Small-\(x\) QCD studies with CMS at the LHC

David d'Enterria for the CMS collaboration
CERN, PH-EP, CH-1211 Geneva 23

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 \(dN_{ch}/d\eta\) and (ii) the ultraperipheral (photo)production of \(\Upsilon\); 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 \cite{1} and BFKL \cite{2} evolution equations. The fast growth of the gluon densities \(xG(x,Q^2)\) for decreasing \(x\) conspicuously observed in DIS \(ep\) at HERA \cite{3}, cannot however continue indefinitely since this would violate unitarity even for scatterings with \(Q^2 \gg \Lambda_{QCD}^2\). For small enough \(x\) values, gluons must start to recombine in a process known as gluon saturation \cite{4}. This phenomenon occurs when the size occupied by the partons becomes similar to the size of the hadron \(\pi^2R^2\), or in terms of the saturation momentum \(Q_s\) when: \(Q^2 \lesssim Q_s^2(x) \approx \alpha_s xG(x,Q^2)/\pi R^2\). \(Q_s\) 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 \cite{5}. The corresponding evolution is given in this case by the BK/JIMWLK \cite{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 \(\gamma\), ...) at large \(\sqrt{s}\) and forward rapidities \cite{7}. For a \(2 \rightarrow 2\) parton scattering, the minimum \(x\) probed in a process with a particle of momentum \(p_T\) produced at pseudo-rapidity \(\eta\), 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 \(\sim 10\) 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 (\(|\eta| < 6.6\)), \(\gamma\) 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 \(\eta\). 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 \(dN_{ch}/d\eta\) is within \(\sim 2\%\) of the true primary multiplicity (Fig. 1 right) [12].

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure1.png}
\caption{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 \(\gamma\) 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].}
\end{figure}

\(2)\) \(\Upsilon\) photoproduction in ultra-peripheral PbPb (\(\rightarrow \gamma Pb\) → \(\Upsilon + Pb^+ Pb^{(\star)}\) 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 \(Q\bar{Q}\) photoproduction [14]. Lead beams at 2.75 TeV have Lorentz factors \(\gamma = 2930\) 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 $\gamma$Pb$\rightarrow$ $\Upsilon$Pb 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 $\Upsilon \rightarrow e^+e^-$, $\mu^+\mu^-$ within $|\eta| < 2.5$, in UPCs tagged with neutrons detected in the ZDCs. Fig. 2 shows the reconstructed $dN/dm_{l^+l^-}$ around the $\Upsilon$ mass for 0.5 nb$^{-1}$ integrated PbPb luminosity. With a total yield of $\sim 400$ $\Upsilon$, detailed $p_T, \eta$ studies can be carried out, to constrain the low-$x$ gluon density in the Pb nucleus.

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

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

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 $E_T$’s systematic uncertainties can be as large as $\sim 30\%$, the available statistics for this study is very high.

(4) Mueller-Navelet dijets: $pp \rightarrow jet_1 + jet_2$, 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 $\sim 2$ for jets separated by $\Delta \eta \approx 9$ [18]. In order
Small-x QCD studies with CMS at the LHC

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 $\eta$ separation indicate that these studies are clearly statistically feasible at the LHC.

Acknowledgments. Supported by 6th EU Framework Programme MEIF-CT-2005-025073.

References

[1] Altarelli G and Parisi G 1977 Nucl. Phys. B126 298; Dokshitzer Yu L 1977 Sov. Phys. JETP 46 641
[2] Kuraev E A et al. 1977 Zh. Eksp. Teor. Fiz 72 3; Balitsky I I et al. 1978 Sov. J. Nucl. Phys. 28 822
[3] See e.g. Devenish R 2002 Proceedings PIC 2002, Stanford, CA, 20-22 Jun 2002, Preprint hep-ex/0208043
[4] Gribov L 1983 Phys. Rept. 100 1; Mueller A H and Qiu J w 1986 Nucl. Phys. B268 427
[5] Gelis F 2007 these proceedings, Preprint hep-ph/0701225 and refs. therein
[6] Balitsky I 1996 Nucl. Phys. B 463 99; Kovchegov Yu 2000 Phys. Rev. D 61 074018; Jalilian-Marian J et al. 1997 Nucl. Phys. B504 415; Iancu E et al. 2001 Nucl. Phys. A692 583
[7] d’Enterria D 2006 Eur. J. Phys. A to appear, Preprint hep-ex/0610061
[8] Betts R [CMS Collaboration] 2007, these proceedings
[9] CMS/TOTEM Prospects for Diﬀeractive and Forward Physics at the LHC, CERN-LHCC-2006-039/G-124
[10] Kharzeev D et al. 2005 Nucl. Phys. A747 609
[11] Armesto N et al. 2005 Phys. Rev. Lett. 94 022002
[12] CMS Physics TDR: High Density QCD with Heavy-Ions, CERN-LHCC-2007-009
[13] Armesto N and Pajares C 2000 Int. J. Mod. Phys. A15 2019
[14] Baltz A et al. 2007 Ultraperipheral Collisions at the LHC, J. Phys. G: Nucl. Phys. in preparation
[15] Klein S R and Nystrand J 1999 Phys. Rev. C 60 014903; Baltz A et al. 2002 Phys. Rev. Lett. 89 012301
[16] Jager B et al. 2004 Phys. Rev. D 70 034010
[17] Müller A H and Navelet H 1987 Nucl. Phys. B282 727; Vera A S and Schwennsen F 2007 hepph/0702158
[18] Marquet C and Royon C 2006 Nucl. Phys. B739 131