MAInz Microtron MAMI:
Low-Energy Precision Physics with Electron Fixed-Target Experiments

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The MAMI Accelerator

MAMI-C:
- since 2007 in routine operation
- Beam energy $E_{e \text{max}} = 1.604 \text{ GeV}$

**HIGH Intensity** (max. 100 $\mu$A)
**HIGH Resolution** ($\sigma_E < 0.100 \text{ MeV}$)
**HIGH Polarization** (ca. 80%)
**HIGH Reliability** (7000 h / year)
Experiment A1: High-Resolution Spectrometers

- 4 magnetic focussing spectrometers
- Resolution: $\delta p/p < 10^{-4}$
- Angular acceptance: <30 mrad
Experiment A2: Tagged Photon Beam

**Experiment A2: Photon Scattering**
- “Tagged” bremsstrahlung photons
- $4\pi$ calorimeter setup around target

  **Crystal Ball** (672 NaI, $20^\circ<\Theta<160^\circ$)
  **TAPS** (384 BaF$_2$, $1^\circ<\Theta<20^\circ$)
Recent Results

Nucleon Structure

- Nucleon EM FFs to determine the proton radius

Rare meson decays

- Input to HLbL contribution to $(g-2)_\mu$: $\eta \rightarrow e^+ e^- \gamma$
- Test of ChPT through rare decay $\eta \rightarrow \pi^0 \gamma \gamma$

Search for New Physics

- Dark photon searches
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Search for New Physics
→ Dark photon searches
→ Measurement of the electroweak mixing angle \( \sin^2 \Theta_W \)

Outlook: MESA accelerator
Nucleon EM Form Factors to determine the Proton Radius
EM Form Factors of the Proton

Elastic form factors in ep scattering:

\[ \frac{d\sigma}{d\Omega} = \left( \frac{d\sigma}{d\Omega} \right)_{\text{Mott}} \frac{1}{\varepsilon (1 + \tau)} \left[ \varepsilon G_E^2 \left( Q^2 \right) + \tau G_M^2 \left( Q^2 \right) \right] \]

\[ \varepsilon = \left( \frac{1 + 2 (1 + \tau) \tan^2 \frac{\theta_e}{2}}{2} \right)^{-1} \]

\[ \tau = \frac{Q^2}{4m_p^2} \]

\( G_E \): spatial electric charge distribution

\( G_M \): distribution of magnetic moments
EM Form Factors of the Proton

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Super-Rosenbluth measurement

average of all fit models with uncertainties
**EM Form Factors of the Proton**

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- **Gₜ:** spatial electric charge distribution
- **Gₘ:** distribution of magnetic moments

**Super-Rosenbluth measurement**

Average of all fit models with uncertainties

**Proton charge radius:**

\[
\langle r_{E/M}^2 \rangle = -\left. \frac{6\hbar^2}{G_{E/M}(0)} \frac{dG_{E/M}(Q^2)}{dQ^2} \right|_{Q^2=0}
\]

PRL10 (A1): \( <r_E> = 0.879(8) \text{ fm} \)

PRL '10, 242001: Bernauer et al.

arXiv 1307:6227: new technical paper
Proton Radius Puzzle

Comparison btw. electron scattering and atomic physics evaluations

H/D spectroscopy + QED (10 eV) → 0.8760 (78) fm → HFS hydrogen

Mainz electron-proton scattering (200 Mev - 1 GeV) → 0.879 (6) fm → CODATA

<\textit{r_E}\text{> (fm)}
Proton Radius Puzzle

Comparison btw. electron scattering and atomic physics evaluations

HFS hydrogen
Lamb shift muonic hydrogen
CODATA

<\textit{r_E} (fm)>
Proton Radius Puzzle

Comparison btw. electron scattering and atomic physics evaluations

HFS hydrogen

Electron scattering

Error(s) or New Physics?

Hadronic or QED uncertainties? → No obvious mistake found!

Dark photon or other new physics? → Only dedicated models viable!

Several new experiments planned to shed new light on puzzle → Mainz: Initial State Radiation
New: ISR Measurement of EM Form Factors

Strategy:
- Reach very low values of $Q^2$ by using events with Initial State Radiation
- Measure momentum spectrum of scattered electron after ISR
- Needs very good understanding of QED radiative corrections

→ determine proton radius with competitive precision
**New: ISR Measurement of EM Form Factors**

**Recent beam time (08/13):**

- 3 MAMI energy settings: 495, 330, 195 MeV
- luminosity measurement with second spectrometer

→ after few online calibrations agreement with QED prediction on few % level

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**Counts/0.1 mC**

![Graph with data points and labels](image-url)
Rare eta decays* at the Crystal Ball /TAPS:

\[ \eta \rightarrow e^+ e^- \gamma \]
\[ \eta \rightarrow \pi^0 \gamma \gamma \]

* Results based on 6x10^7 eta mesons produced in 6 weeks of beam time in 2007/2009
Timelike EM Form Factor: $\eta \rightarrow e^+ e^- \gamma$

\[
\frac{d\Gamma(\eta \rightarrow l^+ l^- \gamma)}{dm_{ll} \Gamma(\eta \rightarrow \gamma \gamma)} = [QED] \cdot |F_\eta(m_{ll})|^2
\]

pointlike eta

$F_\eta(m_{ll})$

$\eta \rightarrow e^+ e^- \gamma$

$\gamma^* \rightarrow l^+ l^-$
**Timelike EM Form Factor:** \( \eta \rightarrow e^+ e^- \gamma \)

\[
\frac{d\Gamma(\eta \rightarrow l^+ l^- \gamma)}{d\mu l \Gamma(\eta \rightarrow \gamma \gamma)} = [QED] \cdot |F_\eta(m_{\mu l})|^2
\]

Features:
- Upgrade of existing result (PLB 701, 562) → factor 10 more statistics: **18,000 events**
- Normalization to \( \eta \rightarrow \gamma \gamma \)
- Accuracy:
  - \( m_{ee} < 2m_\mu \): most accurate measurement
  - \( m_{ee} > 2m_\mu \) similar to recent NA60/CERN measurement of \( \eta \rightarrow \mu \mu \gamma \)

\[
m(e^+ e^-) = 45\text{MeV}/c^2 \quad \text{370MeV}/c^2
\]

\(Ev=1353\pm42\) \( Ev=168\pm24\)
Timelike EM Form Factor: $\eta \rightarrow e^+ e^- \gamma$

Measurement to be submitted to Phys. Rev. C: S. Prakhov, M. Unverzagt et al. (A2 collab.)

Vector Meson Dominance model:

$$F(m_{ll}) = \frac{1}{1 - \frac{m_{ll}^2}{\Lambda^2}}$$

$\Lambda^{-2} = (1.95 \pm 0.15_{\text{stat}} \pm 0.10_{\text{syst}}) \text{GeV}^{-2}$

in good agreement with all previous results

TL calculation: S. Leupold, C. Terschüsen
Padé calculation: R. Escribano, P. Masjuan, P. Sanches-Puertas
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Important test of phenomenological models in view of HLbL contribution to $(g-2)_\mu$

TL calculation: S. Leupold, C. Terschlüsen
Padé calculation: R. Escribano, P. Masjuan, P. Sanches-Puertas
Test of ChPT: Rare eta decay $\eta \rightarrow \pi^0 \gamma \gamma$

**Features:**
- No $O(p^2)$, $O(p^4)$ contrib. $\Rightarrow$ *starts with* $O(p^6)$ contribution
  $\Rightarrow$ **Interesting test of chiral dynamics**
- Previous **measurements** from CB@AGS, GAMS, WASA, KLOE, CB@MAMI **inconclusive**
  $\Rightarrow$ **Experimentally very difficult channel**
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- No $O(p^2), O(p^4)$ contrib. $\rightarrow$ starts with $O(p^6)$ contribution
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  $\rightarrow$ Experimentally very difficult channel

![Graph showing $\eta \rightarrow \pi^0 \gamma \gamma$ and $\eta \rightarrow \pi^0 \pi^0$ decays with data points and theoretical curves.](image_url)
A Search for the Dark Photon at MAMI
Dark Photon Search

New massive force carrier of extra $U(1)_d$ gauge group; predicted in almost all string compactifications

$\alpha' = \varepsilon^2 \cdot \alpha_{em}$

Search for the $O(\text{GeV}/c^2)$ mass scale in a world-wide effort

- Could explain large number of astrophysical anomalies
  Arkani-Hamed et al. (2009)
  Andreas, Ringwald (2010); Andreas, Niebuhr, Ringwald (2012)

- Could explain presently seen deviation of $3.6\sigma$ between $(g-2)_\mu$
  Standard Model prediction and direct $(g-2)_\mu$ measurement
  Pospelov (2008)
The $(g-2)_\mu$ Parameter Range

 allowed parameter range for Dark Photon explanation of $(g-2)_\mu$
Searches using Fixed-Target Experiments

Bjorken, Essig, Schuster, Toro (2009)

Low-energy, high-intensity accelerators are ideally suited for Dark Photon searches

→ MAMI: $E_\gamma < 1.6$ GeV
→ A1 spectrometer setup

QED background processes:

(a) 

(b)
Results from A1 Pilot Run (2010)

Exclusion range from MAMI / A1 spectrometers during 4-day pilot run

A1/MAMI
PRL 2011
Expected Range from 2012/13 A1-Runs

Expected exclusion range from runs taken in spring 2012/spring 13

Achim Denig
Dark Photon Search @ MAMI/MESA
Outlook: Perspectives for precision physics at MESA
**MESA Accelerator**

Mainz Energy-Recovering Superconducting Accelerator

\[ E_{\text{max}} = 200 \text{ MeV} \]
\[ I_{\text{max}} = 10 \text{ mA} \]

2 Modes:
- Internal Gas Target (ERL mode)
- Extracted Beam (Non-ERL mode)
Phase 3: Accessing the Low Mass Region

Expected exclusion range from MESA runs (Xe gas target, dual arm spectrometers)
MESA contribution to $\sin^2\theta_W$

Scattering of long-polarized electrons (150 MeV) on protons

→ Z boson exchange introduces parity-violating effect

→ Measure Parity-violating Left-Right cross section asymmetry $A_{LR}$ of $20 \times 10^{-9}$

\[
A_{LR} = \frac{\sigma(e \uparrow) - \sigma(e \downarrow)}{\sigma(e \uparrow) + \sigma(e \downarrow)} = -\frac{G_F Q^2}{4\sqrt{2}\pi\alpha} (Q_W - F(Q^2))
\]

\[
Q_W = 1 - 4\sin^2\theta_W(\mu)
\]

hadron structure
**MESA contribution to $\sin^2\theta_W$**

Scattering of long. polarized electrons (150 MeV) on protons

$\rightarrow$ Z boson exchange introduces parity-violating effect

$\rightarrow$ Measure Parity-violating Left-Right cross section asymmetry $A_{LR}$ of $20 \times 10^{-9}$

**MESA:** $\Delta\sin^2\theta_W = 4 \times 10^{-4}$
Conclusions

**SFB1044:**
*The low-energy frontier of the Standard Model*

- **Hadron physics:** Improve our understanding of low-energy QCD
- **Mainz programme related to puzzles in low-energy particle physics**
  - \((g-2)_{\mu}\)
  - Proton radius
  - \(\sin^2\Theta_W\)
- **Complementing MAMI expts. with e+e- expts. at BESIII**
**Dark Photon Search @ A1**

**Features 2010 pilot run (4 days)**

- Beam energy 855 MeV
- Target: 0.05 mm Tantalum
- Beam current \( \sim 100\mu A \) \( \rightarrow \) Luminosity \( \sim 10^{39} \) cm\(^{-2}\)s\(^{-1}\)
- Kinematic configuration:  
  - complete energy transfer to \( \gamma' \) boson  
  - symmetric \( e^- \) and \( e^+ \) momenta
- Cerenkov detector for electron/positron identification

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**Graphs**

1. **Time difference between spectrometers A, B**
   - \( \Delta T_{AB} < 1 \text{ ns} \)

2. **QED bkg., \( \delta M_{ee} \sim 0.5 \text{ MeV} \)**
   - Hypothetical Dark Photon signal: bump in one single bin
Internal Target Experiments at MESA

Energy-Recovering (ERL) mode:
105 MeV beam energy @ 10 mA

Projects:
- Dark Photon
- Proton Radius
- Nuclear physics
- .....
A Low-$Q^2$ Measurement of $\sin^2\theta_W$ at MESA

Scattering of longitudinally polarized electrons on protons

→ Z boson exchange in electron-proton scattering introduces parity-violating effect

→ Measure parity-violating Left-Right cross section asymmetry $A_{LR}$
Possible Scenarios 2017+

Scenario: Scenario:

Metastable universe $\rightarrow$ No Physics beyond the SM

<table>
<thead>
<tr>
<th>Scenario</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metastable universe</td>
</tr>
<tr>
<td>$\rightarrow$ No Physics beyond the SM</td>
</tr>
</tbody>
</table>

\[
\begin{align*}
\sin^2 \theta^\text{eff} &
\begin{array}{c}
0.23 \\
0.2305 \\
0.231 \\
0.2315 \\
0.232 \\
0.2325 \\
0.233
\end{array}
\end{align*}
\]

Higgs Boson Mass (GeV)

- 70
- 100
- 200

\[
\begin{align*}
\Delta \alpha_{\text{had}} &\pm 0.22\
m_{\text{top}} &\pm 0.6\
m_{\text{Higgs}} &\pm 1
\end{align*}
\]

SLD | LEP | MESA | ATLAS
New: ISR Measurement of EM Form Factors

Recent beam time (08/13):
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  → after few online calibrations agreement with QED prediction on few % level

Electron energy $E'$ [MeV]

Counts/ 0.1 mC

August ‘13
EM Form Factors of the Proton

Elastic form factors in electron proton scattering:

\[
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\(G_E\): spatial electric charge distribution

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Super-Rosenbluth measurement (MAMI B):

- Fit of form factor directly to cross section
- Extreme redundancy in kinematics → all \(Q^2\) and \(\varepsilon\) values in one fit
- Systematic issues (e.g. luminosity) independently cross checked
- Various fit functions for form factors

PRL '10, 242001: Bernauer et al.
arXiv 1307:6227: new technical paper
**EM Form Factors of the Proton**

**Proton radius:**

\[ \left\langle r_{EM}^2 \right\rangle = \frac{6\hbar^2}{G_{EM}(0)} \left. \frac{dG_{E/M}(Q^2)}{dQ^2} \right|_{Q^2=0} \]

- **PRL10 (A1):** \( <r_E> = 0.879(8) \text{ fm} \)
- **1307:6227** (incl. world data set e-scatt.)
  \( <r_E> = 0.879(8) \text{ fm} \)

**Full Q^2 range**

- \( G_E \)
- \( G_M \)

Average of all fit models with uncertainties.
EM Form Factors of the Proton

The cross section in terms of G’s has no interference terms:

\[ \frac{d\sigma}{d\Omega} = \frac{\alpha^2}{4E^2 \sin 4\left(\frac{\theta_{e'}}{2}\right)} \frac{E'}{E_0} \left\{ \frac{G_E^2 + \tau G_M^2}{1 + \tau} + 2\tau G_M^2 \tan^2 \left(\frac{\theta_{e'}}{2}\right) \right\} \]

Dividing kinematic factors out yields the reduced cross section convenient for ‘Rosenbluth separations’ for \( X(e,e') \):

\[ \sigma_R \equiv \tau G_M^2 + \varepsilon G_E^2 \]

\[ \tau \equiv \frac{Q^2}{4M^2} \quad \varepsilon = \left[ 1 + 2(1 + \tau) \tan^2 \left(\frac{\theta_{e'}}{2}\right) \right]^{-1} \quad Q^2 = 4EE'\sin^2 \left(\frac{\theta_{e'}}{2}\right) + m_e^2 \quad (= -q^2) \]