PROCEEDINGS OF SCIENCE

Status of the P2 Experiment: A Measurement of the Weak Mixing Angle at Low Energy

S. Baunack*
PRISMA cluster of Excellence and Institut für Kernphysik, Johannes Gutenberg-Universität Mainz, Germany
E-mail: baunack@kph.uni-mainz.de

D. Becker
PRISMA cluster of Excellence and Institut für Kernphysik, Johannes Gutenberg-Universität Mainz, Germany
E-mail: beckerdo@uni-mainz.de

K. Imai
PRISMA cluster of Excellence and Institut für Kernphysik, Johannes Gutenberg-Universität Mainz, Germany
E-mail: imai@uni-mainz.de

F. E. Maas
PRISMA cluster of Excellence and Institut für Kernphysik, Johannes Gutenberg-Universität Mainz, Germany
Helmholtz-Institut Mainz, Johannes Gutenberg-Universität Mainz, Germany
E-mail: maas@him.uni-mainz.de

The P2 experiment at the upcoming MESA accelerator in Mainz aims for a high precision measurement of the Weak Mixing Angle at low momentum transfer. Access is given by measuring the parity violating asymmetry in the elastic scattering of polarized electrons off unpolarized protons. Deviations in the observed value from the Standard Model expectation give hints to new physics beyond the Standard Model. We present the planned setup and studies on the achievable precision. Further options by using nuclear targets are also discussed.

23rd International Spin Physics Symposium - SPIN2018 -
10-14 September, 2018
Ferrara, Italy

*Speaker.

PoS(SPIN2018)081

1. The Weak Mixing Angle and the Search for New Physics

The weak mixing angle, denoted as θ_W, is an important parameter of the Standard Model. It relates for example the masses of the W-boson and the Z-boson or the electric charge e with weak isospin g. Universal quantum corrections are absorbed into an effective, running weak mixing angle which is denoted as $\sin^2\theta_W(\mu)$, where μ is the energy scale. The running is shown in fig. 1 together with measurements that were already performed and measurements that are planned. The most precise measurements were done at the Z-pole. The P2 experiment is shown at $\mu \approx$

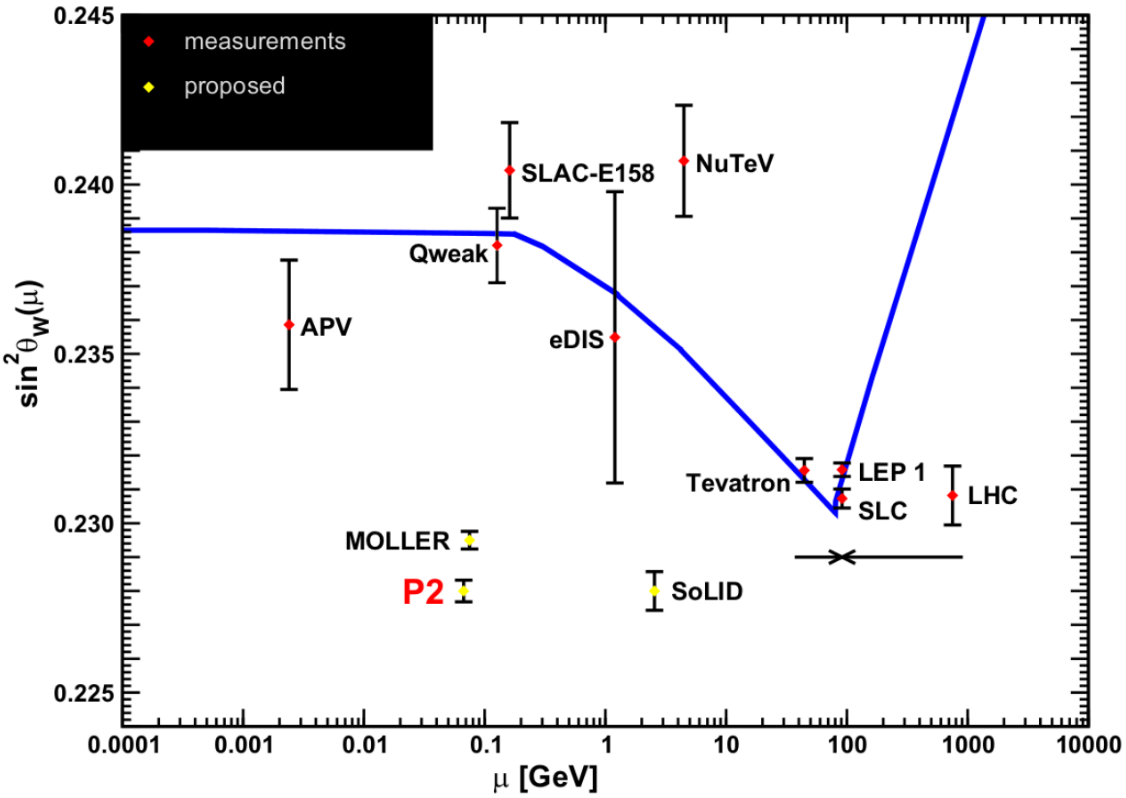

Figure 1: Standard Model prediction for the running of $\sin^2\theta_W(\mu)$, where μ is the energy scale. Also shown are measurements for this quantity (red diamonds) and proposed experiments (yellow diamonds) with their predicted precisions, among them the P2 experiment at MESA. The y-position of these points are chosen arbitrarily.

0.006 GeV^2. New physics beyond the Standard Model leads to additional quantum corrections and hence modifies the running of $\sin^2\theta_W$. At low momentum transfer $Q^2 \ll 1$ GeV^2/c^2, for example dark photon models or supersymmetry predict such deviations [1, 2, 3].

2. Parity violating electron scattering

For the elastic scattering of longitudinally polarized electrons off unpolarized protons an parity violating asymmetry for the cross section is observed. The asymmetry is defined as

$$A_{RL} = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-} \tag{2.1}$$

where $\sigma^{\pm}$ is the cross section for positive and negative electron helicity. Fig. 2 shows the principle of the measurement: The polarized electrons hit a target of liquid hydrogen and the flux of electrons which are elastically scattered at a certain scattering angle θ is measured for the two helicity states. From these fluxes, the asymmetry can be determined. This asymmetry can be expressed as

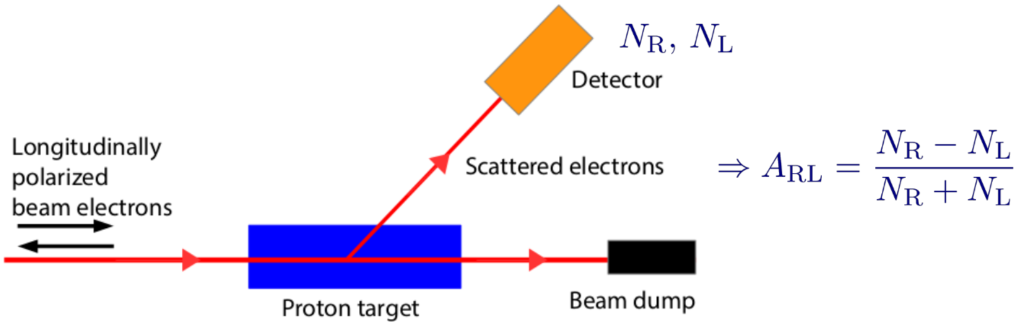

Figure 2: Principle of the measurement of a parity violating asymmetry A_{RL}. The flux of scattered electrons is measured for the two helicity states. From these fluxes the asymmetry can be determined.

$$A_{RL} = \frac{-G_F Q^2}{4\pi\alpha_{\mathrm{EM}}\sqrt{2}} \left[Q_w(p) - F(Q^2)\right] \tag{2.2}$$

G_F is the Fermi coupling constant, $F(Q^2)$ parameterizes contributions from the hadronic structure of the proton to the asymmetry and $Q_W(p)$ is the weak charge of the proton, which can be written at tree level as

$$Q_W(p) = 1 - 4\sin^2\theta_W \tag{2.3}$$

At low momentum transfer and at forward scattering angles, the form factor contribution $F(Q^2)$ is well under control and one can see that a measurement of A_{RL} gives access to the weak mixing angle $\sin^2\theta_W$. Fig. 3 shows the contributions from the weak charge and the proton form factors to the asymmetry as a function of the scattering angle θ for the planned MESA electron energy of 155 MeV. The proton form factor contribution $F(Q^2)$ has been split into three terms here: A^{EM} coming from the well-known proton electromagnetic form factors G_E and G_M, A^A coming from the axial form factor $G_A^{p,Z}$ and A_S coming from the strange form factors G_E^s and G_M^s. The contribution from the weak charge dominates for scattering angles below $theta = 70^\circ$ and the total asymmetry is at the order of a few tens of a ppb for forward scattering angles. Precision studies involving full Monte Carlo simulations with GEANT4 have been performed to determine the optimal kinematic conditions for the P2 experiment [4, 5]. Fig. 4 shows a result of this study: For different electron beam energies E_{beam} and electron scattering angles $\bar{\theta}_f$ the achievable precision is shown according to the color code. One can identify a "valley of precision", where the precision is $\Delta\sin^2\theta_W < 3.4\cdot 10^{-4}$. Based on these studies and taking into account that the maximum beam energy of the new MESA accelerator will be 155 MeV, the P2 experiment will use a central electron scattering angle of $\theta = 35^\circ$, a beam energy of $E = 155$ MeV and a polar detector acceptance of $\Delta\theta = 20^\circ$. A slightly lower beam energy is currently under discussion so that no charged pions could be produced which would reduce the possible background for the so-called DarkMESA project [6] which will run as a beam dump experiment parallel to the P2 experiment and searches for dark

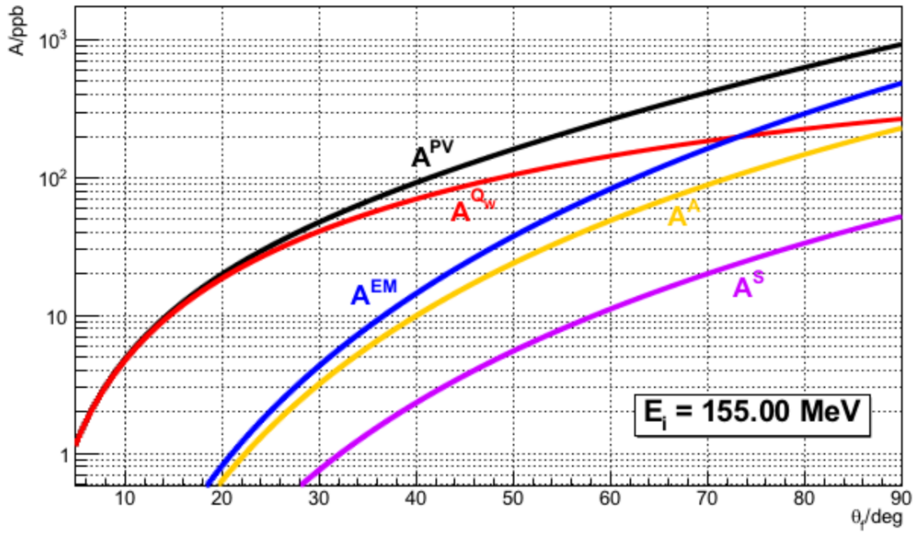

Figure 3: Contributions from the proton weak charge $Q_W(p)$ and the proton form factors to the asymmetry as a function of the scattering angle θ for the MESA beam energy of 155 MeV.

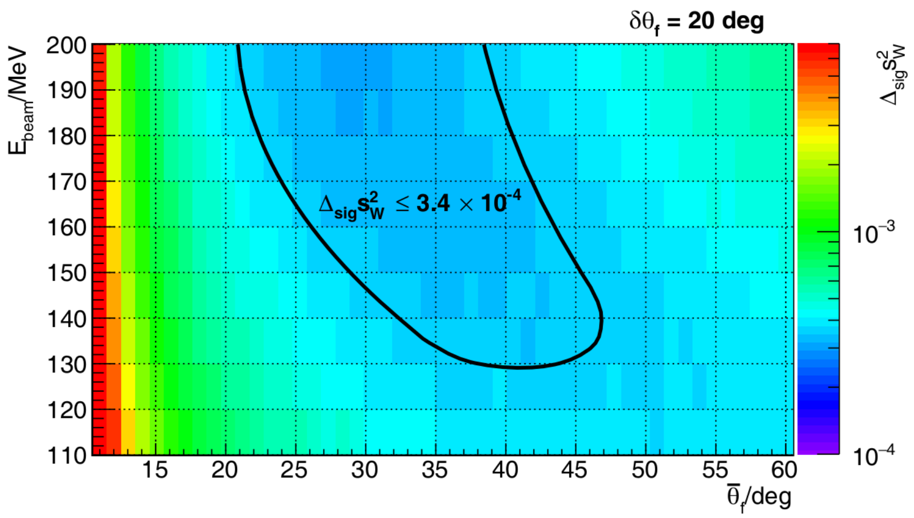

Figure 4: Achievable precision for $\sin^2\theta_W$, denoted as $\Delta_{\rm sig}s^2_w$, for different scattering angles and beam energies in the P2 experiment.

photons. The expected parity violating asymmetry is $A_{RL} = -39.9$ ppb which will be measured with a total uncertainty of $\Delta A_{RL} = 0.6$ ppb. The weak mixing angle can be extracted with an uncertainty of $\Delta\sin^2\theta_W = 3.7\cdot 10^{-4}$. Table 1 shows the dominant sources of this uncertainty.

3. P2 experimental setup

The P2 collaboration plans to measure the parity violating asymmetry A_{RL} within 10.000 h of data taking. In order to achieve the precision that was presented in the previous chapter, the luminosity must be high and the coverage of the detector as high as possible. The MESA accelerator will deliver a beam current of $I = 150$ μA. The P2 experiment will use a 60 cm long liquid

Error source	**Contribution to** $\Delta \sin^2 \theta_w$	**Contribution to** $\Delta \sin^2 \theta_W / \sin^2 \theta_W$
Total uncertainty	$3.7 \cdot 10^{-4}$	0.16%
Statistics	$3.1 \cdot 10^{-4}$	0.13%
Target windows	$1.2 \cdot 10^{-4}$	0.05%
Form factors	$1.2 \cdot 10^{-4}$	0.05%
Beam polarization	$0.7 \cdot 10^{-4}$	0.03%
Beam false asymmetries	$0.6 \cdot 10^{-4}$	0.03%
Gamma-Z box graph	$0.4 \cdot 10^{-4}$	0.02%

Table 1: Dominant sources of uncertainty for $\Delta \sin^2 \theta_W$ in the P2 experiment

hydrogen target so that the luminosity will be

$$\mathscr{L} = 2.38 \cdot 10^{39} cm^{-2} s^{-1} \tag{3.1}$$

A superconducting solenoid will generate a field with a magnetic flux density of about 0.6 T. In this field the electrons coming from the elastic scattering can be well separated from those coming from Moller scattering which would be a main background in the measurement. Bremsstrahlung photons can be blocked with lead shielding. In contrast to a toroid, the solenoid design allows an azimuthal detector coverage of $\Delta\phi = 2\pi$. Fig. 5 shows a CAD design of the planned P2 setup.

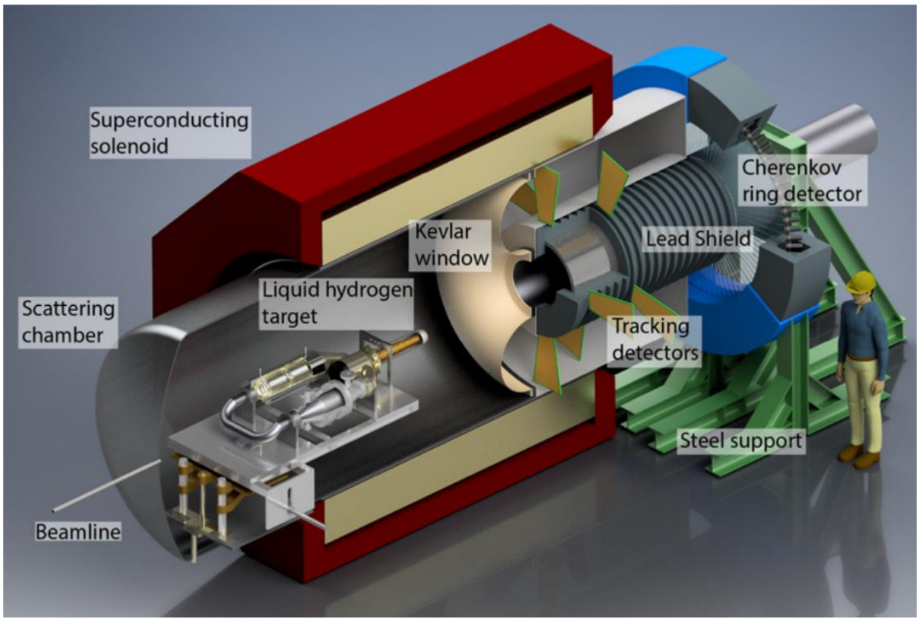

Figure 5: CAD design for the P2 experimental setup. The electrons scatter off the 60 cm long liquid hydrogen target and reach the Cherenkov ring detector. A superconducting solenoid generates a magnetic field which separates electrons coming from Moller scattering. The design allows also the installation of a lead shield to block bremsstrahlung photons.

The elastically scattered electrons will be detected by a ring of 82 bars made of fused silica. This material is a pure Cherenkov radiator and hence intrinsic fast and is known to be very radiation hard. The material and the geometry of the fused silica bars were tested in test beams at the MAMI

PoS(SPIN2018)081

electron accelerator facility and studied in MC simulations. Depending on the angle of incidence and the energy of the electron that hits the bar, the light yield will be between 50 and 120 photoelectrons per event which is more than sufficient for this experiment. The average momentum transfer $< Q^2 >$ of the scattered electrons will be determined by tracking detectors which consist of so-called High-Voltage Monolithic Active Pixel Sensors (HV-MAPS) [7].

4. P2 further physics program

4.1 Measurements with Carbon-12

High precision measurements of the weak charges of different nuclei offer complementary sensitivities to physics beyond the Standard Model. The feasibility of a measurement with carbon-12 was investigated for the P2 experiment. The weak charge of the carbon nucleus is at tree level

$$Q_W(^{12}C) = -24\sin^2\theta_W \tag{4.1}$$

which is 78 times larger than the weak charge of the proton. Moreover, the cross section of the elastic scattering off carbon is 36 times higher than off the proton. As a consequence, a relevant measurement of the asymmetry with carbon-12 can be measured in a significantly shorter time than in the proton case. Within 2500 h of beamtime, the weak charge of the ^{12}C nucleus can be measured with a relative precision of 0.3%. The Cherenkov ring detector must be adapted to this measurement and the precision of the beam polarimetry measurement must be increased. Further investigations will be necessary.

4.2 Neutron Skin Measurement

Heavy nuclei are expected to develop a neutron-rich skin where many neutrons collect near the surface. Since the parity-violating asymmetry is particularly sensitive to the neutron density, it provides a clean and model independent measurement of the neutron skin of nuclei. The neutron-skin thickness of a nucleus ΔR_{np}, defined as the difference between the neutron and proton rms-radii is strongly related to a key parameter of the nuclear Equation of State (EoS), the symmetry energy [8]. The feasibility of a measurement of the parity violating asymmetry using a ^{208}Pb nucleus in the P2 experiment was studied. As in the case of a carbon target , the P2 Cherenkov ring detector needs to be adapted for such a measurement. With the MESA beam energy of 155 MeV and a polar scattering angle range between $theta_{min} = 30°$ and $theta_{max} = 34°$, the parity violating asymmetry expected to be $A_{RL} = 0.66$ ppm. This asymmetry can be measured within 1440 h of beamtime to a precision of $\Delta A_{RL}/A_{RL} = 1.44\%$ which allows the determination of the neutron radius R_n with a relative uncertainty of $\Delta R_n/R_n = 0.52\%$ [5].

5. Conclusion and outlook

The P2 experiment will perform a new high precision measurement of the weak mixing angle at low momentum transfer. It will be built at the upcoming MESA accelerator in Mainz. Extensive MC simulations and beam tests at MAMI were done in order to design the experiment and determine the achievable precision. After 10.000 h of data taking, the weak mixing angle can be determined with a precision of $\Delta \sin^2 \theta_W = 3.7 \cdot 10^{-4}$ which makes this measurement sensitive for new physics beyond the Standard Model.

In the P2 experiment, also nuclear targets can be used. A measurement with carbon-12 offers a complementary access to new physics and will need only a forth of the beam time needed for the proton target. The neutron skin of the lead nucleus can be measured using a ^{208} nucleus target with unprecedented precision in the parity violation approach within 1.440 h of data taking. Both measurements require modifications of the P2 setup.

The construction of the P2 experiment is planned in parallel to the construction of the MESA accelerator and is expected to begin in the year 2021. First measurements will be performed in 2023.

References

[1] Davoudiasl, H., Lee, H.-S., and Marciano, W. J, *'Dark' Z implications for Parity Violation, Rare Meson Decays, and Higgs Physics*, *Phys. Rev.* **D85** (115019) 2012 [hep-ph/1203.2947]

[2] Davoudiasl, H., Lee, H.-S., and Marciano, W. J, *Muon $g-2$, rare kaon decays, and parity violation from dark bosons*, *Phys. Rev.* **D89** (095006) 2014 [hep-ph/1402.3620]

[3] Ramsey-Musolf, M. J. and Su, S., *Low Energy Precision Test of Supersymmetry*, *Phys. Rept.* **456** (1-88) 2008 [hep-ph/0612057]

[4] Becker, D., *Voruntersuchungen zur Messung der schwachen Ladung des Protons im Rahmen des P2-Experiments*, *Dissertation, Johannes Gutenberg-Universität Mainz* 2019

[5] Becker, D. et al., *The P2 experiment - A future high-precision measurement of the weak mixing angle at low momentum transfer*, *Eur. Phys. J. A* **54** (208) 2018 [nucl-ex/1802.04759]

[6] Doria, L. et al., *Search for light dark matter with the MESA accelerator*, *CIPANP2018* Doria 2018 [hep-ex/1809.07168]

[7] Peric, I., Kreidl, C. and Fischer P., *Large monolithic particle pixel-detector in high-voltage CMOS technology*, *Nucl. Instrum. Meth.* **A624** (504 - 508) 2010

[8] Roca-Maza, X. et al., *Neutron skin of ^{208}Pb, nuclear symmetry energy, and the parity radius experiment Phys. Rev. Lett.* **106** (252501) 2011 [nucl-th/1103.1762]