AWAKE++ particle physics applications

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(with input from AWAKE and AWAKE++ teams)

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LEVERHULME TRUST

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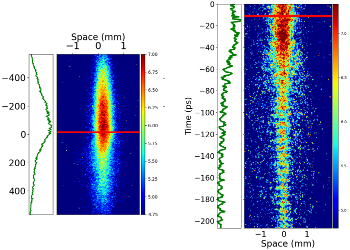
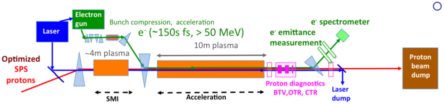
[W. Bartmann et al, AWAKE++, CERN-PBC-REPORT-2018-005]

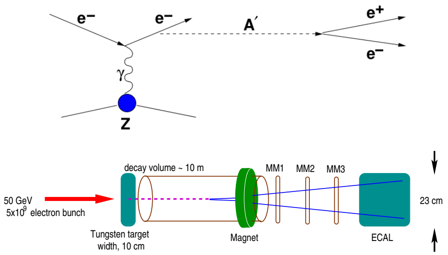




- **Goals for AWAKE Run 1 (2016-2018) achieved**: Self modulation of proton bunch in plasma, Electron capture and GeV level acceleration
- **AIMs for run 2 (2021-2024)**:
  - Scalable acceleration: 0.5-1 GV/m, 100 pC
  - Control emittance to ~ 20 mm mrad
  - High energy electron beams (to order 10 GeV)
- **Goals after the end of run 2:** Increase beam energy ($\geq$ 50 GeV). Use beams for novel and worthwhile physics experiments
- **We are studying three possible experiments (will only discuss first two)**
  - Dark photon beam dump experiment
  - Non perturbative QFT tests
  - High energy ep collisions

AWAKE Dark Photon beam dump experiment

[A. Caldwell et al, AWAKE Particle physics applications, arXiv:1812.11164]

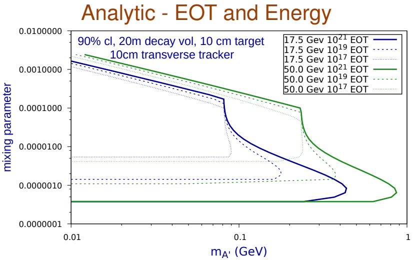


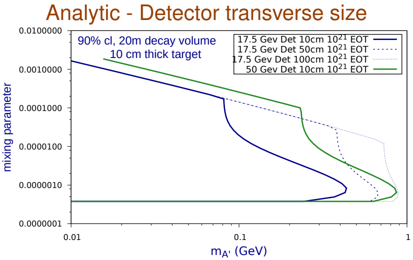
Parameter	AWAKE-upgrade-type	HL-LHC-type
Proton energy E_p (GeV)	400	450
Number of protons per bunch N_p	3×10^{11}	2.3×10^{11}
Longitudinal bunch size protons σ_z (cm)	6	7.55
Transverse bunch size protons σ_r (μm)	200	100
Proton bunches per cycle n_p	8	320
Cycle length (s)	6	20
SPS supercycle length (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}

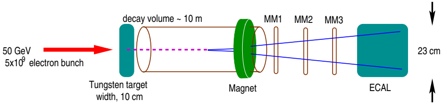
Table 2: Potential achievable number of electrons on target for an AWAKE-based fixed target experiment for two different drive beam configurations. Assumes a 12 week experimental period with a 70% SPS duty cycle.

- What is dark matter? BSM mechanism, mixing ϵ to SM
- Dark photon searches making good progress $(m_{A'}, \epsilon)$ coverage
- AWAKE can contribute to the global effort through increased luminosity
- 5x10^9 EOT per bunch $\rightarrow$ 10^{16} per year
- Simulated beam target dark photon experiment (Based on NA64 software)
- Full study in GEANT to understand backgrounds
- Analytic/GEANT studies to generate sensitivity (m$_{A'}, \epsilon$)

Analytic sensitivity: luminosity, energy, decay angle



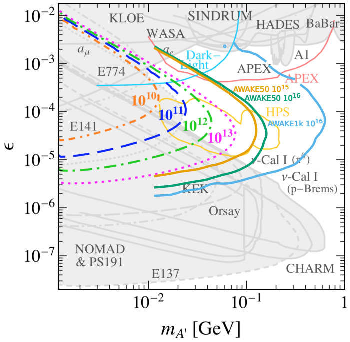


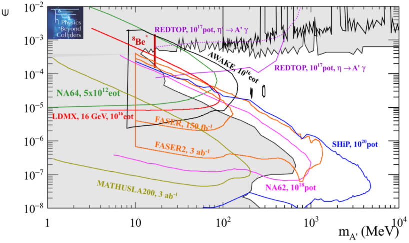


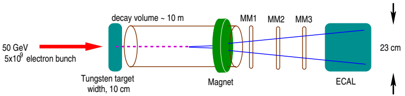
- Dark photon mass, coupling $m_{A'}, \epsilon$
- Bremsstrahlung spectrum $I_e(E_e, z_{targ})$
- Dark photon x-sect, $\frac{d\sigma}{dE_{A'}}(E_e, E_{A'})$
- Dark photon decay rate, $\Gamma_{A'}(m_e, m_{A'}, \epsilon)$
- Decay length, $l_{A'} = \frac{1}{\Gamma_{A'}}\sqrt{\left[\frac{E_{A'}}{m_{A'}}\right]^2 \text{-}1}$
- Expt constraints (target, decay volume lengths), $E_c = e^{-l_{targ}/l_{A'}} - e^{-l_{DV}/l_{A'}}$
- Dark photon spect, $I_{A'} = \int dz\, dE_e\, I_e \frac{d\sigma}{dE_{A'}}$
- No. of A', $N_{A'} = \frac{N_0 X_0}{A} \int dE_{A'}\, I_{A'} E_c$
- 90% confidence limit=2.44 events
- Step function acceptance based on approx radiation angles (Z$\rightarrow \gamma', \gamma' \rightarrow e^+e^-$)

AWAKE/dark photon sensitivity reach (2018)

[J. Beacham et al, BSM working group, CERN-PBC-REPORT-2018-007]

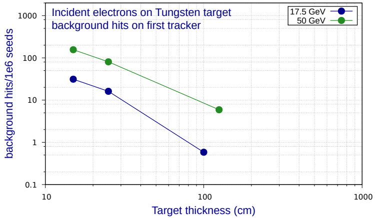




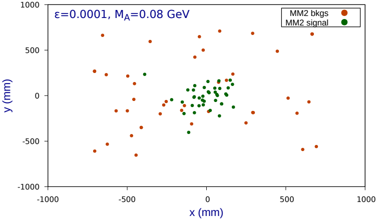


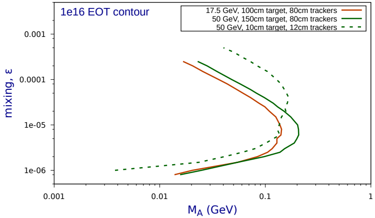
- Preliminary AWAKE/Dark Photon ϵ, $M_{A'}$ landscape obtained
- Visible A'$\rightarrow$ e^+e^- decays
- Based on GEANT studies, well separated hits in the tracker planes ($>$ 1 mm transverse)
- 50 GeV AWAKE electron bunches on target covers new ground
- Future 1 TeV AWAKE electrons even more beneficial
- Background studies will be extended
- Other channels will be investigated (A'$\rightarrow$ $\mu^+\mu^-$, A' $\rightarrow$ invisible)

Tracker and target optimisation



- Optimise tracker transverse size (acceptance) and target thickness (backgrounds)
- Can tolerate no more than 1000 bkg hits per 1e9 seeds (1 bunch).
- Magnetic field can help separate signal/background
- Sensitivity contour coverage is a trade off (acceptance vs bkgs)

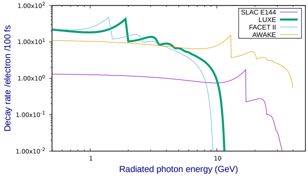


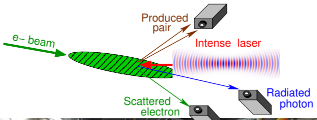


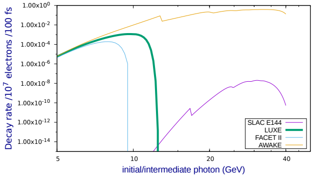
Non-perturbative electron/laser experiments

[A. Hartin, IJMP A33 1830011 (2018), M. Altarelli et al. arXiv:1905.00059]

- Test non-perturbative QFT in ultra intense, relativistic e^-/laser collisions
- Intense background field polarises the vacuum. Particles gain effective complex mass
- Nonlinear Compton, trident pair production, higher order strong field resonances, even BSM searches! **"boil the vacuum"**
- Parameters to maximise non-perturbative events, most energetic electrons available at XFEL, ultra-intense lasers and expertise on hand





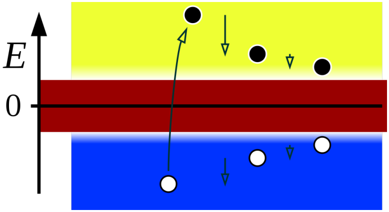


Experiment	$\lambda(nm)$	E_{laser} (J)	focus (μm^2)	pulse (fs)	E_{e^-} (GeV)	ξ	χ
SLAC E144	527/1053	2	50	1880	46.6	0.66	2.7
LUXE Phase0	800	0.35	100	35	17.5	1.54	0.29
LUXE Phase1	800	7	100	35	17.5	6.9	1.29
FACET II	800	0.7	64	35	10	2.3	0.29
ELI-NP	1053	2.2	100	22	0.750	6.4	0.04
AWAKE	800	3	64	20	50	7.45	4.0

ξ is laser intensity parameter, χ is electron recoil parameter

Strong Field QFT: polarising the vacuum

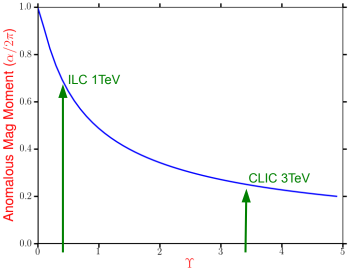
Schwinger limit



- Quantum vacuum becomes more dispersive with field strength
- At Schwinger limit quantum vacuum decays into a real pair
- The Schwinger critical field ($E_{\text{cr}} = m_e^2 c^3 / e\hbar = 1.32 \times 10^{18}$ V/m)
- How do we incorporate these vacuum changes into our theories?

Anomalous magnetic moment

$$\frac{\Delta\mu}{\mu_0} = \frac{\alpha}{2\pi} \int_0^\infty \frac{2\pi \, dx}{(1+x)^3} \left(\frac{x}{\Upsilon}\right)^{1/3} \mathrm{Gi}\left(\frac{x}{\Upsilon}\right)^{1/3}$$



- There is a predicted strong field correction to the AMM. strong field
- Υ, (χ_e) is the external field strength in electron (muon) rest frame
- Strong field ”running” of the QED coupling. A background field changes the QED vacuum

Furry Picture - a non perturbative, semi classical QFT

- Separate gauge field into external A_μ^{ext} and quantum A_μ parts. Shift A_μ^{ext} into Dirac Lagrangian

$$\mathcal{L}_{\text{QED}}^{\text{Int}} = \bar{\psi}(i\partial\!\!\!/ - m)\psi - \tfrac{1}{4}(F_{\mu\nu})^2 - e\bar{\psi}(A\!\!\!/^{\text{ext}} + A\!\!\!/)\,\psi$$

$$\mathcal{L}_{\text{QED}}^{\text{FP}} = \bar{\psi}^{\text{FP}}(i\partial\!\!\!/ - eA\!\!\!/^{\text{ext}} - m)\psi^{\text{FP}} - \tfrac{1}{4}(F_{\mu\nu})^2 - e\bar{\psi}^{\text{FP}}\, A\!\!\!/\, \psi^{\text{FP}}$$

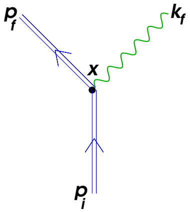
- Lagrangian satisfies Euler-Lagrange equation $\to$ new equation of motion for the non-pertubative (bound) Dirac field (w.r.t. A^{ext}). New solutions ψ^{FP}

$$(i\partial\!\!\!/ - eA\!\!\!/^{\text{ext}} - m)\psi^{\text{FP}} = 0$$

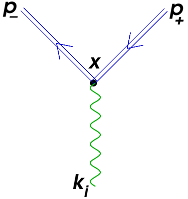
- For certain classes of external fields (plane waves, Coloumb fields and combinations) exact solutions exist **[Volkov Z Physik 94 250 (1935), Bagrov and Gitman,** *Exact solutions of relativistic wave equations* **(1990)]**

$$\psi^{\text{FP}} = \mathbf{E}_p\, e^{-ipx}\, u_p, \quad \mathbf{E}_p = \exp\left[-\frac{1}{2(k\cdot p)}\left(eA\!\!\!/^{\text{ext}} k\!\!\!/ + i2e(A^e\cdot p) - ie^2 A^{\text{ext}\,2}\right)\right]$$

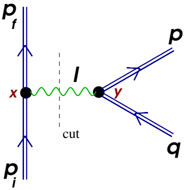
Non perturbative QED: Decays, Resonant production



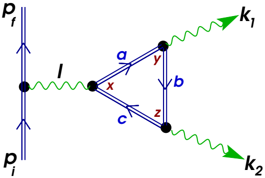
High intensity Compton scatttering (HICS)



One photon pair production (OPPP)



Trident process (one step and two step)

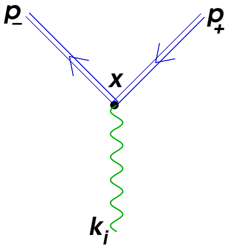


Photon splitting (vacuum birefringence)

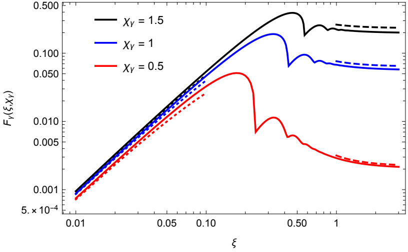
OPPP and Schwinger critical field measurement

[A. Hartin, A. Ringwald, N. Tapia arXiv:1807.10670]

One photon pair production (OPPP)



OPPP rate, non perturbative regime



OPPP Rate at constant χ reaches non perturbative asymptote for $\xi \geq 1$

$$\Gamma_{\text{OPPP}} = \frac{\alpha m^2}{2\omega_i} \sum_{s>s_0}^{\infty} \int_1^{v_s} \frac{dv}{v\sqrt{v(v-1)}} \left[J_s^2 + \frac{\xi^2}{2}(2v-1)\left(J_{s+1}^2 + J_{s-1}^2 - 2\,J_s^2\right)\right] \propto \frac{\alpha m^2}{2\omega_i} \frac{E}{E_c} \exp\left[-\frac{8 m E_c}{3\omega_i E}\right]$$

Theory: $E_c = \dfrac{m^2}{e}$. Experiment: $E_c =$ .... It can now be measured in the lab

Summary

1. **Successful AWAKE Run I. Run II goals: order 10 GeV beams, scalability, good beam qualities**

2. **Beyond run II: energetic AWAKE beams for novel experiments**

3. **Dark photon beam dump experiment with AWAKE bunches. Increased luminosity, energy gives additional $M_{A'}, \epsilon$ sensitivity reach**

4. **Non perturbative QFT tests with intense laser interactions: vacuum polarisation, birefringence, Schwinger pair creation**