First particle physics experiments with advanced accelerator concepts

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- Introduction
- Search for dark photons with fixed-target/beam-dump experiments
- Low-energy *γγ* collider
- Electron beam for TeV-scale *ep* collider (LHeC)
- Summary

Introduction

- Consider first particle physics experiments which could be enabled by plasma wakefield acceleration.
- First applications should have less challenging parameters than a high-energy, high-luminosity collider.
- Are timescales of 5 − 10 years or 10 − 20 years doable ?
- Demonstrate an accelerator technology also doing cutting-edge particle physics

Using a new technology

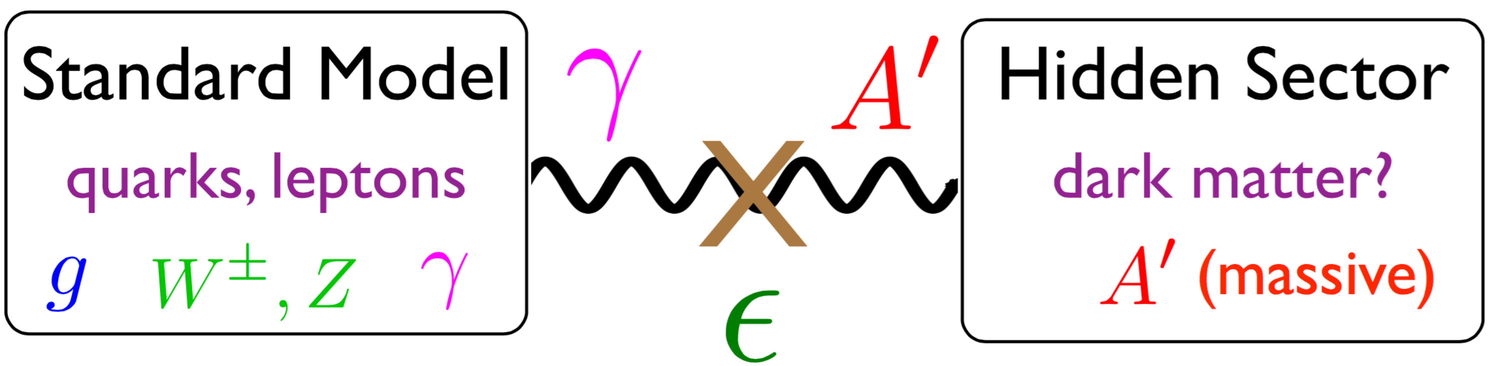
Fixed-target → High *E* *ep* collider → High *E*, high lumi e^+e^- collider

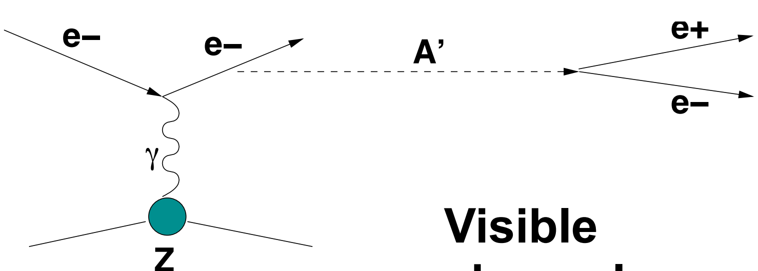
Dark photons

There are models which postulate light (*GeV* and below) new particles which could be candidates for dark matter.

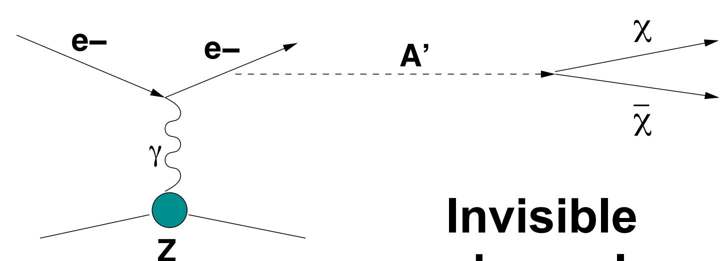
A light vector boson, the "dark photon", A', results from a spontaneously broken new gauge symmetry, $U(1)_D$.

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





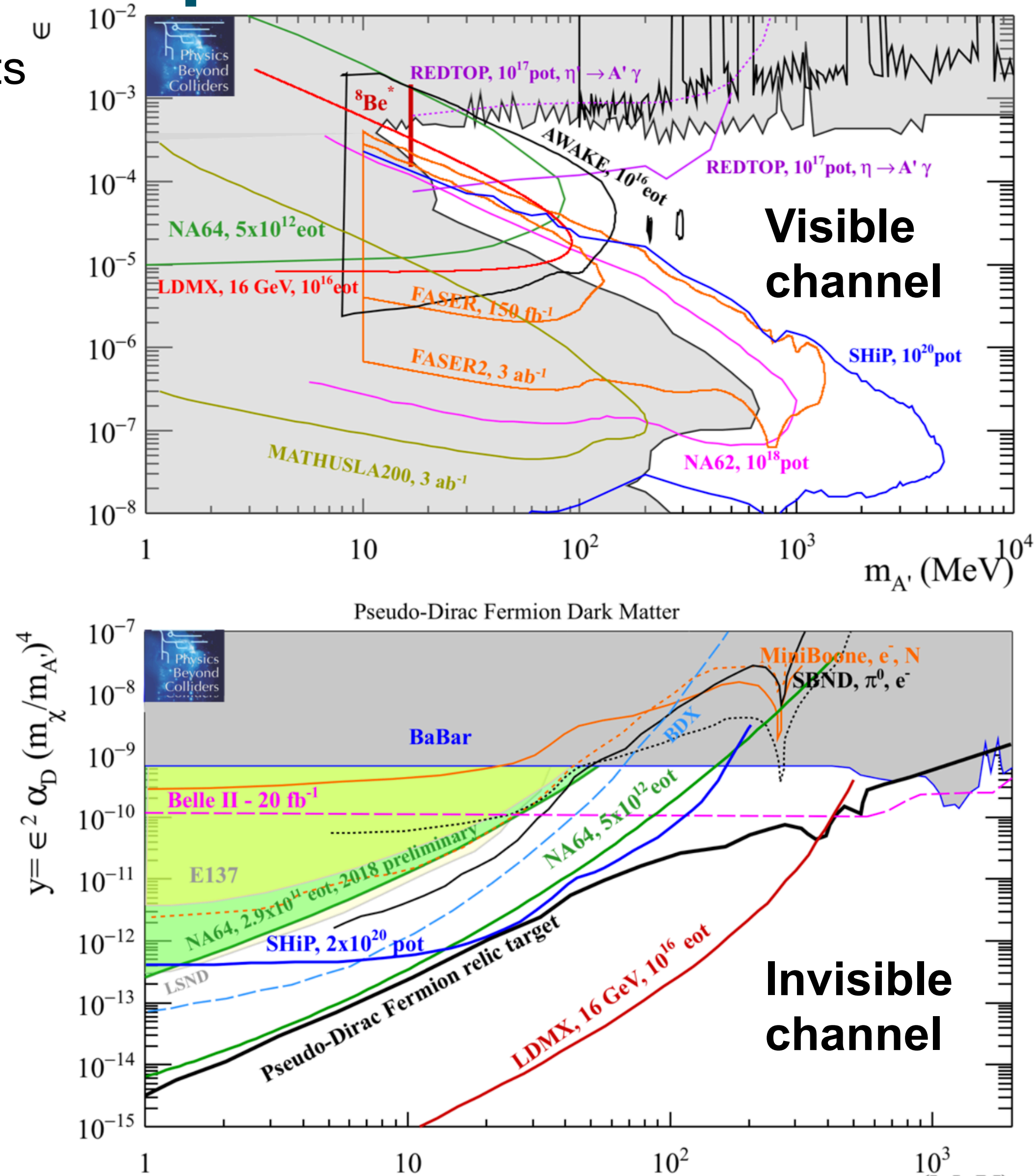
Visible channel



Invisible channel

Beam-dump/fixed-target experiments

- Beam-dump / fixed-target experiments require a less challenging electron beam.
- Sensitivity to dark photon production and other feebly interacting particles.
- Can use bunches or single electrons, e.g. AWAKE or eSPS (LDMX).
- Bunches means only visible channel possible.
- Combination of electron energy and electrons on target.
- Lots of experiments; lots of interest.
- Can also use electron bunches for strong-field QED physics.
- Could also think of deep inelastic scattering experiments.



PBC Summary Report, arXiv:1902.00260

AWAKE parameters — beam-dump experiment

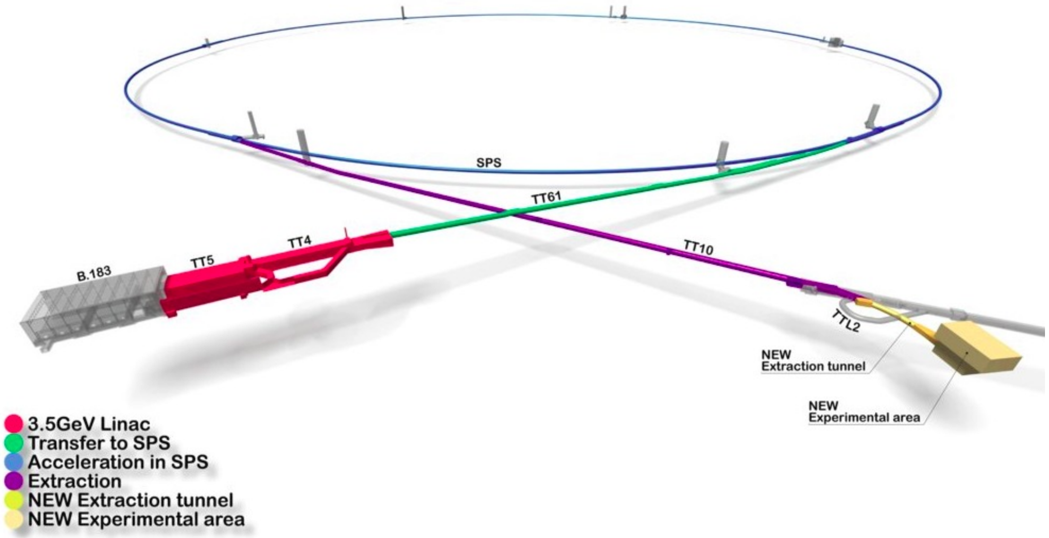
- Example parameters for dark photon search. Assumed high energy. In principle any plasma wakefield accelerator scheme could consider this.

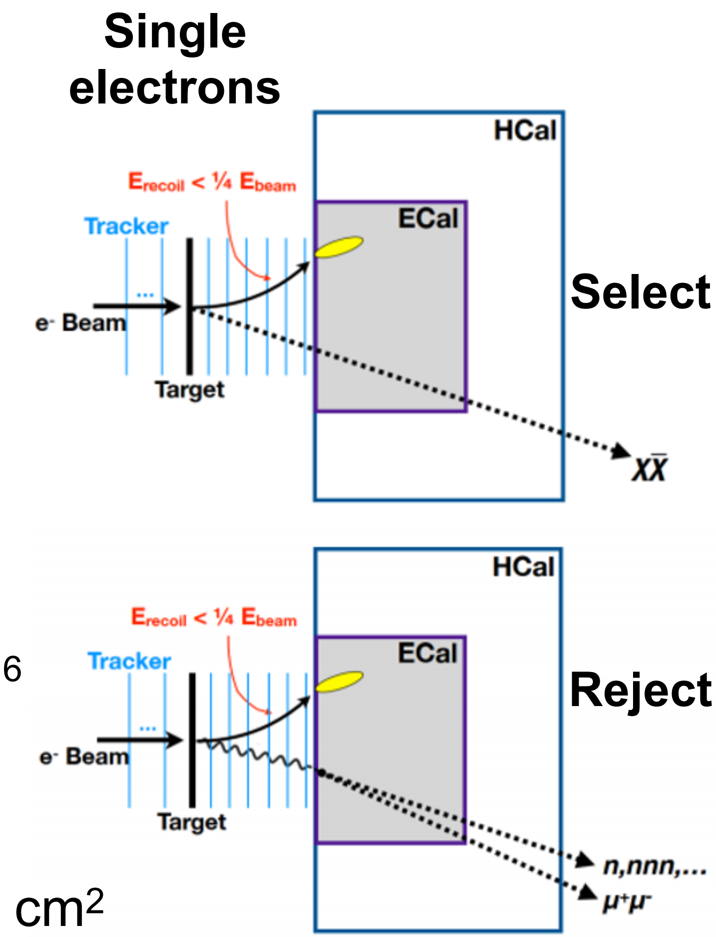
- Higher energy gives gain in $m_{A'}$.
- Electrons on target extends reach.
- Beam quality (emittance, etc.) should not be too challenging.
- Bunches are restrictive. Single (< 5) electrons allow invisible channel. Big challenge for plasma wakefield acceleration.

E_e	50 GeV
N_e	5×10^9
Electrons on target (3 months)	10^{16}
Emittance	O(10 μm)

arXiv:1812.11164, CERN-PBC-REPORT-2018-005

eSPS/LDMX — fixed-target experiment



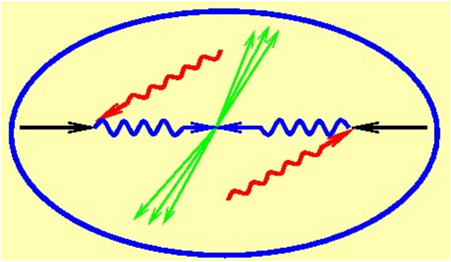


- Energy ~ 5 − 20 GeV
- Large number of electrons on target, $10^{14} - 10^{16}$
- Low current, i.e. single electrons
- Momentum spread 0.01%
- Beam size at experiment typically 20 (h) × 2 (v) cm^2
- Bunch spacing (< 10 electrons) is 5 ns
- Such single electrons could also be used for detector test beams

eSPS CDR, arXiv:2009.06938, https://cds.cern.ch/record/2730589/files/CERN-2020-008.pdf

Low energy $\gamma\gamma$ collider

- Study known and search for new resonances up to $b\bar{b}$.
  - Search for glueballs.
  - Search for four-quark resonance states.
  - Measure e.g. rare charm and beauty resonances.
- Low energy electrons
- No positrons needed



$\gamma\gamma$ collider
on the energy W<12 GeV
based on European XFEL

Valery Telnov

Budker INP and Novosibirsk St. Univ.

Probing strong-field QED in electron-photon interactions
21-23 August 2018, DESY, Hamburg

Compelling demonstrator for higher-energy options, whilst investigating novel particle physics.

Telnov, arXiv:2007.14003, JINST 15 (2020) P10028

Low energy $\gamma\gamma$ collider

- Parameters based around using European XFEL.
- Higher energy (unless much higher) not so interesting.
- Polarisation comes from laser.

Table 1. Parameters of the proposed photon collider based on the European XFEL.

$2E_0$	GeV	35
N per bunch	10^{10}	0.62
Collision rate	kHz	13.5
σ_z	μm	70
$\varepsilon_{x,n}/\varepsilon_{y,n}$	mm · mrad	1.4/1.4
β_x/β_y at IP	μm	70/70
σ_x/σ_y at IP	nm	53/53
Laser wavelength λ	μm	0.5
Parameters x and ξ^2		0.65, 0.05
Laser flash energy	J	3
Laser pulse duration	ps	2
f# $\equiv F/D$ of laser system		27
Crossing angle	mrad	~ 30
b (CP–IP distance)	mm	1.8
$\mathcal{L}_{ee,\mathrm{geom}}$	10^{33} cm^{-2}s^{-1}	1.45
$\mathcal{L}_{\gamma\gamma}$ ($z > 0.5z_m$)	10^{33} cm^{-2}s^{-1}	0.19
$W_{\gamma\gamma}$ (peak)	GeV	12

Large Hadron Electron Collider (LHeC)

- Proposal to use LHC proton bunches to collide with electron bunches in TeV-scale collisions.

  - **E_e = 60 GeV, $\sqrt{s}$ = 1.3 TeV, L = 10^{33} cm^{-2} s^{-1} (CDR), 10^{34} cm^{-2} s^{-1} (Higgs)**
  - Precision deep inelastic scattering; strong force; electroweak physics; searches for beyond the Standard Model; electron-ion collisions.
  - Currently based on electron energy recovery linac in ~9 km racetrack configuration (two lots of 1 km, 10 GeV linac and arcs).
  - Strong physics case and collaboration of particle physicists.
  - For plasma wakefield acceleration, less challenging electron beam parameters than e.g. CLIC or similar.

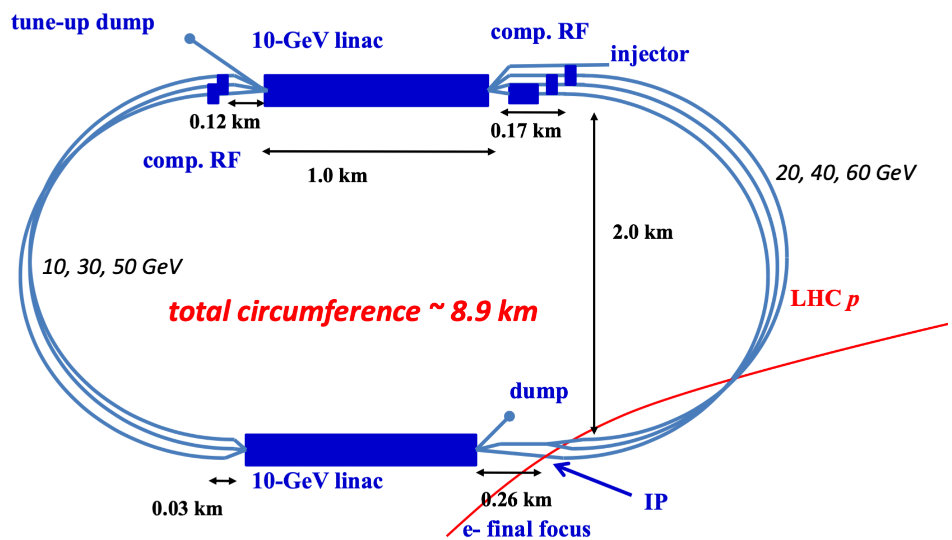


Figure 7.5: LHeC ERL layout including dimensions.

Large Hadron Electron Collider (LHeC)

- Higher energy is good.
- High luminosity is needed.
- High electron polarisation.
- Positron running is part of the programme, although with no polarisation.
- Emittance is driven by the proton bunch.
- Timing with proton bunches, 25 ns spacing.

parameter [unit]	LHeC	
species	e	p, $^{208}\mathrm{Pb}^{82+}$
beam energy (/nucleon) [GeV]	60	7000, 2760
bunch spacing [ns]	25, 100	25, 100
bunch intensity (nucleon) [10^{10}]	0.1 (0.2), 0.4	17 (22), 2.5
beam current [mA]	6.4 (12.8)	860 (1110), 6
rms bunch length [mm]	0.6	75.5
polarisation [%]	90 (e^+ none)	none, none
normalised rms emittance [μm]	50	3.75 (2.0), 1.5
geometric rms emittance [nm]	0.43	0.50 (0.31)
IP beta function $\beta^*_{x,y}$ [m]	0.12 (0.032)	0.1 (0.05)
IP spot size [μm]	7.2 (3.7)	7.2 (3.7)
synchrotron tune Q_s	—	1.9×10^{-3}
hadron beam-beam parameter	0.0001 (0.0002)	
lepton disruption parameter D	6 (30)	
crossing angle	0 (detector-integrated dipole)	
hourglass reduction factor H_{hg}	0.91 (0.67)	
pinch enhancement factor H_D	1.35 (0.3 for e^+)	
CM energy [TeV]	1.3, 0.81	
luminosity / nucleon [10^{33} cm^{-2}s^{-1}]	1 (10), 0.2	

Table 1: LHeC parameters. The numbers give the default values with optimum values for maximum ep luminosity in parenthesis and values for the ePb configuration separated by a comma.

From arXiv:1211.5102.
See also LHeC CDR, arXiv:1206.2913, *J. Phys. G* **29** (2012) 075001

Summary

- Plasma wakefield acceleration aims to be an enabling technology for future particle physics experiments.
- Have considered some realistic applications to novel and interesting particle physics experiments.
- Basic parameters of the beams required have been listed.
- For a given technology, we should consider if / how they can meet the requirements of the proposed experiments.
- Any “first” experiment will be invaluable for future application to the energy frontier with high luminosity.
- Does plasma wakefield acceleration offer special properties that can enhance particle physics experiments ?

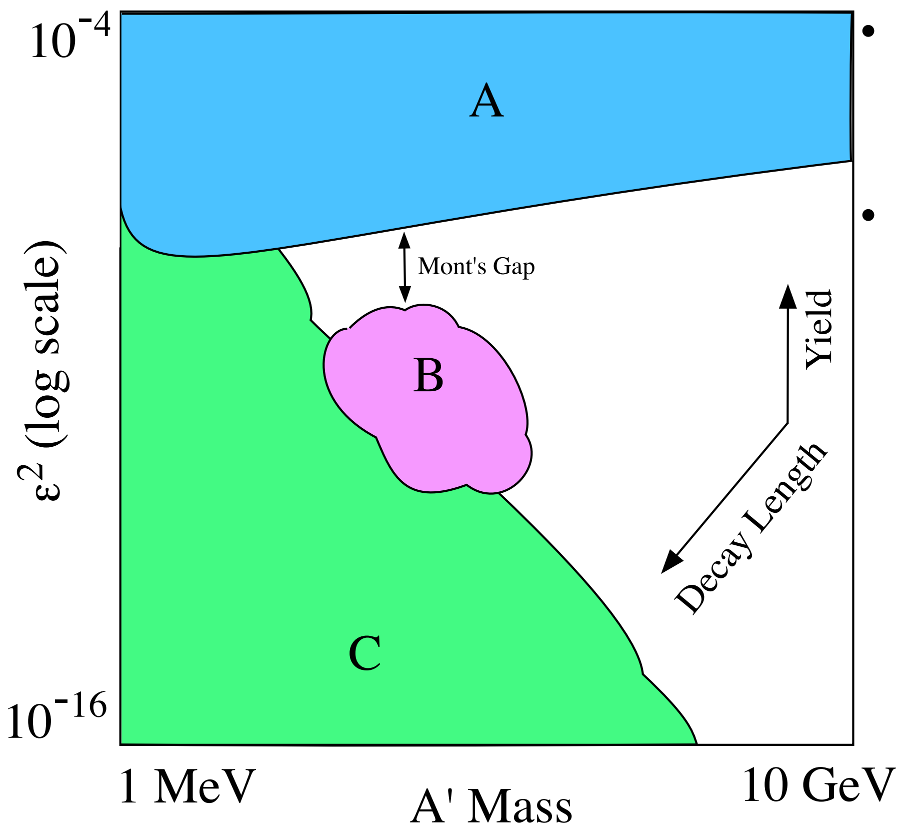
Back-up

The hidden / dark sector

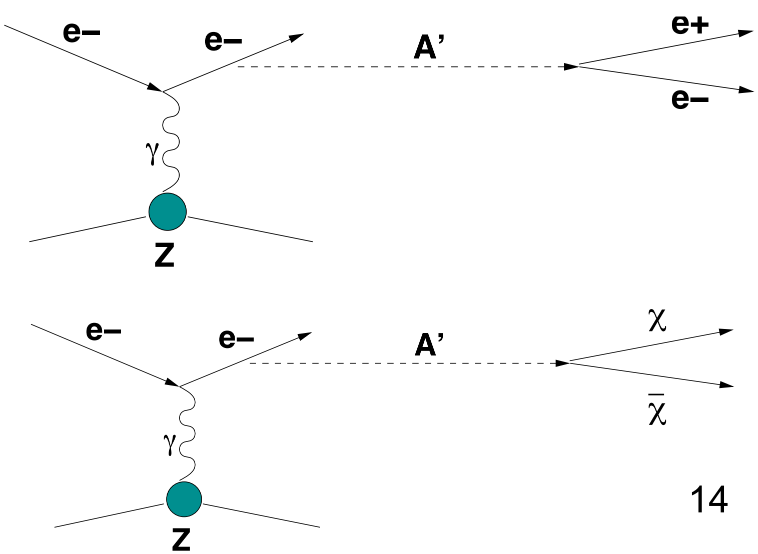
- Baryonic (ordinary) matter constitutes *~5%* of known matter.
  - What is the nature of dark matter ? Why can we not see the dominant constituent of the Universe ?
- LHC Run 1 (and previous high energy colliders) have found no dark matter candidates so far.
- LHC Run 2 to continue that search looking 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.

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

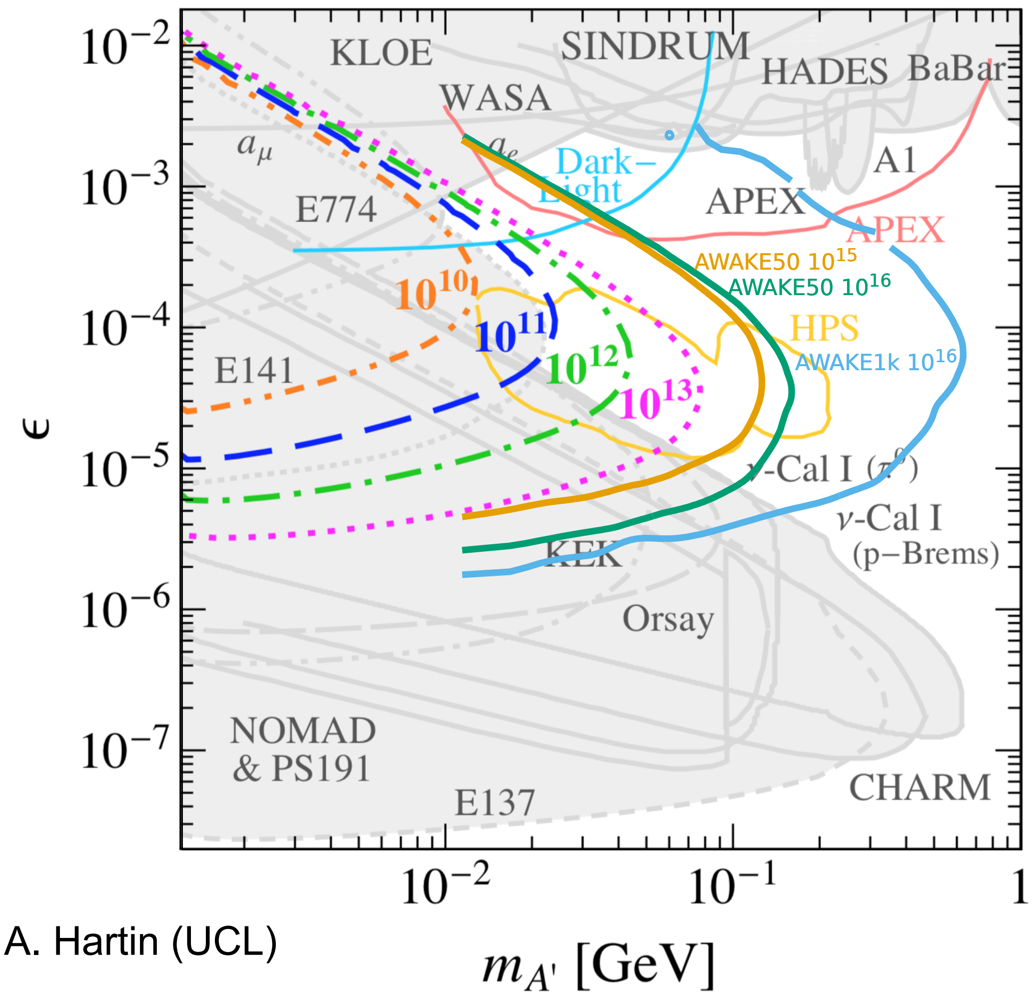


- Search for dark photons, A', up to (and beyond) *GeV* mass scale via their production in a light-shining-through-a-wall type experiment.
- Use high energy electrons for beam-dump and/ or fixed-target experiments.



J. Alexander et al., arXiv:1608.08632

Limits on dark photons, $A' \rightarrow e^+ e^-$ 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 $\varepsilon \sim 10^{-3} - 10^{-5}$.
  - to high masses ~ *0.1 GeV*.
- A *1 TeV* goes to even higher masses:
  - similar ε values.
  - approaching *1 GeV*.
  - beyond any other planned experiments.

A. Caldwell et al., arXiv:1812.11164
M. Wing, arXiv:1810.12254