Physics case of the very high energy electron–proton collider, VHEeP

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• Introduction, motivation, reminder of VHEeP
• Physics case of very high energy $eP$ collisions
  • Total $\gamma P$ cross section
  • Vector meson cross sections
  • Very low $x$ physics and saturation
  • Quark substructure
  • Sensitivity to leptoquarks
• Summary and outlook
Introduction

• Much has been learnt in fixed-target DIS and HERA experiments on proton structure, diffraction, jet physics, etc..

• A high energy $eP$ collider complements the $pp$ programme from the LHC and a potential future $e^+e^-$ linear collider.

• The LHeC is a proposed $eP$ collider with significantly higher energy and luminosity than HERA with a programme on Higgs, searches, QCD, etc..

• We want to ask, what about a very high energy $eP$ collider?
  • Plasma wakefield acceleration is a promising technology to get to higher energies over shorter distances.
  • Considering (e.g.) 7 TeV protons and 3 TeV electrons giving $\sqrt{s} \sim 9$ TeV.
  • Driver will be the physics case: what physics can be done for such a collider?
  • There is no doubt that this is a new kinematic range.
  • Will be able to perform standard tests of QCD.
  • Will be at very low $x$; e.g. can we learn about saturation?
  • The cross section rises rapidly to low $x$; lots of data, when does the rise stop?
Plasma wakefield accelerator (AWAKE scheme)

- Long beam modulated into micro-bunches which constructively reinforce to give large wakefields.
- Self-modulation instability allows current beams to be used, as in AWAKE experiment at CERN.
- With high accelerating gradients, can have
  - Shorter colliders for same energy
  - Higher energy
- Using the LHC beam can accelerate electrons up to 6 TeV over a reasonable distance.
- We choose $E_e = 3 \text{ TeV}$ as a baseline for a new collider with $E_P = 7 \text{ TeV} \Rightarrow \sqrt{s} = 9 \text{ TeV}$.
  - Centre of mass energy $\times 30$ higher than HERA.

Plasma wakefield accelerator

- Emphasis on using current infrastructure, i.e. LHC beam with minimum modifications.
- Overall layout works in powerpoint.
- Need high gradient magnets to bend protons into the LHC ring.
- One proton beam used for electron acceleration to then collider with other proton beam.
- High energies achievable and can vary electron beam energy.
- What about luminosity?
- Assume
  - \( \sim 3000 \) bunches every 30 mins, gives \( f \sim 2 \text{ Hz} \).
  - \( N_p \sim 4 \times 10^{11}, N_e \sim 1 \times 10^{11} \)
  - \( \sigma \sim 4 \mu m \)

\[ \mathcal{L} \sim \frac{f \cdot N_e \cdot N_p}{4 \pi \sigma_x \cdot \sigma_y} \sim 4 \times 10^{28} \text{ cm}^{-2} \text{ s}^{-1} \]

For few \( \times 10^7 \) s, have 1 pb\(^{-1}\) / year of running.

Other schemes to increase this value?

Physics case for very high energy, but moderate (10–100 pb\(^{-1}\)) luminosities.
Physics at VHEeP

• Cross sections at very low $x$ and observation/evidence for saturation. Completely different kind of proton structure.

• Measure total $\gamma P$ cross section at high energies and also at many different energies; relation to cosmic-ray physics.

• Vector meson production and its relation to the above.

• Beyond the Standard Model physics; contact interactions, e.g. radius of quark and electron; search for leptoquarks.

• Proton and photon structure, in particular e.g. $F_L$ given change in beam energy, and $eA$ scattering. Also related to saturation and low $x$.

• Tests of QCD, measurements of strong coupling, etc.. I.e. all usual QCD measurements can and should be done too in a new kinematic regime.

• Other ideas?
Total $\gamma p$ cross section

- Assumed same uncertainties as ZEUS measurement which used 49 nb$^{-1}$.
- Can measure at different energies with the same detector.
- Can provide strong constraints on models and physics.
- Related to understanding of cosmic-ray interactions.
- Great example of where you really gain with energy.
Vector meson cross sections

Strong rise with energy related to gluon density at low $x$.

Can measure all particles within the same experiment.

Comparison with fixed-target, HERA and LHCb data—large lever in energy.

At VHEeP energies, $\sigma(J/\psi) > \sigma(\phi)$!

Onset of saturation?

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σ_γP at large coherence lengths

Look at behaviour of σ_γP in the proton rest frame in terms of Q^2 and coherence length, \( l \).

Electron is a source of photons which is a source of partons.

Coherence length is distance over which quark–antiquark pair can survive.

Low \( x \) means long-lived photon fluctuations (not proton structure)

If cross sections become same as a function of Q^2, the photon states have had enough time to evolve into a universal size.

Look at what HERA data has shown and what the potential of VHEeP is.

Using published HERA data, calculate $F_2$ from e.g. double-differential cross section:

$$F_2 = \frac{\langle Q^2 \rangle^2 \langle x \rangle}{2 \pi \alpha^2 Y_+} \frac{d^2 \sigma}{dx dQ^2}$$

Then calculate $\sigma_{\gamma p}$ from $F_2$:

$$\sigma_{\gamma p} = \frac{4 \pi^2 \alpha (\langle Q^2 \rangle + (2 \langle x \rangle M_P)^2)}{\langle Q^2 \rangle^2 (1 - \langle x \rangle)} F_2$$

Plot $\sigma_{\gamma p}$ versus the coherence length, $l$:

$$l \approx \frac{\hbar c}{\langle x \rangle M_P}$$
\( \sigma_{\gamma p} \) versus \( l \) results example

• Consider HERA inclusive data and transform to \( \sigma_{\gamma p} \) versus coherence length, \( l \).

• Example data for \( Q^2 = 35 \text{ GeV}^2 \).

• \( \sigma_{\gamma p} \) fit as \((\sigma_0 \cdot l^\lambda)\) for individual \( Q^2 \) values (green).

\[
\sigma_{\gamma p} = A \exp \left( B \cdot \sqrt{\log(1/x) \cdot \log(Q^2/L^2)} \right)
\]

• Very good fit of data using simple parametrisations.

• True for all \( Q^2 \) values considered.
\( \sigma_{\gamma p} \) versus \( l \) results

Cross sections for all \( Q^2 \) are rising; again luminosity not an issue, will have huge number of events.

Depending on the form, fits cross; physics does not make sense.

Different forms deviate significantly from each other.

VHEeP has reach to investigate this region and different behaviour of the cross sections.

Can measure lower \( Q^2 \), i.e. lower \( x \) and higher \( l \).

At VHEeP \( Q^2 \sim 1 \text{ GeV}^2 \) is \( l \sim 2 \times 10^7 \text{ fm} \).

VHEeP will explore a region of QCD where we have no idea what is happening.
BSM: Quark substructure

Deviations of the theory from the data for inclusive cross sections could hint towards quark substructure.

Extraction of quark radius has been done

\[ \frac{d\sigma}{dQ^2} = \frac{d\sigma^{SM}}{dQ^2} \left( 1 - \frac{R_e^2}{6} Q^2 \right)^2 \left( 1 - \frac{R_q^2}{6} Q^2 \right)^2 \]

Generate some “data” for VHEeP and look at sensitivity.

Assuming the electron is point-like, HERA limit is \( R_q < 4 \times 10^{-19} \text{ m} \)

Assuming the electron is point-like, VHEeP limit is \( R_q \lesssim 10^{-20} \text{ m} \)
Leptoquark production

Electron–proton colliders are the ideal machine to look for leptoquarks. 

s-channel resonance production possible up to $\sqrt{s}$.

$\sigma^\text{NWA} = (J + 1) \frac{\pi}{4s} \lambda^2 q(x_0, M_{LQ}^2)$

Sensitivity depends mostly on $\sqrt{s}$ and VHEeP = 30 × HERA
Leptoquark production at the LHC

Can also be produced in $pp$ singly or pair production

Reach of LHC currently about 1 TeV, to increase to 2 – 3 TeV.

Coupling dependent.
Leptoquark production at VHEeP

Assumed $L \sim 100 \text{ pb}^{-1}$

Required $Q^2 > 10,000 \text{ GeV}^2$ and $y > 0.1$

Generated “data” and Standard Model “prediction” using ARIADNE (no LQs).

Sensitivity up to kinematic limit, 9 TeV.

As expected, well beyond HERA limits and significantly beyond LHC limits and potential.
Summary and outlook

- Further developed physics case for a very high energy $eP$ collider at $\sqrt{s} \sim 9$ TeV based on plasma wakefield acceleration.

- Initial basic ideas of accelerator parameters, detector design and kinematics also looked into (not shown here).

- VHEeP presents a completely new kinematic region in $eP$ collisions.

- Even with moderate luminosities, $\sqrt{s}$ is crucial and opens up a rich physics programme.

- Developing a programme where we could learn about high-energy cross sections, QCD, saturation, exotics, etc..

- Many other areas to be investigated and lots of “standard” QCD to do too ($eA, \alpha_s$, contact interactions).

- Look out for further developments and ideas. Ideas are also welcome!
Back-up
Plasma wakefield acceleration

Accelerators using RF cavities limited to $\sim 100 \text{ MV/m}$; high energies $\Rightarrow$ long accelerators. Gradients in plasma wakefield acceleration of $\sim 100 \text{ GV/m}$ measured.

Proton-driven plasma wakefield acceleration*

- Electrons ‘sucked in’ by proton bunch
- Continue across axis creating depletion region
- Transverse electric fields focus witness bunch

- Theory and simulation tell us that with CERN proton beams, can get GV/m gradients.
- Experiment, AWAKE, at CERN to demonstrate proton-driven plasma wakefield acceleration for this first time.
  - Learn about characteristics of plasma wakefields.
  - Understand process of accelerating electrons in wakes.
  - This will inform future possibilities which we, however, can/should think of now.

Proof-of-principle experiment at CERN to demonstrate proton-driven plasma wakefield acceleration for the first time.

Using 400 GeV SPS proton bunches.

To start running in October 2016 and to measure modulation of proton bunch in plasma.

Will inject electrons in late 2017 to be accelerated to O(GeV) scales in about 6 m of plasma.

Thinking of future experiments with 10s of GeV electrons over 10s of m of plasma.
DIS variables

- Access down to $x \sim 10^{-8}$ for $Q^2 \sim 1 \text{ GeV}^2$.
- Even lower $x$ for lower $Q^2$.
- Plenty of data at low $x$ and low $Q^2 (L \sim 0.01 \text{ pb}^{-1})$.
- Can go to $Q^2 \sim 10^5 \text{ GeV}^2$ for $L \sim 1 \text{ pb}^{-1}$.
- Powerful experiment for low-$x$ physics where luminosity less crucial.
Kinematics of the final state

• Generated ARIADNE events with $Q^2 > 1$ GeV$^2$ and $x > 10^{-7}$

• Test sample of $L \sim 0.01$ pb$^{-1}$

• Nice kinematic peak at 3 TeV, with electrons scattered at low angles.

• Hadronic activity in central region as well as forward and backward.

• Hadronic activity at low backward angles for low $x$.

• Clear implications for the kind of detector needed.
• Will need conventional central colliding-beam detector.

• Will also need long arm of spectrometer detectors which will need to measure scattered electrons and hadronic final state at low $x$. 