An electron beam for physics experiments based on an AWAKE scheme

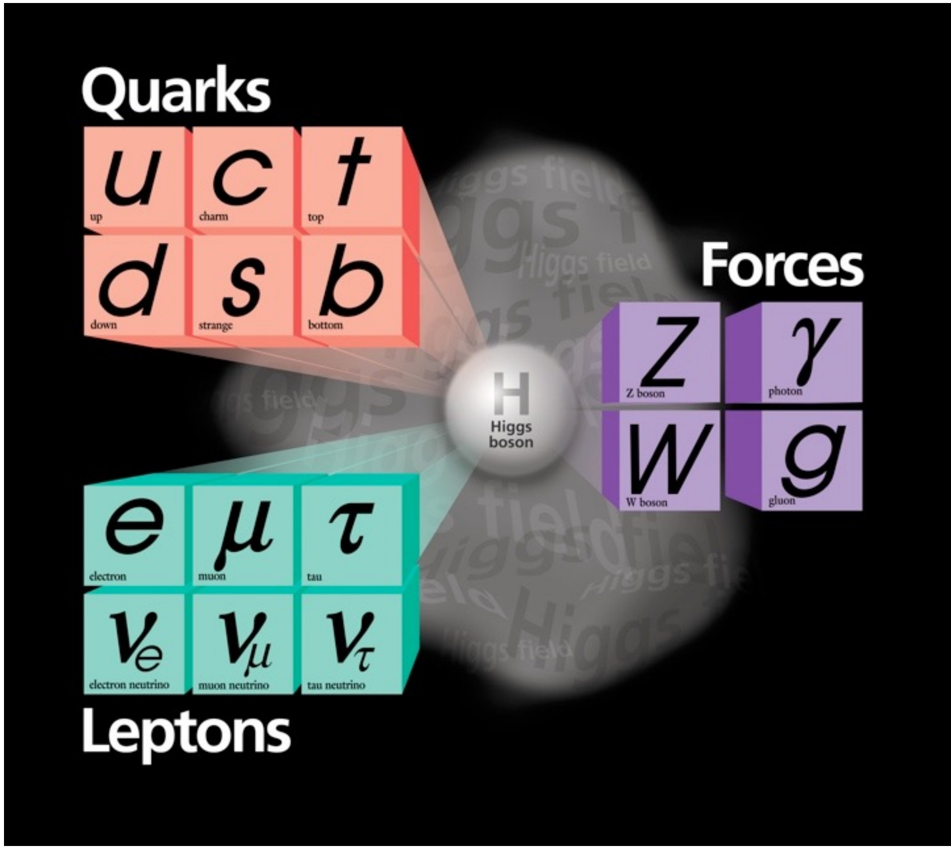
Matthew Wing (UCL)

- Introduction and motivation
- Plasma wakefield acceleration
- The AWAKE Experiment at CERN
- 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

Motivation: big questions in particle physics

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

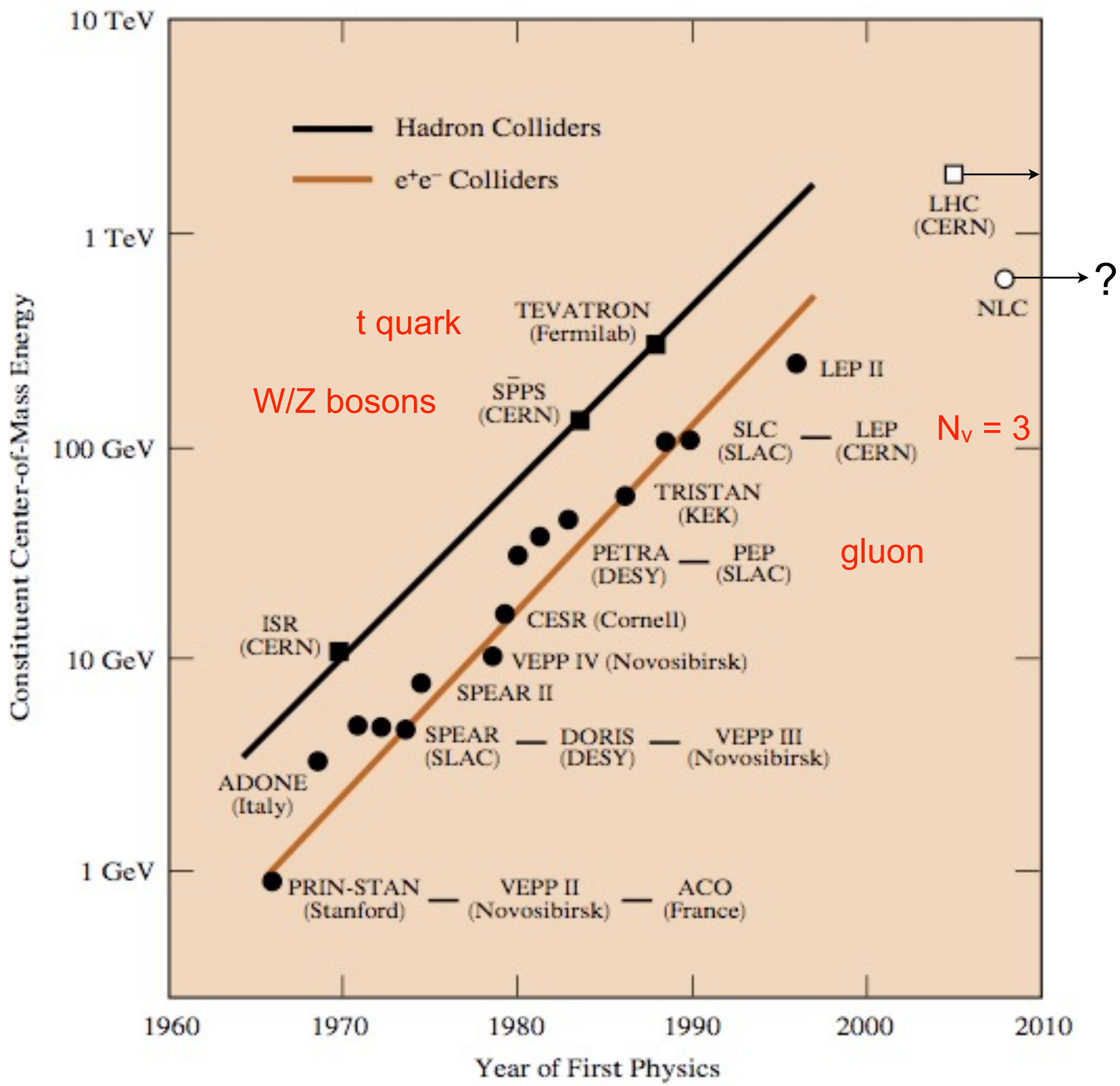
- a detailed understanding of the Higgs Boson/mechanism
- neutrinos and their masses
- why is there so much matter (vs anti-matter) ?
- why is there so little matter (*5%* of Universe) ?
- what is dark matter and dark energy ? Does supersymmetry occur at the *TeV* scale
- why are there three families ?
- 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.

• 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 :

- we need high-energy beams (~ *TeV*);
- high repetition rate and high number of particles per bunch;
- efficient and highly reproducible beam production;
- small beams sizes (potentially down to *nm* scale);
- large-scale accelerator complex.

• Ultimate goal : can we have *TeV* beams produced in a accelerator structure of a few *km* in length ?

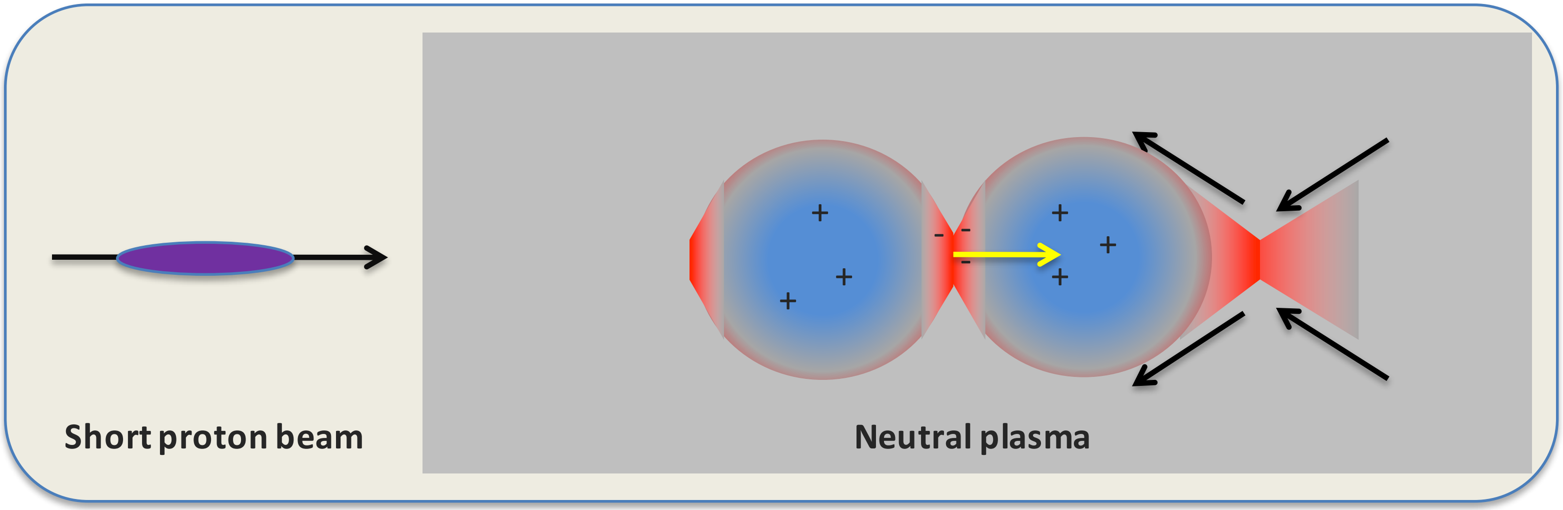
• Here consider realistic applications:

- 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.

Plasma wakefield acceleration and AWAKE

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 at the appropriate place can be accelerated by these strong fields

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

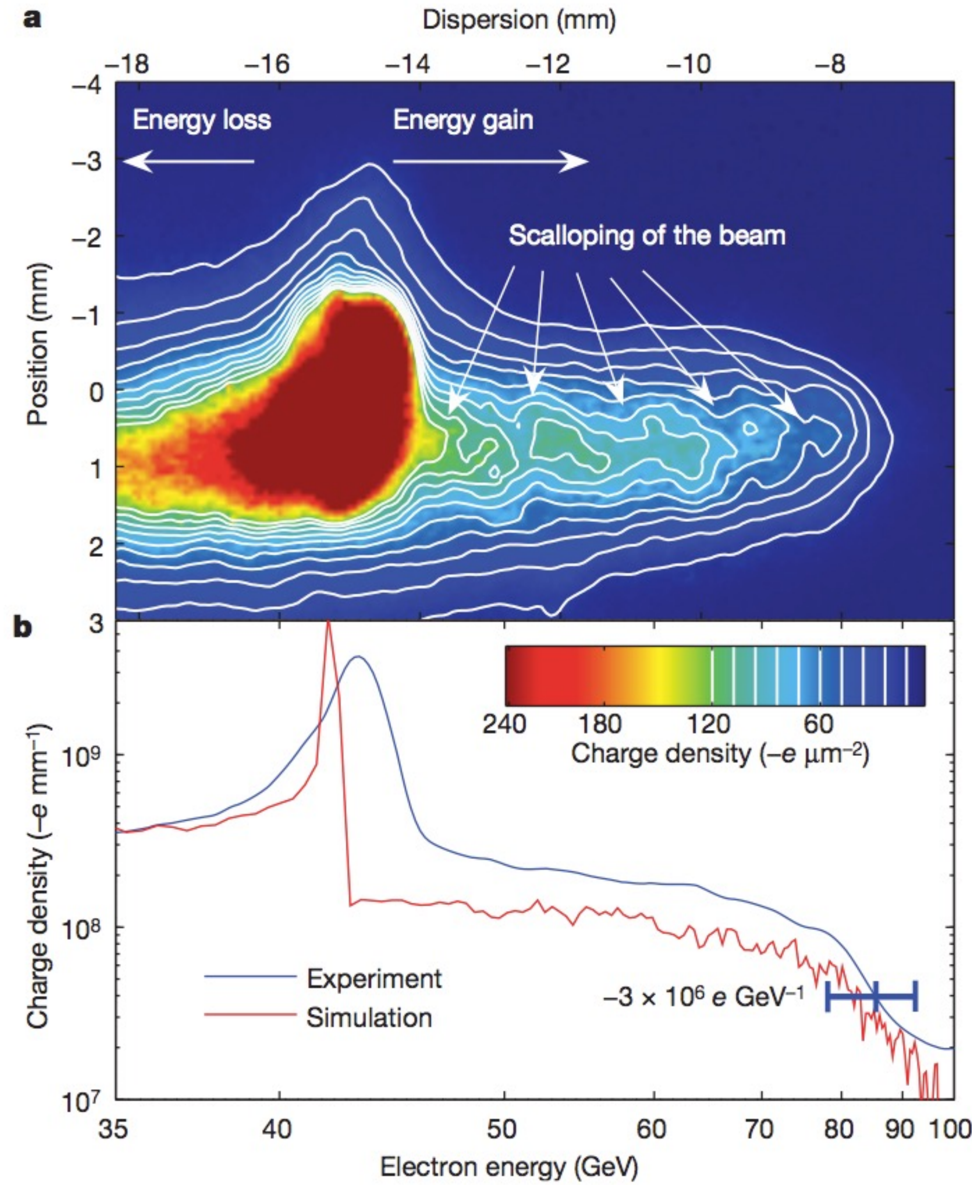
High gradients with :

- **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.

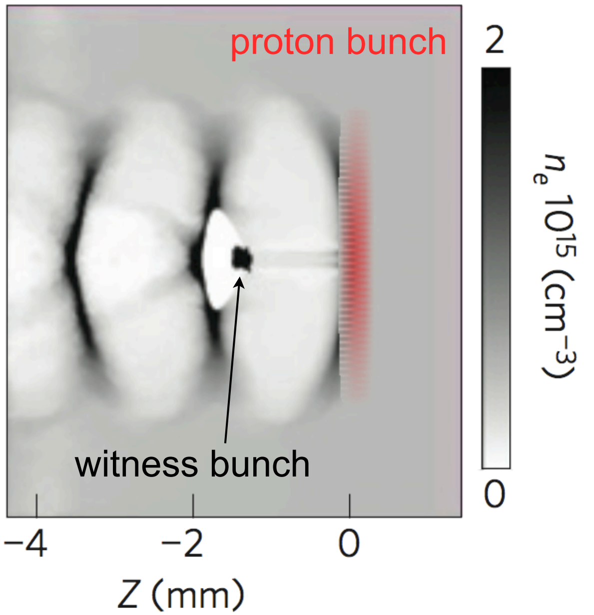
Plasma wakefield experiments

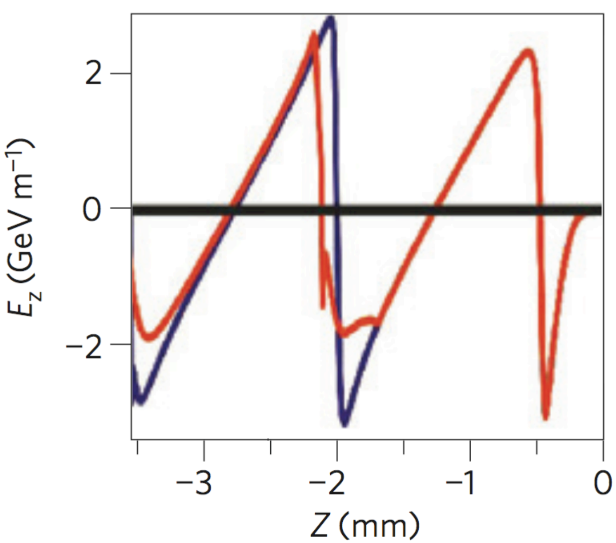
- Pioneering work using a LASER to induce wakefields up to *100 GV/m*.
- Experiments at SLAC§ have used a particle (electron) beam :
    - Initial energy E_e = *42 GeV*
    - Gradients up to ~ *52 GV/m*
    - Energy doubled over ~ *1 m*
    - Next stage, FACET project (http://facet.slac.stanford.edu)
- 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

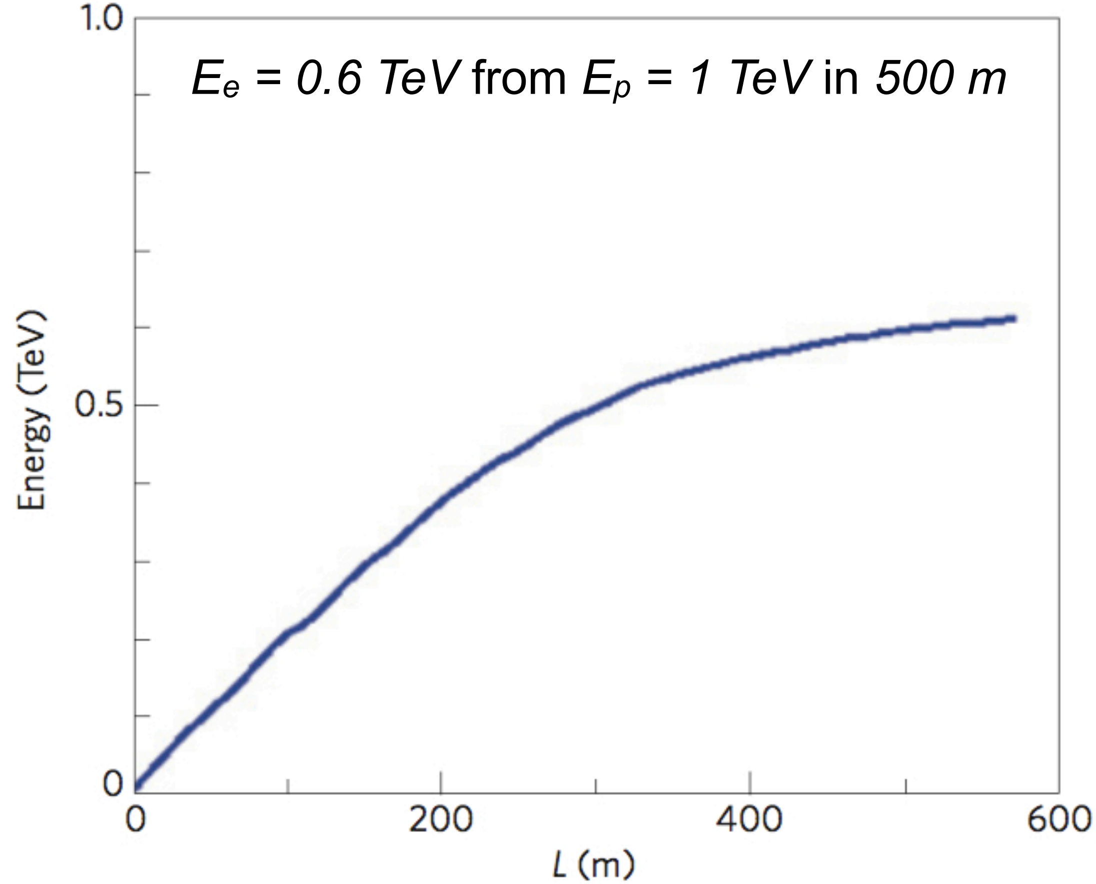


§ I. Blumenfeld et al., Nature **445** (2007) 741.

Proton-driven plasma wakefield acceleration concept*



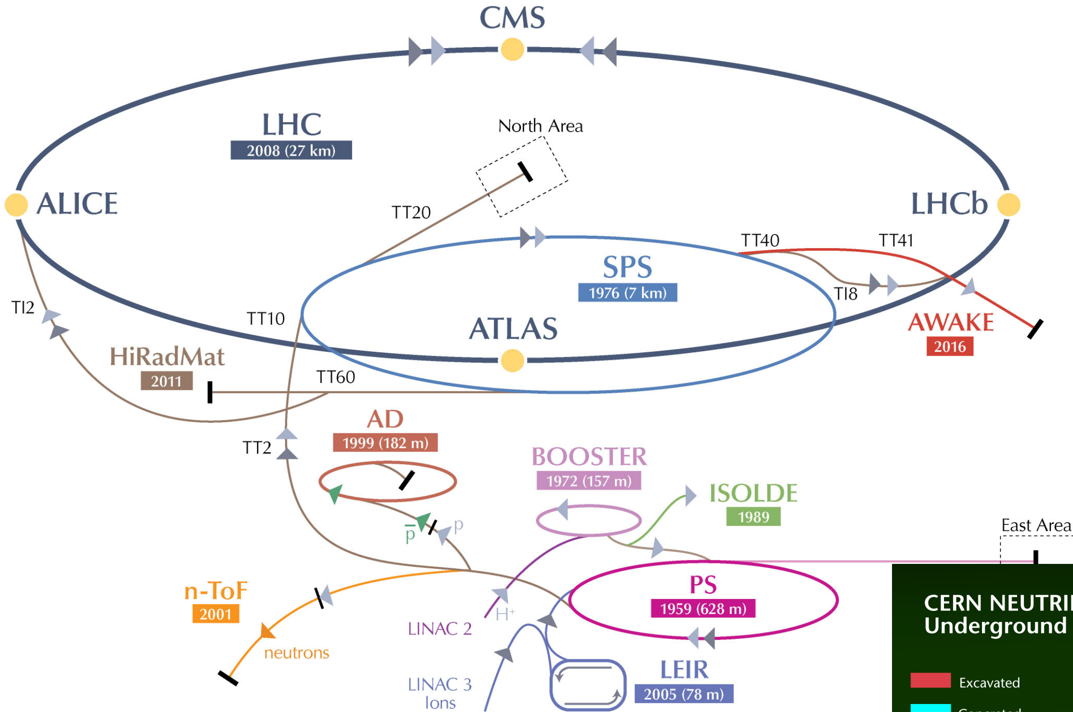




Note proton bunch length, *100 µm*; cf LHC, bunch length, *~10 cm*

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

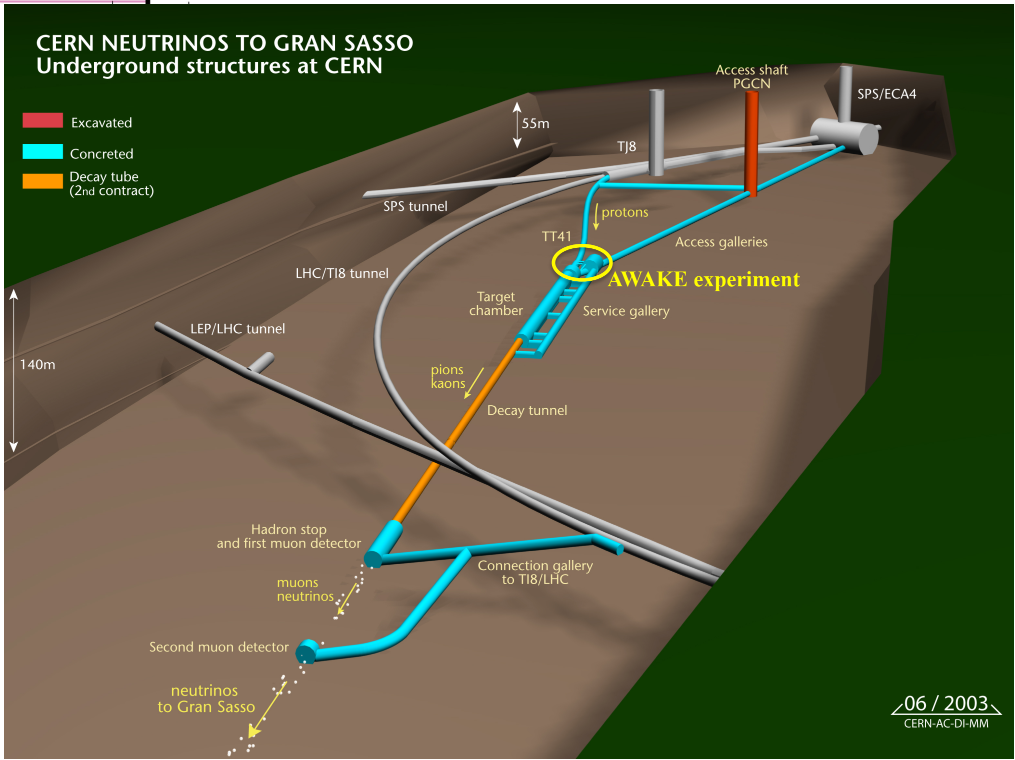
AWAKE experiment at CERN



Demonstrate for the first time proton-driven plasma wakefield acceleration.

Advanced proton-driven plasma wakefield experiment.

Using *400 GeV* SPS beam in former CNGS target area.

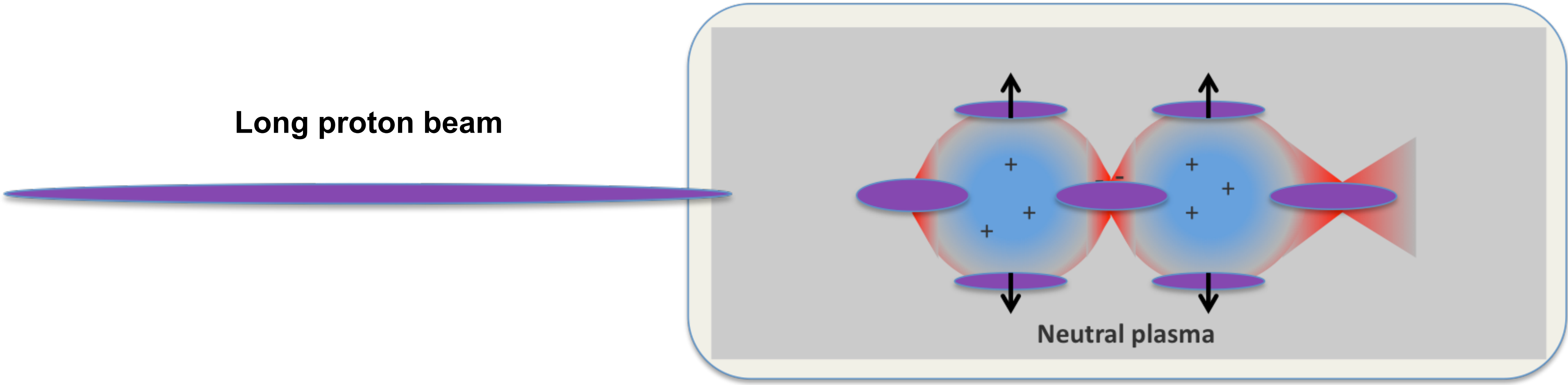


AWAKE Coll., R. Assmann et al., Plasma Phys. Control. Fusion **56** (2014) 084013

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

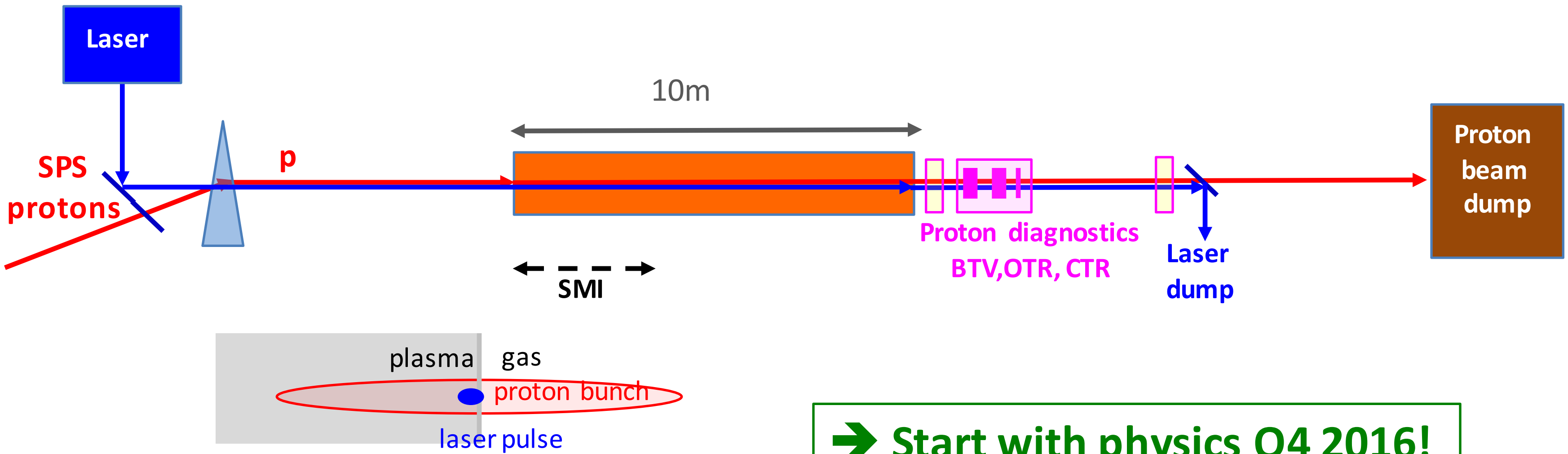


Self-modulated driver beam

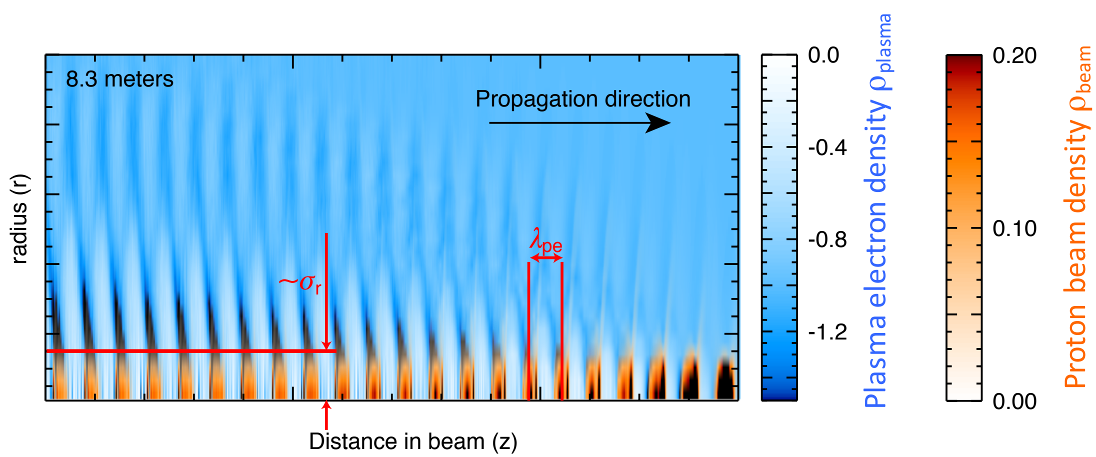
- Micro-bunches are spaced λ_p apart and have an increased charge density.
- Micro-bunches constructively reinforce to give large wakefields, *GV/m*.
- Self-modulation instability allows **current beams to be used.**

AWAKE experimental programme (Run I)

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



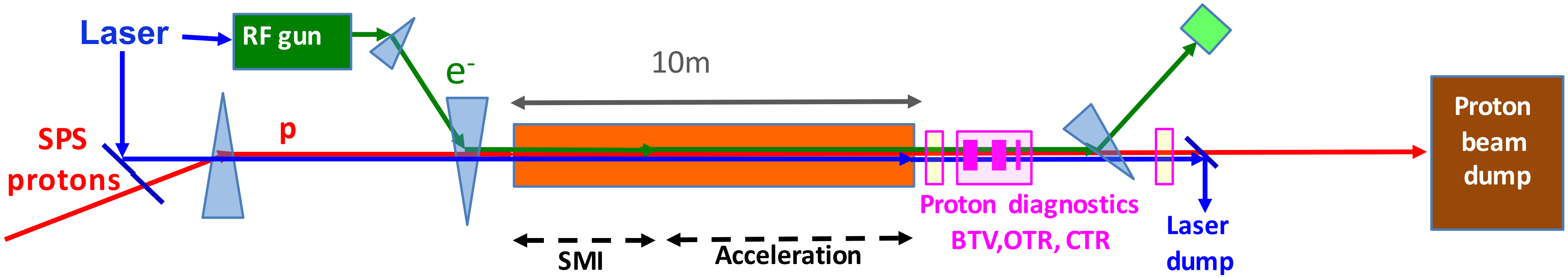
➔ **Start with physics Q4 2016!**

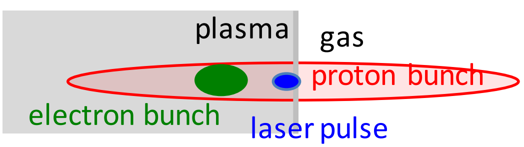


J. Vieira et al., Phys. Plasmas **19** (2012) 063105

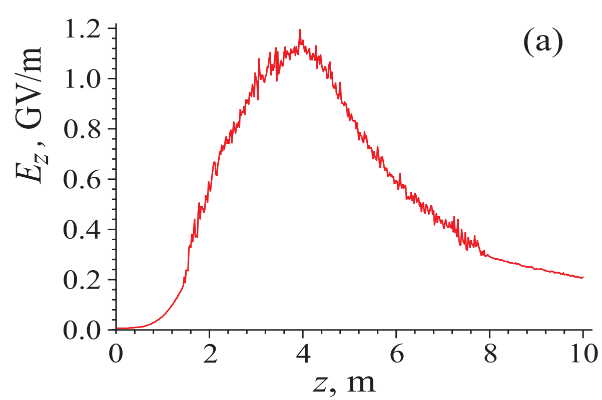
AWAKE experimental programme (Run I)

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





➔ **Start with physics Q4 2017!**

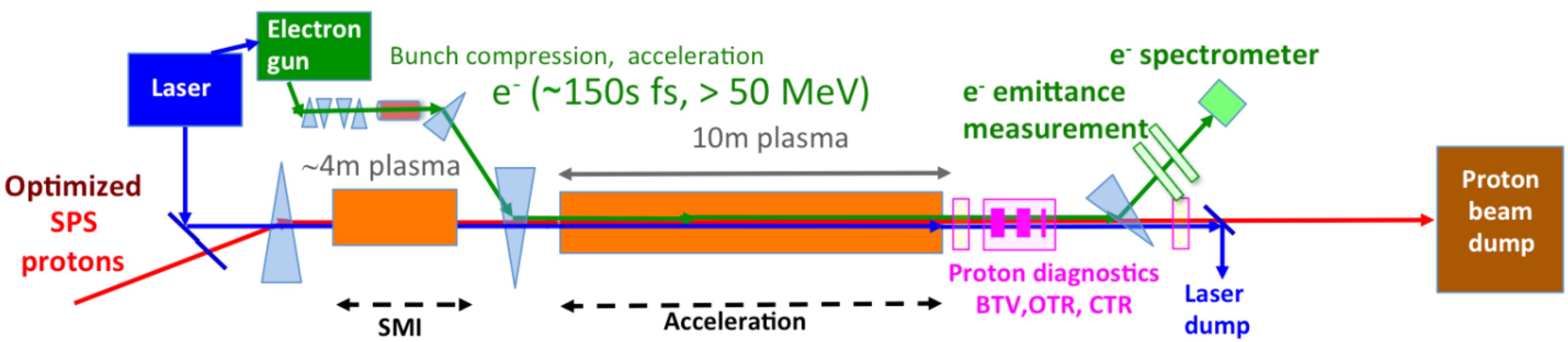


Demonstrate *GeV* acceleration of electrons with proton-driven wakefields of *GV/m*

An AWAKE-like beam for particle physics

AWAKE Run II

- 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 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 scattering.
  - Measurements at high *x*, momentum fraction of struck parton in the proton, with higher statistics than previous experiments.
  - Polarised beams and spin structure of the nucleon. The "proton spin crisis/puzzle" is still a big unresolved issue.

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.
  - A very high energy electron−proton collider.

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

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

Experiments to search for the dark sector based on AWAKE scheme

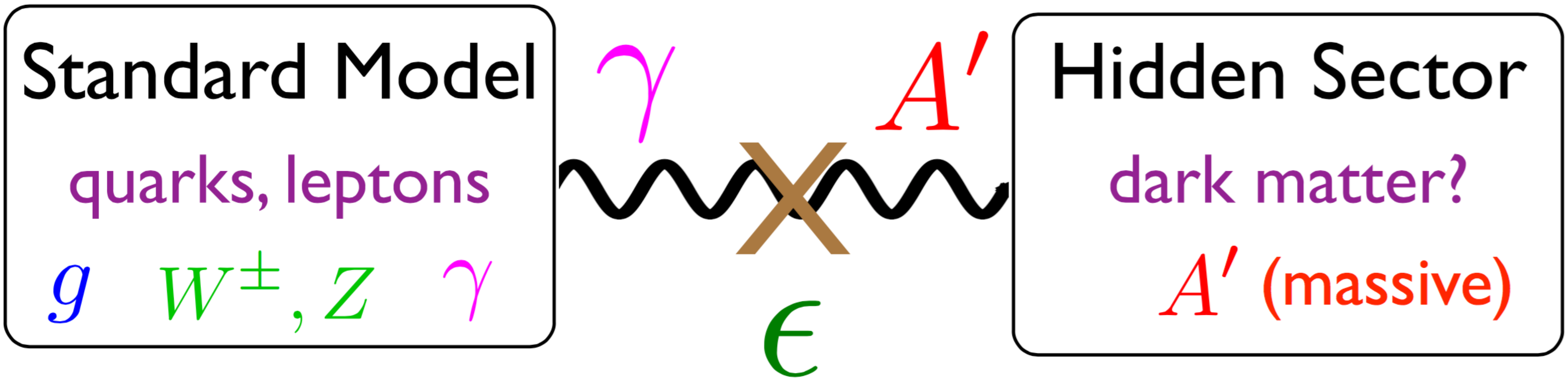
The hidden / dark sector

- 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

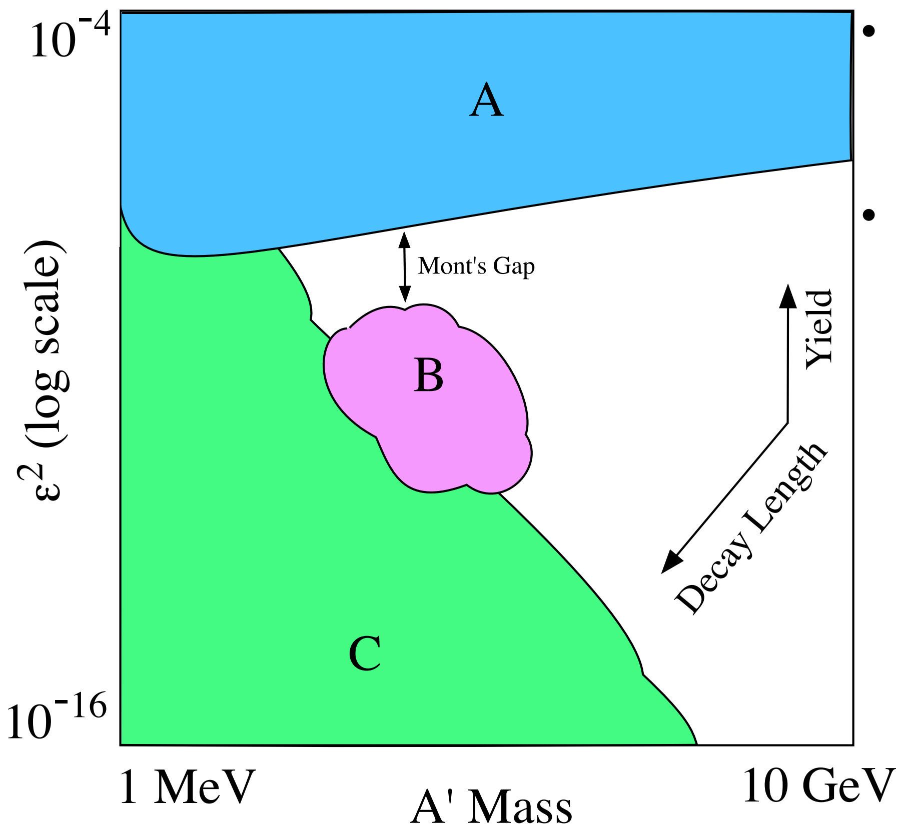


$$\Delta\mathcal{L} = \frac{\epsilon}{2} F^{Y,\mu\nu} F'_{\mu\nu}$$

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

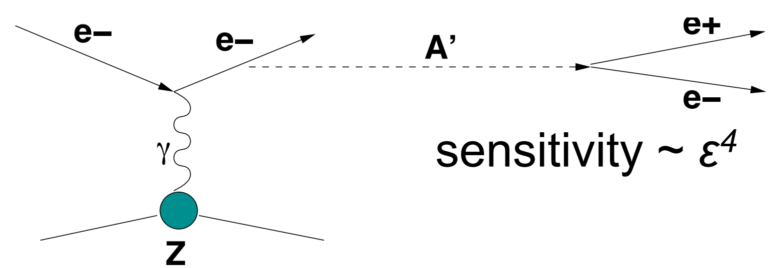
Search for dark photons

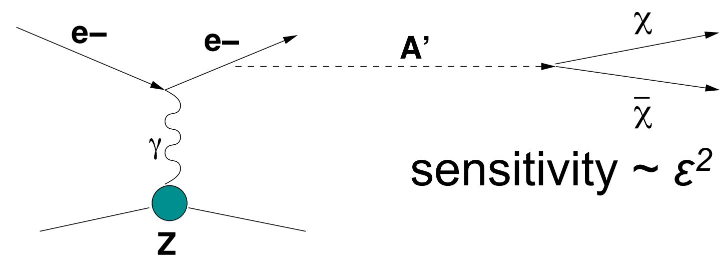
- Several ways to look for dark photons:
  - A: bump-hunting, e.g. $e^+e^- \rightarrow \gamma A'$
  - B: displaced vertices, short decay lengths
  - C: displaced vertices, long decay lengths



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.





NA64 experimental programme

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

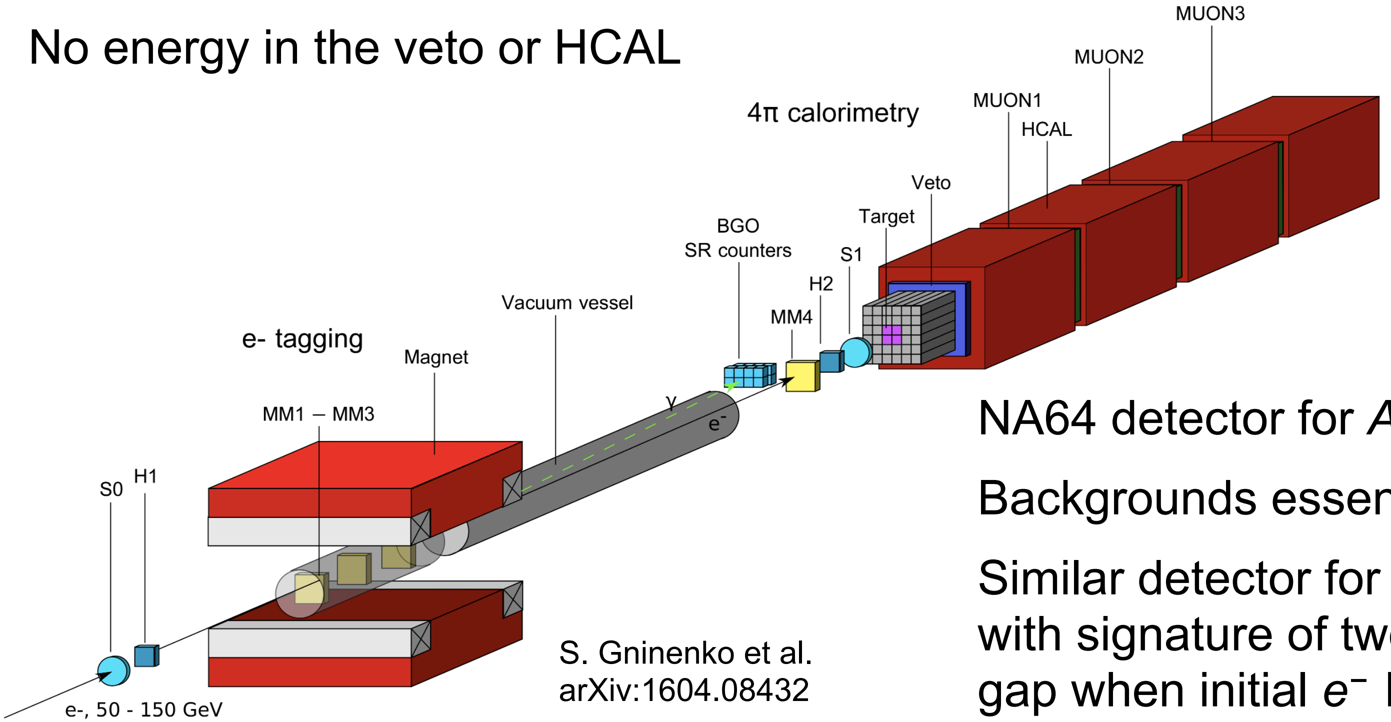
See various papers/proposals from them.

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 ~ 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 ~ 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.

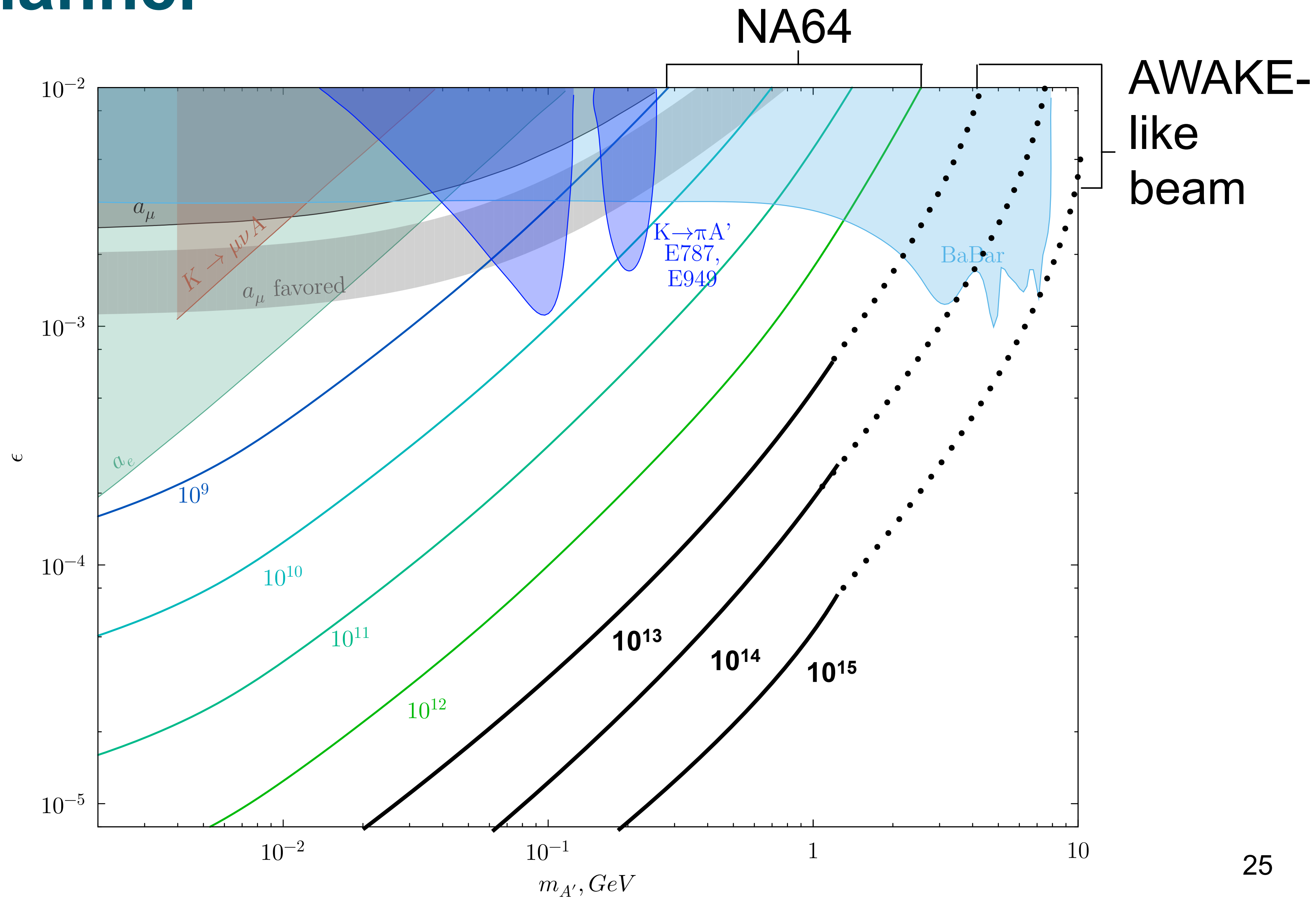
Sensitivity with increased electrons on target

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

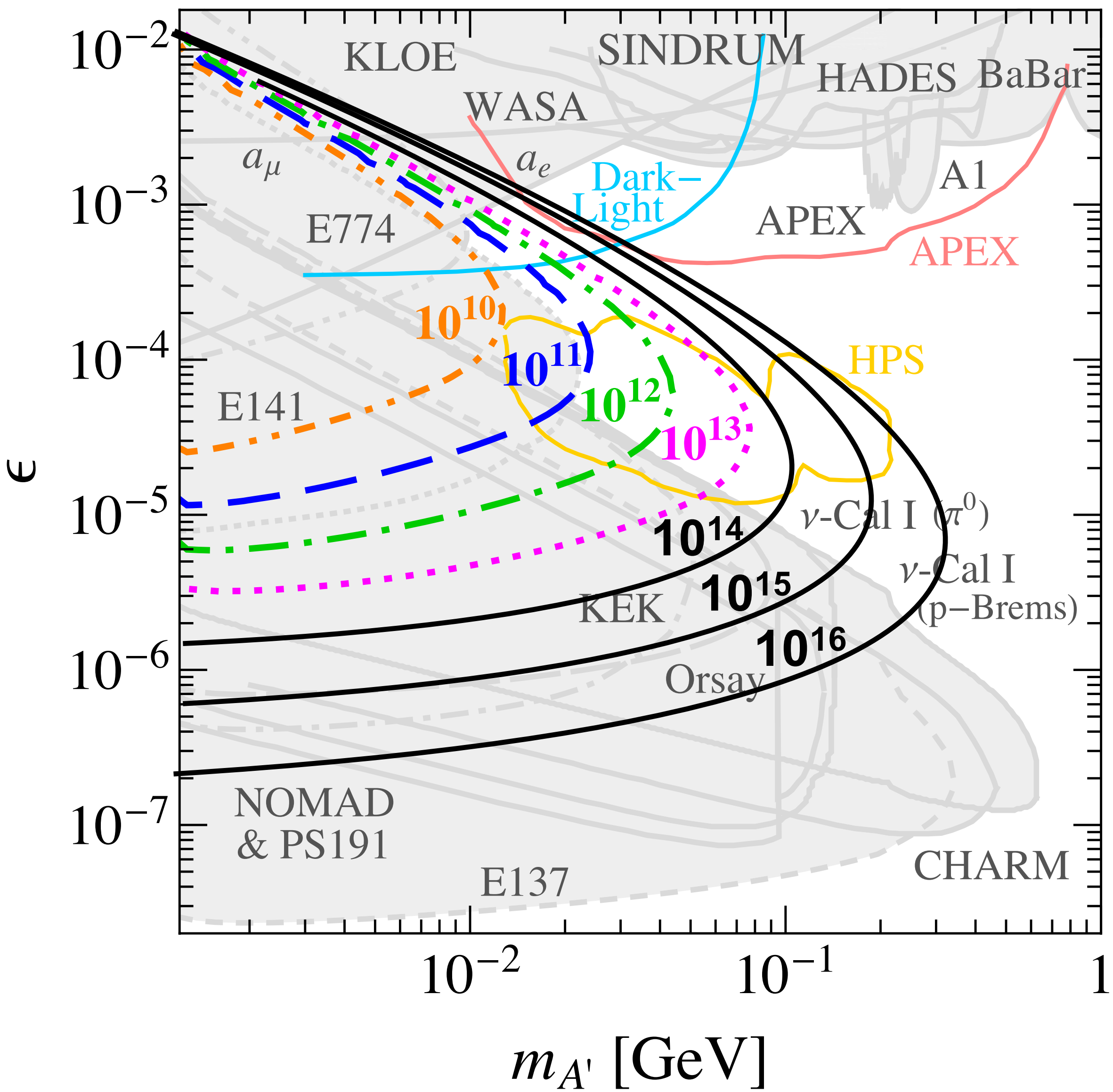
- Considered $A' \to e^+ e^-$ and $A' \to$ *invisible* channels.
- In general, but certainly at high $m_{A'}$ (> *1 GeV*) need more detailed calculations (developed in S.N. Gninenko et al., arXiv:1604.08432).
- More careful study of optimal beam energy needed.
- Evaluation of backgrounds needed; currently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



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

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

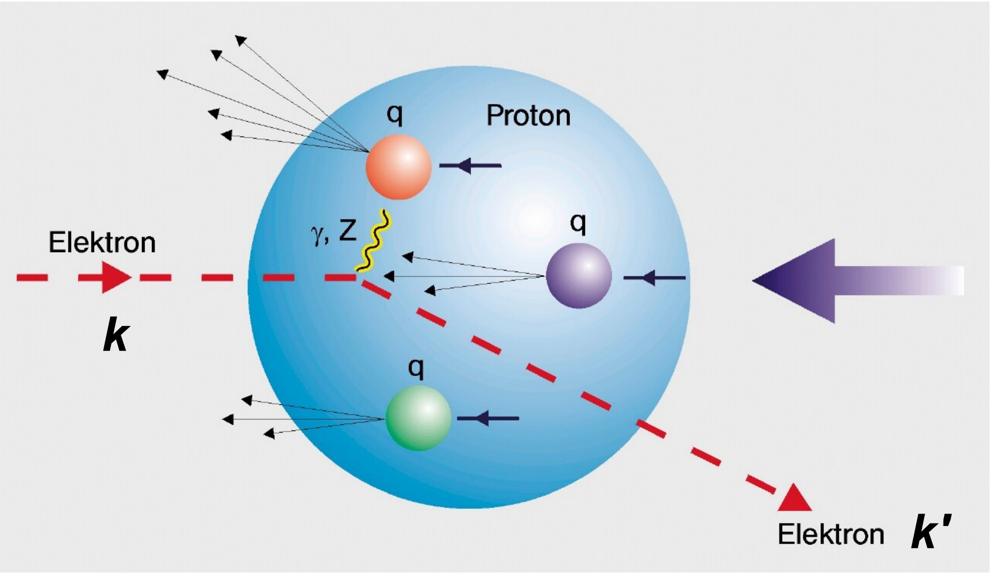
As proposed by NA64 group:

- 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.

Electron–proton colliders based on AWAKE scheme

High energy electron–proton collisions



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

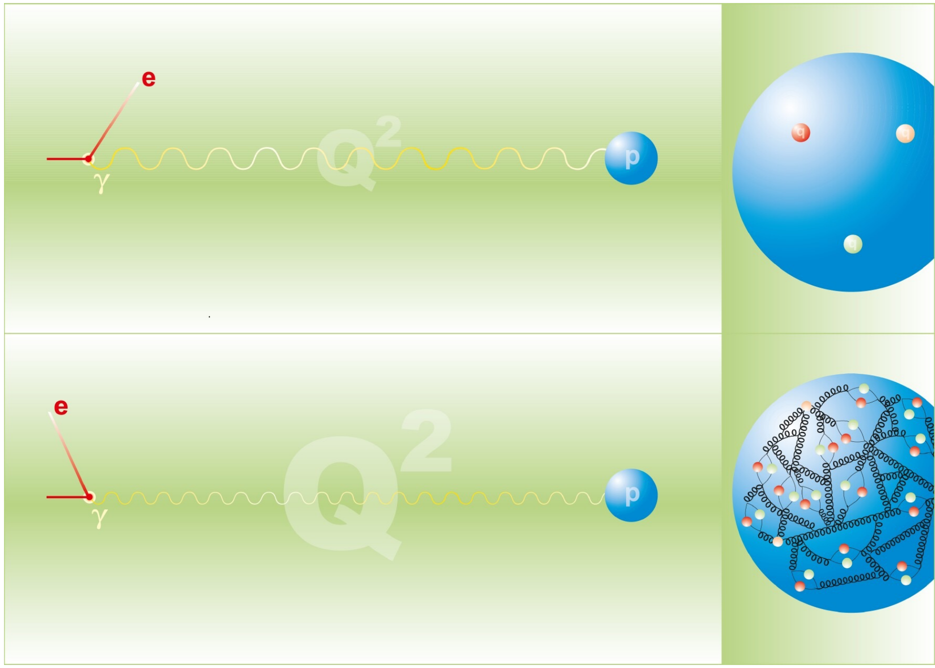
Parton momentum fraction, x

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

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

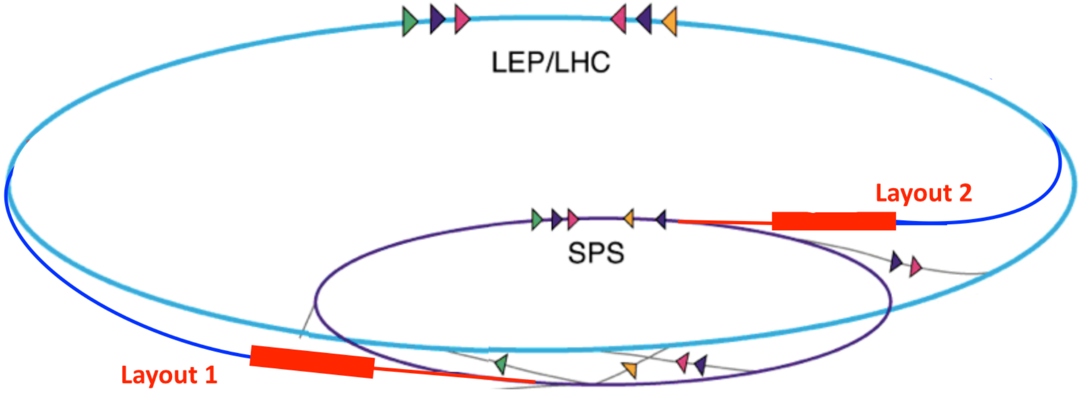
Tells us a lot about the strong force: parton interactions, α_s, etc.

Is there further partonic substructure ?



High energy electron−proton collisions

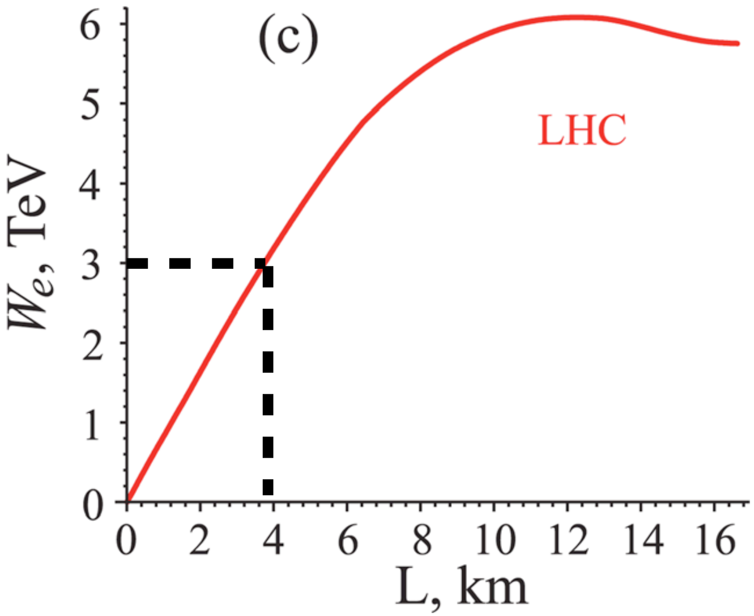
- Consider high energy *ep* collider with E_e up to *O(50 GeV),* colliding with LHC proton *TeV* bunch, e.g. $E_e = 10\ GeV$, $E_p = 7\ TeV$, $\sqrt{s} = 530\ GeV$.
- Can "easily" exceed HERA energies ($\sqrt{s} = 300\ GeV$); can consider different detector and probe different physics.
- Create ~*50 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 $\sim 10^{30}\ cm^{-2}s^{-1}$.
- 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. increasing luminosity, understanding how to build a plasma accelerator, etc..

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

Very high energy electron–proton collisions, VHEeP*

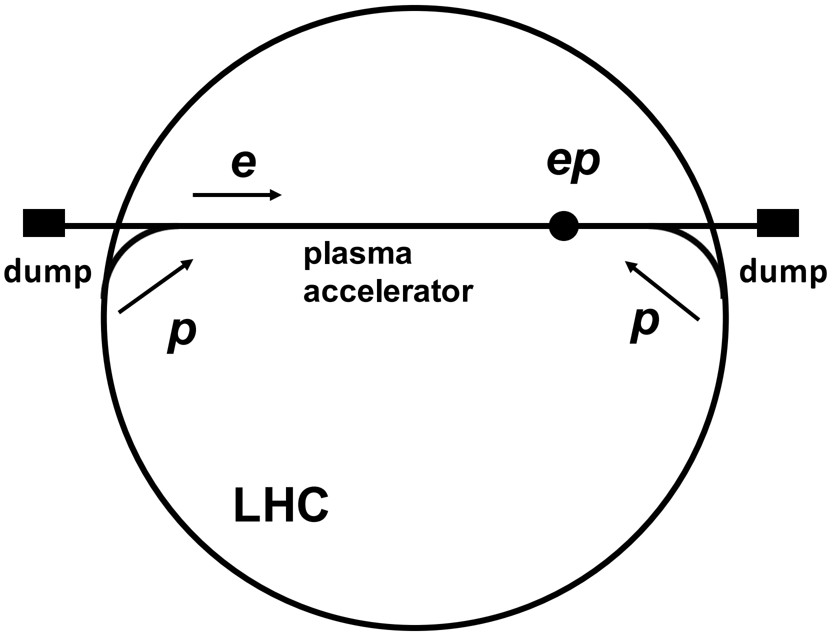


A. Caldwell & K. Lotov, Phys. Plasmas **18** (2011) 103101

- 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.

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

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 ?

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

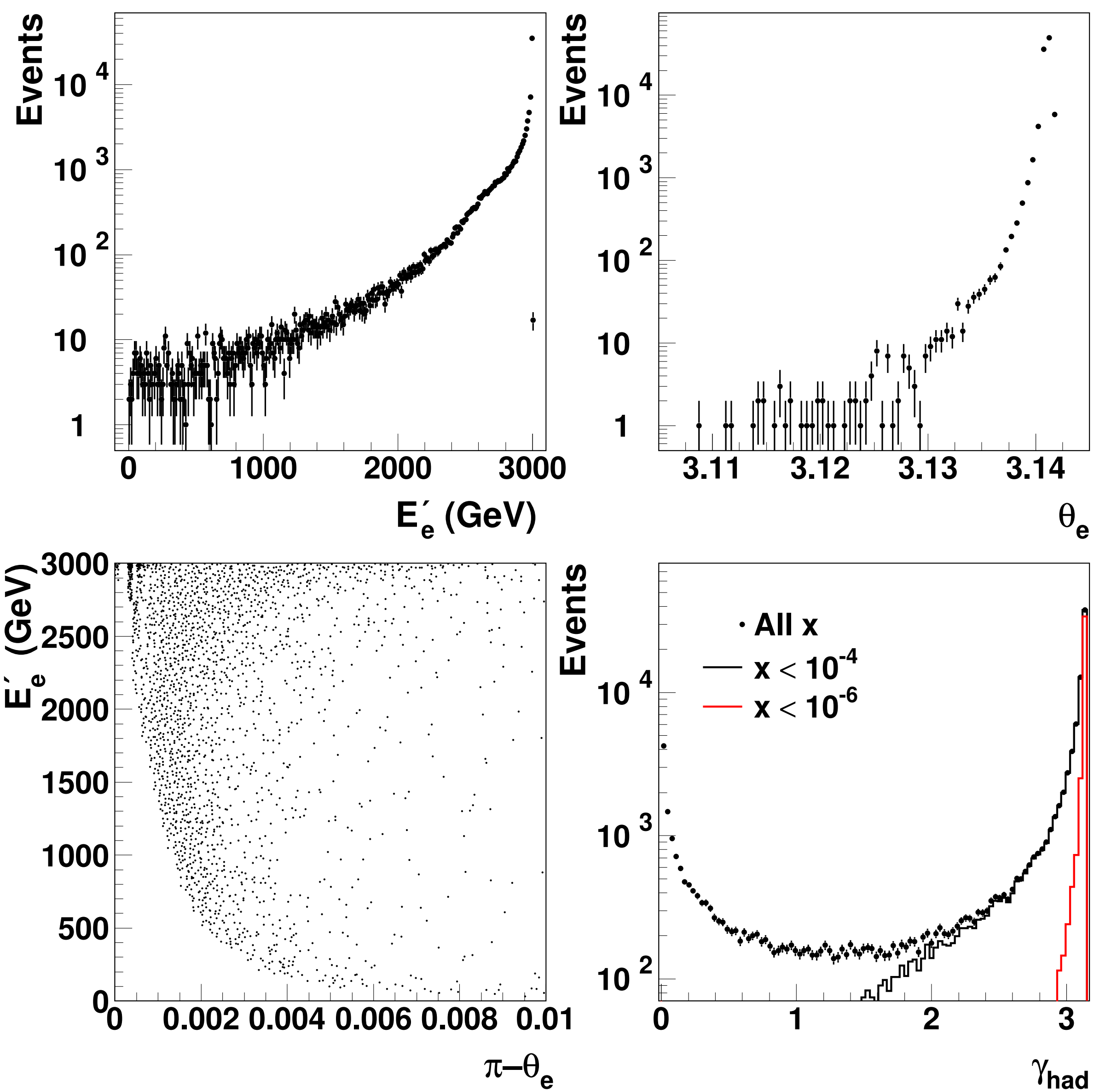
- Assume
  - *~3000* bunches every *30 mins*, gives $f \sim 2$ Hz.
  - $N_p \sim 4 \times 10^{11}$, $N_e \sim 1 \times 10^{11}$
  - $\sigma \sim 4$ *μm*

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

Other schemes to increase this value ?

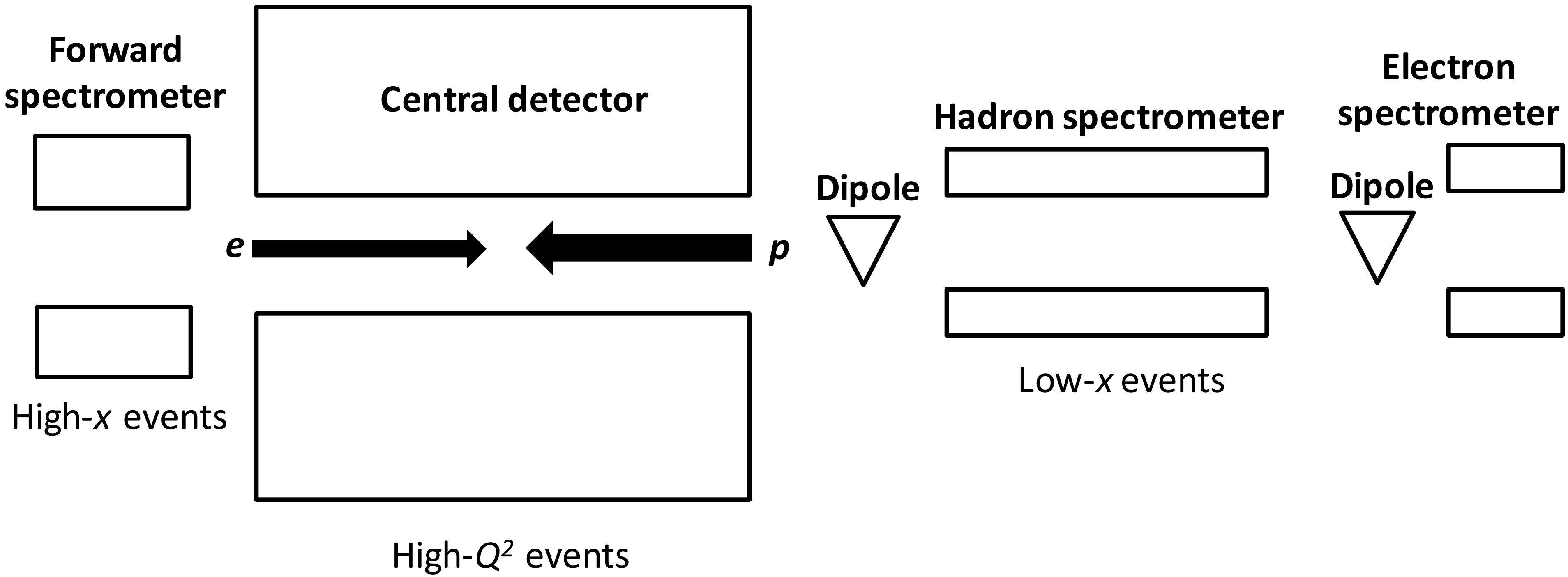
Physics case for very high energy, but moderate (*10−100* pb^{-1}) luminosities.

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.

Physics at VHEeP

• 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.

• Cross sections at very low x and observation/evidence for saturation. Completely different kind of proton structure.

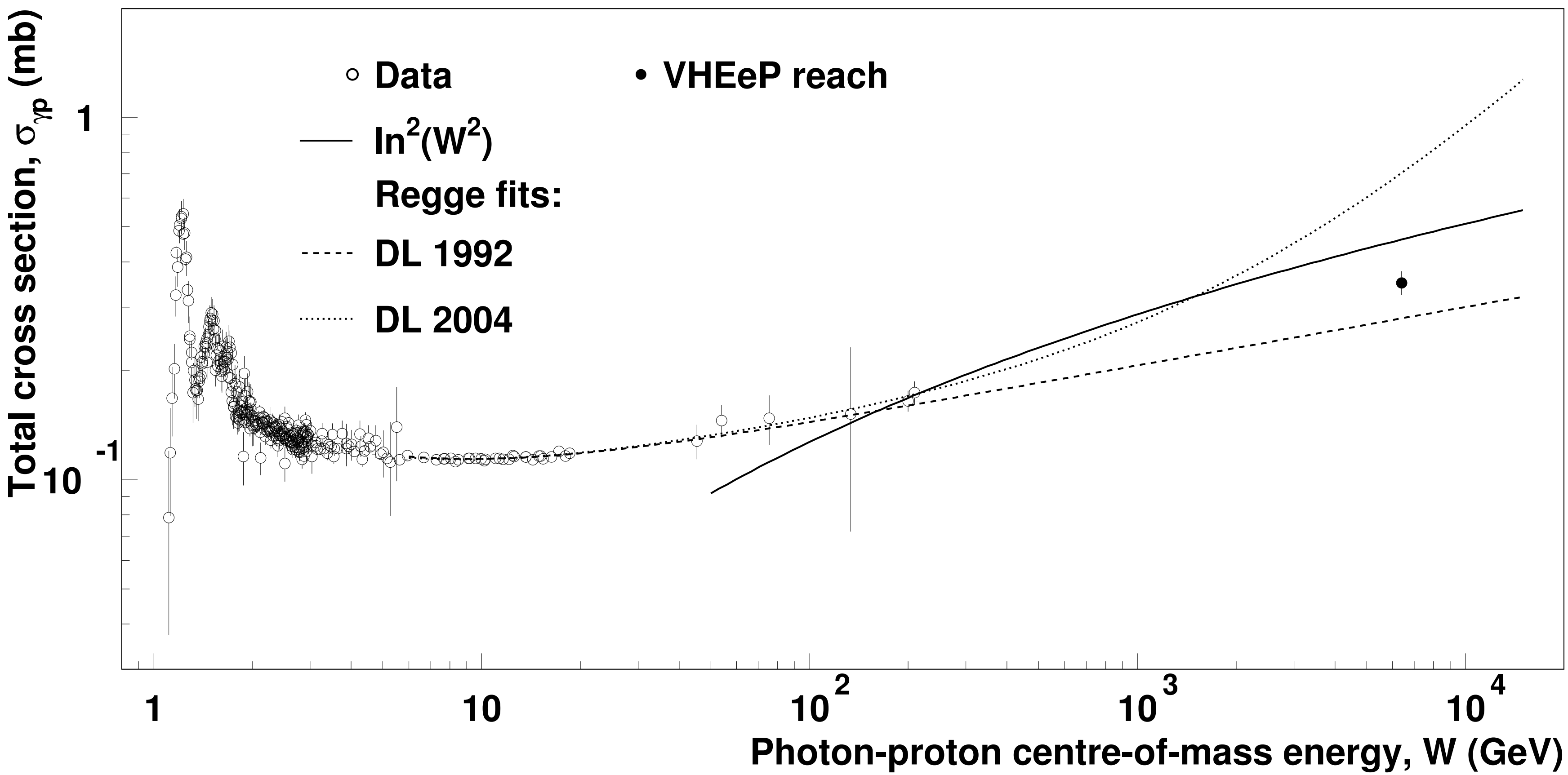
• Beyond the Standard Model physics; contact interactions, e.g. radius of quark and electron; search for leptoquarks.

• 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.

• …

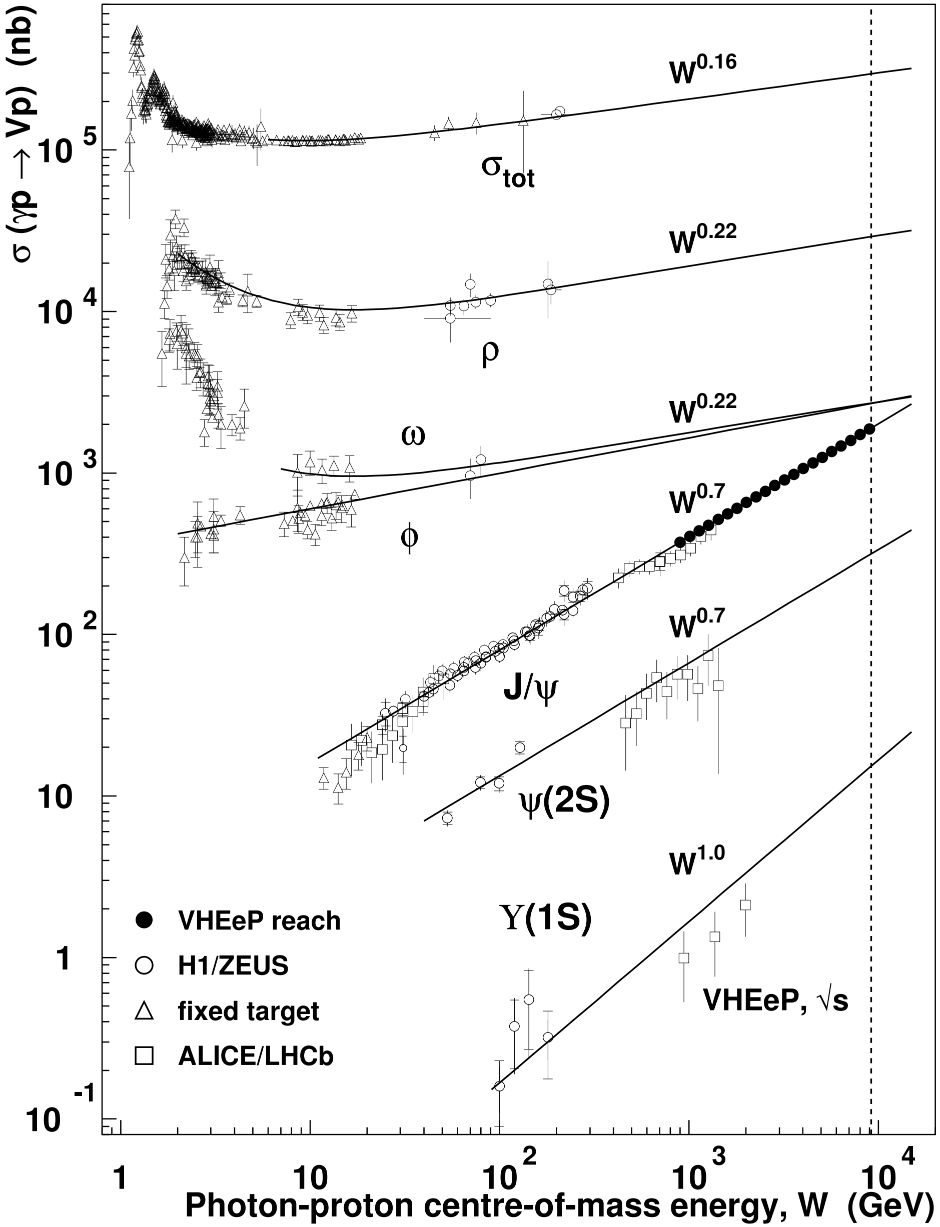
Total photon–proton cross section



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.**

Vector meson cross sections



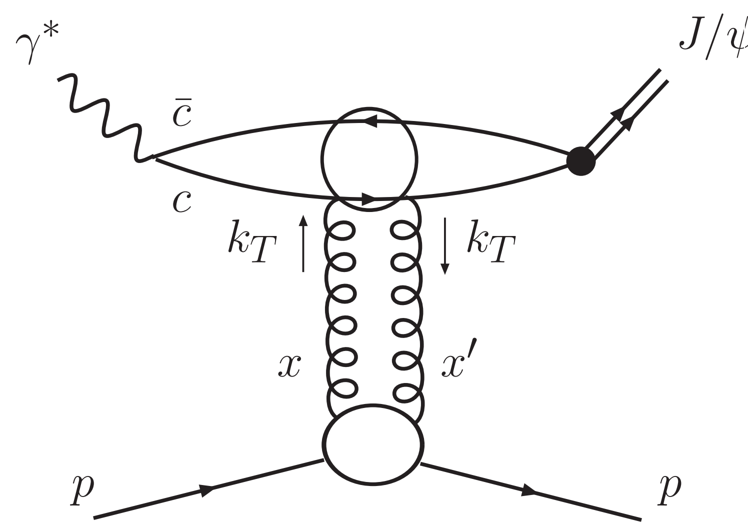
Strong rise with energy related to gluon density at low *x*.

Can measure all particles within the same experiment.

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

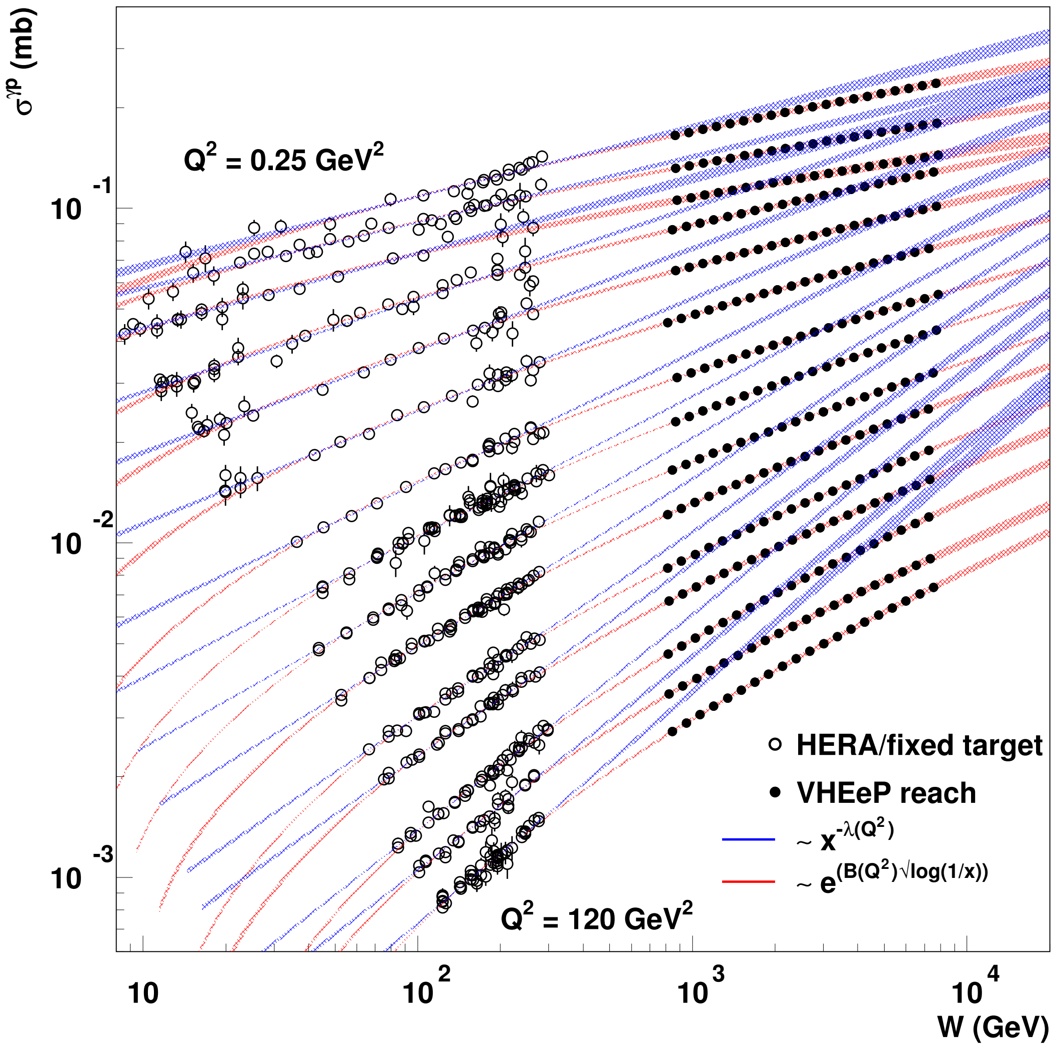
At VHEeP energies, *σ(J/ψ) > σ(φ)* !

Onset of saturation ?



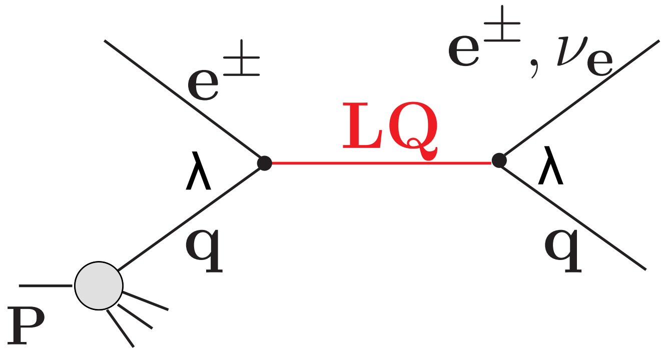
A. Martin et al., Phys. Lett. **B 662** (2008) 252

Virtual-photon–proton cross section



- Again trying to understand energy dependence of hadronic cross sections.
- Cross sections for all Q^2 are rising; again luminosity not an issue, will have huge number of events.
- Contrast “red” and “blue”.
- Note that blue predictions start to cross.
- **Explore a region where QCD is not at all understood.**

Leptoquark production



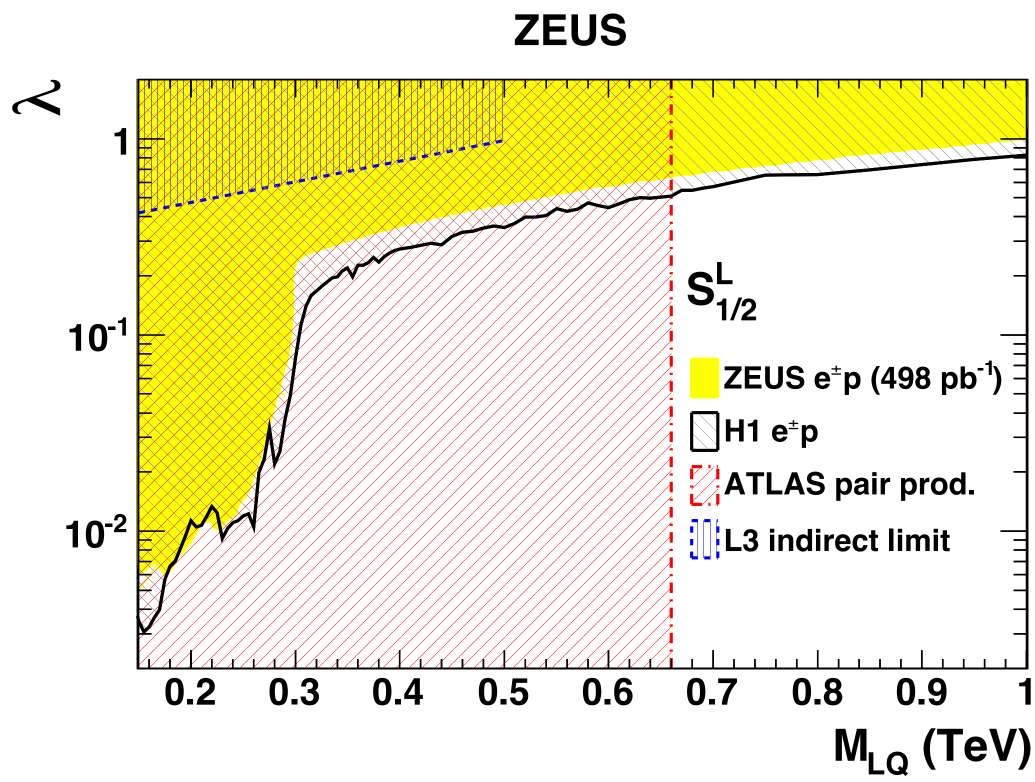
Electron−proton colliders are the ideal machine to look for leptoquarks.

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

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

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

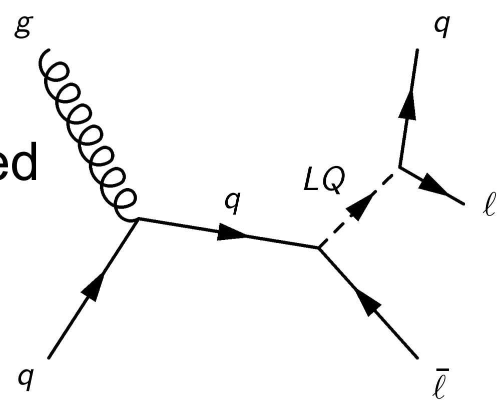
Also sensitive to quark substructure and possible to extract quark radius

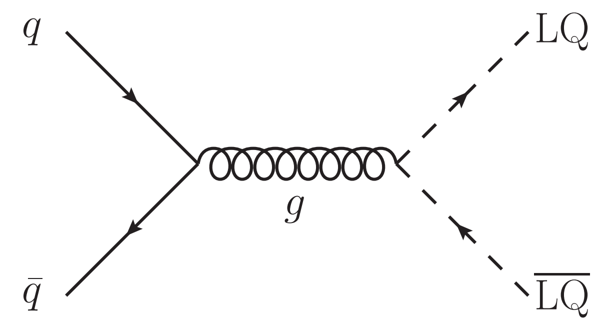


ZEUS Coll., Phys. Rev. **D 86** (2012) 012005

Leptoquark production at the LHC

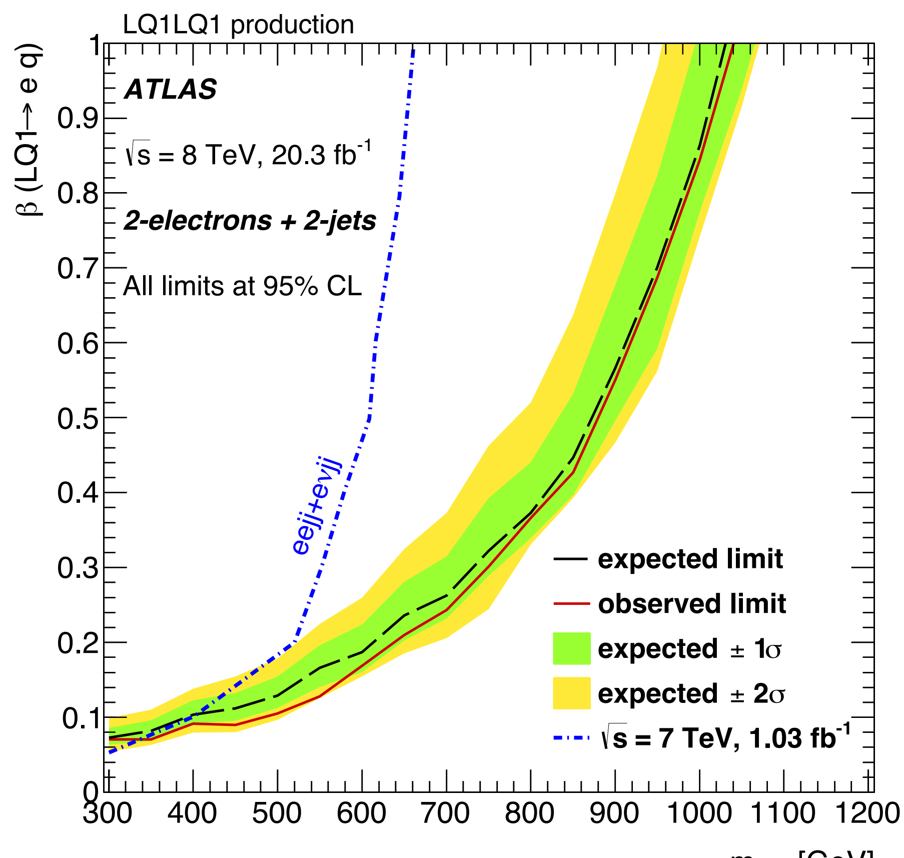
Can also be produced in *pp* singly or pair production





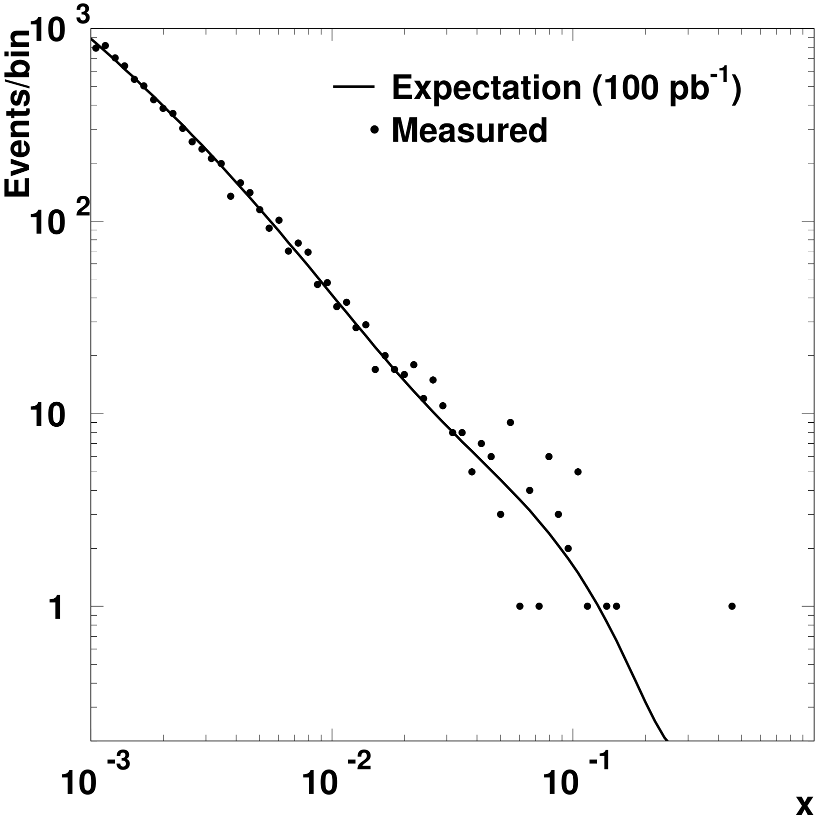
Reach of LHC currently about *1 TeV*, to increase to *2 − 3 TeV*.

Coupling dependent.



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

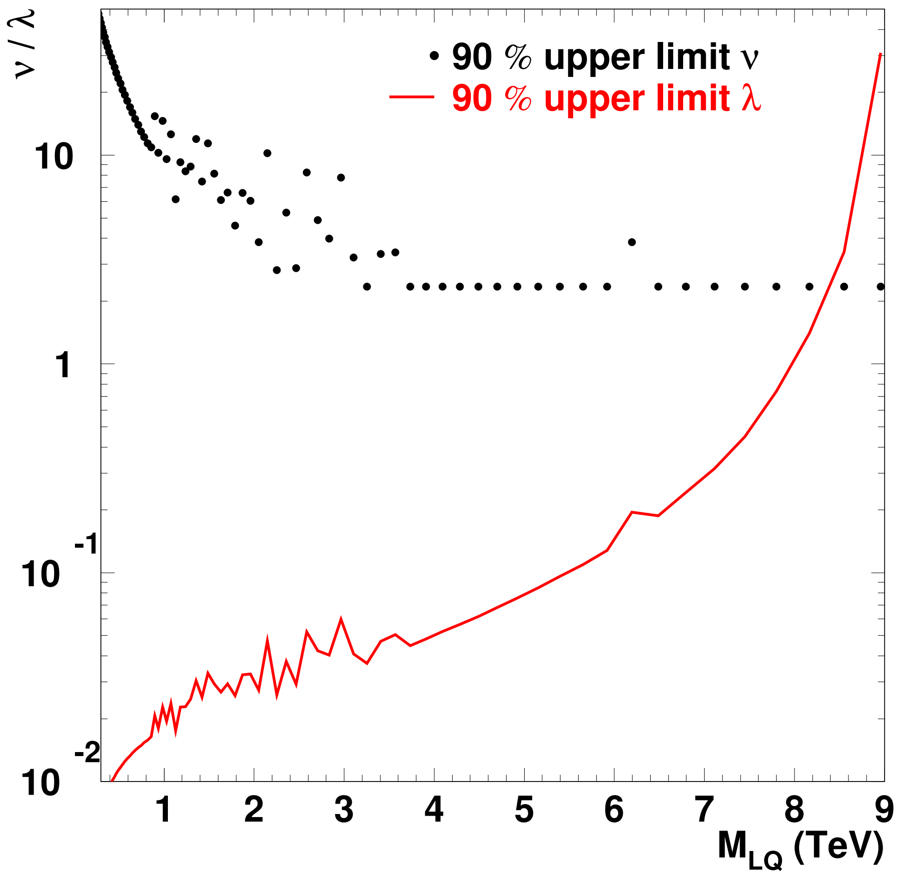
Leptoquark production at VHEeP



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

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

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



Sensitivity up to kinematic limit, *9 TeV*.

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

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.**

Back-up

From: arXiv:1608.08632

TABLE I: Summary of dark photon experiments.

Experiment	Lab	Production	Detection	Vertex	Mass(MeV)	Mass Res. (MeV)	Beam	Ebeam (GeV)	Ibeam or Lumi	Machine	1st Run	Next Run
APEX	JLab	e-brem	$\ell^+\ell^-$	no	$65-600$	0.5%	e^-	1.1–4.5	150 μA	CEBAF(A)	2010	2018
A1	Mainz	e-brem	e^+e^-	no	$40-300$	?	e^-	0.2–0.9	140 μA	MAMI	2011	–
HPS	JLab	e-brem	e^+e^-	yes	$20-200$	1–2	e^-	1–6	50–500 nA	CEBAF(B)	2015	2018
DarkLight	JLab	e-brem	e^+e^-	no	< 80	?	e^-	0.1	10 mA	LERF	2016	2018
MAGIX	Mainz	e-brem	e^+e^-	no	$10-60$	?	e^-	0.155	1 mA	MESA	2020	–
NA64	CERN	e-brem	e^+e^-	no	$1-50$	?	e^-	100	2×10^{11} EOT/yr	SPS	2017	2022
Super-HPS	SLAC	e-brem	vis	yes	< 500	?	e^-	$4-8$	1 μA	DASEL	?	?
(TBD)	Cornell	e-brem	e^+e^-	?	< 100	?	e^-	0.1-0.3	100 mA	CBETA	?	?
VEPP3	Budker	annih	invis	no	$5-22$	1	e^+	0.500	$10^{33}\,\mathrm{cm^{-2}s^{-1}}$	VEPP3	2019	?
PADME	Frascati	annih	invis	no	$1-24$	$2-5$	e^+	0.550	$\leq 10^{14}\, e^+$OT/y	Linac	2018	?
MMAPS	Cornell	annih	invis	no	$20-78$	$1-6$	e^+	6.0	$10^{34}\,\mathrm{cm^{-2}s^{-1}}$	Synchr	?	?
KLOE 2	Frascati	several	vis/invis	no	< 1.1 GeV	1.5	e^+e^-	0.51	$2\times10^{32}\,\mathrm{cm^{-2}s^{-1}}$	DAϕNE	2014	-
Belle II	KEK	several	vis/invis	no	$\lesssim 10$ GeV	$1-5$	e^+e^-	4×7	$1\sim10\ \mathrm{ab^{-1}}$/y	Super-KEKB	2018	-
SeaQuest	FNAL	several	$\mu^+\mu^-$	yes	$\lesssim 10$ GeV	$3-6\%$	p	120	10^{18} POT/y	MI	2017	2020
SHIP	CERN	several	vis	yes	$\lesssim 10$ GeV	$1-2$	p	400	2×10^{20} POT/5y	SPS	2026	-
LHCb	CERN	several	$\ell^+\ell^-$	yes	$\lesssim 40$ GeV	~ 4	pp	6500	$\sim 10\,\mathrm{fb^{-1}}$/y	LHC	2010	2015

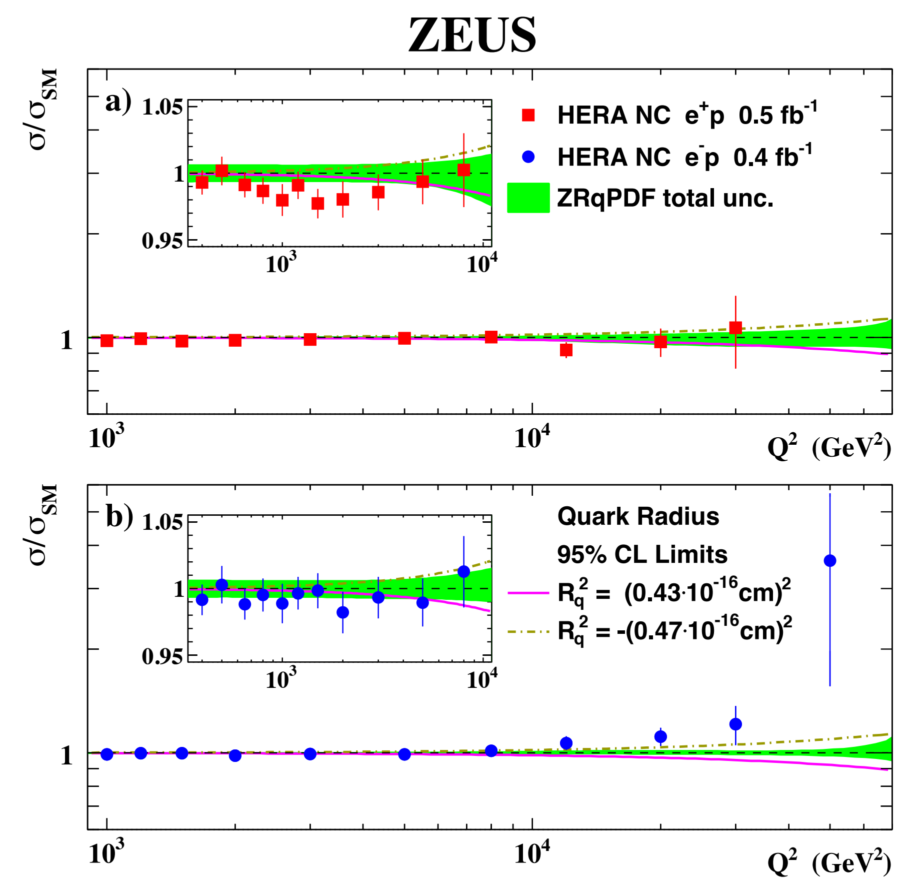
BSM: Quark substructure

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.

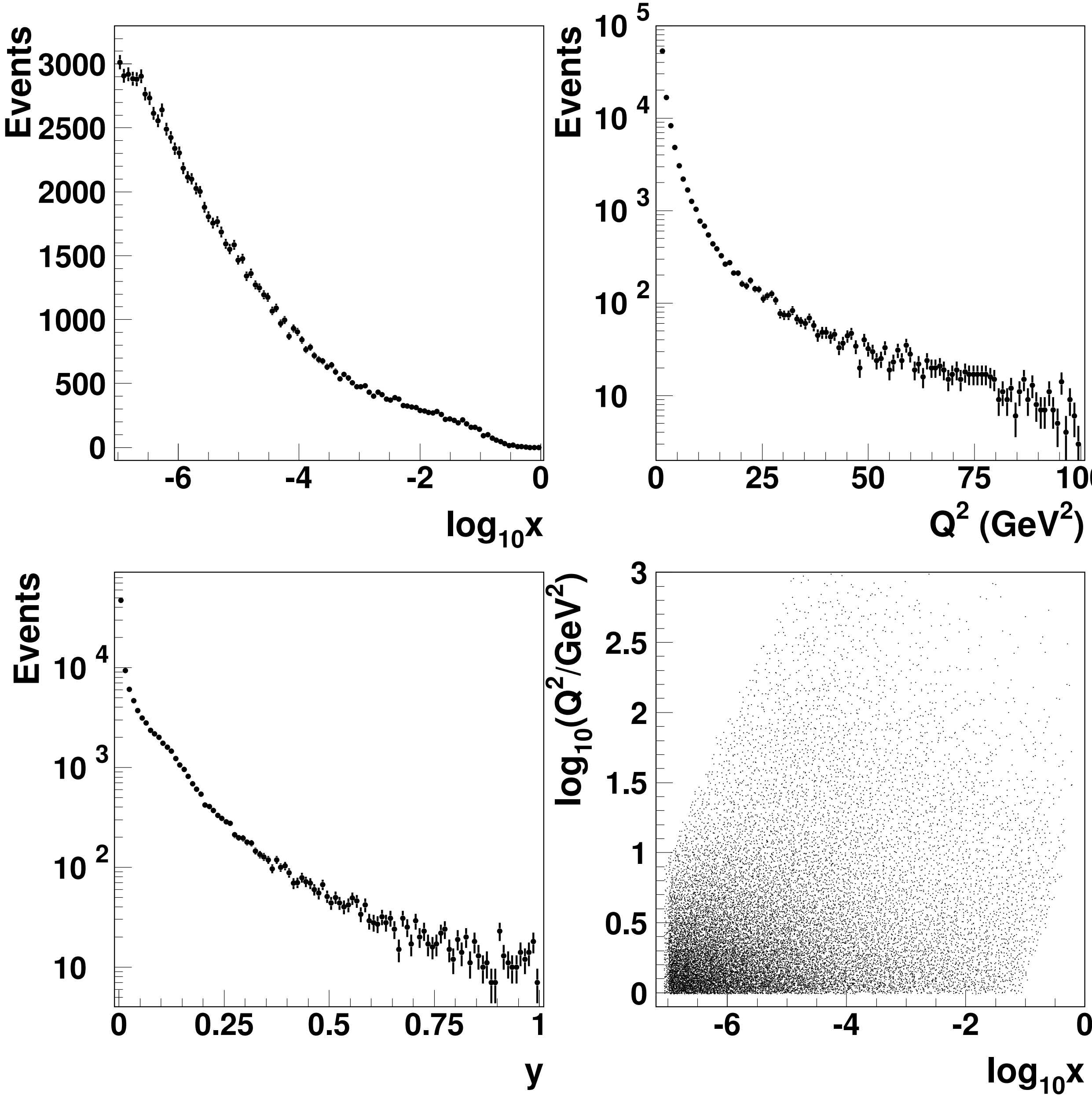


ZEUS Coll., DESY-16-035, accepted by Phys. Lett. B

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

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.