Proposal to Search for a "Dark-Omega" Vector Boson in Direct Electroproduction Processes

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We propose performing an experiment to search for a new hidden sector vector boson coupled via baryonic current (V_B or "dark omega") in the (140–650) MeV mass range. It will be produced on low-Z fixed targets using high energy intense electron beams. The multi-gamma decay of this particle will be detected by a high resolution and large acceptance crystal calorimeter providing a few MeV level resolutions in $M_{\gamma\gamma\gamma}$, critically important for the signal to background separation. The motivation, feasibility studies of the setup and estimation of the realistic parameter space of the proposed experiment is discussed.

1 Introduction

Over the last several years there has been increased theoretical and experimental activities to search for a hidden sector dark photon or A' particle in the MeV-GeV mass range, weakly coupling to the Standard Model (SM) matter through a kinetic mixing mechanism ([1] and references within). These search experiments mostly rely on an assumption that the new particle is coupling predominantly to the leptonic field. Therefore, in most of cases, they look for the production of A' in the Coulomb field of heavy nucleus and consequently decaying to leptonic pairs (e^+e^- or $\mu^+\mu^-$). On the other hand, several other additional $U(1)'$ gauge symmetries and associated vector gauge bosons were proposed soon after the electroweak $SU(2) \times U(1)_Y$ model that are one of the best motivated extensions of the SM. One successful model, a dark-sector gauge vector boson, coupling to the baryonic matter (quarks), was proposed in 1989 [2] and subsequently discussed extensively in the literature (see references in [3]). S. Tulin in his recent article ([3] by analyzing the properties of the interaction Lagrangian and requiring the low-energy symmetries of QCD, demonstrated that this new particle can be assigned the same quantum numbers as the ω meson, J^{PC}=1^{--} with the leading decay channel $V_B \to \pi^0 + \gamma$ for the $M_\pi \leq M_{V_B} \leq 650$ MeV mass range. It was also suggested to search for these new particles in rare radiative decays of light neutral mesons [3, 9]. Here, we are suggesting an alternative experimental approach to search for this new particle in their direct electro-production channels in fixed-target experiments covering the same mass range.

2 Proposed experiment

We propose searching for V_B in direct electroproduction channels $e + A \to e' + V_B + (X) \to e' + \pi^0\gamma + (X) \to e' + \gamma + \gamma + \gamma + (X)$. These particles will be produced on low-Z fixed targets in forward directions by a 11.5 GeV electron beam and they will be identified as a "*bump*" on the continuous experimental background of the $M_{\gamma\gamma\gamma}$ distribution. Four electromagnetic particles, e' and three decay photons will be detected in a crystal calorimeter. One of the major advantages of this experiment is that a high vacuum will be provided between the solid production target and the detection system. This will allow a significant minimization of the direct (by the beam) or secondary production of known particles in between the target and the detectors, which is the main source of so called "kinematical reflections", a typical problem for many other search experiments. The scattered electrons, e' will be detected in forward direction ($\sim 0.5^\circ - 5^\circ$) and within an energy range of (0.5–1.5) GeV to select forward and high energy virtual photons in the reaction. That, in turn, will enhance the production of forwardly directed energetic V_B particles to boost the three decay photons to the forward calorimeter acceptance (see Sec. 4.1). We propose to run this experiment in parallel with the neutral pion form factor $F_{\gamma^*\gamma\pi^o}$ measurement at very low Q^2. Therefore, the trigger in the experiment will be formed on two levels: first level, $E_{calor} \geq 8GeV$, and second level, $N_{cluster} \geq 3$.

3 Experimental setup

We propose using the PRad experimental setup currently being developed for the proton charge radius measurement with a sub-percent precision to address the *"proton charge radius puzzle"* in nuclear and atomic physics [4, 5]. This stand-alone setup consists of the following main elements (see Fig. 1): (i) windowless hydrogen gas flow target; (ii) a set of X-, Y-GEM coordinate detectors; (iii) high resolution, large acceptance PrimEx HyCal electromagnetic calorimeter; and (iv) a vacuum box with a single thin window at the calorimeter only, spanning ~ 5 m, with a 1.7 m diameter thin Al window at the front of HyCal. The Al window will have a thickness of 2.5 mm, with a 4 cm diameter and thin-walled cylindrical Al-pipe attached to the central part of the window for the passage of electron beam. This vacuum pipe is also passing through the centers of GEM and HyCal to reduce the beam-related electromagnetic background in the experiment. For this experiment we plan to use the same gas flow target mechanical structure, attaching thin 0.1-0.3% R.L. solid ^{12}C films to the target ladder, which is able to move remotely on both X- and Y-directions perpendicular to the beam. The HyCal calorimeter [6] is a hybrid electromagnetic calorimeter consisting of two different type of shower detectors, 576 Pb-glass modules ($4.0 \times 4.0 \times 45$ cm^3) and 1152 PbWO$_4$ crystal modules ($2.05 \times 2.05 \times 18.0$ cm^3) in the central part of the calorimeter. The central 2×2 PbWO$_4$ modules are removed from the assembly (4.0×4.0 cm^2 hole) providing passage of the incident electron beam through the calorimeter. The calorimeter with its cross sectional area of 118×118 cm^2 will be located in the beam line at a distance of ~ 5 m from the target, providing a large geometrical acceptance in the experiment. The incident electrons with an 11.5 GeV energy will scatter off a ^{12}C target and together with the 3 decay photons from the produced V_B particles will be detected in the HyCal calorimeter. This experimental setup is nearly ready for the PRad experiment.

4 Expected results and uncertainties

In order to investigate the detection efficiency (including the geometrical acceptances), uncertainties in measured quantities and expected results, a full Monte Carlo (MC) simulation code based on GEANT3.21 package has been developed. This program takes into account the realistic geometry of the setup, including all resolutions of the detectors. It generates events based

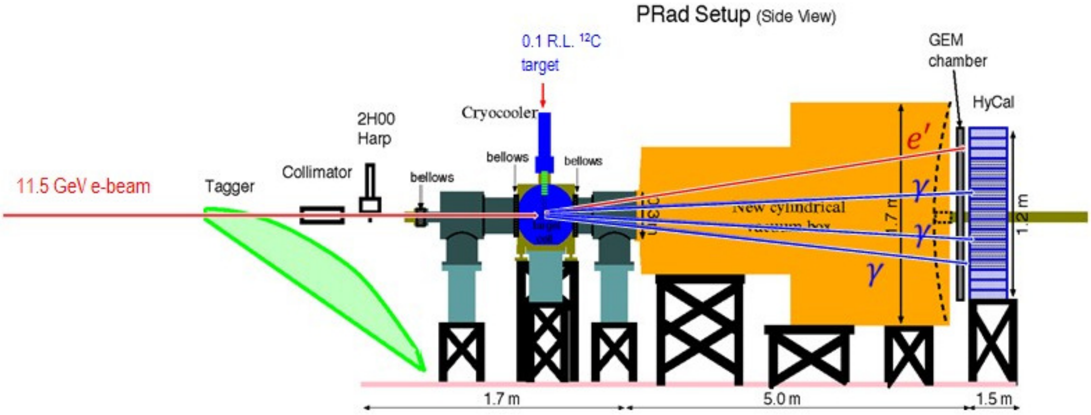

Figure 1: Schematic layout of the PRad experimental setup (not to scale). It will be used for the proposed experiment.

on estimated cross sections which are then traced through the target and detection system. The MC generated events are then analyzed to reconstruct the "measured" experimental quantities.

4.1 Detection efficiency

Four final state particles will be detected in this experiment: the forward scattered electrons and three decay photons from V_B. The scattered electrons within the (0.5–1.5) GeV energy range will be detected in order to select energetic and forwardly directed V_B particles to maximize the detection efficiency in the experiment. The simulated detection efficiency *vs.* target to calorimeter distance are shown in Fig. 2, Left. As it is seen from these simulations, the currently existing $Z = 5$ m distance for the PRad setup, is also well optimized for this proposed experiment, with relatively large (30–60)% detection acceptances for the (140–650) MeV mass range.

4.2 Invariant mass resolution

For the fixed target to calorimeter distance ($Z = 5$ m) the HyCal position and energy resolutions are defining the $M_{\gamma\gamma\gamma}$ invariant mass resolutions. The inner PbWO$_4$ crystal part of the HyCal calorimeter has excellent energy and position resolutions: $\sigma_E/E = 2.6\%/\sqrt{E}$ and $\sigma_{x,y} = 2.5$ mm$/\sqrt{E}$ greatly improving the $M_{\gamma\gamma\gamma}$ resolution. The outer Pb-glass part of HyCal has a factor of 2 less resolution in both energy and position reconstructions. The distribution of simulated invariant masses are shown in Fig. 2, Right, for three typical values of M_{V_B}. The proposed experiment will provide an MeV-level resolutions in reconstructed M_{V_B}, which is critically important for the signal-to-background separation (see Sec. 4.5).

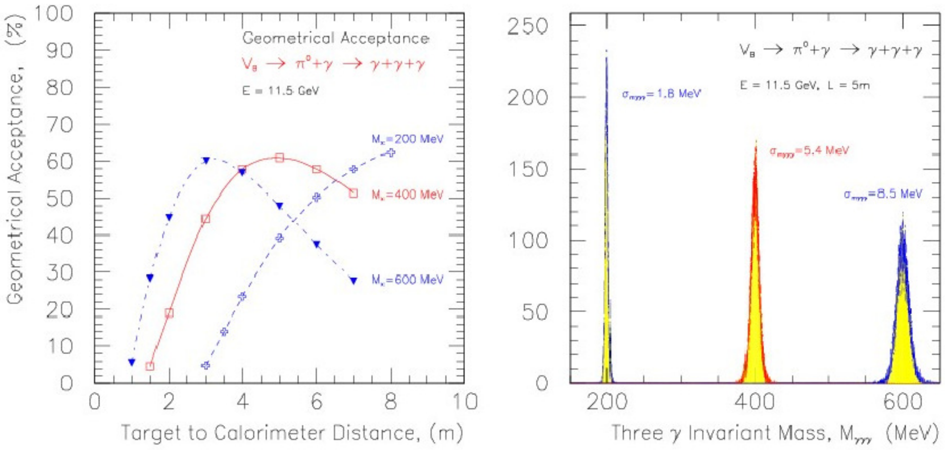

Figure 2: Left: Detection efficiency *vs.* Z for three typical M_{V_B} masses. Right: Distribution of reconstructed invariant mass for three M_{V_B}: 200 MeV, 400 MeV and 600 MeV.

4.3 Displaced vertex resolution

Solid thin-targets offer an additional selection mechanism in search experiments. That requires reconstruction of the decay vertex on event-by-event bases. This usually done by additional set of tracking detectors, in cases when the decay particles are charged [1]. In the proposed experiment the decay particles are three photons, however, there is an interesting way to determine the $V_B \to \pi^0\gamma$ decay vertex by using the $\pi^0 \to \gamma\gamma$ channel, assuming that the M_{π^0} is known. An example of the simulated vertex distribution is shown in Fig. 3, Left for M_{V_B}=400 MeV particles produced in forward direction. Though, our resolutions on this particular selection criterion (cm-level) are not as good as in the case of the charged-particle tracking [1], it can still be used very effectively in search experiments testing different ranges of coupling constants and mass (see Fig. 4).

4.4 Experimental backgrounds

The detection system in this experiment will be able to separate photons from the electromagnetic charge particles in the final states (using GEM and HyCal). Therefore, only events with three energetic photons ($E_\gamma > 0.5$ GeV) in final state will be considered as a background process *vs.* signal events. The potential sources of the background events are: (a) accidental coincidences of events with multi-photon bremsstrahlung processes (beam background); (b) production of particles decaying into three or more energetic photons (physics background). At this stage we have identified and simulated two major physics processes contributing to the physics background: forward electro-production of $2\pi^0$ mesons from the target and second, forward production of ρ mesons with their consequent decay into $\pi^0\gamma$. In both cases the π^0's decay into 2γ. The results of MC simulations for two physics background processes are shown in Fig. 3, Right, for 10 days of beam time (with E_e=11.5 GeV, $I_e = 0.1\mu$A, and 0.1% R.L. ^{12}C target). The beam background was also simulated, it has a typical exponential drop *vs.* $M_{\gamma\gamma\gamma}$

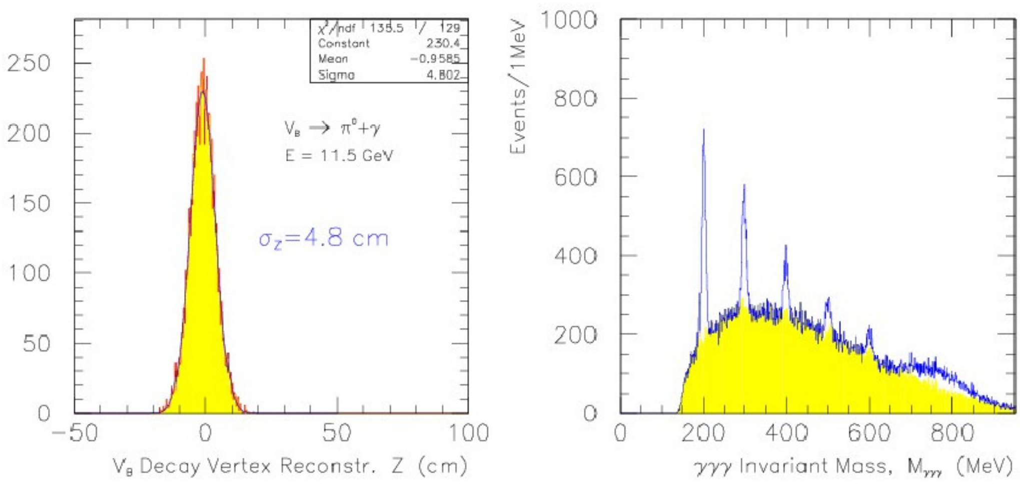

Figure 3: Left: Distribution of reconstructed vertex position. Right: Distribution of total physics background *vs.* $M_{\gamma\gamma\gamma}$. The $2\pi^0$ production process is the dominant background for this experiment (the yellow shaded area), the $\rho \to \pi^0\gamma$ background is the small bump at (650-850) MeV range. The five narrow distributions are the signal events simulated for M_{V_B}= 200, 300, 400, 500 and 600 MeV.

with an order of magnitude smaller than the physics backgrounds (not shown in Fig. 3).

4.5 Sensitivity of the proposed experiment

For the simulation of signal events the V_B production cross sections are required. Currently, theoretical activities are in progress to estimate these cross sections based on realistic models [7]. At this stage, based on general physics considerations, we assumed that these cross sections can be estimated by [8]: $\sigma(\gamma + P \to V_B + X) \sim (\alpha_{em}/\pi)(\alpha_B/\alpha_{em})(M_\omega/M_B)^2\sigma(\gamma + P \to hadrons)$. Then, if we take for $\sigma(\gamma + P \to hadrons) \sim 1\mu$b, we obtain $\sigma(\gamma +^{12} C \to V_B + X) \sim 1$ pb for V_B coupling constant α_B =10^{-8} and mass M_B=200 MeV. The corresponding experimental yields simulated for 10 days of beam time (E_e=11.5 GeV, I_e = 0.1μA, 0.1% R.L. ^{12}C target) are shown in Fig. 3, Right for five different masses of V_B boson. These yields are shown on the top of estimated backgrounds simulated under the same conditions. The sensitivity of this experiment to search for V_B bosons on 5σ level is plotted in Fig. 4 (short-dash red line). This proposed experiment, as it can be seen from the plot, has a good potential to improve the exclusion limits on the coupling constant, α_B for about one order of magnitude *vs.* other experiments/projects (other exclusion limits in Fig. 4 are discussed in [3]).

4.6 Summary

We are proposing a new fixed-target experiment to search for hidden sector leptophobic particles, V_B in the (140-650) MeV mass range. These particles will be produced in a low-Z target by an 11.5 GeV electron beam and detected by their $V_B \to \pi^0\gamma \to \gamma\gamma\gamma$ decay channel. The forward

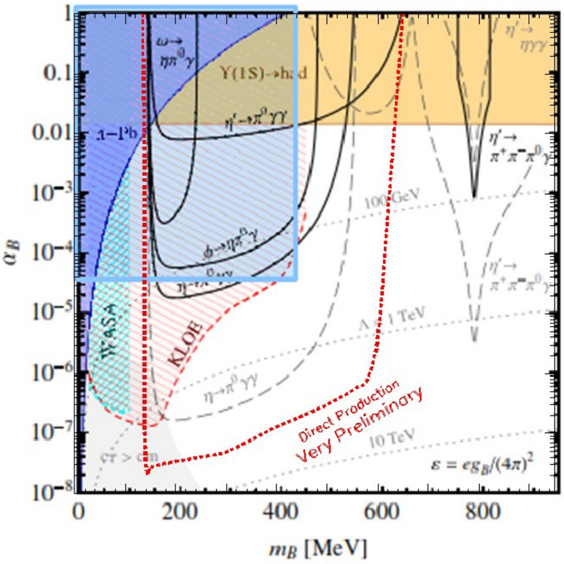

Figure 4: Current exclusion regions on V_B boson coupling *vs.* mass. The sensitivity region of the proposed experiment is shown with short-dash red line. For discussion of other exclusion limits see [3]).

scattered electrons ($\sim$ 1. GeV) and three decay photons will be detected by the high resolution and large acceptance HyCal calorimeter. A narrow resonance ($\sim$ 3 MeV) over the continuum experimental background will signal observation of these particles. The capability of vertex reconstruction (though with a moderate resolutions) will add a new dimension in filtering the background processes. These types of direct production experiments are fully complimentary to already suggested projects to search in rare radiative decays of light mesons [9].

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