PR12-21-003 Response to the Technical Review

A. Gasparian (contact person), H. Gao, D. Dutta, N. Liyanage, T. Hague, C. Peng, R. Paremuzyan
and
The PRad Collaboration

1 The TAC Review

1. There are some concerns about the way the EM background under a possible resonance peak was evaluated: 1) a more conservative estimate based on the same theoretical framework used to evaluate the expected signal, would bring the background x5 to x76, depending on the resonance mass; 2) the formula used to evaluate the bg as S/SQR(B+BG) seems to be oversimplified and does not reflect the sophisticated statistical analyses performed by other experiments.

Answer:

To estimate the expected background level in the proposed experiment we followed the HPS procedure, (see page 48 of [1]): *"... We use two generators to produce events: MADGRAPH for signal and trident events, and EGS5 for beam electrons that interact in the target. In MADGRAPH, we have produced large samples of signal events at various A' masses as well as large samples of Bethe-Heitler and radiative trident events. The passage of the electron beam through the target is simulated using EGS5; ... We use a GEANT-4 based simulation[84] to propagate events through the detector and model the energy deposition. ..."*. For information, EGS is the default generator in GEANT for electromagnetic processes. We also have performed the background simulations in two different ways. As described in section 6 (pg 22) of the proposal, a comprehensive simulation of the experiment was carried out using the GEANT Monte Carlo simulation package developed for this experiment. This simulation takes into account realistic geometry of the experimental setup and detector resolutions. All physical processes included in the standard GEANT package had been activated and tested during these MC simulation processes. The results of these simulations are presented in the proposal (Fig. 24, left) as the estimated background level for the beam time equivalent to 3.5 seconds. Based on this result (which is limited by statistics due to CPU time) we estimated the epsilon reach in Fig. 27. We continued these simulations for the last month, the new results are presented here. As stated in the proposal, the key advantage of this experiment is the detection of the 3 charged particles which arguably helps to suppress the background.
A second simulation was performed using the MADGRAPH5 event generator [2], also used by the HPS collaboration [1]. First, using MADGRAPH5 we generated a large sample (2M events) of trident background events including the Bethe-Heitler, radiative and interference processes. Then, these events were fed into the same GEANT simulation package that was used for the signal processing to trace them through the experimental setup and detection of events. The resulting simulated background for 200 seconds of equivalent beam time is shown in Fig. 1 (left). The background shape is fit to a sum of Landau + log + constant distribution. The fit is then used to scale the background counts to 30 days of beam time with the number of events sampled bin-by-bin, as shown in Fig. 1 (right).

Fig. 2 shows comparison of the background results performed with two methods. There is a slight shape differences (expected) between the two methods *vs.* mass. However, the simulated

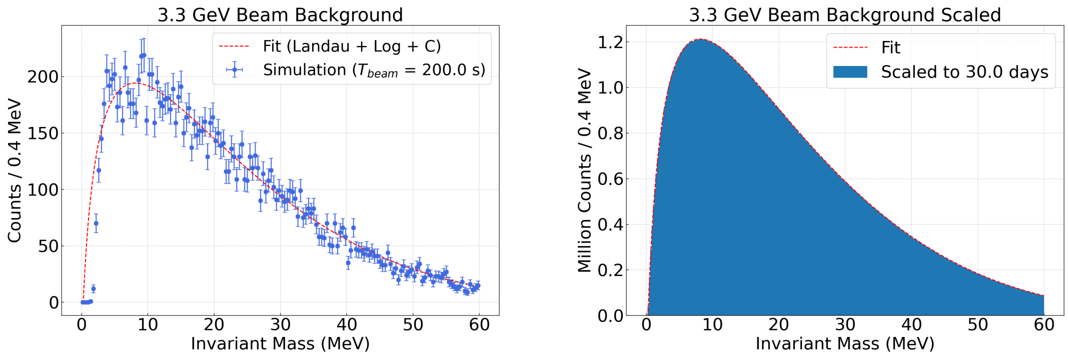

Figure 1: (Left) The MADGRAPH5 generated and simulated background events for the beamt ime equivalent to 200 s (blue points), and fitted by a sum of Landau+log+constant function (red line). (Right) Distribution of the fit result scaled to 30 days of beam time.

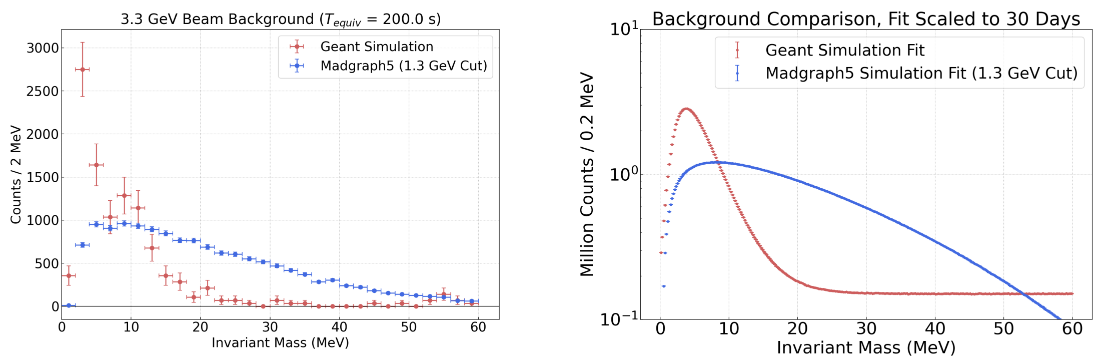

Figure 2: (Left) Comparison of the simulated background distributions performed by GEANT (red points) and by MADGRAPH5 (blue points), they are normalized to the same 200 seconds of equivalent beam time. (Right) Distribution of fitted results scaled to the 30 days of beam time.

background difference is only on the level of 37% for the integrated counts over the entire mass range (14016 *vs.* 10571 events). With that, the two simulations are in general agreement with each other with discrepancies that are acceptable for the level of uncertainty in these type of background simulations. These background distributions are used to estimate the epsilon *vs.* mass sensitivity. The difference in sensitivity when using the first and the second simulation is shown in Fig. 3.
The formula used to evaluate the background and estimate the ϵ sensitivity is the same one used in the APEX and HPS proposals [3, 4]. Note that it is standard practice in such search experiments to use a sensitivity limit of 2.4σ, however, we have used a sensitivity limit of 5σ (discovery criterion used by PDG), which make our estimates more conservative compared to previously approved proposals. We will develop and apply a more sophisticated statistical analysis for the actual high-statistics experimental data set (if approved).

Also, note that the GEANT simulated background shape is similar to what we find from the analysis of the PRad calibration data on a Carbon target (see Fig. 32 in the proposal). This level of agreement is without using any of the additional timing information which will be available in the proposed experiment but had limited availability during the PRad experiment.

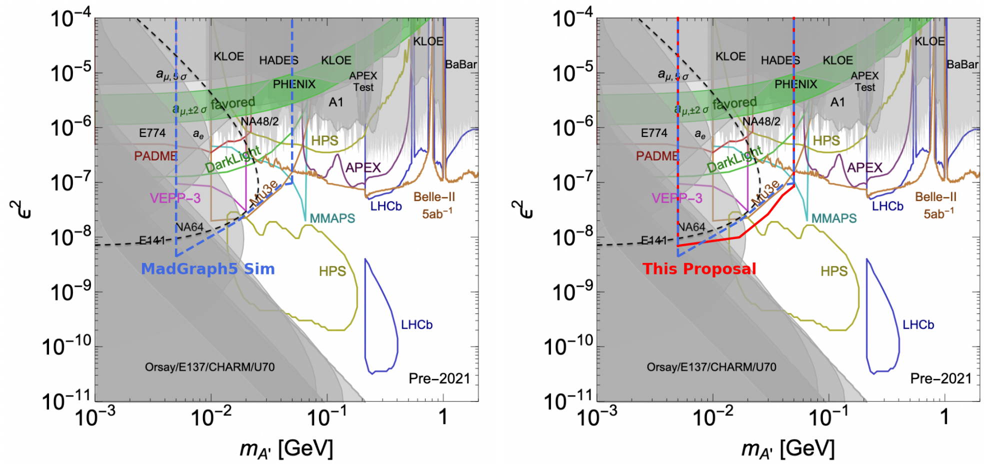

Figure 3: (Left) The $\epsilon^2 - m_X$ sensitivity for backgrounds simulated using the MADGRAPH5 generator. (Right) Comparison of the $\epsilon^2 - m_X$ sensitivity for backgrounds simulated using GEANT (red) *vs.* MADGRAPH5 (blue) generators.

2. The request of two energies requires a careful scheduling. What would be the effect on the reach if the one or both beam energies are chosen differently?

Answer:
It is common practice in search experiments to use multiple beam energies as a check against possible kinematic reflection of known processes. The two energies were chosen as they have high detection efficiencies within the mass region of interest and the relative ease of scheduling during the CEBAF low-energy run periods. Other reasonable choices of beam energies are possible, as can be seen in Fig. 4 where the detection efficiency is shown for four different beam energies. As this figure shows, this experiment (if approved) could run with 2.2 and 4.4 GeV beam energies for ease of scheduling between the different experiment halls.

3. The installation of the vacuum chamber requires a major downtime to work around the beam line.

Answer: The vacuum chamber is a part of the PRad-II and this proposal's experimental setup. The anticipated downtime for installation of the setup, including the vacuum chamber, will be similar to that of the previous PRad experiment (about 3 weeks).

4. Compatibility with PRAD-II installation: can the two experiments runs in sequence or the experimental configuration is significantly different?

Answer: There is no significant difference in experimental configurations between the PRad-II experiment and this proposal. If approved, this experiment could be run in sequence with PRad-II.

5. A 1um thick Tantalum target does not seem to be an issue since it is commercially available but special care must be made when handling the foil to prevent its destruction during beam-line pumping etc. The power upon the target will be less than 1 mW. Tantalum has a very high melting point (3017 C) and a moderate thermal conductivity, so we expect a temperature rise of only a few kelvin due to beam heating. But stresses from beam on/off may be problematic for such a thin

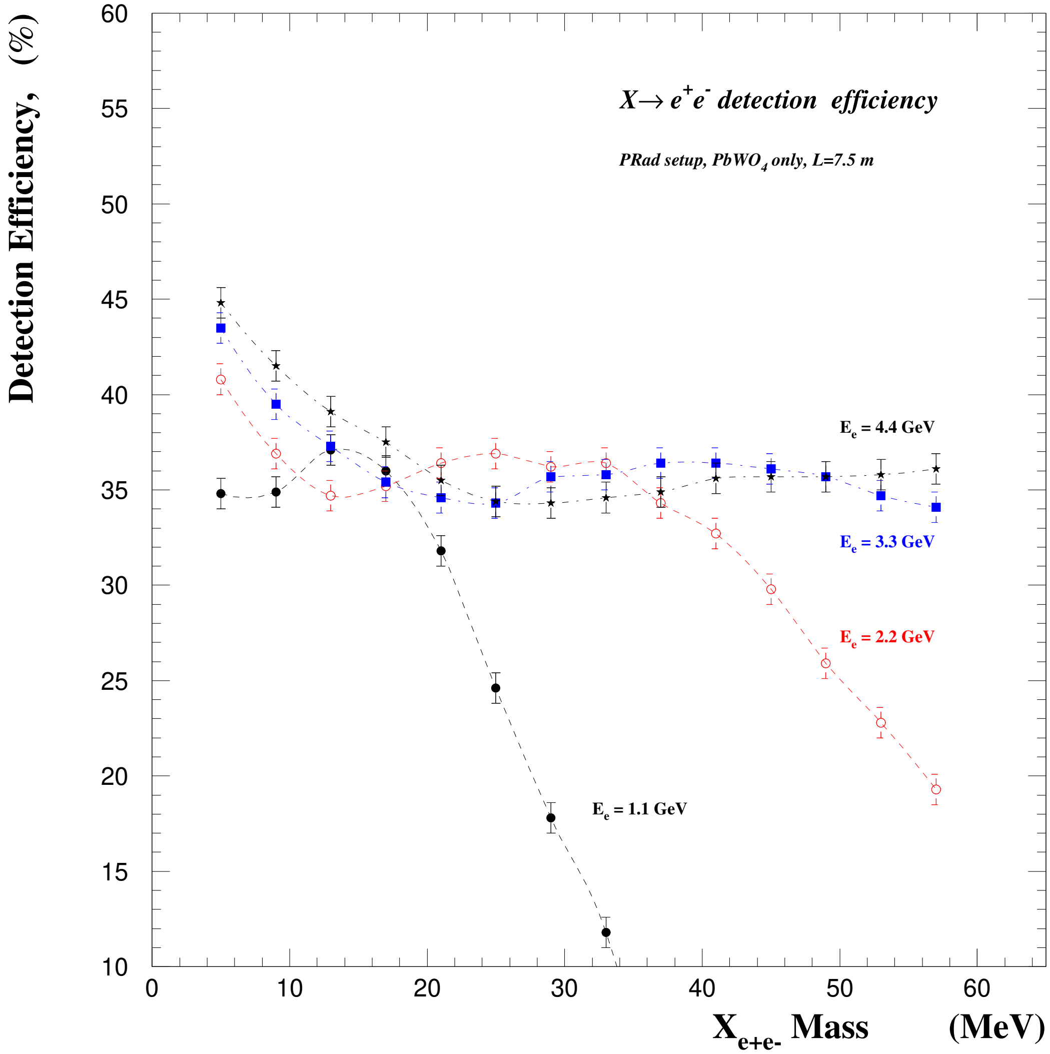

Figure 4: Detection efficiency of an $X \to e^+e^-$ decay for 1.1 GeV, 2.2 GeV, 3.3 GeV and 4.4 GeV beam energies. 1.1 GeV was not chosen due to the rapid efficiency drop at higher masses.

foil, so we suggest more than one sample on the ladder. Elemental tantalum does not pose a major safety risk.

Answer: Thank you for the suggestion and we indeed plan to have multiple target foils available on the target ladder for redundancy.

6. While the proposal indicates that the PRad hydrogen gas target will be in place, it does not state why it is in place. Perhaps only to act as a large diameter beam pipe? This would not be a trivial installation and would require significant modification to the system. It should be avoided if it isn't truly necessary. Also, Fig. 8 is incorrect: there is a short section of small diameter pipe between the PRad target chamber and its upstream turbo chamber.

Response: The PRad target chamber is proposed to be used in this experiment (if approved) to be able run in sequence with the PRad-II experiment. That would keep additional costs as low as possible. If the experiment runs as a stand alone installation, an appropriate diameter beam pipe would be more practical. As mentioned in the proposal, Fig. 8 is just a "schematic of the setup" and it is not meant to show the exact engineering design, including the short section of small diameter pipe.

7. During the PRad experiment, the vacuum in the large downstream chamber was poor, either due to leaks and/or outgassing. Additional pumps should be added to improve the vacuum.

Answer: Yes, we plan on addressing the poor vacuum in the large downstream chamber with additional pumps in the same manner as planned for the PRad-II experiment.

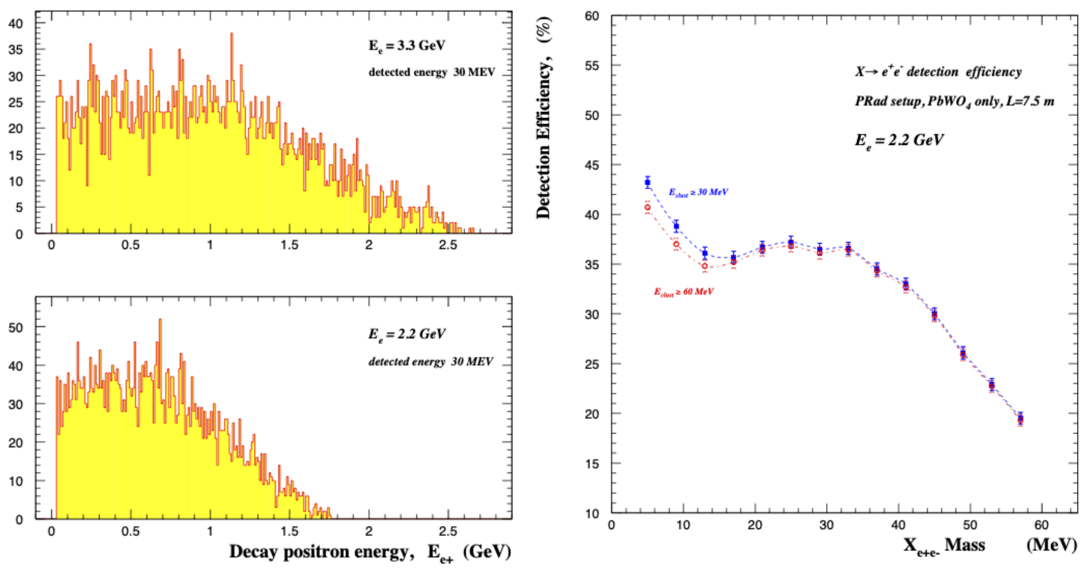

Figure 5: (left) The simulated energy spectrum of the detected positrons from the decay of a 10 MeV mass particle for a 2.2 GeV (bottom) and 3.3 GeV (top) beam energy with a 30 MeV minimum energy threshold. (right) The simulated geometrical detection efficiency as a function of e^+e^- invariant mass, for a minimum energy threshold of 30 MeV (blue) and 60 MeV (red).

8. The invariant mass range of the e+ e- pairs down to 10 MeV requires good energy resolution to detect low energy EM shower. HyCal performance for electron energy <1 GeV should be reported and discussed.

Answer: Good energy resolution is required for all e^+e^- detection for these low-mass range particles. The energies of the decay e^+e^- pairs for beam energies in the GeV range are predominantly defined by the energy of the initial virtual photon that produced the X-particle (the Lorentz-boost effect). As an example, the energy spectra of the decay positrons from a 10 MeV particle are shown in Fig. 5 (left) for both 3.3 GeV (top) and 2.2 GeV (bottom) beam energy for a 30 MeV minimum energy cut (as described in the proposal). To demonstrate the sensitivity of the detection efficiencies to the minimum energy cut, we doubled the minimum energy cut to 60 MeV (see Fig. 5 (right)).

As seen in this figure, the change in the detection efficiency is on the few percent level, mostly in the lower mass range.
As stated in the proposal, only the central $PbWO_4$ crystal part of the HyCal calorimeter will be used in this experiment. That will provide better invariant mass resolutions along the [3 - 60] MeV mass range (shown in Fig. 21 in the proposal). It is well known experimental fact that crystal scintillators (like the $PbWO_4$) provide excellent shower detection characteristics, even at the MeV energy range. A very recent measurement, Ref. [5], on similar $PbWO_4$ crystal detectors was performed at Mainz down to the $\sim$ 30 MeV energy range at room temperature (see Fig. 6), demonstrating the excellent performance of $PbWO_4$ detectors at MeV energies. Their fit: $\sigma_r(E) = \frac{2.92\%}{\sqrt{E}} + 1.18\%$ gives about 4% resolution when extrapolated to 1 GeV, which is slightly higher than measurements at higher energies carried out during the PrimEx experiment. For example, our measurements, shown in Fig.14 in proposal, performed with cooled crystals gives 2.7% at 1 GeV. The authors of the Mainz measurements explain this slight difference with similar arguments about the temperature of the crystals during the measurement.

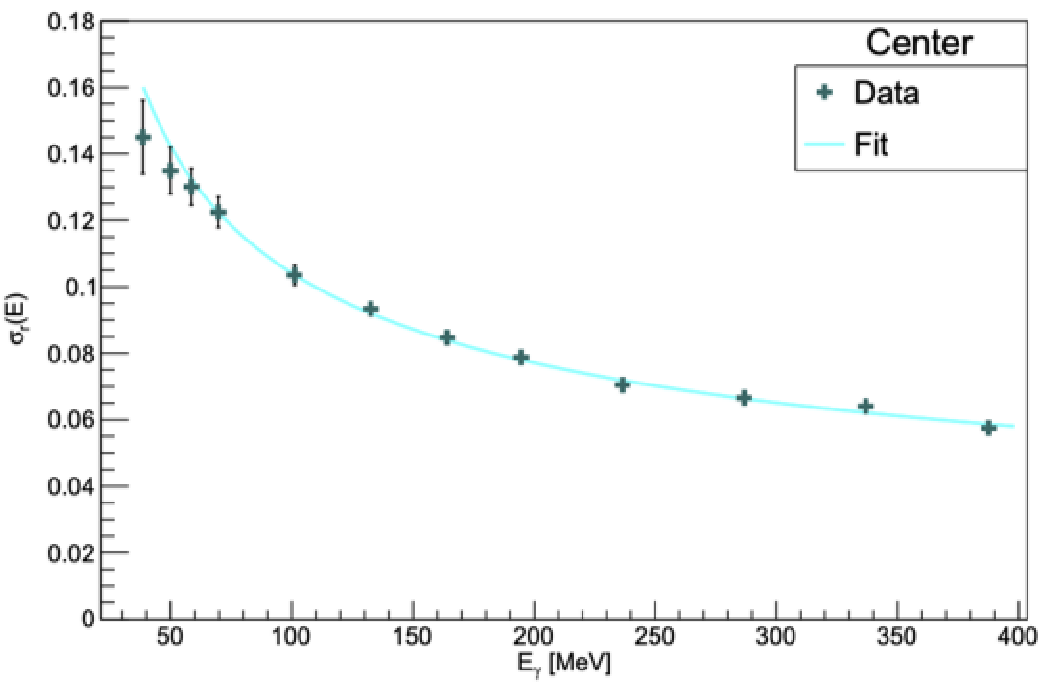

Figure 6: The measured relative resolution of the cluster energy response as function of the incident photon energy E_γ as reported by a recent Mainz experiment [5].

The resolutions shown in the proposal (Fig. 14 and 15) were measured during the PrimEx experiment, where the $\sim$1 GeV limit was due to lowest energy reached by the Hall B Photon Tagger during that experiment.

2 The ITAC Review

1. In order to demonstrate the feasibility of this experiment, namely to extract a signal that is 3 to 4 orders of magnitude smaller than the background, it is necessary to perform detailed simulations of all the background contributions in addition to the signal. Two experiments to search for dark matter candidates have been approved and carried out at JLab: APEX in Hall-A and HPS in Hall-B. In particular, HPS with similar kinematics to this experiment shows the fraction of Bethe-Heitler events is about 70% of total e+e- pairs. There are several software tools available that allow the simulation of the signal and the backgrounds to establish a firm understanding of the signal to background ratio and the analysis workflow to be applied to the data. This has not been done in this proposal. The background simulations used to estimate the S/B ratio are not realistic and do not include all the processes contributing to it.

Answer:

We certainly have done enough Monte Carlo simulations necessary to estimate the expected backgrounds with adequate level of precision. The statement that this proposal has a similar kinematics as the HPS experiment is simply not correct. It could have similar physics processes at the beam-target interaction region but, this proposed experiment is significantly different at both tracking of produced secondary particles and their detection methods. For example, (a) both HPS and APEX are detecting the final 2 leptons only; (b) HPS (and APEX) are using magnetic field to deflect the produced leptons in their detectors. In contrast, in this proposal: (a) we require the detection of all 3 final state particles at the trigger level; and (b) we use a non-magnetic method with a calorimeter/GEM detection of the secondary particles in the very forward solid angle range.

The 2-lepton detection method with a magnetic field (HPS and APEX) leaves a relatively large phase space for the production of many background channels, and, in addition, it also directs a significant amount of e^+e^- pairs produced in the target within a very narrow cone (a process with one of the largest cross sections) towards the detection aperture. The 2-lepton detection method also does not allow any energy conservation or co-planarity selection criteria to be applied. On the contrary, the proposed method is significantly less sensitive to the e^+e^- pairs produced in the target, simply allowing for most of them to pass either through the central non-sensitive part of the detectors ($12{\times}12$ cm^2), or if they hit the PbWO4 calorimeter to be rejected by the minimum shower separation criterion. Finally, the detection of all 3 particles in this proposal allows two additional selection criteria: (a) conservation of the total energy in the reaction; (b) coplanarity between the scattered electron ($e^{'}$) and the virtual photon that produced the e^+e^- pair (a very effective selection criterion for the suppression of: (a) combinatorial background; and (b) events with higher multiplicity.

The statement that the background simulations are not done with appropriate software packages is not correct either (please see our answer to the TAC Question # 1, the text is repeated here). We have performed the background simulations in two different ways. As described in section 6 (pg 22) of the proposal, a comprehensive simulation of the experiment was carried out using the GEANT Monte Carlo simulation package developed for this experiment. This simulation takes into account realistic geometry of the experimental setup and detector resolutions. All physical processes included in the standard GEANT package had been activated and tested during these MC simulation processes. The results of these simulations are presented in the proposal (Fig. 24, left) as the estimated background level for the beam time equivalent to 3.5 seconds. Based on this result (which is limited by statistics due to CPU time) we estimated the epsilon reach in Fig. 27. We continued these simulations for the last month, the new results are presented here. As stated in the proposal, the key advantage of this experiment is the detection of the 3 charged particles which arguably helps to suppress the background. A second simulation was performed using the MADGRAPH5 event generator [2], also used by the HPS collaboration [1]. First, using MADGRAPH5 we generated a large sample (2M events) of trident background events including the Bethe-Heitler, radiative and interference processes. Then, these events were fed into the same GEANT simulation package that was used for the signal processing to trace them through the experimental setup and detection of events. The resulting simulated background for 200 seconds of equivalent beam time is shown in Fig. 1 (left). The background shape is fit to a sum of Landau + log + constant distribution. The fit is then used to scale the background counts to 30 days of beam time with the number of events sampled bin-by-bin, as shown in Fig. 1 (right). Fig. 2 shows comparison of the background results performed with two methods. There is a slight shape differences (expected) between the two methods *vs.* mass. However, the simulated background difference is only on the level of 37% for the integrated counts over the full mass range (14016 *vs.* 10571 events). With that, the two simulations are in general agreement with each other with discrepancies that are acceptable for the level of uncertainty in these type of background simulations. These background distributions are used to estimate the epsilon *vs.* mass sensitivity. The difference in sensitivity when using the first and the second simulation is shown in Fig. 3.

2. The coplanarity cut can only be used for reducing random and 4 cluster backgrounds and not for purification of the 3 cluster signal events.
Answer: Please see our Answer in the previous Statement #1 regarding this Question. In this proposed experiment we do not claim that the coplanarity cut will purify 3-cluster physical events. Rather, the coplanarity cut is used to reject random uncorrelated clusters. This cut is very powerful in that regard, as can be seen in the analysis of PRad data documented in Appendix A of the proposal (Figures 30-32).

3. The expected energy range of the detected leptons in the calorimeter ranges from 3% of the beam energy to 70%. While the PRad experiment measured leptons down to about 1 GeV (fig. 14,15), this experiment requires detection of 60 MeV electrons. It has not been shown that this is possible with the calorimeter and at the same time control the background rates. Later in the proposal where the trigger rate estimates are discussed the measured energy range of the leptons is expanded to 2% to 85% of the beam energy.
Answer: This proposal plan to setup a hardware trigger from 30 MeV to 80% of the beam energy for all three (3) individual clusters energies. In addition, the hardware trigger will also select events with total energy of three clusters grater than 70% of the beam energy. As it is stated in the proposal, the PbWO4 central part of the HyCal calorimeter will be used in this proposed experiment. We specially chose to use the crystal detectors to have a very good detection characteristics (both in energy and position) in the 30 MeV to about 3 GeV range. It is well known experimental fact that crystal scintillators (like the $PbWO_4$) provide excellent shower detection characteristics, even at the MeV energy range. A very recent measurement, Ref. [5], on similar $PbWO_4$ crystal detectors was performed at Mainz down to the $\sim$ 30 MeV energy range at room temperature (see Fig. 6), demonstrating the excellent performance of $PbWO_4$ detectors at MeV energies. Their fit: $\sigma_r(E) = \frac{2.92\%}{\sqrt{E}} + 1.18\%$ gives about 4% resolution when extrapolated to 1 GeV, which is slightly higher than measurements at higher energies carried out during the PrimEx experiment. For example, our measurements, shown in Fig.14 in proposal, performed with cooled crystals gives 2.7% at 1 GeV. The authors of the Mainz measurements explain this slight difference with similar arguments about the temperature of the crystals during the measurement. The resolutions shown in the proposal (Fig. 14 and 15) were measured during the PrimEx experiment, where the

$\sim$1 GeV limit was due to lowest energy reached by the Hall B Photon Tagger during that experiment.

4. The expected signal to background rates presented in fig. 26 are unrealistic where the S/B ratio for a 17 MeV candidate is about 1/10 in the left plot while assuming an epsilon of 0.001 in the legend. A realistic S/B ratio is of the same order as the value of epsilon for such experiments. The argument that ep-elastic, Moller and Bethe-Heitler backgrounds are all kinematically suppressed and only the radiative process is left as the background is not realistic, in particular with an open detector configuration with no magnetic separation and shielding. This will also lead to a background shape that is more complicated to what is shown (fig. 26) and a simple functional form fit approach over the whole mass range will not be possible.
Answer: As mentioned in the caption of Fig. 26, this figure is for "illustration purposes only". In this figure we are only trying to show the width of the invariant mass peaks for the X particles of various masses. It does not show the expected background rates. On the other hand the comparison between the two background simulations and the analysis of the PRad calibration data on ^{12}C (Fig. 32 in the proposal) all conclusively demonstrate that we have made a reasonable estimate of the background rates. In fact, it is shown by our background simulations that a significant part of the Bethe-Heitler events are indeed the background in this experiment. As we stated several times, we have performed background simulations in two ways using most software packages appropriate for this experiment (see our answers to TAC Question #1 and ITAC Question #1).

5. Comparing the carbon data analysis shown in the Appendix with a MC simulation that includes all possible backgrounds would show the feasibility and sensitivity of this experiment.
Response: The carbon data is statistics limited as it was used only for systematic checks in the PRad experiment. A comparison of the shape of Figure 32 with the shape in Figure 24 (right) shows reasonable agreement between the carbon data and the simulated background.

6. This proposal is compatible with the existing HyCAL but requires a different DAQ setup. The proposed flash ADCs require about a 1 million US $ investment and does not include the required VXS crates with CPU, trigger interface and switch slot modules. It would however make the NIM crate system forming the trigger energy sum obsolete as this can be done with the flash ADC system. The DAQ will not be able to read out full wave forms at a trigger rate of 25kHz.
Answer: The updated DAQ is a part of the approved PRad-II experiment and the collaboration is exploring both internal JLab electronics pools to borrow for this experiments and/or external funding to upgrade the HyCal DAQ.
The NIM crate system forming the trigger is one of the integral parts of the HyCal calorimeter (it is using a completely separate, the dynode signals from each shower detector). That is only why we decided to leave it in the presented DAQ layout. We agree that the total sum can be done with the new flash ADC system. The statement that DAQ will not be able to read out full wave forms at a trigger rate of 25 kHz is simply not correct and it contradicting to DAQ systems already running at JLab.

7. The decay length of the dark sector particle in the proposed phase space search is of order 1mm (eq. 2 of Ref 7) or less. In order to measure such a decay length, sub mm tracking resolution is needed which is not attainable by simply adding additional tracking to the proposed experimental setup (referring to page 25 last paragraph).
Answer: We do not state in the proposal that the decay length information will be used in the event selection process. This proposed experiment is not a displaced vertex search experiment. In the sentence prior to the one referenced in the Question, we state *"As designed this proposal does*

not have sufficient vertex resolution to measure the displaced decay vertex.". The tracking system in this proposal (two GEM planes) are designed to select particles coming from the vacuum chamber window and events not from the target (see Fig. 18 in the proposal).

8. Before scheduling this experiment with the non standard 3.3 GeV beam energy, it would be prudent to expect publishable results from the first run with a standard beam energy of 2.2 GeV.
Answer: We proposed 3.3 GeV beam energy due to its good detection efficiency relative to 2.2 GeV (see Fig. 20, in the proposal), as well as, to have a better chance running this experiment (if approved) during the CEBAF low-energy run periods. As shown in Fig. 4, a more standard beam energy of 4.4 GeV would also be acceptable for this experiment. However, We agree that for the first publishable results the 2.2 GeV beam is a better choice.

9. The availability of APV-25 chips will be very limited in the future and an alternative choice(s) should be identified for the GEM readout.
Answer: For the smaller size GEM chambers to be used in the proposed experiment the required amount of APV-25 chips are already on-hand with the UVA group. However, we will also look for an alternative choices as contingency.

10. Target foil: We have no experience with 1 mu thick Ta foils. The 1 mu Fe foils previously used in the Hall A and C Moeller polarimeters were manageably delicate but sometimes were delivered with pinholes.
Answer: We plan to have multiple target foils available on the target ladder for redundancy, thank you.

11. Trigger rate: Although purely electromagnetic processes may dominate the detector rates, electron hadron-production such as (e,e'pi) or (e,e'rho) is likely to contribute significantly to the "¿ 0.7*Ebeam" trigger rate in this experiment. Similarly, electromagnetic background contributions that were underestimated in the simulations will also affect the expected trigger rates.
Answer: The cross sections for hadron productions (like the pi or rho) are usually 2-3 orders of magnitude smaller than the pure EM processes used to estimate the trigger rates. We did not intend to estimate the trigger rate with a sub-percent precision in this proposal. Please see our answers to TAC Question #1 and ITAC Question #1 demonstrating that the background level is estimated correctly.

12. X $\rightarrow$ e+e- acceptance: The kinematics are admittedly complicated, and it is beyond our scope to do a full simulation, but we have tried to check the simulation to the extent feasible.
a. Using the angle formulae in Ref [7] for the 2.2 GeV beam energy, and the 7.5m distance between the target and the calorimeter front face, it appears that the majority of the X $\rightarrow$ e+e- pairs for masses below about 20 MeV/c^2 go down the beam hole. The situation is worse at 3.3 GeV beam energy. Qualitatively, this behavior is not unexpected: with decreasing mX, both the -tmin and the X$\rightarrow$e+e- opening angle decrease. Also, in the limit of mX$\rightarrow$me, normal experience with QED pair production must be recovered.
b. It is perplexing why the simulated accepted in Figure 20 of the proposal does not indicate this expected rapid drop for lower X masses. While it is possible to detect an X$\rightarrow$e+e- with a mass of 10 MeV/c^2 in the proposed setup, this requires the exchange of a higher virtuality photon. Most of the FOM in the X rate equation from ref[7] is from low virtuality photons which leads to the "C" 5 approximation arising from integration of equation A17 using the screened nuclear form factor in equation A18.

Answer: We will detect clusters within the energy range of 30 MeV to 70% of the incident beam energy. This fact will allow for the X-particles production by virtual photons within a wider energy range in the forward direction. The capability of having an events produced in a wider energy range and angles in a single experimental setting is one of the important features of our experiment which stands in contrast to all magnetic spectrometer methods. This fact alone explains the problems stated in the part (a) of this Question. If one takes the beam energy (ether 2.2 or 3.3 GeV) as the initial energy of the produced X-particle then the result for the acceptance will be close to zero, since, as stated in the question, the events will go down the beam hole. In order to calculate the acceptance correctly the entire energy interval of the virtual photons must be considered. For the part (b) of this Question: for the same reasons, as explained above, the detection efficiencies, presented in the proposal in Fig. 20, behave as expected and are correctly simulated for the proposed experiment.

References

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[2] E. Conte, B. Fuks and G. Serret, Comput. Phys. Commun. **184**, 222-256 (2013) doi:10.1016/j.cpc.2012.09.009 [arXiv:1206.1599 [hep-ph]].

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