

Theoretical Framework for the Analysis of Fixed-Target Searches for Hidden Photons

based on: TB, H. Merkel, M. Vanderhaeghen, PRD88
(arXiv:1303.2540)

Tobias Beranek

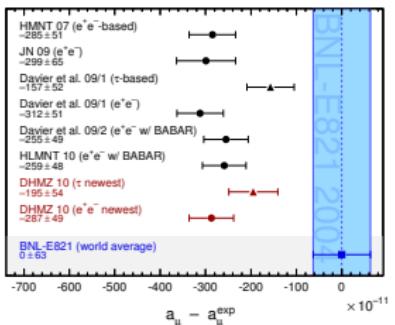
Institut für Kernphysik, Johannes Gutenberg-Universität Mainz, Deutschland

Workshop on Radiative Corrections in Annihilation and Scattering Experiments
Orsay, 07.10. - 08.10.2013



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

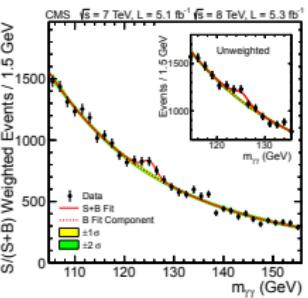
Physics beyond the SM motivated by **various unsolved questions**:



$$(g - 2)_\mu$$



Proton Radius Puzzle

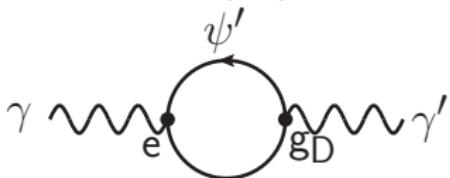


Higgs $\rightarrow \gamma\gamma$

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

Hidden Photons: Kinetic Mixing and $U(1)_D$

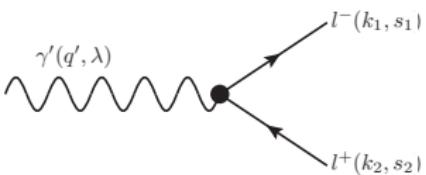
Tree level extensions are strongly constrained, but **loops of heavy particles** are always possible: Holdom, PLB 178



$$\begin{aligned} \mathcal{L} \supset & -\frac{1}{4} F_{Y,\mu\nu} F_Y^{\mu\nu} - \frac{1}{4} F'_{\mu\nu} F'^{\mu\nu} + \frac{\varepsilon_Y}{2} \mathbf{F}'_{\mu\nu} \mathbf{F}_Y^{\mu\nu} \\ & + e A_{Y,\mu} J_Y^\mu + g_D A'_\mu J'^\mu + m^2 A'_\mu A'^\mu \end{aligned}$$

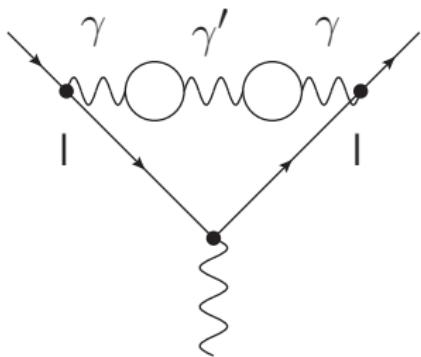
Redefine: $A_Y^\mu \rightarrow A_Y^\mu + \varepsilon_Y A'^\mu$ and $\varepsilon = \varepsilon_Y \cos \theta_W$

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

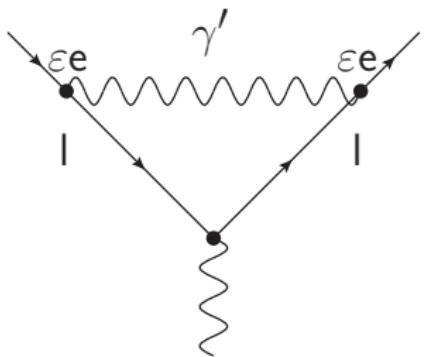


Example: Influence on $(g - 2)_l$

- γ' must influence $(g - 2)_l$
- Complicated to calculate
always the process containing
3 loops

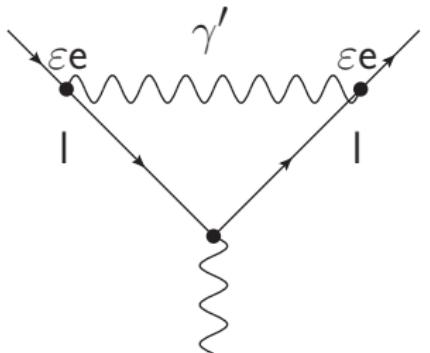


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- Calculate **effective diagram:**
2 parameters
 - mass: $m_{\gamma'}$
 - coupling: kin. mixing factor
 $\epsilon^2 = \frac{\alpha'}{\alpha}, \alpha' = \frac{g_d^2}{4\pi}$

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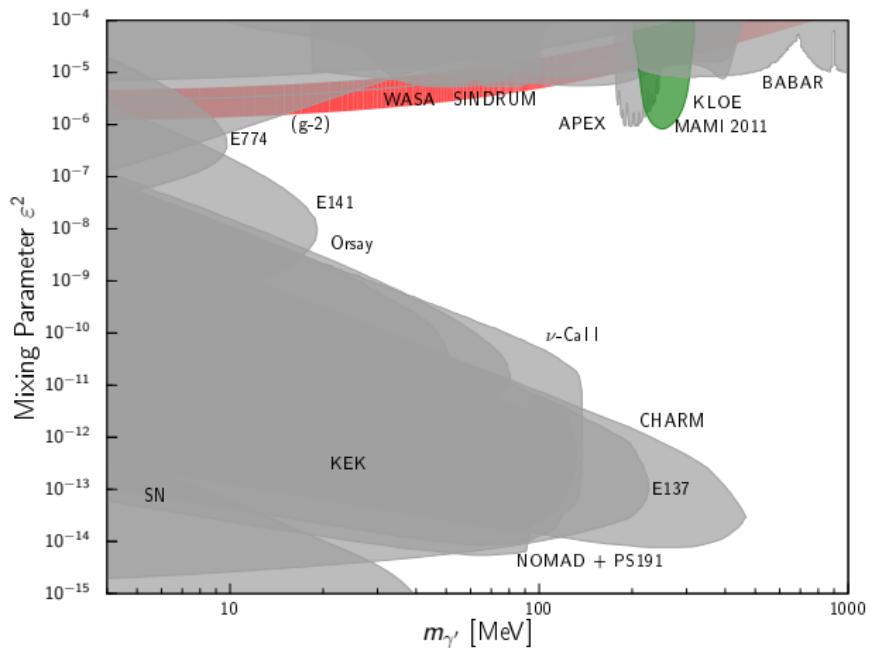
$$\varepsilon^2 = \frac{\alpha'}{\alpha}, \quad \alpha' = \frac{g_d^2}{4\pi}$$

$$a_l^{\gamma'} = \frac{\alpha'}{\pi} \int_0^1 dz \frac{z(1-z)^2 m_l^2}{(1-z)^2 m_l^2 + zm_{\gamma'}^2} \simeq \frac{\alpha'}{2\pi} \times \begin{cases} 1, & m_l \gg m_{\gamma'} \\ 2m_l^2/(3m_{\gamma'}^2), & m_l \ll m_{\gamma'} \end{cases}$$

Pospelov, PRD 80

more than 30 years ago: Fayet, Nucl. Phys. B 187 (in French)

The γ' Parameter Plane for Visible Decays

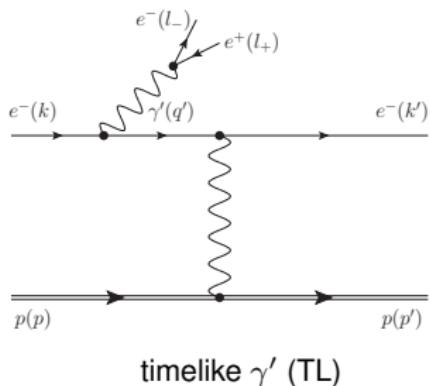


Pospelov (PRD 80)
Bjorken et al. (PRD 80)
MAMI (PRL 106)
WASA (PLB 726)

APEX (PRL 107)
Blumlein, Brunner (PLB 701)
KLOE (PLB 706, PLB 720)

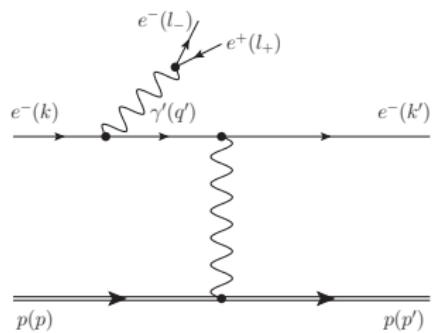
Gninenko (PRD 85, PLB 713, PRD 85)
Davoudiasl et al. (PRD 86)
Andreas et al. (PRD 86)

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



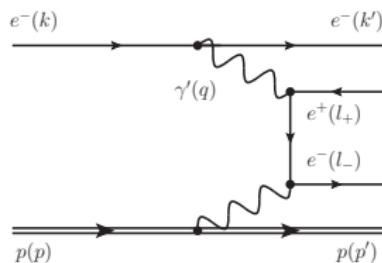
$$\mathcal{M}_{\gamma', TL} \propto \frac{\varepsilon^2}{q'^2 - m_{\gamma'}^2 + im_{\gamma'}\Gamma_{\gamma'}}$$

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



timelike γ' (TL)

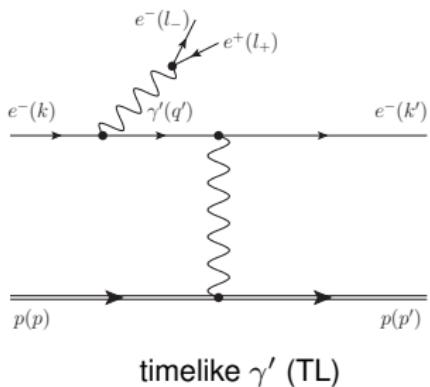
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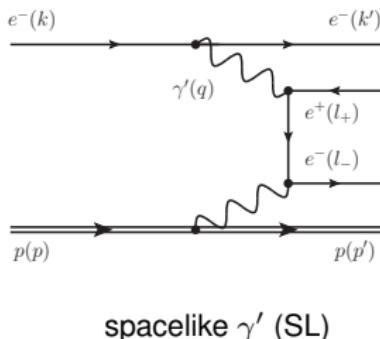
spacelike γ' (SL)

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

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



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

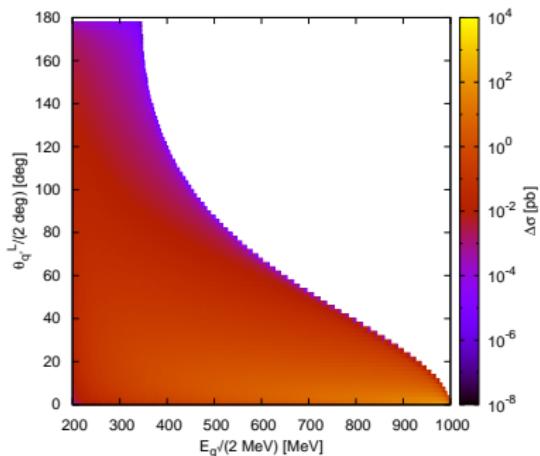


$$\mathcal{M}_{\gamma', SL} \propto \frac{\epsilon^2}{q^2 - m_{\gamma'}^2}$$

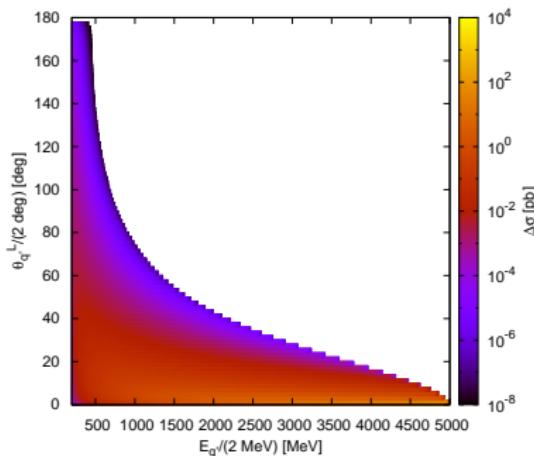
$\Gamma_{\gamma'}$ decay width of γ' : $\mathcal{O}(\text{eV})$, if only SM decay allowed
Signal: γ' will appear as **sharp resonance** from **timelike** production

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

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



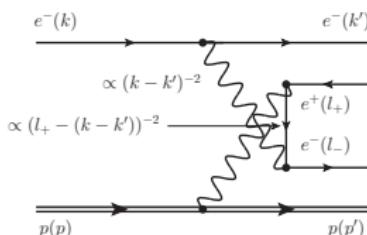
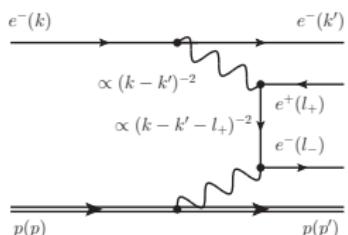
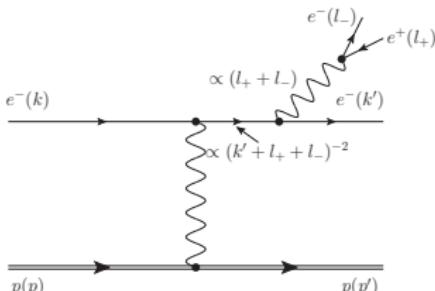
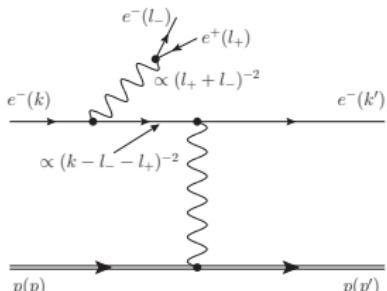
$$E_0 = 1 \text{ GeV}$$



$$E_0 = 5 \text{ GeV}$$

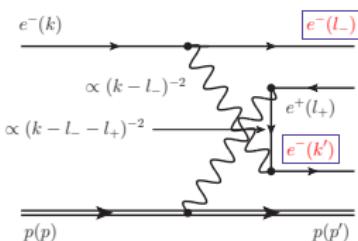
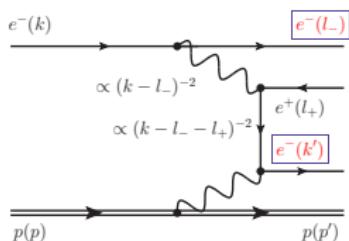
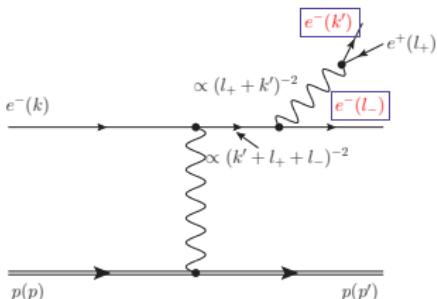
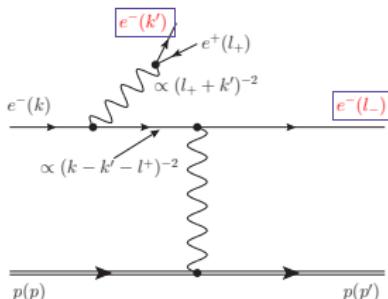
Largest cross section: forward γ' production with $E_{\gamma'} \simeq E_0$

QED background: Direct diagrams (D)



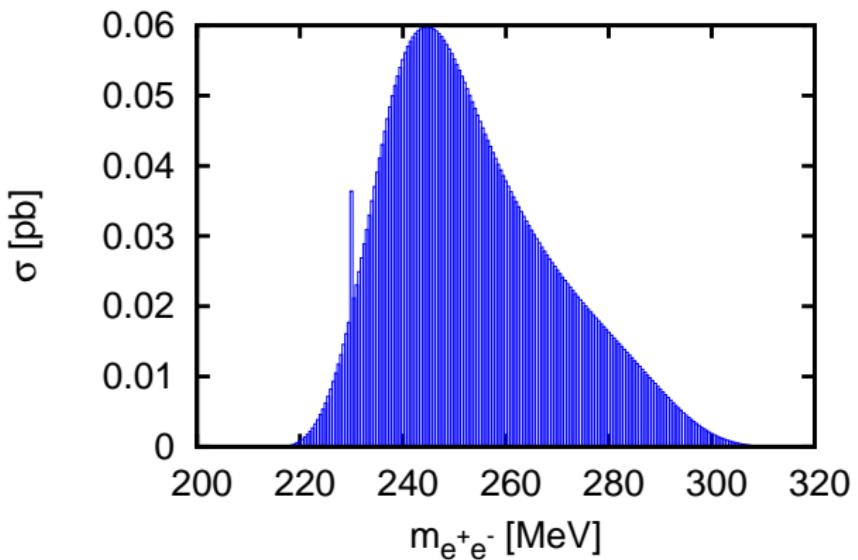
direct diagrams (D):
contributions can be separated kinematically

QED background: Exchange diagrams (X)



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

Simulation: Background vs. (expected) Signal



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

Exclusion Limit Calculation

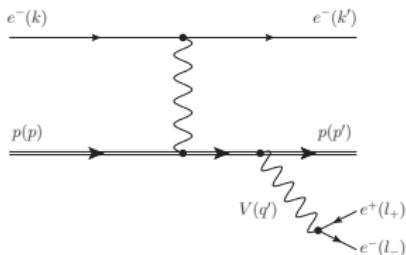
- **Approximation** of cross section ratio $\frac{\sigma_{\gamma'}}{\sigma_{\gamma}^{\text{TL}}} = \frac{3\pi}{2N} \frac{\varepsilon^2}{\alpha} \frac{m_{\gamma'}}{\delta m}$
(Bjorken, Essig, Schuster, Toro, PRD 80)
- **Experimental Quantity:** $\sigma_{\gamma'+\gamma} \propto |\mathcal{M}_{\gamma} +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

ε^2 Exclusion Limit from Data

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

- ⇒ How well do we know σ_{γ} ?
 → approximation of hadronic current, radiative corrections...

QED Background: Doubly Virtual Compton Scattering



Doubly 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

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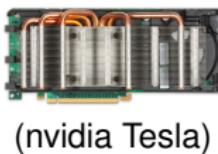
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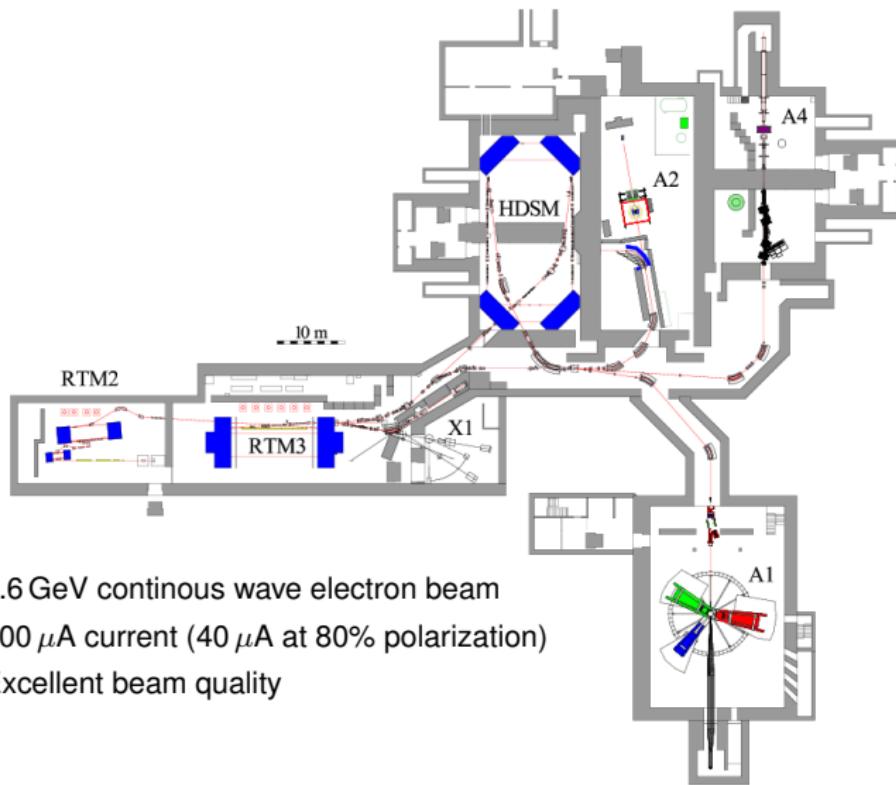
Try to do calculation as “exact” as possible or apply approximations? → “exact”

Run calculations on

General Purpose Graphics Processing Units (GPGPU)



The MAinz Microtron (MAMI)



A1: Spectrometer setup at MAMI



Spectrometer A:

$$\begin{aligned}\alpha &> 20^\circ \\ p &< 735 \frac{\text{MeV}}{c} \\ \Delta\Omega &= 28 \text{ msr} \\ \Delta p/p &= 20\%\end{aligned}$$

Spectrometer B:

$$\begin{aligned}\alpha &> 8^\circ \\ p &< 870 \frac{\text{MeV}}{c} \\ \Delta\Omega &= 5.6 \text{ msr} \\ \Delta p/p &= 15\%\end{aligned}$$

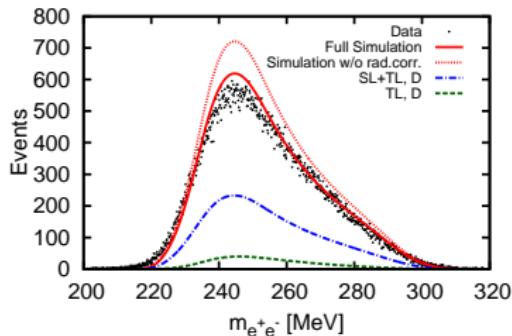
Spectrometer C:

$$\begin{aligned}\alpha &> 55^\circ \\ p &< 655 \frac{\text{MeV}}{c} \\ \Delta\Omega &= 28 \text{ msr} \\ \Delta p/p &= 25\%\end{aligned}$$

$$\delta p/p < 10^{-4}$$

MAMI 2010 (I)

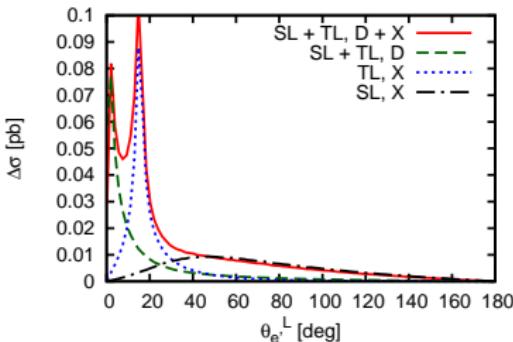
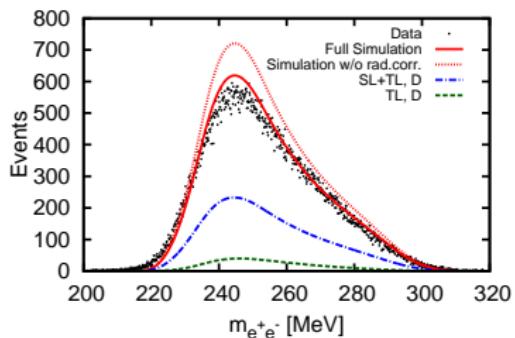
MAMI test run 2010 (Merkel et al. (A1), PRL106)



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

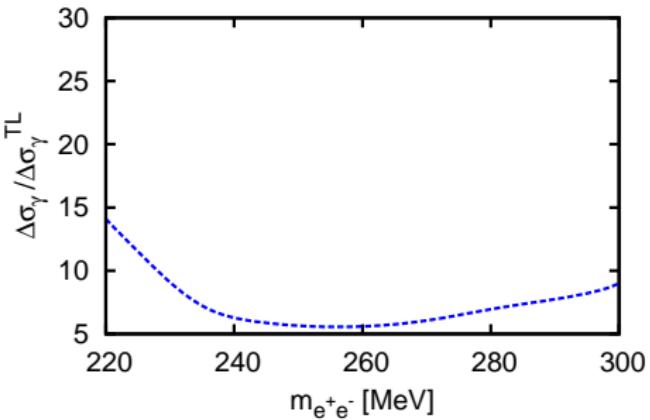
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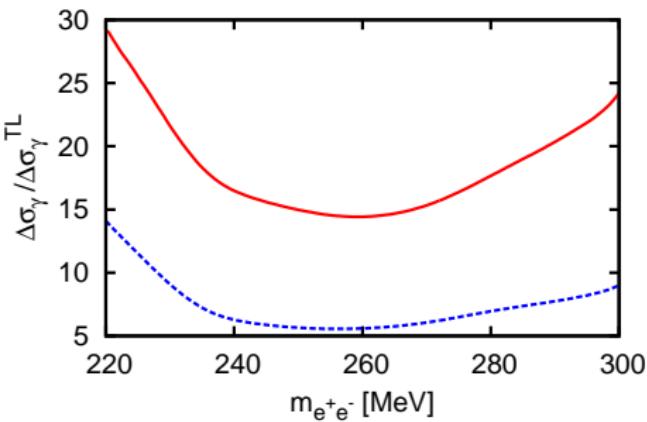
- Data and theory in **good agreement**
- Radiative corrections are crucial to describe the data accurately
- Large contribution from **exchange** term

MAMI 2010 (II)



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

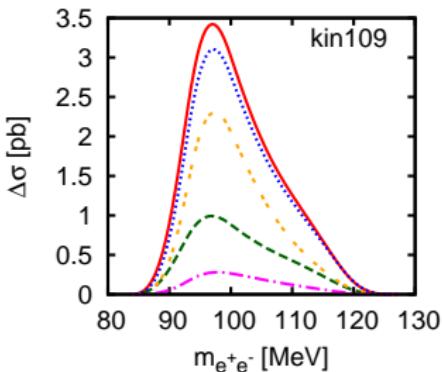
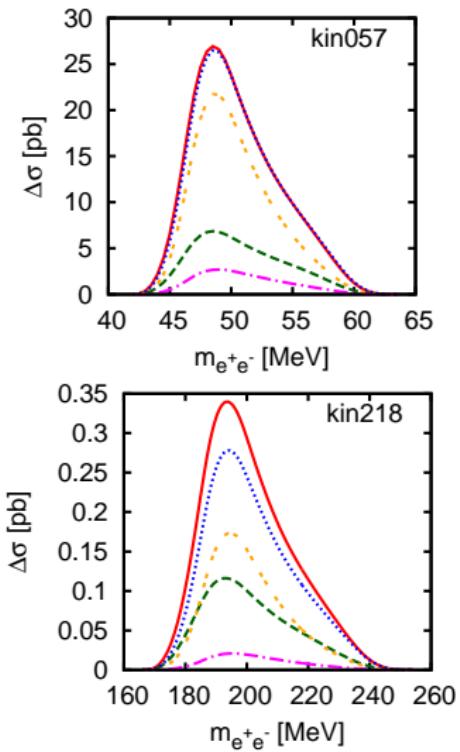
MAMI 2010 (II)



- $\Delta\sigma_\gamma^D / \Delta\sigma_\gamma^{\text{TL}} \simeq 5 - 15$
- $\Delta\sigma_\gamma^{D+X} / \Delta\sigma_\gamma^{\text{TL}} \simeq 15 - 25$
- 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 $m_{e^+e^-} = 57 - 218 \text{ MeV}$



Solid: TL+SL, X+D

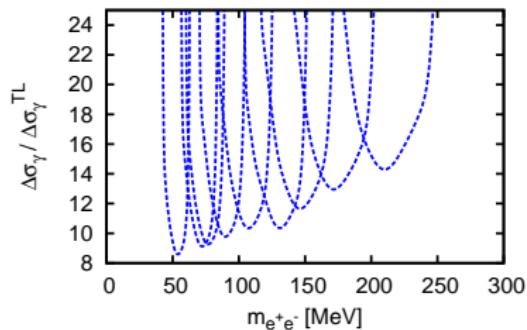
Dotted: TL+SL, X

Double-dashed: SL, X

Dashed: TL+SL, D

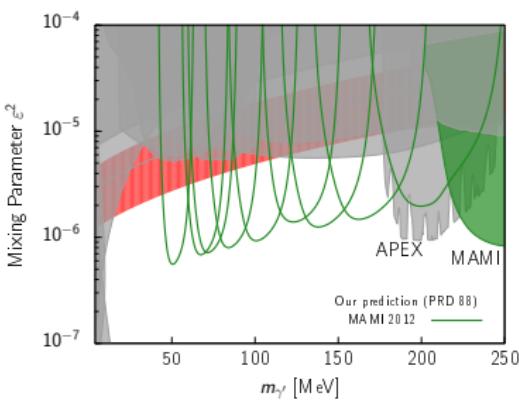
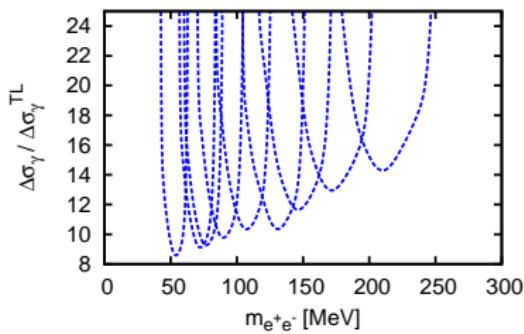
Dashed-dotted: TL, D

MAMI 2012 (II)



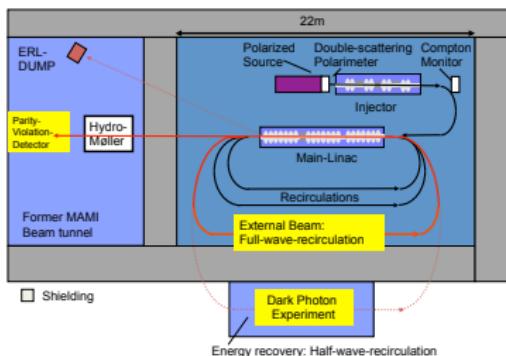
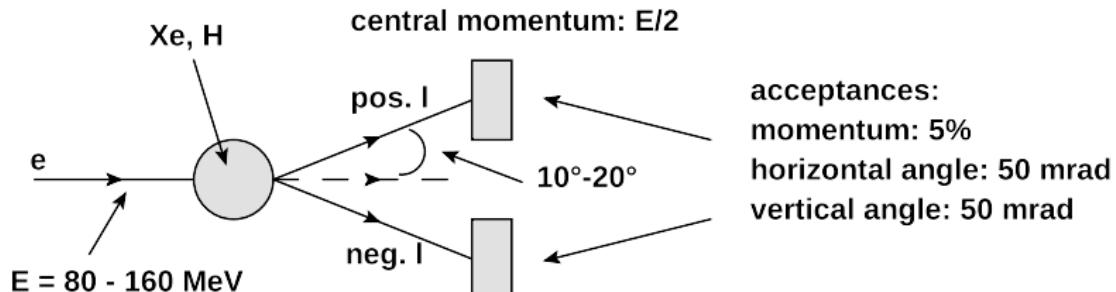
- $\Delta\sigma_\gamma / \Delta\sigma_\gamma^{\text{TL}} \simeq 10 - 15$

MAMI 2012 (II)



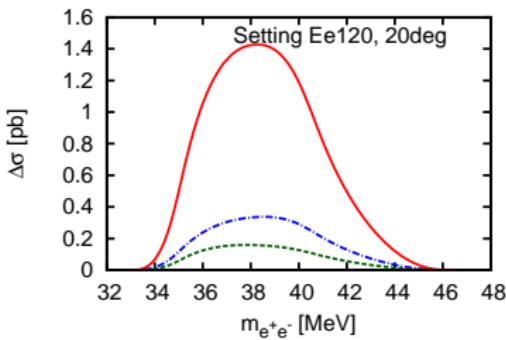
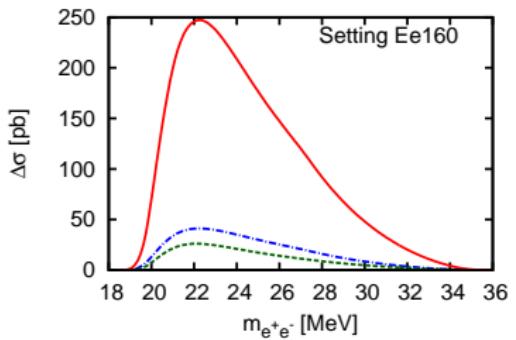
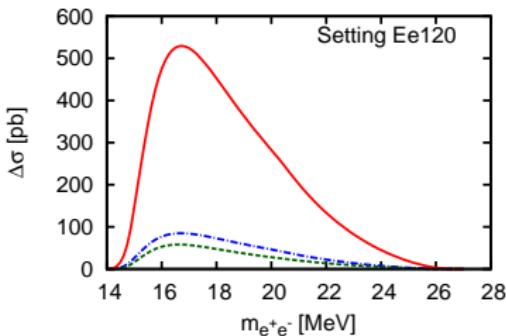
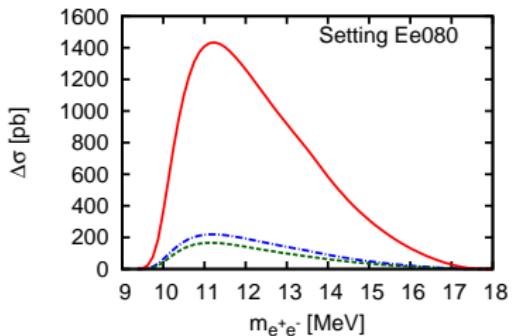
- $\Delta\sigma_\gamma / \Delta\sigma_\gamma^{\text{TL}} \simeq 10 - 15$
- Assumed luminosity of $\sim 10 \text{ fb}^{-1}$ per setting
- **A1 will cover** a large region of the $(g - 2)_\mu$ welcome band

γ' Search at MESA: Feasibility Study (I)

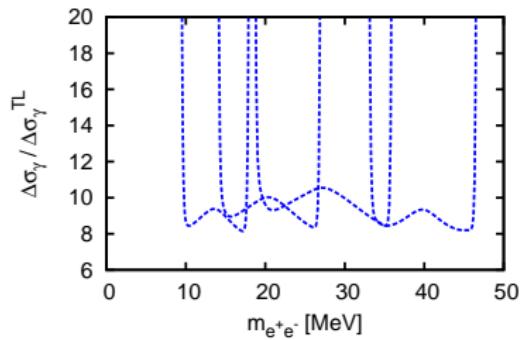


- Use two small spectrometers
- Beam energies: 80, 120, 160 MeV
- Scattering angle: 10° and for higher masses 20°
- Xenon or Hydrogen as target

γ' Search at MESA: Feasibility Study (II)

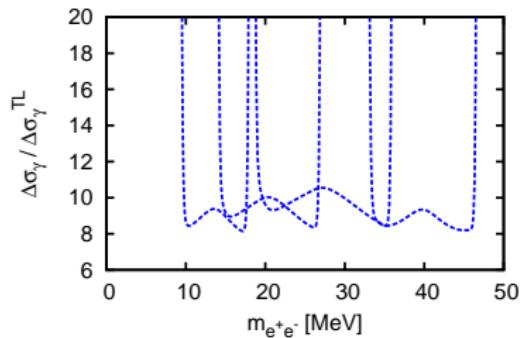


γ' Search at MESA: Feasibility Study (III)



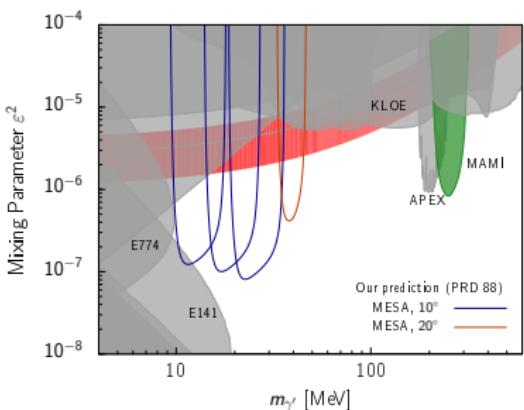
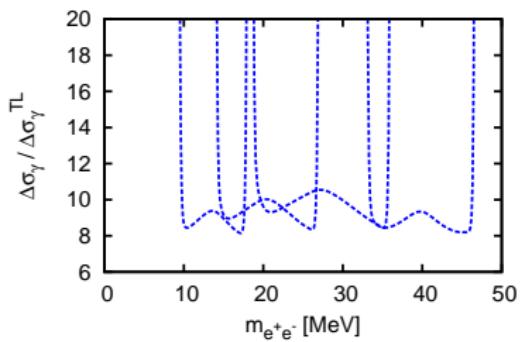
- $\Delta\sigma_\gamma / \Delta\sigma_\gamma^{\text{TL}}$ between 8 - 10

γ' Search at MESA: Feasibility Study (III)



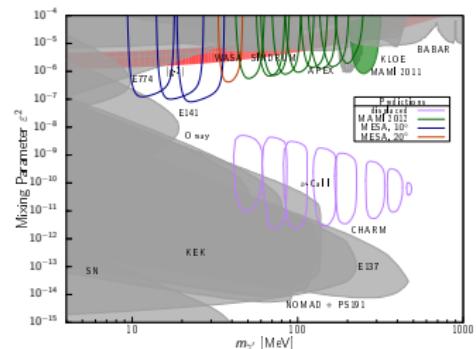
- $\Delta\sigma_\gamma/\Delta\sigma_\gamma^{\text{TL}}$ between 8 - 10
- Suggestion: Xe target and 3 month of beam time

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



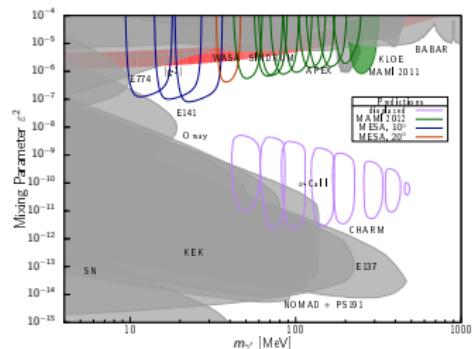
Conclusions:

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

Comparison with data: good agreement

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

Conclusions & Outlook



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

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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)