Measuring the weak mixing angle with the P2 experiment at MESA [*]

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Abstract: The P2 experiment in Mainz aims to measure the weak mixing angle $\sin^2\theta_W$ in electron- proton scattering to a precision of 0.13%. In order to suppress uncertainties due to proton structure and contributions from box graphs, both a low average momentum transfer Q^2 of $4.5{\cdot}10^{-3}$ GeV$^2/c^2$ and a low beam energy of 155 MeV are chosen. In order to collect the enormous statistics required for this measurement, the new Mainz Energy Recovery Superconducting Accelerator (MESA) is being constructed. These proceedings describe the motivation for the measurement, the experimental and accelerator challenges and how we plan to tackle them.

Key words: weak mixing angle, parity violation, electron scattering

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1 Introduction

The weak mixing angle $\sin^2\theta_W$ is one of the fundamental parameters of the Standard Model (SM) of elementary particle physics. It has been measured with great precision at the Z resonance [1], where the determinations from LEP and SLD are marginally consistent. Due to quantum corrections, the effective weak mixing angle is a scale dependent quantity and measurements at different scales become important both for testing the SM and searching for effects of new physics beyond the SM in the running [2, 3].

Measurements at lower scales were obtained in neutrino nucleon scattering [4], deep inelastic electron scattering [5], parity violating electron scattering on electrons [6] and protons [7] and atomic parity violation in Caesium [8]. These measurements were sufficient to establish the running of $\sin^2\theta_W$, more precision is however required for a stringent test of the SM and searches for new physics. The final result from the Qweak experiment is eagerly awaited and should improve on the published result [7] by a factor of three to four. More precise determinations require new experimental approaches, such as the proposed Møller [9] and deep inelastic (SOLID, [10]) scattering experiments at JLAB and the P2 experiment in Mainz, which will be described in the following. An overview of current and planned experiments together with the theory prediction [12] for the running of $\sin^2\theta_W$ is shown in Fig. 1.

A precise determination of the weak mixing angle at low scales is sensitive to contributions of new physics

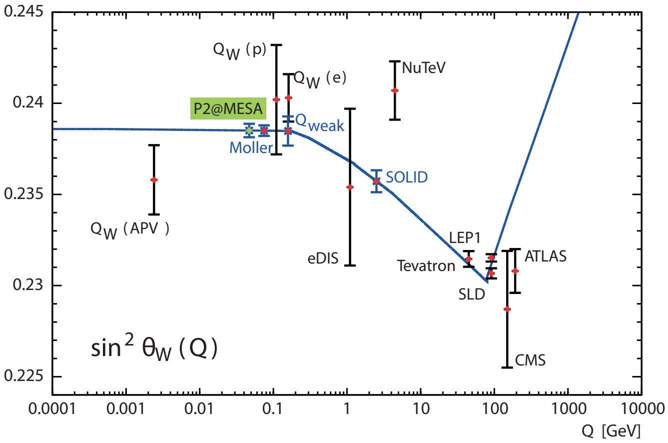

Fig. 1. Scale dependence of $\sin^2\theta_W$ together with completed (black error bars) and planned (blue error bars, value chosen to coincide with theory) experimental measurements.

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beyond the SM which can change the running of $\sin^2\theta_W$ via contributions of new gauge bosons, additional fermions, mixing terms [11] or the exchange of very heavy particles which can be parametrized as four-fermion contact interactions [2]. In the last case, P2 will be sensitive to scales up to 49 TeV, comparable to the experiments at the large hadron collider after collecting 300 fb^{-1} of integrated luminosity.

2 Requirements

The P2 experiment aims to determine $\sin^2\theta_W$ with a precision of 0.13% by performing a measurement of the parity violating asymmetry A_{PV} in electron-proton scattering. This asymmetry between the cross-sections for left- and righthanded electrons σ_L and σ_R is determined by the weak charge of the proton Q_W:

$$A_{PV} = \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R} = \frac{G_F Q^2}{4\sqrt{2}\pi\alpha}(Q_W + F(Q^2)), \qquad (1)$$

where G_F is the Fermi constant, α the fine structure constant and Q^2 the squared four-moment transfer, setting the scale. Contributions stemming from the fact that the proton is not a point-like particle are collected in $F(Q^2)$ and are small for low values of Q^2, thus motivating an experiment at low momentum transfer. Further hadronic uncertainties come from box graphs such as the one shown in Fig. 2. These uncertainties have a weak dependence on the momentum transfer, do however increase steeply with rising center-of-mass energy [13, 14], favouring a low beam energy.

The weak mixing angle is related to Q_W via

$$Q_W = 1 - 4\sin^2\theta_W, \qquad (2)$$

which implies by propagation of uncertainty that a 0.13% measurement of $\sin^2\theta_W$ requires a 1.5% measurement of Q_W, which also corresponds to the target uncertainty in the asymmetry. Due to the small weak charge of the proton and the small Q^2, the expected asymmetry is only 33 ppb, thus requiring a measurement with 0.44 ppb precision. The statistical uncertainty scales with the number of scattered electrons as $\frac{1}{\sqrt{N}}$, which in turn requires the observation of $\mathcal{O}(10^{18})$ electrons. For sociological reasons, the total measurement time is limited to 10'000 hours, which requires observing $\mathcal{O}(10^{11})$ signal electrons per second.

These very high rates can be achieved by directing a 150 μA electron beam onto a 60 cm long liquid hydrogen target, producing a luminosity of $2.4 \cdot 10^{39}\ \text{s}^{-1}\text{cm}^{-2}$.

The aim of determining $\sin^2\theta_W$ with a precision of 0.13% is thus extremely challenging for the accelerator and detector systems. The following sections outline how the MESA accelerator, the polarisation measurement and the P2 experiment intend to tackle these challenges.

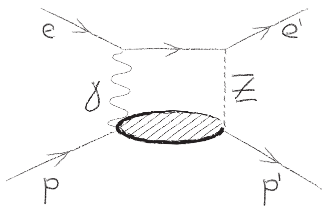

Fig. 2. $\gamma - Z$ box graph for electron-proton scattering. The hadronic uncertainty stems from the possible excited states of the proton indicated by the shaded blob.

3 The MESA accelerator

In order to accommodate the very long running time and demanding stability requirements of the P2 experiment, a new accelerator, the Mainz Energy-Recovery Superconducting Accelerator (MESA, [15]) is being built.

With a maximum extracted beam energy of 155 MeV, MESA is small enough to fit into the existing halls that have become available with the completion of the A4 parity violating electron scattering program at the Mainz Microtron MAMI. P2 and the MAGIX spectrometer (see the contribution of A. Denig to this conference for details on the MESA program beyond the P2 experiment) will be housed in a new hall as part of the recently funded centre for fundamental physics. Fig. 3 shows the overall layout of accelerator and experiments.

P2 requires a highly polarized (> 85%), high intensity (150 μA) beam of 155 MeV electrons with excellent availabiliy (> 4000 h/year). The beam helicity will be flipped several thousand times a second. The main challenge is to reduce any helicity correlated changes in beam intensity, energy, position and angle to less than 0.1 ppb. Here we can profit from the extensive experience in beam stabilization gained at the Mainz Microtron MAMI. Table 1 compares the values for helicity correlated beam fluctuations achieved at MAMI with the requirements for P2 at MESA. Whilst the energy stability already fulfills the demands, improvements of one to two orders of magnitude have to be achieved for position, angle and intensity; new digital feedback electronics for beam stabilization are currently being designed and tested at MAMI.

Table 1. Helicity correlated beam fluctuations.

Beam Quantity	Achieved at MAMI	Contribution to $\delta(A_{PV})$	Required for MESA
Energy	0.04 eV	< 0.1 ppb	fulfilled
Position	3 nm	5 ppb	0.13 nm
Angle	0.5 nrad	3 ppb	0.06 nrad
Intensity	14 ppb	4 ppb	0.36 ppb

The MESA lattice design is finalized, the superconducting RF cavities have been ordered and civil construction on the new hall will start 2016. We plan to start installing the accelerator in 2018 and have beam available for P2 before 2020.

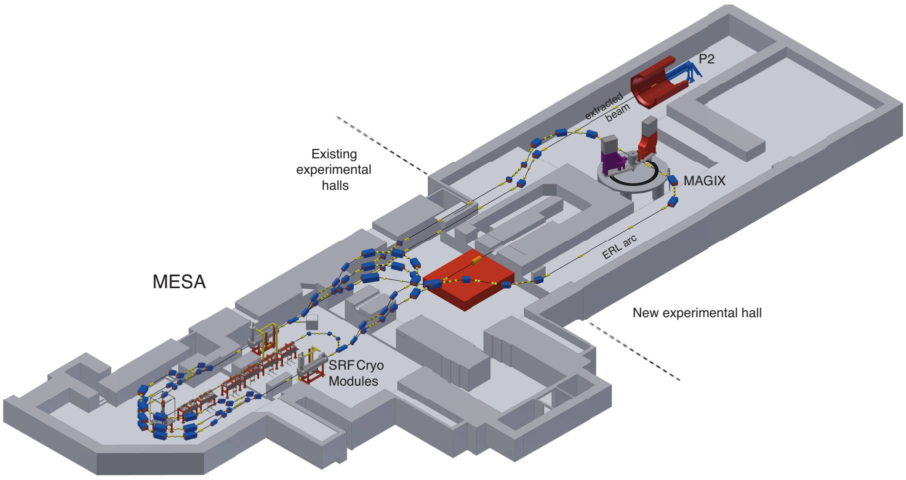

Fig. 3. Layout of the MESA accelerator and experiments, indicating existing and new halls at the institute of nuclear physics in Mainz.

4 Polarimetry

P2 requires a knowledge of the beam polarisation of better than 0.5%. We aim to achieve this precision via two paths [16], namely an invasive double Mott polarimeter at the electron source and a Hydro-Møller polarimeter, which can be operated at the same time as and is placed right in front of the main experiment.

4.1 Double Mott polarimeter

The asymmetry of Mott scattering in thin foils can be used to determine the beam polarization, it however requires a precise knowledge of the analyzing power of the scattering foils which introduces a large uncertainty into the measurement. Double Mott scattering [17] in two foils allows to determine the effective analyzing power within the setup, thus reducing the associated uncertainty which makes it a suitable choice for precise source polarimetry at MESA. A prototype of the double-Mott polarimeter is currently tested with the MESA source prototype in operation in Mainz.

4.2 Hydro-Møller polarimeter

We plan to determine the beam polarization at the final energy with a hydro-Møller polarimeter [18] right in front of the main experiment. Here the asymmetry in Møller scattering of the beam electrons with the electrons in fully polarized atomic hydrogen is used. The hydrogen is polarized using a 7-8 T solenoid magnet. In order to avoid hydrogen recombination, the gas is kept at cryogenic temperatures and the walls of the vessel are coated with superfluid helium. Operating this cryogenic setup with a high intensity electron beam passing through the center is certainly challenging. The cryostat/magnet for this setup is currently under construction.

5 The P2 experiment

For a given electron beam energy, the scattering angle ϑ determines the momentum transfer Q^2. At low Q^2, the uncertainty of the asymmetry measurement is dominated by statistics and helicity correlated beam fluctuations. At large Q^2, uncertainties in the proton form factors become dominant. For our setup, the best accuracy can be reached with a central scattering angle of 35° at an angular acceptance of 20°.

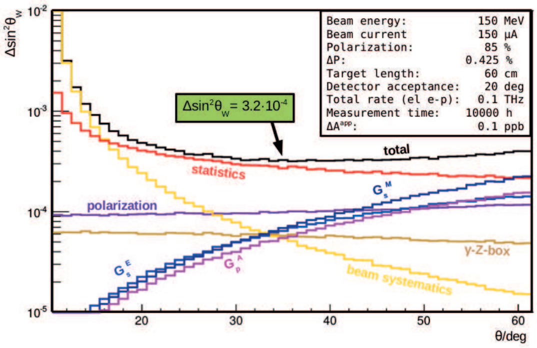

Fig. 4. Contributions to the uncertainty of the $\sin^2\theta_W$ measurement at fixed beam energy, intensity and run time in dependence of the central scattering angle. G_E^S, G_M^S and G_P^A refer to the uncertainties stemming from the electric and magnetic strange form factor and the axial form factor of the proton respectively.

As the very high intensity beam produces several thousand Bremsstrahlung photons for every electron scattered into the angular range of interest as well as a large amount of Møller scattered electrons with low transverse momentum, a magnetic spectrometer is required in order to guide signal electrons to detectors whilst at the same time shielding them from photon and Møller backgrounds. The detectors in turn face the challenge of reliably detecting more than 100 GHz of scattered electrons. The following sections will describe the spectrometer design, the development of integrating Cherenkov detectors as well as a pixellated tracking detector for a precise determination of the momentum transfer Q^2.

5.1 Spectrometer

For the spectrometer design, the main choice is between a toroidal (as used in the QWeak experiment) and a solenoidal magnetic field. The advantages of a toroidal setup, such as zero field in the target region and easy access to instrumentation are compromised by the fact that the coils are necessarily inside of the spectrometer acceptance, typically leading to a loss of about half the signal electrons and consequently a doubling of the measurement time, which is unrealistic in the context of P2.

We have thus decided to employ a solenoidal design and studied possible placements of target, shielding and detectors for several existing solenoids, e.g. from the ZEUS experiment at HERA [19] or the FOPI experiment at GSI [20]. We have shown using both ray-tracing in the magnet field maps and full Geant4 based simulations that with a careful optimization of the shape and placement of lead shields, sufficient signal-to-background ratios can be achieved in the integrating detectors. A possible view of the setup is shown in the rendering in Fig. 5.

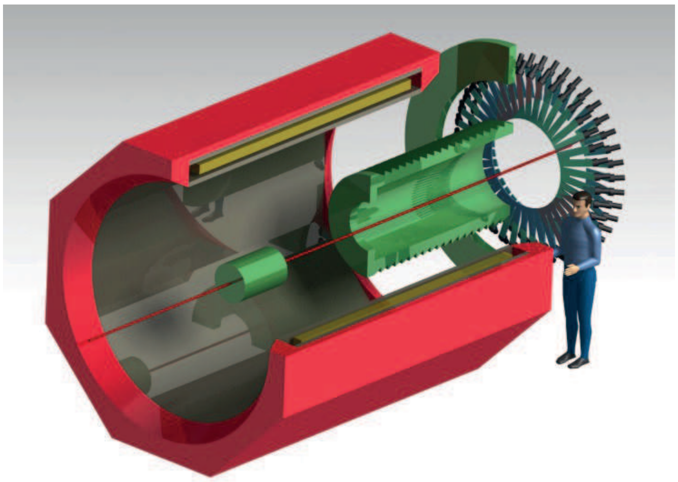

Fig. 5. Rendering of a possible P2 setup, showing the solenoid coil, target, lead shielding and integrating detectors as well as a hunky physicist for scale.

5.2 Integrating detectors

Individually counting hundreds of GHz of electrons is extremely challenging, but not actually required for P2. Instead, we opt for an integrating measurement, where the electrons produce Cherenkov light in bars of fused silica (quartz), which is detected with photomultipliers operated at low gain. The current of these photomultipliers is integrated over one helicity period and read out with high precision (22 bit) analog-to-digital converters.

We are currently testsing different types and polishing finishes as well as wrappings of quartz bars with the MAMI beam and have found both a performance sufficient for P2 as well as an excellent agreement of the light yield at different incident angles with Geant4 based simulations.

The switchable gain photomultiplier base is currently under development in Mainz; for the integrating ADC a joint development with the Møller experiment is ongoing at the University of Manitoba.

5.3 Tracking detectors

In order to determine the average momentum transfer $\langle Q^2 \rangle$ of the scattered electrons creating signals in the integrating detectors, a tracking detector is required. The high rates at MESA, the precision requirements and the low momenta of the scattered electrons (making multiple coulomb scattering in the tracker material the dominating uncertainty in the momentum measurement) call for a fast, high granularity sensor with very little material. We choose to employ high-voltage monolithic active pixel senors (HV-MAPS, [21–25]) as the detector technology. These sensors, manufactured in a commercial CMOS technology, apply a "high" voltage of around 90 V between deep n-wells and the substrate, leading to very fast charge collection from a thin depletion layer. The thin charge collection zone allows for thinning of the sensors to just 50 μm. The sensor is segmented into 80 by 80 μm pixels. The CMOS process used allows for integrating both analog and digital electronics directly on the sensor; the output are zero suppressed hit addresses and timestamps on a fast differential link. In the development of the sensors for P2, we closely collaborate with the Mu3e, ATLAS and Panda experiments.

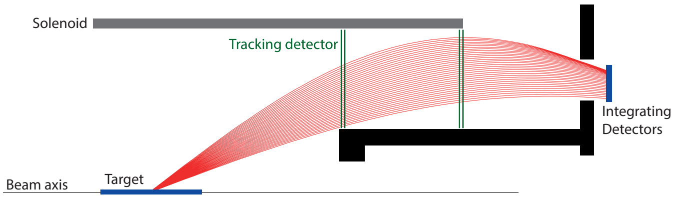

Fig. 6. Schematic view of the P2 tracking detector, consisting of four planes of HV-MAPS sensors.

From these thin sensors, we plan to build a tracking detector with four planes, see Fig. 6. The arrangement in two double planes combines a good momentum and angular resolution in a multiple scattering dominated regime with ease of reconstruction in a high multiplicity environment. We are currently studying tracking algorithms that also perform well in the non-uniform field close to the edge of the magnet and are at the same time robust and fast enough to allow for on-line track finding and fitting, possibly on highly parallel architectures such as graphics processing units (GPUs).

6 Summary and Outlook

The P2 experiment aims to measure $\sin^2\theta_W$ at low momentum transfer with unprecedented accuracy, which both improves the precision on one of the fundamental parameters of the standard model and allows to search for new physics. The new MESA accelerator in Mainz will provide a stable very high intensity electron beam combined with precision polarimetry. P2 will measure the parity violating asymmetry in electron- proton scattering using a solenoid spectrometer with integrating Cherenkov detectors combined with a thin pixel tracker. Accelerator commissioning is scheduled to start in 2018 and a first P2 data taking for 2020. Beyond the $\sin^2\theta_W$ measurement, P2 can also be used to study parity violation with different target materials, giving access e.g. to neutron skins. The MESA accelerator also has a wide physics program beyond P2, described elsewhere in these proceedings.

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