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Minimum bias and underlying event studies at CMS

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Abstract

The Underlying Event (UE) at CMS is studied by examining charged particle and momentum densities in the transverse region in charged particle jet production. The predictions of various QCD models with different multiple parton interaction schemes correctly reproduce Tevatron data, however they fail to agree with each other when extrapolated to the LHC energy. The possibility of discriminating among these models is presented. Exploring QCD dynamics in proton-proton collisions at center-of-mass energy of 14 TeV, and the importance of improving and tuning the QCD Monte Carlo models at start-up are also analyzed.

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MINIMUM BIAS AND UNDERLYING EVENT STUDIES AT CMS

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The underlying event (UE) at CMS is studied by examining charged particle and momentum densities in the transverse region in charged particle jet production. The predictions of various QCD models with different multiple parton interaction schemes correctly reproduce Tevatron data, however they fail to agree with each other when extrapolated to the LHC energy. The possibility of discriminating among these models is presented. Exploring QCD dynamics in proton-proton collisions at center-of-mass energy of 14 TeV, and the importance of improving and tuning the QCD Monte Carlo models at start-up are also analyzed.

1 Introduction

A minimum bias (MB) data sample collected by a collider experiment like CMS at the LHC should in principle contain all possible proton-proton collisions in their natural composition, implying that all processes should be collected with the same overall efficiency. In practical trigger schemes this is only true for inelastic and non-single diffractive events which roughly contribute to two thirds of the total proton-proton cross section. Such a sample of events is naturally dominated by soft QCD processes where the majority of final state particles have low transverse momenta, p_T. At nominal LHC luminosities the in-time pile-up due to interactions of several protons in the same bunch crossing will consist on average of 19 minimum bias events. It is therefore of utmost importance to record, study and model single minimum bias events during low and high luminosity phases of the LHC, and at various center of mass energies if possible.

The so-called underlying event (UE) is the collection of final state particles with low transverse momenta that are produced in combination with the products of a high transverse momentum scatter between two partons. The definition of the soft component is vague in this case, but is usually attributed to the fragmentation of the beam remnants, semi-hard radiation, re-arrangement of the color fields and the occurrence of multiple parton-parton interactions. For all these reasons the underlying event is not simply a superposition of a minimum bias event on top of the hardest scatter in the event. Models that try to describe the underlying phenomenology should be capable of describing simultaneously the minimum bias data and the underlying event with a comparable accuracy.

Many recent models and several of their tuned parameter sets agree very well with each other and with collider data at center of mass energies up to 2 TeV, but diverge drastically when they are extrapolated to the nominal LHC energy of 14 TeV. It is therefore an important challenge for all LHC experiments to validate or re-tune existing models using the first collision data or devise alternatives if this proves necessary.

In what follows I will provide some background information on the modeling of multiple parton interactions, which proved essential to successfully describe MB and UE data,

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followed by a brief description of the possible MB trigger strategies of CMS. I will finally describe a set of CMS analyses that will be applied to minimum bias events and subsamples that contain at least one high p_T jet, which are more suitable for dedicated UE studies.

2 Multiple parton interactions

The possibility of having several independent parton-parton interactions in a single hadron-hadron collision [2] was motivated by the observation of violations of KNO scaling of charged particle multiplicities in proton-antiproton collisions at center of mass energies of 200 GeV and above [3].

The underlying phenomenology of multiple parton interactions is incorporated in several fragmentation models but relies still on the original ideas described in [2]. The model allows the divergent $2 \rightarrow 2$ cross section to exceed the total inelastic non-diffractive cross section, but regularises the calculations by introducing a cutoff in transverse momentum. This cutoff acts like a screening of the color fields and evolves with the center of mass energy of the hadron-hadron collision as a power law. The ratio of the integrated parton-parton cross section above the momentum cutoff with respect to the total cross section determines the average amount of independent parton-parton interactions which is distributed according to a poissonian probability. This model is successful in describing the so-called pedestal effect which implies that collisions with harder interactions, and hence, smaller impact parameters have a larger than average multiple interaction probability.

Multiple interactions and their impact on the charged particle multiplicity and energy flow in the underlying event has been studied in great detail by R. Field and collaborators within the CDF experiment [4] at the Tevatron. The CDF analysis studies events that have minimally one charged particle jet, obtained by clustering charged particles with a simple iterative cone algorithm. The kinematical event plane is segmented in the azimuthal angle, ϕ, measured in the plane perpendicular to the collision axis and the pseudorapidity, η, related to the polar angle, θ by $\eta = -\ln\tan(\theta/2)$. The direction of the jet with the highest transverse momentum, the leading jet, is used as a reference to determine three distinct spatial regions of interest. The *toward* region contains all charged particles with a difference in azimuthal production angle with respect to the leading jet that is less than 60^o. The *transverse* region is defined to be perpendicular to the leading jet axis in the azimuthal plane and corresponds to angular differences in the range $60^o < |\Delta\phi| < 120^o$. The *away* region is finally defined as being opposite to the leading jet direction and contains angular differences in the range $|\Delta\phi| > 120^o$. The pseudorapidity range is usually limited by the central tracking acceptance, which equaled to $|\eta| < 1$ in CDF RunI analyses. The CDF studies showed that the transverse region is particularly sensitive to the modeling of the underlying event and the inclusion of multiple parton interactions. As a general feature the amount of charged particles, as well as the total transverse momentum in the transverse region increases strongly when the transverse momentum of the leading jet increases from zero to roughly 5 GeV/c, after which it develops a much slower rising plateau at higher transverse momenta. The height of this plateau is at least twice that observed in ordinary soft collisions at the same center of mass energy. Comparisons with hadron fragmentation models proved the necessity to incorporate multiple parton interactions. This makes the PYTHIA [5] model still the most accurate to date. Extensions to the HERWIG [6] cluster fragmentation known as JIMMY [7] can describe the underlying event as well but are incapable of describing inclusive minimum bias events. The Tevatron studies demonstrated the necessity to tune the parameters of the underlying event model and showed their interplay with other parton shower parameters and even the parton density functions. A concensive overview is given in [8]. Due to its large flexibility, many underlying event tunes of the PYTHIA model exist. The starting point was the CDF *Tune A* [4, 9], tuned on minimum bias and jet trigger events at center of mass energies of 630 GeV and 1.8 TeV and using the underlying event observables in the presence of a leading jet, as described above. This baseline tune was revised over time as newer releases of the PYTHIA code, more data and different types of events were used, such as Drell-Yan and dijet events. Recent modifications, such as the *DW* and *DWT* tunes show no major differences with respect to older tunes at Tevatron center of mass energies of roughly 2 TeV, but show large differences when extrapolated to the nominal LHC energy of 14 TeV.

3 CMS minimum bias trigger

A full description of the CMS detector and its trigger systems can be found in [10]. The impact of the CMS hardware and software triggers on minimum bias events was studied more recently in [11]. The baseline minimum bias trigger of CMS is based on energy deposits in predefined regions of the forward hadronic calorimeter that covers the pseudorapidity region between $3 < |\eta| < 5$. One variant of this trigger requires a minimal amount of trigger towers on one side of the detector only. This single-sided trigger has an efficiency of 81% for non-diffractive and 15% for diffractive events (with roughly equal efficiencies for single and double diffractive events). A double-sided trigger based on identical requirements on each side of the detector has an efficiency of 47.5% for non-diffractive events and drastically reduces the efficiency for diffractive events to 0.6%. Efficiencies were estimated using simulations of proton-proton collisions at 14 TeV using a sample of PYTHIA events with the DWT tune. The trigger that introduces no bias at all is merely based on a synchronization with the LHC beam crossover frequency. This so called zero-bias trigger is useful a high instantaneous luminosity, but has low efficiency at luminosities below 10^{30} cm^{-2} s^{-1}, where not all of the proton bunches are filled. This trigger can be complemented by a track segment requirement in the pixel detector where it can attain high efficiencies for both non-diffractive and diffractive events (99% and 60% respectively).

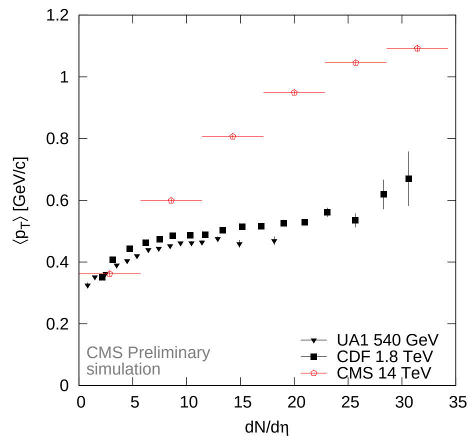

Figure 1: A comparison of CMS predictions using PYTHIA of the average transverse momentum $< p_T >$ at $\eta = 0$ as function of the charged particle density per unit rapidity with measurements from UA1 [12] and FNAL expt E735 [13].

4 CMS minimum bias analyses

Within CMS the QCD analyses based on low transverse momentum tracks fall in two categories. The first category will measure charged particle spectra and charged particle multi-

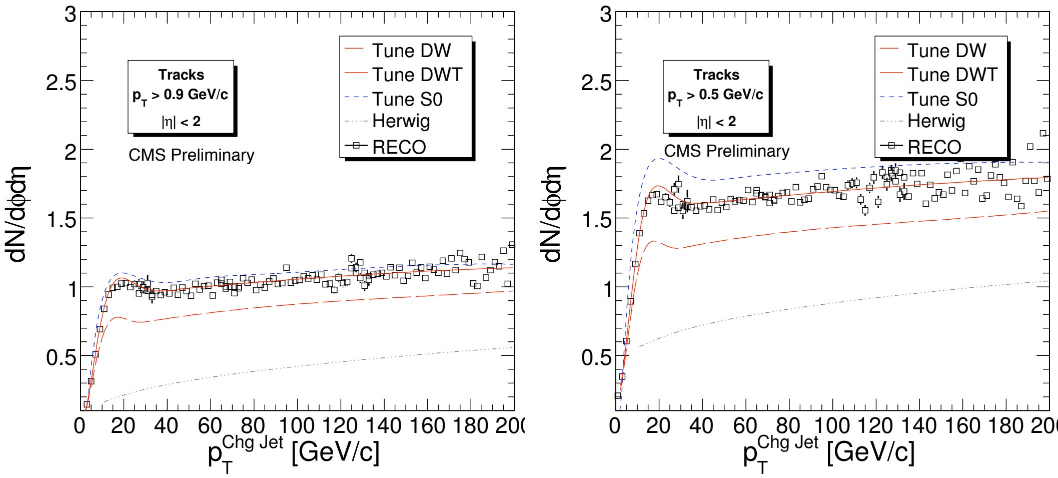

Figure 2: The density of charged particles $d^2N/d\eta d\phi$ in the transverse region with respect to a leading particle jet as function of the transverse momentum of the charged particle jet. Different tunes of PYTHIA including multiple parton-parton interactions are superimposed, in addition to a HERWIG prediction that does not explicitly include multiple parton interactions. The charged particle densities are obtained by correcting the number of reconstructed charged tracks that are obtained using the standard CMS tracking algoritm (left) and an extended tracking algorithm (right), decreasing the p_T threshold for charged particle reconstruction from 900 MeV/c to 500 MeV/c. The statistical uncertainties are scaled to correspond to an integrated luminosity of 100 pb^{-1}.

plicities in pp collisions recorded by minimum bias and zero bias triggers [14]. Since a large fraction of charged hadrons is produced with transverse momenta below 1 GeV/c, the default tracking algorithms of CMS will be extended in order to recover tracks with transverse momenta as low as 150 MeV/c. The pseudorapidity distribution will also be reconstructed based on a count of hit clusters in the innermost layer of the pixel detector, extending the acceptance for charged tracks down to transverse momenta of 30 MeV/c, while keeping the systematic uncertainties due to double counting of looping tracks and detector noise below 8%. For further details on these extended tracking algorithms, I refer to the contribution of L. Mucibello in these proceedings [15]. Besides a detailed study of the height of the pseudorapidity plateau, the average transverse momentum and their evolution with the center of mass energy, the correlation between the charged particle density and the average transverse momentum, as shown in Fig. 1 proves to be an observable that is very sensitive to multiple interaction modeling and tuning. The statistical uncertainties correspond to a sample size of ∼2 million events that can be collected in a month's time.

The second category of analyses [16] focuses on the underlying event using the methodology that was developed within the CDF experiment at the Tevatron [4]. The requirement of a leading particle jet with a transverse momentum over a range of [0-200] GeV/c requires the use of calorimetric jet triggers with increasing transverse momentum thresholds in addition to the aforementioned minimum bias triggers. The sensitivity of the analysis to several tunes and multiple parton interaction models is significantly increased after extending the standard CMS tracking from a minimum transverse momentum of 900 MeV/c down to 500 MeV/c, as can be seen in Fig. 2.

In conclusion, several trigger menus exist within CMS to record minimum bias events with varying efficiencies with respect to diffractive and non-diffractive events, providing the community with very large data sets within days of machine running. Several analysis methods have proven their sensitivity to the modeling of minimum bias events and in particular multiple parton interactions. Many model predictions agree at Tevatron energies, but diverge drastically at 14 TeV. The very successful analysis strategy developed in CDF for analyzing the underlying event has been adopted in CMS. All these analyses rely on an extension of the standard tracking algorithms of CMS to incorporate particles with lower transverse momenta.

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