Overview of soft QCD and diffractive physics at LHC

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1 Introduction

The soft QCD processes dominate the hadronic cross section at the LHC energy. The study of the particle production at low p_T is one of the basic measurements at any hadron collider, providing a wide set of observables useful to model the event generators. Unidentified hadron multiplicity is sensitive to multi parton interactions while identified hadrons allow to test the modeling of strange and heavier quarks production in the event generators. A significant fraction of the inelastic cross section comes from diffractive processes, whose prediction is affected by large uncertainties. The study of the single, double and central diffraction provide a constrain to the Monte Carlo simulations and is therefore a mandatory step to understand the charged particle production at LHC.

2 Inclusive measurements

The study of the inclusive charged particle production was the first physics result obtained at LHC. The proton-proton interactions at $\sqrt{s}$=900 GeV, detected by ALICE during the early phase of the accelerator commissioning, showed results consistent with earlier measurements obtained in proton-antiproton interactions at the same energy[1]. The charged pseudorapidity density, the multiplicity and the p_T distributions, and the dependence of the $<p_T>$ from the charged multiplicity were investigated in detail at LHC. From an experimental point of view the nice agreement in these measurements obtained by ALICE[2],ATLAS[3] and CMS[4] demonstrated the excellent detector performance and showed the experiments capability to control the systematics. The event generators aiming to simulate these data(PHOJET[5],PYTHIA 6[6] and PYTHIA 8[7]) can reproduce the measured distributions only qualitatively. ALICE[2] studied the charged particle pseudorapidity density for inelastic collisions having at least one charged particle at $|\eta| < 1$. The charged particle pseudorapidity density, compared to the one measured at $\sqrt{s}$=900 GeV, increases by $(23.3 \pm 0.4(sta)^{+1.1}_{-0.7}(sys))$ at $\sqrt{s}$=2.36 TeV and by $(57.6 \pm 0.4(sta)^{+3.6}_{-1.8}(sys))$% at $\sqrt{s}$=7 TeV, while the Monte Carlo with the highest values (PYTHIA tune ATLAS-CSC) provides 17.6% and 47.6% respectively[2]. The multiplicity distribution measured by ALICE at $\sqrt{s}$=7 TeV is not reproduced by PHOJET and by several PYTHIA6 tunes: ATLAS-CSC is the closest but this tune underestimates the average p_T as a function of the event charged multiplicity (n_{ch}) at $\sqrt{s}$=900 GeV[2]. CMS found similar results at $|\eta| < 2.4$[4]: PHYTIA

8 reproduces the multiplicity distribution at $\sqrt{s}$=7 TeV but overestimates the same distribution at $\sqrt{s}$=900 GeV. Moreover the agreement with PYTHIA 8 does not hold if a cut p_T >500 MeV/c is applied, showing the softer part of the hadronic production is the most difficult to be reproduced. PHOJET shows an opposite trend: it reproduces the multiplicity distribution measured by ALICE[2] and CMS at $\sqrt{s}$=900 GeV[4], but underestimates the same distribution at $\sqrt{s}$=7 TeV. CMS showed that the average p_T is reproduced at $\sqrt{s}$=900 GeV and $\sqrt{s}$=2.36 TeV by PHTYIA 8, but this model overestimates it at $\sqrt{s}$=7 TeV. ATLAS[3] measured the charged particle multiplicity distribution at $|\eta| < 2.5$, requiring p_T >100 MeV and $n_{ch} \geq$2: by applying these cuts PYTHIA 8 underestimates the data both at $\sqrt{s}$=900 GeV and $\sqrt{s}$=7 TeV by 10-15%. It is worth noting, changing the above cuts to p_T >500 MeV and $n_{ch} \geq$6, PYTHIA tune ATLAS AMBT1 reproduce nicely the data both at $\sqrt{s}$=900 GeV and $\sqrt{s}$=7 TeV. Recently the charged multiplicity (n_{ch} >1) was measured by LHCb in the η interval 2< η <4.5 [8] and by TOTEM at 5.3< η <6.5[9]. In these η regions the event generators (default or tuned) underestimate the charged particle multiplicity too. As a conclusion of this first part we note each model/tuning can reproduce a limited number of observables at few center of mass energies.

3 Exclusive measurements

CMS measured the spectra and the p_T of identified charged particle at $\sqrt{s}$=900 GeV, 2.36 TeV and 7 TeV[10]. The experimental results obtained at midrapidity ($|y| < 1$) have been compared with the expectation provided by several event generator. The average p_T as a function of the track multiplicity is properly reproduced by PYTHIA 8 tune 4C and PYTHIA 6 tune Z2 for pion and kaons at any center of mass energy, but none of the above models/tunes provides an acceptable description of the protons. ALICE shows[11] the ratio π/K as a function of the p_T is missed by PHOJET, PYTHIA tunes Perugia 0 and D6T at $\sqrt{s}$=900 GeV for $p_T > 1.2$ GeV/c. The CMS measurement shows PYTHIA 8 tune 4C is inadequate to reproduce this ratio as a function of the track multiplicity at any center of mass energy. The same event generator underestimate the K^0 and the Λ production in CMS at $\sqrt{s}$=900 GeV and $\sqrt{s}$=7 TeV: the discrepancy increases with the particle mass[10]. Things get worse when focusing on multi-strange hadrons. The ALICE collaboration measured the production of mesons and baryons containing two or three strange quarks in proton-proton collisions at the LHC at $\sqrt{s}$=7 TeV. The ratio $N_\Phi/(N_\rho + N_\omega)$ measured by ALICE in the forward region (2.5< y <4) in the muon channel agrees nicely with the LHCb measurement(2.44< y <4.06) obtained in the K^+K^- channel. The predictions underestimate this ratio up to a factor 2[11], with the exception of the ATLAS CSC tune (PHOJET) giving a reasonable estimate for $p_T > 1.5\ \mathrm{GeV}/c(3\ \mathrm{GeV}/c)$. The study of the Ξ and of the Ω provides an useful tool to check the strangeness production in proton-proton collisions, since these two baryons differ only by a valence quark, with the u-quark replaced by a s-quark in the Ω. ALICE showed[11] PYTHIA 6 tunes Z1, Z2 and Perugia 0 are up to an order of magnitude below the Ω measured spectra and yield and the ratio Ω/Ξ is also underestimated by a factor up to $\simeq$4[11]. The Perugia 2011 gives better results, but underestimates by a factor 4(2) the $\Omega(\Xi)$ yield(Fig. 1). Simulating the strange hadrons is a

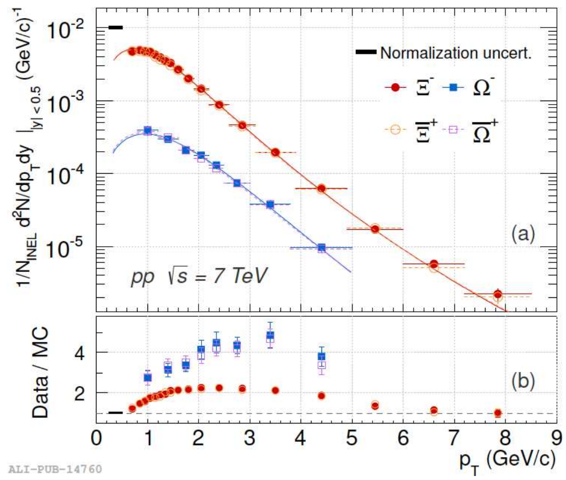

Figure 1: (a) Ω and Ξ spectra measured by ALICE, shown with Tsallis fits. (b) ALICE data to Monte Carlo (PYTHIA Perugia 2011) comparison. The errors are added in quadrature.

difficult task: in PYTHIA the strangeness production is controlled by several parameters, as the suppression of the s quark pair production in the field compared with the u-pair or d-pair production, the extra suppression of strange diquark production compared with the normal suppression of strange quarks, etc. It is worth noting the Perugia 2011 tune makes use of the CTEQ5L parton distribution function, and has a significant increase in multi-strange baryon yields with respect to other tunings/models. Nevertheless the production of strangeness in ALICE is not adequately described by this tune too. An effort to increase the strangeness production has been attempted by the Z1C tuning, increasing the above parameters: as a result the Λ/K ratio increases but the K/π ratio has to be improved at $p_T > 1$GeV/c, where the ratio is still underestimated.

4 Inelastic cross section

The inelastic cross-section is the sum of several contributions: the single diffractive(SD), the double diffractive(DD), the central diffractive(CD) and the non diffractive (ND) cross section. Diffraction study is challenging: most of the proton excitation remains into the beam pipe and low pile-up runs are required. In addition the transition from ND to DD events is smooth; experimental observables requires Monte Carlo corrections to be linked with physics quantities. ATLAS relied on the calorimeters to study the distribution of the forward gap $\Delta\eta^F$[12], defined as the larger of the η regions extending to the limits of the ATLAS sensitivity ($\eta = \pm 4.9$), in which no final state particles are produced above a given p_T threshold. ND events correspond to $\Delta\eta^F \simeq 0$, while SD events have large $\Delta\eta^F$. PYTHIA 8 reproduces the $\Delta\eta^F$ distribution at low and high $\Delta\eta^F$, while the central region ($3 \leq \Delta\eta^F \leq 6$) is overestimated. On the contrary this region is nicely reproduced by PHOJET, missing the low and the high $\Delta\eta^F$ region. None of the models can reproduce the raise at

$\Delta\eta^F$ >6. This region can be matched by decreasing the pomeron intercept from $\alpha \simeq 1.085$ to $\simeq 1.058$, but the price to be paid is an underestimate of the central region ($3 \leq \Delta\eta^F \leq 6$). The fraction of diffractive events in the Monte Carlo has to be constrained from the data: ATLAS used the fraction of events (R_{ss}) giving a signal only in one of the two Minimum Bias Trigger Scintillator detector (single-sided events)[13]. The MC generators predict that less than 1% of the ND process pass the single-sided event selection, whereas 27−41% of the SD and DD processes pass the single-sided selection. R_{ss} was computed for different Monte Carlo codes by varying the fraction of the diffractive cross section with respect to the total inelastic cross section(f_D). The experimental value R_{ss}=$(10.02 \pm 0.03(stat)^{+0.1}_{-0.4}(sys))$ is reproduced assuming a diffractive fraction f_D=$(26.9^{+2.5}_{-0.1})$%. The model closest to the central value is PYTHIA 8 with the Donnachie-Landshof(DL) model with ϵ=0.085 and d=0.25 GeV^{-2}, where $\epsilon + 1$ is the intercept of the pomeron trajectory and d is the pomeron trajectory slope. This code was selected by ATLAS as reference model. The cross section for values of the fractional momentum loss of the scattered proton $\xi = M_x^2/s > 5{\cdot}10^{-6}$ is $\sigma_{inel}(\xi > 5{\cdot}10^{-6})$=$(60.3 \pm 0.05(stat) \pm 0.5(sys) \pm 2.1(lumi))$ mb. To extrapolate the above cross section to the full cross section ($\xi > m_p^2/s$), the fractional contribution to the inelastic cross-section of events passing the cut $\xi > 5{\cdot}10^{-6}$ is determined from the models. The reference model, PYTHIA 8 + DL, gives 87.3%, while other models considered give fractions ranging from 96% (PHOJET) to 86% (DL with ϵ=0.10). The inelastic cross section at $\sqrt{s}$ = 7 TeV for $\xi > m_p^2/s$ measured by ATLAS is σ_{inel}=$(69.1 \pm 2.4(exp.) \pm 6.9(model))$ mb, where the experimental error includes both the statistical and the systematic error. Similar procedures were used by ALICE and CMS, finding respectively σ_{inel}=$(73.2^{+2.0}_{-4.6}(model) \pm 2.6(lumi))$mb[15] and σ_{inel}=$(64.5 \pm 1.1(exp.) \pm 1.5(model) \pm 2.6(lumi))$mb[14]. ALICE used the distribution of the largest pseudorapidity gap in the event and the ratio of events with a single arm to those with two arms to constrain the fraction of the SD and the DD cross section[14]. The result obtained was $\sigma_{SD}/\sigma_{inel}$=$(0.21^{+0.04}_{-0.07})$ and $\sigma_{DD}/\sigma_{inel}$=$(0.12^{+0.05}_{-0.04})$. The cross sections measured by ALICE, ATLAS and CMS agree within the quoted uncertainties, the first one being slighty larger. TOTEM[16] used the elastic cross section and the optical theorem. The result is σ_{inel}=$(73.4 \pm 0.1(stat) \pm 1.9(sys) \pm 2.9(lumi))mb$, in good agreement with the measurements quoted above, specially the ALICE one.

5 Hard diffraction dijet production

Diffractive dijet production is characterised by the presence of a high-momentum proton which escapes undetected, and by a system X, which contains high-p_T jets and is separated from the proton by a large rapidity gap(LRG). One proton emits a pomeron with fractional momentum ξ and then the pomeron interacts with the other proton. This process has been studied at Fermilab and at HERA. Hard-diffractive processes can be described by the convolution of diffractive parton distribution functions (dPDFs) and hard scattering cross sections, which are calculable in pQCD. While in e-p scattering the cross section can be succesfully factorized, in hadron-hadron collider the factorisation is broken because of soft rescattering between the spectator partons. The related cross section reduction factor is usually referred in terms of Rapidity Gap Survival (RGS) probability. Dijets events

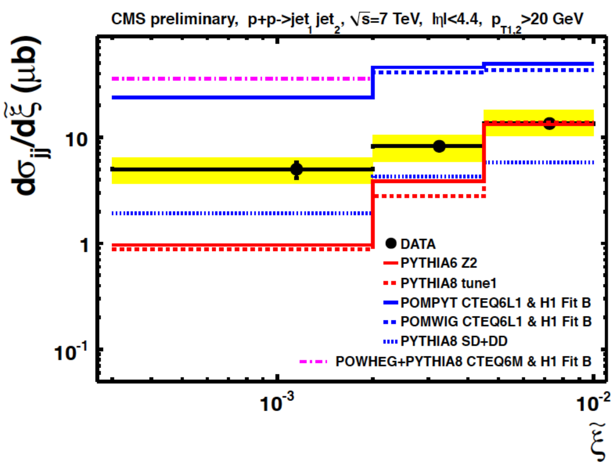

Figure 2: The CMS differential cross section for dijet production as a function of $\tilde{\xi}$.

were selected by CMS at $\sqrt{s}$=7 TeV[17] requiring transverse momentum p_T >20 GeV for both jets, jet axis pseudorapidity in the range -4.4< η <4.4 and η_{max} <3(η_{min} >-3). The dijet cross section was studied as a function of $\tilde{\xi}^{\pm}= C\Sigma(E^i \pm p_z^i)/\sqrt{s}$, a variable that approximates the fractional momentum of the pomeron, where E^i and p_z^i are the energy and the longitudinal momentum of the i^{th} particle-flow object and C is a correction factor for detector effects. The data were compared with several Monte Carlo models: as a first step non diffractive (ND) events were generated by PYTHIA 6 and by PYTHIA 8. These Monte Carlo, as expected, cannot reproduce the data at low $\tilde{\xi}$. Then diffractive events were generated by PYTHIA8(SD+DD), POMWIG (based on HERWIG) and by POMPYT(based on the PYTHIA framework), all of them using a diffractive parton distributions based on H1 experiment data fit. The main difference between POMWIG or POMPYT with respect to PYTHIA 8, is a different pomeron flux parametrization. POMWIG and POMPYT overestimate the event yield at low ξ, while PYTHIA 8(SD+DD) has to be scaled by a factor $\simeq$2 to match the data. Considering both POMWIG and POMPYT do not include the RGS, and that in the data a fraction of the scattered proton excites into a low-mass state which escapes undetected in the forward region, the discrepancy between their expectation and the data, (0.21±0.07) can be considered as a RGS upper limit. After a correction for the proton dissociation, an estimate of the RGS probability can be extracted, giving (0.12±0.05).

6 Conclusions

The data collected from $\sqrt{s}$ = 0.9 to 7 TeV offered the possibility to study many aspects of the soft QCD at LHC. The results from different experiments are in excellent agreement but the event generators still need further improvements to give appropriate predictions: as an example the strangeness production is not properly reproduced yet. The study of the minimum bias event topology allowed a reasonable tuning of the single and double diffraction in the event generators, leading to a succesfull measurement of the total inelastic cross section. The ATLAS and CMS calorimeters succesfully studied the rapidity gap, the dijet and the W production in diffractive events, providing informations on the pomeron flux and on the diffractive structure functions. In the next years LHC will unveil the evolution of the hadronic system beyond 10 TeV and the study of other soft processes, as the central diffraction, will give a more detailed picture of the low p_T event production at high energy.

References

[1] The ALICE collaboration, Eur. Phys. J. C65 (2010) 111.

[2] The ALICE collaboration, Eur. Phys. J. C68 (2010) 89; Eur. Phys. J. C68 (2010) 345.

[3] The ATLAS collaboration, New J. Phys. 13 (2011) 053033.

[4] The CMS collaboration, JHEP 01 (2011) 079.

[5] R. Engel, Z. Phys. C66 (1995) 203.

[6] T. Sjostrand et al. JHEP 05(2006) 026.

[7] T. Sjostrand et al., Comput. Phys. Comm. 178 (2008) 852.

[8] The LHCb collaboration, Eur. Phys. J. C72 (2012) 1947.

[9] The TOTEM collaboration, Eur. Lett. 98(2012) 31002.

[10] The CMS collaboration, CMS PAS FSQ-12-014, CMS PAS QCS-10-007.

[11] The ALICE collaboration, Eur. Phys. J. C71 (2011) 1594; Eur. Phys. J. C71 (2011) 1655; Phys. Rev, B710 (2010) 557; Phys. Rev. Lett. B712 (2012) 309.

[12] The ATLAS collaboration, Eur. Phys. Jour. C72(2012) 1926.

[13] The ATLAS collaboration, Nature Comm.2 (2011) 463.

[14] The ALICE collaboration, arxiv.org/1208.4968v1.

[15] The CMS collaboration, CMS PAS QCD-11-002.

[16] The TOTEM collaboration, CERN-PH-EP-2012-239; see also the talk by F. Ferro at this conference.

[17] The CMS collaboration, CMS PAS FWD-10-004.