

Soft QCD from ATLAS and CMS

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Abstract. Measurements of hadron production in pp collisions by the ATLAS and CMS experiments are presented, including charged particle transverse momentum, pseudorapidity and event-by-event multiplicity distributions at $\sqrt{s} = 0.9, 2.36$ and 7 TeV, for NSD and inelastic events. Diffraction is studied with either diffraction enriched or suppressed data samples. Total inelastic cross-section as well as gap cross-section measurements are shown. Measured spectra of identified strange hadrons, reconstructed based on their decay topology, are also discussed. Comparisons to several QCD Monte Carlo models and tunes are exhibited. Results on two-particle angular correlations over a broad range of pseudorapidity and azimuthal angle in pp collisions are presented. Underlying event activity are studied with different hard probes: tracks, trackjets, calorimeter clusters, or in Drell-Yan events.

1 Introduction

Since the beginning of the collisions at the LHC, the ATLAS and CMS experiments have measured many observables at $0.9, 2.36$ and 7 TeV, through a vast physics program. Although the results presented here are mainly for soft pp collisions, it is a mandatory step to better understand the physics involved, as QCD still needs to be modeled phenomenologically. As soft QCD is a background to many rare particle searches, improving our knowledge in this low- p_T region for 7 TeV will be crucial to many analyses. Moreover, it is the first time data at such high energy has been acquired, thus allowing good tuning of the Monte Carlo generators. It also allows to discriminate between the handful of theoretical models that were built over the years, by allowing them to be confronted to real measurements.

2 The ATLAS and CMS detectors

Complete descriptions of the ATLAS and CMS detectors can be found respectively in [1] and [2]. Both are general-purpose detectors and were built for a broad range of analyses, from low-pt QCD physics to high mass Higgs searches. They are composed first of a silicon pixel and tracker detector covering an acceptance of $|\eta| < 2.5$, plus a transition radiation tracker for ATLAS; then layers of electromagnetic and hadronic calorimeters, everything being embedded in a magnetic field of respectively 2 and 3.8 Tesla for ATLAS and CMS. The muon systems finish the onion-like subdetector layout of both experiments.

Minimum Bias events, where most of the inelastic cross-section is kept, were recorded with dedicated trigger detectors: the Minimum Bias Trigger Scintillator (MBTS, within $2.12 < |\eta| < 3.8$) for ATLAS, and a conjunction of the BPTX (located at ± 175 m from the interaction point) and the Beam Scintillator Counters (BSC, within $3.23 < |\eta| < 4.65$) for CMS. In addition, beam background and beam halo events were discarded using triggers from those same

detectors. For some CMS analyses where only non single diffractive (NSD) events were considered, the hadronic forward calorimeter (HF, within $2.9 < |\eta| < 5.2$) information was added to reject most of diffractive events. The results presented here use a wide range of integrated luminosity. The data samples from the pp collisions delivered by the LHC at the energies of $\sqrt{s} = 0.9$ and 2.36 TeV during the years 2009-2010, and $\sqrt{s} = 7$ TeV during 2009 to 2011, were all analyzed.

3 Results

3.1 Minimum Bias results

Since it needed very few statistics, the first published observables from both experiments were the pseudorapidity (η) and transverse momentum (p_T) spectra[3,4,5,6]. CMS chose an event selection rejecting diffractive events, and corrected up to NSD with Monte Carlo simulation, while ATLAS applied a selection requiring tracks in the central region with defined p_T and η cuts, which is less Monte Carlo specific than the diffractive definition. With more data, CMS managed to extend its p_T reach for the p_T distribution to ~ 100 GeV/ c using jet triggers[7]. Multiplicity distributions, as well as the $\langle p_T \rangle$ evolution with the multiplicity were also published[4,8], each experiment with their own event selection, and again for $\sqrt{s} = 0.9, 2.36$, and 7 TeV. It was finally decided by the Minimum Bias Underlying Event Working Group[9] (MBUEWG) to have a common event selection to compare between experiments, ALICE included: events with at least one track in $|\eta| < 0.8$ with $p_T > 0.5$ GeV, which led to CMS publishing new results[10]. Figure 1 (Top Right) presents such comparison for the η distribution: ATLAS, ALICE and CMS agree very well.

Although data at 0.9 TeV is compatible with previous experiments like UA5[11], the Monte Carlo generators do not describe properly the results, this whatever the event selection. The increase in particle production with energy is underestimated by all generator tunes, which is clearly

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visible in the 7 TeV η density results, as well as in the multiplicity distributions where high multiplicity tails in data are not reproduced by any Monte Carlo, as shown in Fig.1 (Bottom Left). Neither the p_T distribution nor its evolution with multiplicity is well predicted by the Monte Carlo generators: pre-LHC tunes tend to predict too many high p_T particles, particularly at high multiplicity, as seen in Fig.1 (Top Right), except for PHOJET. As big effort on generator tuning was performed by both experiments, new tunes describe much better the 7 TeV data, but none are able to do so perfectly for all distributions, event selections and energies.

In order to look at the effect of diffraction, ATLAS analyzed two samples: a diffraction suppressed one requiring at least six tracks in the event, which decreases the fraction of diffractive events remaining (although depending on the diffraction model used in Monte Carlo generators, a substantial part of diffractive events have a multiplicity higher than six); and a diffraction enriched sample[12], results being not corrected for detector effects. The diffraction suppressed multiplicity distribution from Fig.1 (Bottom Left) indicates that though new tunes are much better, their lack of particle production is blatant, and Monte Carlo diffraction models can not be the only source of it. The results using diffraction enriched samples exhibit the likeness of PYTHIA8 and PHOJET diffraction models, which are much closer to data than the PYTHIA6 one, as illustrated by the p_T distribution in Fig.1 (Bottom Right).

ATLAS and CMS also measured the total inelastic cross-section. To compute this cross-section, ATLAS first looked at events with $\xi > 5 \cdot 10^{-6}$, where $\xi = M_x^2/s$ and M_x represents the higher mass of the two hadron systems separated using the largest rapidity gap in the event, as explained in Fig.2(Left), and then extrapolated to the total acceptance[13]. CMS used the assumption that pile-up events are randomly distributed according to a Poisson distribution to compute the cross-section for events with at least two tracks of $p_T > 200$ MeV and $|\eta| < 2.4$, and then extrapolated the total inelastic cross-section using a model-dependent method[14]. The total inelastic cross-section was found to be 69.1 ± 2.4 (Exp.) ± 6.9 (Ext.) mb for CMS, and 68 ± 2.0 (Syst) ± 2.4 (Lum) ± 4 (Ext.) mb for ATLAS, both being overestimated by most Monte Carlo models. ATLAS also studied diffractive events by measuring the cross-section with respect to the pseudorapidity gap $\Delta\eta^F$ in the event[15]. Monte Carlo generators appear to show quite different behaviors, while not describing correctly the data over the full $\Delta\eta^F$ range, as exhibited in Fig.2(Right).

Strange particle production has been studied in detail by ATLAS[16] and CMS[17]. K_s^0 , Λ and Ξ^- yields show good agreement with Particle Data Group values. Their rapidity, p_T and multiplicity distributions have been measured with different event selection, and while presenting good agreement with other experiments, Monte Carlo tunes have difficulties to reproduce them, predicting too few strange particles and harder p_T spectra, the differences with data increasing with the mass of the strange particle. Ratios of rapidity density between Λ and K_s^0 , and Ξ^- and Λ for both 0.9 TeV and 7 TeV seems to indicate an energy-independent production of strange particles, which is in contradiction with Quark-Gluon Plasma (QGP) production expectancies. $\bar{\Lambda}/\Lambda$ ratios are consistent with unity in data, indicating that no significant transport of baryon number to mid-rapidities

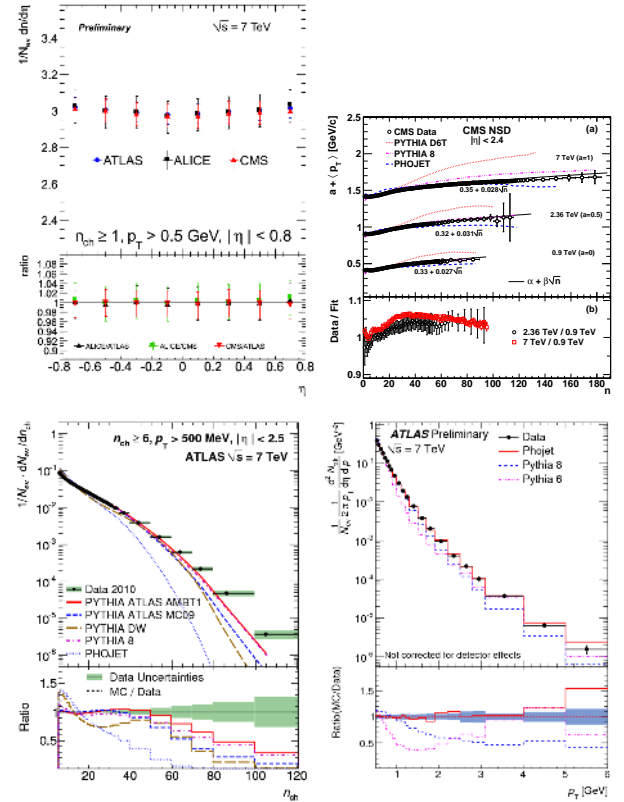


Fig. 1: (Top Left) MBUEWG combination of the η distribution at 7 TeV for ATLAS, ALICE and CMS, for events with at least one track of $p_T > 0.5$ GeV and $|\eta| < 0.8$; (Top Right) Evolution of the mean p_T with the multiplicity for NSD events at 0.9, 2.36, and 7 TeV; (Bottom Left) Multiplicity distribution at 7 TeV for events with at least six tracks of $p_T > 0.5$ GeV and $|\eta| < 2.5$, where diffraction should be greatly suppressed; (Bottom Right) Uncorrected p_T distribution at 7 TeV for diffraction enriched samples. Those minimum bias distributions are also compared with Monte Carlo predictions from different generators and tunes.

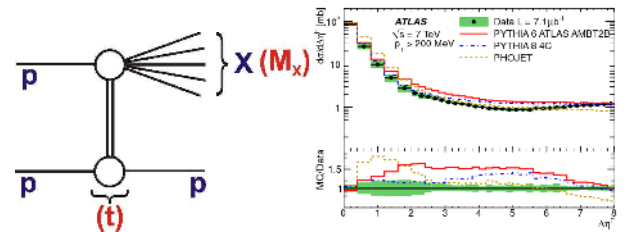


Fig. 2: (Left) Schematic view of a single diffractive event; (Right) Evolution of the cross-section with the pseudorapidity gap for $\sqrt{s} = 7$ TeV.

is present, in accordance with standard model predictions and measurements from other experiments.

One of the first unexpected result from the LHC era appeared in the two-particle correlation study. Using pair of particles from the same event as signal and from different events as background, ATLAS[18] and CMS[19] constructed a two-particle correlation function, and measured its value for different $\Delta\eta$ and $\Delta\phi$ angular separation of the two particles, as illustrated in Fig.3(Left). It showed the expected jet structure for $\Delta\eta = \Delta\phi = 0$, as well as the away structure for $\Delta\phi = \pi$. Though Monte Carlo generators do present the jet and away structure, the strength of the correlation is not well reproduced. Moreover, when looking at particles in a precise range of intermediate p_T

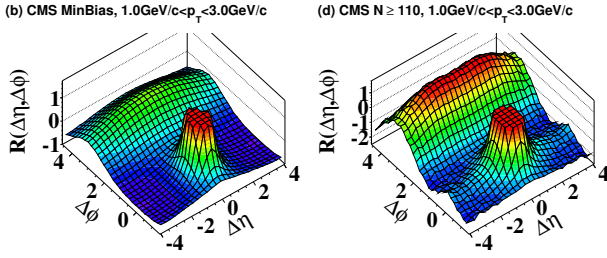


Fig. 3: Two-particle correlation in function of the $\Delta\eta$ and $\Delta\phi$ of the pair at intermediate p_T range $1 < p_T < 3$ GeV, for the whole minimum bias sample (Left) and for high multiplicity events only (Right).

and high multiplicity ($1 < p_T < 3$ GeV and $N_{ch} > 110$), a clear ridge-like structure emerges at $\Delta\phi = 0$ and $\Delta\eta > \pi/2$, as shown in Fig.3(Right) by CMS (ATLAS did not have enough statistics in this narrow phase-space), which is absolutely not reproduced by any Monte Carlo generators simulating pp collisions. Although this feature is well known in heavy ion collisions, it was the first time it was observed in pp collisions. Many explanations were since then proposed, but at the time none has rise above all else and make consensus.

3.2 Underlying Event results

The Underlying Event (UE) is usually defined, in presence of a hard probe in the event, as everything but this probe. Depending on the subdetector used, different hard probes can be considered to get the scale of the event: ATLAS used the highest p_T track[20] or calorimeter cluster[21], while CMS preferred looking at trackjets[22] or muon pairs in Drell-Yan events[23]. Each of those choices have different scales, and thus can not be directly compared: since trackjets are clusters of tracks, they reach higher p_T values than single tracks; calorimeter clusters also take into account neutral particles undetected in the tracker; Drell-Yan events have very clean signals and use the muon systems to get the event scale. Three topological regions of 120° are then defined with respect to the hard probe: the towards region ($0^\circ < |\Delta\phi| < 60^\circ$) where the hard part of the event is, the away region ($120^\circ < |\Delta\phi| < 180^\circ$) balancing the towards p_T , and the transverse region ($60^\circ < |\Delta\phi| < 120^\circ$) where the Underlying Event lies, $\Delta\phi$ being the difference in azimuthal angle ϕ between the hard probe and the track/cluster. For Drell-Yan events, both transverse and towards regions are sensitive to UE.

The Monte Carlo generators seem to underestimate the particle density, especially in the transverse region. When looking, in the transverse region, at the evolution with respect to the leading p_T probe of the mean multiplicity and mean p_T sum, the fast rise at low p_T scale is attributed to multiple partonic interaction (MPI), before reaching a plateau, as Fig.4 (Top) illustrates in case of a calorimeter cluster probe. Moreover, once again no generator tune describes properly neither the rise nor the plateau. For Drell-Yan events, shown in Fig.4 (Bottom), the increase with the p_T of the muon pair comes from ISR increase, while $\langle N_{ch} \rangle$ and $\langle \sum p_T \rangle$ densities being independent of the muon pair

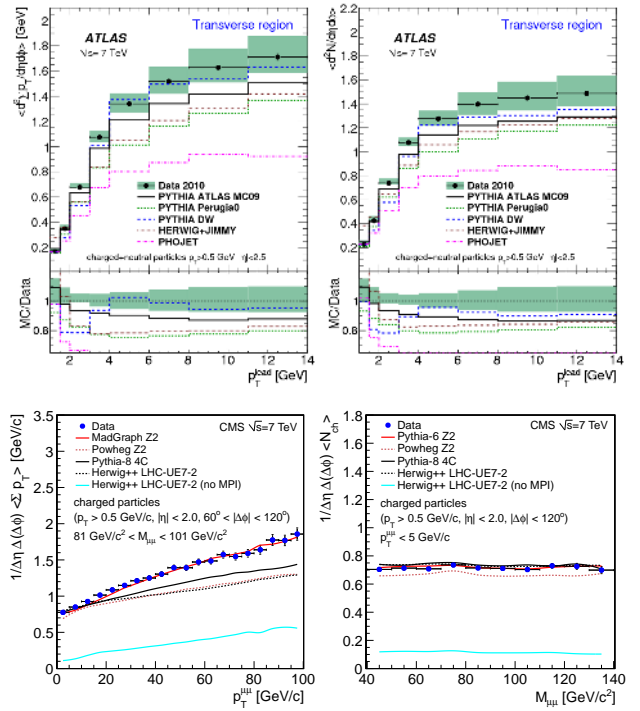


Fig. 4: (Top) $\langle \sum p_T \rangle$ and $\langle N_{ch} \rangle$ densities with respect to p_T of leading calorimeter cluster for the transverse region; (Bottom) $\langle \sum p_T \rangle$ w.r.t. p_T of muon pair and $\langle N_{ch} \rangle$ w.r.t. mass of muon pair, for Drell-Yan events.

mass is explained by the already saturated MPI in the selected event scale.

4 Conclusion

ATLAS and CMS have proven their general purposefulness with many publications of soft QCD physic results. With several event selections, minimum bias distributions of η , p_T , N_{ch} and $\langle p_T \rangle V S N_{ch}$ at $\sqrt{s} = 0.9, 2.36$, and 7 TeV were compared with other experiments when possible, as well as a multitude of Monte Carlo generator tunes, none of which are able to describe the softer p_T and huge rise of particle production with energy. This led to a community-wide effort to improve and tune the available Monte Carlo generators. Extrapolated inelastic cross-section were measured and compatible, though overestimated by Monte Carlo models. Diffraction was also studied, with minimum bias observables for either diffraction enriched or suppressed data samples, as well as the rapidity gap cross-section. Due to excellent tracker performances, strange particle production was examined, Monte Carlo discrepancies with data increasing with the particle mass. An unexpected ridge-like structure was found during the two-particle correlation analysis for mid- p_T and high multiplicity particles, and albeit attracting many attention from theory, its origin is still being discussed. Finally, underlying events have been studied with different hard probes, and despite Monte Carlo generators being tuned with those results, none are able to describe perfectly the data.

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