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Small-x QCD studies with CMS at the LHC

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Abstract. The capabilities of the CMS experiment to study the low-x parton structure and QCD evolution in the proton and the nucleus at LHC energies are presented through four different measurements, to be carried out in Pb-Pb at $\sqrt{s_{NN}} = 5.5$ TeV: (i) the charged hadron rapidity density $dN_{\rm ch}/d\eta$ and (ii) the ultraperipheral (photo)production of Υ; and in p-p at $\sqrt{s} = 14$ TeV: (iii) inclusive forward jets and (iv) Mueller-Navelet dijets (separated by $\Delta\eta \gtrsim 8$).

Introduction

At high energies, the cross-sections of all *hadronic objects* (protons, nuclei, or even photons "fluctuating" into $q\bar{q}$ vector states) are dominated by scatterings involving gluons. Gluons clearly outnumber quarks in the small momentum fraction (low-x) range of the parton distribution functions (PDFs) as a consequence of the QCD parton splitting probabilities described by the DGLAP [1] and BFKL [2] evolution equations. The fast growth of the gluon densities $xG(x,Q^2)$ for decreasing x conspicuously observed in DIS ep at HERA [3], cannot however continue indefinitely since this would violate unitarity even for scatterings with $Q^2 \gg \Lambda^2_{\rm QCD}$. For small enough x values, gluons must start to recombine in a process known as gluon saturation [4]. This phenomenon occurs when the size occupied by the partons becomes similar to the size of the hadron πR^2, or in terms of the *saturation momentum* Q_s when: $Q^2 \lesssim Q_s^2(x) \simeq \alpha_s\, xG(x,Q^2)/\pi R^2$. Q_s grows with the number A of nucleons in the "target", the collision energy $\sqrt{s}$, and the rapidity of the gluon $y = \ln(1/x)$, according to: $Q_s^2 \sim A^{1/3}\, x^{-0.3} \sim A^{1/3}(\sqrt{s})^{0.3} \sim A^{1/3} e^{0.3y}$. The A dependence implies that, at equal energies, saturation effects will be enhanced by factors as large as $A^{1/3} \approx 6$ in a heavy nucleus (A = 208 for Pb) compared to protons. Theoretically, the regime of low-x QCD can be effectively described in the "Color Glass Condensate" (CGC) framework, where all gluon fusions and multiple scatterings are "resummed" into classical high-density gluon wavefunctions [5]. The corresponding evolution is given in this case by the BK/JIMWLK [6] *non-linear* equations.

Experimentally, the most direct way to access the low-x PDFs in hadronic collisions is by measuring perturbative probes (heavy-Q, jets, high-p_T hadrons, prompt γ, ...) at large $\sqrt{s}$ and *forward* rapidities [7]. For a $2 \to 2$ parton scattering, the *minimum* x probed in a process with a particle of momentum p_T produced at pseudo-rapidity η, is $x_2^{min} = x_T\, e^{-\eta}/(2 - x_T\, e^{\eta})$ where $x_T = 2p_T/\sqrt{s}$. Thus, x_2^{min} decreases by a factor of ~10 every 2 units of rapidity. The experimental capabilities of the CMS experiment are extremely well adapted for the study of low-x phenomena with proton and ion beams. The acceptance of the CMS/TOTEM system is the largest ever available in a collider, and the detector is designed to measure different particles with excellent momentum resolution [8]: jets ($|\eta| < 6.6$), γ and $e^{\pm}$ ($|\eta| < 3$), muons ($|\eta| < 2.5$), hadrons ($|\eta| < 6.6$), plus neutrals in the Zero-Degree Calorimeters (ZDCs, $|\eta| > 8.3$). We present a selection of four observables measurable in CMS which are sensitive to parton saturation effects in the proton and nucleus wave-functions at LHC energies. Other relevant measurements (e.g. forward Drell-Yan in p-p at 14 TeV) are discussed in [9].

1. Measurements in PbPb collisions at $\sqrt{s_{NN}}$ = 5.5 TeV

(1) Charged hadron PbPb rapidity density: $dN_{ch}/d\eta$

In high-energy heavy-ion collisions, the *hadron* rapidity density $dN/d\eta$ is directly related to the number of initially released *partons* at a given η. CGC approaches which effectively take into account a reduced initial parton flux in the nuclear PDFs, reproduce successfully the absolute hadron yields (as well as their centrality and $\sqrt{s_{NN}}$ dependences) at SPS – RHIC energies [10, 11]. At LHC, the expected PbPb multiplicities are $dN/d\eta|_{\eta=0} \approx 2000$ (Fig. 1, left). CMS simulation studies from hit counting in the innermost Si pixel layer ($|\eta| < 2.5$) indicate that the occupancy remains less than 2% and that, on an event-by-event basis, the reconstructed $dN_{\rm ch}/d\eta$ is within ~2% of the true primary multiplicity (Fig. 1, right) [12].

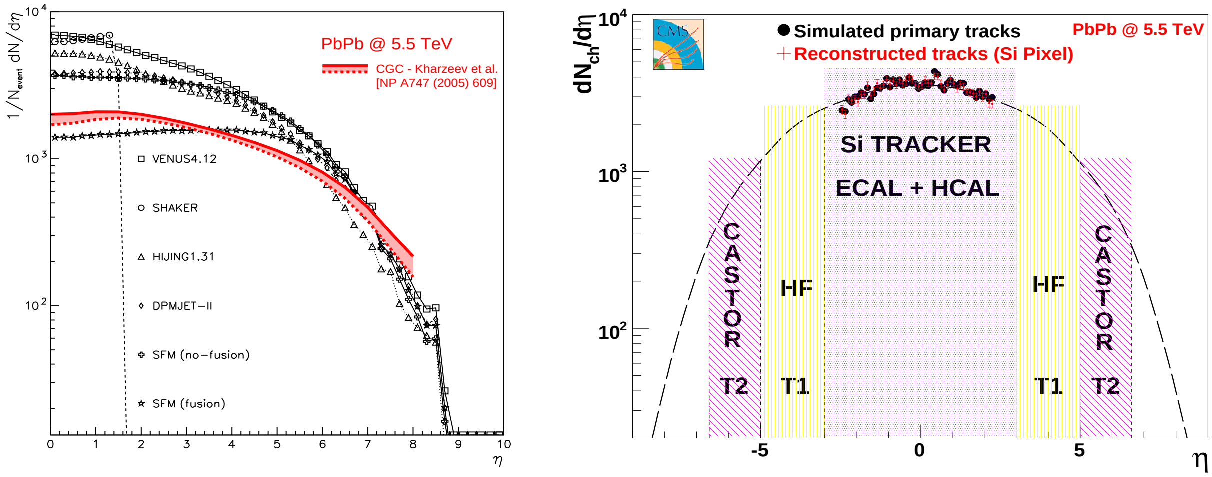

Figure 1. Left: Model predictions for $dN/d\eta$ in central PbPb at the LHC [10, 13]. Right: Range of particle rapidities covered by CMS (Si tracker, HF, CASTOR) and TOTEM (T1, T2 trackers). The HIJING PbPb distribution of primary simulated tracks within $|\eta| < 2.5$ (black dots) is compared to the reconstructed hits in the first layer of the Si tracker (red crosses) [12].

(2) Υ photoproduction in ultra-peripheral PbPb $(\to \gamma Pb) \to \Upsilon + Pb^{*}\ Pb^{(*)}$ collisions

Ultraperipheral collisions (UPCs) of heavy ions generate strong electromagnetic fields (equivalent to a flux of quasi-real photons) which can be used to study $xG(x,Q^2)$ via $Q\overline{Q}$ photoproduction [14]. Lead beams at 2.75 TeV have Lorentz factors γ = 2930 leading to maximum photon energies $\omega_{max} \approx \gamma/R \sim 100$ GeV (for a nuclear radius $R = 6.5$ fm) and c.m.

energies $W_{\gamma\gamma}^{max} \approx 160$ GeV and $W_{\gamma A}^{max} \approx 1$ TeV. The x values probed in γPb→ ΥPb processes at $y = 2.5$ can be as low as $x \sim 10^{-4}$. Full simulation+reconstruction [12] of input distributions from the STARLIGHT MC [15] show that CMS can measure $\Upsilon \to e^+e^-$, $\mu^+\mu^-$ within $|\eta| < 2.5$, in UPCs tagged with neutrons detected in the ZDCs. Fig. 2 shows the reconstructed $dN/dm_{l^+l^-}$ around the Υ mass for 0.5 nb^{-1} integrated PbPb luminosity. With a total yield of ~ 400 Υ, detailed p_T,η studies can be carried out, to constrain the low-x gluon density in the Pb nucleus.

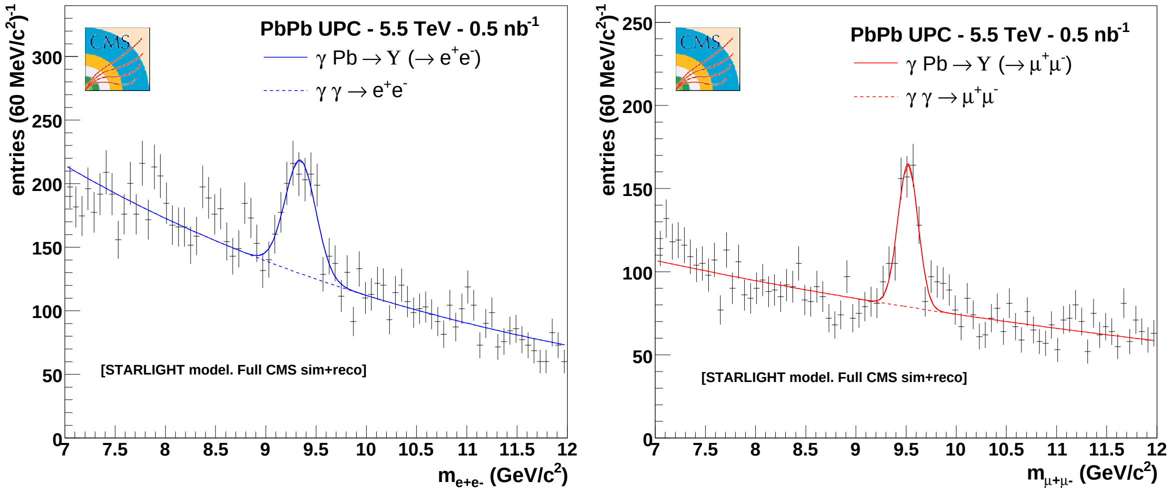

Figure 2. Expected e^+e^- (left), $\mu^+\mu^-$ (right) invariant mass distributions from γPb→ ΥPb* ($\Upsilon \to l^+l^-$, signal) and $\gamma\gamma \to l^+l^-$ (background) in UPC PbPb at $\sqrt{s_{NN}} = 5.5$ TeV in CMS.

2. Measurements in pp collisions at $\sqrt{s}$ =14 TeV

(3) Inclusive forward jet production: pp → jet+X, with $3 < |\eta_{\rm jet}| < 5$

Jet measurements at Tevatron have provided valuable information on the proton PDFs. At 14 TeV, the production of jets with $E_T \approx 20$–100 GeV in the CMS forward calorimeters (HF and CASTOR) probes the PDFs down to $x_2 \approx 10^{-6}$ [7]. Figure 3-left shows the single inclusive jet spectrum in both HFs (3< $|\eta|$ <5) expected for a short first run with just 1 pb^{-1} integrated luminosity. The spectrum has been obtained from a preliminary study using PYTHIA 6.403 with jet reconstruction at the *particle-level* (i.e. *no* detector effects are included apart from the HF tower $\eta-\phi$ granularity) [9]. Although at such low $E_{\rm T}$'s systematic uncertainties can be as large as ~30%, the available statistics for this study is very high.

(4) Mueller-Navelet dijets: pp → jet$_1$+jet$_2$, with large $\Delta\eta = \eta_2 - \eta_1$

Inclusive dijet production at large pseudorapidity intervals – Müller-Navelet (MN) jets – has been considered an excellent testing ground for BFKL [17] and non-linear QCD [18] evolutions. The large rapidity separation between partons enhances the available longitudinal momentum phase space for BFKL radiation. Gluon saturation effects are expected to reduce the (pure BFKL) MN cross section by a factor of ~2 for jets separated by $\Delta\eta \approx 9$ [18]. In order

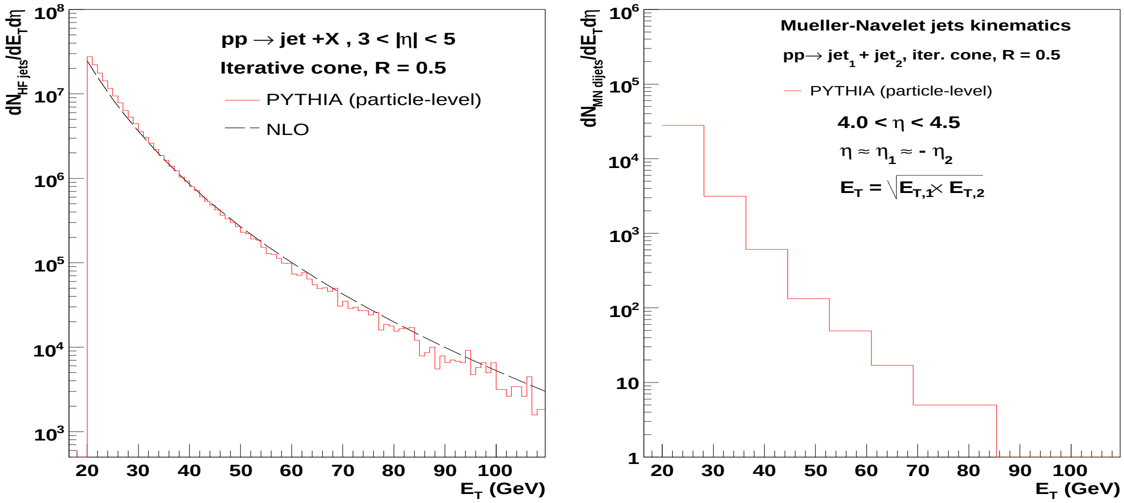

Figure 3. Expected jet yields in pp at $\sqrt{s}$ = 14 TeV (1 pb^{-1}) obtained from PYTHIA 6.403 at the particle-level (*no* full detector response, underlying-event or hadronization corrections). Left: Single inclusive jets in HF ($3 < |\eta| < 5$) (compared to a NLO calculation with scale $\mu = E_T$ [16]). Right: Dijets separated by $\Delta\eta$ = 8–9 with the Müller-Navelet kinematics cuts described in the text, as a function of $E_T \equiv \sqrt{E_{T,1} \times E_{T,2}}$.

to estimate the expected statistics for a short run without pile-up (1 pb^{-1}), we have selected the PYTHIA events which pass the MN kinematics cuts: $|E_{T,1} - E_{T,2}| < 2.5$ GeV, $|\eta_1| - |\eta_2| < 0.25$, and $\Delta\eta = 6 - 10$ [9]. Figure 3-right shows the results for $\Delta\eta$ = 8–9. The expected dijet yields for this η separation indicate that these studies are clearly statistically feasible at the LHC.

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