Theoretical framework to analyze searches for hidden light gauge bosons in electron scattering fixed target experiments


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The $\gamma'$ Parameter Plane for Visible Decays

- Pospelov (PRD 80)
- Bjorken et al. (PRD 80)
- MAMI (PRL 106)
- APEX (PRL 107)
- Blumlein, Brunner (PLB 701)
- KLOE (PLB 706, PLB 720)
- Gninenko (PRD 85, PLB 713)
- Davoudiasl et al. (PRD 86)
- Andreas et al. (PRD 86)
Theoretical framework to analyze searches for hidden light gauge bosons in electron scattering fixed target experiments
\( \gamma' \) Production from \( ep \rightarrow epe^+e^- \)

\[
\mathcal{M}_{\gamma', \text{TL}} \propto \frac{\varepsilon^2}{q^2 - m_{\gamma'}^2 + im_{\gamma'} \Gamma_{\gamma'}}
\]

\( \gamma' \) (TL)

\[
\mathcal{M}_{\gamma', \text{SL}} \propto \frac{\varepsilon^2}{q^2 - m_{\gamma'}^2}
\]

\( \gamma' \) (SL)

Signal: \( \gamma' \) will appear as sharp resonance from timelike production.
\( \gamma' \) Production from \( ep \rightarrow epe^+ e^- \)

\[
\begin{align*}
M_{\gamma', TL} & \propto \frac{\varepsilon^2}{q^2 - m_{\gamma'}^2 + i m_{\gamma'} \Gamma_{\gamma'}} \\
M_{\gamma', SL} & \propto \frac{\varepsilon^2}{q^2 - m_{\gamma'}^2}
\end{align*}
\]

\( \Gamma_{\gamma'} \) decay width of \( \gamma' : O(\text{eV}) \), if only SM decay allowed

**Signal:** \( \gamma' \) will appear as sharp resonance from timelike production
QED background: Direct diagrams (D)

\[\begin{align*}
e^{-}(k) & \to e^{+}(l_{+}) & \propto (l_{+} + l_{-})^{-2} & \to e^{-}(k') \\
& \propto (k - l_{+} - l_{-})^{-2} & p(p) & \to p(p')
\end{align*}\]

\[\begin{align*}
e^{-}(k) & \to e^{+}(l_{+}) & \propto (l_{+} + l_{-})^{-2} & \to e^{-}(k') \\
& \propto (k' + l_{+} + l_{-})^{-2} & p(p) & \to p(p')
\end{align*}\]

\[\begin{align*}
e^{-}(k) & \to e^{+}(l_{+}) & \propto (k - k')^{-2} & \to e^{-}(l_{-}) \\
& \propto (k - k' - l_{+})^{-2} & p(p) & \to p(p')
\end{align*}\]

\[\begin{align*}
e^{-}(k) & \to e^{+}(l_{+}) & \propto (k - k')^{-2} & \to e^{-}(l_{-}) \\
& \propto (l_{+} - (k - k'))^{-2} & p(p) & \to p(p')
\end{align*}\]
QED background: Exchange diagrams (X)

\[ e^-(k') \] \( \propto (l_+ + k')^{-2} \)

\[ e^-(k) \] \( \propto (k - k' - l^+)^{-2} \)

\[ e^-(l_-) \]

\[ p(p) \] \( \rightarrow \) \[ p(p') \]

\[ e^-(k') \] \( \propto (l_+ + k')^{-2} \)

\[ e^-(k) \] \( \propto (k' + l_+ + l_-)^{-2} \)

\[ e^-(l_-) \]

\[ p(p) \] \( \rightarrow \) \[ p(p') \]
Background vs. Signal

- Assume: $m_{\gamma'} = 230$ MeV, $\varepsilon^2 = 10^{-4}$
- Excess in 1 bin at $m_{e^+e^-} = 230$ MeV
Exclusion Limit Calculation

- **Approximation** of cross section ratio $\frac{\sigma_{\gamma'}}{\sigma_{TL}} = \frac{3\pi \varepsilon^2}{2N \alpha} \frac{m_{\gamma'}}{\delta m}$
  (Bjorken, Essig, Schuster, Toro, PRD 80)

- **Experimental Quantity:** $\sigma_{\gamma'+\gamma} \propto |M_{\gamma} + M_{\gamma'}|^2$

  $\Rightarrow$ **Decomposition:** $\sigma_{\gamma'+\gamma} = \sigma_{\gamma} + \sigma_{\gamma'} + \sigma_{\text{int}}$

### $\varepsilon^2$ Exclusion Limit from Data

$$\varepsilon^2 = \left( \frac{\sigma_{\gamma'} + \gamma}{\sigma_{\gamma}} - 1 \right) \left( \frac{\sigma_{\gamma}}{\sigma_{TL}} \right) \left( \frac{2N \alpha}{3\pi} \right) \left( \frac{\delta m}{m_{\gamma'}} \right)$$

$\Rightarrow$ How well do we know $\sigma_{\gamma}$?

$\rightarrow$ approximation of hadronic current, radiative corrections...
QED Background: Double Virtual Compton Scattering

Double virtual Compton scattering amplitude:

- **Heavy nucleus** target: *negligible* (large target mass); in the approximation used: low computing effort
- **Proton**: can be *notable* contribution, cross checked with VCS data

**Double VCS contribution is included**
Technical Challenges

Experiments have finite acceptances

⇒ Evaluate \( \Delta \sigma = \int \frac{d\sigma}{d|\vec{l}_+| d\Omega_+ d\Omega_- d\Omega_{e'} dq'^2} \) within the exp. limits

Problem: 8-fold numerical integration and integrand contains several strongly peaked structures

Key Question:

Try to do calculation as “exact” as possible or apply approximations? → “exact”
Technical Challenges

Experiments have finite acceptances

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Run calculations on General Purpose Graphics Processing Units (GPGPU) (nvidia Tesla)
MAMI 2010 (I)

MAMI test run 2010 (Merkel et al. (A1), PRL106)

- Data and theory in **good agreement**
- Radiative corrections are crucial to describe the data accurately
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MAMI test run 2010 (Merkel et al. (A1), PRL106)

- **Data and theory in good agreement**
- Radiative corrections are crucial to describe the data accurately
- Large contribution from exchange term
MAMI 2010 (II)

Direct: SL background dominating

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MAMI 2010 (II)

- **Direct**: SL background dominating
- **Exchange**: SL and TL contribution of comparable size
- Background from **exchange term twice as large as direct** contribution
MAMI 2010 (III)

\[
\Delta \sigma_{\gamma}^D / \Delta \sigma_{\gamma}^{TL} \approx 5 - 15
\]
MAMI 2010 (III)

\[ \Delta \sigma_D^\gamma / \Delta \sigma_{\gamma \gamma}^{TL} \approx 5 - 15 \]

\[ \Delta \sigma_{\gamma^+X} / \Delta \sigma_{\gamma \gamma}^{TL} \approx 15 - 25 \]
\[ \frac{\Delta \sigma_D^\gamma}{\Delta \sigma_{\gamma}^{\text{TL}}} \approx 5 - 15 \]

\[ \frac{\Delta \sigma_D^{\gamma + X}}{\Delta \sigma_{\gamma}^{\text{TL}}} \approx 15 - 25 \]

exchange contribution increases \( \frac{\Delta \sigma_{\gamma}}{\Delta \sigma_{\gamma}^{\text{TL}}} \) by \( \approx \) factor 2 - 3
MAMI 2012 (I)

Invariant mass distributions for kinematics centered around $m_{e^+e^-} = 57 – 218$ MeV

\[ \frac{\Delta \sigma}{\Delta \sigma_{\gamma}} \simeq 10 - 15 \]
MAMI 2012 (II)

- $\Delta \sigma_{\gamma}/\Delta \sigma_{\gamma}^{TL} \simeq 10 - 15$
- Assumed luminosity of $\sim 10 \text{ fb}^{-1}$ per setting
- **A1 will cover** a large region of the $(g - 2)_\mu$ welcome band
\( \gamma' \) Search at MESA: Feasibility Study (I)

- **Xe, H**
- **E = 80 - 160 MeV**
- **Central momentum: E/2**
- **Acceptances:**
  - Momentum: 5%
  - Horizontal angle: 50 mrad
  - Vertical angle: 50 mrad
- **Use two small spectrometers**
- **Beam energies:** 80, 120, 160 MeV
- **Scattering angle:** 10° and for higher masses 20°
- **Xenon or Hydrogen as target**
Search at MESA: Feasibility Study (II)

**Graphs:**

1. **Setting Ee080**
   - \( \Delta \sigma \) vs. \( m_{e^+e^-} \) [MeV]
   - Peaks at various energies showing changes in \( \Delta \sigma \) with \( m_{e^+e^-} \)

2. **Setting Ee120**
   - \( \Delta \sigma \) vs. \( m_{e^+e^-} \) [MeV]
   - Similar to Setting Ee080 with peak shifts

3. **Setting Ee160**
   - \( \Delta \sigma \) vs. \( m_{e^+e^-} \) [MeV]
   - Additional peaks and variations

4. **Setting Ee120, 20deg**
   - \( \Delta \sigma \) vs. \( m_{e^+e^-} \) [MeV]
   - Further modifications with angular dependence
Search at MESA: Feasibility Study (III)

Xenon or Hydrogen target?

\[ \Delta \sigma \gamma / \Delta \sigma_{\gamma}^{TL} \] does not seem to be affected by kind of target

\[ Xe \] cross section by \[ Z^2 = 54^2 \] enhanced
Search at MESA: Feasibility Study (III)

Xenon or Hydrogen target?

- $\Delta \sigma_{\gamma}/\Delta \sigma_{\gamma}^{TL}$ does not seem to be affected by kind of target
- \textbf{Xe} cross section by $Z^2 = 54^2$ enhanced
- no notable effect from VCS contribution in case of protons

\textbf{Xe} \hspace{2cm} \textbf{p} \hspace{2cm} \textbf{p, VCS}
Search at MESA: Feasibility Study (IV)

\[ \frac{\Delta \sigma_{\gamma}}{\Delta \sigma_{\gamma}^{TL}} \text{ between } 8 - 10 \]
Search at MESA: Feasibility Study (IV)

- $\Delta \sigma_\gamma / \Delta \sigma_{\gamma}^{TL}$ between 8 - 10
- Suggestion: Xe target and 3 month of beam time
Search at MESA: Feasibility Study (IV)

- $\Delta \sigma_{\gamma}/\Delta \sigma_{\gamma}^{TL}$ between 8 - 10
- Suggestion: Xe target and 3 month of beam time
- MESA covers low $m_{\gamma'}$ region of the $(g - 2)_\mu$ welcome band
Conclusions & Outlook

- Study of the underlying processes to high accuracy
- Comparison with data: good agreement
- Predictions for MAMI and MESA

Outlook:
- Analysis of 2012 MAMI run data underway
- Further Experiments planned at MAMI and JLAB (APEX, HPS, DarkLight)
- Low mass \( \gamma' \) search by MESA

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Diagram:

- Mixing Parameter $\varepsilon^2$
- Mass $m_{\gamma}$ [MeV]
- (g-2)$_e$ vs. $\alpha$
- $|\text{(g-2)$_\mu$}| < 2\sigma$
- E141
- E774
- KLOE
- MAMI
- APEX

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Mixing Parameter $\varepsilon^2$

$m_{\gamma'}$ [MeV]

$10^{-8}$

$10^{-7}$

$10^{-6}$

$10^{-5}$

$10^{-4}$

$10^{-3}$

$10^{-2}$

$10^{-1}$

$10^{0}$

$10^{1}$

$10^{2}$

$10^{3}$

$10^{4}$

$10^{5}$

$10^{6}$

$10^{7}$

$10^{8}$

(g-2)$_\mu$ vs. $\alpha$

(g-2)$_e$

KLOE

MAMI

APEX

E774

E141

MAMI 2012

Prediction of arXiv:1303.2540

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Mixing Parameter $\varepsilon^2$

$m_\gamma$ [MeV]

$|\Delta (g-2)_e| < 2 \sigma$

Prediction of arXiv:1303.2540

MAMI 2012

MESA, 10°
MESA, 20°
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