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Future accelerators and high energy physics experiments

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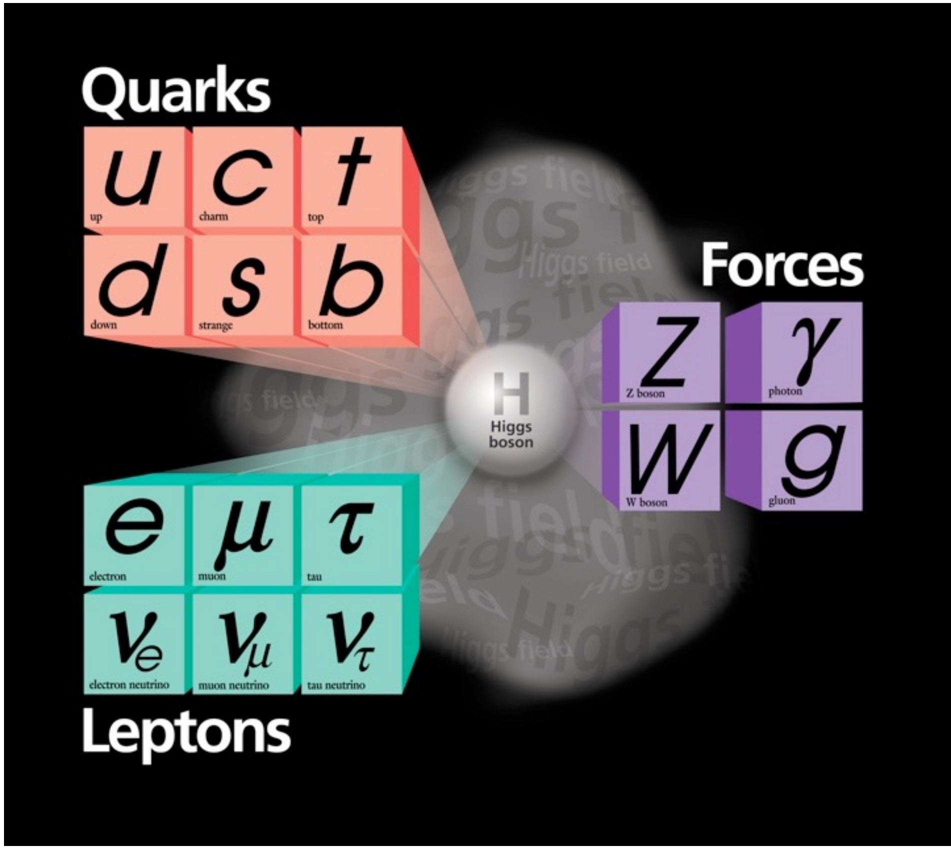
- Introduction: motivation, considerations, challenges, issues
- What (not) considering
- Proton-driven plasma wakefield acceleration as a solution
- Possible near- and medium-term experiments
- Discussion and summary

Future Frontiers in Accelerators Workshop — 6 December 2016, Scharbeutz, Schleswig-Holstein

Motivation: big questions in particle physics

The Standard Model is amazingly successful, but some things remain unexplained :

- a detailed understanding of the Higgs Boson/mechanism
- neutrinos and their masses
- why is there so much matter (vs anti-matter) ?
- why is there so little matter (*5%* of Universe) ?
- what is dark matter and dark energy ? E.g. supersymmetry or the hidden sector.
- why are there three families ?
- hierarchy problem; can we unify the forces ?
- what is the fundamental structure of matter ?
- …



Need to keep these questions in mind when considering new particle physics projects.

Colliders and use of high energy particle beams will be key to solving some of these questions

The challenge

Energy frontier machines are routes to new and exciting physics but are becoming very big and harder to justify:

- Having complementary colliders, e.g. HERA/LEP/Tevatron or LHC/ILC, is a big plus.
- No doubt that you will be probing new particle physics as it is a new kinematic range.
- However it is not now obvious that a new particle is just around the corner as for *W/Z*, Higgs, top.
- Smaller projects investigating dedicated physics have complemented the energy frontier well.

There is not really a compelling energy scale to probe:

- Need to have colliders which are more compact; need to develop technology.
  - E.g. plasma wakefield acceleration, dielectrics, etc..
- The intensity and precision frontier can continue to be probed.
- Dedicated, small-scale experiments are needed more than ever:
  - E.g. Belle2, $g-2$, cLFV searches, EDMs, etc..

What (not) considering

The following are not considered:

- Currently running colliders / projects, i.e. LHC and smaller machines.
- Proposed future energy frontier projects with developed concepts (at different levels), i.e. HL-LHC, HE-LHC, ILC, CLIC, FCC, CEPC, LHeC
- Future long baseline neutrino programme
- Other proposed future ideas, i.e. muon collider, neutrino factory.
- Anything very big, based on "conventional" acceleration techniques.

What I will look at:

- Small, dedicated experiments based on new accelerator technology.
- (Simplest) energy frontier machines based on new accelerator technology.
- Possibilities in the next 30 years with the implication that if this is successful, we will be able to build more powerful and high-performance machines in the future.

Using a new technology

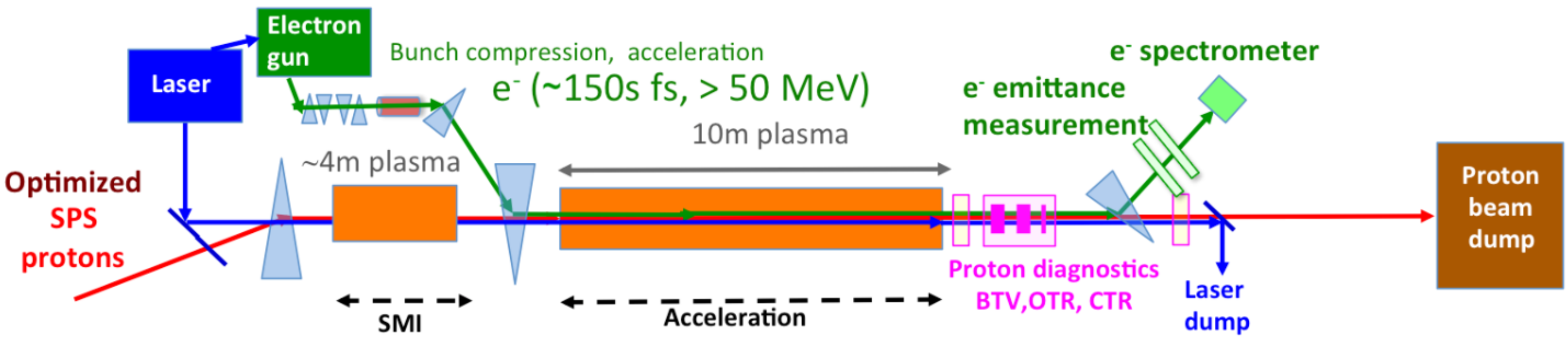
Fixed-target → High E ep collider → High E, high lumi e^+e^- collider

Proton-driven plasma wakefield acceleration as a technological solution

- Plasma wakefield acceleration can sustain very high gradients and is a promising technology for future particle colliders.
- Proton-driven plasma wakefield acceleration is well-suited to high energy physics applications.
- AWAKE will demonstrate the phenomena for the first time.
- We need to turn this promising scheme into a realisable technology.
- Ultimate goal is to be able to e.g. produce high-precision TeV beams, but this should not be the first application.
- There are lots of challenges for plasma wakefield acceleration:
  - Luminosity, i.e. high repetition rate and high number of particles per bunch.
  - Efficient and highly reproducible beam production.
  - Small beam sizes (down to *nm* scale).
- Here consider realistic applications, i.e particle physics experiments:
  - Based on AWAKE scheme of proton-driven plasma wakefield acceleration.
  - Strong use of CERN infrastructure.
  - Need to have novel and exciting physics programme.

AWAKE Run II

- Preparing AWAKE Run II, 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* × *10¹¹ 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 I

- Use of electron beam for test-beam campaigns.
  - Test-beam infrastructure for detector characterisation often over-subscribed.
  - Accelerator test facility. Also not many world-wide.
  - Characteristics:
    - Variation of energy.
    - Provide pure electron beam.
    - Short bunches.
- Fixed-target experiments using electron beams, e.g. deep inelastic electron−proton/*A* scattering.
  - Measurements at high *x*, momentum fraction of struck parton in the proton, with higher statistics than previous experiments. Valuable for LHC physics.
  - Polarised beams and spin structure of the nucleon. The "proton spin crisis/puzzle" is still a big unresolved issue.
  - Use of different targets and understanding the physics of that (Stodolsky).

Possible physics experiments II

- **Search for dark photons à la NA64**
  - Consider beam-dump and counting experiments.
- **High energy electron−proton collider**
  - A low-luminosity LHeC-type experiment: *~50 GeV* beam within *50−100 m* of plasma driven by SPS protons; low luminosity, but much more compact.
  - A very high energy electron−proton (VHEeP) collider with $\sqrt{s}$ **= 9 TeV,** *×30* higher than HERA. Developing physics programme.

This is not a definitive list, but a quick brainstorm.

These experiments probe exciting areas of physics and will really profit from an AWAKE-like electron beam.

- **Demonstrate an accelerator technology whilst doing interesting physics.**

Search for dark photons using an AWAKE-like beam

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

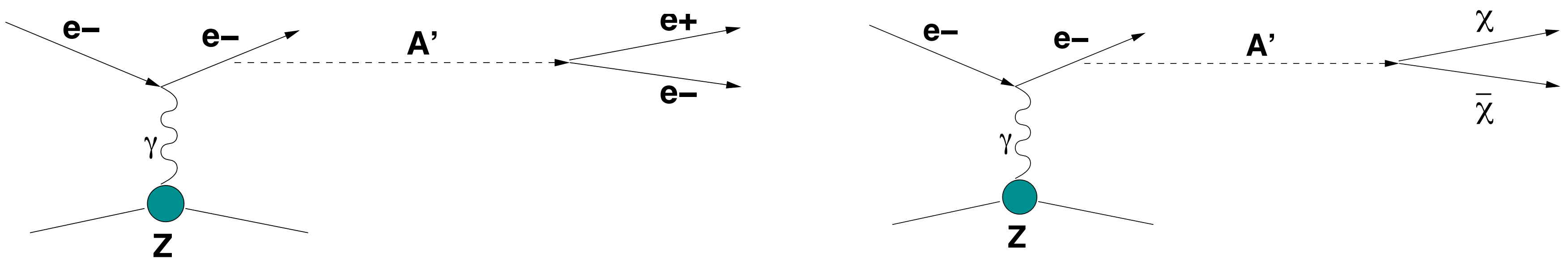
See talks/papers/proposals from NA64.

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

Provide upgrade/extension to NA64 programme.

Physics motivation

- 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*.

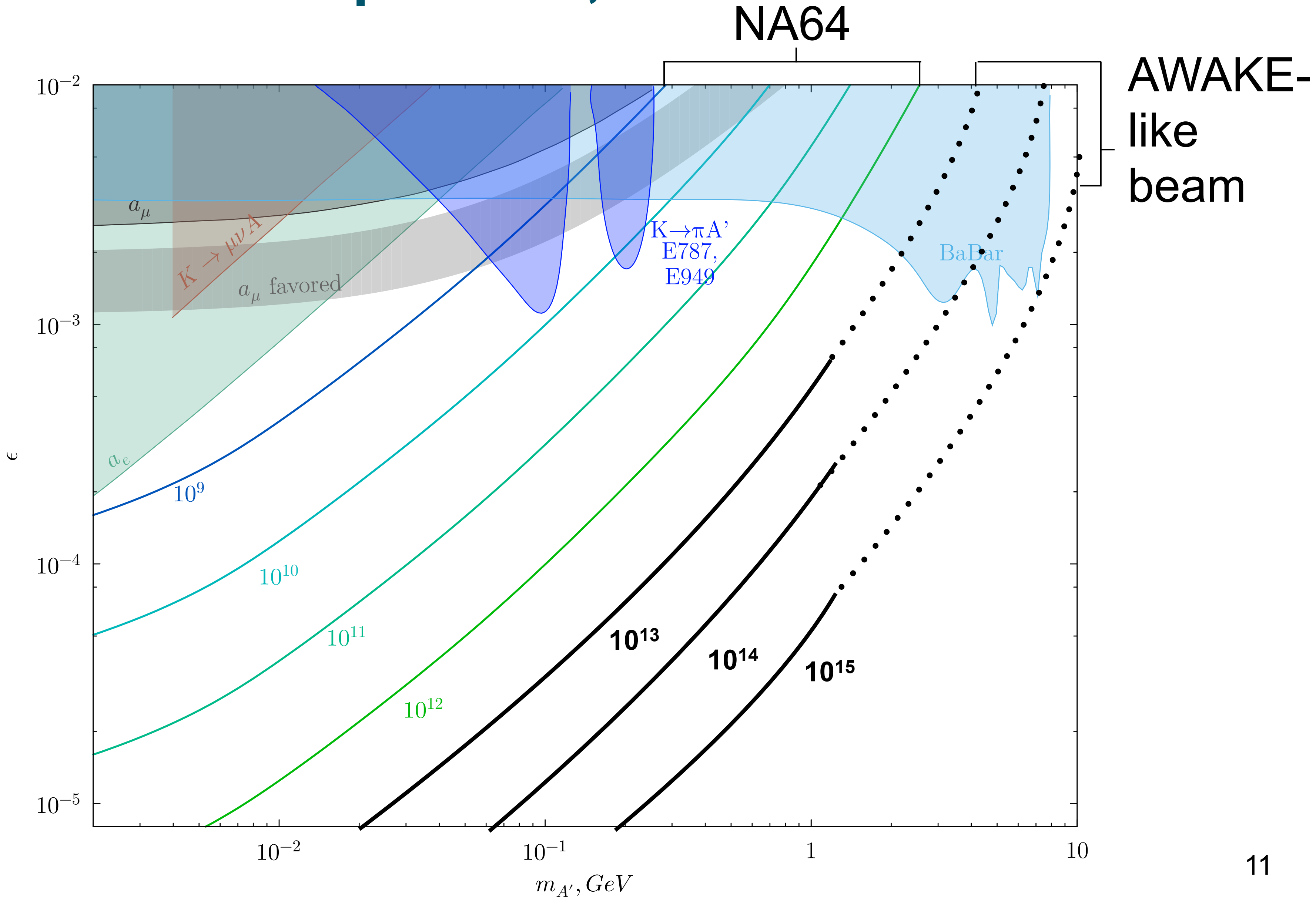
Different beam energies or higher intensities (bunch charge, SPS cycle time) possible.

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

- More careful study of optimal beam energy 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.

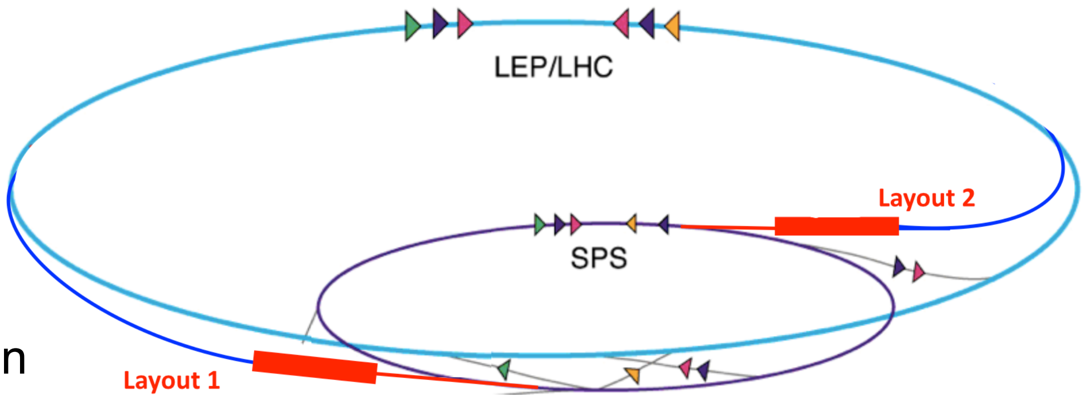
Results shown here should be considered as indicative.

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



High energy electron−proton collisions

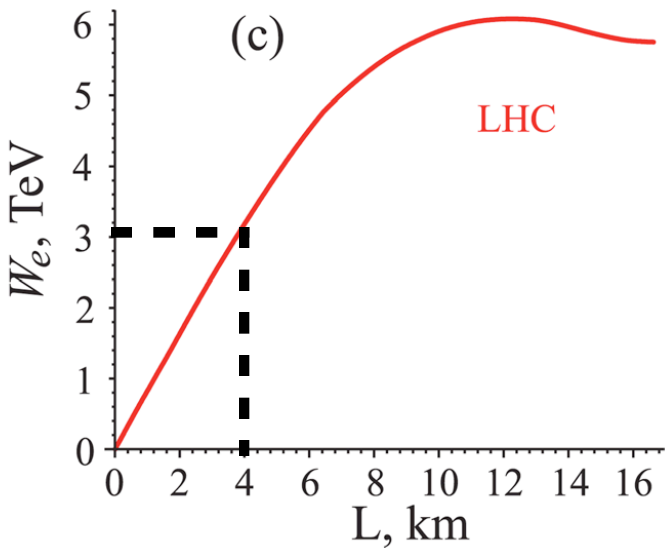
- Consider high energy *ep* collider with E_e up to *O(50 GeV)*, colliding with LHC proton *TeV* bunch, e.g. $E_e = 10$ *GeV*, $E_p = 7$ *TeV*, $\sqrt{s} = 530$ *GeV*.
- Create ~*50 GeV* beam within *50−100 m* of plasma driven by SPS protons and have an LHeC-type experiment.
- Clear difference is that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

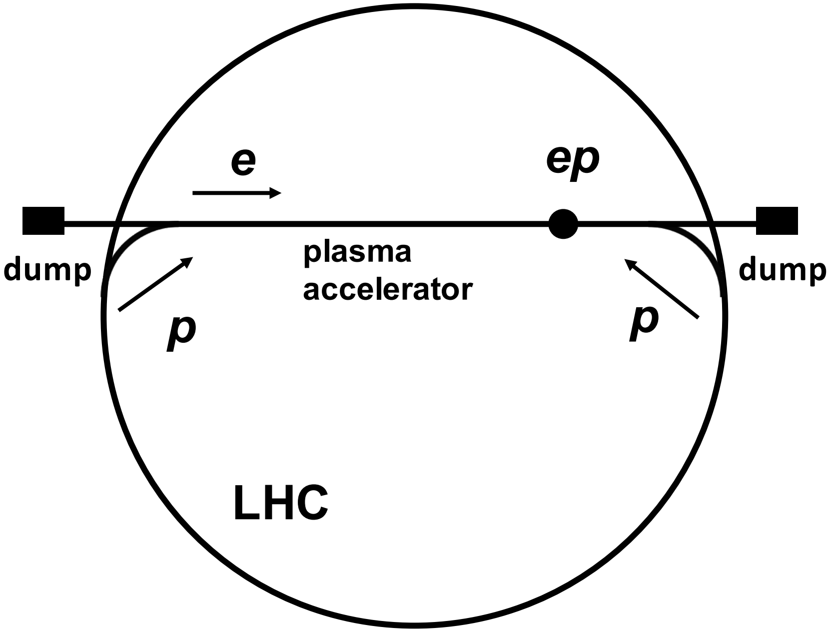


A. Caldwell & K. Lotov, Phys. Plasmas **18** (2011) 103101

- 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.

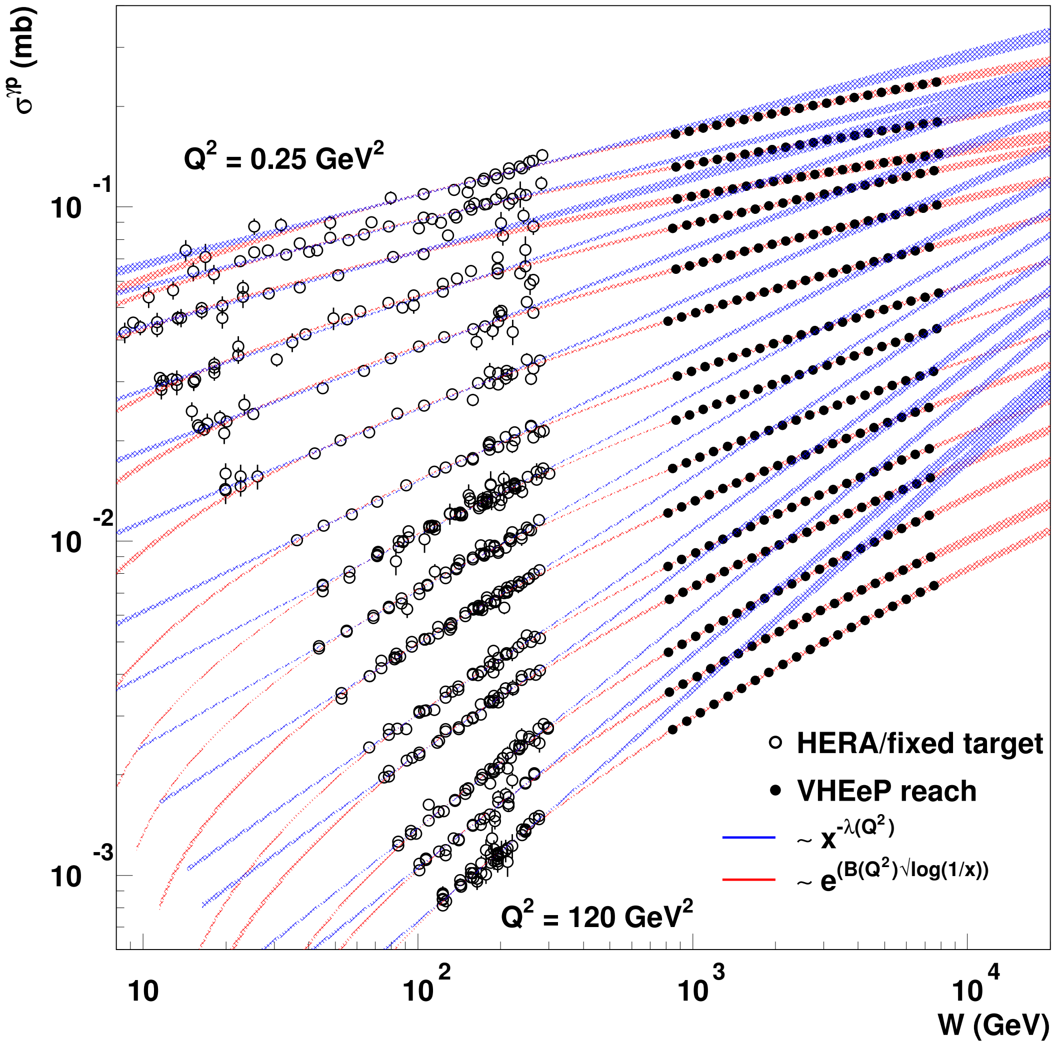
- Overall (simple) layout using current infrastructure.
- One proton beam used for electron acceleration to then collide with other proton beam
- Luminosity ~ $10^{28} - 10^{29}$ cm^{-2}s^{-1} gives ~ 1 pb^{-1} per year

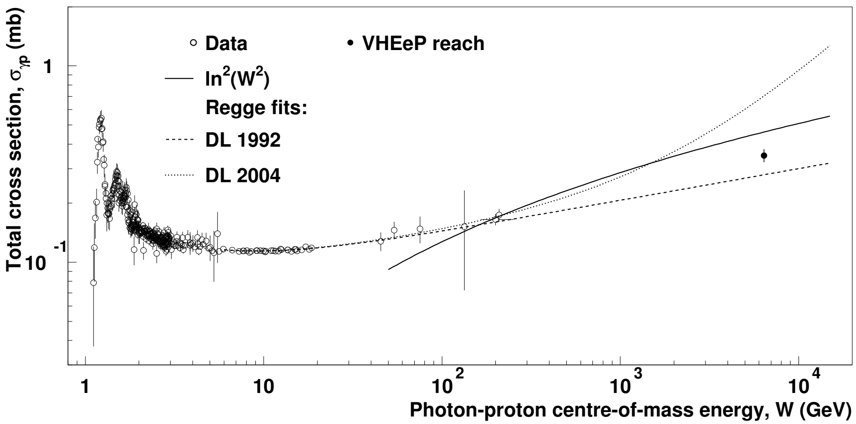
There is a physics case for very high energy, but moderate (*10−100 pb^{-1}*) luminosities.



*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

Discussion and summary I

- *What will be the likely needs and applications for future accelerators in the second half of the 21st century ?*
  - I am sure there will be high energy physics questions to answer, but I don't know what right now.
  - Machines at the energy and intensity frontiers will always be needed.
- *How would these accelerators likely look like and how would we construct them ?*
  - I think they can not be behemoths and we must develop novel, compact acceleration schemes also (in particular) for the energy frontier.
- *Can we see any "neglected" solutions that can help us solving future accelerator challenges?*
  - We need more concerted investment and effort in novel techniques. This has to have higher priority.

Discussion and summary II

- *Are there any methods and concepts that are becoming possible with latest technology?*
  - I can see a path for applications to real and interesting particle physics experiments based on proton-driven plasma wakefield acceleration.
- *What are the grand challenges for accelerators and what do we need to solve them ?*
  - In particular the energy frontier needs to be more affordable, i.e. more compact, whilst maintaining all other high-performance properties.
  - Novel acceleration techniques need to do a lot of catching up. Needs more investment.
- *Can we identify trends or directions for new technologies and concepts ?*
  - I have presented some ideas and a general direction.

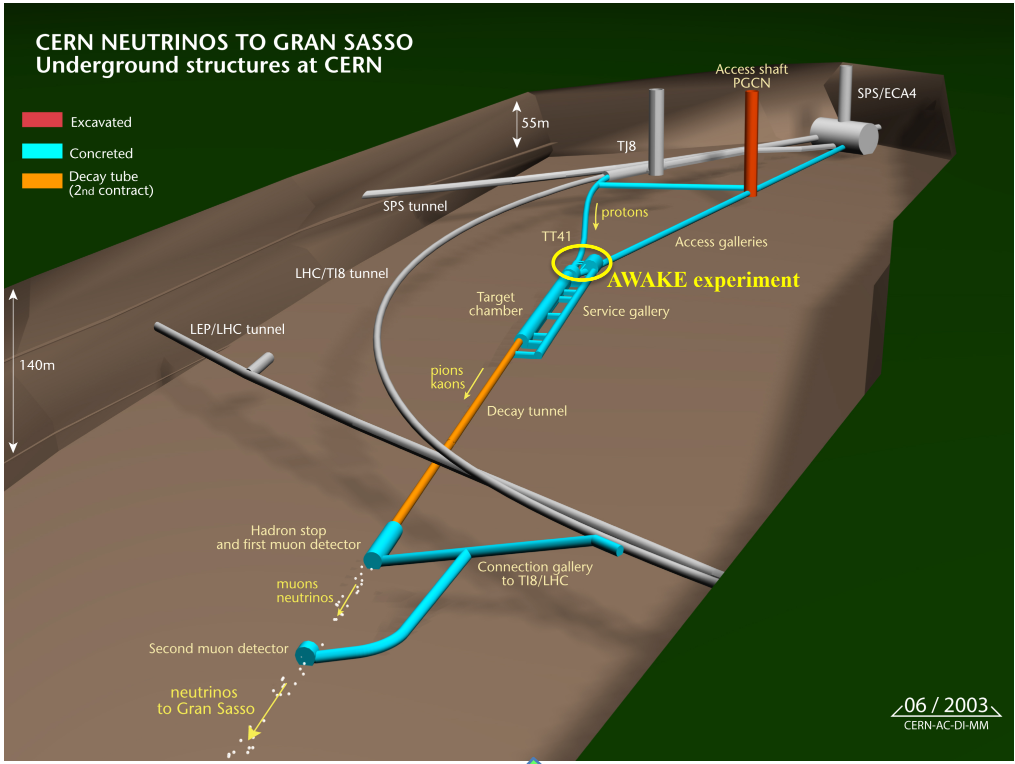
Discussion and summary final

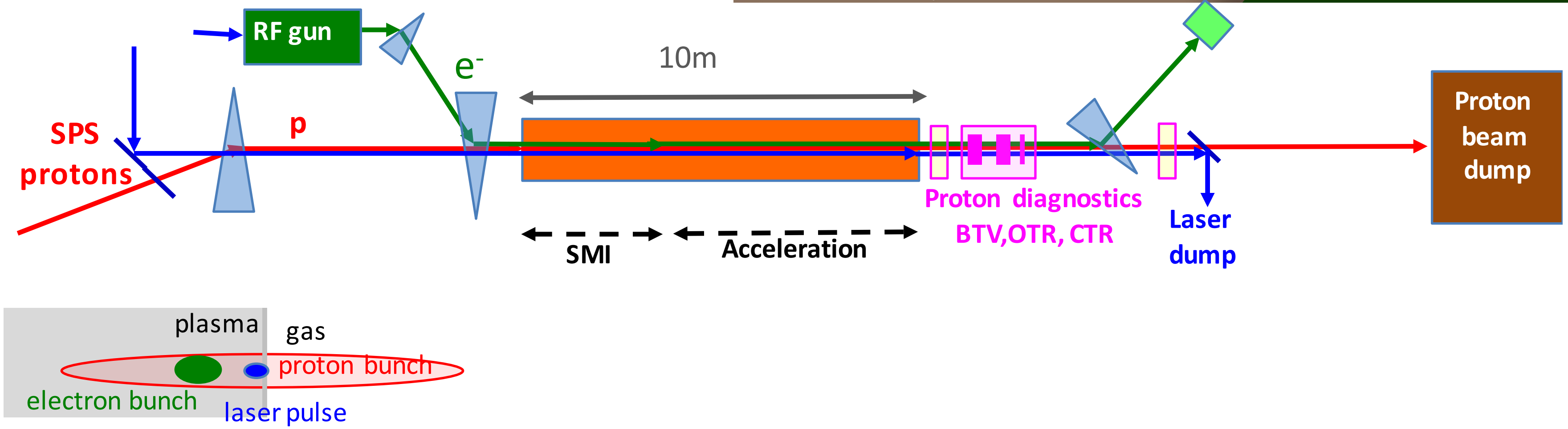
- Plasma wakefield acceleration is a **promising scheme** for production of high energy electron beams.
- Have started to consider **realistic** applications to novel and interesting particle physics experiments.
- If we want to have cutting-edge accelerators based on new technology for high energy physics at the energy and intensity frontier, **we will not get there in one go and this talk presents a path** to try and do it for proton-driven plasma wakefield acceleration.
- We have to do **more to develop** novel acceleration techniques.
- Particle physics needs to consider (more) **smaller dedicated experiments** using both conventional and novel acceleration schemes.
- Consider **combination** of conventional and novel schemes in designs such as upgrade of conventional e^+e^- accelerator with plasma wakefield acceleration.

Back-up

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.



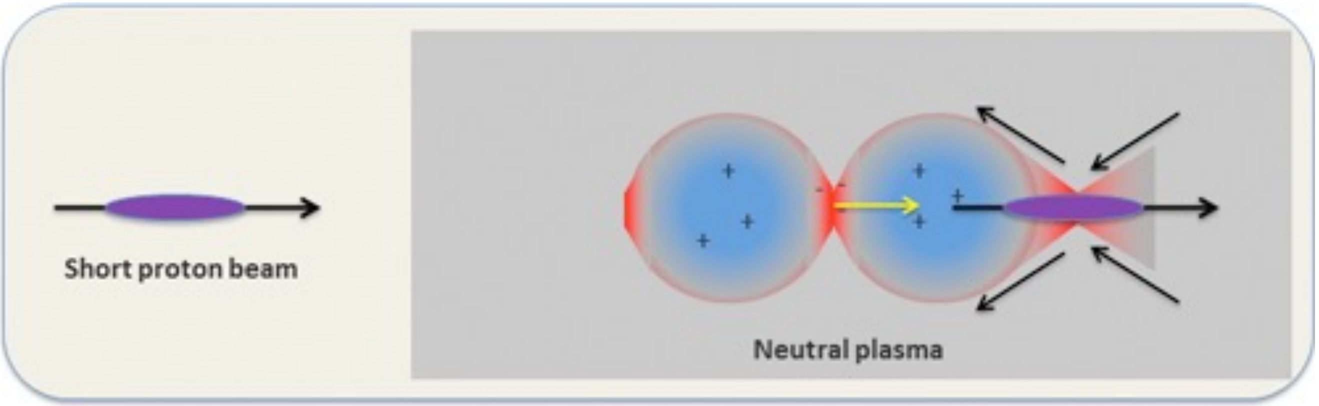


Plasma wakefield acceleration

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*

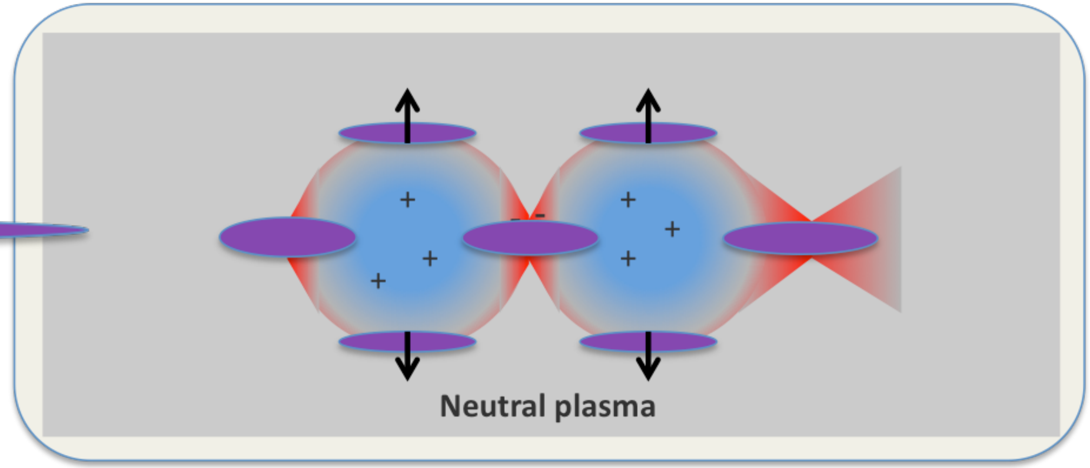


- Electrons 'sucked in' by proton bunch
- Continue across axis creating depletion region
- Transverse electric fields focus witness bunch

- 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.

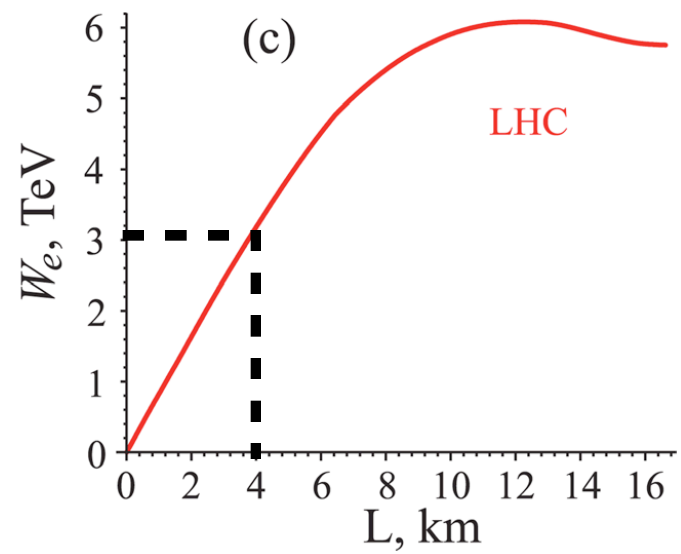
* A. Caldwell *et al*., Nature Physics **5** (2009) 363.

Plasma wakefield accelerator (AWAKE scheme)



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

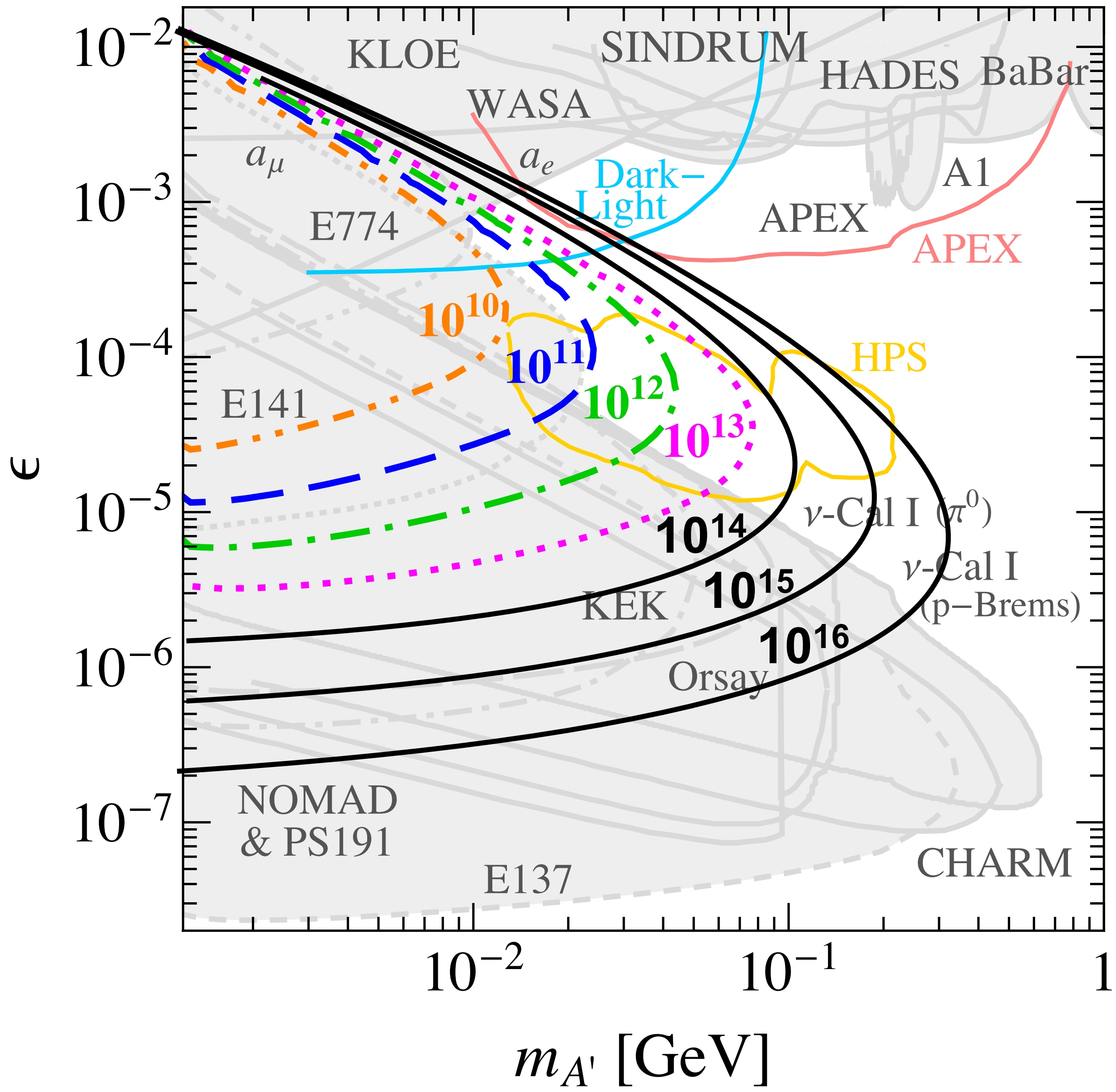
Sensitivity with increased electrons on target

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, $A' \rightarrow e^+ e^-$



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

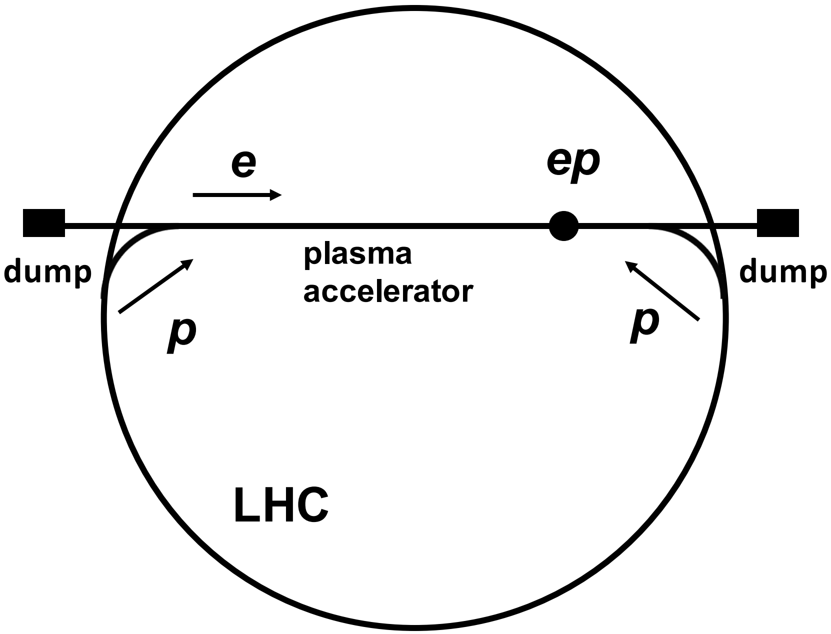
For $10^{14} - 10^{16}$ electrons on target with AWAKE-like beam.

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.

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 ?

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

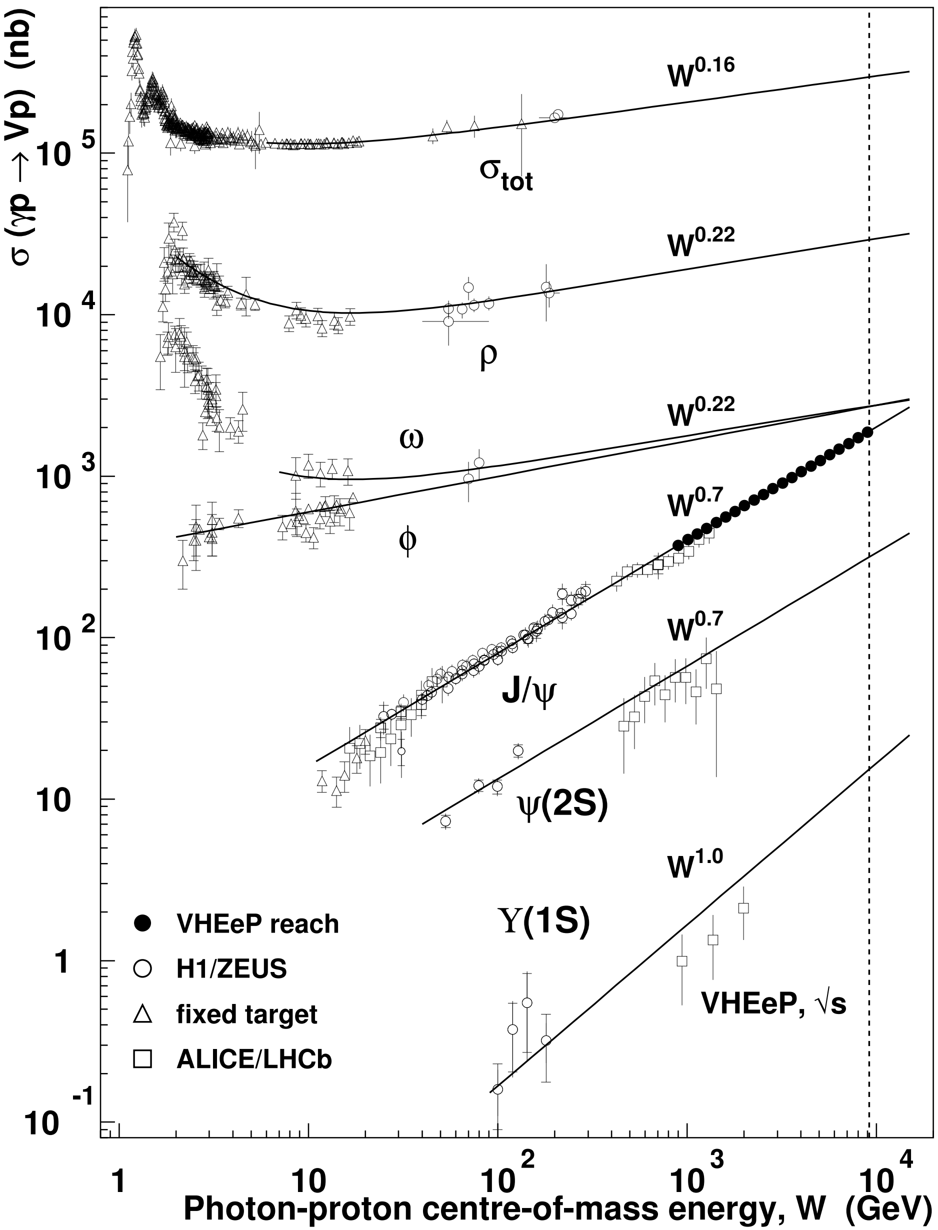
- Assume
  - *~3000* bunches every *30 mins*, gives *f ~ 2 Hz*.
  - $N_p \sim 4 \times 10^{11}$, $N_e \sim 1 \times 10^{11}$
  - $\sigma \sim 4\ \mu m$

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



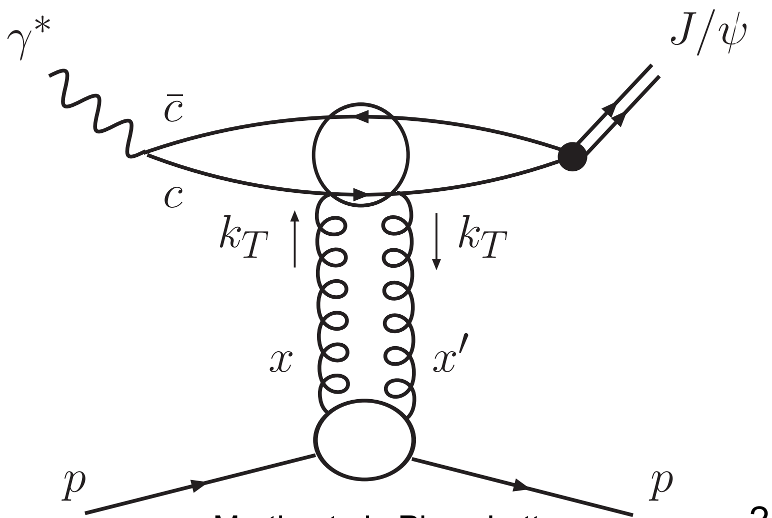
Strong rise with energy related to gluon density at low *x*.

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

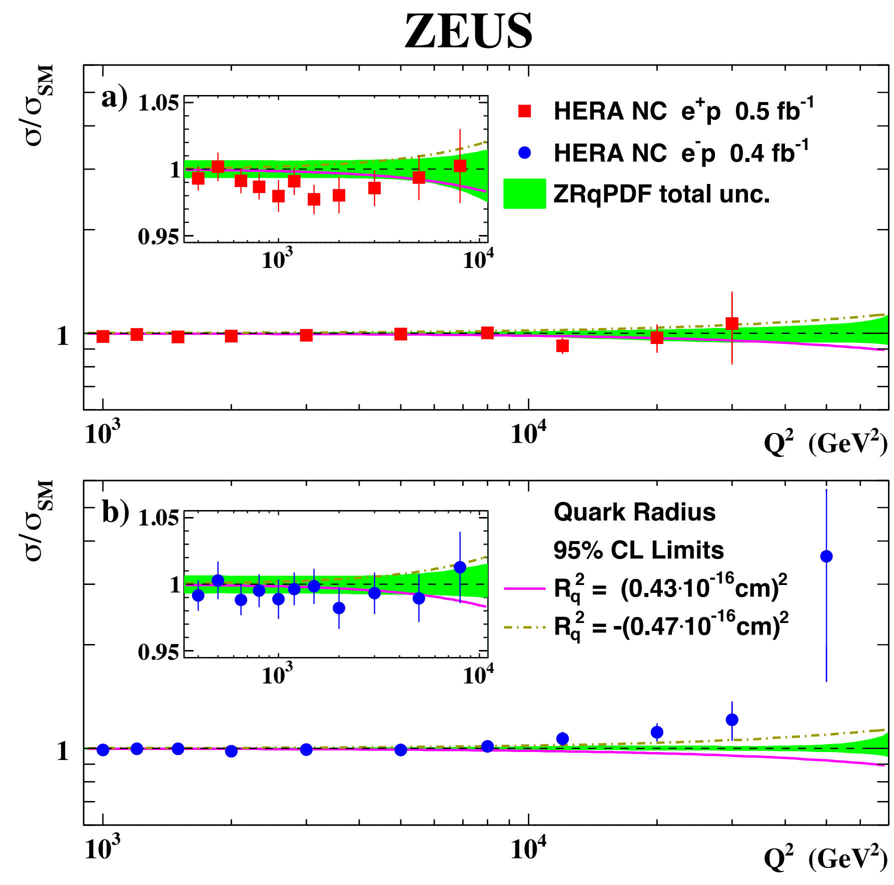
BSM: Quark substructure

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.

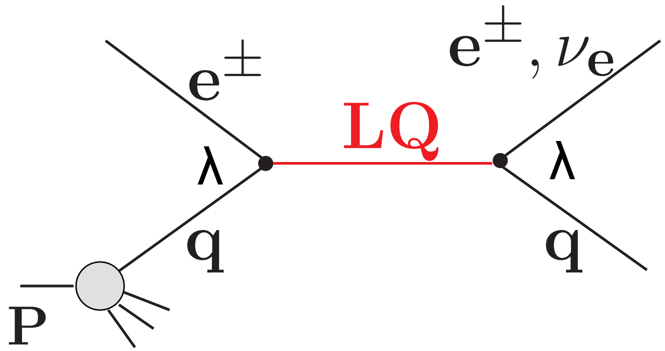


ZEUS Coll., DESY-16-035, accepted by Phys. Lett. B

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

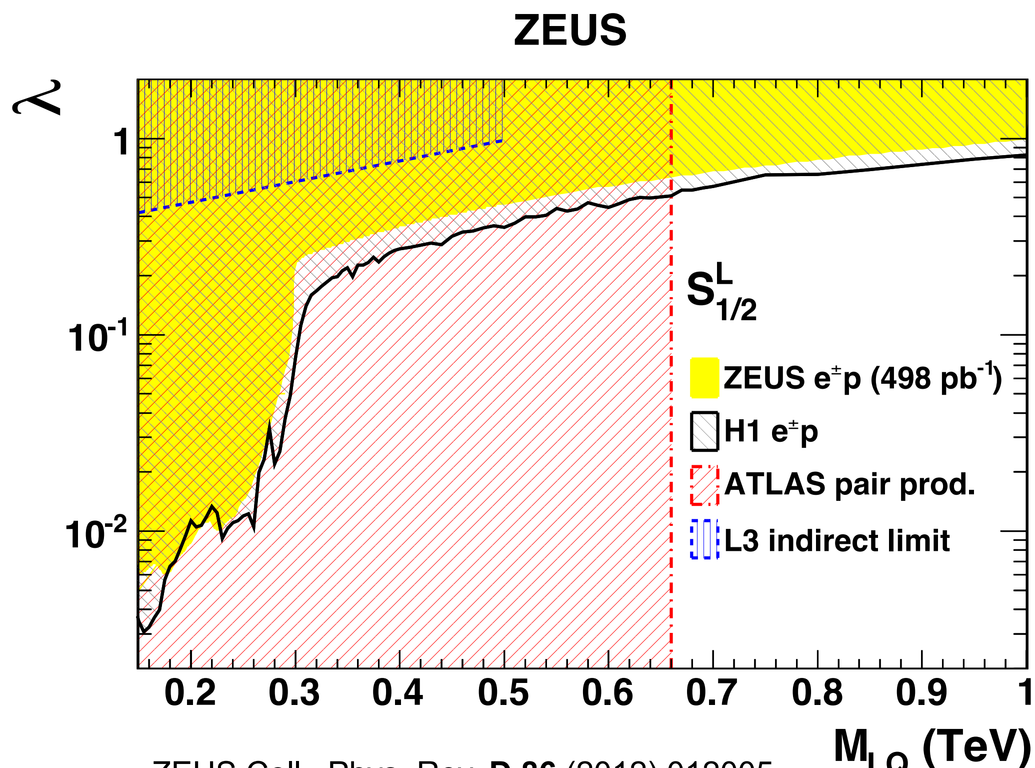


Electron−proton colliders are the ideal machine to look for leptoquarks.

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

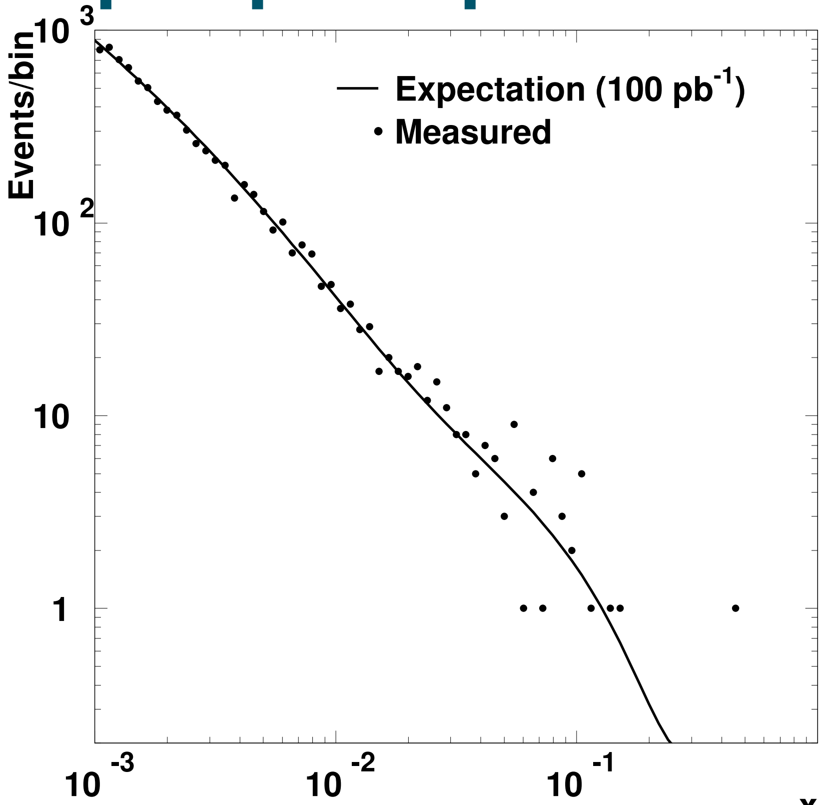
$$\sigma^{\mathrm{NWA}} = (J+1)\frac{\pi}{4s}\lambda^2\, q(x_0, M_{\mathrm{LQ}}^2)$$

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



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

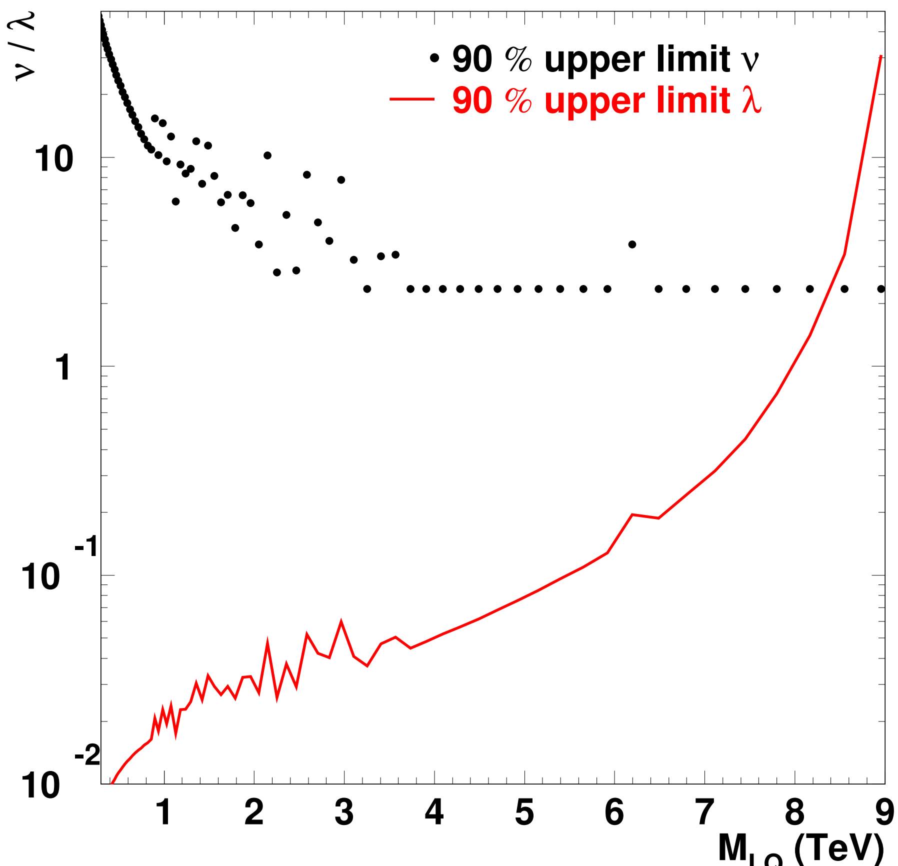
Leptoquark production at VHEeP



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

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

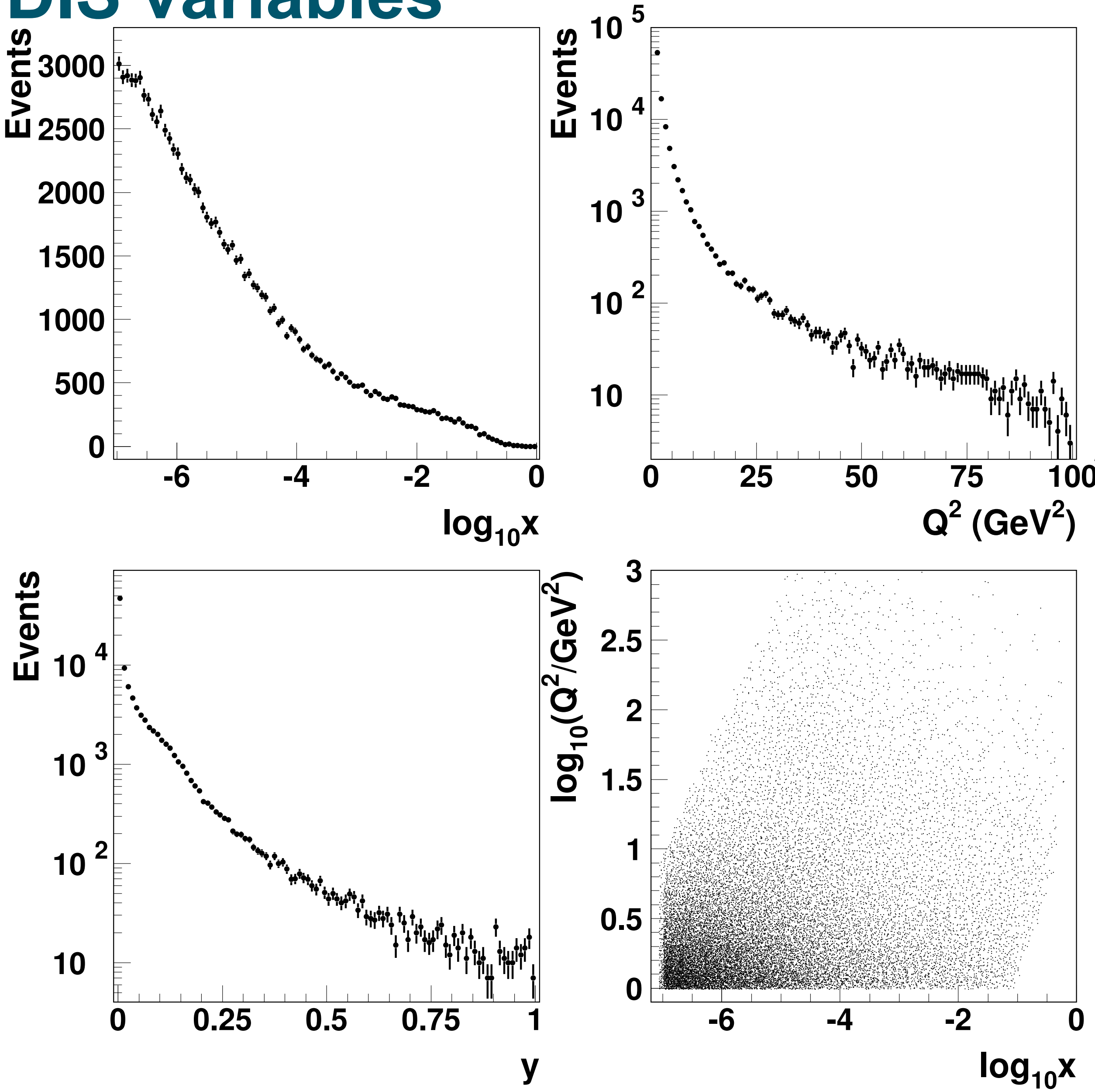
Generated "data" and Standard Model "prediction" using ARIADNE (no LQs).



Sensitivity up to kinematic limit, 9 TeV.

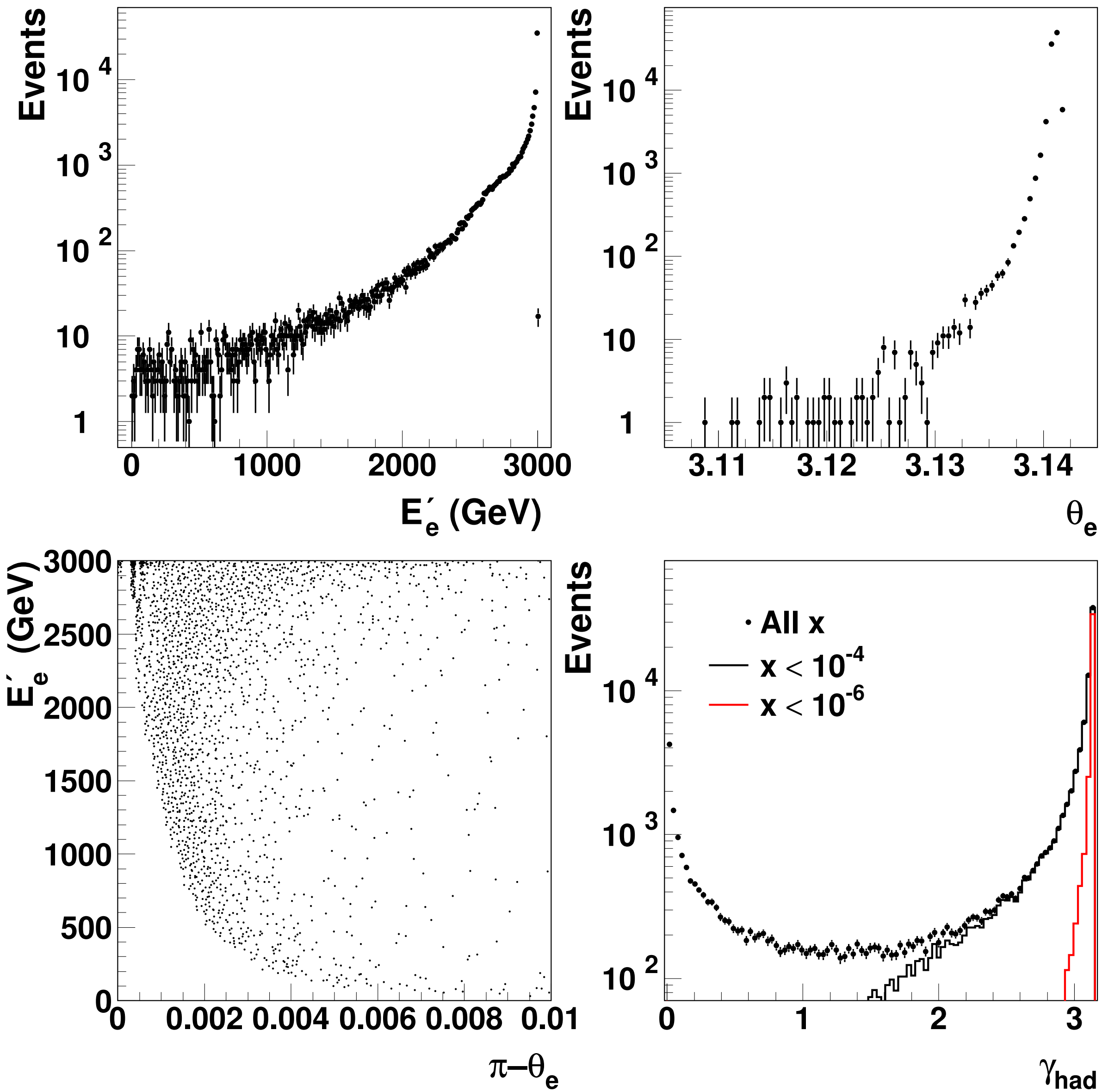
As expected, well beyond HERA limits and significantly beyond LHC limits and potential.

DIS variables



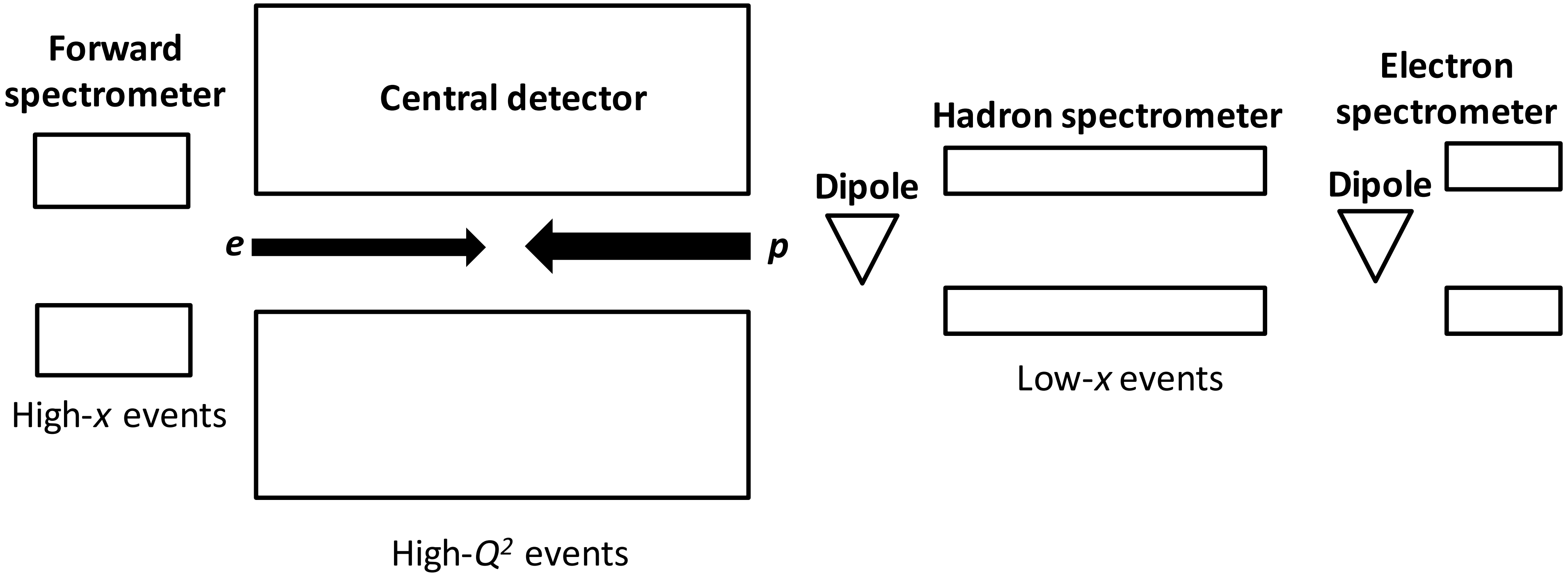
- Access down to $x \sim 10^{-8}$ for $Q^2 \sim 1\ GeV^2$.
- Even lower x for lower Q^2.
- Plenty of data at low x and low Q^2 ($L \sim 0.01\ pb^{-1}$).
- Can go to $Q^2 \sim 10^5\ GeV^2$ for $L \sim 1\ pb^{-1}$.
- Powerful experiment for low-x physics where luminosity less crucial.

Kinematics of the final state



- Generated ARIADNE events with $Q^2 > 1\ GeV^2$ 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.