Light Dark Gauge Boson Searches in Electroweak Processes

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Frascati, 16.10. - 19.10.2012

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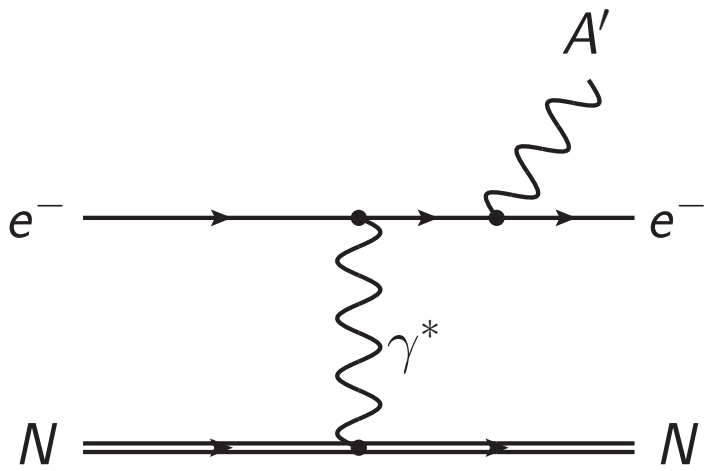
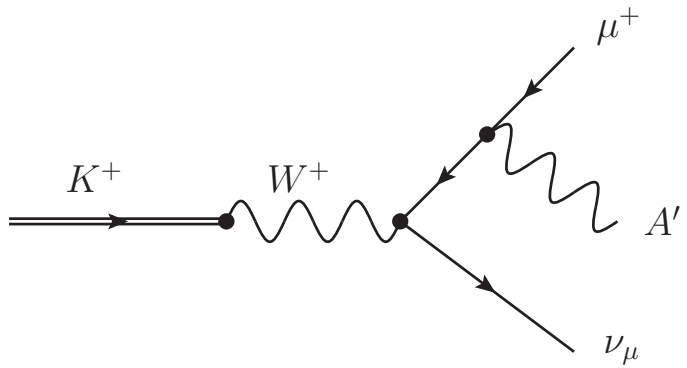
Outline

Study of A' search in...

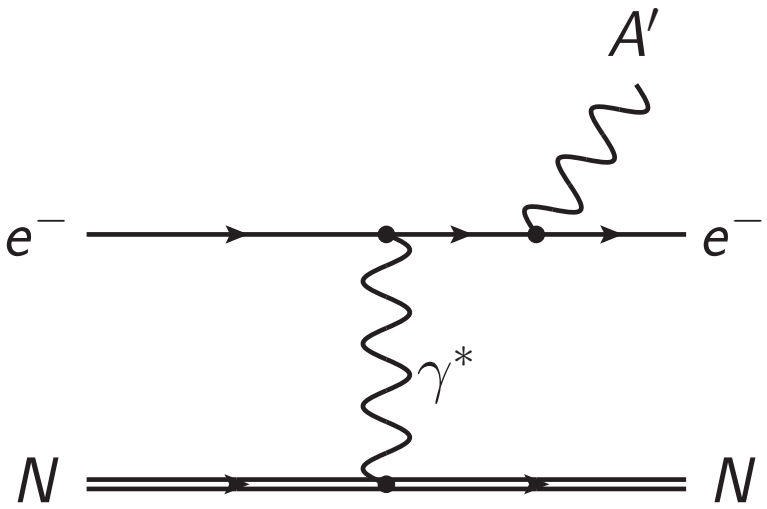




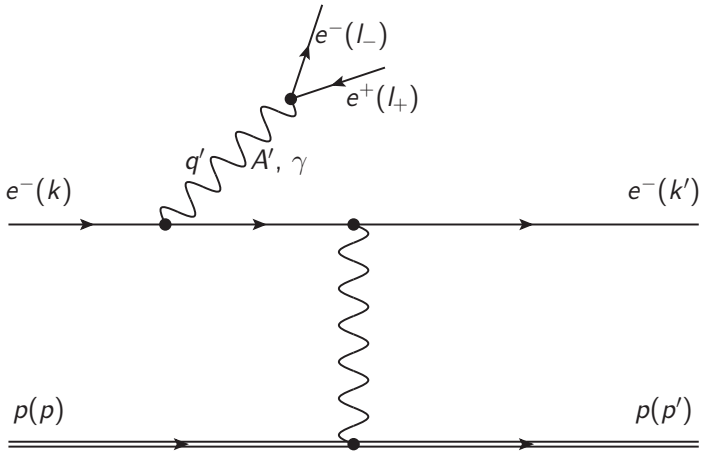
low energy fixed target experiments

rare kaon decays

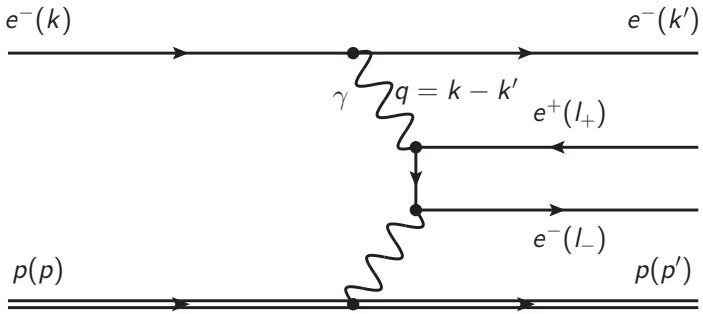
A' search at Fixed Target Experiment



A' Production from $ep \to epe^+e^-$



(a) timelike gauge boson



(b) spacelike gauge boson

$$\mathcal{M}_{A',a} \propto \frac{\varepsilon^2}{q'^2 - m_{A'}^2 + i m_{A'} \Gamma_{A'}}, \qquad \mathcal{M}_{\gamma,a} \propto \frac{1}{q'^2},$$

$$\mathcal{M}_{A',b} \propto \frac{\varepsilon^2}{-Q^2 - m_{A'}^2 + i m_{A'} \Gamma_{A'}}, \qquad \mathcal{M}_{\gamma,b} \propto \frac{1}{Q^2}, \qquad Q^2 = -q^2$$

Signal peaking $\Leftrightarrow$ A' propagator is on-shell: $q'^2 = m_{A'}^2$

Background large $\Leftrightarrow$ q'^2 or $q^2 \to 0$; $\left|\vec{l_+}\right|$ or $\left|\vec{l_-}\right| \to |\vec{q}|$

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A' Production from $ep \to epe^+e^-$: Exclusion Limit Calculation

- **Approximation** for Cross Section Ratio $\frac{\sigma_{A'}}{\sigma_\gamma^a} = \frac{3\pi}{2N}\frac{\varepsilon^2}{\alpha}\frac{m_{A'}}{\delta m}$
  (Essig et al., PRD 80)
- **Experimental Quantity:** $\sigma_{A'+\gamma} \propto \left|\mathcal{M}_\gamma^{\text{full}} + \mathcal{M}_{A'}\right|^2$
  $\Rightarrow$ **Decomposition:** $\sigma_{A'+\gamma} = \sigma_\gamma + \sigma_{A'} + \sigma_{\text{int}}$

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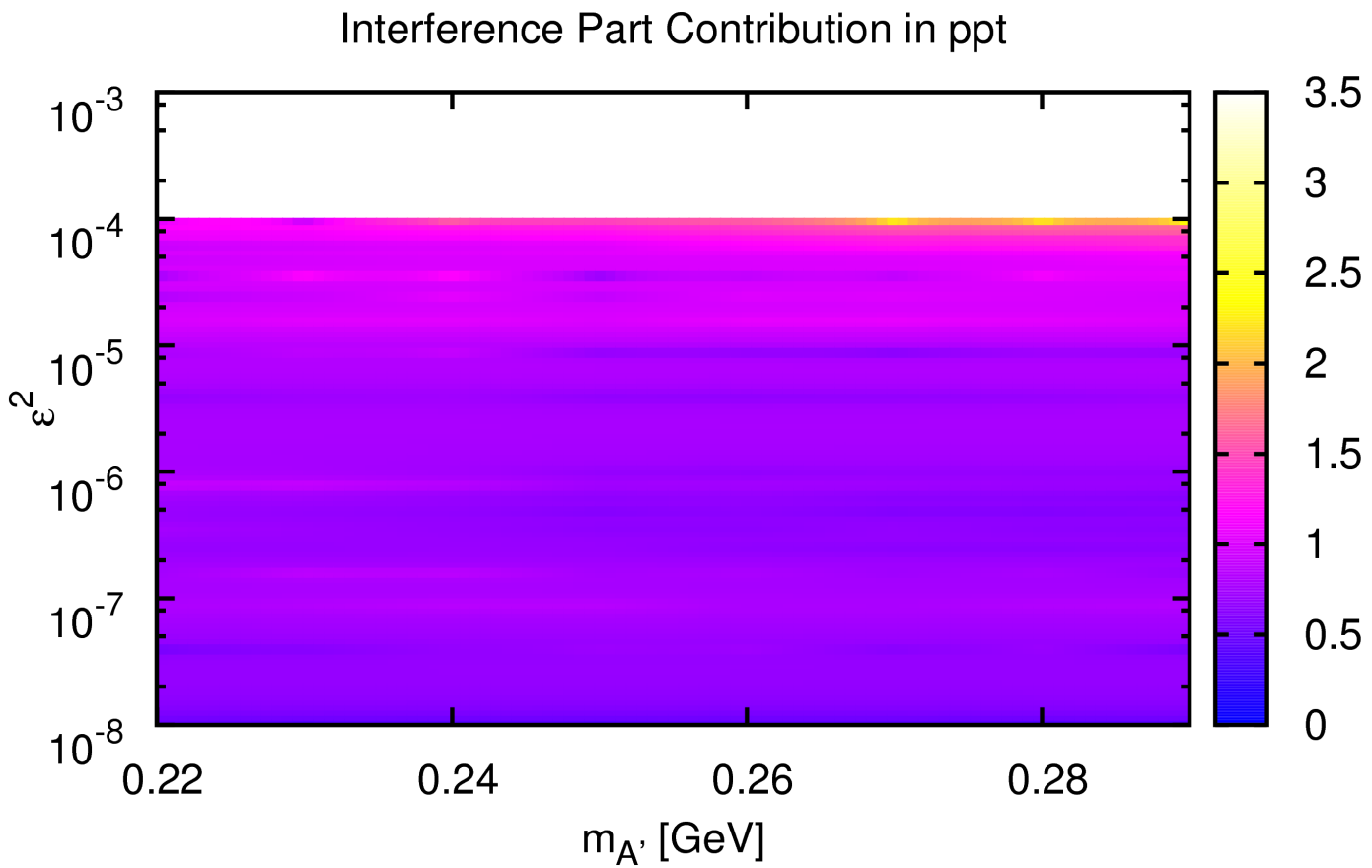

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ε^2 Exclusion Limit from Data

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

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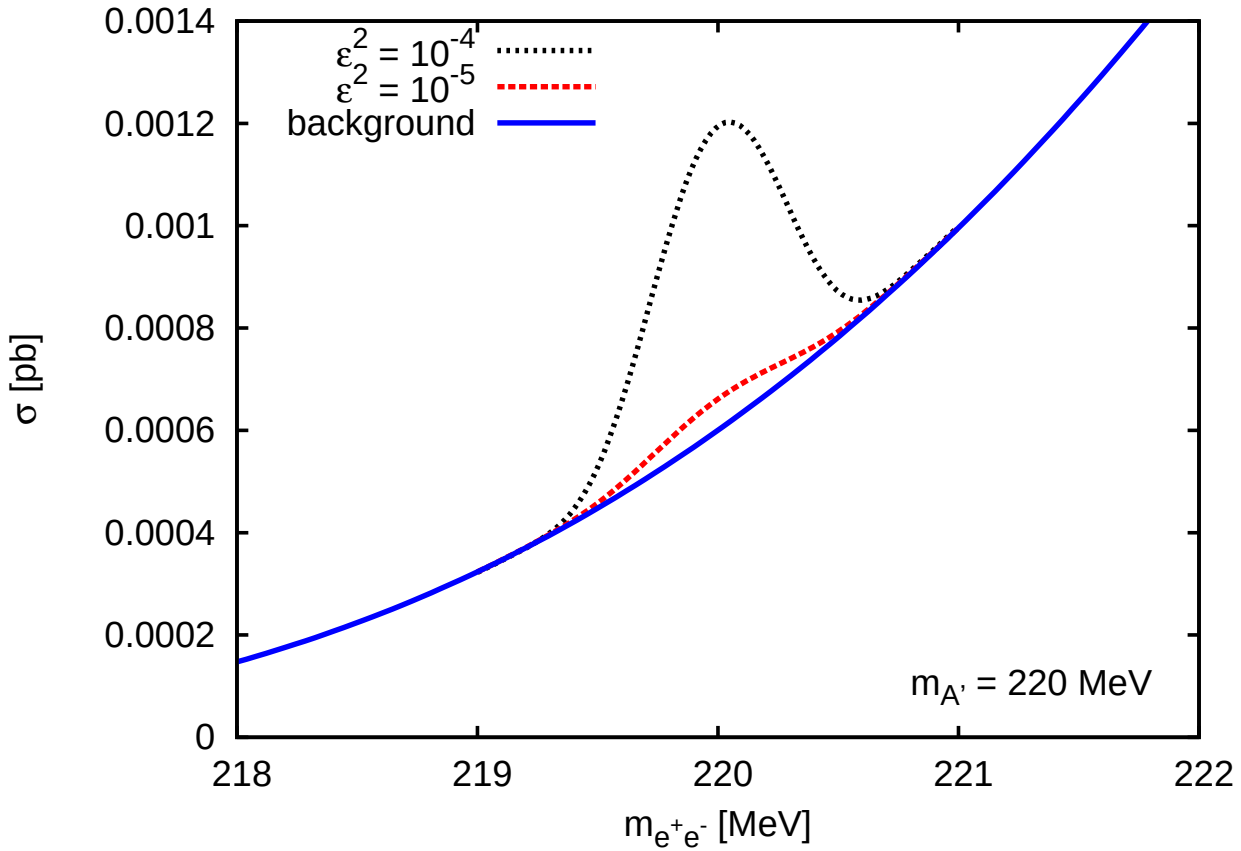
$\Rightarrow$ How well do we know σ_γ?

A' Production from $ep \to epe^+e^-$: Background vs. Signal



$\Gamma_{A'}$ is very narrow, broad peak due to finite mass resolution

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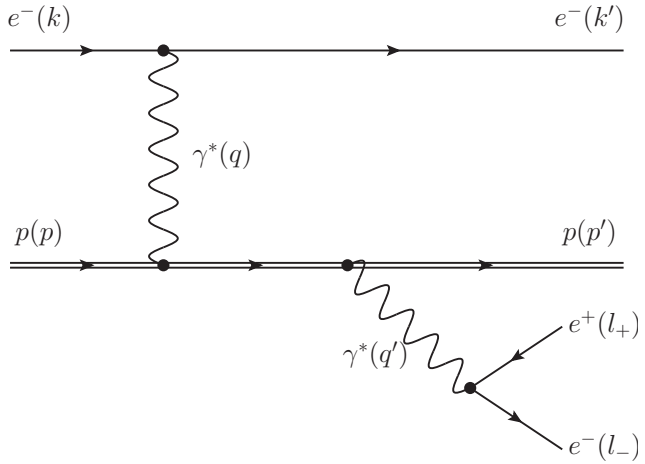
A' Production from $ep \to epe^+e^-$: QED Background: Compton Scattering



Double virtual Compton scattering amplitude:

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

Double VCS contribution is **included**

A' Production from $ep \to epe^+e^-$: Technical Challenges

Experiments have finite acceptancies

$\Rightarrow$ Evaluate $\int \frac{d\sigma}{d\left|\vec{l_+}\right| \, d\Omega_+ \, d\Omega_- \, d\Omega_{e'} \, dq'^2}$ within the exp. limits

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Problem: 7-fold numerical integration and integrand contains several **strongly peaked structures**

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Key Question:

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

A' Production from $ep \to epe^+e^-$: Technical Challenges

Try to perform calculation as precise as possible:

- Use Monte Carlo (VEGAS) algorithm
- Large number of random numbers needed

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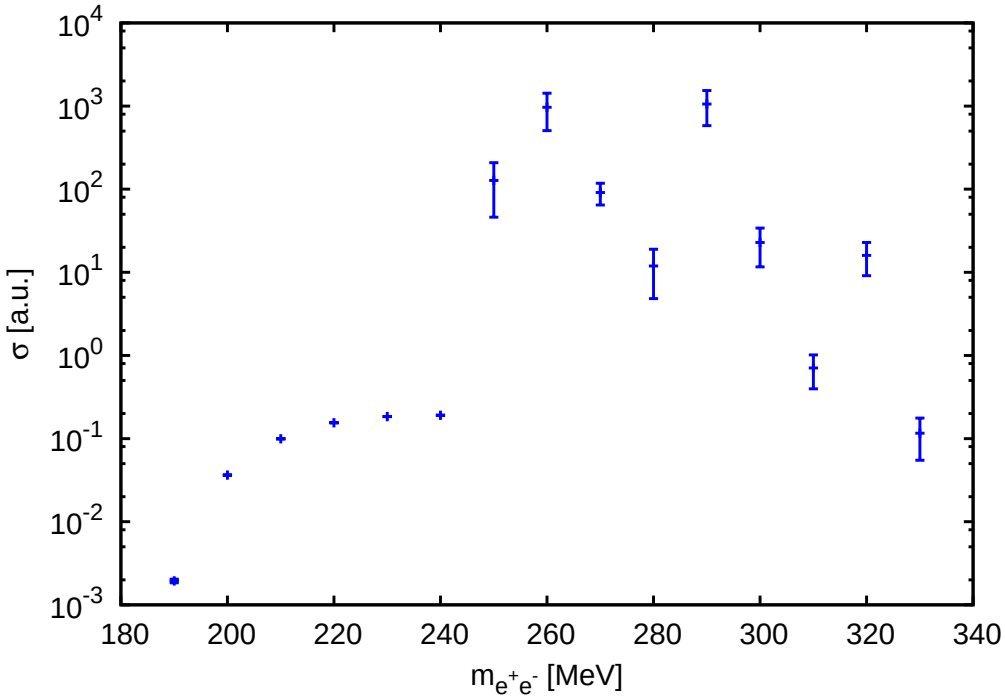

A' Production from $ep \to epe^+e^-$: Technical Challenges

Estimate: Speedup of factor $\sim 100 - 200$ needed

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Two Possibilities

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2. Optimize Code

$\Rightarrow$ Try to apply both

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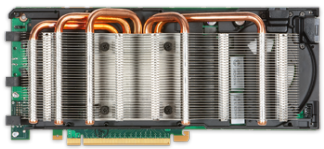

(NVidia Tesla)

Run calculations on **General Purpose Graphics Processing Units (GPGPU)**

Programming framework:
C extensions **NVIDIA CUDA** existing

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A' Production from $ep \to epe^+e^-$: Technical Challenges

My **Motivation** for Performing the **Calculation on GPU's**

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- designed for **massively parallel applications**
- large number of (CUDA) cores **(1 GPU $\simeq$ 450 cores)** at low costs
- Curiosity: Is it feasible to run a **Monte Carlo** on it?

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Some **Problems** of GPU programming
GPU's are...

- specialists in performing **"easy" floating point operations**
- strongly **constraint by memory**
- much **different from CPU's**

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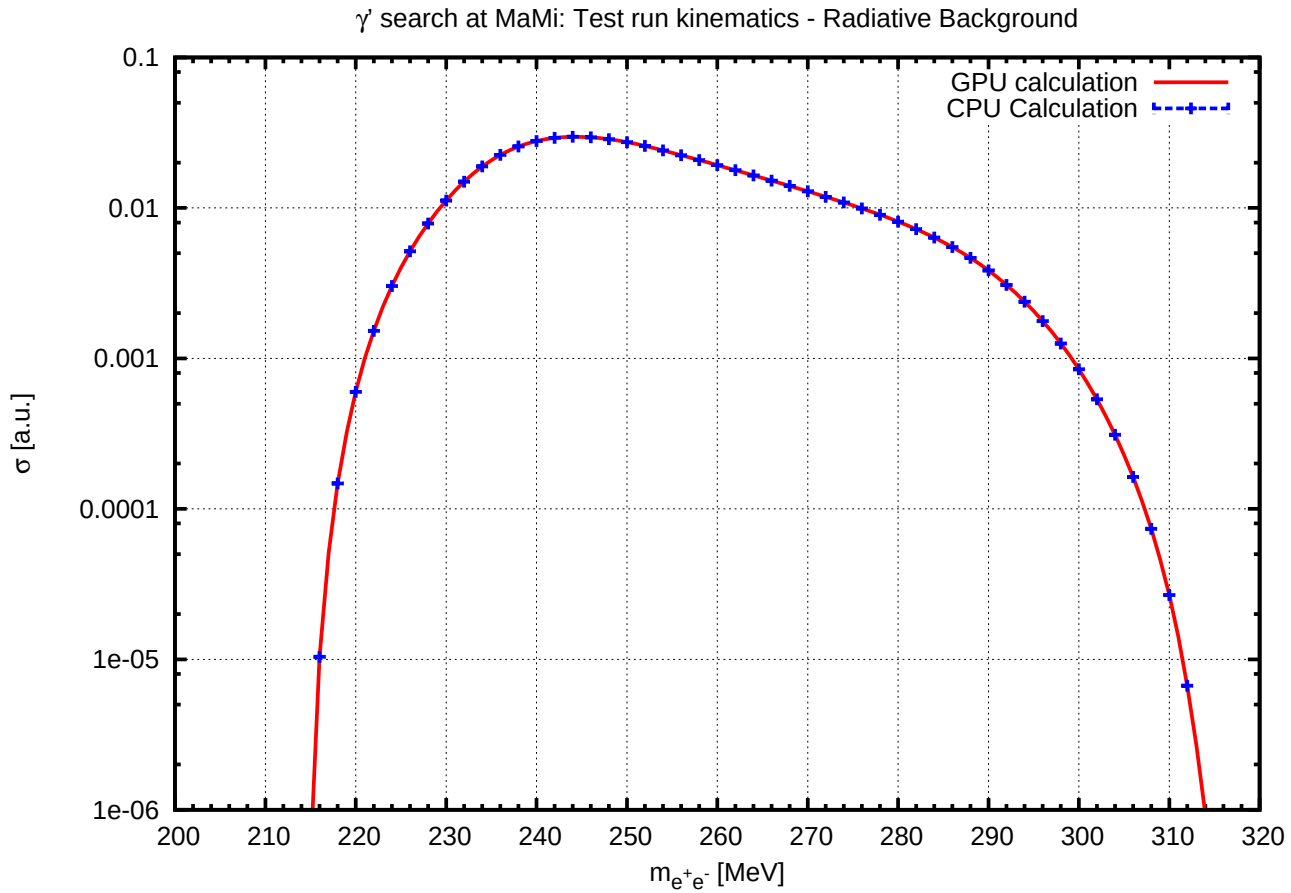
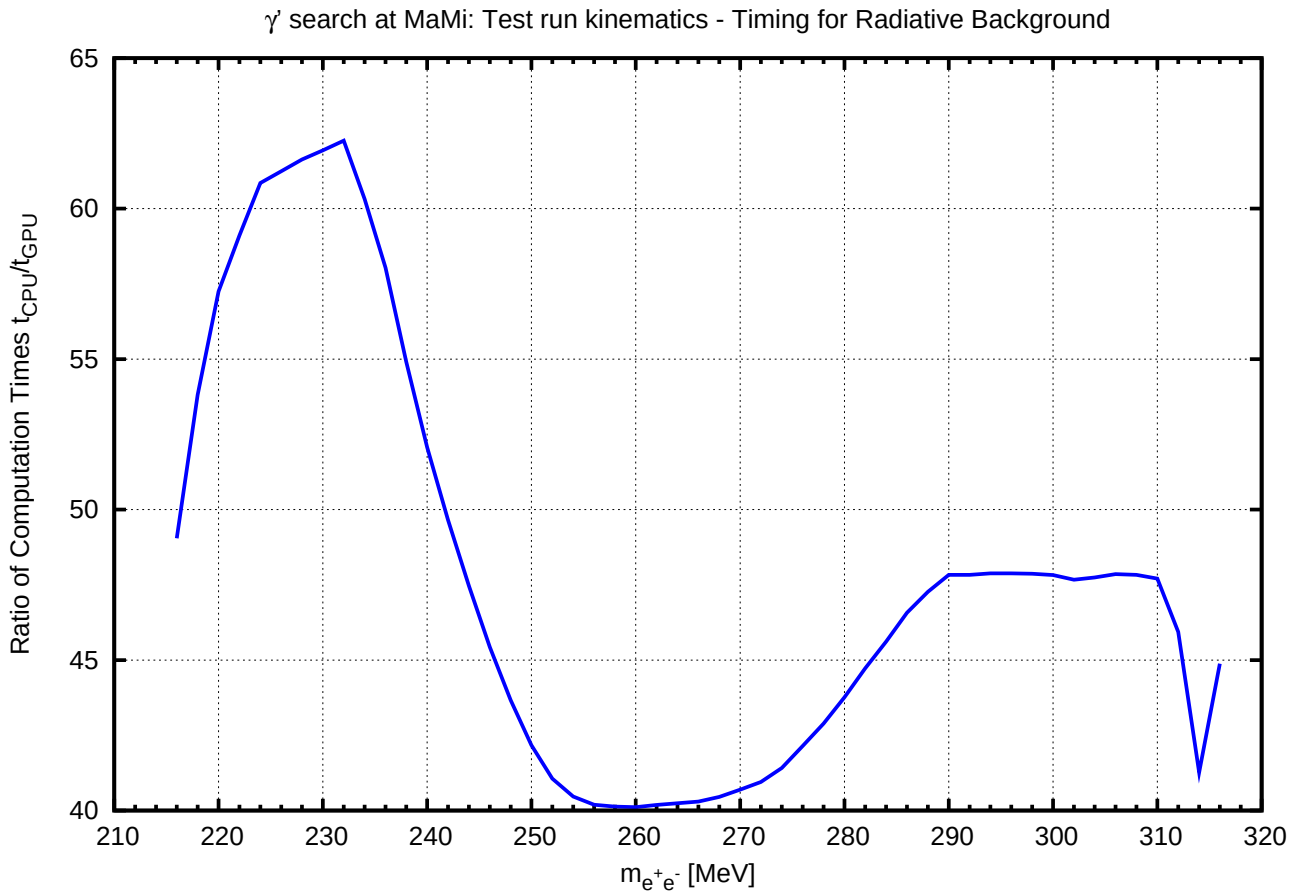
A' Production from $ep \to epe^+e^-$: Technical Challenges

Results of CPU and GPU calculation:
Comparison of numerical values



A' Production from $ep \to epe^+e^-$: Technical Challenges

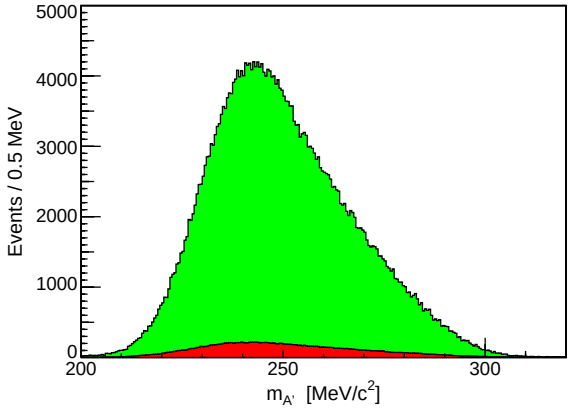
Results of CPU and GPU calculation:
Comparison of computing times



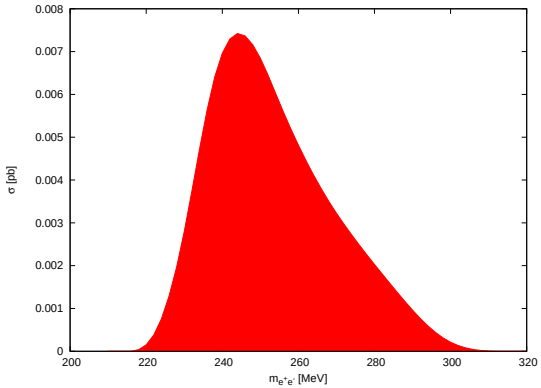
A' Production from $ep \to epe^+e^-$: Results (I)

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

Experiment



Theory



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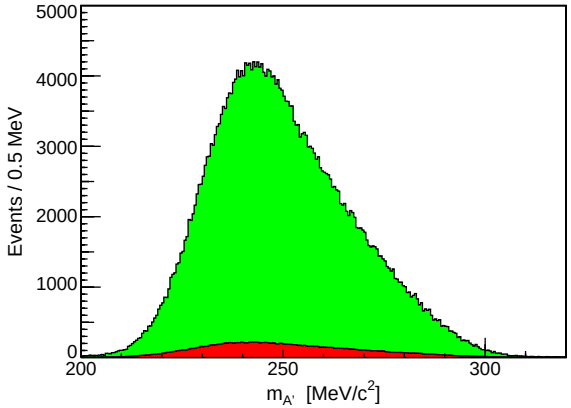
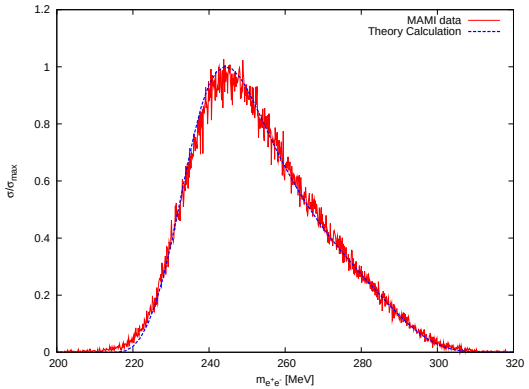


Comparison



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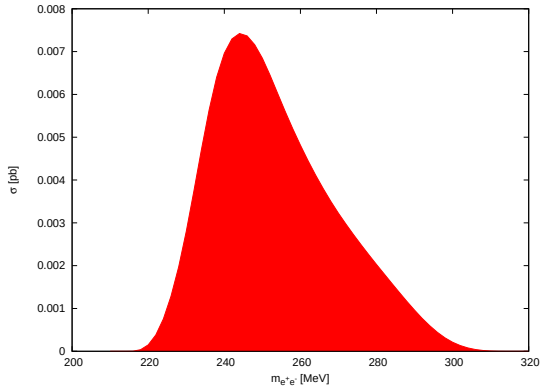

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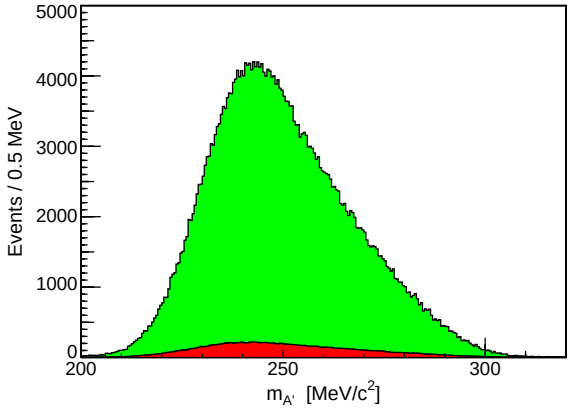

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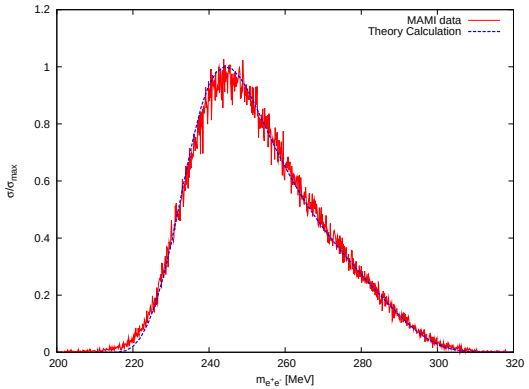

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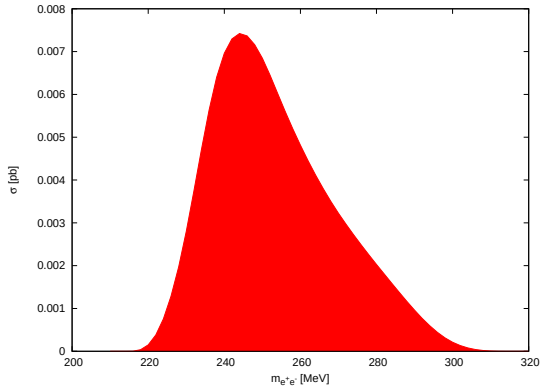
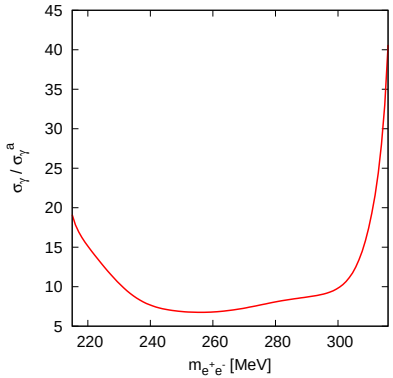


Ratio $\sigma_\gamma / \sigma_\gamma^a$



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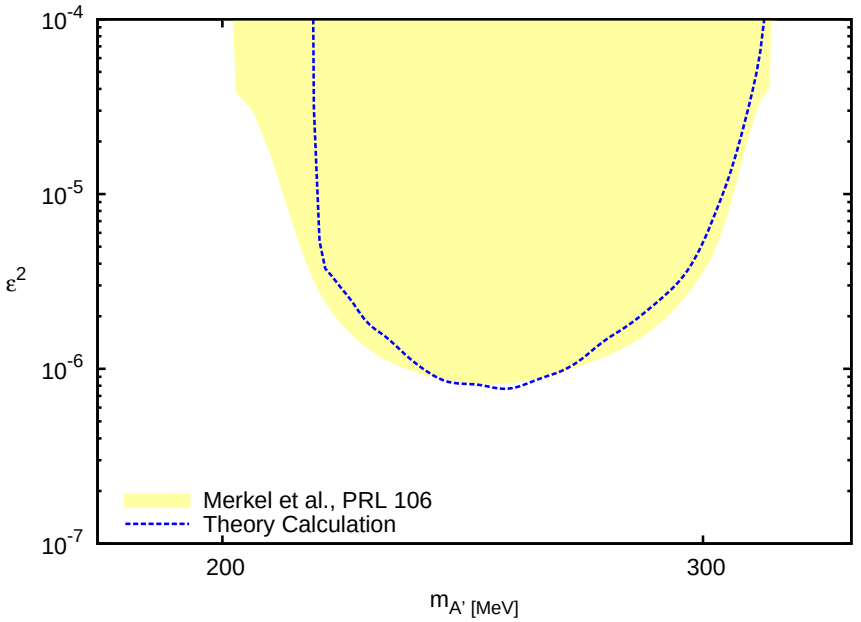
A' Production from $ep \to epe^+e^-$: Results (II)

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

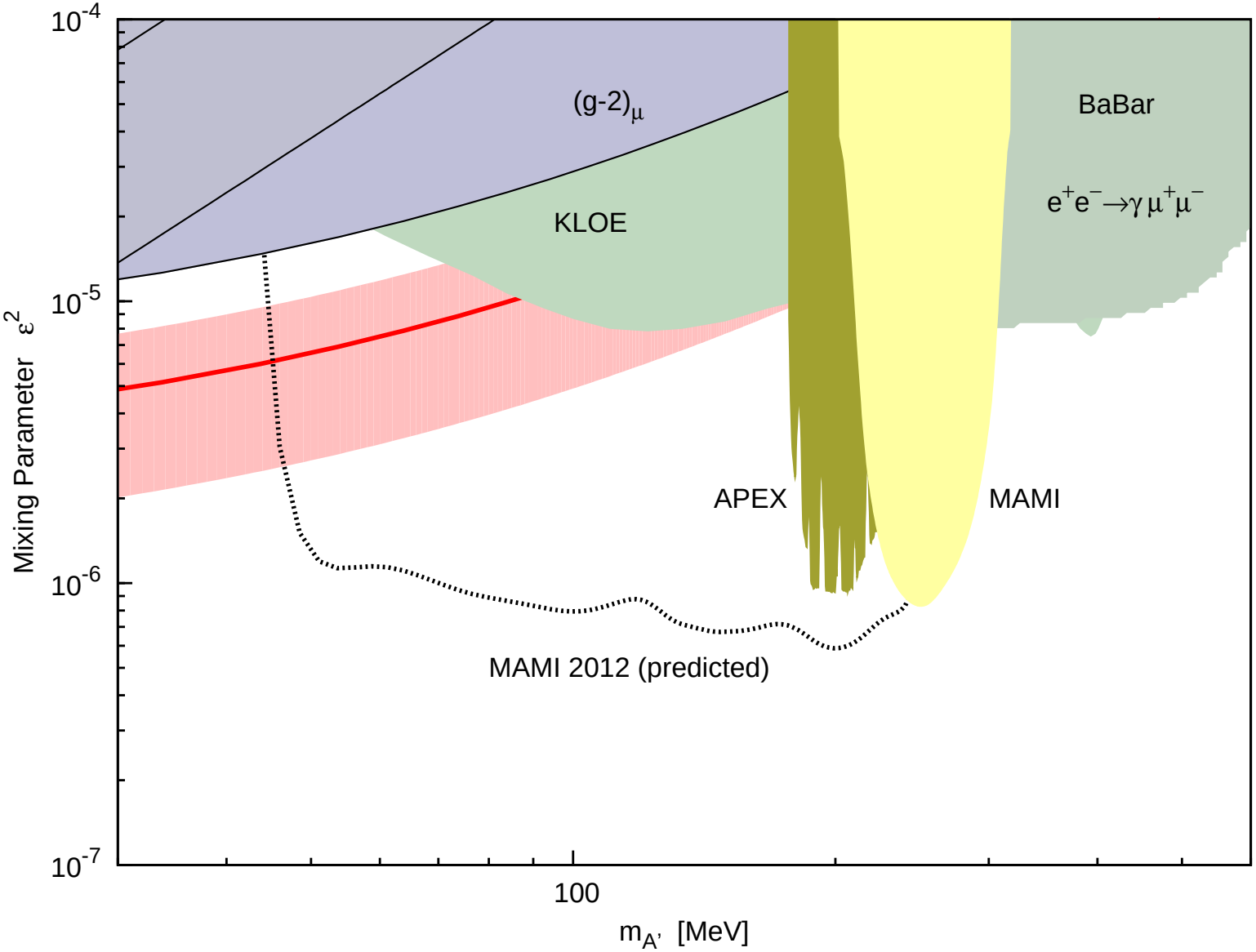


Input:

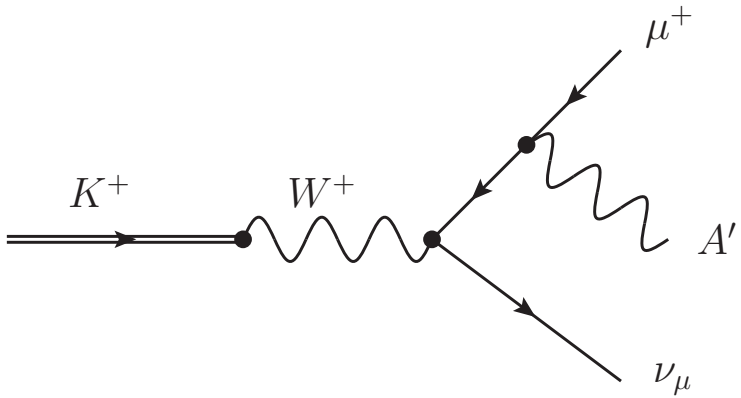
- kinematics
- detector acceptance
- experimental limits

Both calculations are **in good agreement**

A' Production from $ep \rightarrow epe^+e^-$: Results (III)

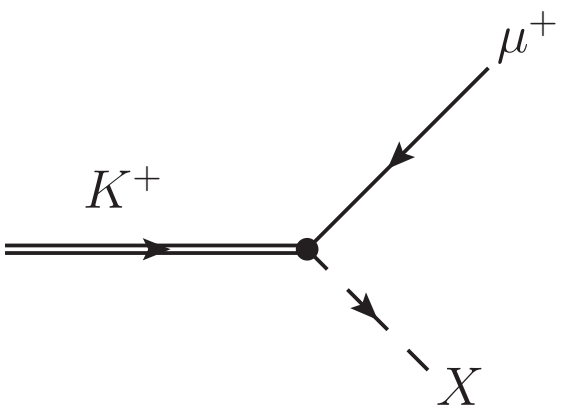


A' Search Using Rare Kaon Decays



TB, M. Vanderhaeghen, arXiv:1209.4561

Search for Neutral States in Rare Kaon Decays



Pioneering Work 40 Years Ago

- **Kaon stopped** inside a detector
- Search for the Leptonic decay $K^+ \to \mu^+ X$
- X may **not** contain a **charged** state or a **photon**

Pang et al., PRD8, 1973

- Large (**separable**) background from $K^+ \to \mu^+ \nu_\mu$
- Remaining SM background, e.g. $K^+ \to \mu^+ \nu_\mu \nu_l \bar{\nu}_l$, **strongly suppressed**
- Data taken in 1973 can be **utilized to search for A'**
- **Future experiments** (NA62@CERN, JPARC) with larger kaon flux existing

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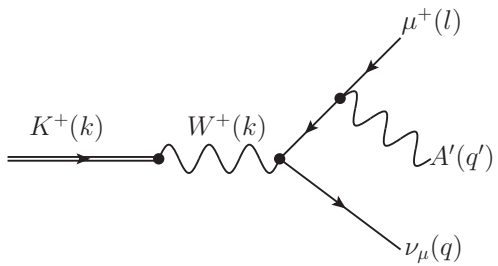
A' Production in Rare Kaon Decays: Decay Rate



(a)

Model 1:

Invoked to explain the proton radius puzzle: ***A′* radiated only from the μ^+**, $1/m_{A'}^2$ enhancement (gauge invariance broken)

(Pospelov et al., PRL 107)

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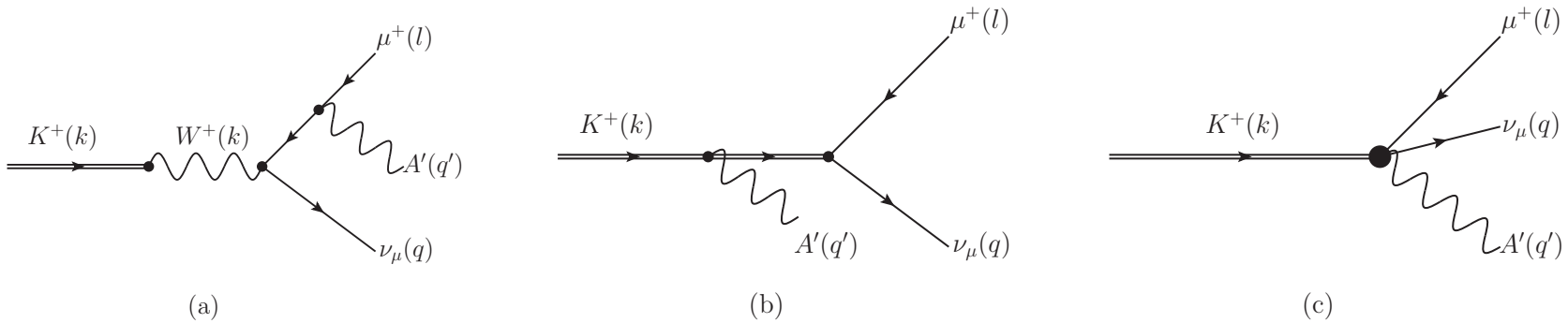

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Model 2:

Kinetic mixing (gauge invariance fulfilled)

$\mathcal{M} \propto$ internal bremsstrahlung + structure dependent

(Bijnens et al., Nucl.Phys.B396)

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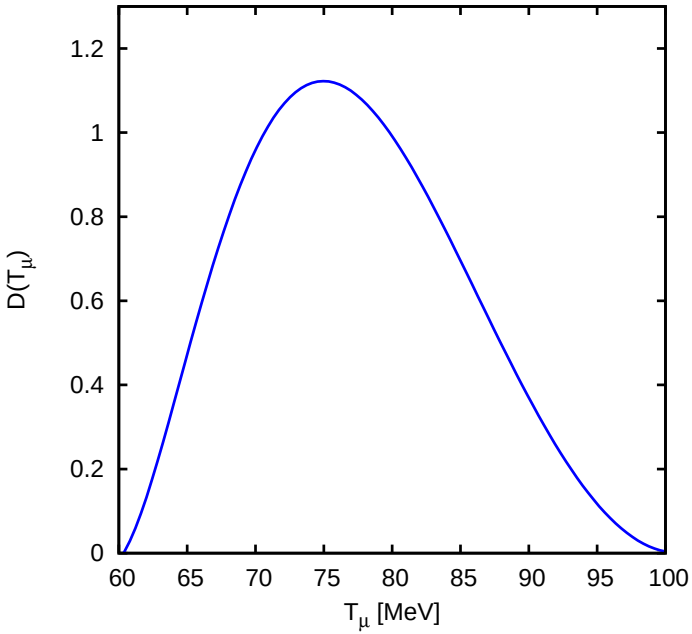
A' Production in Rare Kaon Decays: Exclusion Limit Calculation



Pang et al. (1973)

finite detector efficiency,
$(60\ \text{MeV} \leq T_\mu \leq 100\ \text{MeV})$

Their result:
BR < $2 \cdot 10^{-6}$

Coupling Strength Bound:

$$\varepsilon^2 < \frac{\text{BR} \cdot \Gamma(K^+ \to \mu^+ \nu_\mu)}{\int \frac{d\tilde{\Gamma}}{dE_\mu}(K^+ \to \mu^+ \nu_\mu A') D(E_\mu) dE_\mu}$$

$$\tilde{\Gamma} = \Gamma / \varepsilon^2$$

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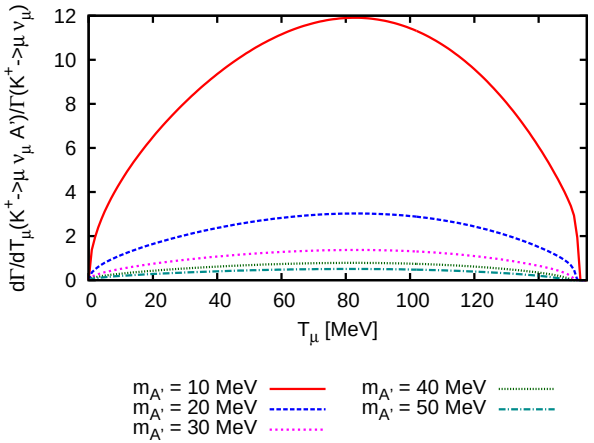
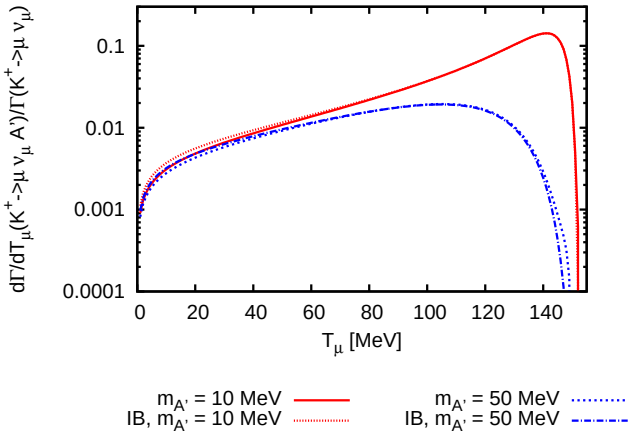
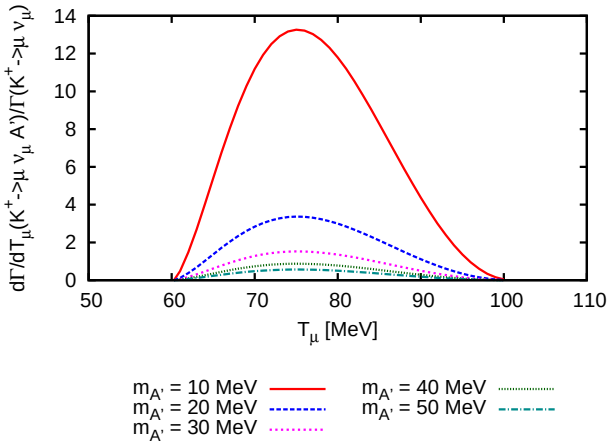
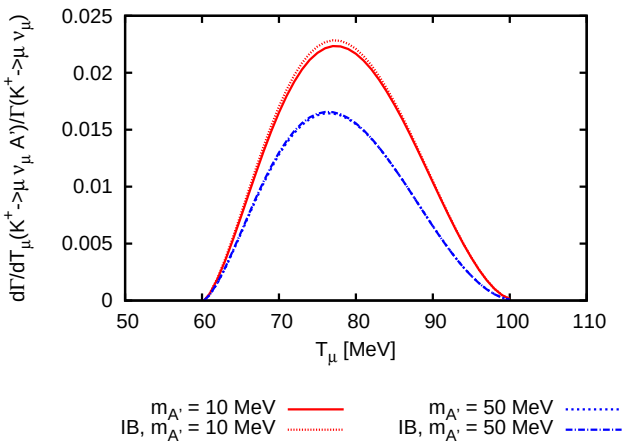




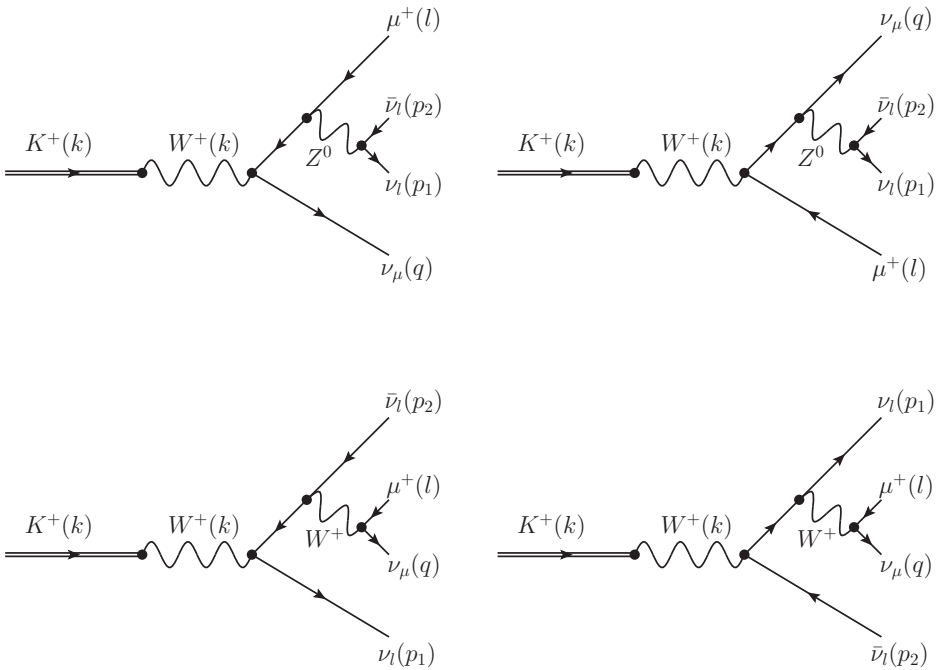




Model 1:
A' couples to μ^+ only

Model 2:
kinetic mixing

The Rare Kaon Decay $K^+ \to \mu^+ \nu_\mu \nu_l \bar{\nu}_l$ (I)



- Calculable in electroweak theory
- Suppressed by G_F^2

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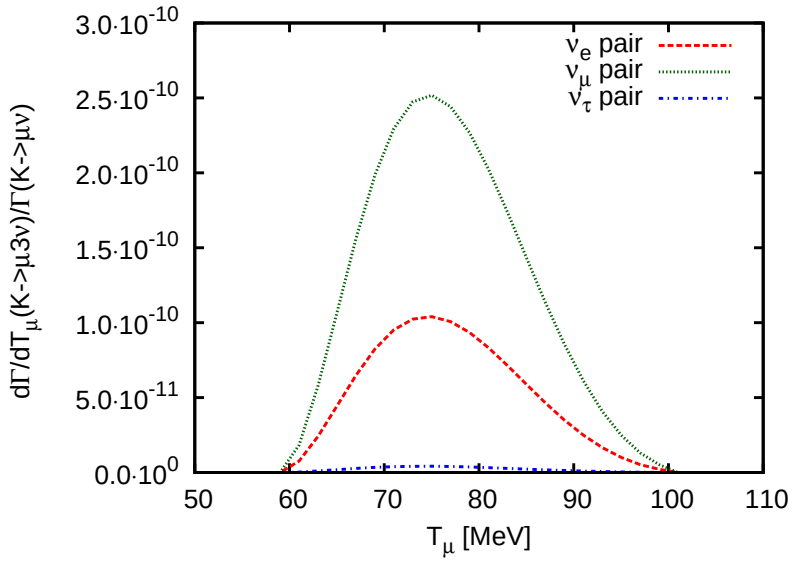
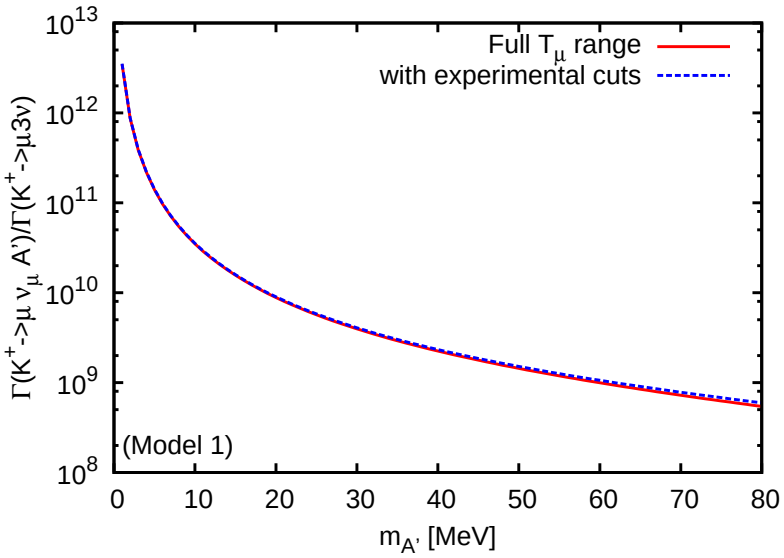
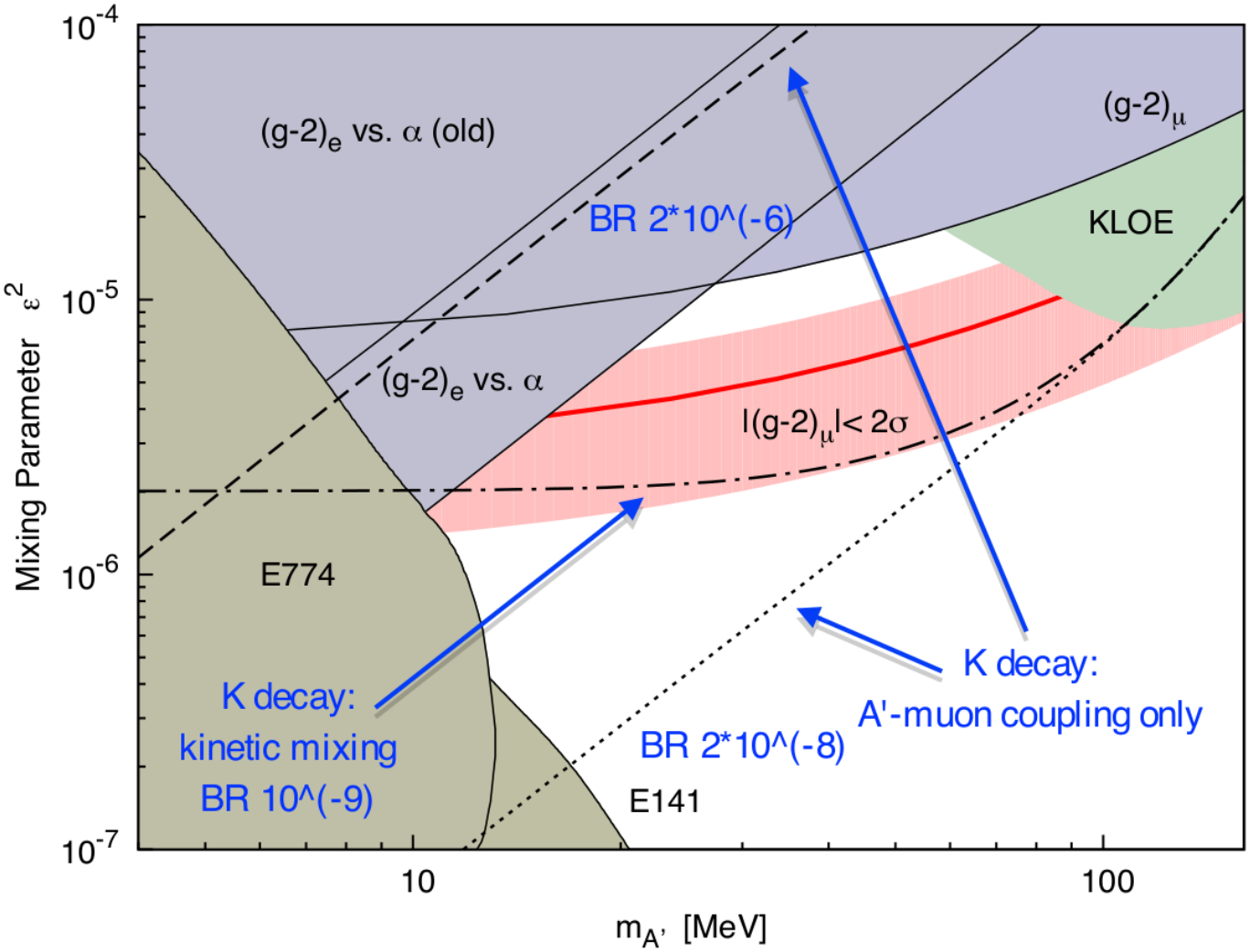
The Rare Kaon Decay $K^+ \to \mu^+ \nu_\mu \nu_l \bar{\nu}_l$ (II)



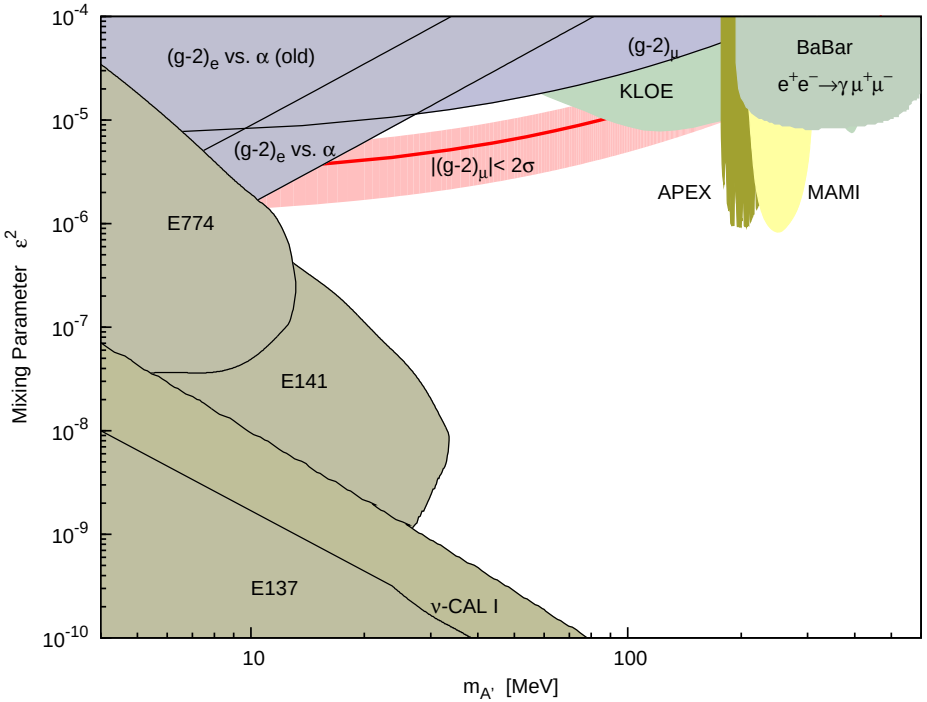


Signal dominates over background up to $\varepsilon^2 \approx 10^{-9}$ (model 1)

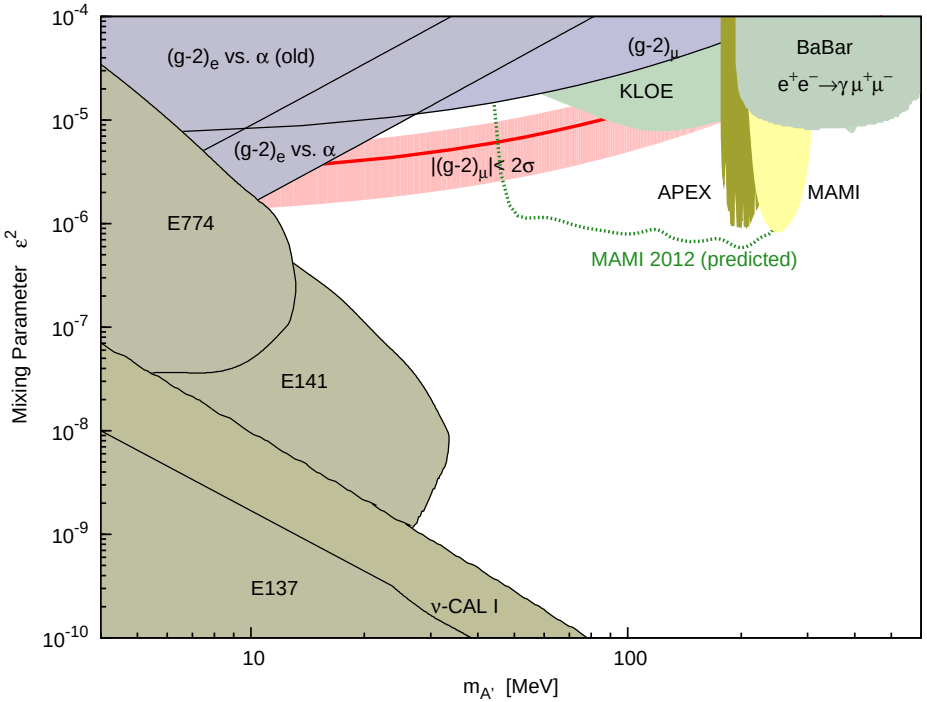
Exclusion Limits



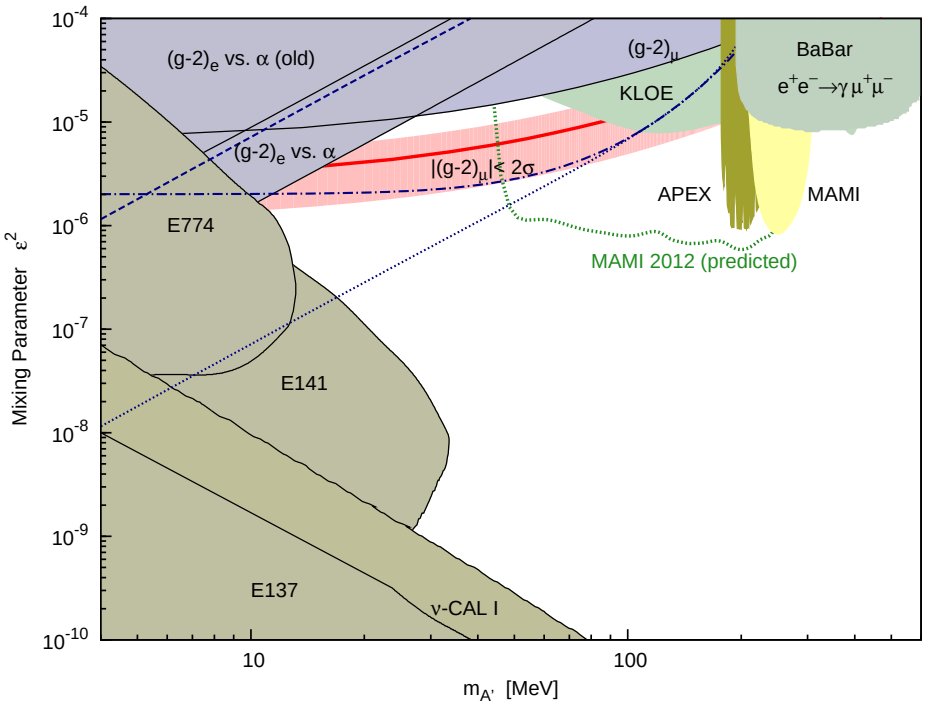
Conclusions & Outlook



Conclusions & Outlook



Conclusions & Outlook



Outlook:

Analsyis of 2012 MAMI run data on the way

Study of further experiments planned at MAMI and JLAB (APEX, HPS, DarkLight)

Study of the low mass A' search planned at MESA

Search using rare kaon decays at NA62@CERN or JPARC

$K^+ \to \mu^+ \nu_\mu A'$ bound:

dashed and dotted curve:
Model 1: limit for BR $< 2 \cdot 10^{-6}$ and $2 \cdot 10^{-8}$

dash-dotted curve:
Model 2: limit for for BR $< 10^{-9}$

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