CMS.

Finally, a call to the theoretical community is open to provide predictions on the dependence of the double parton scattering effective cross-section σ_{eff} as a function of the energy in the center of mass and on the particular process. The enhanced energy in the center of mass, at which LHC is operating since the beginning of Run 2, will provide further experimental points to characterize such a dependence.

References

[1] D. J. Gross and F. Wilczek, *Ultraviolet Behavior of Nonabelian Gauge Theories*, *Phys. Rev. Lett.* **30** (1973) 1343–1346.

[2] H. D. Politzer, *Reliable Perturbative Results for Strong Interactions?*, *Phys. Rev. Lett.* **30** (1973) 1346–1349.

[3] CMS Collaboration collaboration, *Measurement of the inelastic proton-proton cross section at* $\sqrt{s} = 13$ TeV, Tech. Rep. CMS-PAS-FSQ-15-005, CERN, Geneva, 2016.

[4] ATLAS collaboration, M. Aaboud et al., *Measurement of the Inelastic Proton-Proton Cross Section at* $\sqrt{s} = 13$ *TeV with the ATLAS Detector at the LHC*, 1606.02625, CERN-EP-2016-140.

[5] ATLAS collaboration, G. Aad et al., *Charged-particle distributions in* $\sqrt{s}$*=13 TeV pp interactions measured with the ATLAS detector at the LHC*, *Phys. Lett.* **B758** (2016) 67–88, [1602.01633], CERN-EP-2016-014.

[6] CMS collaboration, V. Khachatryan et al., *Pseudorapidity distribution of charged hadrons in proton-proton collisions at $\sqrt{s}$ = 13 TeV*, Phys. Lett. **B751** (2015) 143–163, [1507.05915], CMS-FSQ-15-001, CERN-PH-EP-2015-180.

[7] T. Pierog, I. Karpenko, J. M. Katzy, E. Yatsenko and K. Werner, *EPOS LHC: Test of collective hadronization with data measured at the CERN Large Hadron Collider*, Phys. Rev. **C92** (2015) 034906, [1306.0121], DESY-13-125.

[8] T. Sjostrand, S. Mrenna and P. Z. Skands, *A Brief Introduction to PYTHIA 8.1*, Comput. Phys. Commun. **178** (2008) 852–867, [0710.3820], CERN-LCGAPP-2007-04, LU-TP-07-28, FERMILAB-PUB-07-512-CD-T.

[9] P. Skands, S. Carrazza and J. Rojo, *Tuning PYTHIA 8.1: the Monash 2013 Tune*, Eur. Phys. J. **C74** (2014) 3024, [1404.5630], CERN-PH-TH-2014-069, MCNET-14-08, OUTP-14-05P.

[10] *Leading Track Underlying Event at 13 TeV*, Tech. Rep. ATL-PHYS-PUB-2015-019, CERN, Geneva, Jul, 2015.

[11] CMS COLLABORATION collaboration, *Underlying Event Measurements with Leading Particles and Jets in pp collisions at* $\sqrt{s} = 13$ *TeV*, Tech. Rep. CMS-PAS-FSQ-15-007, CERN, Geneva, 2015.

[12] STAR collaboration, B. I. Abelev et al., *Long range rapidity correlations and jet production in high energy nuclear collisions*, Phys. Rev. **C80** (2009) 064912, [0909.0191].

[13] CMS collaboration, S. Chatrchyan et al., *Long-range and short-range dihadron angular correlations in central PbPb collisions at a nucleon-nucleon center of mass energy of 2.76 TeV*, JHEP **07** (2011) 076, [1105.2438], CERN-PH-EP-2011-056, CMS-HIN-11-001.

[14] CMS collaboration, S. Chatrchyan et al., *Observation of long-range near-side angular correlations in proton-lead collisions at the LHC*, Phys. Lett. **B718** (2013) 795–814, [1210.5482], CMS-HIN-12-005, CERN-PH-EP-2012-320, CMS-HIN-12-015.

[15] LHCB collaboration, R. Aaij et al., *Measurements of long-range near-side angular correlations in* $\sqrt{s_{NN}} = 5$ TeV *proton-lead collisions in the forward region*, 1512.00439, LHCB-PAPER-2015-040, CERN-PH-EP-2015-308.

[16] CMS collaboration, V. Khachatryan et al., *Observation of Long-Range Near-Side Angular Correlations in Proton-Proton Collisions at the LHC*, JHEP **09** (2010) 091, [1009.4122], CMS-QCD-10-002, CERN-PH-EP-2010-031.

[17] CMS collaboration, V. Khachatryan et al., *Measurement of long-range near-side two-particle angular correlations in pp collisions at* $\sqrt{s}$ *=13 TeV*, Phys. Rev. Lett. **116** (2016) 172302, [1510.03068], CMS-FSQ-15-002, CERN-PH-EP-2015-271.

[18] F. Gelis, *Color Glass Condensate and Glasma*, Int. J. Mod. Phys. **A28** (2013) 1330001, [1211.3327], IPHT-T12-121.

[19] CMS collaboration, G. Flouris, *Jet production and* α_s *measurement at CMS*, Nucl. Part. Phys. Proc. **270-272** (2016) 8–12.

[20] Z. Nagy, *Next-to-leading order calculation of three jet observables in hadron hadron collision*, Phys. Rev. **D68** (2003) 094002, [hep-ph/0307268].

[21] S. Catani and M. H. Seymour, *A General algorithm for calculating jet cross-sections in NLO QCD*, Nucl. Phys. **B485** (1997) 291–419, [hep-ph/9605323], CERN-TH-96-029, CERN-TH-96-29.

[22] CMS collaboration, V. Khachatryan et al., *Measurement of the double-differential inclusive jet cross section in proton-proton collisions at sqrt(s) = 13 TeV*, 1605.04436, CMS-SMP-15-007, CERN-EP-2016-104, FERMILAB-PUB-16-197-CMS.

[23] *Measurement of the inclusive-jet cross section in proton-proton collisions at 13 TeV centre-of-mass energy with the ATLAS detector*, Tech. Rep. ATLAS-CONF-2015-034, CERN, Geneva, Jul, 2015.

[24] ATLAS collaboration, G. Aad et al., *Measurement of the charged-particle multiplicity inside jets from $\sqrt{s} = 8$ TeV pp collisions with the ATLAS detector*, 1602.00988, CERN-PH-EP-2016-001, CERN-EP-2016-001.

[25] J. Gao, M. Guzzi, J. Huston, H.-L. Lai, Z. Li, P. Nadolsky et al., *CT10 next-to-next-to-leading order global analysis of QCD*, *Phys. Rev.* **D89** (2014) 033009, [1302.6246], SMU-HEP-12-23.

[26] LHCb collaboration, R. Aaij et al., *Identification of beauty and charm quark jets at LHCb*, *JINST* **10** (2015) P06013, [1504.07670], LHCB-PAPER-2015-016, CERN-PH-EP-2015-101.

[27] R. E. Schapire and Y. Freund, *A decision-theoretic generalization of on-line learning and an application to boosting*, *Jour. Comp. and Syst. Sc.* **55** (1997) 119.

[28] LHCb collaboration, R. Aaij et al., *Measurements of prompt charm production cross-sections in pp collisions at $\sqrt{s} = 13$ TeV*, *JHEP* **03** (2016) 159, [1510.01707], LHCB-PAPER-2015-041, CERN-PH-EP-2015-272.

[29] CMS collaboration, C. Collaboration, *Measurement of the B^+ hadron production cross section in pp collisions at 13 TeV*, CMS-PAS-BPH-15-004.

[30] LHCb collaboration, R. Aaij et al., *Measurement of forward J/ψ production cross-sections in pp collisions at $\sqrt{s} = 13$ TeV*, *JHEP* **10** (2015) 172, [1509.00771], LHCB-PAPER-2015-037, CERN-PH-EP-2015-222.

[31] CMS collaboration, *Quarkonium production cross sections in pp collisions at* $\sqrt{s} = 13$ TeV, CMS-PAS-BPH-15-005.

[32] The ATLAS collaboration, *Measurement of the differential non-prompt J/ψ production fraction in $\sqrt{s}$ = 13 TeV pp collisions at the ATLAS experiment*, ATLAS-CONF-2015-030.

[33] LHCb collaboration, R. Aaij et al., *Forward production of Υ mesons in pp collisions at $\sqrt{s} = 7$ and 8TeV*, *JHEP* **11** (2015) 103, [1509.02372], CERN-PH-EP-2015-232, LHCB-PAPER-2015-045.

[34] H. Han, Y.-Q. Ma, C. Meng, H.-S. Shao, Y.-J. Zhang and K.-T. Chao, *$\Upsilon(nS)$ and $\chi_b(nP)$ production at hadron colliders in nonrelativistic QCD*, 1410.8537.

[35] L. S. Kisslinger and D. Das, *Ψ and Υ Production In pp Collisions at 8.0 TeV*, *Mod. Phys. Lett.* **A29** (2014) 1450082, [1403.2271].

[36] LHCb collaboration, R. Aaij et al., *Production of associated Υ and open charm hadrons in pp collisions at $\sqrt{s} = 7$ and 8 TeV via double parton scattering*, 1510.05949, CERN-PH-EP-2015-279, CERN-LHCB-PAPER-2015-046, LHCB-PAPER-2015-046.

[37] CMS Collaboration collaboration, *Double Parton Scattering cross section limit from same-sign W bosons pair production in di-muon final state at LHC*, Tech. Rep. CMS-PAS-FSQ-13-001, CERN, Geneva, 2015.

[38] R. Konrath, *Double parton scattering at the lhc*, *Journal of Physics: Conference Series* **706** (2016) 052031.