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Studying gluon GPDs at the EIC via DVMP

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Summary. — The Electron Ion Collider (EIC) is a next-generation hadron physics facility, planned to be built in the coming decade at Brookhaven National Laboratory (BNL), with the intention of further exploring the quark and gluon substructure of hadrons and nuclei. The EIC will address fundamental questions in QCD, probing the interplay of quarks and gluons to learn how they contribute to overall nucleon properties, and how they are affected by the nuclear environment. With heavy ion beams to enable in-depth studies of nuclear matter, alongside the precision of the electromagnetic interaction and the determinative properties of polarised nucleon beams, the EIC is expected to provide scientific opportunities for decades to come. Hard exclusive meson electroproduction processes, also known as deeply virtual meson production (DVMP), are complimentary to the deeply virtual Compton scattering (DVCS) reaction. In DVMP, the scattering reaction produces a meson instead of a photon, and through the study of heavy vector meson reactions, such as J/Ψ, it is possible to probe gluon GPDs and ultimately provide information about saturation when studying the evolution of gluon spatial distribution. The work presented focuses on studies of $J/\Psi \to e^+e^-$ events from ep collisions, and the evaluation of projected detector performance for DVMP measurements in an EIC detector concept. Prospects for extending these studies to other vector meson channels, from ϕ to Υ, are also discussed.

1. – Introduction

Our understanding of the internal structure of the nucleon has been built up via electron scattering experiments, with the measurement of form factors describing the transverse position of partons, and Parton Distribution Functions (PDFs) providing information on their longitudinal momenta. More recently, Generalised Parton Distributions, or GPDs, have been able to relate the transverse and longitudinal information accessible from form factors and PDFs, respectively, to provide a three-dimensional description of the nucleon.

GPDs can be accessed via the complimentary electron scattering processes of DVCS (Deeply Virtual Compton Scattering) and DVMP (Deeply Virtual Meson Production). In the DVMP case, the scattering reaction produces a meson instead of the photon produced in DVCS. In heavy vector meson channels, such as J/ψ, DVMP can probe gluon GPDs and provide information about saturation by measuring the change in gluon spatial distribution from low to high x_B [1].

2. – The electron ion collider

The Electron Ion Collider (EIC) is an upcoming multi-purpose facility which will combine the precision of the electromagnetic interaction with the determinative properties of polarised nucleon beams, as well as perform in-depth studies of nuclear matter. It will do this by colliding polarised electrons with either polarised protons, polarised light ions, or a range of unpolarised heavy ions, and will be built at Brookhaven National Laboratory within the coming decade.

Covering a wide range of centre-of-mass energies (20–100 GeV) and with high luminosities by collider standards (reaching $10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$), the EIC will unlock a new kinematic regime for hadron structure, reaching well into gluon-dominated kinematics and enabling the mapping of 3D and inclusive structure with unprecedented precision. The fully hermetic detector, developed by the ePIC Collaboration, will take the best aspects of the ECCE (EIC Comprehensive Chromodynamics Experiment) [2] and ATHENA (A Totally Hermetic Electron-Nucleus Apparatus) [3] design studies for the EIC, and allow measurement of all final state particles. Instrumentation in the far-forward and far-backward directions is additionally aimed at fully exclusive reconstruction of diffractive processes and photoproduction, respectively.

3. – DVMP studies in ECCE

Building on the EIC Yellow Report [1], the detector performance and efficiency in the context of $J/\psi \to e^+e^-$ events from *ep* collisions were evaluated with ECCE, a predecessor detector concept which is the basis of that being developed by ePIC [4]. An overview of the ATHENA concept can be found in [3]. The main goal of this study was to quantify the detector acceptance for this reaction in one of the kinematic regions. The final results are estimated for $10\,\mathrm{fb}^{-1}$ luminosity.

For this study, events for the $J/\psi \to e^+e^-$ reaction were generated with the lAger generator. Described as a modular accept-reject generator, lAger is capable of simulating both fixed target and collider kinematics, and has previously been used for vector meson studies at EIC kinematics, with significant recent developmental effort in support of DVMP. The kinematics studied in this analysis correspond to electron and proton beam energies of 18 GeV and 275 GeV, respectively, and the event samples were processed through a Geant4-based simulation to recreate the full ECCE detector response. These ECCE-simulated events were selected with the requirements summarized in table I.

TABLE I. – *Kinematic limits in the J/ψ study.*

Variable	Definition	Range
Q^2 [GeV]	$Q^2 = -q^2 = -(k_e - ke')$	0 to $50\,\mathrm{GeV}^2$
x_B	$x_B = \frac{Q^2}{2\cdot k_p \cdot q}$	0 to 0.15
η	$\eta = -\ln\left(\tan\frac{\theta}{2}\right)$	-4 to 4

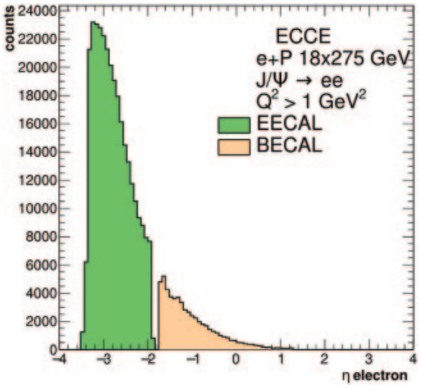

Fig. 1. – Scattered electron detection, showing most electrons go to the far-backward region.

To select $J/\psi \to e^+e^-$ events, three tracks were required. Two of these were positive and the third negative, with J/ψ selection attempted via the negative track and its two possible combinations with the positive tracks. If the J/ψ reconstructed mass was in the 2 to 5 GeV window for a single combination of tracks (1 negative and 1 positive), the event was processed, otherwise, the event was discarded. Figure 1 shows the η distribution of the scattered electron from reconstructed J/ψ events, indicating these are mostly detected in the backward region, with some detected in the barrel. The left-hand side of fig. 2 shows that the lepton pair daughter of the J/ψ is detected in three regions (backward, central, and forward). The proton was detected in the far-forward region, which has several detector subsystems, including Roman Pots and a B0 silicon detector. More details of the detector subsystems in ECCE can be found in [2]. The B0 was out of the acceptance for this kinematic sample, and fig. 3 shows the distribution of the protons detected in the Roman Pots. These studies have shown that, in the ECCE design, a

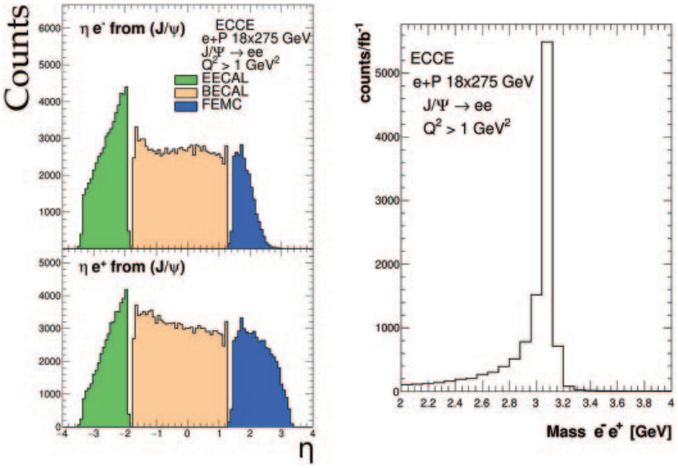

Fig. 2. – Electron (top left) and positron (bottom left) from J/ψ detection in the calorimeters, with reconstructed J/Ψ mass (right).

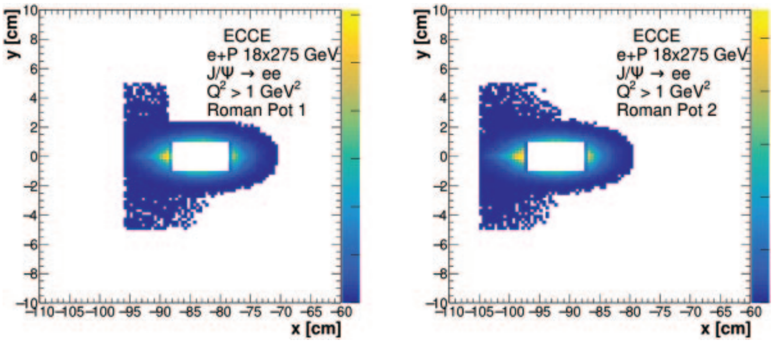

Fig. 3. – Proton detection in Roman Pot 1 (left) and 2 (right).

large number of protons go through the beam pipe and cannot be detected.

The e^+e^- invariant mass, and the missing mass reconstruction for the whole process, will be essential to check the exclusivity of the measurement. The right-hand side of fig. 2 shows the e^+e^- reconstructed mass from this simulation.

The cross-section, assuming a luminosity of $10\,\mathrm{fb}^{-1}$, was extracted as a function of $-t$ and is displayed in fig. 4. The acceptance of the ECCE detector was fully considered for the events generated, but primary limiting factor in the measurement of these processes comes from the far-forward detectors.

The physics interest resides in the evolution of the $-t$ dependence of the cross-section,

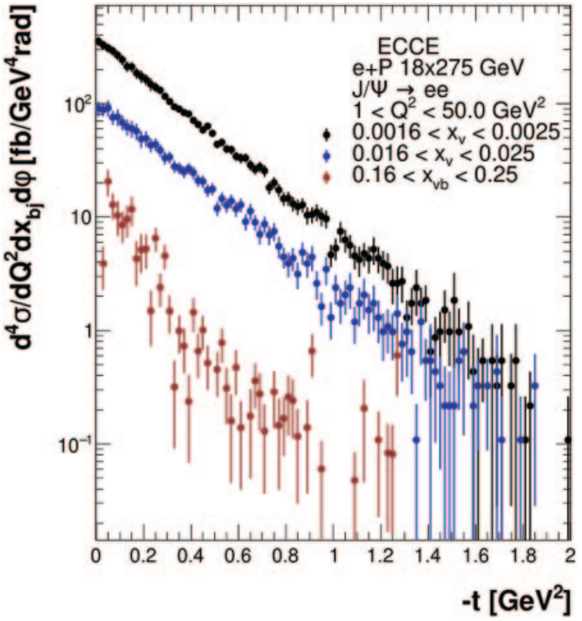

Fig. 4. – (Color online) Differential cross-section *vs.* Momentum transfer t for the 18×275 beam setting studied in x_v slices, $0.0016 < x_v < 0.0025$ (black), $0.016 < x_v < 0.025$ (blue) and $0.16 < x_v < 0.25$ (red).

with the Q^2 dependence important to allow for multi-dimensional binning. To a large extent, the Q^2 accepted range is independent of the $-t$ range, and we have shown the evolution with $-t$ only here.

3˙1. *Future work.* – The ECCE studies shown are just a starting point, demonstrating the capabilities of an EIC detector concept. Now, in the ePIC Collaboration, future optimisation of detector design can be motivated by the lessons learned in previous design studies, including ECCE and ATHENA. For example, it is clear from figs. 1 and 2 that a significant proportion of $J/\psi \to e^+e^-$ events will have their scattered electron, and the J/ψ decay electron, falling in the same detector region. It will be important to develop means of reliably separating these in real data.

$J/\psi \to e^+e^-$ is just one channel through which DVMP can be studied at EIC. Alternative final states, such as $\mu^+\mu^-$, should also be evaluated, as should other vector mesons, such as Υ. This will form the basis of future efforts in DVMP within ePIC.

4. – Summary and outlook

The EIC is one of the next big machines in Nuclear Physics, with first beam expected in the early 2030s. This facility will reach well into gluon-dominated kinematics with unprecedented precision, leveraging polarisation, electromagnetic probes and heavy ions to enhance its determinative properties. A preliminary evaluation of $J/\psi \to e^+e^-$ events in the ECCE EIC detector concept has shown that DVMP on this channel is feasible at such a facility, and has enabled the identification of future priorities for this work.

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This work is part of the Exclusive, Diffractive and Tagging group of the ePIC Collaboration, with all figures shown from an earlier iteration of this working group as part of the ECCE consortium. The analysis shown was led by this paper's by NS, and the authors acknowledge the wider ECCE coonsortium's contributions, particularly from the software group for developing the tools necessary to realise this work.

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