JLab Letter of Intent:

An Amplitude-level Search for a Dark Photon in Bhabha Scattering

D. Mack (TJNAF)

May 21, 2023

Executive Summary

This is an LOI to see if I'm on the right track. Development of a full proposal would take at least 2 years.

The main physics goal is to do an amplitude level search in Bhabha scattering ($e^+e^- \rightarrow e^+e^-$) for an A' over the mass range of roughly 10-100 MeV/c2.

The best observable for a search over a broad mass range appears to be the cross section (or yield). Asymmetry-based searches are more difficult, but may be useful in a discovery scenario.

The conceptual design of the experiment:

- Positron beam, unpolarized, 0.1 muA
- Several beam energies between 500 MeV and 10.8 GeV
- Be targets distributed in z, totaling 10% RL
- A dipole-based pair spectrometer with detector for trigger, PID, and tracking

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Introduction:

I am trying to optimize a search for a lepto-philic dark photon (henceforth called the A') in Bhabha scattering, $e^+e^- \rightarrow e^+e^-$. Two aspects of this reaction potentially make it unusually sensitive in an A' search:

- the search can seemingly be done at amplitude-level, and
- because there is no coherent, real photon in the reaction, there is no suppression of the sensitivity by a factor of $\alpha = 1/137$.

In a narrow mass range, this reaction appears to be capable of excluding phase space down to ε = 1E-5 in minutes, or as low as ε = 3E-8 in days. There is currently a large, allowed region of phase space which falls between exclusions based on bump-on-background-hunts from dark bremsstrahlung

$$e^- + \text{nucleus} \rightarrow e^- + \text{nucleus} + A' \qquad (\text{followed by } A' \rightarrow e^+e^-)$$

and the exclusions from detached vertex-type measurements where an $A' \rightarrow e^+e^-$ would materialize out of the vacuum downstream of a target (as in the JLab HPS program) or downstream of a beam dump at a high energy facility. My hope is to design an experiment which excludes most of this remaining phase space in a year-long run with a positron beam, making use of a target system distributed along the z axis as was used in APEX in order to broaden the beam energy spectrum at the vertex so fewer primary beam energies will be necessary. (However, because the reaction of interest does not benefit from Z^2 enhancements, the targets are more likely to be cm-scale Be slabs rather than thin W foils.)

Due to the remarkable s-channel annihilation contributions in Bhabha scattering, as one approaches a resonance at sqrt(s) = m_A', cusp-like features not surprisingly appear in all observables I have examined so far. For larger values of the mixing, these can appear to be bump-ish, but for the small mixings targeted in this LOI, the effect at a specific sqrt(s) in the cross section can even be negative. However, because both the real and imaginary parts of the amplitudes reverse sign when a resonance is crossed, it seems one should expect a bi-polar modulation vs sqrt(s). (See Figure 1.)

The signal templates for an A' search are in principle well-defined once the experimental resolution is well simulated. The cross-section signal template in Figure 1 is completely insensitive to the sign of the vector coupling. However, it is interesting that in a purely axial coupling scenario, terms proportional to g_v*g_a of course vanish, hence the remaining term proportional to g_v^2 - g_a^2 becomes simply -g_a^2. Thus, in the purely axial coupling scenario, the sign reverses, and the appropriate signal template is the mirror image of that in Figure 1.

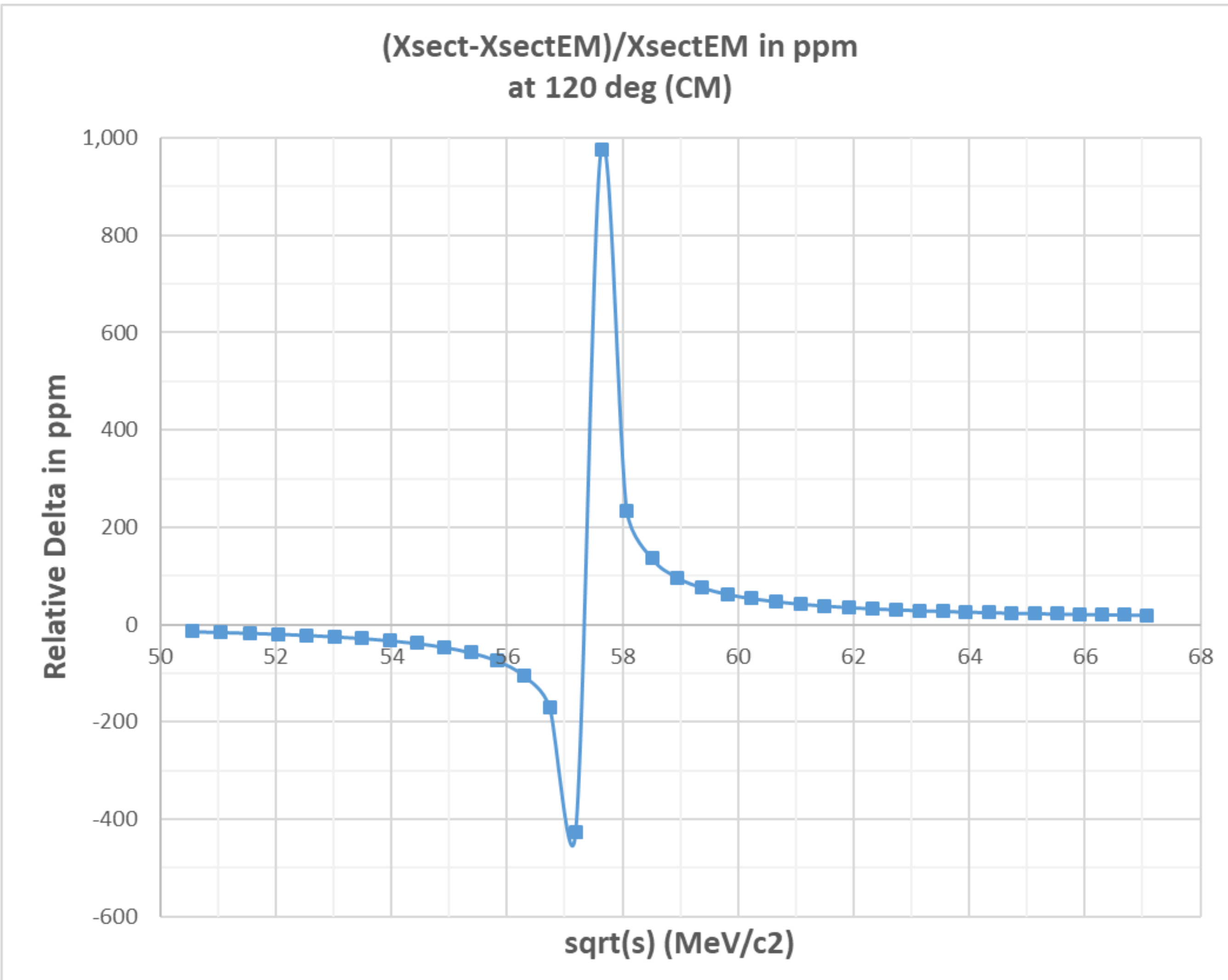

Figure 1 Excitation curve for ε = 1E-5 and an A' mass of 57.5 MeV/c^2. This is the difference between the full calculation and the QED contribution. The reconstruction resolution is not included, and the goal of 1 MeV/c^2 will make this plot look less interesting. This gives an idea of the signal template for purely vector coupling with a negligibly small decay width.

Theoretical Methods:

I started with a formalism for Bhabha scattering by Olsen and Osland which includes photon and Z0 exchange. [1] Their paper seems exceptionally clear, and their Figure 2 is insightful. Then I modified the Z0 mass and couplings to resemble an A' with purely vector couplings, including the mixing, ε. In the best case scenario, I wouldn't quantitatively trust what I did within a factor of pi at this stage. I also explored the purely axial coupling scenario, and the combined vector and axial scenario. If this approach is not appropriate, I'd love to hear alternative suggestions.

In reference [2], Y Kahn et al. discuss the axial coupling scenario, as well as the mixed vector and axial coupling scenarios. I did not use any formalism from their paper.

Some other experimental considerations:

I looked at the cross section, two parity-conserving double-spin asymmetries (A_LL and A_TT), and one parity violating single-spin asymmetry (A_LU). Although my prejudice was that the asymmetry measurements would be more sensitive, this does not appear to be the case when beam intensity, polarization, and dilutions from unpolarized electrons in magnetized iron foils are considered. The asymmetries need more study though since the cusp-like effects occur in both the spin-dependent numerator and unpolarized cross section in the denominator, hence the net effect can be a factor of several larger or smaller than in the cross section case.

The ability to search for amplitude-level signals in the cross-section may seem counter-intuitive. In both an A' search and a PV measurement, the interference term of interest is between the relatively large EM amplitude and a small amplitude. In the PV case, the interference term merely produces a small offset in the cross section which is impractically too small to observe. In the case of an A' with a mass inside the window of interest, however, the interference term can be observed via the cusp-like feature.

Generally speaking, the impact of s-channel contributions is larger for backward positron CM angles. This is because, at far forward angles, s-channel effects are diluted by the steeply rising amplitude from t-channel photon exchange. Fortunately for experiments, the cross section at backward positron CM angles drops relatively slowly, due in part to these s-channel contributions.

Figure 1 was plotted for theta_cm = 120 degrees. Calculations show this provides a good signal in the cross section for both the purely vector and purely axial coupling scenarios. However, there are parts of the phase space for the mixed vector and axial coupling scenario where the optimum angle can be as low as theta_cm = 70 degrees. This means a broad search needs to cover a theta_cm range of something like 50-130 degrees.

The invariant mass in the e^+e system, assuming the e^- is at rest, is sqrt(s) = sqrt(2me + 2Ee+me).

Neglecting radiation in the target, for primary beam energies between 500 MeV and 10 GeV, the invariant mass coverage at JLab is 22.6 to 101 MeV/c^2. Due to the relatively high expected emittance of the positron beam, it will be a challenge to deliver lower energies without scraping in the accelerator. Lower A’ masses can be reached by degrading the beam energy with thick targets; this is actually essential for a search covering an order of magnitude in A’ mass without needing 100 separate beam energies.

The invariant mass will be calculated from the e^- and e^+ detected in coincidence in a pair spectrometer. To keep from washing out a bi-polar signal, the resolution in sqrt(s) needs to be 1 MeV/c2 or better. For this, a momentum resolution of ~1% appears to be sufficient. The resolution on the opening angle of the e^+e- pair needs to be 1 mrad or better; this requirement will challenge the design of the target system and pair spectrometer, especially as the A’ mass search pushes down toward O(10) MeV/c^2. For these lightest A’ candidates, one might have to settle for worse angular resolution hence somewhat weaker constraints.

Benchmarking the resolution of the pair spectrometer will be a challenge. There are no Standard Model calibration standards that give a clean peak e^+e^- in the invariant mass range of interest. One possibility just outside the range of interest is to use double pair conversions in the target to reconstruct an invariant mass peak in pi0→2gamma→2(e^+e^-).

Conclusion:

A straw-man JLab schedule presented by the Science Director earlier this year indicates that positron beams would not be delivered until perhaps 2035. In the intervening dozen years, other experiments around the world will whittle away at the remaining A’ lepto-philic phase space. Thus, it is important that any A’ search with a JLab positron beam be extremely sensitive.

The highest figure-of-merit observable for a broad survey in Bhabha scattering appears to be the cross section or yield. In a discovery scenario, it would immediately be clear whether vector couplings were dominant as expected, or whether axial couplings were dominant. But feedback from theory reviewers is needed. I have re-purposed an old gamma-Z model from an especially clear theory paper, and there may be some subtleties that I am missing. At this early stage there is barely a concept of the hardware for experimental reviewers to critique. The important thing is to be sure the quantum mechanics are right first, then the hardware design can proceed.

References:

[1] “Polarized Bhabha and Moller Scattering in left-right-asymmetric theories”, H.A. Olsen and Per Osland, **PRD 25**, p2895 (1982)

[2] “Light Weakly Coupled Axial Forces: Models, Constraints, and Projections”, Y. Kahn et al, arXiv:1609.09072v2 [hep-ph] 21 Oct 2016 https://arxiv.org/abs/1609.09072