Soft QCD Results from the CMS Experiment

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Recent CMS soft QCD results in proton-proton collisions at three LHC center-of-mass energies are highlighted. The properties of minimum bias events such as charged particle transverse momentum spectra, event-by-event multiplicity distributions, the production of the strange particles are measured. Particle correlations, such as long- and short-range angular correlation as well as Bose-Einstein correlation are studied. Characteristics of the underlying event and comparisons to MC tunes have been made.

1. Introduction

In a high energy proton-proton collision environment such as the Large Hadron Collider (LHC), the majority of the collisions are quite soft, without hard parton scatterings. In an event that does have parton scatterings with high-$Q^2$ transfer, the outgoing partons have to go through the parton showering and hadronization process. In addition, there will also be the accompanying Underlying Events (UE), which are mainly from Multiple Parton Interactions (MPI) and Beam-Beam Remnants.

All those QCD processes are soft, which means no perturbative predictions are available. The experiments usually have to rely on the Monte Carlo (MC) descriptions to model them phenomenologically. The models prior to LHC data were tuned on previous measurements. When extrapolated to LHC energy, different models diverge at the predictions.

Early LHC data collected by the Compact Muon Solenoid (CMS) experiment [1] thus provide a unique chance to deepen our knowledge on the soft QCD through the well designed measurements. They are crucial for precision measurements of the standard model processes and for new physics searches.

In addition, these measurements on the pp collisions will provide necessary references for physics studies with heavy ion collisions at CMS.

2. Properties of the Minimum Bias Events

In CMS, the minimum bias (MB) events are mainly triggered by the designed triggers through coincidence of signals from monitoring components of Beam Pickup Timing for experiments (BPTX) and Beam Scintillator Counters (BSC). Further selections from information recorded in other detectors are applied offline to select the events. In order to extend the transverse momentum reach, some single jet triggers based on signals from calorimeters are also used in the analysis.

The transverse momentum spectra of charged particles in MB events as measured in CMS [2] are shown in the Fig. 2. The left plot shows the yield with respect to the jet transverse momenta from different data sets with different triggers, which are fully efficient above the trigger thresholds as shown in the bottom panel. The middle plot compares the phase-space invariant event yield from the data to various MC models. None of them can describe the spectra perfectly, but Pythia8 is more compatible than Pythia6 models. The right plot confirms the scaling behavior with the variable $x_T = 2p_T/\sqrt{s}$ from measurements performed by different experiments at different energies.

Charged particle multiplicities in MB events as measured by CMS [3] at three LHC energies (0.9 TeV, 2.36 TeV and 7 TeV) are shown in Fig. 3 with different shifts in the scales for visibility. A large tail in multiplicities is observed in 7 TeV, which can reach nearly 200 tracks. Most MC models can not describe the multiplicities well in all energies for these unprecedented measurements, especially in the large multiplicity end. Further tunings are thus required, but Pythia8 shows better agreements with data.

Strange particle productions are also studies from MB events, at both at 0.9 and 7 TeV, and compared [4]. In the MB data sets, strange meson $K_S^0$ and hyperons $\Lambda, \Xi^-$ can be reconstructed from their decay products well with very good mass resolutions and low background contaminations. The masses and widths are all consistent with PDG values. The differential event yields are studied with respect to both strange particle transverse momentum and pseudorapidity (denoted as $\eta$). For the $p_T$ spectra shown in Fig. 4 the empirical fits can describe the data well at both energies. With increase of the LHC energy, the strange particle $p_T$ spectra all become harder. At 7 TeV, all the $p_T$ spectra are flatter at the middle where exponential falling dominates. For
K_{S}^{0} spectrum (left), it is also flatter at the higher end where the negative power law dominates. This is not as obvious as in the case of \Lambda (middle) and \Xi^{-} (right).

The \eta distributions of strange particles are compared to different MC models and tunes for both LHC energies, as shown in Fig. 4. From 0.9 TeV to 7 TeV, the strange particle yields are doubled, with respect to total Non Single Diffractive (NSD) events. All MC models show big amount of underestimation and need further tuning to be used for future studies of possible strange particle suppression.
3. Measurements of Particle Correlations

3.1. Two-particle correlation in \( \Delta \eta \) and \( \Delta \phi \)

Two-particle correlation in \( \Delta \eta \) and \( \Delta \phi \) reflects the underlying production mechanism. While the CMS measurements of this correlation in the inclusive MinBias events at 0.9 and 7 TeV [5] have shown all known features as predicted by MC models, the exclusive measurements with the events selected from the specially designed high multiplicity triggers have shown some unexpected features as shown in Fig. 5.

The near side, long range, angular correlation is established at high multiplicities. It is especially pronounced for the intermediate transverse momenta range \( 1.0 \, \text{GeV}/c < p_T < 3.0 \, \text{GeV}/c \). This feature could not be reproduced from MC simulations. Together with some heavy ion observations, it may indicate the formation of new state of matter in \( pp \) collisions at this energy, so it provides a new test ground for high density QCD physics.

3.2. Bose-Einstein Correlation (BEC) measurements

The production probability of the identical boson pairs with similar momenta could be enhanced due to the Bose-Einstein Correlation (BEC). The measurements of BEC can provide important information for the size, shape, space-time development of the emitting source.

CMS makes BEC measurements at 0.9 and 7 TeV and studies the dependences of this enhancement on kinematic and topological features of the events [6]. The ratio of the enhancement is quantified with respect to reference samples with non interfering boson pairs. Its dependence on the Lorentz-invariant variable \( Q = \)
\[ \sqrt{-(p_1 - p_2)^2} \] is usually parameterized with several physical parameters such as the correlation length, long distance correlations, effective size of the emission region, etc.

Figure 6: Effective BEC emission size $r$ as a function of the charged-particle multiplicity in the event.

Fig. [6] clearly establishes the effective emission size $r$ as a function of the charged-particle multiplicity in the event. It confirms for the first time the growth of BEC effective emission region with multiplicity which was ambiguously inferred from previous measurements. This dependence can also account for the growth with $\sqrt{s}$ very well.

4. Underlying event (UE) measurements and MC Tunes

The underlying event (UE) includes hadronic activity that is additional to those from hard scattering processes. It arises mainly from multiple parton scattering (MPI) and beam-beam remnants etc. It is most sensitive in the transverse region, $60^\circ < |\Delta \phi| < 120^\circ$, as a function of the $p_T$ of the leading track-jet. CMS has performed the fully corrected measurements of charged particles from UE of 0.9 TeV and 7 TeV [7] [8].

Fig. [7] shows the measurements of charged particles with $p_T > 0.5$ GeV/c and $|\eta| < 2$ in the transverse region. The left plot shows the average multiplicity per unit pseudorapidity and per radian; the center plot shows the average scalar $\Sigma p_T$ per unit pseudorapidity and per radian.
The center-of-mass energy dependence of the hadronic activity in the transverse region is also studied. The right plot of Fig. 7 shows the average scalar $\Sigma p_T$, per unit pseudorapidity and per radian, as a function of the leading track-jet $p_T$, for data at 0.9 TeV and 7 TeV; Predictions of three Pythia tunes are compared to the data.

Figure 7: Fully corrected measurements of charged particles in the transverse region.

Ratios of three MC predictions to the measurements in the transverse region are studied and shown in Fig. 8. The left plot shows multiplicity distributions; the center one shows scalar $\Sigma p_T$ distributions; the right shows the particle $p_T$ spectra. The leading track-jet is required to have $|\eta| < 2$ and $p_T > 3$ GeV/c. The inner band corresponds to the systematic uncertainties and the outer band corresponds to the total experimental uncertainties. Here, statistical and systematic uncertainties are added in quadrature.

Figure 8: Ratio of MC predictions to the corrected measurements of charged particles in the transverse region.

Pythia Z1 tune turns out to describe most of these UE distributions and the $\sqrt{s}$ dependences quite well. Tune Z2 and Pythia8 default tune 4C with new MPI model built in also do rather decent jobs. However, from the MC/data comparisons above, there are still cases and regions that none of them describe well enough. These CMS measurements could thus provide important input for future tunes.

5. Summary

Measuring and understanding soft QCD processes at LHC are important for precision Standard Model measurements and new physics searches. CMS experiment has performed many studies in this area in pp collisions at $\sqrt{s} = 0.9, 2.36$ and 7 TeV at LHC.

Properties of hadron production are measured, including charged particle transverse momentum spectra, event-by-event multiplicity distributions and spectra of identified strange hadrons, reconstructed based on their decay topology. Two-particle angular correlation over a broad range of pseudorapidity and azimuthal angle in pp collisions was measured and a pronounced structure was observed in the two-dimensional correlation.
function for particle pairs with intermediate transverse momentum of 1-3 GeV/c in high multiplicity events. Bose-Einstein correlation between identical particles was measured with respect to reference samples without correlation. Furthermore, measurements of the underlying activities in scattering processes with $p_T$ scale in the several GeV region were also shown and compared to several QCD Monte Carlo models and tunes.

All these measurements have contributed new information of strong interactions in the low transverse momenta domain, serving as inputs to future MC modelings.

References

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