Theoretical Framework for the Analysis of Hidden Light Gauge Boson Searches

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Various kinds of physics phenomena can be probed by electron scattering fixed target experiments. Recently, fixed target experiments investigating the reaction $e(A, Z) \to e(A, Z)l^+l^-$, where $(A,\, Z)$ denotes a nucleus of atomic number Z, were utilized to search for physics beyond the Standard Model at modest energies. In these experiments a search for a small, narrow resonance in the invariant mass spectrum of the lepton-antilepton pair, arising from the exchange of a new light gauge boson $\gamma\,'$ coupling to the dark sector as well as very weakly to standard model particles, is performed. Such a signal would appear as an enhancement over a smooth QED background, which therefore requires a precise understanding of the background. We present a theoretical analysis of the cross sections describing this process, which are then used to extract exclusion limits on the parameter space of the $\gamma\,'$, and compare our results to existing experimental data taken at MAMI.

1 Cross section calculations for exclusion limits

The calculation of an exclusion limit for the kinetic mixing factor ε^2, where the coupling of the γ' to charged particles is given by εe, as function of the γ' mass $m_{\gamma'}$ can be conveniently done by using Eq. (19) of Ref. [3] as approximation of the signal cross section $\Delta\sigma_{\gamma'}$, which relates $\Delta\sigma_{\gamma'}$ to the direct TL cross section $\Delta\sigma_\gamma^{\mathrm{TL}}$ given by the diagrams on the two left panels of Fig. 1. This upper bound for the kinetic mixing factor given in Ref. [3] reads

$$\varepsilon^2 = R\,\frac{\Delta\sigma_\gamma}{\Delta\sigma_\gamma^{\mathrm{TL}}}\,\frac{2\,N\,\alpha}{3\pi}\,\frac{\delta m}{m_{\gamma'}}, \tag{1}$$

where R is the exclusion limit for a possible peak found in experiment, $\Delta\sigma_\gamma/\Delta\sigma_\gamma^{\mathrm{TL}}$ is the ratio of the background cross section $\Delta\sigma_\gamma$, given by sum over all Feynman diagrams of Fig. 1, to $\Delta\sigma_\gamma^{\mathrm{TL}}$, N is a factor accounting for the effective degrees of freedom and δm is the mass resolution. Therefore the understanding of the background for these kind of experiments is essential. The precise knowledge of the ratio $\Delta\sigma_\gamma/\Delta\sigma_\gamma^{\mathrm{TL}}$ from theory is crucial to obtain an accurate exclusion limit. Furthermore, to achieve the best signal to noise ratio, one needs to analyze the kinematic structure of the individual background contributions. The signal cross section is largest when almost all energy is carried by the created lepton pair and in addition, the propagator appearing in the two SL diagrams, $(k - k' - l_+)^{-2}$, is suppressed, if the momentum is distributed nearly equally between the two leptons of the pair [5]. For beam and pair leptons of the same species,

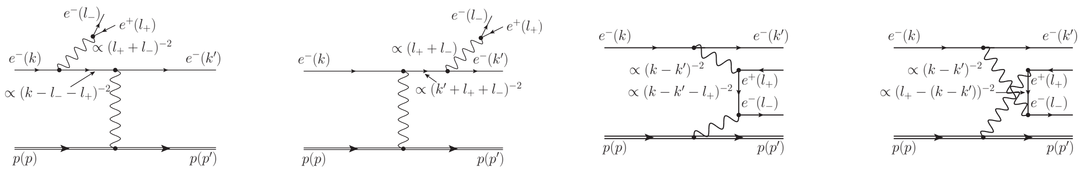

Figure 1: Direct tree level Feynman diagrams contributing to the $ep \to epl^+l^-$ amplitude. Left panels: Exchange of the timelike boson V and a spacelike γ (TL). Right panels: Spacelike boson V and a spacelike γ (SL).

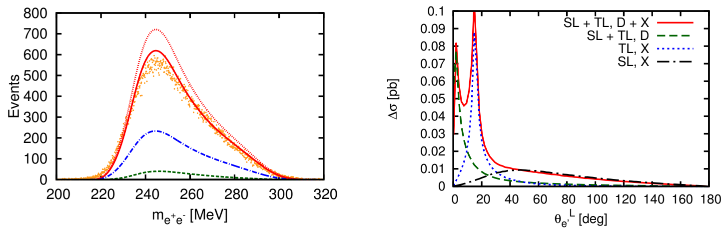

Figure 2: Left panel: Comparison of theory calculations and experimental data for a $m_{e^+e^-}$ bin width of 0.125 MeV. Right panel: Angular distributions per 0.5° with respect to the polar angle of the scattered electron for the MAMI 2010 experiment.

due to the indistinguishability, the amplitude needs to be anti-symmetrized and in addition to the discussed direct contribution the exchange term contributions need to be included in the analysis. Due to these contributions such a clean kinematical separation of signal and background is not possible anymore since the same kinematical structures which enhance the desired cross section are also contributing to the background cross section [10].

2 Comparison with data and predictions for MAMI and MESA

As seen on the left panel of Fig. 2, our calculation (solid curve) of the radiative background and the experimental data (points) [4] are in good agreement. Radiative corrections were estimated by applying those of the corresponding elastic scattering process. The influence of the radiative corrections is displayed by the solid and dotted curve in Fig. 2 which are calculated with and without radiative corrections, respectively. It is obvious from Fig. 2, that the applied radiative corrections lower the result of the theory calculation by an amount in the range of $10 - 20\,\%$. Obviously, our approximate treatment of the radiative corrections already provides a very good description, as theory and data already are in good agreement.
The dashed (dashed-dotted) curve shows the direct TL (SL + TL) cross section. It indicates, that a large contribution to the cross section results from the anti-symmetrization due to the indistinguishability of the scattered beam electron and the pair electron.

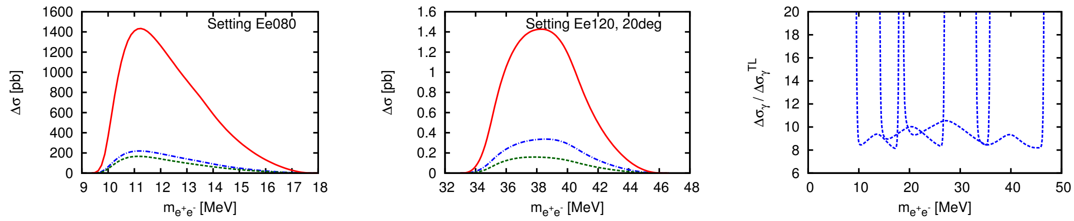

Figure 3: Left and center panel: Invariant mass distributions from the feasibility study for the MESA experiment for selected kinematic settings. Solid curve: SL+TL (direct + exchange term), dashed curve: direct TL, dashed-dotted curve: direct SL+TL. Right panel: Ratio $\Delta\sigma_\gamma/\Delta\sigma_\gamma^{\mathrm{TL}}$ of different settings for the planned MESA experiment.

The angular distribution with respect to the polar angle of the scattered electron presented on the right panel of Fig. 2 shows, that for the 2010 A1 experiment the crossed TL amplitude is responsible for a second peak in the background cross section compared to the direct amplitude (dashed curve) which only peaks at very forward scattering followed by a rapidly dropping tail. The exchange SL term nevertheless enhances the tail of the angular distribution significantly.

In 2012 a γ' search run has been started by the A1 collaboration, in which no signal was found. In this experiment 9 kinematic settings, starting from the one centered around $m_{e^+e^-} = 57\,\mathrm{MeV}$ up to one centered around $m_{e^+e^-} = 218\,\mathrm{MeV}$, are probed. For the chosen kinematical settings, which can be found in Tab. 2 of Ref. [10], we have performed the same calculations as for the 2010 setting. Due to the particular choice of kinematics in that experiment, the ratio $\Delta\sigma_\gamma/\Delta\sigma_\gamma^{\mathrm{TL}}$ has a value between $10 - 15$ in the probed mass range.
In Figure 4 our predictions for the exclusion limits on ε^2 for this set of kinematics are indicated by the dashed curve for an assumed integrated luminosity of around $10\,\mathrm{fb}^{-1}$.

MESA is aimed to provide a high intensity electron beam up to beam energies of about $160\,\mathrm{MeV}$ and thus should be ideally suited to probe the γ' parameter space at low masses. A feasibility study for carrying out this search by using two small spectrometers has been performed, assuming a Xenon target in order to obtain as large cross sections as possible [10]. The results for the obtained invariant mass distributions are shown on the right and central panel of Fig. 3. The kinematical settings we have calculated were chosen in such a way, that the full so-called $(g-2)_\mu$ welcome band is covered together with the MAMI 2012 settings, where the settings were optimized to obtain signal cross sections as large as possible while the QED background is suppressed. The projected limits from this study are shown in Fig. 4.

3 Conclusions

We have performed a detailed study of the underlying process of fixed target γ' searches. A comparison of our calculations with a sample of data taken at MAMI has been performed. We find that, after applying the leading order QED radiative corrections for the corresponding elastic electron-hadron scattering process, our calculations and the data sample are in good agreement. Using the cross sections obtained in our analysis, we are able to provide predictions for the expected exclusion limits for MAMI and MESA. Following our predictions, the exper-

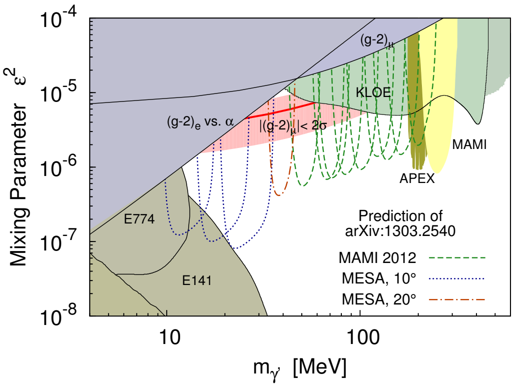

Figure 4: Compilation of existing exclusion limits and our predictions in the parameter space region currently accessible at fixed-target experiments. A detailed discussion of the different limits can be found in literature, e.g. Refs. [3, 4, 6, 10, 11]. The prediction of this work for the exclusion limit expected for the MAMI 2012 experiment is depicted by the dashed curves. The prediction for MESA is indicated by the dotted (dashed-dotted) curve for the setups with a central scattering angle of 10° (20°).

iments at MAMI and MESA will be able to probe the entire $(g-2)_\mu$ welcome band and in addition, increase the existing limits by one order of magnitude.

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