Can One Make an Amplitude-level Search for a Dark Photon in Bhabha Scattering?

D. Mack

Positron Working Group Meeting

Aug 9, 2023

Motivation

A positron program needs a great series of experiments.

DVCS is a golden reaction channel, well-suited to making interesting measurements in spite of of extremely slow reversals between e+ and e- running. More such channels are needed.

I started collecting papers on Bhabha scattering (e+e- → e+e-) a few years ago, then chose one to code up. Bhabha scattering is a fascinating, purely leptonic reaction with very different behavior than Moller scattering.

I’m interested in dark matter and other BSM topics, so today I take a look at a possible dark matter application.

(A relevant LOI is available at the following link, but these slides are probably clearer:
An Amplitude-level Search for a Dark Photon in Bhabha Scattering,
https://hallcweb.jlab.org/doc-private/ShowDocument?docid=1229 .)

Exclusion of Visible A' Phase Space

There is a region of phase space, relevant to the Jlab positron program, which has proven resistant.

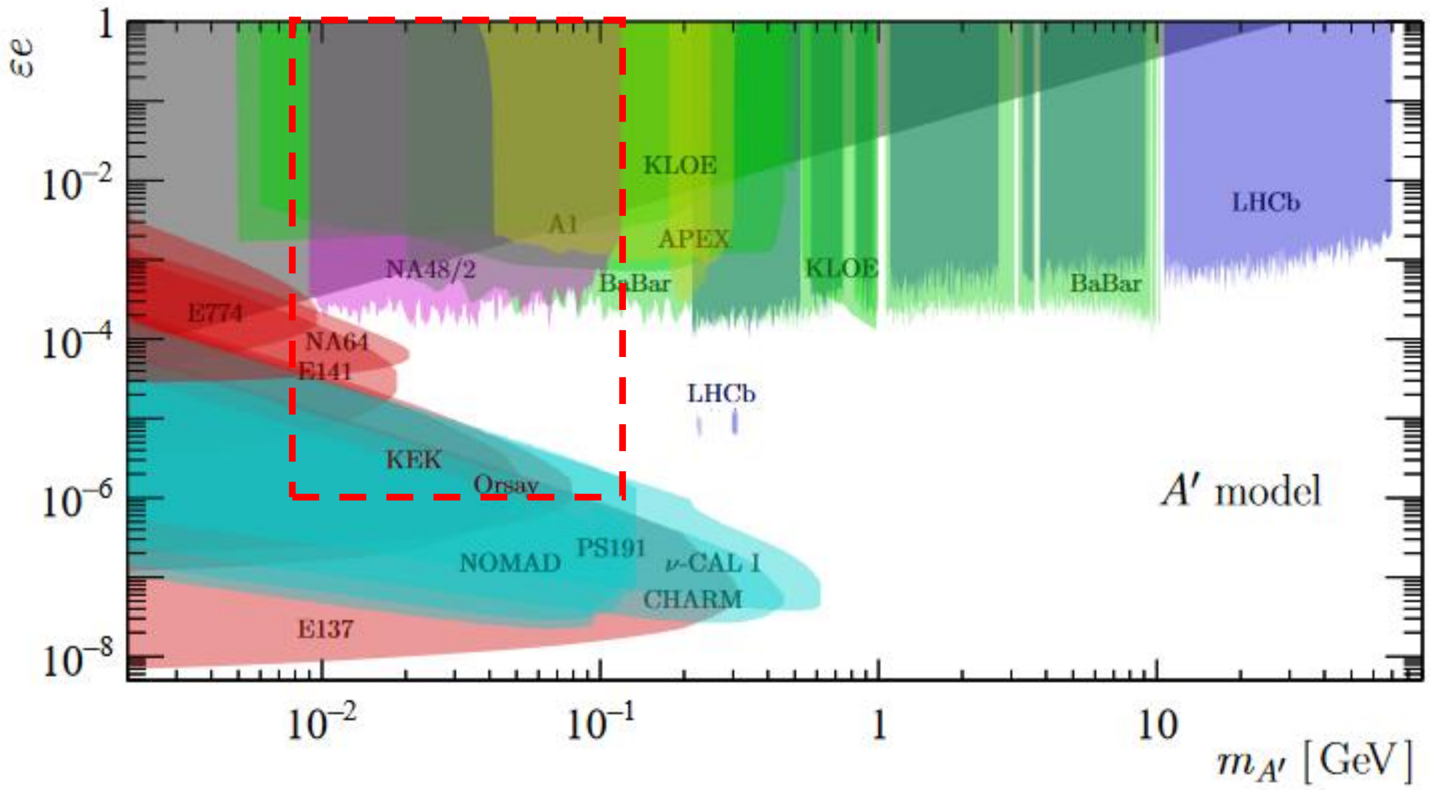
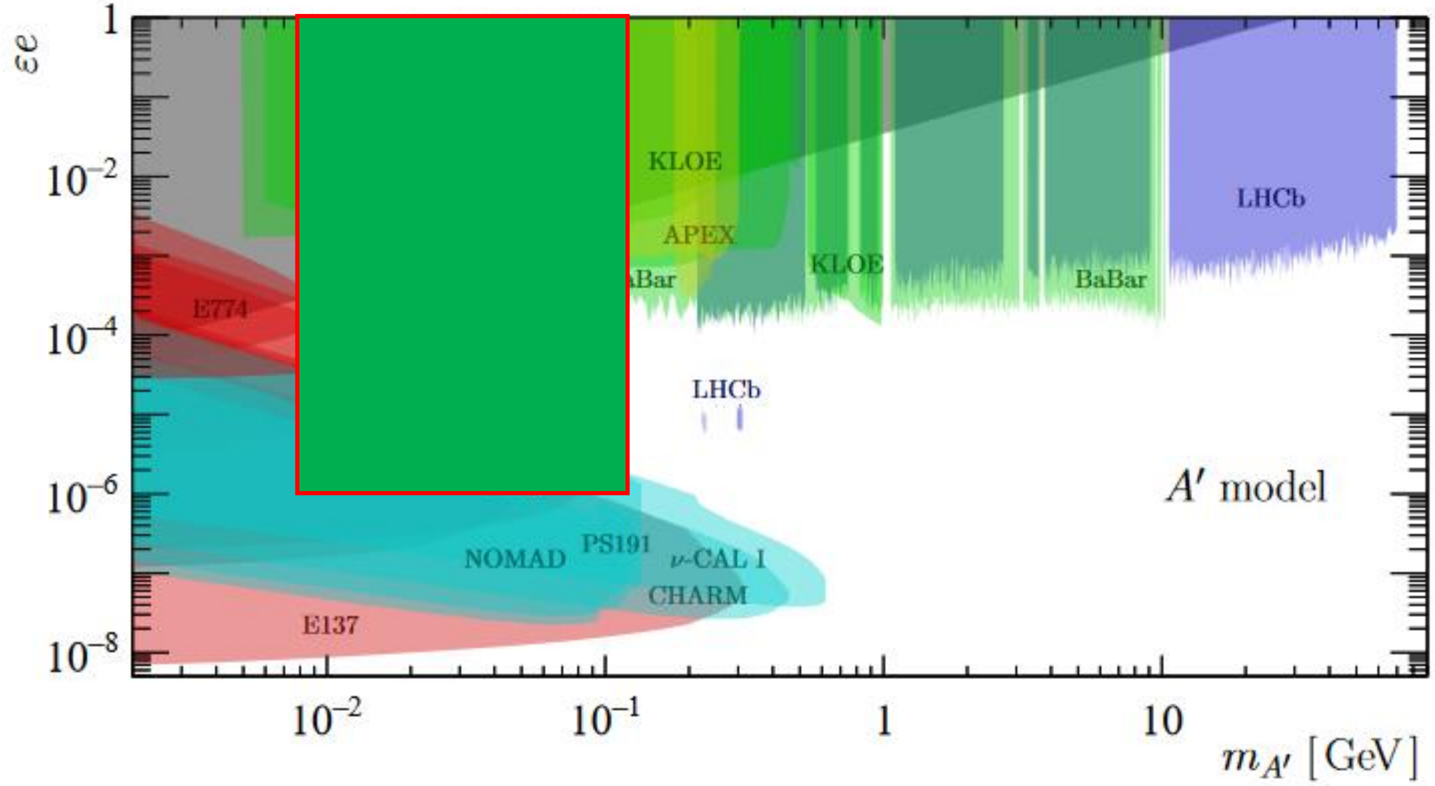


Figure 4. Constraints on visible A' decays considered in this study from (red) electron beam dumps, (cyan) proton beam dumps, (green) e^+e^- colliders, (blue) pp collisions, (magenta) meson decays, and (yellow) electron on fixed target experiments. The constraint derived from $(g-2)_e$ is shown in grey [90, 91].

arXiv:1801.04847v2 [hep-ph] 9 Jul 2018

Exclusion of Visible A’ Phase Space

Is there a way to exclude it with a positron beam?



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Can We Search for A' Via an Amplitude?

Assume the total amplitude is the sum of a large SM and small BSM amplitude:

$A_{tot} = A_{big} + A_{small}$

An on-shell A' is a manifestation of A^2_{small}, which then decays to e+e-.

The background is given by A^2_{big}.

As A' searches become more sensitive, the cross sections are approaching the weak interaction scale.

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As A' searches become more sensitive, the cross sections are approaching the weak interaction scale.

Can we find the dark photon signal we're looking for in some sort of interference term, $A_{big}*A_{small}$, as we do in PV experiments?

Even if the yield of A'→e+e- yield were only 1 part in 10^8, there might be some sort of asymmetry or cusp feature which appears at the 1 part in 10^4 level.

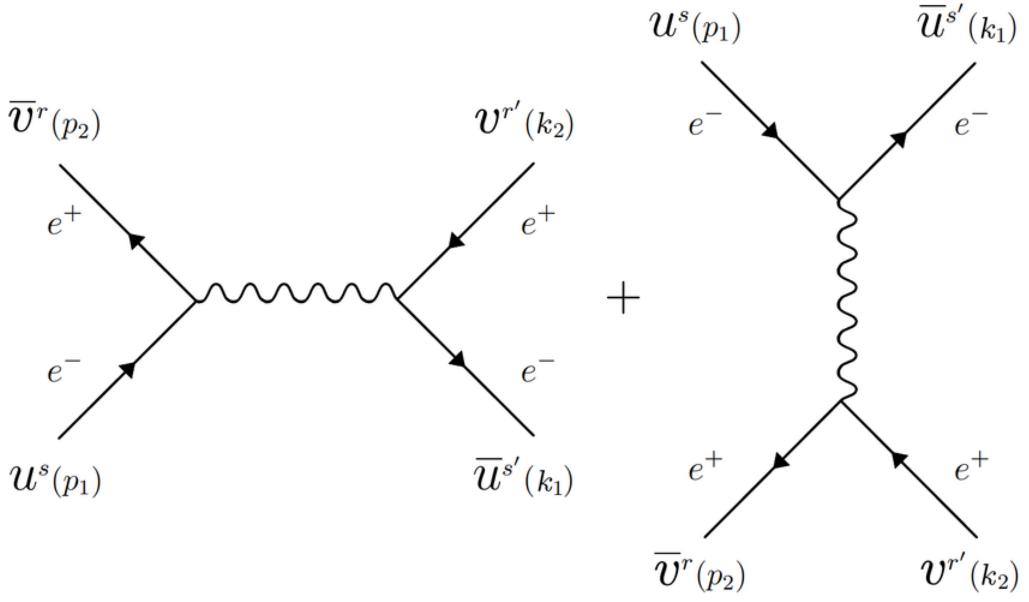
Ironically, an amplitude could be detectable even if the integrated luminosity were too low to produce a single A' → e+e- event.

Bhabha Scattering: e+e- → e+e-

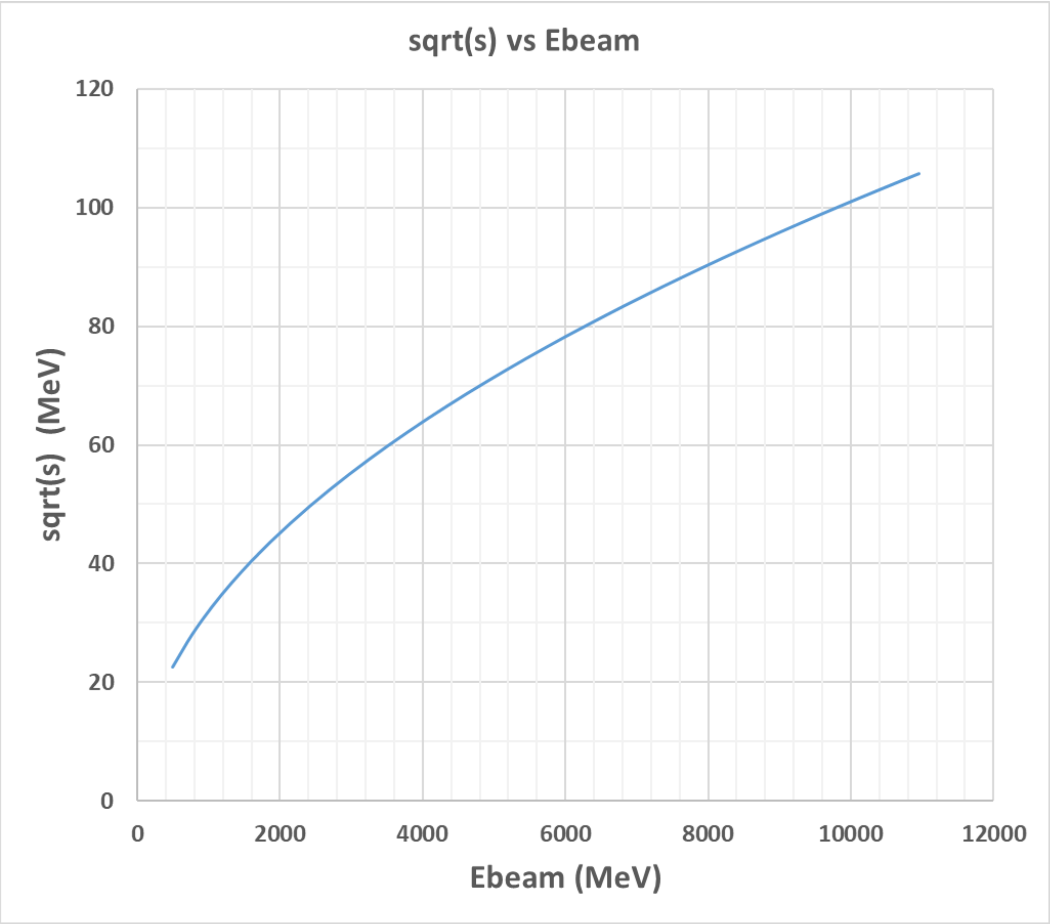
The s-channel annihilation diagram in Bhabha is interesting.

Jlab will be below mu+mu- threshold even at 22 GeV.
Ignoring e+e- → nu nubar, we are limited to e+e- → e+e- , without or with extra photons in the final state.

In the SM, the exchanged boson below can be a gamma or a Z0.



Research Gate uploaded by [Kort Beck](#)



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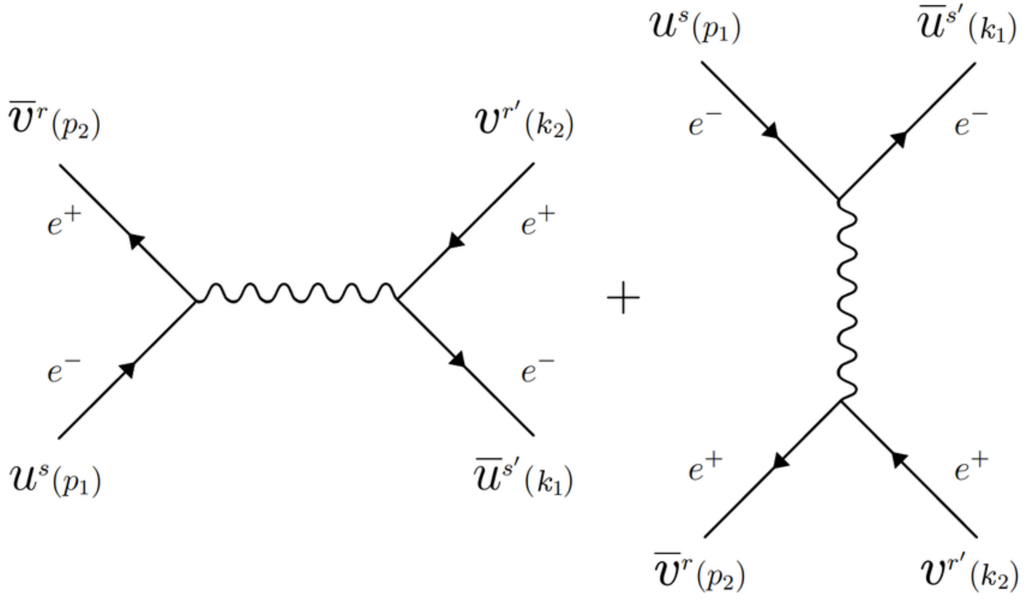

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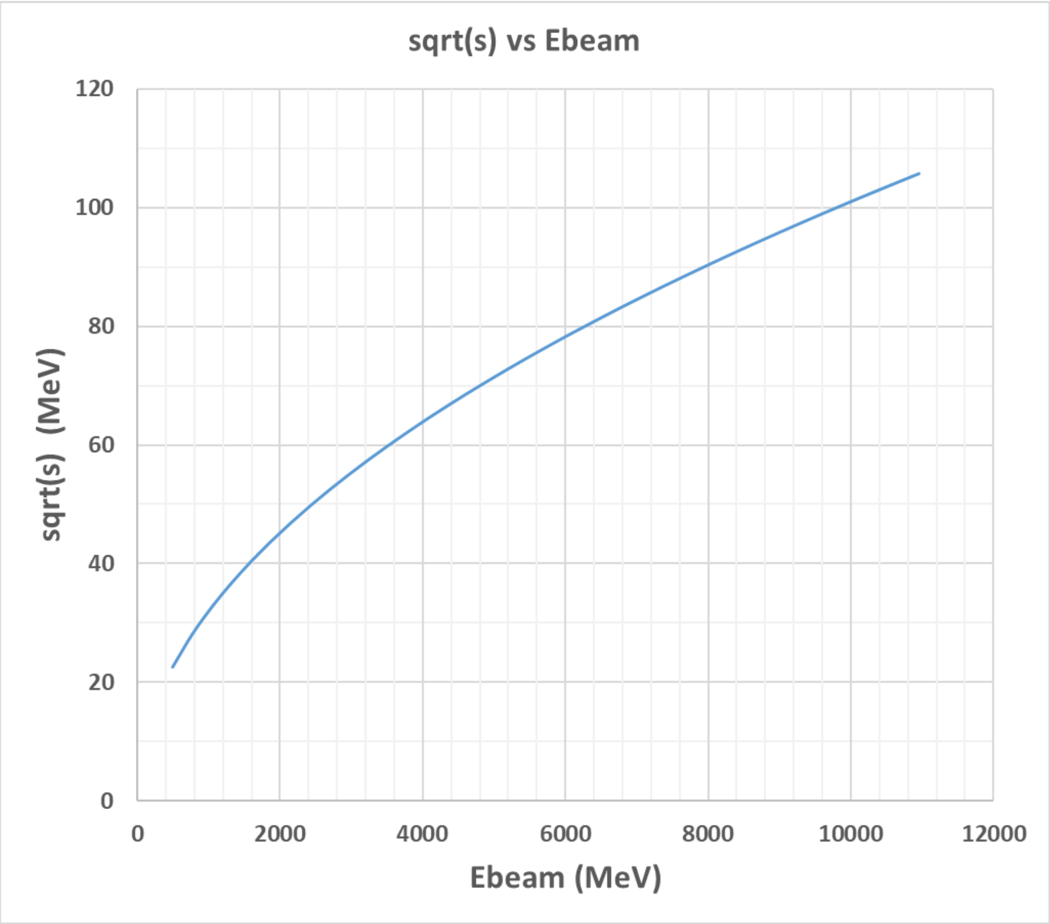

How would low energy Bhabha phenomenology change if I replace the Z0 with an A'?

SM Formalism for gamma and Z0 Interference

PHYSICAL REVIEW D VOLUME 25, NUMBER 11 1 JUNE 1982

Polarized Bhabha and Møller scattering in left-right-asymmetric theories

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Per Osland
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(Received 30 November 1981)

We identify and calculate the independent quantities that determine arbitrarily polarized Bhabha and Møller scattering, for left-right-asymmetric theories. Longitudinal polarization of either beam appears most useful, in either Bhabha or Møller scattering, in discriminating between the SU(2)×U(1) theory and certain classes of extended theories. Transverse beam polarization would in Bhabha scattering at high energies, $\sqrt{s} \simeq M_Z$, provide a very clear distinction between theories in which the $e^+e^-Z^0$ coupling is dominantly axial vector and theories where it is dominantly vector.

I. INTRODUCTION

Present electron-positron accelerators have reached energies where weak-interaction effects are on the verge of being observed. The nonobservation of these effects has indeed served to constrain[1]

a position to give a quantitative discussion of the dependence on beam polarization. It will be shown that, in contrast to the QED limit, the Bhabha cross section develops a strong dependence on transverse beam polarization, as the energy increases toward the Z^0 pole. Beyond the Z^0 pole

I used H.A. Olsen and P. Osland, PRD 25, 2895 (1982) “Polarized Bhabha and Moller scattering in left-right-asymmetric theories” because this paper was clear, and provided the xsect and two PC and two PV asymmetries. It also gives insightful comparisons to Moller scattering.

A Suite of Observables in Bhabha Scattering

Eqn (1) of Olsen and Osland gives the different xsect and asymmetries for all combination e+ or e- longitudinal or transverse polarization.

Simplifying and dumbing down the notation a bit:

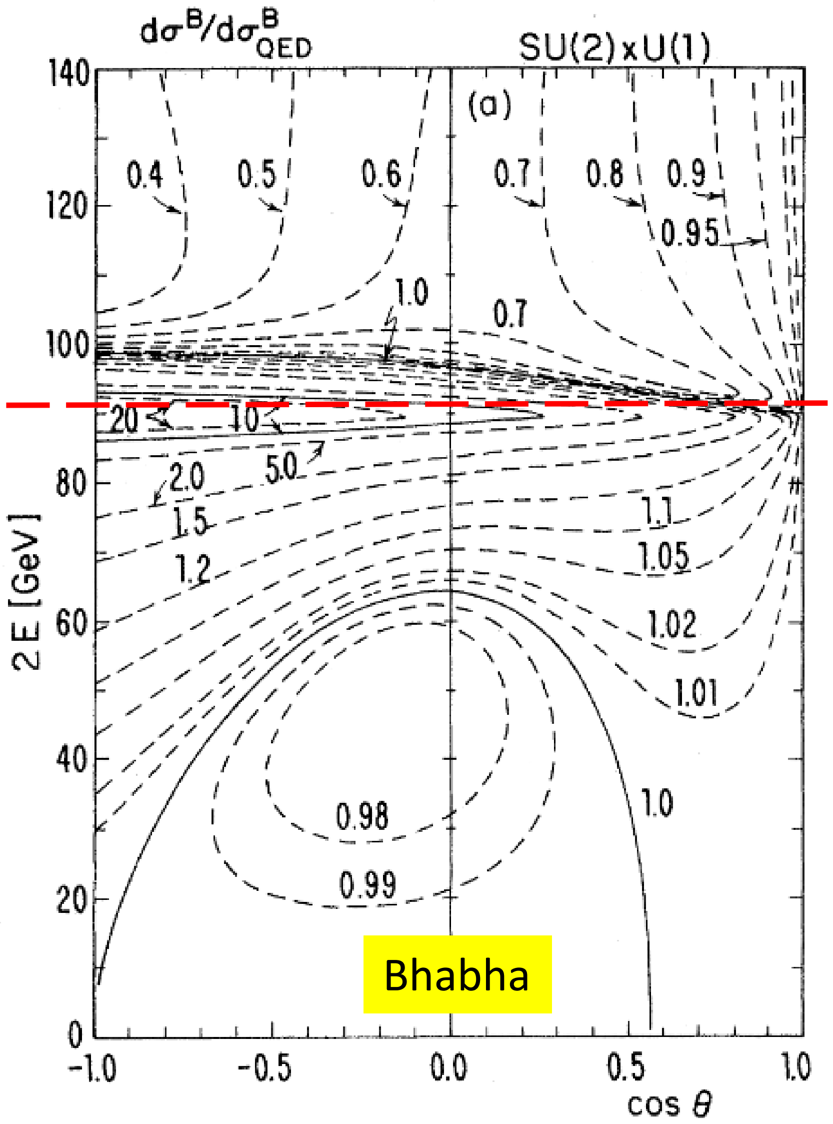
$$\sigma(\theta,\phi) = \sigma_0 \{ 1 + \mathbf{A_{LL}} P_-^{para} P_+^{para} + \mathbf{A_{LU}}(P_-^{para} - P_+^{para}) + P_-^{perp} P_+^{perp} [\mathbf{A_{TT}} \cos(2\phi) + \mathbf{A_{TT}}' \sin(2\phi)] \}$$

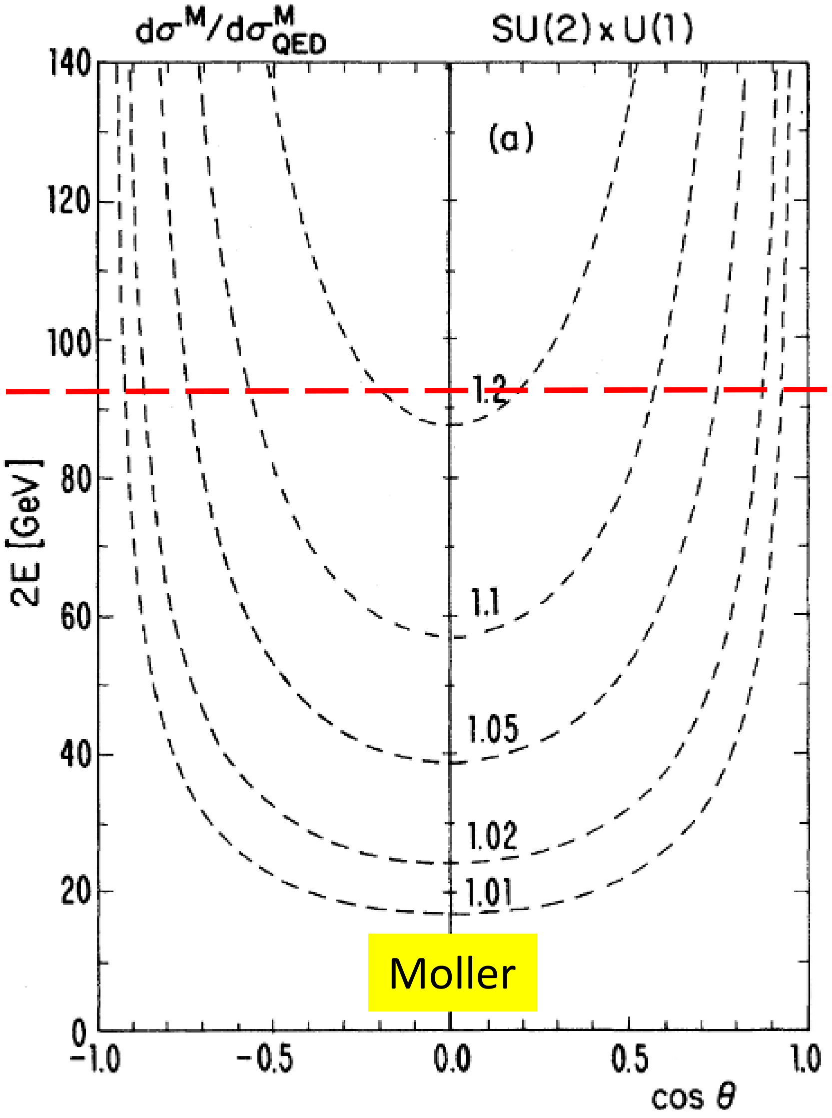
If I drop the PV terms, it looks just like the Moller polarimetry equations:

$$\sigma(\theta,\phi) = \sigma_0 \{ 1 + \mathbf{A_{LL}} P_-^{para} P_+^{para} + P_-^{perp} P_+^{perp} \mathbf{A_{TT}} \cos(2\phi) \}$$

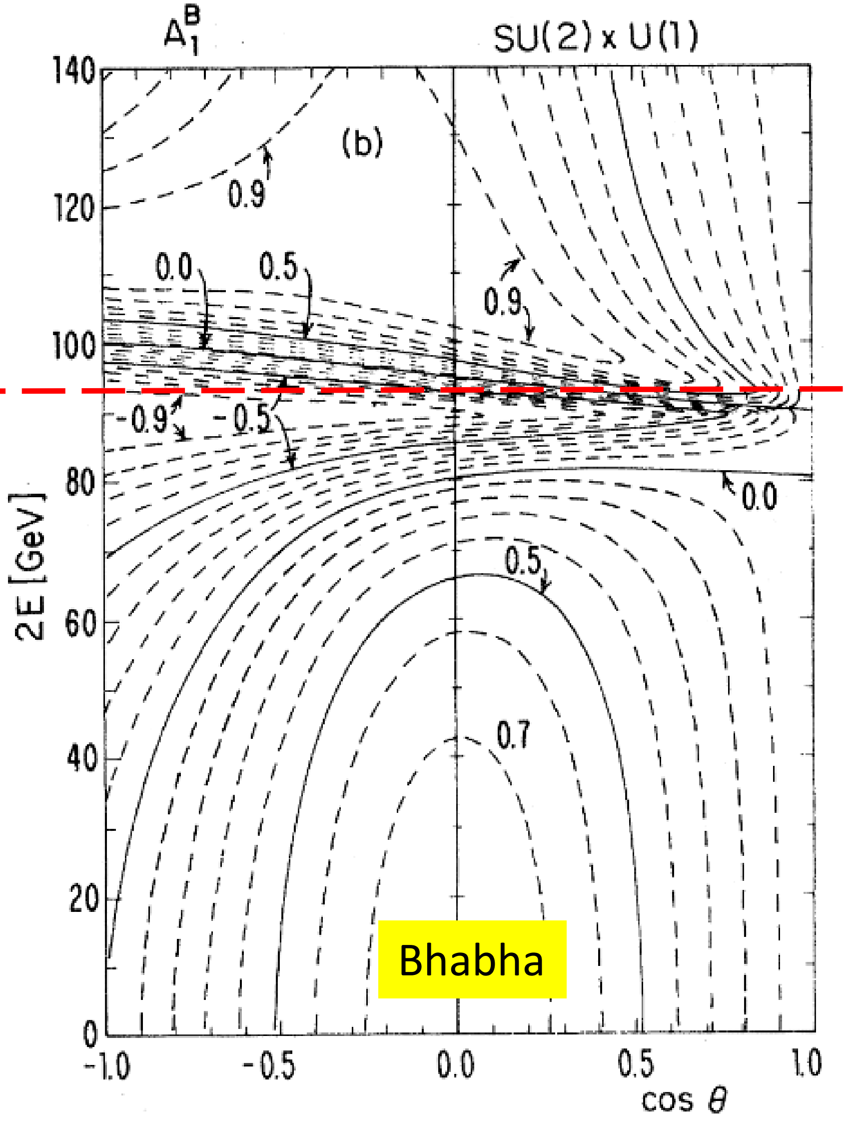
Let's look at the σ_0 term first.

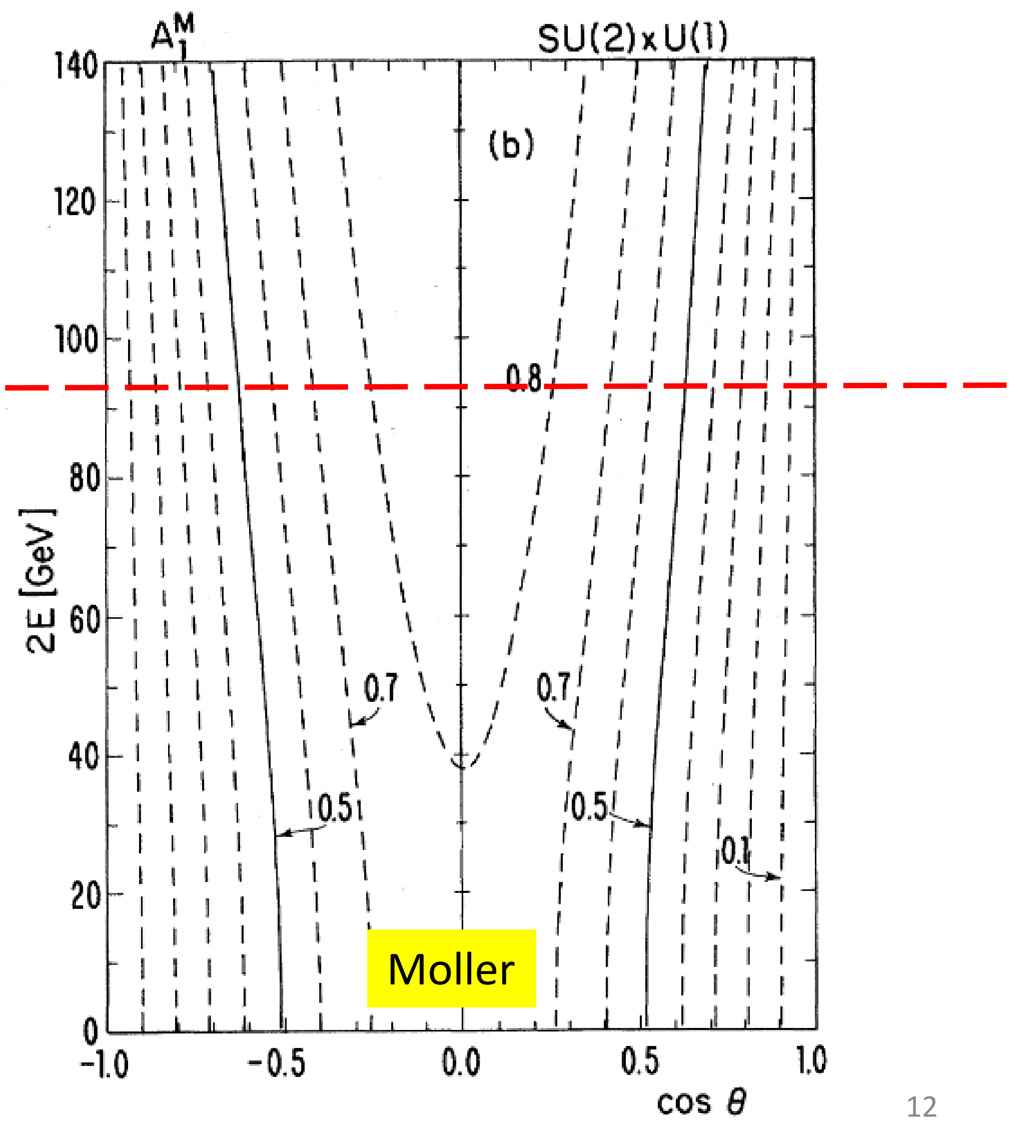
Xsect/Xsect$_{QED}$ Up to 140 GeV/c2





A_{LL} Up to 140 GeV/c2





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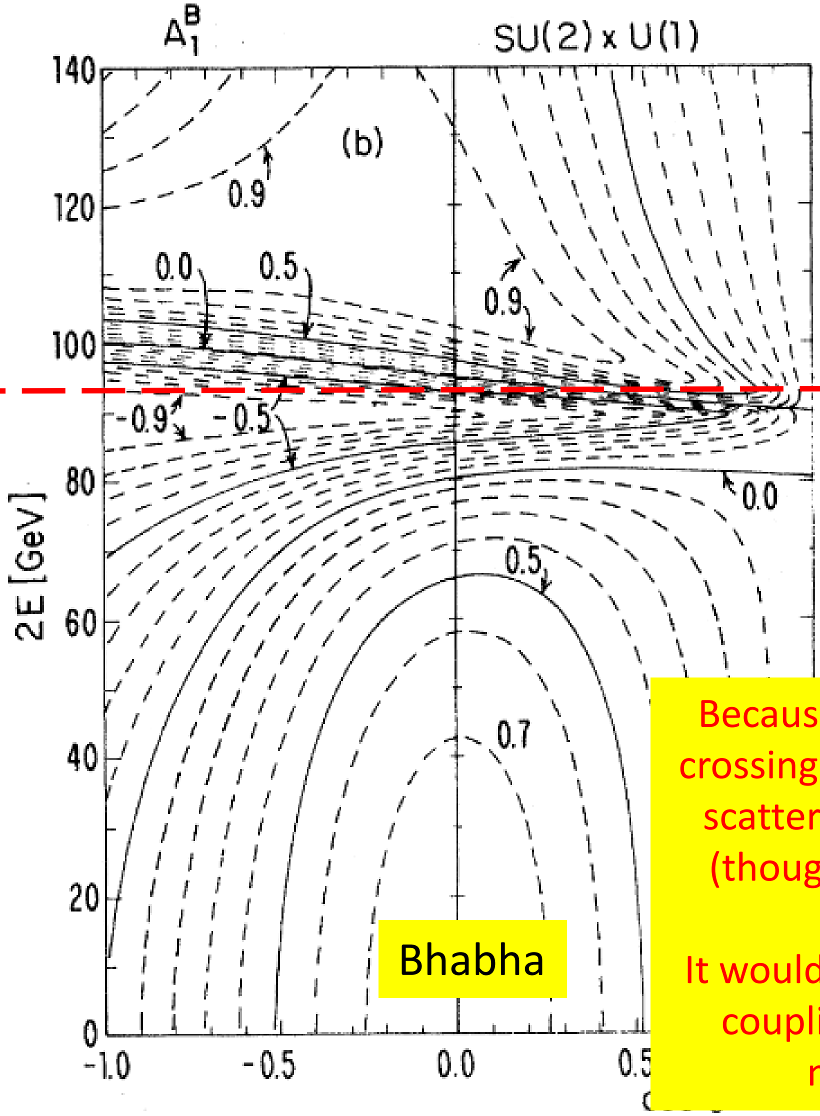
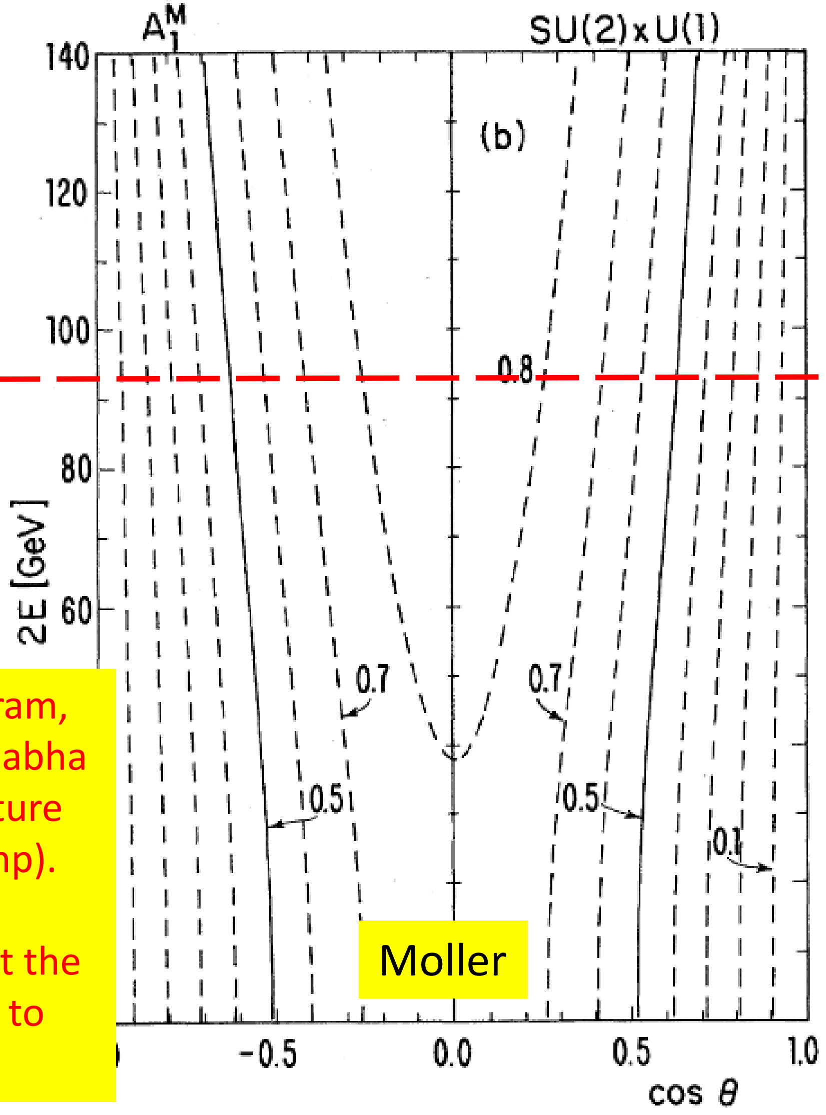




Because of the s-channel diagram, crossing the Z0 resonance in Bhabha scattering leaves a clear signature (though not necessarily a bump).

It would be interesting to adjust the couplings and mass of the Z0 to mock up A' exchange.

The SM Xsects in Bhabha Scattering

The unpolarized xsect is proportional to alpha^2:

$$\frac{d\sigma_0^B}{d\Omega}=\frac{\alpha^2}{4s}\left\{\cos^4(\theta/2)\left[\left|1+f(s)g_L{}^2-\frac{1+f(t)g_L{}^2}{\sin^2(\theta/2)}\right|^2+\left|1+f(s)g_R{}^2-\frac{1+f(t)g_R{}^2}{\sin^2(\theta/2)}\right|^2\right]\right.$$
$$\left.+2\sin^4(\theta/2)\,|\,1+f(s)g_Rg_L\,|^2+[2/\sin^4(\theta/2)][1+f(t)g_Rg_L]^2\right\}, \qquad (14)$$

(Polarized xsect differences can be defined from the asymmetries in Eqns 15-18.)

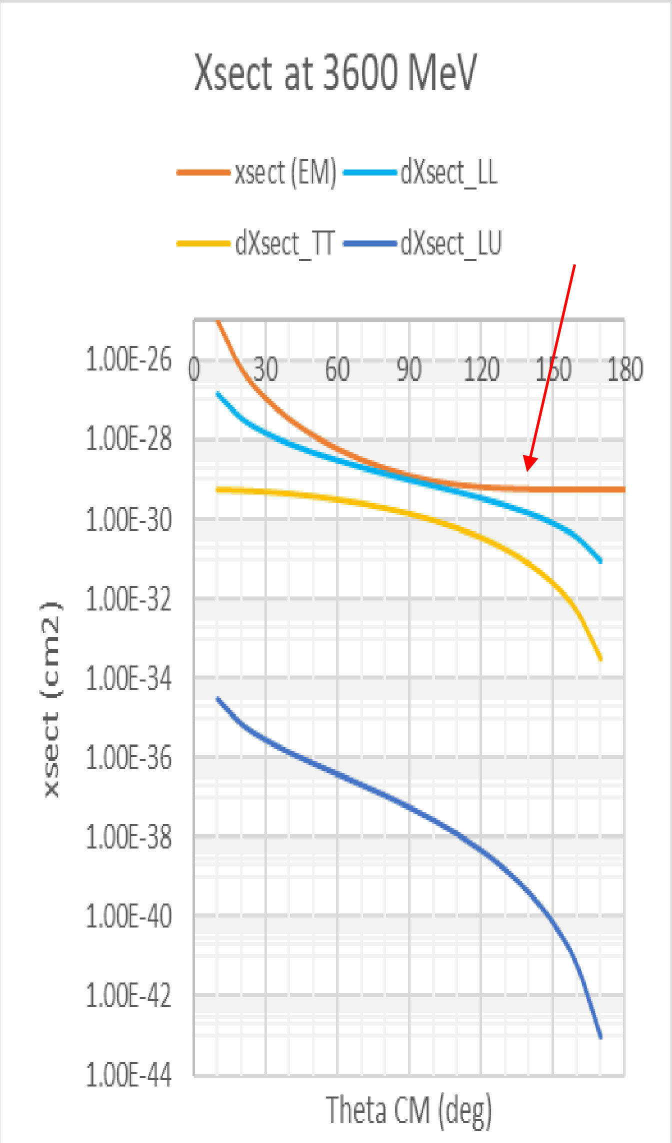
f(t) is for spacelike Z and is purely real. These terms tend to grow as theta → 0 deg, which will probably dilute any interesting A' resonant effects.

f(s) is for time-like Z, has a Real part and an Imaginary part. These terms have a flatter theta dependence. Generally, effects from a resonant A' will be most apparent at backward angles. (See red arrow at right, pointing to "the shelf".) But interferences can sometimes surprise.

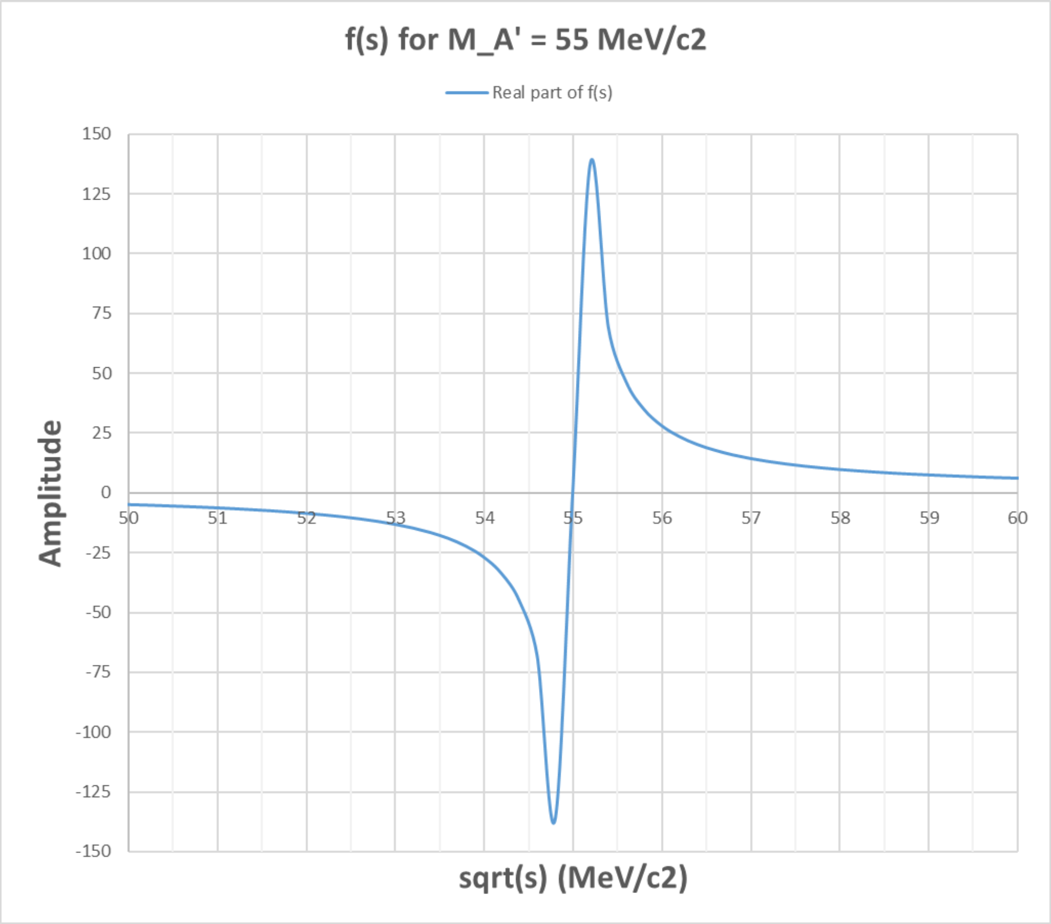
$$f(q^2)=\begin{cases}\dfrac{1}{4\sin^2(2\theta_W)}\,\dfrac{q^2}{q^2-M_Z{}^2+iM_Z\Gamma_Z^{\rm tot}}, & q^2>0\ \ (q\ \text{timelike})\,, \\[2ex] \dfrac{1}{4\sin^2(2\theta_W)}\,\dfrac{q^2}{q^2-M_Z{}^2}, & q^2\le 0\ \ (q\ \text{spacelike})\,.\end{cases} \qquad (12)$$

i.e., **f(s)**

i.e., **f(t)**



Real Part of the Timelike A’ Propagator



The Real part is arguably the most important. Once you define the A’ mass, then the Real part is known.

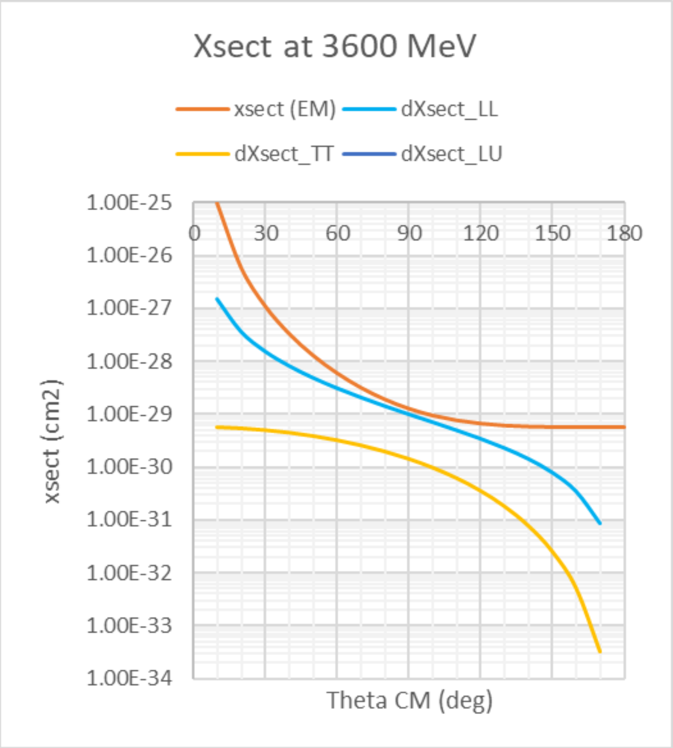
I don’t have a deep understanding of the Imaginary part. A significant decay width could weaken constraints.

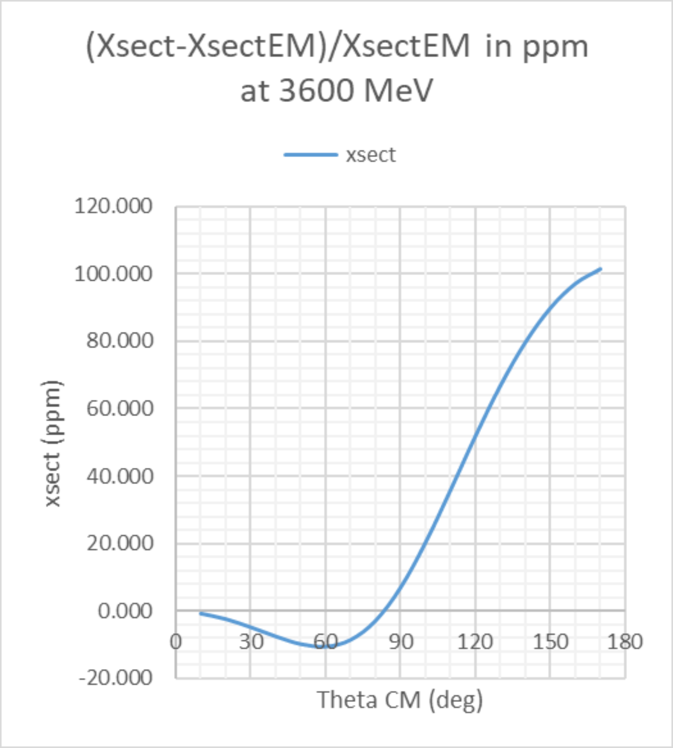
(Most papers seem to assume the A’ decay width is negligible. But if the A’ decays rapidly to lighter particles in the dark sector, the width may not be negligible. There are two relatively obscure asymmetries which are proportional to the Imaginary part.)

Modifying the Calculation
Z0 → A'

<u>Z0</u>	<u>A'</u>
Mass = 98,187.6 MeV/c2 Width = 2495 MeV/c2	Mass = 57.5 MeV/c2 Width = 0.575 MeV/c2
g_a = -1 g_v = -0.0748	g_a = 0 g_v = 1
g_l = g_v + g_a g_r = g_v – g_a	g_l = (g_v + g_a)*sqrt(epsilon) g_r = (g_v – g_a)*sqrt(epsilon)
$4\sin^2(2\text{theta\_W}) = 2.845$ (a normalization factor in the propagator) →	I just lamely set this to 1.

Xsect Study: Purely Vector Coupling, Mixing = 1E-5, Mass = 57.5 MeV/c2





As naively expected, the A' effects are largest at backward angles.

(In the SM, the deviations from PV are less than 0.1 ppm.)

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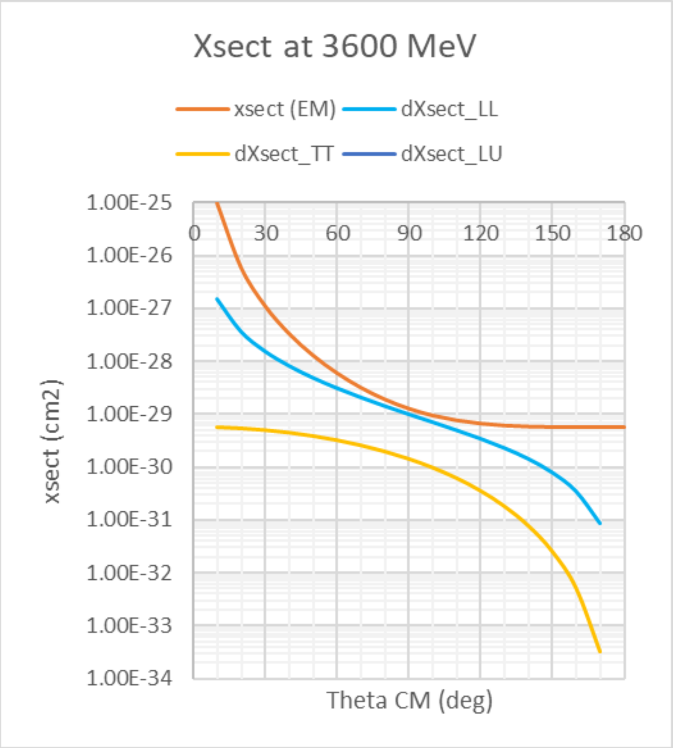

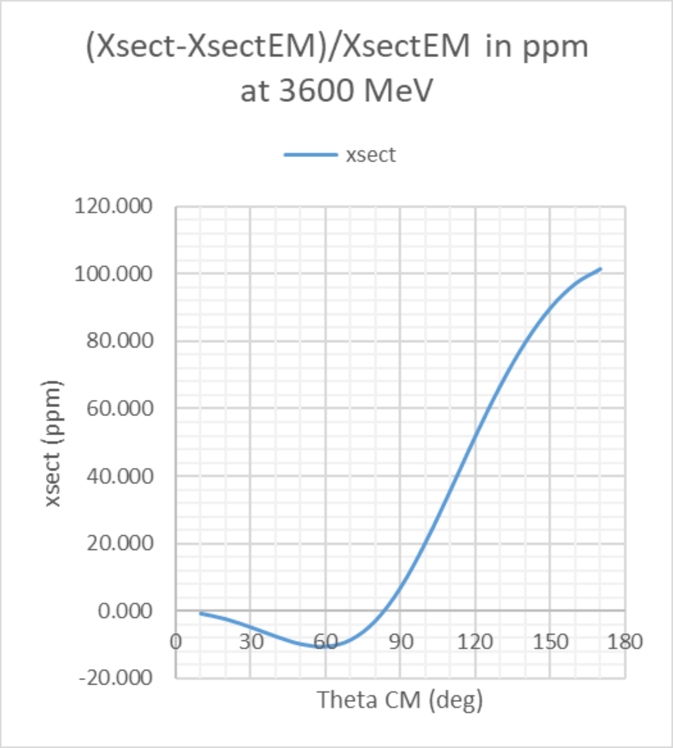

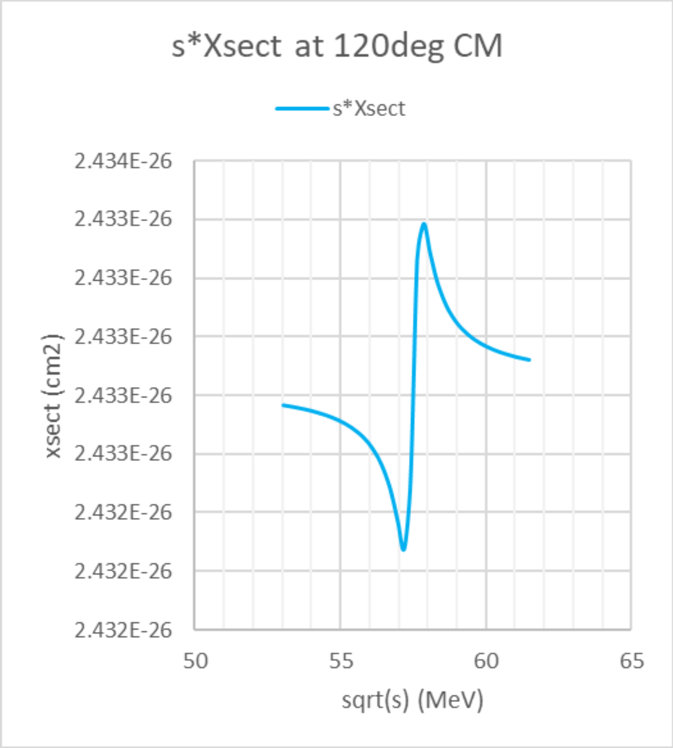

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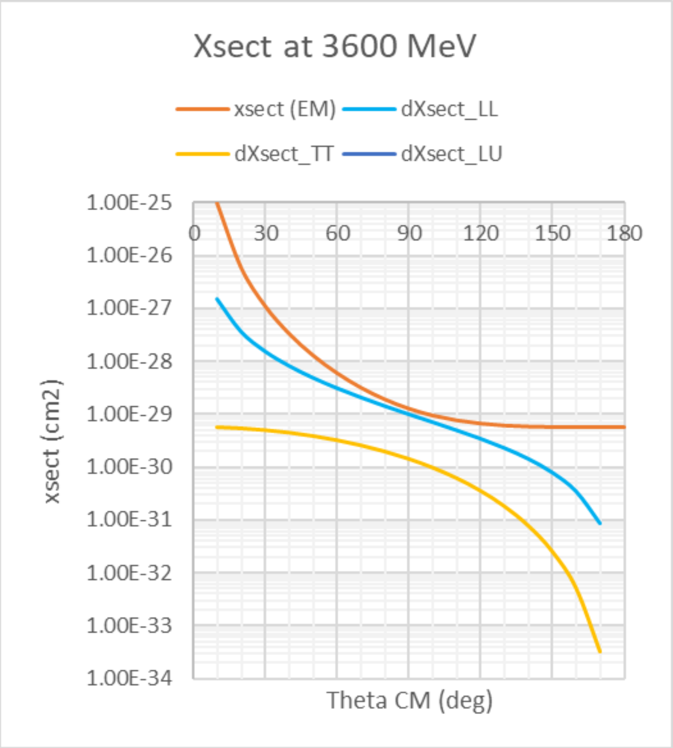
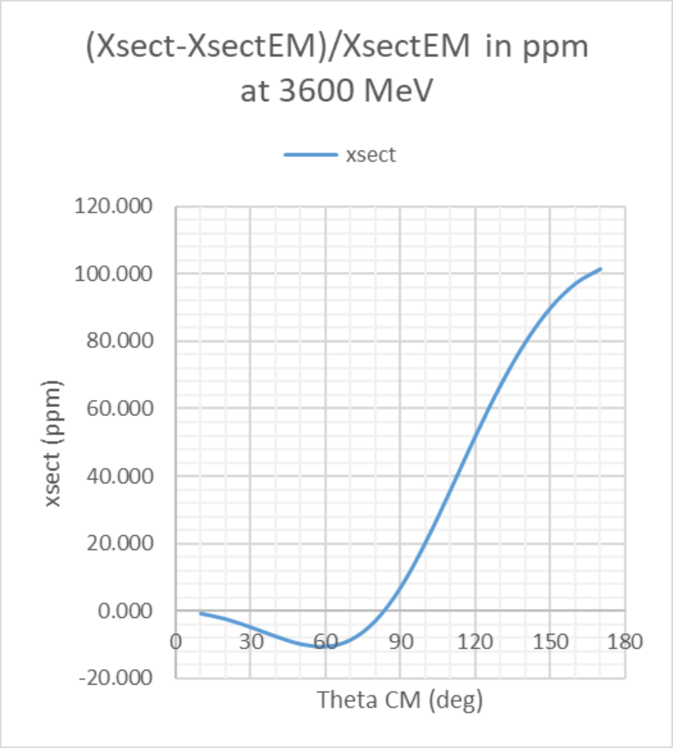
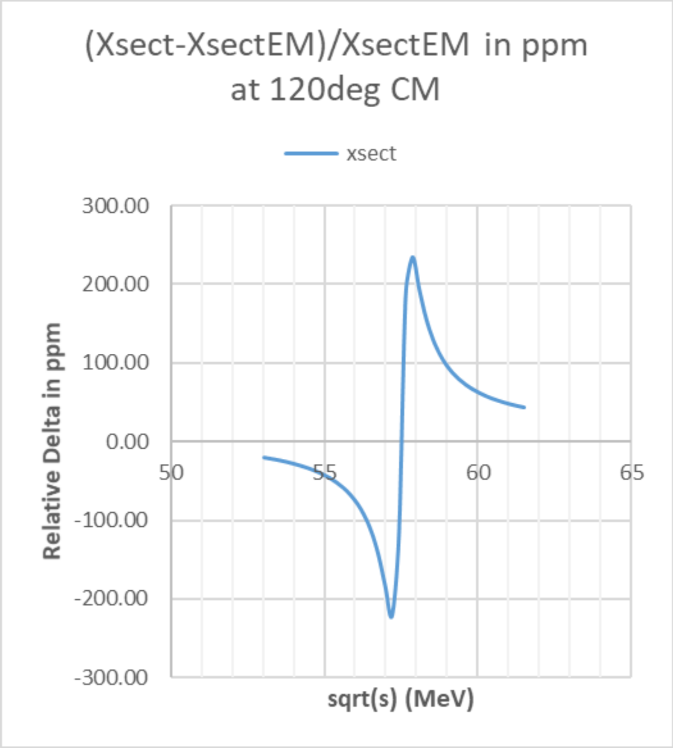
(In the SM, the deviations from PV are less than 0.1 ppm.)

There is a modulation of the xsect as the resonance is crossed. This mirrors the Real part of the A’ propagator.

Xsect Study: Purely Vector Coupling, Mixing = 1E-5, Mass = 57.5 MeV/c2





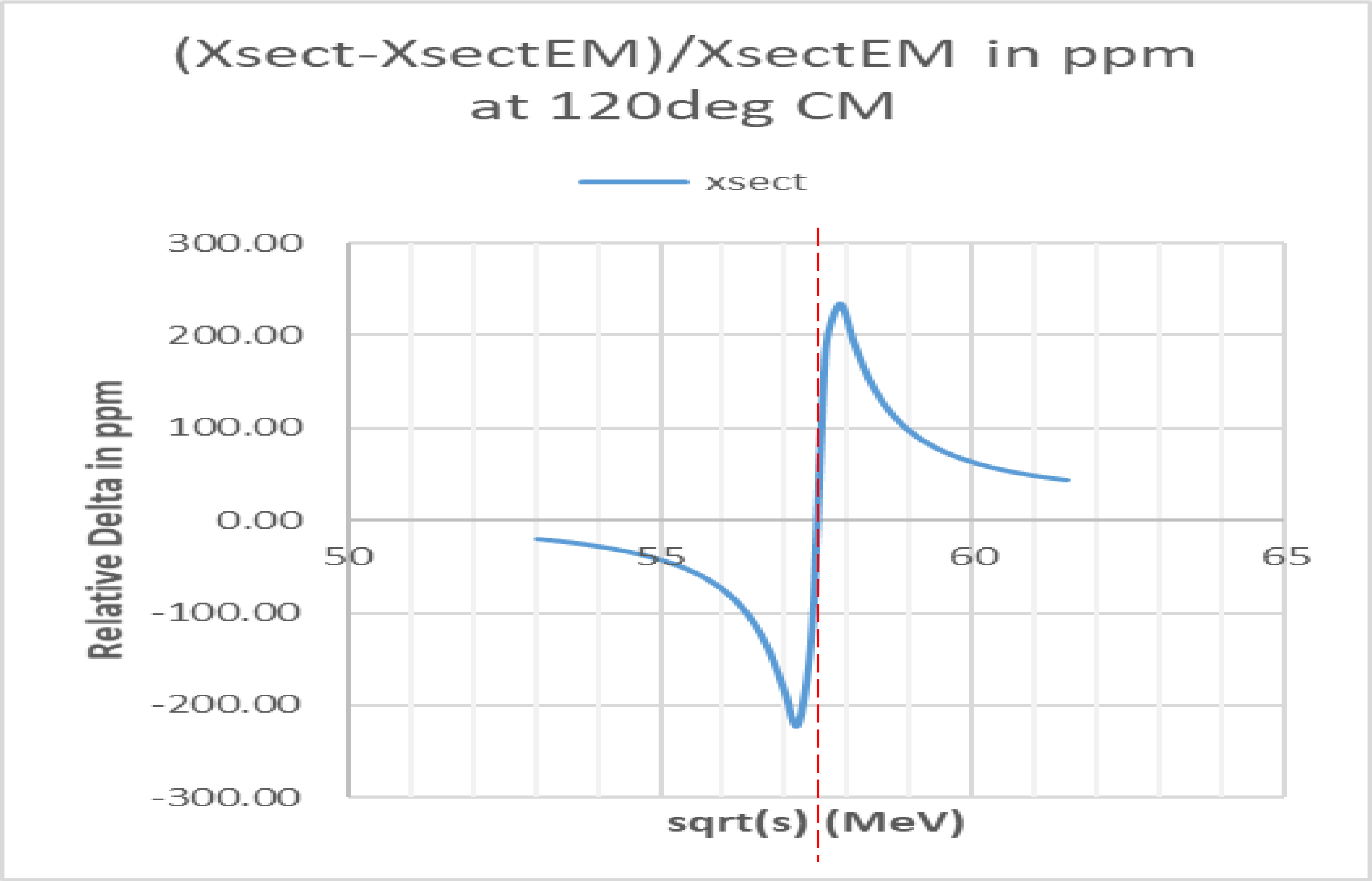


As naively expected, the A' effects are largest at backward angles.

(In the SM, the deviations from PV are less than 0.1 ppm.)

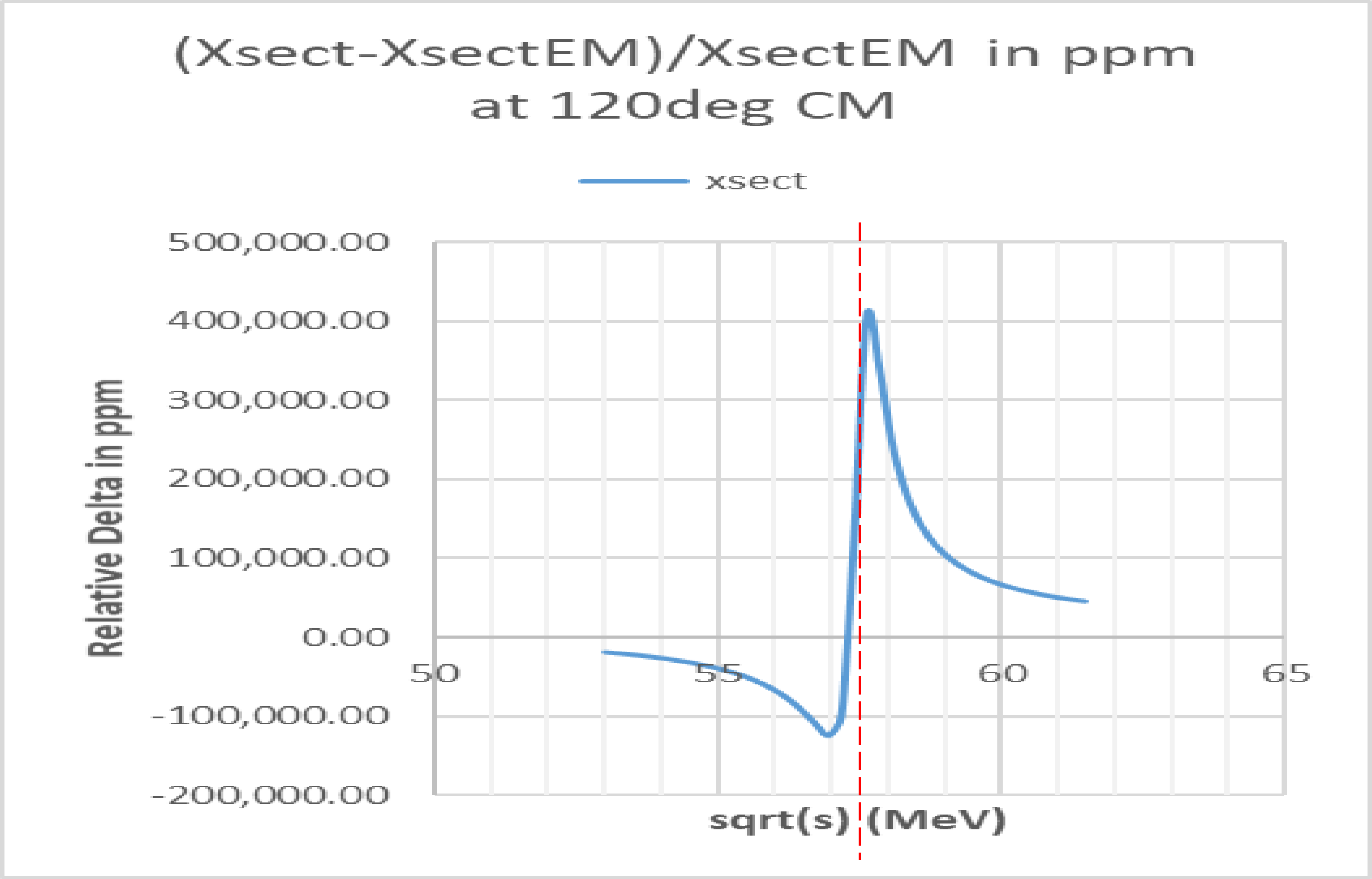
Slightly different plot to show the magnitude in ppm.

Zoomed (A' mass = 57.5 MeV/c2, mixing = 1E-5)



A 100 MeV change in beam energy will change sqrt(s) by only ~1 MeV/c2.
This means it's not as hard as one might think to resolve these MeV-scale features.
But it makes it hard to search the entire mass range from 20 to 100 MeV/c2.

Zoomed (A’ mass = 57.5 MeV/c2, mixing = 0.01)



Idiot check: if I increase the mixing to order 0.01, we start to see a peak close to the resonance instead of just a zero crossing. In other words, for large couplings, the A’ appears as a “bump” as naively expected (this slide), but for small couplings one mainly just sees the bi-polar interference pattern (last slide).

The Olsen and Osland Formalism is Axial-ready

There is some literature on dark photons which have significant axial couplings.*

It's easy to explore that in this formalism.

*i.e., beyond that due to inevitable mixing with the Z0.

Prepared for submission to JHEP
FERMILAB-PUB-16-385-PPD, UCI-HEP-TR-2016-15, MITP/16-098, PUPT 2507

arXiv:1609.09072v2 [hep-ph] 21 Oct 2016

Light Weakly Coupled Axial Forces: Models, Constraints, and Projections

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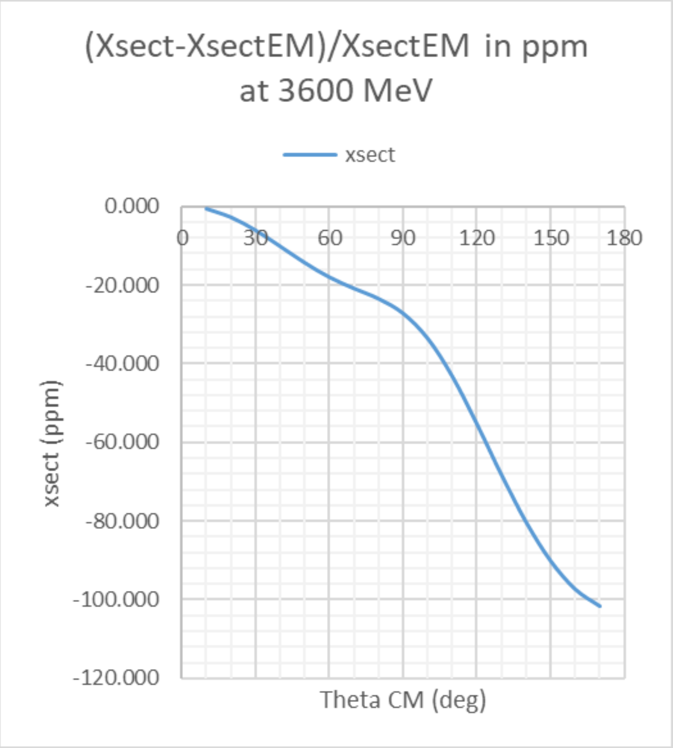
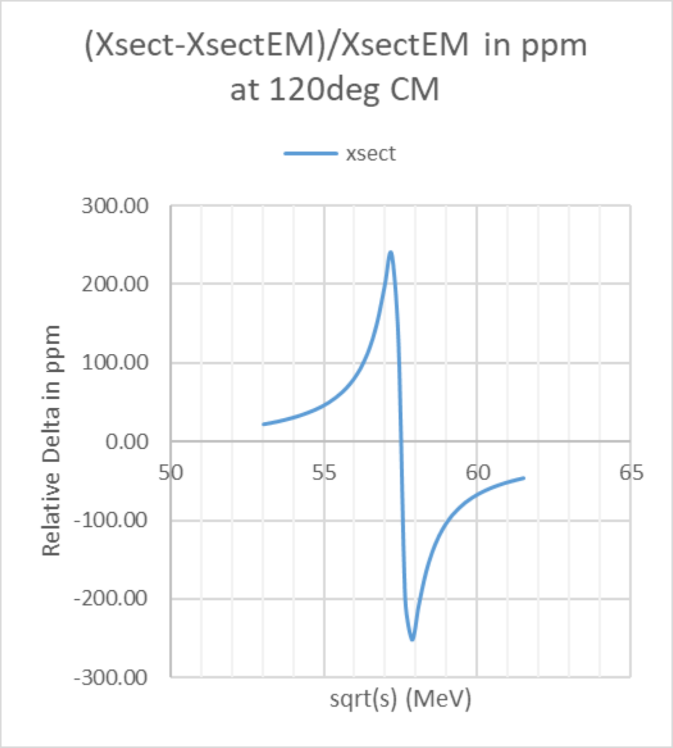
Abstract: We investigate the landscape of constraints on MeV-GeV scale, hidden $U(1)$ forces with nonzero axial-vector couplings to Standard Model fermions. While the purely vector-coupled dark photon, which may arise from kinetic mixing, is a well-motivated scenario, several MeV-scale anomalies motivate a theory with axial couplings which can be UV-completed consistent with Standard Model gauge invariance. Moreover, existing constraints on dark photons depend on products of various combinations of axial and vector couplings, making it difficult to isolate the effects of axial couplings for particular flavors of SM fermions. We present a representative renormalizable, UV-complete model of a dark photon with adjustable axial and vector couplings, discuss its general features, and show how some UV constraints may be relaxed in a model with nonrenormalizable Yukawa couplings at the expense of fine-tuning. We survey the existing parameter space and the projected reach of planned experiments, briefly commenting on the relevance of the allowed parameter space to low-energy anomalies in π^0 and $^8\text{Be}^*$ decay.

Xsect Study: Purely Axial Coupling, Mixing = 1E-5, Mass = 57.5 MeV/c2

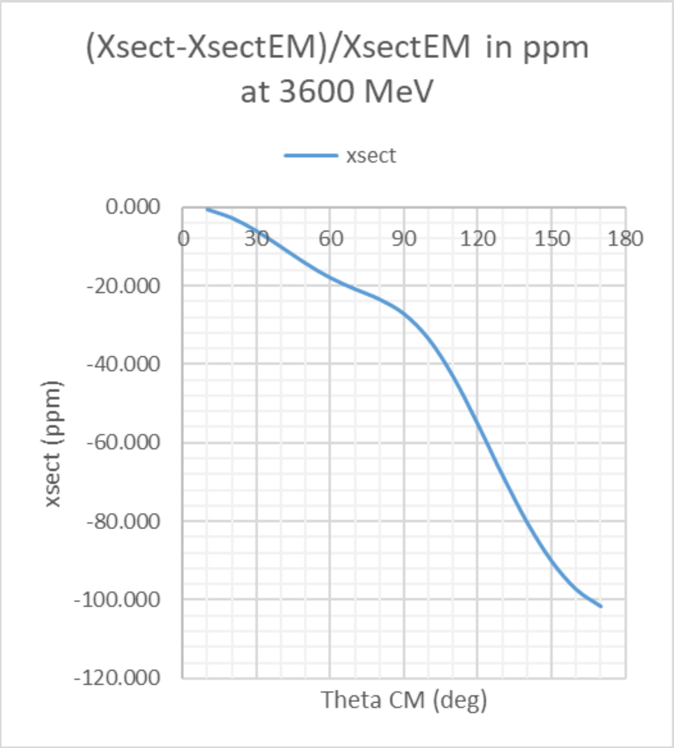


The effect with purely axial coupling is also backward peaked.



It looks like the vector plot in terms of magnitude.

Xsect Study: Purely Axial Coupling, Mixing = 1E-5, Mass = 57.5 MeV/c2



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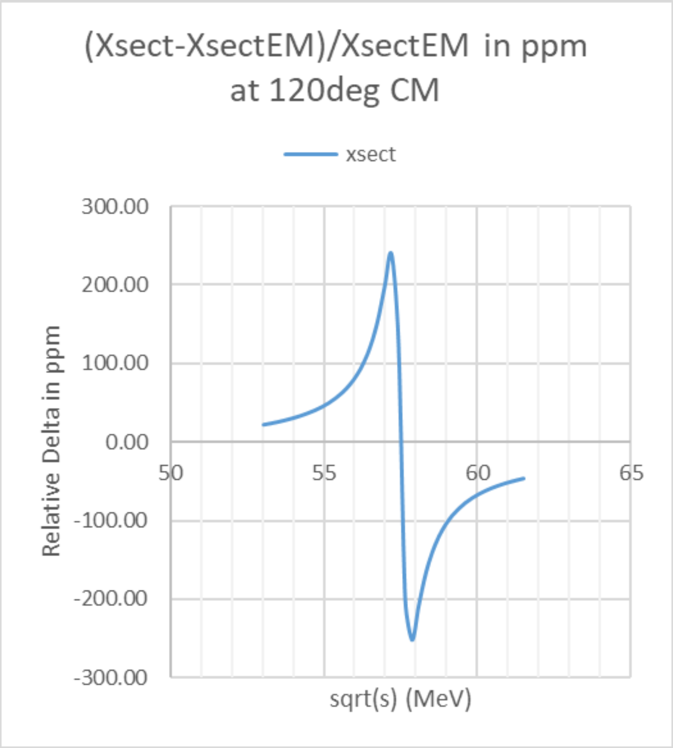


It looks like the vector plot in terms of magnitude.

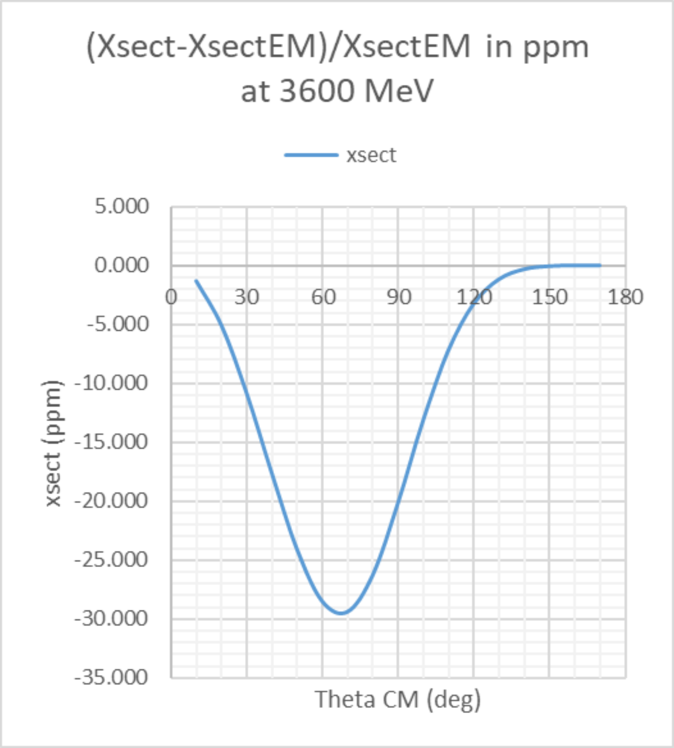
But in fact, this is the mirror image of the vector plot.

In the purely vector or purely axial scenario, terms proportional to g_v*g_a vanish, leaving a g_v^2 – g_a^2 term which switches sign.

Brief Comment on Mixed Vector+Axial Couplings

When Vector and Axial couplings interfere, the largest effects can shift forward somewhat.
In this example with g_a = 1 and g_v = 1, the largest effects occur at the non-backward angle of 70deg.

(A detector at 120deg CM would obviously have relatively little sensitivity.
This should be kept in mind when designing an experiment.)



How to Measure These Dramatic But Small Line Shapes?

1. For e+e- →e+e- with no radiation, it would take a 1 GeV beam energy change to cover 10 MeV/c2 window in A' mass. In this approximation, detection of the backward e+ alone would define the kinematics.

(Frequent energy changes are impractical at a multi-user facility.
And by the time the beam energy was changed again and again and again, the yield would have drifted.
Asymmetries are the obvious way to avoid normalization drifts, but the loss of FOM due to unpolarized e-
in the Fe foil target is ~150. Eric Voutier may be proven correct that asymmetries are the way to go. We'll see!)

2. One could use thick target bremsstrahlung to straggle the beam energy, with multiple targets as used in APEX. Then fewer beam energies would be needed. (One has to detect the e+e- pair to define the kinematics.)

(This is what I suggested in the LOI.)

3. Allowing for radiation, then ISR will also allow a wide range of A' masses to be accessed all at one time. The cost might be one order of alpha in sensitivity though. We don't need to detect the photon (it will be of order 1 deg). The mass of the A' can still be reconstructed by detecting the e+e- pair.

(This is how the e+e- colliders like Babar and Belle do resonant BSM searches.)

Some combination of doors #2 and #3?

Summary

Can One Make an Amplitude-level Search for a Dark Photon in Bhabha Scattering?

I don't know yet. The Theory Advisory Committee comments did not address whether the gamma and A' can interfere this way. (In their defence, the PAC and advisory committees had a very heavy load this year, and LOIs are naturally lowest priority.)

I will send the usual radiative corrections experts these slides for comment. (Wally M, Andrei A, …. Any other suggestions?)

If the physics case is compelling, then an appropriate pair spectrometer can be designed.

extras

What’s Next?

Near term:

i. I will send Wally M and Andrei A these slides for comment as to whether I am abusing the Olsen and Osland formalism.

ii. Finish putting Imaginary contributions into the asymmetries A_LL, etc.

Longer term:

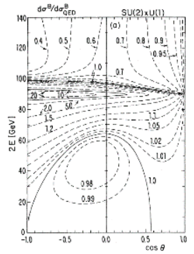
i. Switch to a different formalism which includes radiation

ISR will allow A’ production off the naïve resonance via radiative return.

(FSR will just make a mess of the final e+e- kinematics, but it’s unavoidable and all radiation needs to be included in any realistic experiment design anyway.)

ii. Make 2D plots like those in Olsen and Osland for all observables:

Do this for Vector, Axial, and representative Mixed scenarios.



iii. Talk to theory colleagues about a formalism for Bhabha scattering appropriate for Jlab

In Jlab kinematics, one cannot assume the mass of the electron is zero. One impact of this is that the beam normal Single Spin Asymmetry (which I’ll call A_TU) does not vanish. It has probably been calculated, but I haven’t found a reference yet. For Jlab beam energies, it could be of order alpha*m_e/sqrt(s) → 10 to 100 ppm .

I would like to understand the impact of an A’ on A_TU. This is a parity-conserving asymmetry (so not insanely small) with access to the Imaginary part of the amplitude.

$$\frac{d\sigma_0^B}{d\Omega}=\frac{\alpha^2}{4s}\left\{\cos^4(\theta/2)\left[\left|1+f(s)g_L{}^2-\frac{1+f(t)g_L{}^2}{\sin^2(\theta/2)}\right|^2+\left|1+f(s)g_R{}^2-\frac{1+f(t)g_R{}^2}{\sin^2(\theta/2)}\right|^2\right]\right.$$
$$\left.+2\sin^4(\theta/2)\,|1+f(s)g_Rg_L|^2+[2/\sin^4(\theta/2)][1+f(t)g_Rg_L]^2\right\}, \tag{14}$$

A_LL (PC)→

$$A_1^B=\left\{-\cos^4(\theta/2)\left[\left|1+f(s)g_L{}^2-\frac{1+f(t)g_L{}^2}{\sin^2(\theta/2)}\right|^2+\left|1+f(s)g_R{}^2-\frac{1+f(t)g_R{}^2}{\sin^2(\theta/2)}\right|^2\right]\right.$$
$$\left.-2\sin^4(\theta/2)\,|1+f(s)g_Rg_L|^2+[2/\sin^4(\theta/2)][1+f(t)g_Rg_L]^2\right\}\Big/\left[\frac{4s}{\alpha^2}\frac{d\sigma_0^B}{d\Omega}\right], \tag{15}$$

A_LU (PV) →

$$A_2^B=\cos^4(\theta/2)(g_R{}^2-g_L{}^2)$$
$$\times\mathrm{Re}\left\{\left[f(s)-\frac{f(t)}{\sin^2(\theta/2)}\right]\left[2+f^*(s)(g_R{}^2+g_L{}^2)-\frac{2+f(t)(g_R{}^2+g_L{}^2)}{\sin^2(\theta/2)}\right]\right\}\Big/\left[\frac{4s}{\alpha^2}\frac{d\sigma_0^B}{d\Omega}\right], \tag{16}$$

A_TT (PC) →

$$A_3^B=2\sin^2(\theta/2)\cos^2(\theta/2)$$
$$\times\mathrm{Re}\left\{[1+f(s)g_Rg_L]\left[2+f^*(s)(g_R{}^2+g_L{}^2)-\frac{2+f(t)(g_R{}^2+g_L{}^2)}{\sin^2(\theta/2)}\right]\right\}\Big/\left[\frac{4s}{\alpha^2}\frac{d\sigma_0^B}{d\Omega}\right], \tag{17}$$

A'_TT (PV) →

$$A_4^B=-2\sin^2(\theta/2)\cos^2(\theta/2)(g_R{}^2-g_L{}^2)\,\mathrm{Im}f(s)\left[1+\frac{f(t)g_Rg_L}{\sin^2(\theta/2)}\right]\Big/\left[\frac{4s}{\alpha^2}\frac{d\sigma_0^B}{d\Omega}\right]. \tag{18}$$

Dilution in A_LL and A_TT experiments

Dave Gaskell says the electron’s in the Fe foil target are ~8% polarized.