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An electron beam for physics experiments based on AWAKE scheme

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- Introduction and AWAKE
- Future electron beam based on AWAKE scheme
- Possible physics experiments
  - Search for dark photons, NA64-like
  - High energy electron−proton collisions, LHeC-like and VHEeP
- Summary and outlook

Physics Beyond Collider Kickoff Workshop — 7 September 2016, CERN

Introduction

Plasma wakefield acceleration is a promising scheme as a technique to realise shorter or higher energy accelerators in particle physics.

One method is to partly utilise current infrastructure and use current beams to generate the accelerator system, in CERN's case using bunches of protons to accelerate electrons, AWAKE.

There are various different techniques and some (ambitious) potential applications of plasma wakefield acceleration.

Want to here initiate ideas for use of beams which could be produced by AWAKE scheme.

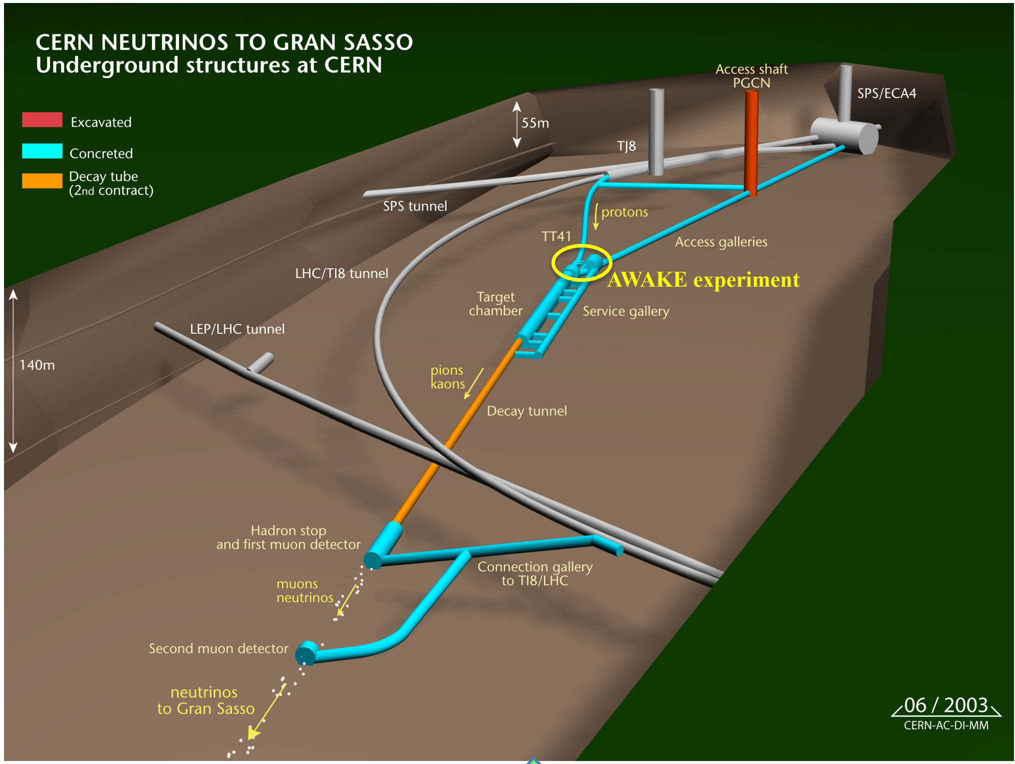
Briefly present AWAKE programme and expected electron bunches to be produced.

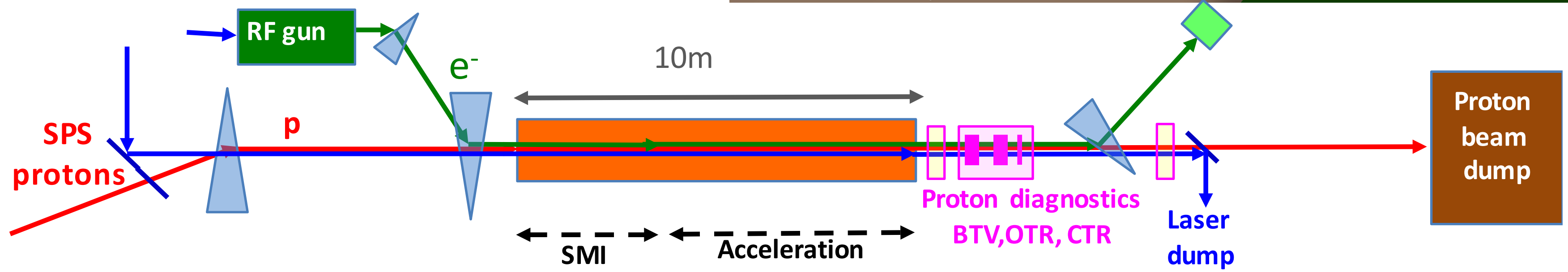
Present some ideas of experiments that could significantly benefit from this.

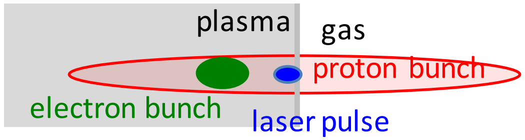
Happy to hear of other ideas of experiments that could utilise a high energy electron beam.

AWAKE: proton driven plasma wakefield experiment

- Demonstration experiment to show effect for first time and obtain *GV/m* gradients.
- Use *400 GeV* SPS proton bunches with high charge.
- To start running this year and first phase to continue to LS2.
- Apply scheme to particle physics experiments leading to shorter or higher energy accelerators.

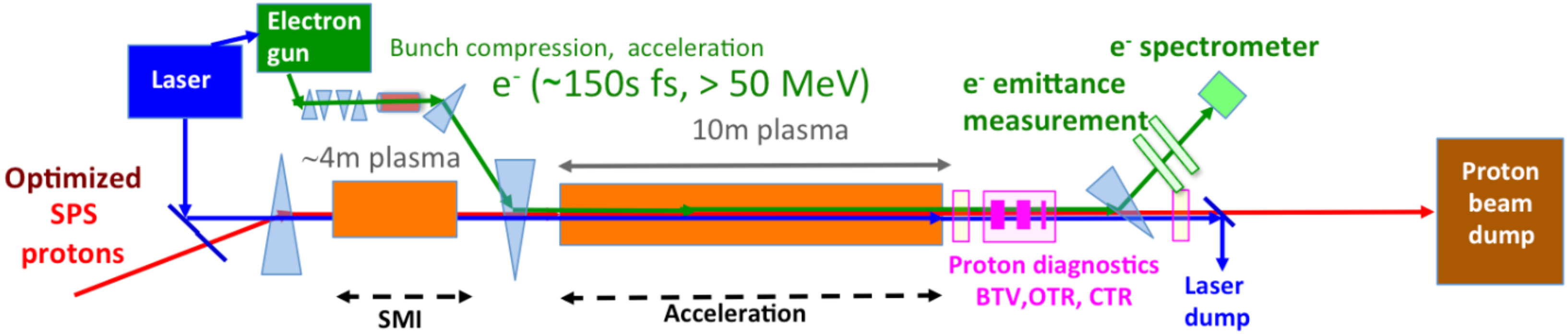






AWAKE Run 2

- 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 campaigns.
  - Test-beam infrastructure for detector characterisation often over-subscribed.
  - Also accelerator test facility.
  - Variation of energy.
  - Provide pure electron beam.
- Fixed-target experiments using electron beams, e.g. deep inelastic scattering.
  - Measurements at high x with higher statistics than previous experiments.
  - Polarised beams and spin structure of the nucleon.
- **Search for dark photons à la NA64**
  - Consider beam-dump and counting experiments.
- **High energy electron−proton collider**
  - A low-luminosity LHeC-type experiment.
  - A very high energy electron−proton collider.

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

Search for dark photons using an AWAKE-like beam

NA64 have put forward a strong physics case to investigate the dark sector.

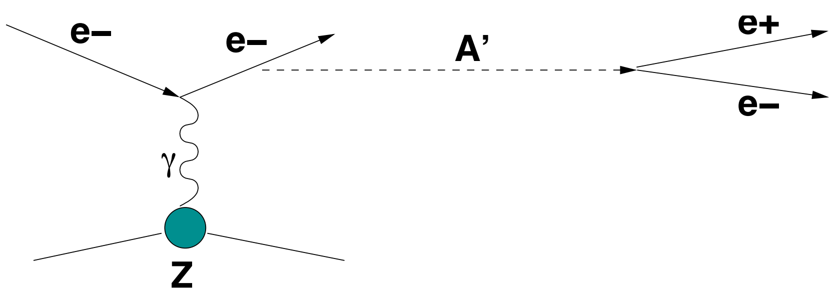
See talk by S. Gninenko and various papers/proposals from them.

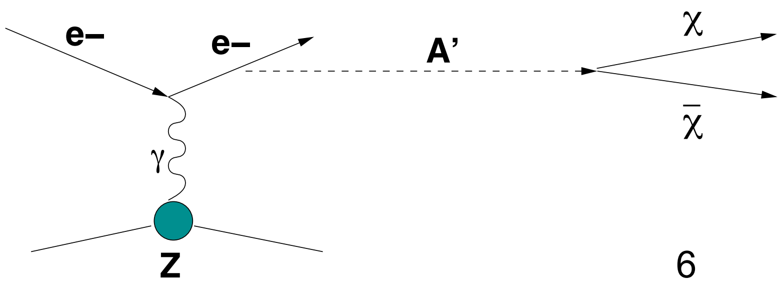
An AWAKE-like beam should have higher intensity than the SPS secondary beam.

Provide upgrade/extension to NA64 programme.

Physics reminder

- Dark sectors with light, weakly-coupling particles are a compelling possibility for new physics.
- Search for dark photons, *A′*, up to *GeV* mass scale via their production in a light-shining-through-a-wall type experiment.
- Use high energy electrons for beam-dump and/or fixed-target experiments.





Electrons on target

NA64 will receive about *10^6 e^-/spill* or *2×10^5 e^-/s* from SPS secondary beam

➡ $N_e \sim 10^{12}\, e^-$ for 3 months running.

AWAKE-like beam with bunches of $10^9\, e^-$ every (SPS cycle time of) ~ *5 s* or *2×10^8 e^-/s* *(1000* × higher than NA64/SPS secondary beam*)*

➡ $N_e \sim 10^{15}\, e^-$ for 3 months running.

Will assume that an AWAKE-like beam could provide an **effective upgrade** to the NA64 experiment, increasing the intensity by a factor of *1000*.

Different beam energies or higher intensities (e.g. bunch charge, SPS cycle time) may be possible, but are not considered in this talk.

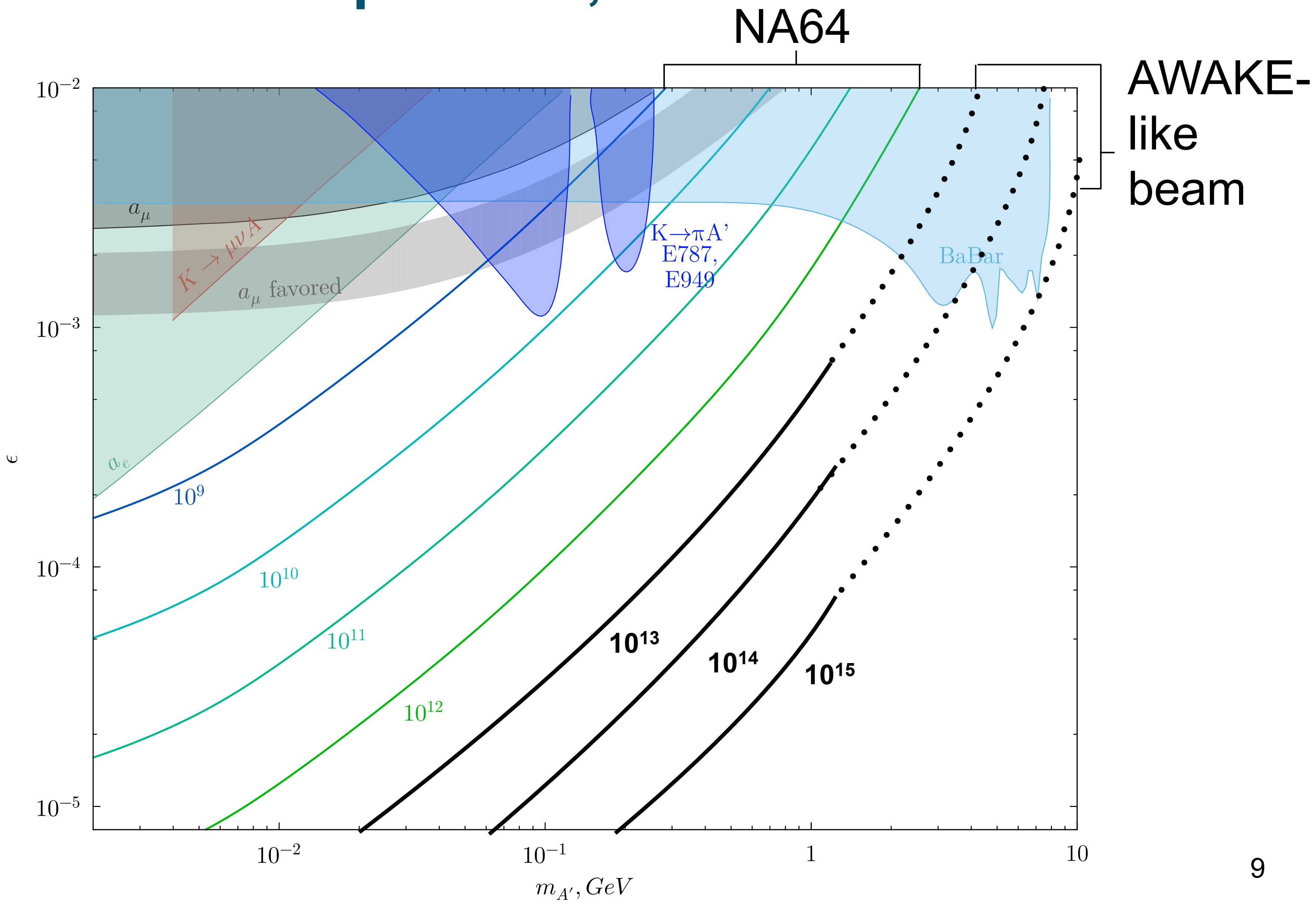
Sensitivity with increased electrons on target

Have taken plots of mixing strength, ε, versus mass, $m_{A'}$, from NA64 studies/ proposals and added curves "by hand" to show increased sensitivity.

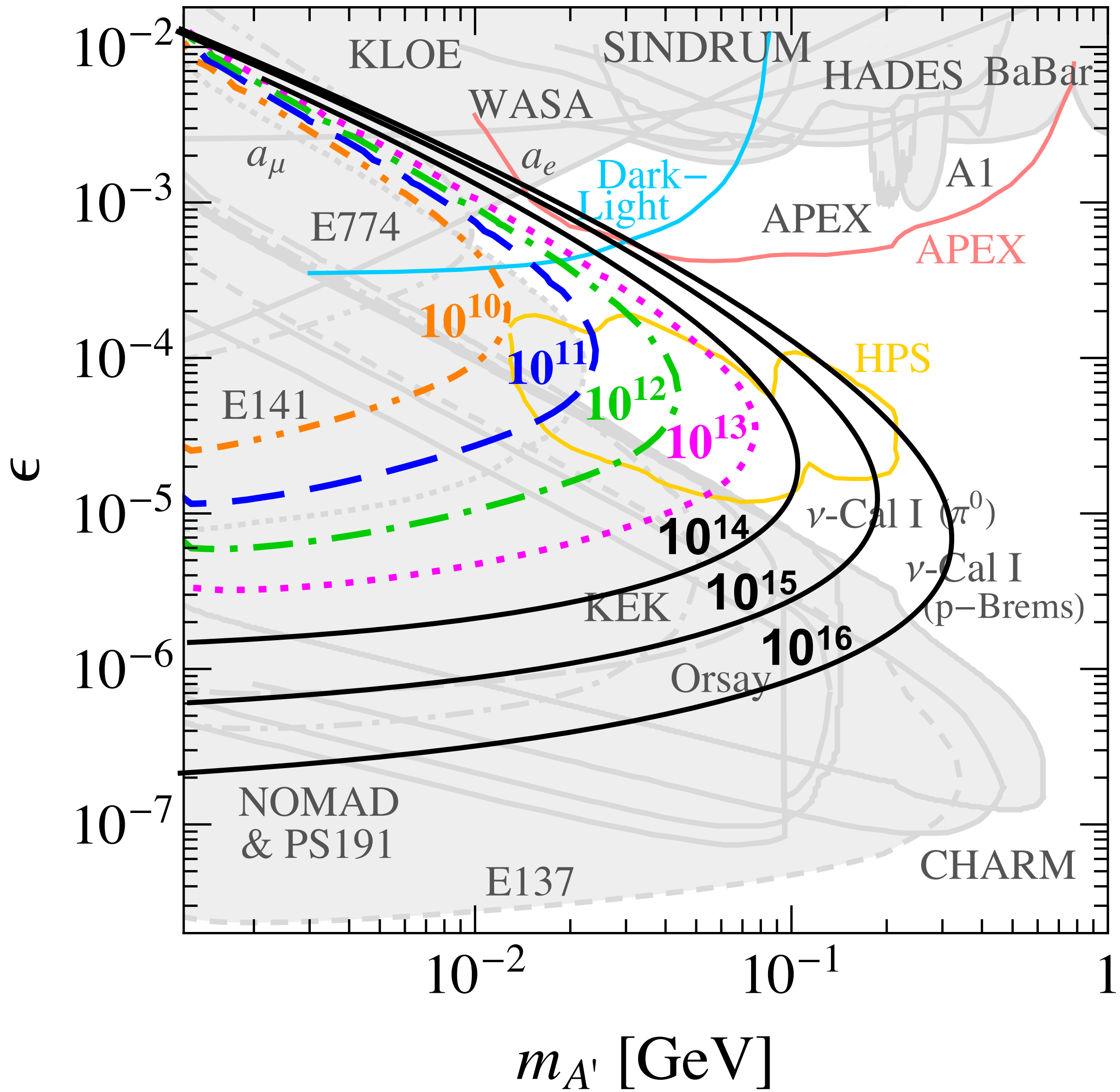
- Considered $A' \rightarrow e^+ e^-$ and $A' \rightarrow$ *invisible* channels.
- In general, but certainly at high $m_{A'}$ (> *1 GeV*) need more detailed calculations (developed in S.N. Gninenko et al., arXiv:1604.08432).
- More careful study of optimal beam energy needed.
- Evaluation of backgrounds needed; currently assume background-free for AWAKE-like beam.
- More careful study of possible detector configurations.
- Could consider other channels, e.g. $A' \rightarrow \mu^+ \mu^-$.
- For a beam-dump experiment ($A' \rightarrow e^+ e^-$), high intensities possible; for a counting experiment ($A' \rightarrow$ *invisible*), need to cope/count high number of electrons on target.

Results shown here should be considered as indicative.

Limits on dark photons, *A'* → *invisible* channel



Limits on dark photons, $A' \rightarrow e^+ e^-$



For 10^{10} – 10^{13} electrons on target with NA64.

For 10^{14} – 10^{16} electrons on target with AWAKE-like beam.

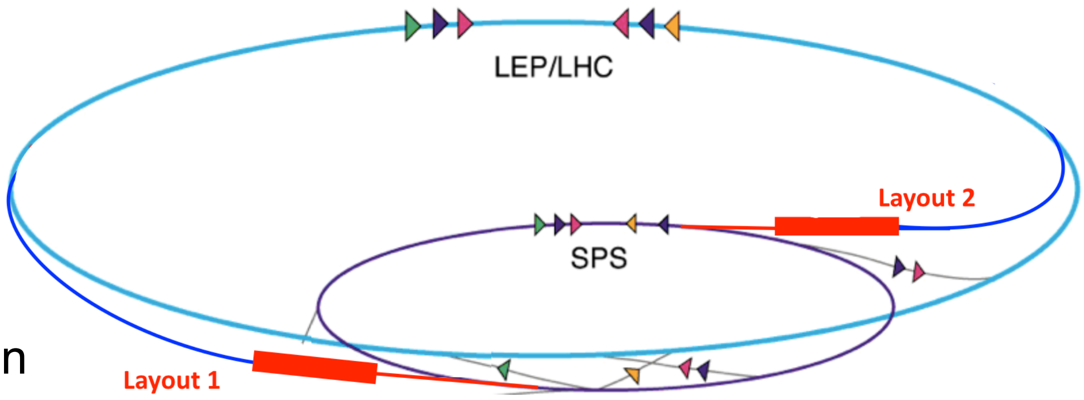
As proposed by NA64 group:

- extend into region not covered by current limits.
- similar to and complement other future experiments.

Using an AWAKE-like beam would extend sensitivity further around $\varepsilon \sim 10^{-5}$ beyond any current or planned experiment.

High energy electron−proton collisions

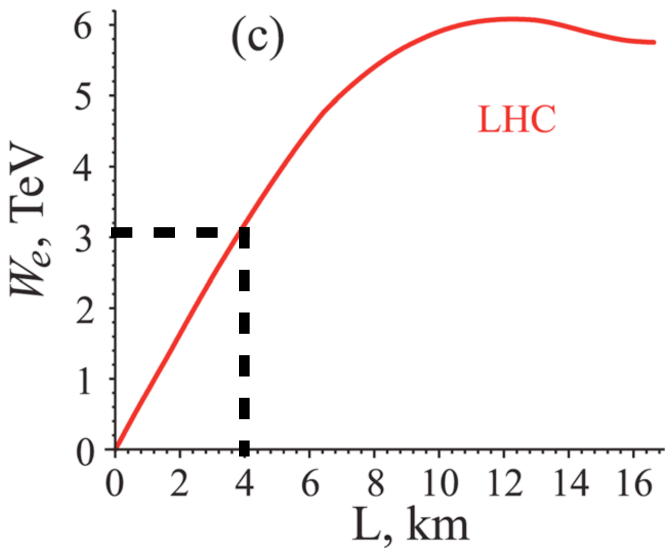
- Consider high energy *ep* collider with E_e up to $O(50\ GeV)$, colliding with LHC proton *TeV* bunch, e.g. $E_e = 10\ GeV$, $E_p = 7\ TeV$, $\sqrt{s} = 530\ GeV$.
- Create ~*50 GeV* beam within *50−100 m* of plasma driven by SPS protons and have an LHeC-type experiment.
- Clear difference is that 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.



- Opportunity for further studies to consider the design of a collider using this plasma wakefield acceleration scheme and leading to an experiment in a new kinematic regime.

*G. Xia et al., Nucl. Instrum. Meth. **A 740** (2014) 173.

Very high energy electron–proton collisions, VHEeP*

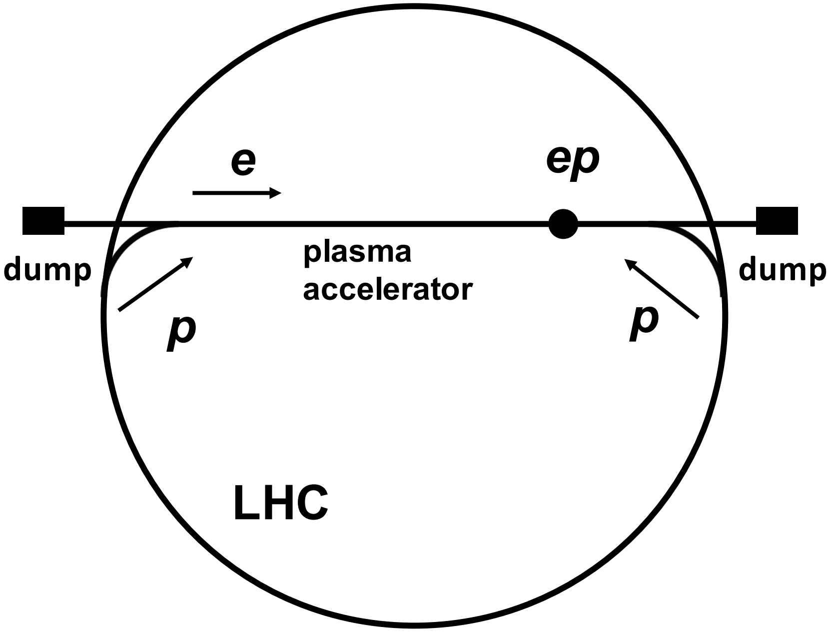


A. Caldwell & K. Lotov, Phys. Plasmas **18** (2011) 103101

- What about very high energies in a completely new kinematic regime ?
- Choose E_e = *3 TeV* as a baseline for a new collider with E_P = *7 TeV* ⇒ $\sqrt{s}$ ***= 9 TeV***. Can vary.
  - Centre-of-mass energy ×30 higher than HERA.
  - Reach in (high) Q^2 and (low) Bjorken x extended by ×1000 compared to HERA.

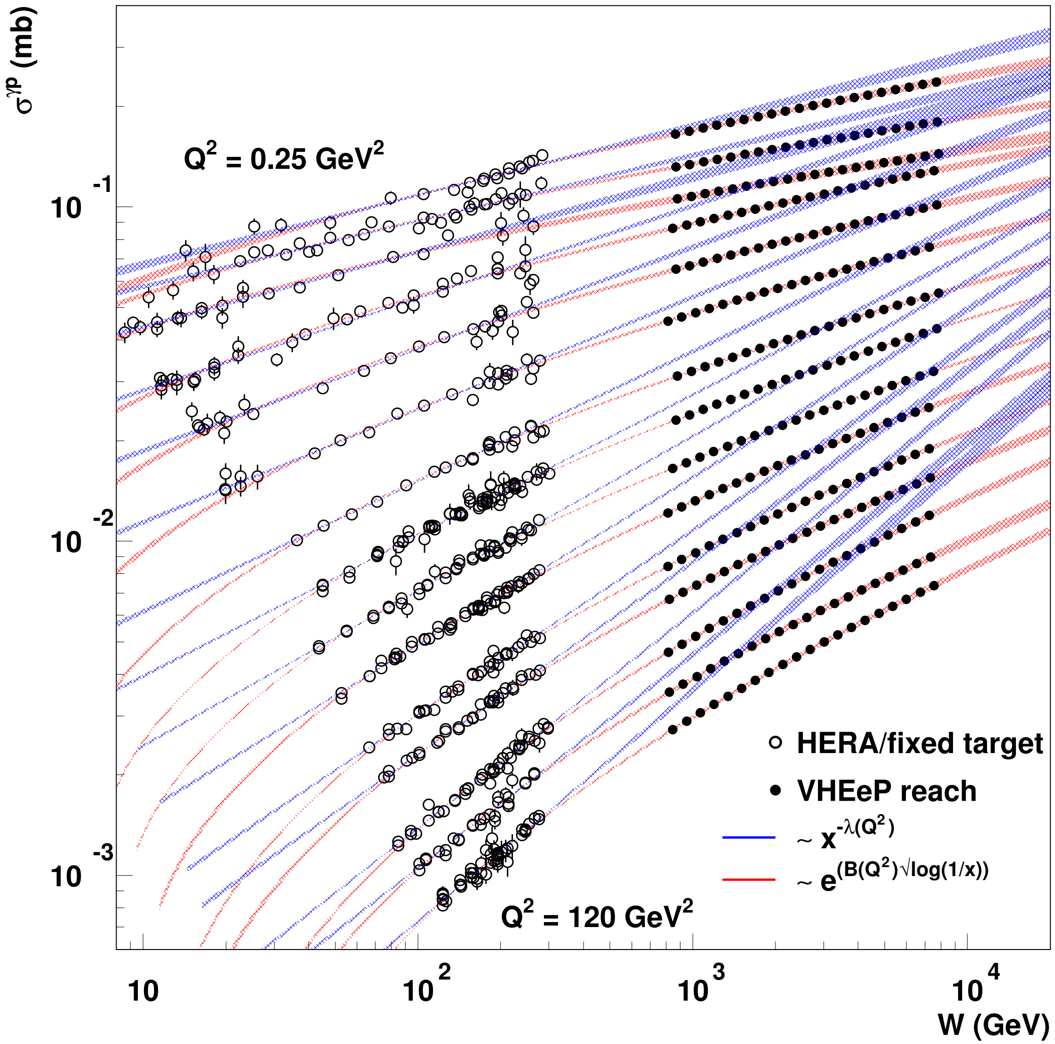
- Overall (simple) layout using current infrastructure.
- One proton beam used for electron acceleration to then collide with other proton beam
- Luminosity ~ $10^{28} - 10^{29}$ cm^{-2}s^{-1} gives ~ 1 pb^{-1} per year

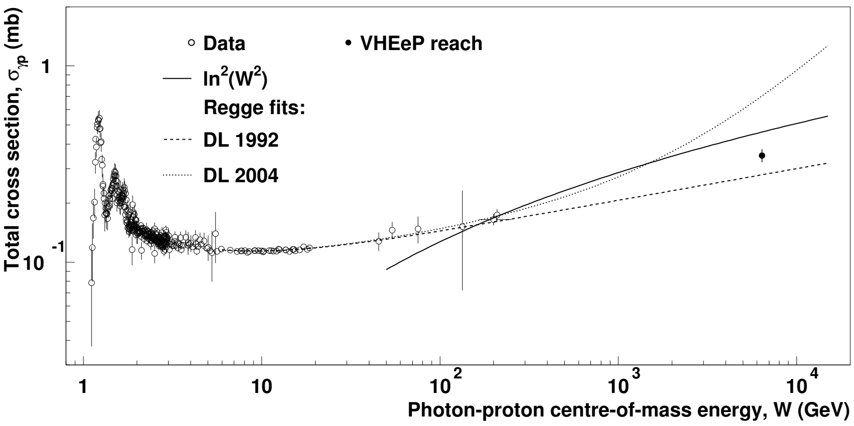
Physics case for very high energy, but moderate (*10–100 pb^{-1}*) luminosities.



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

Very high energy electron−proton collisions, VHEeP





- Energy dependence of hadronic cross sections poorly understood.
  - Large lever arm at VHEeP.
  - Relation to cosmic-ray physics.
  - Onset of saturation ?
- **Explore a region where QCD is not at all understood.**
- Also strongly sensitive to leptoquarks and much else.

To organise a workshop to better understand the physics case and feasibility.

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

Summary

- Plasma wakefield acceleration is a promising scheme for production of high energy electron beams.
- The AWAKE collaboration has an exciting programme of R&D aiming to make this a useable technology.
- Emphasis is on what can be done with a proton-driven scheme and using CERN infrastructure.
- Have started to consider applications to particle physics experiments:
  - Fixed-target/beam-dump experiments in particular those sensitive to dark photons.
  - Electron−proton collider up to very high energies.
  - Encourage other ideas for use of a high energy electron beam.

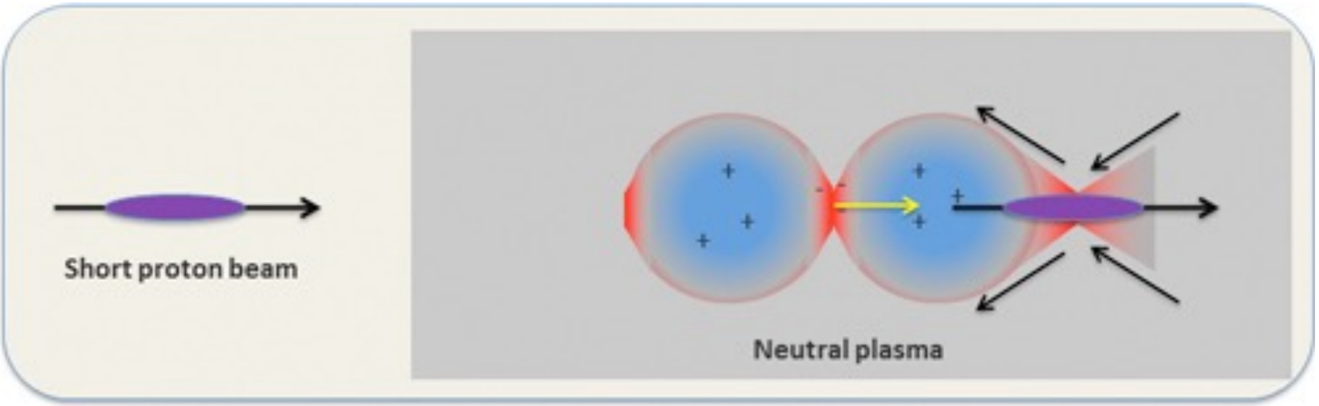
Back-up

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*



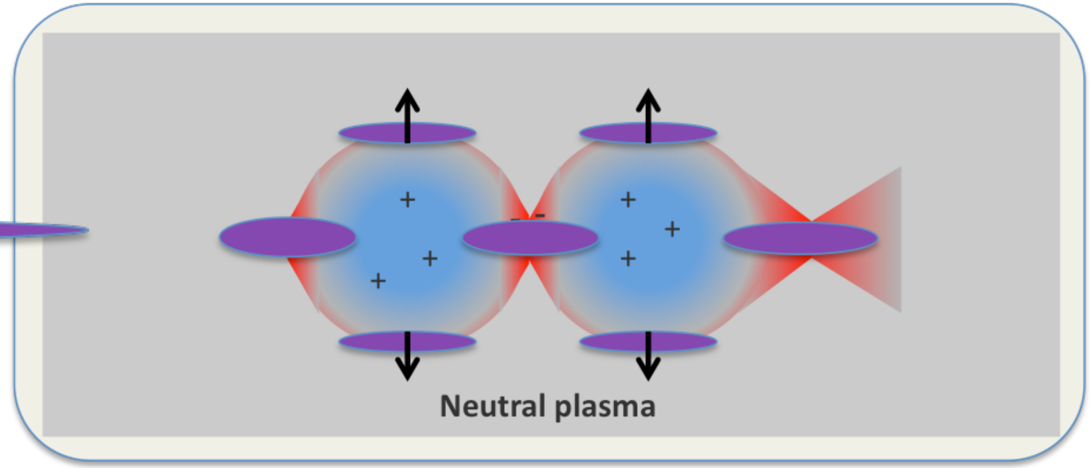
- Electrons ‘sucked in’ by proton bunch
- Continue across axis creating depletion region
- Transverse electric fields focus witness bunch

- 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.

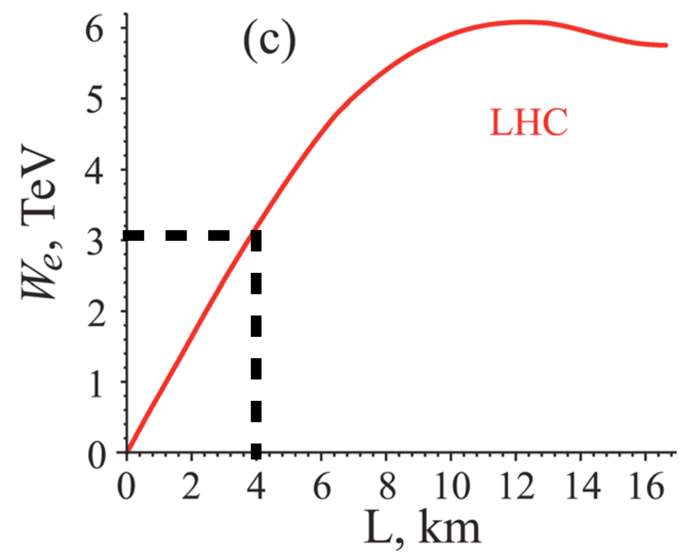
Plasma wakefield accelerator (AWAKE scheme)

Long proton beam



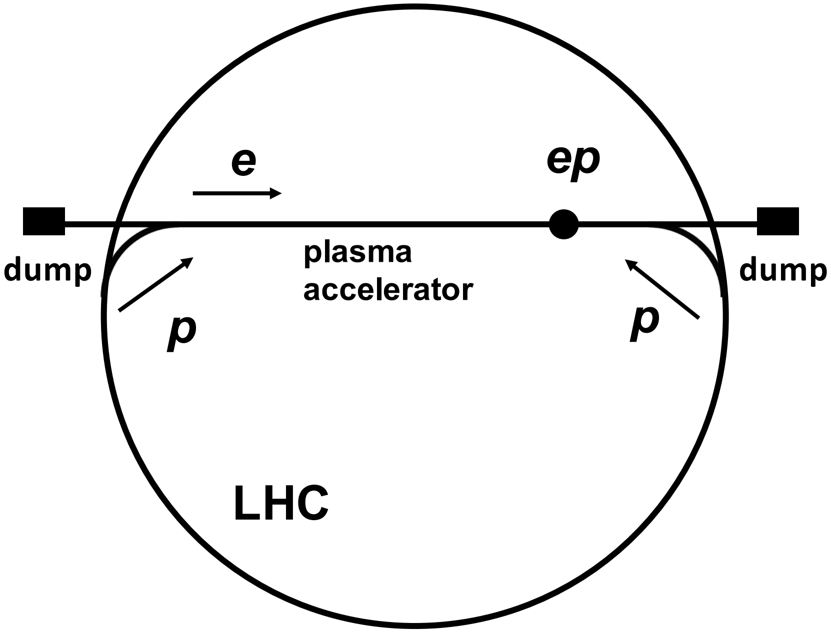
Self-modulated driver beam

- Long beam modulated into micro-bunches which constructively reinforce to give large wakefields.
- Self-modulation instability allows **current beams to be used**, 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**.
  - Centre of mass energy ×30 higher than HERA.



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

Plasma wakefield accelerator



- Emphasis on using current infrastructure, i.e. LHC beam with minimum modifications.
- Overall layout works in powerpoint.
- Need high gradient magnets to bend protons into the LHC ring.
- One proton beam used for electron acceleration to then collider with other proton beam.
- High energies achievable and can vary electron beam energy.
- What about luminosity ?

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

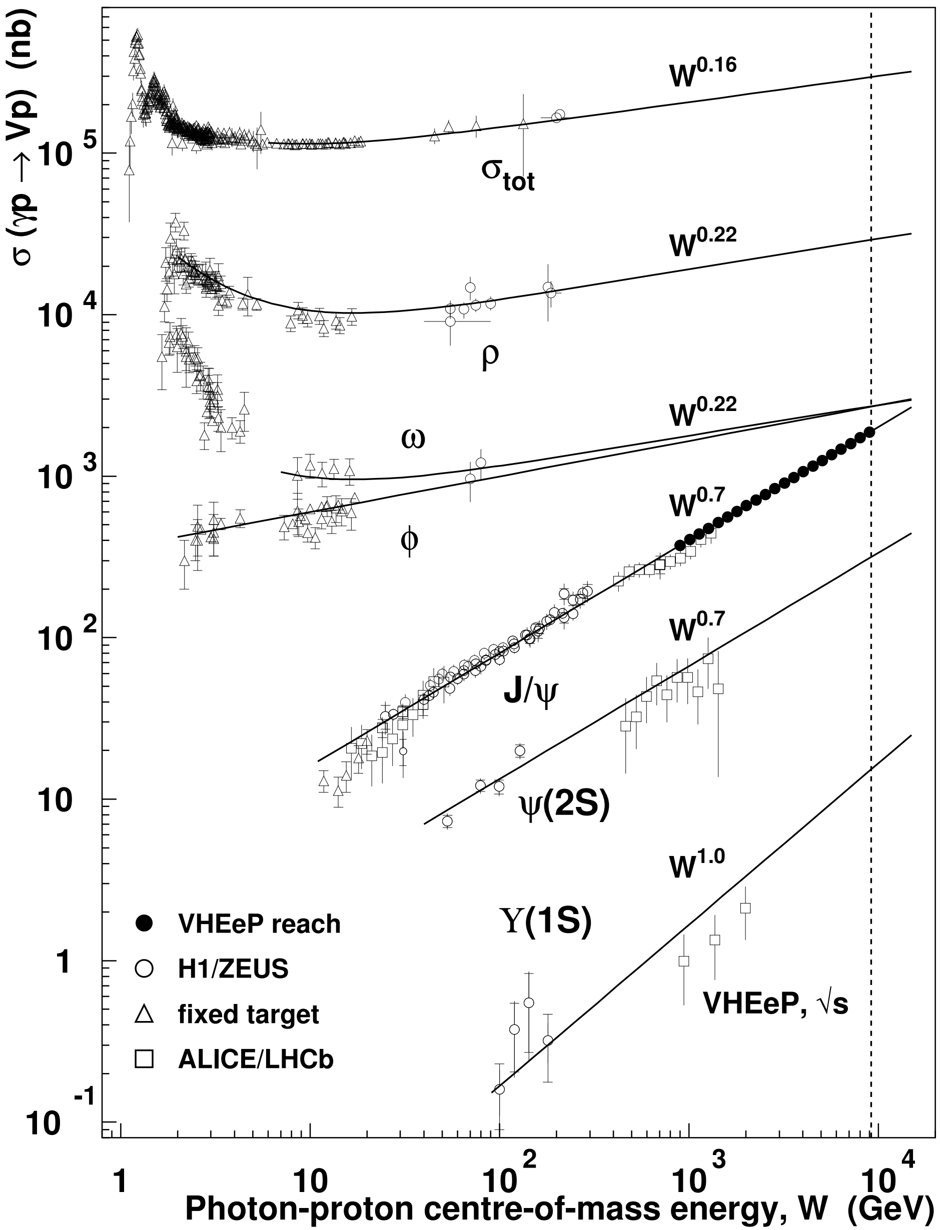
- Assume
  - *~3000* bunches every *30 mins*, gives *f ~ 2 Hz*.
  - $N_p \sim 4 \times 10^{11}$, $N_e \sim 1 \times 10^{11}$
  - $\sigma \sim 4\ \mu m$

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

Other schemes to increase this value ?

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

Vector meson cross sections



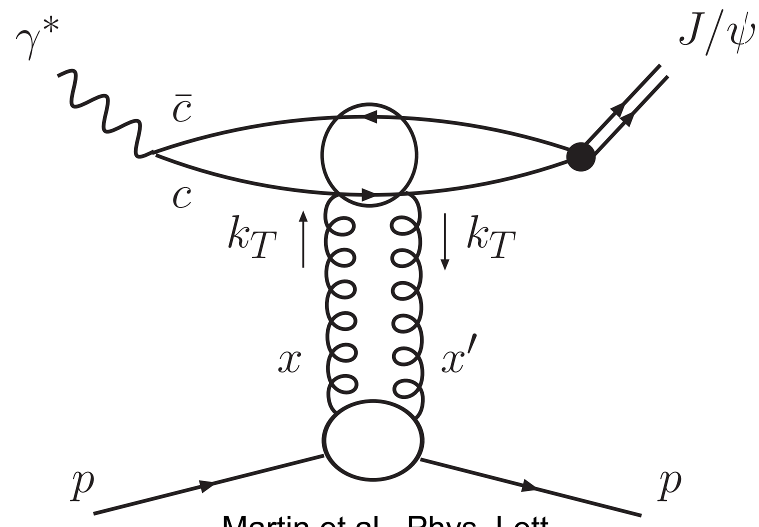
Strong rise with energy related to gluon density at low *x*.

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

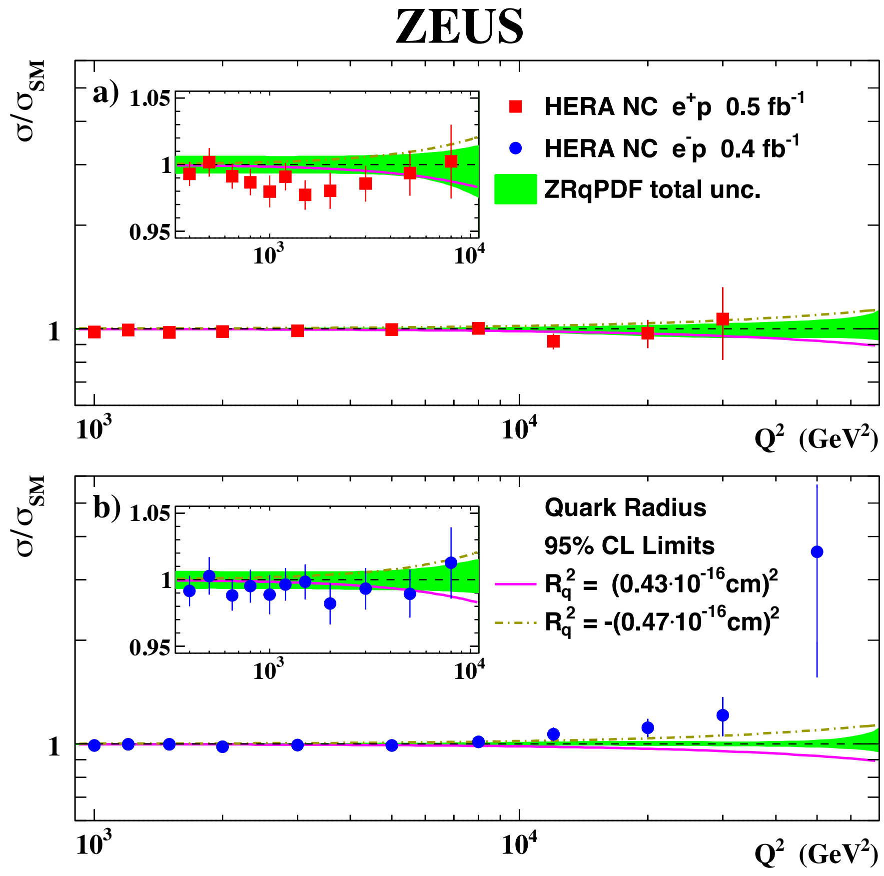
BSM: Quark substructure

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.

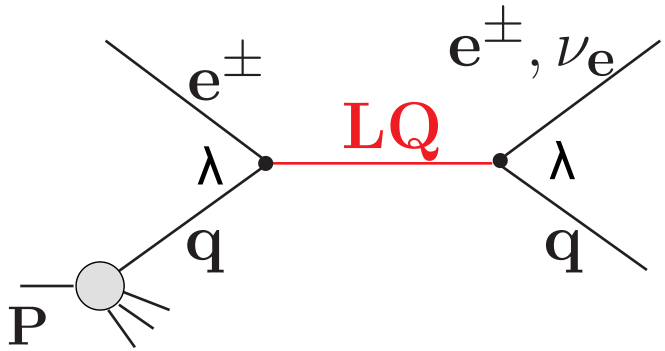


ZEUS Coll., DESY-16-035, accepted by Phys. Lett. B

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 $R_q \lesssim 10^{-20}\ m$

Leptoquark production

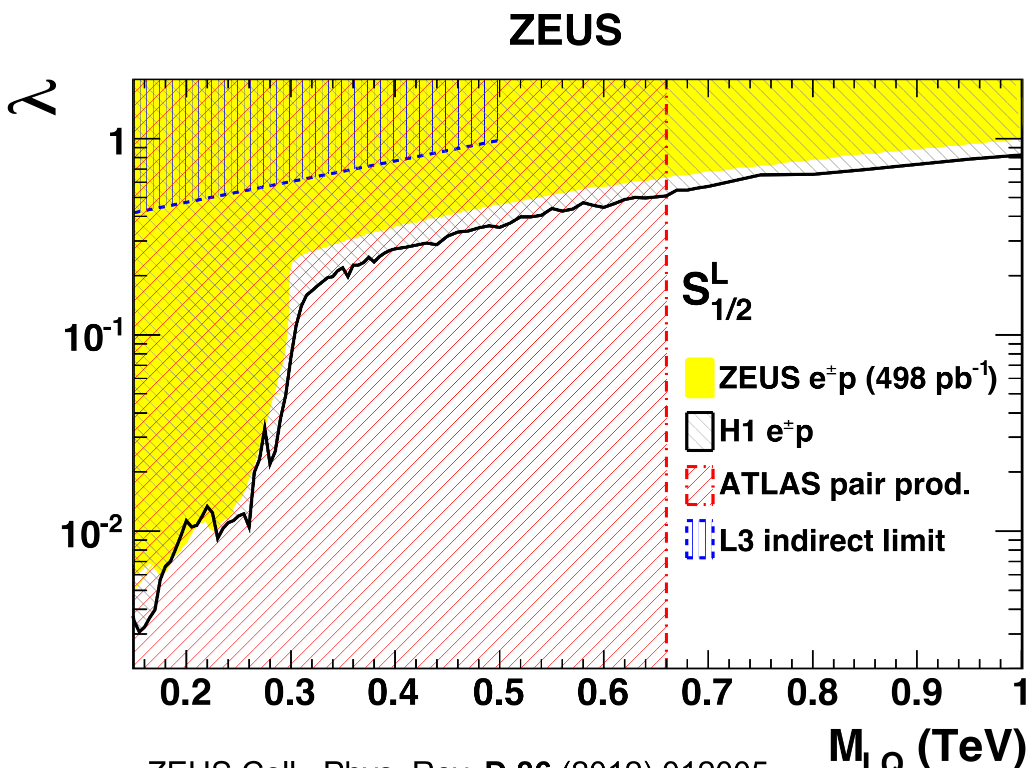


Electron−proton colliders are the ideal machine to look for leptoquarks.

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

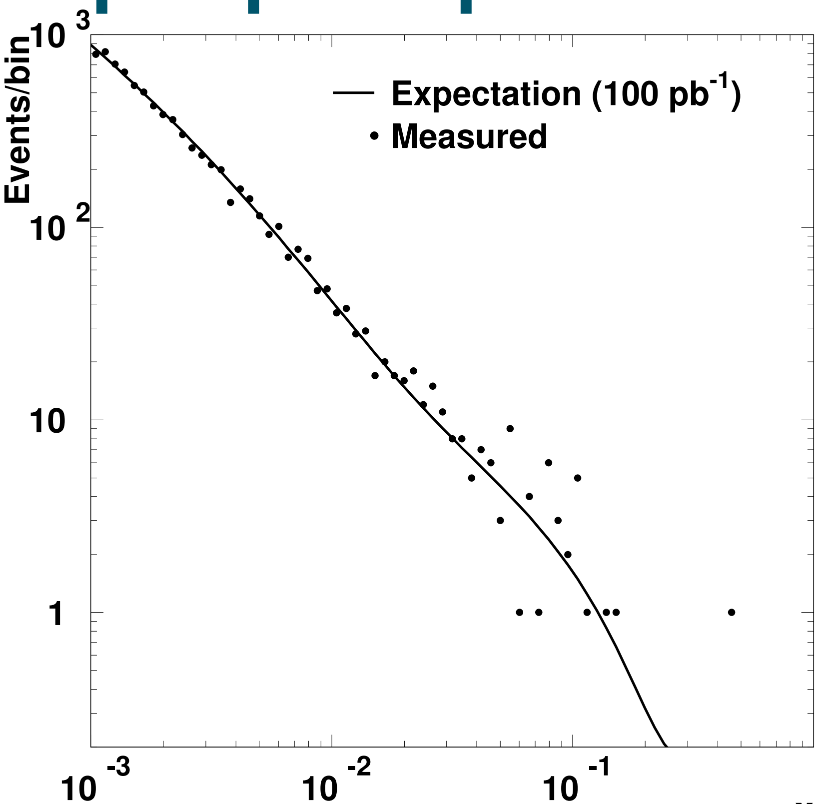
$$\sigma^{\mathrm{NWA}} = (J+1)\frac{\pi}{4s}\lambda^2\, q(x_0, M^2_{\mathrm{LQ}})$$

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



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

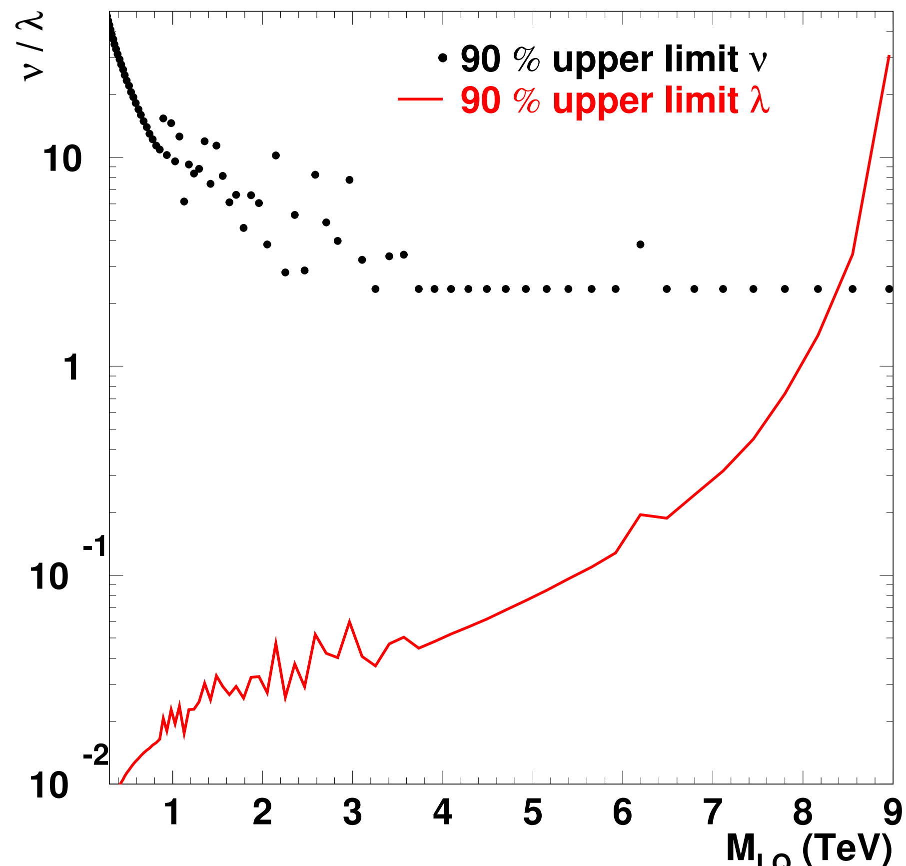
Leptoquark production at VHEeP



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

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

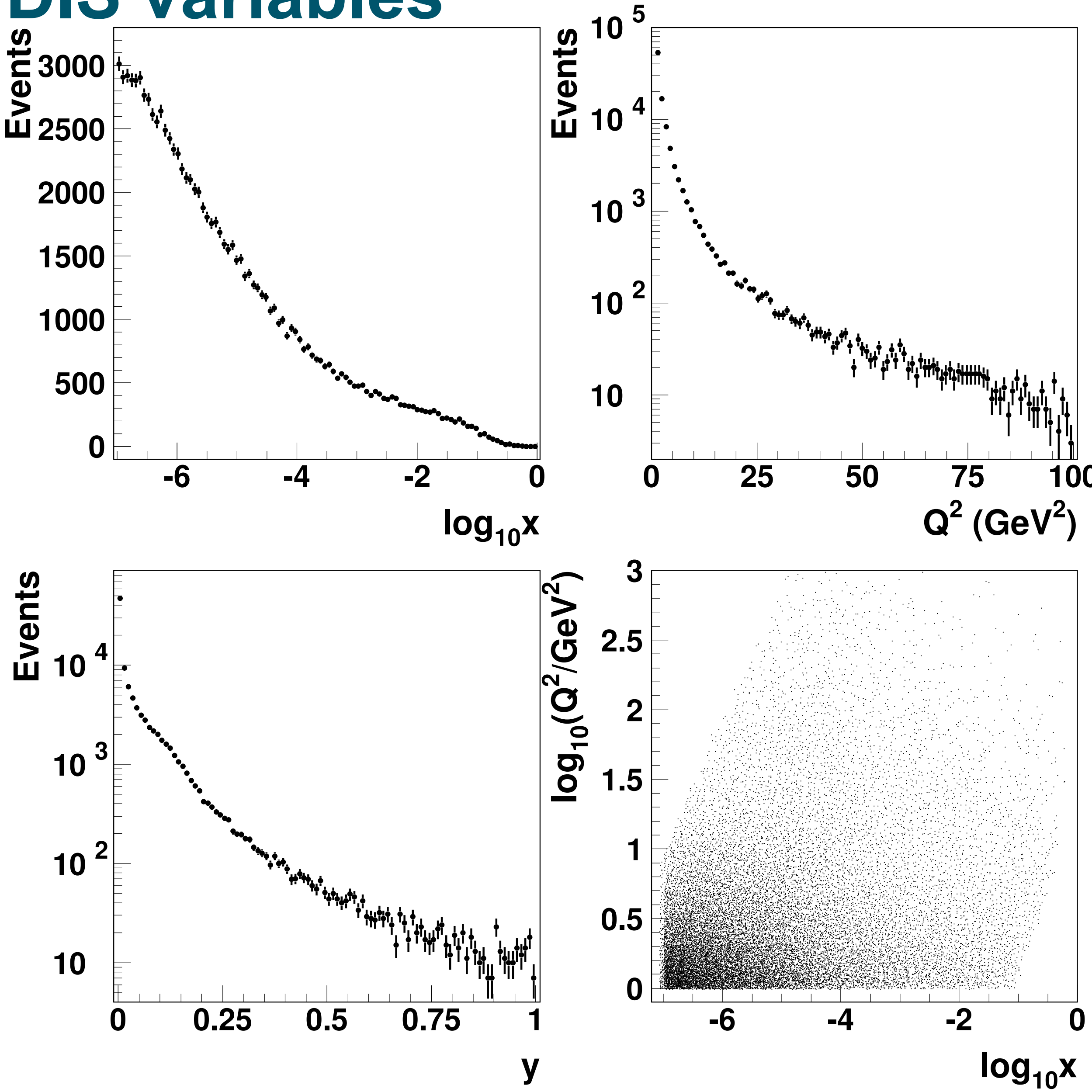
Generated "data" and Standard Model "prediction" using ARIADNE (no LQs).



Sensitivity up to kinematic limit, 9 TeV.

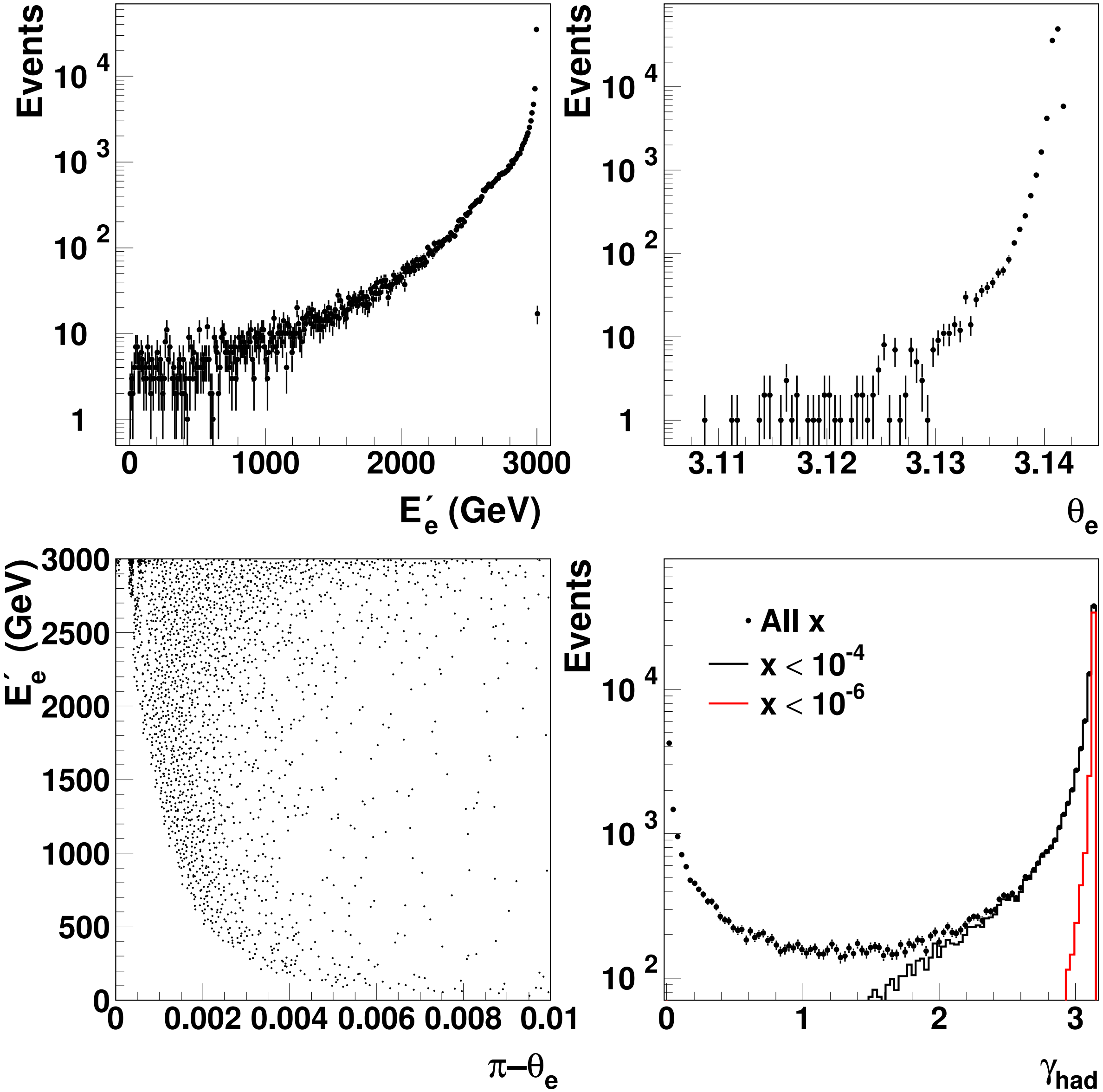
As expected, well beyond HERA limits and significantly beyond LHC limits and potential.

DIS variables



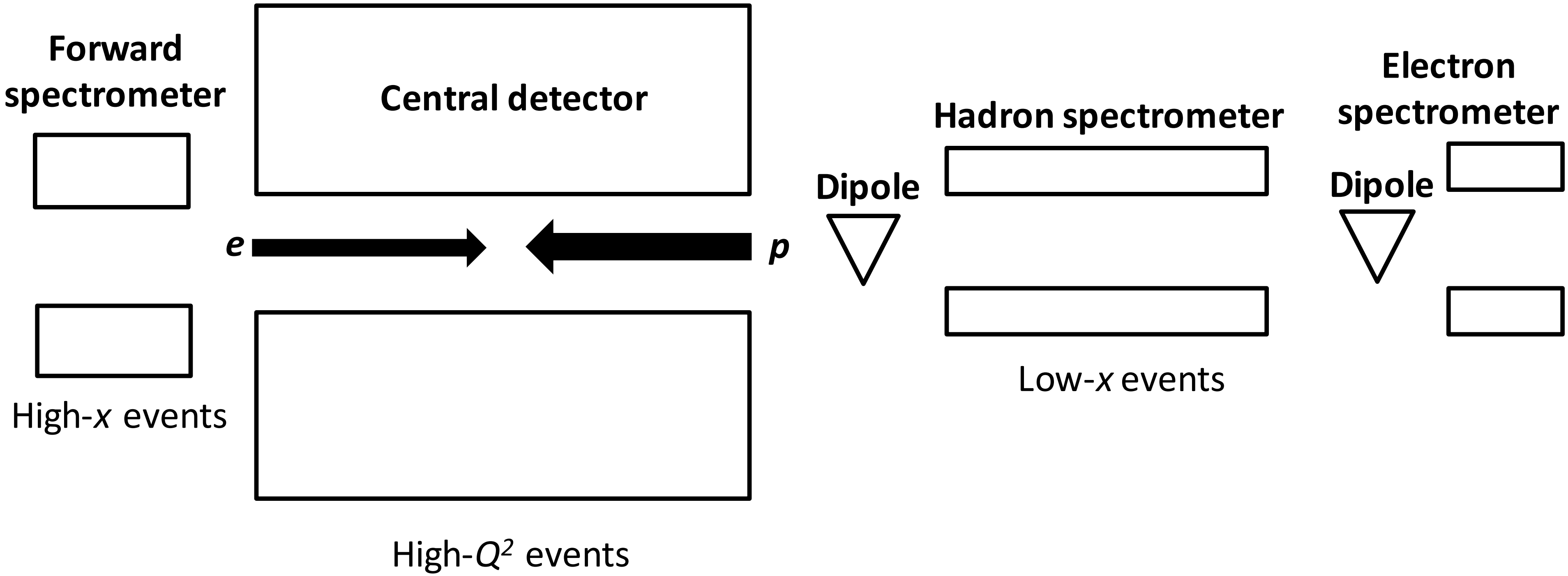
- Access down to $x \sim 10^{-8}$ for $Q^2 \sim 1\ GeV^2$.
- Even lower x for lower Q^2.
- Plenty of data at low x and low Q^2 ($L \sim 0.01\ pb^{-1}$).
- Can go to $Q^2 \sim 10^5\ GeV^2$ for $L \sim 1\ pb^{-1}$.
- Powerful experiment for low-x physics where luminosity less crucial.

Kinematics of the final state



- Generated ARIADNE events with Q^2 > *1 GeV²* and *x* > 10^{-7}
- Test sample of $L \sim 0.01\ pb^{-1}$
- Nice kinematic peak at *3 TeV*, with electrons scattered at low angles.
- Hadronic activity in central region as well as forward and backward.
- Hadronic activity at low backward angles for low x.
- Clear implications for the kind of detector needed.

Sketch of detector



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

Proton beam cycle

- Basic period is 1.2 sec → any cycle length is proportional to BP
- 400 GeV/c proton beam in SPS:
  - 1sec for PS for 26 GeV/c proton injection
  - 3 sec ramp to 400 GeV/c
  - Several 100ms flat top
  - 1.5 sec down-ramp to 26 GeV/c

  → **total minimum cycle length: 6 sec cycle**

  Note:

  Today ramp up to 400 GeV/c is ~3.6 sec, so AWAKE cycle length is 7.2sec

  RF power will be increased in LS2, then it's possible to ramp in 3sec
- 300 GeV/c proton beam in SPS:
  - 1 sec for PS for 26 GeV/c proton injection
  - 2.1 sec ramp up
  - ~some 100ms flat top
  - 1s ramp down
  - → **total minimum cycle length: 4.8 sec**
- Number of protons and bunches per cycle:
  - 1 bunch with 3.5 E11 protons
- **Electrons** from Proton Driven PWA:
  - 1E9 electrons per cycle
  - → with 6sec cycle we get **>1E8 electrons/sec.**
- **Possible improvements:**
  - Have several bunches per cycle and have extractions for each bunch → issues: need certain time for plasma diffusion, depending on laser frequency needed for seeding (today that's 10Hz), need to have very fast kickers for several extractions, etc…