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UCL

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

Allen Caldwell (MPI, Munich)

Matthew Wing (UCL / DESY)

- Introduction, motivation, reminder of VHEeP
- Physics case of very high energy *eP* collisions
  - Total *γP* cross section
  - Vector meson cross sections
  - Very low *x* physics and saturation
  - Sensitivity to leptoquarks
- Latest news
- Summary and outlook

Now published in
A. Caldwell and M. Wing,
Eur. Phys. J **C 76** (2016) 463

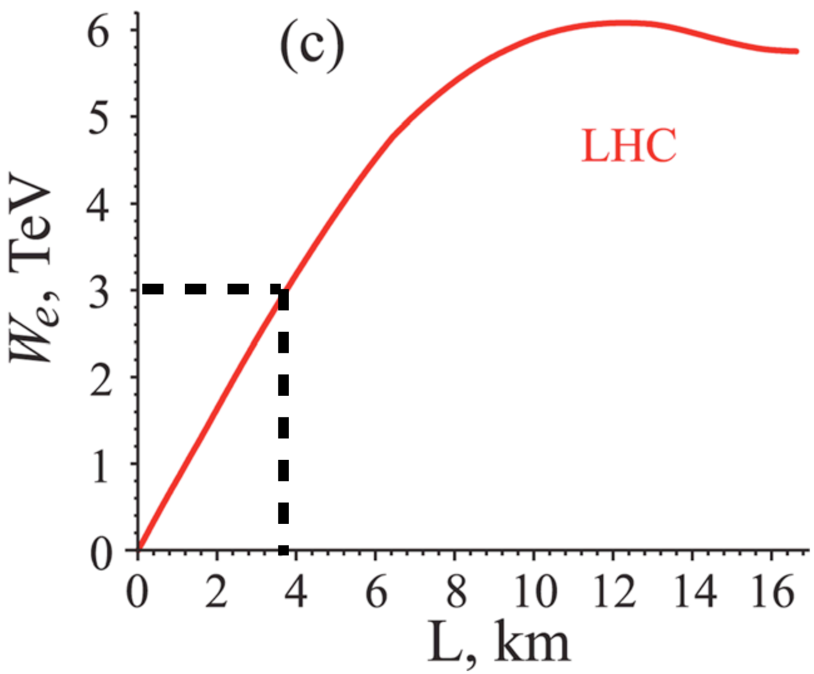
DIS 2017 Workshop — 5 April 2017, Brum

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 electrons at the TeV energy scale.
  - 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 ?

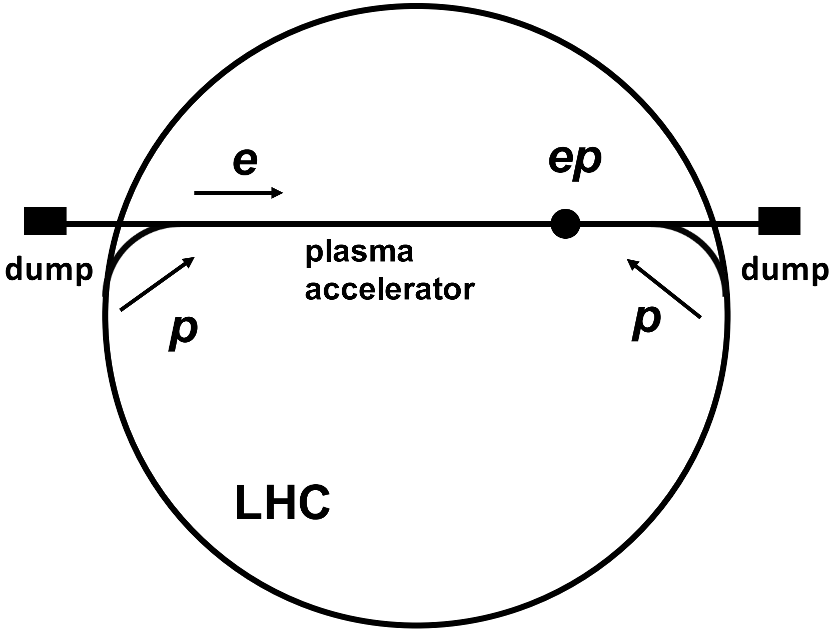
Plasma wakefield accelerator (AWAKE scheme)

- Can use current beams, 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 TeV* as a baseline for a new collider with E_P = *7 TeV* ⇒ $\sqrt{s}$ **= 9 TeV**
  - Acceleration of electrons in under 4 km.
  - Can vary the electron energy.
  - Centre of mass energy ×*30* higher than HERA.
  - Kinematic reach to low Bjorken *x* and high Q^2 extended by ×*1000* compared to HERA.



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

Plasma wakefield accelerator



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

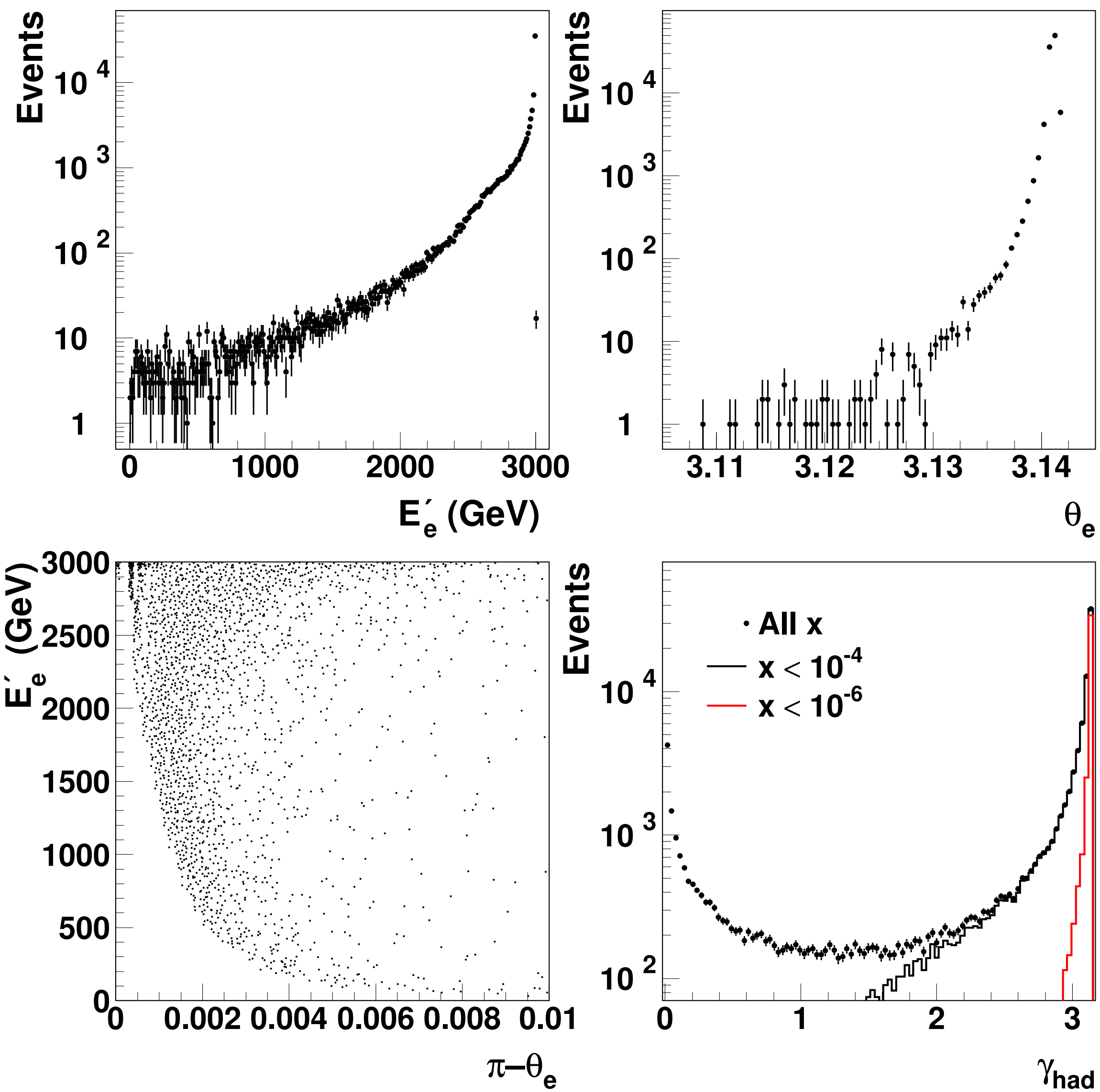
For few × 10^7 *s*, have *1* pb^{-1} / year of running.

Other schemes to increase this value ?

- 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 per *30 min*, gives $f \sim 2$ *Hz*.
  - $N_p \sim 4 \times 10^{11}$, $N_e \sim 1 \times 10^{11}$
  - $\sigma \sim 4\ \mu m$

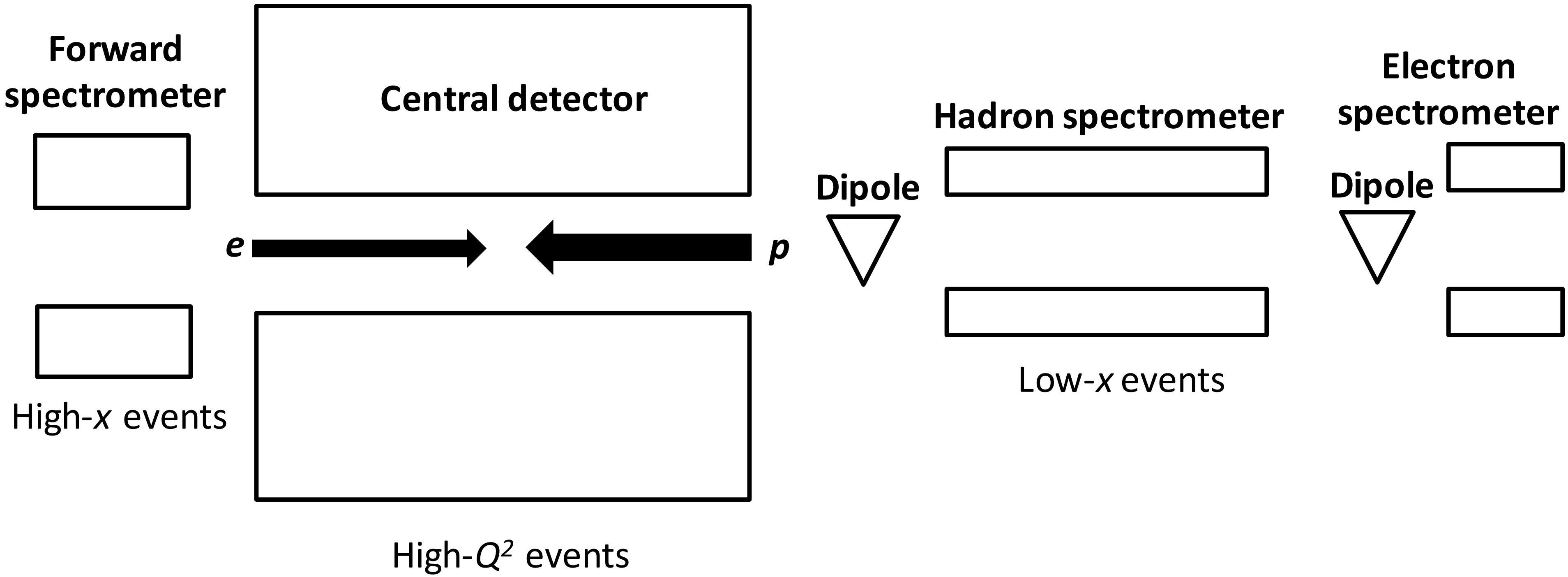
Physics case for very high energy, but moderate (*10–100* pb^{-1}) luminosities.

Kinematics of the final state



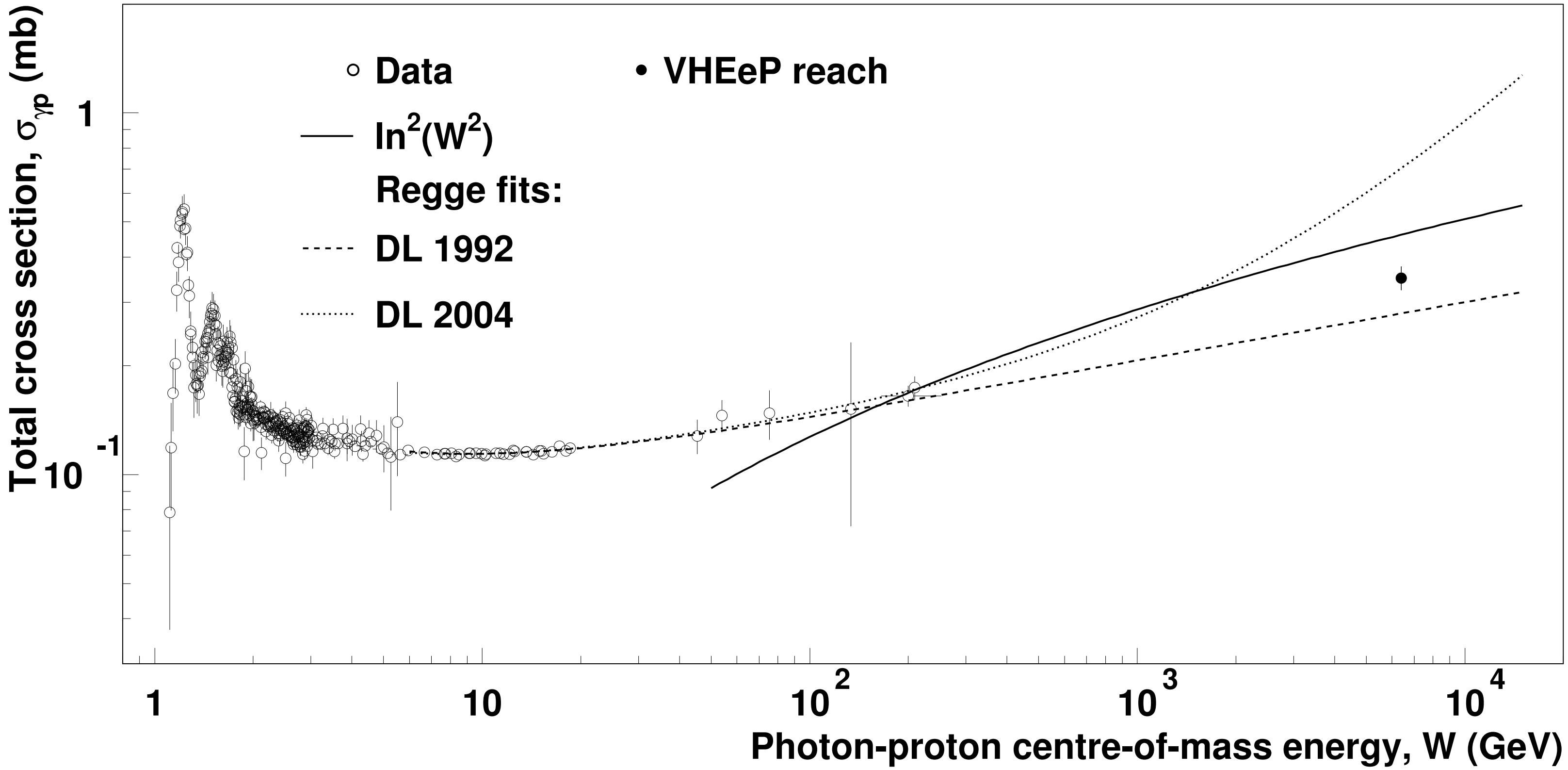
- Generated ARIADNE events with Q^2 > *1* GeV^2 and $x > 10^{-7}$
- Test sample of $L \sim 0.01\ pb^{-1}$
- Kinematic peak at *3 TeV*, with electrons scattered at low angles.
- Hadronic activity in central region as well as forward and backward.
- Hadronic activity at low backward angles for low x.
-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

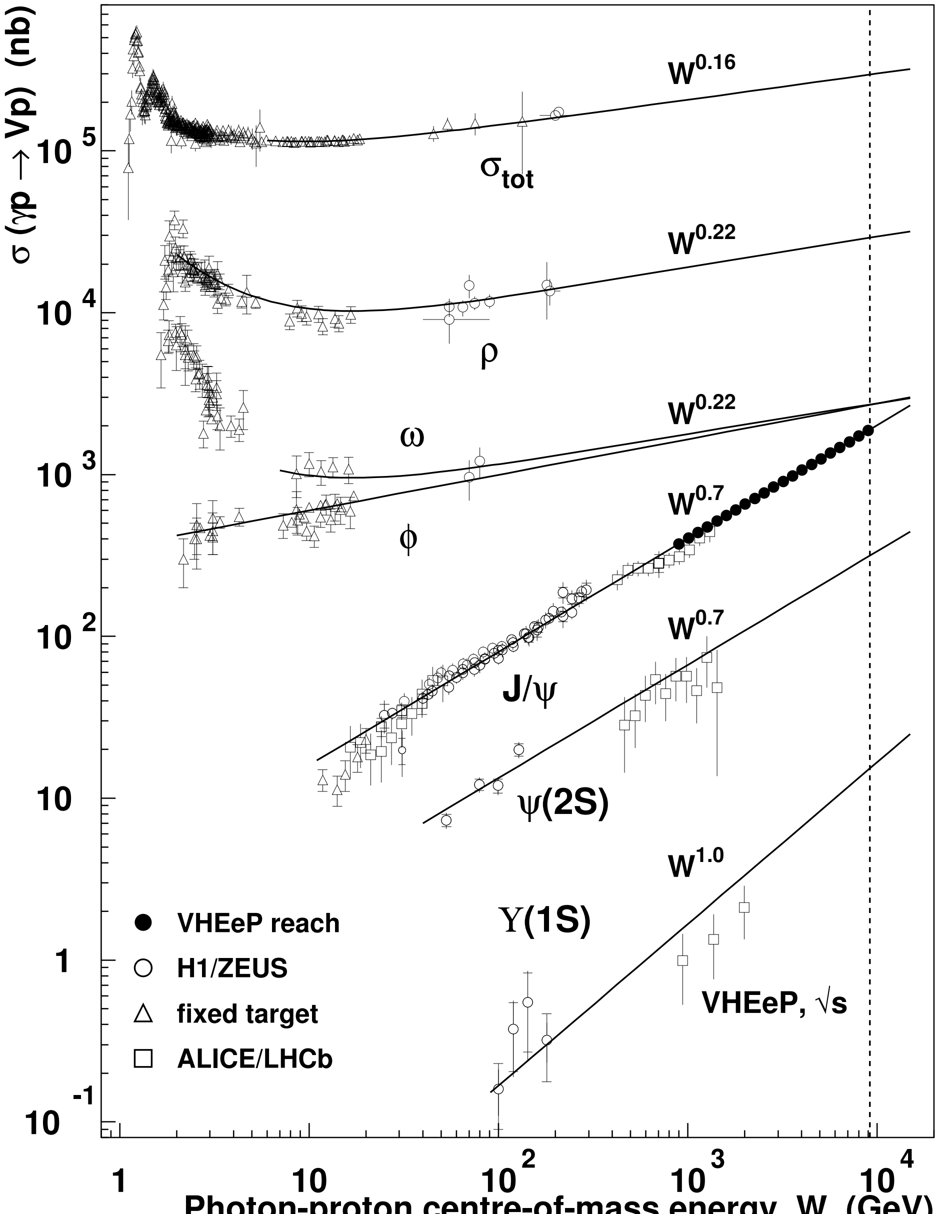
Total *γP* cross section



- 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.**

Equivalent to a 20 PeV photon on a fixed target.

Vector meson cross sections



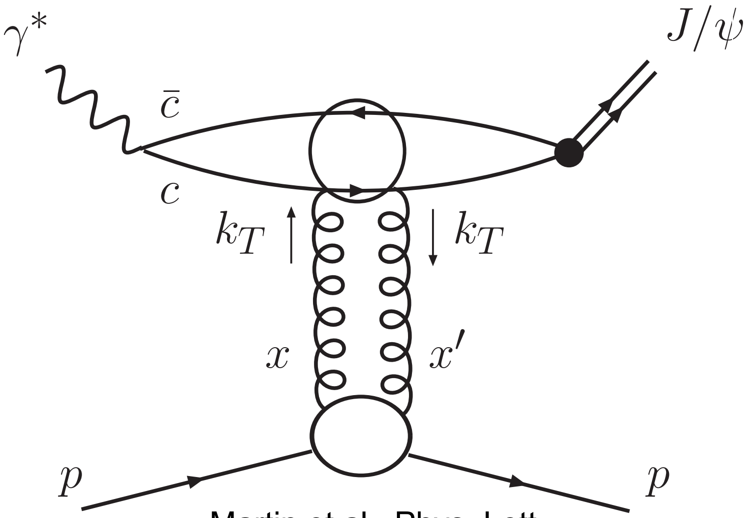
Strong rise with energy related to gluon density at low *x*.

Can measure all particles within the same experiment.

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

At VHEeP energies, *σ(J/ψ)* ≳ *σ(φ)* !

Onset of saturation ?



Martin et al., Phys. Lett. **B 662** (2008) 252

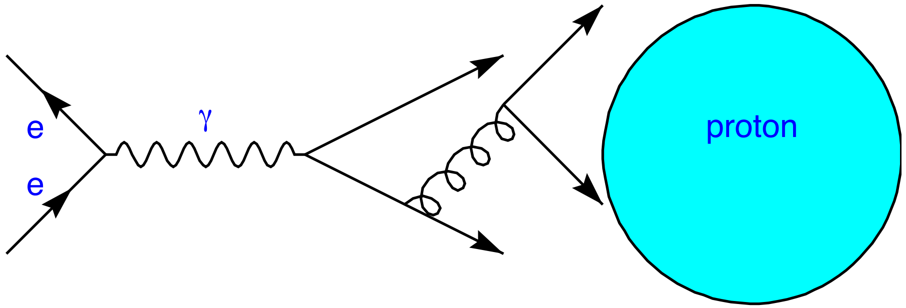
$\sigma_{\gamma P}$ at large coherence lengths

Look at behaviour of $\sigma_{\gamma P}$ in the proton rest frame.

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

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

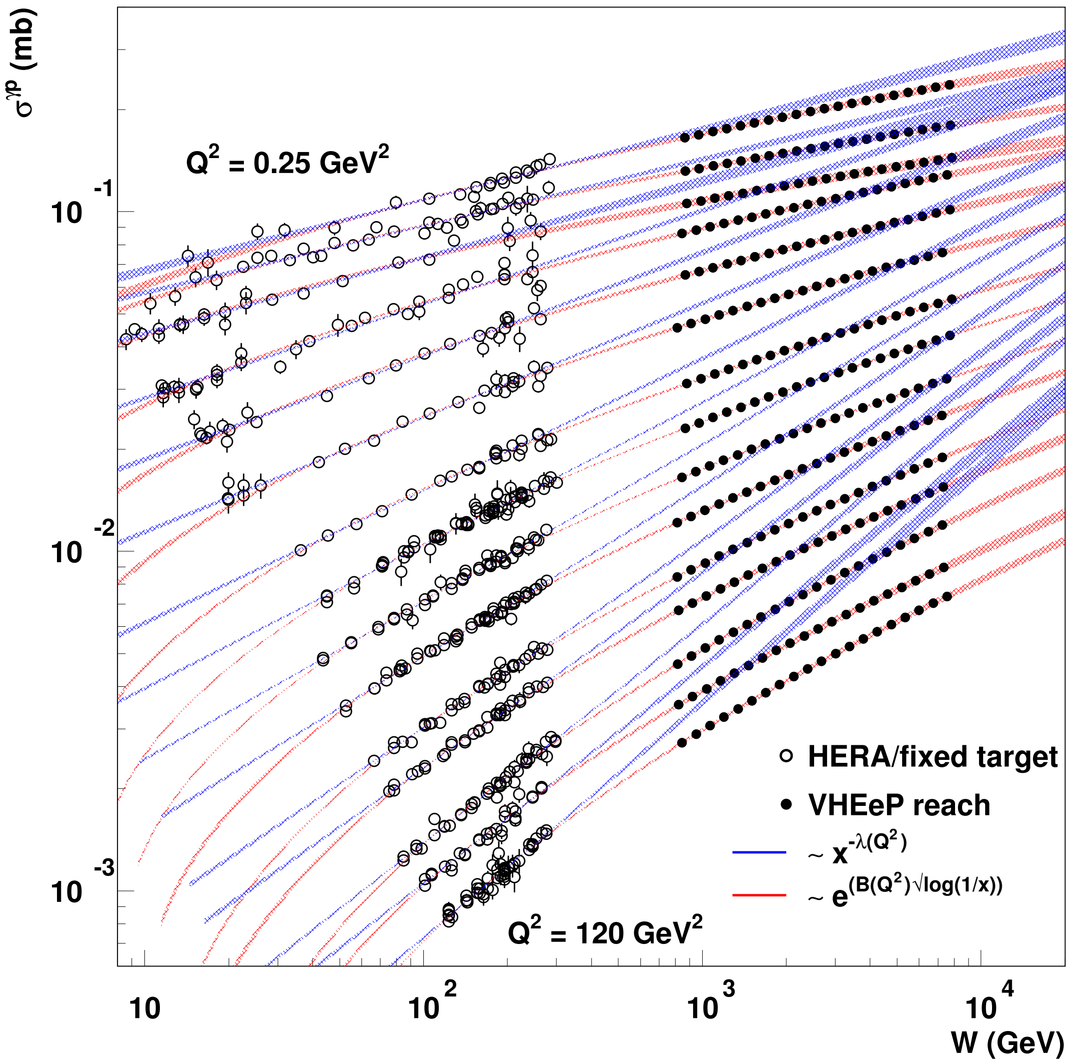
Low x means long-lived photon fluctuations (not proton structure)



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.

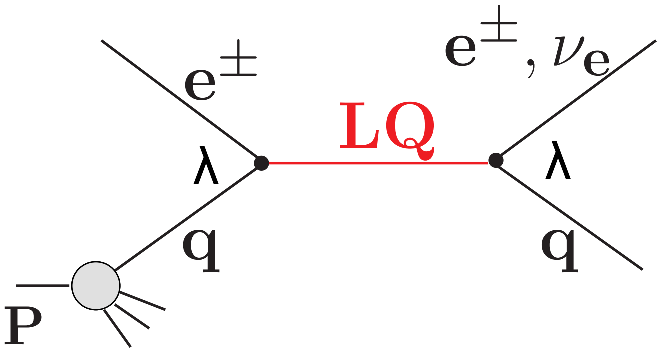
$\sigma_{\gamma P}$ versus *W*



- 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 *W*.
- Unique information on form of hadronic cross sections at high energy.

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

Leptoquark production

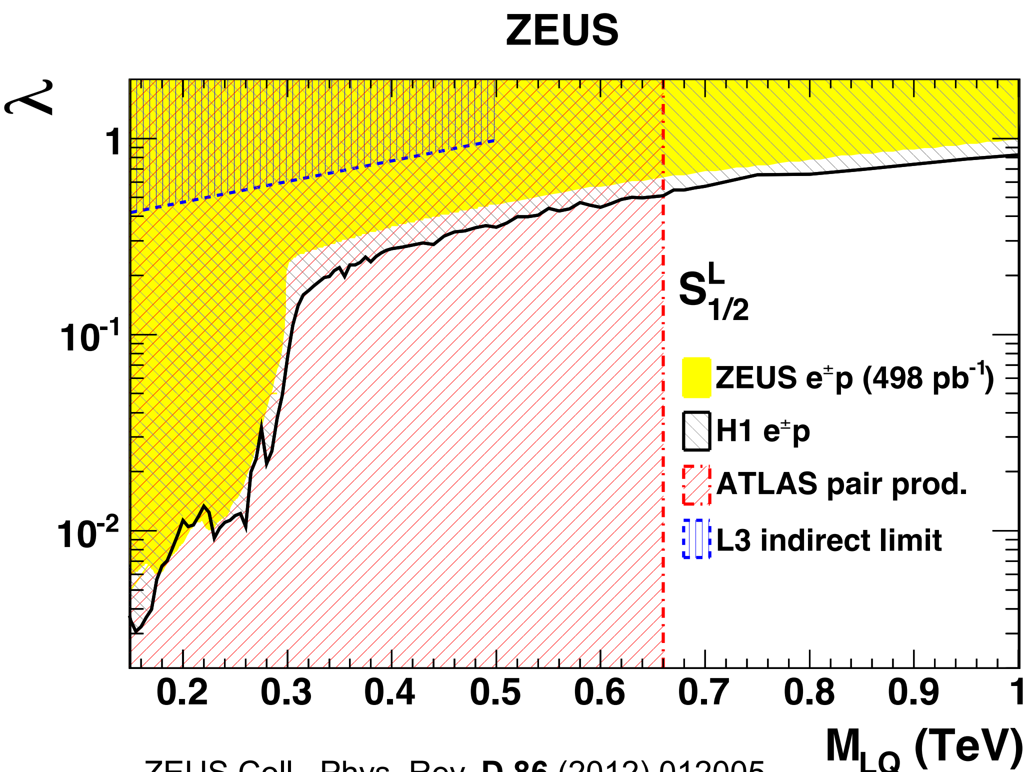


Electron−proton colliders are the ideal machine to look for leptoquarks.

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

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

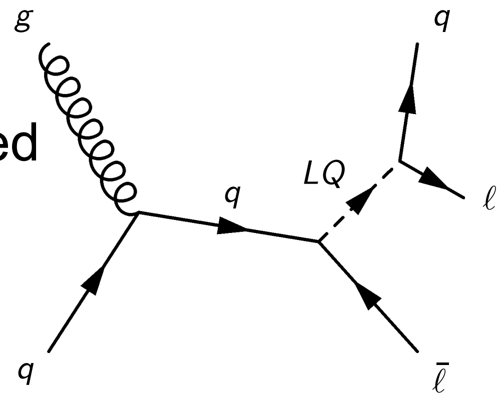
Sensitivity depends mostly on $\sqrt{s}$ and VHEeP = 30 × HERA

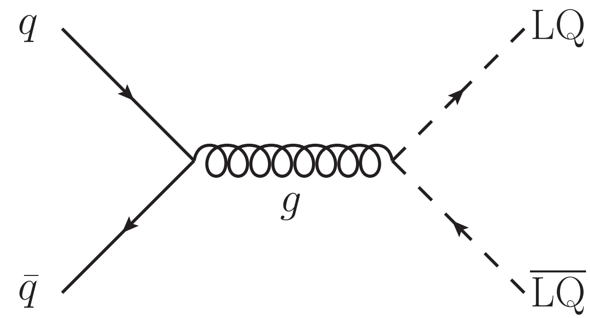


ZEUS Coll., Phys. Rev. **D 86** (2012) 012005

Leptoquark production at the LHC

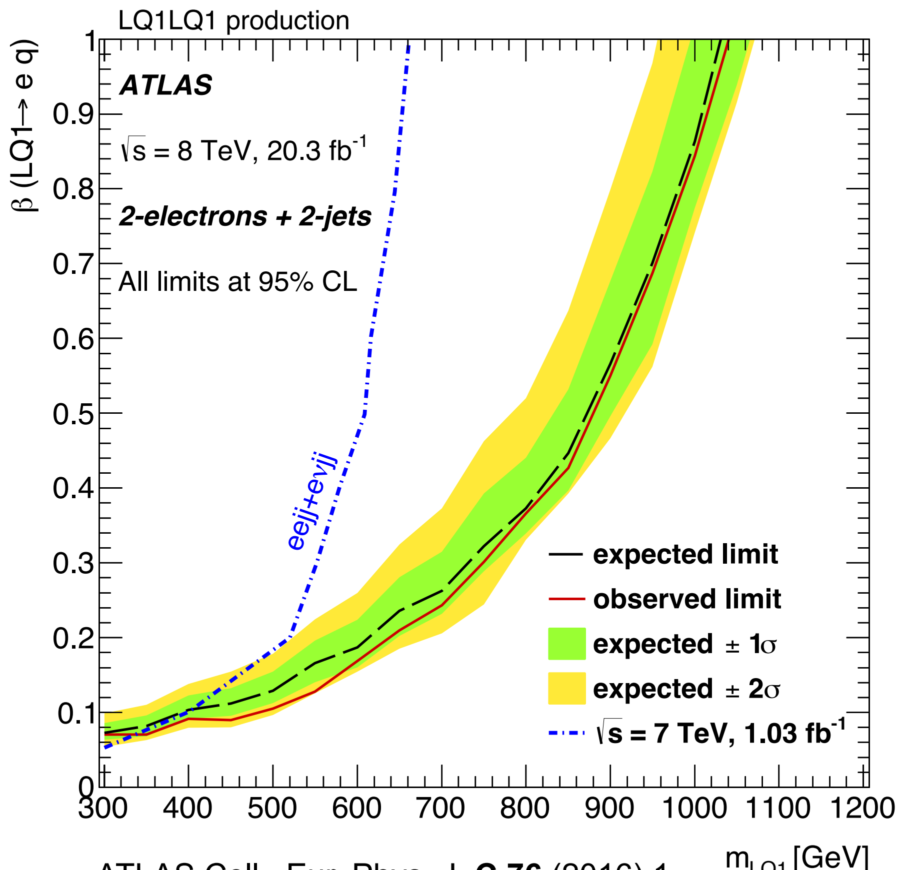
Can also be produced in *pp* singly or pair production





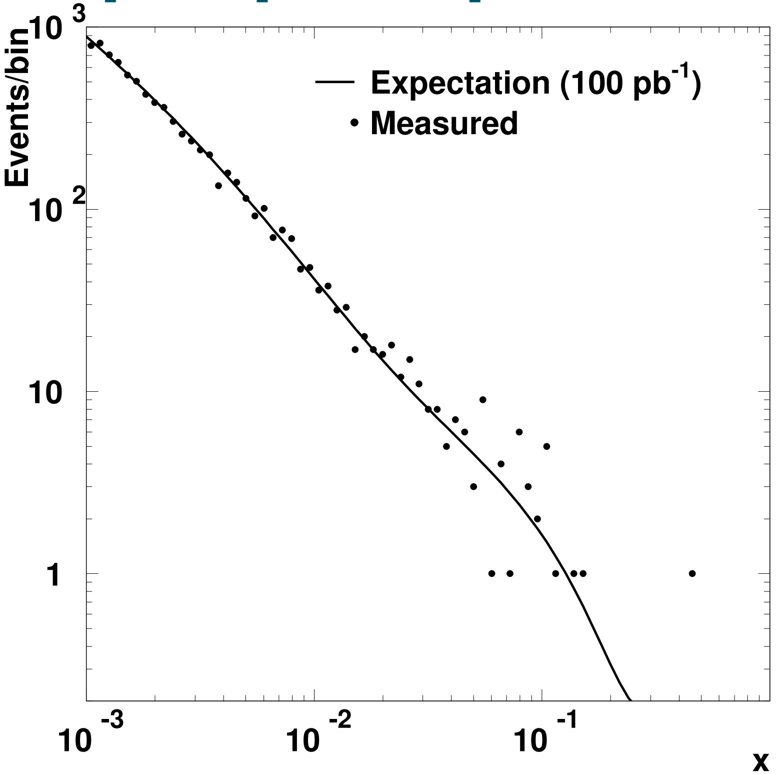
Reach of LHC currently about *1 TeV*, to increase to *2 − 3 TeV*.

Coupling dependent.



ATLAS Coll., Eur. Phys. J. **C 76** (2016) 1

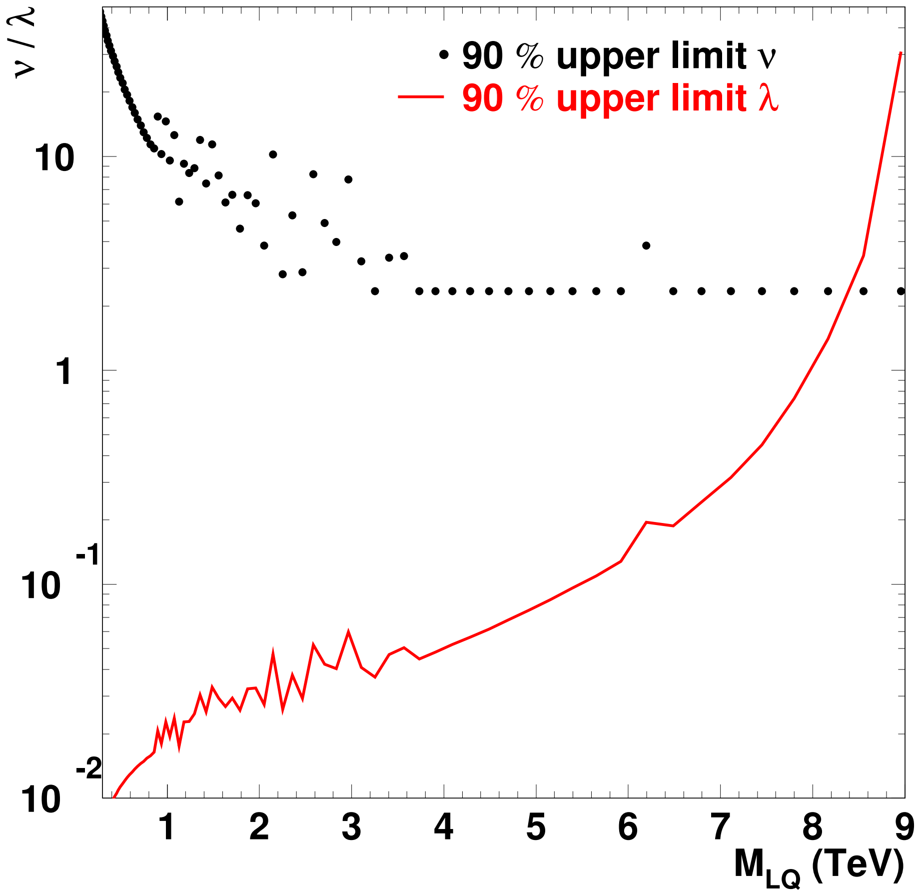
Leptoquark production at VHEeP



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

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

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

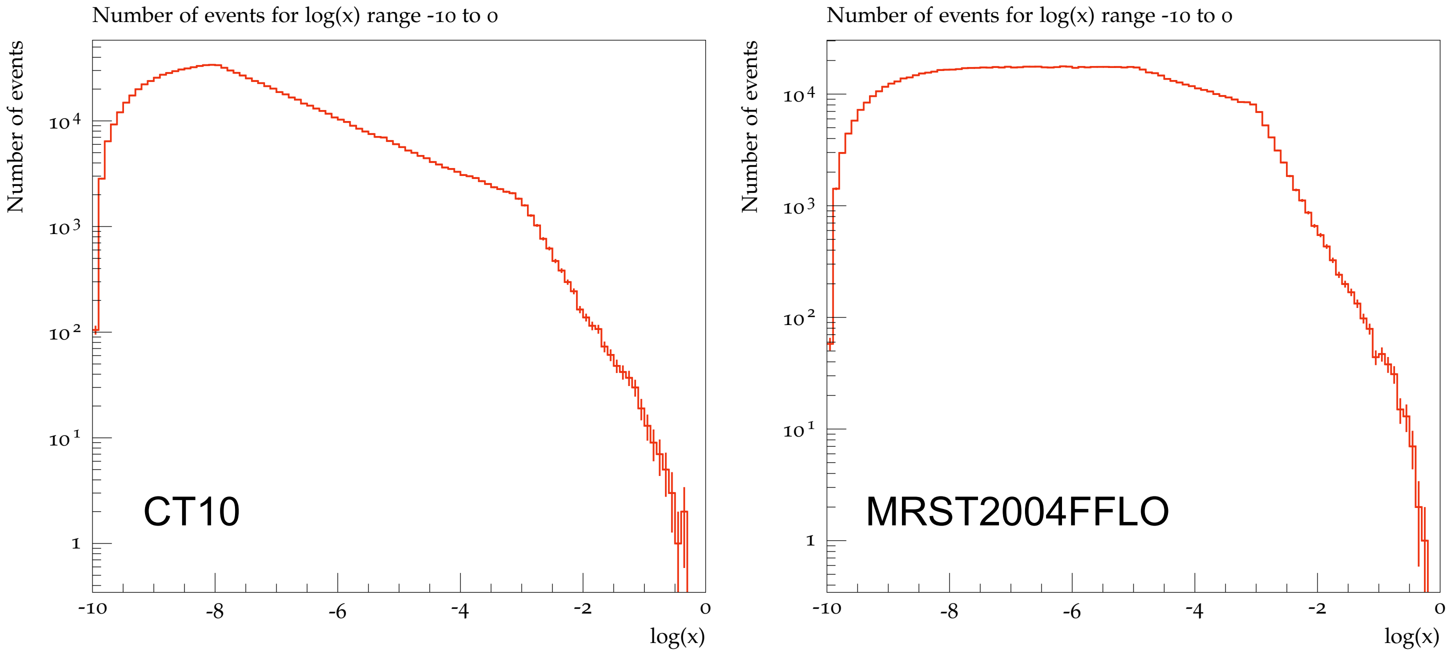


Sensitivity up to kinematic limit, 9 TeV.

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

Latest news

Emma Simpson Dore &
Fearghus Keeble (UCL)



Have a VHEeP inclusive analysis using RAPGAP running in Rivet:

- Can use more modern PDFs, but still not the latest
- Should be able to use with HERWIG and in principle other MCs
- More modern infrastructure than standalone Fortran ARIADNE
- Can check that chosen parameters agree with HERA data
- Can simulate events at very low *x*

Also looking at J/ψ production

Workshop

https://indico.mpp.mpg.de/event/5222/overview

indico.mpp.mpg.de

UCL ZEUS ILC COMET/PRISM XFEL PDPWA HEP Physics Admin Travel Computing Apple Kino/Kultur News Wohnung

iCal export More Europe/Berlin M. Wing

Prospects for a very high energy eP and eA Collider

1-2 June 2017
MPI Meeting rooms
Europe/Berlin timezone

- Overview
- Scientific Programme
- Timetable
- Contribution List
- Author List
- My Conference
- Registration
  - Modify my Registration
- Accommodation
- Payment
- Participant List

The workshop will investigate the physics potential of a very high energy electron-proton and electron-ion collider with nominal (eP) center-of-mass energy of 9 TeV, a factor of 30 higher than HERA.
The workshop will be over 2 days, 1st and 2nd June 2017, in MPI Munich, starting at 9am on the 1st and finishing by 16:00 on the 2nd.
The basis for the accelerator concept is proton-driven plasma wakefield acceleration of electrons, and this approach will be reviewed. A number of invited speakers will cover aspects of QCD and the behavior of high-energy cross sections in general. The sensitivity to physics beyond the Standard Model will also be described. Further contributions are also greatly encouraged; we have purposefully left significant free time in the agenda for additional contributions and discussions.
There will be participation fee of 50,- Euro which will cover the lunches in the MPP canteen, the coffee breaks as well as a social dinner in the evening of June 1. You can pay either cash upon arrival or by making a bank transfer to the following account:
Max-Planck-Institut fur Physik
AWAKE K1086, name of participant
BIC DEUTDEMMXXX
IBAN DE60 7007 0010 0195 1300 43

All welcome ! Please register

Starts 1 Jun 2017 09:00
Ends 2 Jun 2017 16:00
Europe/Berlin

MPI Meeting rooms
Auditorium
Max-Planck-Institut für Physik
Föhringer Ring 6
80805 München

Workshop

Scientific Programme

Confirmed speakers (status 05.03.2017):

Polarised eP and eA physics

Elke Aschenauer, Brookhaven National Laboratory

Aspects of small-x physics

Jochen Bartels, DESY and Universität Hamburg

Proton-driven plasma wakefield acceleration of electrons

Allen Caldwell, Max Planck Institute for Physics

High energy cross-sections and classicalization

Gia Dvali, Max Planck Institute for Physics

Applying AdS/CFT to very low x physics

Johanna Erdmenger, Universität Würzburg

BKFL and dipoles

Henri Kowalski, DESY

Low x physics

Alfred Mueller, Columbia University

LHeC studies and relation to VHEeP

Paul Newman, University of Birmingham

Simulations for high energy eP collisions

Simon Plaetzer, Durham University

Total scattering cross sections

Anna Stasto, Pennsylvania State University

Study of the Formation Zone Concept in Multiproduction Via High Energy e-Nucleus Scattering

Leo Stodolsky, Max Planck Institute for Physics

eA collisions at high energies

Raju Venugopalan, Brookhaven National Laboratory

VHEeP studies and parameters

Matthew Wing, University College London and DESY, Hamburg, Germany

Let us know if you would like to make a contribution

Summary and outlook

• Developed physics case for a very high energy *eP* collider at $\sqrt{s}$ ~ *9 TeV* based on plasma wakefield acceleration.

• Initial basic ideas of accelerator parameters, detector design and kinematics.

• 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*, α_s, contact interactions).

• New ideas are also welcome ! So we’re having a workshop to discuss them.

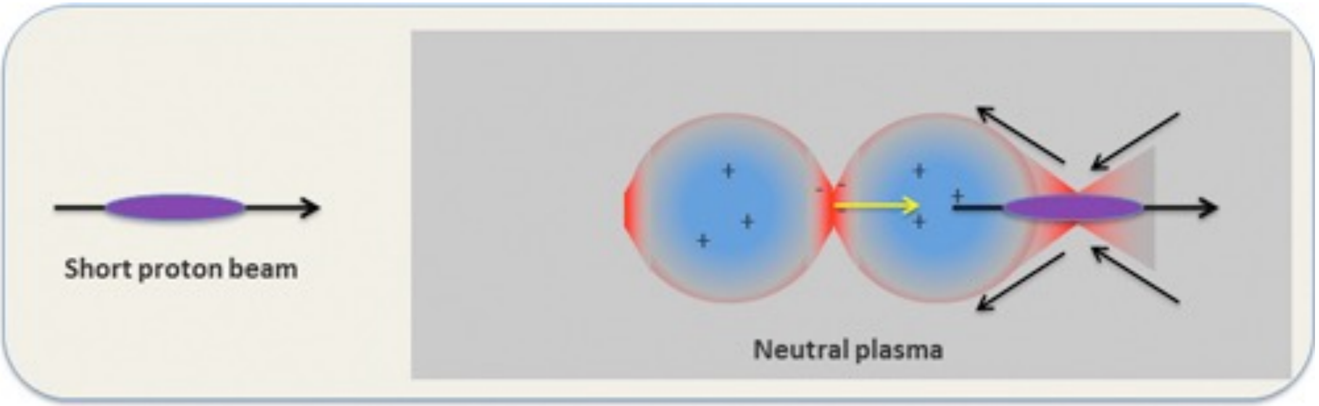
Back-up

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.

AWAKE

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.

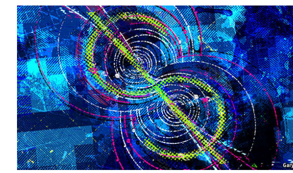
The Economist

Particle physics

A new awakening?

Accelerators are getting bigger and more expensive. There may be a way to make them smaller and cheaper

Jan 31st 2015 | From the print edition

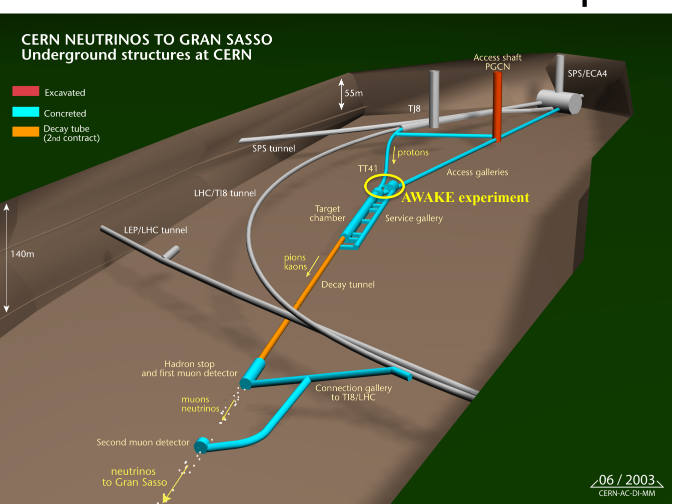


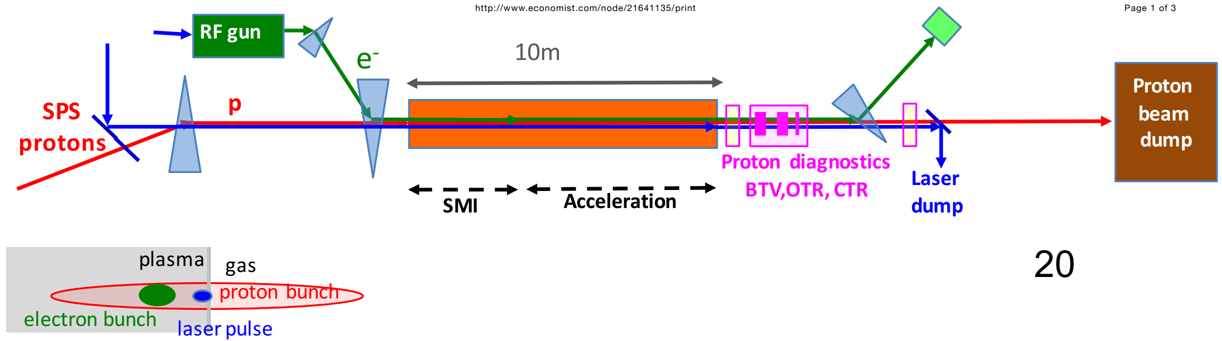
FOR more than 80 years particle physicists have had to think big, even though the things they are paid to think about are the smallest objects that exist. Creating exotic particles means crashing quotidian ones (electrons and protons) into each other. The more exotic the output desired, the faster these collisions must be. That extra speed requires extra energy, and therefore larger machines. The first cyclotron, built in 1931 in Berkeley, California, by Ernest Lawrence, had a circumference of 30cm. Its latest successor, the Large Hadron Collider (LHC) at CERN's laboratory near Geneva—which reopens for business in March after a two-year upgrade—has a circumference of 27km.

The bill for this big thinking, though, is enormous. The LHC, which started work in 2008, cost $5 billion. An even more ambitious American machine, the Superconducting Super Collider, would have had a circumference of 87km but was cancelled in 1993 after $2 billion had been spent building less than a third of the tunnel it would have occupied. Most particle physicists thus understand that the LHC may be the end of the road for their subject unless they can radically scale down the size and cost of their toys.

And that is what they are now trying to do. A group of them, working at CERN on what is known as the AWAKE collaboration, are experimenting with a way of shrinking their machines using a phenomenon called the wakefield effect. At the moment their devices are closer in size and power to the first cyclotrons than to the LHC. But even when scaled up, wakefield accelerators will not need to approach the LHC in size, for they should pack as much punch as conventional machines 30 times as big.

Rise and shine!

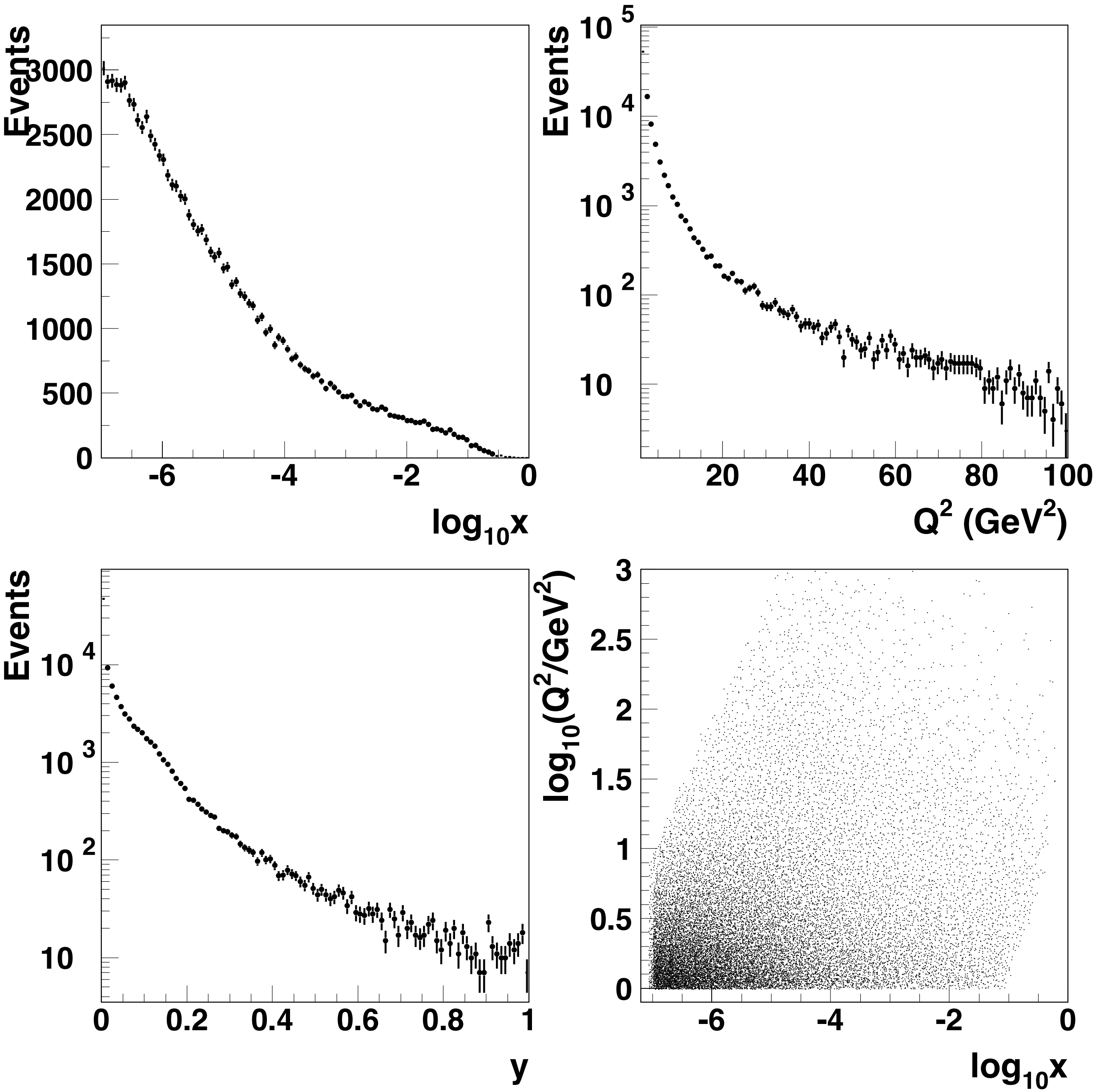




Physics at VHEeP

- Cross sections at very low *x* and observation/evidence for saturation. Completely different kind of proton structure.
- Measure total *γP* 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 ?

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.

$\sigma_{\gamma P}$ maths

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:

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

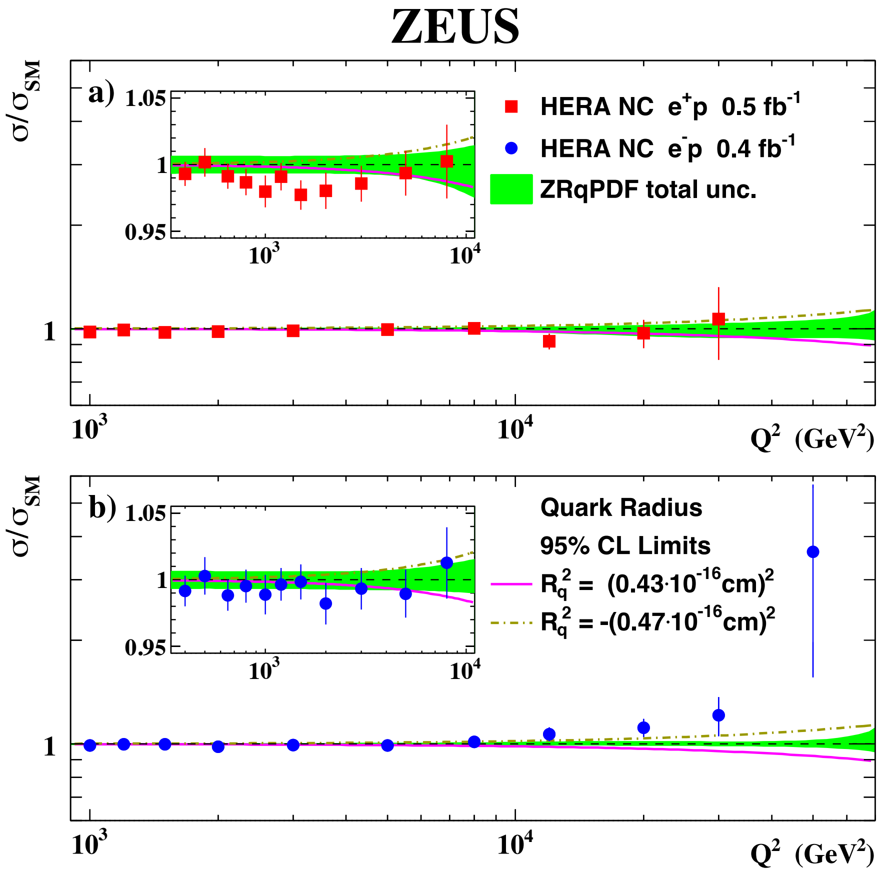
BSM: Quark substructure

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

Extraction of quark radius has been done

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

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



ZEUS Coll., Phys. Lett. **B 757** (2016) 468.

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

Assuming the electron is point-like, VHEeP limit is $R_q \lesssim 1 \times 10^{-19}\ m$

Fuller analysis would lead to stronger limits.