Particle physics applications of the AWAKE acceleration scheme

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Abstract

The AWAKE experiment had a very successful Run 1 (2016–8), demonstrating proton-driven plasma wakefield acceleration for the first time, through the observation of the modulation of a long proton bunch into micro-bunches and the acceleration of electrons up to 2 GeV in 10 m of plasma. The aims of AWAKE Run 2 (2021–4) are to have high-charge bunches of electrons accelerated to high energy, about 10 GeV, maintaining beam quality through the plasma and showing that the process is scalable. The AWAKE scheme is therefore a promising method to accelerate electrons to high energy over short distances and so develop a useable technology for particle physics experiments. Using proton bunches from the SPS, the acceleration of electron bunches up to about 50 GeV should be possible. Using the LHC proton bunches to drive wakefields could lead to multi-TeV electron bunches, e.g. with 3 TeV acceleration achieved in 4 km of plasma. This document outlines some of the applications of the AWAKE scheme to particle physics and shows that the AWAKE technology could lead to unique facilities and experiments that would otherwise not be possible. In particular, experiments are proposed to search for dark photons, measure strong field QED and investigate new physics in electron–proton collisions. The community is also invited to consider applications for electron beams up to the TeV scale.

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1 Introduction

The AWAKE experiment shows great promise to be able to provide electron beams at high energy ranging up to the TeV scale. The experiment and its plans are described in another submission to this process [1] and assuming AWAKE continues to successfully demonstrate the technique, particle physics applications of the AWAKE scheme can already be considered. The advantage of using proton-driven plasma wakefield acceleration as used by AWAKE is the promise to be able to accelerate electrons to high energy in one acceleration stage with relatively high gradients of $\mathcal{O}$(GV/m). This means that using proton bunches from the SPS, the acceleration of electron bunches up to about 50 GeV should be possible. Using the LHC proton bunches to drive wakefields could lead to multi-TeV electron bunches, e.g. with 3 TeV acceleration achieved in 4 km of plasma [2].

Currently, high energy electrons ($> 50\,\mathrm{GeV}$) are only possible as part of the secondary SPS beam and at low rate. Therefore, using the AWAKE scheme would provide the highest energy, high charge electron bunches in the world. The acceleration of electrons to high energies opens up the possibility of new particle physics experiments [3]: the search for dark photons (see Section 3.1); measurement of quantum electrodynamics (QED) in strong fields (see Section 3.2); and high energy electron–proton collisions (see Section 3.3). Further experimental ideas may emerge and the community is invited to consider possible uses of high-energy electron beams. In parallel, the AWAKE technology will be further developed which is critical for any application to particle physics. The integration and technical issues related to realising these experiments within the CERN site are part of a separate submission [4].

2 AWAKE experiment

The AWAKE experiment had a tremendously successful Run 1 (2016–8), demonstrating proton-driven plasma wakefield acceleration for the first time, through the observation of the modulation of a long proton bunch into micro-bunches [5, 6] and the acceleration of electrons up to 2 GeV in 10 m of plasma [7].

The AWAKE Run 1 programme finished in November 2018 along with all experiments that rely on the CERN proton accelerators. The SPS will start up again in 2021 and run for four years until 2024 and an ambitious AWAKE Run 2 programme is being developed for this period. The aims of AWAKE Run 2 are to have high-charge bunches of electrons accelerated to high energy, about 10 GeV, maintaining beam quality through the plasma and showing that the process is scalable. This will require development of the initial electron source, beam and plasma diagnostics as well as development of the plasma technology which can fulfil these ambitious goals. The final goal by the end of AWAKE Run 2 is to be in a position to use the AWAKE scheme for particle physics experiments.

3 Possible particle physics experiments

A high-energy electron beam with high-charge bunches from tens of GeV up to TeV energies has many potential applications. Three are outlined in detail in the following sub-sections, but other possibilities are briefly discussed here. A condition of any application is that the particle physics goals must be new, interesting and do something not done elsewhere. An oft mooted application of plasma wakefield acceleration is the development of a high energy, high luminosity linear e^+e^- collider. However, such a collider is a challenge for all accelerator technology and so to have this as the first application of plasma wakefield acceleration is ambitious. Hence, the approach taken here is to consider experiments, such as fixed-target experiments and an electron–proton collider, which have less stringent requirements on the quality of the beam. A natural progression would be to build such accelerators before attempting to develop a high energy, high luminosity linear e^+e^- collider. In this way, the accelerator technology can be developed whilst still carrying out cutting-edge particle physics experiments.

A high-energy electron beam could be used as a test-beam facility for either detector or accelerator studies. There are not many such facilities world-wide and they are often over-subscribed. The characteristics of the electron beam which would make it rather distinct are: the high energy which can be varied; a pure electron beam with low hadronic backgrounds; a high bunch charge; and longitudinally short bunches. These properties may not be ideal or will be challenging for detector studies which usually rely on single particles. However, as an accelerator test facility the bunched structure and flexibility in energy will be useful properties.

The AWAKE scheme could be used to accelerate bunches of muons to high energies with small losses through decay of the muons. In the recently proposed scheme for the front end of a muon collider [8], bunches of 6×10^9 μ^+ and μ^- are produced with $\sigma_z = 100\,\mu$m and $\sigma_r = 40\,\mu$m. Initial estimates indicate that such bunches of muons could be effectively accelerated given electric fields of 2 GV/m, which can be achieved with LHC proton bunches.

The future circular collider (FCC) would be an excellent driver of plasma wakefields given the very high proton energy and the small bunch emittance [9]. Introducing long plasma cells in the straight sections of the FCC could lead to the production of multi-TeV electron bunches, further greatly extending the physics capability of the FCC. It may also be possible to accelerate electron bunches to 50 GeV or more in the straight sections without significant loss of protons, thus allowing for a high luminosity ep or e^+e^- programme at moderate additional cost.

There are most certainly other possible applications of proton-driven plasma wakefield acceleration, encapsulated in the AWAKE scheme, that could be proposed and investigated. This document represents some compelling ideas, with the following sections discussing the most developed ideas.

3.1 Dark photon experiment

Dark photons [10–12] are postulated particles which could provide the link to a dark or hidden sector of particles. This hidden sector could explain a number of issues in particle physics, not least of which is that they are candidates for dark matter which is expected to make up about 80% of known matter in the Universe. Dark photons are expected to have low masses (sub-GeV) [13, 14] and couple only weakly to the Standard Model particles and so would have not been seen in previous experiments. The dark photon, labelled A', is a light vector boson which results from a spontaneously broken new gauge symmetry and kinetically mixes with the photon and couples to the electromagnetic current with strength $\epsilon \ll 1$. Recently, experimental and theoretical interest in the hidden sector has increased and is discussed in recent reviews on the subject [15, 16].

A common approach to search for dark photons is through the interaction of an electron with a target in which the dark photon is produced and subsequently decays. This process is shown in Fig. 1 in which the dark photon decays to an e^+e^- pair. The NA64 experiment is already searching for dark photons using high-energy electrons on a target [17–19], initially measuring the dark photon decaying to dark matter particles ("invisible mode") and so leaving a signature of missing energy in the detector. Although high-energy electrons of 100 GeV are used, a limitation of the experiment is that the rate of electrons is about 10^6 electrons per second as they are produced in secondary interactions of the SPS proton beam.

Based on a GEANT4 [20] simulation of the NA64 experiment, the setup has been modified to cater for the use of electron bunches rather than single electrons. Default physics processes, including dark photon production and decay, are implemented in the GEANT4 simulation. A schematic of the setup is shown in Fig. 2 where the main components are shown. A 10 cm long tungsten target is followed by a 10 m long volume in which the dark photon can decay. The decay products, the e^+e^- pair, are then separated via a dipole magnet and detected in micromegas tracker planes (MM1, MM2 and MM3), followed by a tungsten–plastic shashlik electromagnetic calorimeter (ECAL). The analysis is based on well-separated hits (> 1 mm) in the three tracker planes, as well as low background rates from the opti-

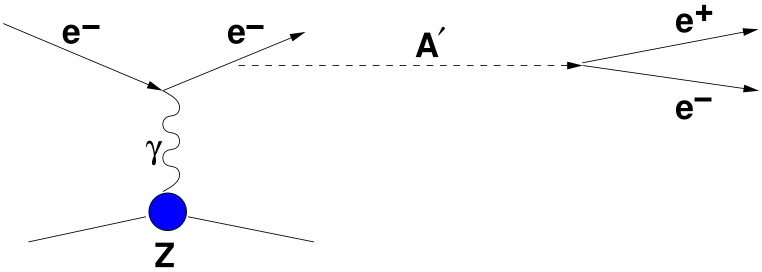

Fig. 1: A representation of the production of a dark photon, A', in a fixed-target experiment with an electron beam. The dark photon subsequently decays to an e^+e^- pair.

mised target thickness. Therefore a dark photon decay is determined via detection of the decay products, reconstruction of a displaced vertex and reconstruction of the A' invariant mass. The sensitivity to dark photon production is evaluated at 90% confidence level in the $\epsilon - m_{A'}$ plane, assuming a background-free case and an overall signal reconstruction efficiency of ∼50%.

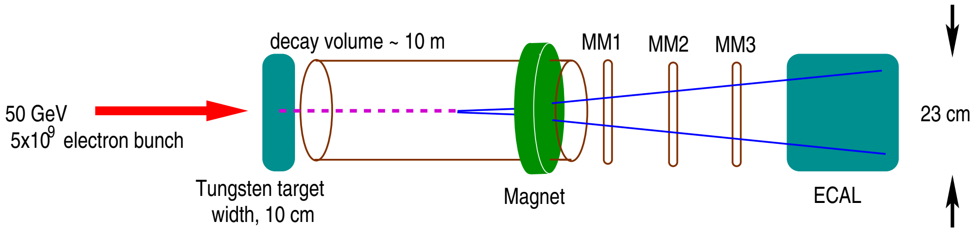

Fig. 2: A sketch of the experimental setup for a bunch of 5×10^9 electrons each of 50 GeV produced via the AWAKE scheme impinging on a tungsten target of depth 10 cm. The target is followed by a decay volume and a dipole magnet to separate the electrons and positrons which are then tracked through three tracker planes (MM1, MM2 and MM3), followed by an electromagnetic calorimeter (ECAL).

The NA64 experiment is, however, already making significant progress investigating new regions of phase space for dark photons and as shown in Fig. 3 will cover much new ground in the $\epsilon - m_{A'}$ plane. Given the limitations of the number of electrons on target, the AWAKE acceleration scheme could make a real impact as the number of electrons is expected to be several orders of magnitude higher. Assuming a bunch of 5×10^9 electrons and a running period of 3 months gives 10^{16} electrons on target and this is shown in Fig. 3; to visualise the effect of the number of electrons on target, the expectation for 10^{15} electrons is also shown. Our results in the figure clearly show that we will be able to probe a new region, in particular extending to higher masses in the region of $10^{-3} < \epsilon < 10^{-5}$. Also shown in the figure are results using bunches of electrons, each of energy 1 TeV, again with 10^{16} electrons on target. Such a search could be part of a future collider programme, e.g. a very high energy ep collider (discussed in Section 3.3), in which active use of the beam dump is made. The higher energy electron beam extends the sensitivity significantly to higher mass dark photons, covering a region unexplored by current or planned experiments, between the regions covered by current colliders and previous high intensity beam-dump experiments.

Further studies are ongoing and a higher number of electrons on target should be possible depending on the SPS injection scheme as well as the success of AWAKE in accelerating bunches of electrons. An optimised detector configuration will be investigated, as will other decay channels, such as $A' \to \mu^+\mu^-$ or $A' \to \pi^+\pi^-$ as well as the invisible modes, and effects of the beam energy. Such an experiment could be realised during and after LS3 in extensions of the current AWAKE area; technical studies of this possibility and infrastructure requirements are discussed elsewhere [4].

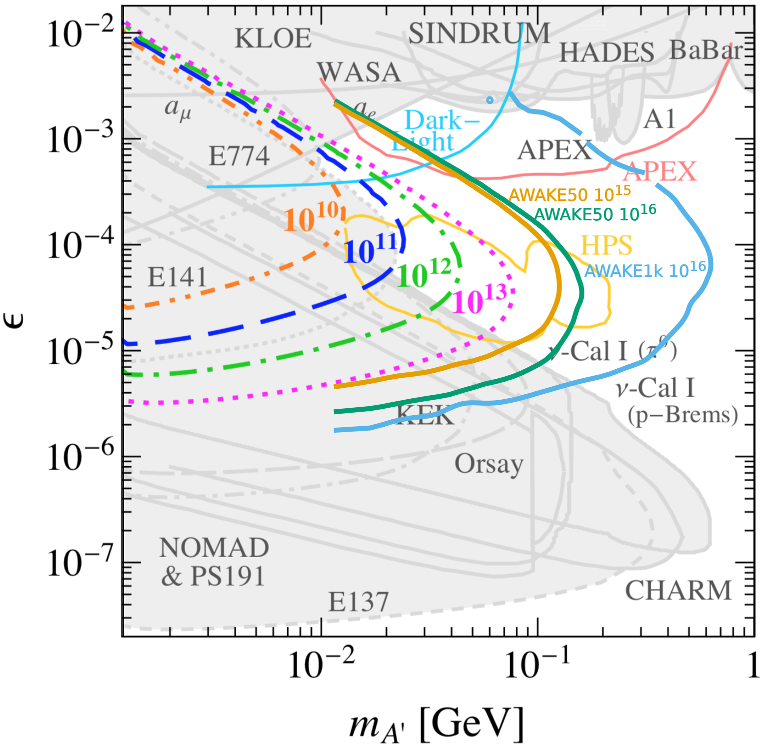

Fig. 3: Limits on dark photon production decaying to an e^+e^- pair in terms of the mixing strength, ϵ and dark photon mass, $m_{A'}$, from previous measurements (light grey shading). The expected sensitivity for the NA64 experiment is shown for a range of electrons on target, $10^{10} - 10^{13}$. Expectations from other potential experiments are shown as coloured lines. Expected limits are also shown for 10^{15} (orange line) or 10^{16} (green line) electrons of 50 GeV ("AWAKE50") on target and 10^{16} (blue line) electrons of 1 TeV ("AWAKE1k") on target provided to an NA64-like experiment by a future AWAKE accelerator scheme; these are the the results of work performed here.

3.2 Strong-field quantum electrodynamics

The theory of electromagnetic interactions, QED, has been studied and tested in numerous reactions, over a wide kinematic range and often to tremendous precision. The collision of a high-energy electron bunch with a high-power laser pulse creates a situation where QED is poorly tested, namely in the strong-field regime. In the regime around the Schwinger critical field, $\sim 1.3 \times 10^{18}$ V/m, QED becomes non-linear and these values have so far never been achieved in controlled experiments in the laboratory. Investigation of this regime could lead to a better understanding of where strong fields occur naturally such as on the surface of neutron stars, at a black hole's event horizon or in atomic physics.

In the presence of strong fields, rather than the simple $2 \to 2$ particle scattering, e.g. $e^- + \gamma \to e^- + \gamma$, multi-particle absorption in the initial state is possible, e.g. $e^- + n\gamma \to e^- + \gamma$, where n is an integer (see Fig. 4). Therefore an electron interacts with multiple photons in the laser pulse and a photon can also interact with multiple photons in the laser pulse to produce an e^+e^- pair, also shown in Fig. 4. For more details on the processes and physics, see a recent review [21].

The E144 experiment [22] at SLAC investigated electron–laser collisions in the 1990s using bunches of electrons, each of energy about 50 GeV, but due to the limitations of the laser, they did not reach the Schwinger critical field in the rest frame of the electrons. With the advances in laser technology over the last 20 years, these strong fields are now in reach [23]. However, the current highest-energy bunches of electrons of high charge are delivered by the European XFEL at 17.5 GeV and the AWAKE

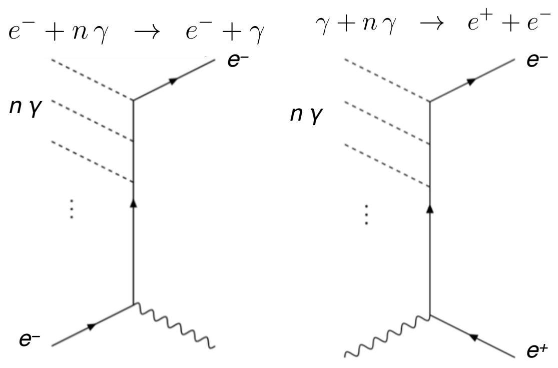

Fig. 4: A Feynman diagram representation of (left) Compton scattering of an electron and (right) production of an e^+e^- pair in the field of a high-power laser in which absorption of multiple photons has taken place.

scheme has the possibility to provide a higher-energy electron beam which would then be more sensitive to the e^+e^- pair production process and probe a different kinematic regime. This is shown in Fig. 5, where the production rates for an AWAKE beam are much higher, particularly at high energies. AWAKE is compared to E144 and two potential experiments at FACET II and LUXE; typical parameters for the experiments are given in Table 1.

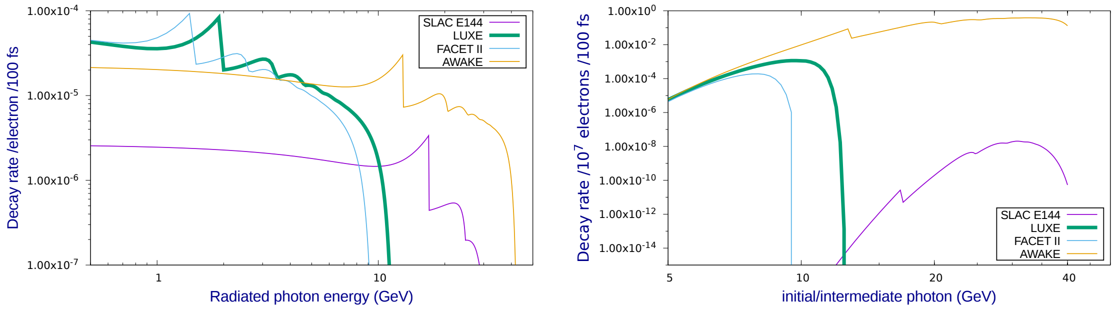

Fig. 5: (Top) energy of produced photons in reaction $e^- + n\gamma \rightarrow e^- + \gamma$ and (bottom) energy of photons in the pair production process, $\gamma + n\gamma \rightarrow e^- + e^+$, where n is an integer. Results are shown for the only experiment that has so far probed close to this strong-field regime (SLAC E144), two proposed experiments (LUXE and FACET II) and what would be possible with 50 GeV electrons from AWAKE.

Table 1: Laser and electron bunch parameters achieved for the E144 experiment. Typical parameters are shown for planned experiments; they will use much shorter pulses leading to higher power than E144.

Parameter	E144	LUXE	FACET II	AWAKE
Laser wavelength (nm)	527/1053	527/1053	527/800/1053	527
Laser energy (J)	2	2	1	1
Laser transverse size (μm^2)	50	100	64	64
Laser pulse length (ps)	1.88	0.05	0.04	0.04
Electron energy (GeV)	46.6	17.5	15	50
Electrons per bunch	5×10^9	6×10^9	5×10^9	5×10^9

With the higher rates possible for strong field pair production with AWAKE electrons, the Schwinger tunnelling regime will be reached in the rest frame. The signature of this regime will be an asymptote to a simple exponential dependence on the Schwinger critical field. This makes accessible the first experimental measurement of the Schwinger critical field strength [24].

3.3 High energy electron–proton collisions

A natural avenue of study with a high-energy electron beam is the deep inelastic scattering of electrons off protons or ions in order to study the fundamental structure of matter [25]. The simplest experimental configuration is where a lepton beam impinges on a fixed target and many such experiments have been performed in the past. So far only one lepton–hadron collider, HERA [26], has been built. Potential physics that could be studied at a future deep inelastic scattering fixed-target experiment are to measure the structure of the proton at high momentum fraction of the struck parton in the proton, which could be valuable for the LHC, and to understand the spin structure of the nucleon, which is still poorly known [27].

A thorough survey of previous as well as planned experiments must be carried out to assess the potential of a deep inelastic scattering fixed-target experiment based on a high-energy electron beam of $\mathcal{O}(50)$ GeV from AWAKE. The use of TeV electron beams would lead to fixed-target experiments at significantly higher energies ($\sqrt{s} = 75$ GeV for a 3 TeV electron beam) and comparable to the next generation nuclear physics collider, the EIC, which expects centre-of-mass energies between 20 and 140 GeV.

A high-energy electron–proton/ion (ep/eA) facility could be the first application of plasma wakefield acceleration to particle colliders. In such collisions, the electron generally emits a photon of virtuality Q^2 and strikes a parton carrying a fraction, x, of the proton's momentum. The higher the Q^2, the smaller the probe and hence a more detailed structure can be seen; also low values of x probe low momentum particles and hence the dynamic structure of quark and gluon radiation within the proton. As such, ep/eA collisions provide a detailed picture of the fundamental structure of matter and investigate the strong force of nature and its description embodied within quantum chromodynamics (QCD). Some of the open issues to be investigated in ep/eA collisions are: when does this rich structure of gluon and quark radiation stop or "saturate" as it surely must otherwise cross sections would become infinite; in general, the nature of high-energy hadronic cross sections; and is there further substructure or are partons fundamental point-like objects.

Initial collider designs [28] considered generating electron bunches via the AWAKE scheme with electrons up to about 100 GeV. This has been formulated into the PEPIC (Plasma Electron–Proton/Ion Collider) project in which the SPS protons are used to drive wakefields and accelerate electrons to about $50 - 70$ GeV which then collide with LHC protons. Given the high-luminosity LHC beam parameters and the rate of SPS bunches, the luminosity for PEPIC is currently estimated to be about $1.5 \times 10^{27}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ [4]. Therefore, PEPIC would have essentially the same energy reach as the LHeC project, but with luminosities several orders of magnitude lower. Given integrated luminosities of about $10\,\mathrm{nb}^{-1}$ per year, it would focus on studies of the structure of matter and QCD in a new kinematic domain, in particular at low values of x, and total cross sections where the event rates are high. This collider would be an option for CERN should the LHeC not be realised. Investigation of increasing the luminosity through larger electron bunch population, proton bunch size and the SPS bunch frequency should also be pursued.

A very high energy electron–proton (VHEeP) collider has been proposed [29] in which LHC bunches are used to drive wakefields and accelerate electrons to 3 TeV in under 4 km, which then collide with the counter-propagating proton (or ion) bunch, creating electron–proton collisions at centre-of-mass energies, $\sqrt{s}$, of over 9 TeV. The energies of the electrons could be varied; the distance of 4 km fits comfortably within the circumference of LHC ring, so although there maybe an upper energy limit, lower energies should be achievable. Such centre-of-mass energies represent a factor of 30 increase compared to HERA which allows an extension to low x and to high Q^2 of a factor of 1000. The luminosity is currently estimated to be around $10^{28} - 10^{29}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ which would lead to an integrated luminosity of $1\,\mathrm{pb}^{-1}$ per year. Different schemes to improve this value are being considered such as squeezing the proton (and electron) bunches, multiple interaction points, etc.. However, even at these modest luminosities, such a high-energy electron–proton collider has a strong physics case.

The kinematic reach in Q^2 and x for VHEeP is shown in Fig. 6, with e.g. a minimum requirement of $Q^2 = 1\,\mathrm{GeV}^2$ corresponding to a minimum value of $x \sim 10^{-8}$. At such values, even with integrated luminosities of $10\,\mathrm{pb}^{-1}$, 10s of millions of events are expected. It should be noted that the lowest value of Q^2 measured at HERA was $Q^2 = 0.045\,\mathrm{GeV}^2$, which at VHEeP corresponds to a minimum x value of 5×10^{-10}. At this Q^2, a significantly larger number of events is expected. Hence high precision measurements with negligible statistical uncertainties will be possible at VHEeP. Also shown in Fig. 6 are isolines for the angles of the scattered electron and final-state hadronic system. This highlights the need for instrumentation close to the beam-pipe in the direction of the electron beam in order to be able to measure the scattered electron at low x. It also highlights the need for hermetic instrumentation to measure the hadronic final state where events at low x have a hadronic system at low angles in the direction of the electron beam. Conversely, events at high x have a hadronic system at low angles in the direction of the proton beam. Clearly the detector design for VHEeP will have a number of challenges and will need to be different from conventional collider experiments such as at the LHC.

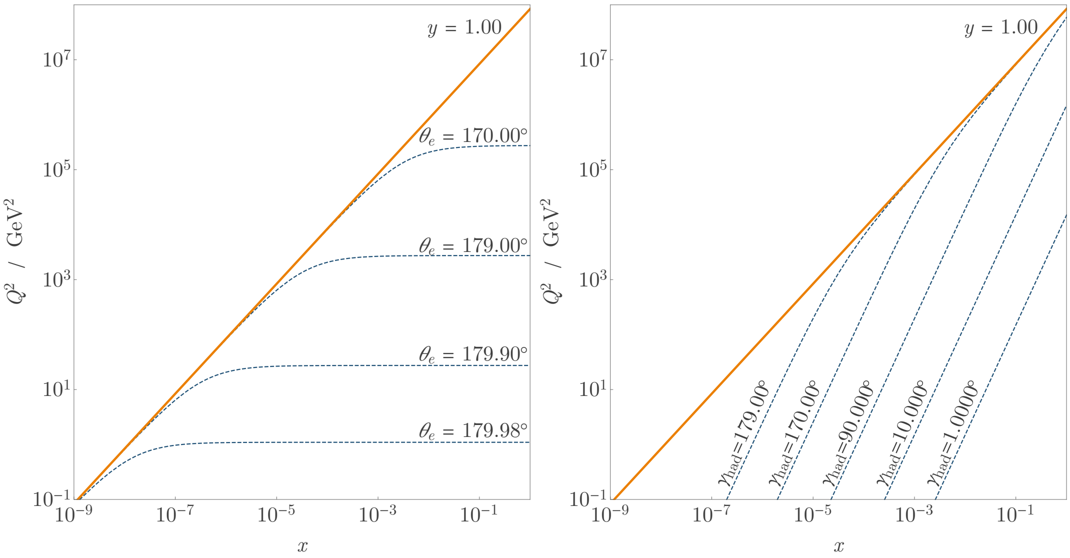

Fig. 6: The accessible Q^2 and x coverage for VHEeP with $\sqrt{s} = 9\,\mathrm{TeV}$ with the kinematic limit of the inelasticity variable $y = 1$ shown. Also shown are (left) lines indicating the electron scattering angle and (right) lines indicating the angle of the final-state hadronic system, where $\theta_e = 0, \gamma_{\mathrm{had}} = 0$ indicates the direction of the proton beam.

The physics potential of VHEeP was discussed in the original publication [29]. An example and recently updated result is shown in Fig. 7, in which the total γp cross section is shown versus the photon–proton centre-of-mass energy, W. This is a measurement which relies on only a modest luminosity and will be dominated by systematic uncertainties. As can be seen from the expected VHEeP data, the measurement is extended to energies well beyond the current data, into a region where the dependency of the cross section is not known. Some models are also shown and they clearly differ from each other at the high energies achievable at VHEeP. These data could also be useful in understanding more about cosmic-ray physics as such collisions correspond to a 20 PeV photon on a fixed target.

The energy dependence of scattering cross sections for virtual photons on protons is also of fundamental interest, and its study at different virtuality is expected to bring insight into the processes leading to the observed universal behaviour of cross sections at high energies. In deep inelastic scattering of elec-

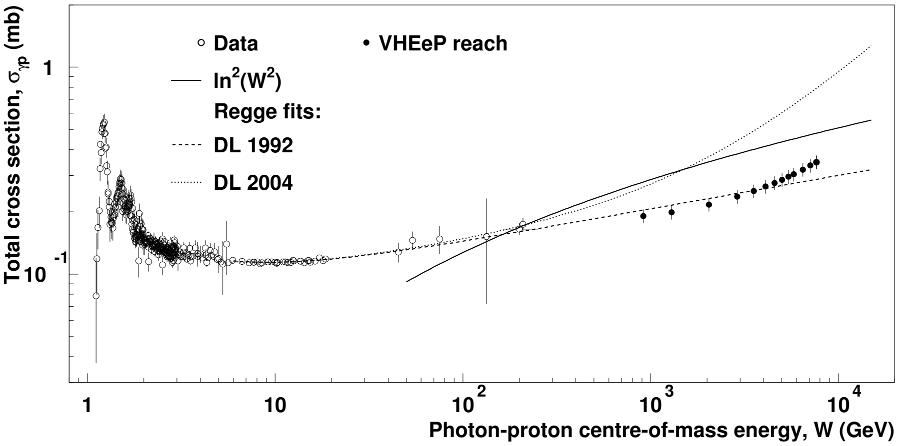

Fig. 7: Total γp cross section versus photon–proton centre-of-mass energy, W, shown for data compared to various models [30–32]. The data is taken from the PDG [33], with references to the original papers given therein. The highest VHEeP data point is shown at $y = 0.7$ (where $y = W^2/s$); the cross section at this point is assumed to be double the ZEUS value. The other VHEeP points assume different values of y down to 0.01 and are plotted on a straight line (linear in W) between the ZEUS and highest VHEeP point. All VHEeP points have the same uncertainty as the ZEUS point: a systematic uncertainty of 7.5% and a negligible statistical uncertainty. The ZEUS measurement is at $\sqrt{s} = 209\,\text{GeV}$ and used a luminosity of $49\,\text{nb}^{-1}$. This result has been updated from the original paper with the addition of newly-calculated points for VHEeP.

trons on protons at HERA, the strong increase in the proton structure function F_2 with decreasing x for fixed, large, Q^2 is usually interpreted as an increasing density of partons in the proton, providing more scattering targets for the electron. This interpretation relies on choosing a particular reference frame to view the scattering – the Bjorken frame. In the frame where the proton is at rest, it is the state of the photon or weak boson that differs with varying kinematic parameters. For the bulk of the electron–proton interactions, the scattering process involves a photon, and we can speak of different states of the photon scattering on a fixed proton target. What is seen is that the photon–proton cross section rises quickly with W for fixed Q^2 [34]. In the proton rest frame, we interpret this as follows: as the energy of the photon increases, time dilation allows shorter lived fluctuations of the photon to become active in the scattering process, thereby increasing the scattering cross section.

Figure 8 shows the results of extrapolation of fits to the energy dependence of the photon–proton cross section for different photon virtualities as given in the caption [35], for two different assumptions on the energy behaviour. It is found that the simple behaviour cannot continue to ever smaller values of x as this would result in large-Q^2 cross sections becoming larger than small-Q^2 cross sections. A change of the energy dependence is therefore expected to become visible in the VHEeP kinematic range. This should yield exciting and unique information on the fundamental underlying physics at the heart of the high energy dependence of hadronic cross sections.

At the very highest Q^2 values, searches for high energy phenomenon beyond the Standard Model will be possible. Higher luminosities will allow a comprehensive search to complement those at the LHC; however, even with modest luminosities, some specific processes can be investigated with higher sensitivity at VHEeP than at the LHC. As an example, the production of leptoquarks, which would be produced on mass shell, is possible up to the kinematic limit of the centre-of-mass energy, i.e. 9 TeV. Other examples of physics that could be investigated at VHEeP were presented and discussed at the workshop [36]. It was discussed how high-energy ep collisions are sensitive to new descriptions and general theories of particle interactions [37] as well as having connections with black holes and gravity [38].

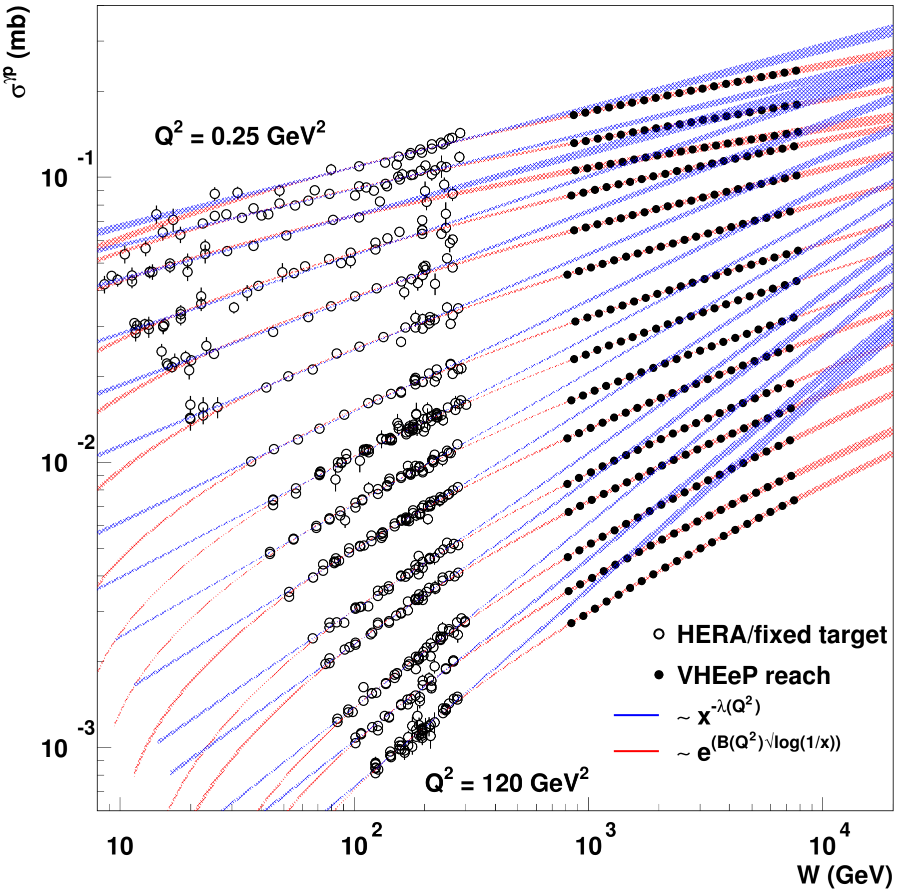

Fig. 8: Measurements (open points) of $\sigma^{\gamma p}$ versus W for $0.25 < Q^2 < 120\,\mathrm{GeV}^2$ from HERA and fixed-target experiments. The blue and red lines show fits to the data, performed separately for each Q^2 value, of the forms given in the key. The reach of VHEeP is shown as projected data points (closed points). The points are placed on the red curve. The uncertainties are assumed to be of order 1%, given the increased cross section expected and similar systematics to those at HERA and are not visible as error bars on this plot.

The work presented here has focused on the use of protons as wakefield drivers and as the collision particles, i.e. ep physics, however, the studies will be extended to consider ions as both wakefield drivers and collision particles. Ions, in particular those which are partially stripped (this technique is also discussed as part of the Physics Beyond Colliders study) [39], could be significantly cooled such that the bunches are more intense and so will be more effective wakefield drivers and lead to much high luminosities for eA collisions.

4 Summary

The AWAKE scheme is a promising method to accelerate electrons to high energy over short distances using proton-driven plasma wakefield acceleration. The AWAKE collaboration has already demonstrated strong fields and electron acceleration and is now embarking on a new programme to demonstrate this as a useable technology for particle physics experiments. This document outlines some of these applications and shows that the AWAKE technology could lead to unique facilities and experiments that would otherwise not be possible. In particular, experiments are proposed to search for dark photons, measure strong field QED and investigate new physics in electron–proton collisions. The community is also invited to consider applications for electron beams up to the TeV scale.

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