Search for the gluon saturation in the deep small-x region with the LHCb Experiment.

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Abstract

High-energy collisions and the excellent instrumentation in the forward direction makes LHCb one of the best candidates to confirm and explore the expected gluon saturation regime. This manuscript describe the ongoing efforts in LHCb to explore the small-x region in the search of the gluon saturation scale Q_S^2.

1 Introduction

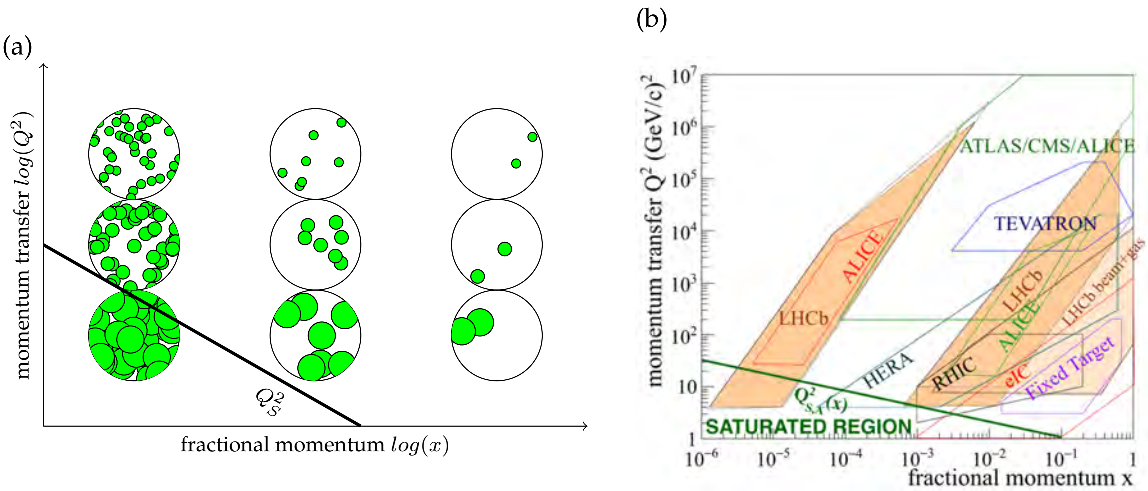

Figure 1: (a) Gluon (green circles) distribution evolution in a nucleus. (b) Kinematic coverage of past, current and future experimental facilities and the expected gluon saturation scale as estimated in [1, 2].

One of the most impacting results from DESY was the observation of a rapid growing of gluon densities towards the small-x region [3]. The measurement immediately implied that the unitarity must be violated at some point at small-x if gluon densities grow on the scales which was observed in these $e-p$ collisions. The increasing gluon densities towards small-x are attributed to bremsstrahlung of large-x gluons. Gluon with virtuality smaller than $Q_S(x)$ will start to overlap their wave functions with neighbors (Fig. 1-a). In this saturated scenario gluons may start to fuse forming large-x gluons. Phenomenological work in [1] used HERA data to parameterize the saturation scale according to $Q_S(x) = (x_0/x)^\lambda$. Later work in [2] stipulated that in nucleus collisions the gluon density is enhanced by the Lorentz contraction of the nucleus at the probe rest frame. That is, the saturation scale in the nucleus is amplified by a factor $A^{1/3}$ relative to the saturation in protons. This theory turns pA collisions an interesting environment for the gluon saturation search, not requiring a too small virtuality of the probe to observe it.

The observation of gluon saturation would be a benchmark in QCD studies and astrophysics. At some point after the Big Bang there was a gluon saturated regime which may defined the fate of the universe. Saturated gluon regime and gluon fluxes, such as glasmas, may dominate the initial stages of high-energy nuclear collisions. Future high-energy colliders, such as FCC, may have particle production mostly from the gluon saturated regime. The Color-Glass Condensate (CGC) is the effective theory to calculate non-perturbative QCD using the saturation scale as a reference. The model presume that in the saturated regime the wall of condensate gluons in the nucleon looks static in the short time scale of the crossing species [4].

The unambiguous experimental evidence of the gluon saturation regime is still lacking. The approache to observe gluon saturation in hadronic colliders is to measure particle yields at forward directions in pA and pp collisions. If gluon saturation is amplified in pA collisions, we should see a large suppression of particle yields in these collisions relative to the same scaled yields in pp. Large π^0 [5] and dijet-like [6] yield suppression were observed in forward measurements at RHIC. However, other nuclear effects can also produce yield suppressions, such as parton shadowing and initial-state parton energy loss. A review of initial-state effects in nucleus can be found in [7]. Similar measurements at LHC usually lacks the forward coverage to reach the small-x region or the probes which can be measured carry a large virtuality Q^2 which is out of the range of the expected saturation scale in nucleus.

2 The LHCb Experimental Apparatus.

The LHCb experiment [8] is a single arm general purpose detector covering the pseudorapidity range 1.6< η <4.9 with e, μ, π, K, p, γ identification in a momentum range 1< $p(GeV/c)$ <100. The detector has jet reconstruction capabilities and interaction point detection resolution < 80 μm. During the LHC Run1 and Run2 the experiment operate with data acquisition rate of 1 MHz which is going to increase to 40 MHz rate with no hardware trigger and online reconstruction after the current long shutdown. This setup makes LHCb the sole detector fully instrumented at forward rapidity at LHC. Figure 1-b shows the kinematic coverage of several experimental facilities with emphasis on the broad coverage of LHCb and its reach into the expected gluon saturated regime.

Central exclusive processes (CEP) in pp and ultra-peripheral in PbPb events are detected with a high-rapidity detector (HeRSHeL) covering 5< $|\eta|$ <9 [9]. LHCb has two modes of operation for nuclear physics: i) the collider mode which is what all LHC detectors operate, and ii) the fixed target mode, or SMOG, where the beam species collide with a low pressure noble gas inside the vertex detector (VELO). The center of mass energies reached in SMOG mode are $\sqrt{s_{NN}}$ =110 GeV in p+gas and $\sqrt{s_{NN}}$=69 GeV in Pb+gas. The rapidity at the center of the mass in p+gas is -3< y^* <0.5 and in Pb+gas is -2.5< y^* <1, depending on the gas. Details on the current and future SMOG program can be found in [10].

3 Recent results from the LHCb nuclear physics program.

Thanks to its excellent particle identification, momentum resolution and vertex determination, the LHCb is pioneering in the study of exotic particles in high multiplicity environments. A 20-year long debate on the nature of the X(3872) particle may be close to the end with the observation of its significant suppression in high multiplicity pp collisions at $\sqrt{s}$ =8 TeV [11]. The rate which the X(3872) suppress may be crucial in determining if it is a compact tetraquark or a molecular two-mesons structure. The X(3872) peak was also observed in pPb and Pbp collisions at $\sqrt{s_{NN}}$= 8.16 TeV.

Heavy flavor production in pPb collisions is one of the well known probes for initial-state nuclear effects and nuclear Parton Density Function (nPDF) constraints. LHCb has measured D-hadrons [12], B-hadrons [13] and non-prompt J/ψ [14] in forward (pPb collisions) and backward (Pbp collisions) rapidities spanning its coverage between -4.5< $|y^*|$ <4. The LHCb data is typically more precise than the current nPDFs and it has been used to additionally constrain the EPPS16 nPDF [15].

LHCb has accumulated several results with quarkonia in CEP events covering different scales of γ-pomeron fusion with J/ψ and ψ(2S) [16, 17] and bottomonia [18]; di-pomeron exchange with χ_c [19]; and double pomeron exchange with double charmonia [20]. Photon interaction with nucleus is explored with coherent J/ψ production in ultra-peripheral PbPb collisions [21]. The most recent PbPb data taken in 2018 provided 20 times more statistics for the coherent J/ψ measurement which will allow the discrimination of several models describing the small-x gluon distribution inside the nucleus.

4 Upcoming results with direct photons.

One of the few gaps of opportunities to access the expected gluon sautared region is direct photon production from inverse Compton process ($q + g \rightarrow \gamma + q$). This process has no significant NLO contribution and the kinematic variables Q^2 and x can be easily calculated from

$$x_{Pb} \approx \frac{p_{T,\gamma}}{\sqrt{s_{NN}}} e^{-y_\gamma} + \frac{p_{T,\gamma}}{\sqrt{s_{NN}}} e^{-y_h} \qquad\qquad Q^2 \approx 2p^2_{T,\gamma}, \tag{4.1}$$

assuming the transverse momentum of the photon $p_{T,\gamma}$ and the final-state quark are balanced. The rapidity of the photon y_γ and the leading hadron in the fragmented quark y_h complete the input needed in the calculation. Initial-state effect computations including dynamical shadowing and quark energy loss indicate that these effects are small in forward measurements at LHC [22]. The CGC indicates a strong suppression of direct photon [23] compared to other nuclear effects.

In LHCb photons can be measured mostly in the electromagnetic calorimeter (ECAL) but with limited momentum resolution and background from neutral pion mergers. Photons converted in di-electron pairs inside the detector material, despite its small detection efficiency, are cleaner and profits from the good tracking momentum resolution. Isolated photon+hadron angular correlations provides large statistics, nearly full access to the Compton process kinematics and the possibility to implement a subtraction technique to statistically remove the large dijet background contribution. Figure 2 shows the kinematic reach of the isolated γ+hadron pairs and the angular distribution in three distinct kinematic regions. The excess in the away-side peak indicates the inverse Compton signal.

5 Conclusions.

Despite the large theoretical work regarding gluon saturation, experimental evidences are still blurred by limited experimental coverage at small-x, small Q^2 and competing initial-state effects in

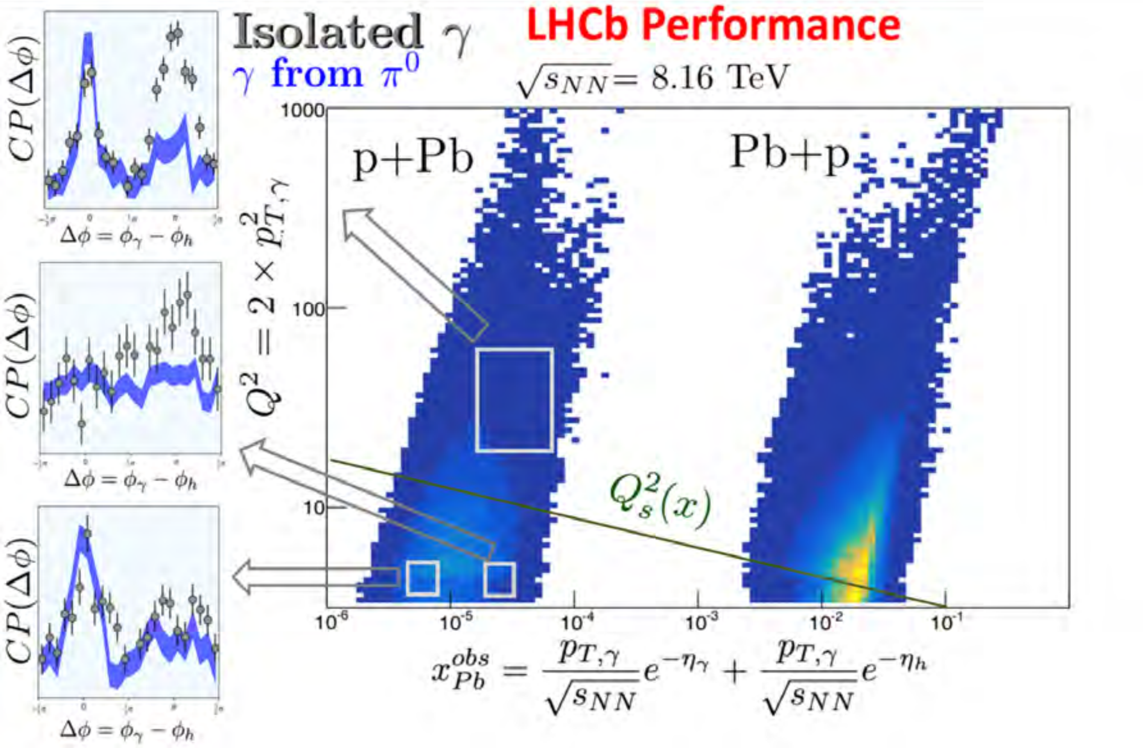

Figure 2: Correlated isolated γ+hadron angular distribution in three kinematic regions measured in pPb and Pbp collisions at $\sqrt{s_{NN}}$=8.16 TeV by LHCb. The blue band in the angular distributions corresponds to scaled dijet contributions measured from $\pi^0\gamma$+hadron pairs.

nucleus. LHCb has to date a unique coverage and instrumentation in the potential gluon saturated region. The experiment is already able to impose stringent constraints to nuclear PDFs with heavy flavor probes, CEP and γ+A processes. Further exploration in the small-x, small Q^2 region has been explored with a well control inverse Compton process obtained in isolated γ+hadron or γ+jet correlations.

Acknowledgements

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