$\sin^2 \theta_W$ with P2 in Mainz

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PhiPsi Hefei
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Overview

• The Idea:
  Precision measurement of and search for new physics with the weak mixing angle

• The Machine:
  Mainz Energy-Recovery Superconducting Accelerator

• The Experiment:
  Parity violating electron scattering with P2
Scale dependence (running) of $\sin^2 \theta_W$
Scale dependence (running) of $\sin^2 \theta_W$

![Graph showing scale dependence (running) of $\sin^2 \theta_W$](image-url)
Scale dependence (running) of $\sin^2 \theta^W$
New Physics in the running

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

- LEP1
- SLD
- P2@MESA
- Moller
- NuTeV
- SOLID
- eDIS
- Tevatron
- ATLAS
- CMS

Q [GeV]

0.245
0.24
0.235
0.23
0.225
Dark Z in mixing

Marciano et al.

Anticipated sensitivities

Log_{10} Q [GeV]

\sin^2 \Theta_W

\begin{align*}
0.230 \\
0.232 \\
0.234 \\
0.236 \\
0.238 \\
0.240 \\
0.242 \\
\end{align*}

\begin{align*}
-3 \\
-2 \\
-1 \\
0 \\
1 \\
2 \\
3 \\
\end{align*}

m_{\text{dark } Z} = 100 \text{ MeV}

m_{\text{dark } Z} = 200 \text{ MeV}

APV(Cs)

E158

\text{Qweak (first)}

\text{\nu-DIS}

SLAC

LEP

Moller

\text{MESA}

\text{Qweak}

\text{\"Anticipated sensitivities\"}
Contact interactions up to 49 TeV (comparable to LHC at 300 fb⁻¹)
Measuring the weak charge
Weak mixing angle and charges

Proton electric charge
+1

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

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

Momentum transfer sets scale

Weak charge - what we want

Proton structure - small nuisance if \( Q^2 \) small

Detector

Electron beam

Proton Target
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

$$\sin^2 \theta_W = \frac{1 - Q_W}{4}$$

Electron beam

Detector

Proton Target
• Large uncertainty due to hadronic uncertainty

• Uncertainty rises with beam energy

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

\[ \delta(A_{PV}) \]

\[ A_{PV} \]

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

Sample points:
- G0
- G1
- E122
- PVDIS-6
- SOLID
- Moller
- MESA-P2
- MESA-12C
- PREX-I
- PREX-II
- Qweak
- E158
- H-I
- H-II
- H-He
- H-III
- MIT-12C
- Mainz-Be
- SAMPLE
How much statistics do we need?

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

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

• 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
Can we get that rate?

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$^{-1}$
10'000 hours is \textit{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).
- Fit into existing halls at MAMI (plus funded new hall)
- Extremely stable
The main worry are beam fluctuations correlated with the helicity:

<table>
<thead>
<tr>
<th></th>
<th>Achieved at MAMI</th>
<th>$A_{PV}$ 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>

Currently testing beam monitoring and feedback at MAMI
Polarimetry: Double Mott Polarimeter

Mott Polarimetry:
- 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

Møller scattering from polarized (8 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

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

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

- $B = 1.00 B_{\text{max}}$
- Target center @ $z = -700$ mm
- $E_{\text{beam}} = 155.0$ MeV
- $\epsilon_{\text{e-p-scattering}}$: $0 \in [25.00 \text{ deg}, 45.00 \text{ deg}]$
- $\epsilon_{\text{e-cp-scattering}}$: $0 \in [0.00 \text{ deg}, 90.00 \text{ deg}]$
- $\epsilon_{\text{e-e-scattering}}$: $0 \in [0.00 \text{ deg}, 90.00 \text{ deg}]$
Solenoid spectrometer

Detector

Shield
Counting detectors

Electron beam

Detector

Proton Target
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

![Graph showing number of photons vs angle of electron incidence]
Tracking detector for $Q_2$ measurement

- Low momentum electrons: Thin detectors
- Very high rates: Fast and granular detectors
- Use high-voltage monolithic active pixel sensors (HV-MAPS) thinned to 50 μm
P2 Timeline

<table>
<thead>
<tr>
<th>Year</th>
<th>Polarimeter</th>
<th>Spectrometer</th>
<th>Tracking</th>
<th>Theory</th>
</tr>
</thead>
<tbody>
<tr>
<td>2012</td>
<td>Double Mott Tests with 100 keV source</td>
<td>Spectrometer conceptual design</td>
<td>Detector tests at MAMI</td>
<td>one loop radiative corrections</td>
</tr>
<tr>
<td>2013</td>
<td>Hydro Moller: Cryostat R&amp;D</td>
<td>Technical design</td>
<td>Requirements, Geometry</td>
<td></td>
</tr>
<tr>
<td>2014</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2015</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>2016</td>
<td>Polarimeter concept</td>
<td>Spectrometer technical design</td>
<td>Components assembling</td>
<td></td>
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<tr>
<td>2017</td>
<td>Atomic trap R&amp;D</td>
<td>R&amp;D: Track reconstruction</td>
<td>Construction</td>
<td></td>
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<tr>
<td>2018</td>
<td>Systematic studies</td>
<td></td>
<td>Installation at experimental site</td>
<td></td>
</tr>
<tr>
<td>2019</td>
<td></td>
<td></td>
<td>Commissioning: 5% data</td>
<td></td>
</tr>
<tr>
<td>2020</td>
<td></td>
<td></td>
<td></td>
<td>Data taking Full data set</td>
</tr>
<tr>
<td>2021</td>
<td></td>
<td></td>
<td></td>
<td>Analysis</td>
</tr>
<tr>
<td>2022</td>
<td></td>
<td></td>
<td></td>
<td>Search for New Physics</td>
</tr>
<tr>
<td>2023</td>
<td></td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>

- ΔP/P ≤ 0.5%
- Δsin²θW = 0.00032
- Box graph uncertainties
- Two-loop electroweak corrections
- Full Monte Carlo generator QED corrections
- Reliable operation
- Trap operational
- Installation at experimental site
- Systematic studies
- Operation
- Data taking
- Analysis
- Operation
• P2 aims to measure $\sin^2 \theta_W$ to 0.13%

• Parity violating electron scattering

• New electron accelerator MESA in Mainz:
  - 150 μA of 150 MeV electrons
  - extremely stable
  - excellent polarimetry
  - wide program (→ Achim Denig)

• Solenoid spectrometer with integrating
  Cherenkov detectors

• Data taking starts before end of this decade

Summary
Backup
• 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”

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

- Use second option from here on

\[
\begin{align*}
\cos \theta_W &= \frac{m_W}{m_Z} \\
\sin^2 \theta_W &= \frac{g'^2}{g^2 + g'^2} \\
\sin^2 \theta_W (q^2) &= \ldots
\end{align*}
\]
Superconducting Cryomodules

Teichert et al. NIM A 557 (2006) 239
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)
HV-MAPS chips: AMS 180 nm HV-CMOS

- 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
Position Resolution

Position resolution given by pixel size
Hit efficiency above 99% without tuning
Time resolution

Hit timestamp resolution better than 17 ns
(significant setup contribution in the measurement)

Timestamp frequency 100 MHz

$\sigma = 16.6 \text{ ns}$

Hits per 10 ns bin vs Difference between trigger and timestamp [ns]
Mechanics

- 50 μm silicon
- 25 μm Kapton™ flexprint with aluminium traces
- 25 μm Kapton™ frame as support
- Less than 1‰ of a radiation length per layer