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QCD, soft physics, and heavy flavor measurements at the LHC

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Summary. — Recent measurements in QCD, soft physics, and heavy flavor made with the CMS detector at the LHC are presented. A selection of first results at the new frontier collision energy of 13 TeV at LHC Run2 is shown. The collision environment is characterized by studying charged particle distributions and correlations. Inclusive jet, exclusive dimuon and b-hadron production cross section measurements are reported.

1. – Introduction

The LHC has been providing collisions of different hadrons at different center-of-mass energies, reaching with Run2 the unprecedented $\sqrt{s}$ of 13 TeV in pp collisions. Studies of the underlying LHC collision environment are essential for characterizing the background processes for the measurement and search of rarer processes and possible detection of new physics beyond the standard model. Such studies are also important for improving the understanding of the underlying quantum chromodynamics processes leading to particle production.

2. – Underlying event

The underlying event (UE) is the collision activity that is not part of the final-state activity originating from the most energetic parton scattering of the collision. An accurate understanding of the UE is required for precise measurements of standard model processes at high energies and searches for new physics. Since the semi-hard and low-momentum partonic processes, which dominate the UE, cannot be adequately calculated with perturbative QCD methods alone, the UE activity requires a phenomenological description containing parameters that must be tuned to data.

To access experimental observables sensitive to the UE activity, the collision topology may be exploited, by studying particle properties in regions away from the direction of the products of the hard scattering (transverse region). The particle densities and

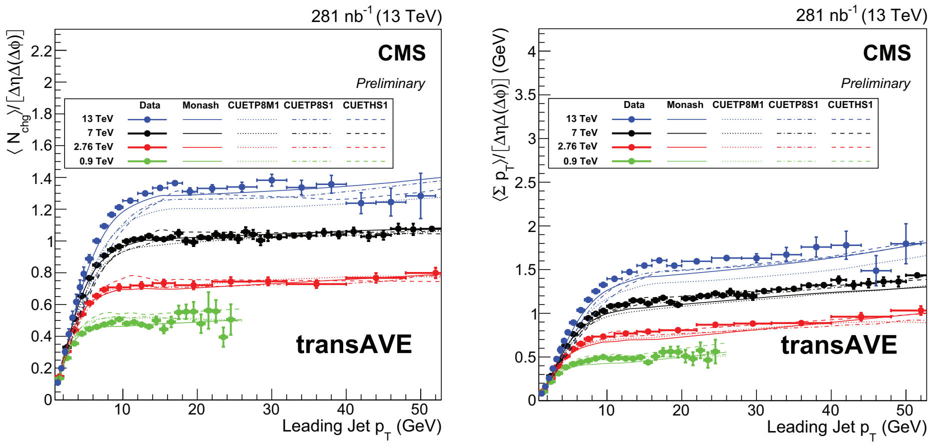

Fig. 1. – Charged-particle densities as a function of leading track-jet p_T measured at $\sqrt{s} = 0.9$, 2.76, 7, and 13 TeV and comparisons with various Monte Carlo simulations.

momentum sum $(\sum p_T)$/average energy densities of charged particles in the region orthogonal to the azimuthal direction of the leading charged-particle jet ($60° < \Delta\phi < 120°$) are measured [1]. The results are summarized in fig. 1 as a function of the transverse momentum of the leading charged-particle jet. Comparisons between various MC-simulated samples and data across centre-of-mass energies of 0.9, 2.76, 7, and 13 TeV are shown. There is a strong rise in the UE activity as a function of the centre-of-mass energy as predicted by the MC tunes. This is attributed to an increase in the of number partons with smaller fractional momenta, $x \approx 2p_T/\sqrt{s}$.

3. – Soft particle production

Soft interactions give rise to a significant fraction of the produced particles in hadronic collisions. The inclusive production of charged hadrons is driven by a combination of perturbative and nonperturbative QCD phenomena, such as saturation of parton densities, multiparton interactions, parton hadronization, and soft diffractive scattering. The yields of primary charged hadrons are commonly studied using their multiplicity as a function of pseudorapidity, $\mathrm{d}N_{ch}/\mathrm{d}\eta$. Such measurements do not demand large ammounts of data but require non-ovelapping collisions. An analysis [2] has been performed at the begining of Run2, which is based on 11.5 million events recorded at zero magnetic field during a special low-intensity beam configuration with 0.25% proton-proton interaction probability per bunch crossing. The $\mathrm{d}N_{ch}/\mathrm{d}\eta$ measurement is shown in fig. 2. In the central region, the measurement is consistent with predictions of the PYTHIA8 (with the CMS underlying event tunes CUETP8S1 and CUETP8M1) and EPOS LHC (LHC tune) event generators, while those in a wider η range are better described by the latter.

Of particular interest for understanding the physics of hadron production is the dependence of $\mathrm{d}N_{ch}/\mathrm{d}\eta$ on the collision energy, which reflects the relative roles of soft- and hard-scattering contributions. Such dependency is shown in fig. 2. The measured values are empirically fitted using a second-order polynomial $(1.55 - 0.113 \ln s + 0.0168 \ln s^2$, where s has the units GeV^2), which provides a good description of the available data over the full energy range. The PYTHIA8 and EPOS LHC event generators globally reproduce the collision-energy dependence of hadron production in inelastic pp collisions.

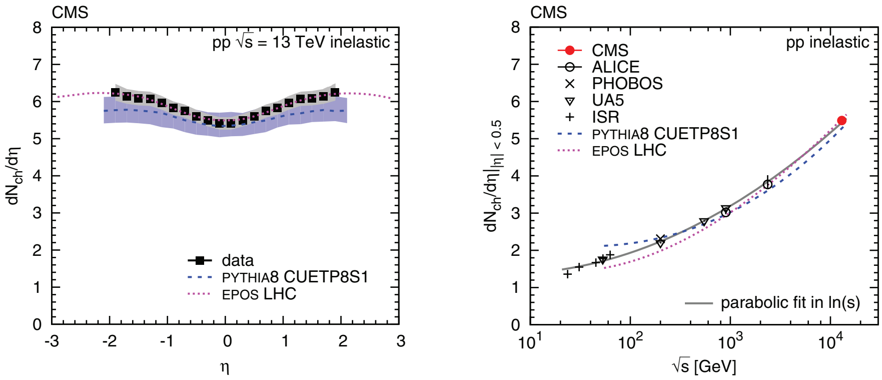

Fig. 2. – Mesurement of charged-hadron multiplicities in inelastic pp collisions, as a function of rapidity (left) and center-of-mass energy (right). Predictions by the PYTHIA8 CUETP8S1 and the EPOS LHC event generators are also shown.

4. – Two-particle correlations

The study of multi-particle correlations provides further insight into the nature of soft QCD processes, and in particular about collective effects and the dynamics of the interaction. Angular two-particle correlations are studied [3] as a two-dimensional correlation function in $(\Delta\eta, \Delta\phi)$ coordinates. In fig. 3 (left), expected structures are visible: a "near-side" peak (which is truncated) around (0,0) from jets, and a "long-range away-side" structure about $\Delta\phi \approx \pi$ due to momentum conservation. What is also observed however is the correlation of particles produced with similar ϕ (or $\Delta\phi \approx 0$) along the η coordinate, in a ridge-like shape. Such correlations are referred to as "long-range near-side". It is most pronounced in an intermediate momentum range ($1 < p_T < 2$ GeV). The effect is observed in events with large charged-particle multiplicity, and above a

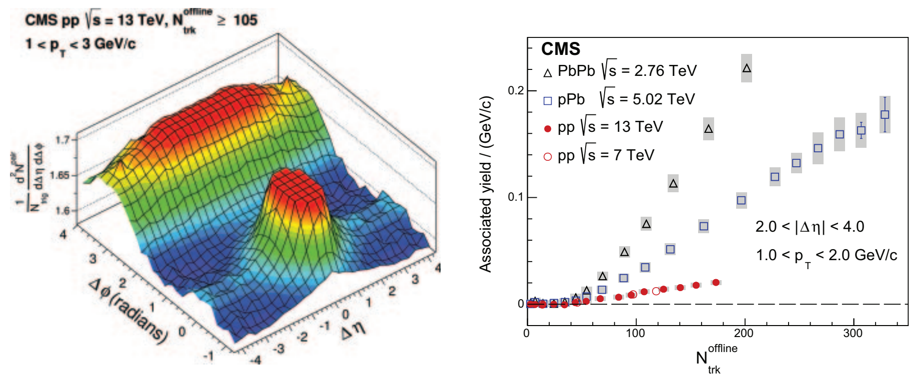

Fig. 3. – Two-particle correlations. Left: two-particle correlation as a function of the azymuthal angle difference and speudorapidity difference for particle pairs in pp collisions at 13 TeV. The results are displayed for particle momenta in the range $1 < p_T < 3$ GeV, and event charged-particle multiplicites $N_{track} > 105$. Right: associate yield of long-range near-side two-particle correlations for $1 < p_T < 2$ GeV in pp collisions at $\sqrt{s} = 13$ and 7 TeV, pPb collisions at $\sqrt{s} = 5.02$ TeV, and PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV.

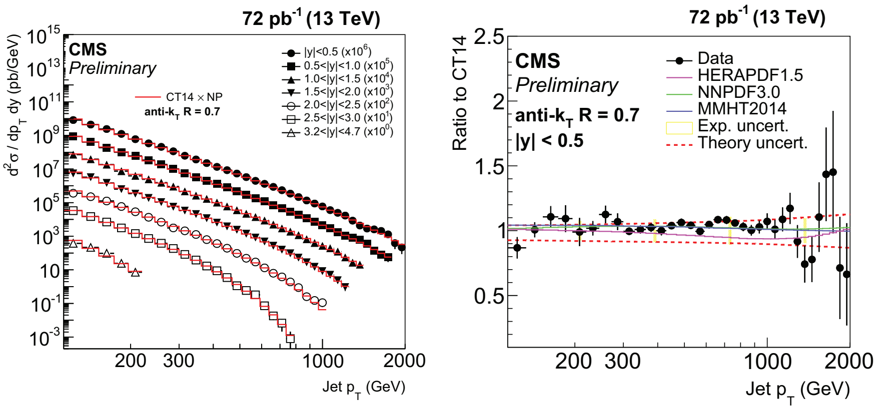

Fig. 4. – Inclusive jet cross section at 13 TeV. Left: double-differential inclusive jet cross section as function of jet p_T. Right: ratio of measured values to theoretical predictions. The prediction from NLOJET++ based on the CT14 PDF set corrected for the NP and electroweak effects are used, while predictions employing three other PDF sets are also shown for comparison in the ratio.

threshold of about $N_{track} \approx 40$ its magnitude is seen in fig. 3 (right) to increase approximately linearly.

These correlations are thought to arise from the response of a hydrodynamically expanding partonic medium to fluctuations of the initial collision geometry. Similar correlations, with consistent magnitude, have been detected in pp collisions also at lower collision energies. Similar ridge effects have been previously observed as well in collisions involving heavy ions. As summarized in fig. 3 (right), the magnitude of the correlation effect strongly depends on the size of the collision system, when comparing pp, pPb, and PbPb.

5. – Hard interactions and jet production

Inclusive jet production (p + p → jet + X) is a key process to test predictions of perturbative QCD over a wide region in phase space. Differential measurements are a sensitive probe for the calculation of the hard partonic cross section as well as for the parton densities.

A measurement of the double-differential inclusive jet cross section in pp collisions at 13 TeV is shown in fig. 4 as a function of the jet p_T for seven absolute rapidity $|y|$ ranges, after unfolding for detector effects [4]. The measurements are compared to the NLOJET++ predictions based on the CT14 PDF set, corrected for NP and electroweak effects. The data are consistent with predictions over a wide range of jet p_T from 114 GeV to 2 TeV.

These results complement the precise measuremens that were previously perfomed at lower collision energies. From the measured spectrum at 8 TeV [5], the strong coupling constant was extracted, with a best fitted value of $\alpha_s(m_Z) = 0.1164^{+0.0060}_{-0.0043}$ with the CT10 NLO PDF set.

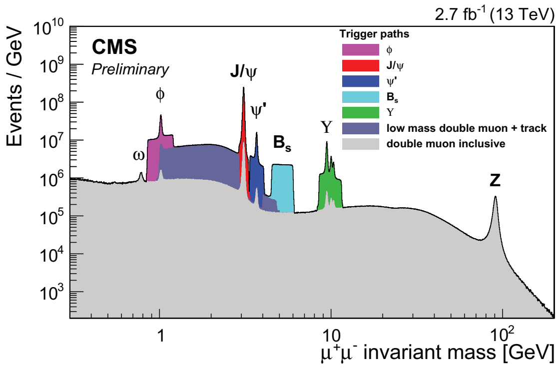

Fig. 5. – Dimuon invariant-mass spectum in pp collisions at 13 TeV. Data collected with dedicated heavy-flavor triggers are highlighted.

6. – Dimuon spectrum

Muon signals are reconstructed at CMS with high precision down to low transverse momentum, reaching precisions of 1–2% in the central detector. Fake rates at the permil level are also achieved. Figure 5 displays the dimuon spectrum, obtained with the full datatset collected during 2015 at 13 TeV [6]. It illustrates the ability of the detector to explore a wide-range of precision measurements across the mass spectrum, from the low-mass vector mesons, ω, ϕ, to quarkonia $(J/\psi, \Upsilon)$, to beyond the Z^0 vector boson. Note that in order to display the precision achieved across different orders of magnitude, the graph is constructed with a variable width binning.

Multi-muon signals are explored extensively in CMS, and form in particular the baseline for online selection of heavy flavors. In addition to generic, high-p_T double muon trigger algorithms, shown in light gray, fig. 5 highlights dedicated algorithms, with low-p_T thresholds, in specific mass windows.

7. – Hidden heavy-flavor production

The study of heavy-quark production in high-energy hadronic interactions plays a critical role in testing next-to-leading order (NLO) QCD calculations. Heavy-quark bound states can be described by the NRQCD effective theory. This assumes factorization of the production process into two stages. The generation of the heavy QQ pair, in a given spin and orbital angular momentum state, in either a color singlet or color octet configuration, are described perturbatively. The subsequent hadronization producing the bound state is controlled by the so-called long-distance matrix elements (LDMEs), which are process-independent and need to be constrained by the data.

Quarkonium production has been studied extensively in Run1, through measurements of yields and angular distributions, as a function of different observables, in different collisions systems. Measurements performed at the new pp collision energy allow a more precise mapping of the energy dependence and provide the opportunity to probe higher p_T regions. This will allow in turn a more conclusive clarification of the pre-LHC so-called quarkonium puzzle.

The initial Run2 dataset has been explored to measure the production cross sections of each S-wave quarkonium state at 13 TeV [7]. The measurements are performed

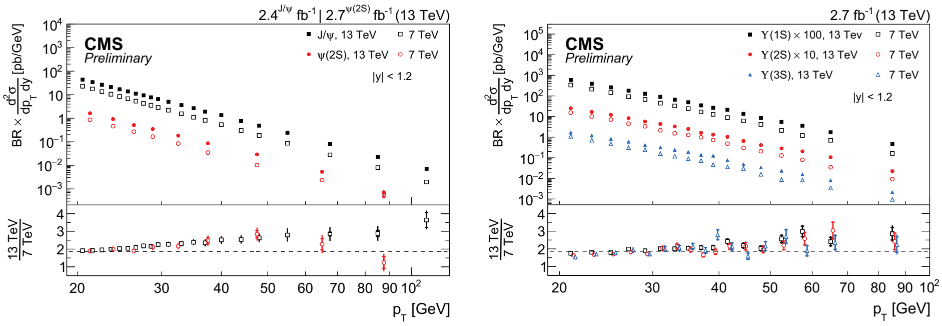

Fig. 6. – Quarkonium production at 13 TeV. Differential cross sections times branching fractions for the S-wave: charmonium $\Psi(nS)$ (left) and bottomonium $\Upsilon(nS)$ (right) states. The inner error bars represent the statistical uncertainty while the total errors show the statistical and systematic uncertainties. The uncertainty on the luminosity measurement is not included. The resuls are shown for 7 and 13 TeV, while the respective ratio is provided in the bottom pannels.

differentially in p_T and absolute rapidity. Measurements extend from 20 to 120 GeV. A comparison between 13 and 7 TeV is shown in fig. 6. These results will contribute to consolidate the underlying hypotheses of NRQCD and provide further input to constrain the theory parameters.

8. – Open heavy-flavor production

Measurements of b-hadron production at higher energies represent important tests of the theoretical QCD calculations. Improved production measurements, at current energies and central kinematic acceptances, are also important for they constitute relevant ingredients in searches for rarer processes.

The initial Run2 data, collected in summer 2015 during a data-taking period with 50 ns LHC bunch-spacing, has been explored for initial production measurements. The higher-rate decay channel $B^+ \to J/\psi K^+$ has been utilized [8]. The reconstructed invariant mass distribution is shown in fig. 7 (left). The shoulder that appears to the left

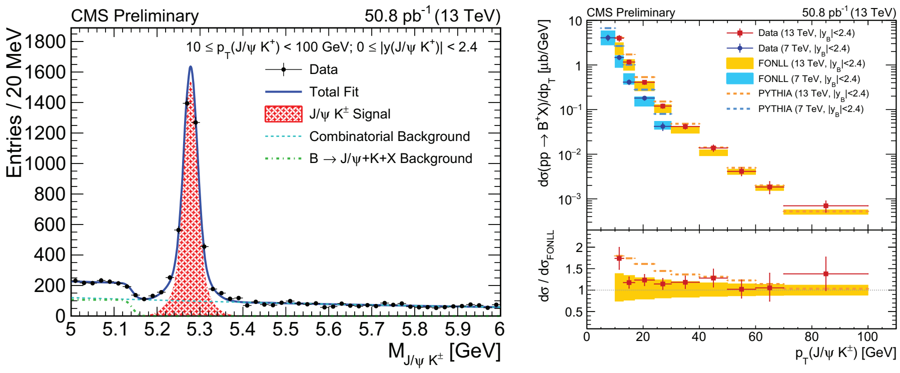

Fig. 7. – B meson production at 13 TeV. Left: invariant mass distribution of the $B^+ \to J/\psi K^+$ candidates, integrated in the phase space region $10 < p_T < 100$ GeV and $|y| < 2.4$. Right: differential cross section, $\mathrm{d}\sigma/\mathrm{d}p_T$. Comparisons of 7 and 13 TeV results and with theory predictions are shown.

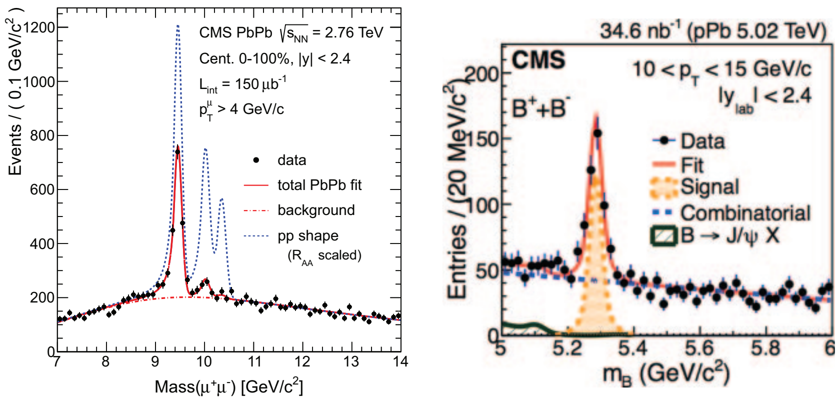

Fig. 8. – Left: dimuon invariant-mass distribution in the vicinity of the $\Upsilon(nS)$ states in PbPb collisions at $\sqrt{s_{NN}} = 2.76\,\text{TeV}$. The red line shows the fit to the PbPb data; the blue dashed line shows the shape obtained from the fit to the pp data. Right: invariant-mass distributions of $B^+ \to J/\psi K^+$ candidates in pPb collisions at $\sqrt{s_{NN}} = 5.02\,\text{TeV}$.

of the signal peak due to partially reconstructed b-hadrons. The cross-section measurement is performed differentially in p_T, in the range $20 < p_T < 100\,\text{GeV}$. The results are compared in fig. 7 (right) with those performed earlier at 7 TeV, and with theory predictions.

9. – Heavy-flavor production in heavy-ion collisions

Heavy-ion collisions at the LHC produce a hot and dense environment. Under such extreme conditions, a strongly interacting state consisting of deconfined quarks and gluons, the quark-gluon plasma (QGP), is predicted by lattice-QCD calculations. Heavy flavor constitute crucial hard probes for the study of the properties of the produced medium.

Extensive measurements of quarkonium production were performed during Run1. The relative production cross sections in PbPb and pp were measured. Sequential suppression was observed for the first time inspecting the $\Upsilon(nS)$ familiy of states [9]: as illustrated in fig. 8 (left), the excited states are more suppressed than the $\Upsilon(1S)$ state. This is in agreement with expectations in the presence of QGP. The experimental pattern of quarkonium sequential suppression was established by measuring all five S-wave states.

The exclusive reconstruction of b-hadrons was also achieved in pPb data [10]. The B^+ meson signal is seen in fig. 8 (right). Hard-scattered partons are expected to lose energy as they traverse the QGP via elastic collisions and medium-induced gluon radiation.

Extended heavy flavor measurements, performed across different collision systems, and through additional states and observables, will contribute to further our understanding of the QGP properties, and the behaviour of QCD matter under extreme conditions.

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