Amplitude-level Searches for Dark Photons in Bhabha Scattering

D. Mack

Hall C Winter Meeting

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Motivation

The positron program is our foot in the door to a 20 GeV program. The foot may be there for a while ….

For the continued existence of a fixed target program at Jlab, it would be nice to have at least half a decade of highly rated positron experiments on the books.

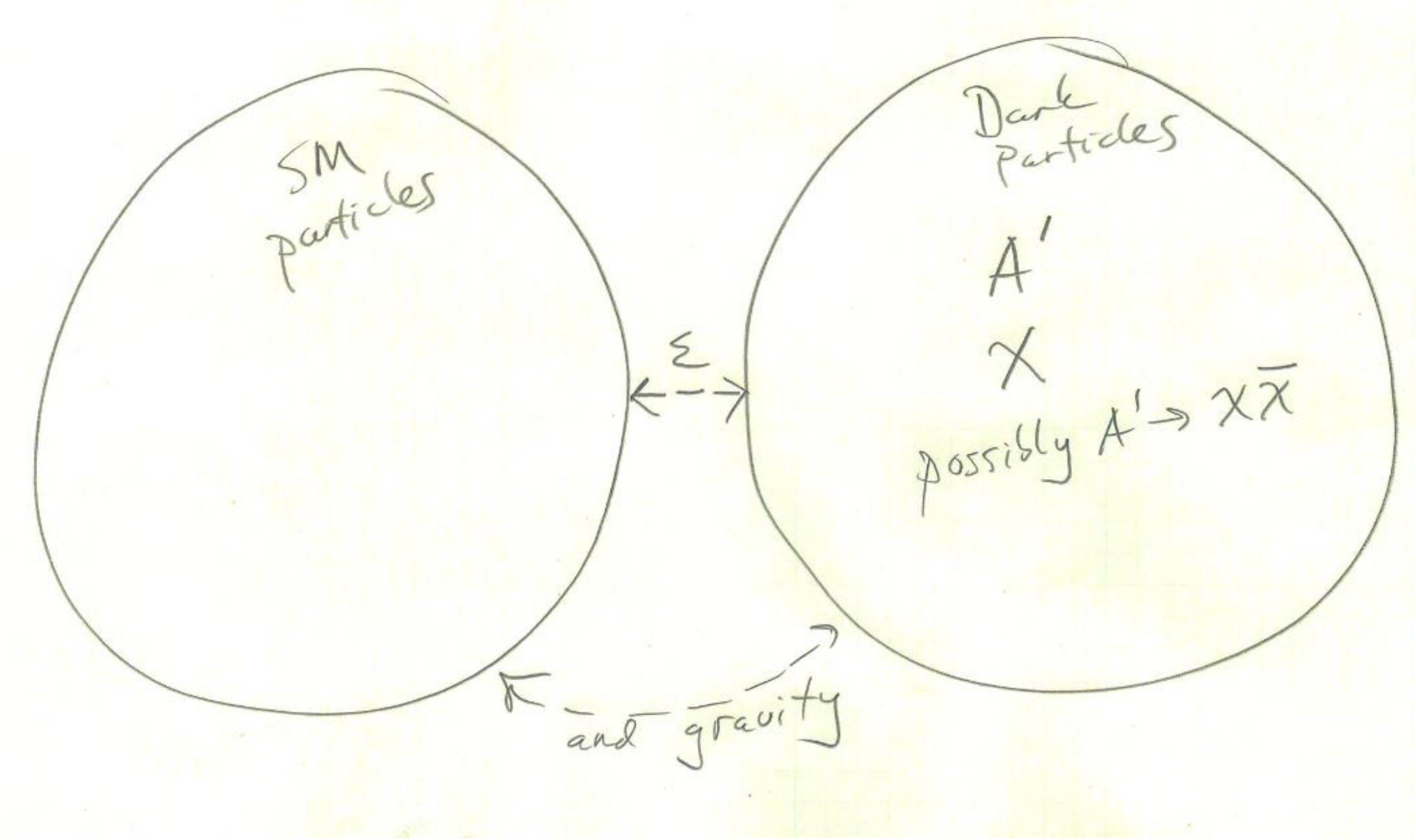
DVCS can anchor a 2 year positron beam program.

In addition to studies of hadronic effects in two-photon exchange, let us not forget that e+ beams open up the possibility of doing $e^+e^- \rightarrow e^+e^-$ (called Bhabha scattering), as well as explicit annihilation channels $e^+e^- \rightarrow 2\gamma, 3\gamma$.

In this talk, I will report my ongoing studies of the potential of Bhabha scattering for BSM studies.

The Standard Model and Beyond

One class of SM extensions assumes a small mixing between the photon and a dark photon, A'.



Excluded A' Phase Space (visible decays)

The mixing between the photon and dark photon is parameterized as ε.

The coupling of the dark photon to the electron is ε*e where e ~ sqrt(α).

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

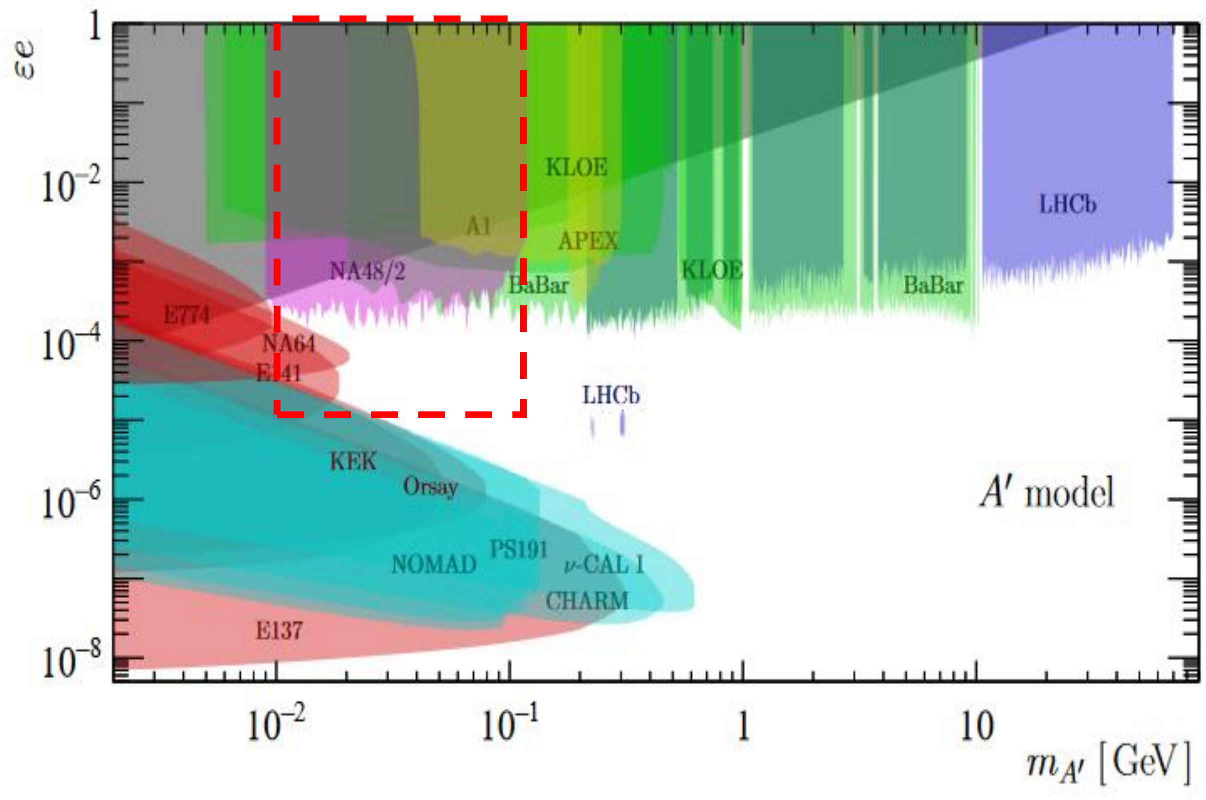


Figure 4. Constraints on visible A' decays considered in this study from (red) electron beam dumps, (cyan) proton beam dumps, (green) e^+e^- colliders, (blue) pp collisions, (magenta) meson decays, and (yellow) electron on fixed target experiments. The constraint derived from $(g-2)_e$ is shown in grey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

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

Why "Visible" vs "Invisible" Decays are a Thing

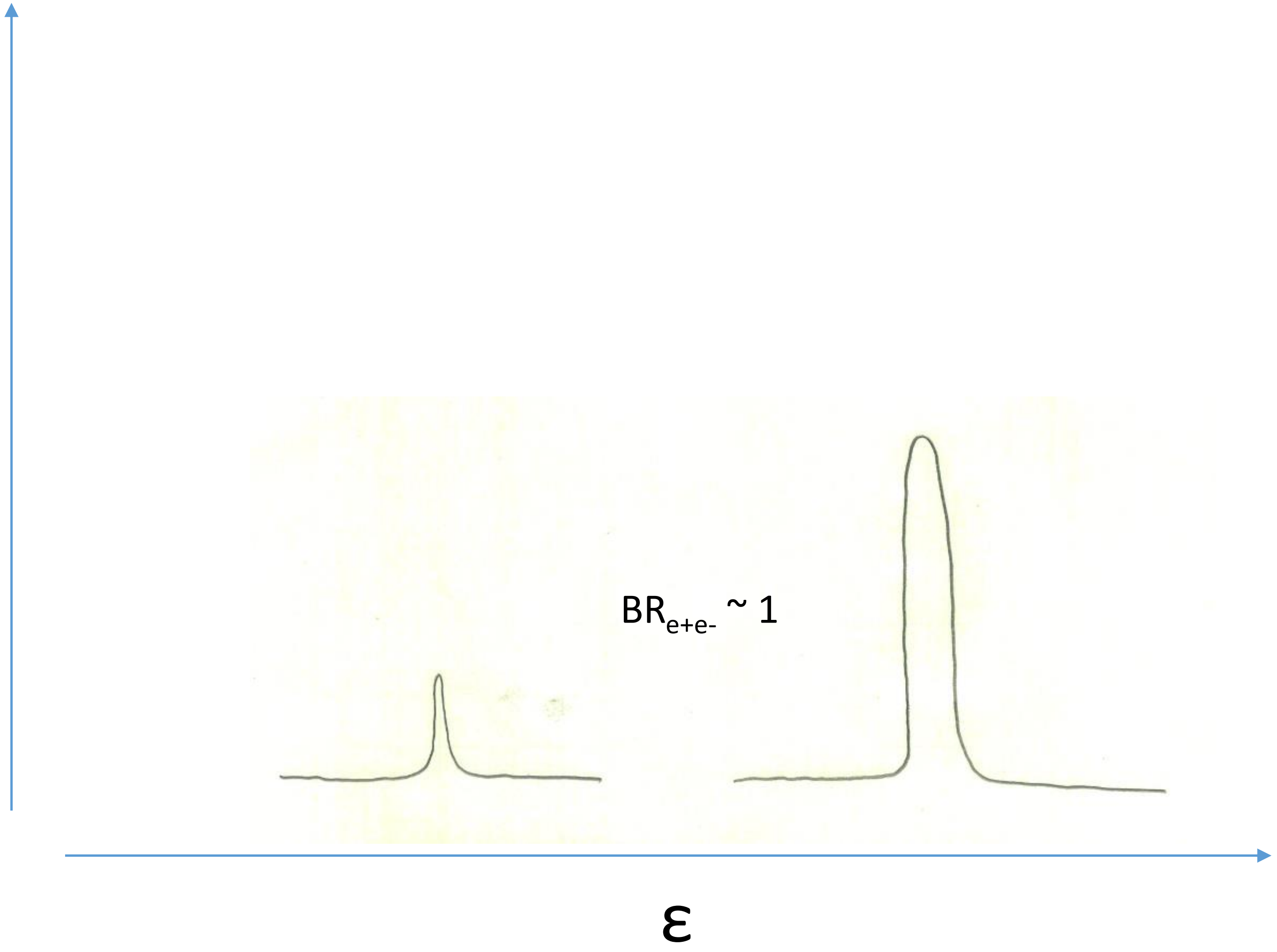
$M_{A'} \rightarrow \chi + \chi$bar (mostly)

$M_{A'} > M_{\chi}/2$

Unknown Dark Sector Mass Hierarchy

$M_{A'} \rightarrow e^+e^-$ (mostly)

$(M_{A'} < M_{\chi}/2)$



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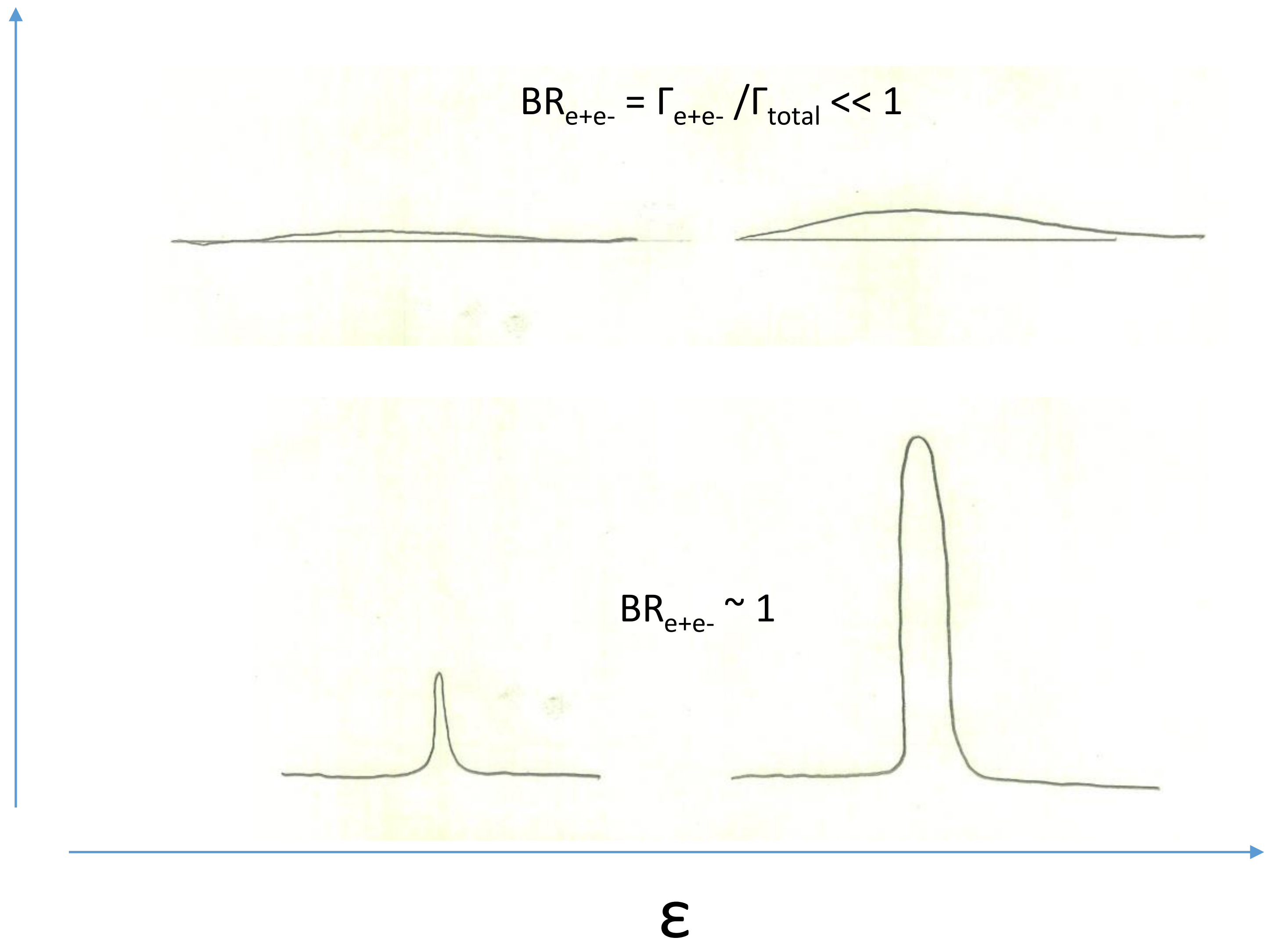

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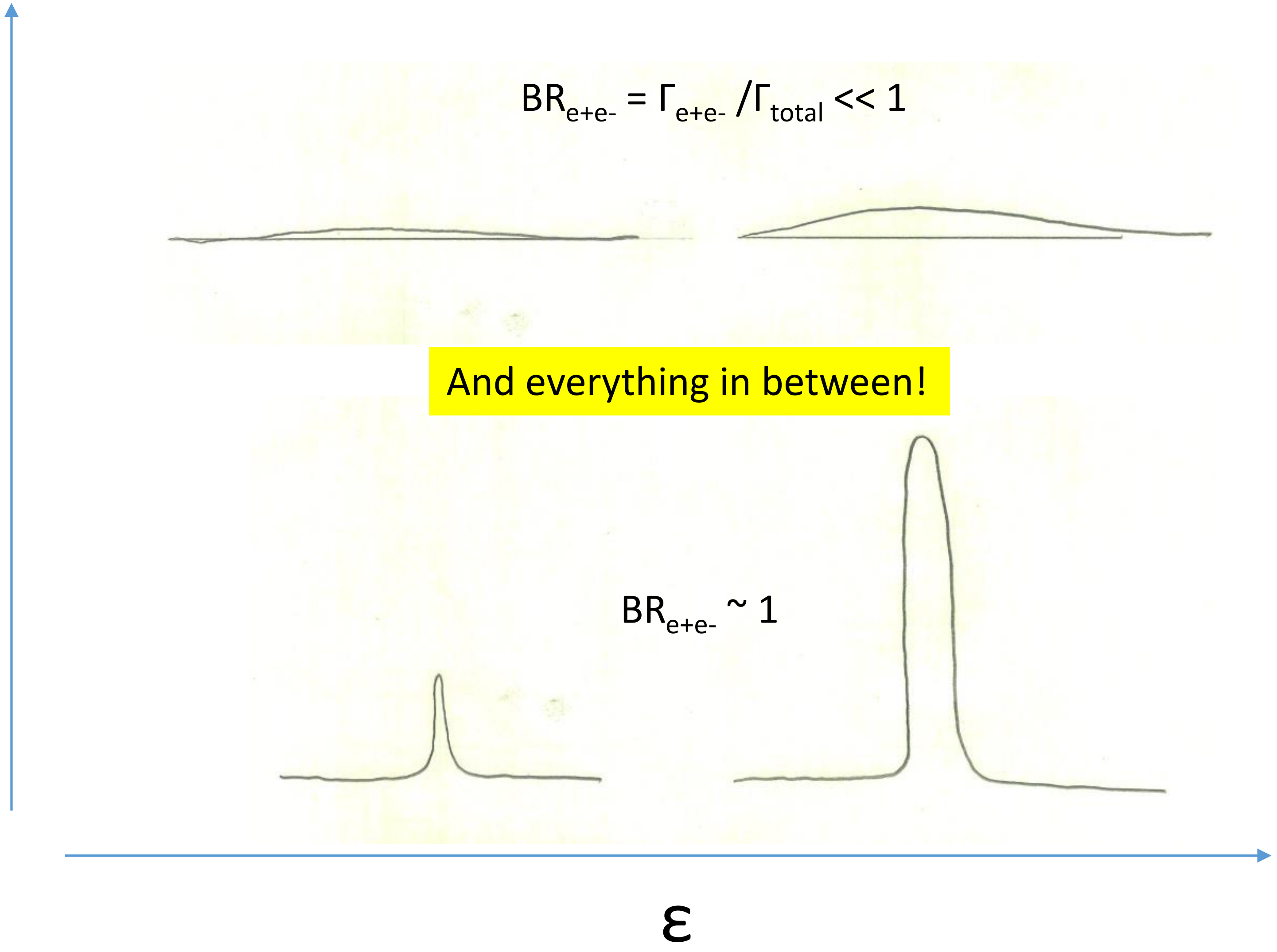


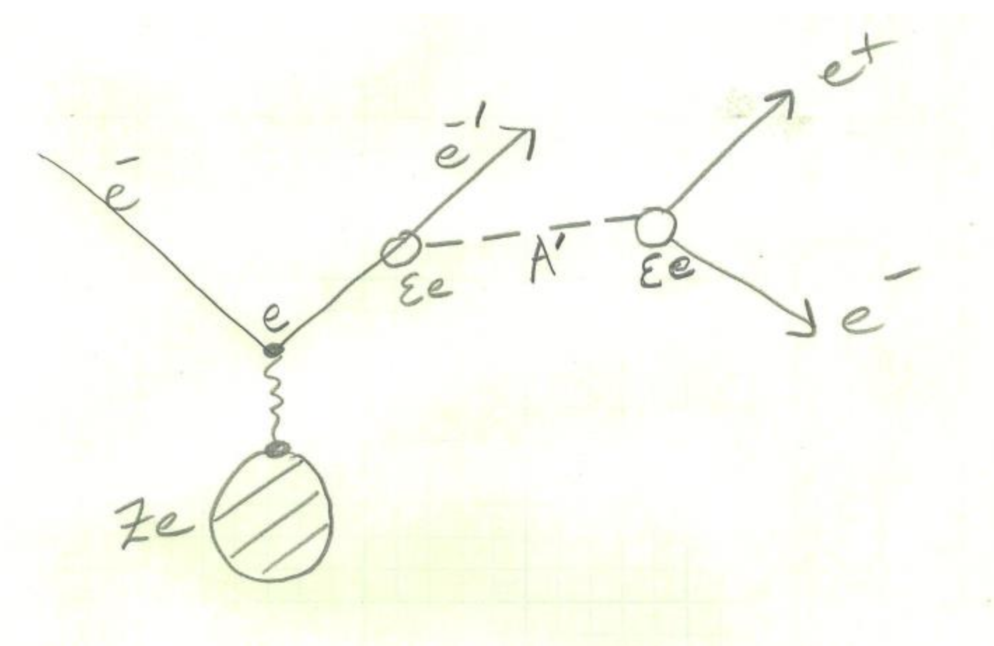
Ambiguities in Hunting for an A'

- We don't know the mass.
- We don't know the width. (E.g., we don't know the dominant decay mode. I.e., A' $\rightarrow$ e+e- or χχbar)
- We don't know the coupling.

So to design an experiment which will still be a high priority 10+ years from now, we would like to:

  - search a broad mass range,
  - as sensitively as feasible,
  - in a manner which is relatively insensitive to the A' decay mode

Example A’ Signal Proportionality in terms of e and ε



For incoherent production and decay:

Yield for production ~ $|Z\,F(q)\,e^3\,\varepsilon\,|^2$

Yield for A’ decay ~ $BR_{A' \rightarrow e+e-}\,|e\varepsilon|^2$

Visible decay scenario: net signal yield for detecting A’ → e+e-

$$\sim Z^2\,F^2(q)\,\alpha^4\varepsilon^4$$

All decays scenario: signal yield for detecting a narrow A’ by MM_x^2 in e + p → e + p (X)

$$\sim Z^2\,F^2(q)\,\alpha^3\,\varepsilon^2$$

Because ε is a small number, one would like to design an experiment with a small exponent and low backgrounds.

Incomplete Table of Sensitivities of Experiments

General Technique	Technique	Signal Proportional To:	Constrains	Comment
Dark Bremsstrahlung with e^- beams	$M(e^+e^-)$ peak in e- + A → e' + e+e- (X)	$Z^2F(q)^2\ \alpha^4\varepsilon^4$	Visible decays only	E.g., Hall A APEX and MAMI-A1 experiments. Especially sensitive when searching for a detached vertex (hence minimal bkg) as in Hall B HPS
	MM_x^2 peak in e- + p → e' + p' (X)	$F(q)^2\ \alpha^3\varepsilon^2$	All decays*	The DarkLight proposal planned to measure the fore-mentioned reaction as well as e- + p → e' + p' +e+e- .
	Missing energy in e- + calorimeter → almost nothing	$Z^2F(q)^2\ \alpha^3\varepsilon^2$	Invisible decays only	NA64 placed impressive constraints on invisible decays that would be extremely hard to beat.
Positron Beams	MM_x^2 peak in e^+e^- → γ (X) A' undetected	$\alpha^2\varepsilon^2$	All decays*	Bogdan/Ashot proposal

*Any sort of peak search constraining invisible decays is potentially weakened if the A' width is broader than the resolution.

The Strategy

Assume the total amplitude is the sum of a large SM and small BSM amplitude: $A_{tot} = A_{EM} + A_{small}$

The Yield is proportional to $A_{tot}^2 = (A_{EM} + A_{small})^2$

Instead of looking for a dark photon as a cross section bump with relative magnitude A^2_{small}/A^2_{EM}, can we search sensitively for resonance signatures in the amplitude proportional to A_{small}/A_{EM} ?*

The answer will be, “Yes”.

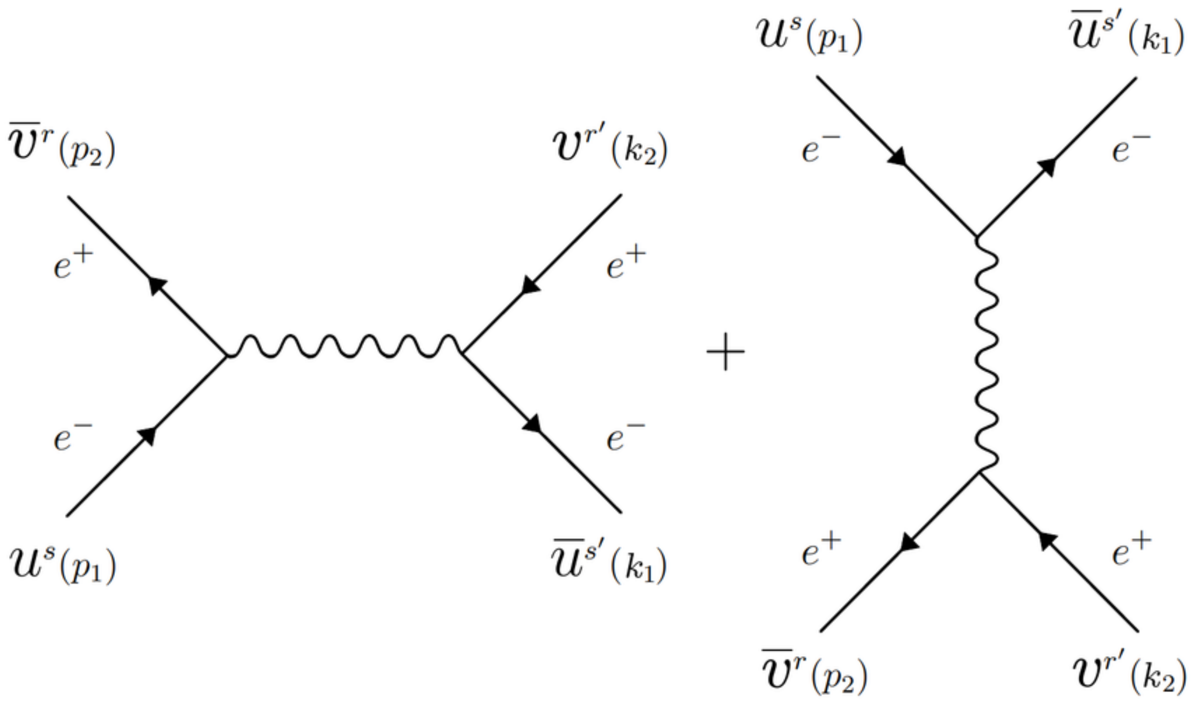
Bhabha Scattering: $e^+e^- \rightarrow e^+e^-$

Bhabha scattering is a purely leptonic reaction with very different behavior than Moller scattering.

The e+ and e- are of course not identical, and there is a fascinating s-channel annihilation diagram.

In the SM, the exchanged boson is a γ and a Z0.

In BSM, it is a γ, Z0, and A’ (or Z’)



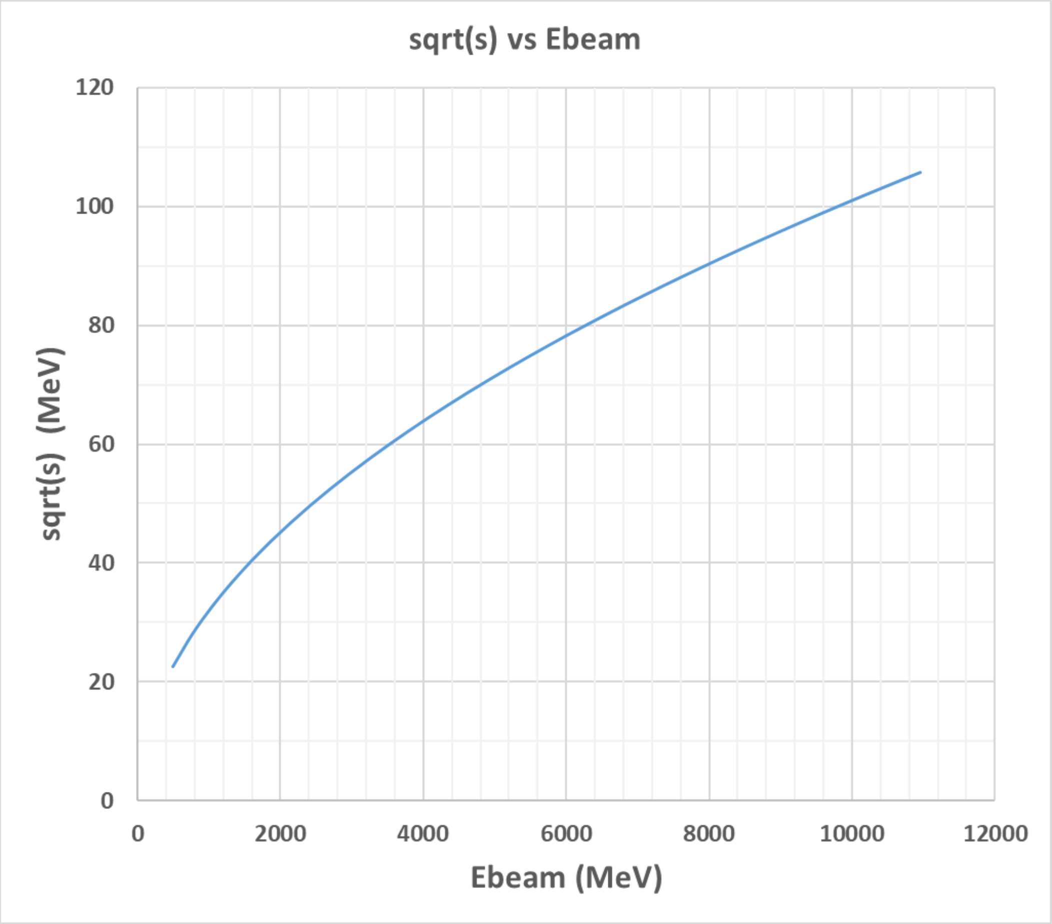
Research Gate uploaded by Kort Beck

Bhabha Scattering: $e^+e^- \rightarrow e^+e^-$

At a 12 GeV CEBAF, the CM energy range will be 20-105 MeV/c2.

Due to the s-channel annihilation diagram, one can expect dramatic changes in observables if a resonance occurs in or near this E_{cm} range.

$$s = 2m_e^2 + 2E_{beam}*m \sim E_{beam}$$



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Positron Beams	MM_x^2 peak in $e^+e^- \to \gamma$ (X) A' undetected	$\alpha^2\varepsilon^2$	All decays	Bogdan/Ashot proposal
	Asymmetry in $e^+e^- \to e^+e^-$	$\alpha\varepsilon^2$	All decays	Bhabha scattering
	Asymmetry in $e^+e^- \to \gamma\ e^+e^-$	$\alpha^{1.5}\varepsilon^2$	All decays	Bhabha scattering with Initial State Radiation.

An amplitude search in Bhabha scattering has interesting sensitivity.

SM Formalism with γ + Z0 (with option for a Z’)

PHYSICAL REVIEW D VOLUME 25, NUMBER 11 1 JUNE 1982

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

Haakon A. Olsen
Institute of Physics, University of Trondheim, Norges Laererhøgskole, N-7000 Trondheim, Norway

Per Osland
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02138
(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, “Polarized Bhabha and Moller scattering in left-right-asymmetric theories”. This paper was clear, provided the xsect and two PC and two PV asymmetries, and insightful comparisons to Moller scattering.

But it does not include radiation which will be important for designing realistic experiments.

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:

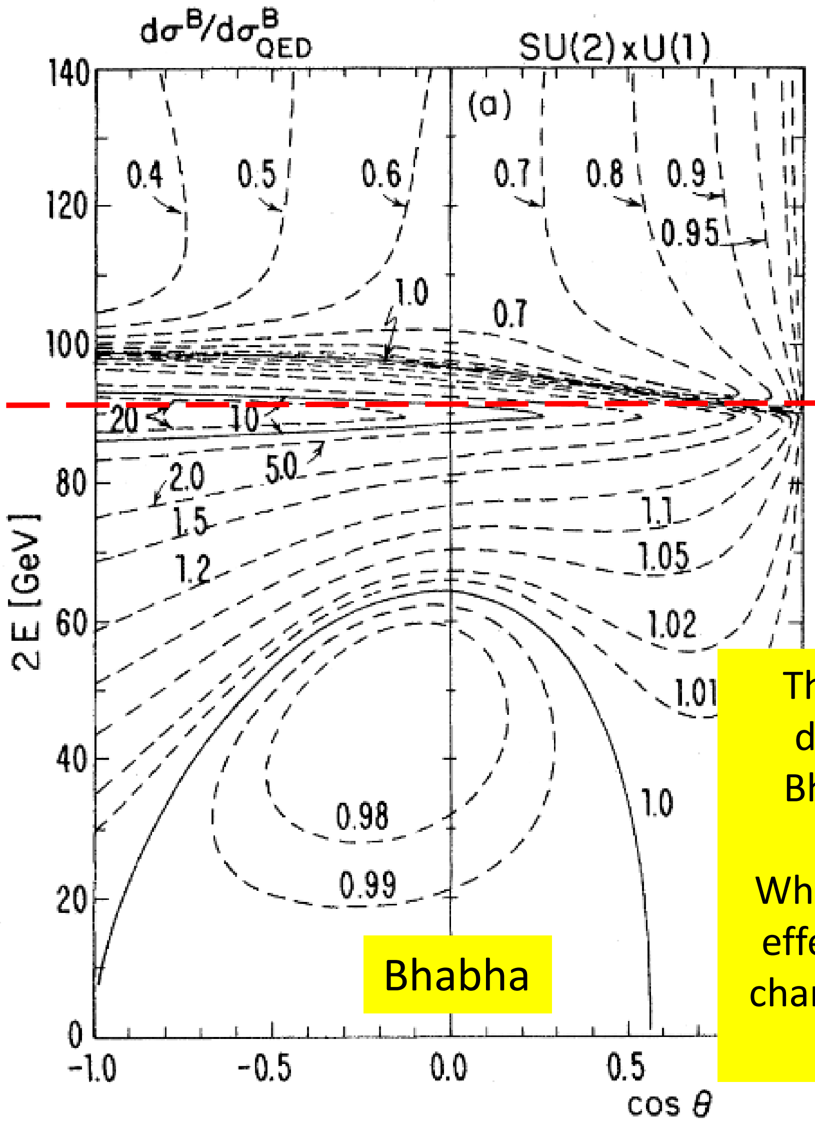
$$\sigma(\theta,\phi) = \sigma_0 \{ 1 + \mathbf{A_{LL}} P_-^{\,para} P_+^{\,para} + \mathbf{A_{LU}} (P_-^{\,para} - P_+^{\,para}) + P_-^{\,perp} P_+^{\,perp} [\, \mathbf{A_{TT}} \cos(2\phi) + \mathbf{A_{TT}}' \sin(2\phi) \,] \}$$

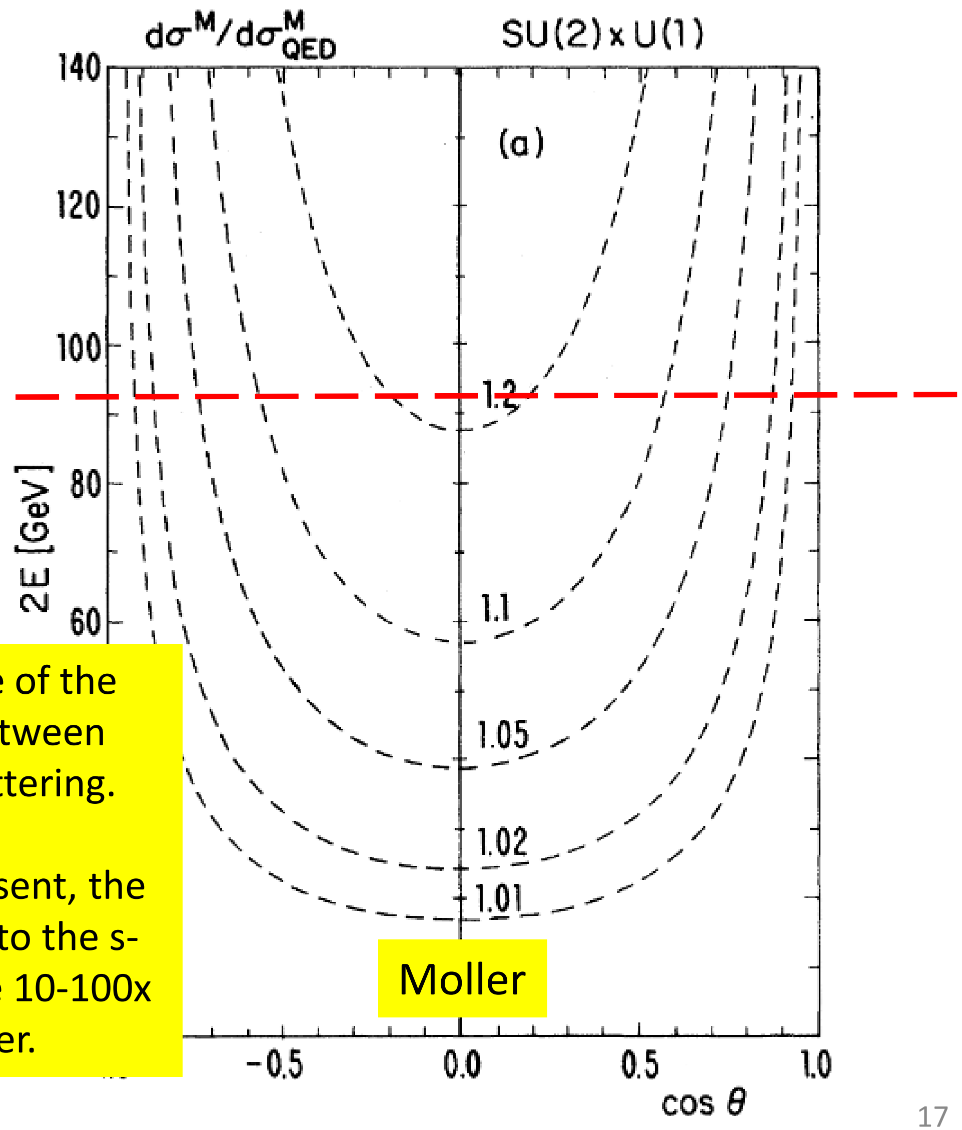
If I drop the predominantly PV terms, it looks just like the Moller polarimetry equations:

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

Let's look at the σ_0 term first.

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

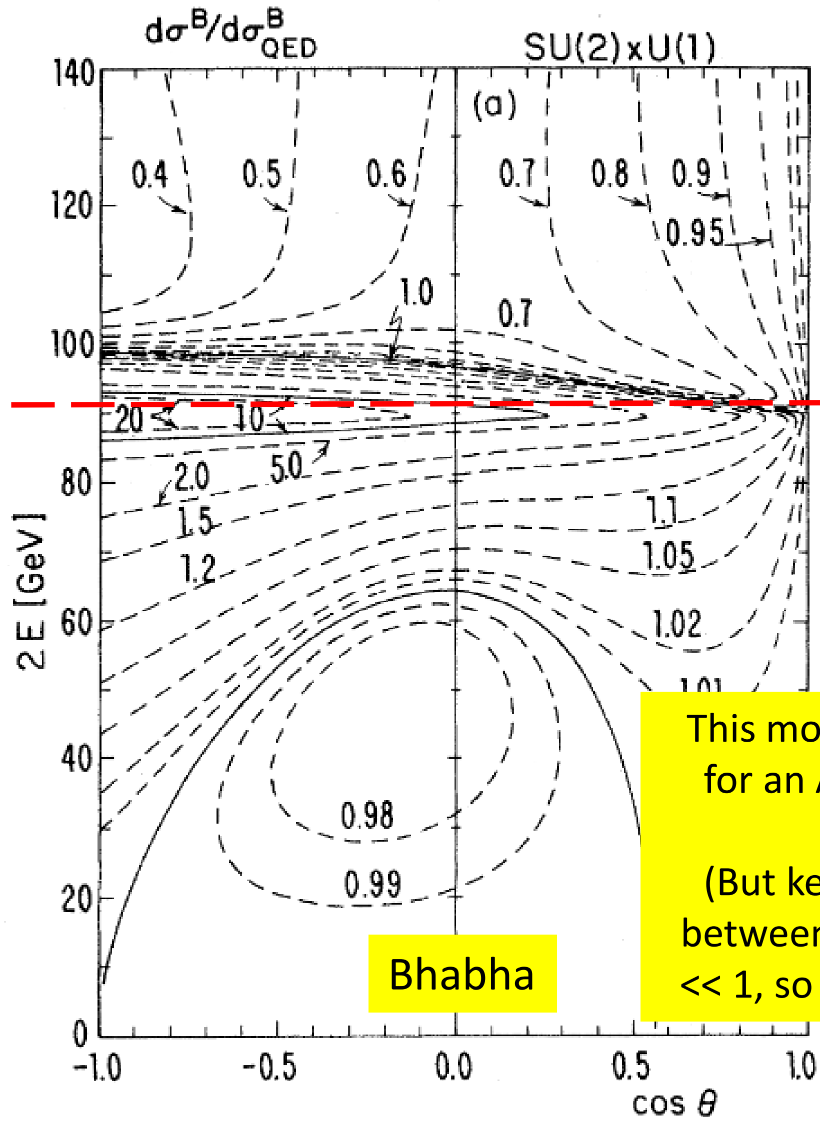




This is just one example of the dramatic difference between Bhabha and Moller scattering.

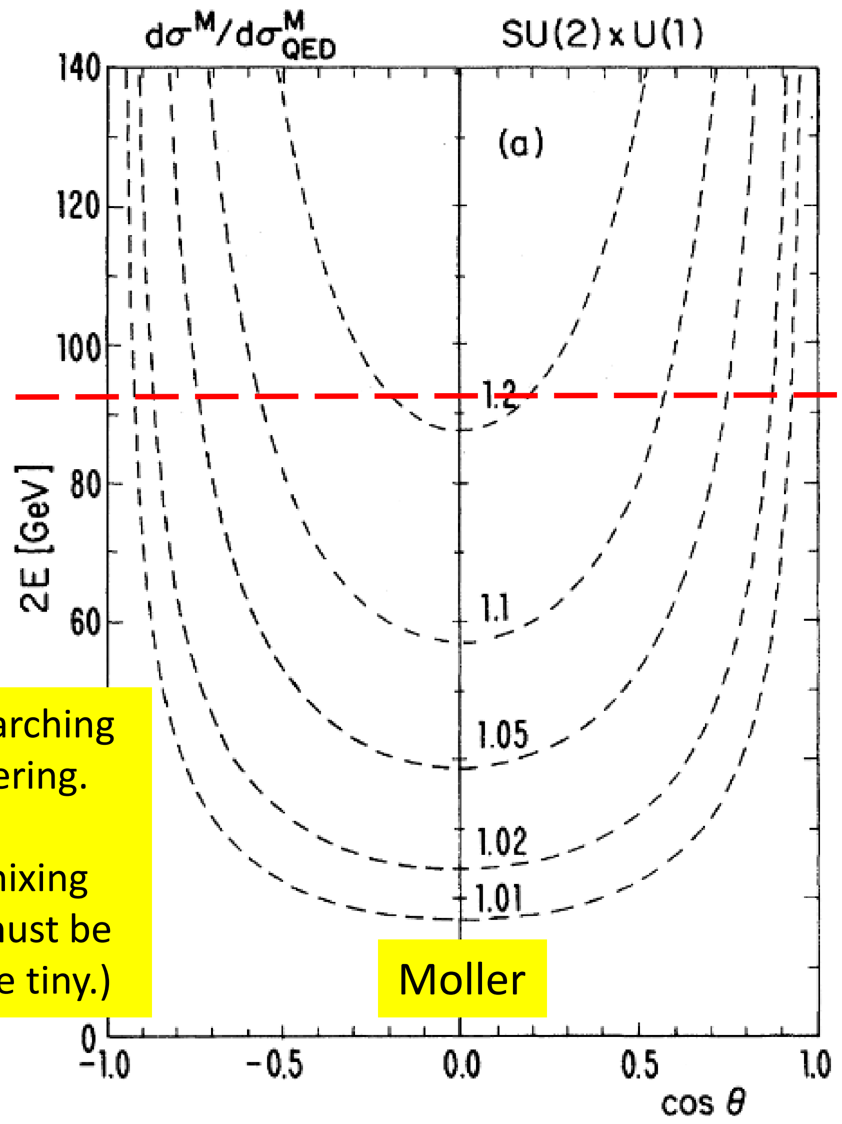
When a resonance is present, the effects on the xsect due to the s-channel in Bhabha can be 10-100x larger than in Moller.

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



This motivates the idea of searching for an A’ using Bhabha scattering.

(But keep in mind that the mixing between the photon and A’ must be << 1, so an A’ signal will still be tiny.)



Contributions to the Bhabha Xsect: t channel

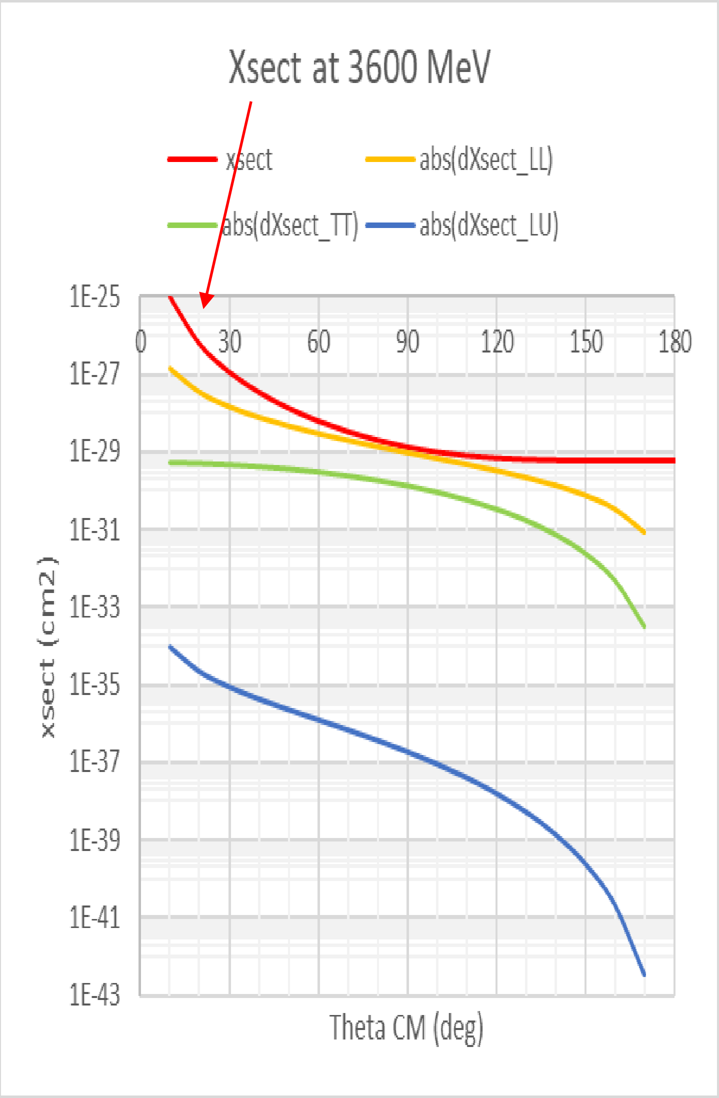
The unpolarized xsect is proportional to α^2:

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

(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 diverge as theta → 0 deg, which will dilute any interesting A' effects in the s-channel.

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



Contributions to the Bhabha Xsect: s channel

The unpolarized xsect is proportional to α^2 :

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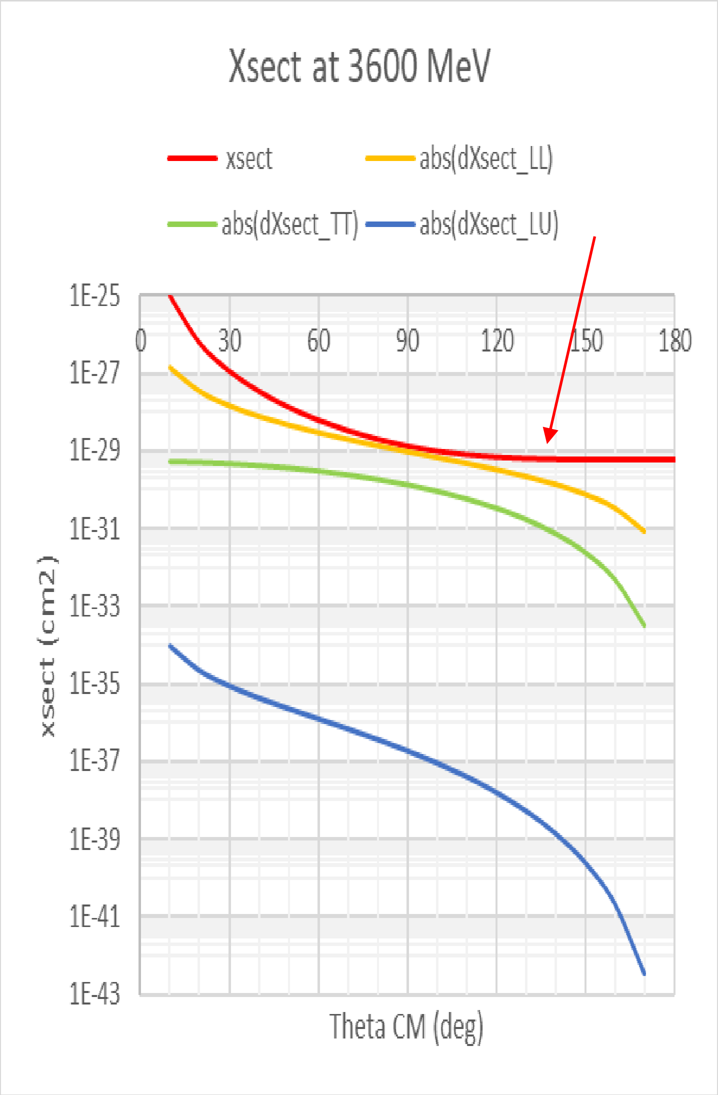
$$\left.+2\sin^4(\theta/2)\,|\,1+f(s)g_Rg_L\,|^2+[2/\sin^4(\theta/2)][1+f(t)g_Rg_L]^2\right\}, \quad (14)$$

(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 diverge as theta → 0 deg, which will dilute any interesting A' effects that we add to the s-channel.

f(s) is for time-like Z, has a Real part and an Imaginary part. Generally, effects from a resonant A' will be largest at backward angles (see red arrow at right, pointing to a "shelf" in the xsect).

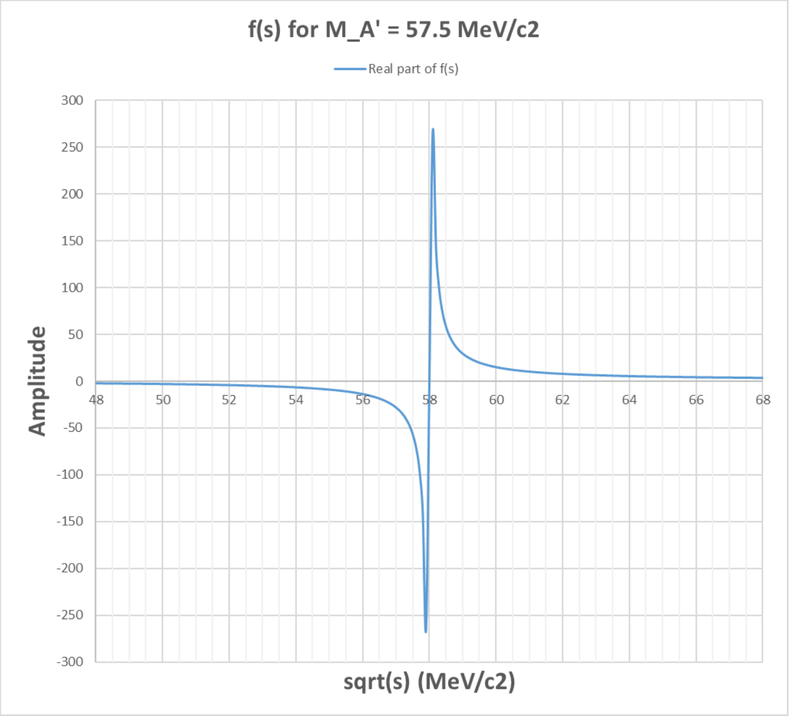
$$f(q^2)=\begin{cases}\dfrac{1}{4\sin^2(2\theta_W)}\,\dfrac{q^2}{q^2-M_Z{}^2+iM_Z\Gamma_Z^{\rm tot}}, & q^2>0\ (q\ \text{timelike})\,, \quad \text{i.e., } \mathbf{f(s)}\\[2ex] \dfrac{1}{4\sin^2(2\theta_W)}\,\dfrac{q^2}{q^2-M_Z{}^2}, & q^2\le 0\ (q\ \text{spacelike})\,. \quad \text{i.e., } \mathbf{f(t)}\end{cases}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

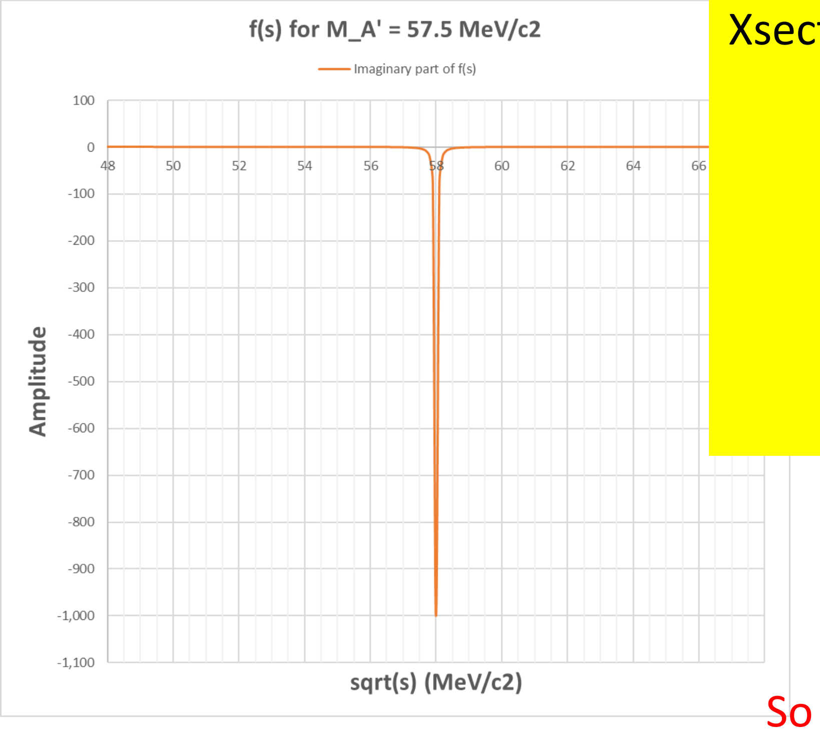


Looking for Amplitude-level Effects in the Xsect: Idiot Check

$M_{A'}$ = 57.5 MeV/c2, Width = 57.5 keV

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





Xsect $\sim |1 + f(s)\, g_L{}^2|^2$

$\sim |1 + \mathrm{Re}f(s)\, g_L{}^2 + i^*\mathrm{Im}f(s)\, g_L{}^2|^2$

$\sim 1 + 2\mathrm{Re}f(s)\, g_L{}^2 + [\mathrm{Re}f(s)^2 + \mathrm{Im}f(s)^2]\, g_L{}^4$

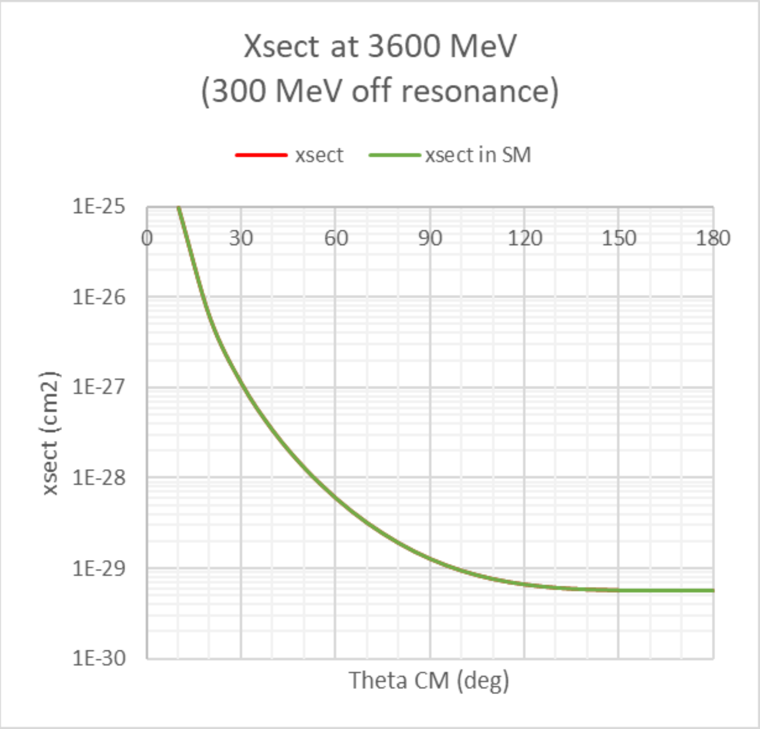
$\sim 1 + 2\mathrm{Re}f(s)\, g_L{}^2$ + H.O.T.

proportional to ε^2 proportional to ε^4

So at small and interesting values of ε, the signal will have the shape of Ref(s).

A’ signals in the Yield

Yields: Purely Vector Coupling, ε = 1E-4, $M_{A'}$ = 57.5 MeV/c^2



On this plotting scale, the A’ effects are invisibly small.
Note again the flattening of the xsect at backward angles.

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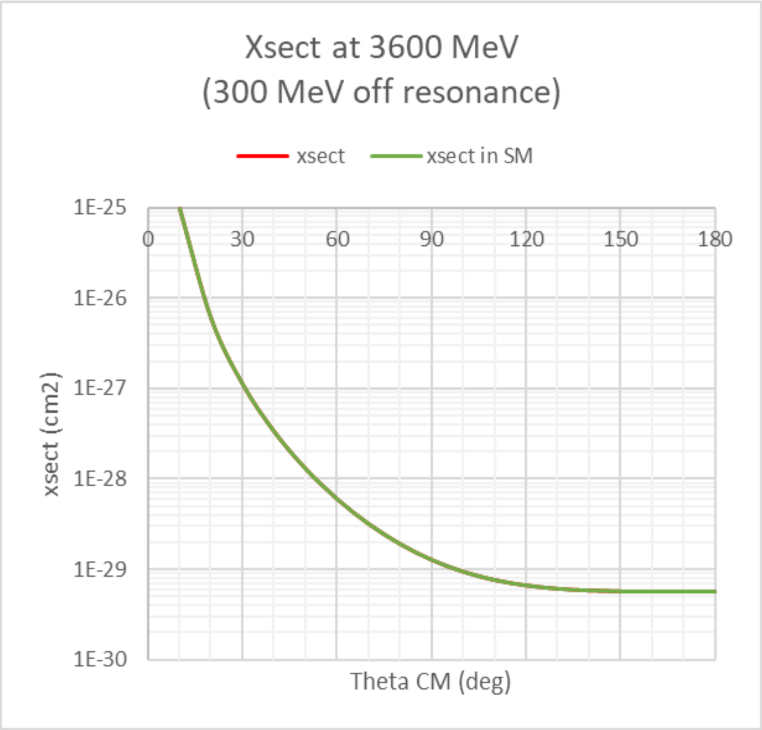

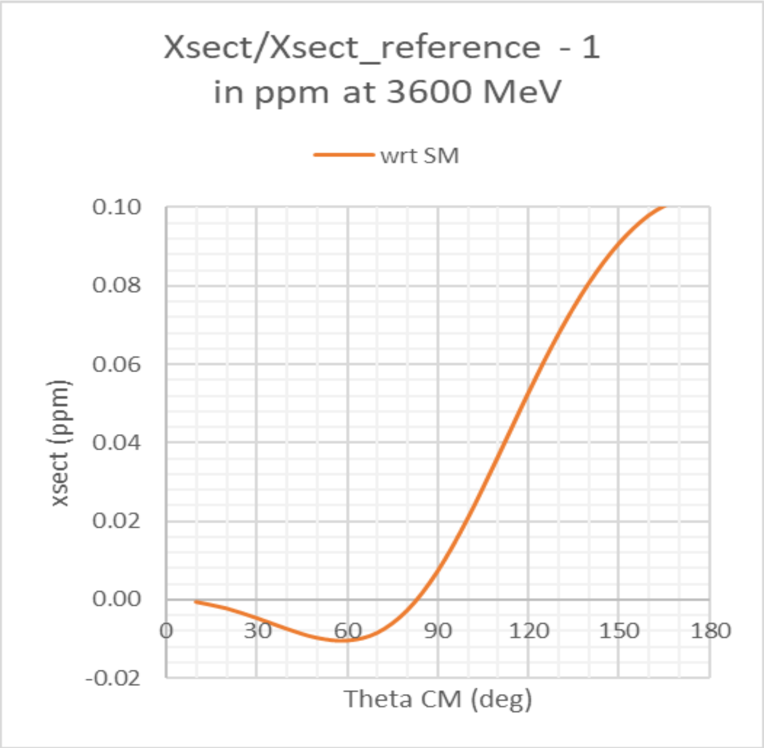

On this plotting scale, the A' effects are invisibly small.
Note again the flattening of the xsect at backward angles.

Taking the difference wrt SM, off resonance effects are tiny, comparable to Z0 exchange.
Anything < 1% is too small to measure!

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

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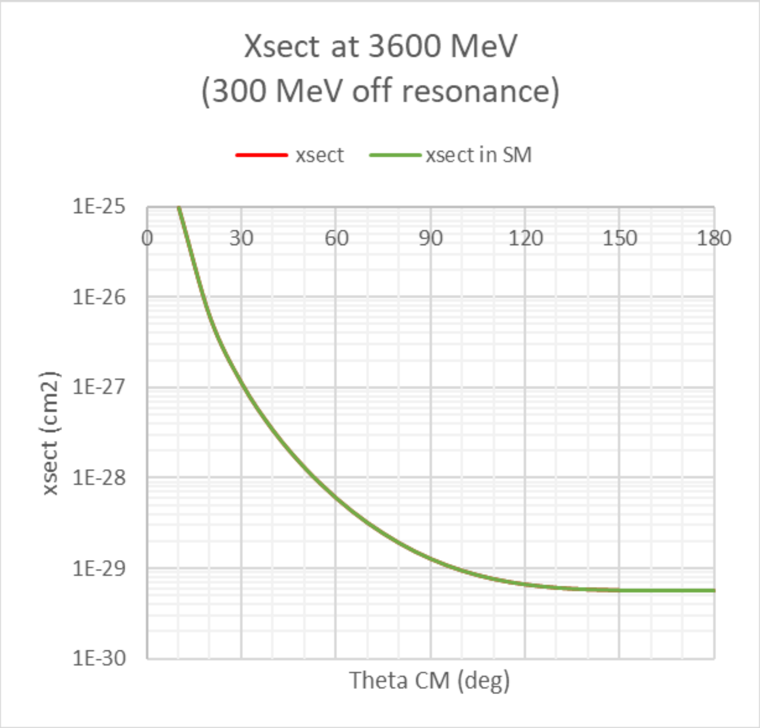

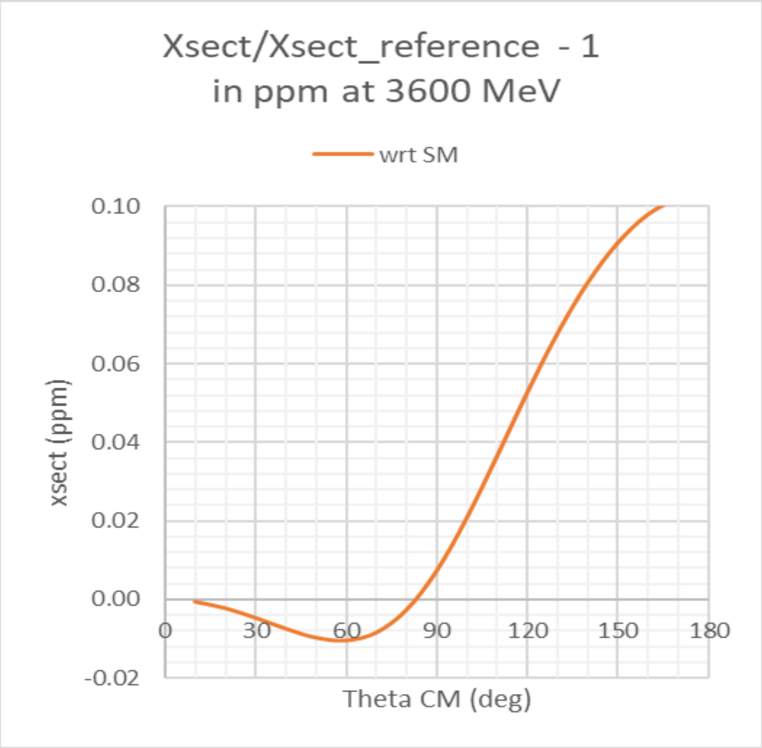

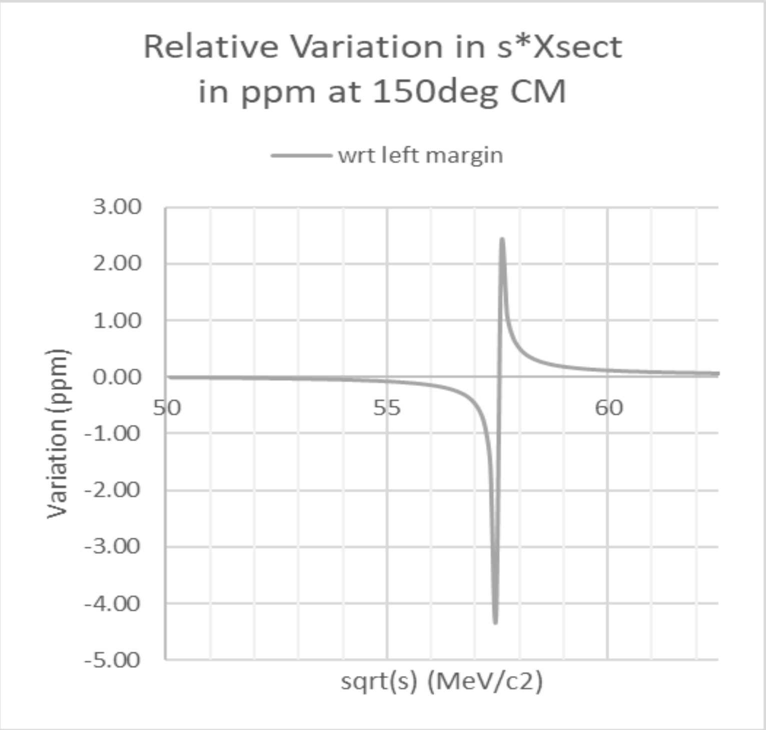

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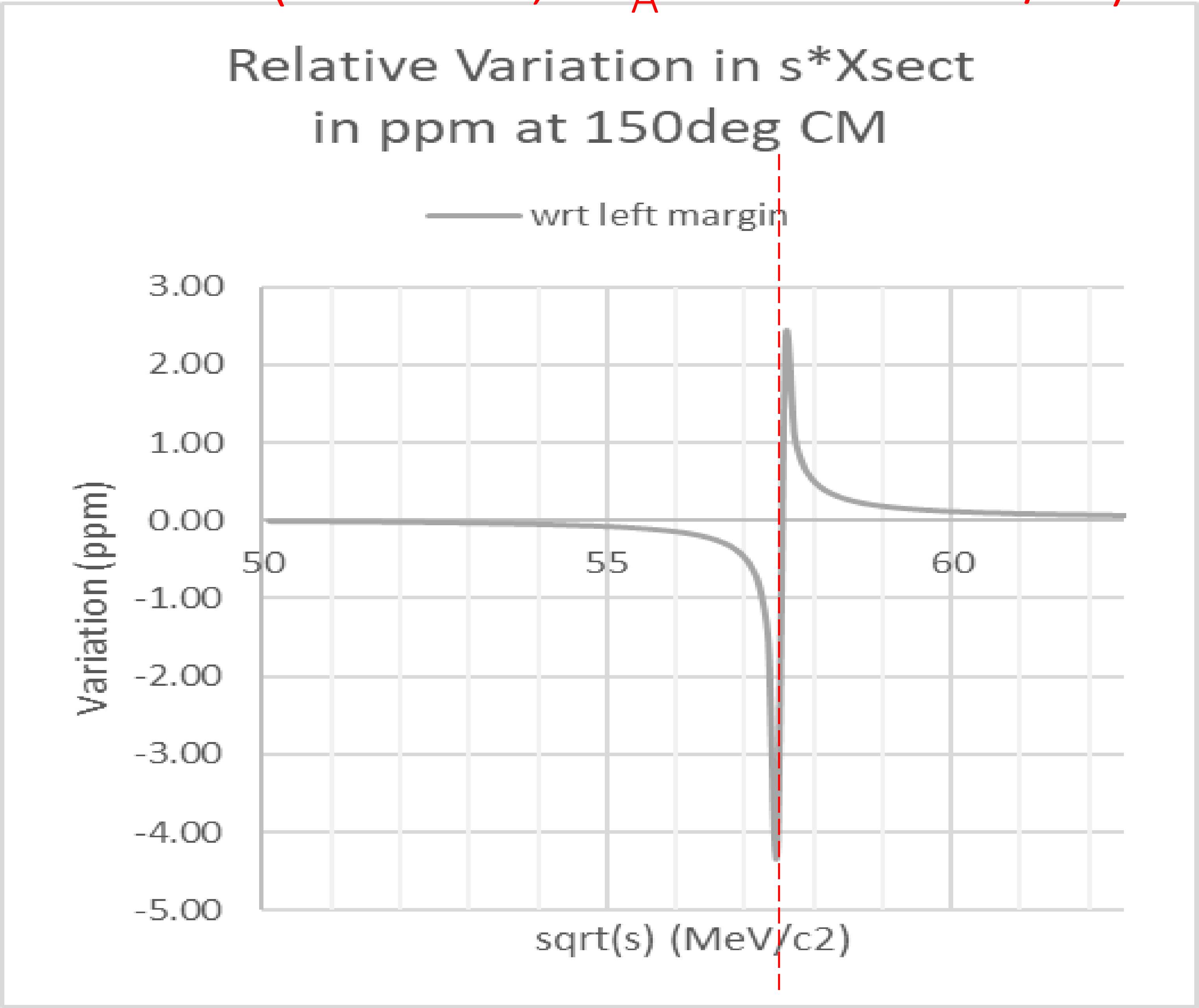
Note again the flattening of the xsect at backward angles.

Taking the difference wrt SM, off resonance effects are tiny, comparable to Z0 exchange.
Anything < 1% is too small to measure!

(As naively expected, A’ effects are largest at backward angles.)

Plotted vs sqrt(s), there is a few ppm modulation of the xsect as the resonance is crossed, similar to the Real part of the A’ propagator.
(Width here is 57.5 keV.)

Zoomed (ε = 1E-4, $M_{A'}$ = 57.5 MeV/c^2)



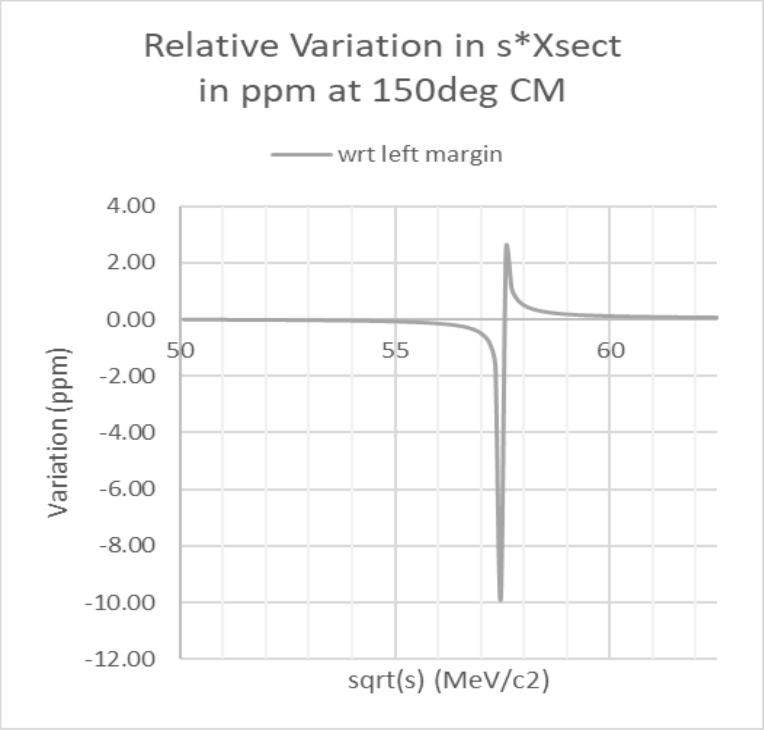
This is potentially measureable.

But the mass window with high sensitivity is only +-O(100)MeV in beam energy.

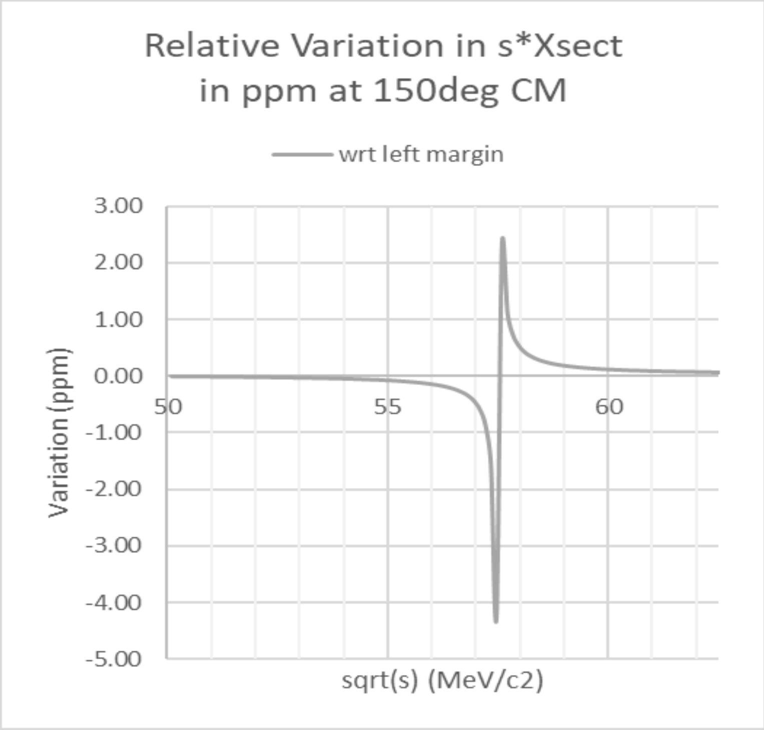
Initial State Radiation (ISR) will likely broaden this window.

Yield Signal Dependence on the Decay Width

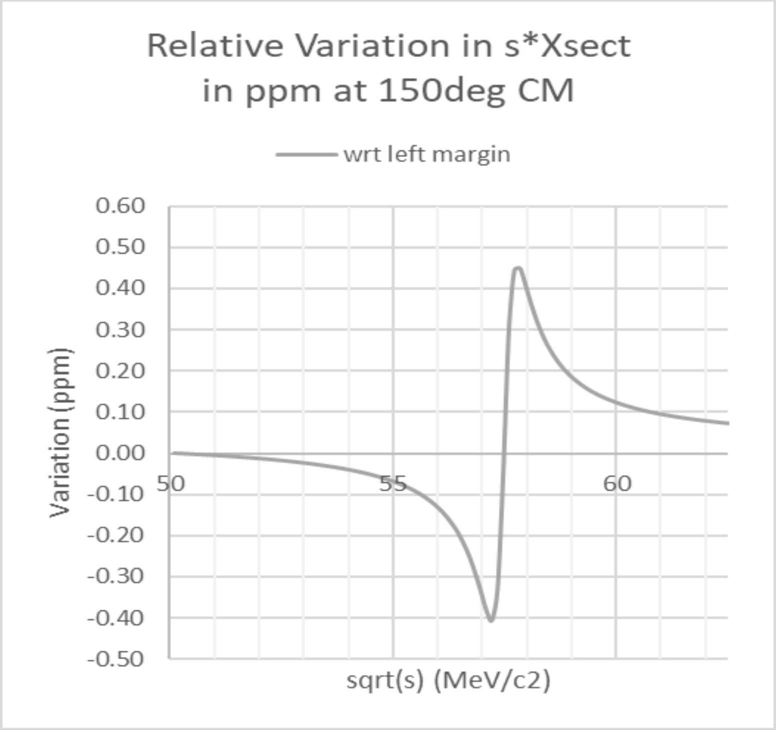
(Purely Vector Coupling, ε = 1E-4, $M_{A'}$ = 57.5 MeV/c2)



Width = 0% (0 keV)



Width = 0.1% (57.5 keV)

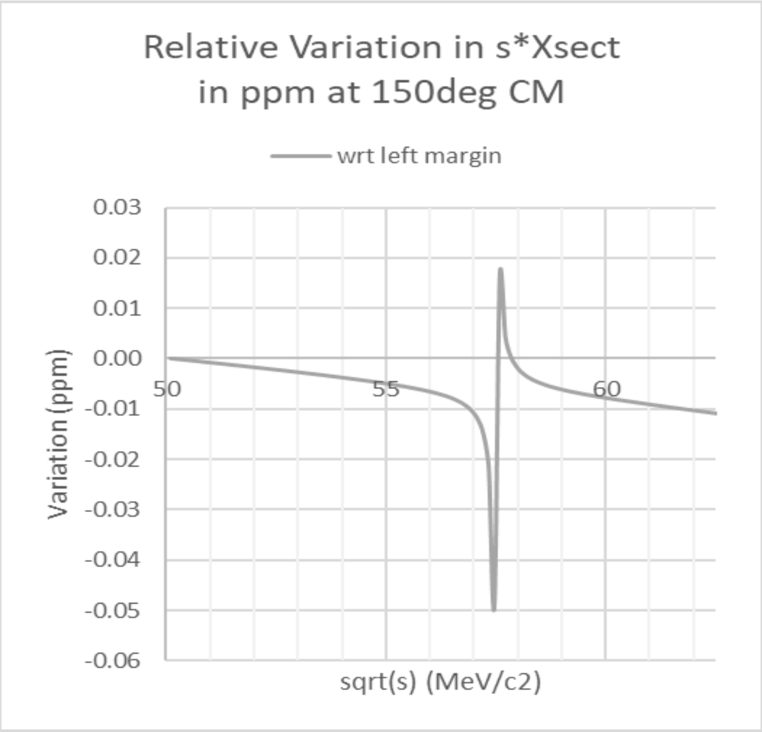


Width = 1% (57.5 keV)

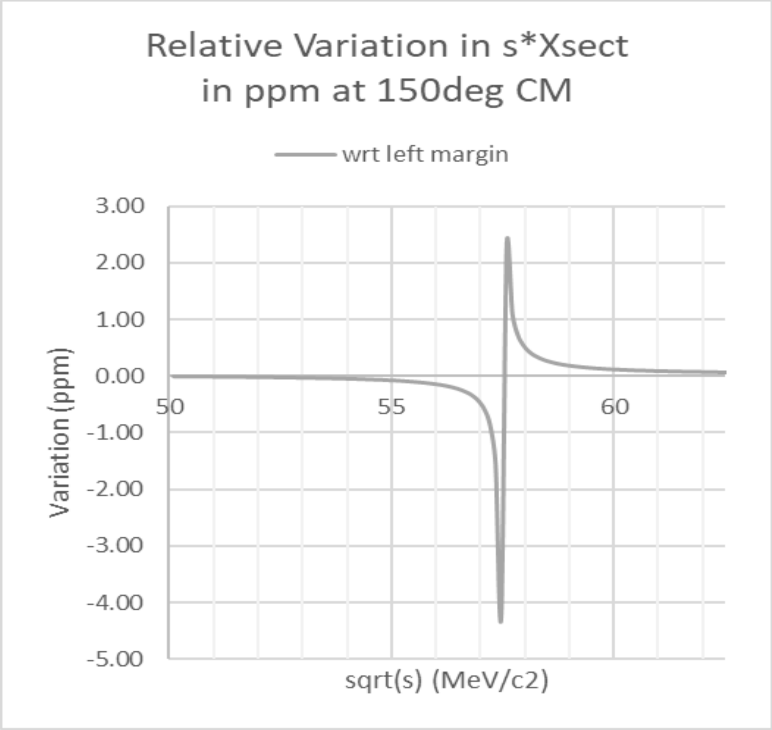
Signal amplitudes get smaller with increasing decay width.
(But they also get broader in a way that seems to roughly preserve the area. I need to study this.)

Yield Signal Dependence on ε

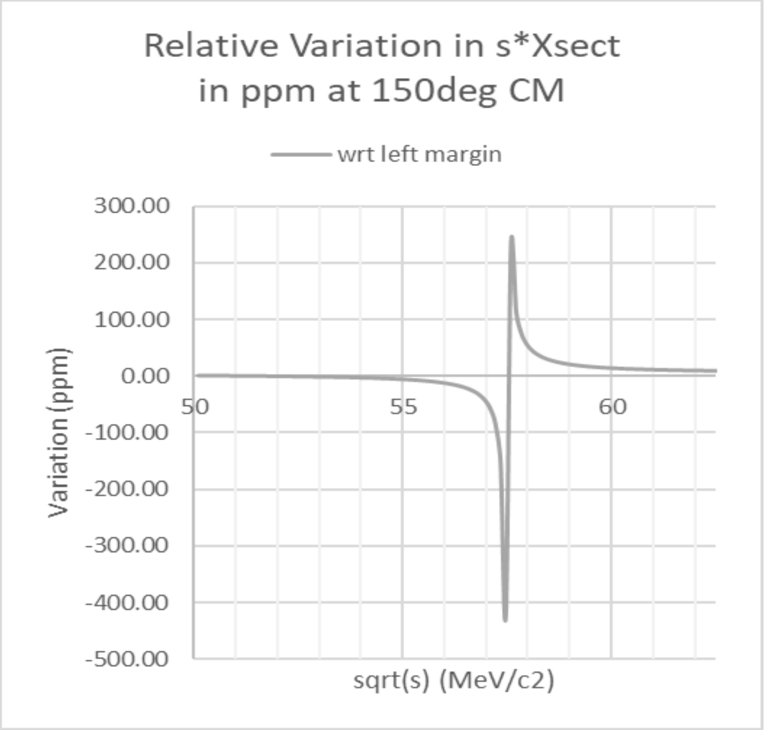
(Purely Vector Coupling, $M_{A'}$ = 57.5 MeV/c2, Width = 57.5 keV)



ε = 1E-5



ε = 1E-4

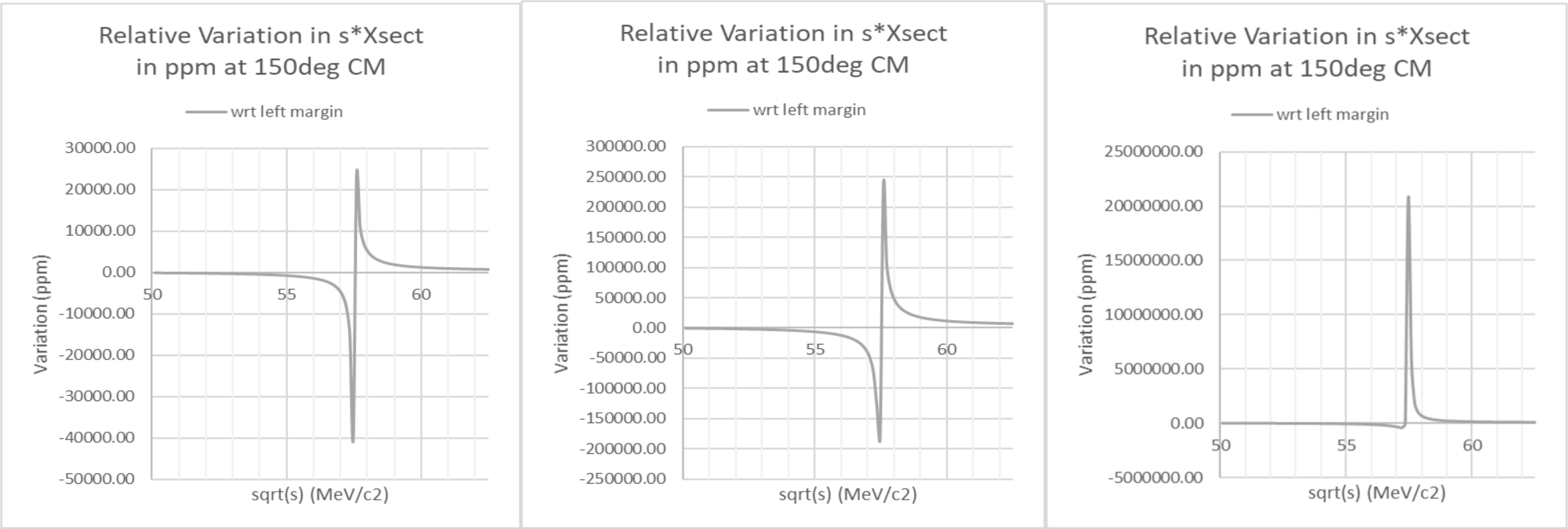


ε = 1e-3

Signal amplitudes scale like ε^2 , so ε = 1E-4 is difficult and ε = 1E-5 almost impossible.
(For the latter case, the effects of an A' are only several times larger than the slope from Z0 exchange.)

Evolution into a Bump with Increasing ε: another idiot check

(Purely Vector Coupling, $M_{A'}$ = 57.5 MeV/c2, Width = 57.5 keV)

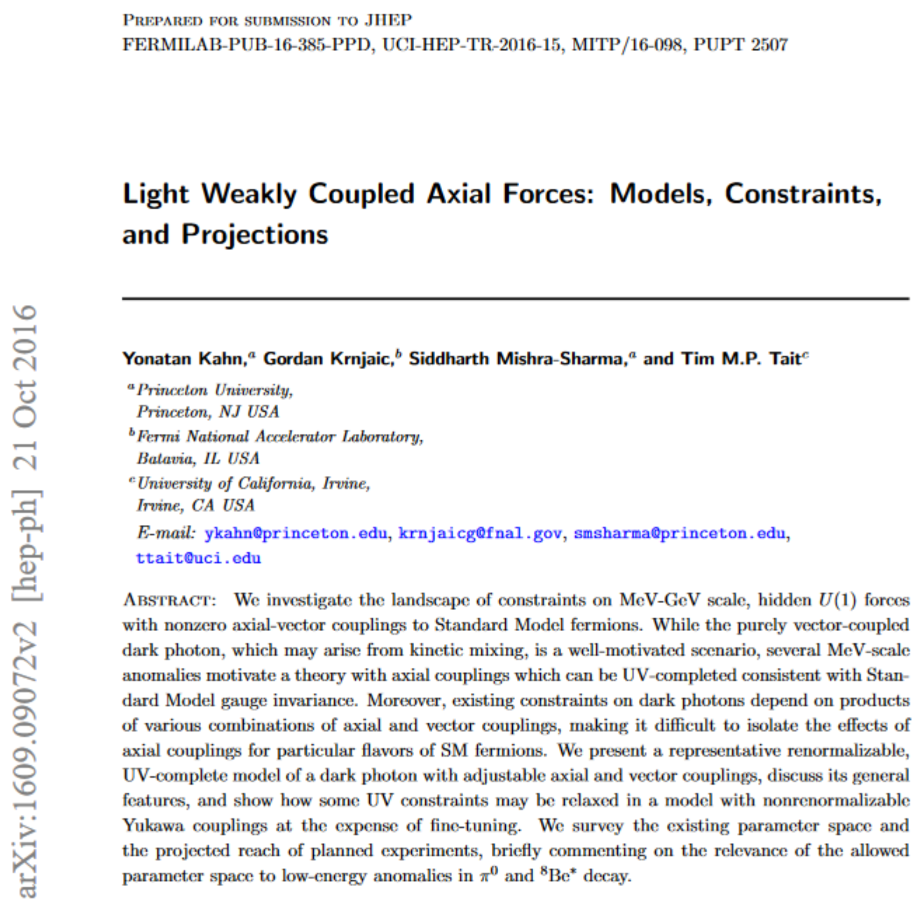


ε = 1e-3 | ε = 0.03 | ε = 0.1

The interference pattern evolves into a bump as ε → 1.
The bump represents the production of real (as opposed to virtual) A'.

Purely Vector vs Purely Axial-Vector Couplings

There is some literature on BSM particles which have significant axial-vector couplings. It's easy to explore that in this formalism.



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

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

Yonatan Kahn,[a] Gordan Krnjaic,[b] Siddharth Mishra-Sharma,[a] and Tim M.P. Tait[c]

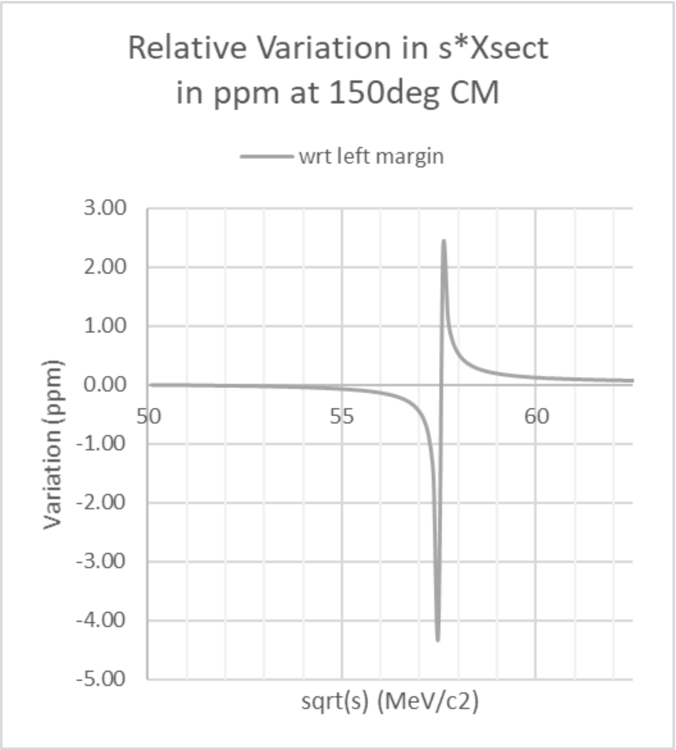
[a] *Princeton University, Princeton, NJ USA*
[b] *Fermi National Accelerator Laboratory, Batavia, IL USA*
[c] *University of California, Irvine, Irvine, CA USA*

E-mail: ykahn@princeton.edu, krnjaicg@fnal.gov, smsharma@princeton.edu, ttait@uci.edu

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 $^8Be^*$ decay.

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

Purely vector



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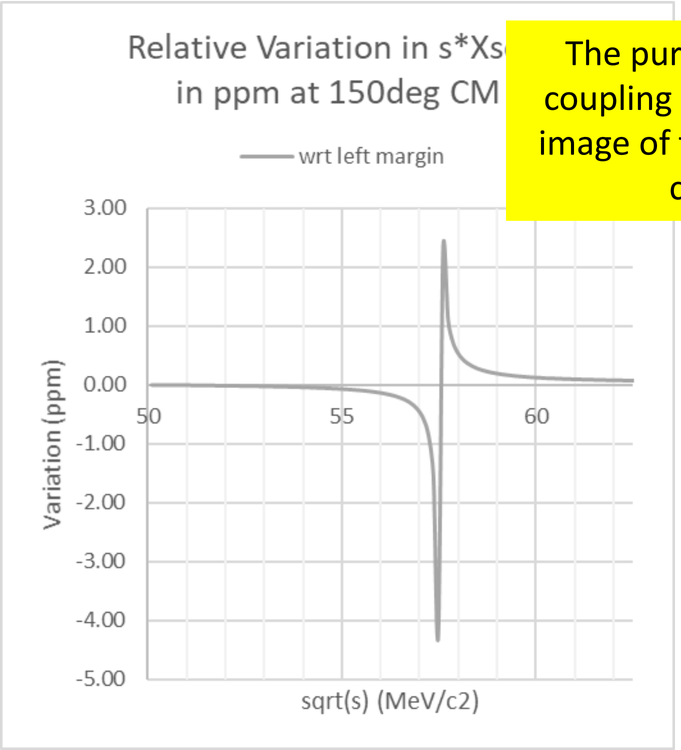
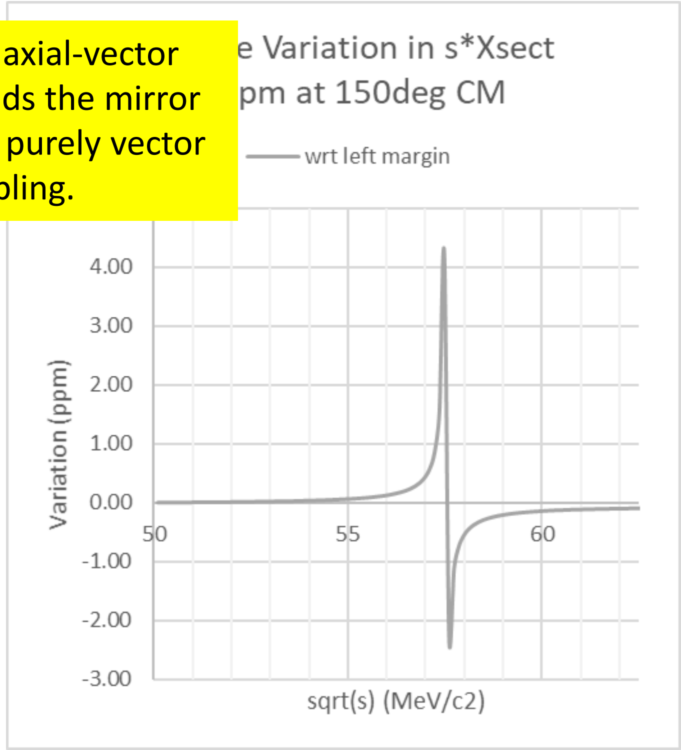


The purely axial-vector coupling yields the mirror image of the purely vector coupling.

Purely axial-vector



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

Yield vs sqrt(s) Summary

Yield vs sqrt(s) in e+e- → e+e- + gamma (ie, e+e- →e+e- with Initial State Radiation)

Determination of sqrt(s) requires measuring e^+ and e^- in coincidence.

→ Must do an event mode experiment

→ To place exclusions at the ε ~ 1e-4 level, one needs a frightfully large number of events, which implies a frightfully large daq rate in order to finish within several years.

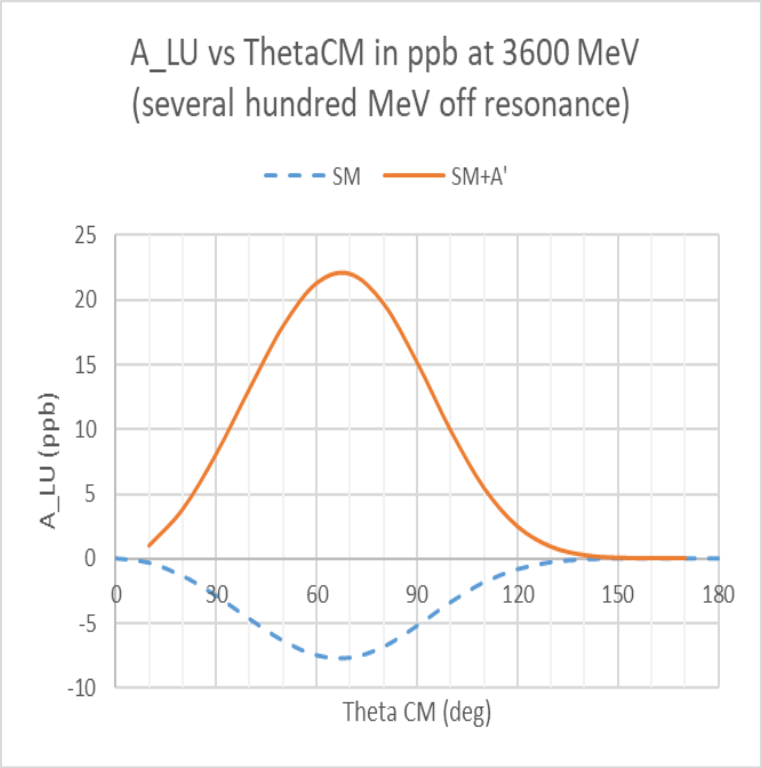
At such small ε, this method seems a good way to study an already discovered A' where sqrt(s) is known.

E.g., if the X(17) particle isn't excluded within the next decade, one could do a targeted measurement near 17 MeV/c2 to refute it (or confirm it and measure its properties such as mass, width, degree of mixing with the photon, and whether the couplings are vector or axial-vector).

Maybe I'll change my mind with more study, but sensitive searches over a broad mass range with this event-mode technique seems a little nuts.
Let's now see if there's something better suited to a search over a broad mass range.

Dark Z’ signals in the PV Asymmetry

A_{PV}: $g_A = g_V = 1$, $\varepsilon = 1E\text{-}4$, $M_{A'} = 57.5$ MeV/c^2



The tree-level SM A_{PV} in Bhabha is very small.
Even several hundred MeV in beam energy off resonance, the effect on A_{PV} is dramatic.

Of course, one would need 10 ppb sensitivity.

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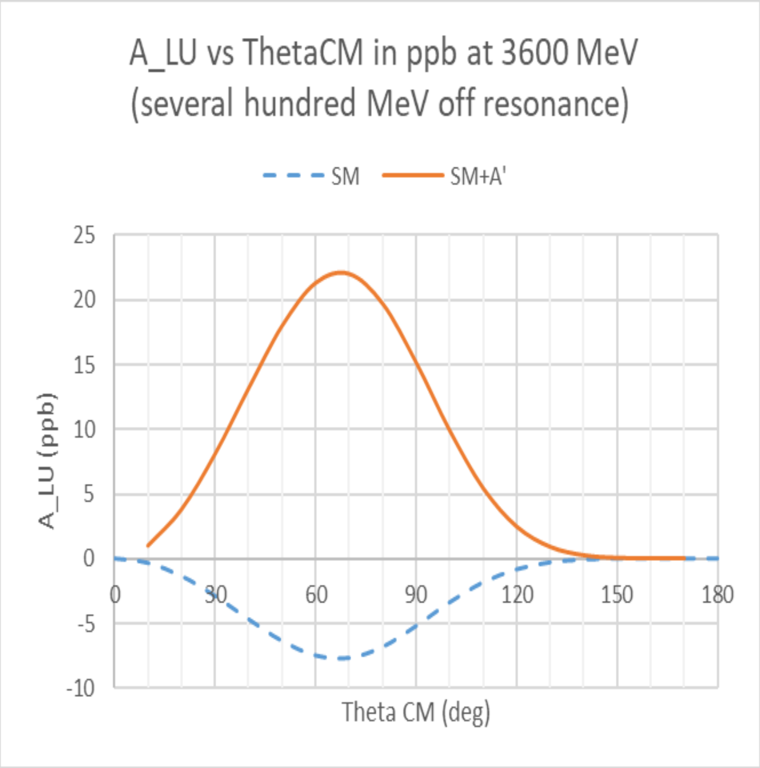

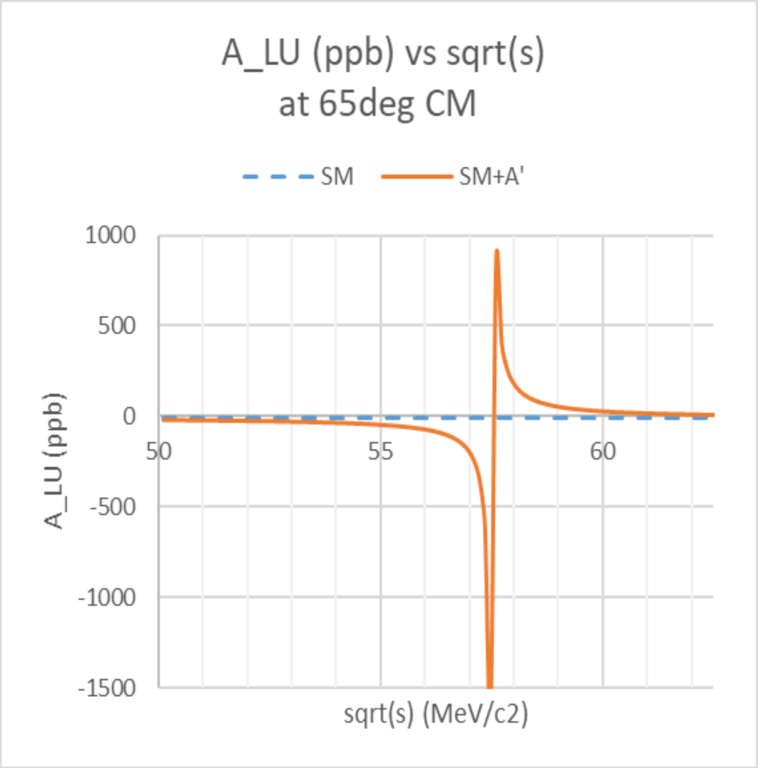

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Near resonance, the asymmetry approaches the O(1) ppm level, which is 100x the SM value.
But we don't want to count on being near a resonance: we want to search a broad range.

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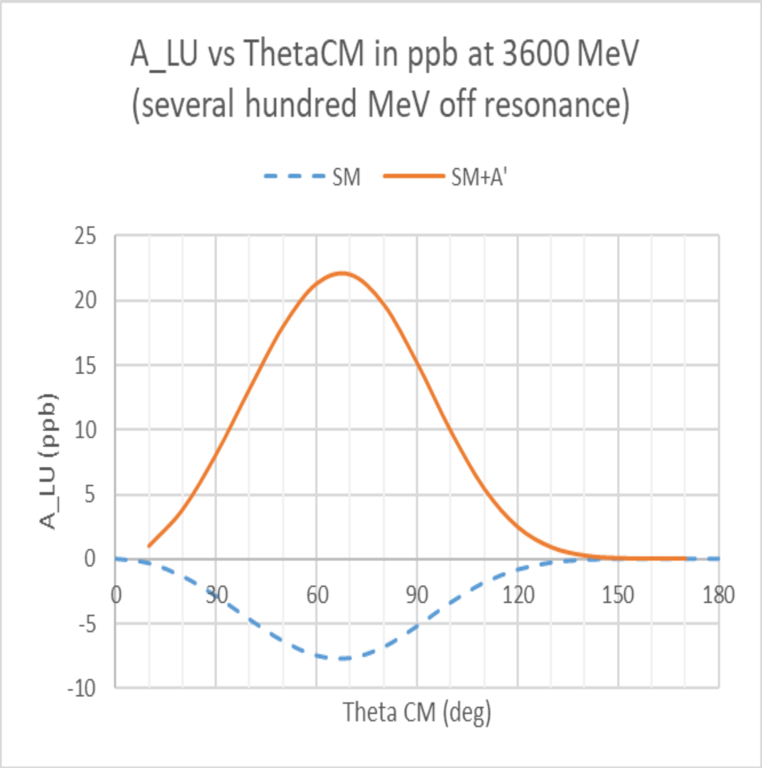

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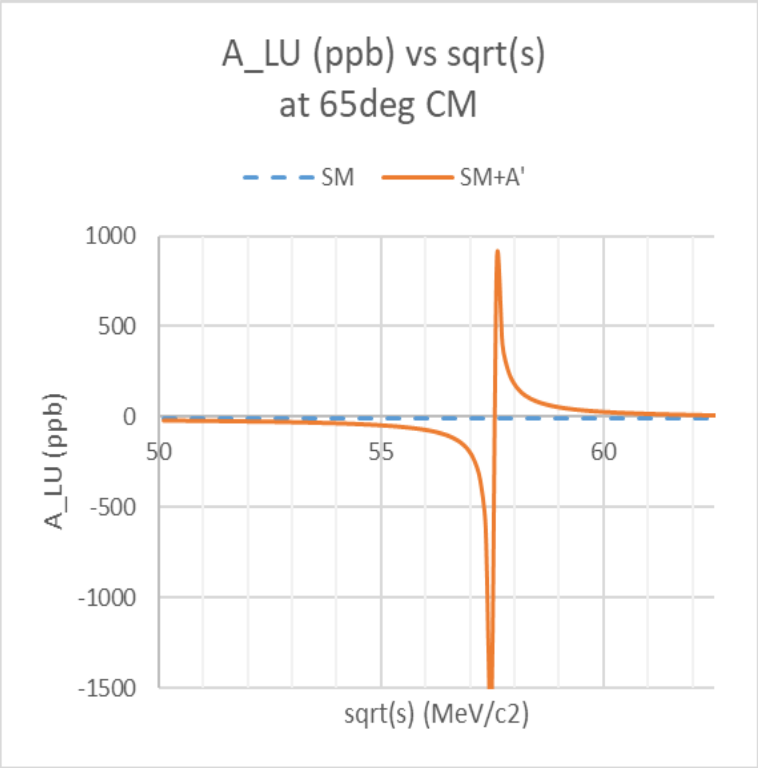

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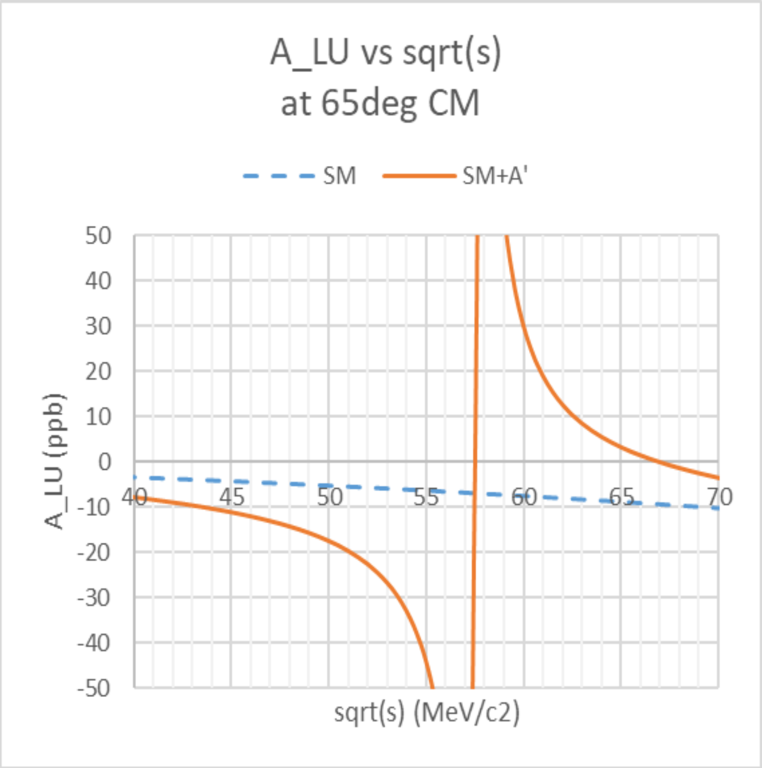
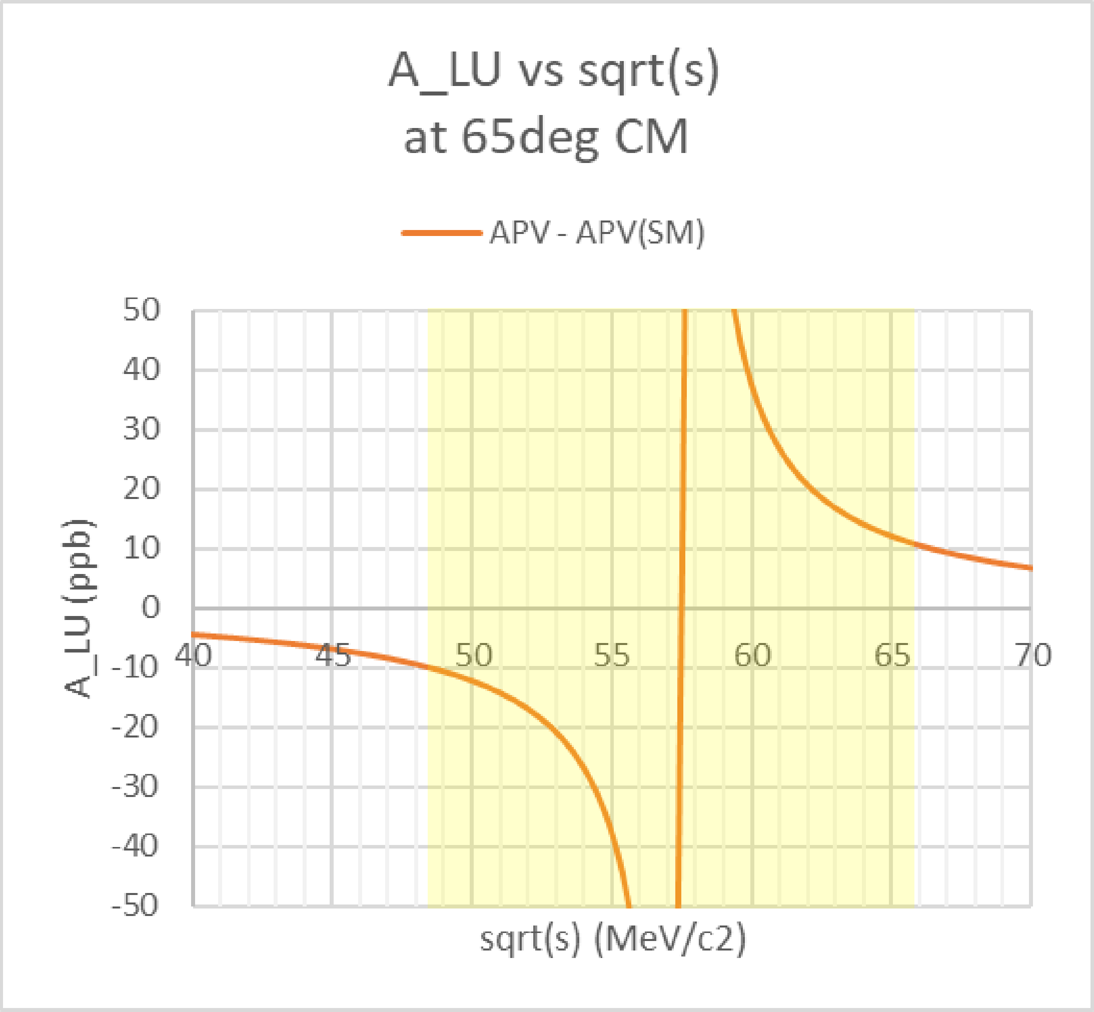


Same plot, changing scale.

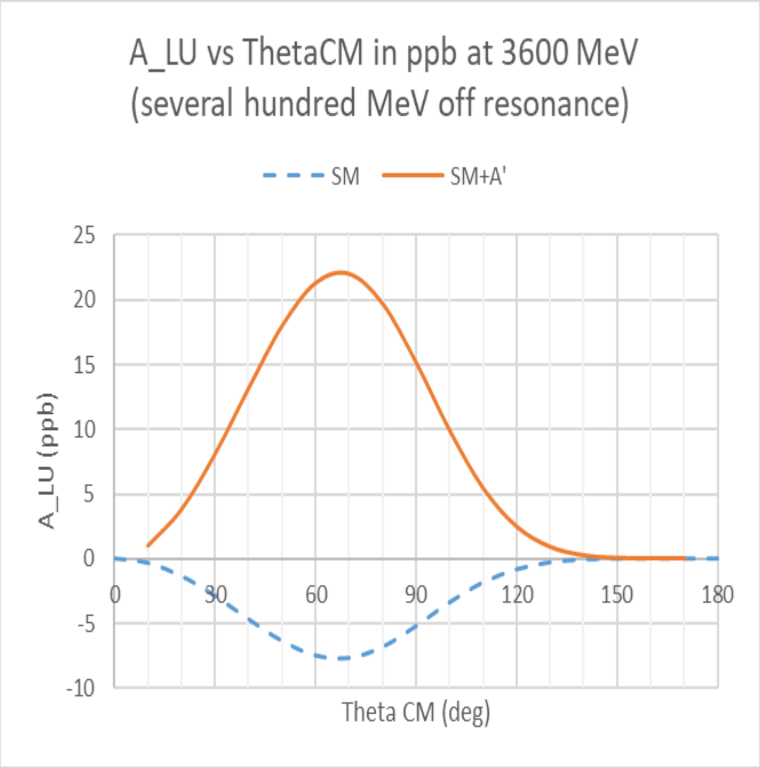
(Continued on the next slide.)

A_{PV}: $g_A = g_V = 1$, ε = 1E-4, $M_{A'} = 57.5$ MeV/c^2

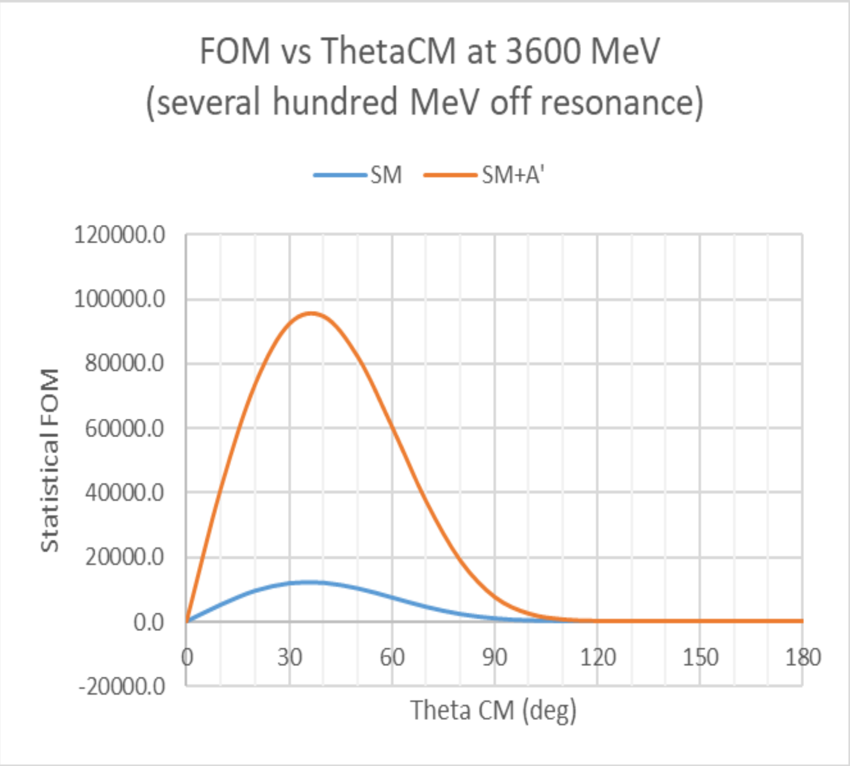


The dark Z' effects exceed 10 ppb over a fairly large 20 MeV/c2 mass range, corresponding to over 2 GeV in beam energy even without ISR.

A_{PV}: $g_A = g_V = 1$, $\varepsilon = 1E\text{-}4$, $M_{A'} = 57.5\ MeV/c^2$



Same plot from a few slides ago.
With the assumed couplings, A_{PV} peaks around 65degCM.



With the assumed couplings, the statistical FOM = Rate*A_{PV}^2 peaks near 35 degCM where rates are 1 GHz.

Issues:

- Can a spectrometer detecting only the e- in current mode provide crude binning in sqrt(s)?
- How much will ISR extend the sqrt(s) range covered by a single beam energy?
- Looking at the rates without ISR, it seems one would be able to complete at least one O(10) ppb measurement in a calendar year. (100 nA on a 10% RL LH2 target)
- Will the accelerator have trouble delivering positron beams as low as 1 GeV in energy?

A_{PV} Experiment Summary

A_{PV} in e+e- → e+e- + γ (ie, e+e- →e+e- with Initial State Radiation)

One would hope to do several measurements, covering the Jlab sqrt(s) range, each with 10 ppb statistical sensitivity.

→ Must be integrating mode measurement

→ no coincidence is possible, so need to choose which single particle to detect

→ e- detection will have the lowest background (since the beam is e+) So there's no Mott scattering background!

Note that because the tree-level asymmetry is so crazy small, loop level EW corrections are likely to make an O(100)% correction.

Overall Summary

- The exchange of a virtual A' could indeed induce measureable, amplitude-level effects in Bhabha scattering.

- Regarding an event mode measurement of the yield vs sqrt(s) at thetaCM = 120-150deg:

  This seems a good way to study A' properties after a supposed discovery. E.g., one could refute or confirm the X(17).

- Regarding an integrating mode measurement of APV vs sqrt(s) for thetaCM = 20-60 degCM:

  Because the PV SM background is so small, this might be a better way of sensitively covering a broad mass range, but only for a dark photon with vector and axial couplings.

- Regarding other observables:
  i. A_LL doesn't seem to have any advantages over the yield. (And there is a big dilution from the Fe foil.)
  ii. A_TT is still under study.
  iii. The transverse single spin asymmetry A_TU is not in the Olsen and Osland formalism. In the SM in JLab kinematics, A_TU is small but not too small. An A' might induce measureable pulls.

extras

Methods

To study the potential amplitude sensitivities in Bhabha scattering, I look for a formalism for e+e- → e+e- containing tree-level gamma and Z exchange. I then added a BSM particle which can be identified as a

i. dark A' (purely vector coupling) or

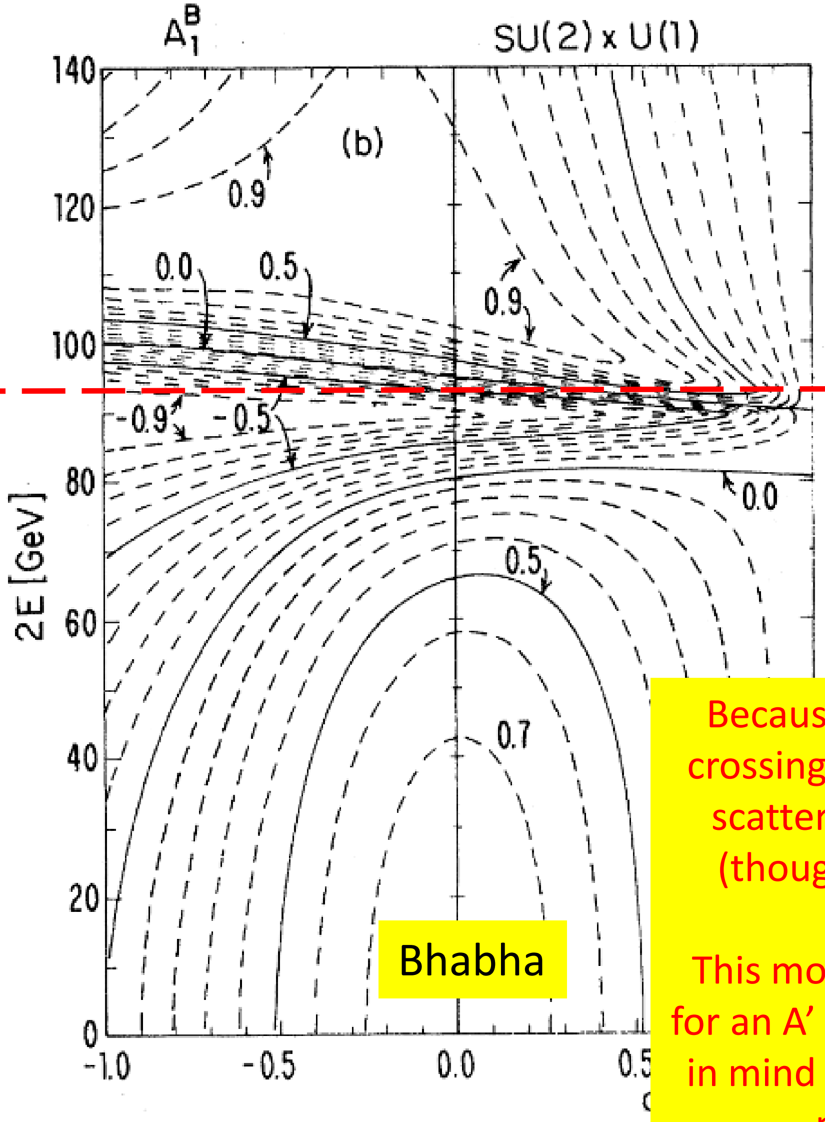
ii. a dark Z (mixed axial and vector couplings).

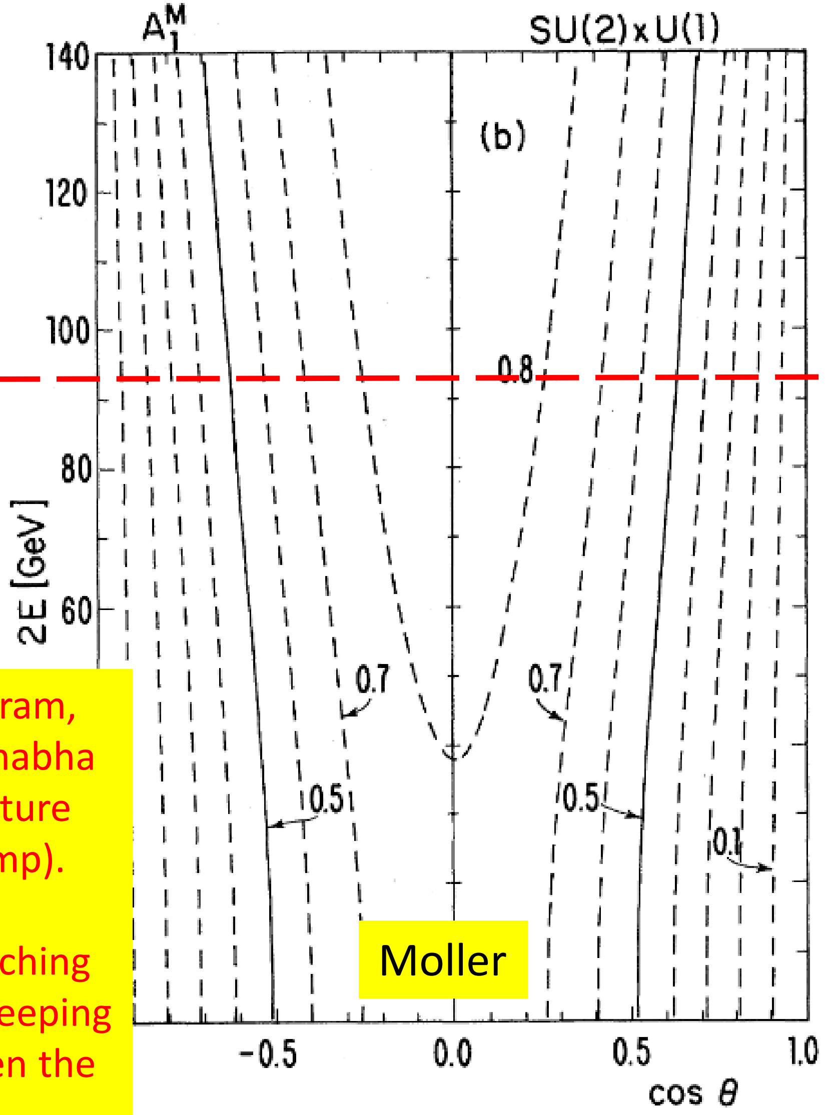
This formalism includes the polarization-dependent cross sections.

Modifying the Formalism to Turn a Z' into an A'

Z0	A'
Mass = 98,187.6 MeV/c2 Width = 2495 MeV/c2	Mass = 57.5 MeV/c2 Width = 0.575 MeV/c2 (for example)
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)*epsilon g_r = (g_v – g_a)*epsilon
$4\sin^2(2\text{theta\_W}) = 2.845$ (a normalization factor in the propagator)	I just lamely set this to 1 for now.

A_{LL} up to E_{cm} = 140 GeV/c^2

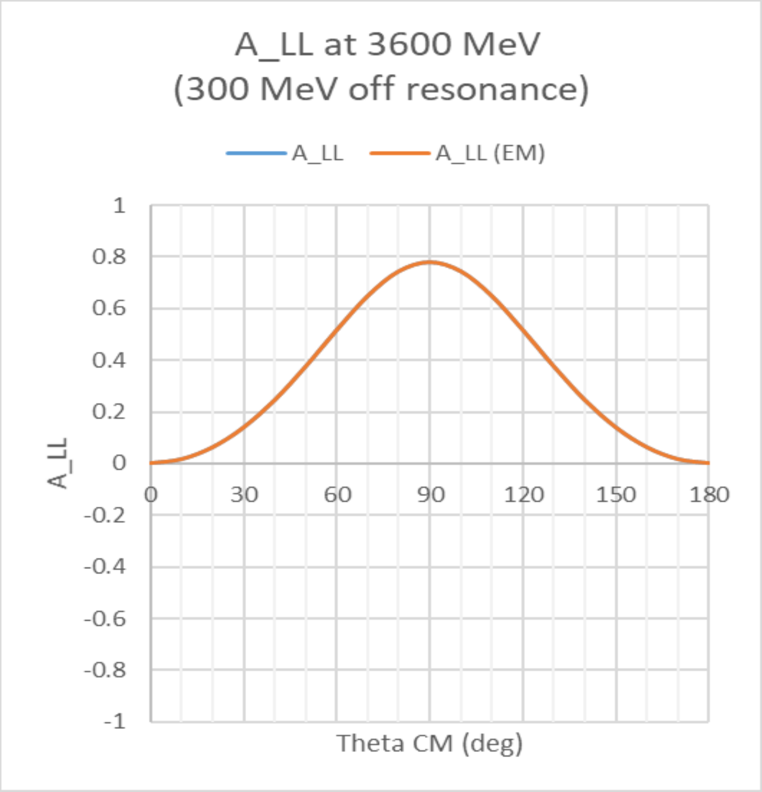


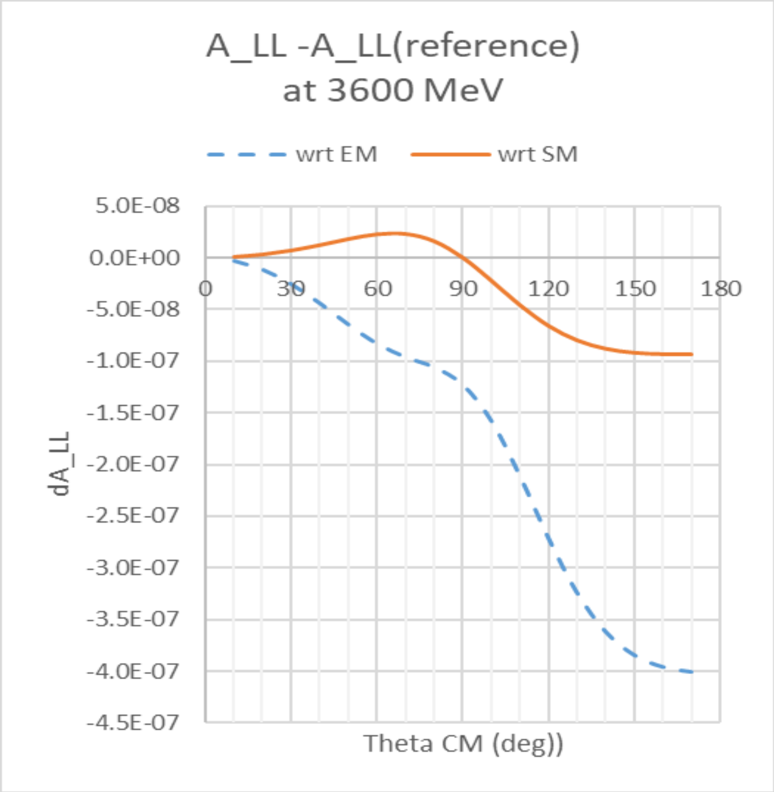


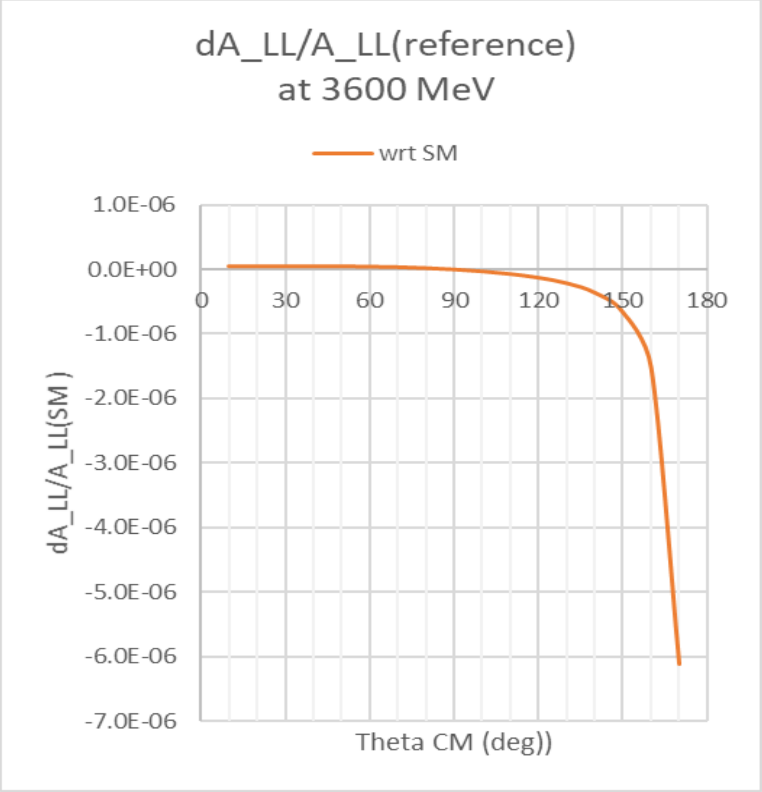
Because of the s-channel diagram, crossing the Z0 resonance in Bhabha scattering leaves a clear signature (though not necessarily a bump).

This motivates the idea of searching for an A’ in Bhabha scattering, keeping in mind that the mixing between the photon and A’ is << 1.

A_{LL}: Purely Vector Coupling, ε = 1E-4, $M_{A'}$ = 57.5 MeV/c^2







Again, on this plotting scale, the A' effects are invisibly small.

Near 180deg, ALL is not zero due to a surprisingly large PC contribution from Z exchange. Even this far off resonance, the A' can shift that result by O(100)%.

But the relative change in the asymmetry is << 1% so impossible to measure.

Moving on!

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.)

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. 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?

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

$$\left.+2\sin^4(\theta/2)\,|\,1+f(s)g_Rg_L\,|^2+[2/\sin^4(\theta/2)][1+f(t)g_Rg_L]^2\right\}, \qquad (14)$$

A_LL (PC)→

$$A_1^B=\left\{-\cos^4(\theta/2)\left[\left|1+f(s){g_L}^2-\frac{1+f(t){g_L}^2}{\sin^2(\theta/2)}\right|^2+\left|1+f(s){g_R}^2-\frac{1+f(t){g_R}^2}{\sin^2(\theta/2)}\right|^2\right]\right.$$

$$\left.-2\sin^4(\theta/2)\,|\,1+f(s)g_Rg_L\,|^2+[2/\sin^4(\theta/2)][1+f(t)g_Rg_L]^2\right\}\bigg/\left[\frac{4s}{\alpha^2}\frac{d\sigma_0^B}{d\Omega}\right], \qquad (15)$$

A_LU (PV) →

$$A_2^B=\cos^4(\theta/2)({g_R}^2-{g_L}^2)$$

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

A_TT (PC) →

$$A_3^B=2\sin^2(\theta/2)\cos^2(\theta/2)$$

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

A'_TT (PV) →

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

Dilution in A_LL and A_TT experiments

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