

PRECISION TESTS OF THE STANDARD MODEL USING THE ATLAS DETECTOR AT THE LHC*

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This article discusses the recent tests of the Standard Model using pp -collision events at $\sqrt{s} = 7$ TeV collected with the ATLAS detector at the Large Hadron Collider (LHC) during 2010 data taking period. The paper focuses on measurements of hard and soft sectors of quantum chromodynamics (QCD), a theory describing interactions of quarks and gluons.

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1. Introduction

The Standard Model (SM) is often regarded as an unshakable foundation of our current knowledge on elementary particles. Having been tested in many experiments in the past, the only conclusion drawn was that its predictions agree with the available data, at least in the areas where reliable calculations can be made and where particle-collision data are available. A typical precision with which the SM can be verified is within 5–10% for QCD jets. For the electroweak sector, such tests have reached a few percent precision. Nevertheless, the SM has many unanswered questions as well as many free parameters used to derive predictions. Therefore, it is possible that the SM is a mere stepping stone to something else.

With the arrival of new pp data from the Large Hadron Collider (LHC), the ATLAS experiment [1] is in the position of testing the SM at the new energy frontier. The ATLAS detector has been designed to study a wide range of physics processes, covering almost the entire solid angle around the collision point with layers of tracking detectors, calorimeters and muon chambers.

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The ATLAS experiment was built as a discovery machine which allows to search for Higgs particles and to look at TeV-scale physics. But before any discovery can be claimed, a detailed understanding of the detectors should be reached and benchmark SM processes should be measured. At this early stage of the LHC operation, ATLAS is already capable of observing (directly or indirectly) all sixteen particles of the SM, *i.e.* the twelve matter particles (quarks and leptons) and four force-carrier particles (γ , g , $W^\pm$ and Z^0). However, the Higgs particle, which is usually considered as the last ingredient of the SM responsible for particle masses¹ in the SM scheme, is still missing.

While to perform high-precision measurements of the masses for the key SM states (vector bosons and top quarks) is beyond the current LHC reach due to low integrated luminosity ($\sim 40 \text{ pb}^{-1}$), the available data are already sufficient to study the production cross-sections of these states in great detail. This is crucial for our understanding of the SM and for future searches. The measured production cross-sections can be compared to perturbative QCD calculations at leading order (LO), next-to-leading order (NLO) and next-to-next-to-leading order (NNLO). Monte Carlo (MC) generators based on hard-QCD calculations and phenomenological approaches for soft QCD are also available for such comparisons.

2. Hard QCD

High- p_T jets are a sensitive probe of many aspects of perturbative QCD. In particular, jet measurements can be confronted with theoretical calculations based on LO and NLO matrix elements. They can also be used to constrain parton-density functions and to study the strong coupling constant α_s . Jet studies can also help us to perform searches beyond the SM model, assuming that soft-QCD effects contributing to jet production are well understood.

ATLAS uses the anti- k_T algorithm [3] for jet reconstruction. The fine granularity of the ATLAS calorimeter with transverse and longitudinal samplings allows the definition of three-dimensional clusters of energy (“topological” clusters) which are closely associated with individual particles [4,5]. These objects are used as input for the anti- k_T jets. Figure 1 shows the inclusive jet cross-sections measured by the ATLAS experiment over a wide range of jet transverse momenta [6]. Good agreement between the data and the theoretical NLO QCD calculations is observed over many orders of magnitude in the jet cross-section values. The dominant experimental un-

¹ It should be noted that the Higgs mechanism is only responsible for less than 0.1% of masses of the visible universe through the electroweak-symmetry breaking mechanism [2].

certainty is the jet energy scale (typically 5–10% depending on p_T) and the uncertainty on luminosity determination (which is about 11%). It should be pointed out that a typical contribution from soft hadronization effects is at the level of 5%. This contribution was subtracted from the shown cross-sections using Monte Carlo generators. The precision of this measurement, together with statistical uncertainties at large transverse momenta, sets the limit on the value of cross-sections of any new states which can potentially contribute to the tail of the p_T distributions.

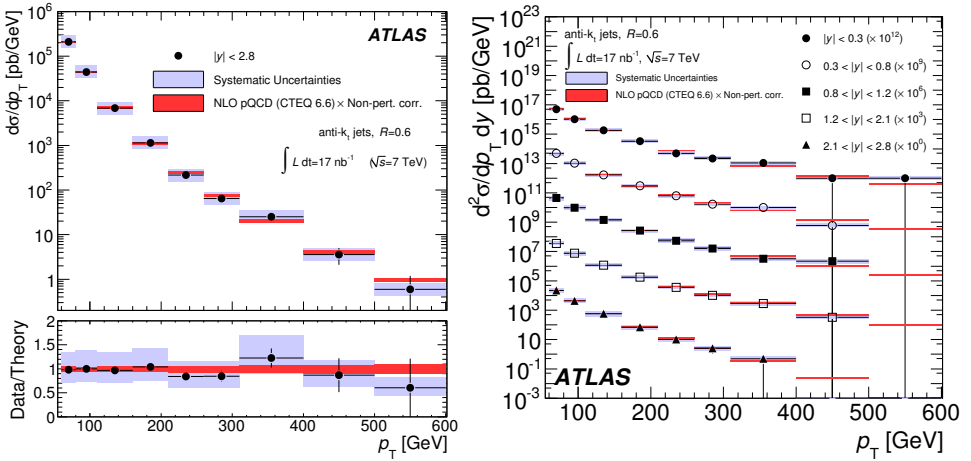


Fig. 1. Inclusive jet differential cross-section as a function of jet p_T integrated over the full rapidity region $|y| < 2.8$ for jets reconstructed using the anti- k_T algorithm with $R = 0.6$ (left). The double-differential cross-section as a function of jet p_T in different regions of $|y|$ is shown on the right. The data are compared to NLO QCD calculations with soft QCD corrections included.

Future discoveries in the electroweak sector also require a good understanding of SM processes. For example, events with jets accompanying vector bosons are a significant background for Higgs searches. Another example is the top-quark production for which the knowledge of the jets + W channel is essential (here I put “jets” in front of W , emphasizing that I came to this topic from the jet sector). Figure 2 shows the cross-sections [7] for jets + W events compared to MC generators and NLO calculations [8]. Good agreement is observed up to event configurations with more than four jets associated with W .

Hard interactions are always associated with extra QCD radiation which is responsible for jet structure. Jet shapes and jet substructure are difficult topics for perturbative QCD since such observables are largely determined by higher-order QCD corrections. But such measurements are essential in refin-

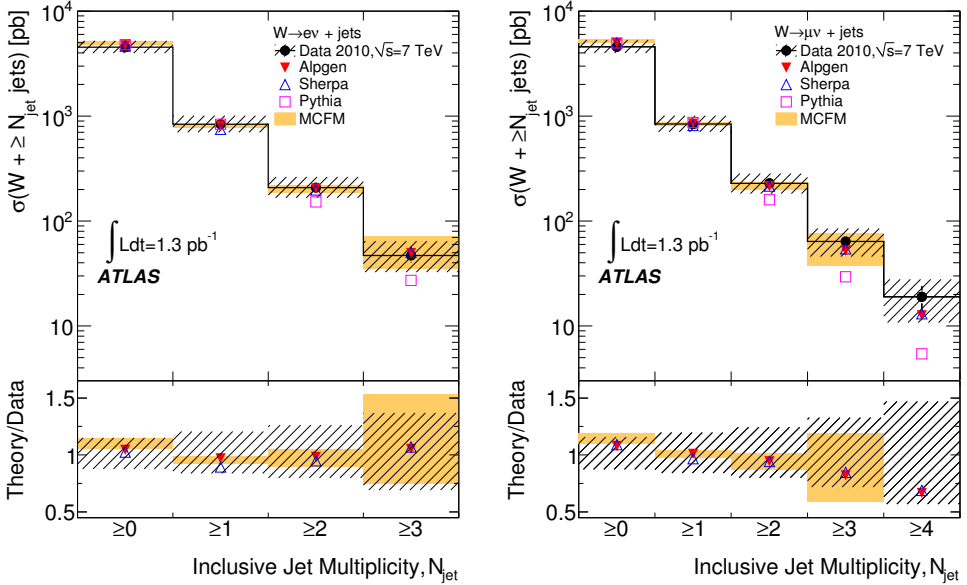


Fig. 2. jets + W cross-sections [7] as a function of corrected jet multiplicity for the electron (left) and muon (right) decay channels of the W bosons. Also shown are predictions from several Monte Carlo generators and the MCFM program [8] which gives the predictions at NLO QCD. The theoretical uncertainties are shown only for MCFM.

ing the current models of soft QCD re-summation and soft-QCD in general. Jets can originate either from quarks or gluons and jet shapes can reflect their origin. Finally, jet-shape characteristics can be useful in reducing large rates of conventional QCD jets when searching for new particles with partial or complete overlap of decay products that cannot be reconstructed as separate jets using the traditional jet algorithms. Currently, the models used to describe jet shapes incorporate the leading-order hard-scattering matrix elements complemented with the parton shower formalism for QCD radiative corrections at the leading-log approximation.

Figure 3 shows the differential jet shape $\rho(r)$ as a function of the distance r (defined in η and ϕ) to the jet axis. $\rho(r)$ is defined as the average fraction of the jet p_T that lies inside an annulus of inner radius $r - \Delta r/2$ and outer radius $r + \Delta r/2$ around the jet axis. The value r is defined in the range $\Delta r/2 < r < R - \Delta r/2$, where $R = 0.6$ is a distance parameter of the anti- k_T jet algorithm and $\Delta r = 0.1$. Figure 3 shows two extreme ranges of the jet transverse momenta: for low (left) and high (right) jet p_T . It can be seen that jets become narrower as the jet transverse momentum increases. The data are reasonably well described by the MC generators, indicating

that all major physics effects are included in the MC generators. Even with an integrated luminosity of only 3 pb^{-1} , the measurements indicate the potential of jet shape measurements to constrain the current models for soft-gluon radiation and non-perturbative fragmentation processes.

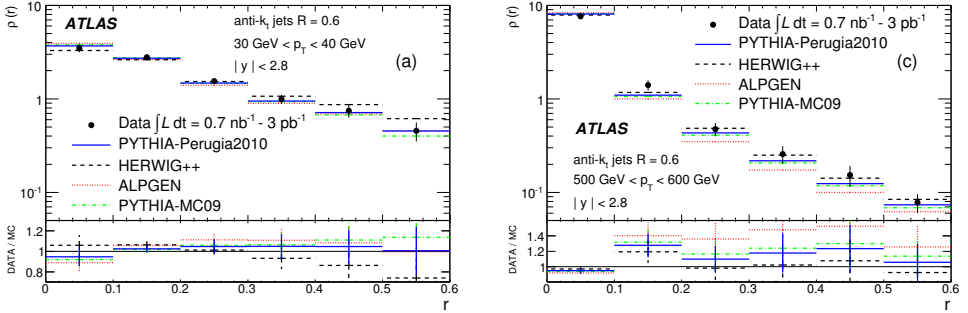


Fig. 3. Differential jet shapes, $\rho(r)$, in inclusive jet production for jets with $30 < p_T < 40 \text{ GeV}$ (left) and at the high jet transverse momenta $500 < p_T < 600 \text{ GeV}$. See [9] for details. The total integrated luminosity is 0.7 nb^{-1} for the lowest p_T region and 3 pb^{-1} for the highest- p_T region.

Another way to enter the regions where high-order QCD effects are large is to reconstruct multijet events beyond the simplest dijet topology from $2 \rightarrow 2$ partonic processes. Experimentally, measurements of low- p_T jets are challenging due to large instrumental uncertainties and because of soft fragmentation processes which are modeled using Monte Carlo simulations. However, one can learn about the multijet cross-sections by reconstructing the angular distance between two leading jets. For a perfect $2 \rightarrow 2$ parton configuration, the value of the angle should be π . Any softer jet leads to a smaller value of this angle. Figure 4, left sketches the azimuthal angle $\Delta\phi$ in jet events in pp collisions, while the actual analysis performed by ATLAS [10] is shown in Fig. 4, right. Overlaid on the data points are the NLO pQCD predictions. The results are well described by the fixed-order NLO QCD. Some discrepancy is observed near $\Delta\phi \simeq \pi/2$, where soft processes dominate and contributions from logarithmic terms are enhanced.

Studies of direct photons provide another ideal arena for testing perturbative QCD predictions and for constraining the parton-density functions. Direct photons are important for understanding perturbative QCD since they are not affected by not-well understood soft hadronization. As is the case of jets + W , prompt-photon processes are important background contributing to other physics processes of the SM and beyond. Recent results on inclusive direct-photon production [11] demonstrate that direct-photon cross-sections are well understood within the precision given by the renormalization and factorization scale uncertainties of NLO QCD calculations as

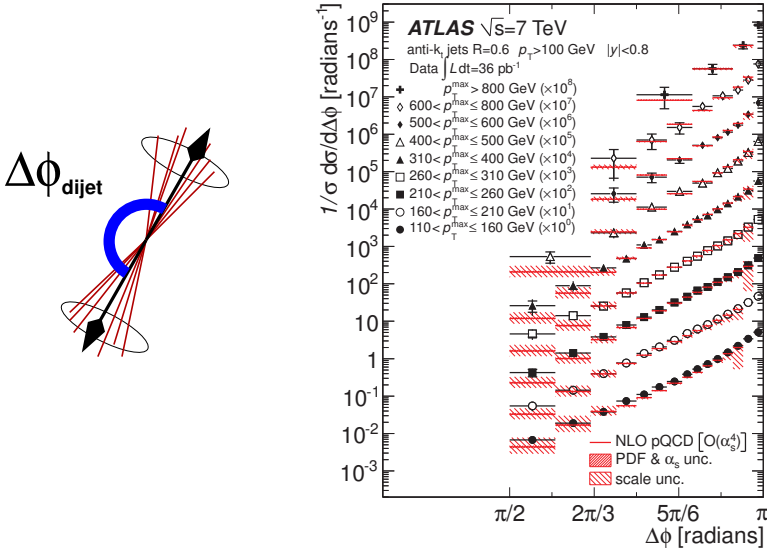


Fig. 4. Left: A sketch of the azimuthal angle $\Delta\phi$ in jet events. Right: The normalized differential cross-section binned in several regions based on the p_T of the leading jet as a function of $\Delta\phi$ compared to NLO QCD calculations (see Ref. [10]). The theory uncertainties are indicated by the hatched regions.

shown in Fig. 5. The scales were varied independently between 0.5 and 2.0 times the nominal scale, leading to changes in the predicted cross-section by 20% at low transverse momentum. The NLO QCD calculation describes the data down to the lowest transverse momenta. The results are somewhat sur-

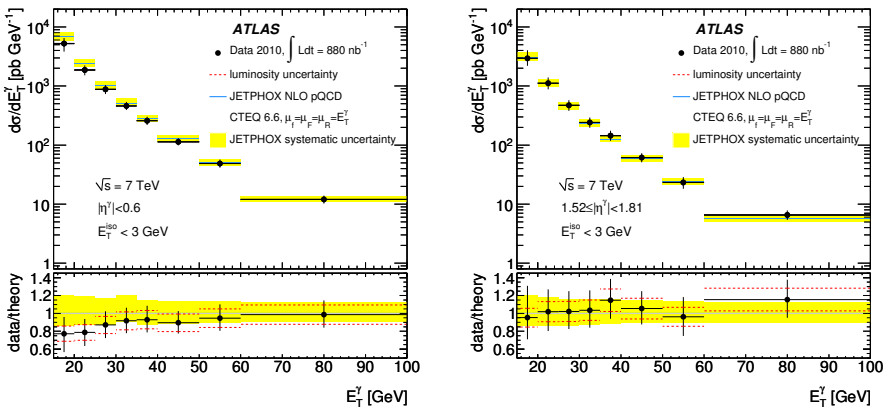


Fig. 5. Inclusive prompt-photon production cross-sections, for photons with transverse energies above 15 GeV and in the pseudorapidity range $|\eta| < 0.6$ (left) and $0.6 < |\eta| < 1.37$ (right).

prising given that, in the past, the Tevatron experiments claimed an excess of the data over the NLO predictions [12] for direct photons in the region of $p_T(\gamma) \sim 20$ GeV.

The observation of top quarks at the LHC is one of the milestones for the LHC physics programme. The measurement of the top-quark cross-section requires good understanding of background processes (such as jet+ W discussed above) and thus can be considered as the culmination of many electroweak measurements at the LHC. Figure 6 shows the top-quark cross-sections at hadron colliders as measured at Tevatron and at the LHC. The ATLAS [13] and CMS [14] measurements of the $t\bar{t}$ cross-section are consistent with the NNLO QCD predictions.

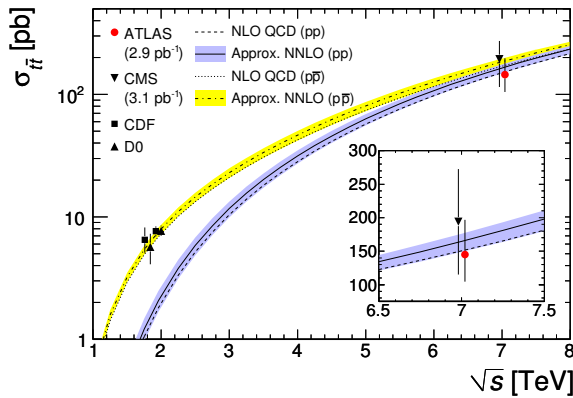


Fig. 6. Top-quark cross-sections at hadron colliders as measured at Tevatron and at the LHC.

3. Soft QCD

The understanding of inclusive inelastic particle production at a new energy frontier was a primary task at ATLAS as soon as first pp data appeared. It is an important milestone to understand soft QCD which, by itself, is an important topic. In addition, inelastic pp collisions represent a background for many better understood processes with large transverse momenta, thus good understanding of such processes is vital for high-precision QCD measurements and for future searches. There is no need for large luminosity for such studies, since the cross-section for such processes is large and high-precision measurements can be performed using less than one pb^{-1} of LHC data. Given that no solid theory exists to describe soft QCD processes, the current emphasis for such studies is comparisons with MC generators tuned using data from previous experiments and to provide data for constraining parameters of such models when they are used to estimate soft-QCD background.

In order to select inelastic pp collisions, the events are required to pass some minimal criteria. In ATLAS, this is achieved by triggering events with at least one hit on either side of the tracking detector using plastic scintillators. Then, tracks were required to originate from the primary event vertex. Finally, the selection requirements $p_T > 500$ MeV and $|\eta| < 2.5$ were applied. The measurements at such low transverse momenta are rather challenging due to low tracking efficiency in this region (which is of the order of 40%). The distributions obtained using tracks were corrected for detector effects using a MC simulation.

Figure 7 shows the recent ATLAS results [15] on multiplicity distributions for the $\sqrt{s} = 7$ TeV data (left plot), together with the average transverse momenta of charged particles (right plot), compared to a number of Monte Carlo generators. The distribution shown in Fig. 7, left was reconstructed after removing low-multiplicity events that are affected by diffraction. Thus, this comparison with the Monte Carlo generators mainly sheds light on soft-QCD processes other than diffraction. All MC generators fail, especially for the tails of the distributions. For the average transverse momentum distribution as a function of the track multiplicity, all pre-LHC MC

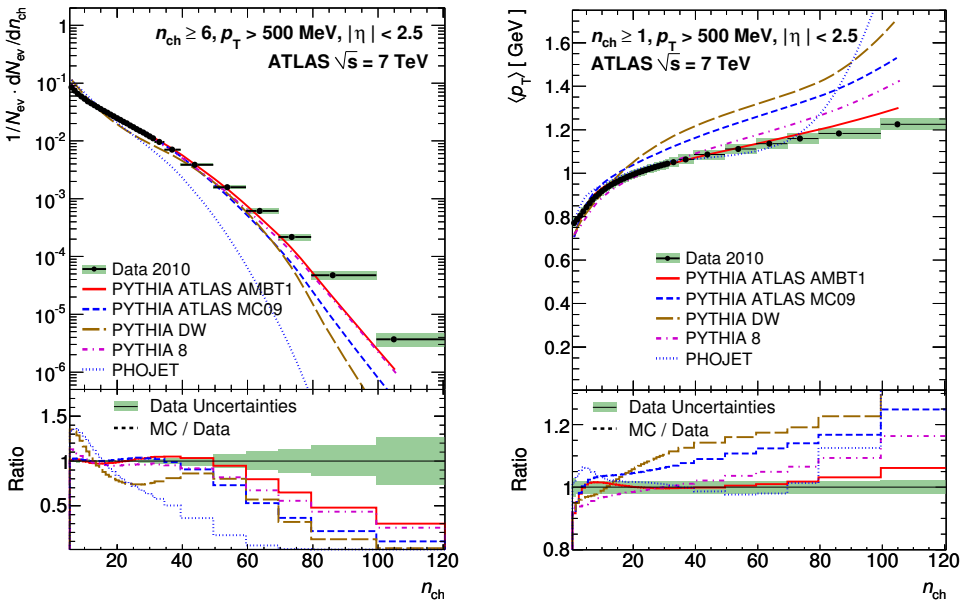


Fig. 7. Charged-particle multiplicity distributions [15] for events with more than 6 particles per event to reduce the contribution of diffractive events (left) and the average transverse momentum as a function of the number of charged particles in the event (right). The data are compared to several MC generators.

predict too large average transverse momenta. The PYTHIA generator [16] with the AMBT1 tune, which was obtained by ATLAS using previously published results [17] on charged-track multiplicity, is closest to the data.

Soft QCD processes which collectively contribute to particle activity that is not associated to hard scattering processes are termed the underlying event (UE). The UE is an important and unavoidable background to many measurements and searches. In general, these soft processes include many processes, such as multiple-parton interactions, color reconnection or soft component of initial- and final-state radiation. In addition, the UE has contributions from beam–beam remnants. For high-precision measurements, the activity of particles in UE must be modeled using phenomenological models included into MC generators [18]. Such models must be tuned to experimental data to constrain parameters of such models. In the past, such measurements have only been performed using tracks [19, 20, 21].

One possible way to isolate the UE from the hard-subprocess effects is to look at the transverse region of events. The transverse region of a pp event is defined as $60^\circ < |\Delta\phi| < 120^\circ$, where $\Delta\phi = \phi - \phi_{\text{lead}}$ is the azimuthal angular distance between a leading in p_T particle and other particles. The transverse region is most sensitive to the UE, since it is perpendicular to the axis of hardest scattering approximated by the direction of the leading particle.

The density $d\langle N \rangle / d\Delta\phi$ of stable particles reconstructed from calorimeter clusters as a function of $\Delta\phi$ is shown in Fig. 8. This density has a peak at $\Delta\phi \simeq 0$ which reflects the particle activity due to hard interactions. The heights of the peaks increase with the increase of the transverse momenta

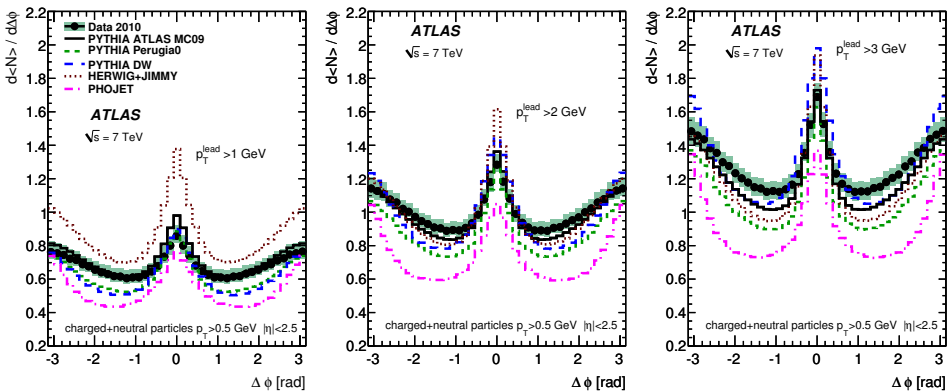


Fig. 8. The average number of stable particles as a function of the azimuthal-angle difference between the leading particle and other particles in an event, Ref. [22]. The leading particle at $\Delta\phi = 0$ is excluded from this distribution. The total uncertainty, computed from the statistical and systematic uncertainties in quadrature, is shown as a shaded band.

of the leading particle which approximates the direction and the energy of the hard interaction. The enhancements at $\Delta\phi = -\pi$ and π are due to the hadronic activity which balances the leading jet. The Monte Carlo generators fail to describe this distribution.

Figure 9, left shows the charged-particle density, *i.e.* the mean number of stable particles per unit area in η - ϕ . This density is measured as a function of the transverse momenta of the leading in p_T particle. All generators quantitatively predict the trends of the data, but fail in detailed description. In particular, the MC generators indicate a smaller particle density, suggesting that they have to be improved for the description of the UE. Similarly, Fig. 9, right shows the same distribution for neutral and charged particles using the topological clusters *e.g.* the same objects which are used for the jet reconstruction. Being systematically independent, the conclusion about the lack of activity of the hadronic final state in the transverse region agrees with that for charged particles.

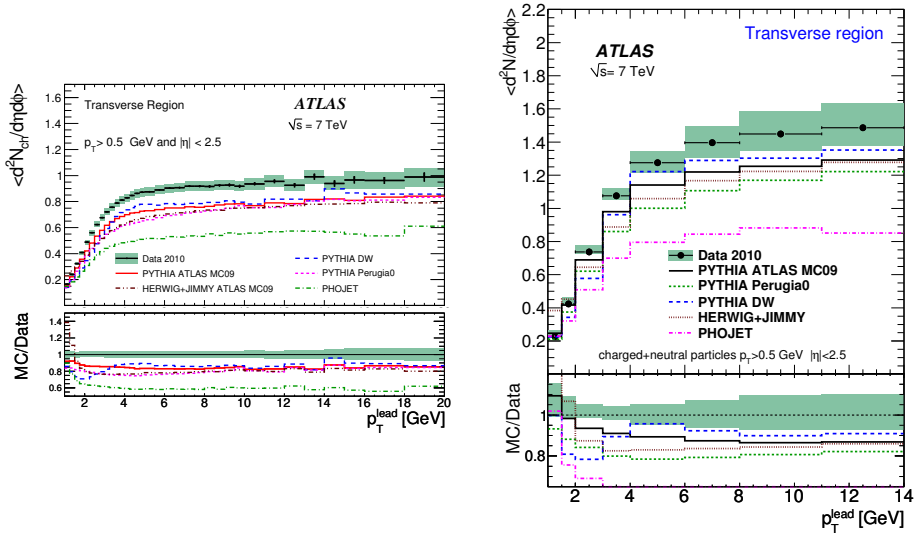


Fig. 9. Density of charged particles (left) and all-stable particles (right) measured in the transverse region as a function of the transverse momenta of the leading in p_T particle (Ref. [23]).

4. Summary

Initial studies of the ATLAS experiment on hard-QCD confirm the validity of the SM at the new center-of-mass energies. First of all, this includes benchmark measurements of high- p_T physics, such as jets, direct photons and vector bosons. For all such measurements, NLO QCD predictions describe the data within the renormalization and factorization uncertainties.

For soft QCD, the currently available Monte Carlo models reproduce the trends of particle distributions, but fail in detailed description. The current state-of-the-art approach is to tune Monte Carlo models to data, which will enable high-precision measurements for high- p_T physics where reliable perturbative QCD calculations are available. The measurements of particle multiplicities provided by the ATLAS experiment can be used as inputs to constrain parameters of Monte Carlo generators. However, it should be emphasized that such an approach, being well justified for high- p_T measurements, does not provide a solid ground for soft-QCD theory itself, as well as for searches for new physics in soft-QCD events. Therefore, the presented measurements should also serve as inputs and encouragement for solving long-distance QCD from first principles.

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