LEVERHULME TRUST

UCL

The very high energy electron–proton collider, VHEeP

Allen Caldwell (MPI, Munich), Matthew Wing (UCL / DESY)

- Introduction and motivation
- Physics case of very high energy *eP* collisions
  - Challenges
  - Total *γP* cross section
  - Vector meson cross sections
  - Very low *x* physics and saturation
  - Sensitivity to beyond the standard model physics
- Baseline parameters and comparison of colliders
- Summary and outlook

INT-18-3 Workshop — 23 October 2018, Washington

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.

• HERA is so far the world's only *ep* collider.

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

• The EIC does not have such high energy but has intrinsic flexibility in energy, colliding species, polarisation and has high luminosity.

• What about very high energy collisions (VHEeP) ?

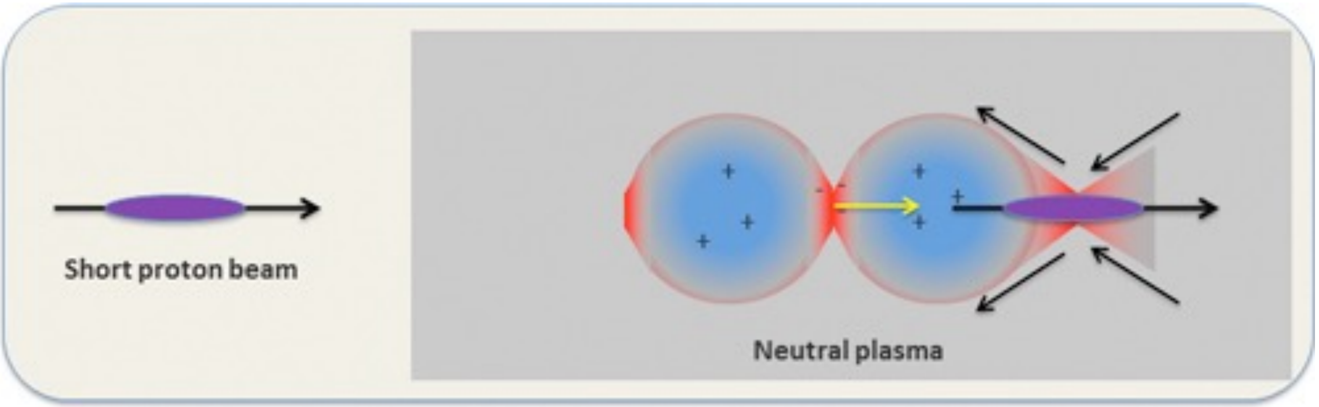
• The various possibilities EIC, LHeC, (FCC-he), VHEeP, (PEPIC) are complementary machines with complementary physics programmes.

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

- Experiment, AWAKE, at CERN demonstrated proton-driven plasma wakefield acceleration for this first time.
  - Accelerated electrons to 2 GeV in 10 m of plasma§.
  - 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.

§ AWAKE Coll., E. Adli *et al*., *Acceleration of electrons in the plasma wakefield of a proton bunch*, Nature **561** (2018) 363.

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

Possible physics experiments

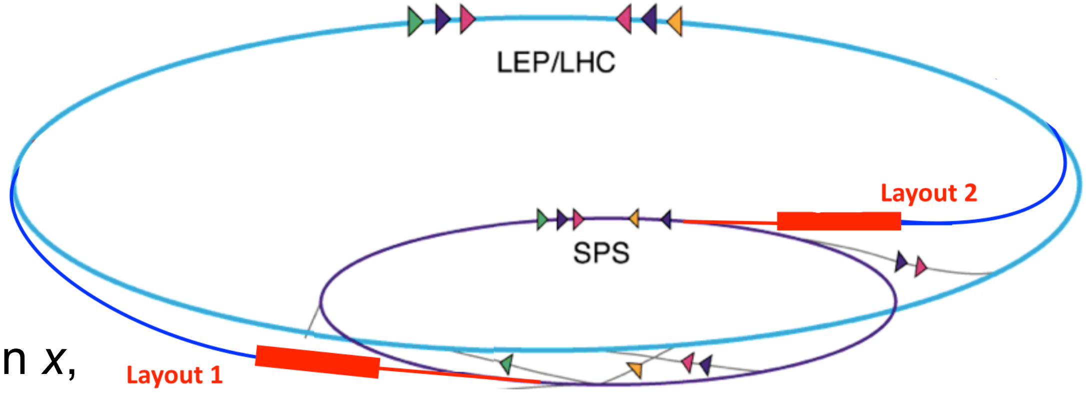
Given a high energy electron beam:

- 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 (plasma electron−proton/ion collider, PEPIC). Uses SPS as driver.**
- **Very high energy electron−proton collider (VHEeP). Uses LHC as driver.**

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

Plasma electron–proton/ion collider (PEPIC)

- 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 $\sim 10^{30}\ cm^{-2}s^{-1}$.
- 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.

- 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.

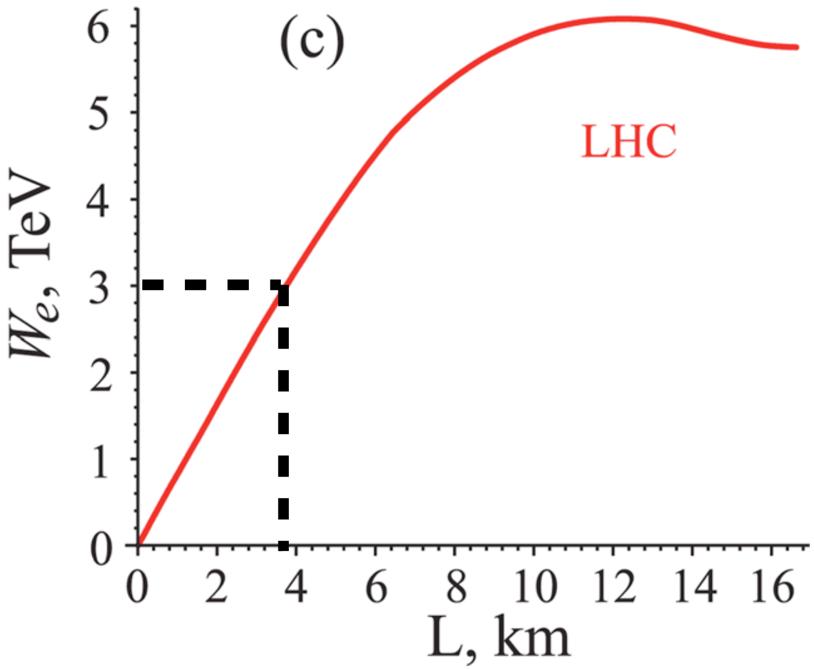
Introduction – VHEeP

- What about a very high energy *ep* collider (VHEeP) ?
  - 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 ?

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

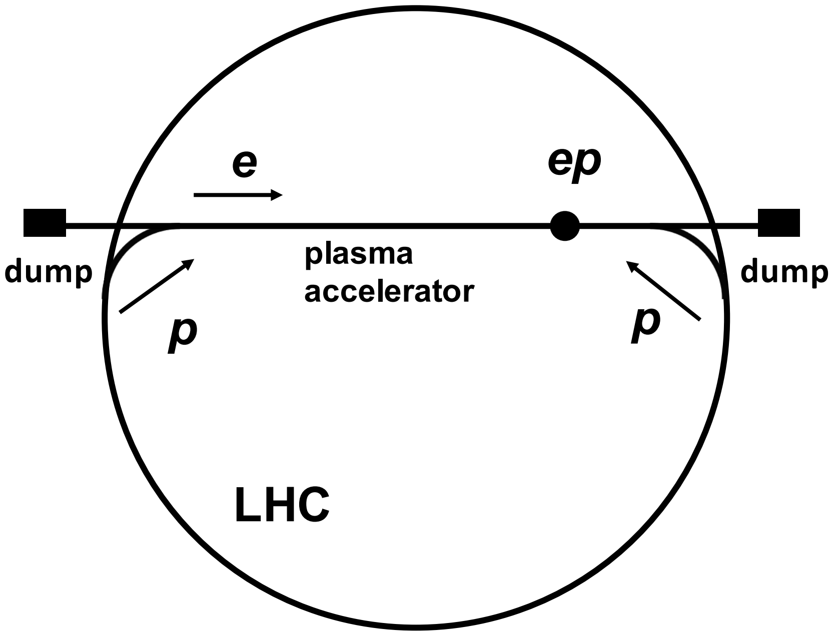
Plasma wakefield accelerator (AWAKE scheme)

- Can use current beams at CERN using AWAKE scheme.
- 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



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

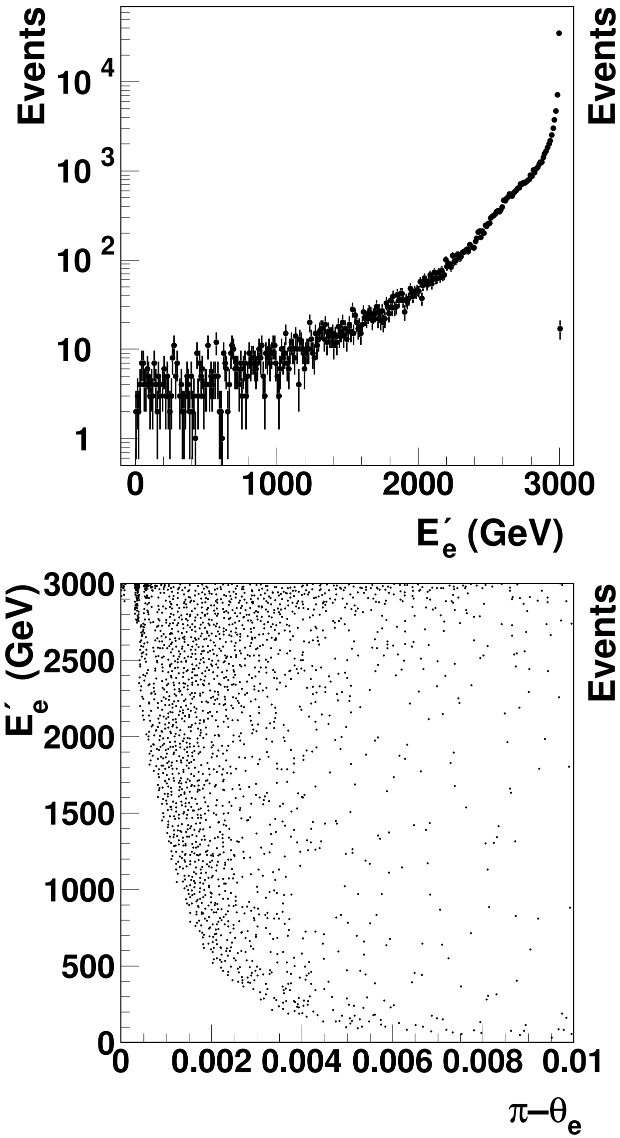
For few × 10^7 *s*, have *1* pb^{-1} / year of running.

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

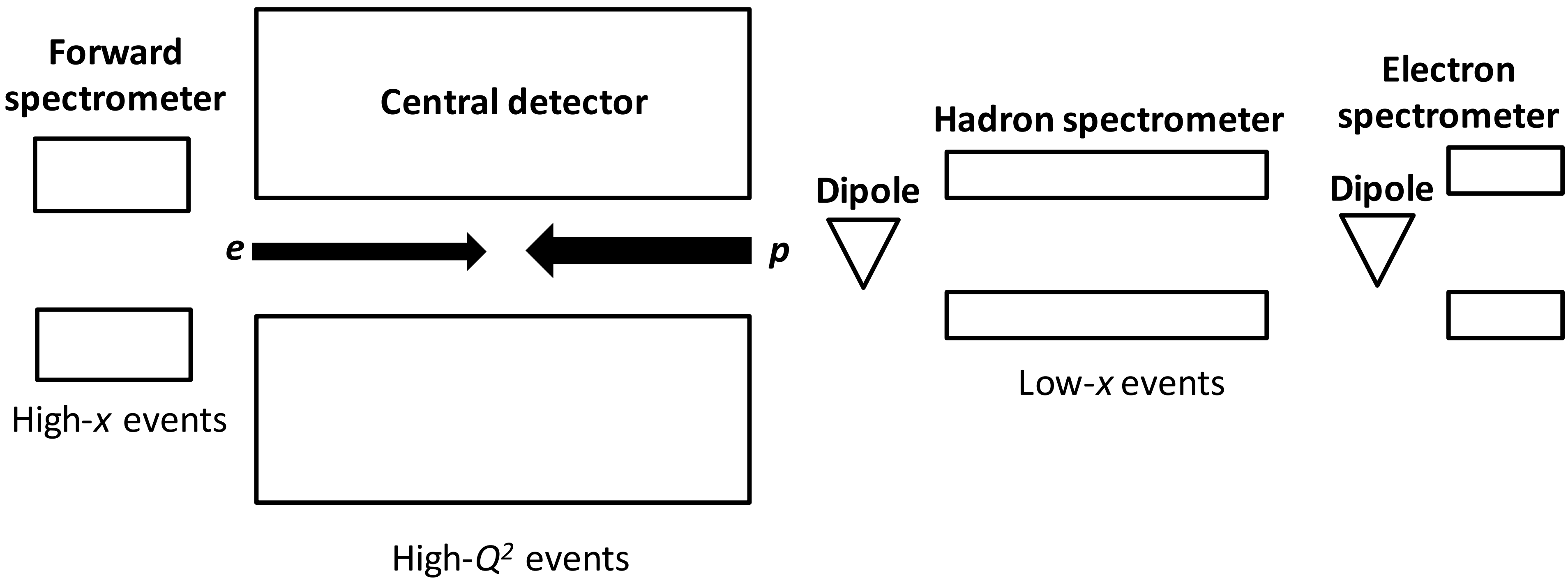
Physics case for very high energy, but moderate (*10−100* pb^{-1}) luminosities.

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

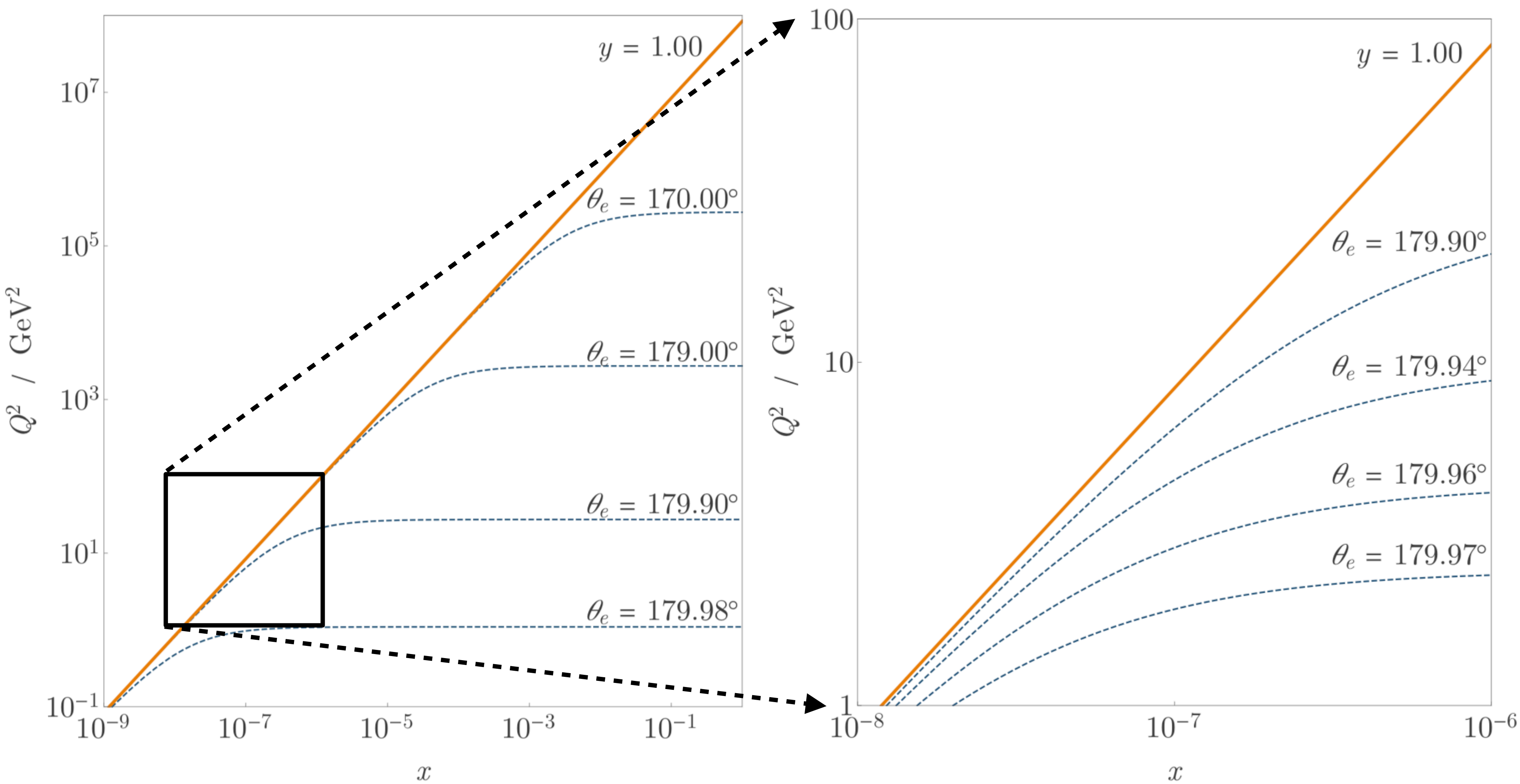


- Will need conventional central colliding-beam detector.
- **Will also need long arm of spectrometer detectors which will need to measure scattered electrons and hadronic final state at low *x* and at high *x*.**

Kinematics and detector challenge

F. Keeble, UCL

Electron kinematics

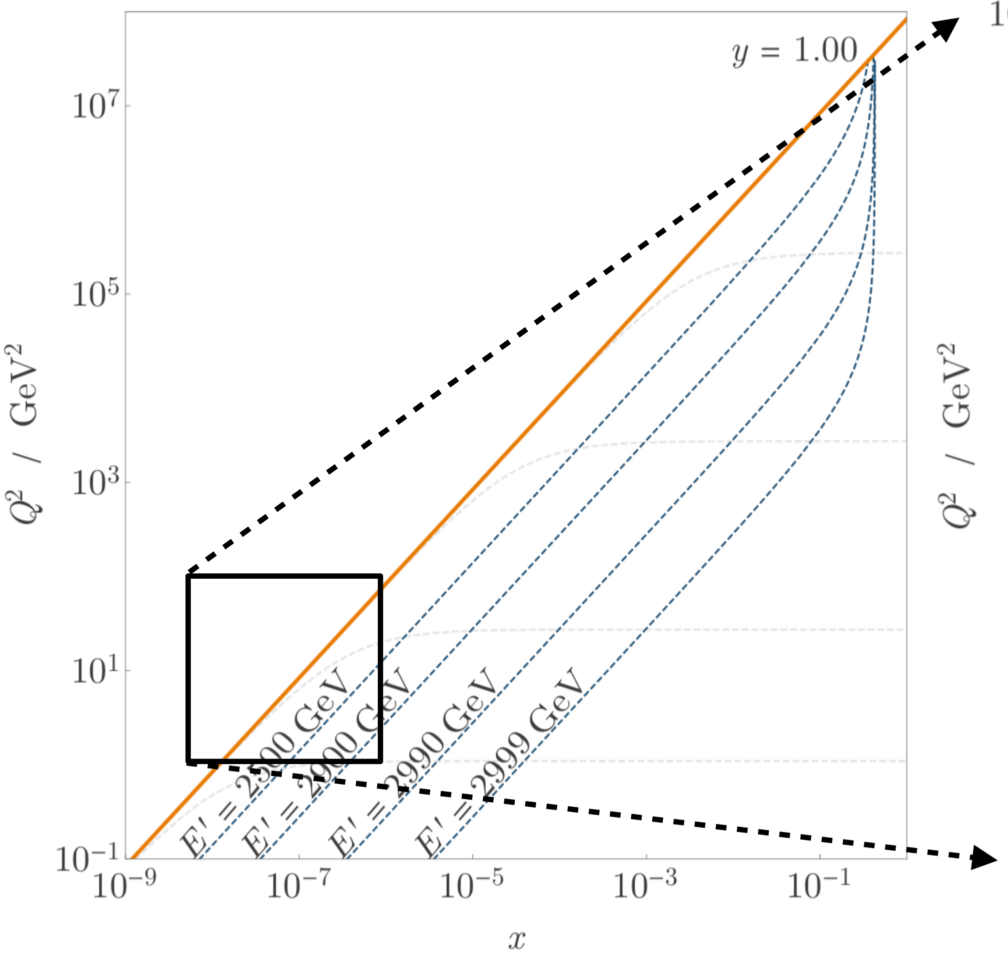


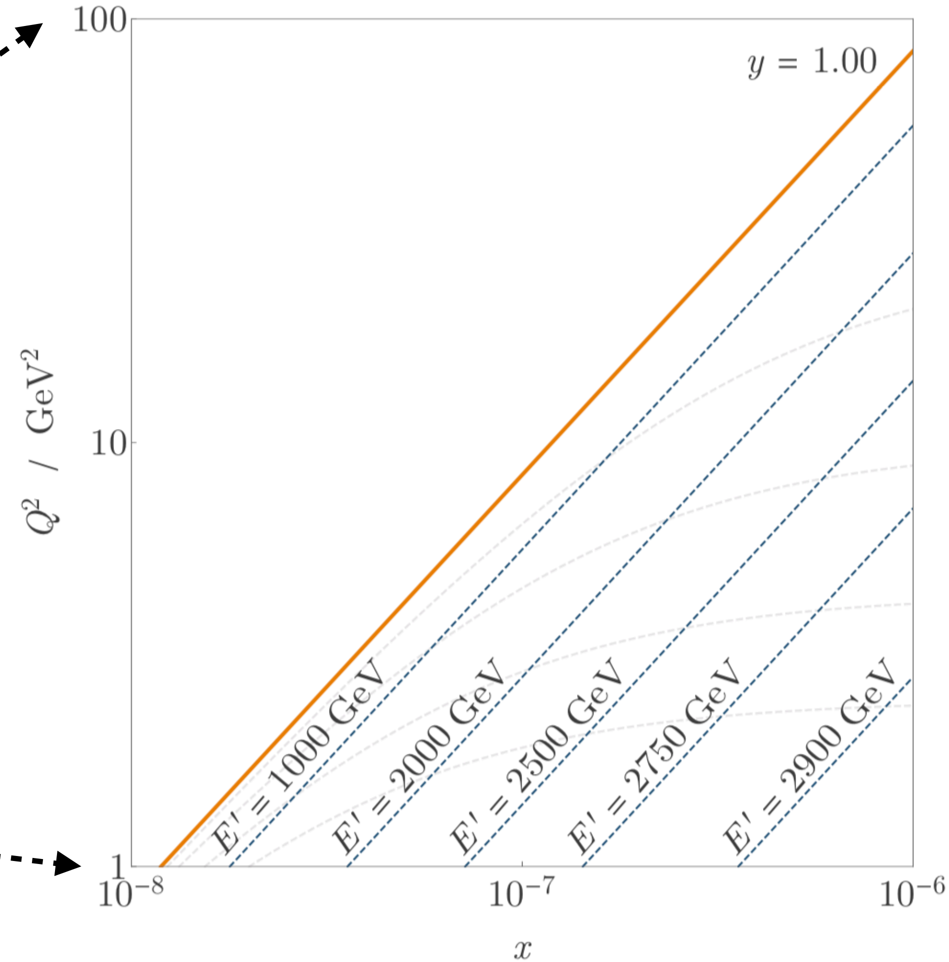
Scattered electrons are close to collinear with the initial electron beam

Kinematics and detector challenge

F. Keeble, UCL

Electron kinematics



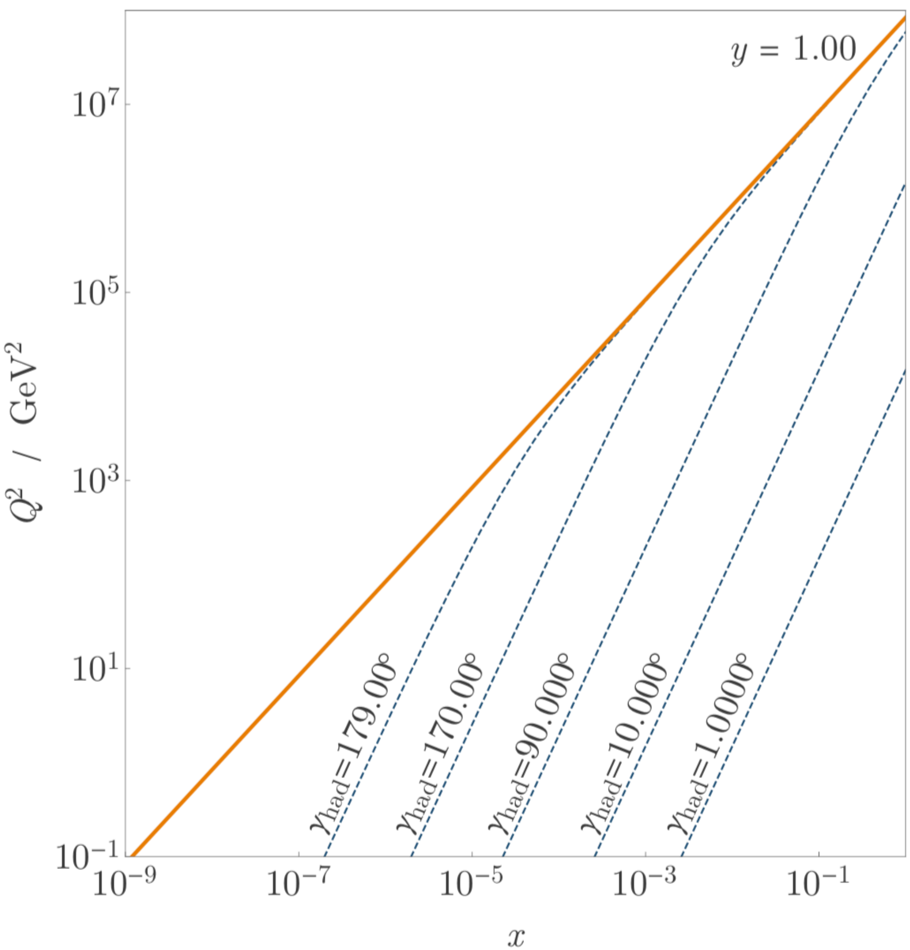


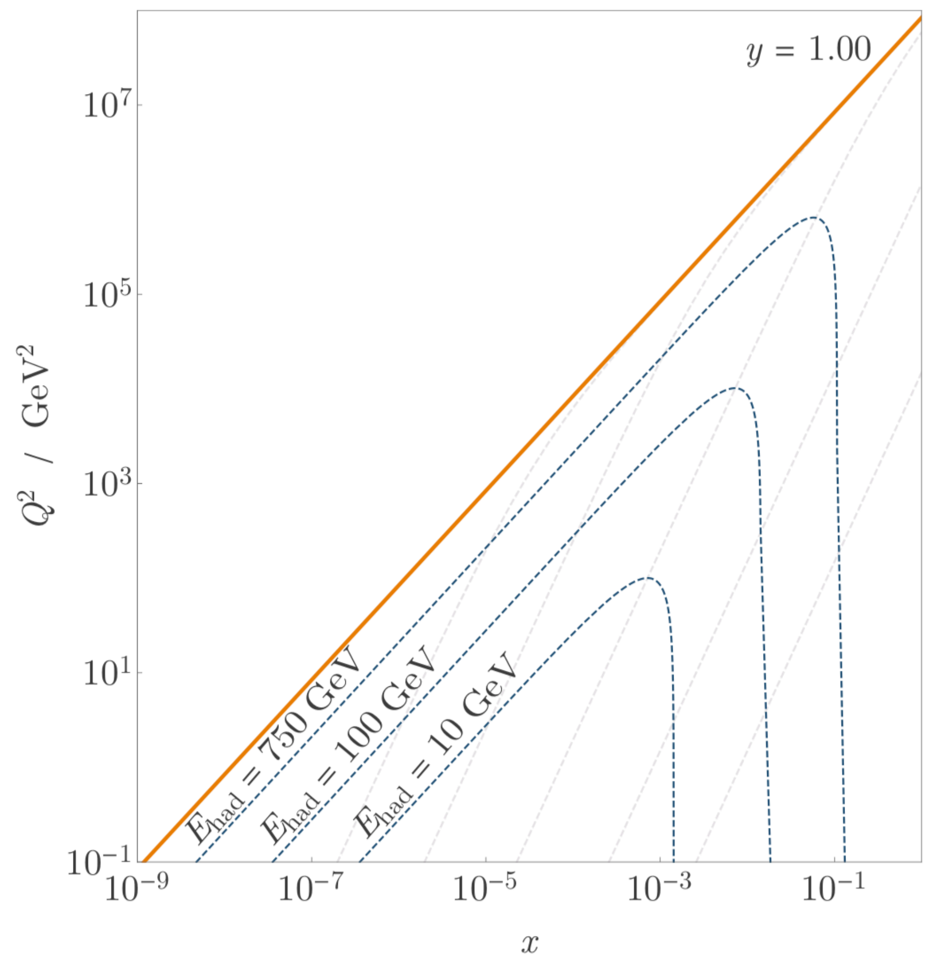
Scattered electrons at low *x* can have very different energies

Kinematics and detector challenge

F. Keeble, UCL

Hadronic final state



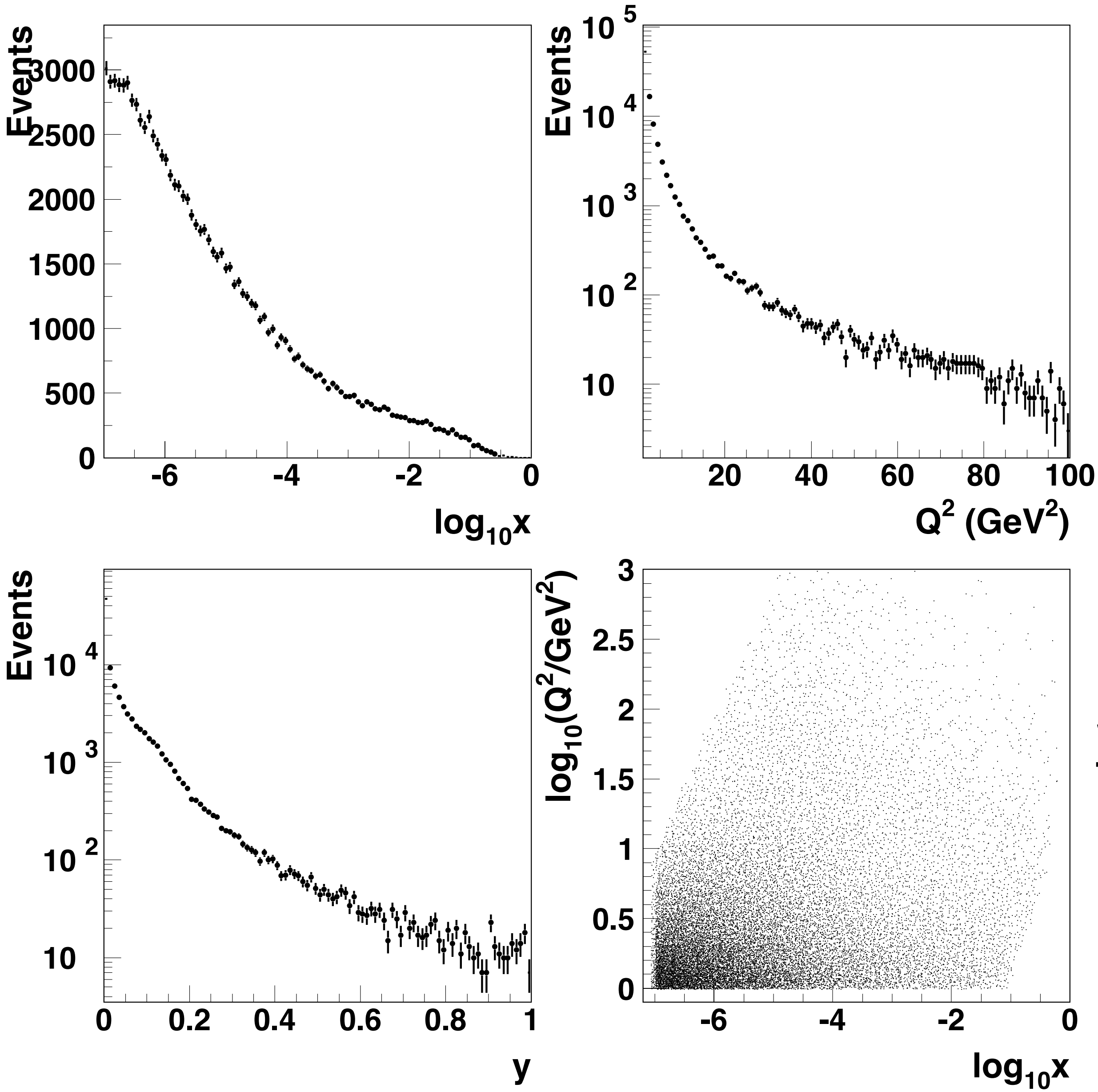


Very forward, high energy jets produced at low *x* and Q^2.

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 ?

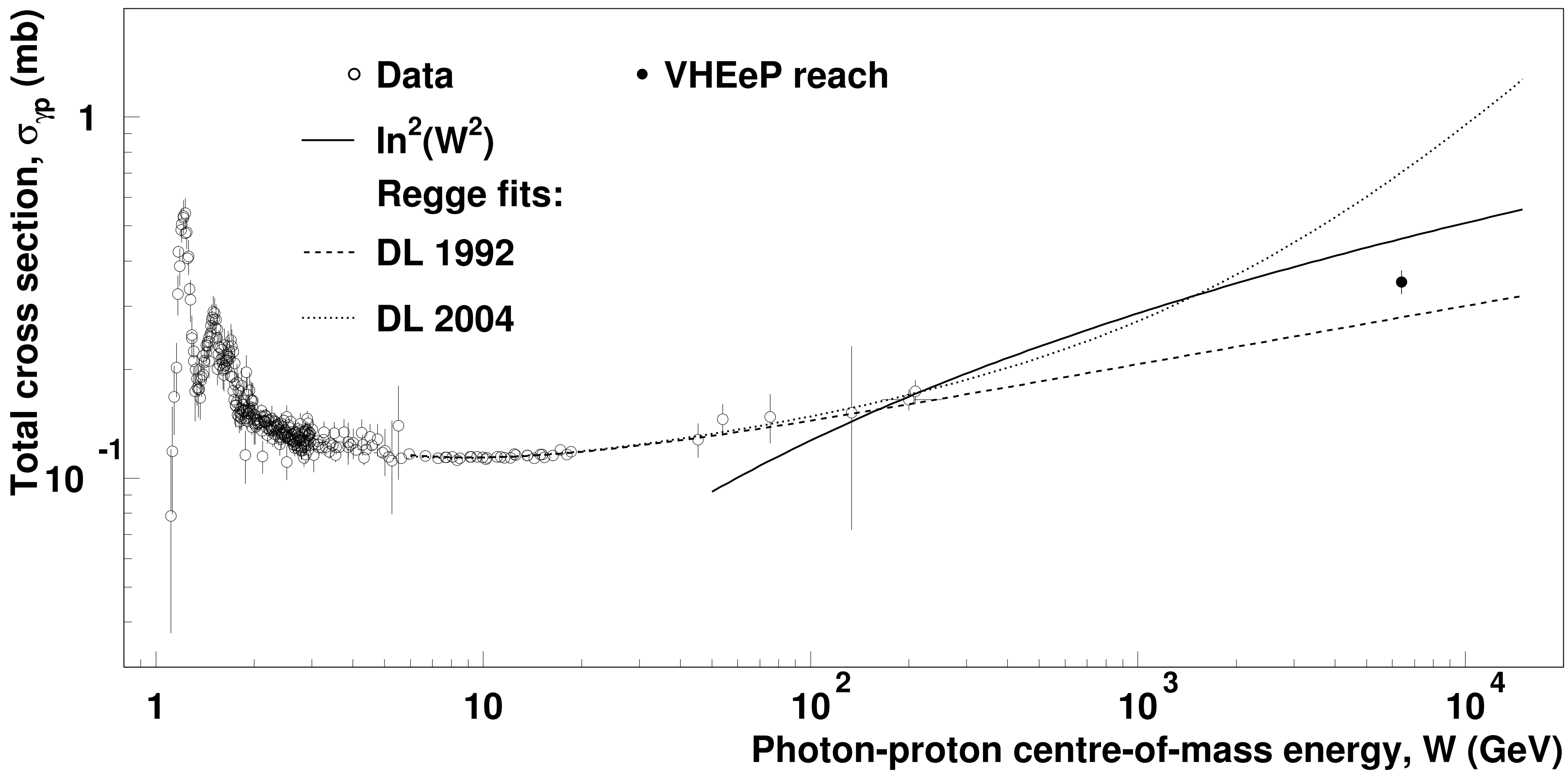
DIS variables



- 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.

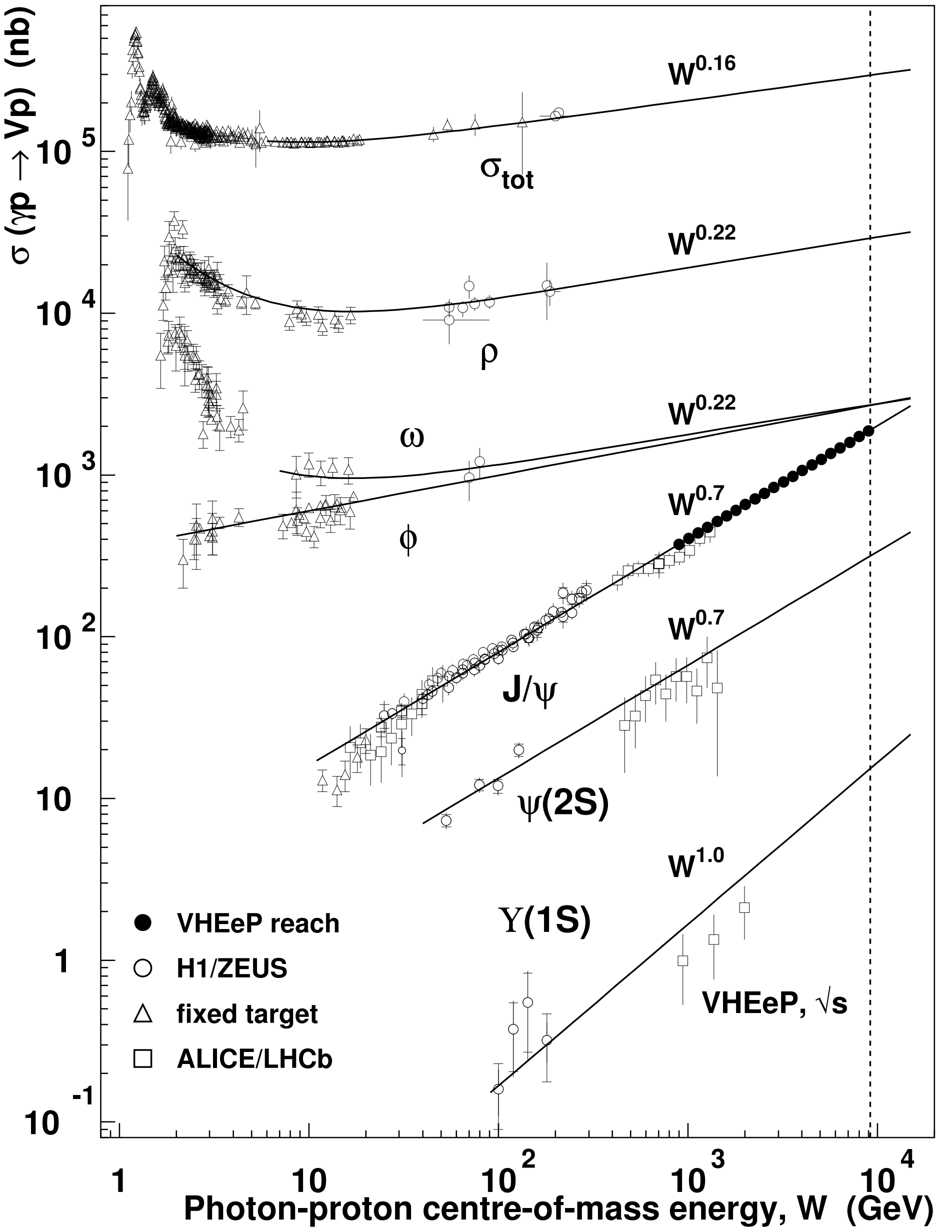
Total *γP* cross section



- 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



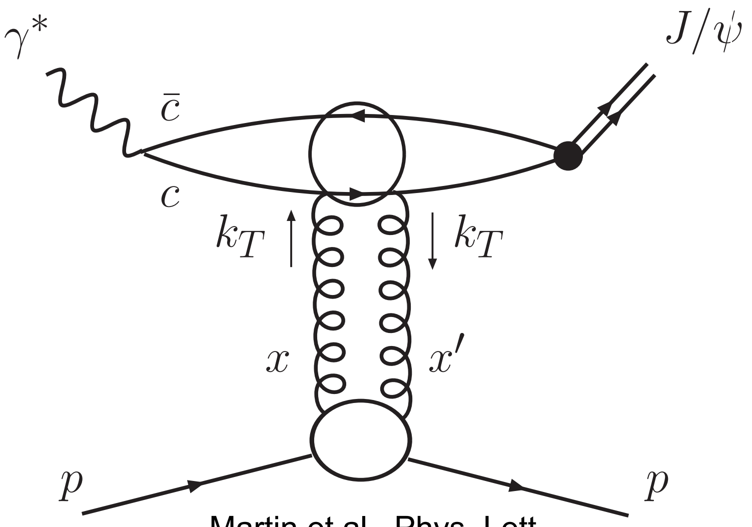
Strong rise with energy related to gluon density at low *x*.

Can measure all particles within the same experiment.

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

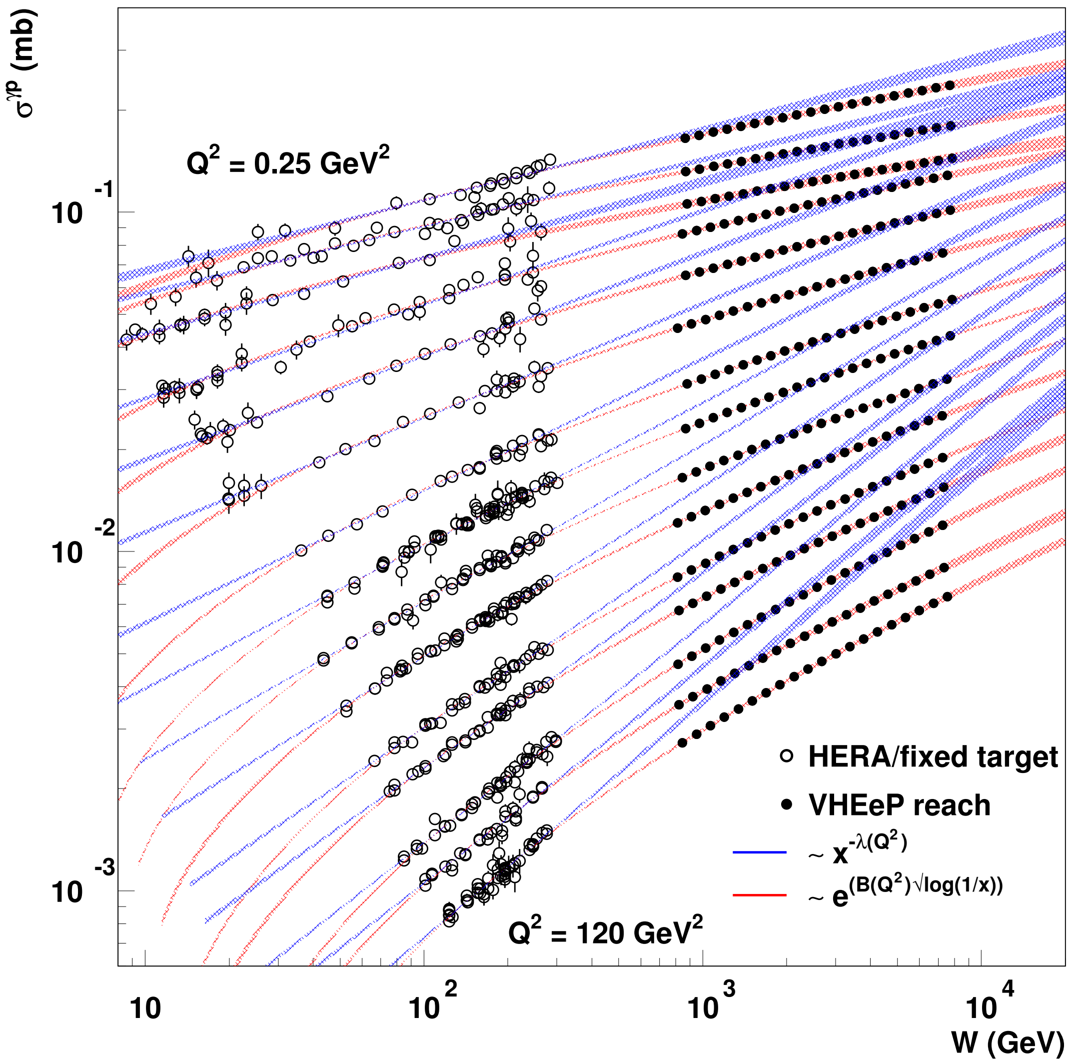
At VHEeP energies, *σ(J/ψ) ≳ σ(φ)* !

Onset of saturation ?



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

$\sigma_{\gamma P}$ 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.

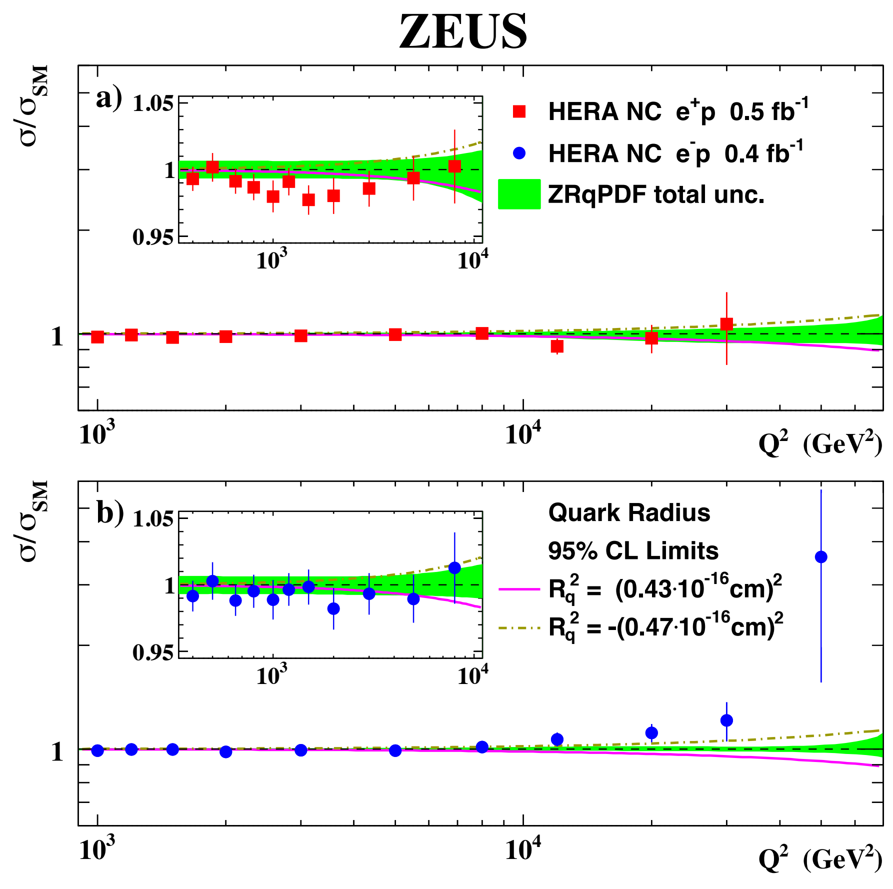
BSM: Quark substructure

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

Extraction of quark radius has been done

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

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



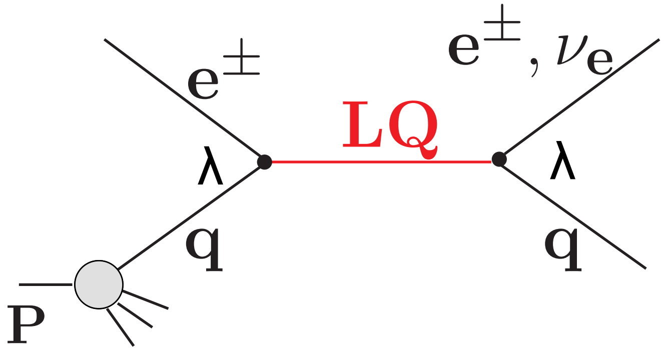
ZEUS Coll., Phys. Lett. **B 757** (2016) 468.

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 needed.

Leptoquark production

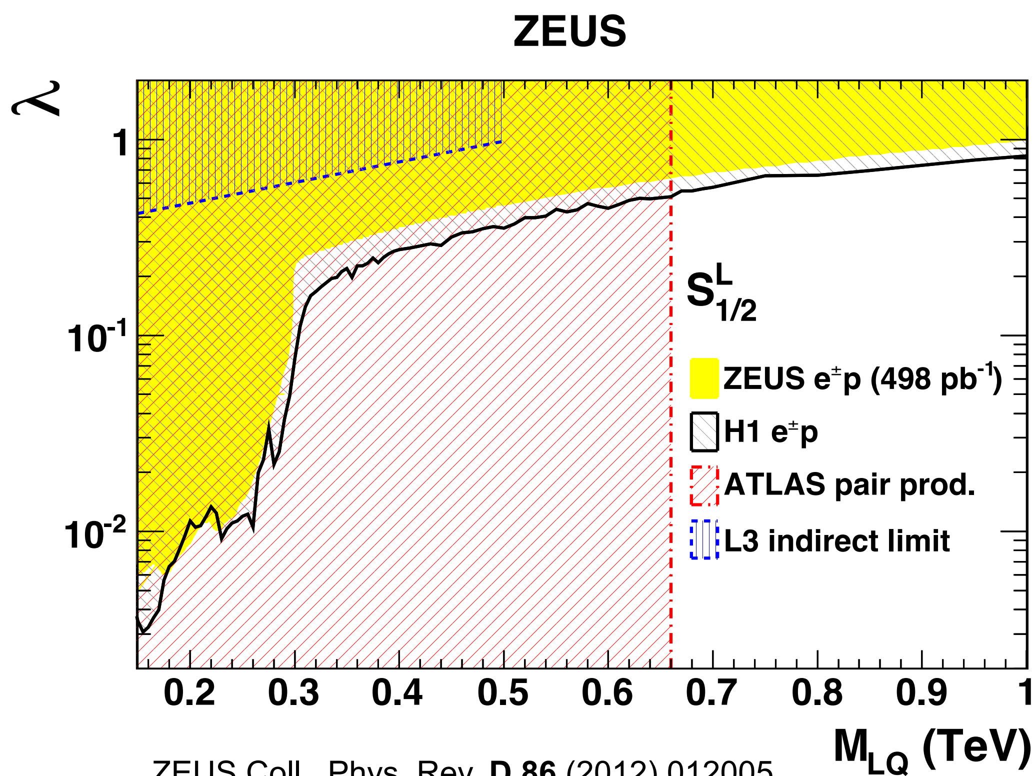


Electron−proton colliders are the ideal machine to look for leptoquarks.

s-channel resonance production possible up to √*s*.

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

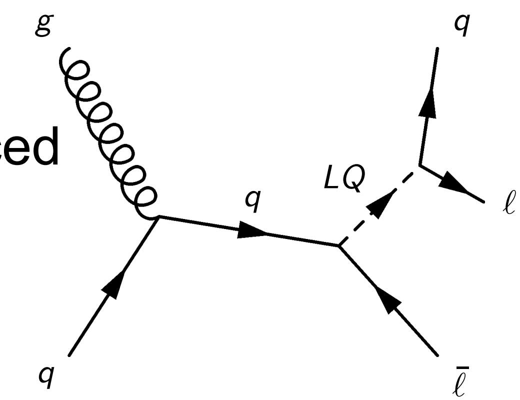
Sensitivity depends mostly on √*s* and VHEeP = 30 × HERA

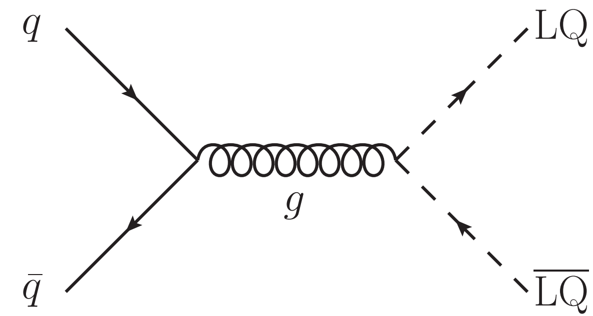


ZEUS Coll., Phys. Rev. **D 86** (2012) 012005

Leptoquark production at the LHC

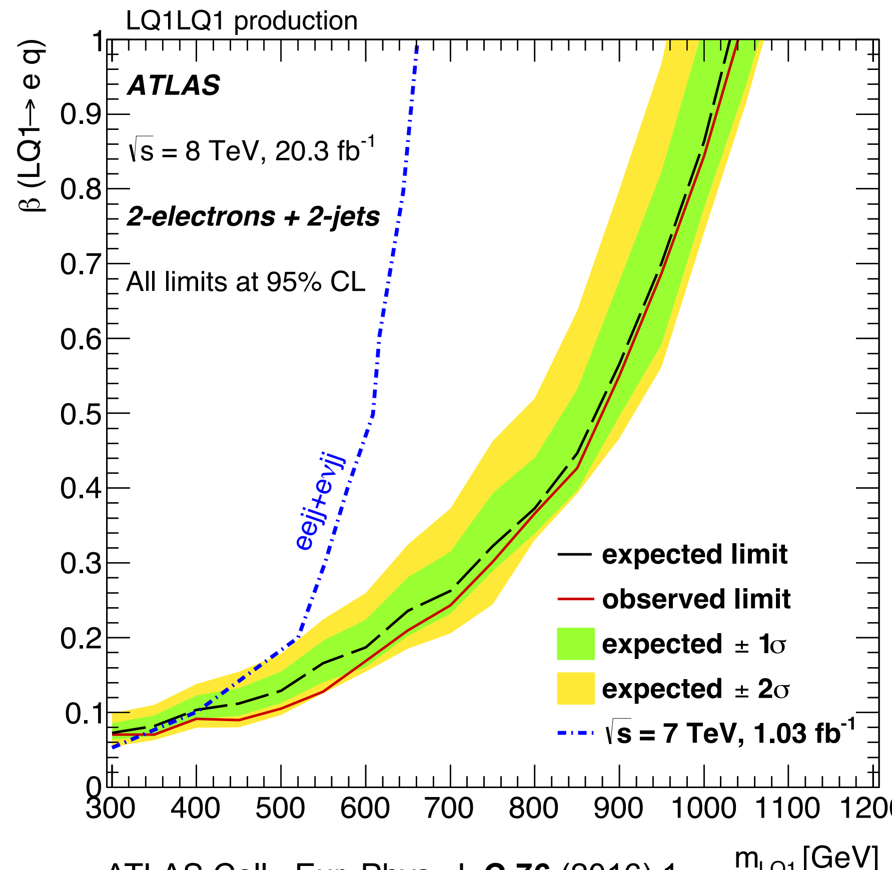
Can also be produced in *pp* singly or pair production





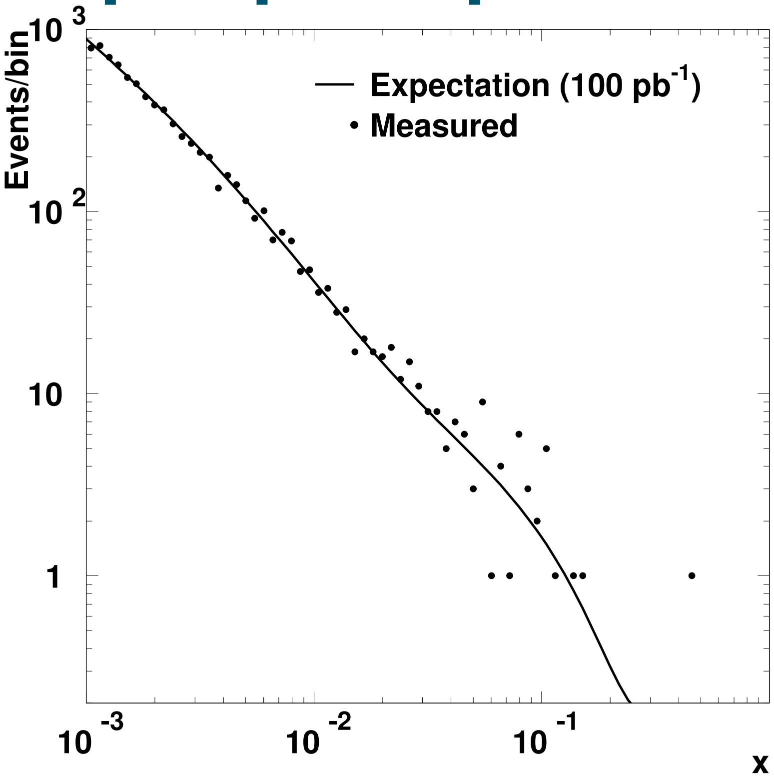
Reach of LHC currently about *1 TeV*, to increase to *2 − 3 TeV*.

Coupling dependent.



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

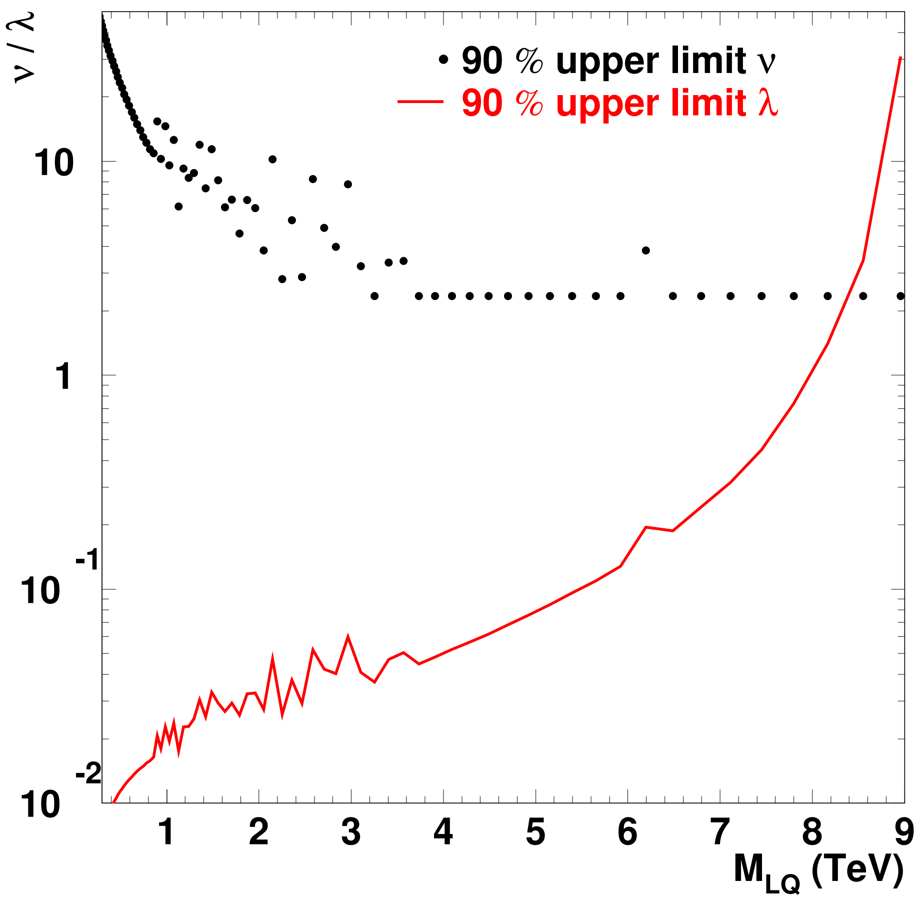
Leptoquark production at VHEeP



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

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

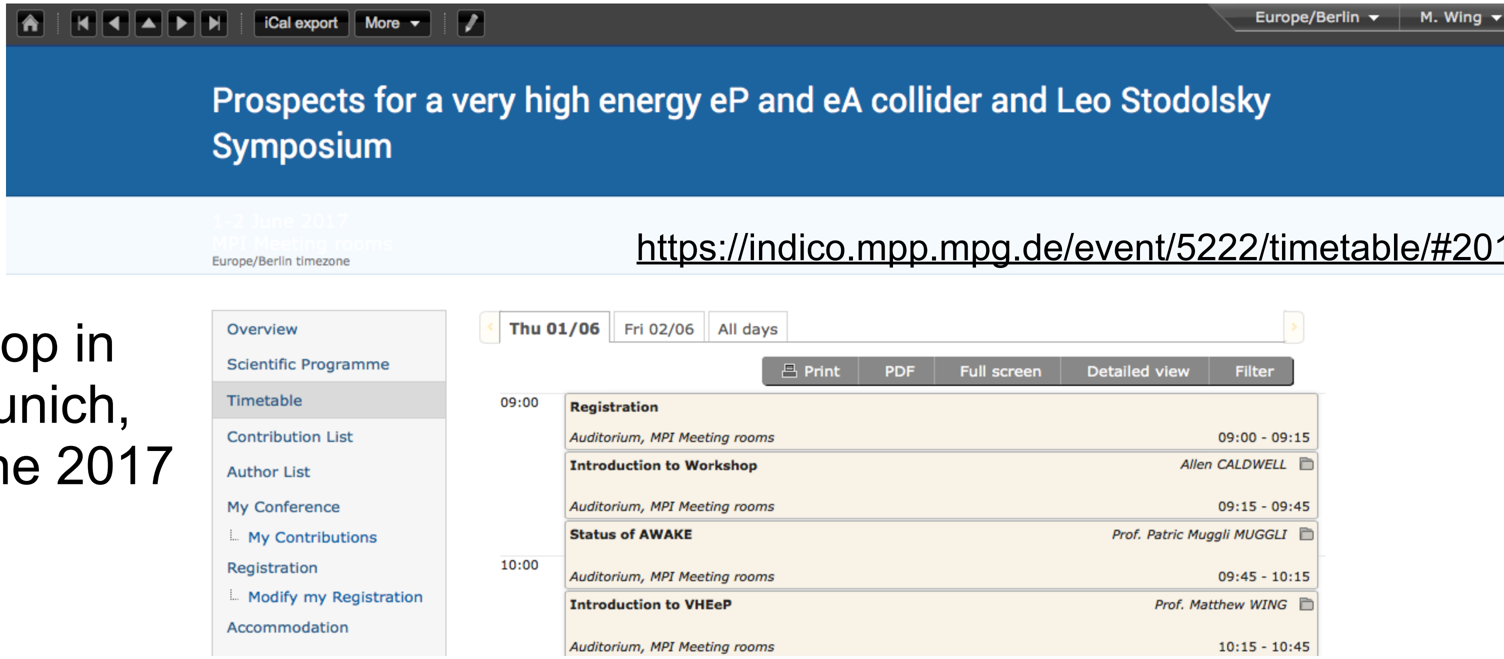
Generated "data" and Standard Model "prediction" using ARIADNE (no LQs).



Sensitivity up to kinematic limit, 9 TeV.

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

VHEeP workshop: new ideas



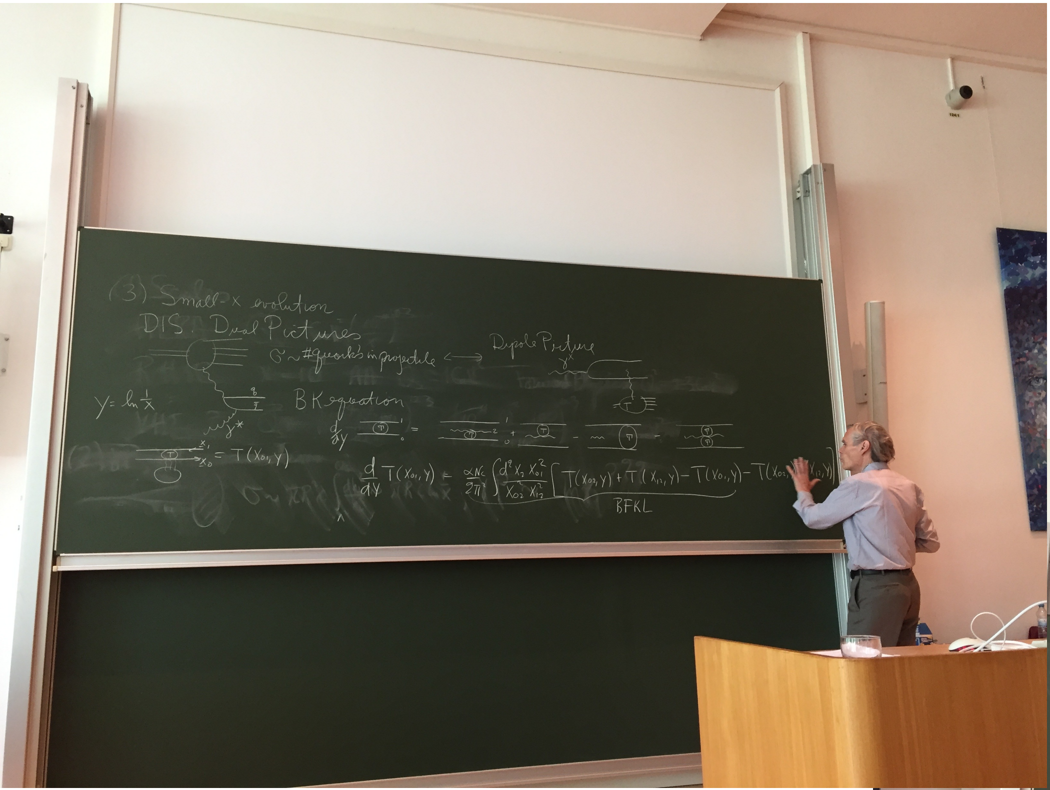
https://indico.mpp.mpg.de/event/5222/timetable/#20170601

Workshop in MPI, Munich, 1−2 June 2017

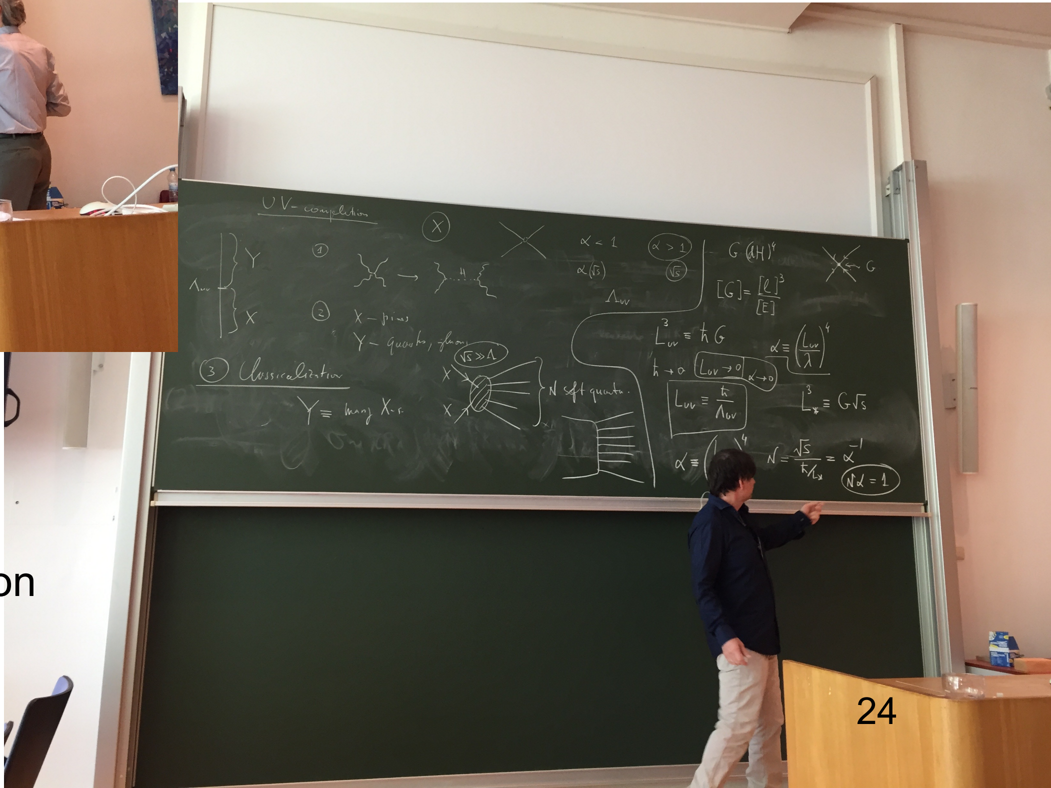
Some highlights:

- Observe saturation; theory of hadronic interactions (Bartels, Mueller, Stodolsky, etc.)
- Relation of low-x physics to cosmic rays (Stasto); to black holes and gravity (Erdmenger); and to new physics descriptions (Dvali, Kowalski)
- Status of simulations (Plätzer)
- Challenge of the detector (Keeble)
- What understood from HERA data (Myronenko)

VHEeP workshop: new ideas



Alfred Mueller, Columbia University,
Approach to saturation in eA collisions



Georgi Dvali, Max Planck Institute Munich,
Alternative high energy theory - classicalisation

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.

Collider parameters

	EIC	LHeC	FCC-he	VHEeP
E_e / E_p	3 − 20 GeV / 20 − 250 GeV	60 GeV / 7 TeV, some variation	60 GeV / 50 TeV	3 TeV / 7 TeV, variable
$\sqrt{s_{ep}}$	15 − 140 GeV	1.3 TeV	3.5 TeV	9 TeV
Polarisation	$P_e, P_{p/A} > 70\%$	$P_{e^{\mp}}$ = 90% / 0%	$P_{e^{\mp}}$ = 90% / 0%	P_e can be maintained
Luminosity	$10^{33} - 10^{34}$ $cm^{-2}s^{-1}$	$10^{33} - 10^{34}$ $cm^{-2}s^{-1}$	$>10^{33}$ $cm^{-2}s^{-1}$	$\sim10^{29}$ $cm^{-2}s^{-1}$
ep / eA	Yes, many *A*.	Yes	Yes ?	Yes

Comparison of colliders

- EIC:
  - is lowish energy, but high luminosity.
  - intrinsically flexible, with varying energy, ion species, etc.
  - has high polarisation of both beams.
  - is most advanced through approval.

- LHeC:
  - is high energy and high luminosity.
  - has some flexibility in energy and particle species.
  - has broad physics programme including EW sector and high-Q^2 searches.

- VHEeP:
  - is very high energy, but low luminosity.
  - has flexibility in energy and also in other beam parameters.
  - relies on an as-yet unproven technology, also opportunity.

Summary

- 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).

Outlook

- Lots to do to develop VHEeP further
  - Accelerator scheme
    - Separation of drive protons and electrons
    - Can luminosity be increased
    - Electron (and proton/ion) beams after interaction and beam dump, e.g. active for hidden sector search
    - Design of interaction point
    - How to fit into the CERN infrastructure
  - Physics case
    - Electron−ion collisions
    - Low *x* physics, search for saturation, and relation to AdS/CFT, confinement, etc,
    - High energy cross sections
    - Beyond the Standard Model physics
  - Detector
    - Central detector
    - Forward detectors in both directions.
- Welcome input, new ideas and studies.

Back-up

AWAKE

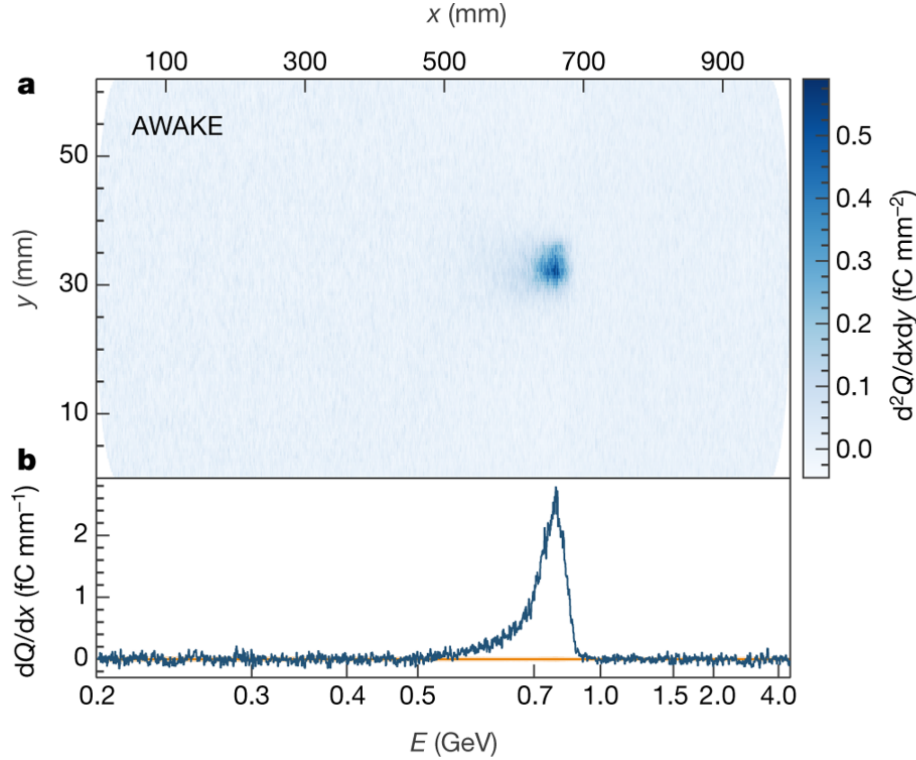
Proof-of-principle experiment at CERN demonstrates proton-driven plasma wakefield acceleration for the first time.

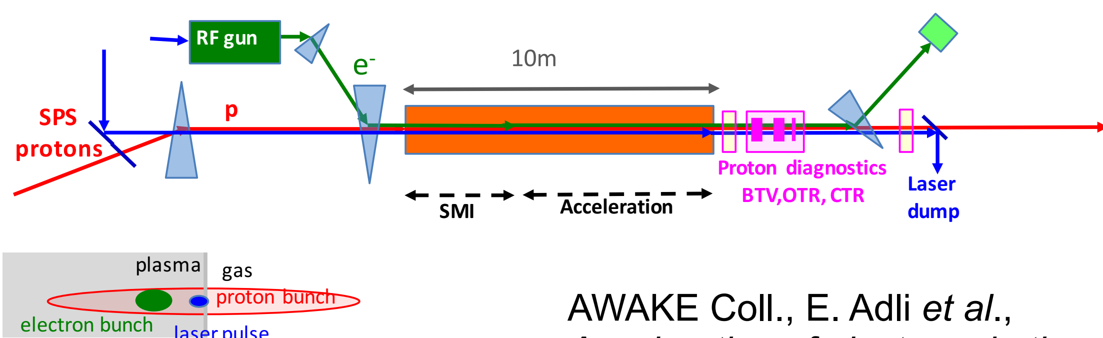
Using 400 GeV SPS proton bunches.

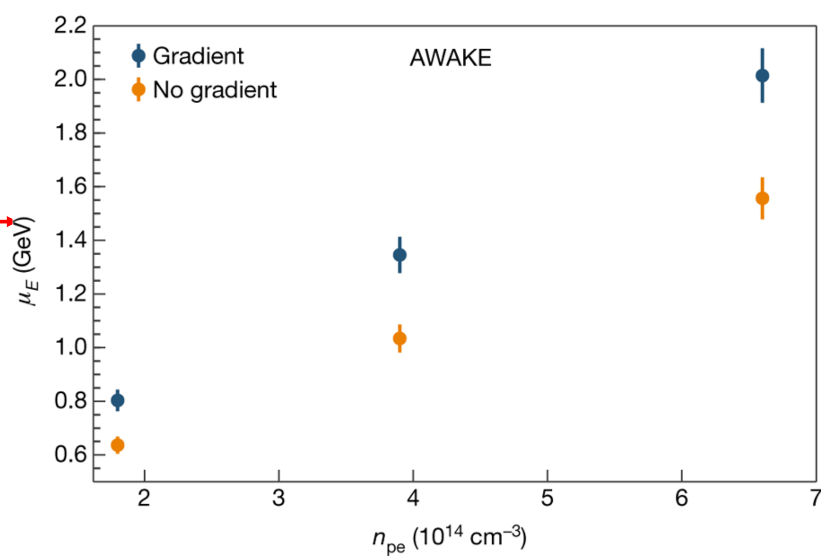
Started running in October 2016 and measured modulation of proton bunch in plasma.

In 2018, accelerated electrons to 2 GeV.

Thinking of future experiments with 10s of GeV electrons over 10s of m of plasma. And beyond



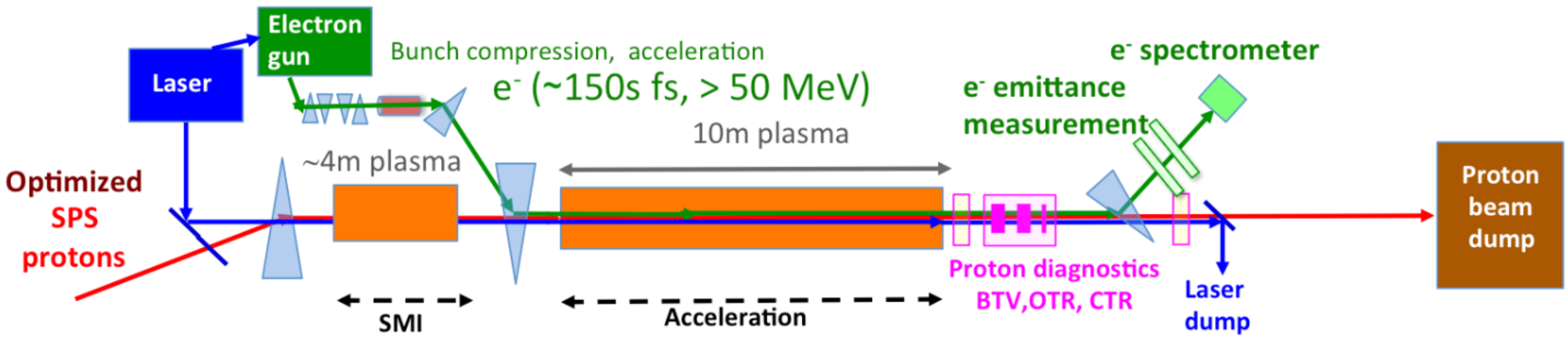




AWAKE Coll., E. Adli *et al.*, *Acceleration of electrons in the plasma wakefield of a proton bunch*, Nature **561** (2018) 363.

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).

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.

$\sigma_{\gamma P}$ 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:

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

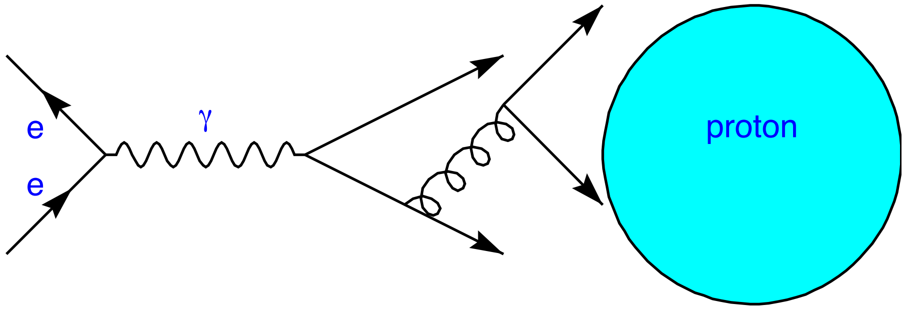
$\sigma_{\gamma P}$ at large coherence lengths

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.