Electron scattering in Mainz

Plans for the next decade

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Overview

• The Idea:
  Searching for new physics with the weak mixing angle

• The Machine:
  Mainz Energy-Recovery Superconducting Accelerator

• Experiment I:
  Weak mixing angle with P2
Overview

• Experiment II:
  Dark photons, proton radius etc. with MAGIX

• More experiments:
  Dark matter, electron electric dipole moment etc.

• Even more:
  Continuing program at MAMI
The weak mixing angle
(also: Weinberg-angle)
• One of the fundamental parameters of the standard model

• Electroweak symmetry breaking creates photon and $Z^0$

• Angle shows up both in masses and couplings (charges)

\[
\begin{pmatrix}
\gamma \\
Z^0
\end{pmatrix} =
\begin{pmatrix}
\cos \theta_W & \sin \theta_W \\
-\sin \theta_W & \cos \theta_W
\end{pmatrix}
\begin{pmatrix}
B^0 \\
W^0
\end{pmatrix}
\]

\[
\cos \theta_W = \frac{m_W}{m_Z}
\]

\[
\sin^2 \theta_W = \frac{g'^2}{g^2 + g'^2}
\]
Which weak mixing angle?

- The last slide is true at tree level
- But there are quantum corrections...

Two options:

- Use the masses for the definition:
  (at all orders of perturbation theory)
  “On-shell scheme”

\[ \cos \theta_W = \frac{m_W}{m_Z} \]

- Or use the couplings:
  (which change with energy, and so does the angle)
  “\( \overline{\text{MS}} \)-scheme”

\[ \sin^2 \theta_W = \frac{g'^2}{g^2 + g'^2} \]

\[ \sin^2 \theta_W (q^2) \]
Weak mixing angle and charges

Proton electric charge
+1

Proton weak charge
\(1 - 4 \sin^2 \theta_W\)
Scale dependence (running) of $\sin^2\theta_W$
Scale dependence (running) of $\sin^2 \theta_W$

$Q \ [\text{GeV}]$

$1000 \ 0 \ 100 \ 0 \ 10 \ 0 \ 1 \ 0 \ .1 \ 0 \ .01 \ 0 \ .001 \ 0 \ .0001$

$0 \ .245 \ 0 \ .24 \ 0 \ .235 \ 0 \ .23 \ 0 \ .225$

$\sin^2 \theta_W \ (Q)$

$Q_W \ (p)$

$Q_W \ (e)$

$NuTeV$

$Q_W \ (APV)$

$eDIS$

$\text{Tevatron}$

$\text{SLD}$

$\text{LEP1}$

$\text{ATLAS}$

$\text{CMS}$

$\text{hs}$

$Q \ [\text{GeV}]$
Scale dependence (running) of $\sin^2 \theta_W$ 

![Graph showing scale dependence of $\sin^2 \theta_W$]
New Physics in the running

\[ \sin^2 \theta_W (Q) \]

\[ Q_{W (p)} \]
\[ Q_{W (e)} \]
\[ Q_{\text{weak}} \]

[Graph showing various experiments and data points such as LEP1, SLD, P2@MESA, NuTeV, eDIS, Tevatron, SLD, CMS, ATLAS, QW (e), QW (p), Qweak.]
Dark Z in mixing

Marciano et al.

$\sin^2 \Theta_W (Q^2)$

![Graph showing $\sin^2 \Theta_W (Q^2)$ against $\log_{10}(Q [\text{GeV}])$ with different experimental sensitivities marked, including E138, Qweak, Moller, and LEP. The graph also shows anticipated sensitivities for $m_{\text{dark}Z} = 100 \text{ MeV}$ and $m_{\text{dark}Z} = 200 \text{ MeV}$.](image-url)
Contact Interactions

Contact interactions up to

49 TeV

(comparable to LHC at 300 fb⁻¹)
How to measure the weak charge?
Weak mixing angle and charges

Proton electric charge
\[ +e \]

Proton weak charge
\[ 1 - 4 \sin^2 \theta_W \]
Weak mixing angle and charges

Proton electric charge
\[ +e \]

Proton weak charge
\[ 1 - 4 \sin^2 \theta_W \]

Violates parity!
Parity violating electron scattering

Diagram:
- Electron beam
- Proton Target
- Detector
Parity violating electron scattering

\[ A_{PV} = \frac{N_R - N_L}{N_R + N_L} \]
Parity violating electron scattering

\[ A_{PV} = \frac{N_R - N_L}{N_R + N_L} = \frac{G_F Q^2}{4 \sqrt{2} \pi \alpha} (Q_W - F(Q^2)) \]
Parity violating electron scattering

\[ A_{PV} = \frac{N_R - N_L}{N_R + N_L} = \frac{G_F Q^2}{4 \sqrt{2} \pi \alpha} (Q_W - F(Q^2)) \]

- Momentum transfer sets scale
- Weak charge - what we want
- Proton structure - small nuisance if \( Q^2 \) small
Why is this difficult?

- $\sin^2 \theta_W \approx 0.25$: Weak charge is tiny

- At low $Q^2$: Asymmetry is tiny (40 parts per billion): need very large statistics

$$Q_W = 1 - 4 \sin^2 \theta_W$$

$$A_{PV} = \frac{N_R - N_L}{N_R + N_L} = \frac{G_F Q^2}{4 \sqrt{2} \pi \alpha} (Q_W - F(Q^2))$$

- We are subtracting two huge numbers from each other (not really - switching helicity with a few KHz)
- Large uncertainty due to hadronic uncertainty

- Uncertainty rises with beam energy

[Gorchstein, Horowitz, Ramsey-Musolf 2011]
PVeS Experiment Summary

- Strange Form Factor (1998-2009)
- S.M. Study (2003-2005)
- JLab 2010-2012
- Future

Log-log plot with data points representing various experiments:

- **Mainz-Be**
- **MIT-12C**
- **SAMPLE**
- **E122**
- **PVDIS-6**
- **PREX-I**
- **PREX-II**
- **Qweak**
- **E158**
- **MESA-12C**
- **MESA-P2**

Y-axis: $\delta(A_{PV})$

X-axis: $A_{PV}$
How much statistics do we need?

- Want to measure $\sin^2 \theta_W$ to 0.13%

- Need $Q_W$ at 1.5%

- Essentially means 1.5% on $A_{PV}$

- $A_{PV}$ is 40 parts per billion

- $\delta(A_{PV})$ is 0.6 parts per billion

- $N$ a few $10^{18}$

- Measure 10'000 hours (absolute maximum anyone thinks shifts are organisable)

- Need close to $10^{11}$ electrons/s - 100 GHz

\[
\frac{\Delta \sin^2 \theta_W}{\sin^2 \theta_W} = \frac{1 - 4 \sin^2 \theta_W}{4 \sin^2 \theta_W} \frac{\Delta Q_W}{Q_W}
\]

\[
\delta(A_{PV}) \propto \frac{1}{\sqrt{N}}
\]
Yes!

- 150 μA of electron beam current
- 60 cm long liquid hydrogen target
- Luminosity $2.4 \times 10^{39} \text{ s}^{-1}\text{cm}^{-2}$
- Integrate 8.6 ab$^{-1}$
MAMI in Mainz

Mainz Microtron

Up to 100 μA
Up to 1.5 GeV
80 % polarisation (80 μA)
MAMI in Mainz

Mainz Microtron

Up to 100 μA
Up to 1.5 GeV
80 % polarisation (80 μA)

A1: Real electron scattering
Four high-precision spectrometers
MAMI in Mainz

Mainz Microtron

Up to 100 μA
Up to 1.5 GeV
80 % polarisation (80 μA)

A2: Tagged photon beam

Crystal ball plus TAPS
MAMI in Mainz

Mainz Microtron

Up to 100 μA
Up to 1.5 GeV
80 % polarisation (80 μA)

A4: Parity violation
Now decommissioned
MAMI in Mainz

Mainz Microtron

Up to 100 μA
Up to 1.5 GeV
80 % polarisation (80 μA)

A4: Parity violation
Now decommissioned
Space for something new
10'000 hours is 417 days 24/7 of measurements

Hard to get that amount of time at a shared accelerator facility...
If you cannot rent it, build it:

The MESA accelerator

Mainz Energy-recovery Superconducting Accelerator
Requirements

- Beam current 150 μA
- Polarisation > 85%
- High precision polarimetry
- High runtime (more than 4000 h/year)
- Extremely stable
- Fit into existing halls at MAMI
More space: Centre of Fundamental Physics

Research building recently funded:

- Lab and office building
- Experimental hall for MESA
Mainz Energy Recovering Superconducting Accelerator

Existing experimental halls

New experimental hall (Forschungsbau)

SRF Cryo Modules

MESA

P2

MAGIX

EPL arc

extracted beam
Superconducting Cryomodules: Ordered

Teichert et al. NIM A 557 (2006) 239
### Stability Requirements

The main worry are beam fluctuations correlated with the helicity:

<table>
<thead>
<tr>
<th></th>
<th>Achieved at MAMI</th>
<th>$\sin^2 \theta_W$ uncertainty</th>
<th>requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Energy fluctuations</td>
<td>0.04 eV</td>
<td>&lt; 0.1 ppb</td>
<td>ok!</td>
</tr>
<tr>
<td>• Position fluctuations</td>
<td>3 nm</td>
<td>5 ppb</td>
<td>0.13 nm</td>
</tr>
<tr>
<td>• Angle fluctuations</td>
<td>0.5 nrad</td>
<td>3 ppb</td>
<td>0.06 nrad</td>
</tr>
<tr>
<td>• Intensity fluctuations</td>
<td>14 ppb</td>
<td>4 ppb</td>
<td>0.36 ppb</td>
</tr>
</tbody>
</table>

Now testing upgraded stabilization at MAMI
Mainz Energy Recovering Superconducting Accelerator (MEGA)

Existing experimental halls

New experimental hall (Forschungsbau)

SRF Cryo Modules

MESA

MAGIX

P2

extracted beam
Mott Polarimmetry:

• Measure left/right asymmetry to obtain spin polarisation
• Analysing power of foils needs to be extrapolated

Double Mott Polarimeter:

• Obtain analysing power from measurement
• Precise measurement of spin polarisation
• Invasive measurement at source

Polarimetry: Hydro-Møller Polarimeter

Møller scattering from polarized (7 T field) atomic hydrogen in a trap

- Online capability
- High accuracy (< 0.5%)
- About 2 h to reach 0.5% statistical accuracy

- Cryostat under construction in Mainz
P2:

How to detect 100 GHz of (the right) electrons...
Solenoid Spectrometer

Integrating Cherenkov Detectors

Shielding

H Target
Choice of scattering angle

\[ \Delta \sin^2 \theta_w = 3.2 \times 10^{-4} \]

- Beam energy: 150 MeV
- Beam current: 150 µA
- Polarization: 85%
- \( \Delta P \): 0.425%
- Target length: 60 cm
- Detector acceptance: 20 deg
- Total rate (e+ e-): 0.1 THz
- Measurement time: 10000 h
- \( \Delta A_{\text{app}} \): 0.1 ppb
Solenoid spectrometer
Solenoid spectrometer

Detector

Shield
Counting detectors

Electron beam

Proton Target

Detector
Integrating detectors

Electron beam

Proton Target

Detector
Quartz-Bars & Photomultipliers

Detect Cherenkov-light created by electrons
Integrate photomultiplier current
Quartz-Bars & Photomultipliers

Detect Cherenkov-light created by electrons
Integrate photomultiplier current
Measuring $Q^2$:

Tracking a lot of low momentum particles
Tracker requirement

- Low momentum electrons: Thin detectors
- Very high rates: Fast and granular detectors
Fast, thin, cheap pixel sensors

High Voltage Monolithic Active Pixel Sensors
Fast and thin sensors: HV-MAPS

High voltage monolithic active pixel sensors - Ivan Perić

- Use a high voltage commercial process (automotive industry)
- Small active region, fast charge collection via drift
- Implement logic directly in N-well in the pixel - smart diode array
- Can be thinned down to < 50 μm
- Logic on chip: Output are zero-suppressed hit addresses and timestamps

(I. Perić, P. Fischer et al., NIM A 582 (2007) 876)
The MUPIX chip prototypes

HV-MAPS chips: AMS 180 nm HV-CMOS

- Developed for Mu3e
- 5 generations of prototypes
- Current generation: MUPIX7
  - 40 x 32 pixels
  - 80 x 103 μm pixel size
  - 9.4 mm² active area
- MUPIX7 has all features of final sensor
- Left to do: Scale to 2 x 2 cm²
Hit efficiency above 99% without tuning
Time resolution

Trigger TimeStamp Difference Distribution for Single Events

Timestamp resolution better than 15 ns
P2
Neutron Skins: Concettina Sfienti on Tuesday

Where are the neutrons in the nucleus?

Graphs showing the distribution of neutrons and protons in a nucleus, indicating neutron skins in neutron-rich nuclei.
Neutron Skins

Where are the neutrons in the nucleus?

- Gives access to the equation of state of neutron matter
- Tells us how big/small neutron stars are
How to see the neutrons?

- Not charged: Photons not a good probe
- Use parity violating electron scattering: Proton weak charge is almost zero - see mostly neutrons

\[
A_{PV} = \frac{G_F Q^2}{2 \pi \alpha \sqrt{2}} \left( 1 - 4 \sin^2 \theta_W - \frac{F_n(Q^2)}{F_p(Q^2)} \right) \approx 0
\]
Mainz Energy Recovering Superconducting Accelerator (MESA) - New experimental hall (Forschungsbau)
Energy recovery

Can we go to higher beam currents?

- In principle yes...
- But power is expensive
- Why dump electrons?
Energy recovery

- Put energy back into field!
- Can go up to 1 (10) mA beam current
- But not with a thick target
High current, high resolution:

MAGIX

Mesa Gas Internal Target Experiment
Requirements

Energy recovery: We want the beam back

- Energy loss less than $10^{-3}$
- As little scattering as possible

No target window

High resolution spectrometer

- No beam interactions in target window
- As little scattering as possible

Thin walls, thin detectors

Extremely intense beam: Do not need very high acceptance
Internal gas target

- Inject gas directly into the beam pipe
- Differential pumping to keep beam vacuum
Twin-arm dipole spectrometer
• Image momentum to position
• $10^{-4}$ momentum resolution for 50 μm position resolution

TARDIS

• Image angle to position
Focal plane detectors

Gas Electron Multipliers (GEMs)
The proton, dark photons and more:

Physics at MAGIX
How big is a proton?
(electromagnetic charge radius)

- Measure in scattering experiments (Mainz!)
- Measure in spectroscopy (Lamb-shift)
- Lamb shift is tiny - except in muonic hydrogen
- Big surprise!
  4 - 7 σ discrepancy - why?

Proton Radius Puzzle

![Proton Charge Radius](chart.png)
Scattering, $Q^2$ and substructure

- Scattering experiments happen at finite momentum transfer $Q^2$
- They will see some of the proton substructure
- Charge radius is defined at $Q^2 = 0$
- Need to extrapolate: Potentially large error
- Want to measure at as small $Q^2$ as possible
Before MESA: A1 at MAMI - Miha Mihovilovic

- A1 measurements a pillar of scattering radius measurements
- Limited by extrapolation to $Q^2 = 0$
- How to get lower $Q^2$?
Initial state radiation at A1

Strategy:

- Access very low $Q^2$ region via initial state radiation events
- Measure momentum spectrum of scattered electrons
- Needs very good understanding of radiative corrections and final state radiation
Strategy:

- Access very low $Q^2$ region via initial state radiation events
- Measure momentum spectrum of scattered electrons
- Needs very good understanding of radiative corrections and final state radiation

Plan:

- Gas jet target (less wall background)
- Go to lower energies
- Extract proton radius
Low $Q^2$ with MAGIX

- 100 MeV beam
- Down to 14° scattering angle
Dark photons
There is dark matter out there...

- There could be additional U(1) gauge symmetries with an exchange particle (dark photon, mass $m_{\gamma'}$)

- It could mix with the photon via heavy fermions (mixing parameter $\varepsilon$)

- It would then show up as a narrow bump in the $e^+e^-$ spectrum

- It could explain the muon g-2 anomaly
Invisible dark photons

- Measurement via missing mass method
- Requires detection of low energy proton; challenging
Dark photons at A1

- $E_{\text{beam}}$ 180-855 MeV
- 100 μA beam current
- Stack of tantalum targets
- 22 kinematic settings
- Coincidence between spectrometers for $e^+e^-$
- Best limits in the g-2 region at the time of publication

Dark photons at MESA/MAGIX
Dark Matter with the Beam Dump

BDX
Search for dark matter

MESA: More than $10^{22}$ electrons hit beam dump per year

- Some of them could produce dark matter particles
- "Dark matter beam"
- Detect with DM detector (xenon?) behind beam dump
Beam dump dark matter
Beam dump dark matter

- FLUKA calculations of neutron flux behind dump look promising

- MESA operates below the pion threshold, no neutrinos produced

- Boost gives access to low mass dark matter
And one more:

Electric dipole moment of electrons
• An EDM of a fundamental particle violates CP and T

• Essentially 0 in the SM (tiny contribution from CKM)

• Potentially large in BSM models

• Some more CP violation needed
Dipole moments and precession

\[
\frac{d\vec{s}}{dt} = \vec{d} \times \vec{E} + \vec{\mu} \times \vec{B}
\]

- Spin precesses in magnetic field due to magnetic dipole moment \( \mu \)
- Spin precesses in electric field due to electric dipole moment \( d \)
- \( \mu \) is large, \( d \) is almost zero
Charged particle EDMs

\[
\frac{d\vec{s}}{dt} = \vec{d} \times \vec{E} + \vec{\mu} \times \vec{B}
\]

For neutral particles:
- Put in a “box”
- Apply large E-field
- Watch precession
- E.g.: Neutron EDM

For charged particles:
- E field leads to acceleration
- Put electron into a neutral, polar molecule (ACME, Imperial/Sussex)
- Put electron/proton/deuteron etc. in a storage ring
Precession in a storage ring

\[ \frac{d\vec{s}}{dt} = \vec{\Omega} \times \vec{S} \]

- Electric and magnetic fields perpendicular to momentum

\[ \vec{\Omega} = \frac{q}{m} \left( a\vec{B} + \left( a - \frac{1}{\gamma^2 - 1} \right) (\vec{v} \times \vec{E}) + \frac{\eta}{2} \left( \vec{E} + \vec{v} \times \vec{B} \right) \right) \]

Magnetic dipole \hspace{1cm} Electric dipole

\[ a = \frac{g-2}{2} \quad \vec{\mu} = 2(a + 1) \frac{q}{2m} \vec{S} \quad \vec{d} = \eta \frac{q}{2m} \vec{S} \]

- How to get rid of magnetic part?
Precession in a storage ring

- No magnetic field!

(about 10 MV/m electric field)

\[ \vec{\Omega} = \frac{a}{m} \left( a \vec{B} + \left( a - \frac{1}{\gamma^2 - 1} \right) (\vec{v} \times \vec{E}) + \frac{n}{2} \left( \vec{E} + \vec{v} \times \vec{B} \right) \right) \]

Magnetic dipole Electric dipole
Precession in a storage ring

- No magnetic field!
- Magic momentum!

\[ \vec{\Omega} = \frac{q}{m} \left( a \vec{B} + \left( a - \frac{1}{\gamma^2 - 1} \right) (\vec{v} \times \vec{E}) + \frac{n}{2} \left( \vec{E} + \vec{v} \times \vec{B} \right) \right) \]

- 0.7 GeV/c for protons
- 14.5 MeV for electrons
Build an electric-only storage ring

- Magic momentum
- Spin rotates with momentum vector
- EDM leads to out of plane precession
- Counter-rotating bunches help to cancel systematics
Systematics

\[ |d_e| < 8.7 \times 10^{-29} \text{e} \cdot \text{cm} \quad (\text{ThO}) \]

ACME collaboration, Science 343, 269 (2014)

- Need very low magnetic field
- Good control of electric field
- Very hard to compete with molecules for limits ...
- ... but only option for a precise measurement ...
- ... and a pathfinder for the proton EDM (Jülich, Korea...)
Exciting physics program for electron scattering in Mainz in the next decade:

- New accelerator MESA, starting 2018/19
- Weak mixing angle measurement with P2
- Also gives access to neutron skins
- Proton radius, dark photon and much more with MAGIX
- Second generation of experiments: Beam dump dark matter and electron EDM ring (?)