The P2 experiment
A high precision measurement of the weak mixing angle
CRC project B01

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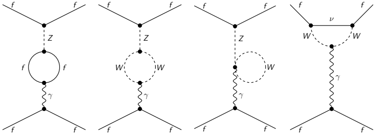
Outline

Motivation

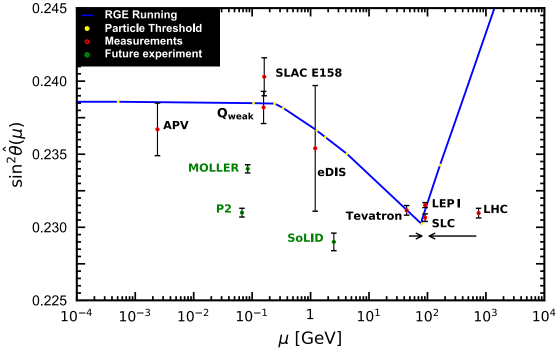
- Standard model very successful
  $\rightarrow$ Prediction of charm-, top-quark, higgs boson, ...
- Known: Still something missing
  - Gravitation not included
  - Cosmic microwave background / galaxy rotation curve
    $\rightarrow$ Dark matter
  - Anomalous magnetic moment $(g-2)_{\mu,e}$
    $\rightarrow$ Maybe something new
- Search for extension of the standard model
  - Direct: High energy
    - LHC: ATLAS, CMS, ...
  - Indirect: High precision measurements
    - Deviations from SM prediction
    $\rightarrow$ P2 experiment

Weak mixing angle

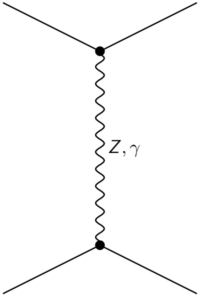
- $\sin^2\theta_w$ central parameter of the standard model
  - Weak charge of the proton: $Q_W(p) = 1 - 4\sin^2\theta_w$
  - Mass ratio $\frac{m_W}{m_Z} = \cos\theta_w$
  - ...
- $Q_W(p)$ sensitive to $\sin^2\theta_w$: $\frac{\Delta\sin^2\theta_w}{\sin^2\theta_w} \approx 0.09\frac{\Delta Q_W(p)}{Q_W(p)}$
- Scale dependence of $\sin^2\theta_w$



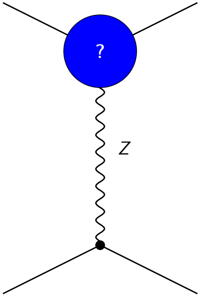
- Z-pole: high precision, deviations
- Low Q: large uncertainties



Portals for SM-extensions

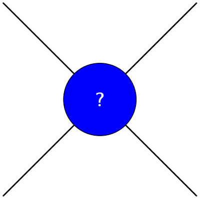


- Extra Z



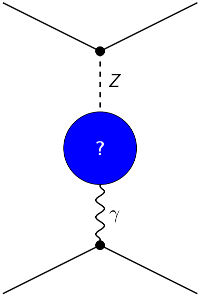
- Mixing with dark photon
  - Complementary to LHC
  - Sensitivity to low masses

  $\rightarrow$ $m > 70\,\mathrm{MeV}$



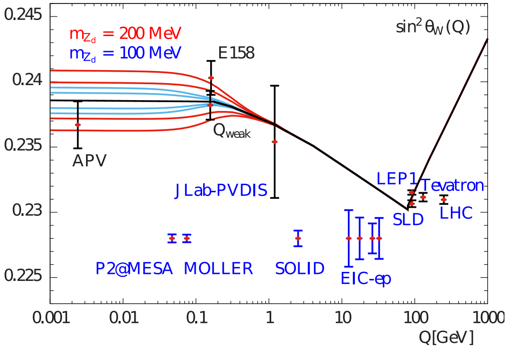
- Contact interaction
  - Only parameter: Mass of new physics scale

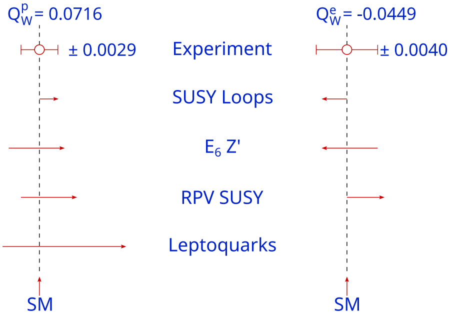
  $\rightarrow$ Scale: $49\,\mathrm{TeV}$



- New fermions

Physics beyond the standard model





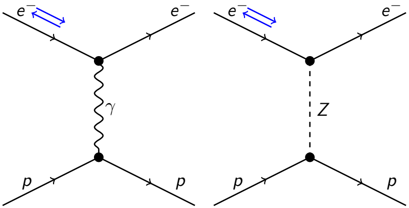
- Sensitivity towards hypothetical new particles/interactions
- Dark Z-boson
  - New light vector boson
  - Kinematic and mass mixing with γ/Z
- Combination of $Q_W(p)$ and $Q_W(e)$

$\Rightarrow$ Complementary access to new physics

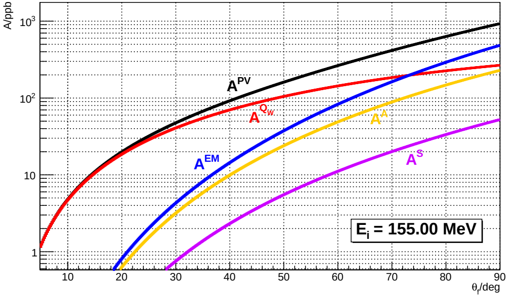
Parity-violating electron scattering

- Longitudinally polarized electron beam
- Detect scattered electrons
- Cross-section: $\sigma_{ep}^{\pm} = |M_\gamma + M_Z^{\pm}|^2$
- Weak interaction: Parity violating

  $\Rightarrow \quad \sigma_{ep}^{+} \neq \sigma_{ep}^{-}$



$$A_{ep}^{PV} = \frac{\sigma_{ep}^{+} - \sigma_{ep}^{-}}{\sigma_{ep}^{+} + \sigma_{ep}^{-}} = \frac{-G_F Q^2}{4\sqrt{2}\pi\alpha_{em}} \left[Q_W(p) - F(E, Q^2) \right]$$

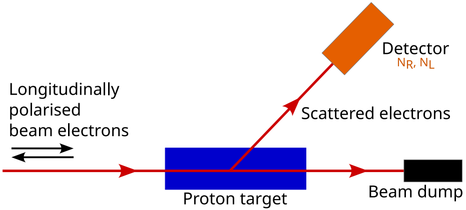


- $Q_W(p)$: Weak charge (dominant at low Q^2)
- $F(E, Q^2)$: Hadron structure

Parity violating electron scattering

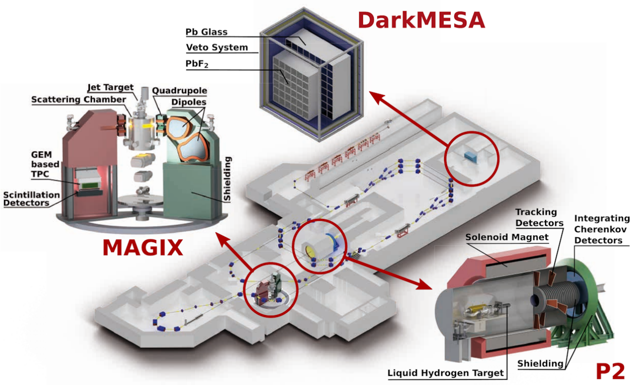
$$A_{RL}^{exp} = \frac{N_R - N_L}{N_R + N_L} = -P\frac{G_F Q^2}{4\sqrt{2}\pi\alpha_{em}}\left[Q_W(p) - F(E, Q^2)\right] + A_F$$

- Cross-section asymmetry: A_{RL}^{exp}
  - Magnetic spectrometer
- Beam polarization: P
  - Polarimetry
  - Different systems (5MeV-Mott, Hydro/Iron-Moller)
- Momentum transfer: Q^2
  - Tracking system
- Theory: $Q_W(p) - F(E, Q^2)$
  - QED corrections
  - Hadron structure $F(E, Q^2)$
  - Strangeness/Axial form factor
- False asymmetries: A_F
  - Monitoring the accelerator

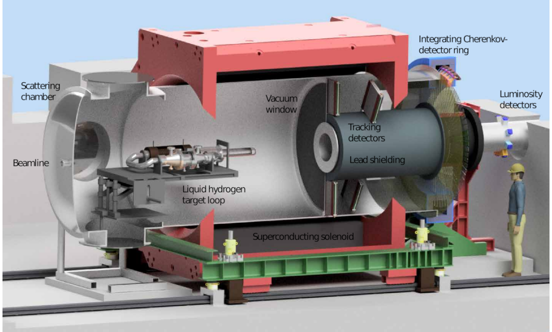


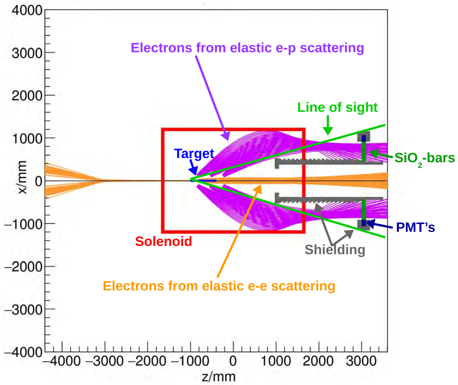
MESA – Mainz Energy-recovering Superconducting Accelerator

- Future accelerator in Mainz
- Two cryo modules with $\Delta E = 25\,\mathrm{MeV}$
- Beam energy $155\,\mathrm{MeV}$ (3 circulations)
- 85% spin polarized beam ($150\,\mu\mathrm{A}$)
- Helicity switching with $f \sim 1\mathrm{kHz}$
- Two different beam modes
  - External beam
  - Energy recovering
- Three experiments: darkMESA, MAGIX, P2



The P2 detector





- Detect elastic e-p-scattering
- Fast and radiation-resistant detector
  - ⇒ Fused silica Cherenkov detector
  - ⇒ Liquid hydrogen target

- Measurement of Q^2
  - ⇒ Tracking detector (HV-MAPS)
- Suppress other processes
  - ⇒ Lead shielding
  - ⇒ $0.6\,\mathrm{T}$ superconducting solenoid

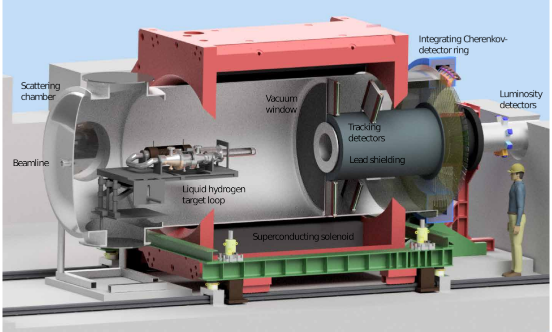
Superconducting solenoid

- Manufacturer: Sigmaphi
- Delivery to Mainz: 22 November 2024
- Currently ongoing: Installation of service turret
- Installation into the yoke end of this year
- Cooldown beginning of 2026

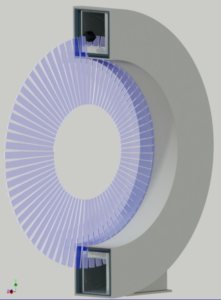
Scattering chamber

- Manufacturer: NTG
- Delivery to Mainz: 10 April 2025
- Consists of six parts
- Installation possible after solenoid test

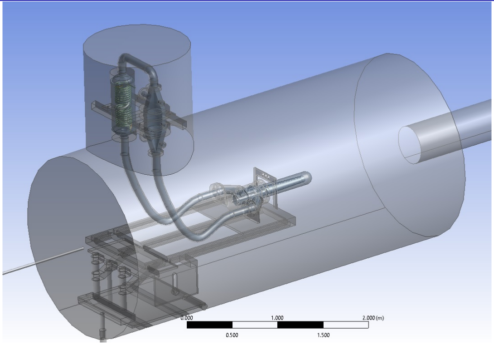
Scattering chamber parts



- Lead for gamma shield already delivered
- CFK window with holding frame ordered (Schunk, NTG)
- Detector mounting/radiation shielding ordered (MTH)
- Gamma shield support structure ordered (NTG)

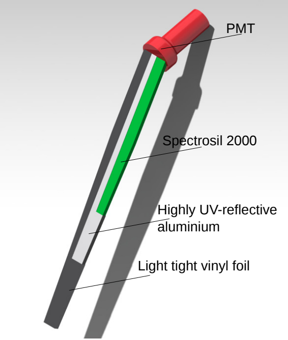


Liquid hydrogen target



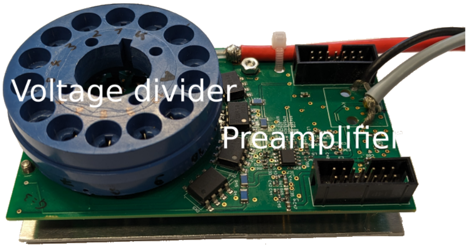
- $90\,\mathrm{m}^3$ hydrogen buffer delivered
- Storing hydrogen at $2\,\mathrm{bar(a)}$
- Liquid hydrogen target
  - Developed in cooperation with Silviu Covrig
  - Based on QWeak and G0 design
  - Cell length: $60\,\mathrm{cm}$
  - Cooling power: $4\,\mathrm{kW}$

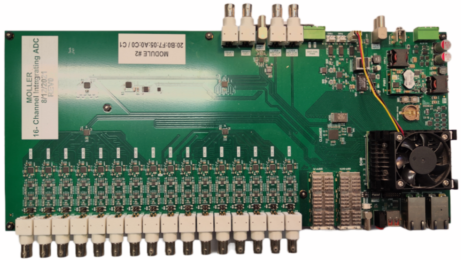
Cherenkov detector



- Detector ring consisting of 72 wedged fused silica bars
- Cover angle range of 25° to 45°
- All PMTs are delivered and characterization ongoing
- All fused silica bars delivered and measured

Readout electronics

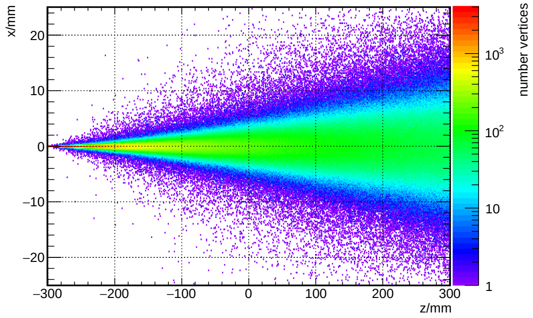


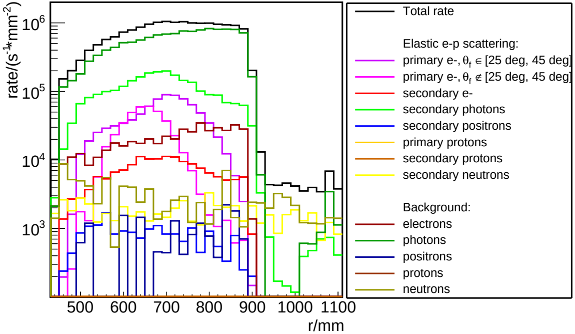


- Development in collaboration with University of Manitoba
- Hit rate 10^{11} Hz
  → Integrating measurement
- Single event detection (Q^2 measurement)
  → Special PMT base developed
- Radiation hardness test for low voltage

- Readout using SADC with FPGA
  - 16 channel
  - SADC with 15 Msps
  - FPGA calculates mean values for each helicity window
  - Network connection for "Trigger Interface" and data transfer

Simulations of the P2 setup





- Geant4 simulation of the P2 setup
- Beam target interaction
- Event generator for e-p scattering
- Simulation of background processes

- Calculate rate distribution
  - $\Rightarrow$ Prediction for signal and background
- Parametrize detector response

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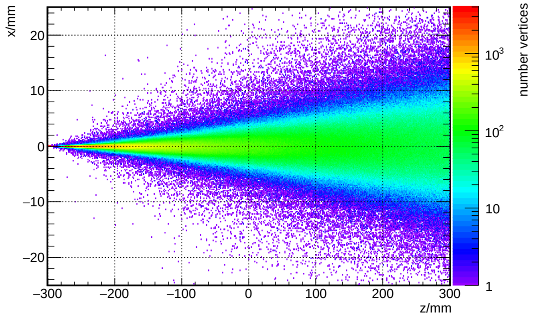

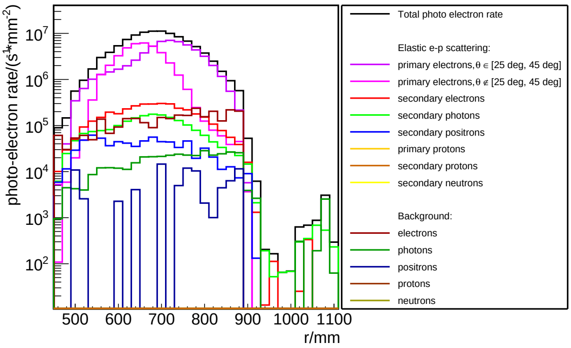

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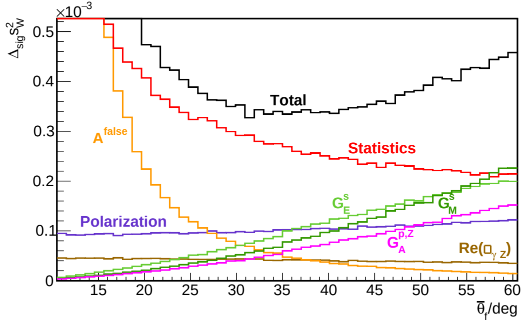
Achievable precision



E_{beam}	$155\,\mathrm{MeV}$	
$\bar{\theta}_f$	$35°$	
$\delta\theta_f$	$20°$	
s_W^2	0.23116	
$\Delta_{exp} s_W^2$	$3.7 \cdot 10^{-4} (0.16\%)$	
$\Delta_{exp,stat} s_W^2$	$3.1 \cdot 10^{-4} (0.13\%)$	statistics
$\Delta_{exp,false} s_W^2$	$0.6 \cdot 10^{-4} (0.03\%)$	false asymmetries
$\Delta_{exp,t.w.} s_W^2$	$1.2 \cdot 10^{-4} (0.05\%)$	target window
$\Delta_{exp,t.p.} s_W^2$	$0.1 \cdot 10^{-4} (0.00\%)$	
$\Delta_{exp,P} s_W^2$	$0.7 \cdot 10^{-4} (0.03\%)$	beam polarization
$\Delta_{exp,\Box_{\gamma Z}} s_W^2$	$0.4 \cdot 10^{-4} (0.02\%)$	
$\Delta_{exp,nucl.FF} s_W^2$	$1.2 \cdot 10^{-4} (0.05\%)$	form factors

- Beam current: $150\,\mu\mathrm{A}$
- Measuring time: $10000\,\mathrm{h}$
- Beam polarization: $P = 0.85, \Delta P/P = 0.5\%$

- Raw asymmetry $\langle A^{\mathrm{raw}} \rangle_{\mathrm{exp}} = -24.03\,\mathrm{ppb}$
- $\Delta_{\mathrm{tot}} \langle A^{\mathrm{raw}} \rangle_{\mathrm{exp}} = 0.58\,\mathrm{ppb}$ (2.41%)

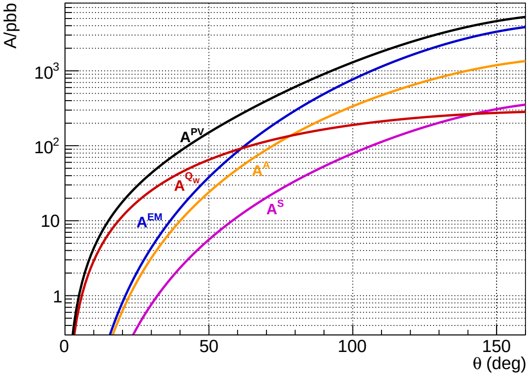
  $\Rightarrow$ Relative uncertainty on $\sin^2\theta_w$: 0.16%

Backward angle measurement

$$A_{ep}^{PV} = \frac{\sigma_{ep}^{+} - \sigma_{ep}^{-}}{\sigma_{ep}^{+} + \sigma_{ep}^{-}} = \frac{-G_F Q^2}{4\sqrt{2}\pi\alpha_{em}} \left[Q_W(p) - F(E, Q^2) \right]$$

$$F(E, Q^2) = F^{EM}(E, Q^2) + F^{A}(E, Q^2) + F^{S}(E, Q^2)$$

- Measure axial form factor $G_A^{p,Z}$, strange magnetic form factor G_M^s
- More sensitivity under backward angle compared to forward angle
- Dedicated measurement
  - Use 3 planes of Micromega detectors
  - → Determine momentum and vertex
    - Cooperation with CEA Saclay
    - Currently: Tender for all parts
    - 2026: Detector assembly
  - Parity violating asymmetry ∼ ppm



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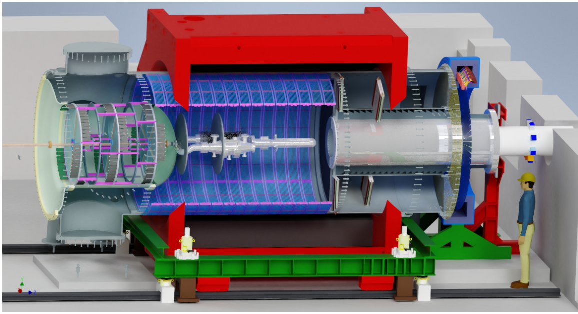

Summary

- P2 optimized to measure asymmetry of an order 10^{-8}
  - Superconducting magnet as spectrometer
  - HV-MAPS to measure $\langle Q^2 \rangle$
- Rich physics program
  - Proton weak charge
    - Very high precision $\frac{\Delta \sin^2 \theta_w}{\sin^2 \theta_w} = 0.15\%$
    - Sensitivity towards new physics on mass scales up to 50 TeV
  - Backward angle measurement
    - Possibility to measure $G_A^{p.Z}$ and G_M^s separately
    - Important contribution for forward angle measurement
  - ^{12}C weak charge
  - ^{208}Pb neutron skin
- Solenoid installation end of 2025, cooldown beginning of 2026
- Detector installation in 2026
- More information: Eur. Phys. J. A (2018) 54, 208