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Using the AWAKE acceleration scheme for beam-dump experiments

Matthew Wing (UCL)

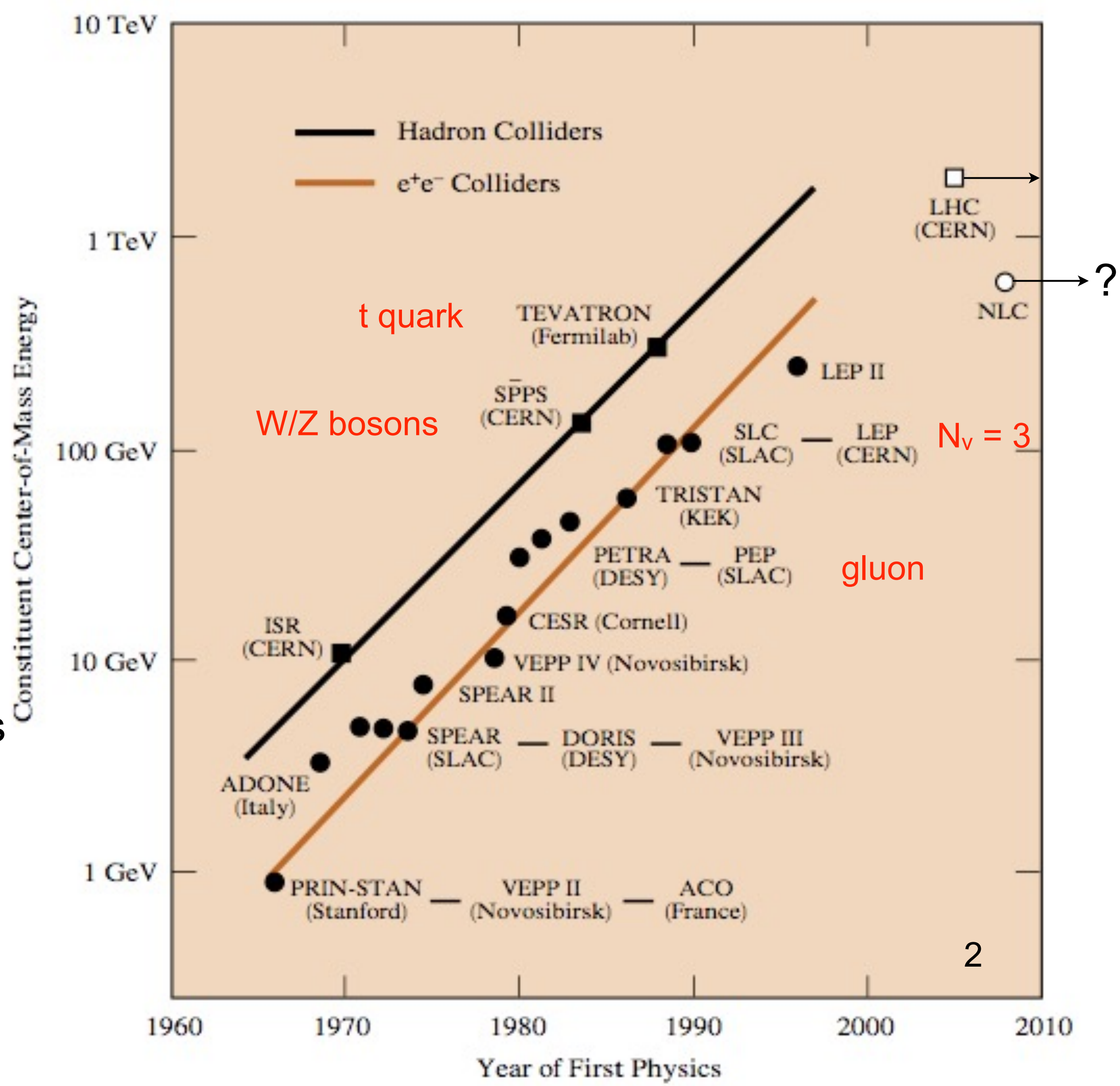
- Introduction and motivation for AWAKE
- Possible physics experiments
    - Possible ideas
    - Search for dark photons, NA64-like
- Summary and discussion

Thanks to: A. Caldwell, J. Chappell, P. Crivelli, S. Gninenko, E. Gschwendtner, A. Hartin, A. Pardons, A. Petrenko

IoP meeting on kaon and beam-dump experiments — Birmingham, 3 December 2018

Introduction: limits on accelerators

- 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 …

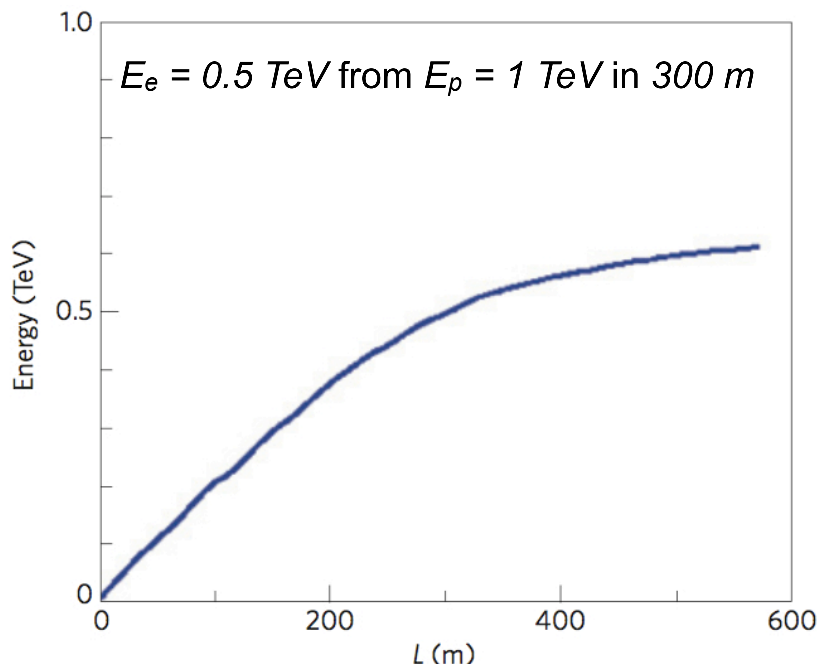


Plasma wakefield acceleration as a solution

• 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*).

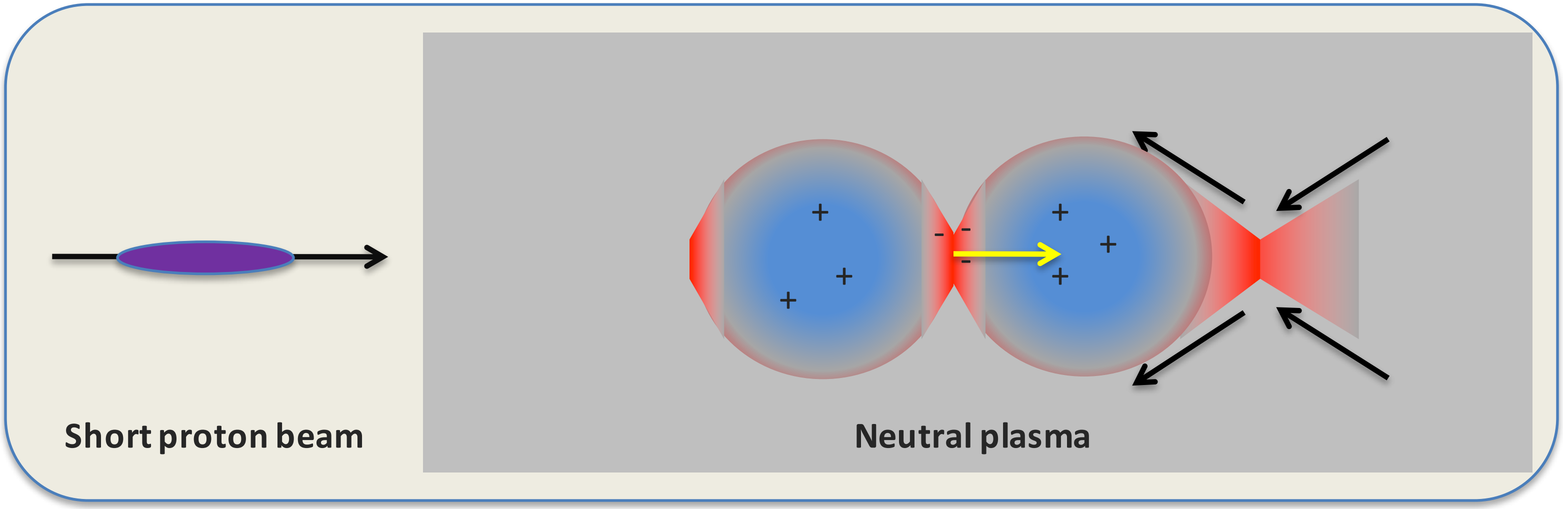
• Proton-driven plasma wakefield acceleration* is well-suited to high energy physics applications. Higher stored energy, ability to drive wakefields over long lengths.



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

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

Plasma wakefield acceleration

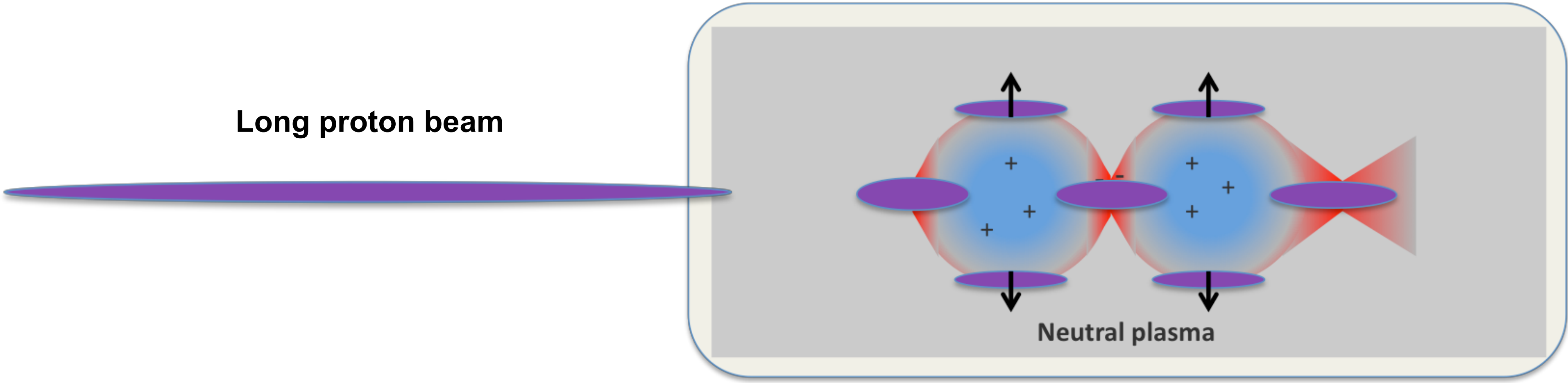


- Electrons ‘sucked in’ by proton bunch
- Continue across axis creating depletion region
- Oscillation of plasma electrons creates strong electric fields
- Longitudinal electric fields can accelerate particles in direction of proton bunch
- Transverse electric fields can focus particles
- **A ‘witness’ bunch of e.g. electrons placed appropriately can be accelerated by these strong fields**
- But proton bunches are not “short” …

Long proton bunches ?

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

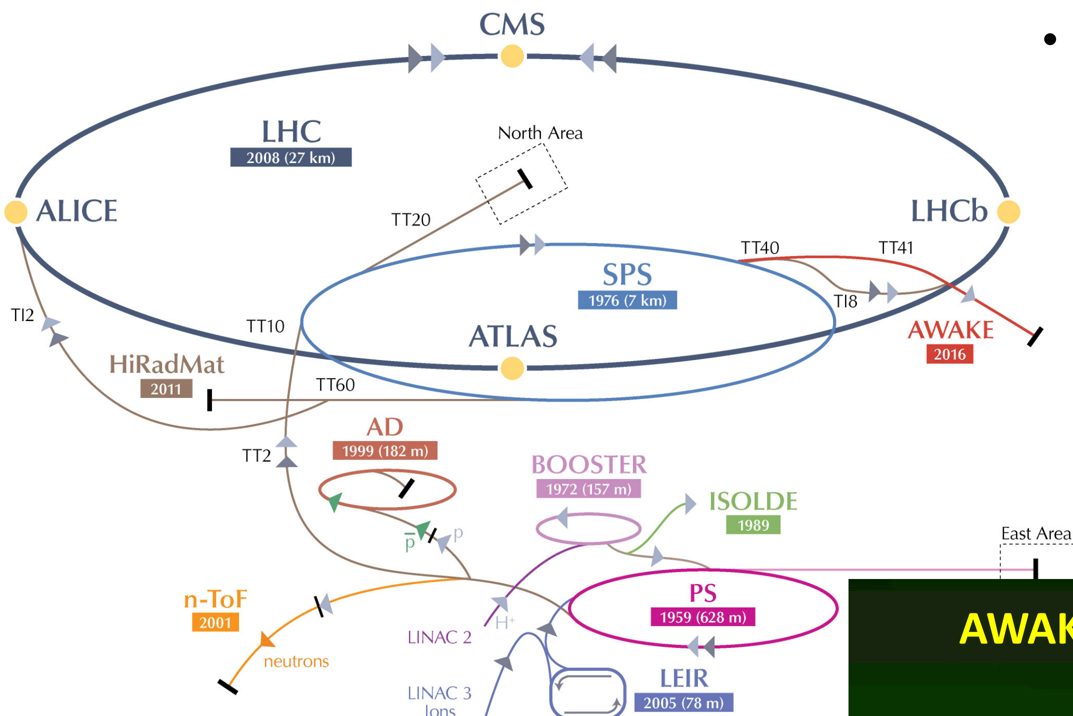
N. Kumar, A. Pukhov, K.V. Lotov, Phys. Rev. Lett. 104 (2010) 255003



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 process allows **current beams to be used.**

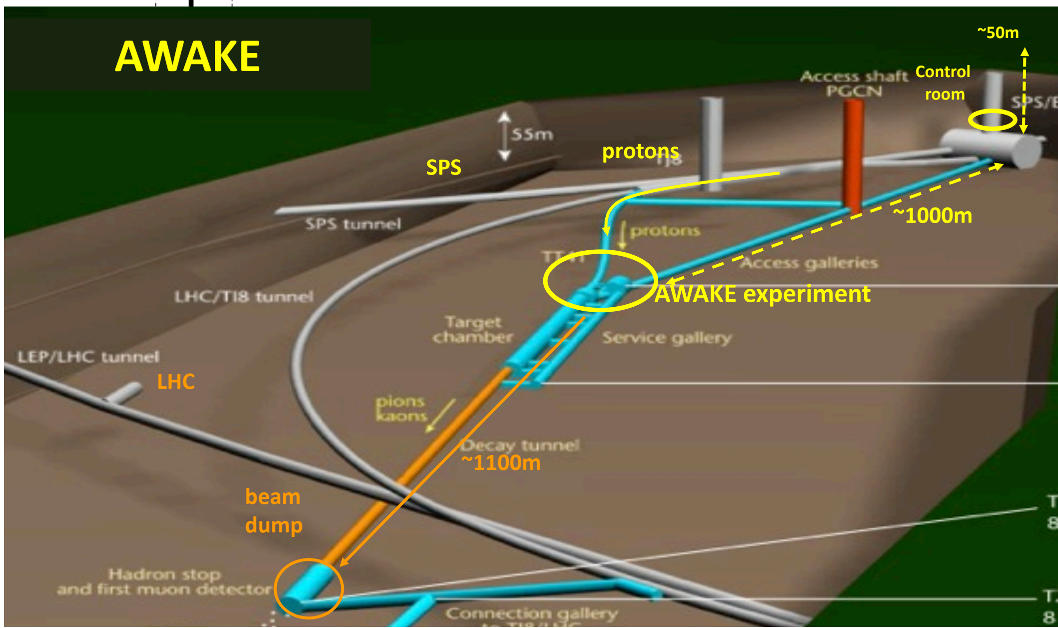
AWAKE experiment at CERN



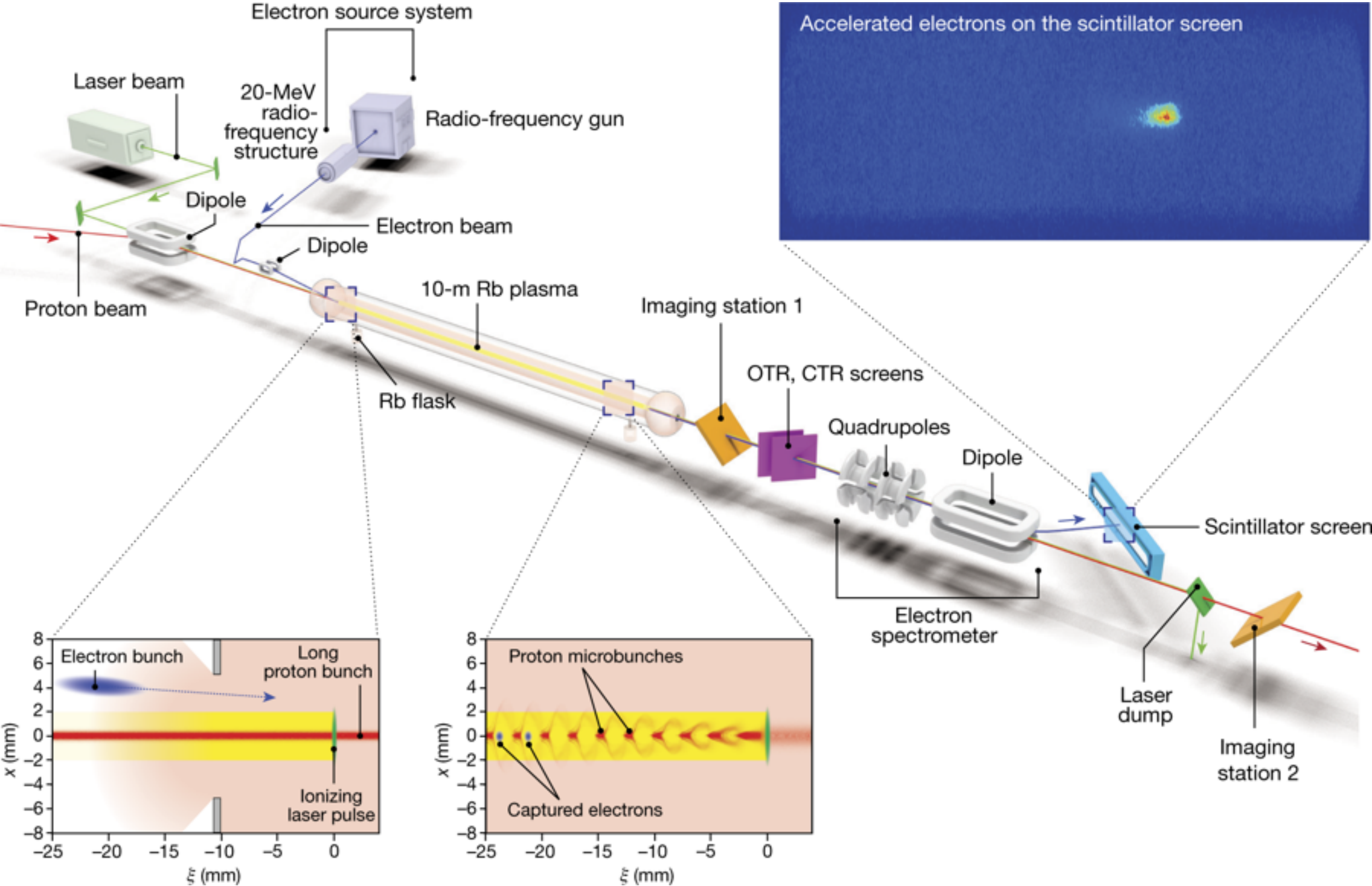
- Demonstrate for the first time proton-driven plasma wakefield acceleration.

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

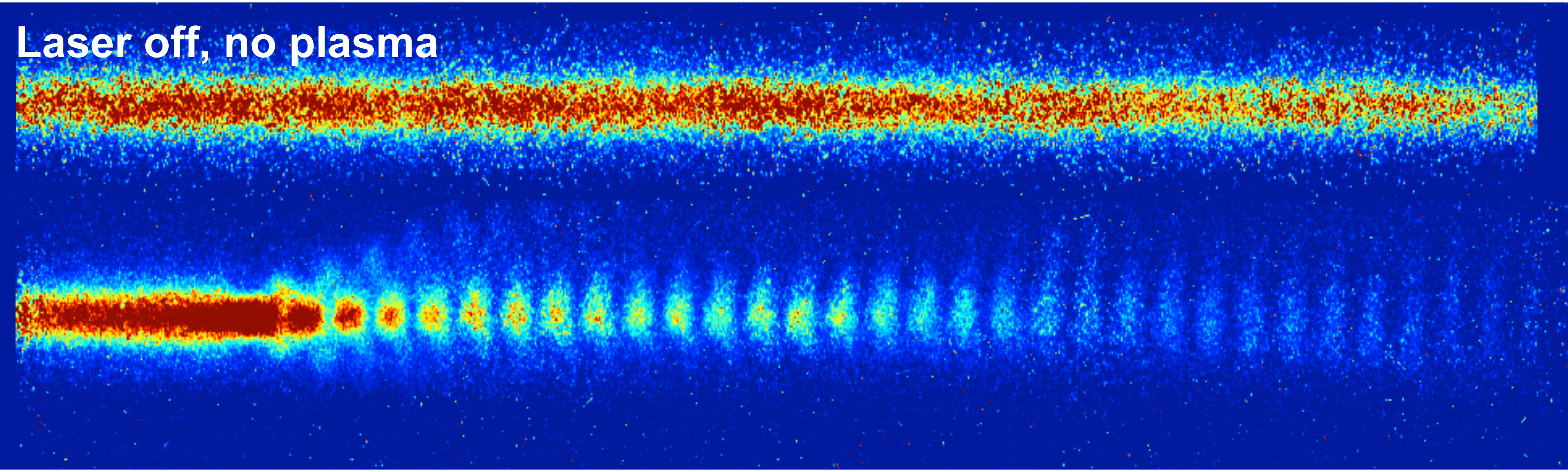
AWAKE Coll., Plasma Phys. Control. Fusion **56** (2014) 084013; Nucl. Instrum. Meth. **A 829** (2016) 3; Nucl. Instrum. Meth. **A 829** (2016) 76.



AWAKE schematic

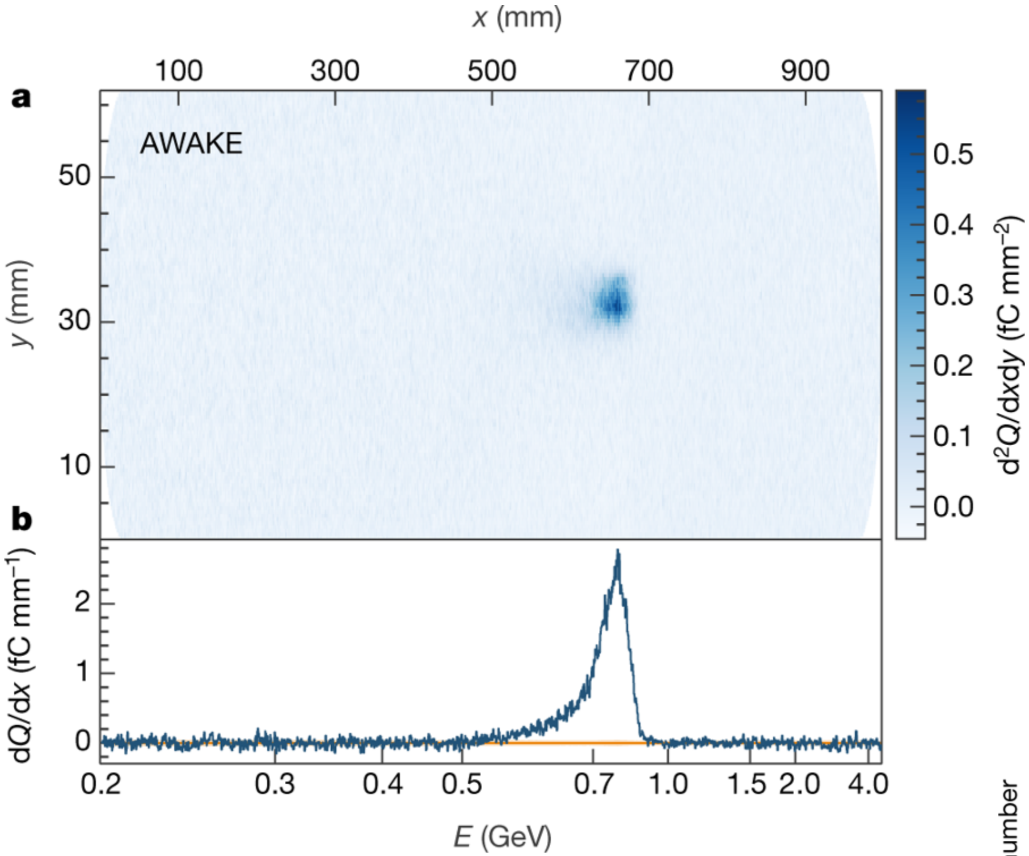


Direct measurement of self-modulation



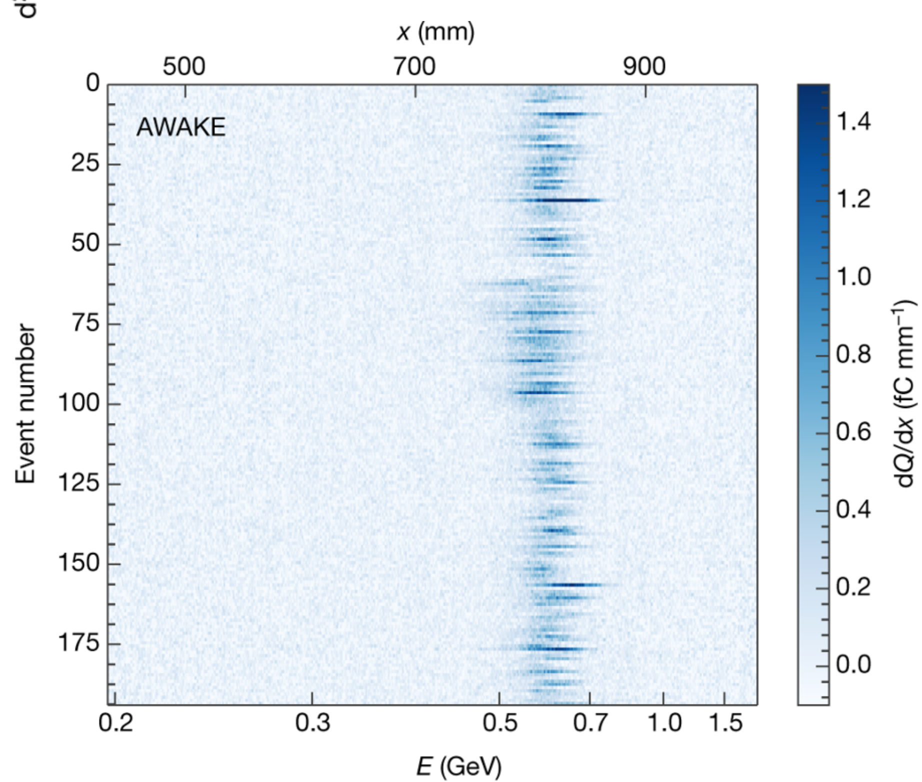
- Events stitched together.
- Clear modulation of the proton bunch.
- Highly reproducible phase between the bunches (and events).
- Crucial for injection of electrons.

Electron acceleration



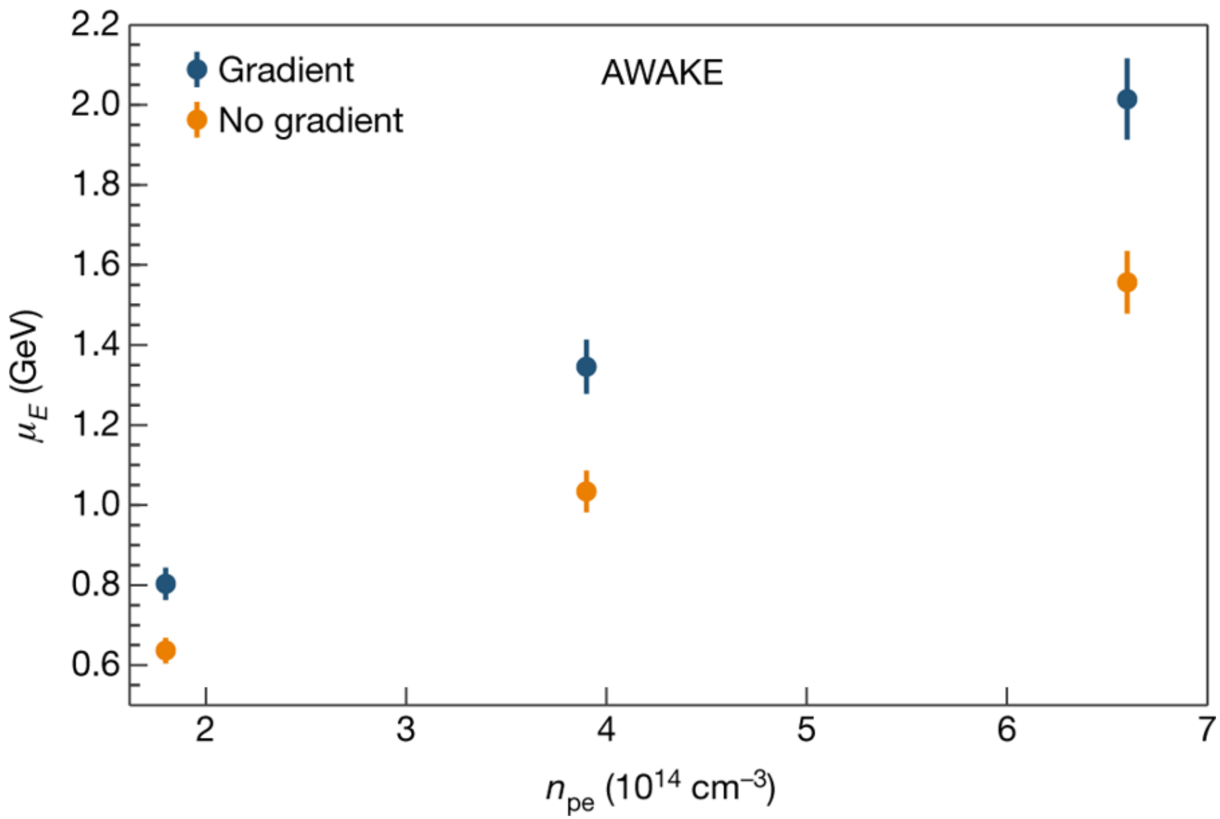
Clear signals

Reproducible acceleration



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

Electron acceleration energy dependence

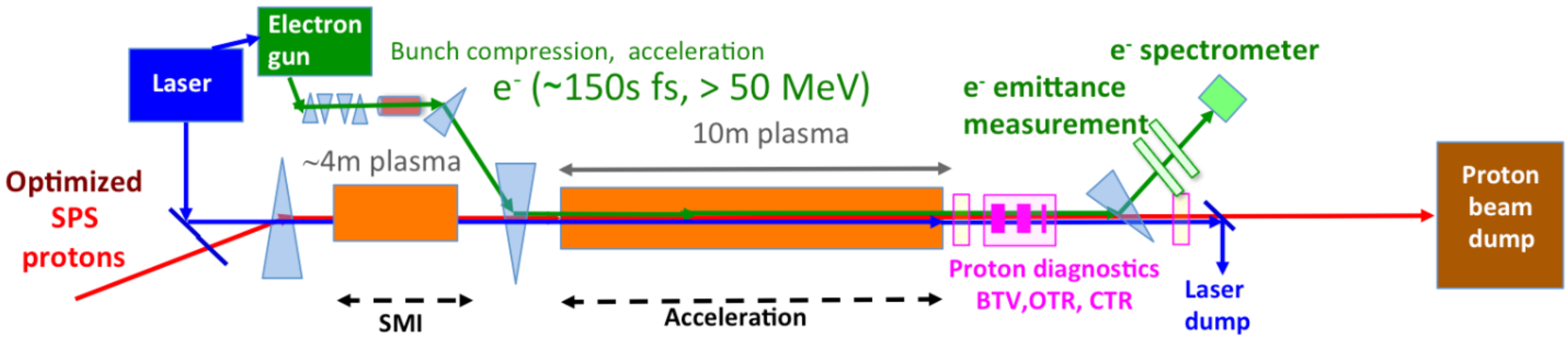


- Acceleration to 2 GeV is a great achievement.
- Simulation/theory predicted similar energy gains.
- Experiment not optimised for electron injection: accelerated charge (~0.25 pC) is low; already increased value.

AWAKE Run 1 achieved all of its original goals and more

AWAKE Run 2

- Preparing AWAKE Run 2, after CERN LS2 and before LS3, 2021–4.
  - Accelerate electron bunch to higher energies (~10 GeV).
  - 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).

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.
  - New regime for QED.
  - Can constrain more exotic physics (e.g. dark photons).

Possible particle physics experiments II

- **Search for dark photons à la NA64**
- 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.
- Acceleration of muons.

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

Interested to hear of other possibilities.

- **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

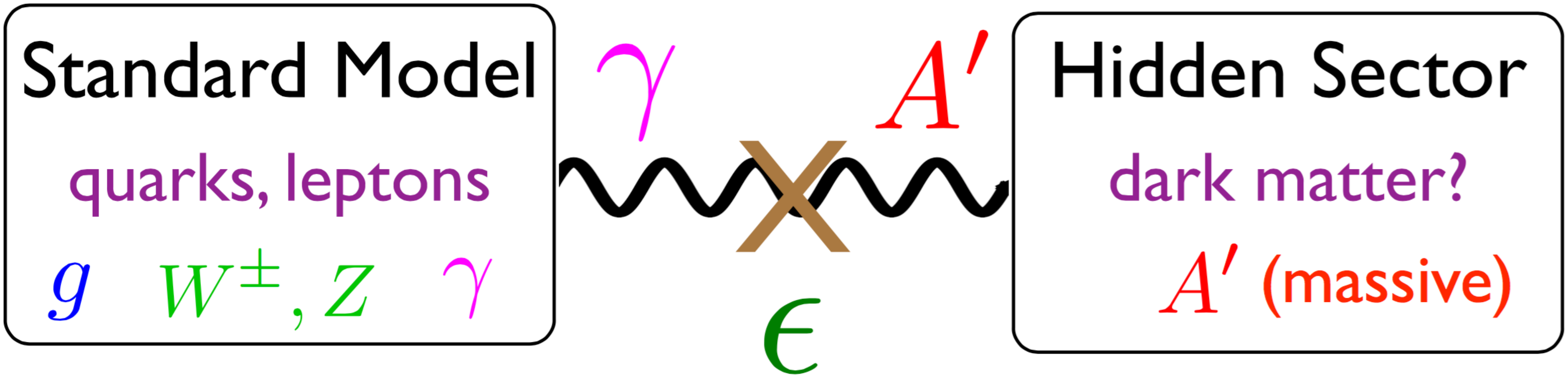
The hidden / dark sector

- 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

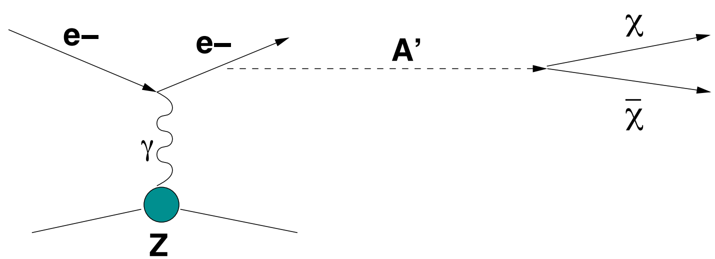


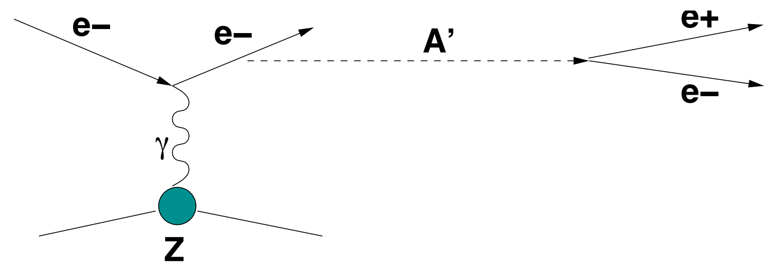
$$\Delta\mathcal{L} = \frac{\epsilon}{2} F^{Y,\mu\nu} F'_{\mu\nu}$$

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

NA64 experimental programme

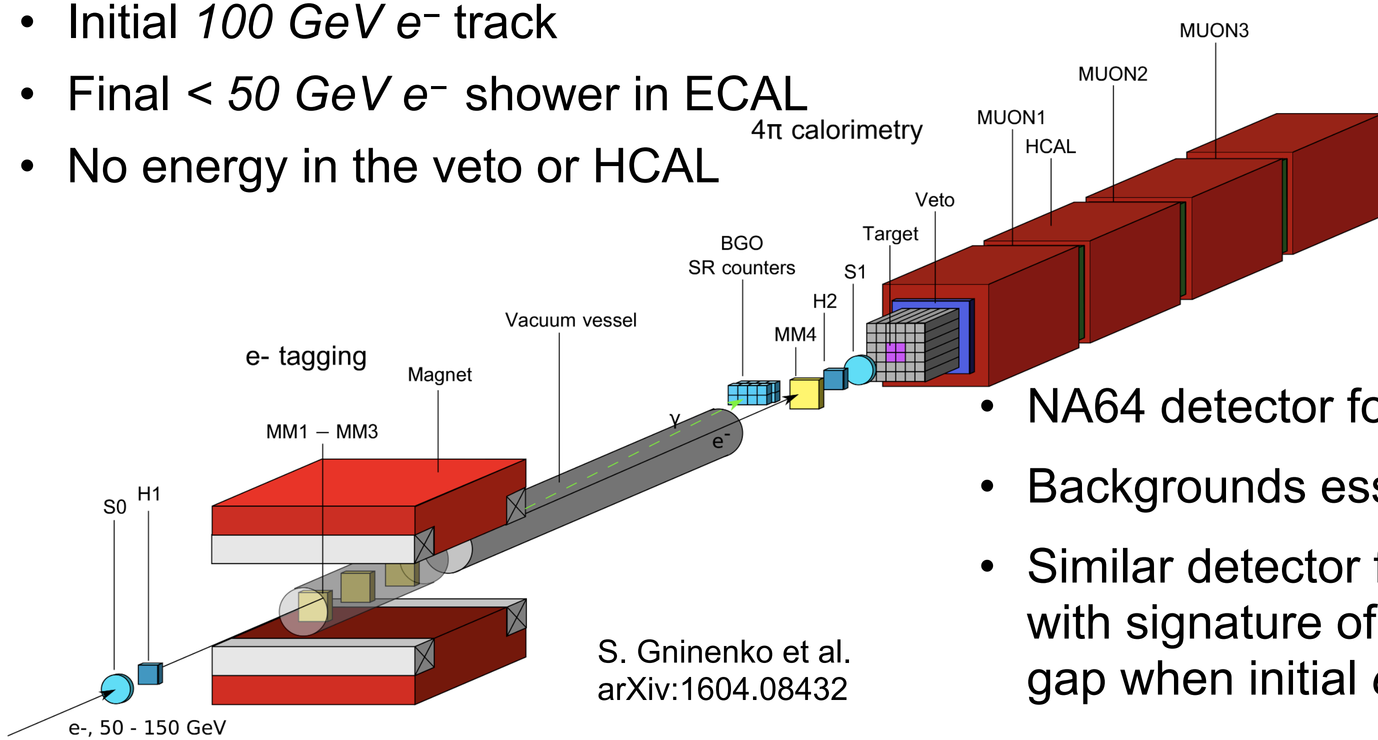
- Initial run in SPS beam focusing on $A' \rightarrow$ *invisible* channel.
- Also programme measuring $A' \rightarrow e^+ e^-$ channel.





Signature:

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



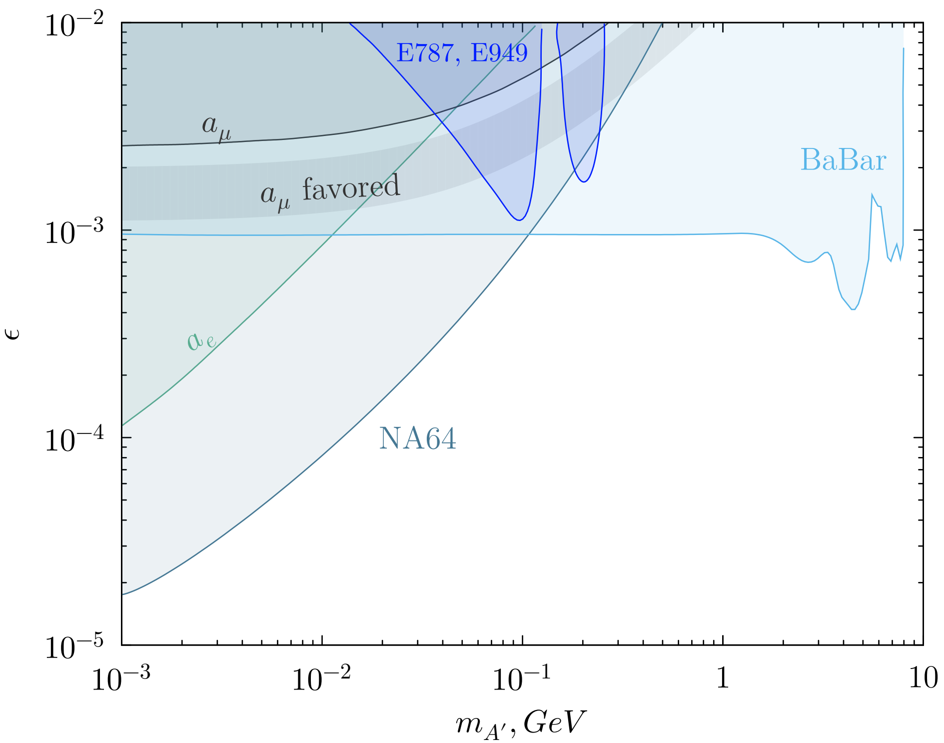
S. Gninenko et al.
arXiv:1604.08432

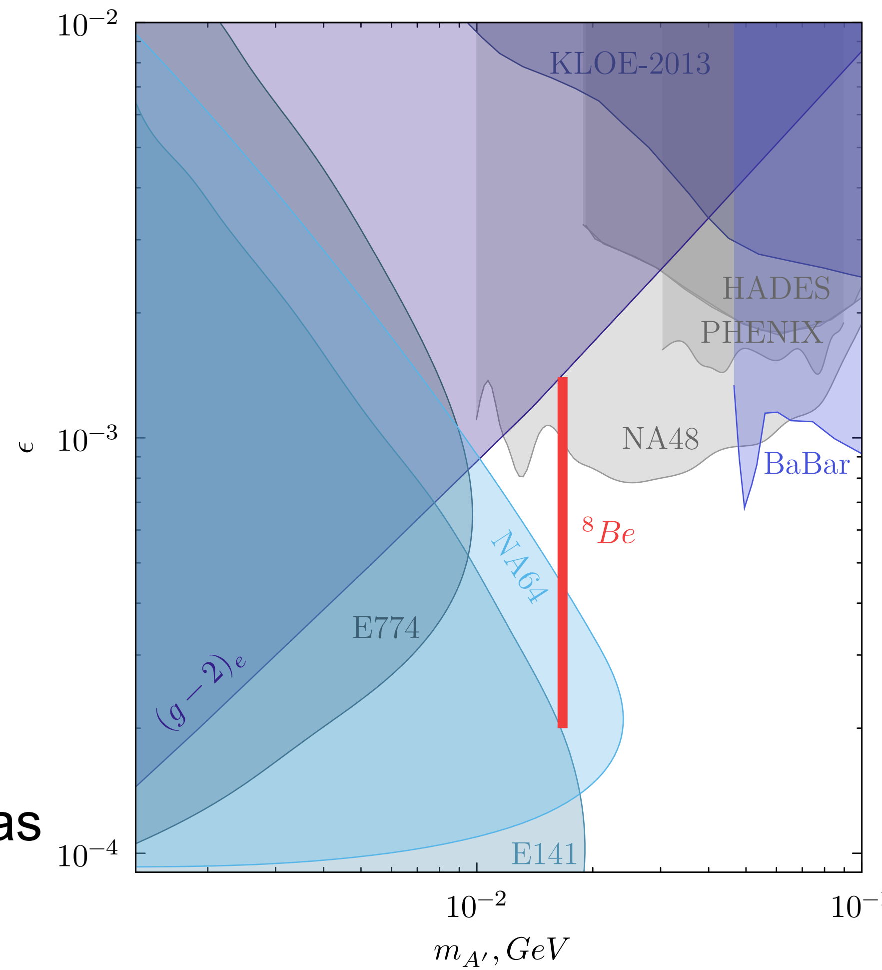
- NA64 detector for $A' \rightarrow$ *invisible* channel.
- Backgrounds essentially zero.
- Similar detector for $A' \rightarrow e^+ e^-$ channel with signature of two EM showers after gap when initial e^- hits target.

NA64 searches

Invisible mode, $A' \to \chi\bar{\chi}$

Visible mode, $A' \to e^+ e^-$





NA64 searches covering significant areas and addressing "new physics" issues.

Phys. Rev. **D 97** (2018) 072002

Phys. Rev. Lett. **120** (2018) 231802

Electrons on target using AWAKE scheme

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

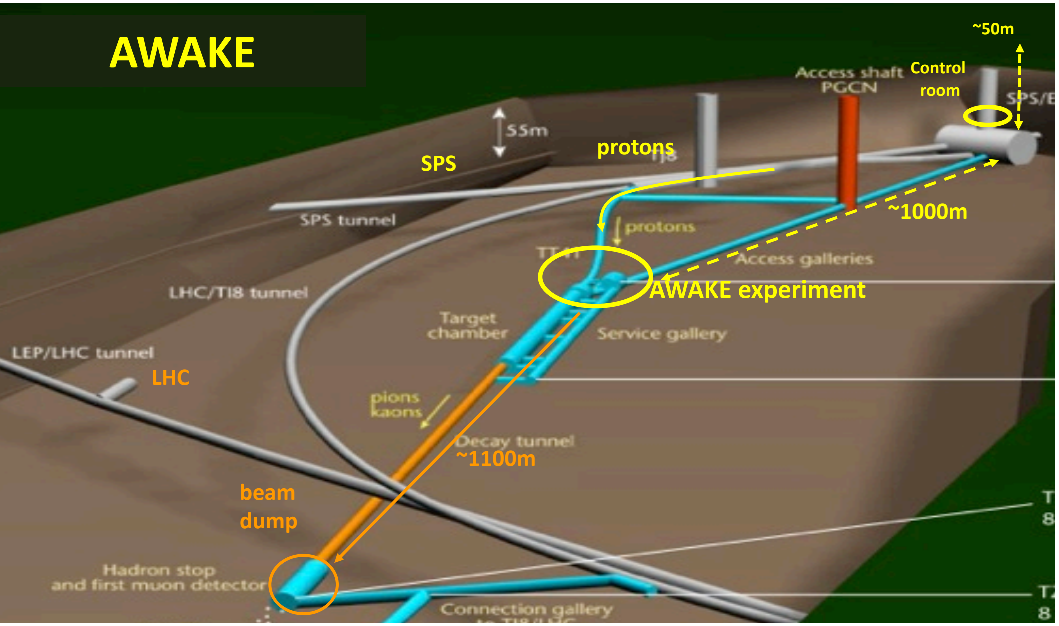
- $N_e \sim 10^{12}$ e^- for 3 months running.
- Optimisation of SPS beam could lead to up to **NA64:** $\boldsymbol{N_e \sim 5 \times 10^{12}\ e^-}$.

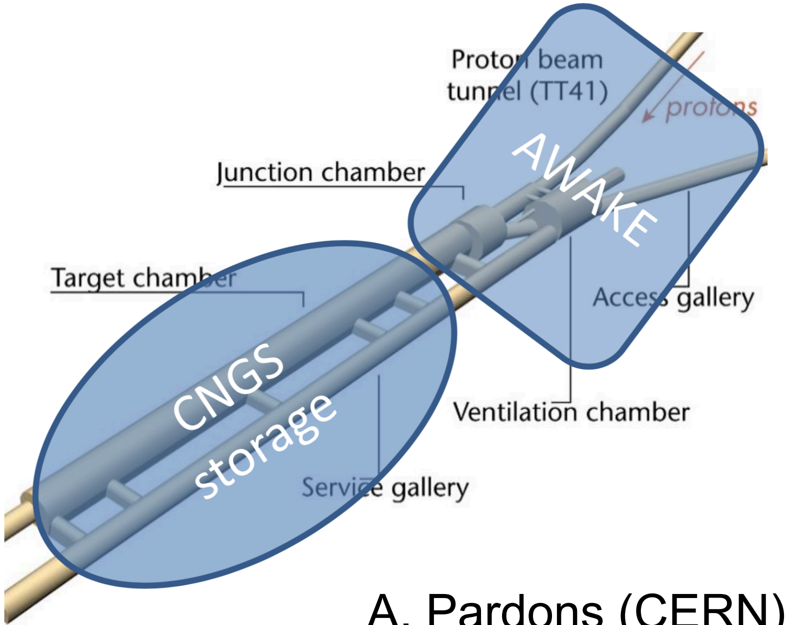
AWAKE-like beam with bunches of $(1-5) \times 10^9$ e^-:

- 16 or 320 bunches every *40 s*.
- 3 months running with *70%* efficiency
- **AWAKE+NA64:** $\boldsymbol{N_e \sim 2 \times 10^{15} - 2 \times 10^{17}\ e^-}$

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

An experiment in the AWAKE area



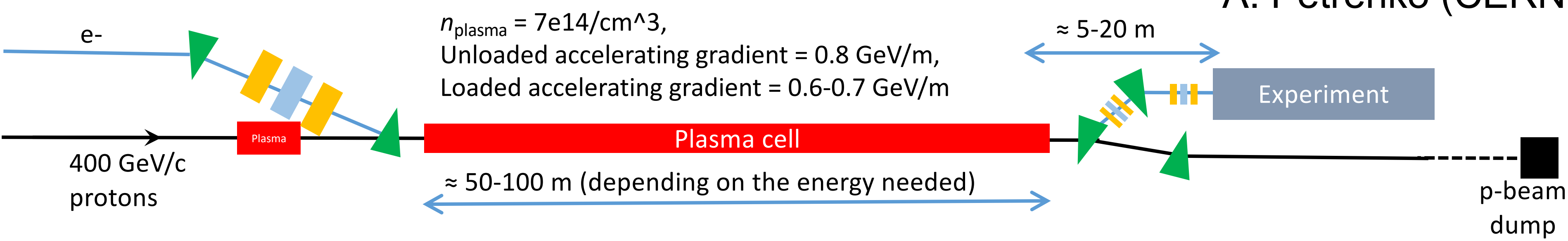


A. Pardons (CERN)

About *100 m* available in old CNGS target area. Would need a clean out.

Possible beam layout

A. Petrenko (CERN)



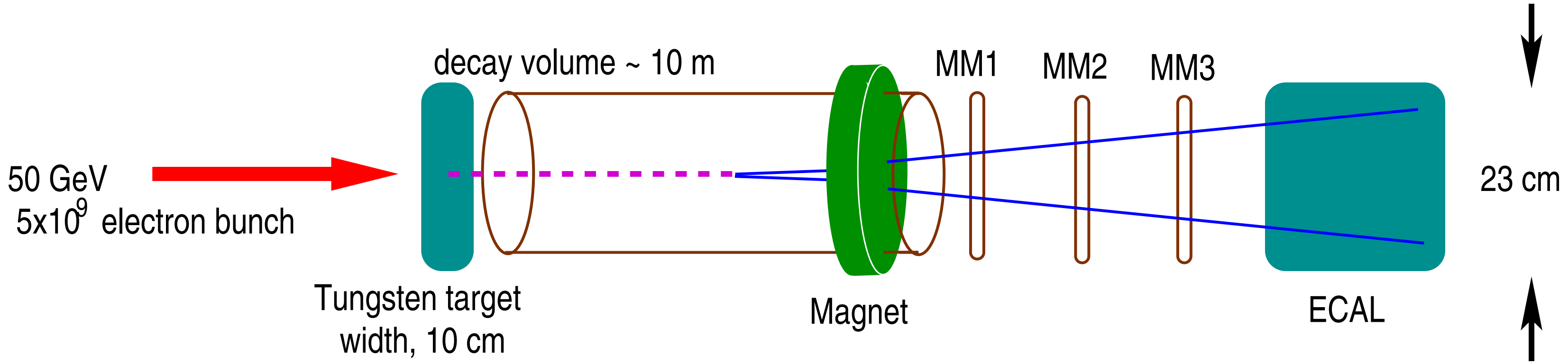
Possible ways to reduce accelerator length:

- Try to use high plasma density with existing proton beam.
- Improved SPS beam transverse emittance: higher beam density means higher wakefields in more dense plasma.
- Use more efficient micro-bunching technique.

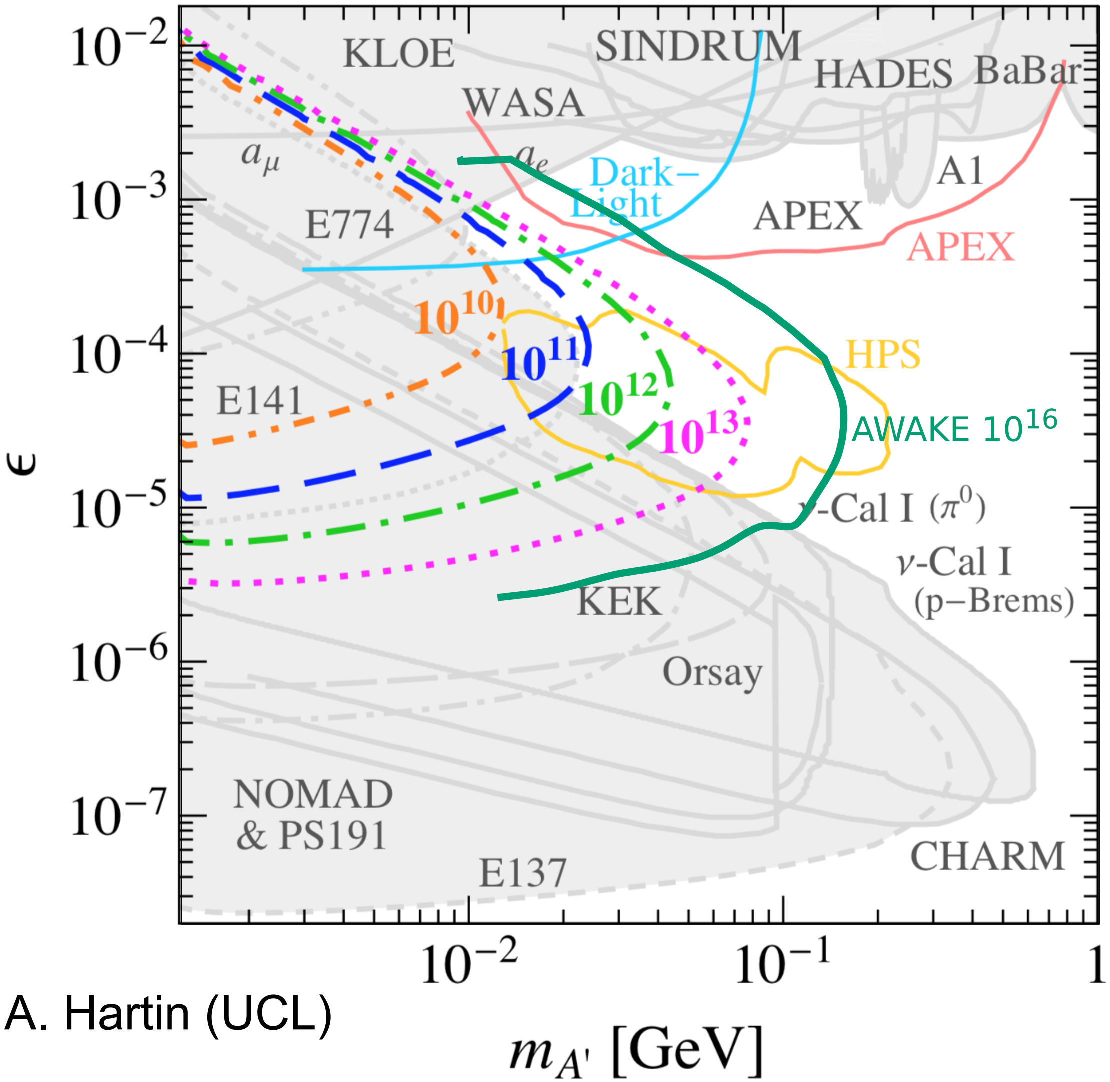
More work ongoing on infrastructure issues and accelerator configuration.

Sensitivity with increased electrons on target

- Have taken plots of mixing strength, ε, versus mass, $m_{A'}$, from NA64 studies/proposals and added curves to show increased sensitivity.
- Simulation from NA64 (theory and experimental layout)
- Modified detector for different configuration; note that this idea uses bunches, rather than single electrons
- Considered $A' \rightarrow e^+ e^-$ channel.
- Analysis based on well separated tracks (due to dipole) on trackers (MM1−3).
- Vertex reconstruction and invariant mass.



Limits on dark photons, *A'* → e⁺ e⁻ channel

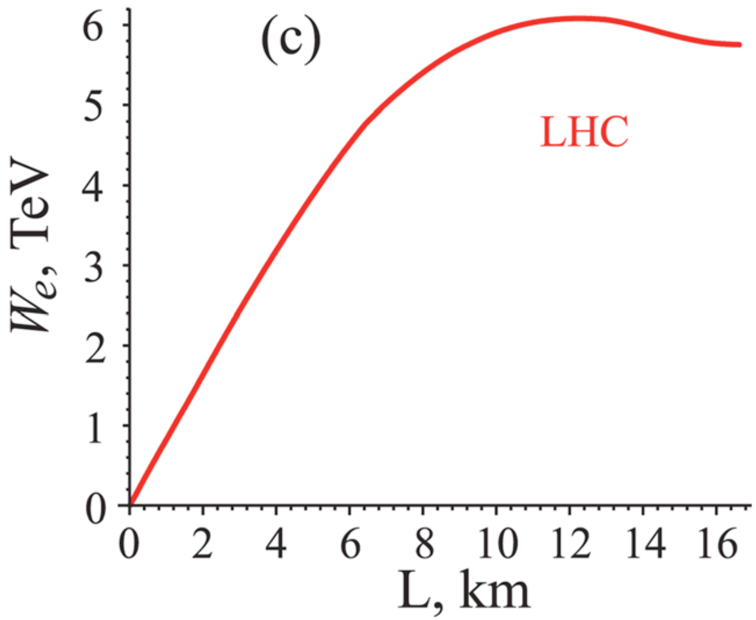


- For *10^{10} – 10^{13}* electrons on target with NA64.
- For *10^{16}* electrons on target with AWAKE-like beam.
- Using an AWAKE-like beam would extend sensitivity further:
  - around *ε ~ 10^{-3} – 10^{-5}*.
  - to high masses ~ *0.1 GeV*.
- Input into the CERN Physics Beyond Colliders study:
  - in combined plots assembling all possible experiments.
  - submit to European Strategy process.

Further studies

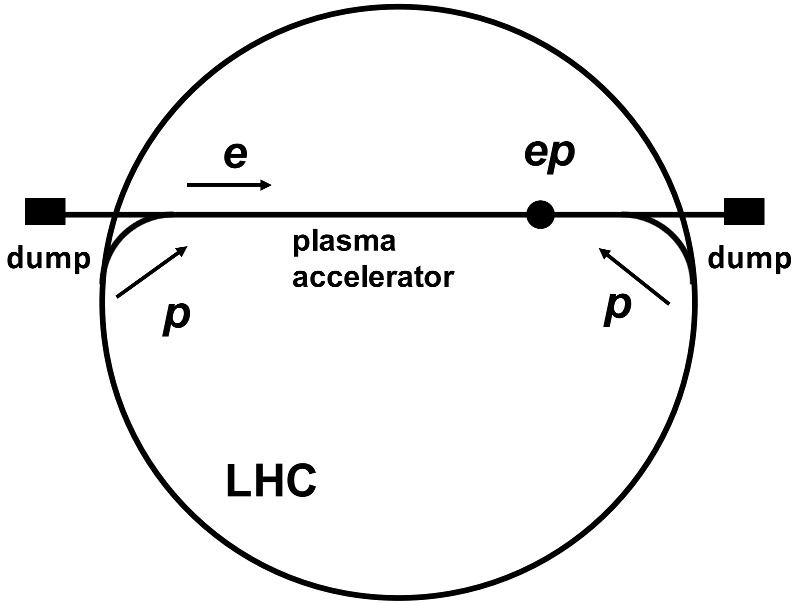
- More study of backgrounds needed.
- More study of possible detector configurations.
- Could consider other channels, e.g. $A' \to \mu^+ \mu^-$, $A' \to \pi^+ \pi^-$.
- More careful study of optimal beam energy needed.

According to simulations, TeV region is possible.



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

TeV electrons would have more applications, including dark photons.



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

Summary and discussion

- The AWAKE collaboration has **demonstrated acceleration of electrons** in proton-driven plasma wakes.
- AWAKE has an exciting programme of R&D aiming to develop a **useable accelerator technology**.
- 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.
- Emphasis what can be done with proton-driven scheme **using CERN infrastructure**.
- Work ongoing studying boundary conditions / possibilities from **physics, technical and integration side**, e.g. de-phasing limit, repetition rate, tunnel space, etc..
- A **high-energy high-charge electron bunch** complements other dark photon searches.
- Welcome **other ideas** on what could be done with AWAKE scheme.

Back-up

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

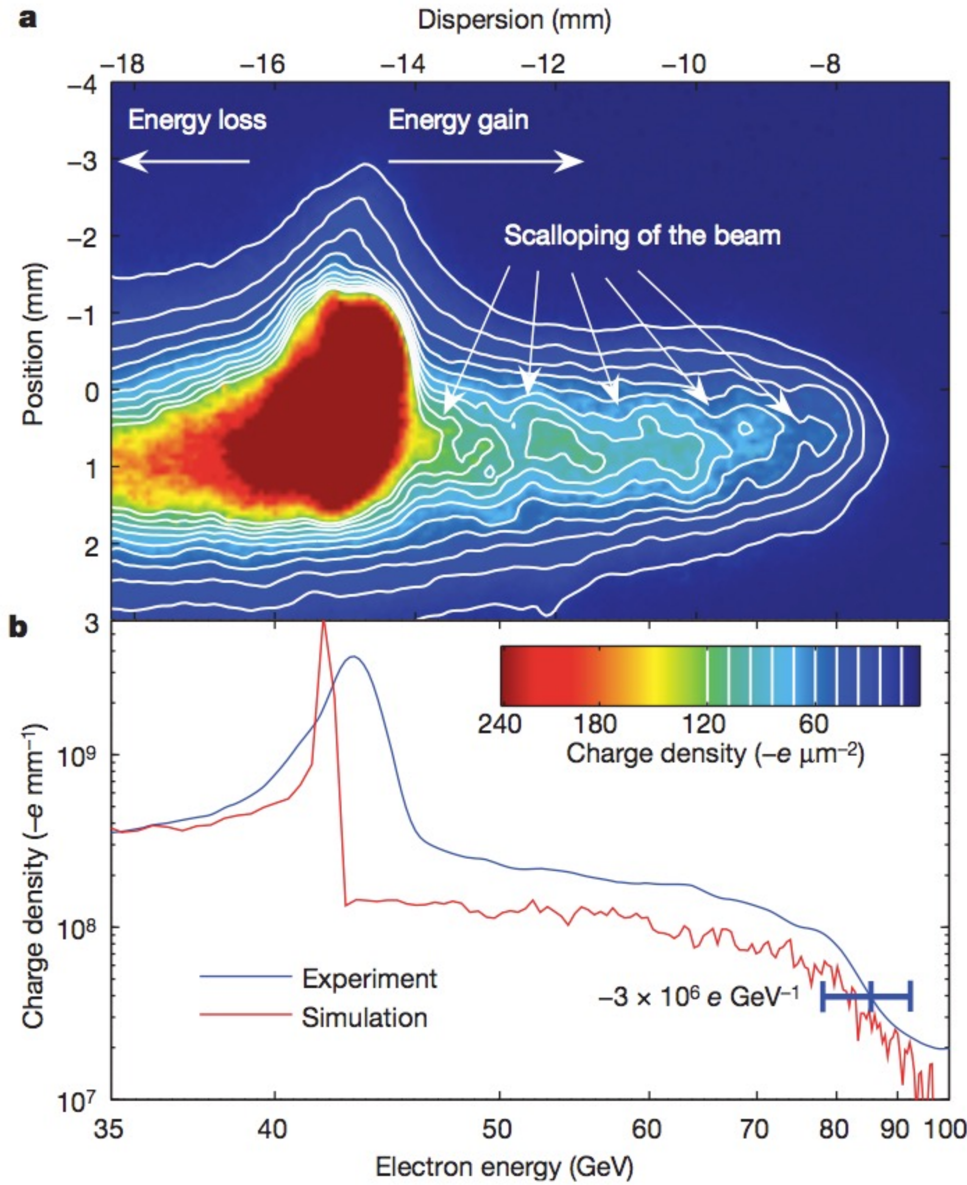
High gradients with :

- **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.

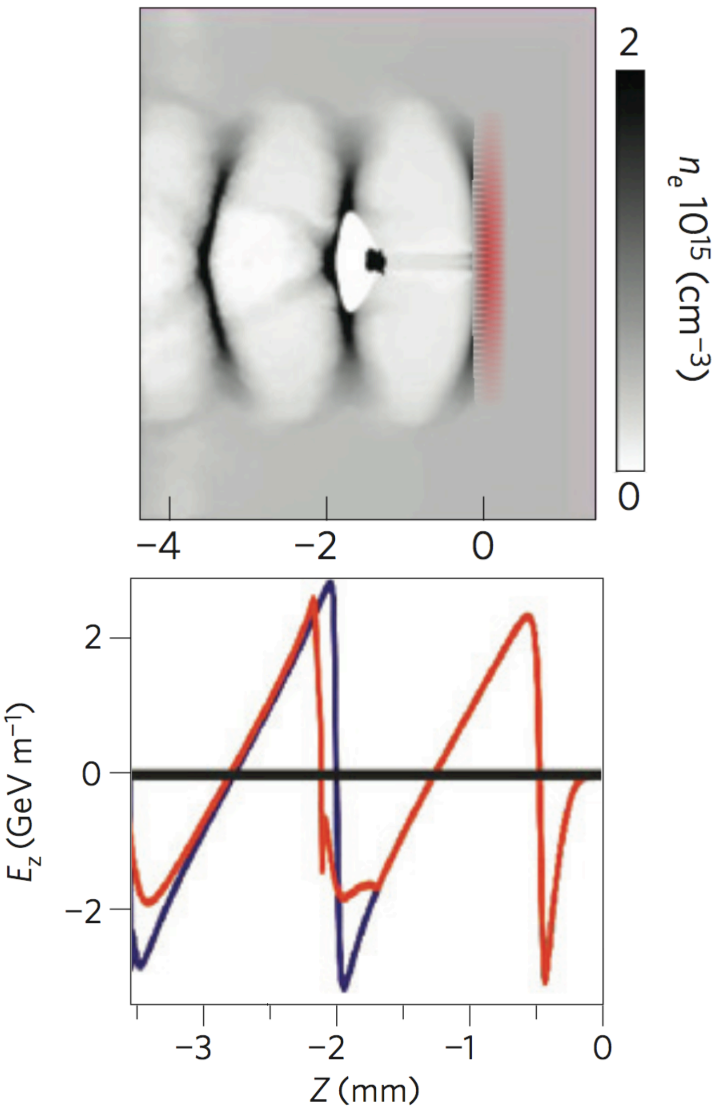
Plasma wakefield experiments

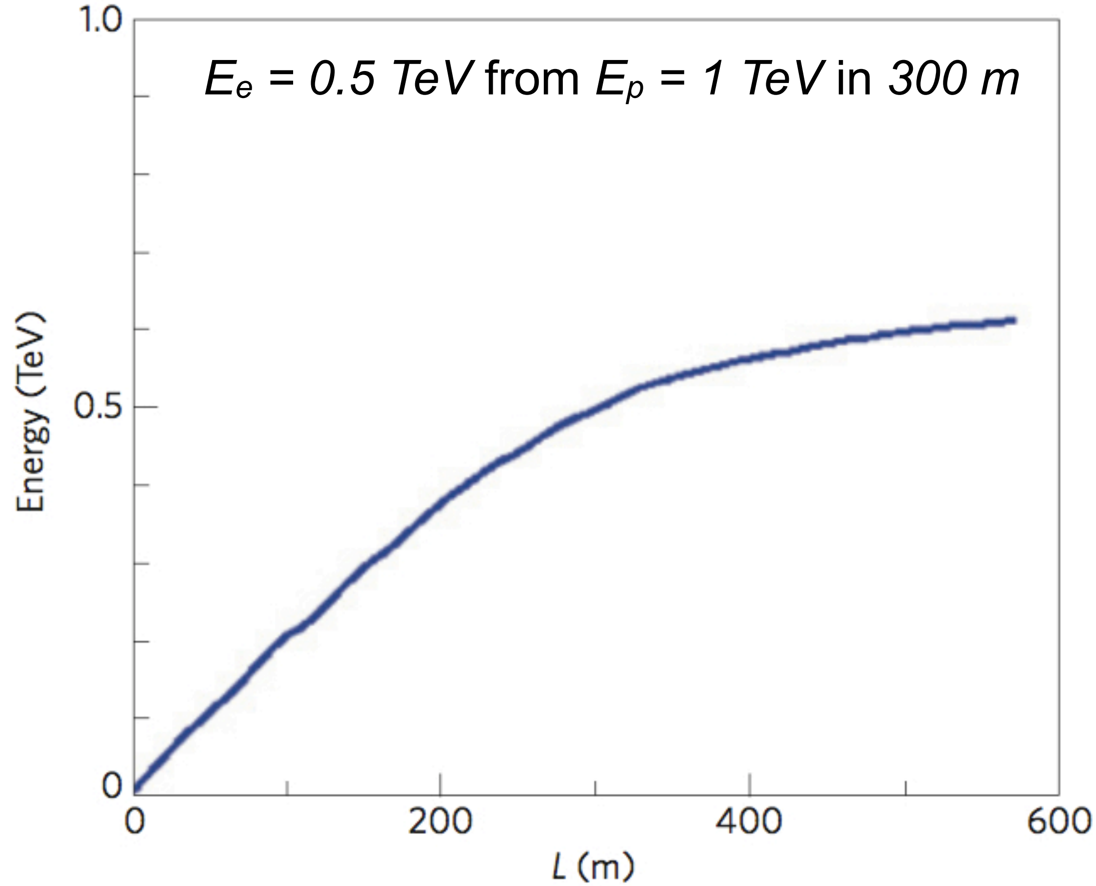
- Pioneering work using a LASER to induce wakefields up to *100 GV/m*.
- Experiments at SLAC§ have used a particle (electron) beam :
    - Initial energy E_e = *42 GeV*
    - Gradients up to ~ *52 GV/m*
    - Energy doubled over ~ *1 m*
    - Next stage, FACET project (http://facet.slac.stanford.edu)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



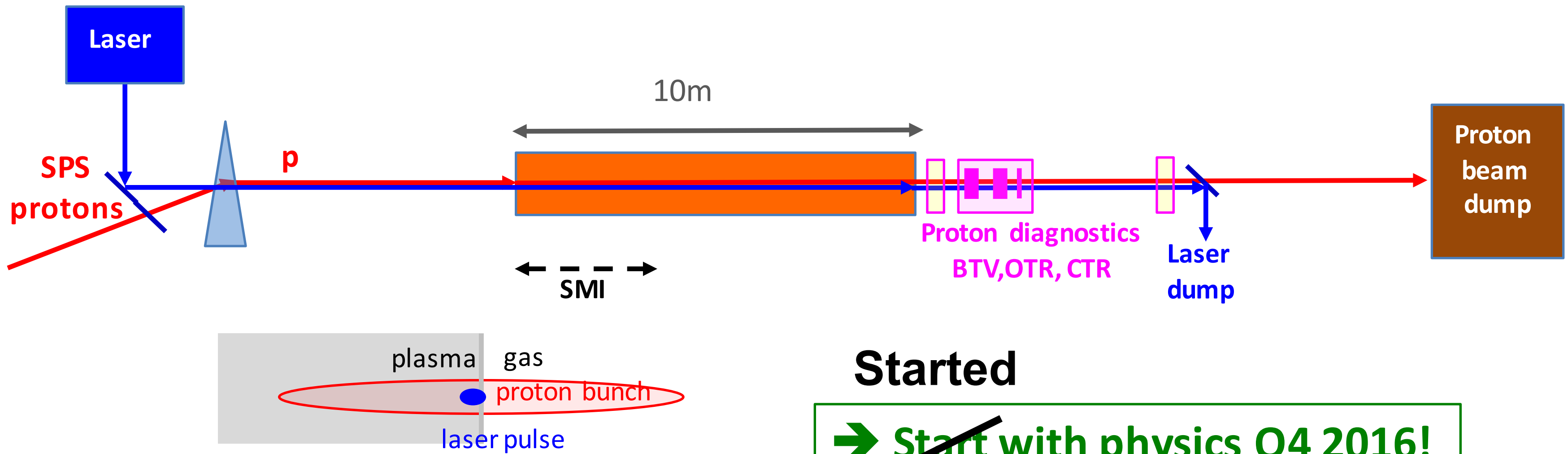


Note proton bunch length, *100 μm*; cf LHC, bunch length, *~10 cm*

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

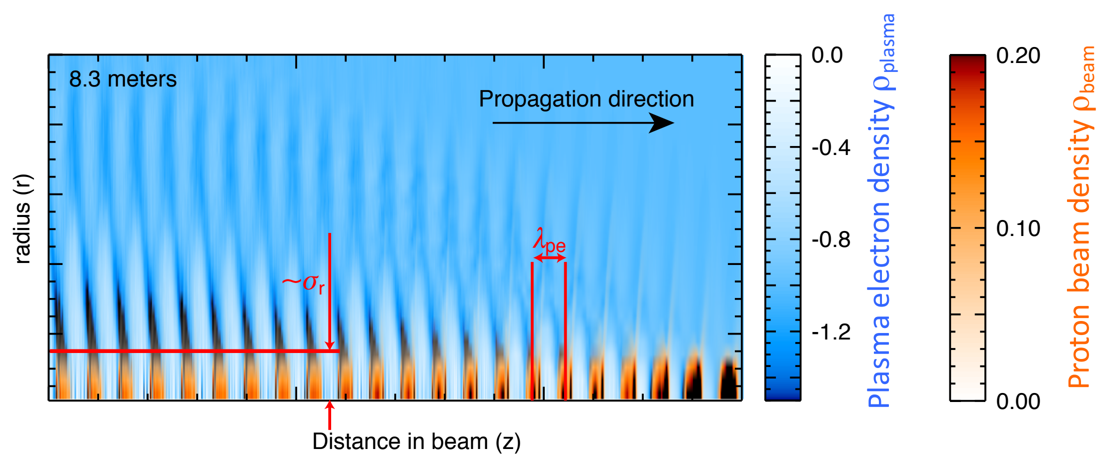
AWAKE experimental programme (Run I)

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



Started

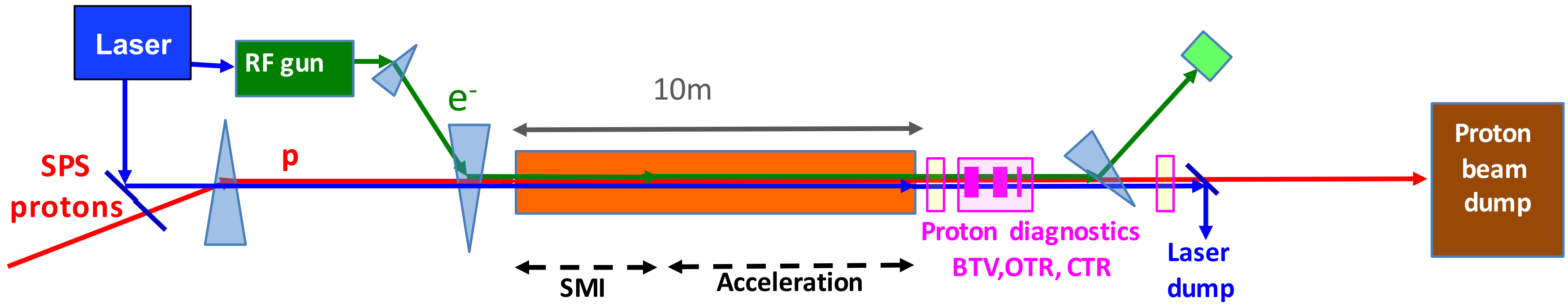
➔ ~~Start~~ with physics Q4 2016!

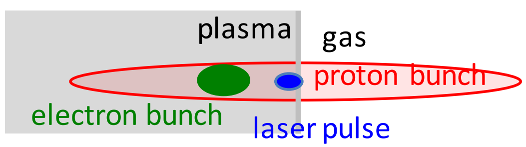


J. Vieira et al., Phys. Plasmas **19** (2012) 063105

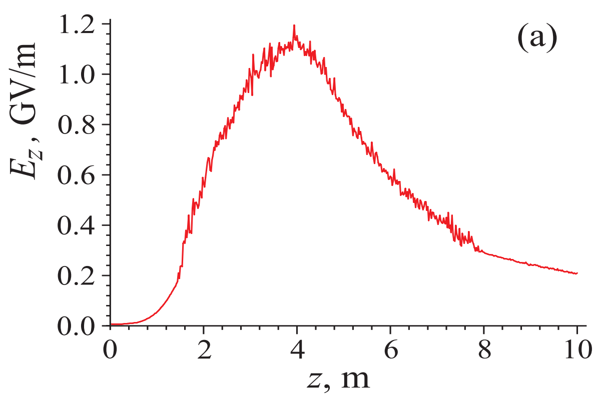
AWAKE experimental programme (Run I)

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





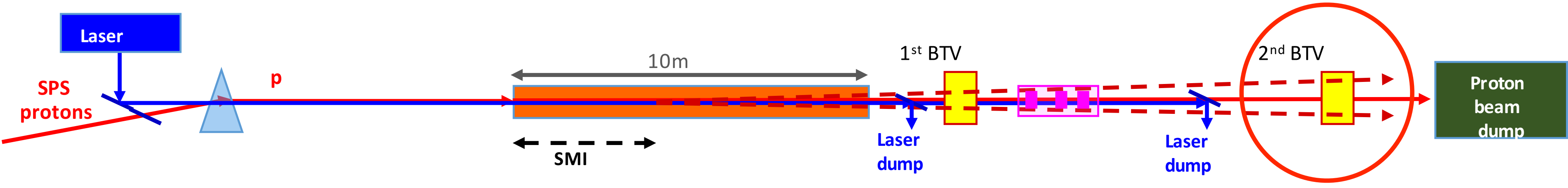
➔ Start with physics Q4 2017!

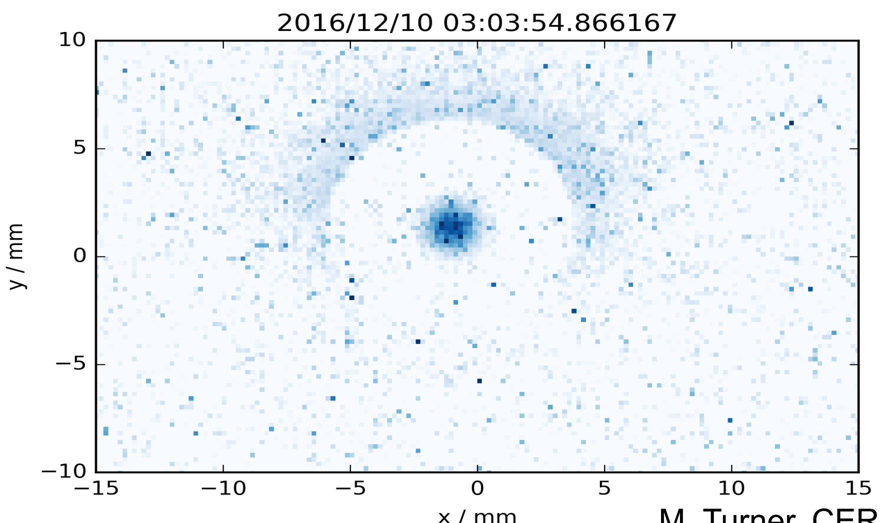


Demonstrate *GeV* acceleration of electrons with proton-driven wakefields of *GV/m*

AWAKE preliminary results

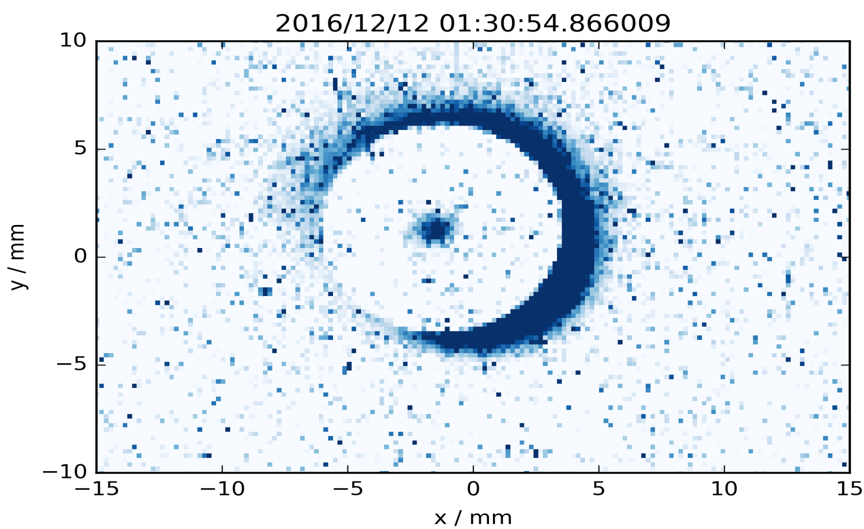
Screen composed of two materials





M. Turner, CERN

Transverse beam profile with **no plasma**

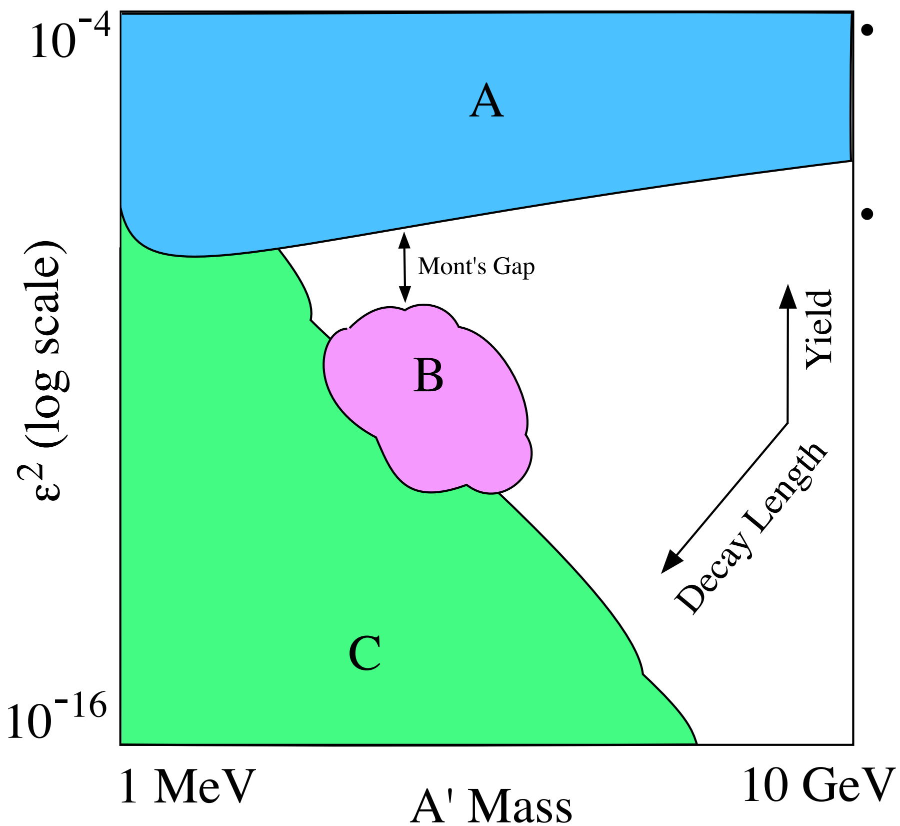


Transverse beam profile with **plasma**

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

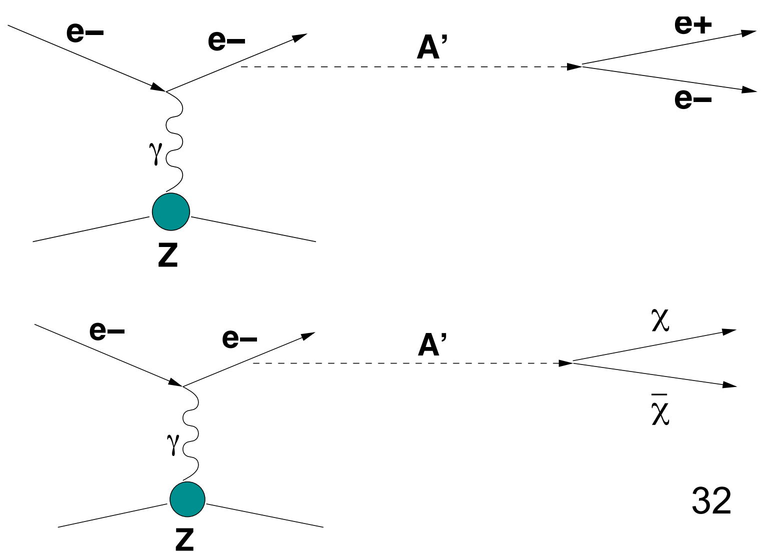
Search for dark photons

- 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.



Strong-field QED

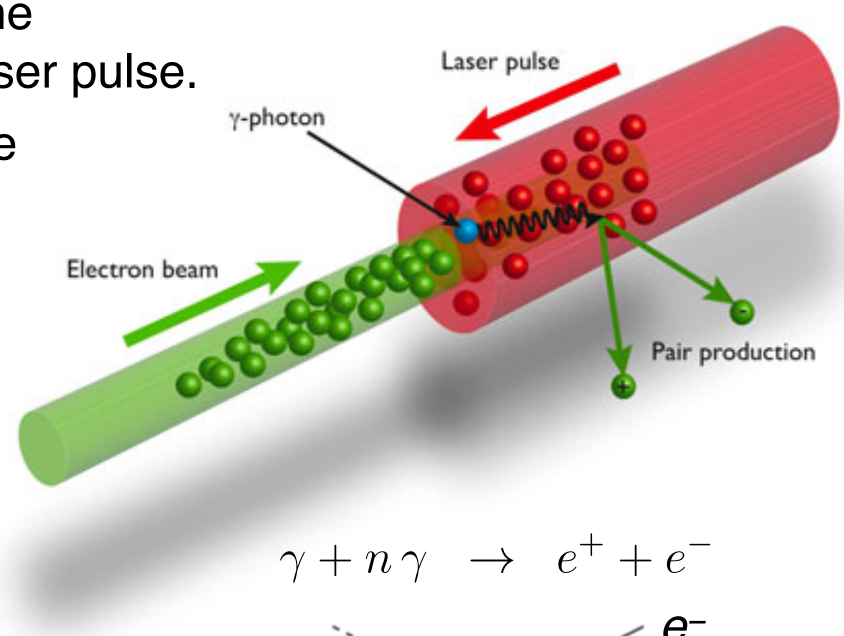
- Quantum mechanics and QED has been investigated and measured with amazing precision in many experiments and high-precision predictions describe this well.
  - However the strong-field regime, where QED becomes non-perturbative, has still not been measured.
- The strong field regime was already considered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

$$E_{\mathrm{crit}} = \frac{mc^2}{e\lambda\!\!\!^{-}_C} = \frac{m^2c^3}{e\hbar} = 1.3 \times 10^{16} \ \mathrm{V/cm}$$

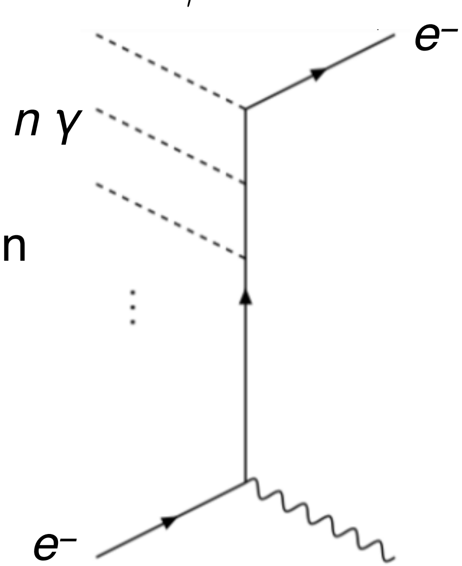
- This has not been reached experimentally, although they are expected to exist:
  - On the surface of neutron stars.
  - In bunches of future linear e^+e^- colliders.
- Can be reached by colliding photons with a high-energy electron beam
  - Pioneering experiment E144 @ SLAC in 1990s.
- **Given increase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

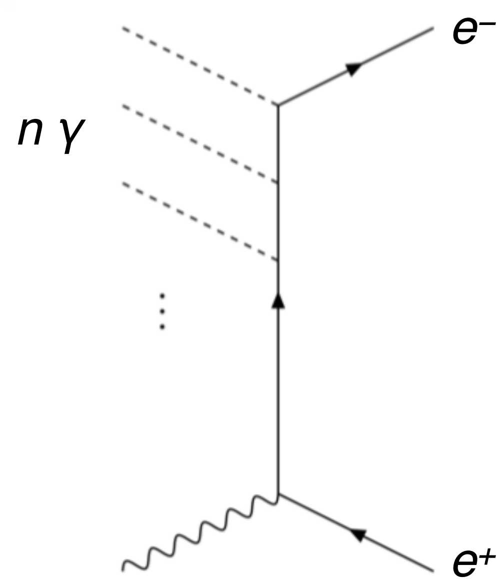


$$e^- + n\gamma \rightarrow e^- + \gamma$$



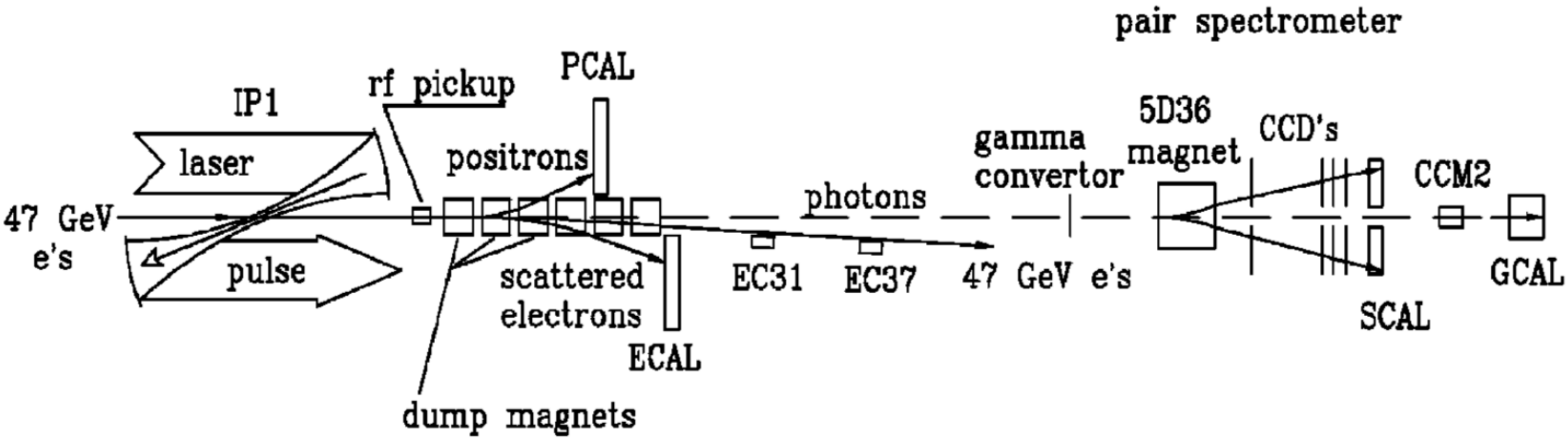
Compton

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



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).