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Minimum Bias and Underlying Event Measurements at the CMS Experiment

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Recent results on the underlying event activity and various quantities related to minimum bias collisions are presented by the CMS experiment. These include charged hadron angular distributions in p+p collisions at 13 TeV and in p+Pb collisions at 8 TeV; identified pion, kaon and proton yields and mean transverse momentum at 13 TeV; and the number and momentum density of charged particles in the underlying event in the presence of a leading jet or a high-mass opposite-sign muon pair.

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1. Introduction

Properties of minimum bias collisions and underlying event activity are the most basic quantities in investigations of the strong interaction, yet they pose a significant challenge to measure experimentally. Theoretical predictions most often rely on phenomenological descriptions of certain processes using effective models, instead of the rigorous solution of Quantum Chromodynamics. These phenomena involve a small or modest transfer of momentum between partons, or various correlations between soft and hard scattering. This research field has been active at the Large Hadron Collider (LHC), involving several related topics: cross sections (total, inelastic and elastic); soft particle distributions (global particle production); identified particles; various scaling features; hadronization phenomena and correlations; energy flow and charged particle production at high rapidities (low Bjorken-x); forward physics (at high density of soft gluons); underlying event features. In these proceedings, a few selected recent experimental results will be presented from the Compact Muon Solenoid (CMS) Collaboration.

2. Minimum bias measurements

Studying hadron-hadron collisions without posing any selection criteria is complicated at hadron colliders, as a fraction of inelastic collisions escape detection. Most of the final state particles originate from soft processes are characterized by low momentum transfer. Distributions of particles created in these 'average' collisions have similarities to cosmic ray showers, and they are also important for understanding the high-pileup environment of the LHC. Particle distributions are also sensitive to the number of interactions between quarks and gluons in a single proton-proton collision. Distributions of identified particles characterize the expansion of strongly interacting matter. Finally, soft particle event multiplicity appears to be a much better scaling parameter between various collision systems than center-of-mass energy ($\sqrt{s}$).

The first charged particle angular distributions measured at the highest, 13 TeV collision energy were published by CMS [1], in good agreement with predictions of models used in cosmic ray physics. Especially interesting was to study particle production at very forward η that corresponds to the highest energy particles created in cosmic ray collisions, and where earlier observations also showed a universal 'limiting fragmentation' feature. CMS and TOTEM have provided results on that, partially from the analysis of unique p+p collisions that were not geometrically centered on the CMS nominal collision point at 8 TeV [2, 3].

More precise comparisons to models and other experiments necessitate partially biasing the measurement, by requiring at least one well detectable charged particle in the acceptance. Four event classes were defined to approximate certain physical categories: inclusive; inelastic-enhanced; single-diffractive-enhanced (SD) and non-single-diffractive-enhanced (NSD) events. $dN/d\eta$ distributions for the inelastic and SD selection are shown on Fig. 1 at 13 TeV. A variety of Monte Carlo (MC) models were tested, and none of them agrees with all presented aspects of the data [4].

Another recent minimum bias measurement from CMS, also connected to cosmic ray physics, is the charged particle η distribution in proton-lead collisions [5]. Charged particle hadrons were reconstructed from pairs of hits in the silicon pixel system at very high efficiency down to low transverse momentum (p_{T}), representing the first measurement of p+Pb collisions at the highest

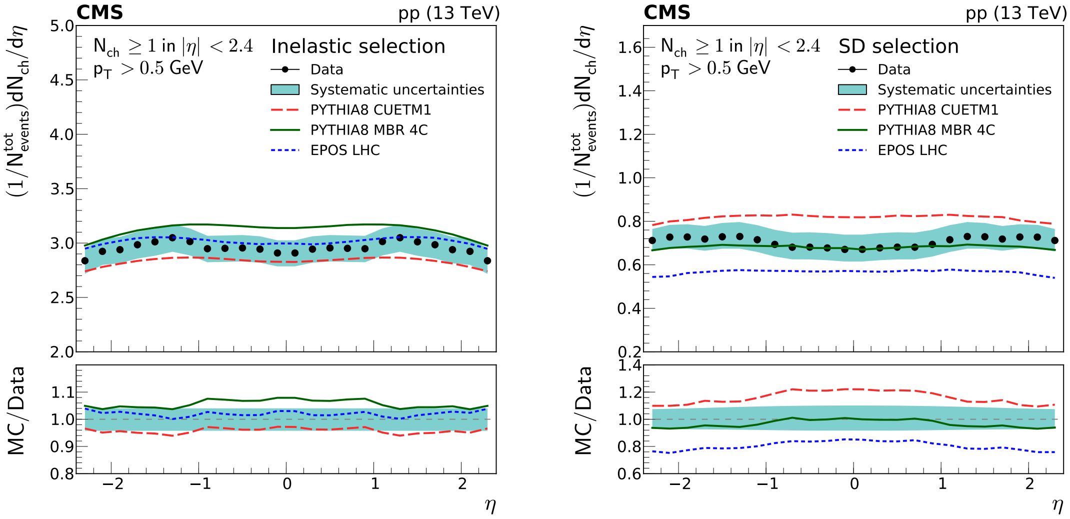

Figure 1: Charged particle pseudorapitidy (η) densities for inelastic enhanced (left panel) and for SD-enhanced (right panel) event samples [1]. The data are compared to the PYTHIA 8 CUETM1 (long dashes), PYTHIA 8 MBR4C (continuous line), and EPOS LHC (short dashes) models. The bands represent the total systematic uncertainty. The lower panel shows the corresponding MC-to-data ratios.

LHC energy. The η distribution is presented on the left panel of Fig. 2, together with the $\sqrt{s_{NN}}$-dependence of the central charged particle density for various collision systems, normalized by the number of participant nucleons in the collision. The EPOS model appears to underestimate the data, while HIJING 1.3 overestimates it.

The CMS silicon pixel and tracker system is capable of identifying low-momentum charged particles based on the specific energy loss in the silicon layers [6]. On the left panel of Fig.3 the energy loss estimator is plotted as a function of momentum, clearly separating pions, kaons and protons. Charged particle yields have been measured as a function of p_T, η and the charged particle multiplicity in the event. Due to the good reconstruction efficiency down to 100 MeV/c, $\langle p_T \rangle$ can be calculated based on Tsallis-Pareto fits to the p_T distributions. Remarkably, the p_T depends on particle mass and multiplicity, but not so much on $\sqrt{s}$, as demonstrated on the right panel of Fig. 3.

3. Underlying event measurements

Investigations of soft interactions accompanying a hard scattering are not only important for empirical tuning of MC event generators and improving the description of p+p collisions at the LHC, but also for searches for new physics, lepton and photon isolation, the reconstruction of the collision point in $H \to \gamma\gamma$ decays, among others. In phenomenological models underlying event activity is related to initial and final state radiation, color connections and multiparton interactions.

Leading charged particle jets were used as reference objects for a comparative analysis of the underlying event activity between p+p collisions at four different $\sqrt{s}$ values [7]. The two main observables were the scalar sum of the p_T of charged particles and the charged particle multiplicity, detected in a unit area of the $\eta - \phi$ plane. The preliminary result is shown on Fig. 4 for the

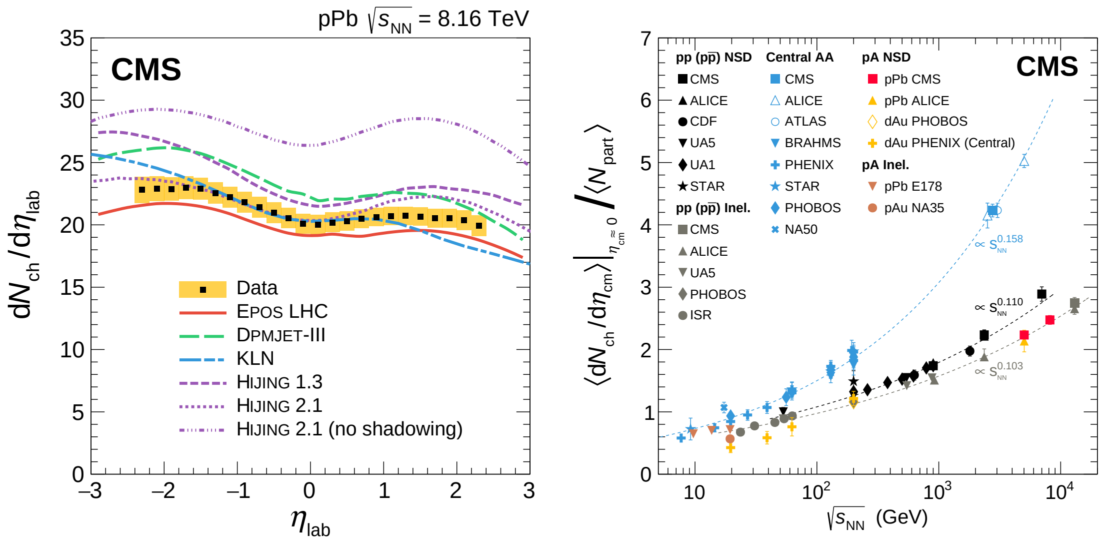

Figure 2: Left panel: distributions of the η density of charged hadrons for non-single-diffractive proton-lead collisions at 8.16 TeV (squares) compared to the EPOS LHC, HIJING, DPMJET-III and KLN models [5]. The shaded boxes around the data points indicate their systematic uncertainties. The proton beam goes in the positive $\eta_{\rm lab}$ direction. Right panel: comparison of the measured $dN_{\rm ch}/d\eta_{\rm cm}$ at midrapidity, scaled by the number of participating nucleons ($N_{\rm part}$) in p+Pb, p+Au, d+Au and central heavy ion collisions, as well as NSD and inelastic p+p collisions. The dashed curves are included to guide the eye.

transverse direction, which is perpendicular to the leading charged particle jet in terms of azimuthal angle. Among the models tested, the PYTHIA8-Monash tune has the best agreement with the data, also reflecting well the increase of the underlying event activity with collision energy.

The underlying event can be tested by selecting reference objects with a large mass, rather than a large $p_{\rm T}$, like the Z boson [8] or top quark pairs [9]. The charged particle multiplicity and the scalar sum of the $p_{\rm T}$ of the particles were measured as a function of the $p_{\rm T}$ of the $\mu^+\mu^-$ pair. Those results are shown on Fig. 5 for various $\sqrt{s}$ values, including the recent CMS result at 13 TeV. Among the models, POWHEG hadronized with PYTHIA 8 agrees with the data, while the combination of POWHEG and HERWIG++ overestimates them by 10-15%. The underlying event activity increases logarithmically with $\sqrt{s}$, which is not described by the studied models precisely.

In summary, soft QCD is an important research field, relevant for many different aspects of LHC physics, like the non-perturbative and global features of the collisions; high pileup simulations; searches for new physics and cosmic ray physics. Experimental challenges include special (low pileup) LHC runs, additional forward instrumentation, and unique analysis techniques. Thus, this is an active field that provides important fundamental information for the interpretation of the transition between soft and hard scattering, multi-parton interactions, and model tuning.

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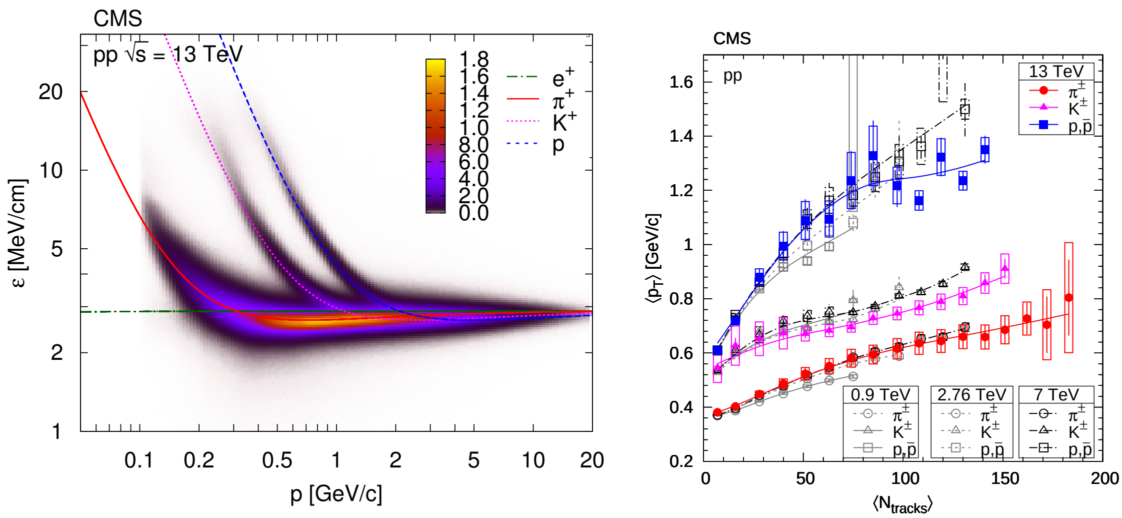

Figure 3: Left: Distribution of the ε energy loss estimator as a function of p for positive particles [6]. The color scale is linear. The curves show the expected ε for e, π, K and p. Right: Average p_{T} of identified charged hadrons (π, K and p) in the range $|y| < 1$ as a function of the corrected track multiplicity for $|\eta| < 2.4$, for p+p collisions at $\sqrt{s} = 13$ TeV (filled symbols) and at lower energies (open symbols). Both $\langle p_{\mathrm{T}} \rangle$ and yield ratios are computed assuming a Tsallis-Pareto distribution in the unmeasured p_{T} range. Lines are drawn to guide the eye.

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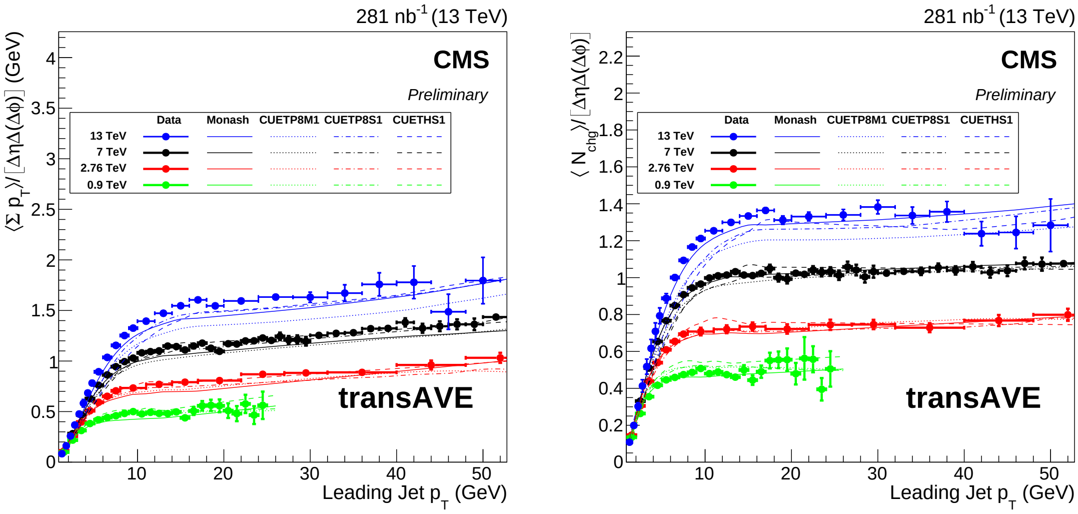

Figure 4: Comparisons of corrected transAVE energy densities (left panel) and particle densities (right panel) with various simulations at $\sqrt{s} = 0.9$, 2.76, 7 and 13 TeV for as a function of the p_T of the leading jet [7].

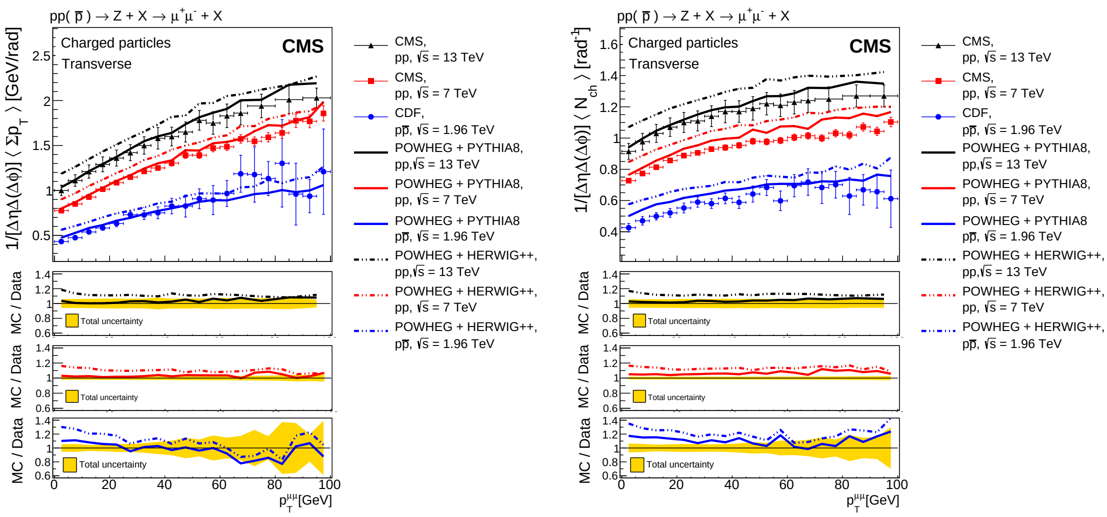

Figure 5: Comparison of the energy density (left panel) and the particle density (right panel) measured in Z events at $\sqrt{s} = 13$ TeV with those measured at 7 TeV (CMS) and 1.96 TeV (CDF) in the transverse region as a function of the p_T of the dimuon pair [8]. The data are also compared with the model predictions of POWHEG + PYTHIA8 and POWHEG + HERWIG++. The bottom panels of each plot show the ratios of model predictions to the measurements. The bands in the bottom panels represent the statistical and systematic uncertainties added in quadrature.