Introduction to 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 γP cross section
  - Vector meson cross sections
  - Very low x physics and saturation
  - Sensitivity to beyond the standard model physics
- Baseline parameters
- Summary and outlook

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

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.

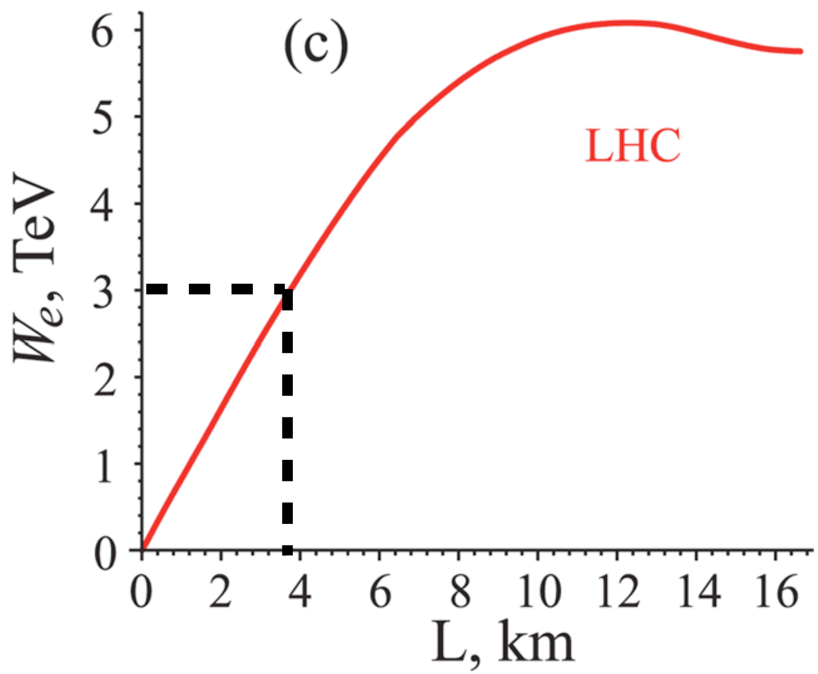
• The LHeC is a proposed *eP* collider with significantly higher energy and luminosity than HERA with a programme on Higgs, searches, QCD, etc..

• 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 ?

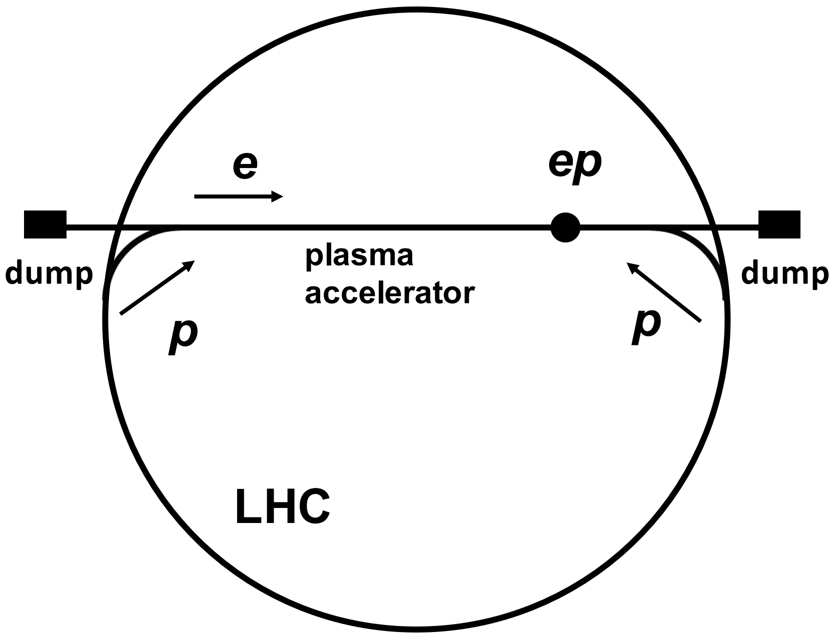
Plasma wakefield accelerator (AWAKE scheme)

- 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* $\Rightarrow$ $\boldsymbol{\sqrt{s} = 9}$ ***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



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

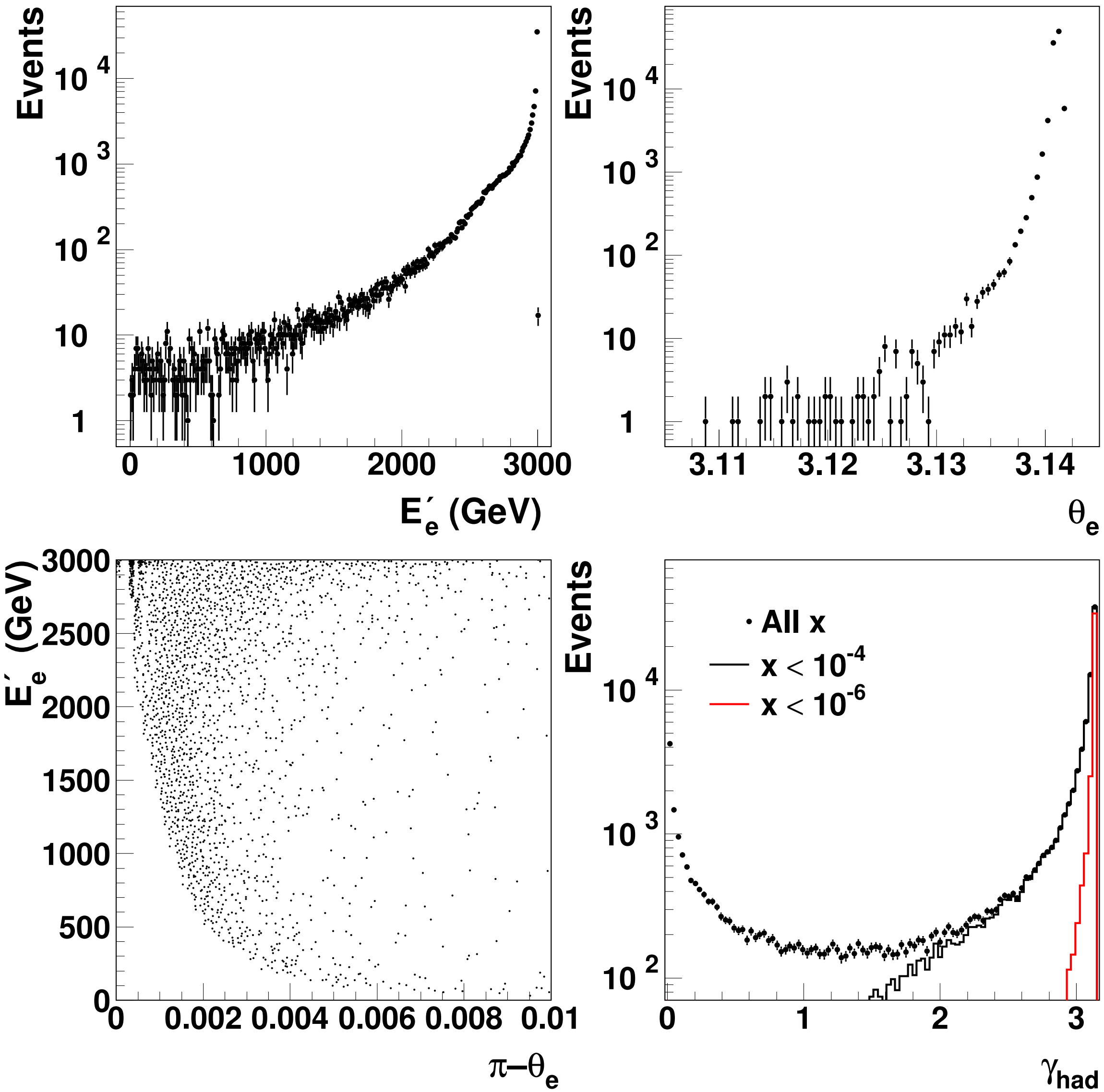
For few × 10^7 *s*, have *1* pb^{-1} / year of running.

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*.
  - $N_p \sim 4 \times 10^{11}$, $N_e \sim 1 \times 10^{11}$
  - $\sigma \sim 4\ \mu m$

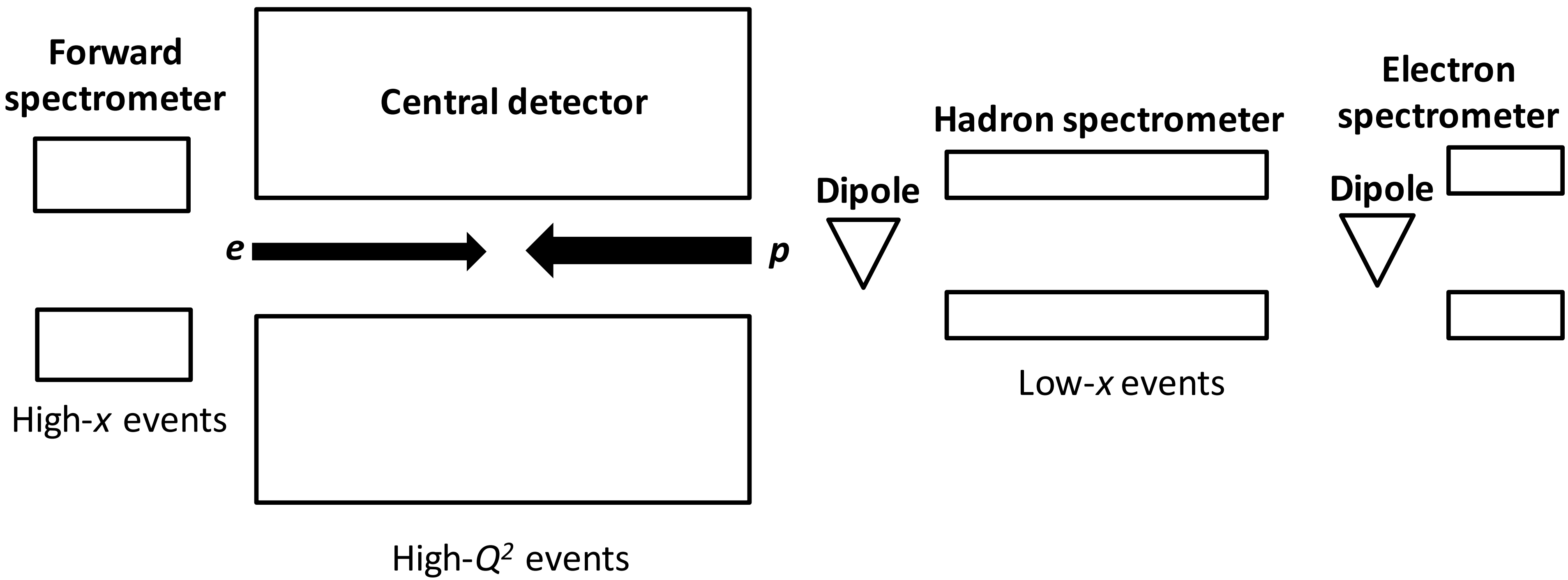
Physics case for very high energy, but moderate (*10–100* pb^{-1}) luminosities.

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



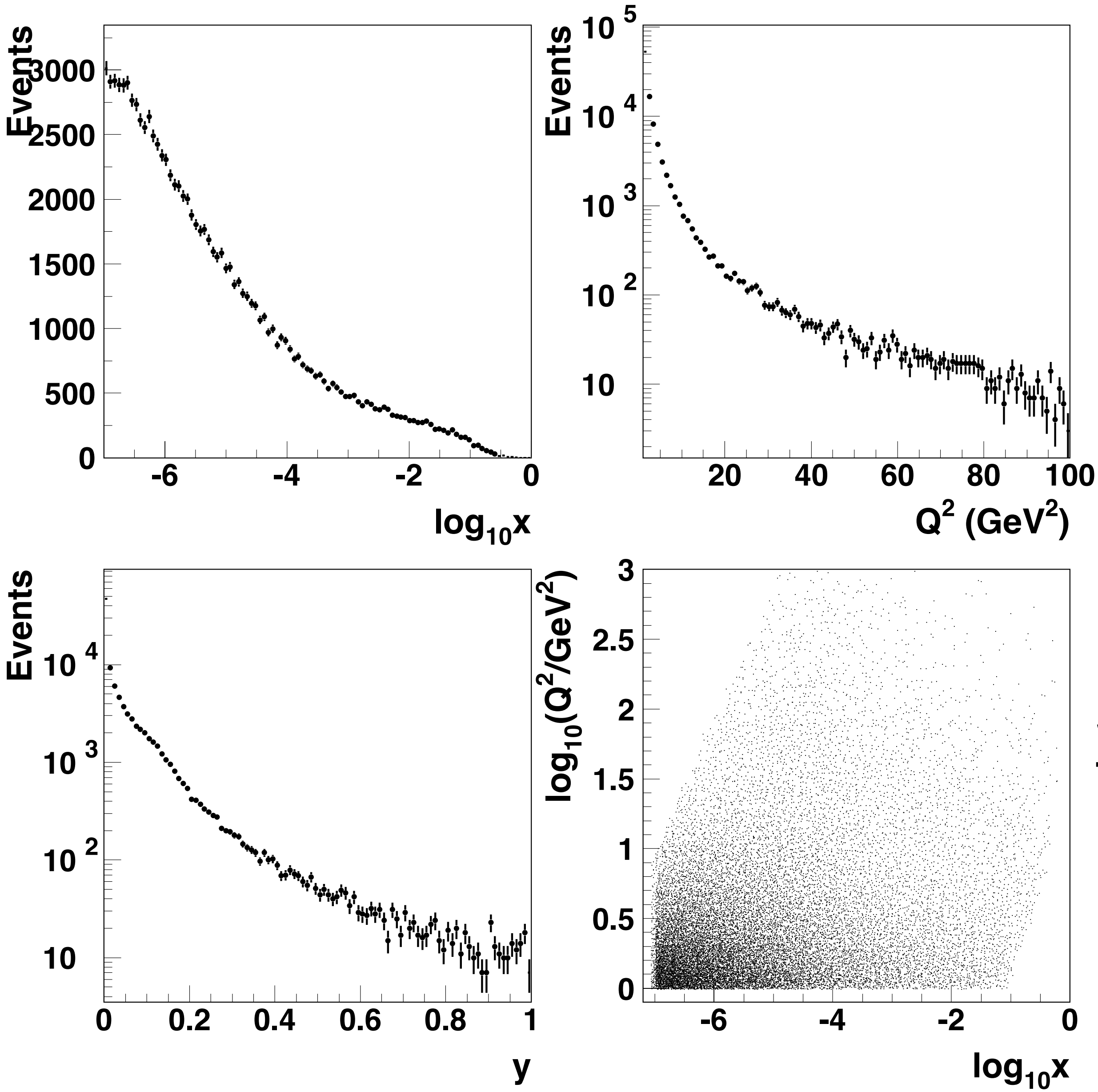
- Will need conventional central colliding-beam detector.
- **Will also need long arm of spectrometer detectors which will need to measure scattered electrons and hadronic final state at low *x* and at high *x*.**

See also Fearghus Keeble's talk.

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 ?

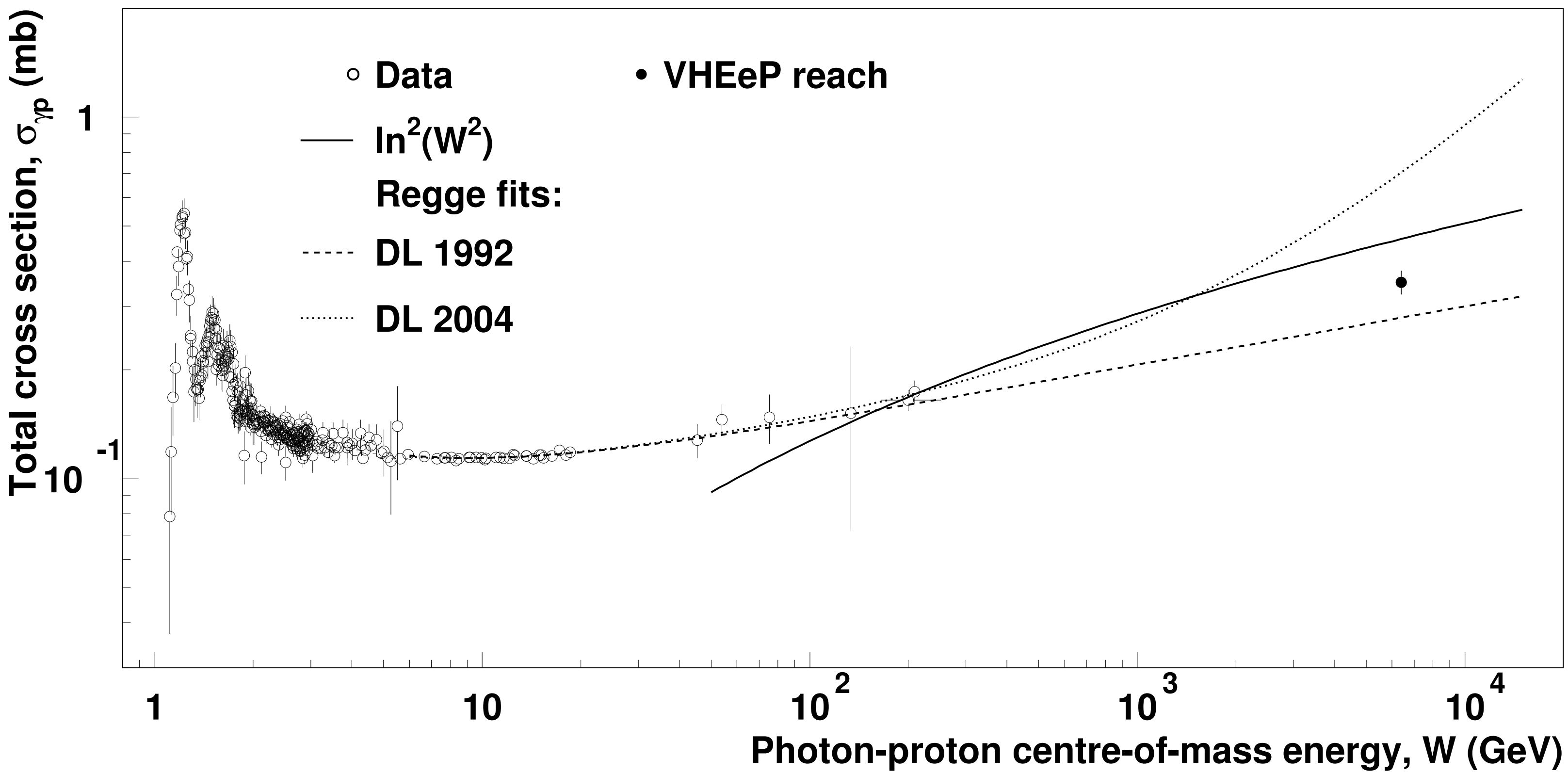
DIS variables



- 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.

See Fearghus Keeble's talk for new results.

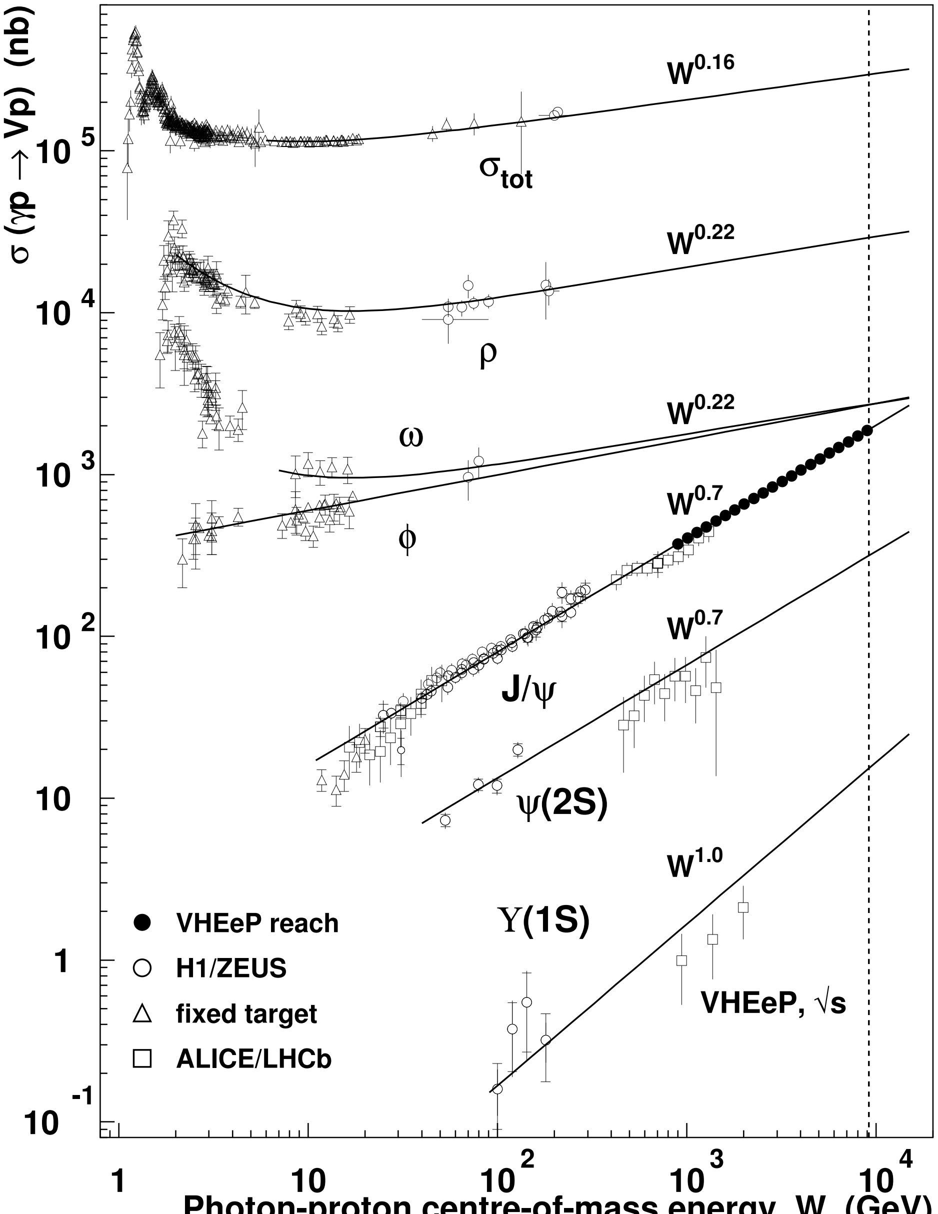
Total γP cross section



- 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



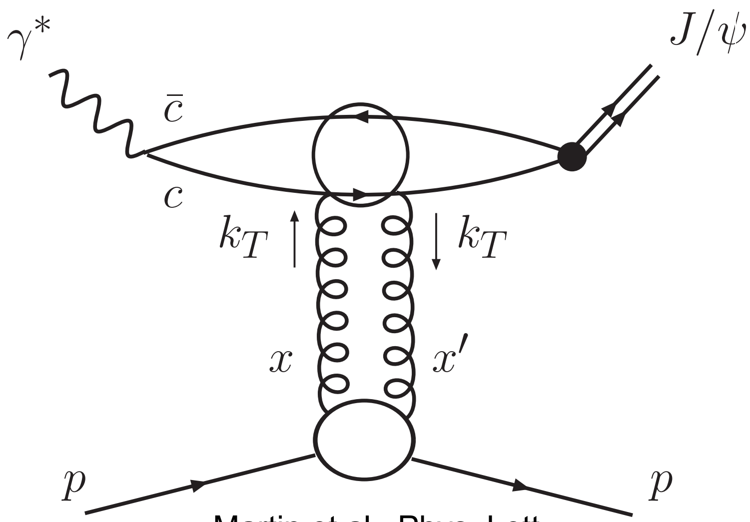
Strong rise with energy related to gluon density at low *x*.

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

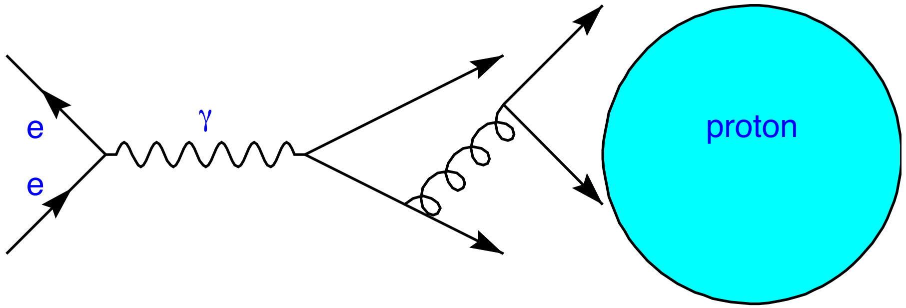
$\sigma_{\gamma P}$ at large coherence lengths

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.

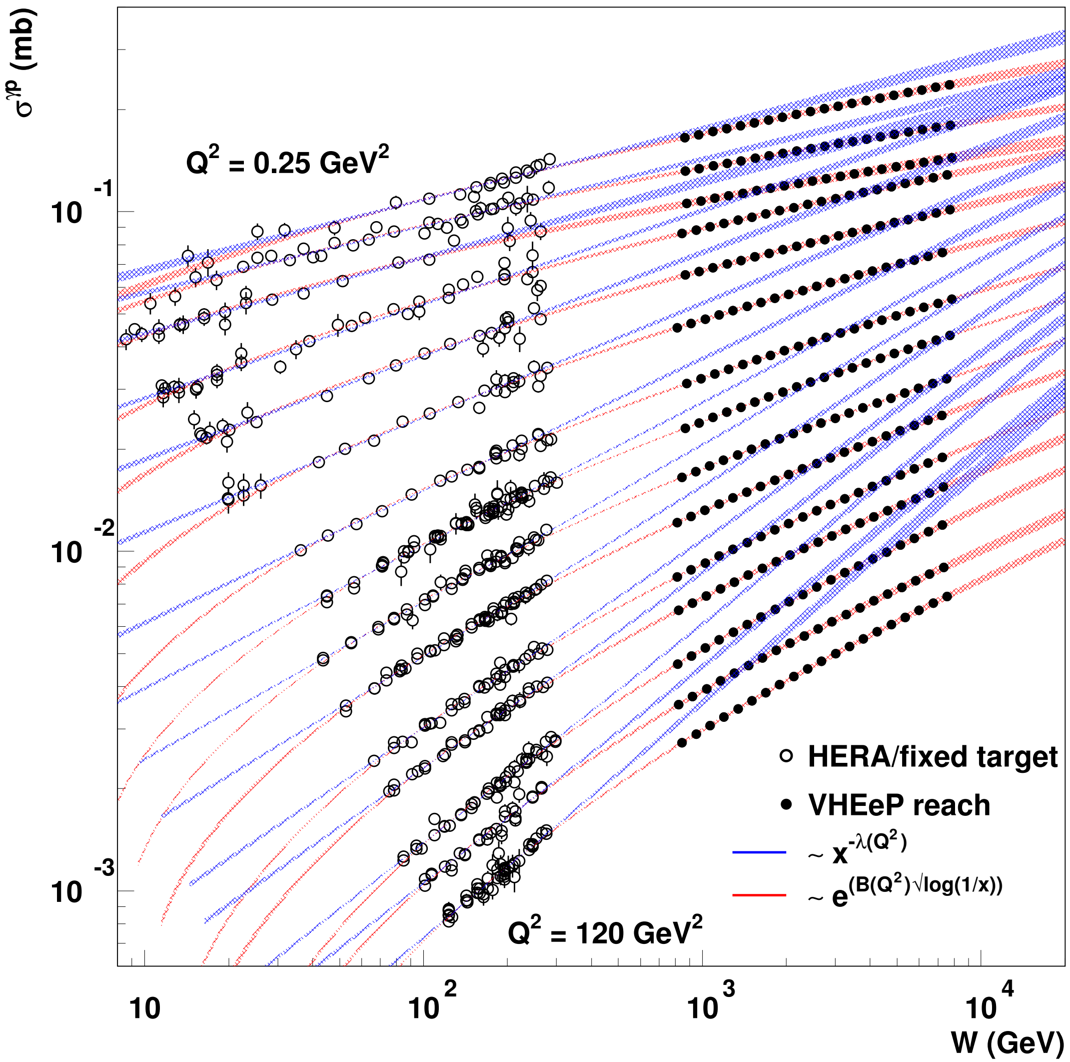
Low x means long-lived photon fluctuations (not proton structure)



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.

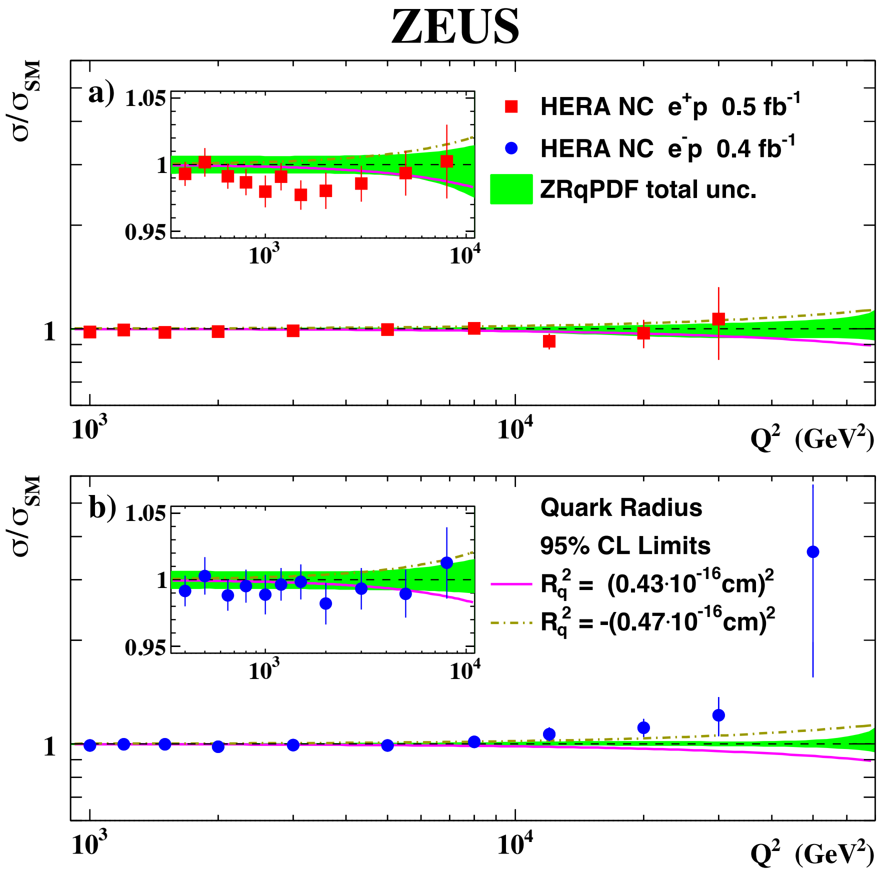
BSM: Quark substructure

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

Extraction of quark radius has been done

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

Generate some "data" for VHEeP and look at sensitivity.



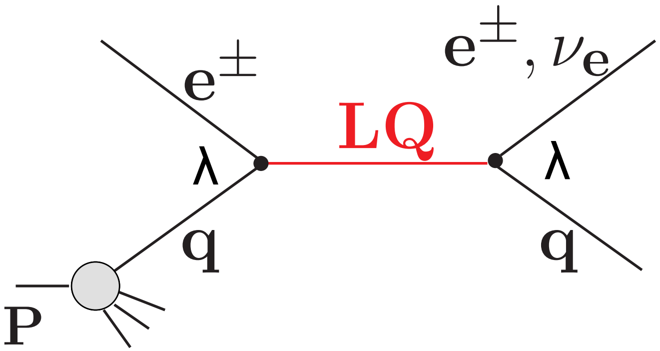
ZEUS Coll., Phys. Lett. **B 757** (2016) 468.

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.

Leptoquark production

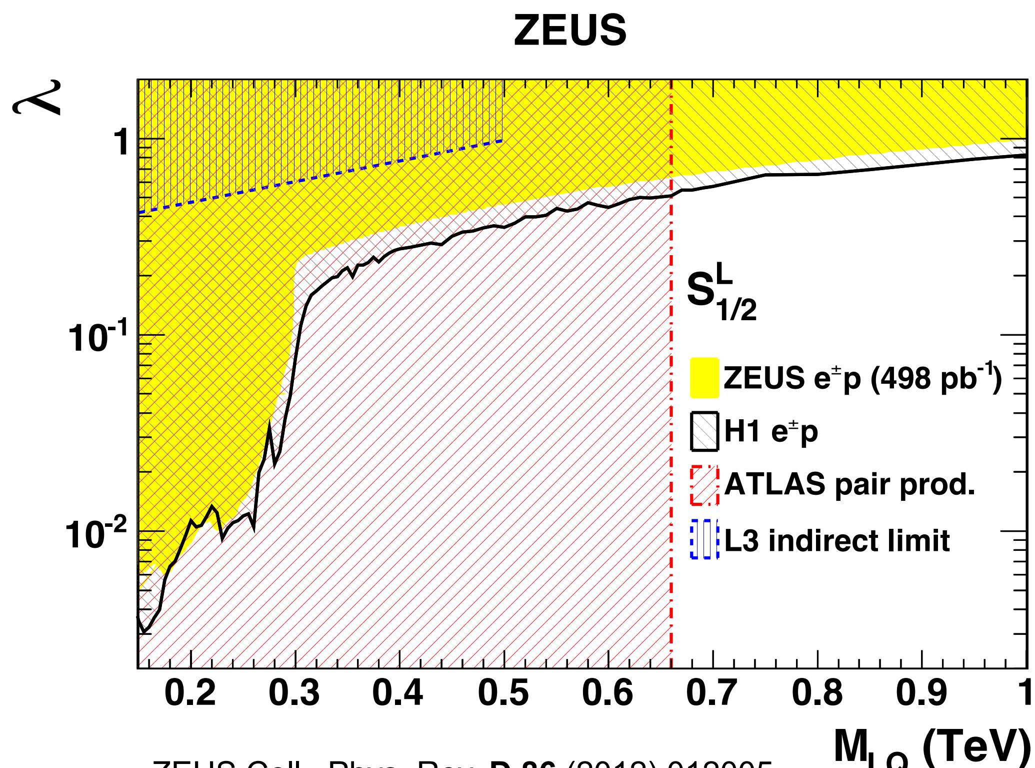


Electron−proton colliders are the ideal machine to look for leptoquarks.

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

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

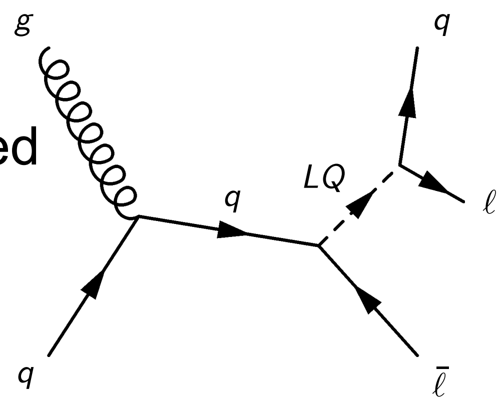
Sensitivity depends mostly on $\sqrt{s}$ and VHEeP = 30 × HERA

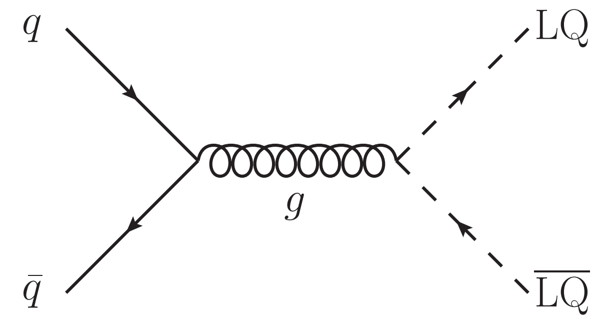


ZEUS Coll., Phys. Rev. **D 86** (2012) 012005

Leptoquark production at the LHC

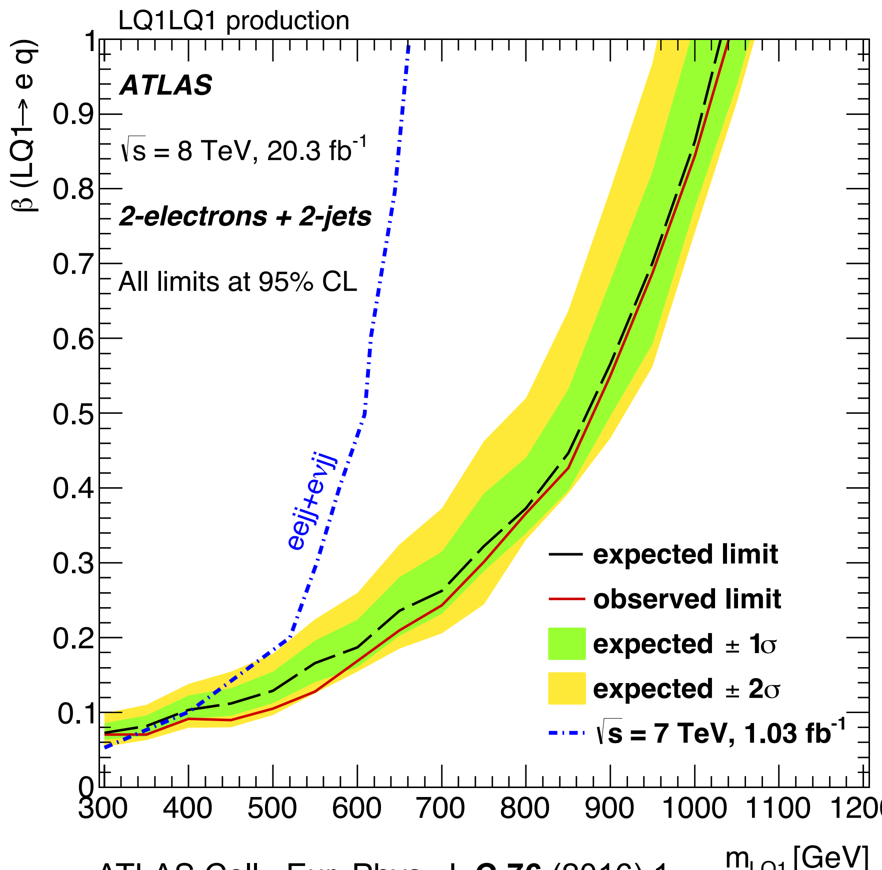
Can also be produced in *pp* singly or pair production





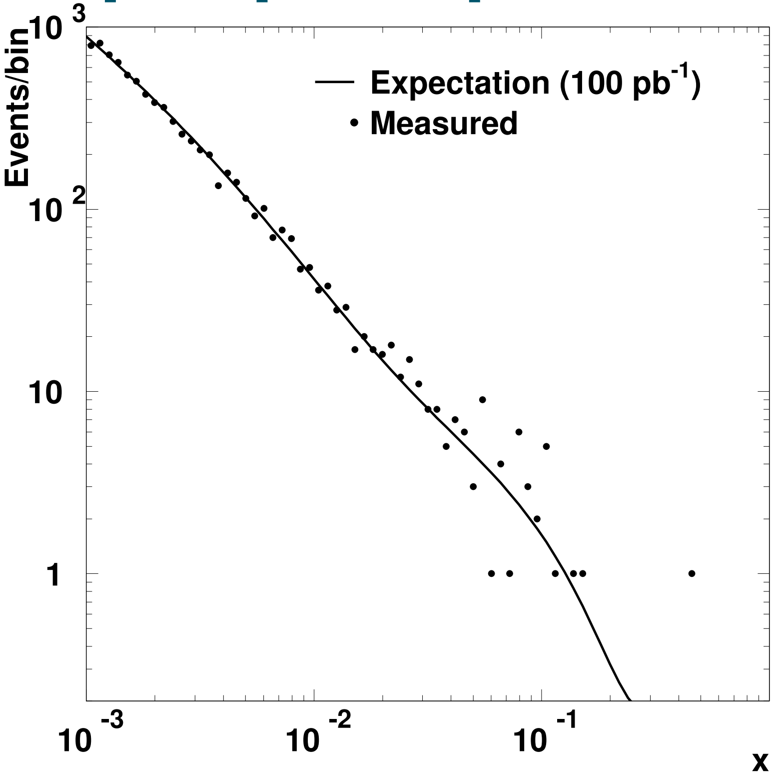
Reach of LHC currently about *1 TeV*, to increase to *2 − 3 TeV*.

Coupling dependent.



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

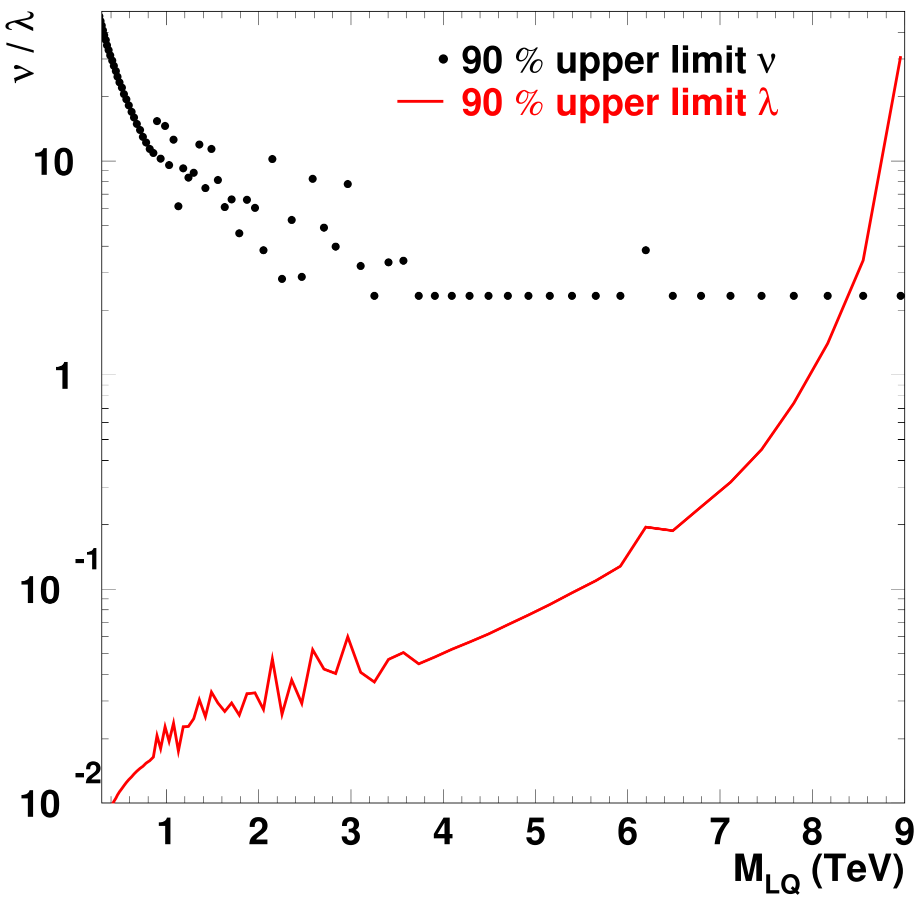
Leptoquark production at VHEeP



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

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.

Baseline parameters for VHEeP

- Nominally electron–proton collisions
- Nominal energies of E_e = *3 TeV*, E_p = *7 TeV* $\Longrightarrow \sqrt{s}$ = *9.2 TeV*
- Can vary electron beam energy, E_e = *0.1 – 5 TeV* $\Longrightarrow \sqrt{s}$ = *1.7 – 11.8 TeV*
- Electron beams, but possibility of positron beams
- Possibility of polarisation
- Integrated luminosity of $10 - 1000\ pb^{-1}$
- Also electron–ion (e.g. electron–lead) collisions

These should be considered for ideas/studies.

If more aggressive parameters are needed, we should look at what is possible for the acceleration scheme.

Summary and outlook

- 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.
- 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 ! That's why we're having this workshop …

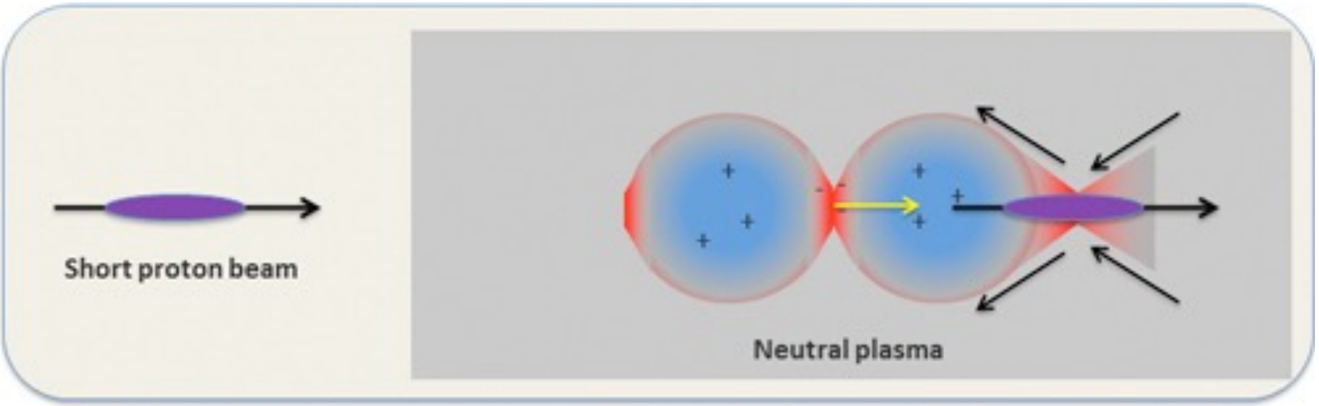
Back-up

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.

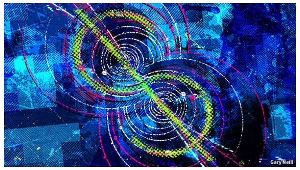
The Economist

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

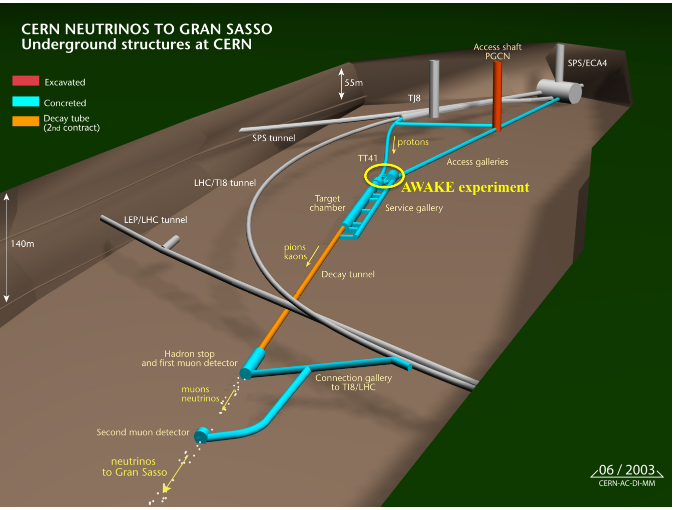


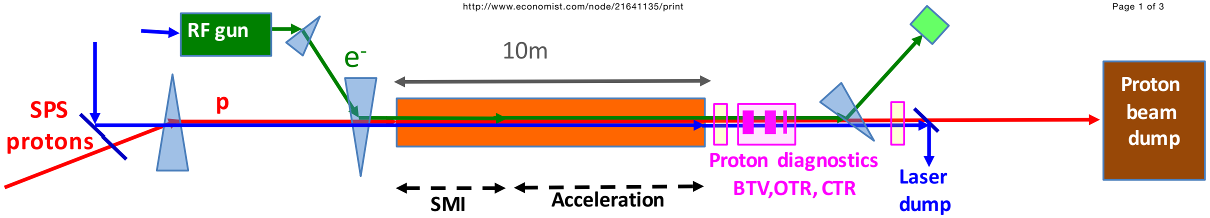
FOR more than 80 years particle physicists have had to think big, even though the things they are paid to think about are the smallest objects that exist. Creating exotic particles means crashing quotidian ones (electrons and protons) into each other. The more exotic the output desired, the faster these 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.

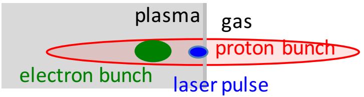
The bill for this big thinking, though, is enormous. The LHC, which started work in 2008, cost $5 billion. An even more ambitious American machine, the Superconducting Super Collider, would have had a circumference of 87km but was cancelled in 1993 after $2 billion had been spent building less than a 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!

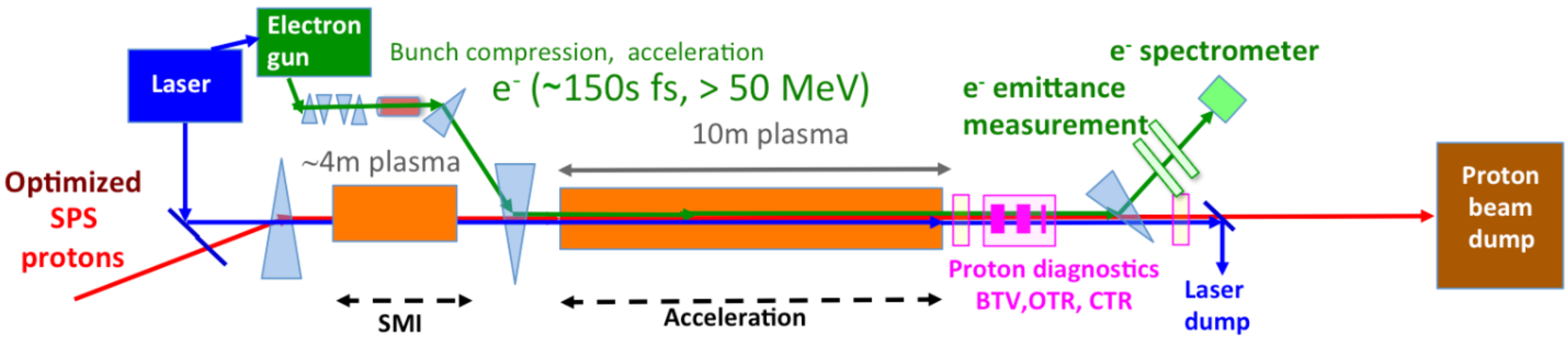






AWAKE Run 2

- Preparing AWAKE Run 2, after LS2 and before LS3.
  - Accelerate electron bunch to higher energies.
  - Demonstrate beam quality preservation.
  - Demonstrate scalability of plasma sources.



Preliminary Run 2 electron beam parameters

Parameter	Value
Acc. gradient	>0.5 GV/m
Energy gain	10 GeV
Injection energy	$\gtrsim$ 50 MeV
Bunch length, rms	40–60 μm (120–180 fs)
Peak current	200–400 A
Bunch charge	67–200 pC
Final energy spread, rms	few %
Final emittance	$\lesssim$ 10 μm

- Are there physics experiments that require an electron beam of up to *O(50 GeV)* ?
- Use bunches from SPS with 3.5×10^{11} *protons* every ~ *5 s*.
- Using the LHC beam as a driver, *TeV* electron beams are possible.

E. Adli (AWAKE Collaboration), IPAC 2016 proceedings, p.2557 (WEPMY008).

Possible physics experiments

- Use of electron beam for test-beam infrastructure, either / or for detector characterisation and as an accelerator test facility.
- Fixed-target experiments using electron beams, e.g. deep inelastic scattering.
- Search for dark photons à la NA64.
- High energy electron−proton collider, i.e. a low-luminosity LHeC-type experiment.
- Very high energy electron−proton collider (VHEeP).

This is not a definitive list and people are invited to think of other possible uses / applications / experiments.

Proposed parameters for AWAKE scheme

Drive wakefield with SPS proton bunches with $N_P = 3.5 \times 10^{11}$ every ~ *5 sec*.

- Minimum cycle length of *6 sec* for *400 GeV*
- Minimum cycle of *4.8 sec* for *300 GeV*
- Cycle length proportional to basic period of *1.2 sec*
- Improvements, e.g. more bunches per cycle ? Other ways to have frequency below *5 sec* ?

Assume electron bunches accelerated with $N_e \sim 10^9$, $E_e \sim 50$ *GeV*, length ~ *100 fs*

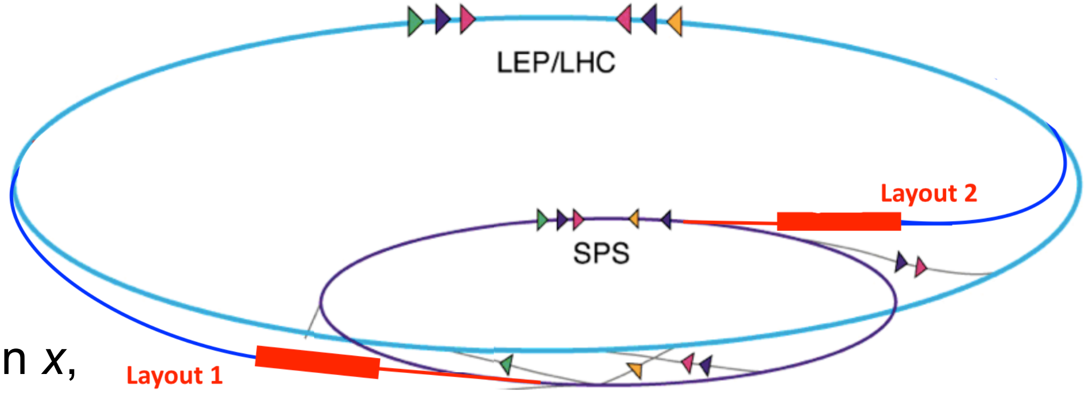
- Possible increase in bunch charge ?
- Variation in energy possible.
- Can we treat the bunches to create spills (of individual particles) ?

Fixed-target deep inelastic scattering experiments

- Measure events at high parton momentum fraction, *x*; have polarised particles and look at spin structure; consider different targets.
  - ✓ Having high energy and variation in energy is good.
  - ✓ Need high statistics to go beyond previous experiments and to have an affect on e.g. high-*x* parton densities. Valuable for LHC.
  - ✓ Should be able to maintain polarisation of electrons during acceleration.
  - ✓ Can use different targets: materials and properties.
  - ➡ Probably need to use bunches rather than individual particles.
  - Need to do a survey of previous experiments and potential for given possible beam configurations. c.f. e.g. HERMES @HERA, $E_e \sim 27.5$ *GeV,* polarisation ~ *0.3.*
- Key issues:
  - The physics case needs to be investigated: need simulations, assessment of physics potential with $E_e \sim 50$ *GeV,* polarised beams and different targets.

High energy electron−proton collider

- Consider high energy *ep* collider with E_e ~ *50 GeV,* colliding with LHC proton *7 TeV* bunch.
- Create ~*50 GeV* beam within *50−100 m* of plasma driven by SPS protons and have an LHeC-type experiment.
- Clear difference is that luminosity* currently expected to be lower ~10^{30} $cm^{-2}s^{-1}$.
- Any such experiment would have a different focus to LHeC.
  - Investigate physics at low Bjorken *x*, e.g. saturation.
  - Parton densities, diffraction, jets, etc..
  - *eA* as well as *ep* physics.



*G. Xia et al., Nucl. Instrum. Meth. **A 740** (2014) 173. Also see O. Mete’s talk.

- Can a high energy *ep* collider be sited at CERN with minimal new infrastructure ? Consider accelerator structure and tunnels as well as experimental cavern.
- Need to revisit luminosity calculation to work out physics programme.
- Opportunity for further studies to consider design of a collider using plasma wakefield acceleration and leading to an experiment in a new kinematic regime.

$\sigma_{\gamma P}$ 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:

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