LEVERHULME TRUST

UCL

Low-x frontier

Matthew Wing (UCL / DESY)

- Introduction
- HERA inclusive data and low *x*
  - Results and successes
  - Indications of new phenomena at low *x*
- Very high energy *eP* (VHEeP) collider — the low-*x* frontier
  - Basic collider idea and comparison to other projects
  - Physics at very low *x* and QCD
- Summary

Introduction

• Understanding the fundamental structure of matter is a primary pursuit of physics.

• Much has been learnt in deep inelastic scattering experiments, both fixed-target and at HERA.

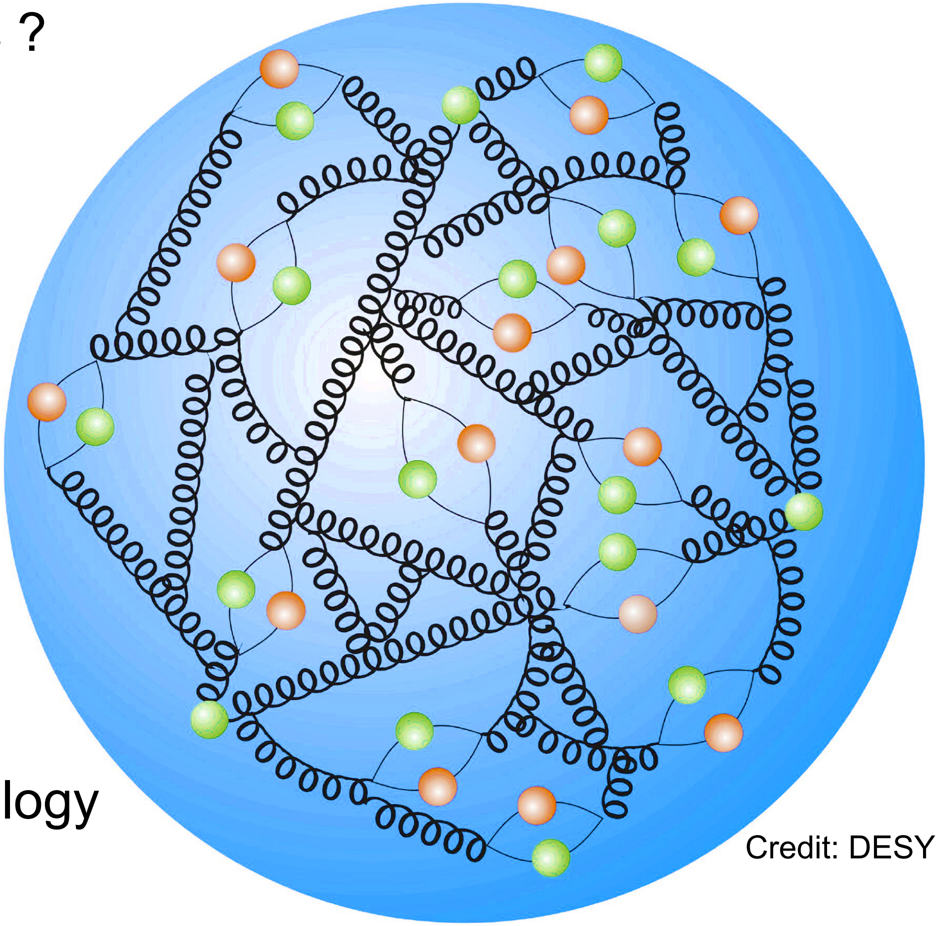
- Coverage of a wide kinematic range
- Heavy quark and photon content of the proton
- Dramatic rise of the gluon density to low *x*

• Significant advances in experiment and theory have gone hand in hand.

• But … what do we know about the physics of low *x* ?

The structure of matter

- What are the fundamental constituents ?
- How are they distributed ?
- What happens at sufficiently low x ?
- Does DGLAP breakdown ?
- Is BFKL the answer ?
- The cross section must saturate ?
- How is this related to confinement ?
- …

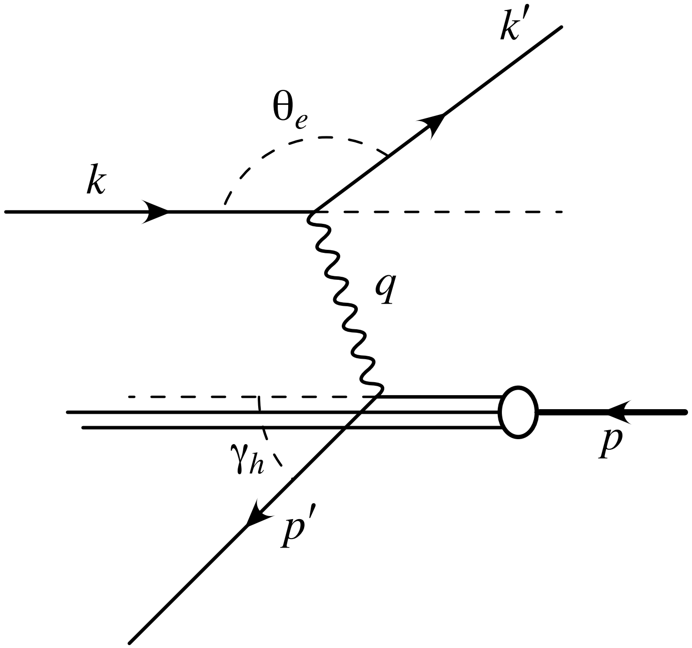


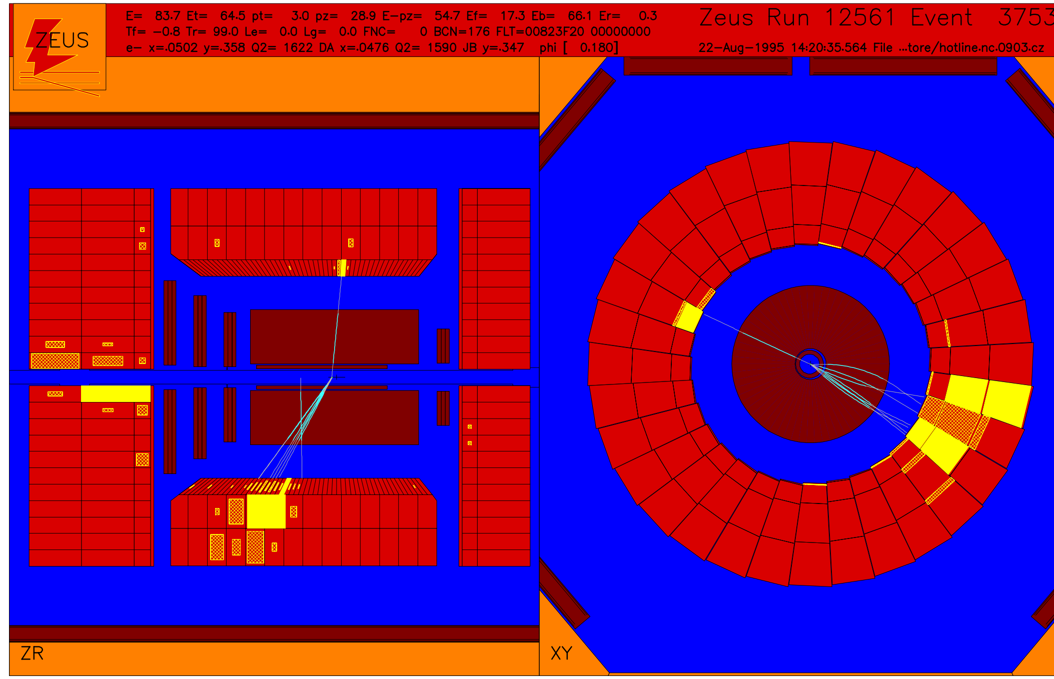
Credit: DESY

Will review some HERA and phenomenology results.

Consider higher energy machine, i.e. the low-*x* frontier.

Deep inelastic scattering (DIS) and HERA





Momentum transfer :

$$Q^2 = -q^2 = -(k-k')^2$$

Momentum fraction carried by struck parton :

$$x = Q^2/(2p\cdot q)$$

Inelasticity :

$$y = (q\cdot p)/(k\cdot p)$$

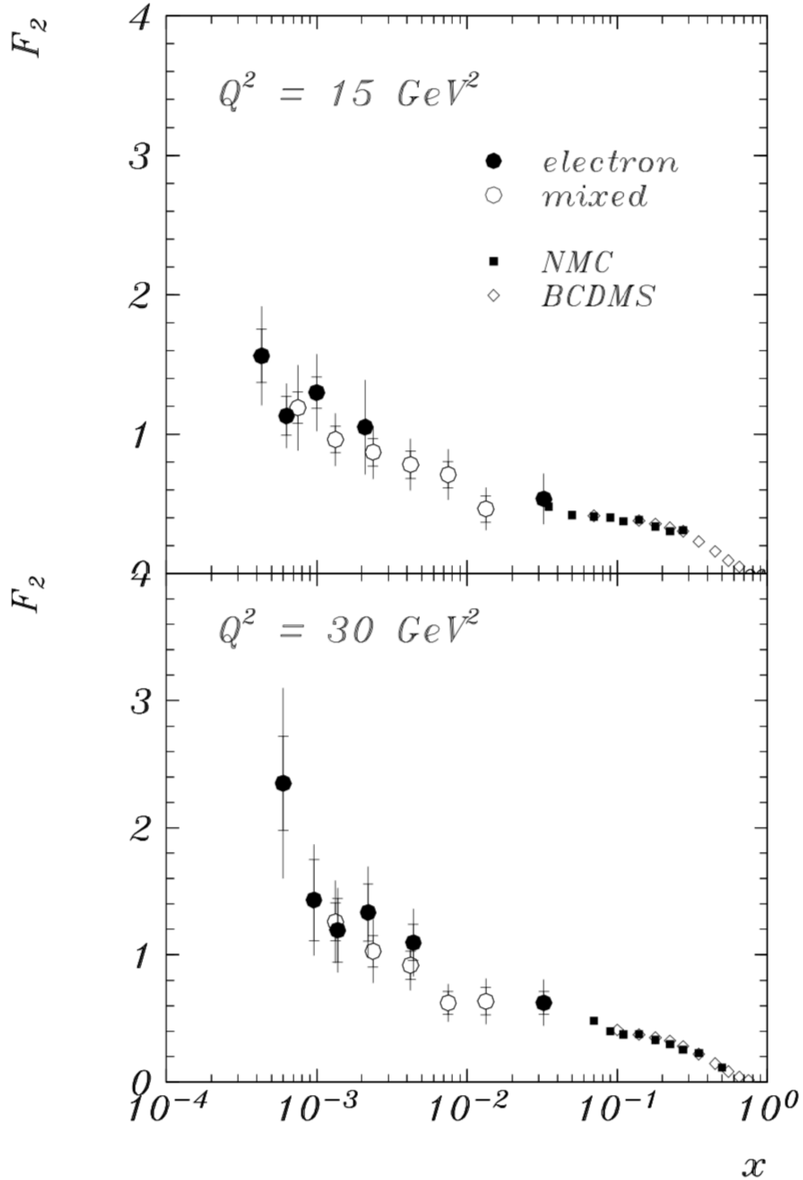
And : $Q^2 = s\cdot x\cdot y$

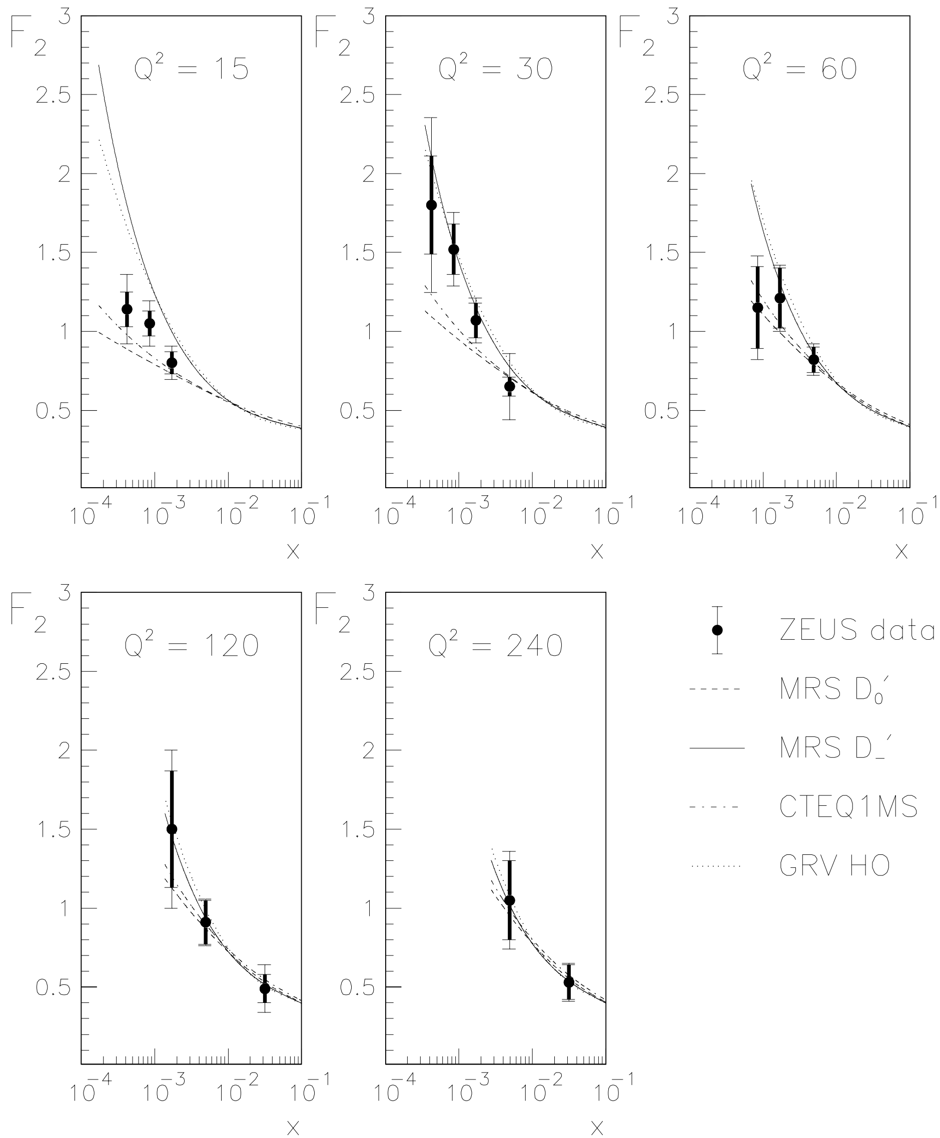
$Q^2 > 1\ GeV^2$ — deep inelastic scattering

$Q^2 < 1\ GeV^2$ — photoproduction

- During 1992–2007, mainly $E_e = 27.5\ GeV$, $E_p = 920\ GeV$ giving $\sqrt{s} \sim 320\ GeV$; and dedicated data at different proton energies.
- Colliding-beam experiments collected combined sample ~ $1\ fb^{-1}$.

First HERA measurements of proton structure F_2





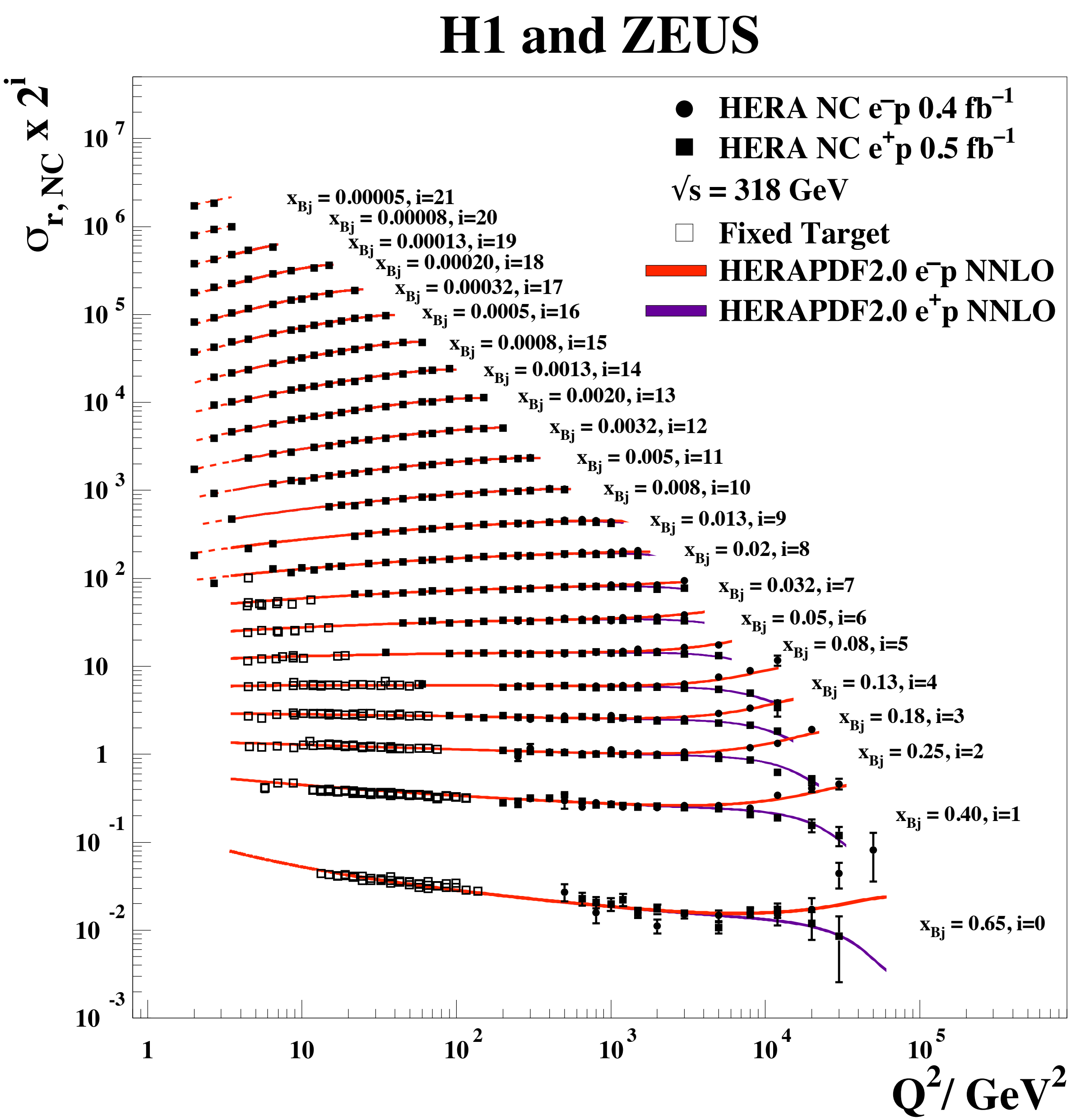
H1 Coll., *Nucl. Phys.* **B 407** (1993) 515

ZEUS Coll., *Phys. Lett.* **B 316** (1993) 412

Full HERA data

A lot in this plot:

- Covers about five orders of magnitude in x and Q^2.
- Consistency of fixed-target and HERA data.
- Scaling at $x \sim 0.08$ and violations elsewhere.
- $\gamma-Z$ interference at high Q^2.
- Strong rise of gluon density.
- Crucial input to PDF fits.
- Still want to go to higher and **lower *x***.



H1 and ZEUS Colls., *Eur. Phys. J.* **C 75** (2015) 580

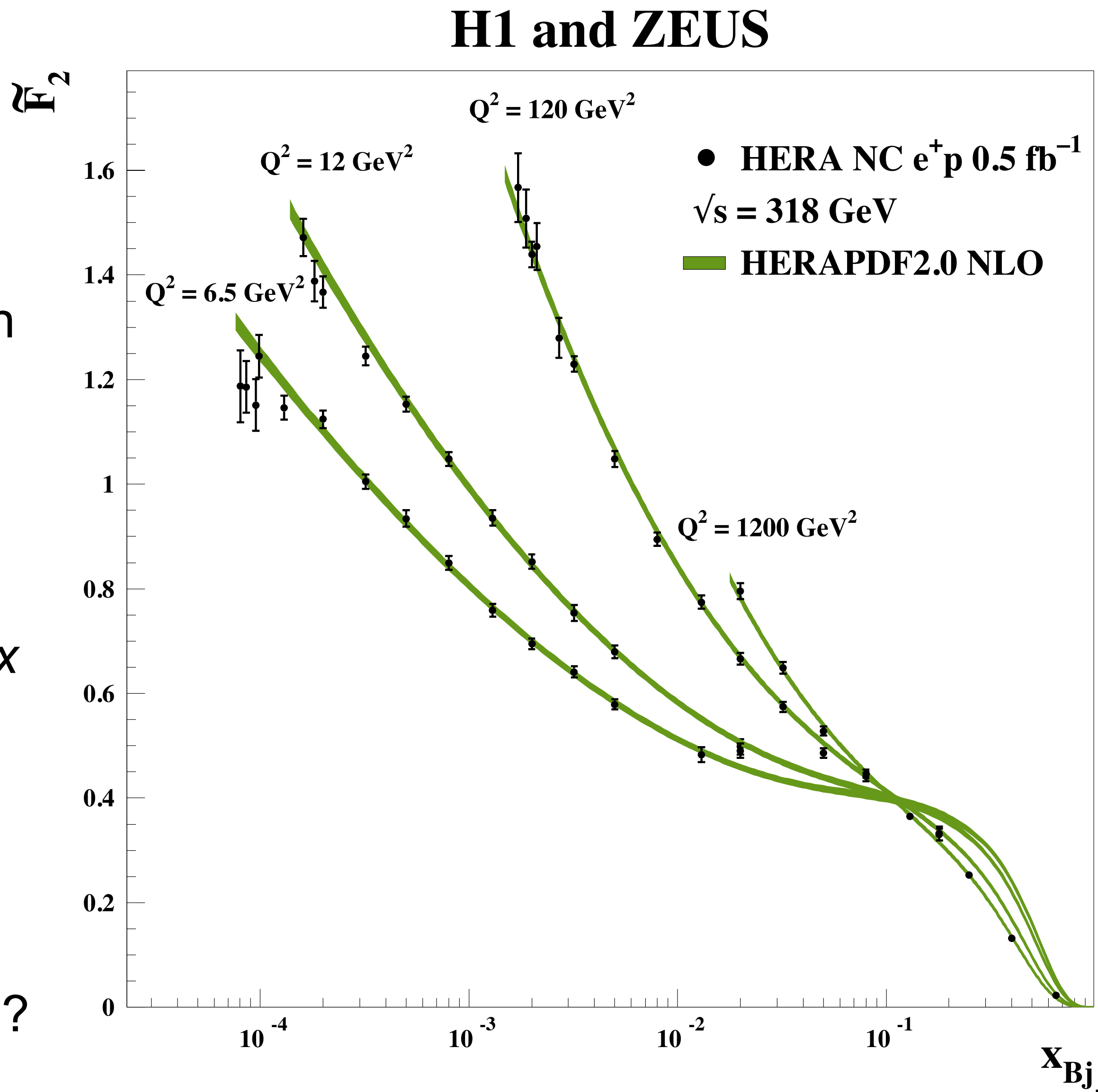
Final HERA measurements of proton structure F_2

Observations:

- Clear strong rise of F_2 to low x
- Rise becomes stronger with increasing Q^2
- Well described by QCD
- Indicative of high gluon density
- High precision (in medium-x range)

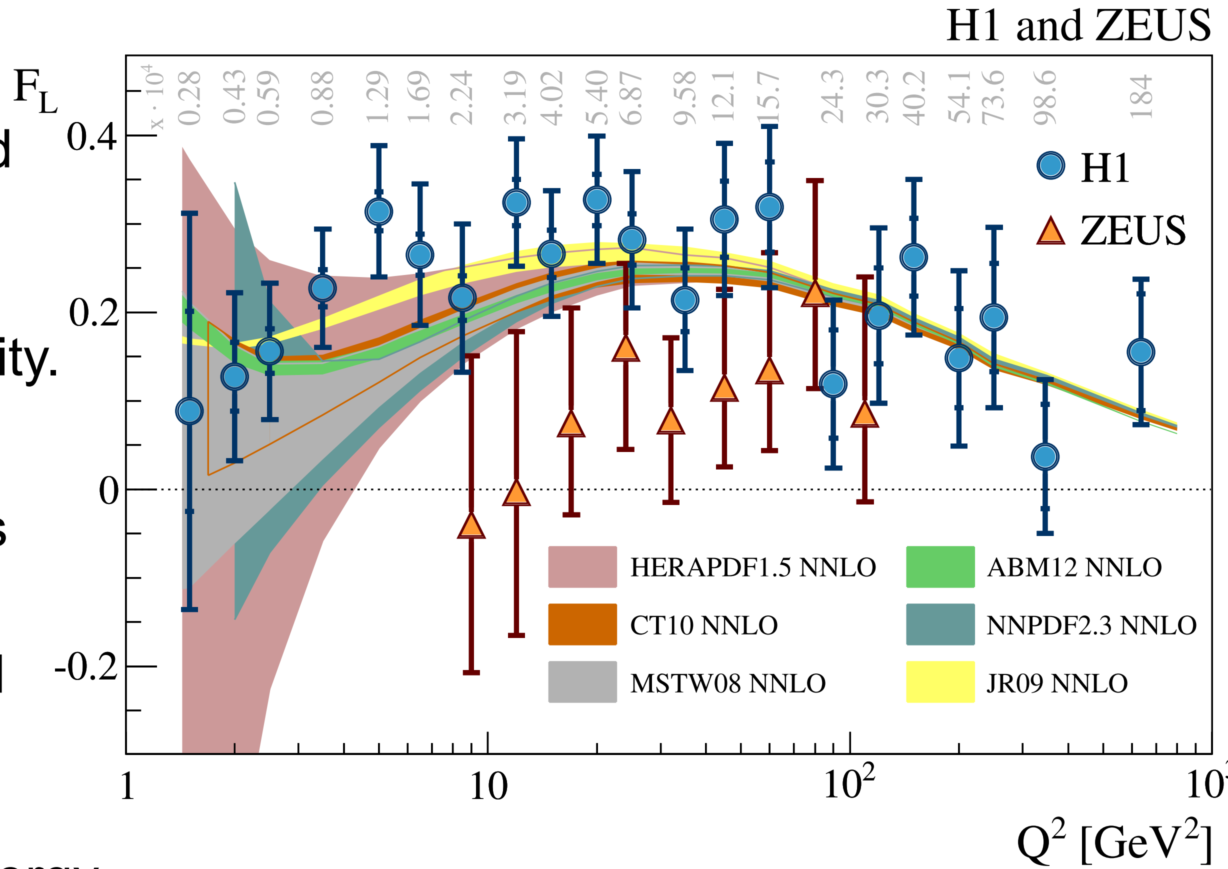
Questions:

- What happens at lower x ?
- When does the rise stop ?
- Are there new phenomena ?



Longitudinal structure function F_L

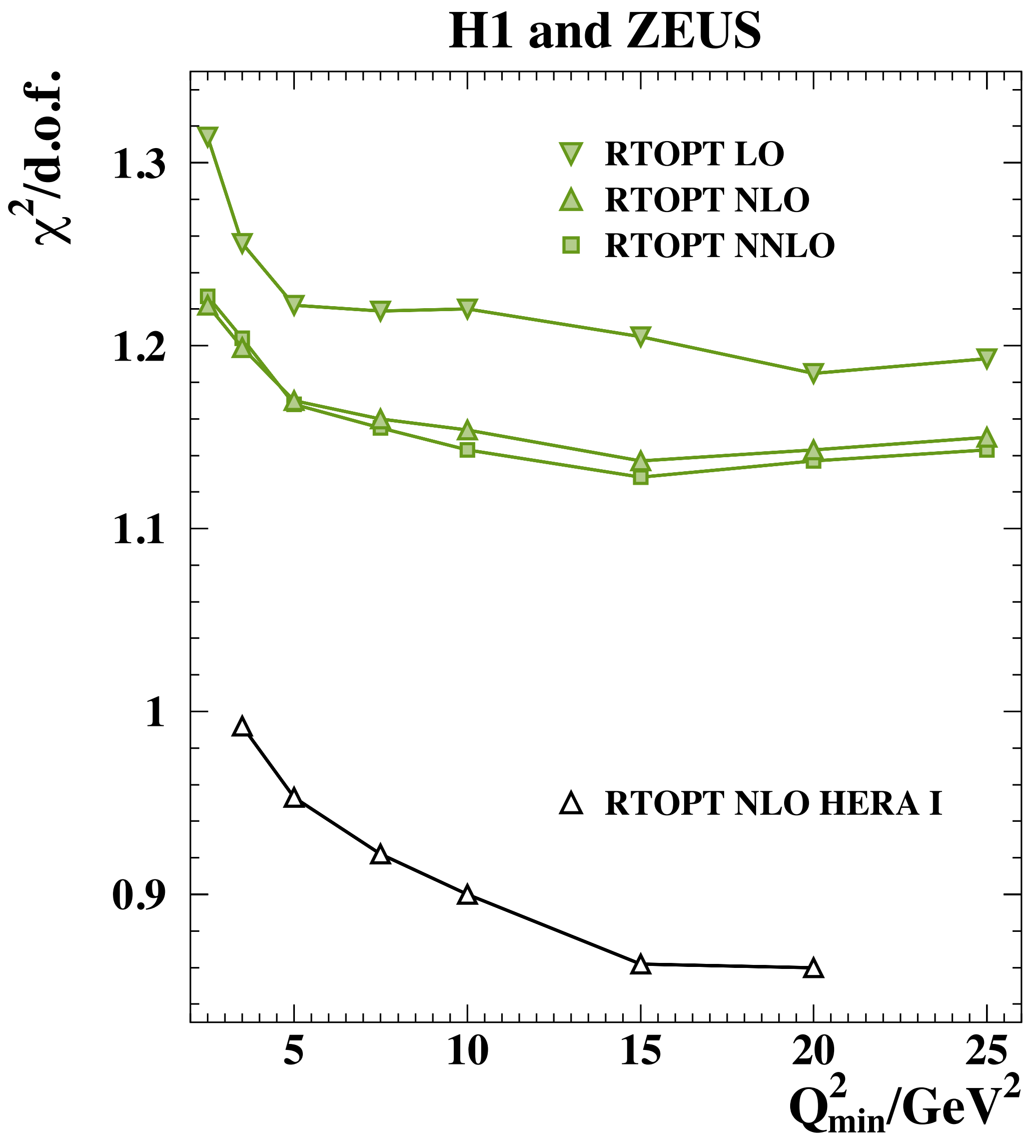
- Lower E_p running allowed extraction of F_L.
- Intrinsically low x and related to the gluon density.
- Data of limited precision.
- Discrimination of theories not possible.
- **Clear area where would want to significantly improve.**
  - Larger variations in energy.
  - Better detector coverage.
  - Larger data samples.



H1 Coll., *Eur. Phys. J.* **C 74** (2014) 2814
ZEUS Coll., *Phys. Rev.* **D 90** (2014) 072002

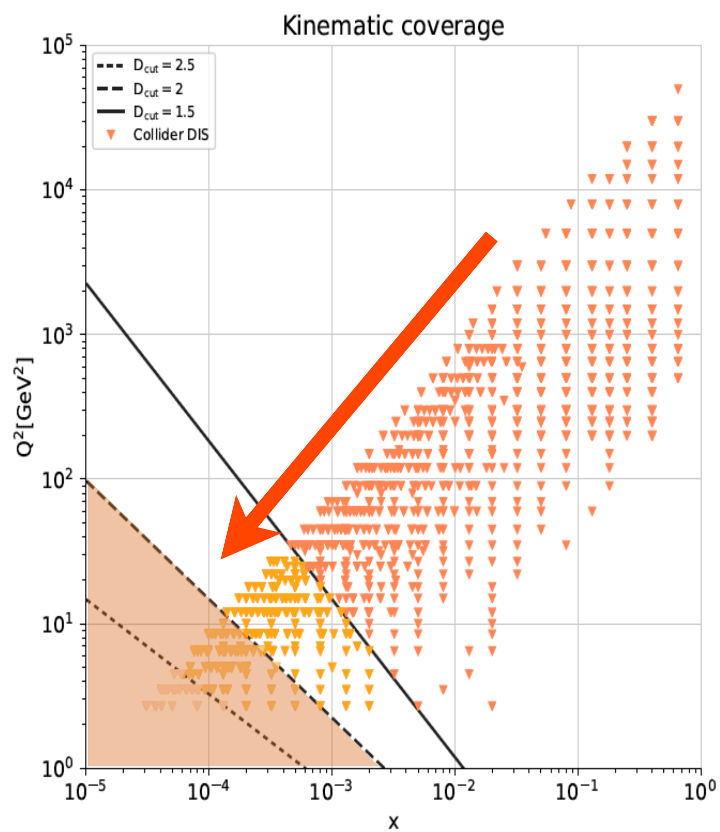
QCD fits to HERA data

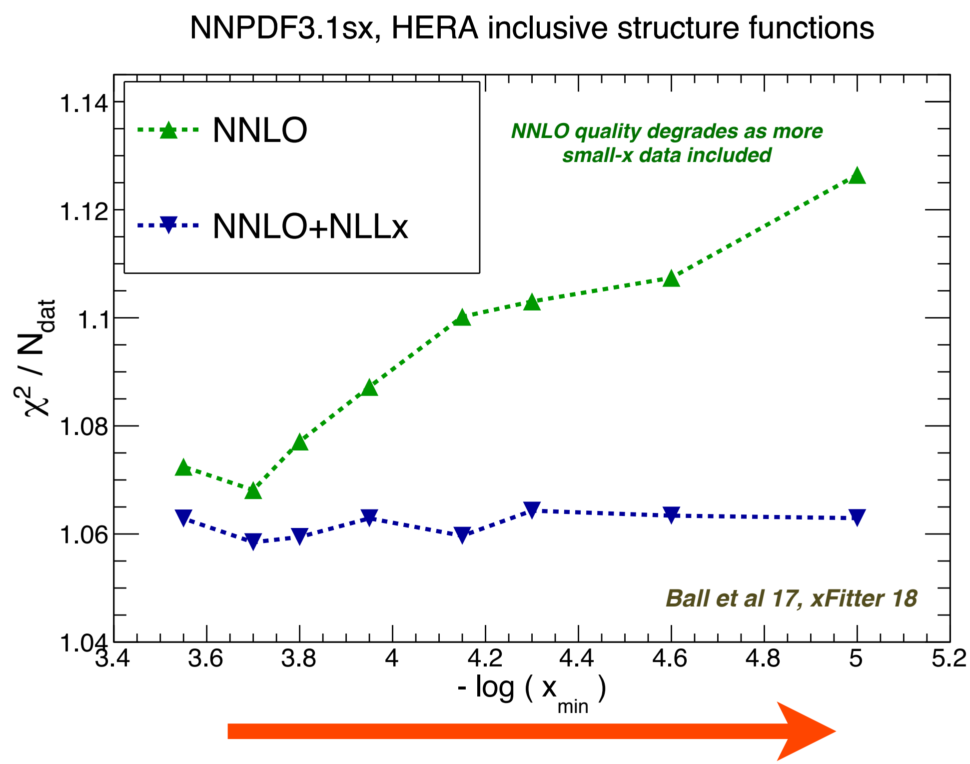
- QCD fits at NLO and NNLO "generally" describe HERA data.
- But in detail:
  - Overall χ^2 about *~1.2* and significant Q^2 dependence.
  - NNLO similar quality to NLO.
  - Note low Q^2 is low x.
  - **Indication of breakdown of DGLAP ?**
  - **Are there new phenomena at low *x* ?**



Evidence for BFKL dynamics

NNPDF3.1 fits based on **fixed order** (NNLO) and **small-*x* resumed** (NNLO+NLLx) theory





Monitor the **fit quality** as one includes more data from the **small-*x* region**

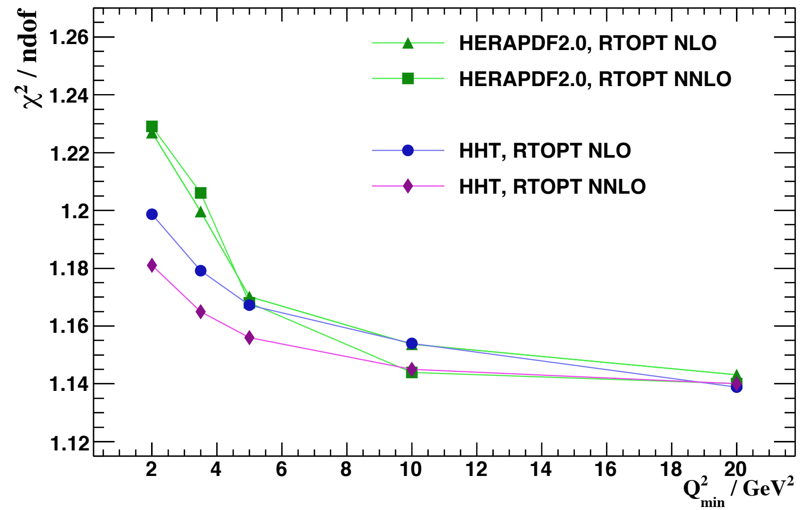
Best description of **small-*x* HERA data** only possible with **BFKL effects!**

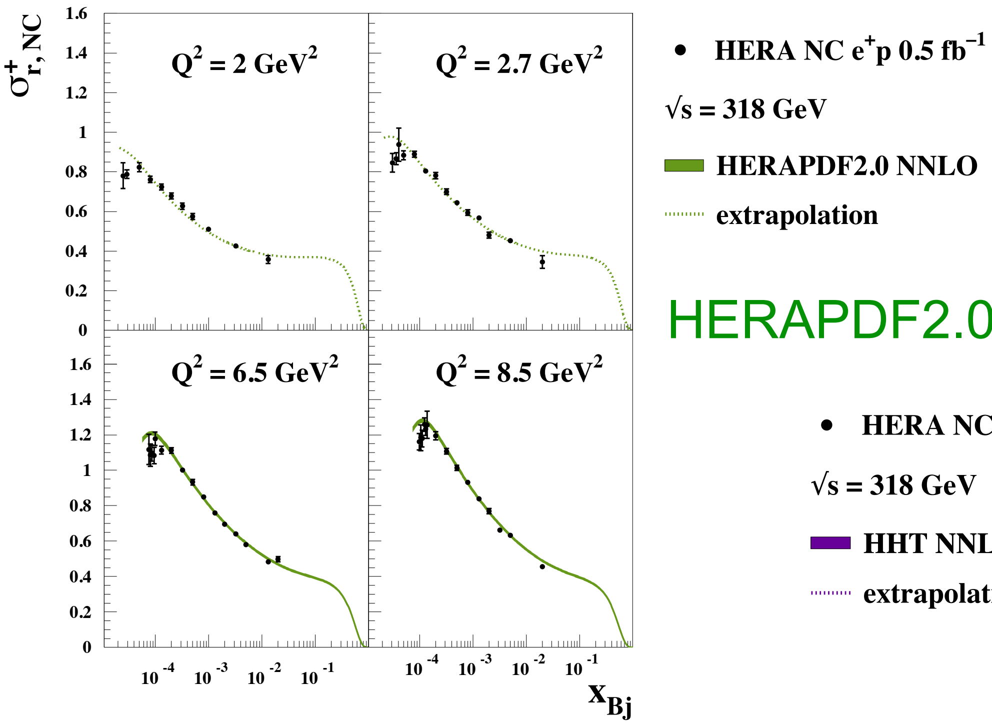
Inclusion of higher-twist term

I. Abt et al., *Phys. Rev.* **D 94** (2016) 034032

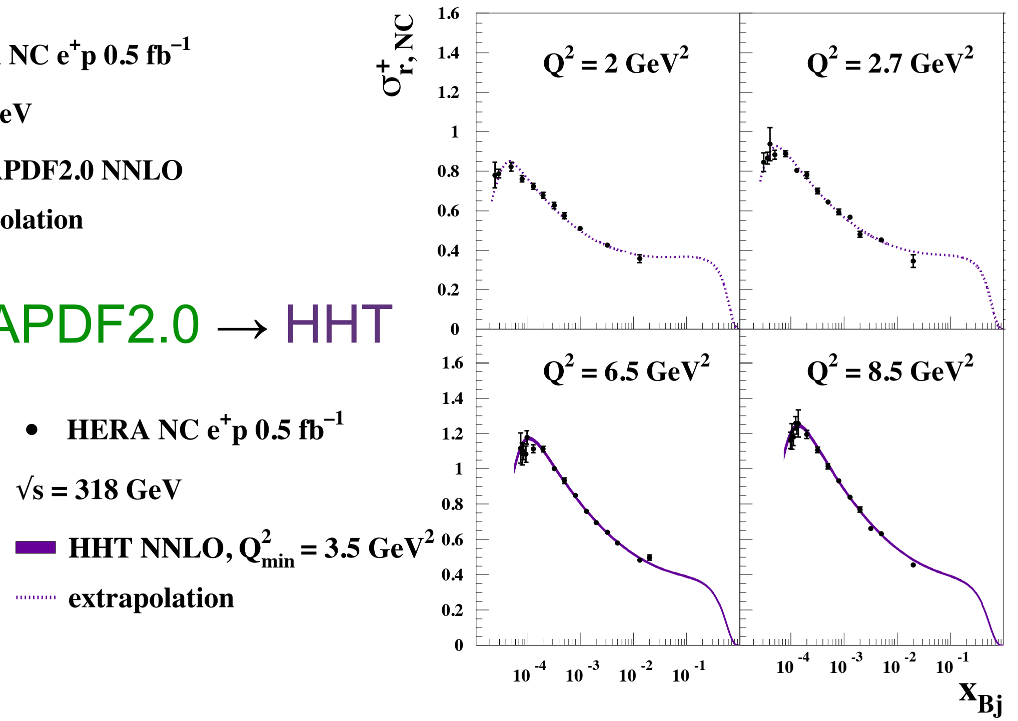
$$F_2^{\mathrm{HT}} = F_2^{\mathrm{DGLAP}} \left(1 + A_2^{\mathrm{HT}}/Q^2\right)$$
$$F_L^{\mathrm{HT}} = F_L^{\mathrm{DGLAP}} \left(1 + A_L^{\mathrm{HT}}/Q^2\right)$$

- Significant effect from adding A_L term
  - Improved χ^2 at both NLO and NNLO
- A_2 term consistent with zero





HERAPDF2.0 → HHT

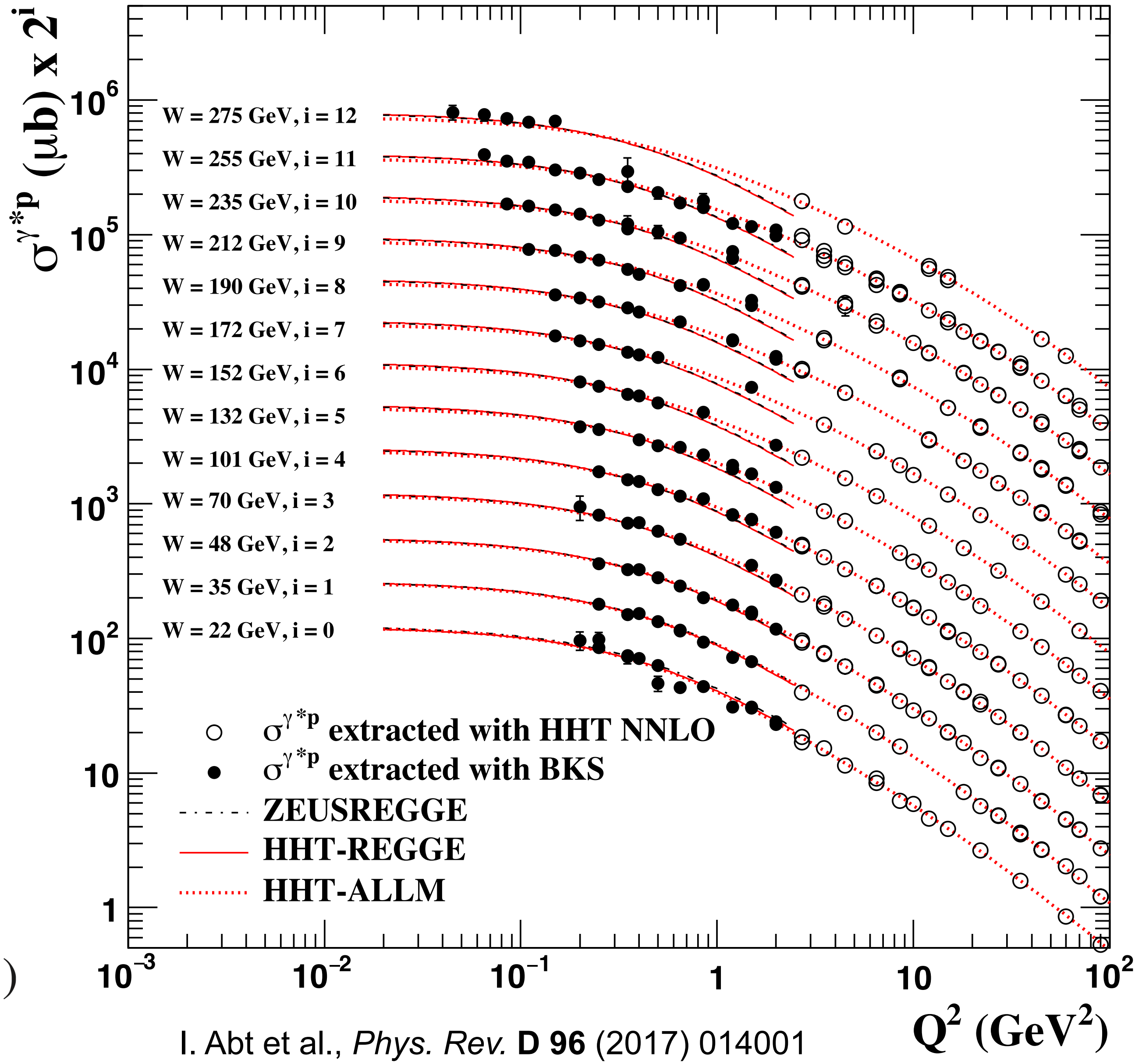


Investigation of very low-Q^2 data

- Transition region to photoproduction at lower Q^2
- Look at data in different ways, recasting as $\sigma^{\gamma^* p}$ and F_2.
- **Strikingly smooth trend at low Q^2.**
- Generally well described by ALLM model.
- Regge theory describes the cross section as a hadron−hadron process
- Regge describes the data up to $Q^2 \sim 0.65\ GeV^2$.

- ALLM parametrisation:

$$F_2 = \frac{Q^2}{Q^2 + m_0^2} \cdot (F_2^{IP} + F_2^{IR})$$

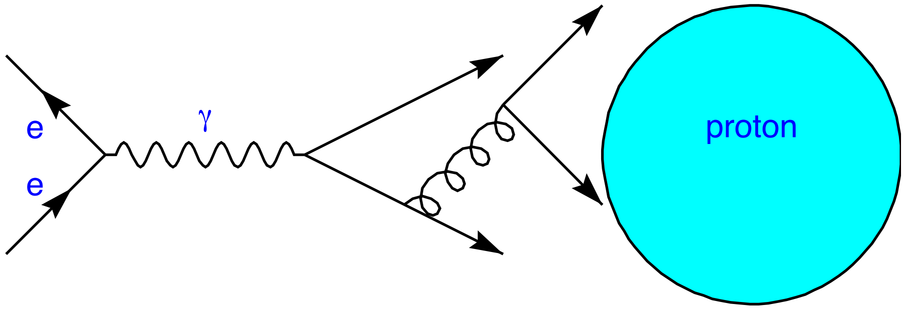


I. Abt et al., *Phys. Rev.* **D 96** (2017) 014001

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

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

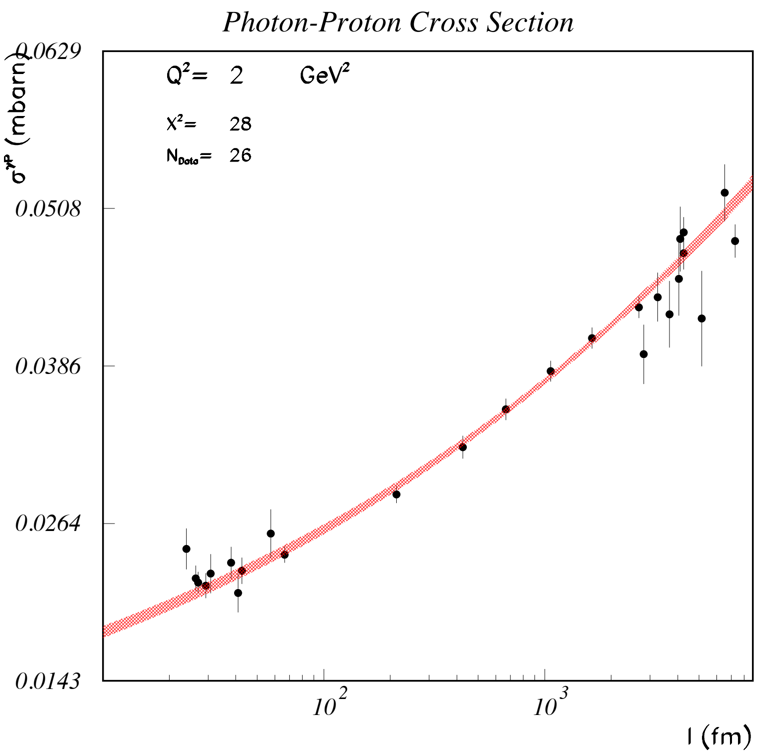
- Electron is a source of photons which is a source of partons.
- Coherence length is distance over which quark−antiquark pair can survive.
- Low x means long-lived photon fluctuations (not proton structure)

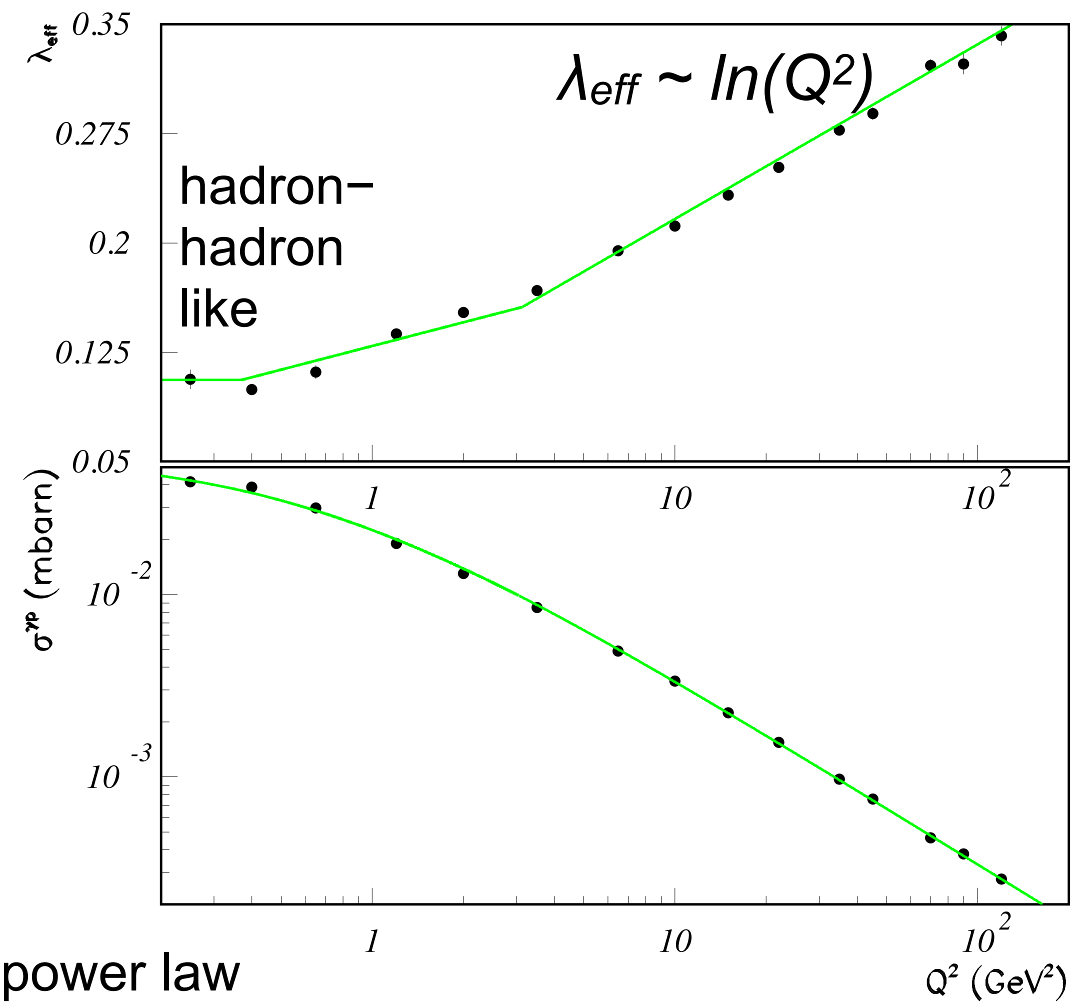


- If cross sections become same as a function of Q^2, the photon states have had enough time to evolve into a universal size.
- Look at what HERA and fixed-target data has shown. Will then consider future higher energy colliders

Coherence length

$$\sigma(l, Q^2) = \sigma_1(Q^2)\left(\frac{l}{1\ \mathrm{fm}}\right)^{\lambda_{\mathrm{eff}}(Q^2)}$$





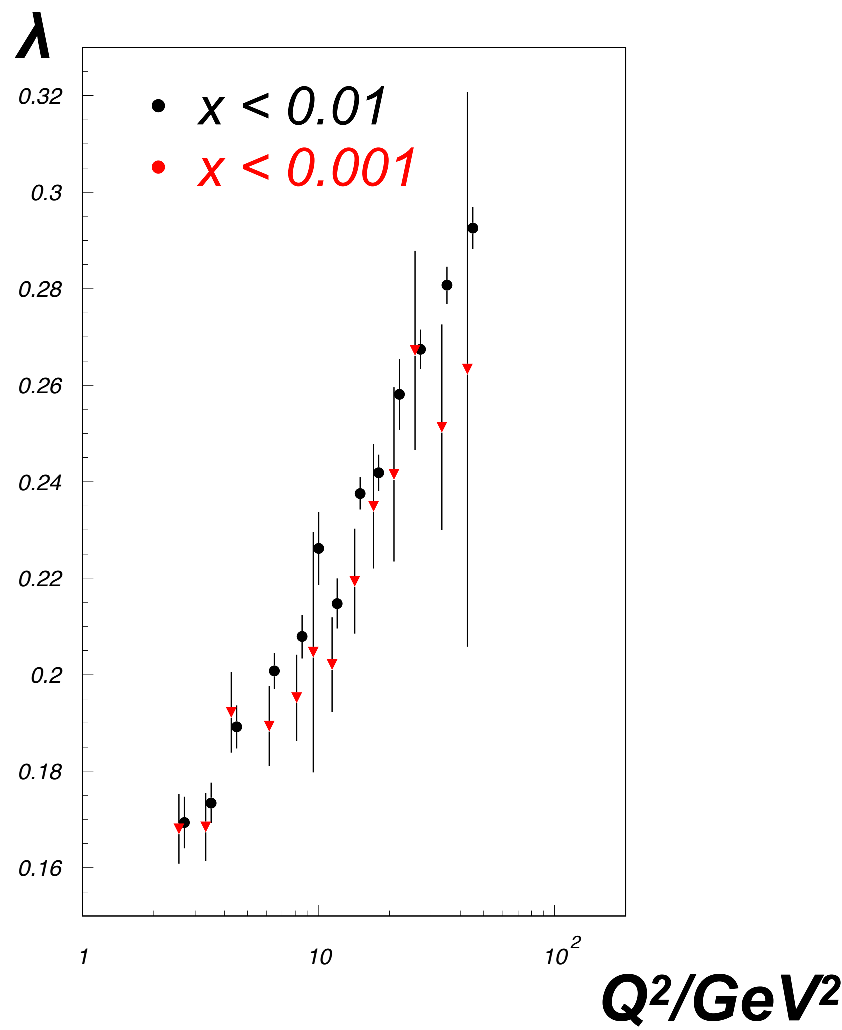
- Data well described by simple power law
- Cross section dependence can lead to interesting effects at high Q^2

A. Caldwell, *New J. Phys.* **18** (2016) 073019

High-energy behaviour — simple fits

- New study considering simple form to fit HERA data
- Now looking at if the rate of rise, λ, is x dependent
  - Well-known Q^2 dependence
  - Indications that there is an x dependence
  - Very low x data have a smaller λ value.
  - Effect is systematic and significant.
  - Onset of BFKL behaviour ?
  - Higher energy / lower x would help

$$F_2 = A(1/x)^{\lambda}$$



A. Luszczak and H. Kowalski, arXiv:1903.09719

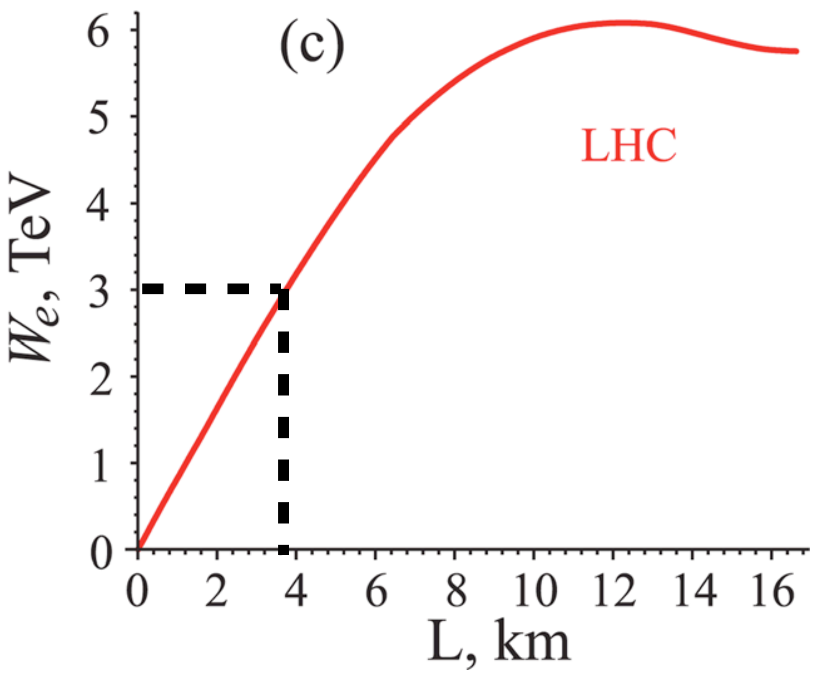
New proposal for the low-*x* frontier – VHEeP

- 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)

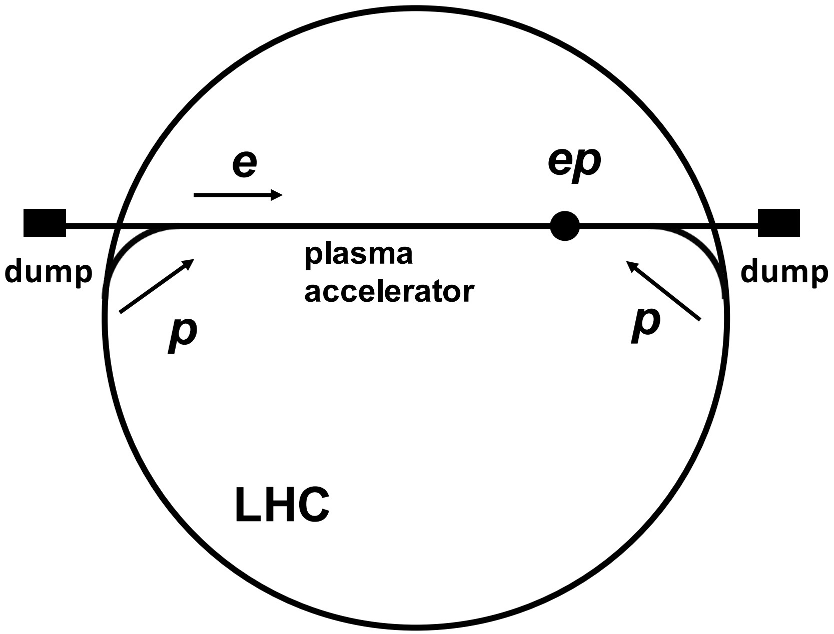
- Can use current beams at CERN using AWAKE* scheme.
- With high accelerating gradients, can have
  - Shorter colliders for same energy
  - Higher energy
- Using the LHC beam can accelerate electrons up to *6 TeV* over a reasonable distance.
- We choose E_e = *3 TeV* as a baseline for a new collider with E_P = *7 TeV* ⇒ $\boldsymbol{\sqrt{s}}$ ***= 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 *et al.*, *Nature Phys.* **5** (2009) 363;
E. Adli et al. (AWAKE Coll.), *Nature* **561** (2018) 363

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 ?

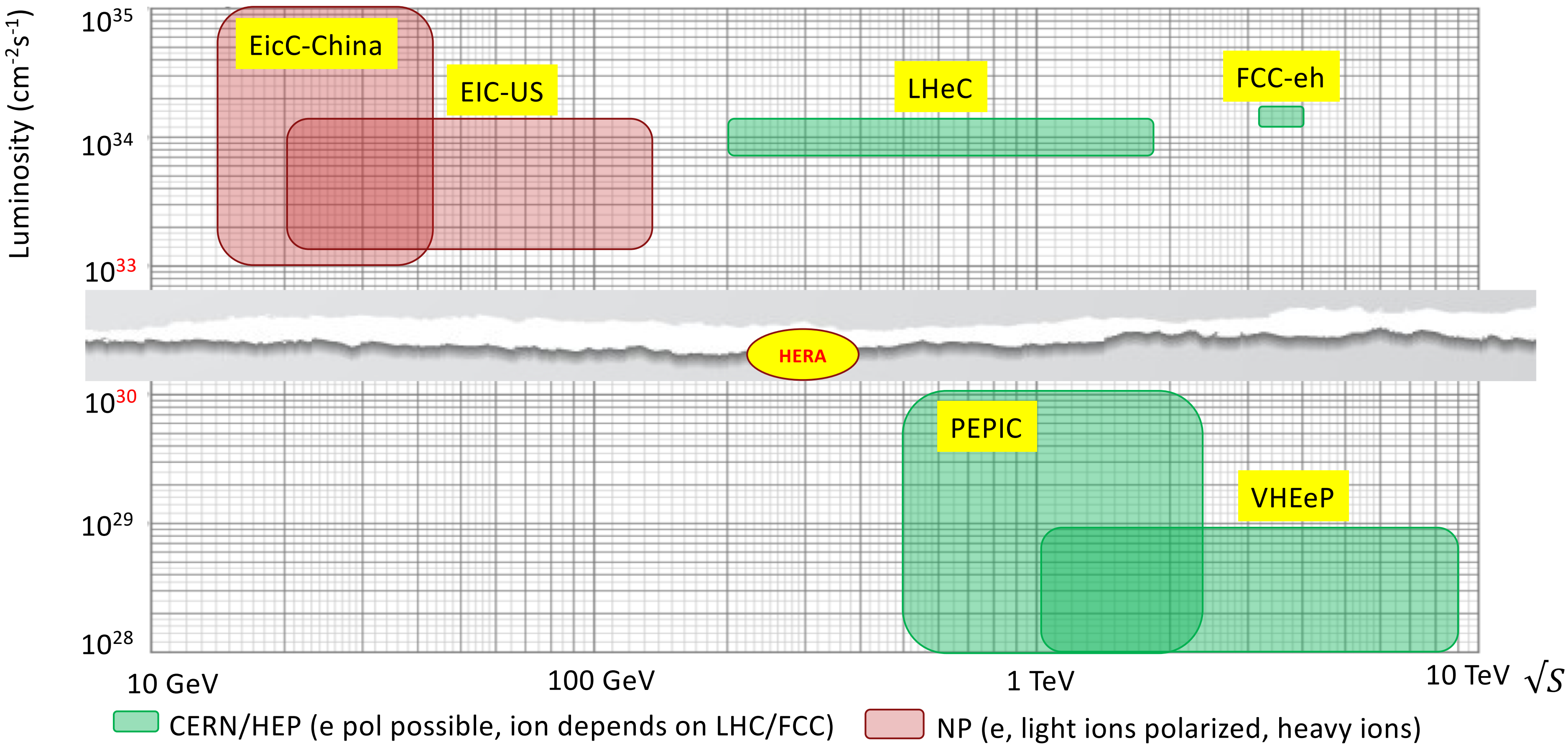
- Emphasis on using current infrastructure, i.e. LHC beam with minimum modifications.
- Overall layout works in powerpoint.
- Need high gradient magnets to bend protons into the LHC ring.
- One proton beam used for electron acceleration to then collider with other proton beam.
- High energies achievable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

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

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

Future DIS colliders



R. Yoshida, DIS 2019

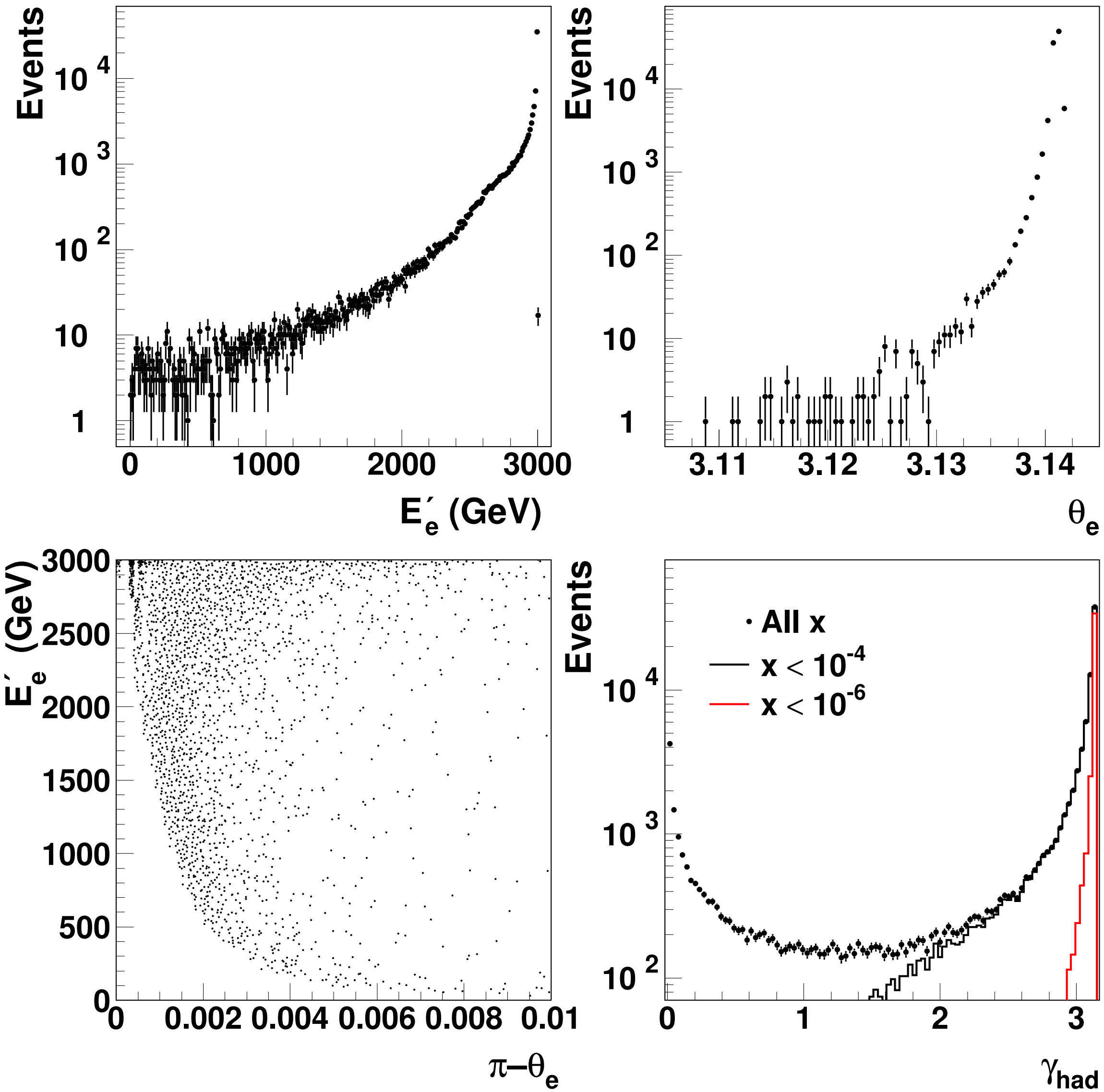
Comparison of colliders

- 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 new accelerator technology, also opportunity.

Kinematics of the VHEeP final state

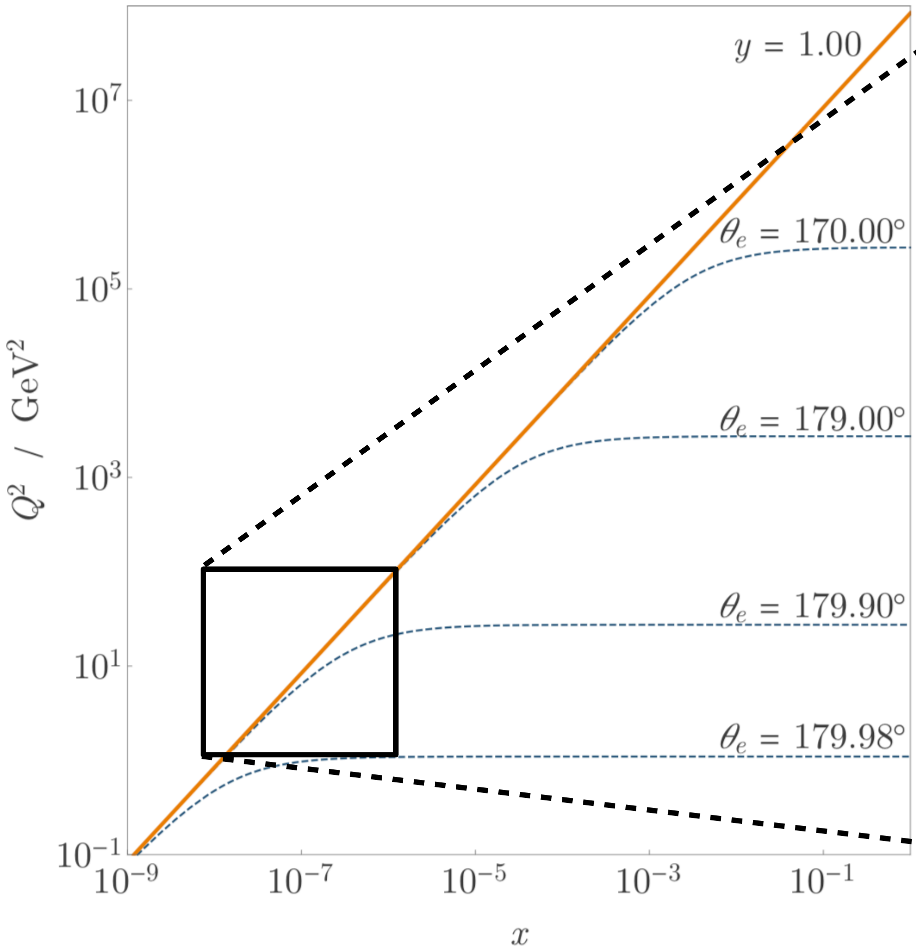


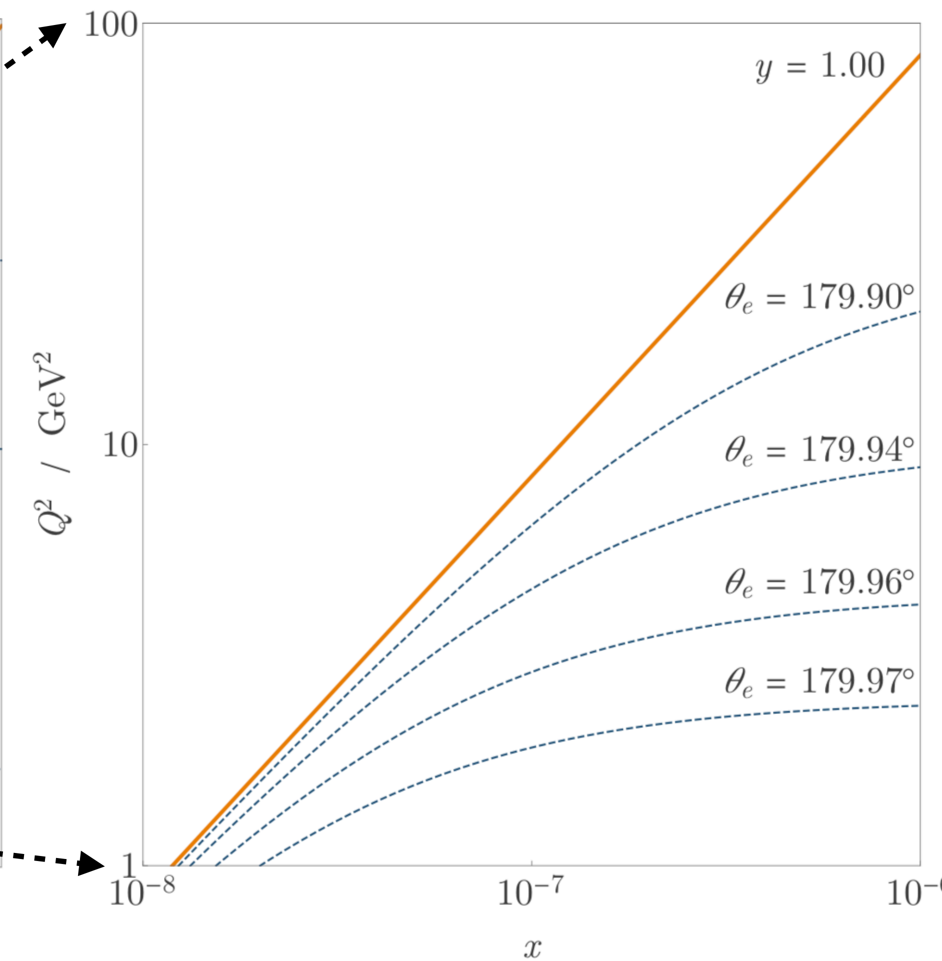
- Generated ARIADNE events with $Q^2 > 1\ GeV^2$ and $x > 10^{-7}$
- Test sample of $L \sim 0.01\ pb^{-1}$
- Kinematic peak at *3 TeV*, with electrons scattered at low angles.
- Hadronic activity in central region as well as forward and backward.
- Hadronic activity at low backward angles for low x.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

Kinematics and detector challenge

F. Keeble, UCL

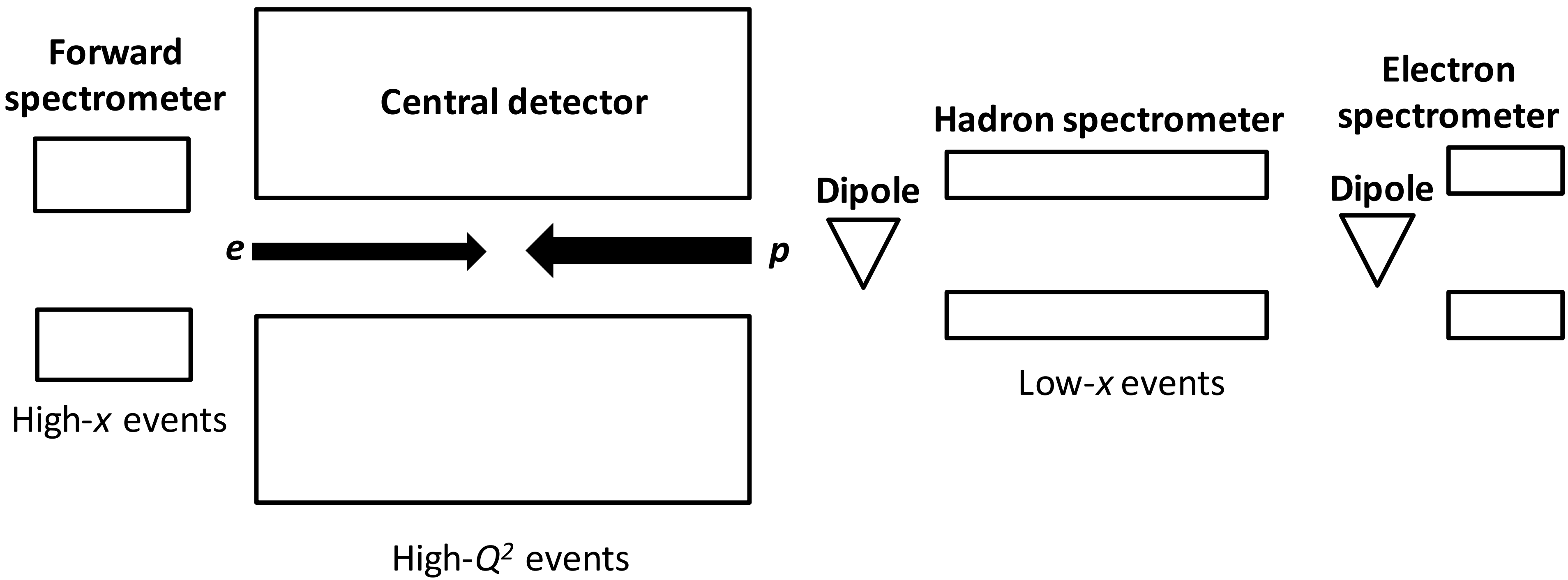
Electron kinematics





Scattered electrons are close to collinear with the initial electron beam

Sketch of detector



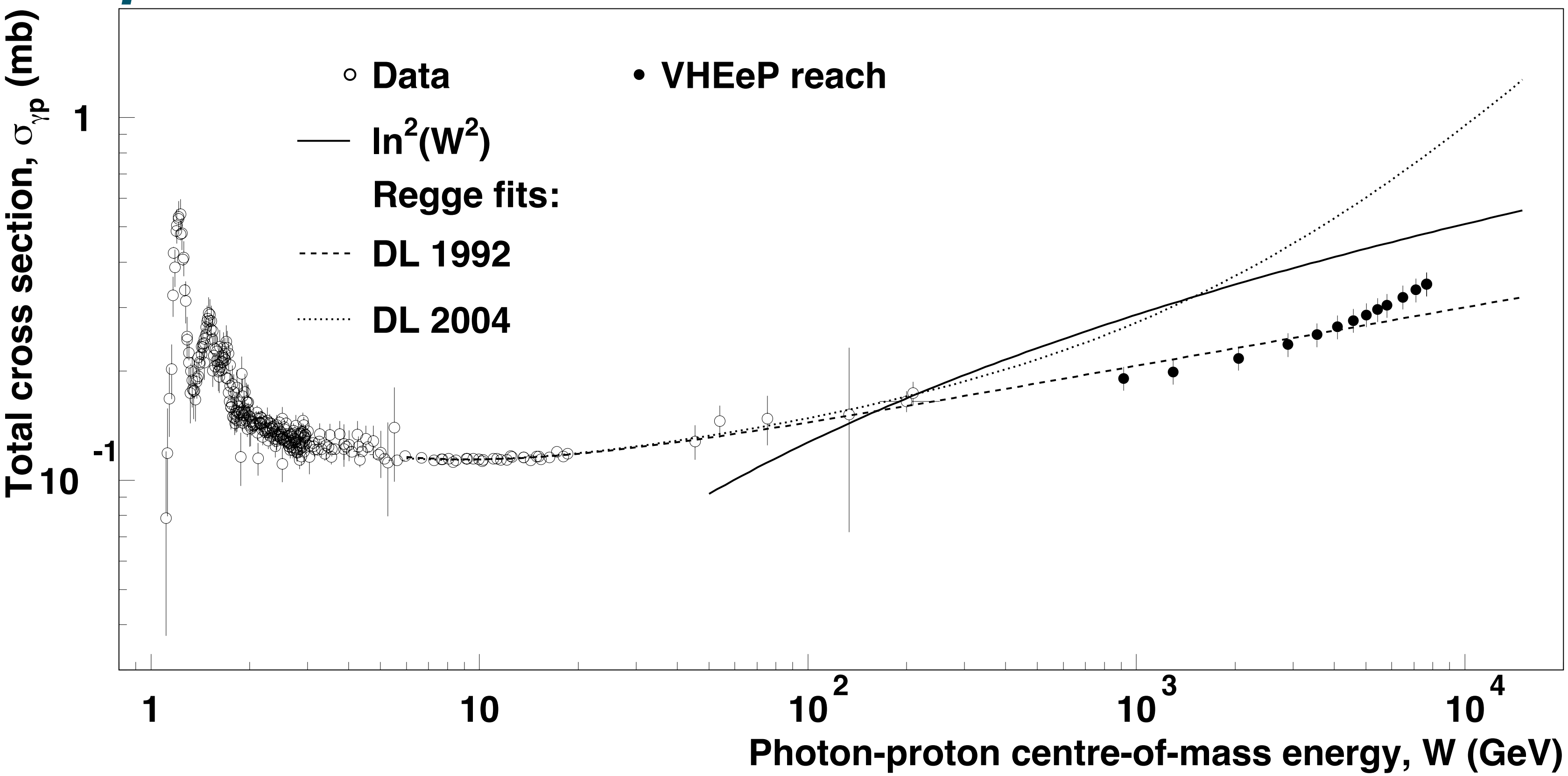
- Will need conventional central colliding-beam detector.
- **Will also need long arm of spectrometer detectors which will need to measure scattered electrons and hadronic final state at low *x* and at high *x*.**

Physics at VHEeP

- Access down to $x \sim 10^{-8}$ for $Q^2 \sim 1\ GeV^2$.
- Even lower x for lower Q^2.
- 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.

- 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 ?

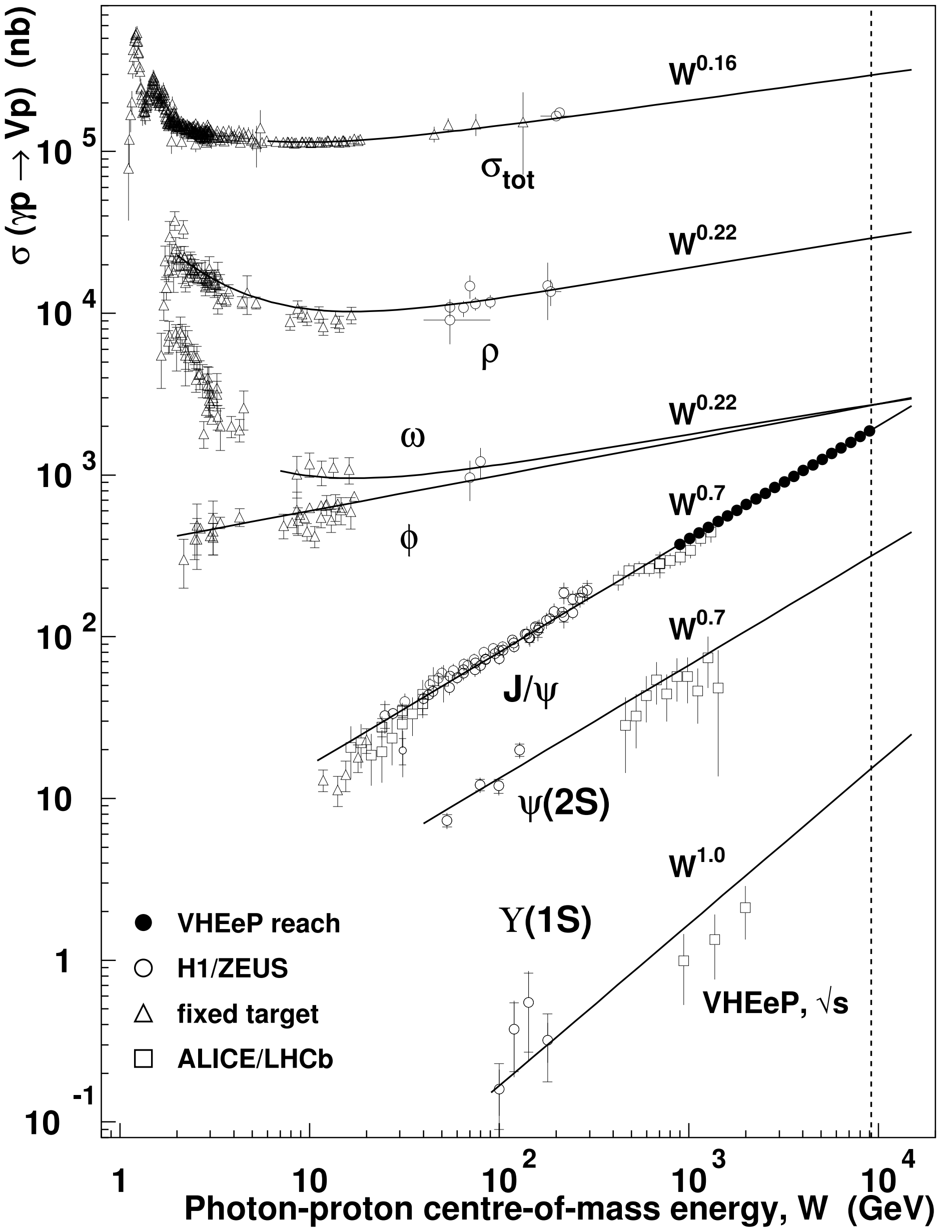
Total γP cross section



- Assumed same uncertainties as ZEUS measurement which used 49 nb^{-1}.
- 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



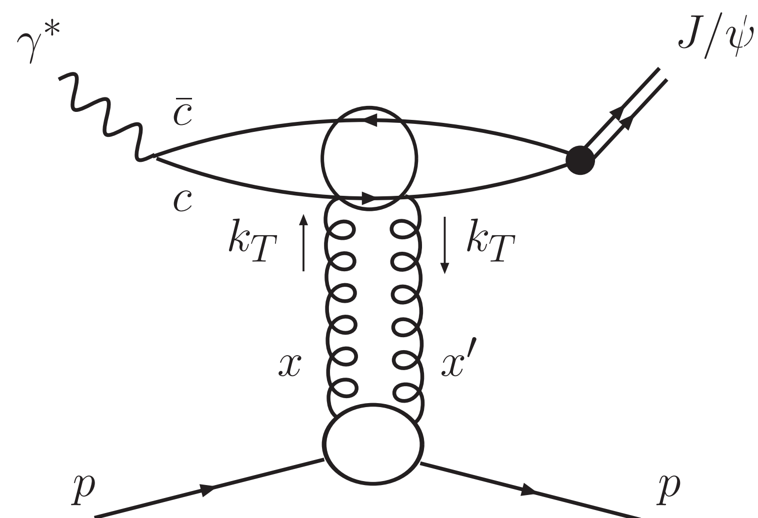
Strong rise with energy related to gluon density at low *x*.

Can measure all particles within the same experiment.

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

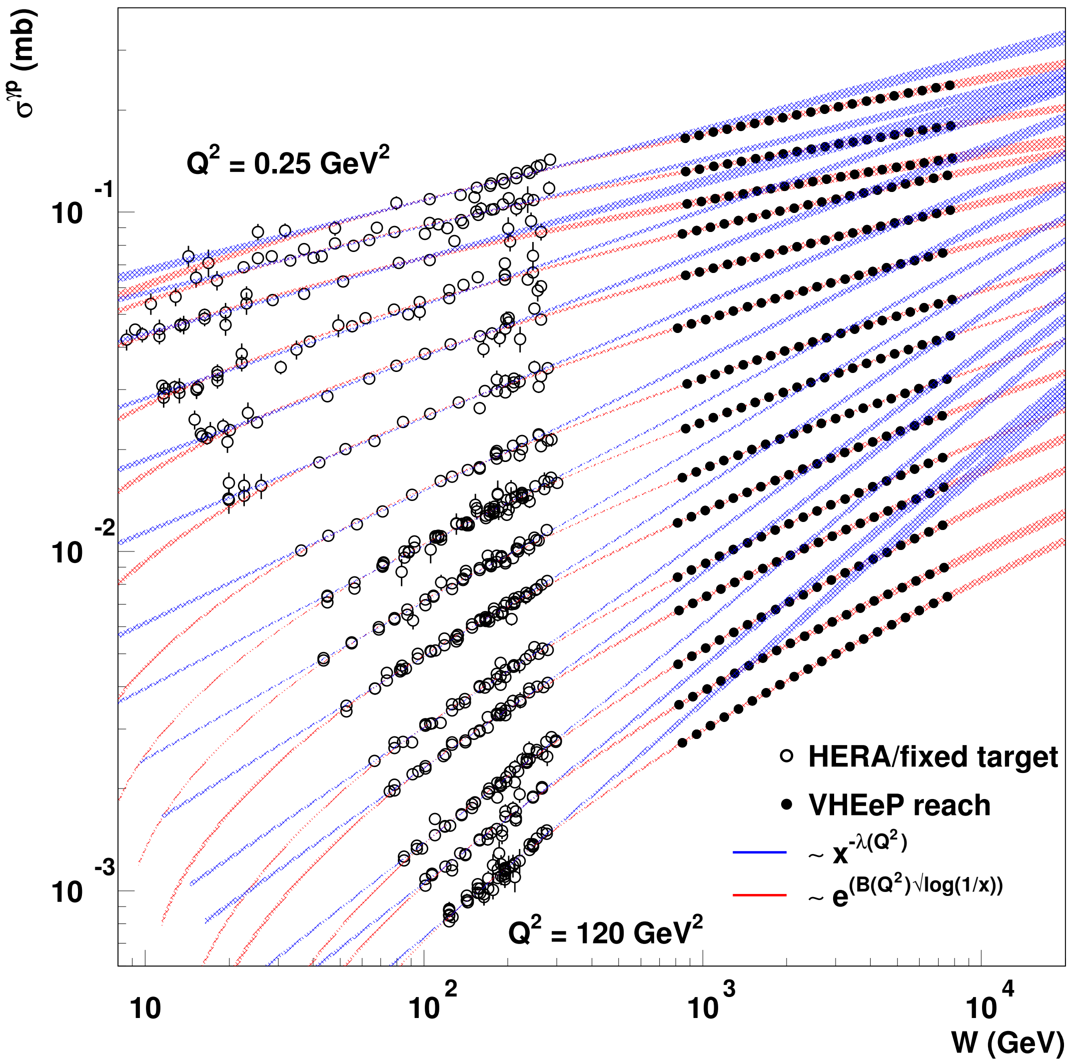
At VHEeP energies, $\sigma(J/\psi) \gtrsim \sigma(\varphi)$!

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.

Summary

• Measurements of deep inelastic scattering have provided an exquisite picture of the structure of nucleons.

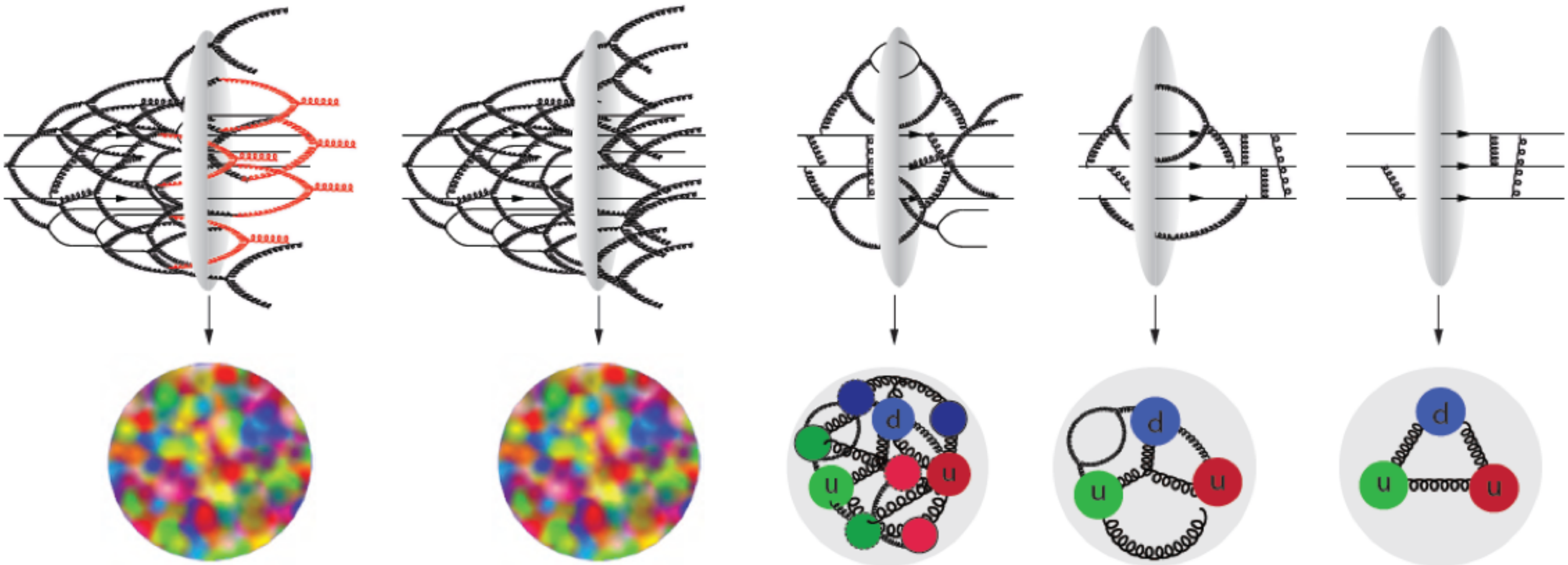
• However, it feels like we are still missing lots at low x ($< 10^{-4}$); some interesting signals and indications of a departure from theory.

• But we need to go further and there is a compelling case to go as low as $x \sim 10^{-8}$

- 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. Need to consider more on *eA* collisions.
- Even with moderate luminosities, $\sqrt{s}$ is crucial and opens up a rich physics programme.
- The VHEeP collider would probe the low-*x* frontier.
- We welcome new ideas and studies for such a machine.

Back-up

Saturation



Saturation is a theme of all discussed projects:

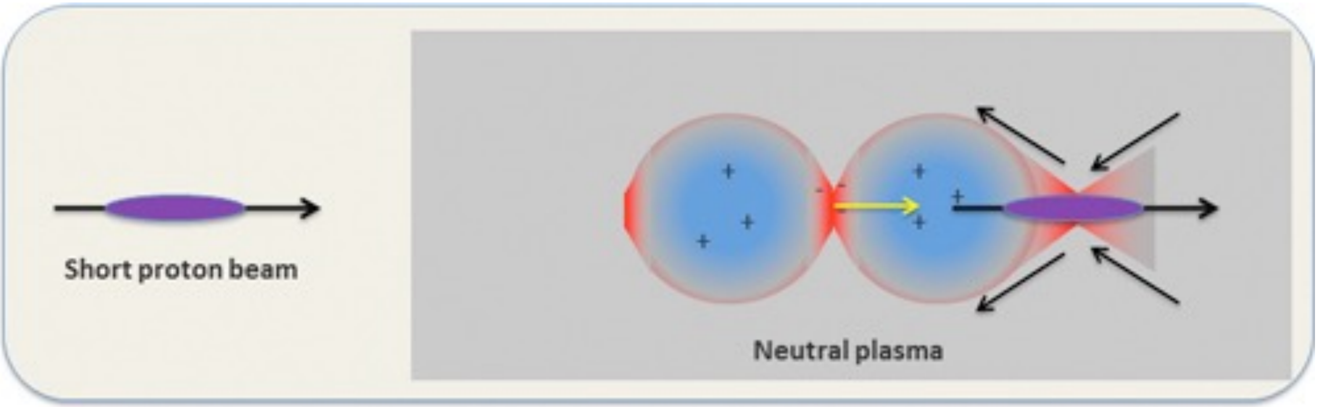
- When does the rise of the gluon PDF stop ?
- The rise cannot continue forever.
- Can investigate in *ep* and *eA* scattering.
- Lead to new description of structure of matter. Effect on confinement ?

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.

AWAKE

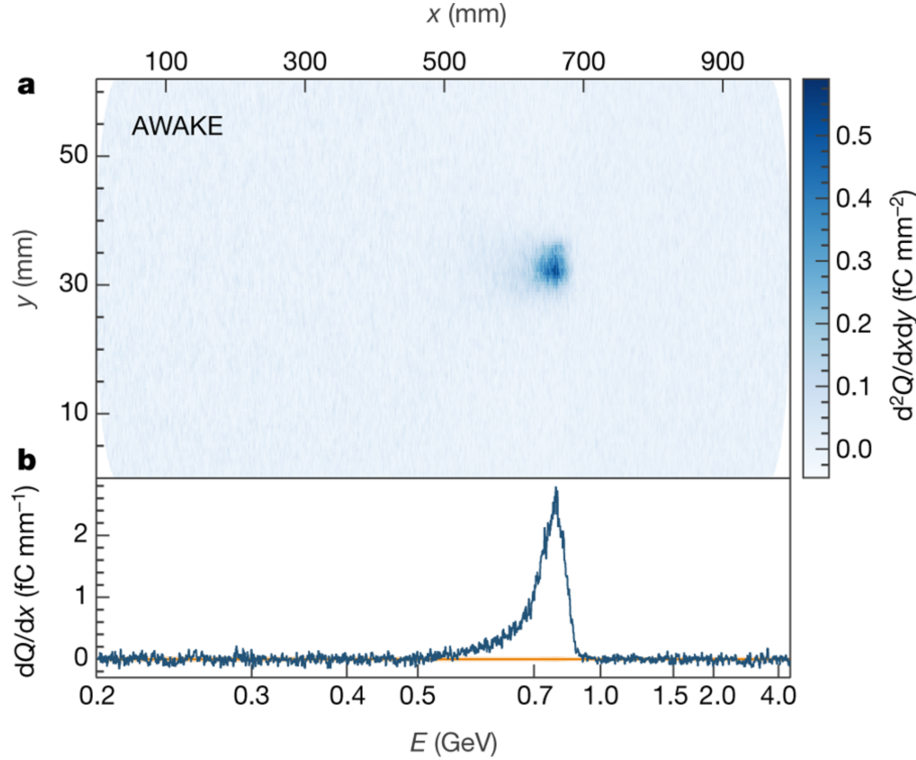
Proof-of-principle experiment at CERN demonstrates proton-driven plasma wakefield acceleration for the first time.

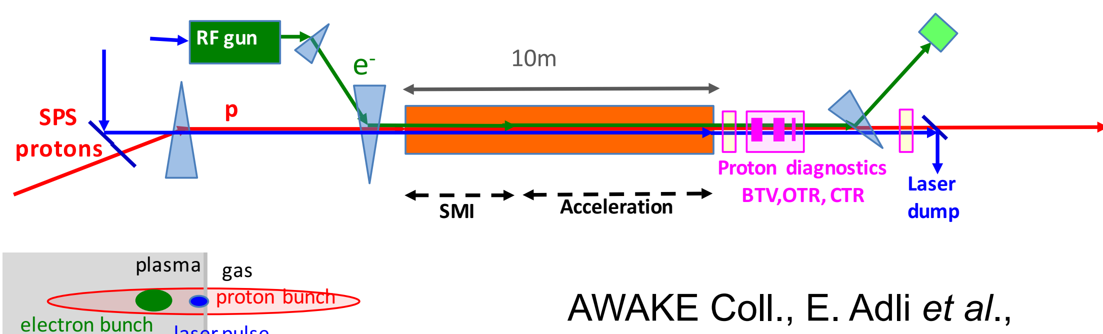
Using 400 GeV SPS proton bunches.

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

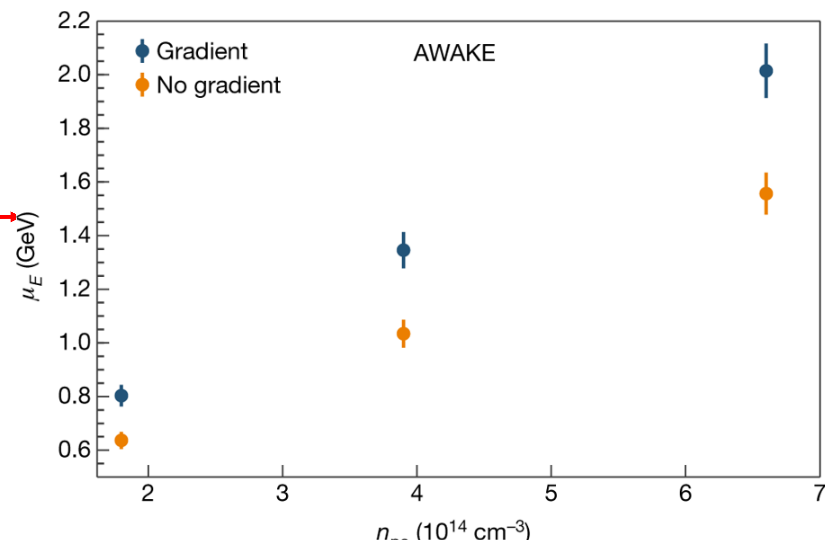
In 2018, accelerated electrons to 2 GeV.

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



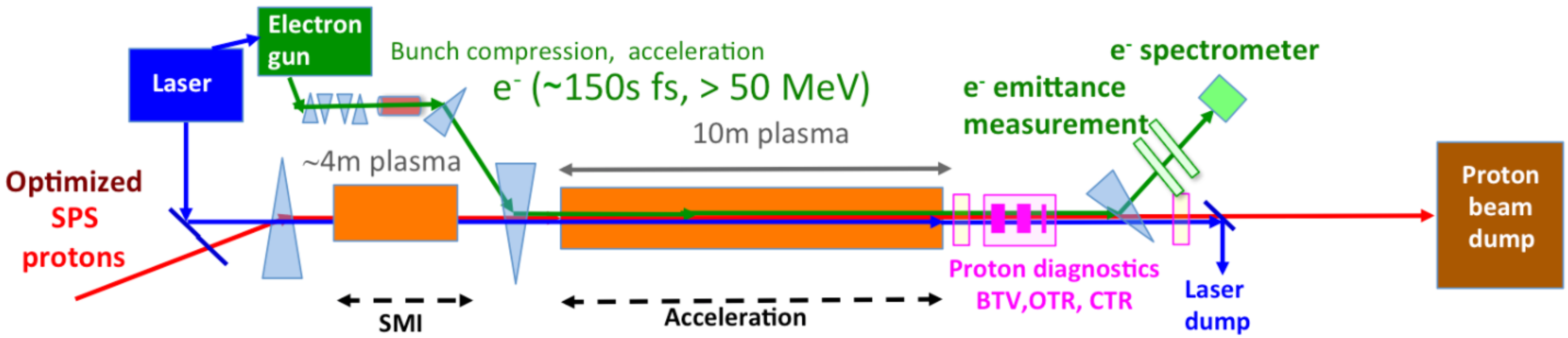


AWAKE Coll., E. Adli *et al.*, *Acceleration of electrons in the plasma wakefield of a proton bunch*, Nature **561** (2018) 363.



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).

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.

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*

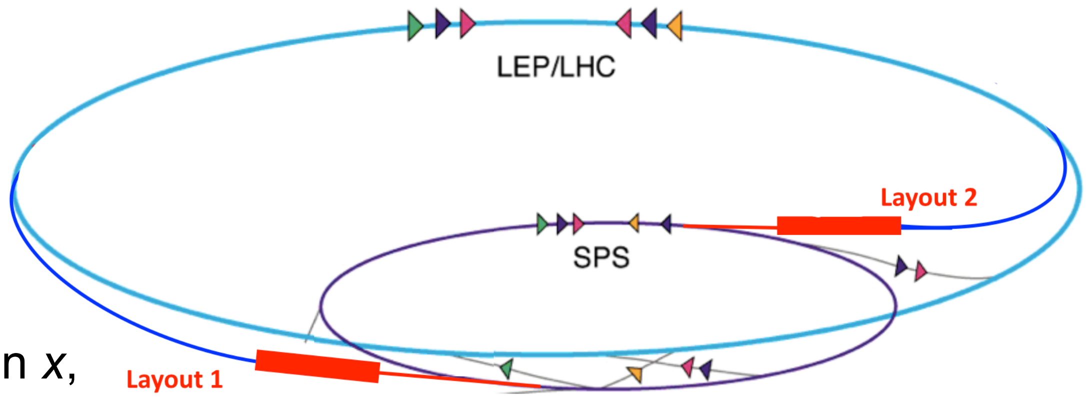
- Possible increase in bunch charge ?
- Variation in energy possible.
- Can we treat the bunches to create spills (of individual particles) ?

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.

Plasma electron−proton/ion collider (PEPIC)

- Consider high energy *ep* collider with $E_e \sim 50$ 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.

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

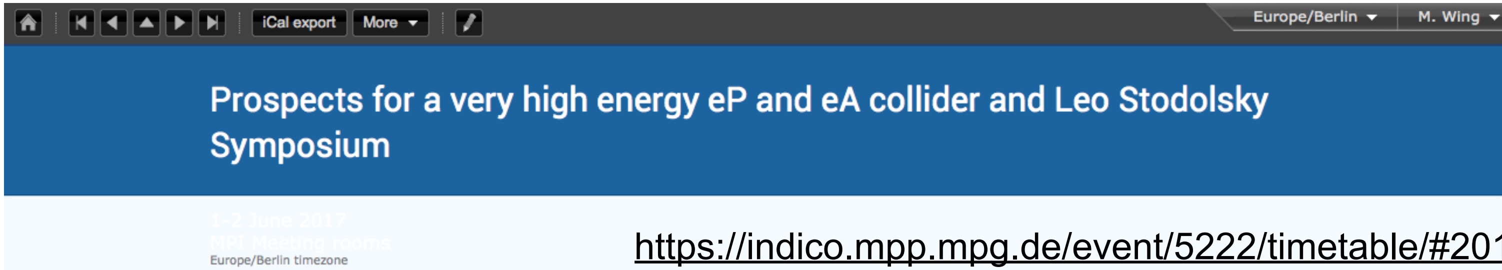
These should be considered for ideas/studies.

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

Outlook

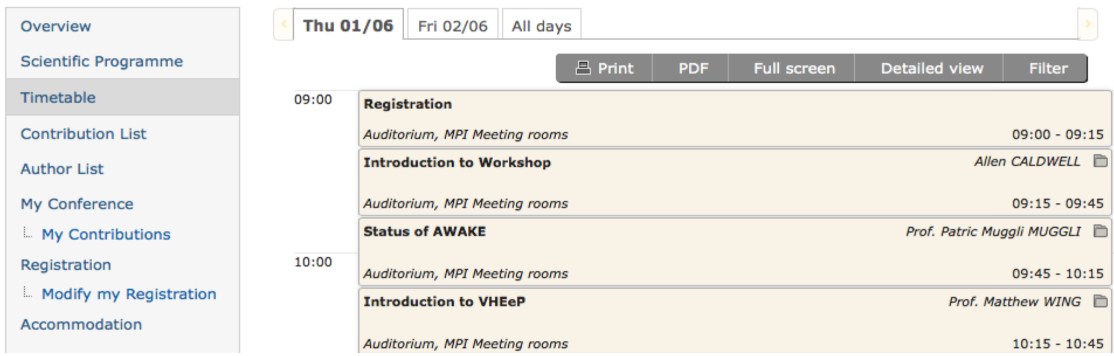
- Lots to do to develop VHEeP further
  - Accelerator scheme
    - Separation of drive protons and electrons
    - Can luminosity be increased
    - Electron (and proton/ion) beams after interaction and beam dump, e.g. active for hidden sector search
    - Design of interaction point
    - How to fit 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.

VHEeP workshop: new ideas



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

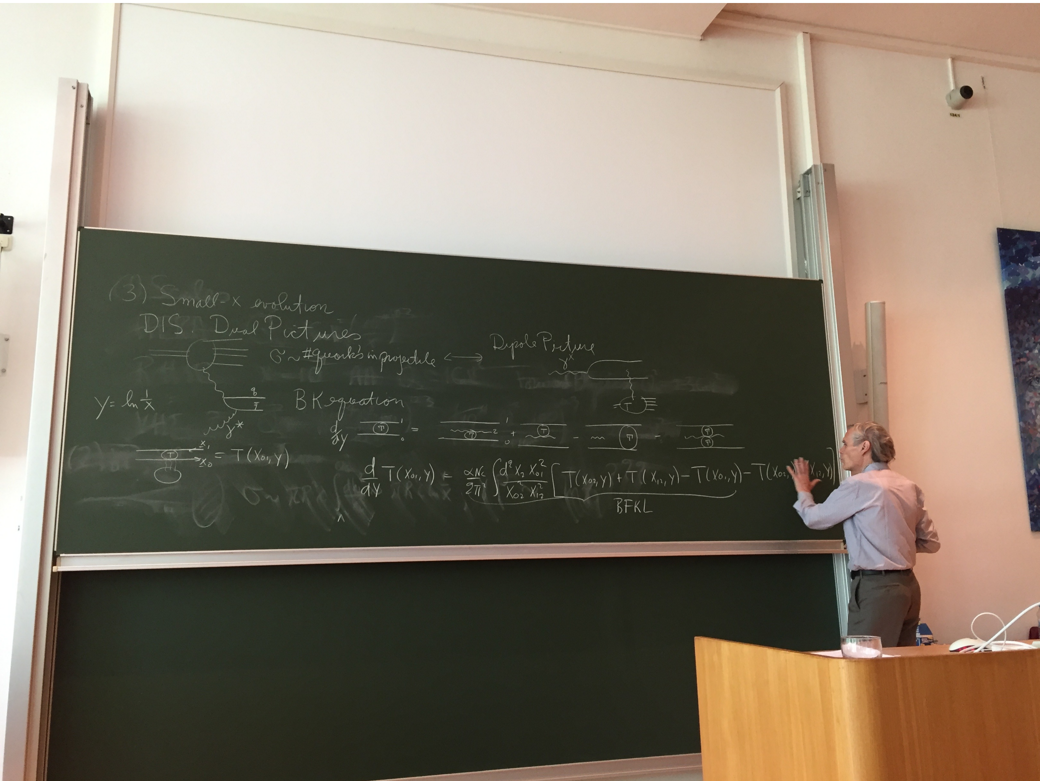
Workshop in MPI, Munich, 1−2 June 2017



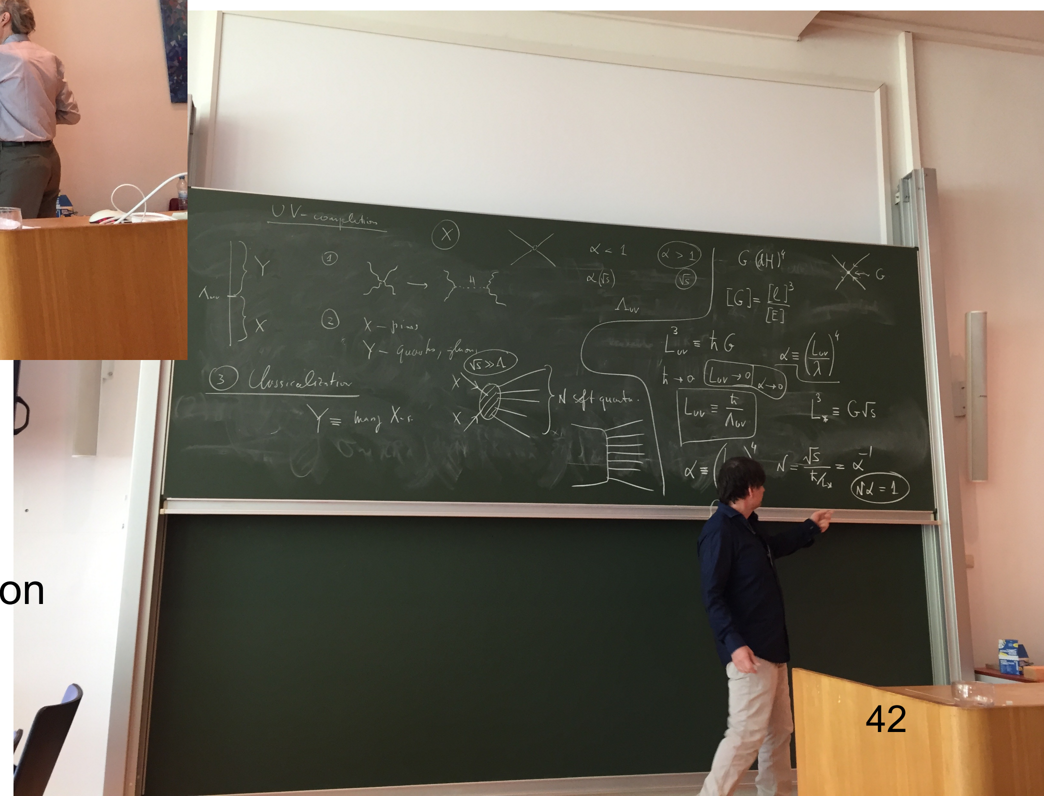
Some highlights:

- 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

$\sigma_{\gamma P}$ 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:

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

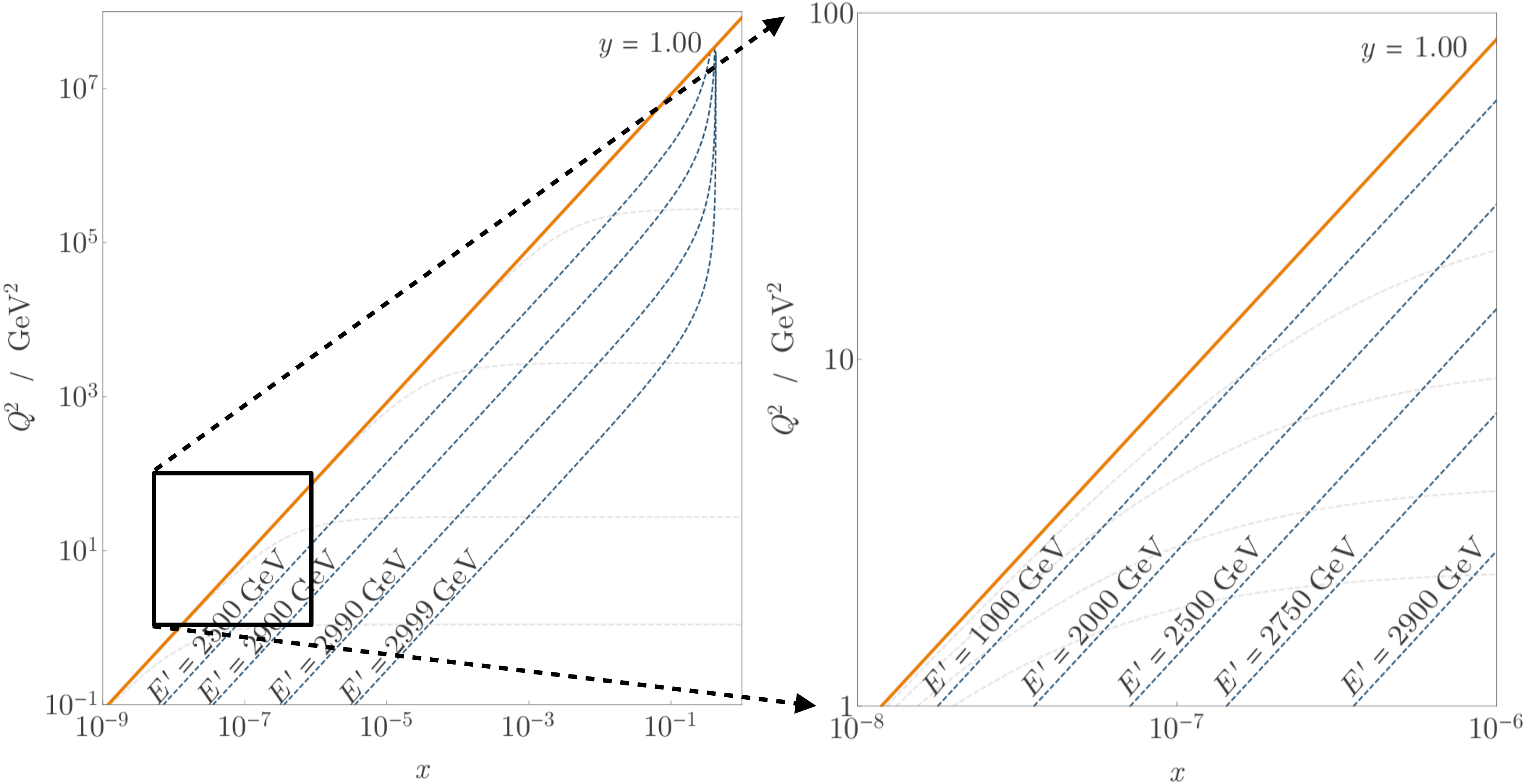
Plot $\sigma_{\gamma P}$ versus the coherence length, l:

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

Kinematics and detector challenge

F. Keeble, UCL

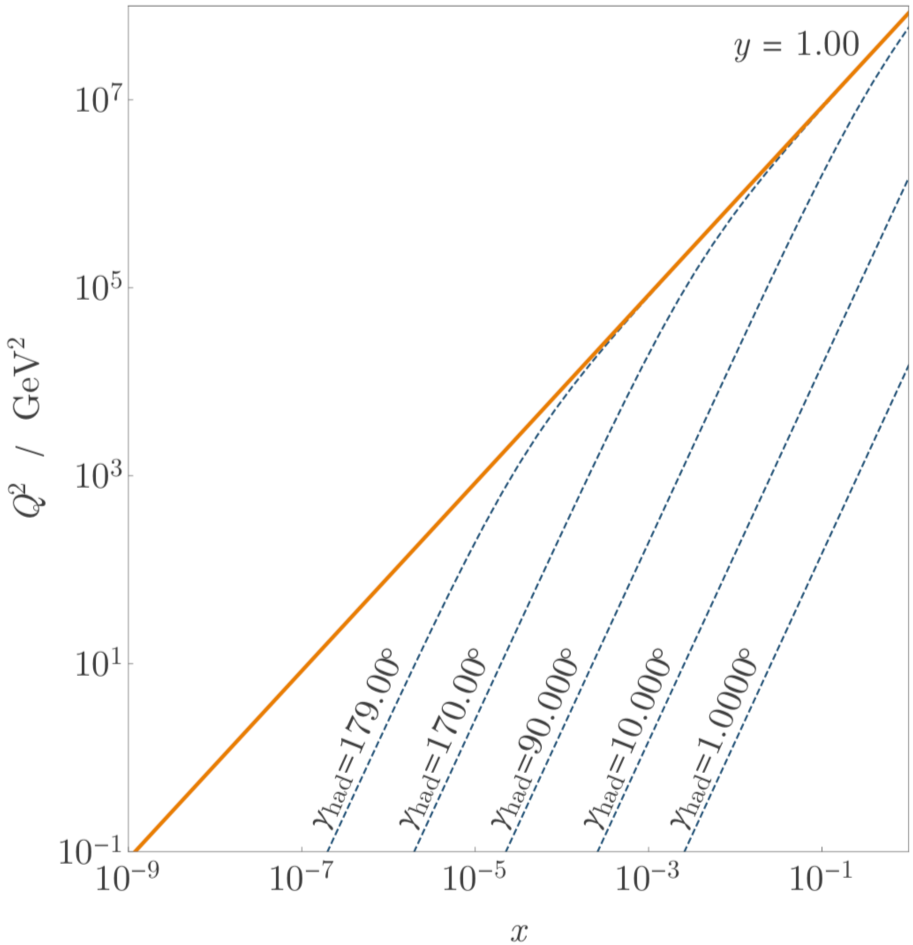
Electron kinematics

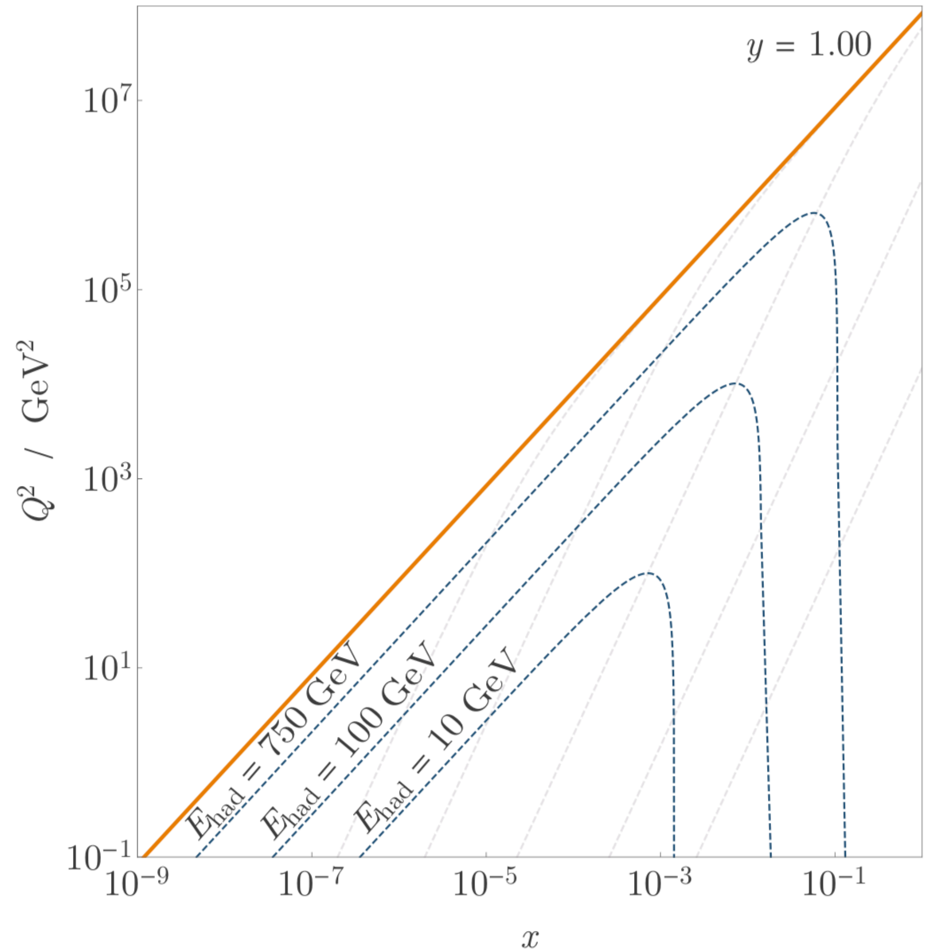


Scattered electrons at low *x* can have very different energies

Kinematics and detector challenge

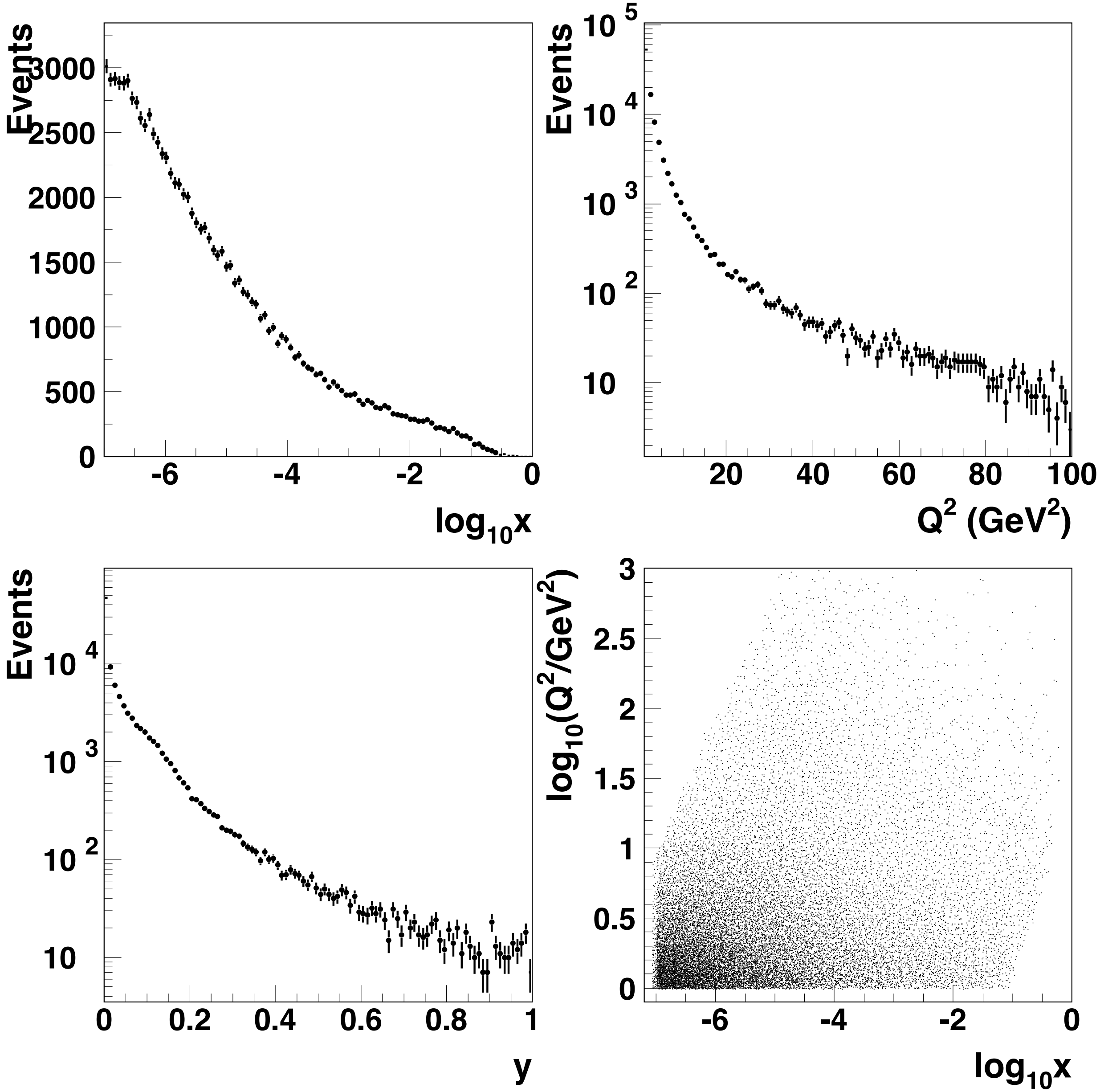
Hadronic final state





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

DIS variables



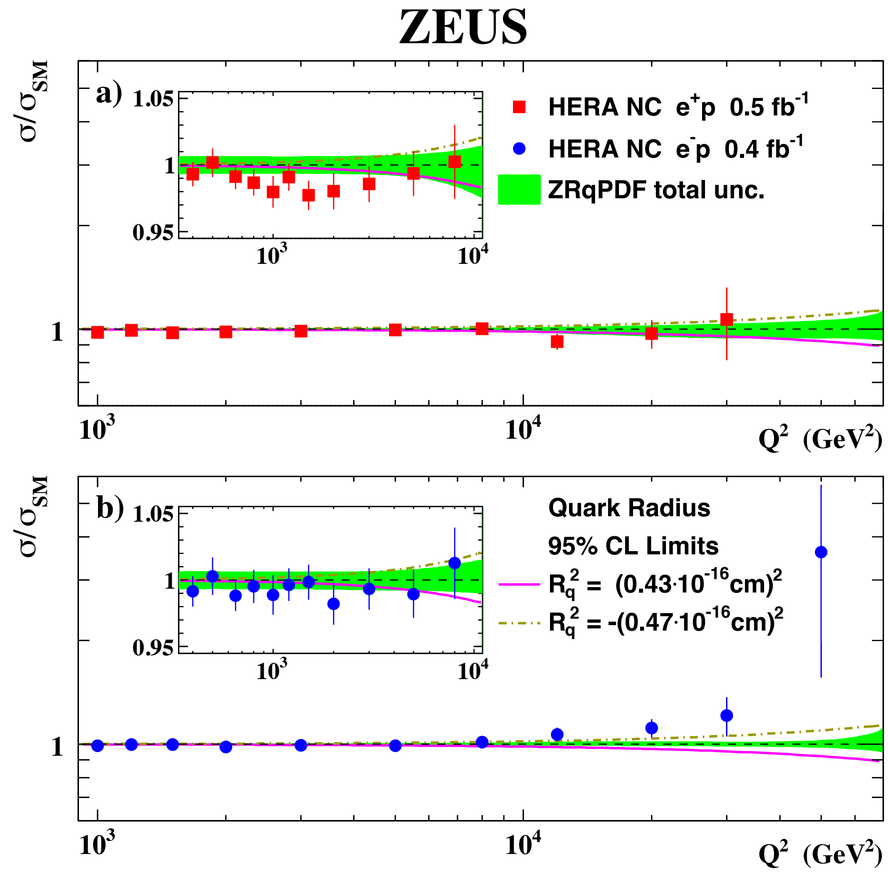
BSM: Quark substructure

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.



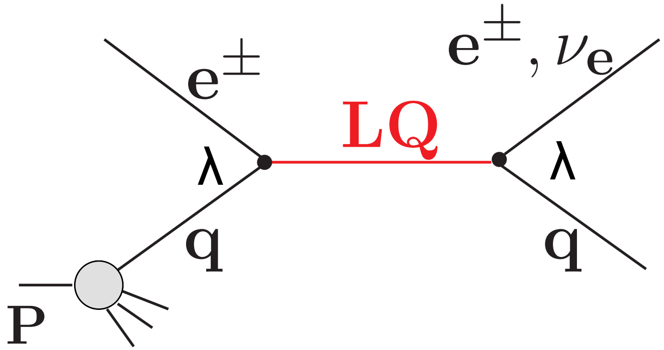
ZEUS Coll., Phys. Lett. **B 757** (2016) 468.

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

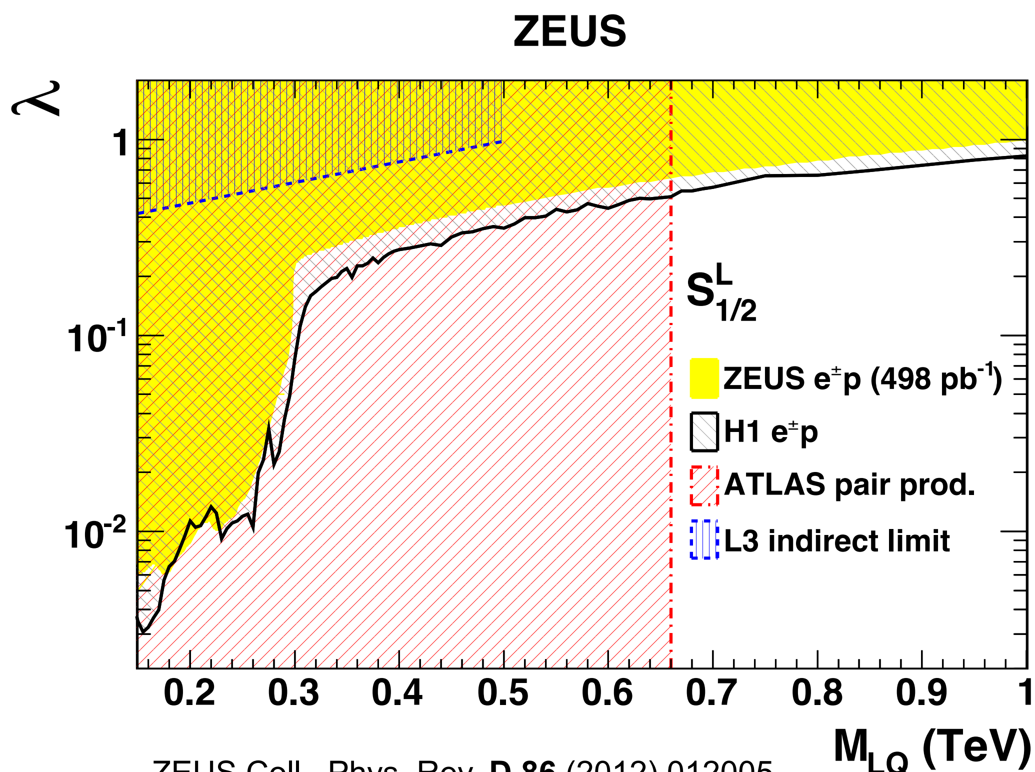


Electron−proton colliders are the ideal machine to look for leptoquarks.

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

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

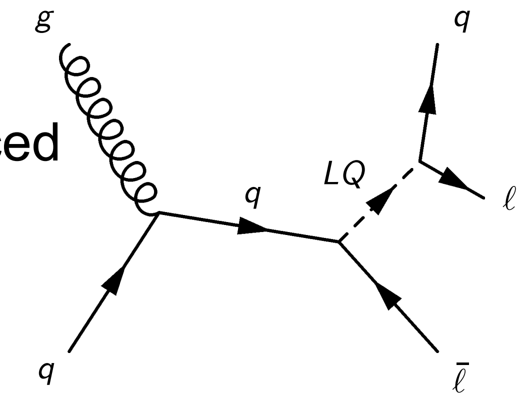
Sensitivity depends mostly on √*s* and VHEeP = 30 × HERA

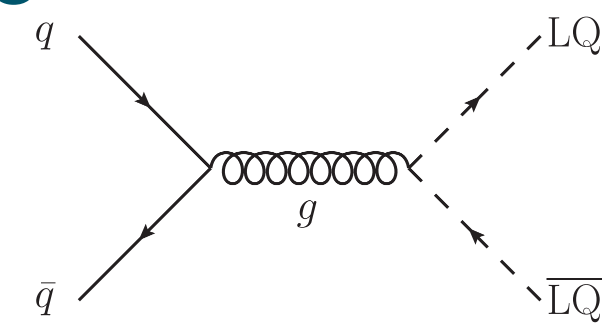


ZEUS Coll., Phys. Rev. **D 86** (2012) 012005

Leptoquark production at the LHC

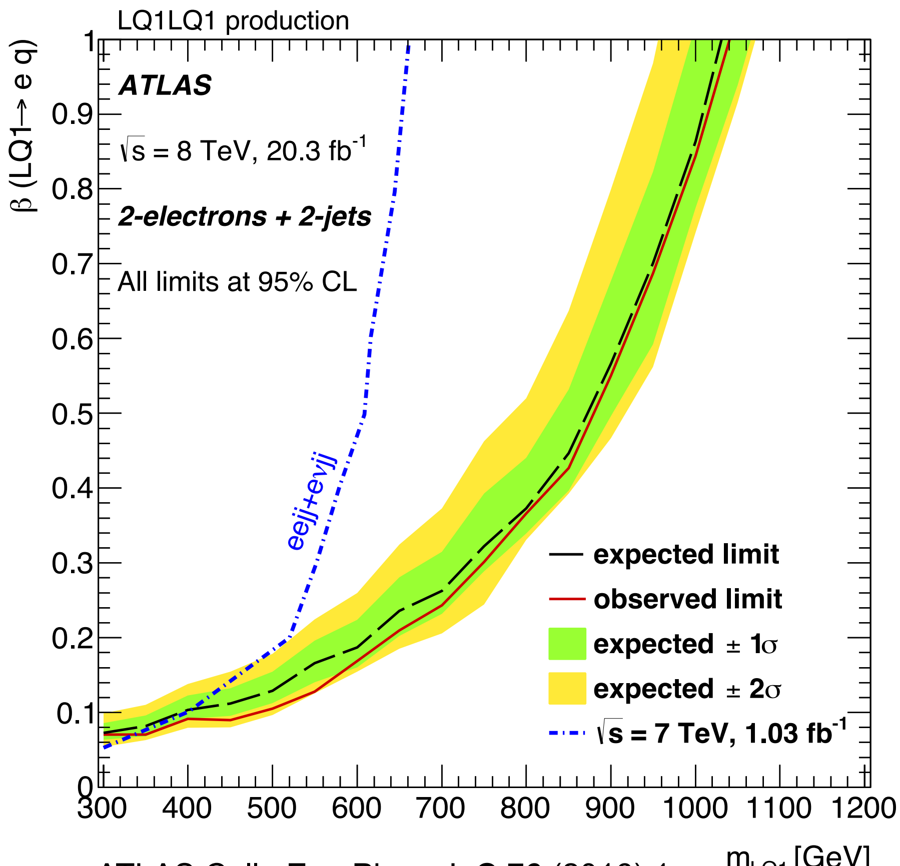
Can also be produced in *pp* singly or pair production





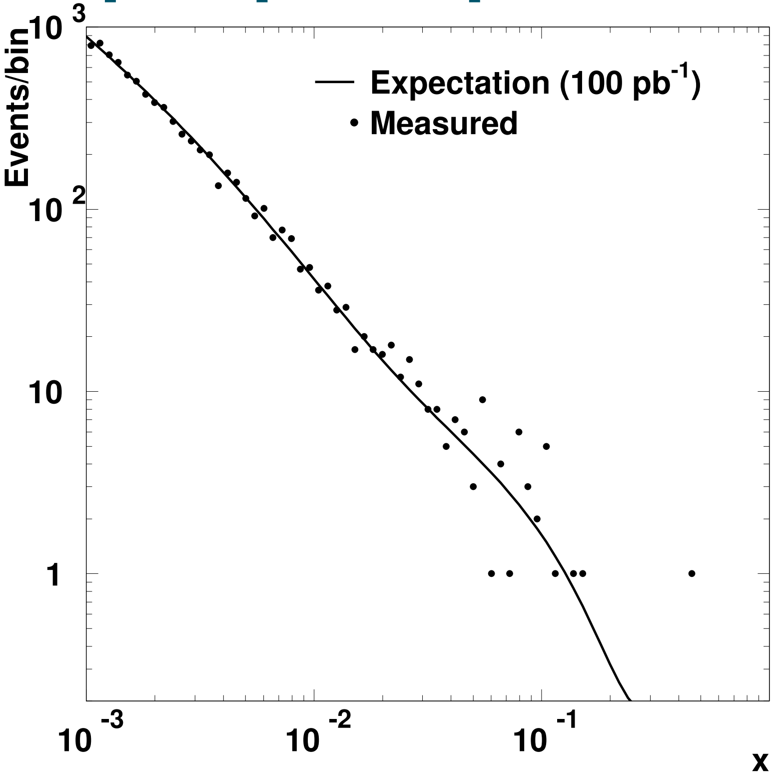
Reach of LHC currently about *1 TeV*, to increase to *2 − 3 TeV*.

Coupling dependent.



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

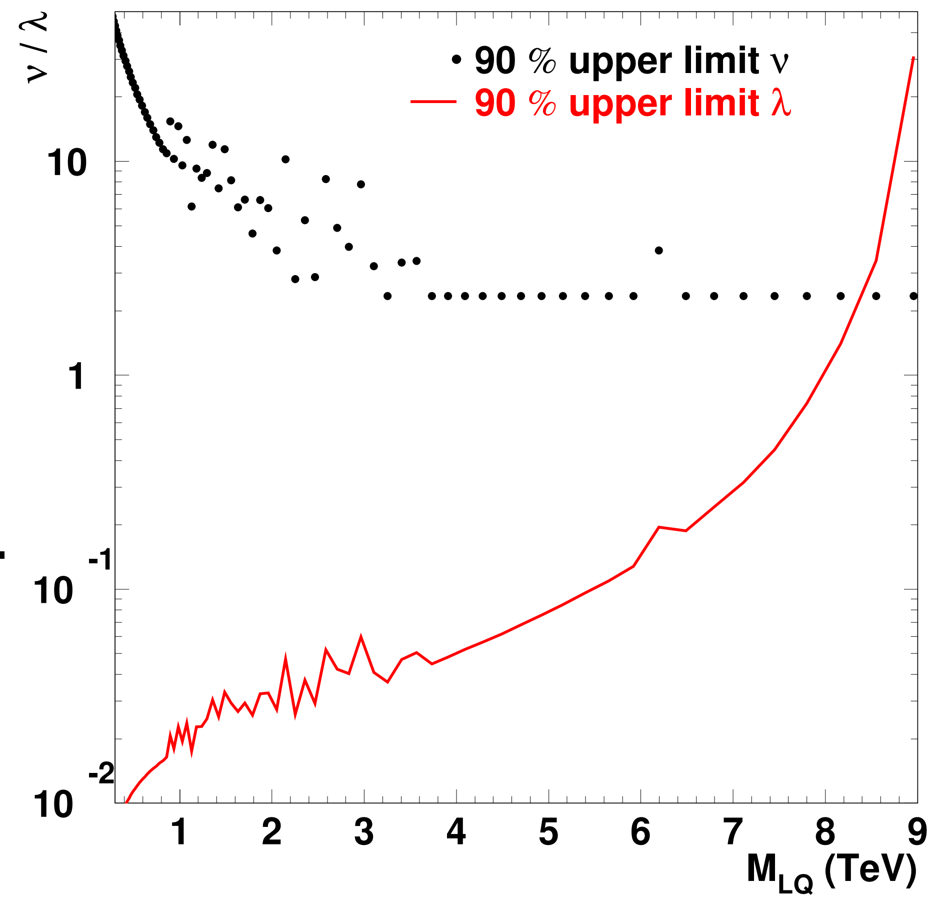
Leptoquark production at VHEeP



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

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.