VHEeP: A very high energy electron–proton collider based on proton-driven plasma wakefield acceleration

Allen Caldwell (MPI)
Matthew Wing (UCL/DESY/Univ. Hamburg)

- Introduction
- Accelerator based on plasma wakefield acceleration
- Physics in very high energy *eP* collisions
- Summary and outlook

DIS 2015 Workshop — 28 April 2015

Introduction

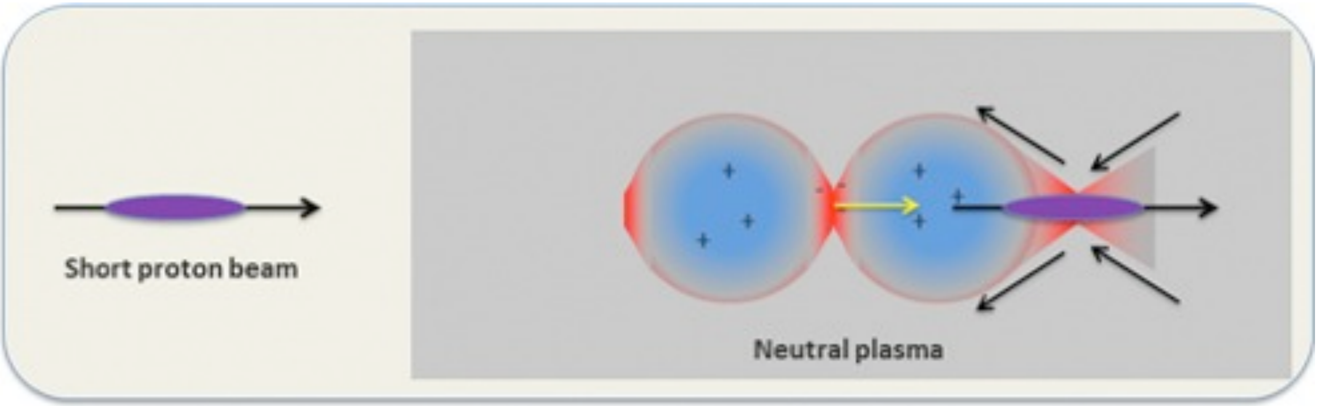
- Much has been learnt in fixed-target DIS and HERA experiments on proton structure, diffraction, jet physics, etc..
- A high energy *eP* collider complements the pp programme from the LHC and a potential future e^+e^- linear collider.
- The LHeC is a proposed *eP* collider with significantly higher 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 standard tests and QCD.
    - Will be at very low x; can we learn about saturation ?
- Will discuss sketch of such a collider and first ideas on physics possibilities.

Plasma wakefield acceleration

Accelerators using RF cavities limited to *~100 MV/m*; high energies ⇒ long accelerators.

Gradients in plasma wakefield acceleration of ***~100 GV/m*** measured.

Proton-driven plasma wakefield acceleration*

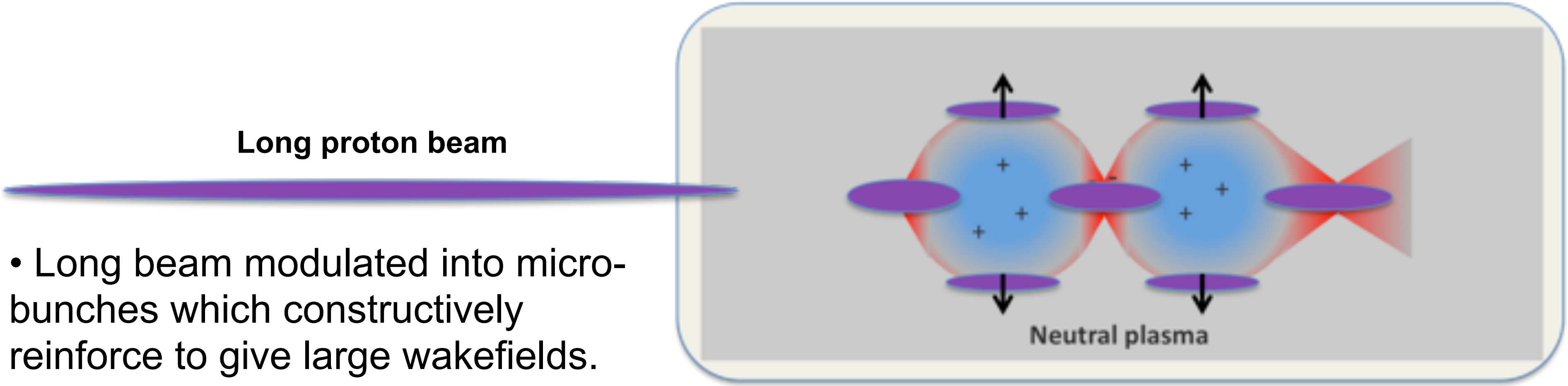


- Electrons 'sucked in' by proton bunch
- Continue across axis creating depletion region
- Transverse electric fields focus witness bunch

- 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.

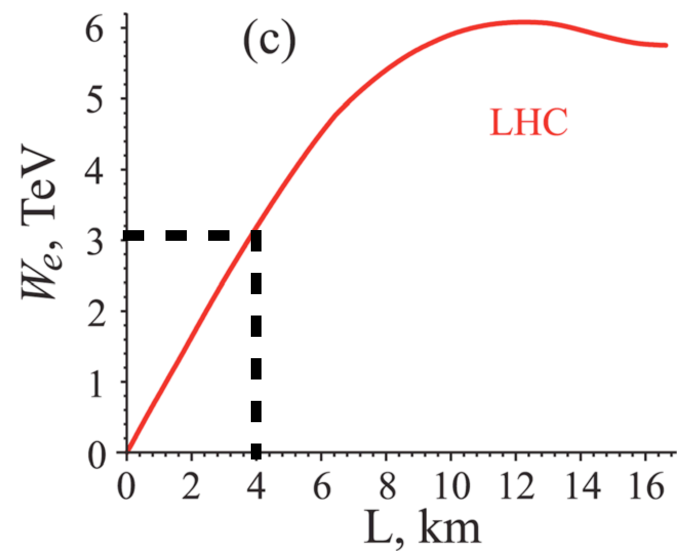
* A. Caldwell *et al.*, Nature Physics **5** (2009) 363.

Plasma wakefield accelerator



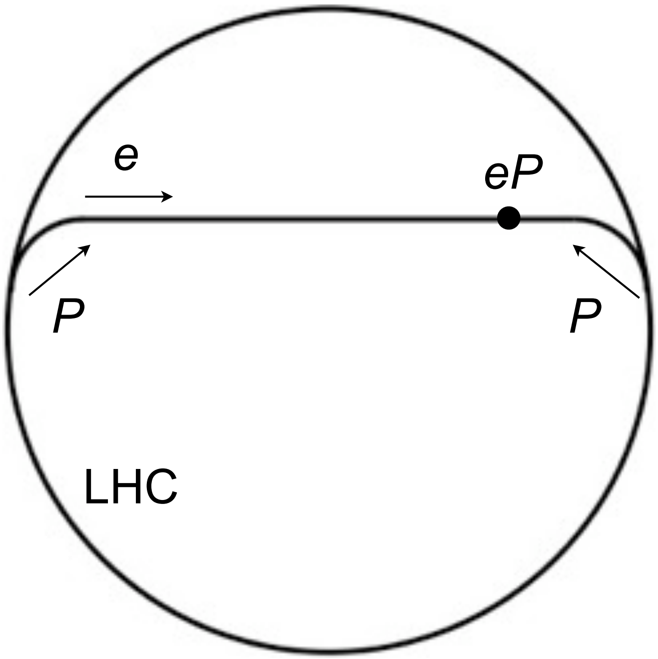
Self-modulated driver beam

- Long beam modulated into micro-bunches which constructively reinforce to give large wakefields.
- Self-modulation instability allows **current beams to be used.**
- 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 TeV* as a baseline for a new collider with E_P = *7 TeV* ⇒ **√*s* = *9 TeV***.
  - Centre of mass energy ×30 higher than HERA.



A. Caldwell & K. Lotov, Phys. Plasmas **18** (2011) 103101

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
  - *~3000* bunches every *30 mins*, gives *f ~ 2 Hz*.
  - $N_p \sim 4 \times 10^{11}$, $N_e \sim 1 \times 10^{11}$
  - $\sigma \sim 4\ \mu m$

$$\mathcal{L} \sim \frac{f \cdot N_e \cdot N_P}{4\pi\sigma_x \cdot \sigma_y}$$
$$\sim 4 \times 10^{28}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$$

For few × 10^7 *s*, have *1* pb^{-1} / year of running.

Physics case for very high energy, but moderate luminosities.

Physics at VHEeP

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

• Contact interactions, e.g. radius of quark and electron.

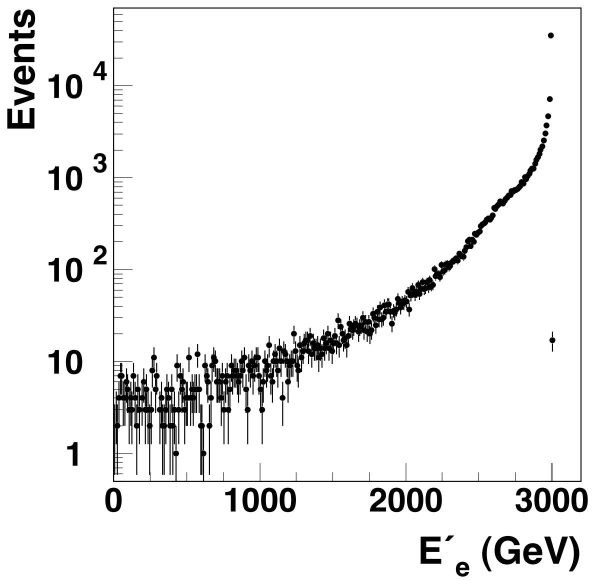
• Measure total γP cross section at high energies and also at many different energies; their relation to cosmic-ray physics. No stat. issues and precise determination of energy dependence.

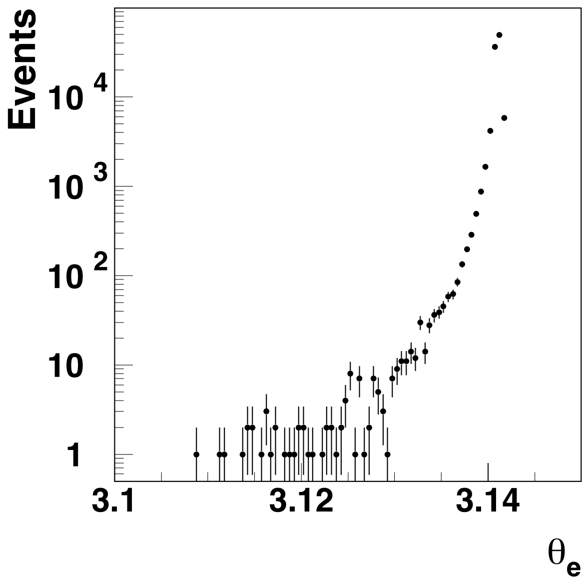
• Proton and photon structure, in particular e.g. F_L given change in beam energy, and *eA* scattering.

• Tests of QCD, measurements of strong coupling, etc..

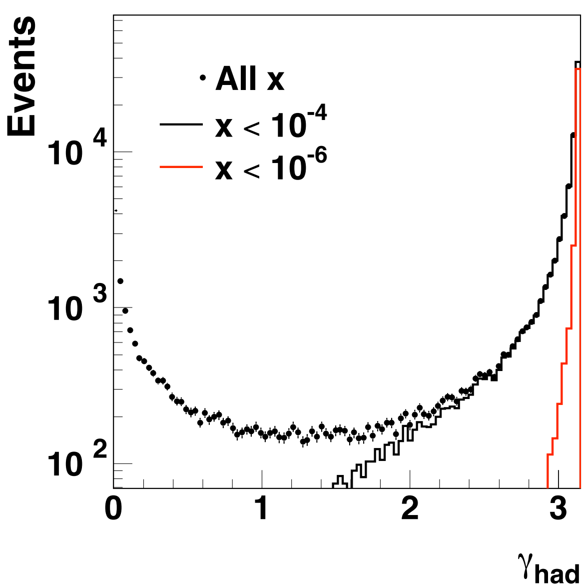
• Other ideas ?

Kinematics of the final state



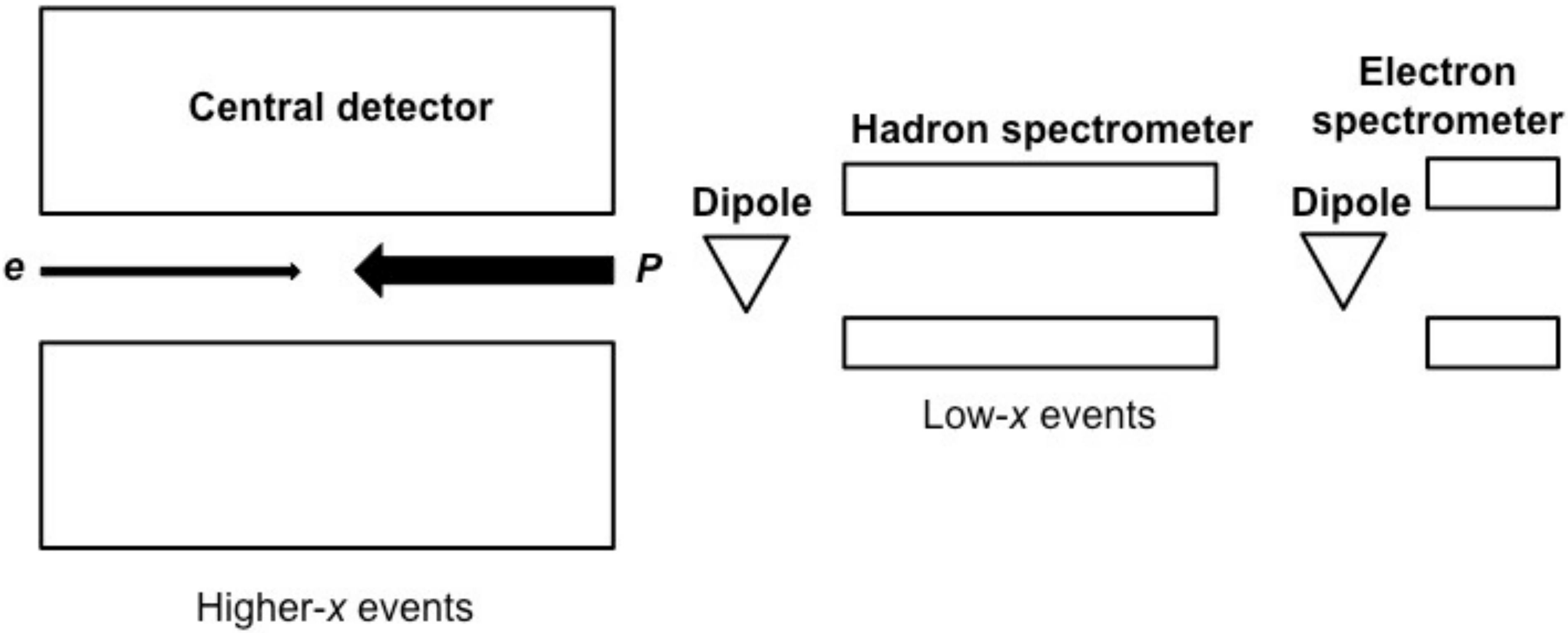


- Generated ARIADNE events with $Q^2 > 1\ GeV^2$ and $x > 10^{-7}$
- Test sample of $L \sim 0.01\ pb^{-1}$
- Nice kinematic peak at *3 TeV*, with electrons scattered at low angles.
- Hadronic activity in central region as well as forward and backward.



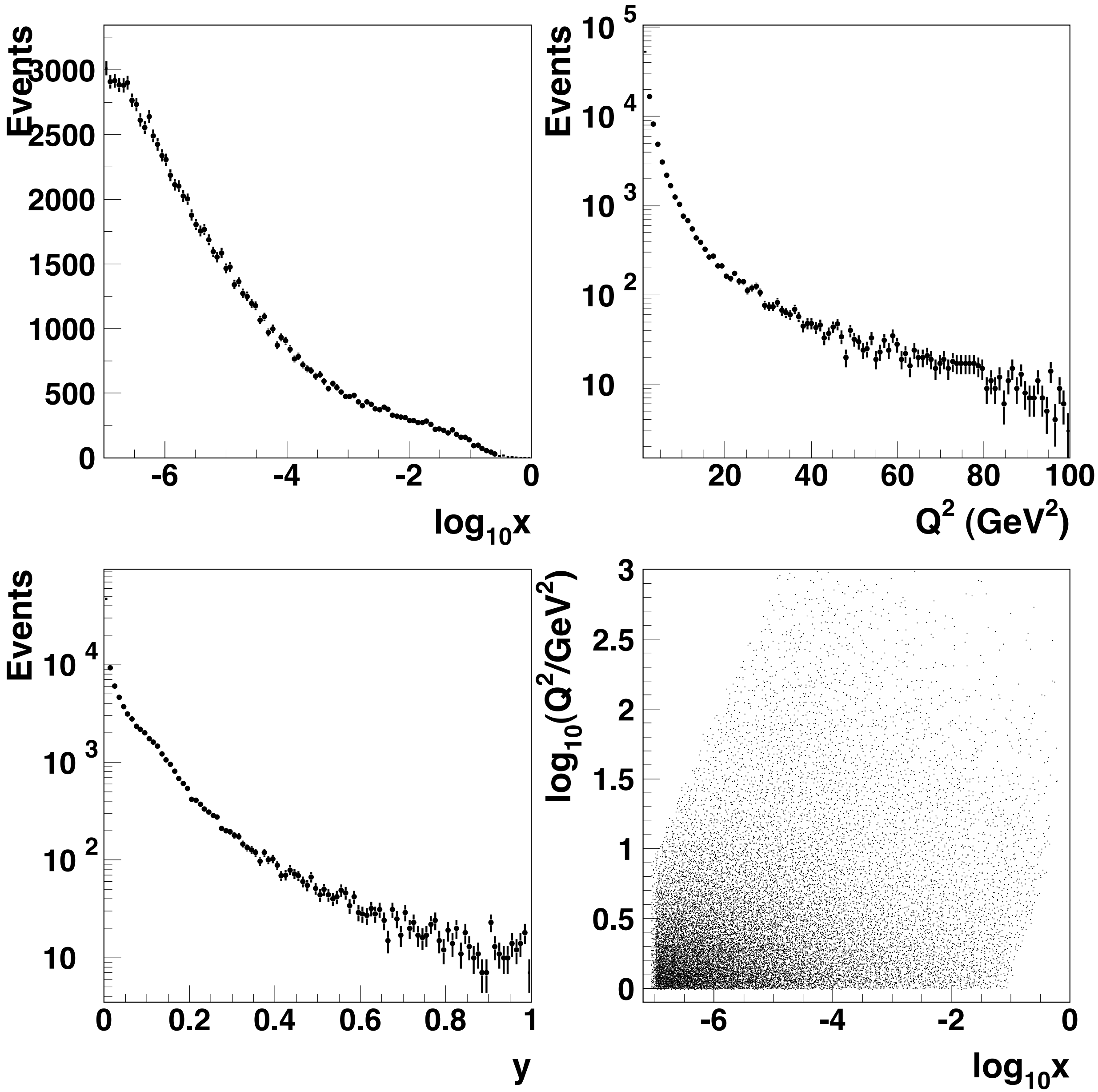
- Hadronic activity at low backward angles for low x.
- Clear implications for the kind of detector needed.

Sketch of detector



- 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.

DIS variables



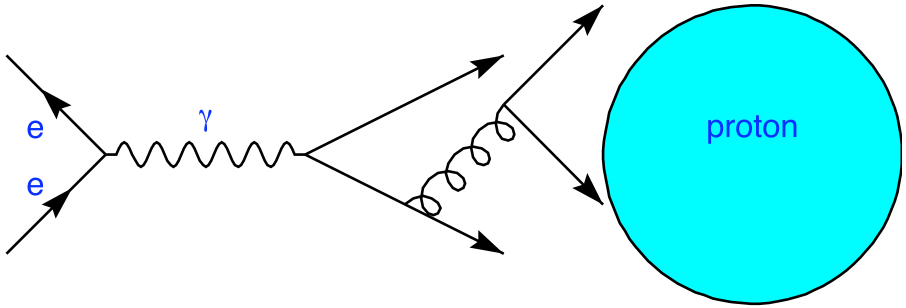
- Access down to $x \sim 10^{-8}$ for $Q^2 \sim 1\ GeV^2$.
- Even lower x for lower Q^2.
- Plenty of data at low x and low Q^2 ($L \sim 0.01\ pb^{-1}$).
- Can go to $Q^2 \sim 10^5\ GeV^2$ for $L \sim 1\ pb^{-1}$.
- Powerful experiment for low-x physics where luminosity less crucial.

$\sigma_{\gamma P}$ at large coherence lengths

Look at behaviour of $\sigma_{\gamma P}$ 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.



If cross sections become same as a function of Q2, 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.

$\sigma_{\gamma P}$ math

Calculate F_2 from e.g. double-differential cross section:

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

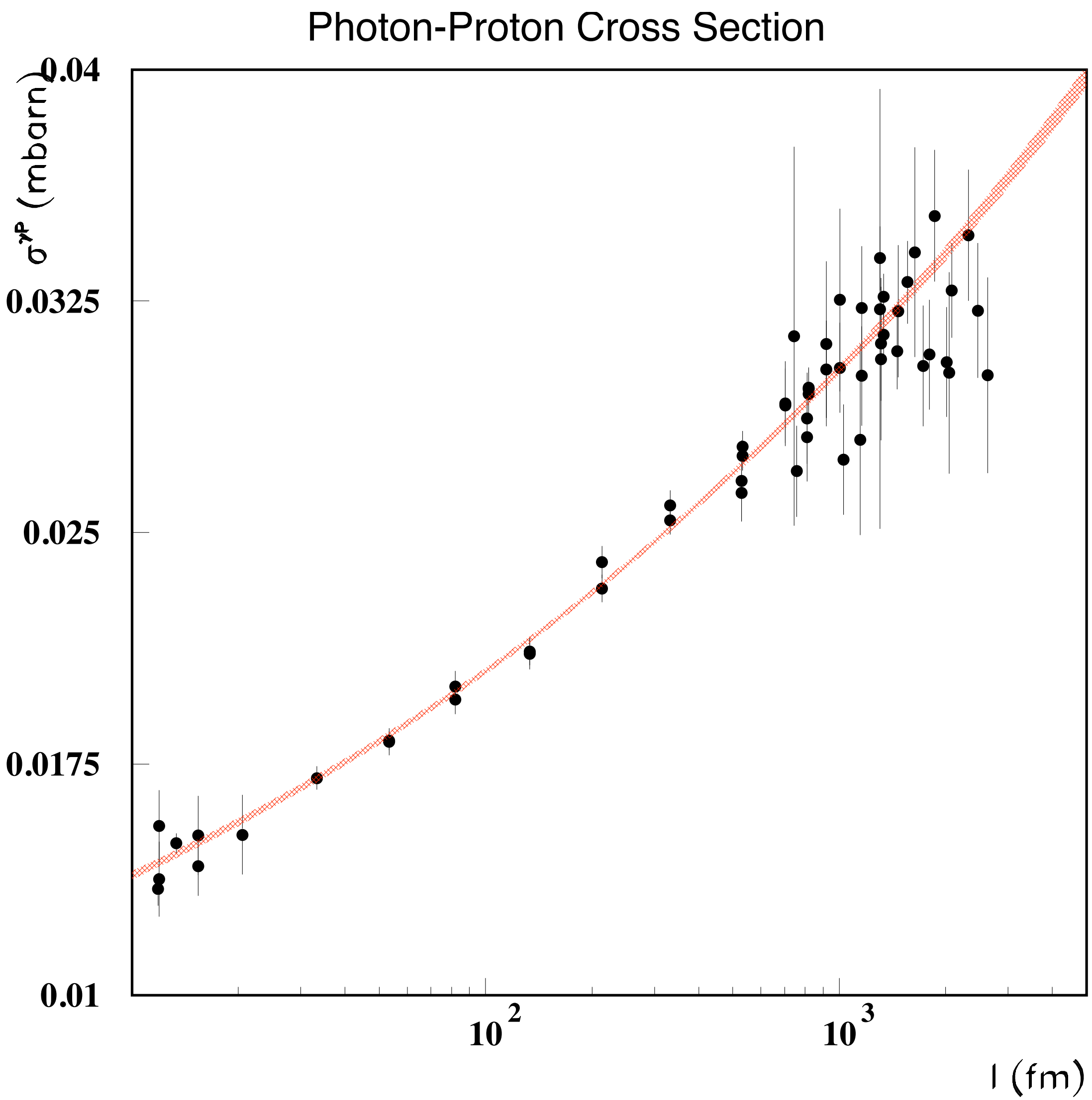
Then calculate $\sigma_{\gamma P}$ from F_2:

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

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

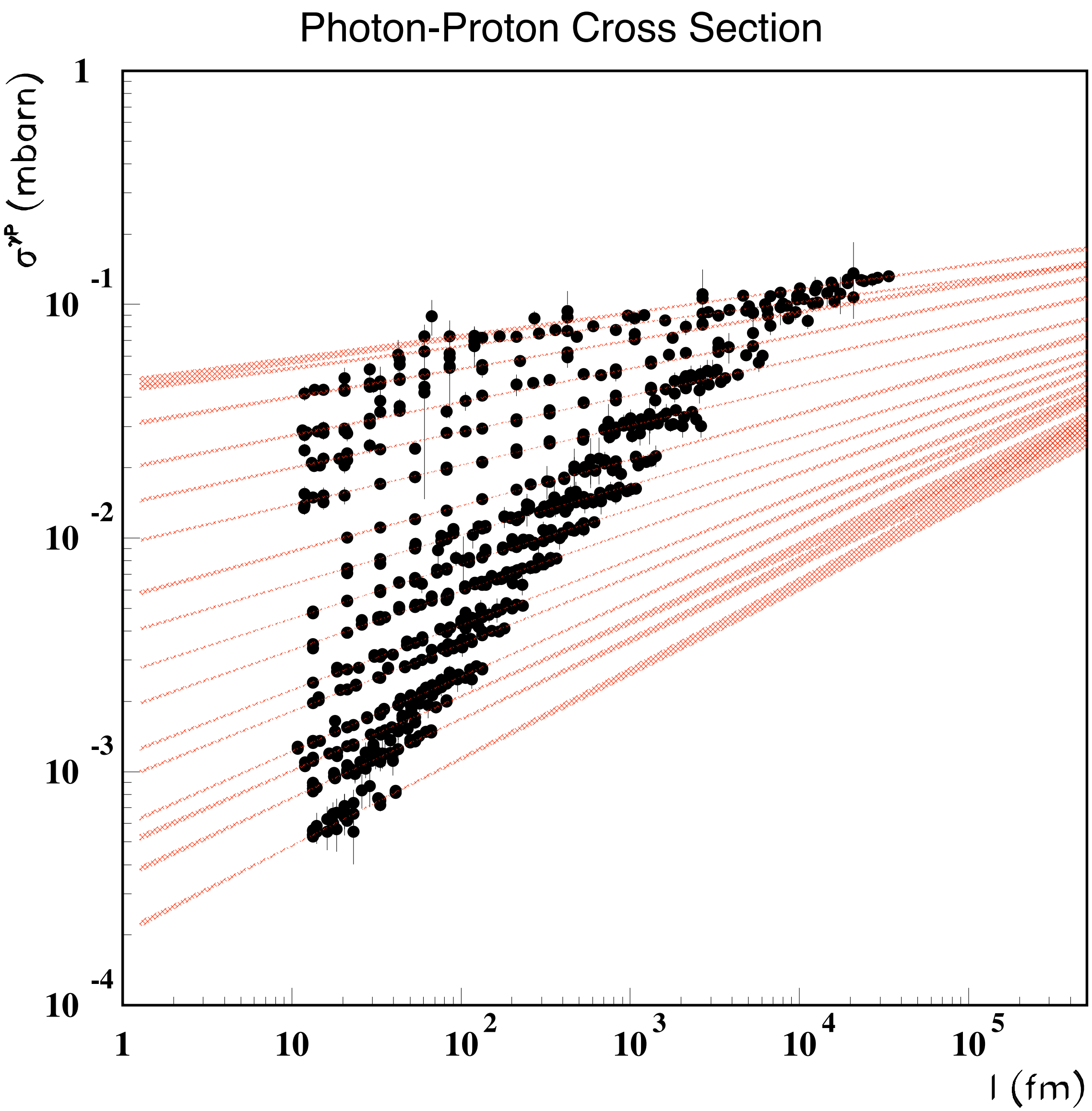
$$l = \frac{\hbar c}{2\langle x\rangle M_P}$$

$\sigma_{\gamma P}$ versus *l* results example



- Consider HERA inclusive data and transform to $\sigma_{\gamma P}$ versus coherence length, *l*.
- Example data for $Q^2 = 3.5\ GeV^2$.
- $\sigma_{\gamma P}$ fit as $(\sigma_0 \cdot l^{\lambda})$ for individual Q^2 values.
- Very good fit of data using this simple parametrisation.
- True for all Q^2 values considered.

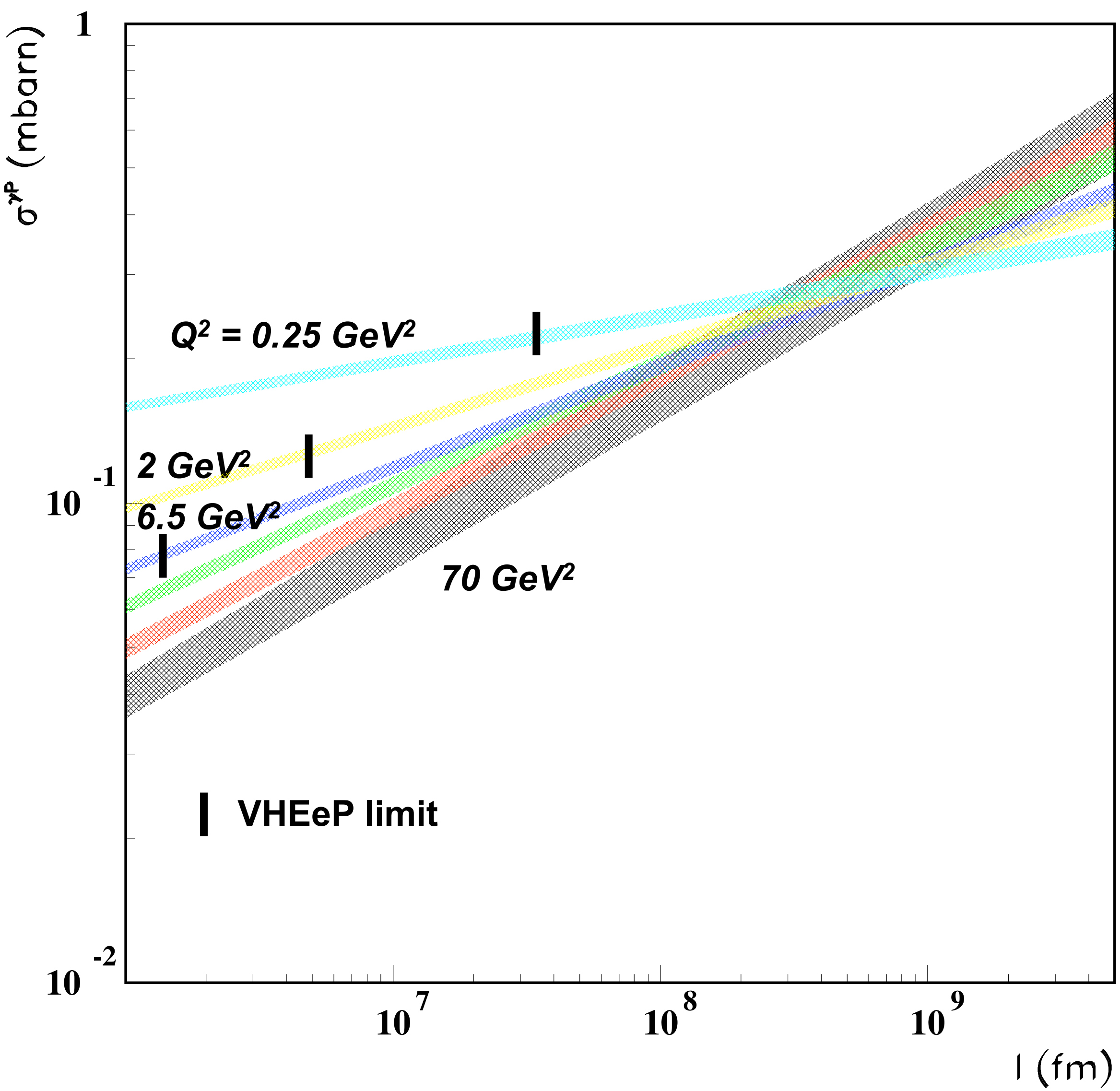
$\sigma_{\gamma P}$ versus *l* results



- Results from HERA shown for $0.25 < Q^2 < 200\ GeV^2$.
- Results for *l* up to 3×10^4 *fm* corresponds to $x \sim 3.5 \times 10^{-6}$.
- $\sigma_{\gamma P}$ fit as $(\sigma_0 \cdot l^\lambda)$ for individual Q^2 values.
- Fits converging at large *l*.
  - Fits cross at some point.
  - $\sigma_{\gamma P}$ becomes independent of Q^2 at large *l*.

$\sigma_{\gamma P}$ at high *l* or low *x*

Photon-Proton Cross Section



- Fits cross at 3×10^8 fm or $x \sim 3.5 \times 10^{-10}$.
- Need low $Q^2 < 1\ GeV^2$ measurements for such low x.
- But will have large numbers of events for $Q^2 \sim 1-10\ GeV^2$ and $l > 10^6\ fm$.
- Can constrain higher Q^2 and improve fit extrapolations.
- More simulations needed and more realistic idea of regions that can be measured.

Summary and outlook

• Presented an idea for a very high energy *eP* collider at $\sqrt{s} \sim 9$ *TeV* based on plasma wakefield acceleration.

• Have reasonable-looking accelerator parameters using the CERN infrastructure.

• Have started to develop a physics programme for high energies, but relatively modest luminosities.

• Many technical challenges in the accelerator and detector.

• VHEeP presents a completely new kinematic region in *eP* collisions.

• Developing a rich physics programme where we could learn about high-energy cross sections, saturation, etc.

• More work and understanding needed.

• Look out for further developments and ideas. Ideas are also welcome !