Spin correlations in dark matter searches

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Based on a paper[1] by: Prof. Jonathan L. Feng, Miša Toman and Eli Welch.

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[1]Coming soon to ArXiv

Talk outline

- Introduction
  - Dark photons as a dark matter portal.
  - Theoretical model.
  - Experimental searches.
- Spin correlations.
- Prior treatments of Dark photon detection assume spin correlations can be ignored.
- Results and future work.

Dark photon model

- $U(1)_D$ massive gauge boson, A', with mass $m_{A'}$ and coupling ε .
- Simplest gauge portal between the SM and the Dark sector.

$$\mathcal{L}_{\gamma A'} = \frac{\varepsilon}{2} B_{\mu\nu} F_D^{\mu\nu} \,.$$

- Equation above gives coupling to SM fermions

$$\mathcal{L}_{\psi A'} = \varepsilon q \bar{\psi} \not{A}' \psi \,.$$

Dark photon searches

A' is predicted to be a long lived particle (LLP).

$$\Gamma\left(A' \to f\bar{f}\right) = \frac{\varepsilon^2 e^2}{12\pi} m_{A'} \sqrt{1 - \frac{4m_f^2}{m_{A'}^2}} \left(1 + \frac{2m_f^2}{m_{A'}^2}\right). \tag{1}$$

Searches such as: FASER, NA62, HPS, APEX all look for signs of $A' \to e^+e^-/\mu^+\mu^-$ decay.

Problem in the literature

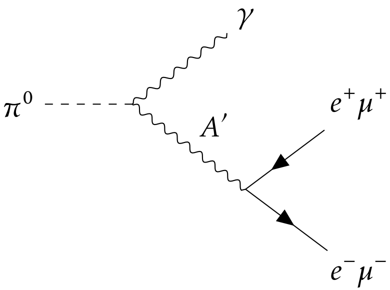
- Two main approximations:
  - Narrow width approximation
  - Neglecting spin correlations in production and decay of A'.
- Event generators often trade accuracy for speed.

Pions coupling to dark photons

FASER experiment. How are pions coupled to dark photons?

- Inspiration: coupling via chiral anomaly

$$\mathcal{L}_{\pi^0\gamma\gamma} \propto \pi^0 F^{\mu\nu} F^{\rho\sigma} \varepsilon_{\mu\nu\rho\sigma} \implies \mathcal{L}_{\pi^0\gamma A'} \propto \varepsilon \pi^0 F^{\mu\nu} F_D^{\rho\sigma} \varepsilon_{\mu\nu\rho\sigma} \,. \quad (2)$$



Narrow width approximation

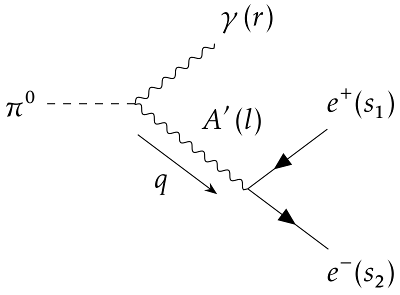
For LLPs we can approximate

$$\frac{1}{\left|q^2 - m_{A'}^2 - i m_{A'} \Gamma(A')\right|^2} = \frac{\pi}{m_{A'} \Gamma(A')} \delta\left(q^2 - m_{A'}^2\right) .$$

Spin correlations

What are spin correlations?

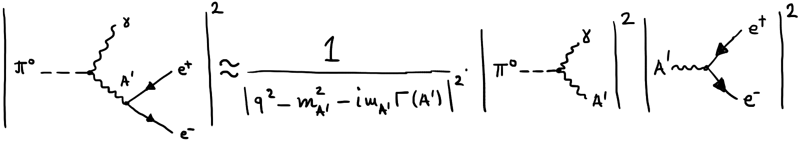
$$\mathcal{M}^{\dagger}\mathcal{M} = \frac{1}{\left|q^2 - m_{A'}^2 - i m_{A'}\Gamma(A')\right|^2} \left|\sum_l \Pi_r^l \cdot \Delta_{s_1,s_2}^l\right|^2 .$$



Spin correlations

To neglect spin correlations we approximate:

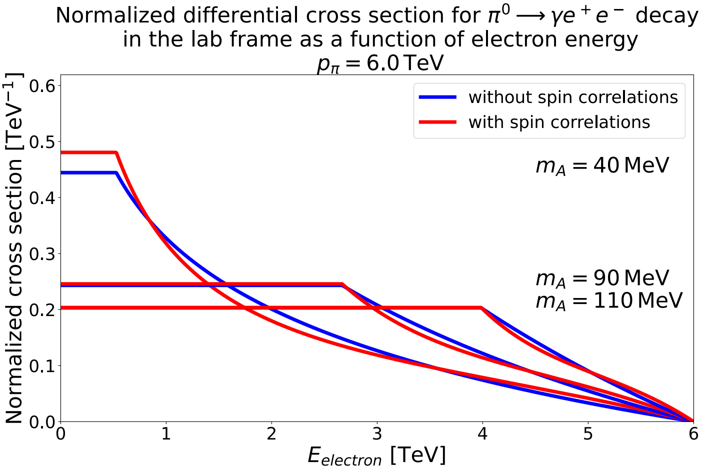
$$\left|\sum_{l} \Pi_r^l \cdot \Delta_{s_1,s_2}^l\right|^2 \approx \left(\sum_l \left|\Pi_r^l\right|^2\right) \cdot \left(\sum_l \left|\Delta_{s_1,s_2}^l\right|^2\right). \tag{3}$$



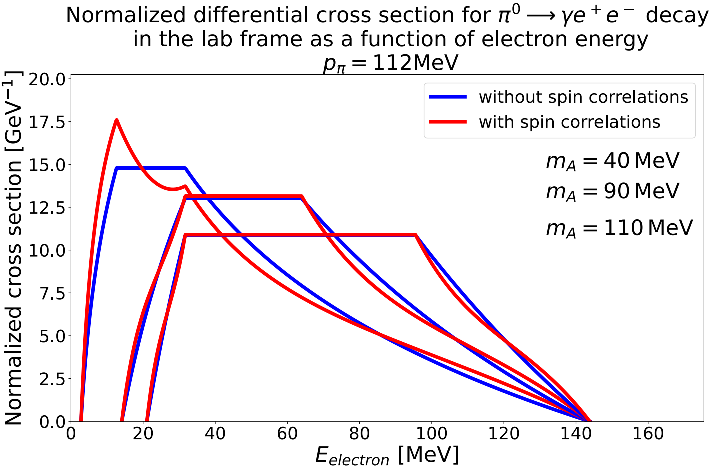
After a lot of calculation...

$$
\begin{aligned}
I(k_2) &= 2\pi \int_{r=0}^{\infty} r^2 \mathrm{d}r \int_{\theta=0}^{\pi} \sin\theta \mathrm{d}\theta \delta\left(E - \sqrt{r^2 + k^2 - 2kr\cos\theta}\right) \delta\left(M - \sqrt{m_f^2 + r^2} - E_2 - E\right) \\
&= 2\pi \int_{r=0}^{\infty} r^2 \mathrm{d}r \int_{u=-1}^{1} \mathrm{d}u \delta\left(E - \sqrt{r^2 + k^2 - 2kru}\right) \delta\left(M - \sqrt{m_f^2 + r^2} - E_2 - E\right) \\
&= 2\pi \int_{r=0}^{\infty} r^2 \mathrm{d}r \delta\left(M - \sqrt{m_f^2 + r^2} - E_2 - E\right) \frac{E}{rk} \Theta\left(E - |r-k|\right) \Theta\left(r + k - E\right) \\
&= \frac{\pi E}{k} \int_{r=0}^{\infty} 2r \mathrm{d}r \delta\left(M - \sqrt{m_f^2 + r^2} - E_2 - E\right) \Theta\left(E - |r-k|\right) \Theta\left(r + k - E\right) \\
&\quad \text{Substitution: } u = r^2, \quad \mathrm{d}u = 2r\mathrm{d}r \\
&= \frac{\pi E}{k} \int_{u=0}^{\infty} \mathrm{d}u \delta\left(M - \sqrt{m_f^2 + u} - E_2 - E\right) \Theta\left(E - |\sqrt{u} - k|\right) \Theta\left(\sqrt{u} + k - E\right) \\
I(k_2) &= \frac{2\pi E}{k} (M - E_2 - E) \Theta(M - E - m_f - E_2) \Theta\left(E - \left|\sqrt{(M - E_2 - E)^2 - m_f^2} - k\right|\right) \Theta\left(\sqrt{(M - E_2 - E)^2 - m_f^2} + k - E\right).
\end{aligned}
$$

Results


Normalized differential cross section for $\pi^0 \longrightarrow \gamma e^+ e^-$ decay
in the lab frame as a function of electron energy
$p_\pi = 6.0\,\text{TeV}$
Normalized cross section [TeV^{-1}]
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0
1
2
3
4
5
6
$E_{electron}$ [TeV]
without spin correlations
with spin correlations
$m_A = 40\,\text{MeV}$
$m_A = 90\,\text{MeV}$
$m_A = 110\,\text{MeV}$

Results


Normalized differential cross section for $\pi^0 \longrightarrow \gamma e^+ e^-$ decay
in the lab frame as a function of electron energy
$p_\pi = 112\text{MeV}$
Normalized cross section [GeV^{-1}]
$E_{electron}$ [MeV]
without spin correlations
with spin correlations
$m_A = 40$ MeV
$m_A = 90$ MeV
$m_A = 110$ MeV
0.0
2.5
5.0
7.5
10.0
12.5
15.0
17.5
20.0
0
20
40
60
80
100
120
140
160

Discrepancy

We used the following measure to define discrepancy between spectra:

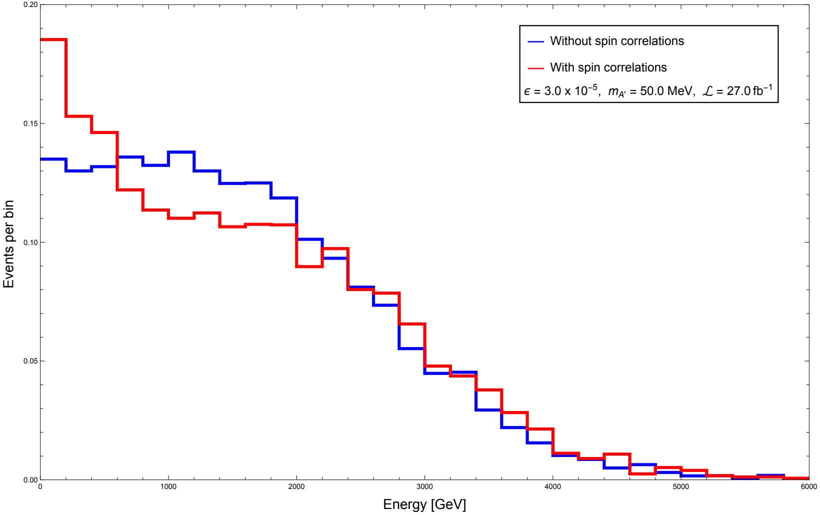
$$\Delta\left(m_\pi, m_f, m_{A'}\right) \equiv \frac{1}{2} \int \left|\rho_{\text{with}}(E) - \rho_{\text{without}}(E)\right| \mathrm{d}E\,. \tag{4}$$

We found the following bound on discrepancy:

$$\Delta\left(m_\pi, m_f, m_{A'}\right) \leq \frac{1}{6\sqrt{3}} \approx 9.6\%\,, \tag{5}$$

over the whole energy spectrum.

Simulating a real detector count



Summary

- We find that spin correlations will not have an effect on current FASER searches.
- Future precision experiments will have to account for spin correlations.

Thank you!