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Particle physics experiments based on the AWAKE acceleration scheme

Matthew Wing (UCL / DESY)

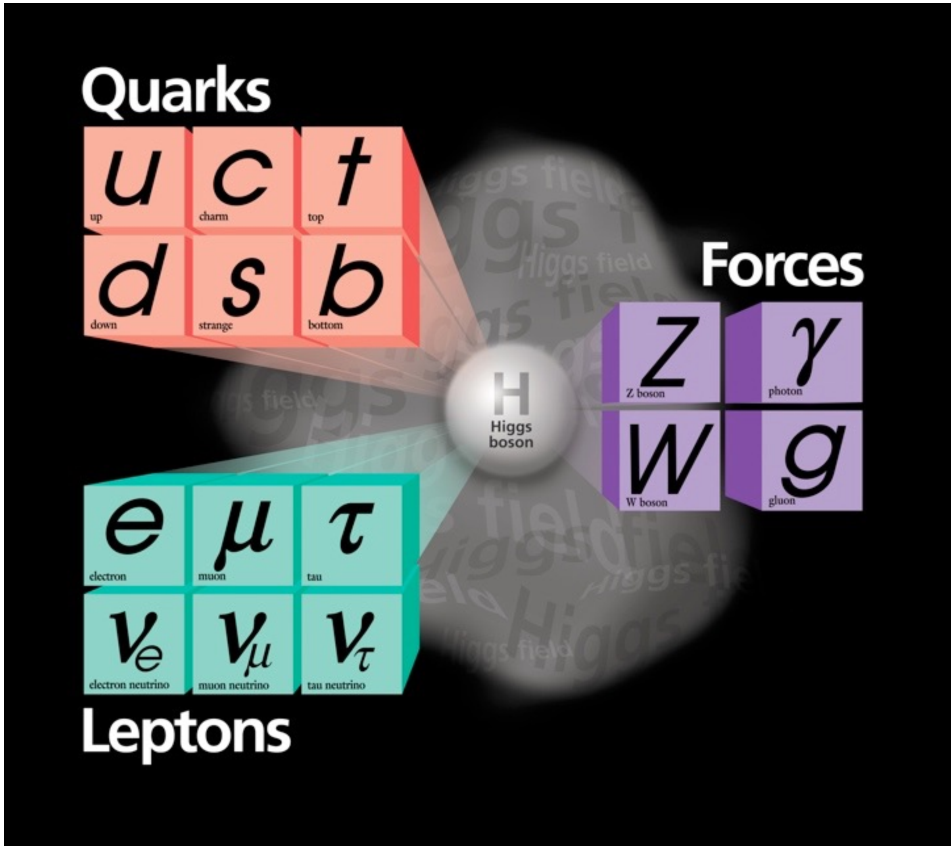
- Introduction and motivation
- Future electron beam based on AWAKE scheme
- Possible physics experiments
    - Strong-field QED at the Schwinger field
    - Search for dark photons, NA64-like
    - High energy electron−proton collisions, LHeC-like and VHEeP
- Summary and discussion

Royal Society Meeting — 5 June 2018

Motivation: big questions in particle physics

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

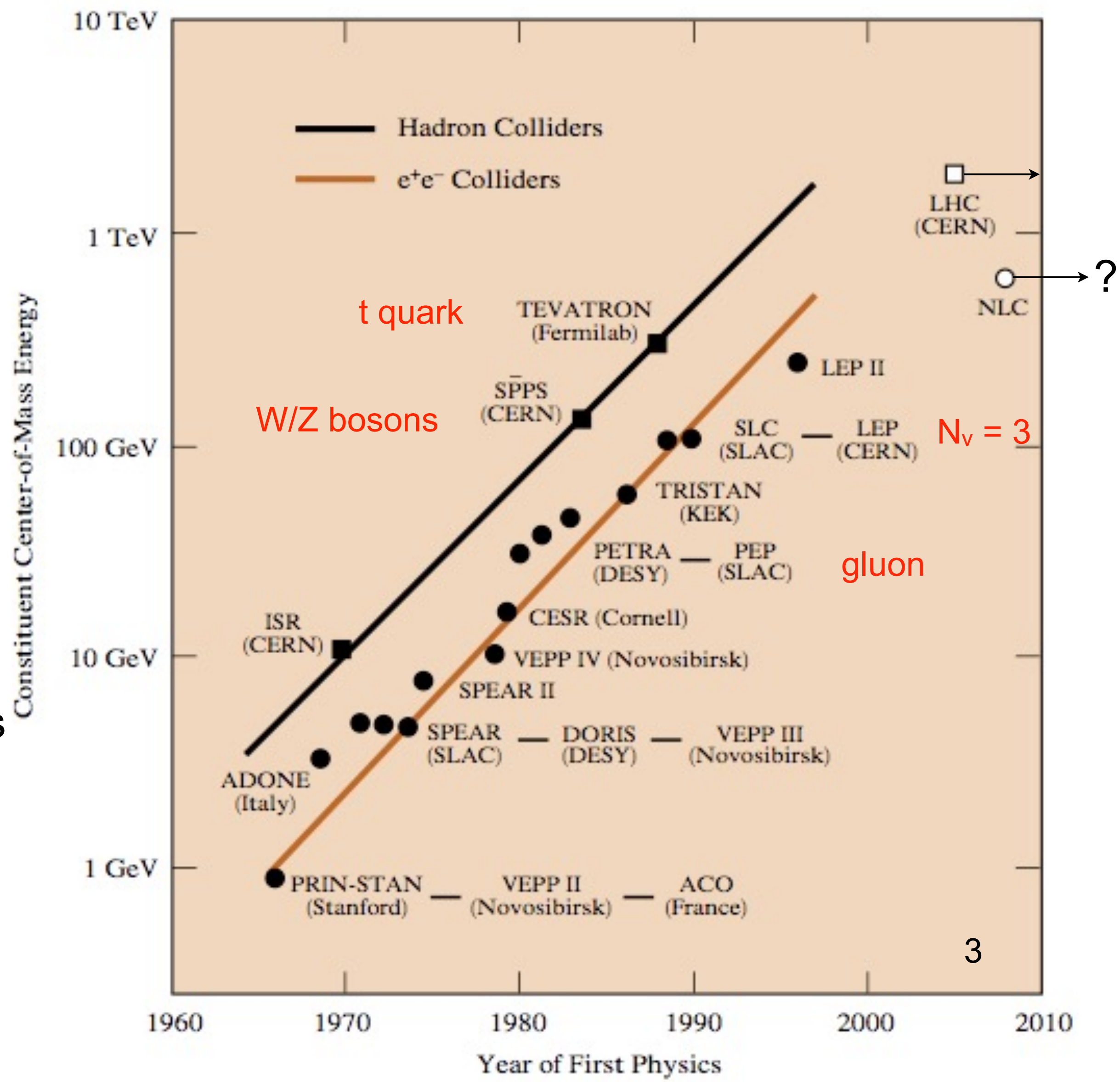
- a detailed understanding of the Higgs Boson/mechanism
- neutrinos and their masses
- why is there so much matter (vs anti-matter) ?
- why is there so little matter (*5%* of Universe) ?
- what is dark matter and dark energy ? Does supersymmetry occur at the *TeV* scale
- why are there three families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



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

Motivation: colliders

- The use of (large) accelerators has been central to advances in particle physics.
- Culmination in *27-km* long LHC (*pp*); e.g. a future e^+e^- collider planned to be *30–50-km* long.
- The high energy frontier is (very) expensive; can we reduce costs ? Can we develop and use new technologies ?
- Accelerators using RF cavities limited to *~100 MV/m*; high energies → long accelerators.
- The Livingston plot shows a saturation …



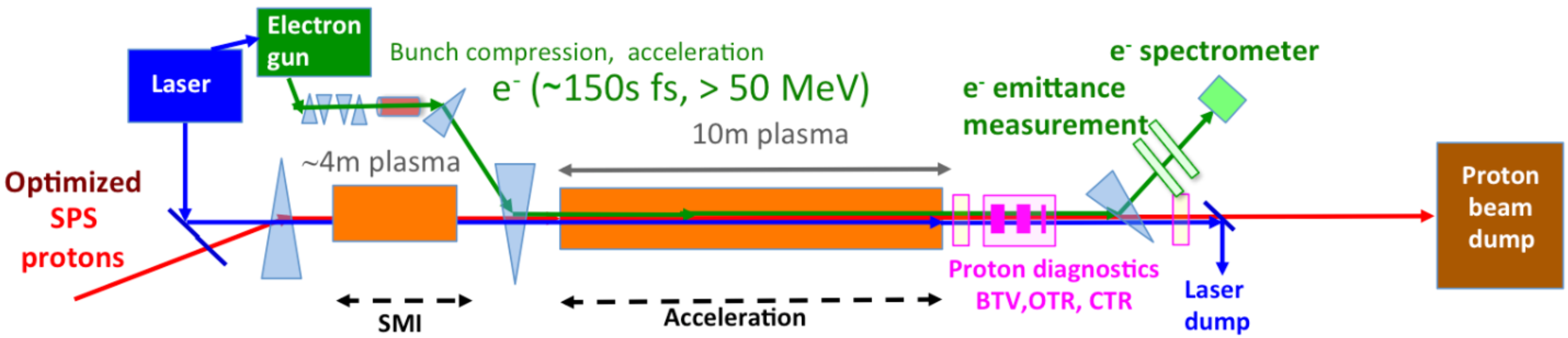
Motivation: plasma wakefield acceleration as a solution

- Plasma wakefield acceleration is a promising scheme as a technique to realise shorter or higher energy accelerators in particle physics.
- Proton-driven plasma wakefield acceleration is well-suited to high energy physics applications.
- Accelerating gradients achieved in the wakefield of a plasma are very high (3 orders of magnitude more than RF acceleration and up to *100 GV/m*), but need :
  - High repetition rate and high number of particles per bunch;
  - Efficient and highly reproducible beam production;
  - Small beams sizes (potentially down to *nm* scale).
- Ultimate goal : can we have *TeV* beams produced in an accelerator structure of a few *km* in length ?
- Here consider **realistic** and **first** applications:
  - Based on AWAKE scheme of proton-driven plasma wakefield acceleration;
  - Strong use of CERN infrastructure;
  - Need to have novel and exciting physics programme.
- A challenge for accelerator, plasma and particle physics.

An AWAKE-like beam for particle physics

AWAKE Run 2

- Preparing AWAKE Run 2, after CERN LS2 and before LS3, 2021–4.
  - Accelerate electron bunch to higher energies.
  - Demonstrate beam quality preservation.
  - Demonstrate scalability of plasma sources.



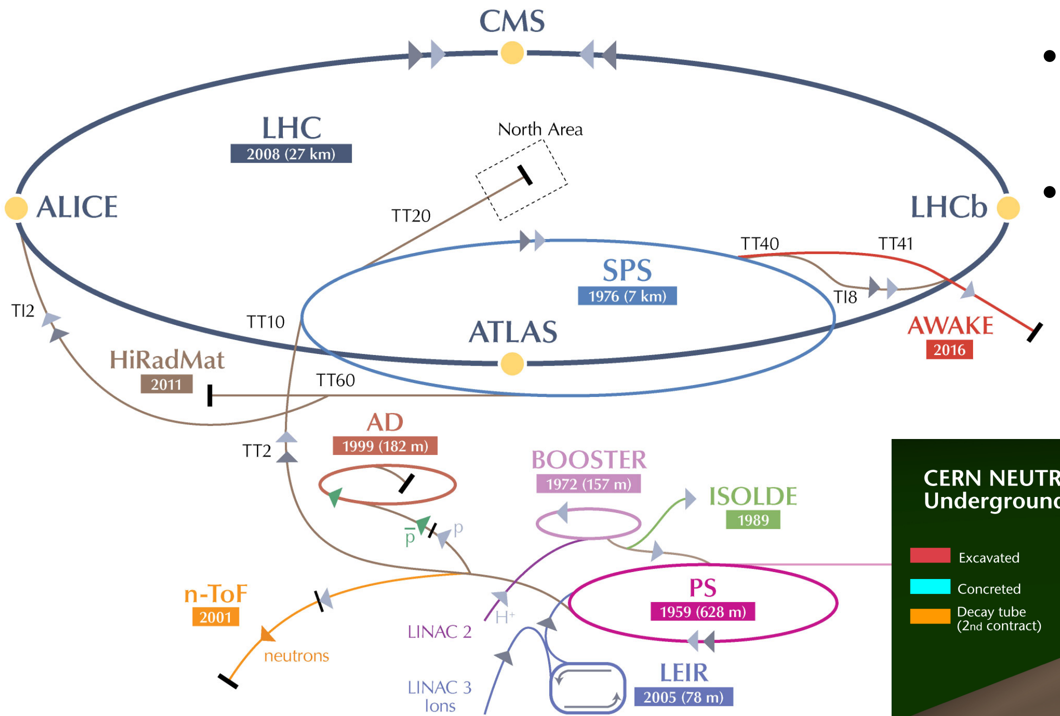
Preliminary Run 2 electron beam parameters

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

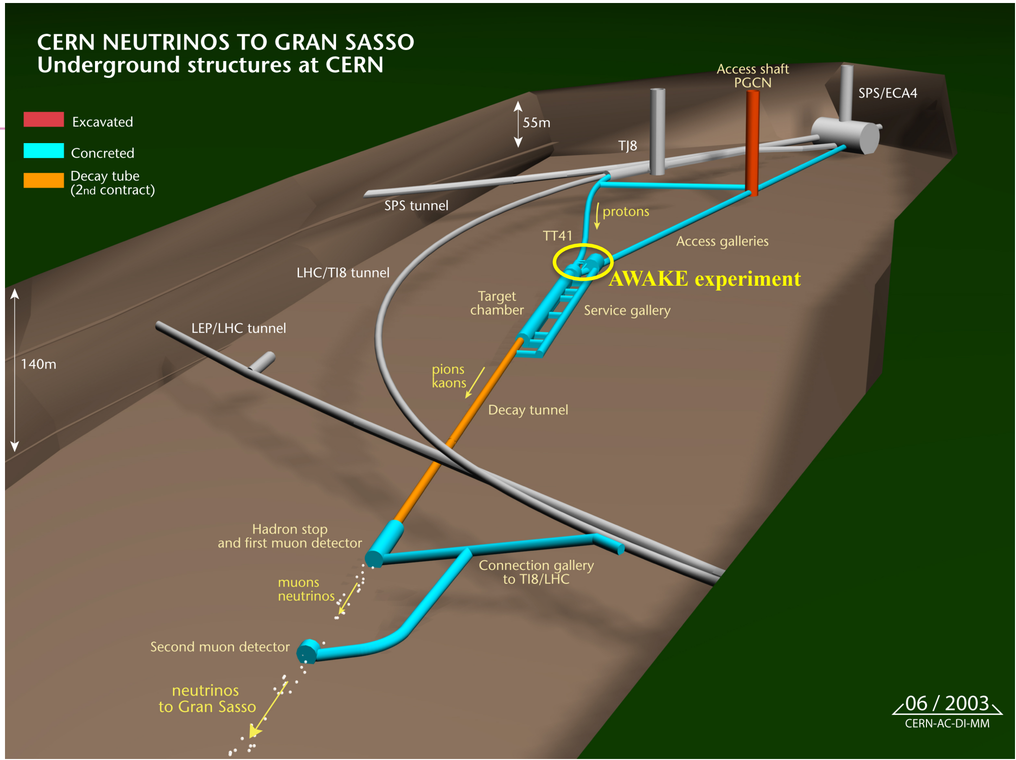
- Are there physics experiments that require an electron beam of up to *O(50 GeV)* ?
- Use bunches from SPS with 3.5×10^{11} *protons* every *~ 5 s*.
- Using the LHC beam as a driver, *TeV* electron beams are possible.

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

AWAKE experiment at CERN



- Demonstrate for the first time proton-driven plasma wakefield acceleration.
- How can an experiment fit into the CERN complex ?



- Advanced proton-driven plasma wakefield experiment.
- Using *400 GeV* SPS beam in former CNGS target area.

AWAKE Coll., R. Assmann et al., Plasma Phys. Control. Fusion **56** (2014) 084013

Possible particle physics experiments I

- Use of electron beam for test-beam campaigns.
  - Test-beam infrastructure for detector characterisation often over-subscribed.
  - Also 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 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.
- **Investigation of strong-field QED at the Schwinger limit in electron−laser interactions.**

Possible particle 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: E_e *~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.

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

- **Demonstrate an accelerator technology also doing cutting-edge particle physics**

Using a new technology

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

Strong-field QED at the Schwinger field

Strong-field QED

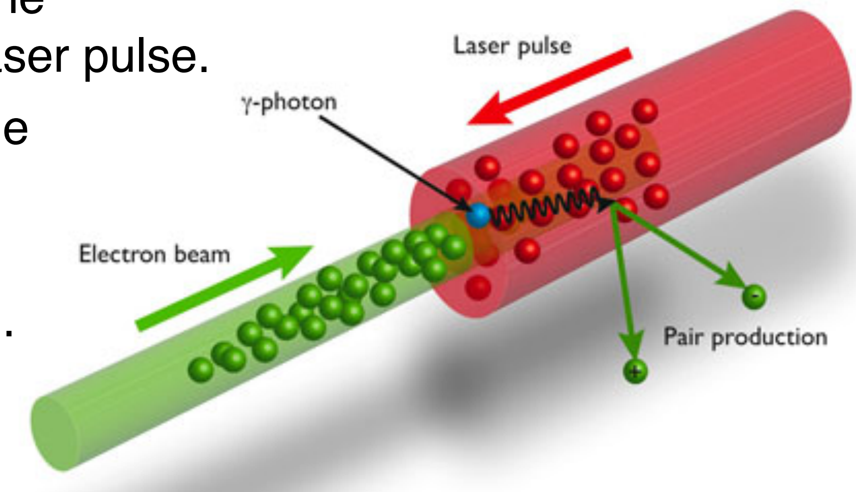
- Quantum mechanics and QED has been investigated and measured with amazing precision in many experiments and high-precision predictions describe this well.
  - However the strong-field regime, where QED becomes non-perturbative, has still not been measured.
- The strong field regime was already considered by Heisenberg, Euler et al. in 1930s.
- Characterised by the Schwinger critical field (1951):

$$E_{\text{crit}} = \frac{mc^2}{e\lambdabar_C} = \frac{m^2c^3}{e\hbar} = 1.3 \times 10^{16} \text{ V/cm}$$

- This has not been reached experimentally, although they are expected to exist:
  - On the surface of neutron stars.
  - In bunches of future linear e^+e^- colliders.
- Can be reached by colliding photons with a high-energy electron beam
  - Pioneering experiment E144 @ SLAC in 1990s.
- **Given increase in laser power, investigate QED in an unexplored region.**

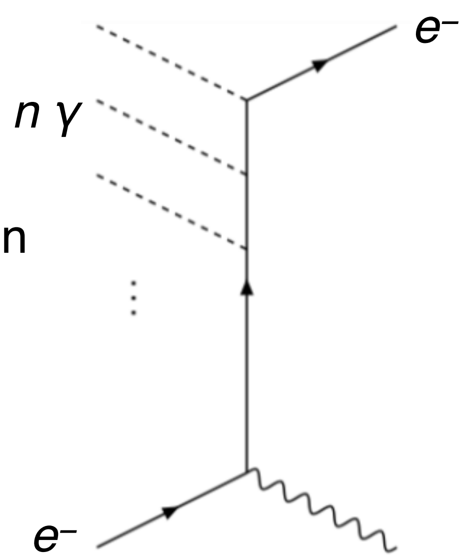
Non-linear QED processes

- Initial interest in two strong-field processes in the interaction of electron beam with high-power laser pulse.
  - Non-linear Compton scattering where multiple laser photons are absorbed and a single photon radiated.
  - One or more such Compton scatters happen.
  - Produced photon interacts with laser field to produce electron–positron pair (Breit–Wheeler)



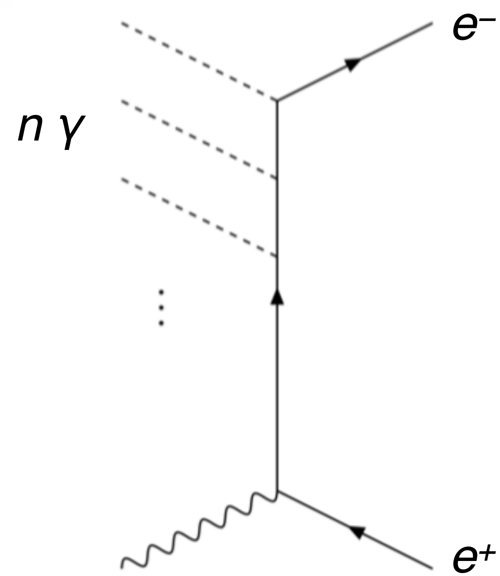
$$e^- + n\gamma \rightarrow e^- + \gamma$$

Compton

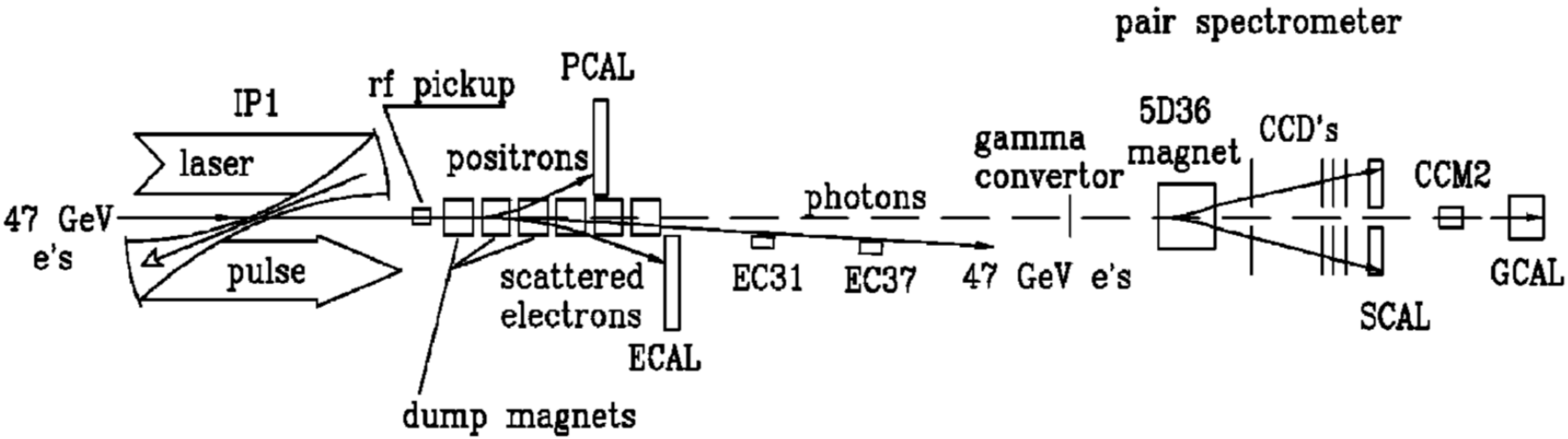


$$\gamma + n\gamma \rightarrow e^+ + e^-$$

Pair production



E144 experiment at SLAC



- Used 46.6 GeV electron beam (Final Focus Test Beam) with 5×10^9 electrons per bunch up to 30 Hz.
- Terawatt laser pulses with intensities of $\sim 0.5 \times 10^{18}$ W/cm^2 and frequency of 0.5 Hz for wavelengths 1053 nm and 527 nm.
- Electron bunch and laser collided with 17° crossing angle.

E144 Coll., C. Bamber et al., Phys. Rev. D 60 (1999) 092004;
T. Koffas, "Positron production in multiphoton light-by-light scattering", PhD thesis, University of Rochester (1998), SLAC-R-626.

New strong-field QED experiments

- New experiments being performed/considered
  - In LWFA with few-GeV electrons and laser.
  - Using FACET and EU.XFEL 10−20 GeV electrons and laser.
  - Using higher-power lasers compared to E144@SLAC.
- Could also be an application of an AWAKE-like bunch
  - Unique feature would be the higher electron energies and hence higher $\sqrt{s}$.
  - Sensitive to different processes.
  - Can constrain more exotic physics (e.g. dark photons).

Experiments to search for the dark sector

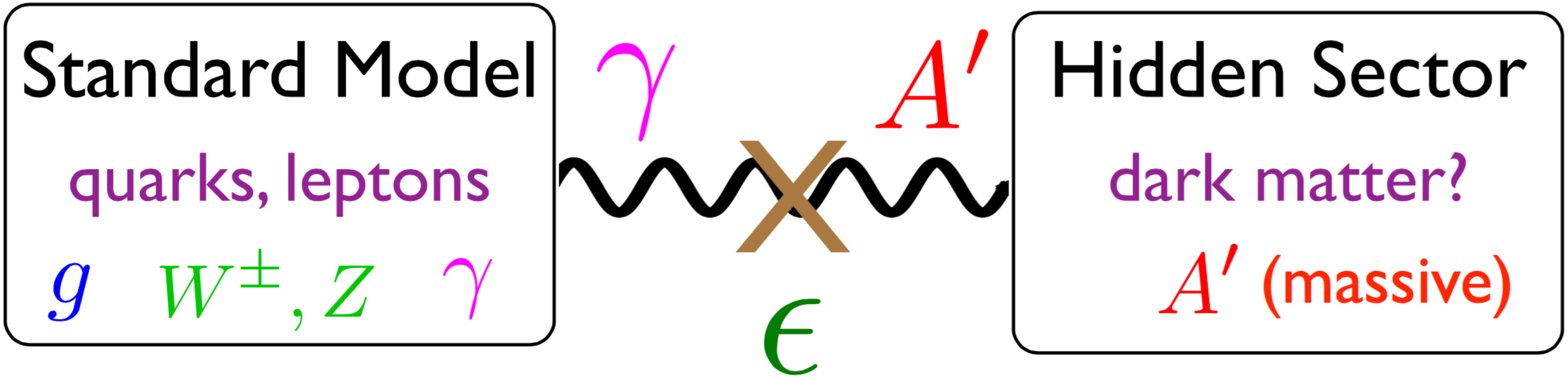
The hidden / dark sector

- Baryonic (ordinary) matter constitutes *~5%* of known matter.
  - What is the nature of dark matter ? Why can we not see the dominant constituent of the Universe ?
- LHC Run 1 (and previous high energy colliders) have found no dark matter candidates so far.
- LHC Run 2 to continue that search looking for heavy new particles such as those within supersymmetry.
- Also direct detection experiments looking for recoil from WIMPs
- There are models which postulate light (*GeV* and below) new particles which could be candidates for dark matter.
- There could be a dark sector which couples to ordinary matter via gravity and possibly other very weak forces.
- Could e.g. explain $g-2$ anomaly between measurement and the Standard Model.

Dark photons

A light vector boson, the "dark photon", *A′*, results from a spontaneously broken new gauge symmetry, $U(1)_D$.

The *A′* kinetically mixes with the photon and couples primarily to the electromagnetic current with strength, εe

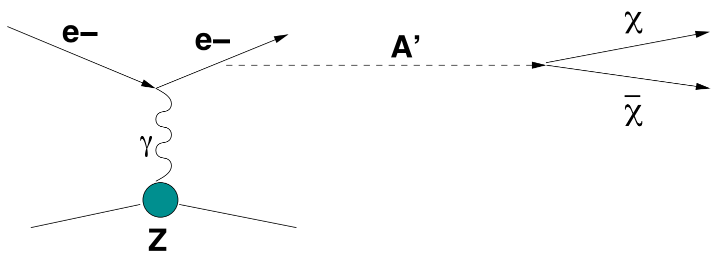


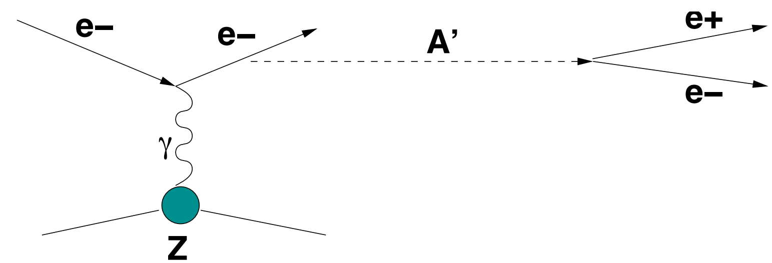
$$\Delta\mathcal{L} = \frac{\epsilon}{2} F^{Y,\mu\nu} F'_{\mu\nu}$$

Growing field of experiments with many running or starting or proposed at JLab, SLAC, INFN, Mainz, etc.

NA64 experimental programme

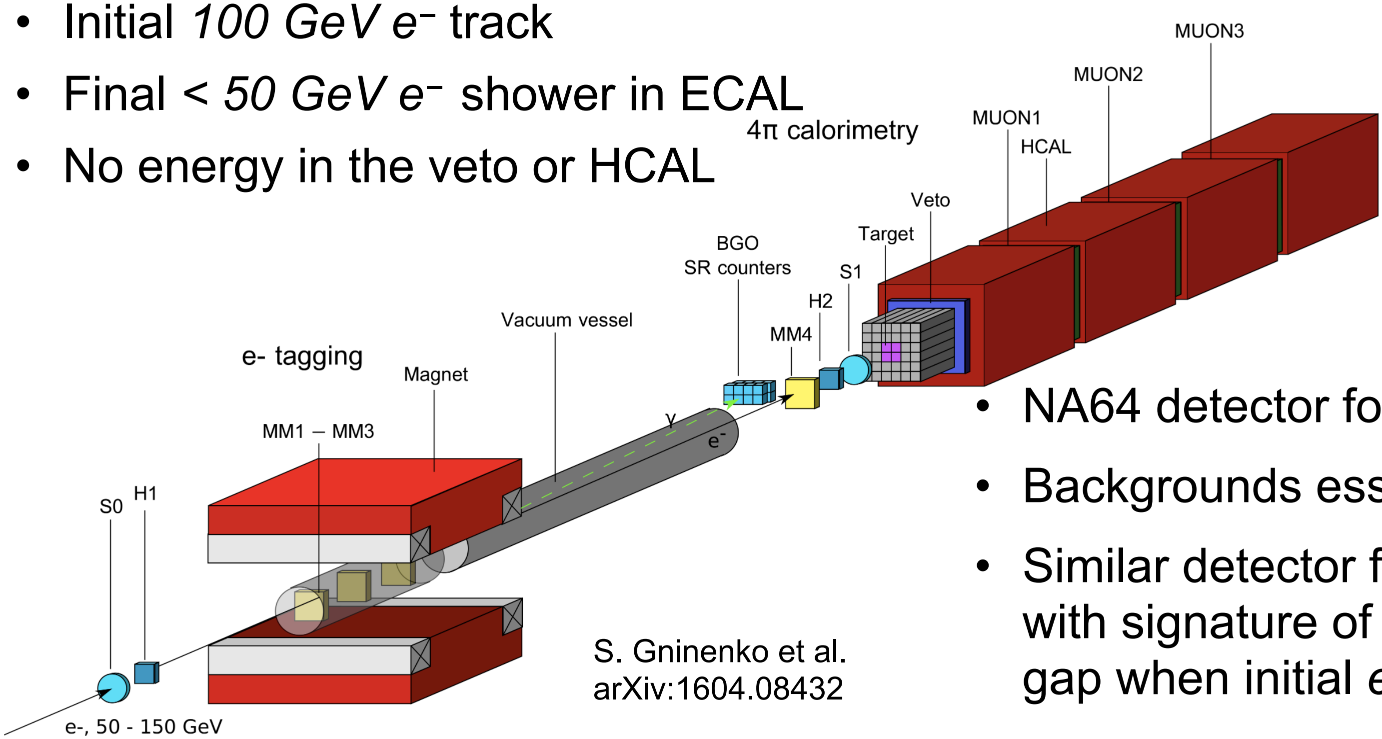
- Initial run in SPS beam focusing on $A' \rightarrow$ *invisible* channel.
- Future programme measuring $A' \rightarrow e^{+} e^{-}$ channel.





Signature:

- Initial *100 GeV* e^{-} track
- Final < *50 GeV* e^{-} shower in ECAL
- No energy in the veto or HCAL



S. Gninenko et al.
arXiv:1604.08432

- NA64 detector for $A' \rightarrow$ *invisible* channel.
- Backgrounds essentially zero.
- Similar detector for $A' \rightarrow e^{+} e^{-}$ channel with signature of two EM showers after gap when initial e^{-} hits target.

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.

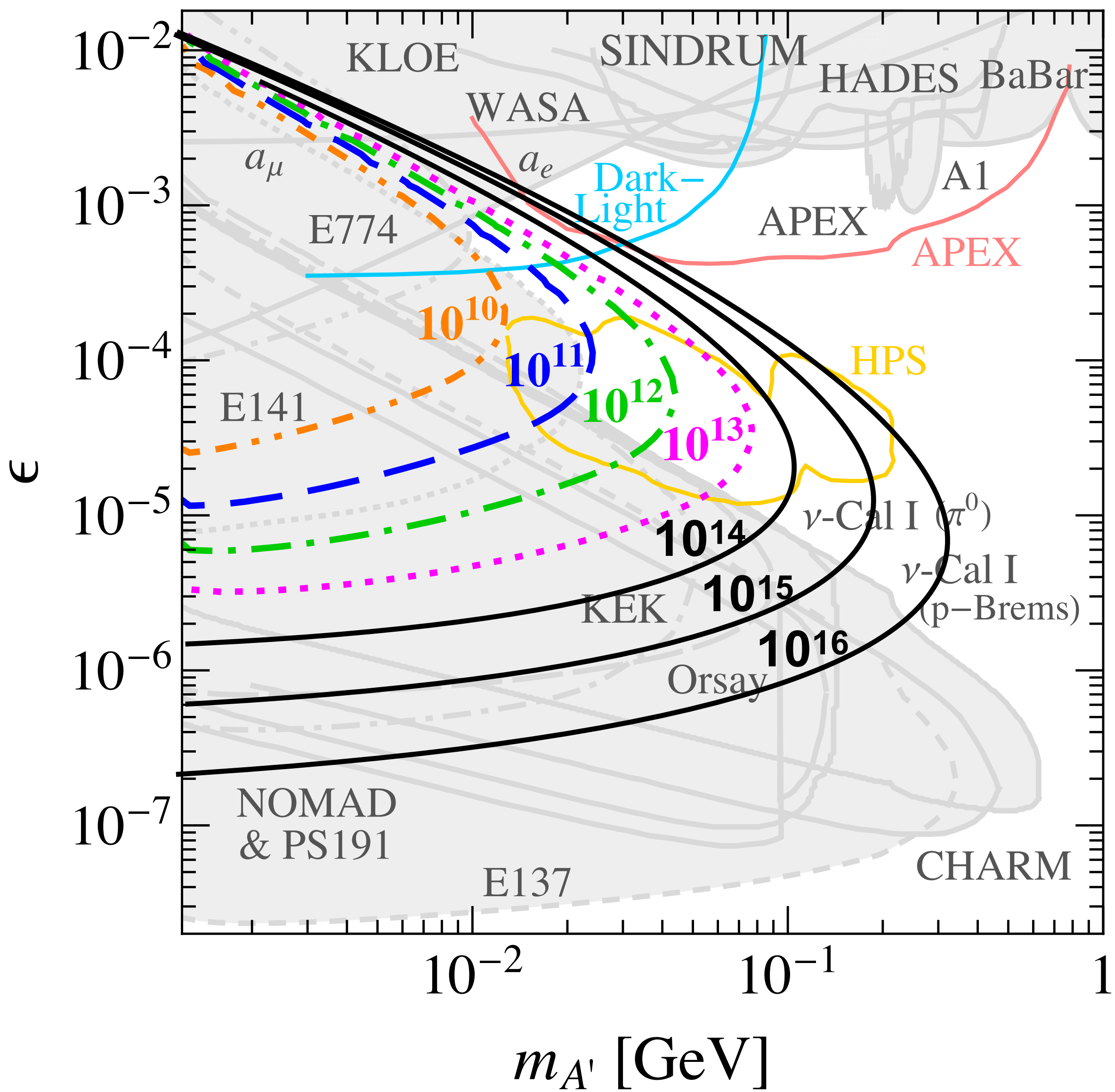
Sensitivity with increased electrons on target

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. $A' \rightarrow \mu^+ \mu^-$.
- **Note that this idea uses bunches, rather than single electrons.**

Results shown here should be considered as indicative.

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



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

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

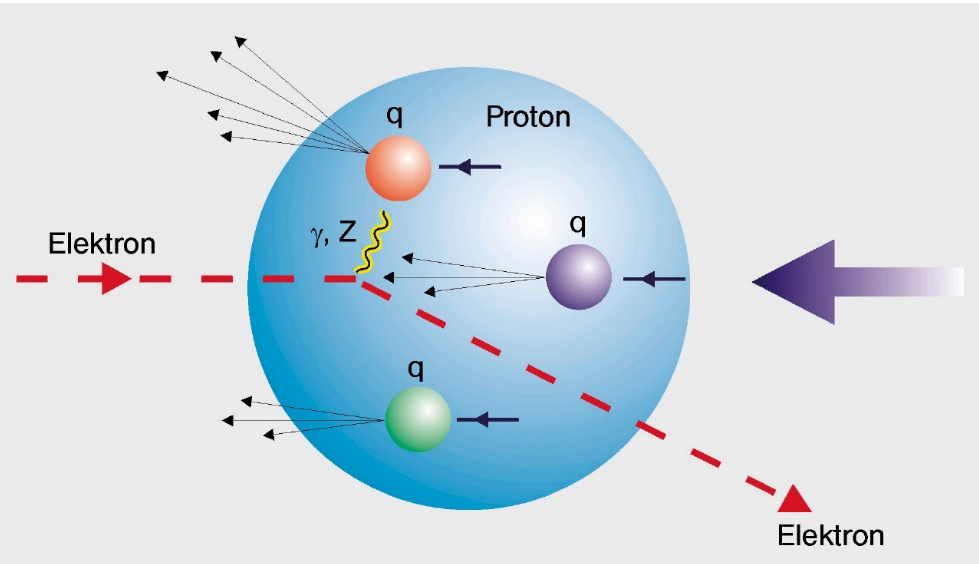
As proposed by NA64 group:

- 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 experiment.

Electron–proton colliders

High energy electron–proton collisions



Energy scale or resolution,
$Q^2 = -(k-k')^2$

Parton momentum fraction, x

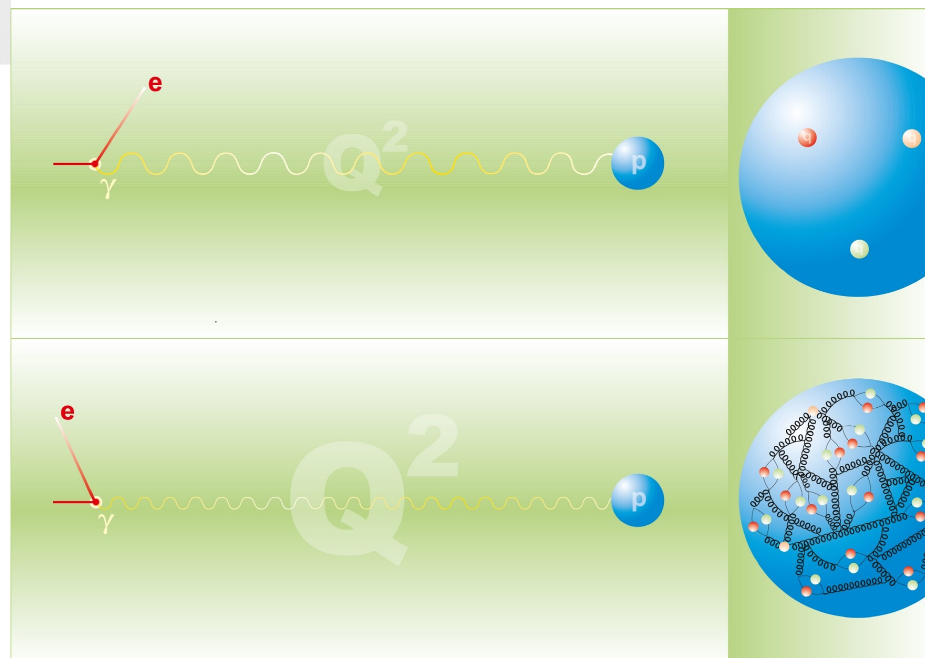
Understand hadronic cross sections as a function of these variables.

Deep inelastic scattering is the way to study the structure of matter.

When does the complex structure "level out" or "saturate" ?

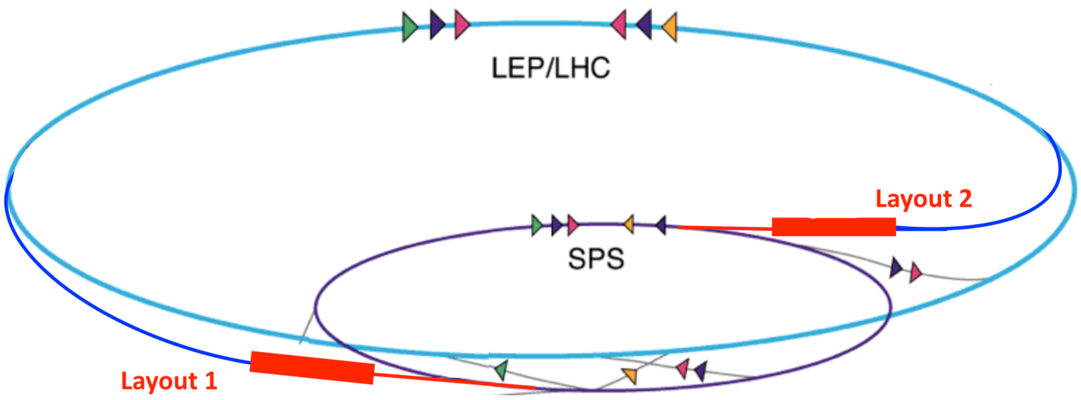
Tells us a lot about the strong force: parton interactions, α_s, etc.

Is there further partonic substructure ?



High energy electron−proton collisions

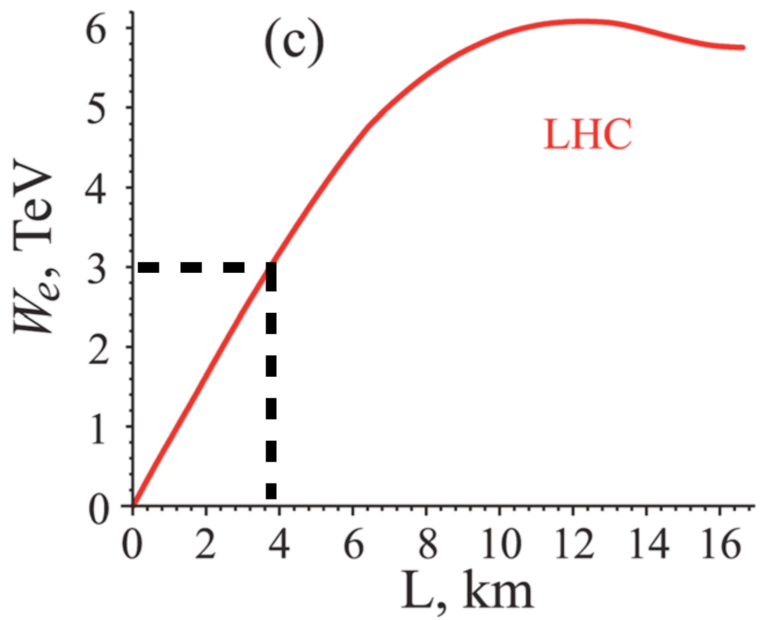
- Consider high energy *ep* collider with E_e up to *O(50 GeV)*, colliding with LHC proton *TeV* bunch, e.g. E_e = *50 GeV*, E_p = *7 TeV*, $\sqrt{s}$ = *1.2 TeV.*
- Can “easily” exceed HERA energies ($\sqrt{s}$ = *300 GeV*); can consider different detector and probe different physics.
- Create ~*50 GeV* beam within *50−100 m* of plasma driven by SPS protons and have an LHeC-type experiment.
- Clear difference is that luminosity* currently expected to be lower $<10^{30}\ cm^{-2}s^{-1}$.
- Any such experiment would have a different focus to LHeC.
  - Investigate physics of the strong force.
  - Little sensitivity to Higgs physics.



- **Consider design further, e.g. luminosity, understanding how to build a plasma accelerator, etc. Can site at CERN with minimal new infrastructure ?**

*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

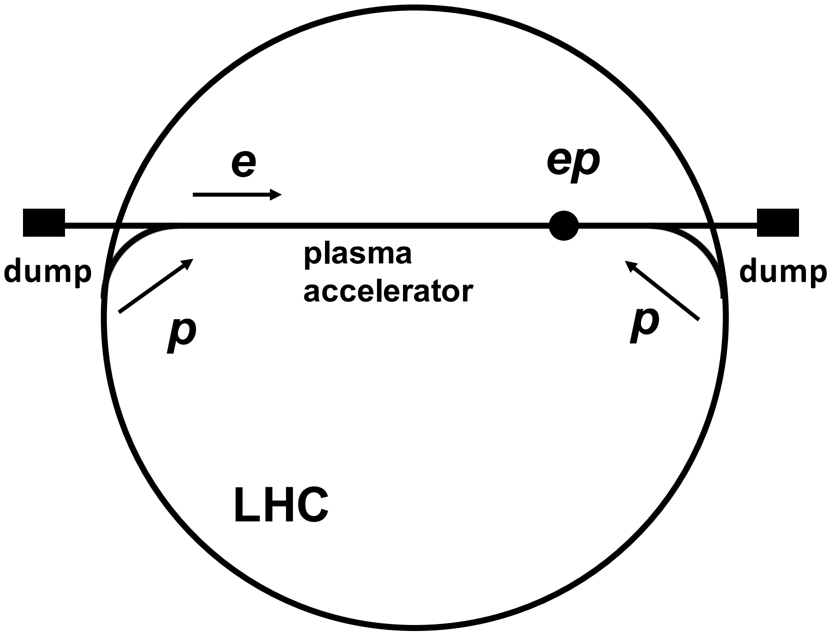
- What about very high energies in a completely new kinematic regime ?
- Choose E_e = *3 TeV* as a baseline for a new collider with E_p = *7 TeV* ⇒ $\sqrt{s}$ **= 9 TeV**.
- Acceleration of electrons in under *4 km*.
- Can vary the energy.
- Centre-of-mass energy ×30 higher than HERA.
- Reach in (high) Q^2 and (low) Bjorken x extended by ×1000 compared to HERA.

Idea presented at various workshops and published*. Also had a workshop to expand particle physics case:

https://indico.mpp.mpg.de/event/5222/overview

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

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 ?

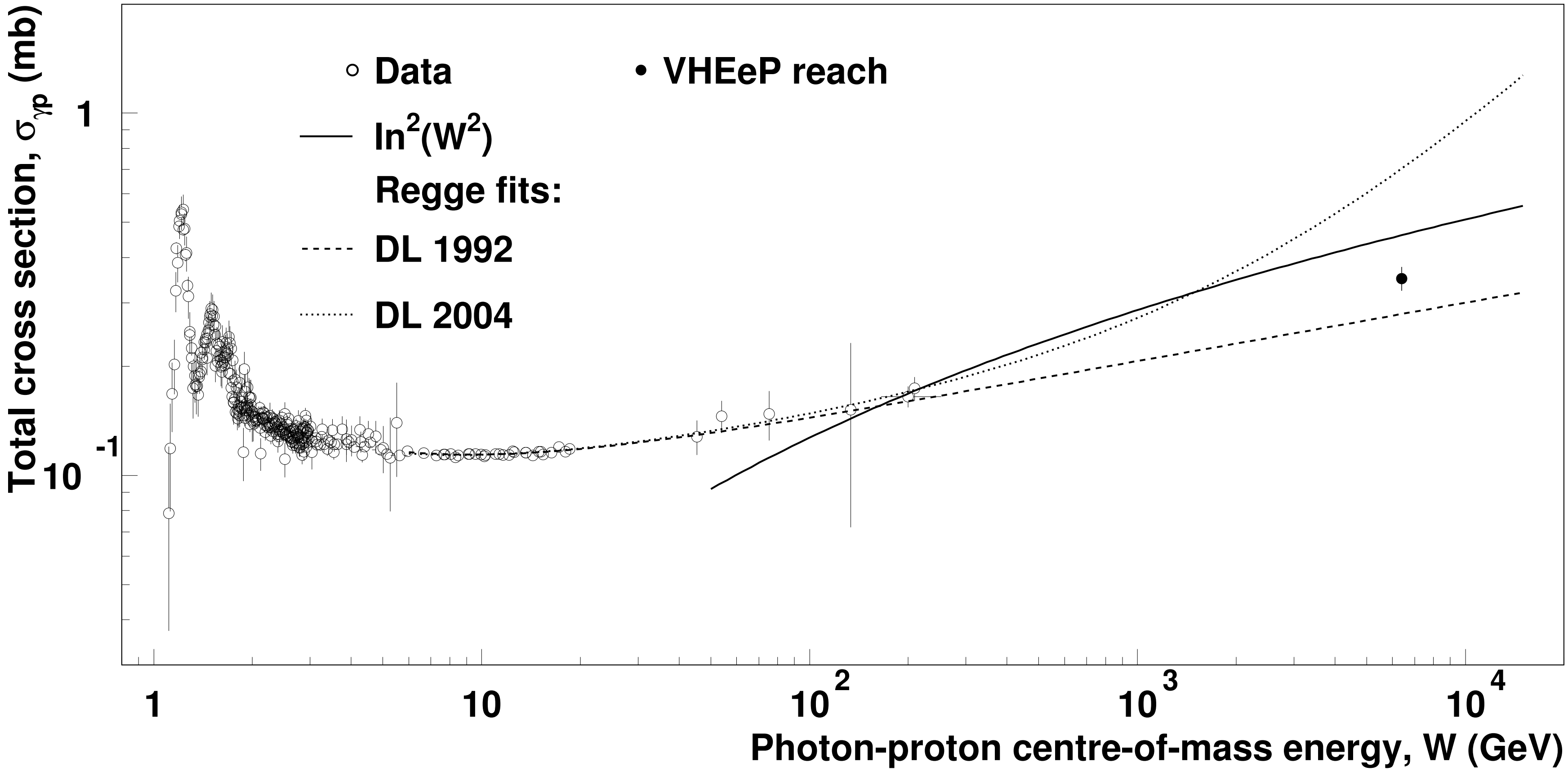
- Emphasis on using current infrastructure, i.e. LHC beam with minimum modifications.
- Overall layout works in powerpoint.
- Need high gradient magnets to bend protons into the LHC ring.
- One proton beam used for electron acceleration to then collider with other proton beam.
- High energies achievable and can vary electron beam energy.
- What about luminosity ?
- Assume
  - *~3000* bunches every *30 mins* ⇒ *f ~ 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.

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.
- …

Total photon−proton cross section

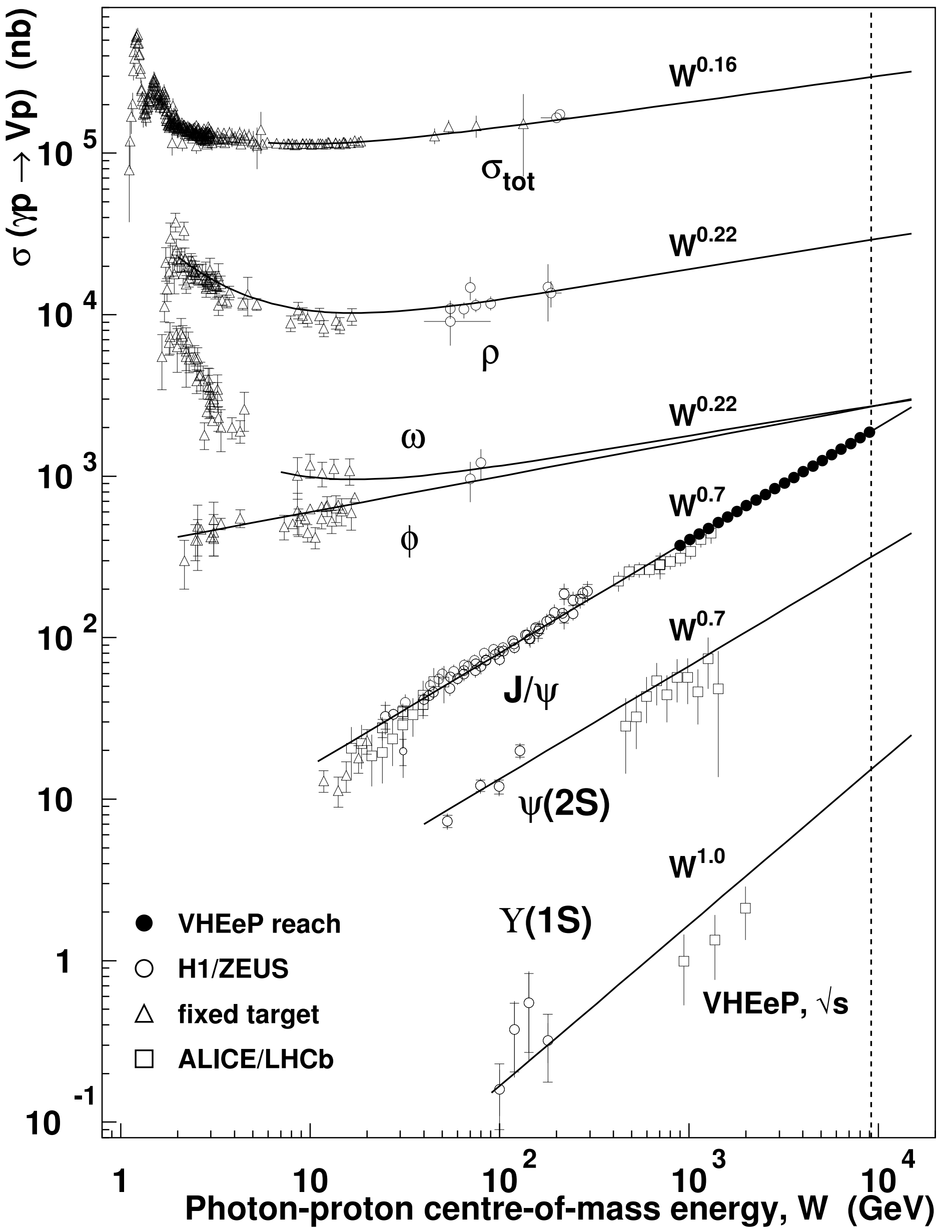


Energy dependence of hadronic cross sections poorly understood.

- Multiple measurements can be made with low luminosities.
- When does the cross section stop rising ?
- Relation to cosmic-ray physics.
- **Great example of where you really gain with energy.**

Equivalent to a 20 PeV photon on a fixed target.

Vector meson cross sections



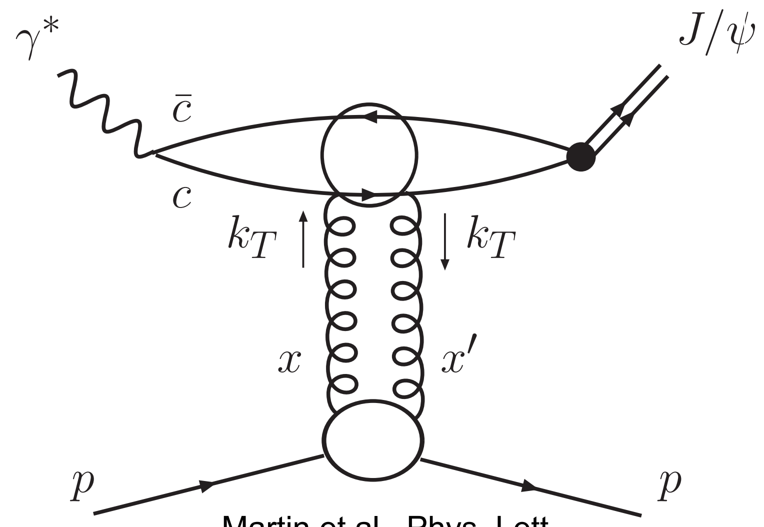
Strong rise with energy related to gluon density at low *x*.

Can measure all particles within the same experiment.

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

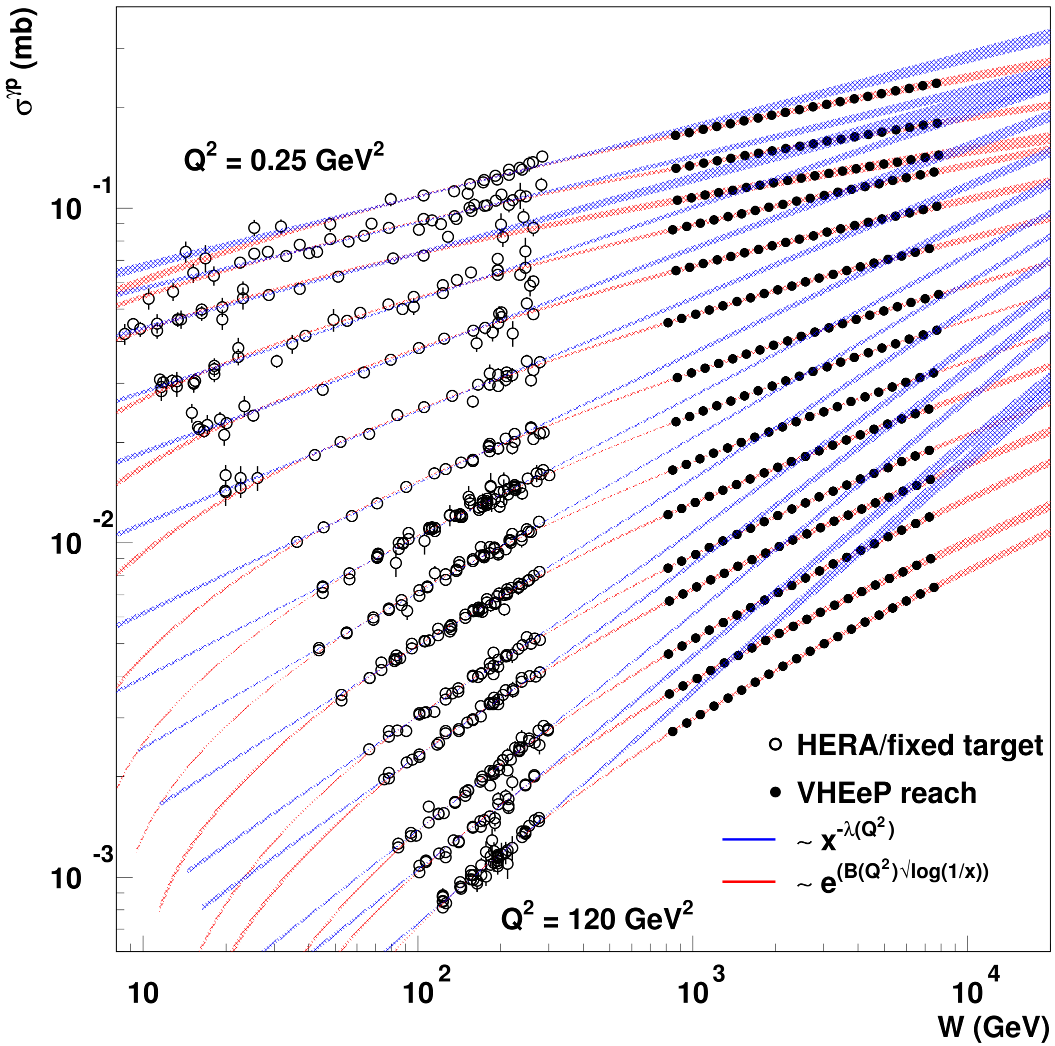
At VHEeP energies, *σ(J/ψ) > σ(φ)* !

Onset of saturation ?



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

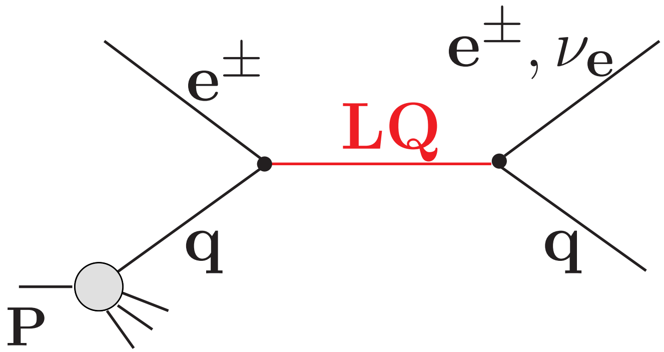
Virtual-photon–proton cross section



- 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.

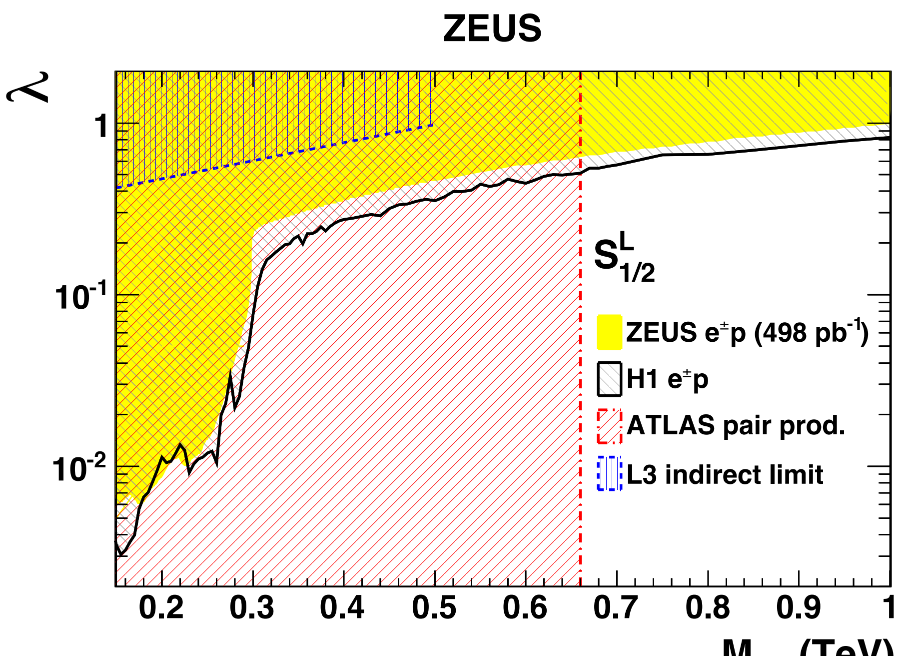
Leptoquark production



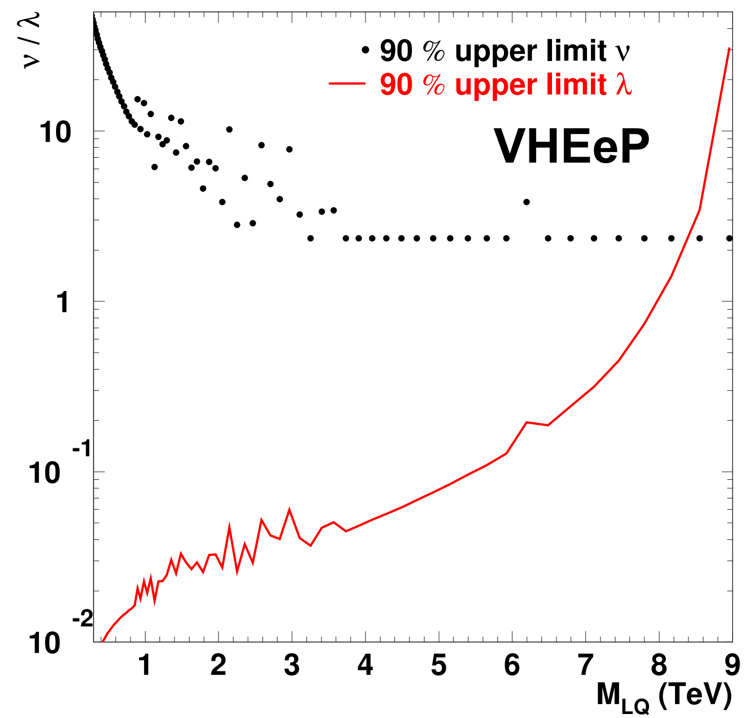
Electron–proton colliders are the ideal machine to look for leptoquarks.

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

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

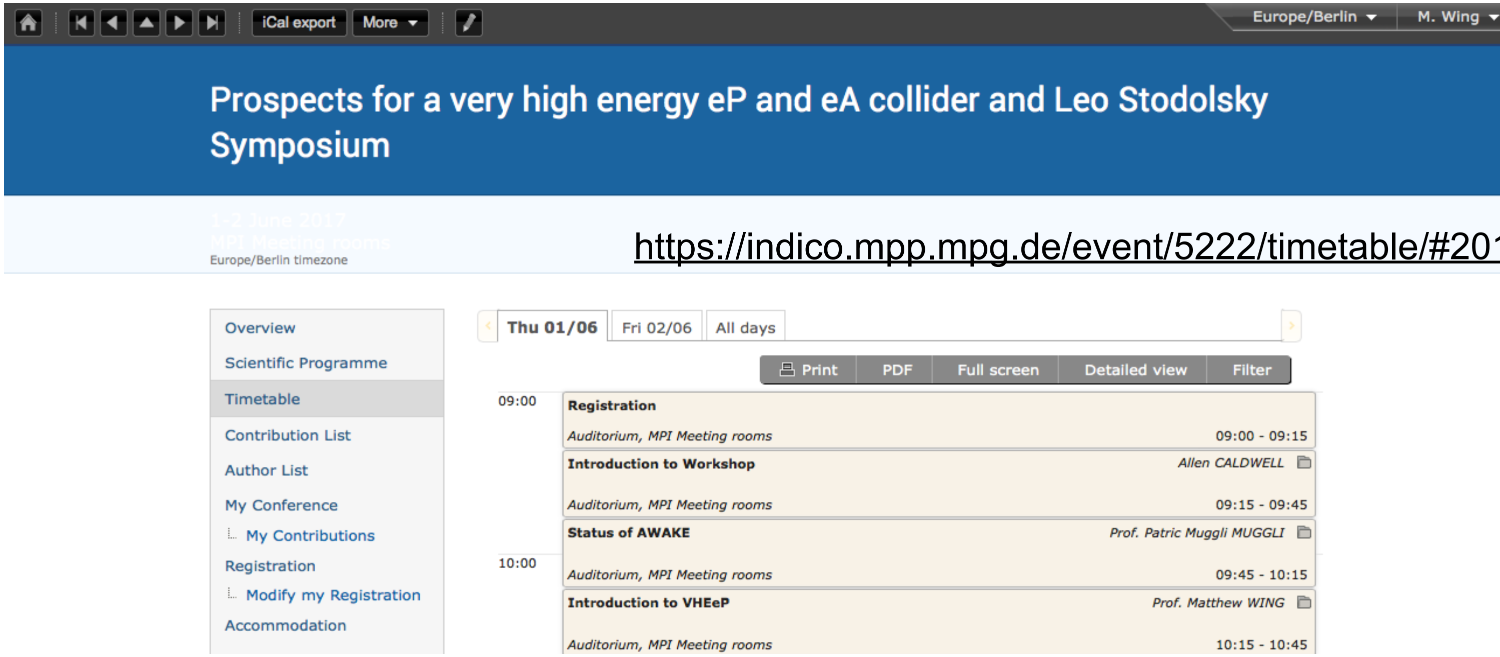


ZEUS Coll., Phys. Rev. **D 86** (2012) 012005



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

VHEeP Workshop



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

Some highlights:

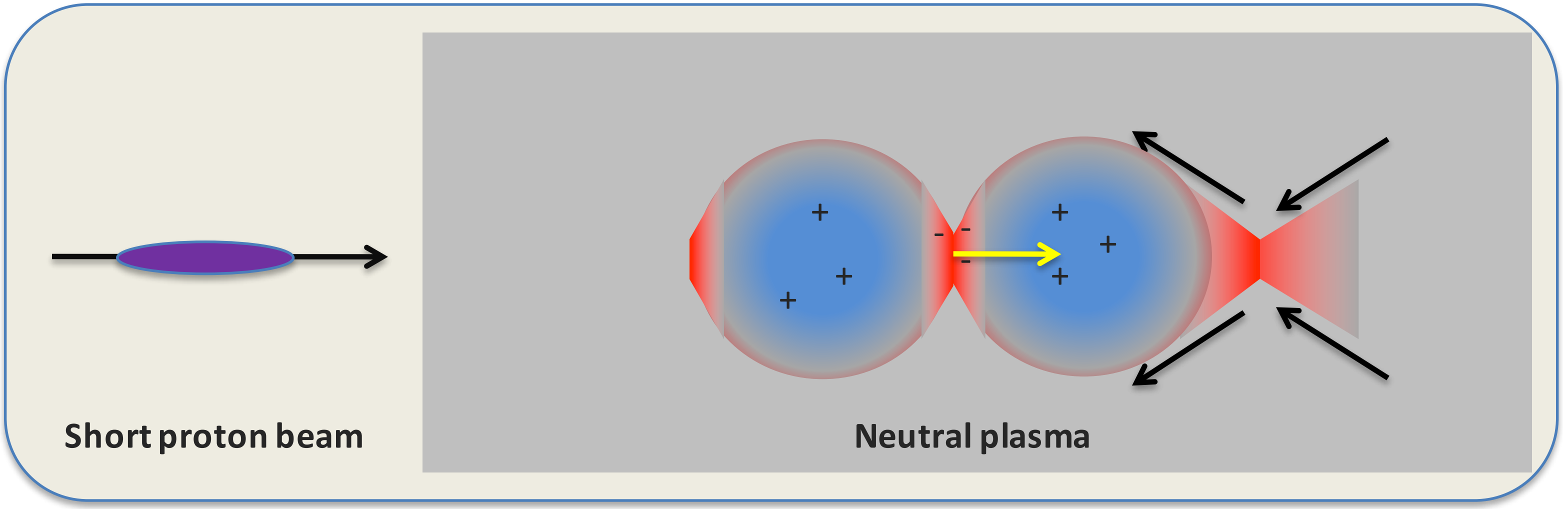
- Observe saturation; theory of hadronic interactions (Bartels, Mueller, Stodolsky, etc.)
- Relation of low-x physics to cosmic rays (Stasto); to black holes and gravity (Erdmenger); and to new physics descriptions (Dvali, Kowalski)
- Status of simulations (Plätzer)
- Challenge of the detector (Keeble)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

Summary and discussion

- The AWAKE collaboration has an exciting programme of R&D aiming to develop a **useable accelerator technology**.
- [Consider **combination** of conventional and novel schemes in designs such as upgrade of conventional e^+e^- accelerator with plasma wakefield acceleration.]
- Emphasis what can be done with proton-driven scheme **using CERN infrastructure**.
- Have started to consider **realistic** applications to novel and interesting particle physics experiments:
  - **Investigation of strong-field QED.**
  - **Fixed-target/beam-dump experiments in particular those sensitive to dark photons.**
  - **Electron–proton collider up to very high energies.**
- Work ongoing studying boundary conditions / possibilities from physics, technical and integration side, e.g. de-phasing limit, repetition rate, tunnel space, etc..
- 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 presents a path** to try and do it for proton-driven plasma wakefield acceleration.

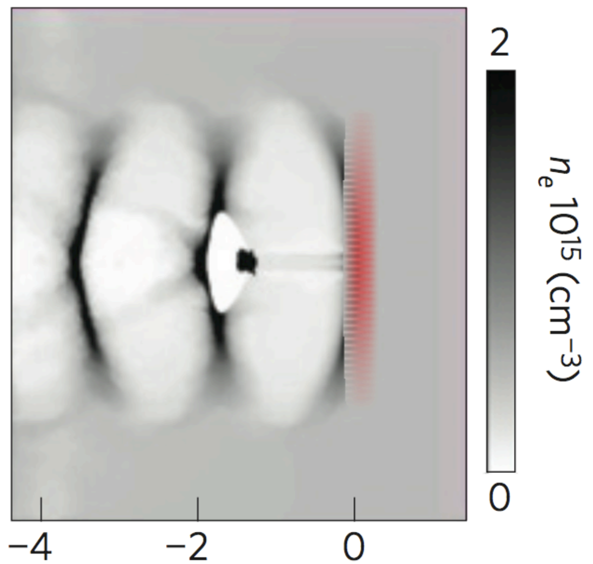
Back-up

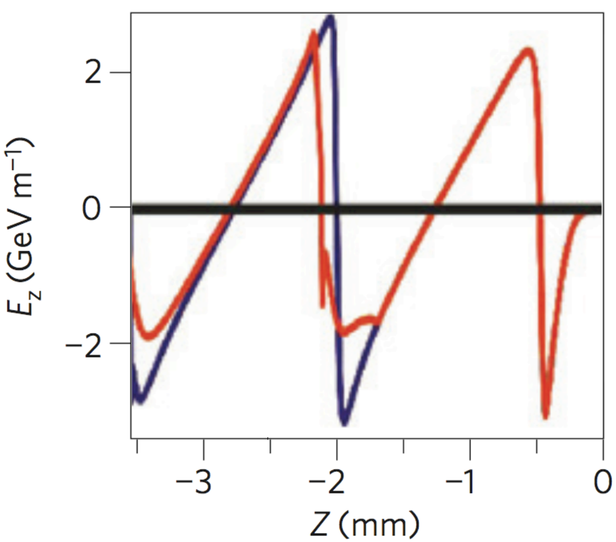
Plasma wakefield acceleration

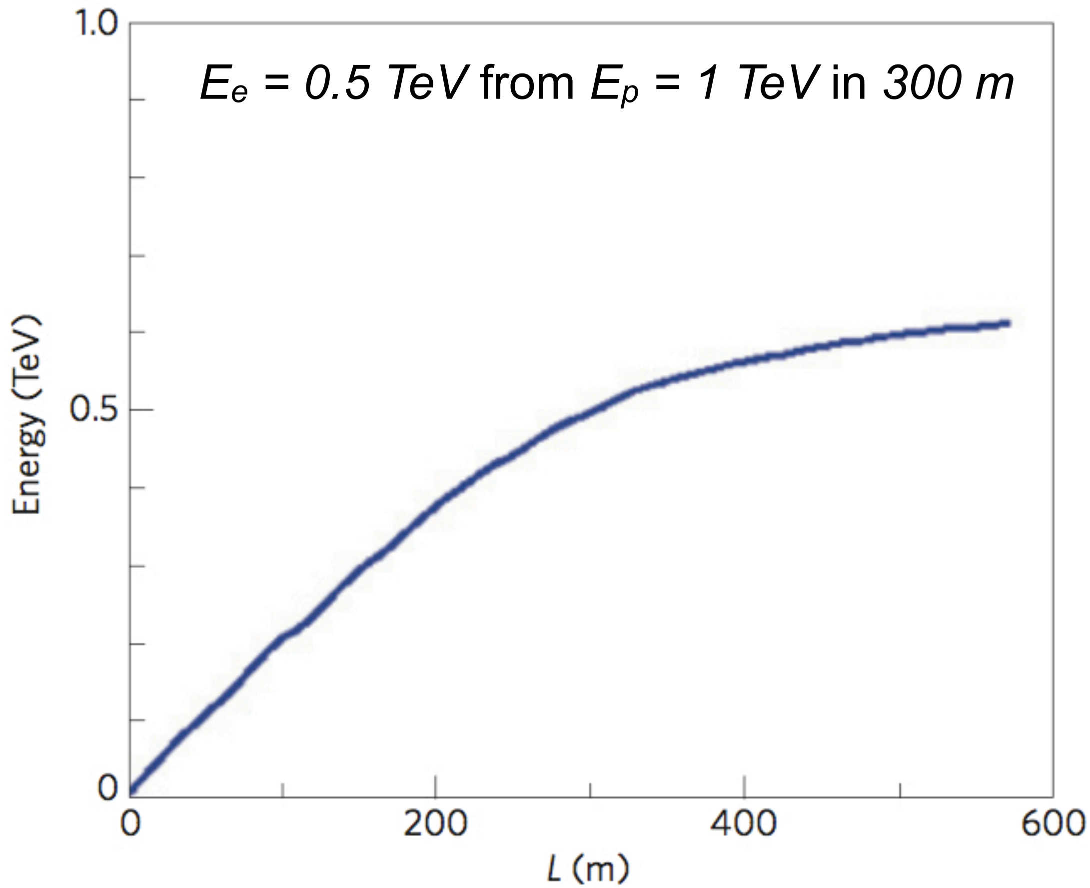


- Electrons ‘sucked in’ by proton bunch
- Continue across axis creating depletion region
- Oscillation of plasma electrons creates strong electric fields
- Longitudinal electric fields can accelerate particles in direction of proton bunch
- Transverse electric fields can focus particles
- **A ‘witness’ bunch of e.g. electrons placed appropriately can be accelerated by these strong fields**

Proton-driven plasma wakefield acceleration concept*







Note proton bunch length, *100 μm*; cf LHC, bunch length, *~10 cm*

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

Plasma considerations

Based on linear fluid dynamics :

$$\omega_p = \sqrt{\frac{n_p\, e^2}{\epsilon_0\, m_e}}$$

$$\lambda_p \approx 1\,[\mathrm{mm}]\sqrt{\frac{10^{15}\,[\mathrm{cm}^{-3}]}{n_p}} \quad \text{or} \quad \approx \sqrt{2}\,\pi\,\sigma_z$$

$$E \approx 2\,[\mathrm{GV\,m}^{-1}]\left(\frac{N}{10^{10}}\right)\left(\frac{100\,[\mu\mathrm{m}]}{\sigma_z}\right)^2$$

Relevant physical quantities :

- Oscillation frequency, ω_p
- Plasma wavelength, λ_p
- Accelerating gradient, *E*

where :

- n_p is the plasma density
- *e* is the electron charge
- ε_0 is the permittivity of free space
- m_e is the mass of electron
- *N* is the number of drive-beam particles
- σ_z is the drive-beam length

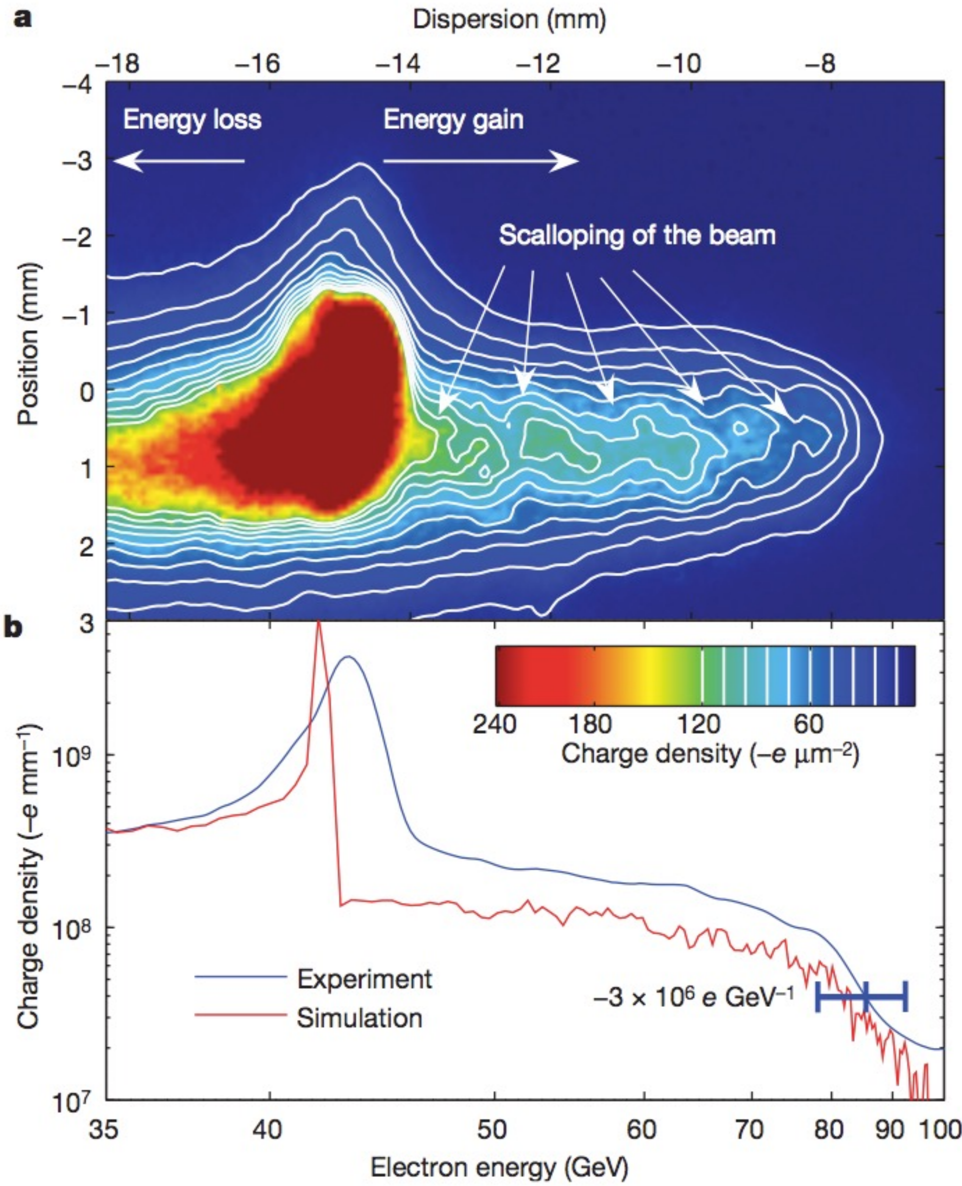
High gradients with :

- **Short drive beams** (and short plasma wavelength)
- **Pulses with large number of particles** (and high plasma density)

Plasma wakefield acceleration first proposed by T. Tajima and J.W. Dawson, Phys. Rev. Lett. **43** (1979) 267; use of particle beams proposed by P. Chen et al., Phys. Rev. Lett. **54** (1985) 693.

Plasma wakefield experiments

- Pioneering work using a LASER to induce wakefields up to *100 GV/m*.
- Experiments at SLAC[§] have used a particle (electron) beam :
    - Initial energy $E_e = 42\ GeV$
    - Gradients up to ~ *52 GV/m*
    - Energy doubled over ~ *1 m*
    - Next stage, FACET project (http://facet.slac.stanford.edu)
- Have proton beams of much higher energy :
    - CERN : *450 GeV* and *6.5 (7) TeV*
    - Can accelerate trailing electron bunch to high energy in one stage

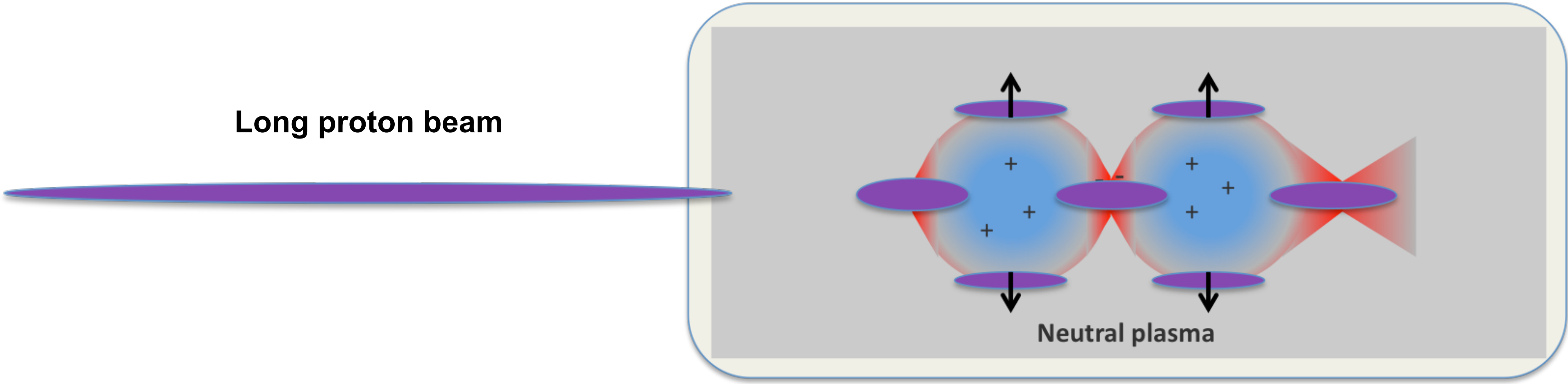


§ I. Blumenfeld et al., Nature **445** (2007) 741.

Long proton bunches ?

Use self-modulation instability where micro-bunches are generated by a transverse modulation of the bunch density.

N. Kumar, A. Pukhov, K.V. Lotov, Phys. Rev. Lett. 104 (2010) 255003

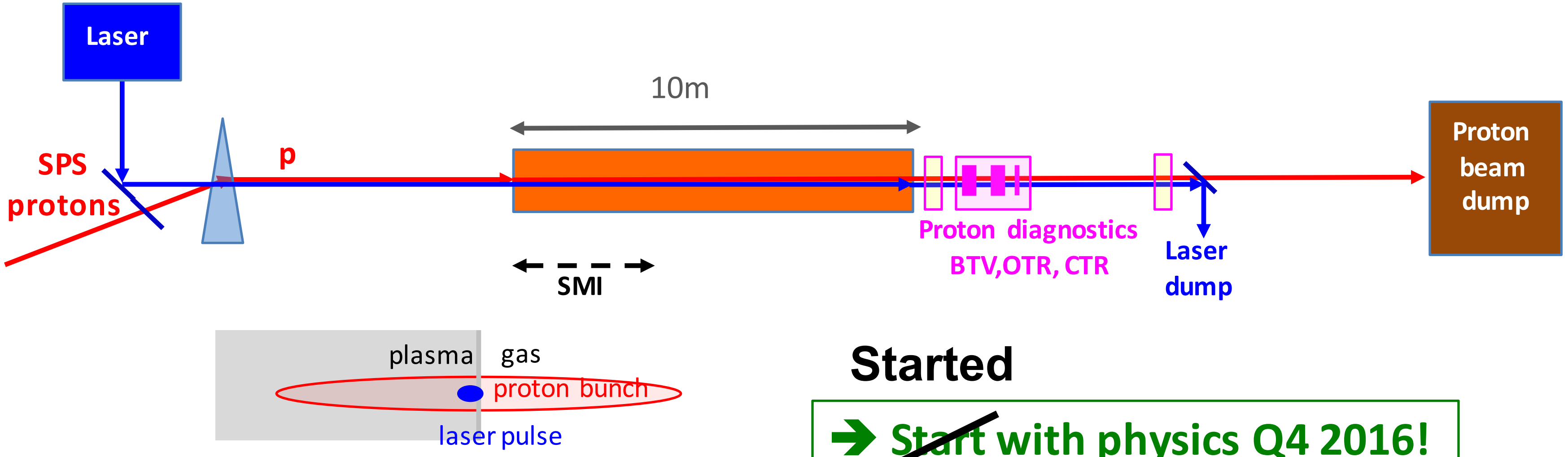


Self-modulated driver beam

- Micro-bunches are spaced λ_p apart and have an increased charge density.
- Micro-bunches constructively reinforce to give large wakefields, *GV/m*.
- Self-modulation instability allows **current beams to be used.**

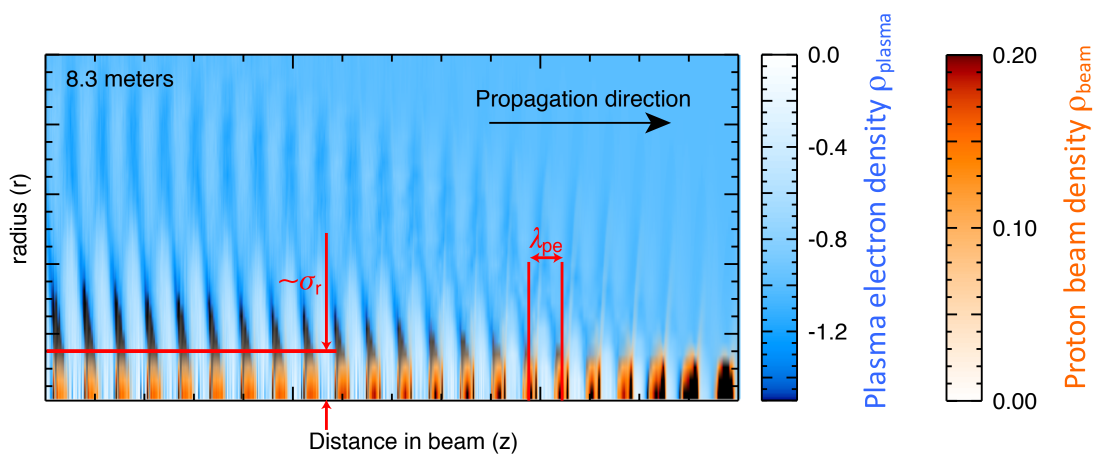
AWAKE experimental programme (Run I)

Phase 1: understand the physics of self-modulation instability process in plasma



Started

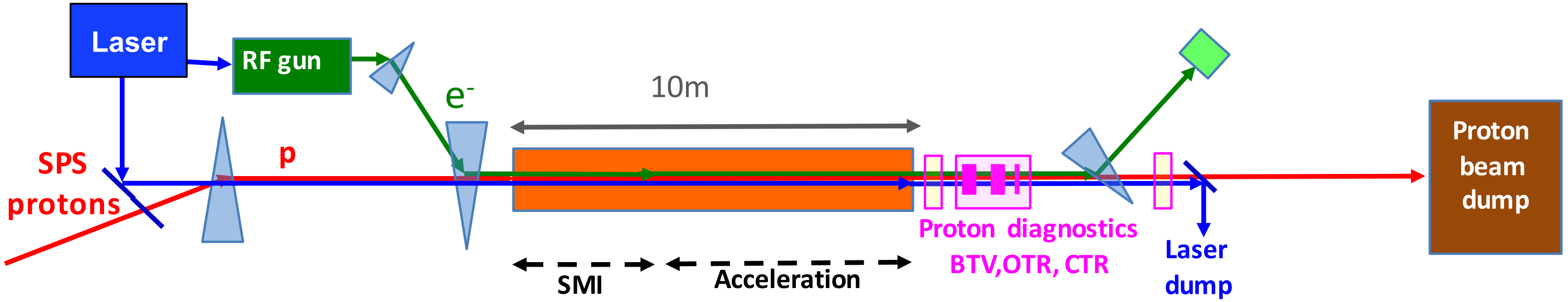
➔ ~~Start~~ with physics Q4 2016!

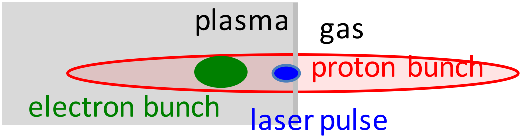


J. Vieira et al., Phys. Plasmas **19** (2012) 063105

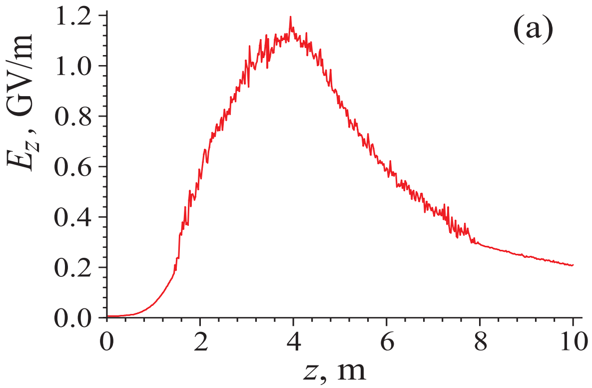
AWAKE experimental programme (Run I)

Phase 2: probe the accelerating wakefields with externally injected electrons.





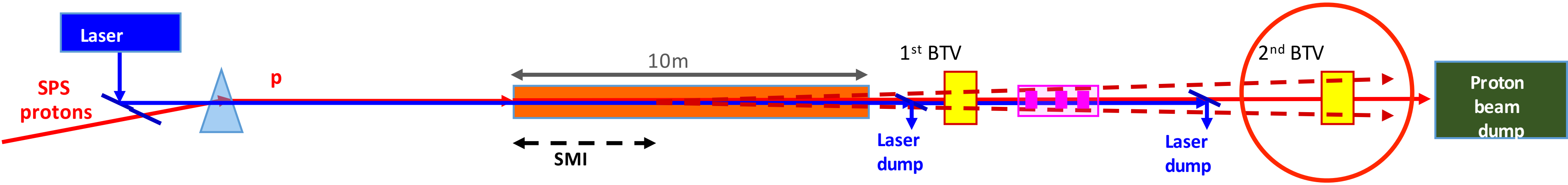
➔ Start with physics Q4 2017!

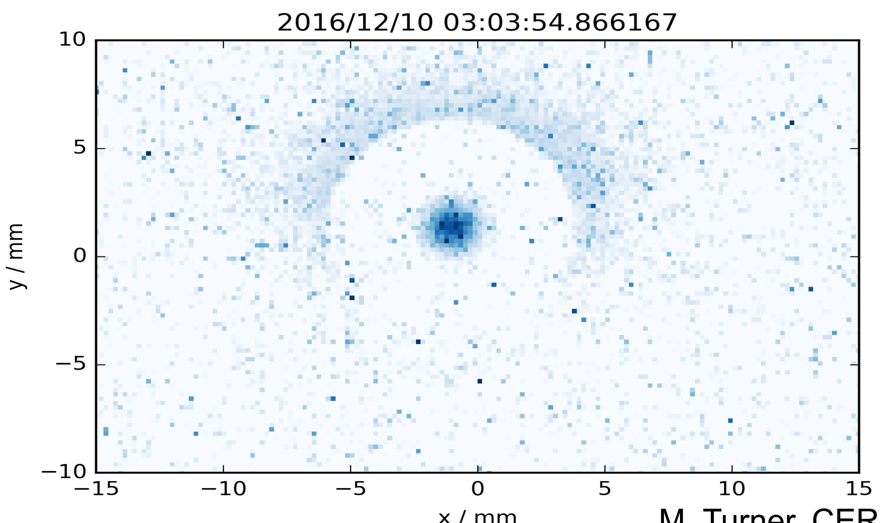


Demonstrate *GeV* acceleration of electrons with proton-driven wakefields of *GV/m*

AWAKE preliminary results

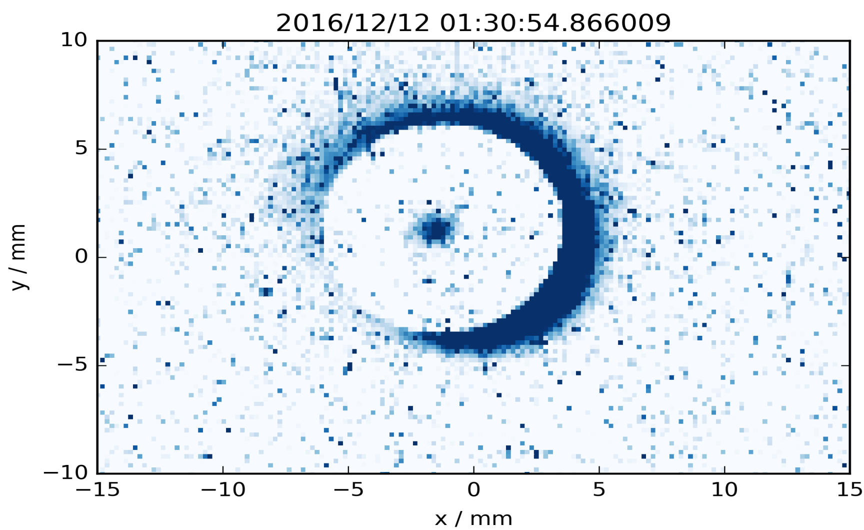
Screen composed of two materials





M. Turner, CERN

Transverse beam profile with **no plasma**



Transverse beam profile with **plasma**

Transverse blow-up of proton beam indicative of strong electric fields.

AWAKE preliminary results

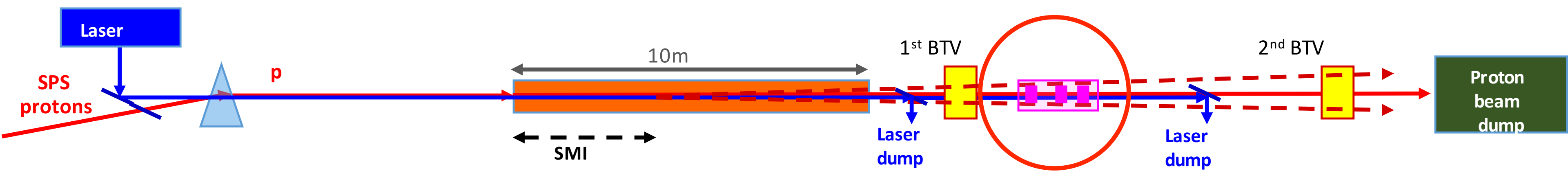
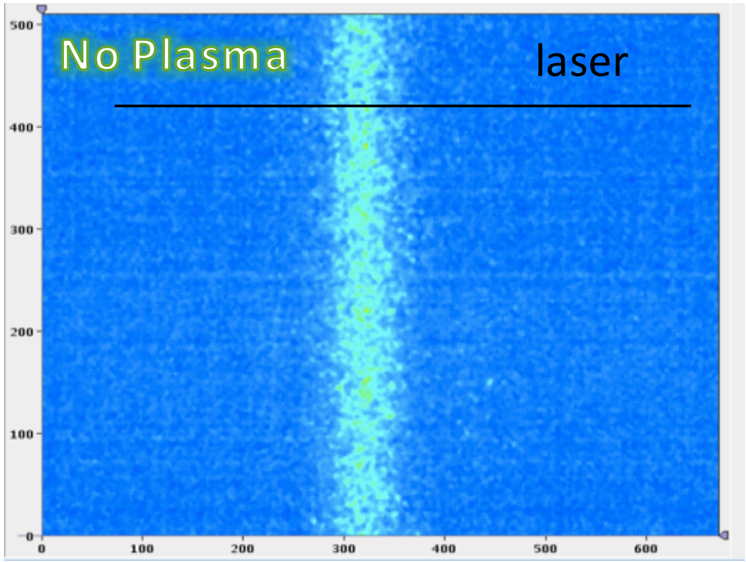
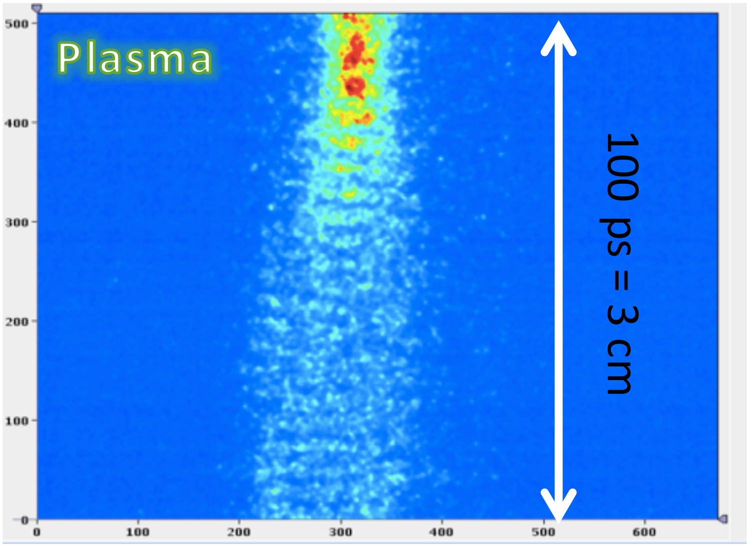


Image of OTR from the proton beam measured with a streak camera





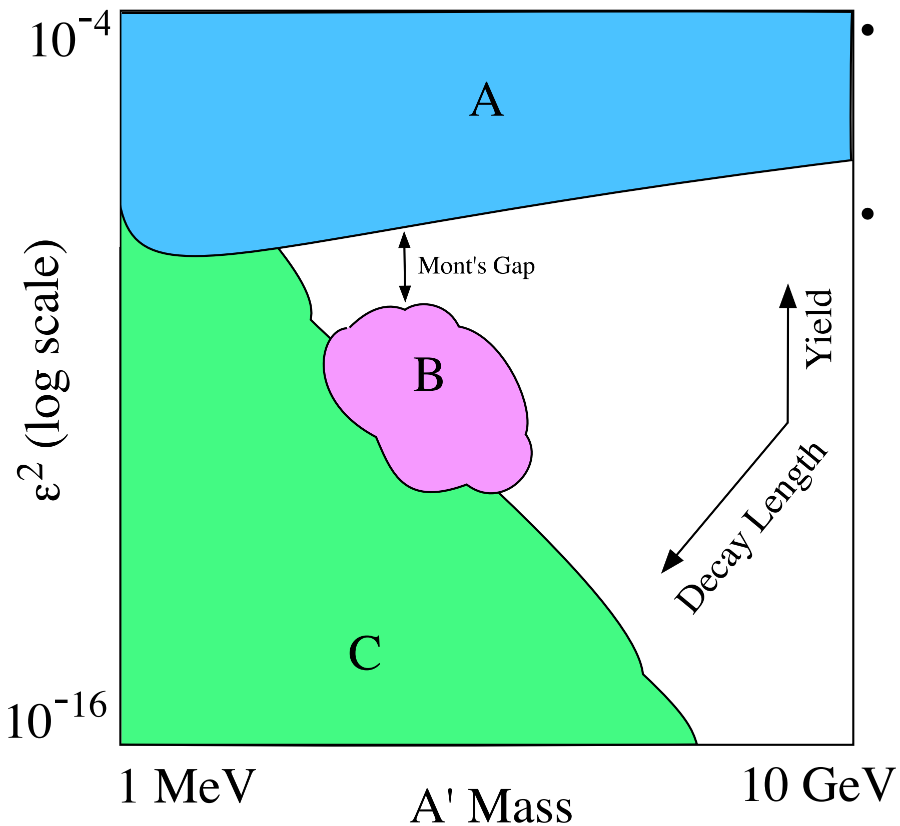
K. Rieger, MPP

Clear modulation of proton beam, with microbunching on few-mm scale expected.

Taking more data right now …

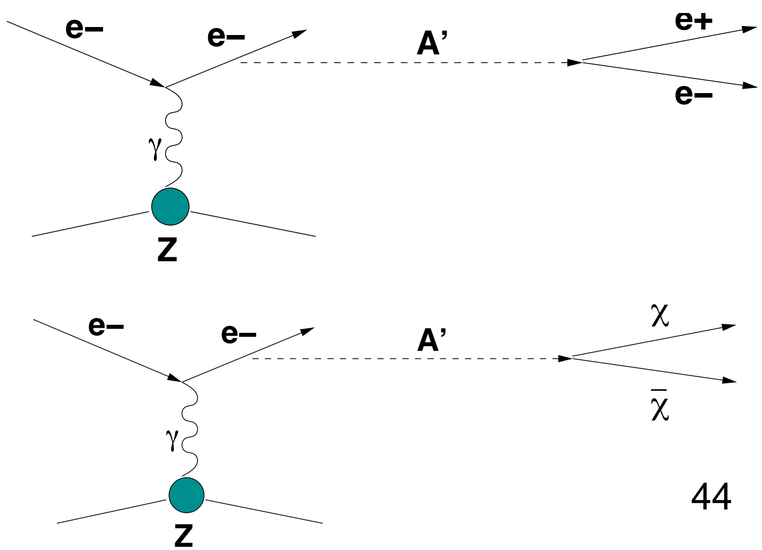
Search for dark photons

- Several ways to look for dark photons:
  - A: bump-hunting, e.g. $e^+e^- \to \gamma A'$
  - B: displaced vertices, short decay lengths
  - C: displaced vertices, long decay lengths

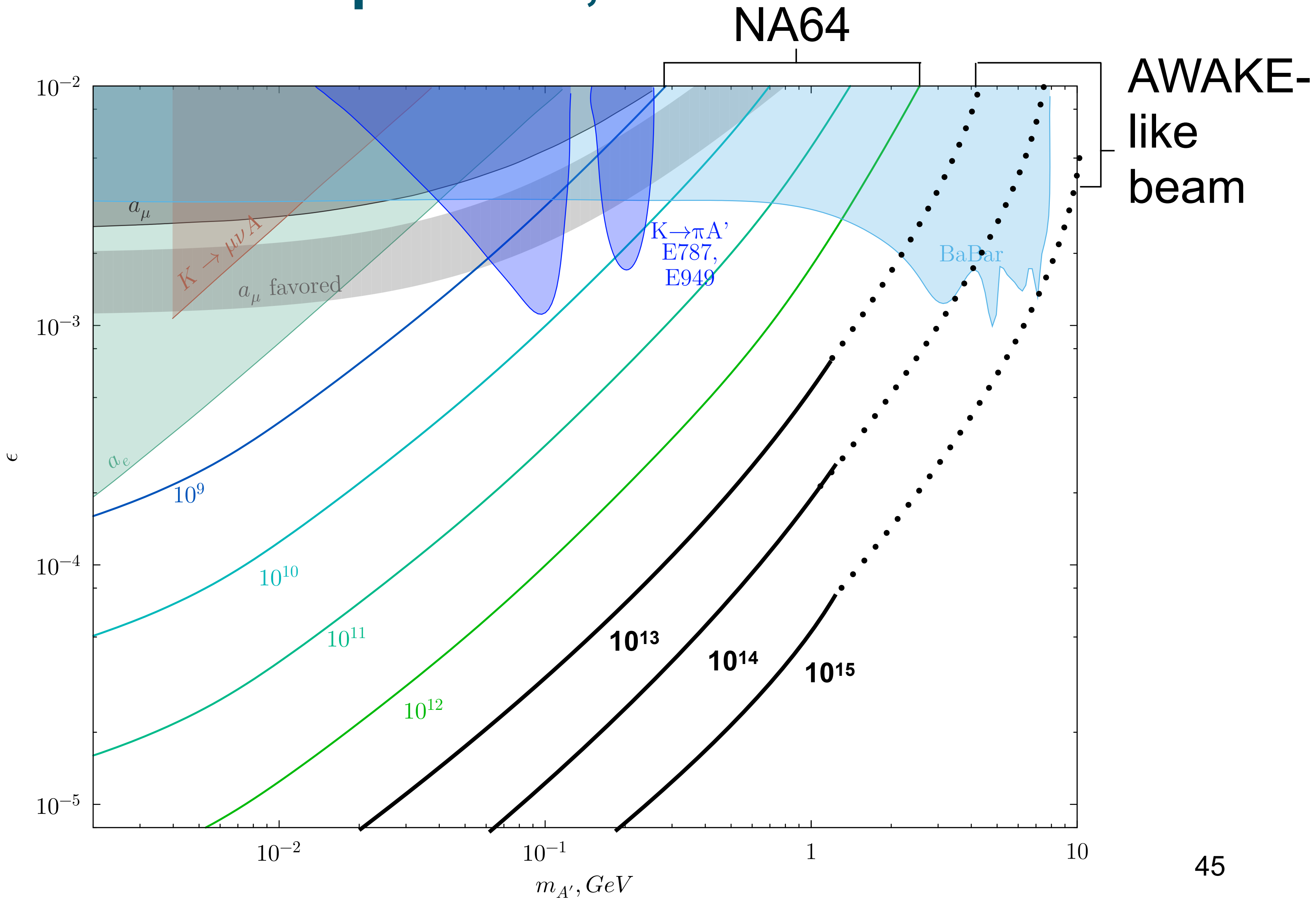


J. Alexander et al., arXiv:1608.08632

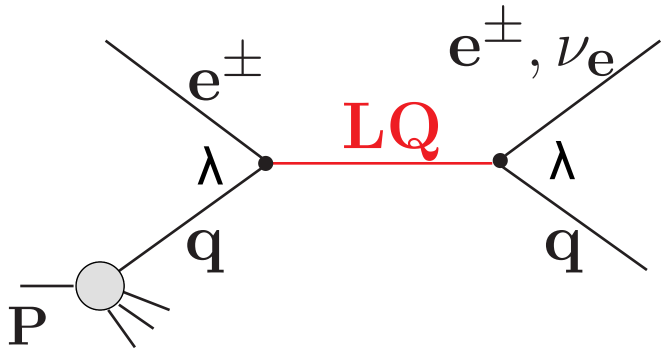
- Search for dark photons, *A′*, up to (and beyond) *GeV* mass scale via their production in a light-shining-through-a-wall type experiment.
- Use high energy electrons for beam-dump and/or fixed-target experiments.



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



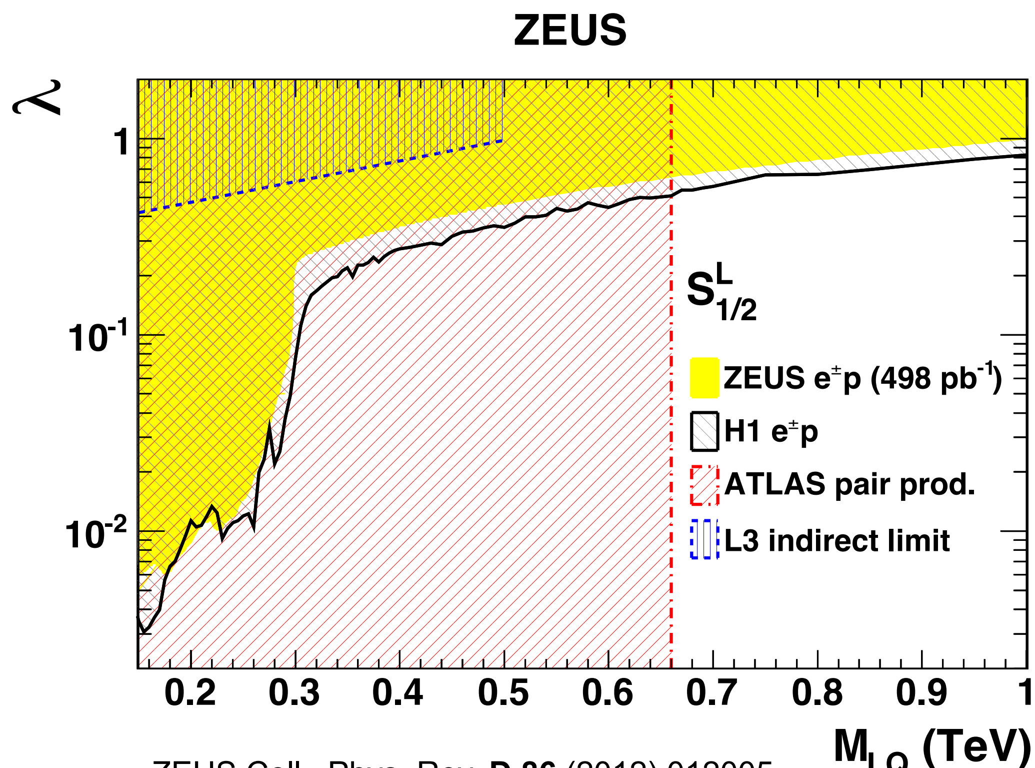
Leptoquark production



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

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

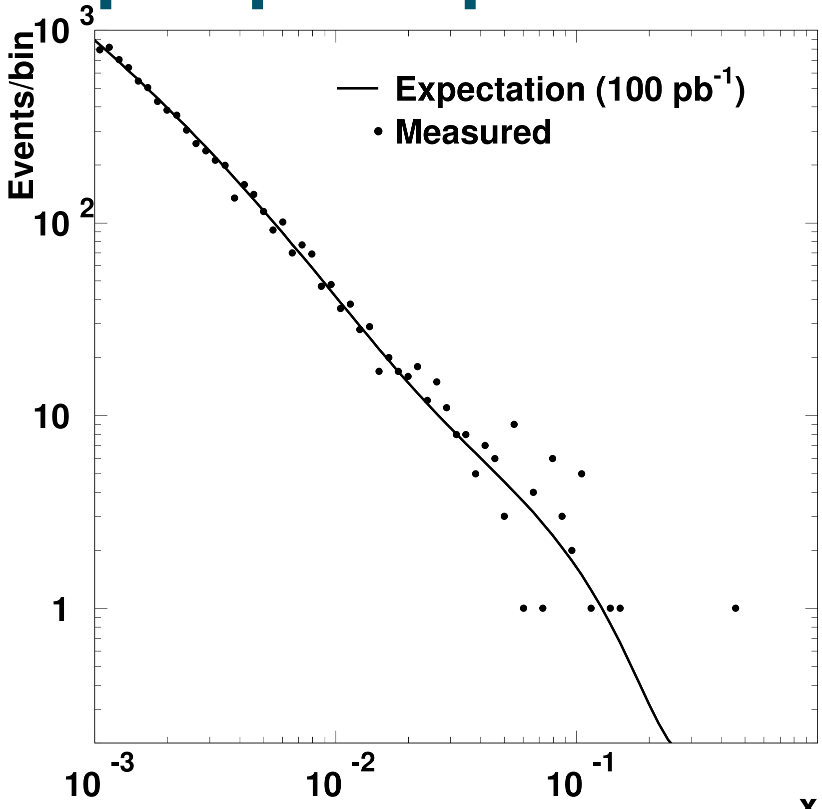
$$\sigma^{\mathrm{NWA}} = (J+1)\frac{\pi}{4s}\lambda^2 q(x_0, M_{\mathrm{LQ}}^2)$$



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

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

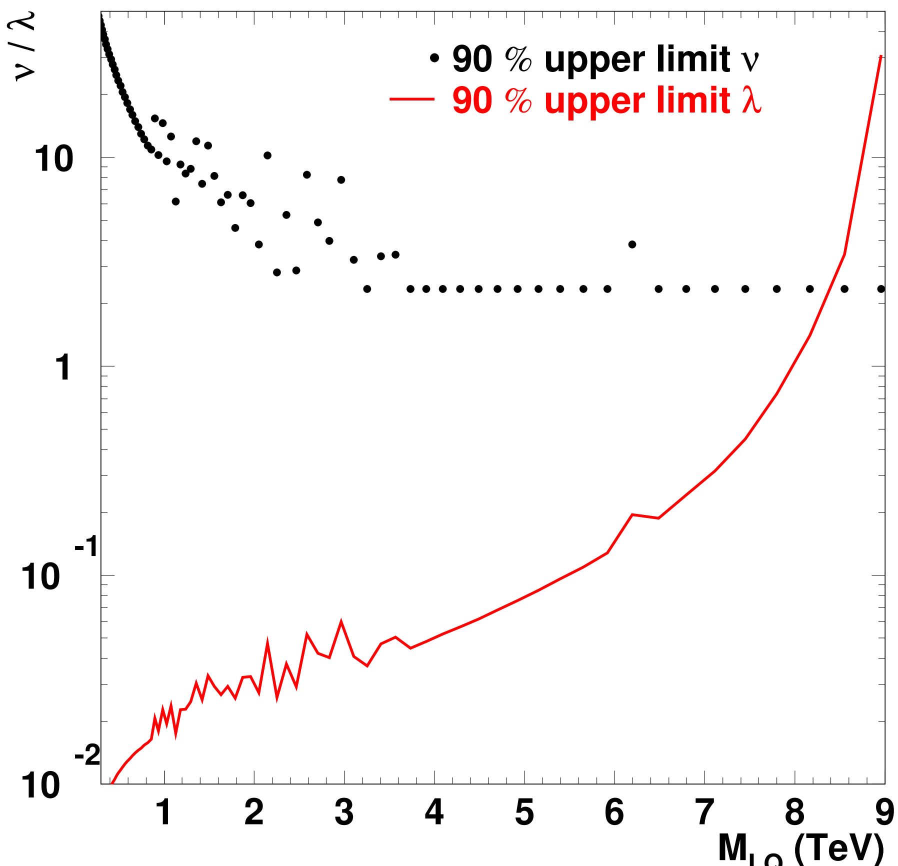
Leptoquark production at VHEeP



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).

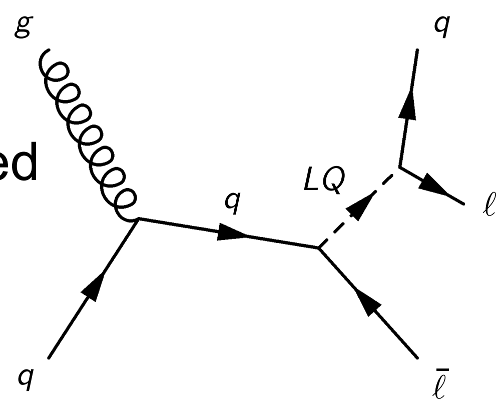


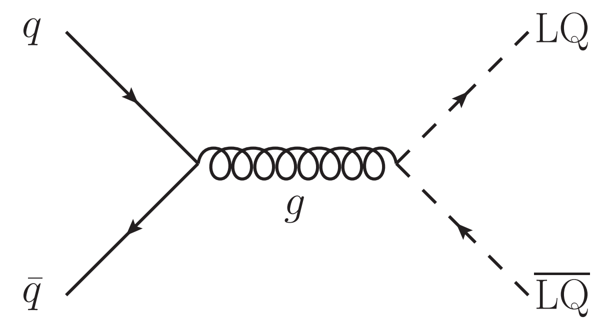
Sensitivity up to kinematic limit, 9 TeV.

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

Leptoquark production at the LHC

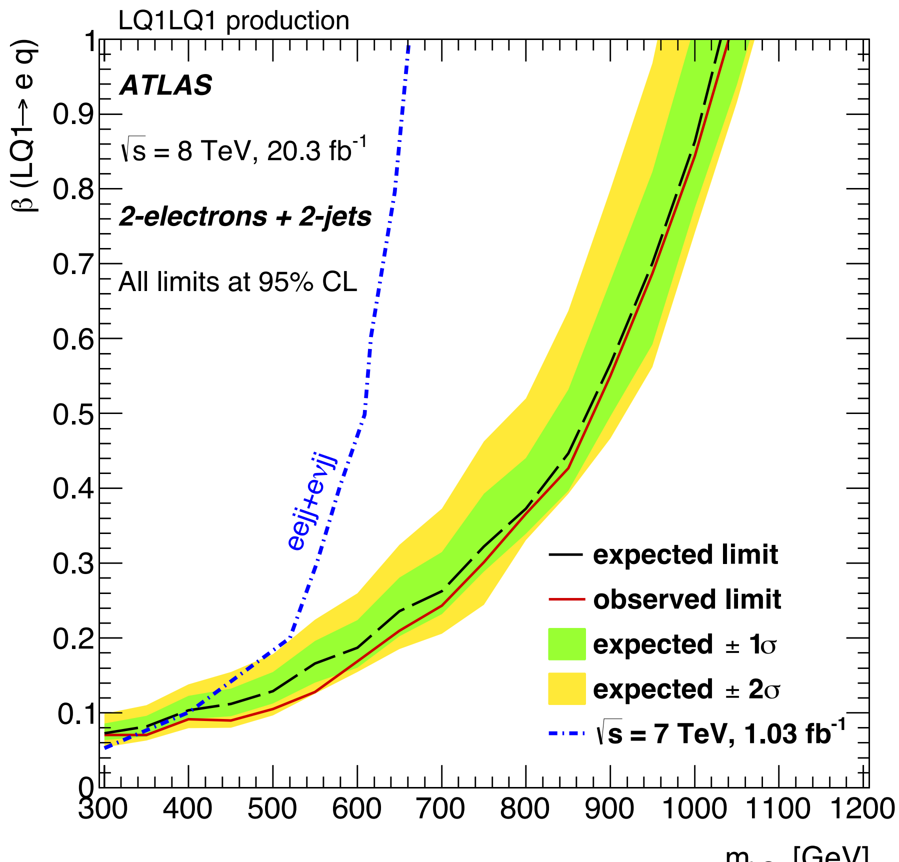
Can also be produced in *pp* singly or pair production





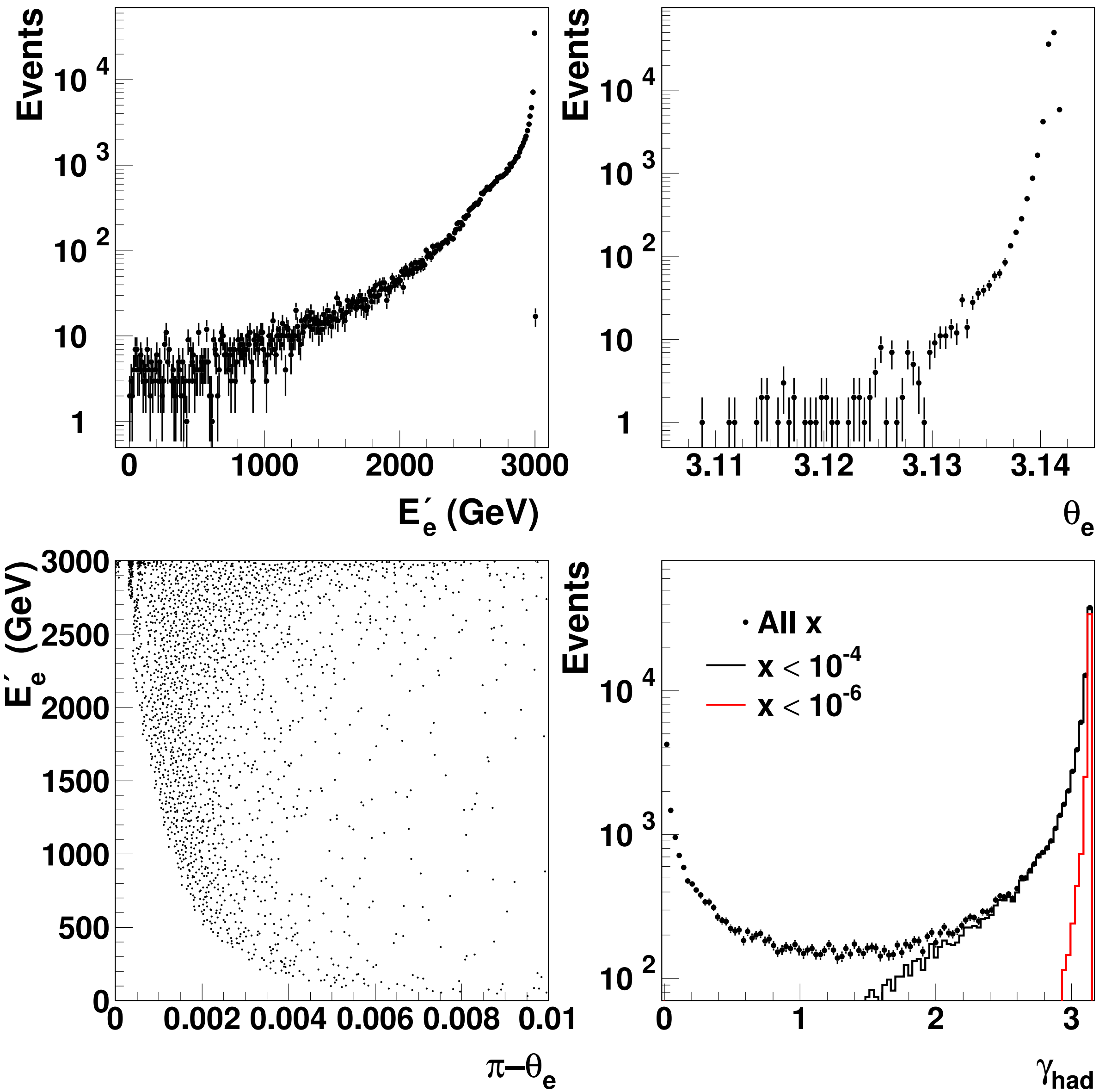
Reach of LHC currently about *1 TeV*, to increase to *2 − 3 TeV*.

Coupling dependent.



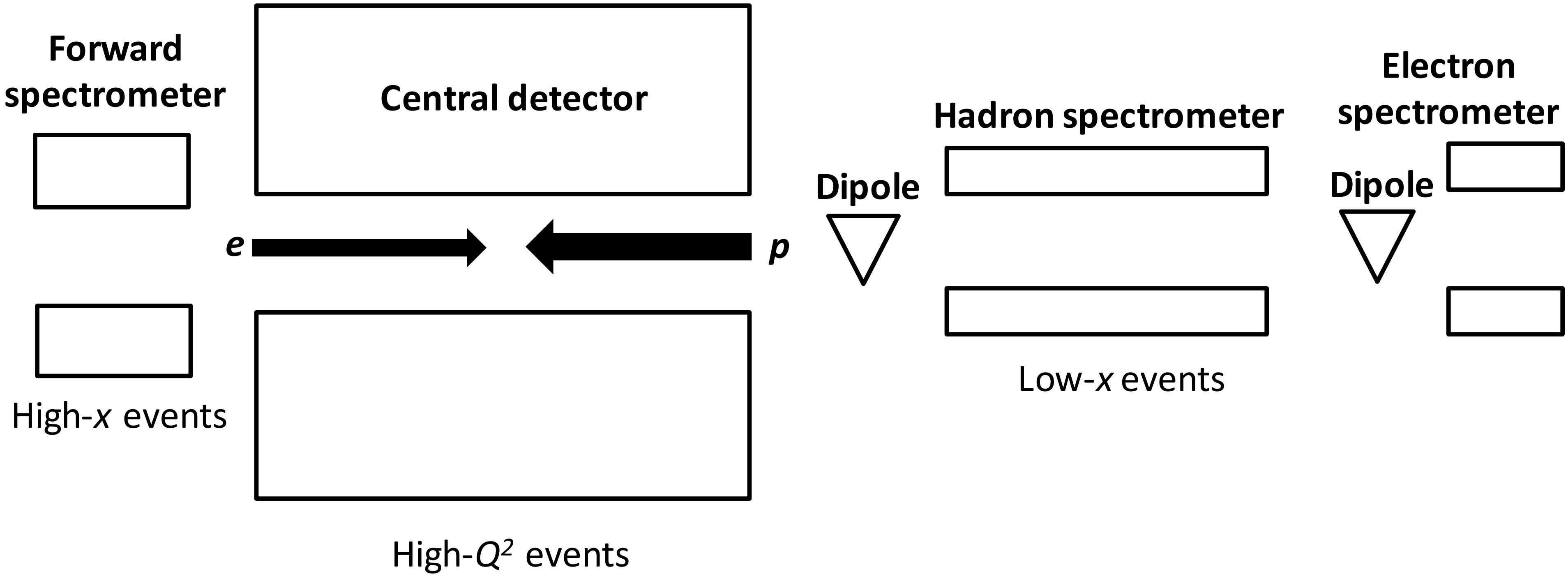
ATLAS Coll., Eur. Phys. J. **C 76** (2016) 1

Kinematics of the final state



- Simulated events $Q^2 > 1$ 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.**

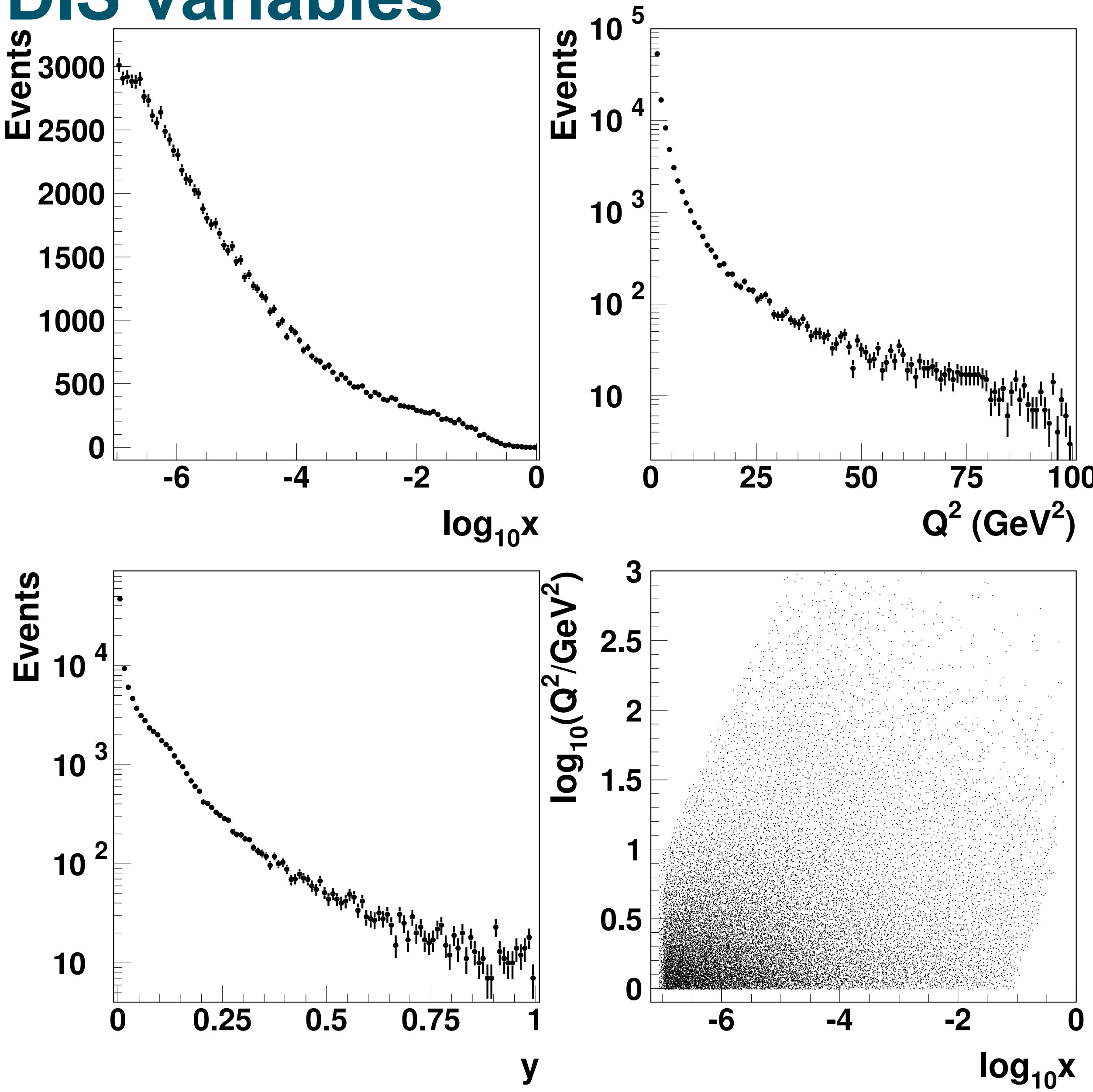
Sketch of detector



• 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 high *x*.**

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.