Searching for Dark Photons at the LHeC & FCC-he

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Motivation

- Dark Matter $\begin{cases} \text{Galaxy rotation curves} \\ \text{Structure formation} \\ \dots \end{cases}$
- Hidden sector theories predict new particles to interact with the Standard Model (SM) field content via feebly coupled mediator particles
- Different portals between the dark sector and the SM: focus on the vector portal and dark photon
- Studied at the HL-LHC, CEPC, FCC-ee/hh, beam-dump, and fixed-target experiments
- Sensitivity of electron-proton colliders may be unique: LHeC & FCC-he

The dark photon model

- Extend the SM gauge group by an additional (broken) gauge group: $\underline{U(1)_X}$

$$\mathcal{L} \supset -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}X_{\mu\nu}X^{\mu\nu} - \frac{\epsilon}{2}X_{\mu\nu}F^{\mu\nu}$$

- Applying a field re-definition to get rid of the kinetic mixing term $X_{\mu\nu}F^{\mu\nu}$

$$\mathcal{L} \supset -\sum_f \bar{f}\,\epsilon\, e\, q_f\, \not{A}'\, f$$

- Mass can stem from e.g. a Higgs mechanism
- SM particles assumed *uncharged* under $U(1)_X$
- Two parameters: $\{m_{\gamma'},\, \epsilon\}$
- One parameter ϵ controls both <u>production</u> and <u>decay</u>
- Focus on <u>MeV-GeV</u> mass range in this work

Portals between the SM and the dark sector

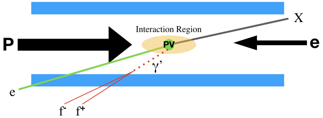
The only non-gravitational portals possible connecting the SM and dark sector:

- scalar: dark Higgs
- pseudoscalar: axion-like particles
- vector: dark photons
- neutrino: heavy neutral leptons

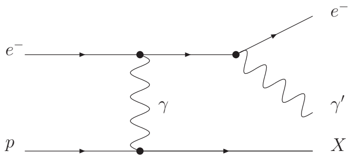
Dark photon could be the messenger to the dark sector or even constitute dark matter, motivating search for dark photons

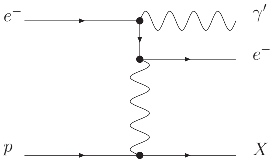
LHeC and FCC-he & Dark photon production

	E_e (GeV)	E_p (TeV)	$\sqrt{s}$ (TeV)	$\mathcal{L}_{\text{int}}$ (ab^{-1})
LHeC	60	7	1.3	1
FCC-he	60	50	3.5	3

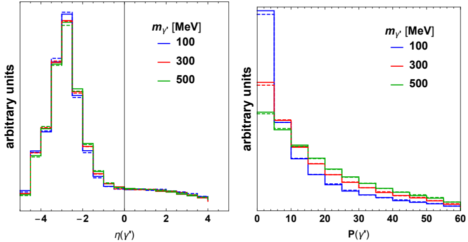


DIS: e^- parton $\to e^-$ parton γ'
$Q^2 \gg m_p^2 \simeq 1\ \text{GeV}^2$





Signal estimation



$$N_{\rm dv}(\sqrt{s}, \mathcal{L}, m_X, \epsilon)$$
$$= \sigma(M,\epsilon)\,\mathcal{L} \times \int D(\vartheta,\gamma)\, P_{\rm dv}(x_{\rm min}(\vartheta), x_{\rm max}(\vartheta), \Delta x_{\rm lab}(\tau,\gamma))\, d\vartheta d\gamma$$

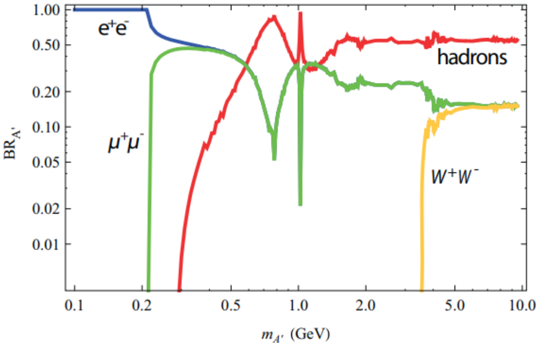
$$P_{\rm dv} = {\rm Exp}\left(\frac{-x_{\rm min}}{\Delta x_{\rm lab}}\right) - {\rm Exp}\left(\frac{-x_{\rm max}}{\Delta x_{\rm lab}}\right)$$

$$x_{\rm min} = 200\mu m, x_{\rm max} = \infty, \Delta x_{\rm lab} = \tau_{\rm lab}|\vec{v}| = \beta_{\gamma'}\gamma_{\gamma'}\,\tau c$$

	$\eta(e/\mu)$	η(jets)
LHeC	(-4.3,4.9)	(-5,5)
FCC-he	(-5.0,5.2)	(-5.5,5.5)

In practice, apply $|\eta| < 4.7$

Dark photon decays



[Raggi, Kozhuharov,'15]

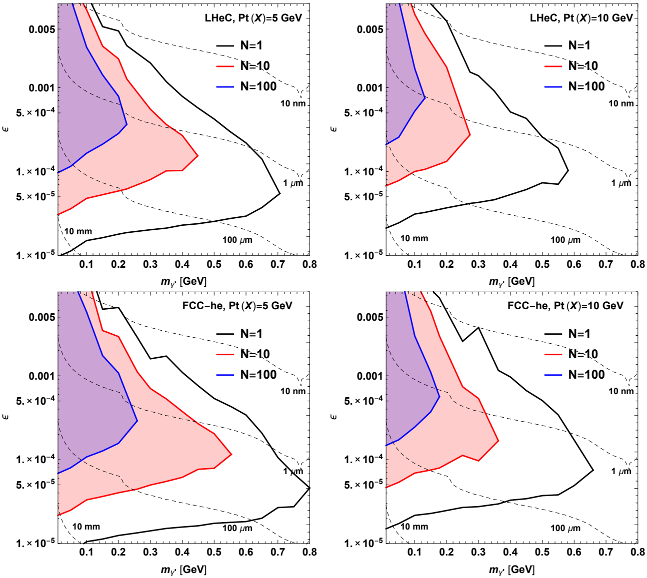
$$\Gamma(\gamma' \to l^+ l^-) = \frac{1}{3}\,\alpha_{\text{QED}}\, m_{\gamma'}\, \epsilon^2 \sqrt{1 - \frac{4m_l^2}{m_{\gamma'}^2}} \left(1 + \frac{2m_l^2}{m_{\gamma'}^2}\right)$$

$$\Gamma_{\text{total}}(\gamma') = \frac{\Gamma(\gamma' \to e^- e^+)}{\text{BR}(\gamma' \to e^- e^+)}$$

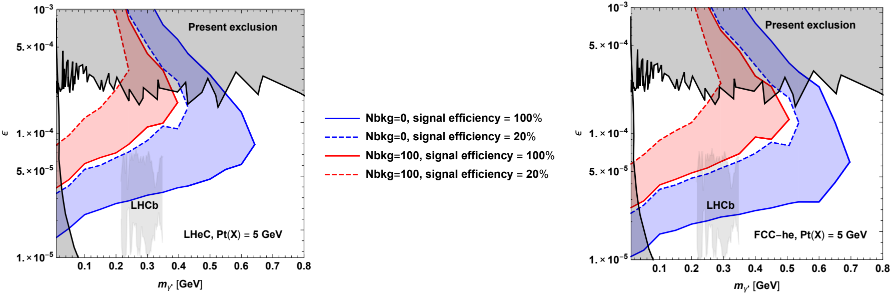
Background

- Real low-energy photons interacting with the detector material or the beam pipe $\rightarrow e^- e^+$ pairs
  - location of the secondary vertex coincides with the detector material or the beam pipe
  - easily rejected
- Long-lived hadrons such as K_S, K_L, and Λ
  - lifetime far away from IP (3cm, 15m, and 8cm)
  - hadronic activity is aligned with the proton beam and propagates mostly into the forward hemisphere of the detector
  - their primary decay channels are only marginally consistent with our signal signature
  - their masses are well known

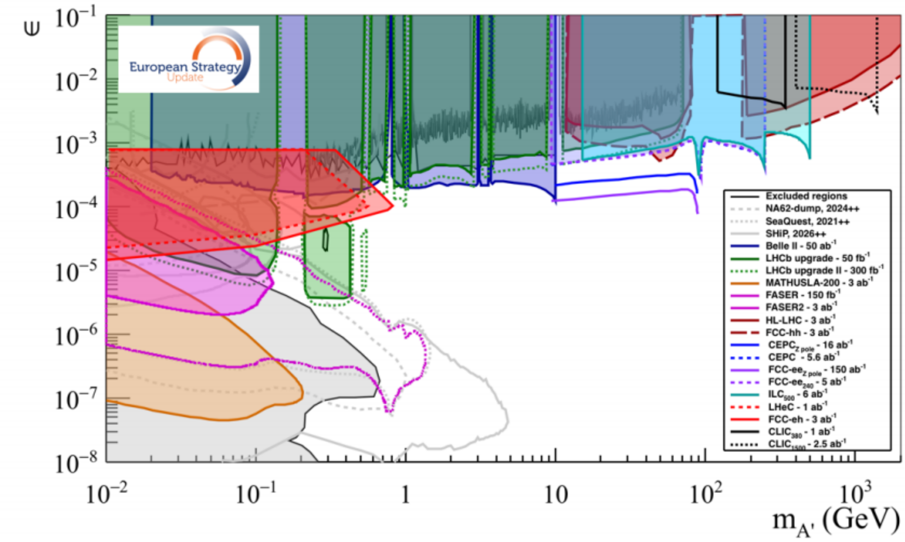
Results I: 0 BG and 100% signal efficiency



Results II: 90% C.L. sensitivity reaches



Results III: 10 SG, 0 BG, 100% Efficiency, $p_T(X) > 5$ GeV



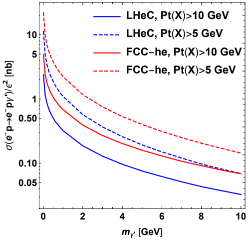
[Physics Briefing Book: Input for the European Strategy for Particle Physics Update 2020 [1910.11775]]

Summary

- DM may reside in a dark sector
- Different portals between the SM and the dark sector
- The vector portal concerns a dark photon which may provide connection to DM or even constitute the DM (kinetic mixing)
- New and existing searches ongoing hunting such dark photons
- Electron-proton colliders may explore a unique territory in the parameter space for MeV-GeV dark photons

Thank You!

Dark photon production and electron-proton colliders



DIS: $Q^2 \gg m_p^2 \simeq 1$ GeV^2

- Ideal laboratory to study common features of electrons and quarks
- Advantages:
  - Small background (no QCD interaction between e and p)
  - Very low pileup
  - Less problem of synchrotron radiation that occurs typically in circular lepton colliders
  - . . .
- Disadvantages:
  - Relatively smaller scattering cross section
  - . . .