Searching for Dark Photons at the LHeC & FCC-he

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Motivation

- Dark Matter
- Hidden sector theories predict new particles to interact with the Standard Model (SM) field content via feebly coupled mediator particles
- Non-gravitational portals between the dark sector and the SM:
  - scalar: dark Higgs
  - pseudoscalar: axion-like particles
  - vector: dark photons
  - neutrino: heavy neutral leptons
- 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: $U(1)_X$

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

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

$$\mathcal{L} \supset - \sum_f \bar{f} \epsilon e q_f A'_f f$$

- Two parameters: mass $m_{\gamma'}$ and mixing $\epsilon$
- Production and decay controlled by one parameter $\epsilon$
- Focus on MeV-GeV mass range in this work
### LHeC and FCC-he, and dark photon production

<table>
<thead>
<tr>
<th></th>
<th>$E_e$ (GeV)</th>
<th>$E_p$ (TeV)</th>
<th>$\sqrt{s}$ (TeV)</th>
<th>$\mathcal{L}_{\text{int}}$ (ab$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LHeC</td>
<td>60</td>
<td>7</td>
<td>1.3</td>
<td>1</td>
</tr>
<tr>
<td>FCC-he</td>
<td>60</td>
<td>50</td>
<td>3.5</td>
<td>3</td>
</tr>
</tbody>
</table>

**DIS:** $Q^2 \gg m_p^2 \approx 1$ GeV$^2$
Signal estimation

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

\[
P_{dv} = \text{Exp} \left( \frac{-x_{\text{min}}}{\Delta x_{\text{lab}}} \right) - \text{Exp} \left( \frac{-x_{\text{max}}}{\Delta x_{\text{lab}}} \right)
\]

\[
x_{\text{min}} = 200 \mu m, \quad x_{\text{max}} = \infty, \quad \Delta x_{\text{lab}} = \tau_{\text{lab}} |\vec{v}| = \beta_{\gamma'} \gamma' \tau c
\]

<table>
<thead>
<tr>
<th></th>
<th>(\eta(e/\mu))</th>
<th>(\eta(\text{jets}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>LHeC</td>
<td>(-4.3, 4.9)</td>
<td>(-5,5)</td>
</tr>
<tr>
<td>FCC-he</td>
<td>(-5.0, 5.2)</td>
<td>(-5.5, 5.5)</td>
</tr>
</tbody>
</table>

In practice, apply \(|\eta| < 4.7\)
Dark photon decays

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

\[ \Gamma_{\text{total}}(\gamma') = \frac{\Gamma(\gamma' \rightarrow e^- e^+) \text{BR}(\gamma' \rightarrow e^- e^+)}{\text{BR}(\gamma' \rightarrow e^- e^+)} \]

[Raggi, Kozhuharov,'15]
Background

- Real low-energy photons interacting with the detector material or the beam pipe → $e^- e^+$ 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 $\Lambda$
  - 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: 90% C.L. sensitivity reaches

LHeC, \( \text{Pt}(X) = 5 \text{ GeV} \)

- \( N=1 \)
- \( N=10 \)
- \( N=100 \)

LHeC, \( \text{Pt}(X) = 10 \text{ GeV} \)

- \( N=1 \)
- \( N=10 \)
- \( N=100 \)

FCC-he, \( \text{Pt}(X) = 5 \text{ GeV} \)

- \( N=1 \)
- \( N=10 \)
- \( N=100 \)

FCC-he, \( \text{Pt}(X) = 10 \text{ GeV} \)

- \( N=1 \)
- \( N=10 \)
- \( N=100 \)
Results II: 90% C.L. sensitivity reaches $0.1 \times 10^{-5}$ to $5.0 \times 10^{-5}$.

**Present exclusion**

- **LHeC, $Pt(X) = 5$ GeV**:
  - Nbkg=0, signal efficiency = 100%
  - Nbkg=0, signal efficiency = 20%
  - Nbkg=100, signal efficiency = 100%
  - Nbkg=100, signal efficiency = 20%

- **FCC-he, $Pt(X) = 5$ GeV**:
  - Nbkg=0, signal efficiency = 100%
  - Nbkg=0, signal efficiency = 20%
  - Nbkg=100, signal efficiency = 100%
  - Nbkg=100, signal efficiency = 20%
Results III: Comparison

Summary

- Portals to the dark sector
- Vector portal and dark photon model
- Electron-proton colliders may explore a unique territory in the parameter space for MeV-GeV dark photons

Thank You!