SOFT QCD AT THE LHC

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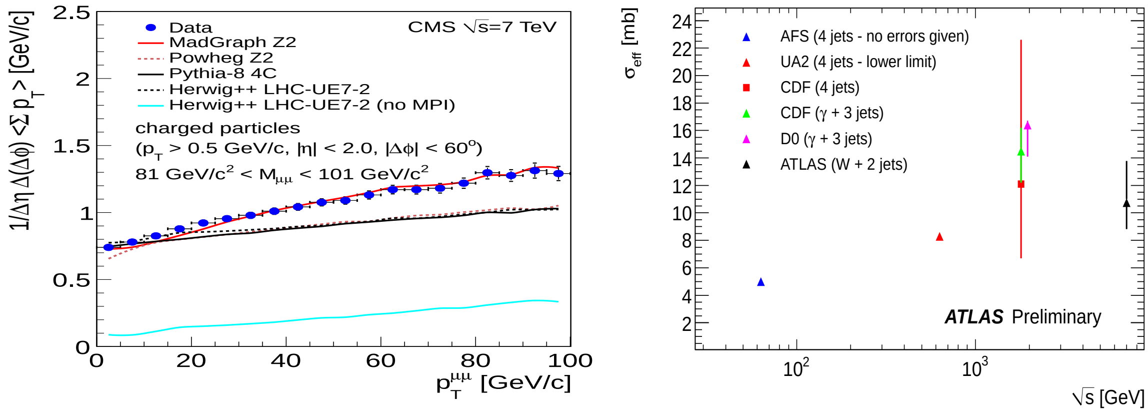
Recent ATLAS and CMS measurements related to non-perturbative QCD are presented. The multiple parton scattering model is tested using two different analysis methods and the data is compared to the predictions of general purpose Monte Carlo event generators. Studies of charged particle correlations are discussed in the context of the physics models commonly used to simulate particle production. Measurements of the inelastic cross section within the fiducial acceptance of the detectors are presented and the issues with extrapolating this cross section to the complete inelastic phase space are discussed. Finally, the latest measurements of soft- and hard- diffractive processes are shown.

1 Introduction

Several phenomenological models have been formulated to explain the dynamics of soft particle production in high-energy hadron-hadron interactions. These models are incorporated in general purpose Monte Carlo (MC) event generators and attempt to describe the features of QCD that cannot be calculated using perturbative techniques alone; features such as hadronisation and multiple parton-parton scattering. The first measurements at the LHC tested the phenomenological models by focussing on the multiplicity and transverse momentum of charged particles produced in inclusive proton-proton interactions[1,2]. A reasonable description of the data was obtained after the internal model parameters had been retuned to fit the data[3], although discrepancies remained in some regions of phase space suggesting that the modelling and/or tuning procedures were incomplete. Recent measurements performed at ATLAS[4] and CMS[5] examined increasingly complicated event topologies in order to push the phenomenological models to breaking point. A selection of those measurements are presented in these proceedings.

2 Multiple parton scattering and the underlying event

Proton-proton collisions are typically pictured as containing a short-distance hard partonic scatter, which produces high transverse momentum objects such as jets, accompanied by additional soft processes that produce extra particle activity in the event, which are collectively called the underlying event. One major source of underlying event activity is that of multiple parton interactions (MPI), which is the scattering between spectator partons in the protons. The CMS Collaboration has recently tested whether the event generator tunes, derived in the early leading-track[6] and leading-jet analyses[7], reliably predict the charged particle multiplicity in events containing a Z-boson[8]. CMS measured the particle activity in various azimuthal ($\Delta\phi$) regions with respect to the Z-boson direction, observing a good agreement between the tuned event generators and the data in distributions such as the summed transverse momentum of



(a) (b)

Figure 1: (a) Measurement of the summed charged particle transverse momentum in events containing a Z-boson candidate. Charged particles are used in the summation if they are nearby the Z-boson in azimuth ($\Delta\phi < 60^\circ$). (b) The measurement of σ_{eff} performed at various hadron colliders in a variety of different final state topologies.

charged particles produced within $\Delta\phi < 60^\circ$ of the Z-boson direction (Figure 1 (a)).

If the MPI model is correct, then the production of hard scale objects from the additional scatters must be possible. For example, the cross section for the production of $pp \to X + Y$ can be written as the sum of direct (dir) and double parton scattering (DPI) components, that is

$$\sigma_{X+Y}^{(\text{tot})} \quad = \quad \sigma_{X+Y}^{(\text{dir})} + \sigma_{X+Y}^{(\text{dpi})} \quad \approx \quad \sigma_{X+Y}^{(\text{dir})} + \frac{\sigma_X\,\sigma_Y}{\sigma_{\text{eff}}}. \tag{1}$$

The quantity σ_{eff} is introduced to parameterize the cross section of DPI in terms of the cross sections for the production of X and Y separately. The ATLAS Collaboration has recently measured σ_{eff} at the LHC using W + 2j events, by examining the fraction of these events in which the jets are balanced in transverse momentum[9]. The result was $\sigma_{\text{eff}}\,(7\,\text{TeV}) = 11 \pm 1\,(\text{stat})\,^{+3}_{-2}\,(\text{syst})$ mb. Figure 1 (b) shows the ATLAS result compared to measurements performed at previous colliders. The scaling of σ_{eff} with the centre-of-mass energy ($\sqrt{s}$) is compatible with (i) no scaling and (ii) a simple Regge-type scaling of the form $\sigma_{\text{eff}} \propto s^{0.12}$.

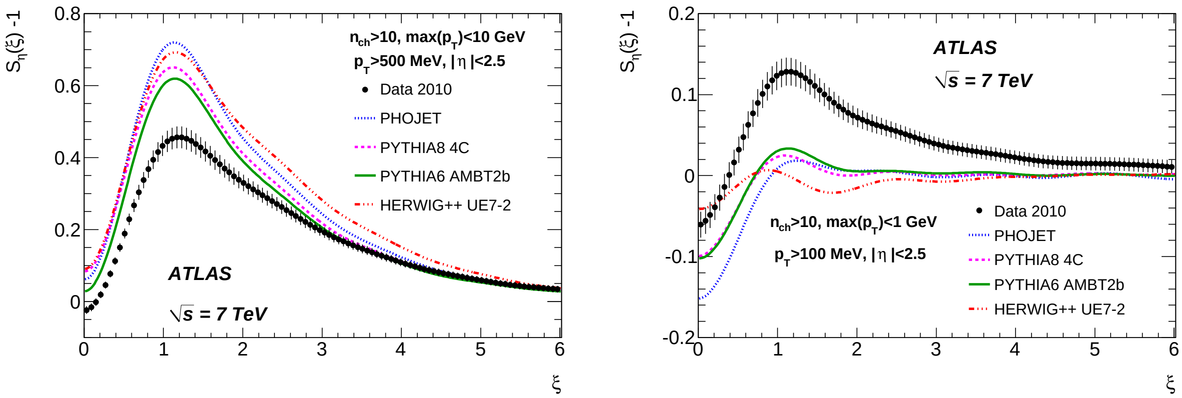
3 Charged particle correlations

ATLAS performed a spectral analysis of correlations between longitudinal and transverse components of the momentum of charged particles, driven by the search for phenomena related to the structure of the QCD field[10]. One particular observable of interest was the power spectrum,

$$S_\eta\,(\xi) = \frac{1}{n_{\text{event}}} \sum_{\text{event}} \frac{1}{n_{\text{ch}}} \left| \sum_{j}^{n_{\text{ch}}} \exp\left(i\left(\xi\eta_j - \phi_j\right)\right) \right|^2, \tag{2}$$

where the summation 'j' runs over a set of charged particles, η and ϕ are the pseudo-rapidity and azimuthal angle of those particles, and ξ is a parameter. Figure 2 shows the power spectrum obtained using charged particles with (a) $p_{\text{T}} > 0.5$ GeV and (b) $0.1 < p_{\text{T}} < 1$ GeV. The event generators predict too strong a correlation in case (a), but too weak a correlation in case (b). Varying model parameters to increase/decrease the underlying event or initial state radiation impacts upon both distributions in the same way. It may not be possible to achieve good agreement in both phase space regions simultaneously by tuning the existing models.

ATLAS and CMS also studied two particle angular correlations, assessing the probability that, for a given particle, there is another particle at a specified distance in pseudo-rapidity and



(a) (b)

Figure 2: Power spectrum obtained using charged particles with (a) $p_{\rm T} > 0.5$ GeV and (b) $0.1 \leq p_{\rm T} < 1$ GeV.

azimuth[11,12]. The CMS measurement at high charged particle multiplicity uncovered a ridge in the correlation function for particles separated by a long distance in pseudo-rapidity but nearby in azimuth. This ridge is not predicted by any of the general purpose event generators. ATLAS also studied correlations between the charged particle multiplicity measured in forward and backward pseudo-rapidity bins[13]. The latest MC tunes give a reasonable description of the data, although they do not completely describe the observed correlation strength as the interval between pseudo-rapidity bins is increased.

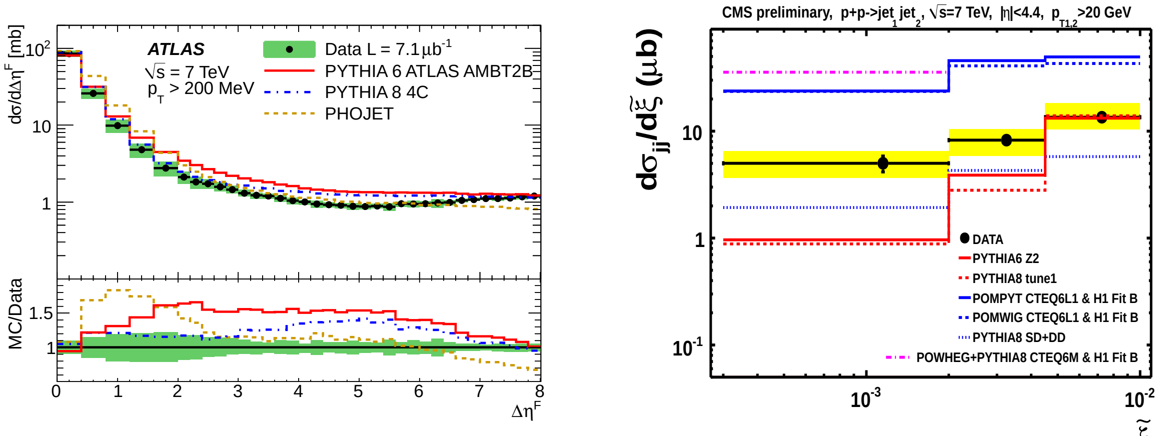
4 Diffractive processes

ATLAS measured the inelastic cross section differential in forward rapidity gap size[14]. The forward rapidity gap ($\Delta\eta_F$) was measured from the edge of the calorimeters at $|\eta| = 4.9$ and defined as containing no particle activity with $p_{\rm T} > 200$ MeV. Figure 3 (a) demonstrates that each of the event generators is incapable of describing the data across the full $\Delta\eta_F$ spectrum. The slope of the distribution at large gap sizes was used to extract a value of the pomeron intercept to be $\alpha_{\mathbb{P}}(0) = 1.058 \pm 0.003({\rm stat})\,^{+0.034}_{-0.039}({\rm syst})$. The measurement was repeated after changing the minimum transverse momentum cut used to define the rapidity gap, to probe different hadronisation models[15].

CMS has made the first measurements of hard diffraction at the LHC, most recently with the measurement of diffractive dijet production[16]. Figure 3 (b) shows the cross section for dijet production measured differentially in $\tilde{\xi}^{\pm} = \sum_i \left(E^i \pm p_z^i\right)/\sqrt{s}$ and the contribution from diffractive dijet production is observed at low $\tilde{\xi}^{\pm}$. CMS used this measurement to place constraints on the rapidity gap survival factor, $S^2 < 0.21 \pm 0.07$. This is on the upper edge of the theoretical expectations. CMS also provided the first indication of diffractive $W \rightarrow l\nu_l$ production at the LHC[17]. The diffractive component was observed as an excess of events with the lepton in the hemisphere opposite to a forward rapidity gap.

5 The inelastic cross section

Both experiments made detailed studies of visible and total (extrapolated) inelastic cross sections. ATLAS measured the visible inelastic cross section ($\xi > 5\times10^{-6}$) to be $\sigma^{\rm vis}_{\rm inel} = 60.3 \pm 0.05({\rm stat}) \pm 0.5({\rm syst}) \pm 2.1({\rm lumi})$ mb, by measuring the event rate for particle activity in the Minimum Bias Trigger Scintillators[18]. The variable $\xi = M^2/s$ is used by the experiments to quantify the phase space that is covered by the detector. CMS measured $\sigma^{\rm vis}_{\rm inel} = 60.2 \pm 0.2({\rm stat}) \pm$



(a) (b)

Figure 3: (a) Inelastic cross section as a function of forward rapidity gap size. (b) Measurement of the dijet cross section as a function of $\tilde{\xi}$; the contribution from diffractive dijet production is observed at low $\tilde{\xi}^{\pm}$.

$1.1(\text{syst}) \pm 2.4(\text{lumi})$ mb, for $\xi > 5\times10^{-6}$, by counting the event rate for activity in the forward calorimeters [19]. Both experiments used event generator models to extrapolate the measurement to the full inelastic cross section ($\xi > m_p^2/s$), finding $\sigma_{\text{inel}} = 69.4 \pm 2.4(\text{exp}) \pm 6.9(\text{extr})$ mb and $\sigma_{\text{inel}} = 64.5 \pm 1.1(\text{syst}) \pm 2.6(\text{lumi}) \pm 1.5(\text{extr})$ mb for ATLAS and CMS, respectively.

The extrapolation from visible to total cross section carries a large theoretical uncertainty due to the poorly known cross section for low mass diffraction. The TOTEM result[20] of $\sigma_{\text{inel}} = 73.5 \pm 0.6(\text{stat})\,^{+1.8}_{-1.3}(\text{syst})$ (for $\xi > m_p^2/s$), inferred from the measured elastic and total cross sections, indicates that the majority of the event generators and theory calculations underestimate low mass diffraction and cannot be reliably used in the extrapolations[14].

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