Application of AWAKE acceleration scheme to high energy physics experiment

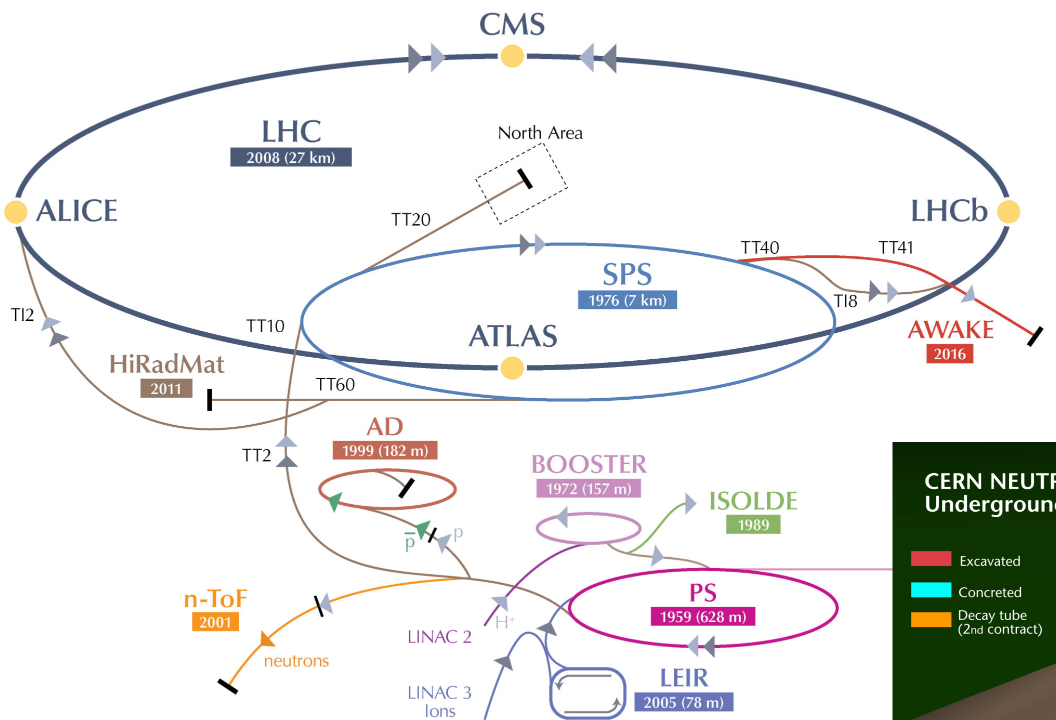
Matthew Wing (UCL)

Input from: W. Bartmann, A. Caldwell, M. Calviani, J. Chappell, P. Crivelli, H. Damerau, E. Depero, S. Doebert, J. Gall, S. Gninenko, B. Goddard, D. Grenier, E. Gschwendtner, A. Hartin, Ch. Hessler, F. Keeble, J. Osborne, A. Pardons, A. Petrenko, A. Scaachi

- Introduction to AWAKE
- Beam properties and “Luminosity” for the SPS as a driver
- Possible experiments with AWAKE scheme
- Search for dark photons
- *ep* colliders
- Summary

Physics Beyond Colliders Annual Workshop — 16−17 January 2019

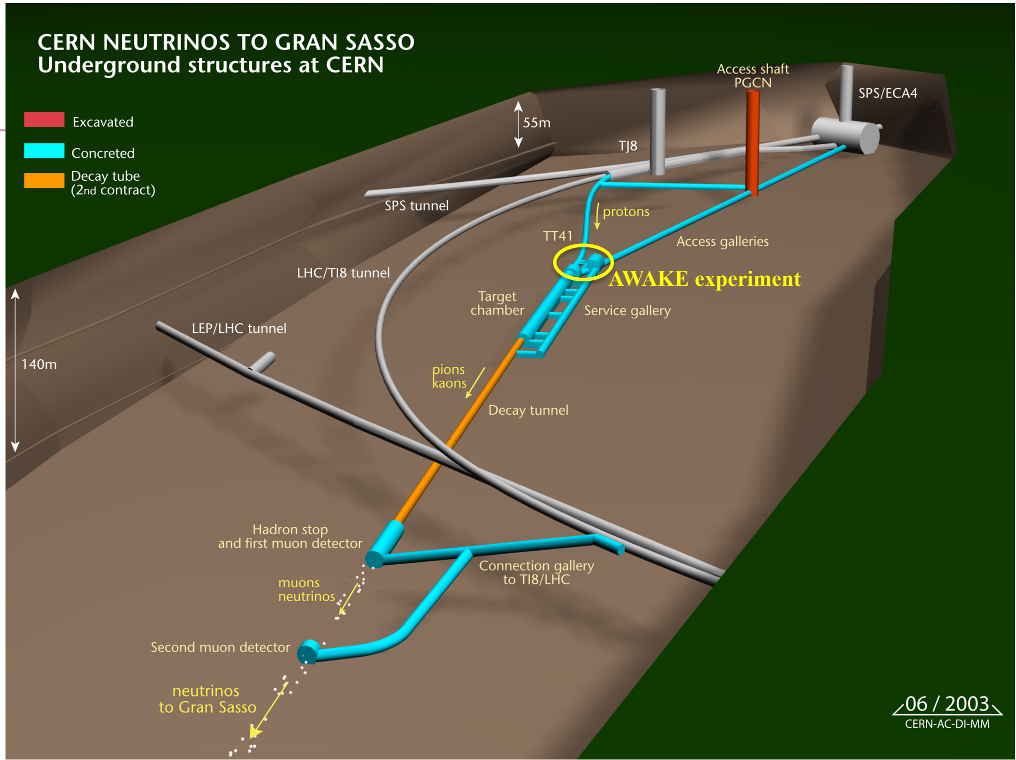
AWAKE experiment at CERN



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

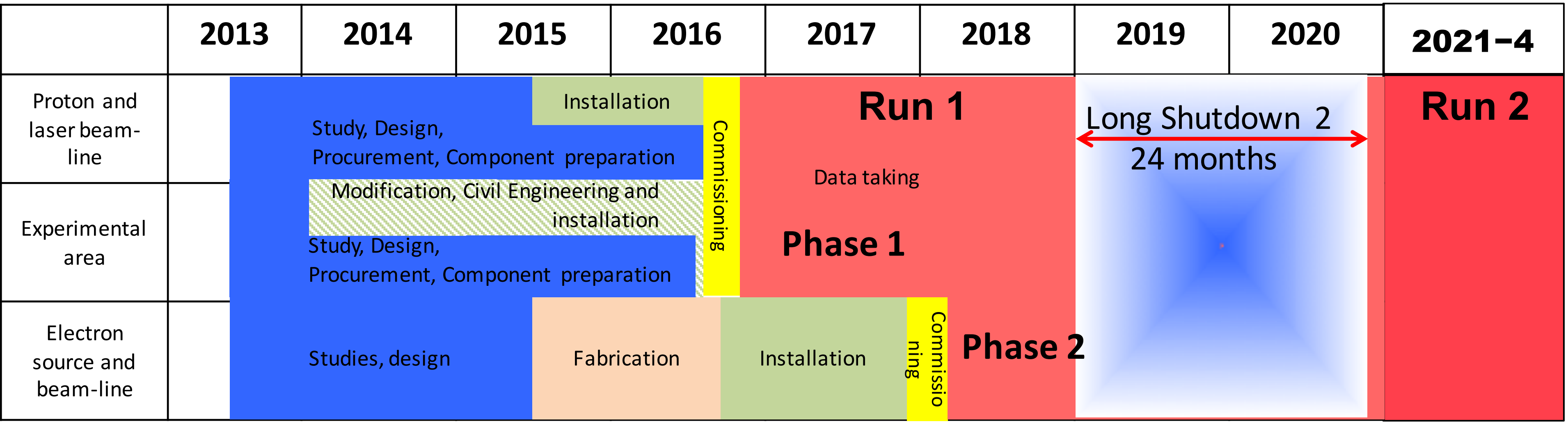
Advanced proton-driven plasma wakefield experiment.

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



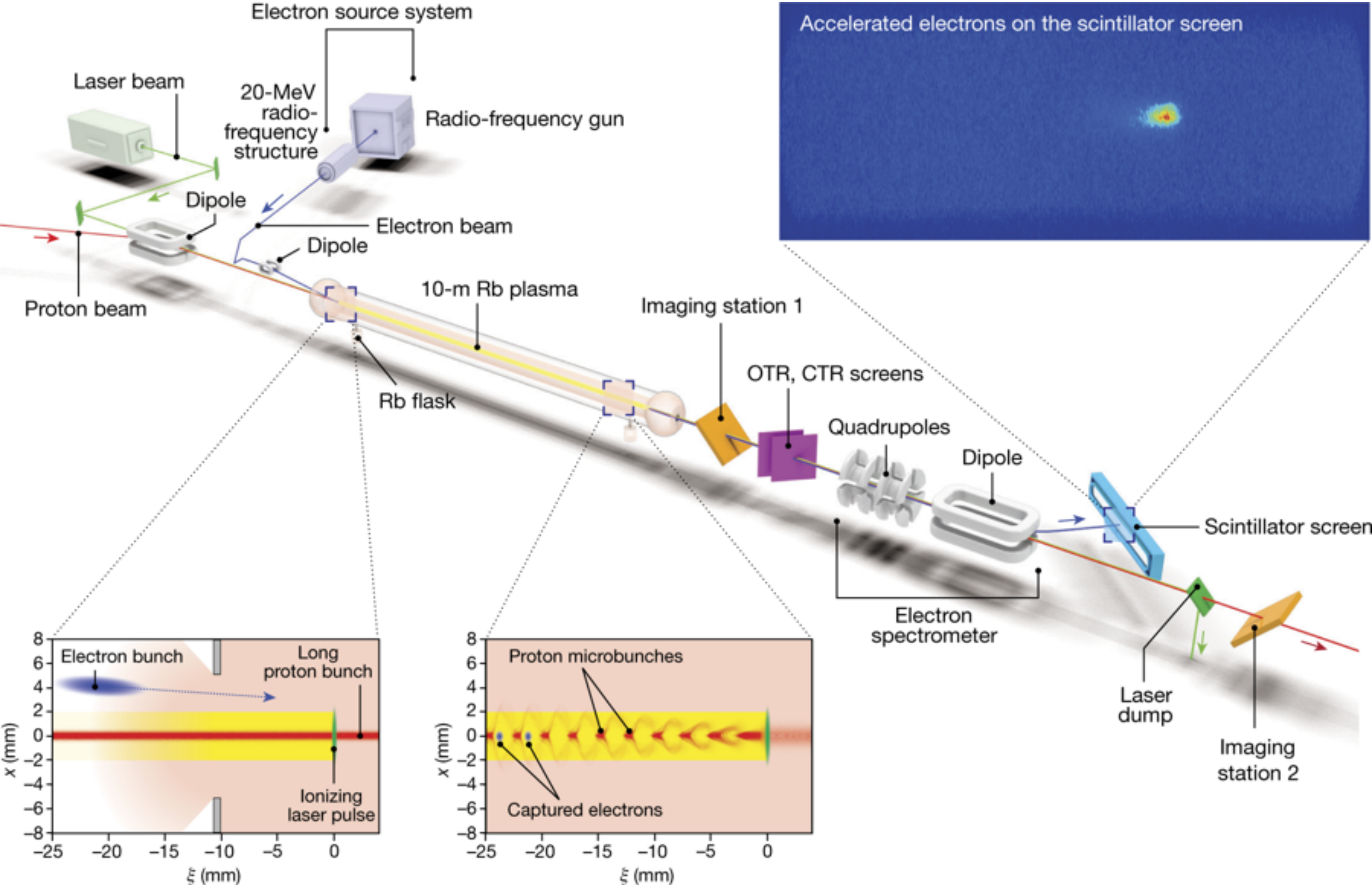
AWAKE Coll., Plasma Phys. Control. Fusion **56** (2014) 084013; Nucl. Instrum. Meth. **A 829** (2016) 3; Nucl. Instrum. Meth. **A 829** (2016) 76.

AWAKE physics and timeline



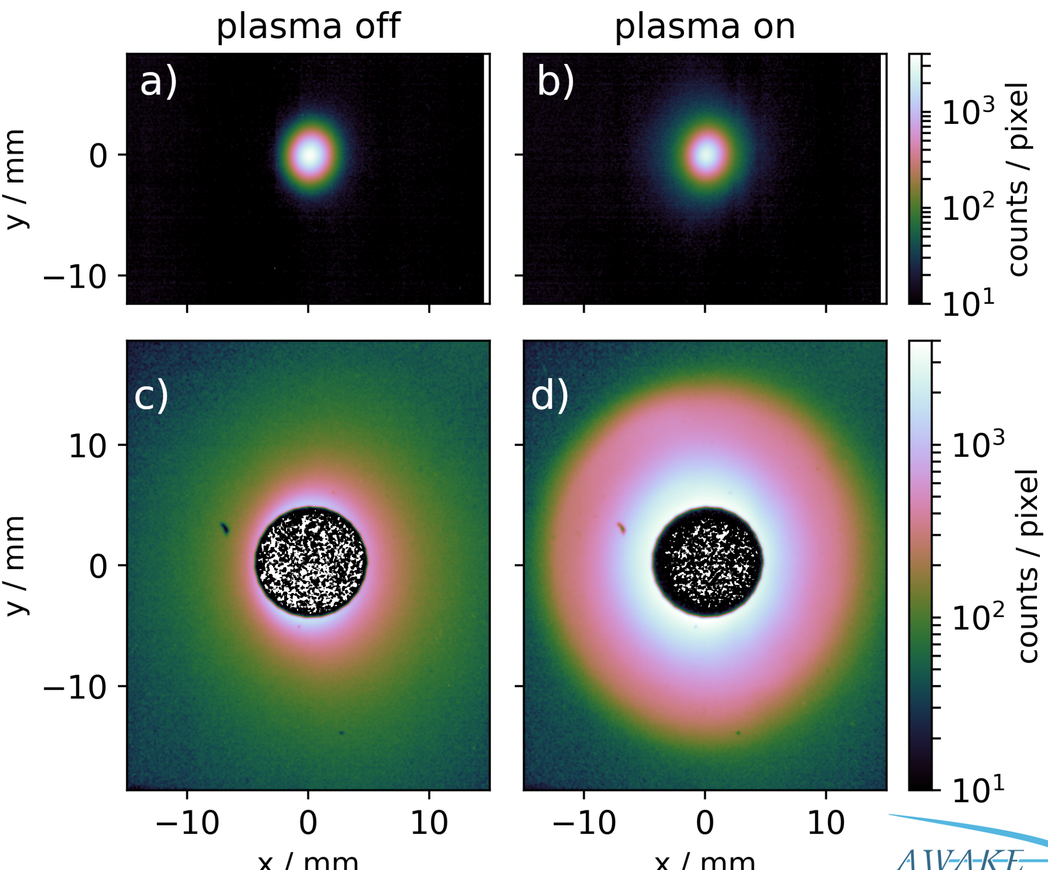
- AWAKE was approved as a CERN project in August 2013.
- Demonstrate and understand self-modulation of long proton bunch [2016−8].
- Sample high-gradient wakefields with electron bunch and accelerate to *O(GeV)* [2018].
- AWAKE Run 2 [2021−4].
- **Then HEP applications …**

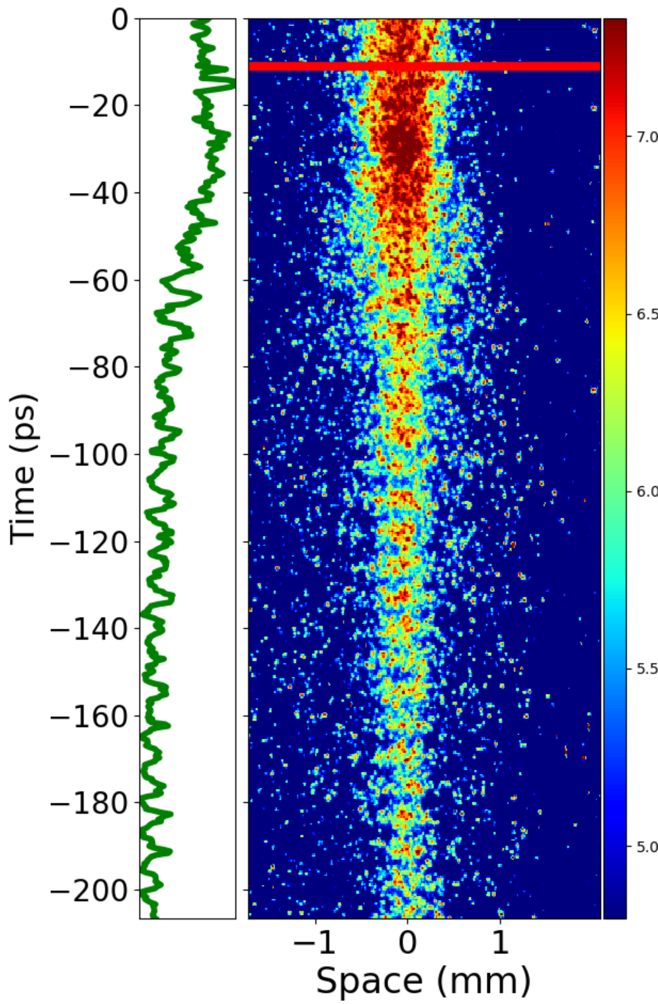
AWAKE schematic



Modulation of proton bunch

- Clear defocusing of proton bunch.
- Clear modulation of proton bunch.
  - **Met first milestone of demonstration of self-modulation of long proton bunch.**



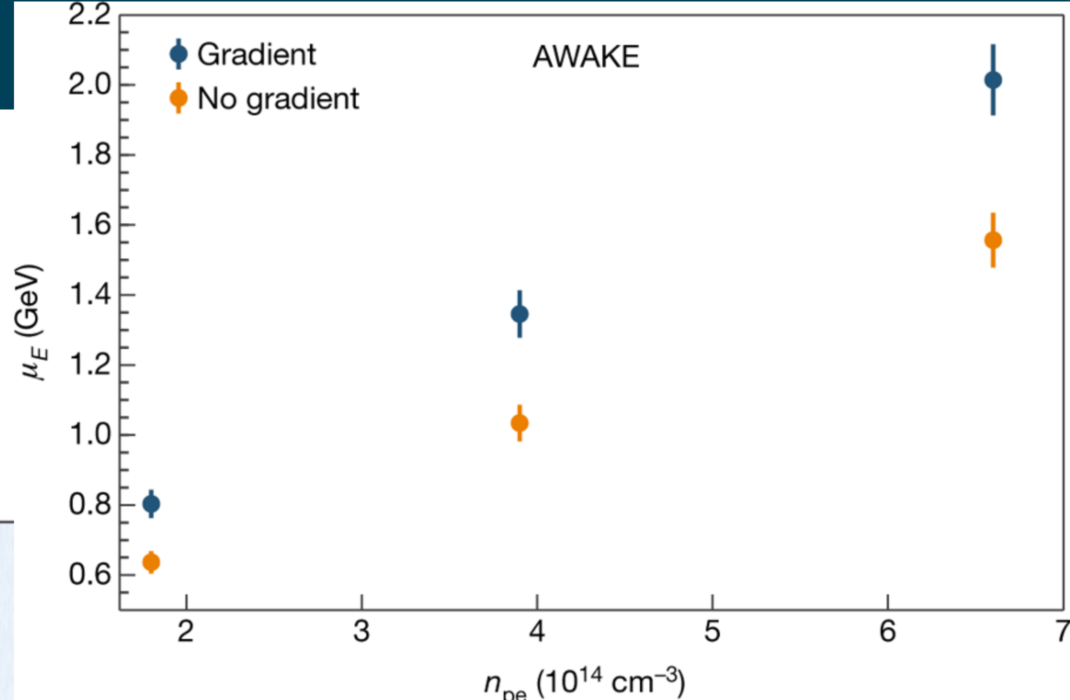


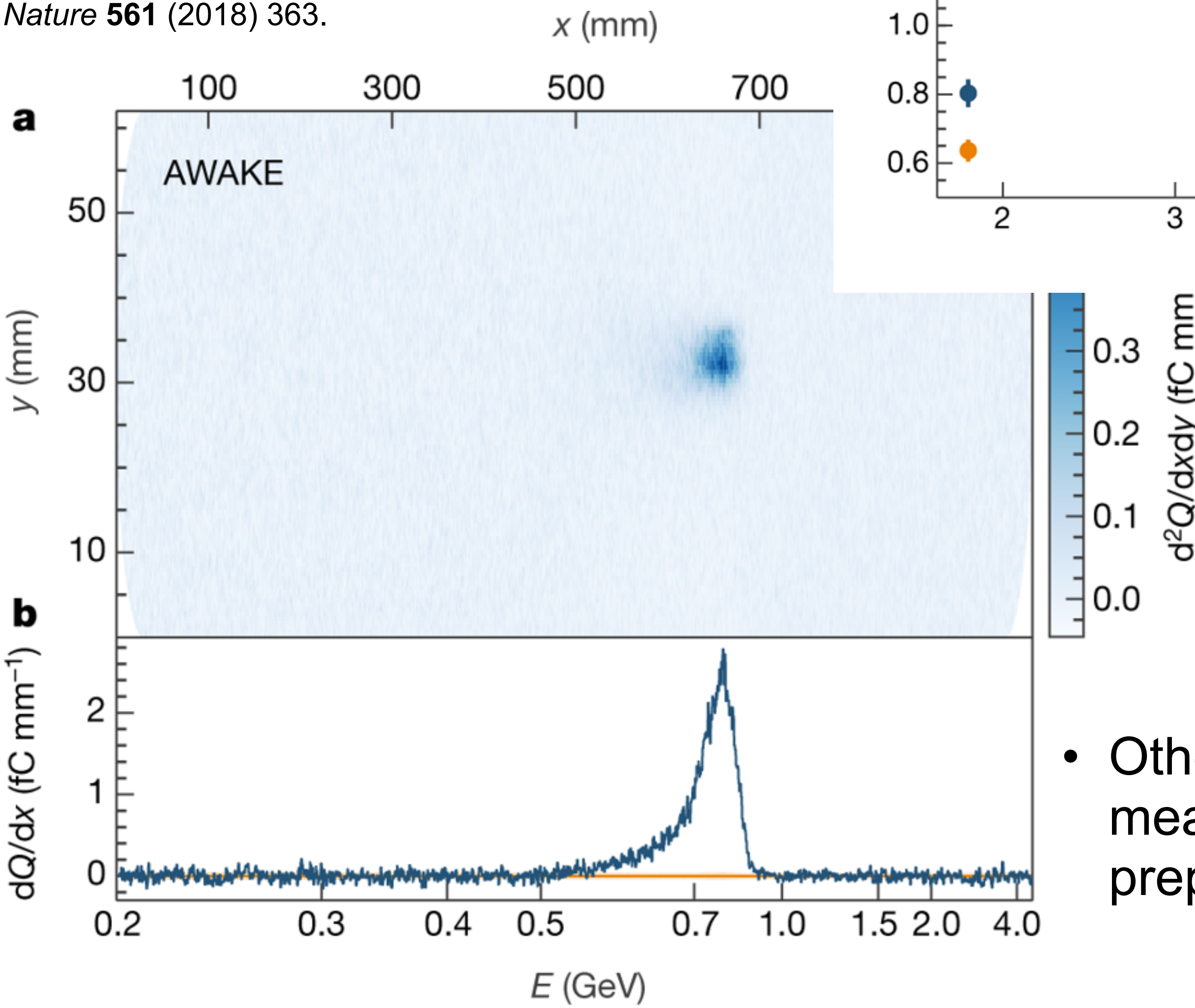
AWAKE Coll., M. Turner et al. “Experimental observation of plasma wakefield growth driven by the seeded self-modulation of a proton bunch”, arXiv: 1809.01191, *Phys. Rev. Lett. (in press).*

AWAKE Coll., E. Adli et al., “Experimental observation of proton bunch modulation in a plasma at varying plasma densities”, arXiv:1809.04478, *Phys. Rev. Lett. (in press)*

Electron acceleration in AWAKE

AWAKE Coll., E. Adli et al.,
Nature **561** (2018) 363.



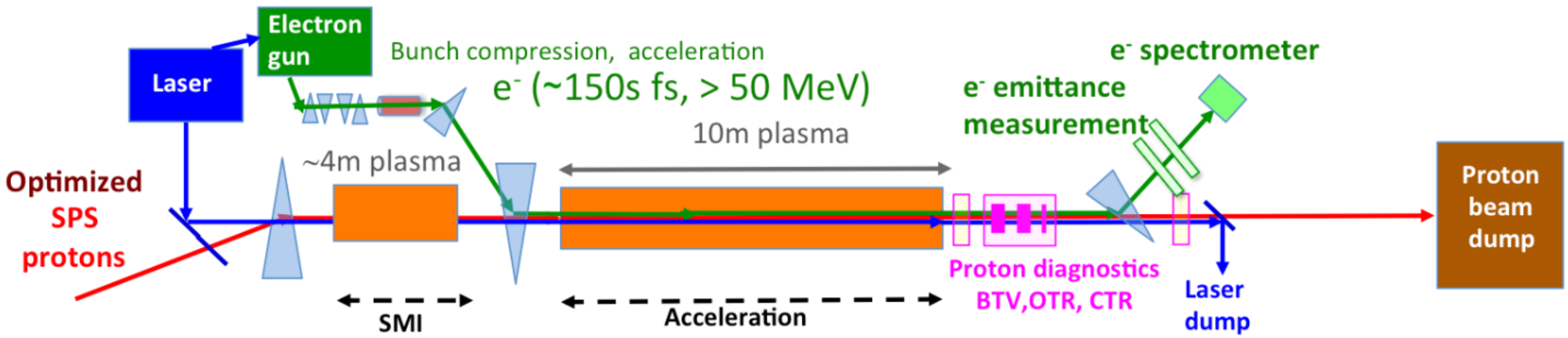


- **Observed up to 2 GeV**
- Data taken in May and published in Nature in August
- Meeting of other major milestone.

- Other studies and measurements ongoing as is preparing for AWAKE Run 2…

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

- **Goal: after Run 2, in a position to provide beam for particle physics experiments**
- **Are there experiments that require an electron beam of up to *O(50 GeV)* ?**
- **Using the LHC beam as a driver, *TeV* electron beams are possible.**

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

Documents submitted to European Strategy

Particle physics applications of the AWAKE acceleration scheme

A. Caldwell[1], J. Chappell[2], P. Crivelli[3], E. Depero[3], J. Gall[4], S. Gninenko[5], E. Gschwendtner[4], A. Hartin[2], F. Keeble[2], J. Osborne[4], A. Pardons[4], A. Petrenko[4], A. Scaachi[2], and M. Wing[*2]

[1]Max Planck Institute for Physics, Munich, Germany
[2]University College London, London, UK
[3]ETH Zürich, Switzerland
[4]CERN, Geneva, Switzerland
[5]INR Moscow, Russia

Abstract

The AWAKE experiment had a very successful Run 1 (2016–8), demonstrating proton-driven plasma wakefield acceleration for the first time, through the observation of the modulation of a long proton bunch into micro-bunches and the acceleration of electrons up to 2 GeV in 10 m of plasma. The aims of AWAKE Run 2 (2021–4) are to have high-charge bunches of electrons accelerated to high energy, about 10 GeV, maintaining beam quality through the plasma and showing that the process is scalable. The AWAKE scheme is therefore a promising method to accelerate electrons to high energy over short distances and so develop a useable technology for particle physics experiments. Using proton bunches from the SPS, the acceleration of electron bunches up to about 50 GeV should be possible. Using the LHC proton bunches to drive wakefields could lead to multi-TeV electron bunches, e.g. with 3 TeV acceleration achieved in 4 km of plasma. This document outlines some of the applications of the AWAKE scheme to particle physics and shows that the AWAKE technology could lead to unique facilities and experiments that would otherwise not be possible. In particular, experiments are proposed to search for dark photons, measure strong field QED and investigate new physics in electron–proton collisions. The community is also invited to consider applications for electron beams up to the TeV scale.

Input to the European Particle Physics Strategy Update

December 2018

[*]Corresponding author: m.wing@ucl.ac.uk

CERN-PBC-REPORT-2018-004

AWAKE++: the AWAKE Acceleration Scheme for New Particle Physics Experiments at CERN

W. Bartmann[1], A. Caldwell[2], M. Calviani[1], J. Chappell[3], P. Crivelli[4], H. Damerau[1], E. Depero[4], S. Doebert[1], J. Gall[1], S. Gninenko[5], B. Goddard[1], D. Grenier[1], E. Gschwendtner[*1], Ch. Hessler[1], A. Hartin[3], F. Keeble[3], J. Osborne[1], A. Pardons[1], A. Petrenko[1], A. Scaachi[3], and M. Wing[3]

[1]CERN, Geneva, Switzerland
[2]Max Planck Institute for Physics, Munich, Germany
[3]University College London, London, UK
[4]ETH Zürich, Switzerland
[5]INR Moscow, Russia

1 Abstract

The AWAKE experiment reached all planned milestones during Run 1 (2016-18), notably the demonstration of strong plasma wakes generated by proton beams and the acceleration of externally injected electrons to multi-GeV energy levels in the proton driven plasma wakefields.
During Run 2 (2021 - 2024) AWAKE aims to demonstrate the scalability and the acceleration of electrons to high energies while maintaining the beam quality.
Within the Physics Beyond Colliders (PBC) study AWAKE++ has explored the feasibility of the AWAKE acceleration scheme for new particle physics experiments at CERN. Assuming continued success of the AWAKE program, AWAKE will be in the position to use the AWAKE scheme for particle physics applications such as fixed target experiments for dark photon searches and also for future electron-proton or electron-ion colliders.
With strong support from the accelerator and high energy physics community, these experiments could be installed during CERN LS3; the integration and beam line design show the feasibility of a fixed target experiment in the AWAKE facility, downstream of the AWAKE experiment in the former CNGS area.
The expected electrons on target for fixed target experiments exceeds the electrons on target by three to four orders of magnitude with respect to the current NA64 experiment, making it a very promising experiment in the search for new physics.
Studies show that electrons can be accelerated to 70 GeV in a 130 m long plasma cell installed in an extended TI 2 extraction tunnel from SPS to the LHC and transported to collision with protons/ions from the LHC. The experiment would focus on studies of the structure of matter and QCD in a new kinematic domain.
The AWAKE scheme offers great potential for future high energy physics applications and it is the right moment now to support further development of this technology leading to unique facilities.

Input to the European Particle Physics Strategy Update

December 2018

[*]Corresponding author: edda.gschwendtner@cern.ch

CERN-PBC-REPORT-2018-005

Using the SPS for high energy electrons

- Bunches of electrons with *O(50 GeV)* each accelerated in 50−100 m plasma.

Parameter	**AWAKE-upgrade-type**	**HL-LHC-type**
Proton energy E_p (GeV)	400	450
Number of protons per bunch N_p	3×10^{11}	2.3×10^{11}
Longitudinal bunch size protons σ_z (cm)	6	7.55
Transverse bunch size protons σ_r (μm)	200	100
Proton bunches per cycle n_p	8	320
Cycle length (s)	6	20
SPS supercycle length (s)	40	40
Electrons per cycle N_e	2×10^9	5×10^9
Number of electrons on target per 12 weeks run	4.1×10^{15}	2×10^{17}

Table 2: Potential achievable number of electrons on target for an AWAKE-based fixed target experiment for two different drive beam configurations. Assumes a 12 week experimental period with a 70% SPS duty cycle.

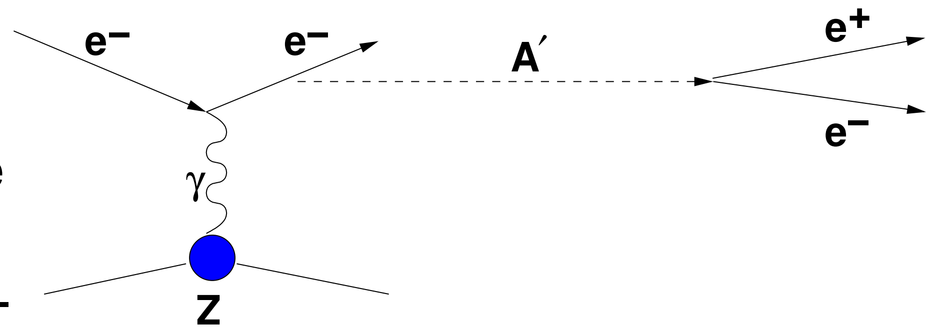
- Estimate of number of electrons on target for dark photon searches.
- Can also be used for other experiments, e.g. deep inelastic scattering, etc.
- If use LHC as a driver, can have *O(TeV)* electron beams.

Possible experiments

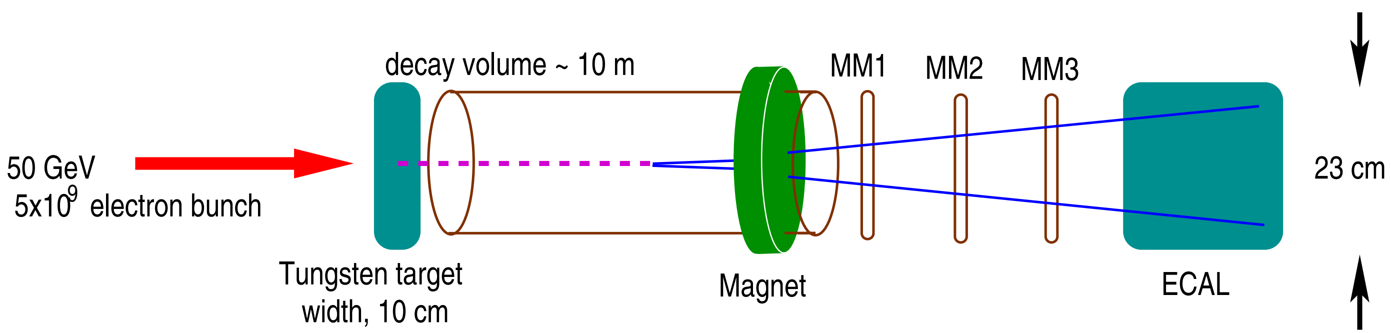
- **Searches for dark photons (à la NA64) with high energy electrons.**
- Investigation of strong-field QED
  - Can measure non-linear QED, e.g. $\gamma + n\gamma \rightarrow e^+e^-$ in $e\gamma$ or $\gamma\gamma$ collisions in which a laser provides a strong field.
  - Complement efforts at EuXFEL, FACET-II and in laser wakefield studies
- **Deep inelastic *ep/eA* collisions with:**
  - **$\sqrt{s}$ = *1.2 TeV* for E_e = *50 GeV* using SPS as a plasma driver**
  - **$\sqrt{s}$ = *9.2 TeV* for E_e = *3 TeV* using LHC as a plasma driver**
  - or fixed-target variants with these electron beams
- The FCC protons would be very effective plasma drivers.
  - Introduce plasma cells in straight section for multi-TeV electrons.
  - Possible to have > 50 GeV electrons with minimal disturbance of protons.
- Acceleration of muons to high energies.
  - "Fast" (> *GV/m*) acceleration could get muons to high energies.
  - Should be considered further.
- More ideas welcome…

Search for dark photons using an AWAKE-like beam

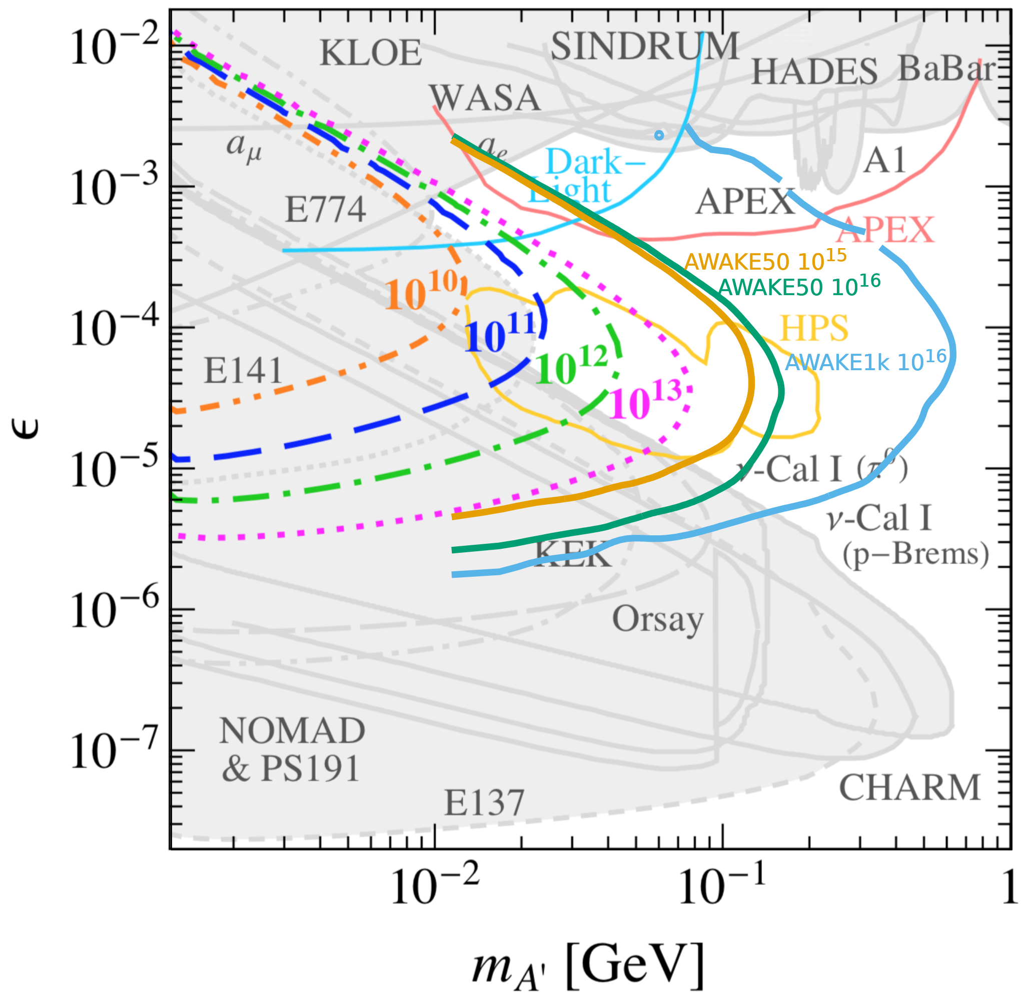
- NA64 are making great progress investigating the dark sector:
  - Dark sectors with light, weakly-coupling particles are a compelling possibility for new physics.
  - Search for dark photons, A', up to *GeV* mass scale via their production in a light-shining-through-a-wall type experiment.
  - Use high energy electrons for beam-dump and/or fixed-target experiments.



- An AWAKE-like beam will have higher intensity than the SPS secondary beam.
- Provide upgrade/extension to NA64 programme.
- Using NA64 software and similar detectors.



Dark photons search, $A' \rightarrow e^+ e^-$ channel

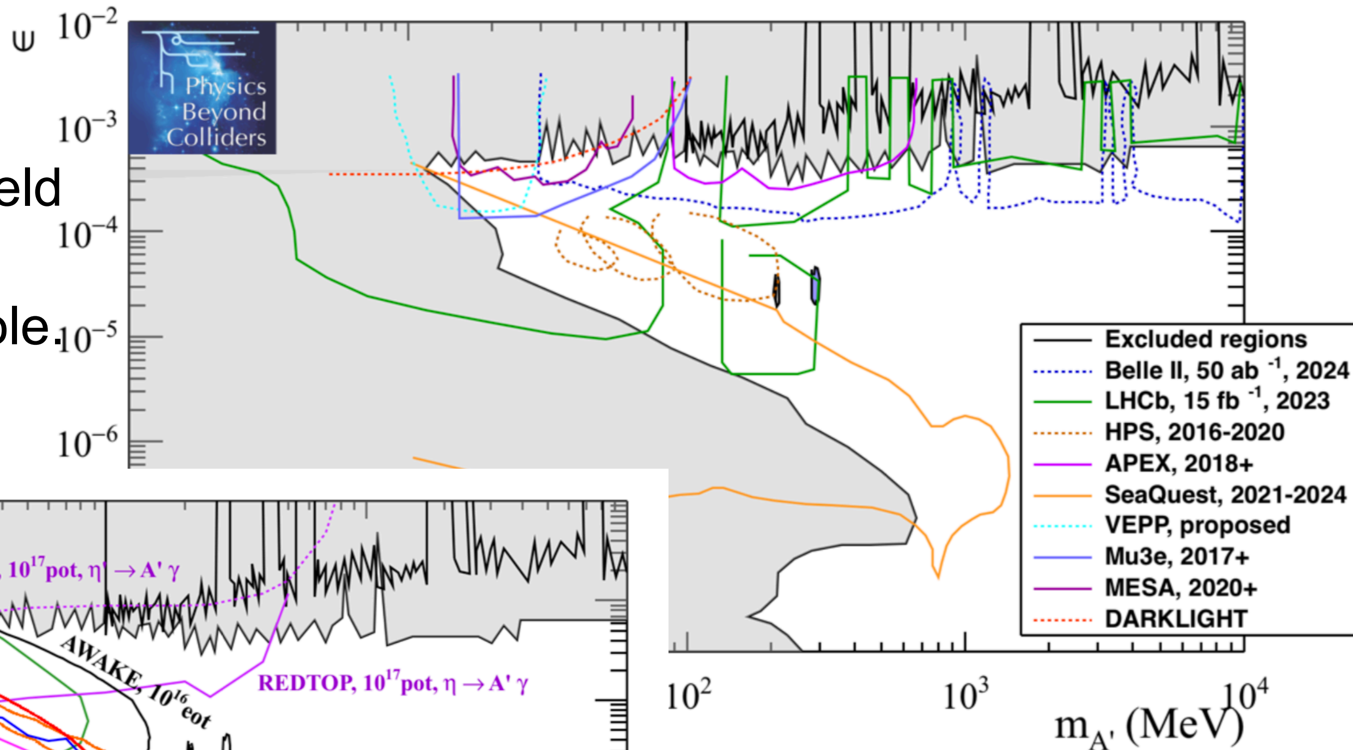


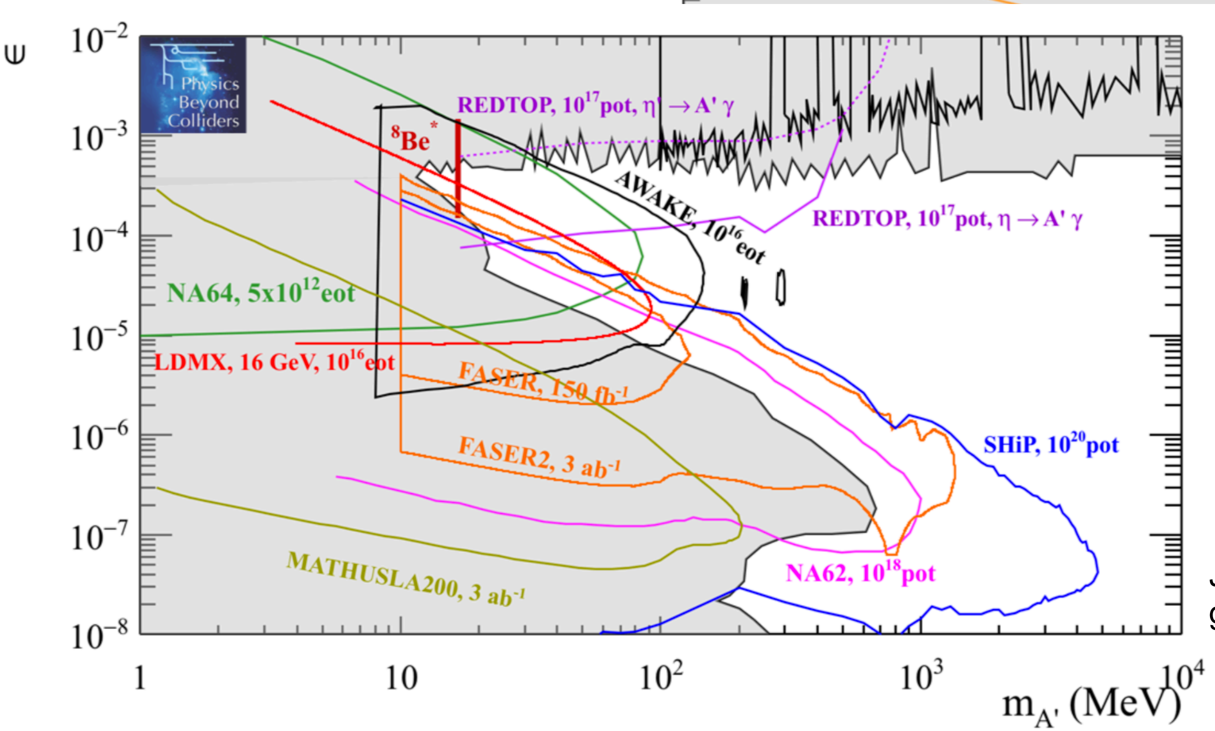
- For $10^{10} - 10^{13}$ electrons on target with NA64.
- For (10^{15} and) 10^{16} electrons on target with AWAKE-like beam.
- Using an AWAKE-like beam would extend sensitivity further:
  - around $\varepsilon \sim 10^{-3} - 10^{-5}$.
  - to high masses ~ *0.1 GeV*.
- At *1 TeV* goes to even higher masses:
  - similar ε values.
  - approaching *1 GeV*.
  - beyond any other planned experiments.

A. Hartin (UCL)

Dark photons search global plots

- Expect significant development in the field in the next decade.
- AWAKE can play a role.





J. Beacham et al., Report of the BSM working group, CERN-PBC-REPORT-2018-007.

Future studies

- Still much to look at for the dark photon search
  - Optimised beam properties, energy, e.o.t., etc.
  - Look at other channels, e.g. $A' \rightarrow \mu^+\mu^-$, $A' \rightarrow \pi^+\pi^-$, $A' \rightarrow \chi\chi$
  - Optimisation of detector size and parts.
  - Better consideration of backgrounds.
- Work will continue.

PEPIC

- PEPIC: Plasma Electron Proton/Ion Collider

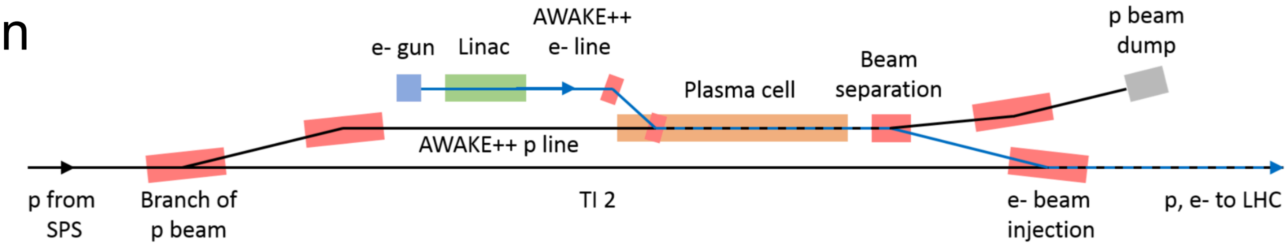
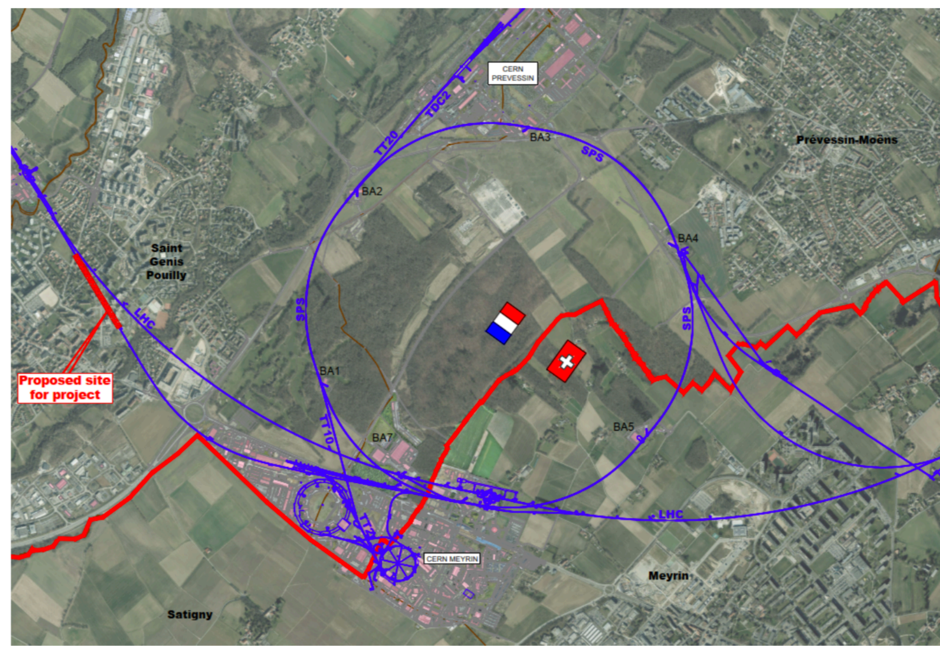


Figure 5: Schematic layout of the AWAKE++ PEPIC facility (not to scale).

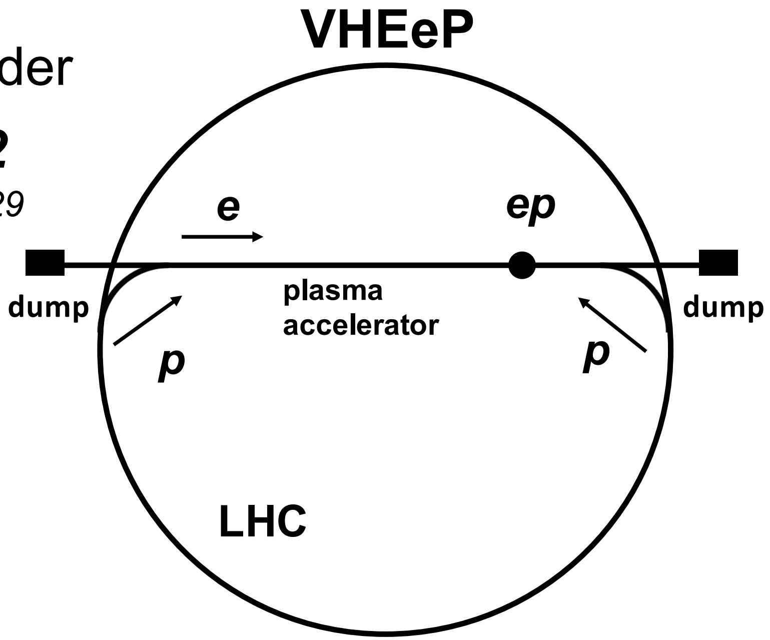
- Use SPS as driver for E_e = *50 GeV* and $\sqrt{s}$ **= 1.2 TeV** (E_p = *7 TeV*), but with modest luminosities, $O(10^{27}\ cm^{-2}\ s^{-1})$; look into ways of increasing luminosity.

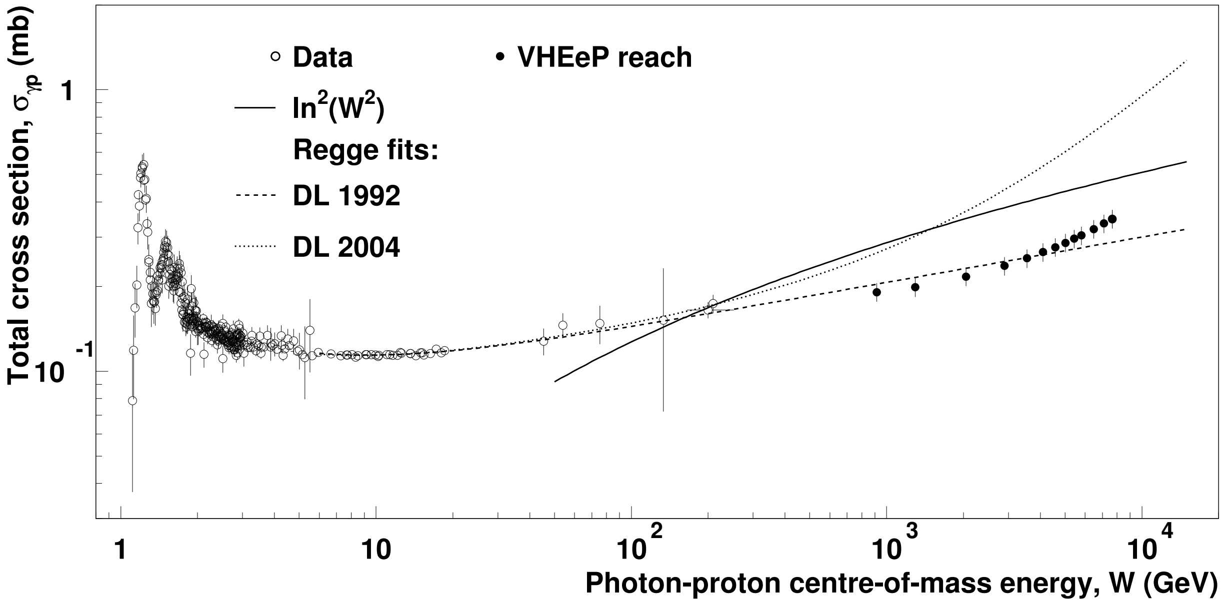
- Possible ideas for accelerator design and integration be considered
- Interesting should the LHeC not go ahead.



VHEeP

- VHEeP: Very high energy electron proton collider
- Use LHC as driver for E_e = *3 TeV* and $\sqrt{s}$ **= *9.2 TeV***, but with modest luminosities, $O(10^{28}-10^{29}\ cm^{-2}\ s^{-1})$; looking into ways of increasing.
- Completely new regime; exciting physics potential
- Revolutionise QCD; new theories; links to gravity, cosmic rays, etc..



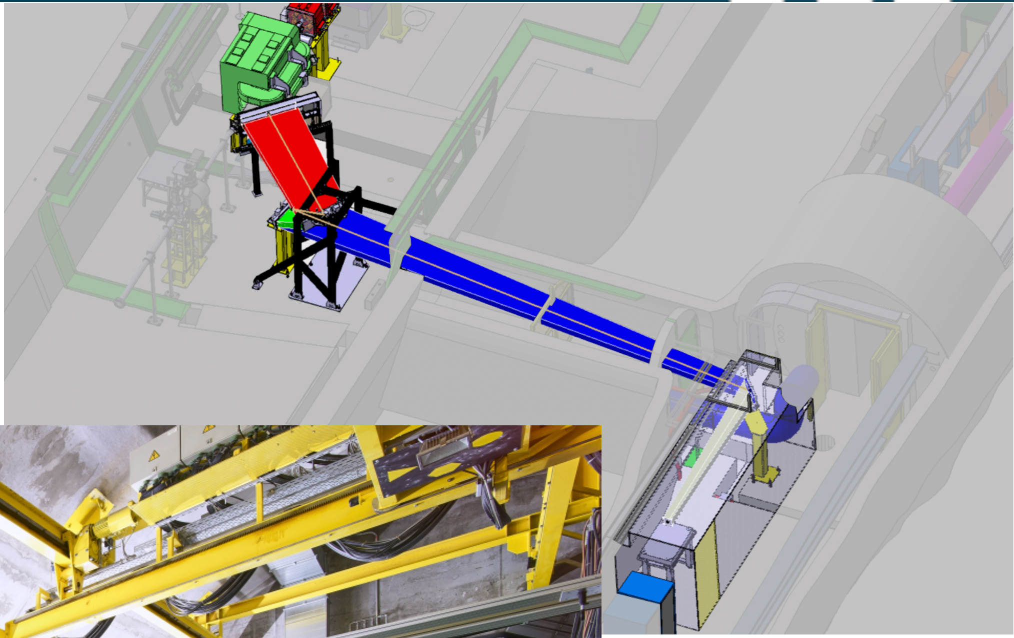


Summary

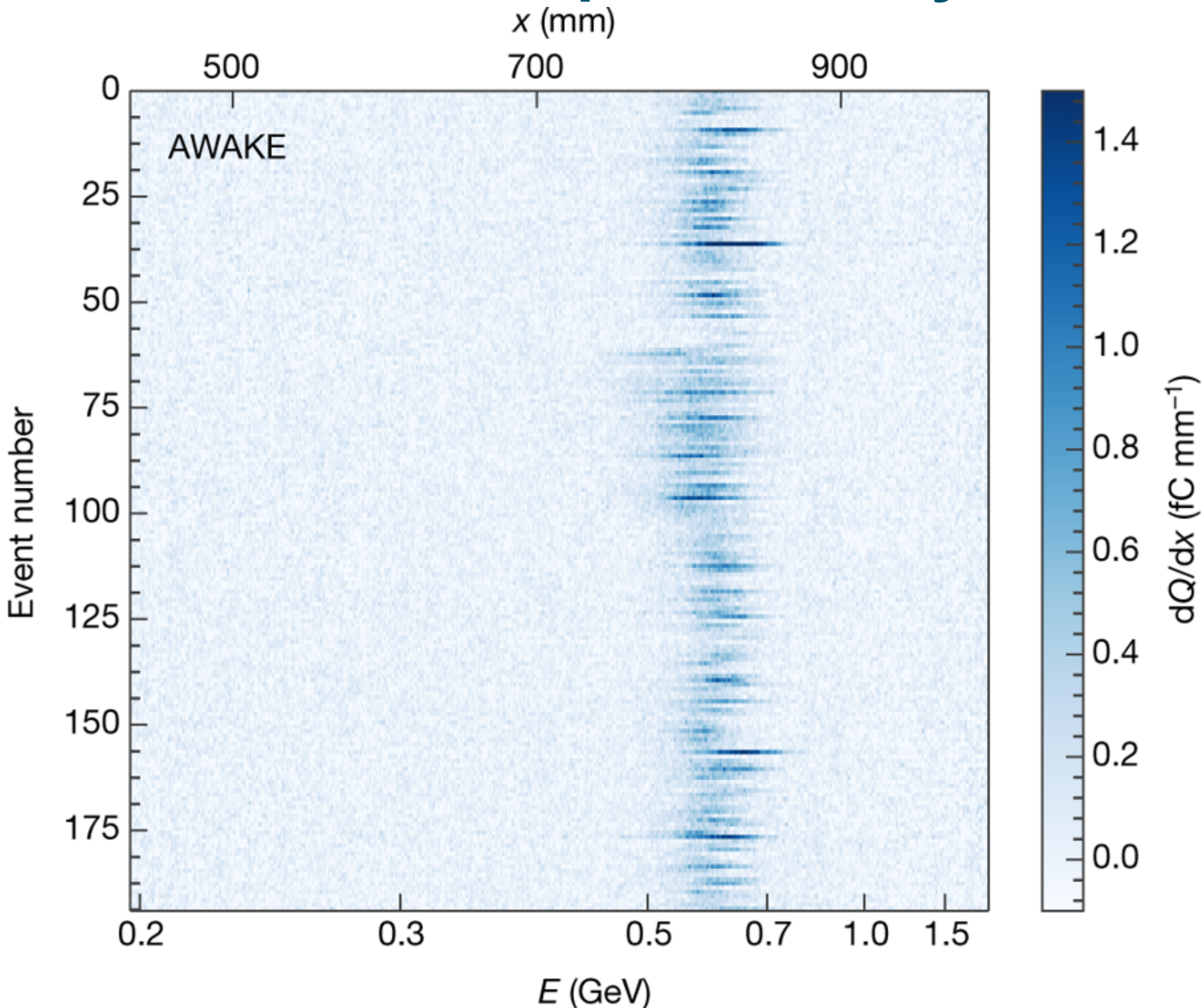
- The AWAKE experiment has had a very successful 2018.
- The application of the AWAKE scheme to particle physics experiments has been advancing well:
  - An increased number of electrons on target can lead to a competitive search for dark photons.
  - Facility and integration issues have been addressed for a fixed-target/beam-dump experiment and for an *ep* collider.
  - There is a novel *ep* physics programme to be pursued.
  - Other ideas have been proposed and hopefully more will come.
- Work will continue on these studies, also as we learn more from the AWAKE experiment.

Back-up, extra

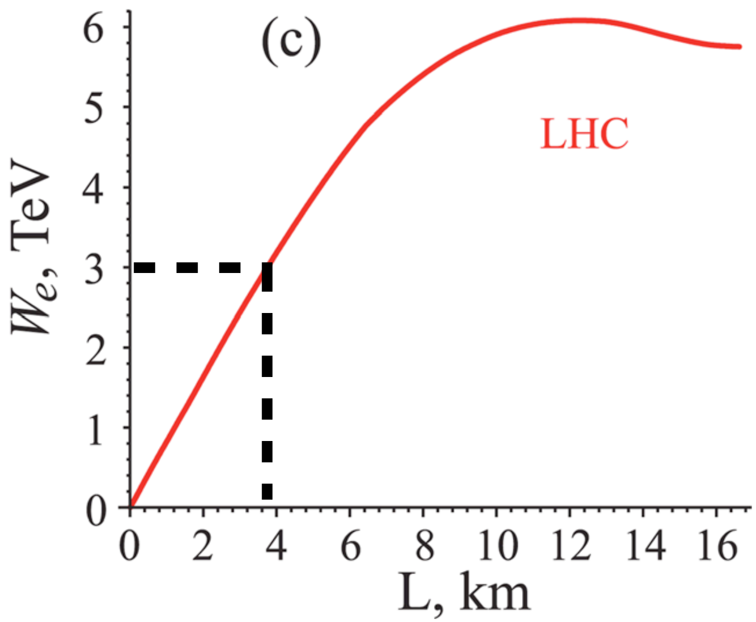
AWAKE spectrometer



Electron acceleration reproducibility



Very high energy electron–proton collisions, VHEeP



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

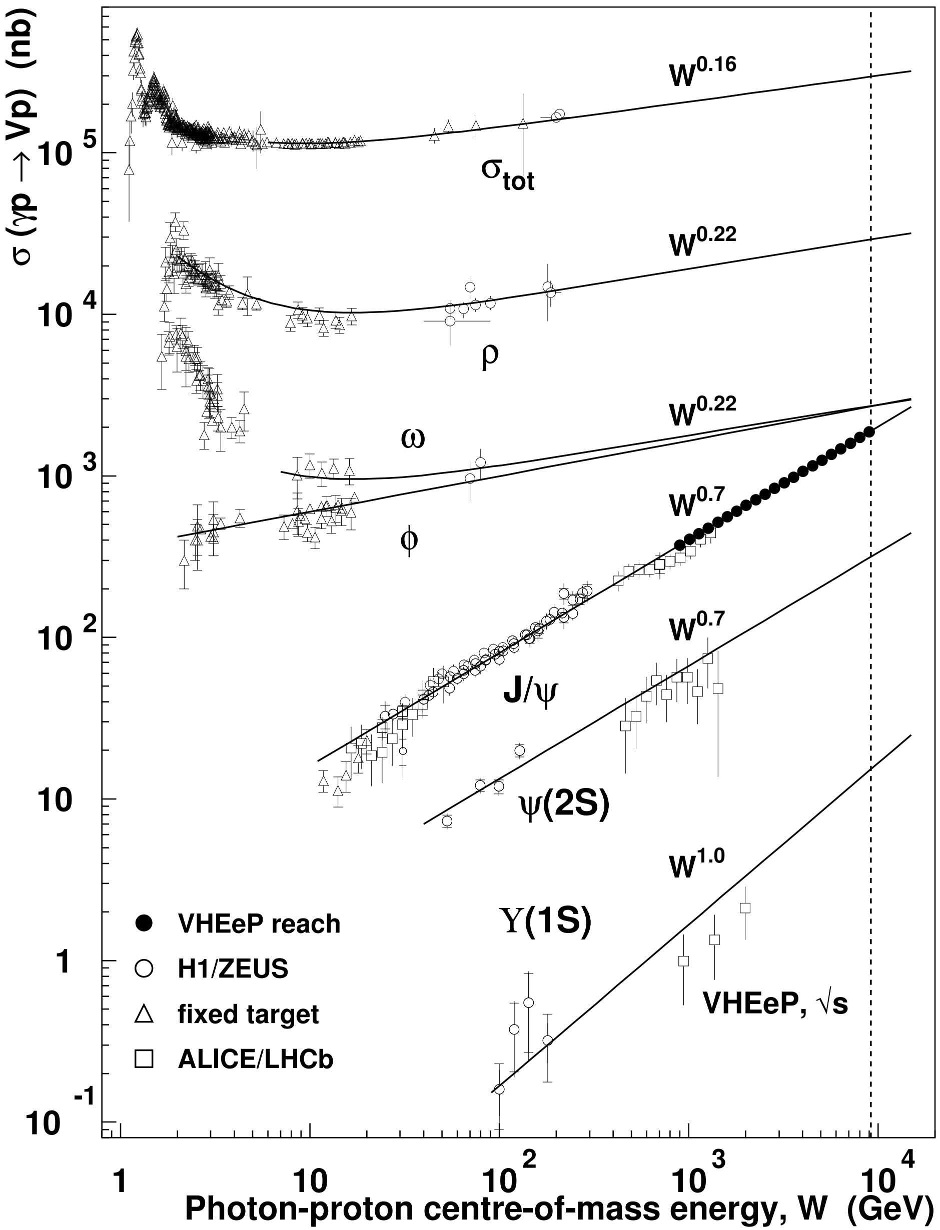
- What about very high energies in a completely new kinematic regime ?
- Choose E_e = *3 TeV* as a baseline for a new collider with E_p = *7 TeV* ⇒ $\sqrt{s}$ **= 9 TeV**.
- Acceleration of electrons in under *4 km*.
- Can vary the energy.
- Centre-of-mass energy ×30 higher than HERA.
- Reach in (high)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

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

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

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

Vector meson cross sections



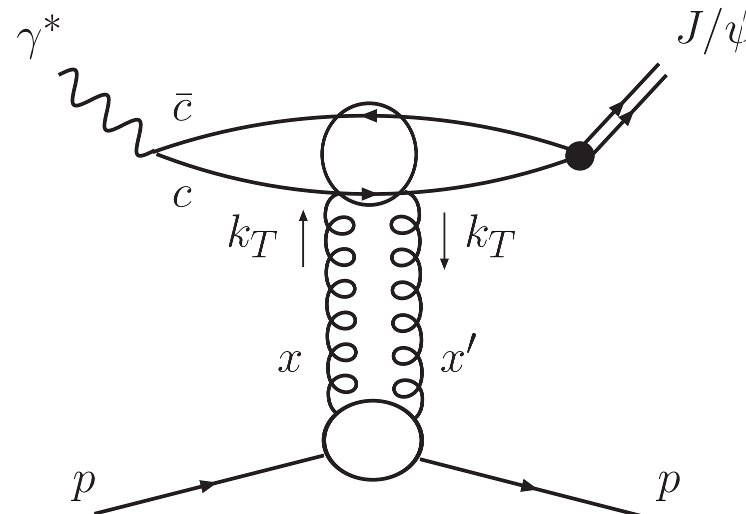
Strong rise with energy related to gluon density at low *x*.

Can measure all particles within the same experiment.

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

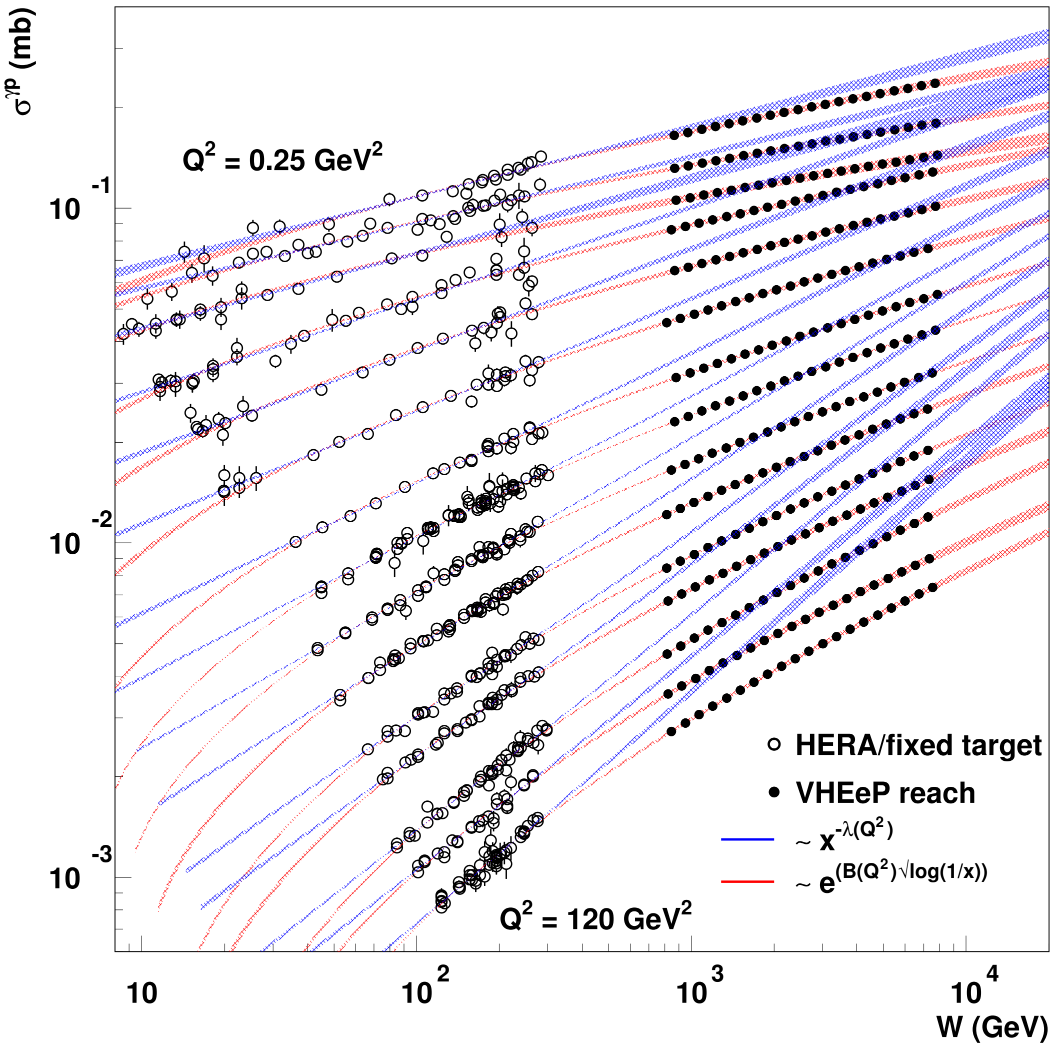
At VHEeP energies, *σ(J/ψ) > σ(φ)* !

Onset of saturation ?



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

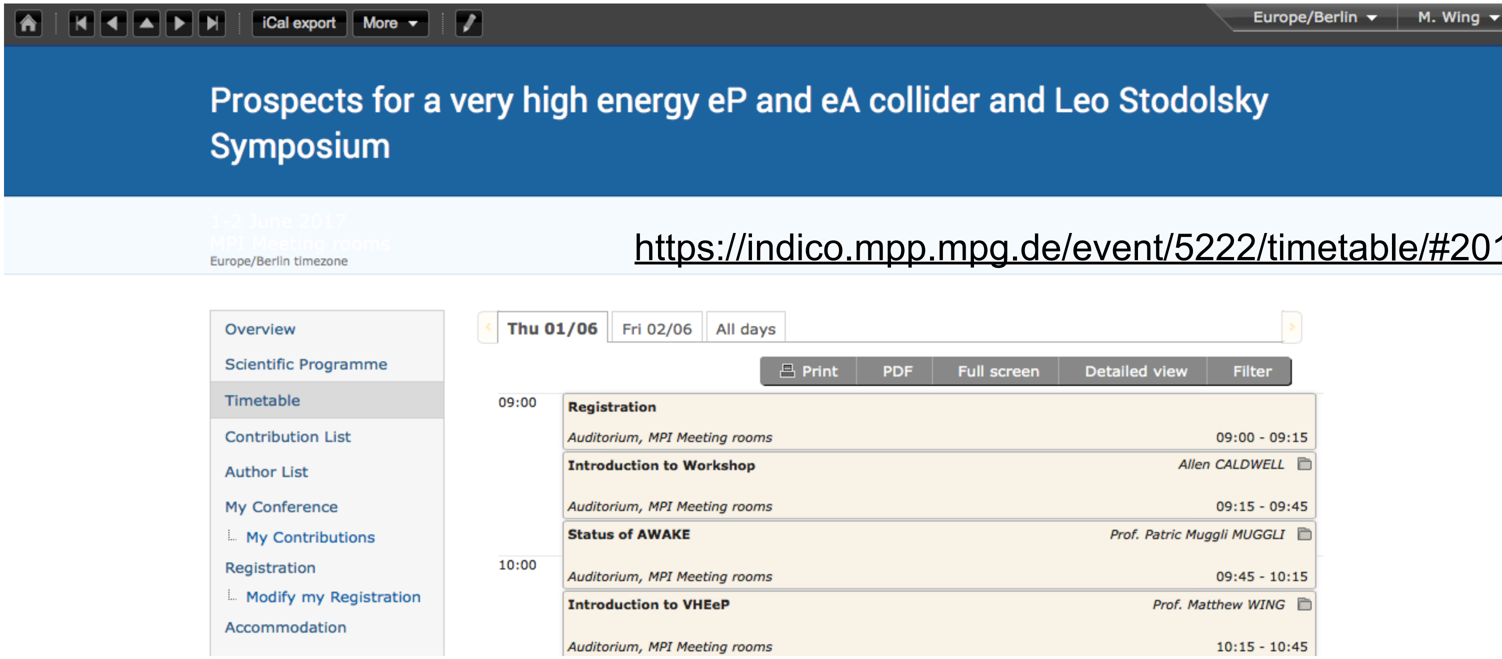
Virtual-photon–proton cross section



- 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.

VHEeP Workshop

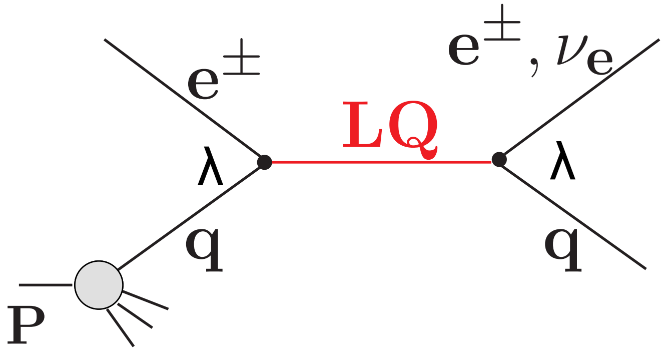


https://indico.mpp.mpg.de/event/5222/timetable/#20170601

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)

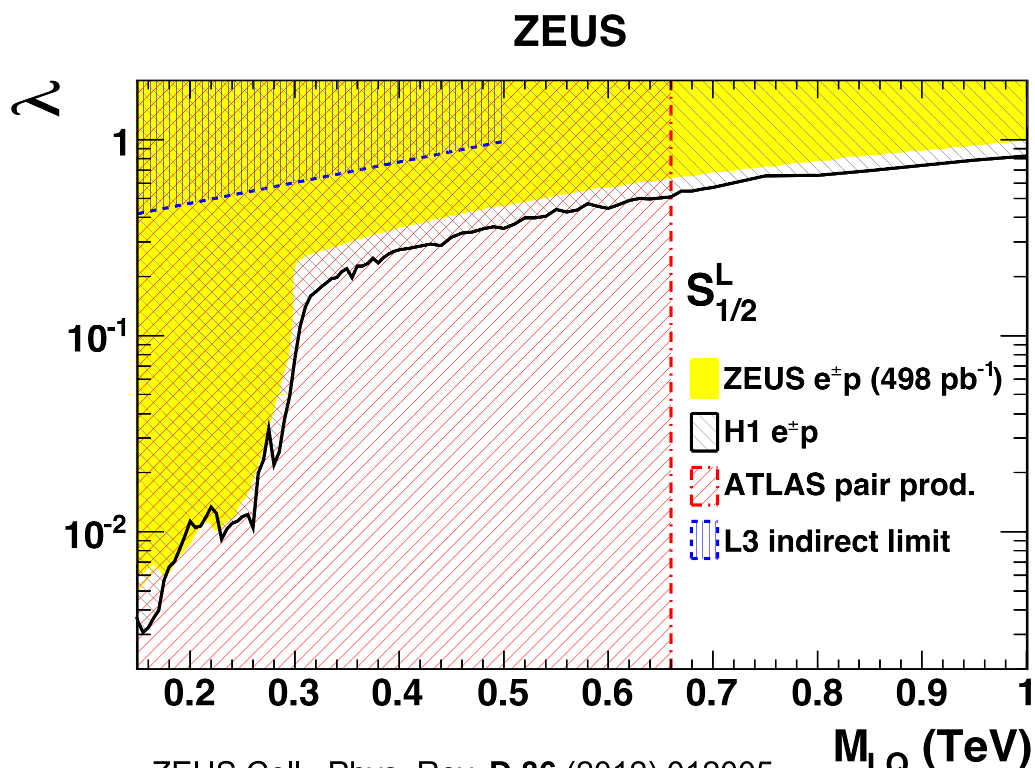
Leptoquark production



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

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

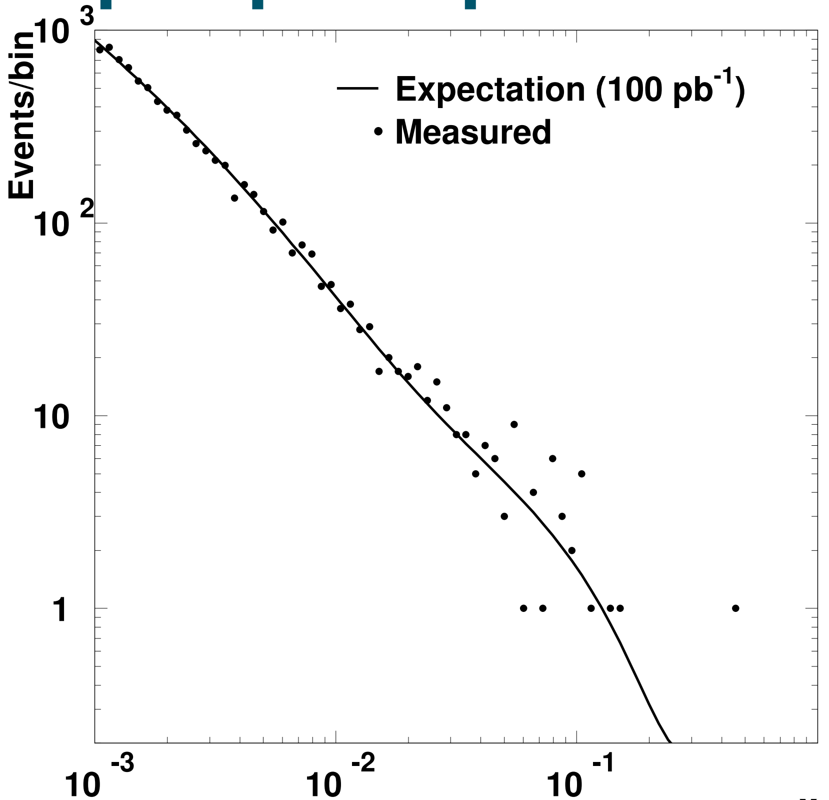
$$\sigma^{\mathrm{NWA}} = (J+1)\frac{\pi}{4s}\lambda^2\, q(x_0, M_{\mathrm{LQ}}^2)$$



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

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

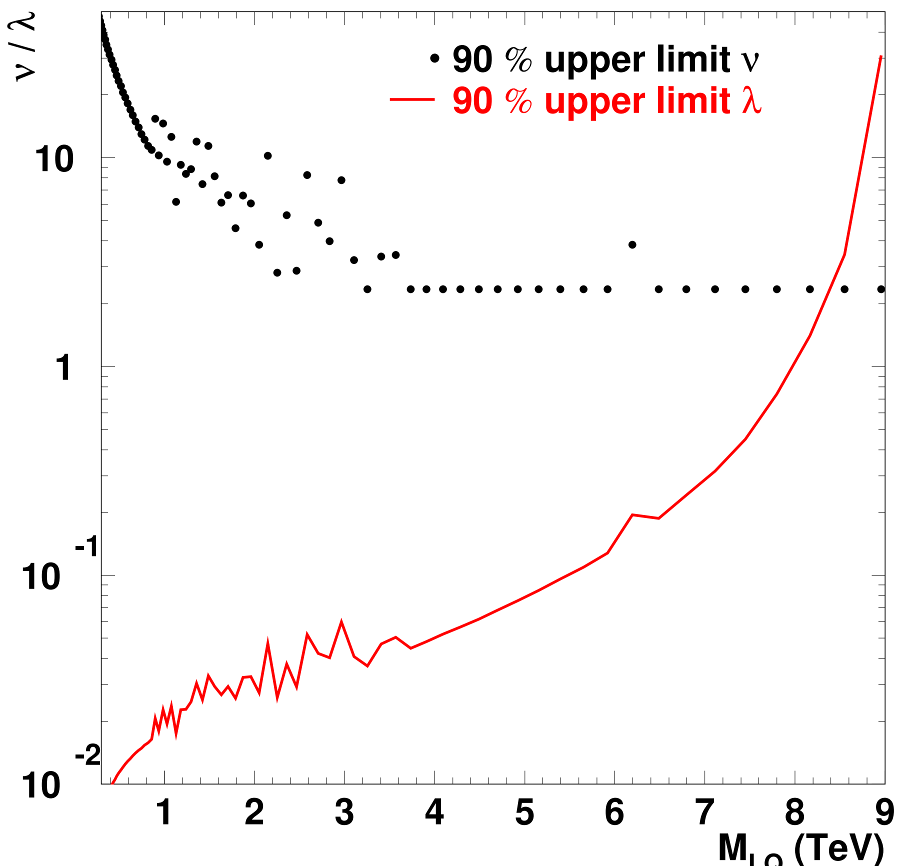
Leptoquark production at VHEeP



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.