PROCEEDINGS OF SCIENCE

Low x and forward physics

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PoS(DIS2024)004

Exclusive diffractive processes that probe low values of parton fractional momenta are a powerful tool to increase our understanding of QCD. This survey highlights new results shown at the conference on the structure of nucleons and nuclei, the existence of saturation, the nature of pomerons and odderons, and the production of exotic forms of matter beyond the quark model.

31st International Workshop on Deep Inelastic Scattering (DIS2024)
8–12 April 2024
Grenoble, France

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[*] Speaker

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1. Introduction

This brief survey concentrates mainly on exclusive diffraction and highlights new results and hot topics. Relevant talks in the parallel sessions are referenced.

The structure of nucleons is revealed in deep-inelastic scattering as a function of the energy scale, Q, at which the nucleon is probed and the fractional momentum, x, of the parton within. Fig. 1 shows the regions in x and Q^2 accessible at the LHC and where measurements were made at previous experiments. For production of a system with mass m, and rapidity, y, at a hadron collider of centre-of-mass energy, $\sqrt{s}$, then $Q^2 \sim m^2$ and $x_\pm \sim (m/\sqrt{s})\exp(\pm y)$. Superimposed on the plot is an axis of rapidity from which it can be seen that particle production in the *forward* region at the LHC probes one higher-x parton ($> 10^{-2}$) from a region that has previously been measured, and one low-x parton. For low-mass systems, e.g. exclusive ρ-meson production, this probes values down to $x \sim 10^{-6}$.

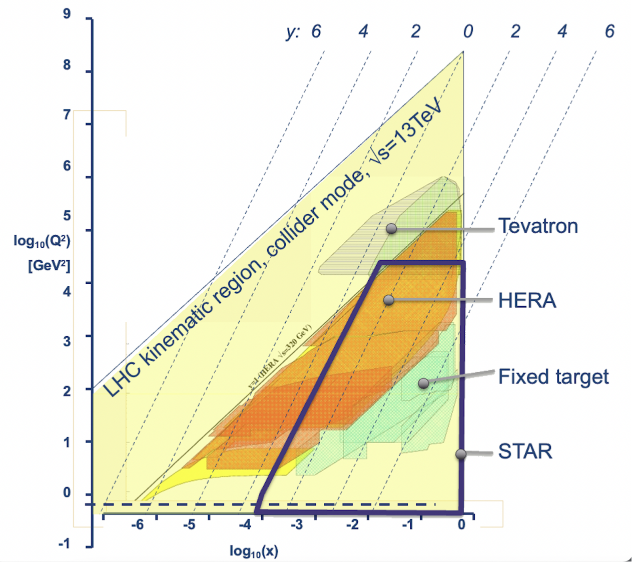

Figure 1: Region in x and Q^2 in which the LHC is sensitive. Also shown are regions where previous measurements were performed at the Tevatron, HERA and at fixed target experiments. The outline shows where STAR is sensitive.

Since all calculations at the LHC rely on knowledge of the partons in the protons, one motivation for measuring forward physics processes is to provide better constraints on the PDFs and GPDs. Most of the processes measured at the LHC are collisions between partons in which hundreds or thousands of particles are produced due to the colour flow that occurs when two partons are removed from the colliding hadrons. Yet these only constitute about half of all interactions. In the remainder, multiple correlated partons (or photons) can be emitted from the hadrons resulting in no net colour-flow, leading to either elastic scattering or diffractive processes. Two colourless propagators emitted from each colliding hadrons give rise to central exclusive diffraction with well-defined quantum numbers for the central system: the three most common configurations are summarised in Fig. 2.

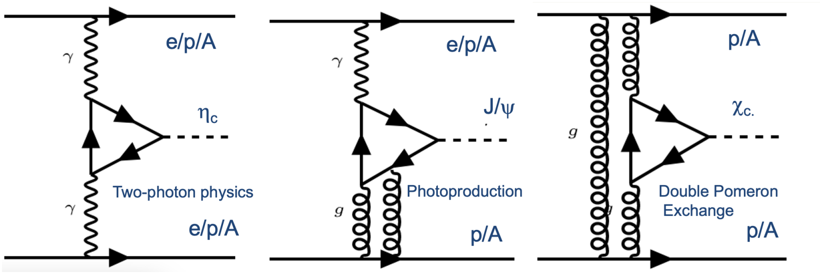

Figure 2: Examples of meson production in central exclusive diffraction in collisions of electrons (e), protons (p) or ions (A).

Because of the simplicity of the final states, studies of particle production through exclusive diffraction are particularly attractive for increasing our understanding of the nature of QCD itself. Firstly, they allow a better understanding of the transition between perturbative and non-perturbative QCD regimes. Secondly, they can improve our understanding of hadrons consistent with the quark model and those that may require extensions such as hybrid states, tetraquarks, molecular states, and glueballs. Thirdly, they increase our understanding of the correlated parton emissions that hide the colour charge, in the form of propagators with even and odd parity, the so-called pomeron and odderon, of which only the former is well established. Fourthly, they can be used to look for saturation. The gluon density in the proton is observed to increase rapidly with decreasing x but this can not continue indefinitely and at some scale it should saturate. Finding unambiguous evidence and seeing this phase-change, is one of the main goals for QCD research.

2. Photo-production

Photo-production of the vector mesons $\omega, \rho, \phi, J/\psi, \psi(2s), \Upsilon$ has been measured at HERA in electron-proton (ep) collisions [1] and are also accessible in proton-proton (pp), proton-ion (pA), and ion-ion (AA) collisions. Since the photon flux is proportional to the square of the charge, the photon emitter can be identified in pA collisions; however, in pp and AA collisions there is a two-fold degeneracy. Photo-production measurements of $\rho, J/\psi, \psi(2s)$ and Υ have been performed at STAR and the LHC [2–12]. In the central region of the LHC the centre-of-mass energy of the photon-proton system is similar to HERA and consistent results are obtained. In the forward region, higher energies (corresponding to lower x values) are accessible and it is of great interest to see whether the cross-sections extrapolate according to QCD or whether additional effects such as saturation are required. A simple linear extrapolation, corresponding to leading-order QCD is insufficient, but next-to-leading order calculations describe the data and can, in principle, be used to extract the gluon parton density functions [13]. Successful fits have also been performed including saturation effects [15–17] showing that the data are not inconsistent with saturation although they also do not require it.

Saturation may be easier to see in AA collisions as the onset of saturation is expected to scale with the nucleon density. Naively the cross-section for $\gamma A \rightarrow VA$ should simply scale from $\gamma p \rightarrow Vp$ with the number of nucleons, but for x below about 0.1 a lower cross-section is observed. This can be due to multiple interactions between the meson and nucleons in the nucleus, as described using the Gribov-Glauber approach [18, 19], but suppression in excess of this may be evidence for saturation. In fact, as shown in Fig. 3 and at this conference, the data seem to require even greater nuclear suppression than predicted in colour-glass condensate models.

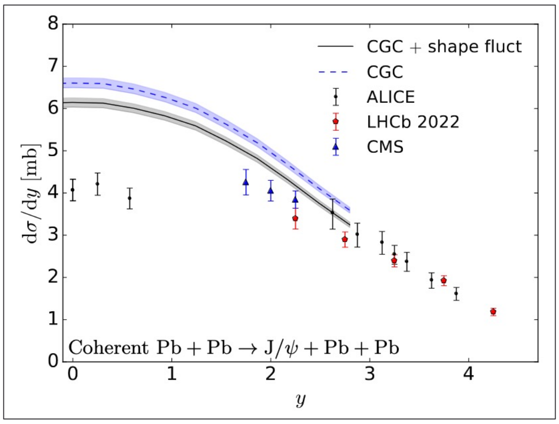

Figure 3: Compilation of J/ψ cross-section results in Pb-Pb collisions at the LHC together with colour-glass condensate predictions, from [14]

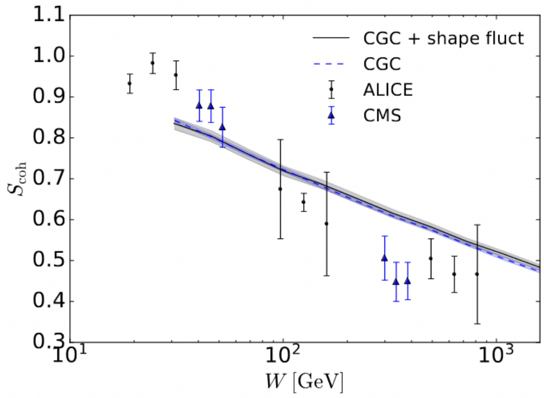

Figure 4: Nuclear suppression factor measured in J/ψ photo-production in Pb-Pb collisions compared to expectations from the colour-glass condensate model, (from [20].)

The inability to identify the photon emitter means that the low-x and high-x partons can not be distinguished. If saturation is truly occurring, one would expect the suppression to become more pronounced with lower values of x. However, as pointed out in [21], when the ions are close, the probability of an additional electromagnetic interactions increases, which can excite one or both ions leading to neutron emission. The presence of zero-degrees calorimeters (ZDC) at ALICE and CMS allow the detection of such neutrons through which the degeneracy can be lifted. At this conference, a summary of results for the nuclear suppression factor was presented and compared to the predictions of the colour-glass condensate model[20]. Higher values of W, the centre-of-mass of the photon-nucleon system, correspond to lower values of x, and the amount of suppression is seen to increase, with a trend as expected from saturation.

Saturation can also manifest itself in the transverse momentum distribution of photo-produced vector mesons. The photon fluctuates into a virtual meson pair long before it passes through the nucleons in the target nucleus. In analogy with optical diffraction, the meson, being obstructed by an obstacle, exhibits a diffraction pattern, where the position of the peaks and troughs depend on the opacity that is proportional to the total cross-section for the meson to interact with a nucleon. In the case of saturation, the target will appear 'blacker' than for the linear QCD expectation. Furthermore, significant shifts in the diffraction pattern as one goes forward, would be a clear signature of saturation since in QCD without saturation only very small shifts are expected due to the total cross-section increasing logarithmically with energy (see [22, 23]). Diffraction patterns have been observed in ρ production by STAR [11] and ALICE [5] while Fig. 5 shows recent results for J/ψ production that were discussed at this conference [24, 25]. At least two diffractive peaks are visible for the ρ meson: higher luminosity running at the LHC is required to see a similar structure for the J/ψ meson.

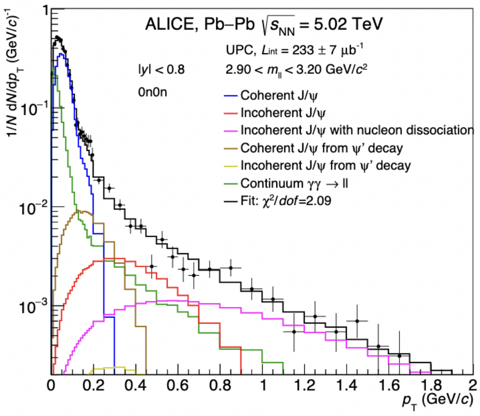

Figure 5: Transverse momentum of J/ψ mesons produced in PbPb collisions where no neutrons are observed.

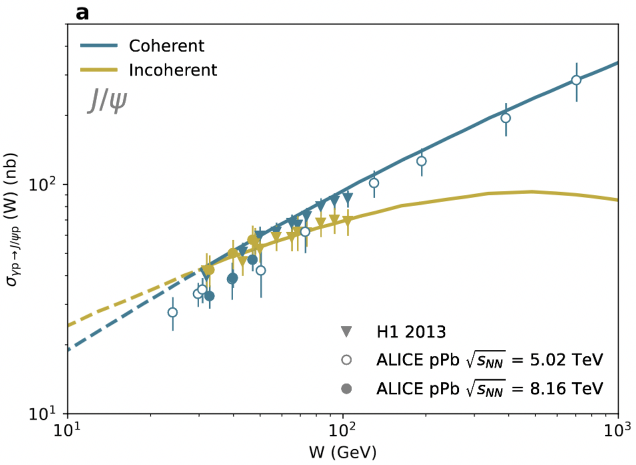

Figure 6: Data and predictions for the relative amount of J/ψ production as a function of photon-nucleon energy from [26].

Incoherent photo-production, in which one of the nuclei breaks up, is a sensitive test of nuclear structure and potentially of saturation too. In the Good-Walker approach [27], the coherent cross-section is proportional to the square of the mean scattering amplitude, $d\sigma_{coh}/dt \sim | < \mathcal{A} > |^2$ and the average colour-charge is probed [28, 29]. Since the total cross-section is proportional to $< |\mathcal{A}|^2 >$, the incoherent cross-section $d\sigma_{incoh}/dt \sim < |\mathcal{A}|^2 > - | < \mathcal{A} > |^2$ and so is sensitive to the variance or fluctuations in the structure. Variously proposed have been models including hot-spots [30], energy-dependent hot-spots [26] and even hot-spots within hot-spots [31], each of which were discussed at this conference. Different features should be testable with data, e.g. in an energy-dependent hot-spot model an interesting feature is shown in Fig. 6, where the incoherent cross-section increases with energy, but when the hot-spots become too numerous, the proton starts to look uniformly full of hot-spots and so the variance (and the incoherent cross-section) then decrease. This should be testable with current LHC data.

Photo-production can also produce direct evidence for the existence of the odderon and support the more indirect evidence for it that comes from differences in elastic scattering at pp and $p\bar{p}$ colliders [32]. Photo-production of C-even mesons would be evidence for the odderon and could be seen either in pA or AA collisions at the LHC [33] or, as reported at this conference, in the potential observation of χ_c mesons at the EIC [34].

3. Double Pomeron Exchange

Colourless exchanges in hadron collisions can also occur through double pomeron exchange. This allows the production of even C-parity mesons and because of the many gluons involved is also an ideal environment in which glueballs might be discovered. A particularly powerful analysis can be performed if both the central system and the outgoing protons can be measured since then the full kinematics of the collision is reconstructed. CMS and TOTEM took data during the unique conditions offered by the LHC beam optics of $\beta^* = 90$ m that occurred for a week in 2018, and in which the beam divergence is reduced allowing the scattered protons to be measured in TOTEM at the same time as the central system was reconstructed in CMS. Di-pion production away from the resonance region was presented at this conference [35] and gives fundamental insights into the pomeron. Fig. 7 shows an azimuthal modulation due to the pure double pomeron exchange mechanism interfering with a re-scattering contribution. Results from the resonance region are eagerly anticipated as they will allow a clean observation of the known f_0 and f_2 mesons as well as a search for exotic phenomena.

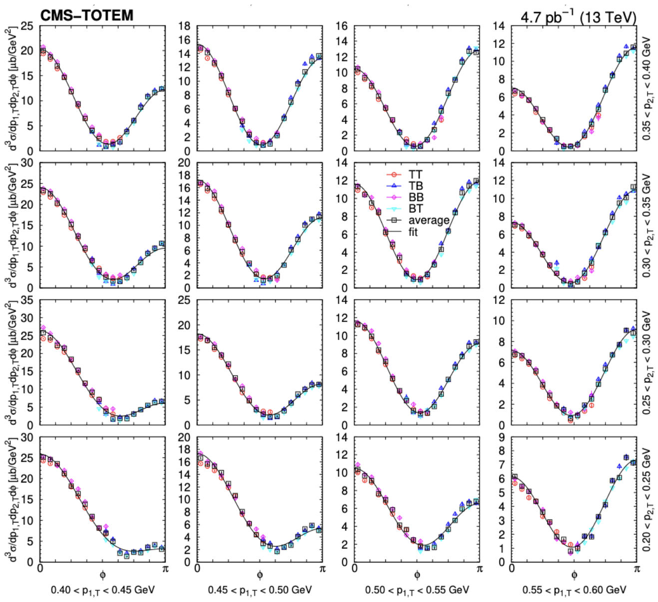

Figure 7: $d^3\sigma/dp_{1,T}dp_{2,T}d\phi$ for di-pion masses between 350 and 650 MeV produced in double pomeron exchange interactions (from [35]).

States beyond the quark model were presented by LHCb at this conference in the analysis of final states containing a J/ψ and a ϕ meson [36]. Fig. 8 shows resonance structures corresponding to $c\bar{c}s\bar{s}$ tetra-quark candidates that were previously seen in the inclusive production and decay of B mesons [37]. Backgrounds are considerably reduced when produced diffractively and the fact that they are produced in gluon-rich environments helps understand their nature. Similar tetra-quark candidates have previously been produced diffractively in the $J/\psi J/\psi$ final state [38].

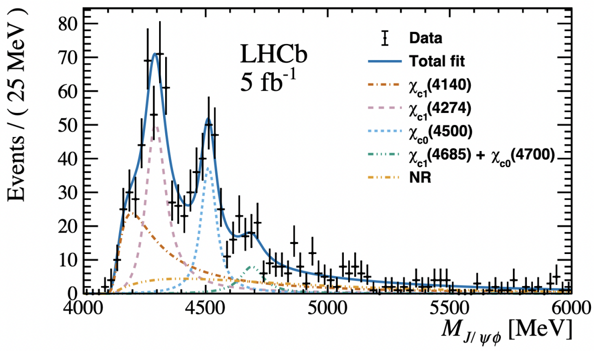

Figure 8: Invariant mass distribution for J/ψ and ϕ mesons produced by double pomeron exchanged (from [36]).

4. Summary

Exclusive diffractive processes are a powerful tool to increase our understanding of QCD. They can uncover the structure of nucleons and nuclei and, particularly in the forward region where they probe low-x gluons, have sensitivity to saturation. Data on the nuclear suppression factor presented at this conference provide preliminary evidence for the existence of saturation. The colourless propagators of QCD, pomerons and odderons, can also be investigated. The clean pure-gluon environment created in double pomeron exchange has recently been used to produce exotic forms of matter beyond the quark model. Searches for glueballs become possible with the precise reconstruction of all final state particles using both central detectors and proton taggers.

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