PROCEEDINGS OF SCIENCE

P2 - The weak charge of the proton

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In early 2012, preparations for a new high precision measurement of the proton weak charge Q_W^p have started in Mainz. Our aim is to determine the electroweak mixing angle $\sin^2(\theta_W)$ to a relative precision of 0.15%, which requires a measurement of Q_W^p to a relative uncertainty of 1.9%. The experimental method comprises a measurement of the parity-violating asymmetry A^{PV} in elastic electron-proton-scattering at a low $Q^2 \sim 0.003$ GeV^2.
We will present studies of the achievable precision in measuring Q_W^p within Project P2. We will also show results of Geant4-simulations, which were designed to explore possible experimental setups.

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1. Introduction

The electroweak mixing angle θ_W may be considered the most important parameter in the theory of electroweak interactions, since boson mass relations, particle weak charges and coupling constants are given in terms of the Weinberg angle.
It is of high interest to perform precision measurements of $\sin^2(\theta_W)$ at all accessible energy scales, because deviations from Standard Model predictions may point at physics beyond. Figure 1 shows the running of $\sin^2(\theta_W)$ in the Standard Model, results of experiments recently performed, and projections of future experiments.
The most recent undertaking in doing a high precision measurement of $\sin^2(\theta_W)$ is Project P2, which was proposed and granted in early 2012 in the scope of SFB 1044 [1] and is currently under development. The experiment will be set up at the Mainz MAMI accelerator facility and the electron beam will be supplied by the new MESA [2] accelerator, which has been granted in mid 2012 in the course of the German Excellence Initiative.
Our aim is to determine $\sin^2(\theta_W)$ to a precision of 0.15%. We are going to do this by measuring the proton weak charge to a precison of 1.9%, which is at tree level related to the electroweak mixing angle by

$$Q_W^p = 1 - 4\sin^2(\theta_W). \tag{1.1}$$

Experimentally, one can gain access to Q_W^p by observing the parity violating asymmetry A^{PV} in elastic e-p-scattering, which is an asymmetry in the cross section of longitudinally polarized elec-

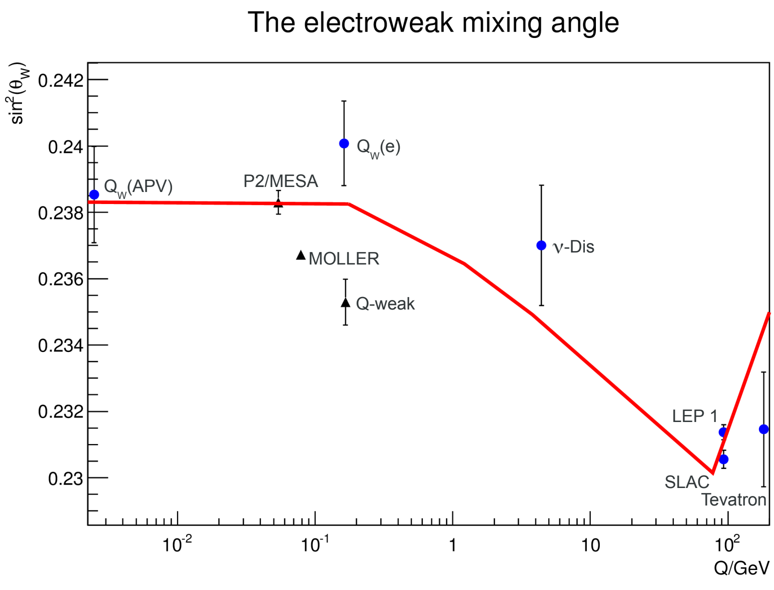

Figure 1: Energy scale dependence of $\sin^2(\theta_W)$: The absorption of universal quantum corrections into $\sin^2(\theta_W)$ leads to a scale dependence of the electroweak mixing angle. The red curve is the Standard Model prediction. The blue dots are results of experiments already performed. The black triangles are projections of future determinations of $\sin^2(\theta_W)$. P2 is going to measure the weak mixing angle to a relative precision of 0.15% and will utilize low beam energies $E \approx 200$ MeV to achieve this goal.

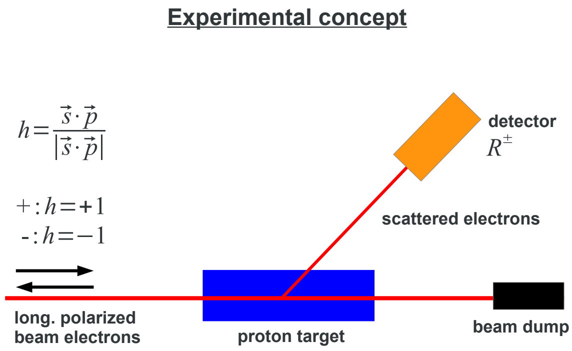

Figure 2: Basic concept of the experiment: A beam of longitudinally polarized electrons is subjected to a target of protons. The cross section for the elastic e-p-scattering is slightly different for electrons with positive helicity and electrons with negative helicity, because the weak interaction violates parity. This leads to nonidentical rates for the two different states. One may now define the partiy violating asymmetry in elastic e-p-scattering as $A^{PV} = \frac{R^+ - R^-}{R^+ + R^-}$.

trons scattered elastically off protons. Figure 2 illustrates the experimental principle, a basic definition of A^{PV} is given in the caption.
Including isospin-symmetry one can write A^{PV} in the following manner:

$$A^{PV} = \frac{-G_F Q^2}{4\pi\sqrt{2}\alpha}(Q_W^p - F(Q^2)), \tag{1.2}$$

where

$$F(Q^2) = F_{em}(Q^2) + F_{axial}(Q^2) + F_{strange}(Q^2) \tag{1.3}$$

stands for hadronic contributions stemming from nucleon structure. G_F is the Fermi-coupling and Q^2 is the negative squared 4-momentum transfer. In order to be sensitive to Q_W^p (and therefore to $\sin^2(\theta_W)$), it is necessary to perform the measurement at low values of Q^2 so that $F(Q^2)$ becomes negligible. Figure 3 shows A^{PV}, averaged over solid angle, at the proposed experimental conditions of P2. The asymmetry is clearly dominated by the contributions stemming from Q_W^p.
Since

$$Q^2 \approx 4EE' \sin^2(\theta_{lab}/2), \tag{1.4}$$

where E is the beam energy, E' the energy of the scattered electron, and θ_{lab} the electron scattering angle in the lab frame, a low Q^2 value can be gained by either choosing a higher beam energy and a lower scattering angle or vice versa. The reason for choosing the latter is that contributions from γ-Z-boxgraphs to the proton weak charge are well under control at low beam energies, as figure 4 illustrates.
In order to support data analysis, a careful revalidation of higher order contributions to the proton weak charge will be performed in Mainz.

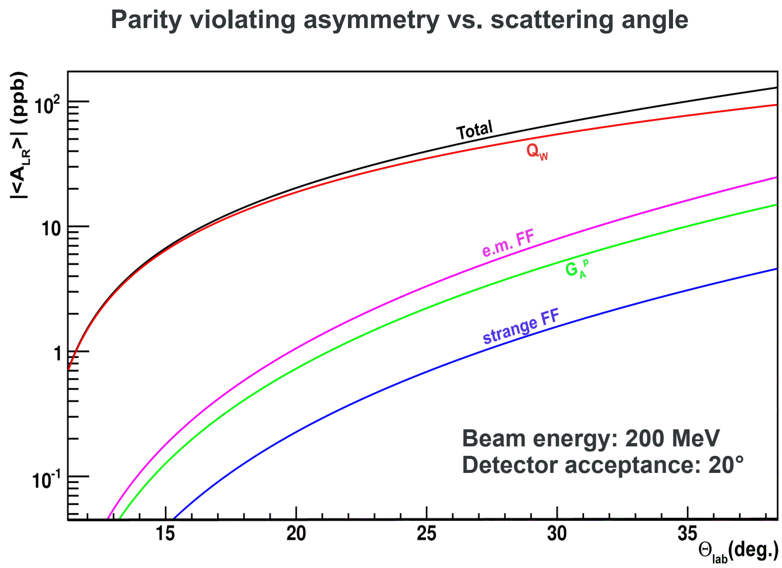

Figure 3: A^{PV}, averaged over solid angle, at a beam energy of $E = 200$ MeV. The total asymmetry is clearly dominated by the contribution of the proton weak charge. P2 is currently considering a central polar angle of $\theta_{lab} = 20°$

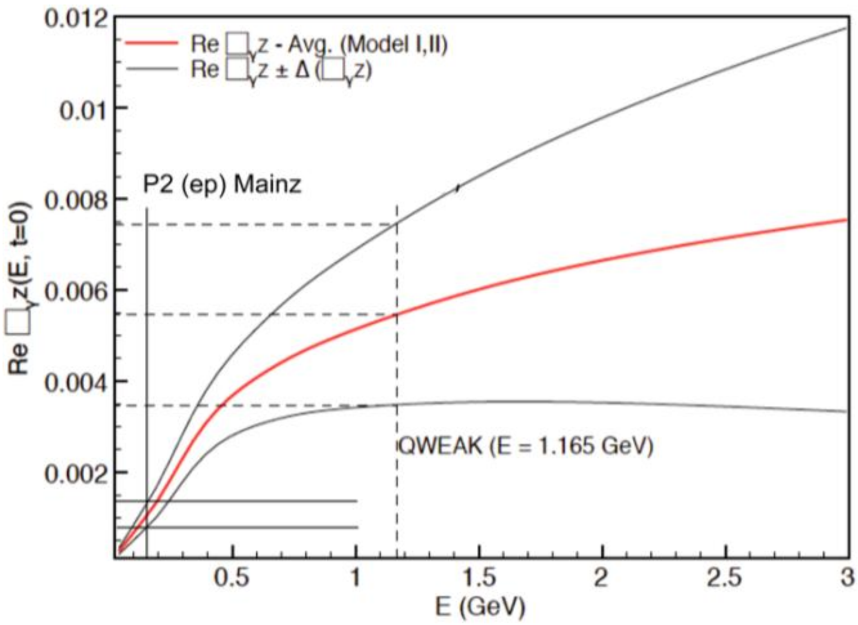

Figure 4: γ-Z-boxgraph correction to Q_W^p, taken from [3]. The uncertainties of the correction quickly grow larger with increasing beam energy. The resulting uncertainties for QWeak and P2 are indicated by dashed and solid lines respectively. The uncertainty of the correction can be neglected at low beam energies.

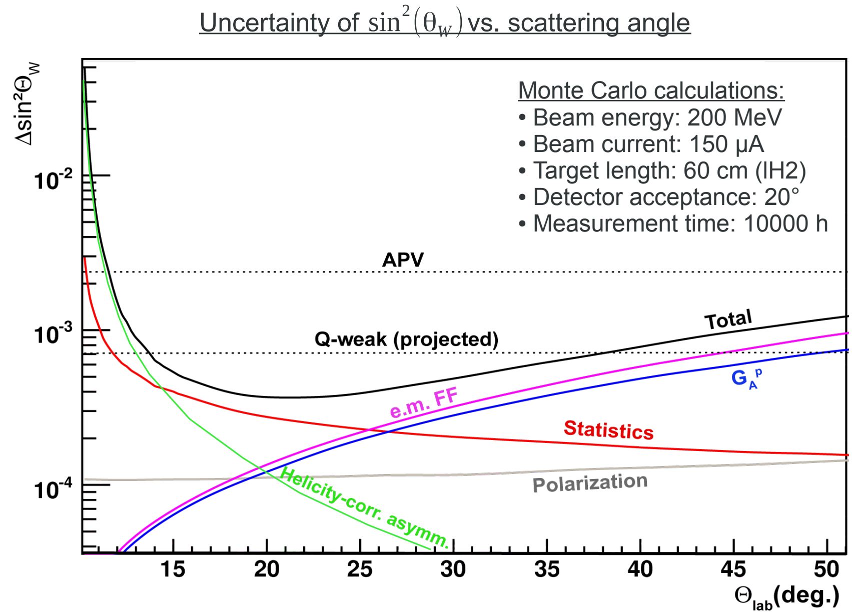

Figure 5: Results of the Monte Carlo calculations w.r.t. the achievable precision within Project P2. The shape of the total uncertainty is determined by the contributions of statistical uncertainties and accelerator-induced helicity-correlated effects at low central scattering angles Θ_{lab}. For larger values of Θ_{lab} the contributions stemming from hadronic structure play an important role.

E_{beam}	200 MeV
I_{beam}	150 μA
P	(85±0.5)%
Target	60 cm liquid-hydrogen
Δt	10000 h
θ_{lab}	$20^\circ \pm 10^\circ$
$\Delta\phi_{lab}$	2π
Q^2	0.0029 GeV^2
A_{PV}	-20.25 ppb
ΔA_{PV}	0.34 ppb (0.25 ppb stat., 0.19 ppb syst., 0.17 % rel.)
$\Delta\sin^2(\theta_W)_{tot}$	$3.6\cdot10^{-4}$ ($2.8\cdot10^{-4}$ stat., 0.15 % rel.)
$\Delta Q_W(p)$	$1.44\cdot10^{-3}$ (1.9 % rel.)

Table 1: Input parameters and results of the error propagation calculations shown in figure 5.

2. Achievable precision

To estimate the achievable precision in the determination of $\sin^2(\theta_W)$ at the experimental conditions of Project P2, error propagation calculations have been performed using Monte Carlo methods. Figure 5 shows an example. Table 1 gives an overview of the optimal configuration. As a result, the calculations yield an achievable precision of

$$\frac{\Delta(\sin^2(\theta_W))}{\sin^2(\theta_W)} = 0.15\% \tag{2.1}$$

in the determination of the electroweak mixing angle, including effects of solid angle averaging and γ-Z-boxgraph corrections to the proton weak charge.

3. Concept studies for the experiment

The high beam current of 150 μA and the long target (60 cm liquid hydrogen) lead to an overall rate of 0.44 THz for the electrons stemming from elastic e-p-scattering. Therefore, at full beam

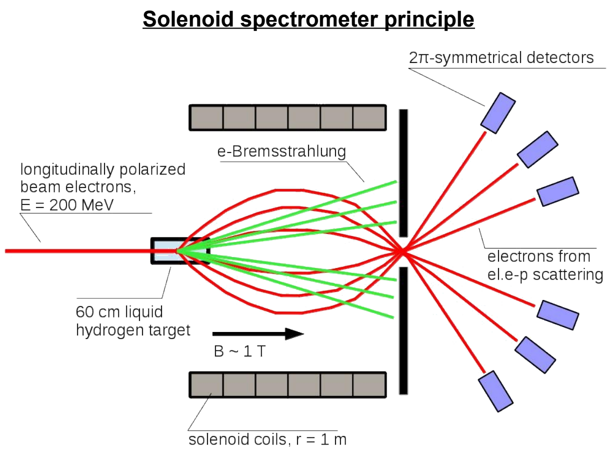

Figure 6: Conceptual sketch of a solenoid spectrometer. The beam electrons are scattered in the liquid-hydrogen target, then subjected to a magnetic field parallel to the beam axis. After passing a collimator, the e- are finally detected in a 2π-symmetrical detector.

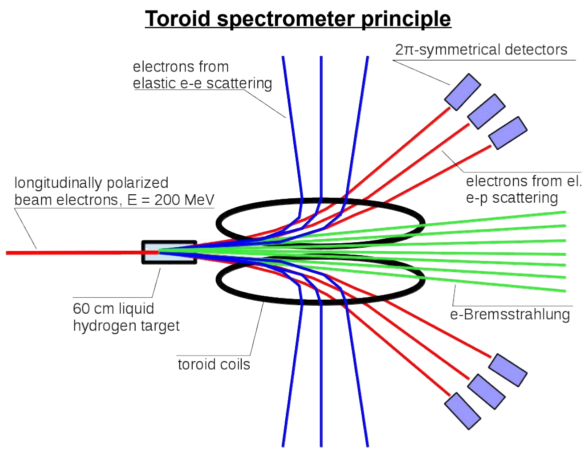

Figure 7: Conceptual sketch of a toroid spectrometer. The beam electrons are scattered in the liquid-hydrogen target, then subjected to an azimuthal magnetic field, where background electrons are filtered out.

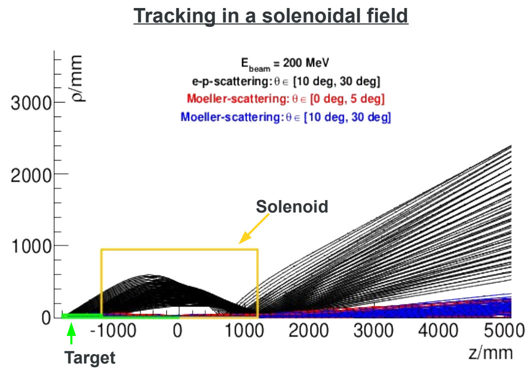

Figure 8: Propagation of electrons in the magnetic field of a solenoid spectrometer. The z-axis is the beam axis and ρ is the distance from the beam axis. The target cell is depicted in green and the solenoid coil is indicated by the yellow rectangle. At the same scattering angles, the energies of e- scattered elastically off protons (black) are higher than the energies of Moller-scattered e- (blue and red). Therefore the radii of the helix-trajectories are larger for the e- stemming from el. e-p scattering. A possible detector position might be at $z = 3000$ mm.

current, an integrating measurement of A^{PV} will be necessary, which means that we require a good background-separation.

Currently, we are studying solenoidal and toroidal magnetic field configurations w.r.t. their focusing and background-separation capabilities. Figures 6 and 7 illustrate the basic ideas for the two design concepts.

To verify the feasibility of these concepts, simulations with Geant4 and ROOT are being developed. Figures 8 and 9 show results of tracking simulations with electrons in the magnetic fields of

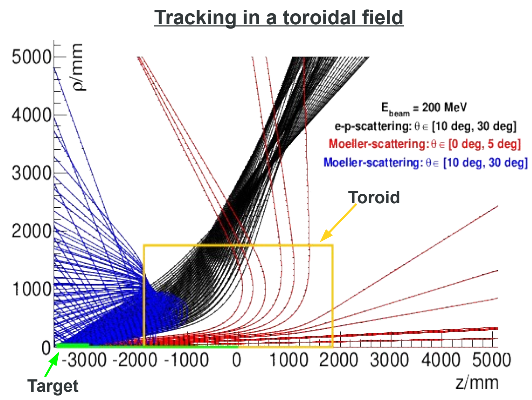

Figure 9: Propagation of electrons in the magnetic field of a toroid spectrometer. The z-axis is the beam axis and ρ is the distance from the beam axis. Target cell and toroid coils are indicated by green and yellow rectangles respectively. Trajectories of e- scattered elastically off protons are drawn in black and trajectories of Moller-scattered e- are shown in blue/red, depending on solid angle. A good position for a 2π-symmetrical detector might be at (z = 500 mm, ρ = 3500 mm).

a solenoid and a toroid respectively. A solenoidal field configuration is highly desirable due to the fact that it allows for using the full azimuth for the measurement, resulting in a quicker completion of the envisaged measurement program. An extensive Geant4-simulation including beam-target interaction, tracking of particles in the magnetic field and simulation of detector response is currently under development.

4. Timeline

The timeline of Project P2 consists of three major phases. Fig. 10 shows a schematic sketch. The first phase is devoted to preparatory work, i.e. concept studies and testing of detector materials. The theoretical work needed to interpret the experimental data will also be carried out here. Phases two and three will be dedicated to data taking and analysis.

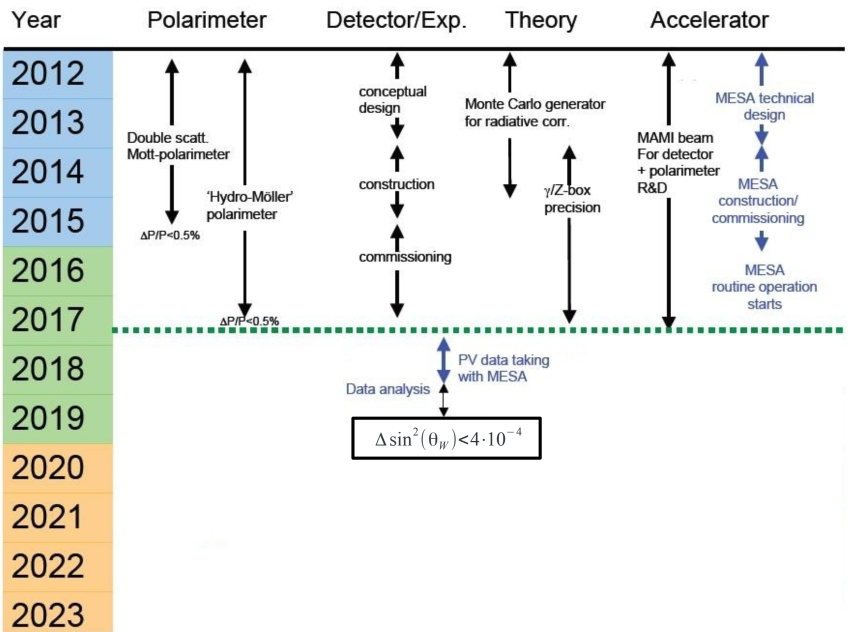

Figure 10: Timeline of project P2. Explanation to be found in the text.

References

[1] http://www.uni-mainz.de/presse/14916_ENG_HTML.php

[2] http://www.prisma.uni-mainz.de/mesa.php

[3] M. Gorchtein, C. J. Horowitz and M. J. Ramsey-Musolf, Phys. Rev. C84, 015502 (2011)

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