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

based on: TB, H. Merkel, M. Vanderhaeghen, arXiv:1303.2540

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Workshop to Explore Physics Opportunities with Intense, Polarized Electron Beams up to 300 MeV, Cambridge, 14.03. - 16.03.2013
The $\gamma'$ Parameter Plane for Visible Decays

| Mixing Parameter $\varepsilon^2$ | $m_{\gamma'}$ [MeV] |
|----------------------------------|---------------------|
| $10^{-12}$                      |                     |
| $10^{-11}$                      |                     |
| $10^{-10}$                      |                     |
| $10^{-9}$                       |                     |
| $10^{-8}$                       |                     |
| $10^{-7}$                       |                     |
| $10^{-6}$                       |                     |
| $10^{-5}$                       |                     |
| $10^{-4}$                       |                     |

$|(g-2)_\mu| < 2\sigma$

KLOE
MAMI
APEX

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)
Production from $ep \rightarrow epe^+e^-$

timelike $\gamma'$ (TL)

\[ M_{\gamma',\text{TL}} \propto \frac{\varepsilon^2}{q'^2 - m_{\gamma'}^2 + i m_{\gamma'} \Gamma_{\gamma'}} \]
\( \gamma' \) Production from \( ep \rightarrow epe^+e^- \)

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

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

Timelike \( \gamma' \) (TL)

Spacelike \( \gamma' \) (SL)
Production from $ep \rightarrow epe^+e^-$

- **Timelike $\gamma'$ (TL):**
  \[ M_{\gamma', TL} \propto \frac{\varepsilon^2}{q'^2 - m_{\gamma'}^2 + im_{\gamma'} \Gamma_{\gamma'}} \]

- **Spacelike $\gamma'$ (SL):**
  \[ M_{\gamma', SL} \propto \frac{\varepsilon^2}{q^2 - m_{\gamma'}^2} \]

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

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

\[
\begin{align*}
\text{QED background: Direct diagrams (D)}
\end{align*}
\]

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

\[
\begin{align*}
\text{e}^{-}(k) & \rightarrow \text{e}^{+}(l_{+}) \\
& \propto (k - k' - l^{+})^{-2} \\
\text{e}^{-}(k) & \rightarrow \text{e}^{-}(l_{-}) \\
& \propto (k - l_{-} - l_{+})^{-2} \\
p(p) & \rightarrow p(p') \\
\text{e}^{-}(k') & \rightarrow \text{e}^{+}(l_{+}) \\
& \propto (l_{+} + k')^{-2} \\
\text{e}^{-}(k') & \rightarrow \text{e}^{-}(l_{-}) \\
& \propto (k' + l_{+} + l_{-})^{-2} \\
p(p) & \rightarrow p(p') \\
\text{e}^{-}(k) & \rightarrow \text{e}^{-}(l_{-}) \\
& \propto (k - l_{-})^{-2} \\
\text{e}^{-}(k) & \rightarrow \text{e}^{+}(l_{+}) \\
& \propto (k - l_{-} - l_{+})^{-2} \\
p(p) & \rightarrow p(p') \\
\end{align*}
\]
Assume: $m_{\gamma'} = 230\text{ MeV}$, $\varepsilon^2 = 10^{-4}$

- Excess in 1 bin at $m_{e^+e^-} = 230\text{ MeV}$
Exclusion Limit Calculation

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

- **Experimental Quantity:** $\sigma_{\gamma'+\gamma} \propto |M_{\gamma} + M_{\gamma'}|^2$
  ⇒ **Decomposition:** $\sigma_{\gamma'+\gamma} = \sigma_{\gamma} + \sigma_{\gamma'} + \sigma_{\text{int}}$

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

$$\varepsilon^2 = \left( \frac{\sigma_{\gamma'+\gamma}}{\sigma_{\gamma}} - 1 \right)$$

⇒ How well do we know $\sigma_{\gamma}$?
→ approximation of hadronic current, radiative corrections...

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

Exclusion Limit from Data:

$$\varepsilon^2 = \left( \frac{\sigma_{\gamma'} + \gamma}{\sigma_{\gamma}} - 1 \right)$$

Theory Input:

$$\frac{\sigma_{\gamma}}{\sigma_{TL}} = \frac{2N\alpha}{3\pi} \frac{\delta m}{m_{\gamma'}}$$

Experimental Limit:

$$\varepsilon^2 = \left( \frac{\sigma_{\gamma'} + \gamma}{\sigma_{\gamma}} - 1 \right)$$

⇒ How well do we know $\sigma_{\gamma}$?
→ 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 \[ \Delta \sigma = \int \frac{d\sigma}{d|l_+|d\Omega_+ d\Omega_- d\Omega_{e'} dq'^2} \] 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

\[ \Rightarrow \text{Evaluate } \Delta \sigma = \int \frac{d\sigma}{d|l_+|d\Omega_+ d\Omega_- d\Omega_{e'} dq'^2} \text{ within the exp. limits} \]

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? \( \rightarrow \) “exact”

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
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
- **Large contribution** from exchange term
MAMI 2010 (II)

direct

- Direct: SL background dominating
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
\[ \Delta \sigma_\gamma^D / \Delta \sigma_\gamma^{TL} \simeq 5 - 15 \]
The exchange contribution increases \( \Delta \sigma_{\gamma}^{D}/\Delta \sigma_{\gamma}^{TL} \) by \( \simeq 5 - 15 \) and \( \Delta \sigma_{\gamma}^{D+X}/\Delta \sigma_{\gamma}^{TL} \) by \( \simeq 15 - 25 \).
\[ \Delta \sigma_{\gamma}^{D}/\Delta \sigma_{\gamma}^{\text{TL}} \approx 5 - 15 \]

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

exchange contribution increases \[ \Delta \sigma_{\gamma}/\Delta \sigma_{\gamma}^{\text{TL}} \] by \( \approx \) factor 2 - 3
MAMI 2012 (I)
Invariant mass distributions for kinematics centered around $m_{e^+e^-} = 57 - 218 \text{ MeV}$

Solid: TL+SL, X+D. Dotted: TL+SL, X. Double-dashed: SL, X. Dashed: TL+SL, D. Dashed-dotted: TL, D
\[ \Delta \sigma_\gamma / \Delta \sigma^{TL}_\gamma \approx 10 - 15 \]
MAMI 2012 (II)

\[ \frac{\Delta \sigma_\gamma}{\Delta \sigma_\gamma^{TL}} \approx 10 - 15 \]

Assumed luminosity of \( \sim 10 \text{ fb}^{-1} \) per setting

A1 will cover a large region of the \((g - 2)_\mu\) welcome band
γ' Search at MESA: Feasibility Study (I)

- Use two small spectrometers
- Beam energies: 80, 120, 160 MeV
- Scattering angle: 10° and for higher masses 20°
- Xenon or Hydrogen as target

E = 80 - 160 MeV

- Parity-Violation Detector
- Hydro-Møller
- Former MAMI Beam tunnel
- Polarized Source
- Double-scattering Polarimeter
- Compton Monitor
- Injector
- Main-Linac
- Recirculations
- External Beam: Full-wave-recirculation
- Energy recovery: Half-wave-recirculation

acceptances:
momentum: 5%
horizontal angle: 50 mrad
vertical angle: 50 mrad

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)

\( \gamma' \)

\[ \Delta \sigma \text{[pb]} \]

\( m_{e^+e^-} \text{[MeV]} \)

Setting Ee080

\[ \Delta \sigma \text{[pb]} \]

\( m_{e^+e^-} \text{[MeV]} \)

Setting Ee120

\[ \Delta \sigma \text{[pb]} \]

\( m_{e^+e^-} \text{[MeV]} \)

Setting Ee160

\[ \Delta \sigma \text{[pb]} \]

\( m_{e^+e^-} \text{[MeV]} \)

Setting Ee120, 20deg

\[ \Delta \sigma \text{[pb]} \]

\( m_{e^+e^-} \text{[MeV]} \)
\(\gamma'\) 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
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
- no notable effect from VCS contribution in case of protons
$\gamma'$ Search at MESA: Feasibility Study (IV)

- $\Delta \sigma_{\gamma}/\Delta \sigma_{\gamma}^{TL}$ between 8 - 10
Search at MESA: Feasibility Study (IV)

- $\Delta\sigma_\gamma / \Delta\sigma^\text{TL}_\gamma$ between 8 - 10
- Suggestion: Xe target and 3 month of beam time
\( \Delta \sigma_{\gamma} / \Delta \sigma_{\gamma}^{\text{TL}} \) 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

| Mixing Parameter | $\varepsilon^2$ |
|------------------|-----------------|
| $m_\gamma$ [MeV] | $10^{-8}$ $10^{-7}$ $10^{-6}$ $10^{-5}$ $10^{-4}$ |

- 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
Conclusions & Outlook

**Conclusions:**

Study of the underlying processes to high accuracy

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**Figure:**

- Diagram showing mixing parameter ε² vs. mass m_γ [MeV]
- Labels for experiments: KLOE, E141, E774, MAMI, APEX
- Regions indicating (g-2)_μ vs. α and (g-2)_μ < 2σ

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Conclusions & Outlook

Conclusions:

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

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Conclusions & Outlook

Conclusions:

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

Diagram showing mixing parameter $\varepsilon^2$ vs. $m_\gamma$ [MeV] with data points from E774, E141, KLOE, MAMI, APEX, and predictions from arXiv:1303.2540.
Conclusions:

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

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Low mass $\gamma'$ search by MESA