

Theoretical Framework for the Analysis of Searches for Hidden, Light Gauge Bosons

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

Tobias Beranek

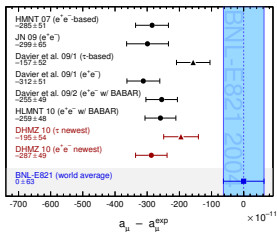
Institut für Kernphysik, Johannes Gutenberg-Universität Mainz, Deutschland

9th Patras Workshop on Axions, WIMPs and WISPs
Schloss Waldthausen, 24.06. - 28.04.2013



Why should one look for new $U(1)$'s?

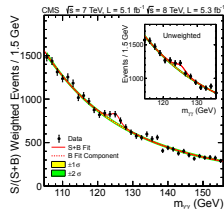
Physics beyond the SM motivated by **various unsolved questions:**



$(g - 2)_\mu$



Proton Radius Puzzle

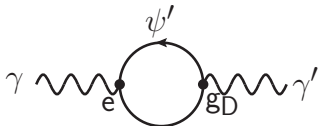


Higgs $\rightarrow \gamma\gamma$

- **Weak Scale Questions**, GUT: Unification of Couplings, number of parameters
- **Dark Matter**
- new $U(1)$'s arise automatically in many SM extensions

Kinetic Mixing and $U(1)_D$

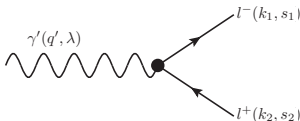
Tree level extensions are strongly constrained, but **loops of heavy particles** are always possible: Holdom, PLB 178



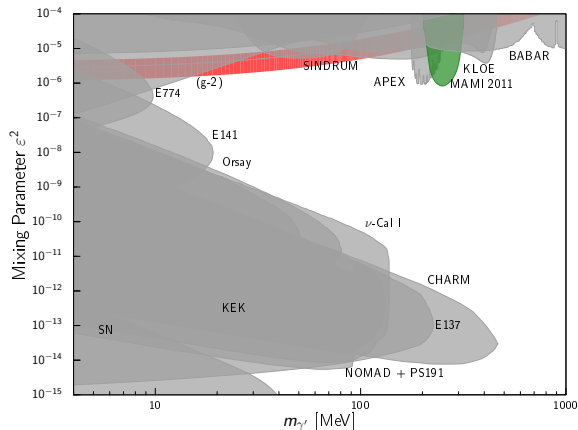
$$\mathcal{L} \supset -\frac{1}{4} F_{Y,\mu\nu} F_Y^{\mu\nu} - \frac{1}{4} F'_{\mu\nu} F'^{\mu\nu} + \frac{\epsilon_Y}{2} F'_{\mu\nu} F_Y^{\mu\nu} + e A_{Y,\mu} J_Y^\mu + g_D A'_\mu J'^\mu + m^2 A'_\mu A'^\mu$$

Redefine: $A'_\mu \rightarrow A'_\mu + \epsilon_Y A_\mu$ and $\epsilon = \epsilon_Y \cos \theta_W$

$\mathcal{L}_I = \epsilon e A'_\mu J_{em}^\mu$ induced



The γ' Parameter Plane for Visible Decays

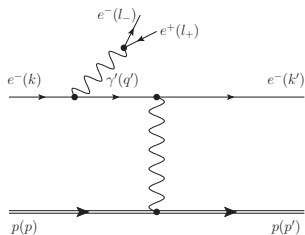


Pospelov (PRD 80)
Bjorken et al. (PRD 80)
MAMI (PRL 106)

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)

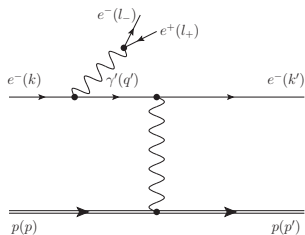
γ' Production from $ep \rightarrow epe^+e^-$ (I)



timelike γ' (TL)

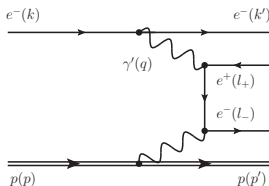
$$\mathcal{M}_{\gamma', TL} \propto \frac{\varepsilon^2}{q'^2 - m_{\gamma'}^2 + im_{\gamma'}\Gamma_{\gamma'}}$$

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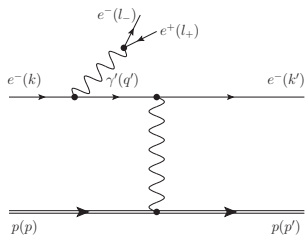
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spacelike γ' (SL)

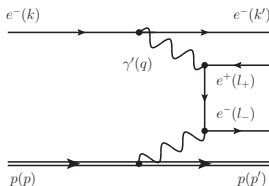
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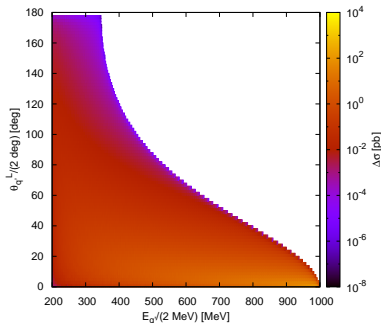
$$\mathcal{M}_{\gamma', SL} \propto \frac{\varepsilon^2}{q^2 - m_{\gamma'}^2}$$

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

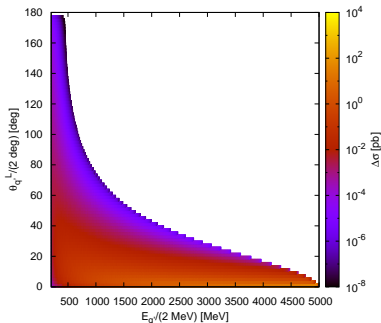
Signal: γ' will appear as **sharp resonance** from **timelike** production

γ' Production from $ep \rightarrow epe^+e^-$ (II)

γ' production cross section for $m_{\gamma'} = 200$ MeV and $\varepsilon^2 = 1$



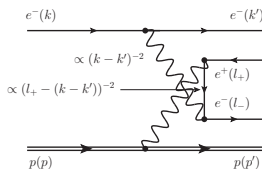
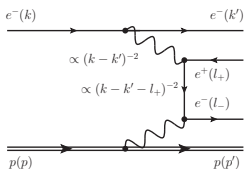
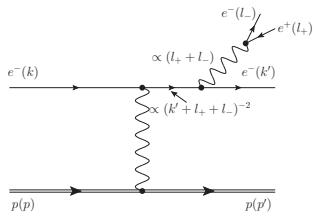
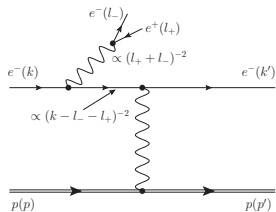
$E_0 = 1$ GeV



$E_0 = 5$ GeV

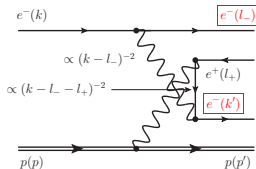
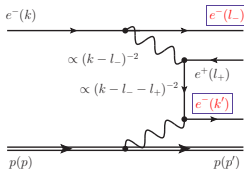
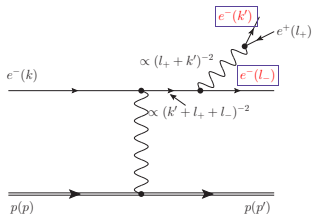
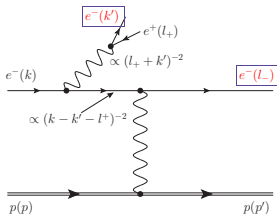
Largest cross section: forward γ' production with $E_{\gamma'} \simeq E_0$

QED background: Direct diagrams (D)



direct diagrams (D):
 contributions can be separated kinematically

QED background: Exchange diagrams (X)



exchange diagrams (X): $e^-(k') \leftrightarrow e^-(l_-)$:
 give large contribution when signal is large

Exclusion Limit Calculation

- **Approximation** of cross section ratio $\frac{\sigma_{\gamma'}}{\sigma_{\gamma}^{\text{TL}}} = \frac{3\pi}{2N} \frac{\epsilon^2}{\alpha} \frac{m_{\gamma'}}{\delta m}$
 (Bjorken, Essig, Schuster, Toro, PRD 80)
- **Experimental Quantity:** $\sigma_{\gamma'+\gamma} \propto |\mathcal{M}_{\gamma} + \mathcal{M}_{\gamma'}|^2$
 \Rightarrow **Decomposition:** $\sigma_{\gamma'+\gamma} = \sigma_{\gamma} + \sigma_{\gamma'} + \sigma_{\text{int}}$

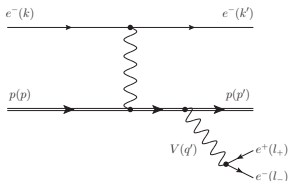
ϵ^2 Exclusion Limit from Data

$$\epsilon^2 = \underbrace{\left(\frac{\sigma_{\gamma'+\gamma}}{\sigma_{\gamma}} - 1 \right)}_{\text{experimental limit}} \overbrace{\frac{\sigma_{\gamma}}{\sigma_{\gamma}^{\text{TL}}}}^{\text{theory input}} \frac{2N\alpha}{3\pi} \frac{\delta m}{m_{\gamma'}}$$

\Rightarrow How well do we know σ_{γ} ?

\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”

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Run calculations on

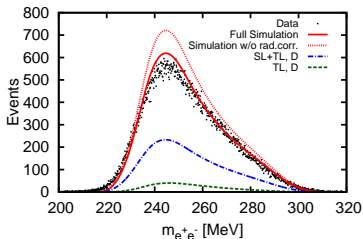
General Purpose Graphics Processing Units (GPGPU)



(nvidia Tesla)

MAMI 2010 (I)

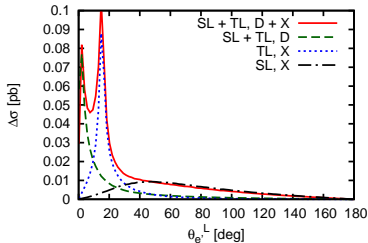
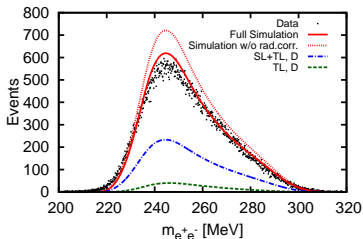
MAMI test run 2010 (Merkel et al. (A1), PRL106)



- Data and **theory** in **good agreement**
- Radiative corrections are crucial to describe the data accurately

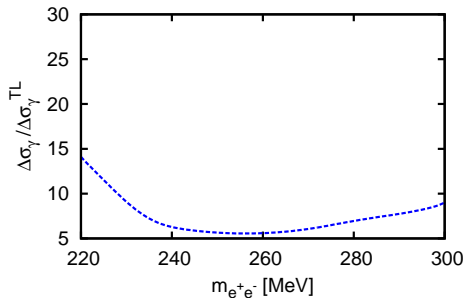
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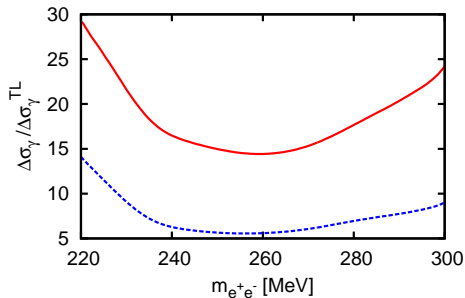
- Data and **theory** in **good agreement**
- Radiative corrections are crucial to describe the data accurately
- **Large contribution** from **exchange** term

MAMI 2010 (II)



• $\Delta\sigma_\gamma^D / \Delta\sigma_\gamma^{TL} \simeq 5 - 15$

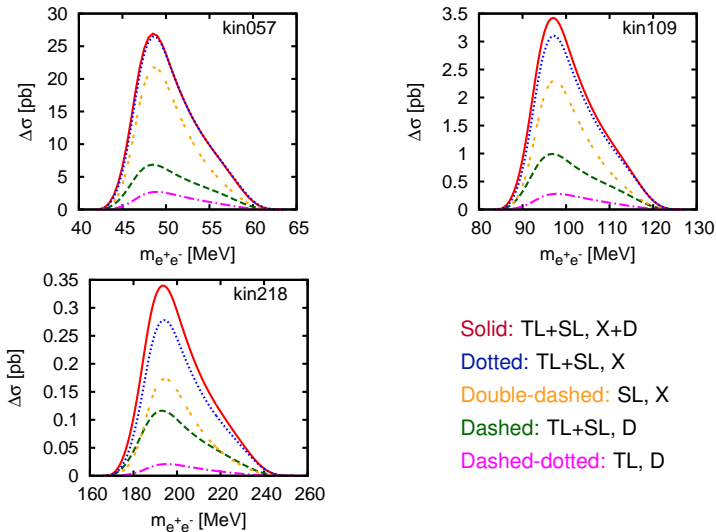
MAMI 2010 (II)



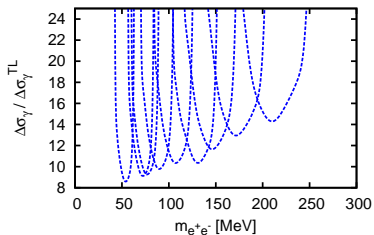
- $\Delta\sigma_\gamma^D / \Delta\sigma_\gamma^{\text{TL}} \simeq 5 - 15$
- $\Delta\sigma_\gamma^{D+X} / \Delta\sigma_\gamma^{\text{TL}} \simeq 15 - 25$
- exchange contribution increases $\Delta\sigma_\gamma / \Delta\sigma_\gamma^{\text{TL}}$
 by \simeq factor 2 - 3

MAMI 2012 (I)

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

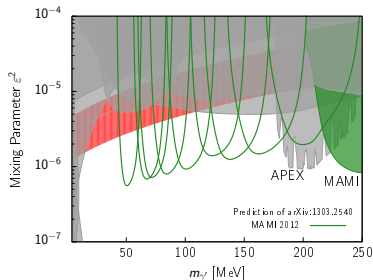
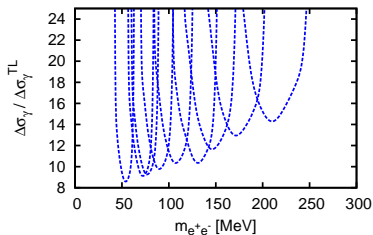


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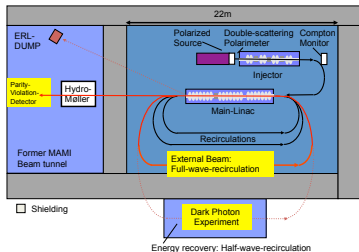
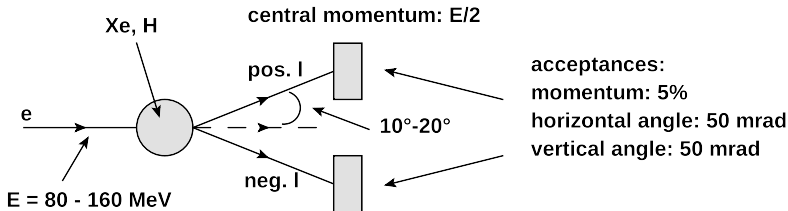
- $\Delta\sigma_\gamma / \Delta\sigma_\gamma^{\text{TL}} \simeq 10 - 15$

MAMI 2012 (II)



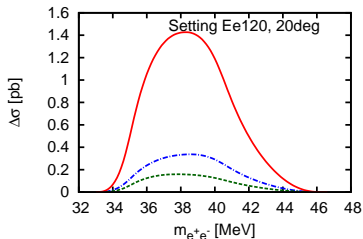
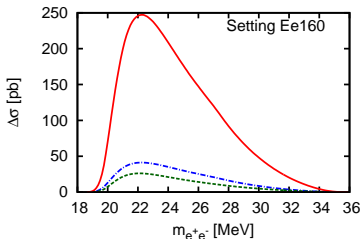
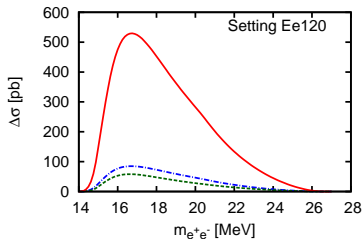
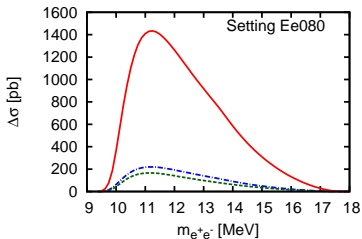
- $\Delta\sigma_\gamma/\Delta\sigma_\gamma^{\text{TL}} \simeq 10 - 15$
- Assumed luminosity of $\sim 10 \text{ fb}^{-1}$ per setting
- **A1 will cover** a large region of the $(g - 2)_\mu$ welcome band

γ Search at MESA: Feasibility Study (I)

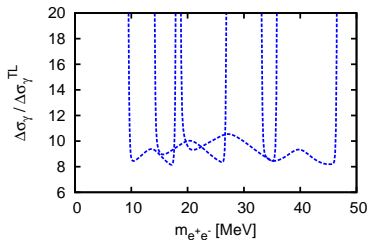


- Use two small spectrometers
- Beam energies: 80, 120, 160 MeV
- Scattering angle: 10° and for higher masses 20°
- Xenon or Hydrogen as target

γ Search at MESA: Feasibility Study (II)

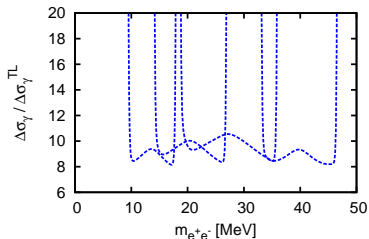


γ' Search at MESA: Feasibility Study (III)



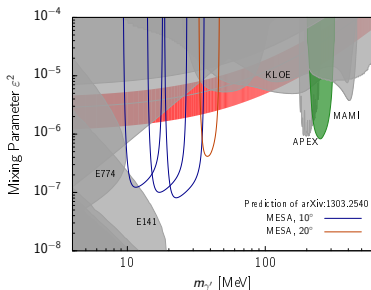
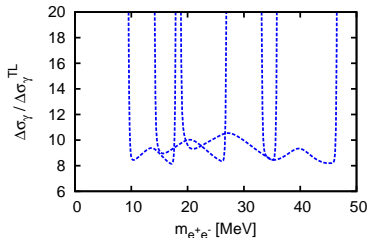
- $\Delta\sigma_\gamma / \Delta\sigma_\gamma^{TL}$ between 8 - 10

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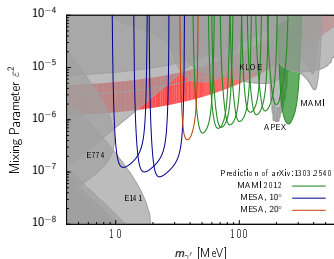
- $\Delta\sigma_\gamma / \Delta\sigma_\gamma^{\text{TL}}$ between 8 - 10
- Suggestion: Xe target and 3 month of beam time

γ' Search at MESA: Feasibility Study (III)



- $\Delta\sigma_\gamma / \Delta\sigma_\gamma^{\text{TL}}$ 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



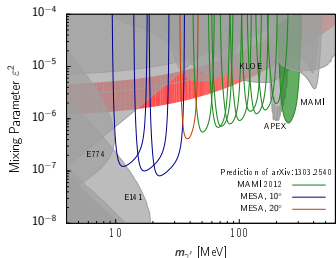
Conclusions:

Study of the underlying processes to **high accuracy**

Comparison with data: good agreement

Predictions for **MAMI** and **MESA**

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Predictions for **MAMI** and **MESA**

Outlook:

Application of calculations to other experiments (APEX, HPS, DarkLight)

Study of other channels, e.g. rare Kaon decays (TB, Vanderhaeghen, PRD87)