The P2 experiment at MESA - A high precision measurement of the weak mixing angle

M. Wilfert

Johannes Gutenberg-Universität Mainz

2023 CAP Congress / Congrès de l'ACP 2023

HIM
Helmholtz-Institut Mainz

JG|U
JOHANNES GUTENBERG UNIVERSITÄT MAINZ

SFB 1044
THE LOW-ENERGY FRONTIER OF THE STANDARD MODEL

Cluster of Excellence
PRISMA+
Precision Physics, Fundamental Interactions and Structure of Matter

Outline

Motivation

- Standard model very successful

  → Prediction of charm-, top-quark, higgs boson,...

- Known: Still something missing
  - Gravitation not included
  - Cosmic microwave background / galaxy rotation curve

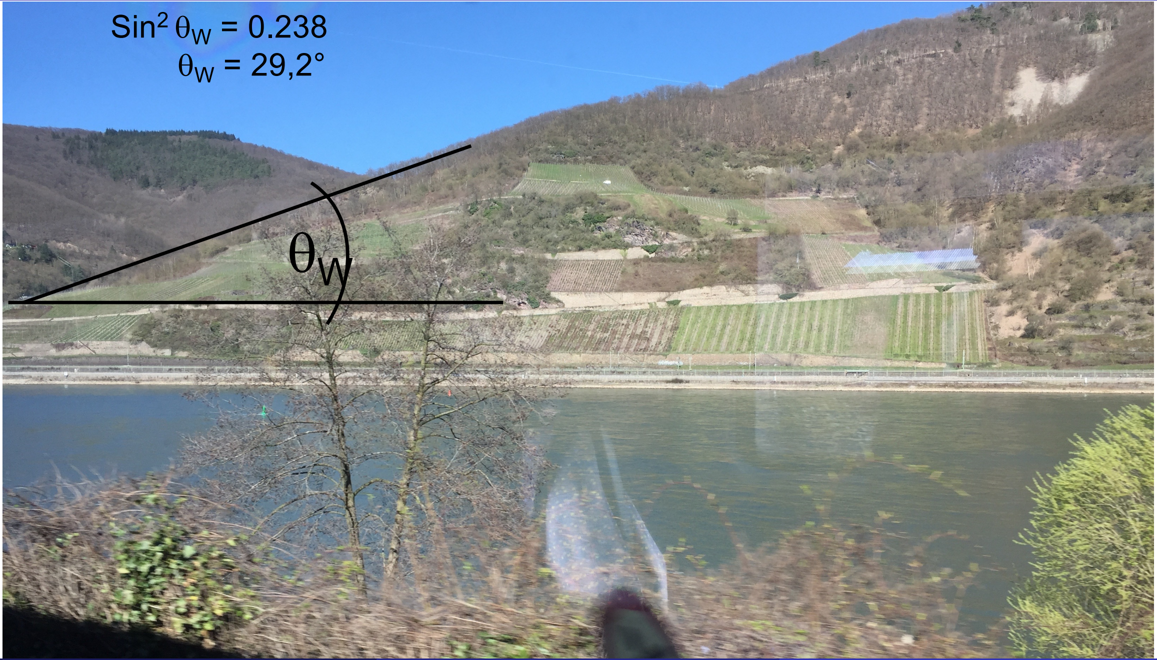
    → Dark matter
  - Anomalous magnetic moment $(g-2)_{\mu,e}$

    → Maybe something new

- Search for extension of the standard model
  - Direct: High energy
    - LHC: ATLAS, CMS, ...
  - Indirect: High precision measurements
    - Deviations from SM prediction

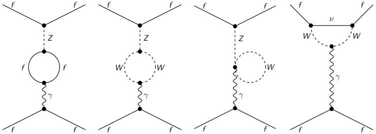
    → P2 experiment

High precision measurements of the Weinberg angle $\sin^2\theta_W$ at low energy

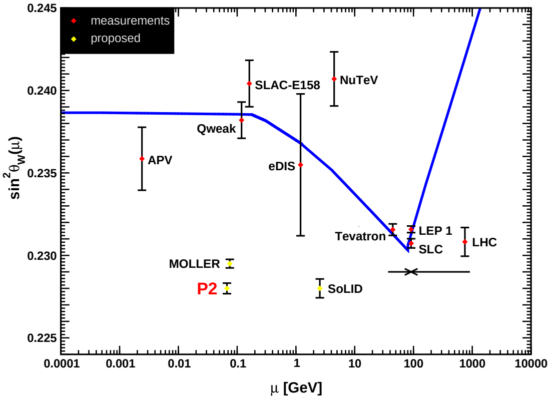


Weak mixing angle

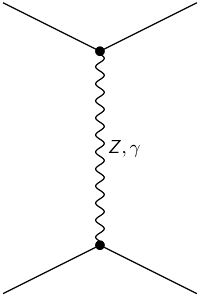
- $\sin^2\theta_W$ central parameter of the standard model
  - Weak charge of the proton: $Q_W(p) = 1 - 4\sin^2\theta_W$
  - Mass ratio $\frac{m_W}{m_Z} = \cos\theta_W$
  - ...
- $Q_W(p)$ sensitive to $\sin^2\theta_W$: $\frac{\Delta\sin^2\theta_W}{\sin^2\theta_W} \approx 0.09\frac{\Delta Q_W(p)}{Q_W(p)}$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



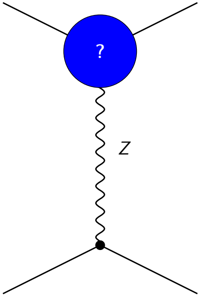
- Z-pole: high precision, deviations
- Low Q: large uncertainties



Portals for SM-extensions

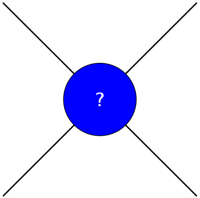


- Extra Z



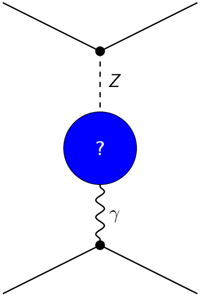
- Mixing with dark photon
  - Complementary to LHC
  - Sensitivity to low masses

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

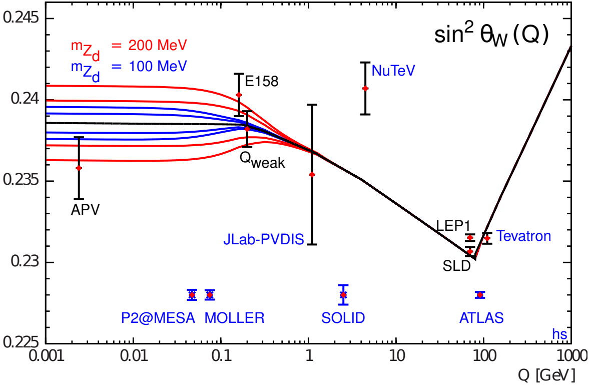


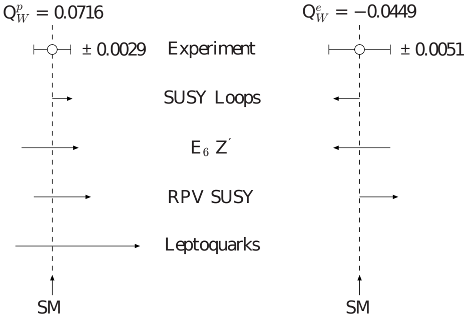
- Contact interaction
  - Only parameter: Mass of new physics scale

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



- New fermions

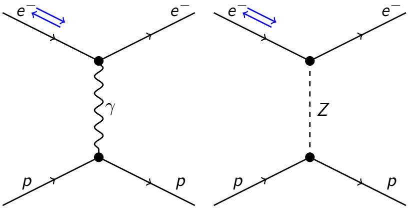




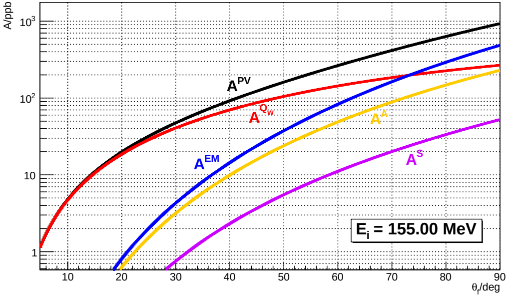
- Sensitivity towards hypothetical new particles/interactions
- Dark Z-boson
  - New light vector boson
  - Kinematic and mass mixing with γ/Z
- Combination of $Q_W(p)$ and $Q_W(e)$

- Longitudinally polarised electron beam
- Detect scattered electrons
- Cross section: $\sigma^{\pm}_{ep} = |M_\gamma + M^{\pm}_Z|^2$
- Weak interaction: Parity violating

  $\Rightarrow \quad \sigma^{+}_{ep} \neq \sigma^{-}_{ep}$



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



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

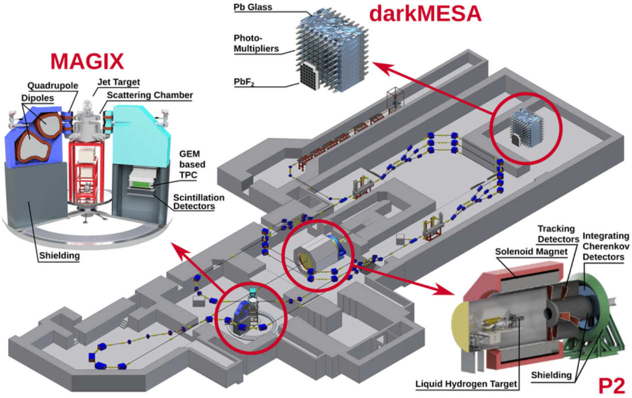
Parity violating electron scattering

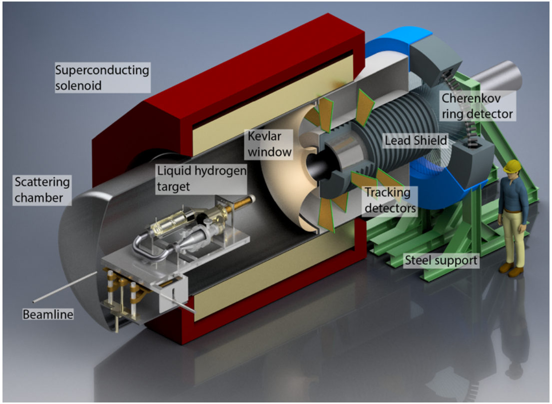
$$A_{LR}^{exp} = -P \frac{G_F Q^2}{4\sqrt{2}\pi\alpha_{em}} \left[Q_W(p) - F(E, Q^2)\right] + A_F$$

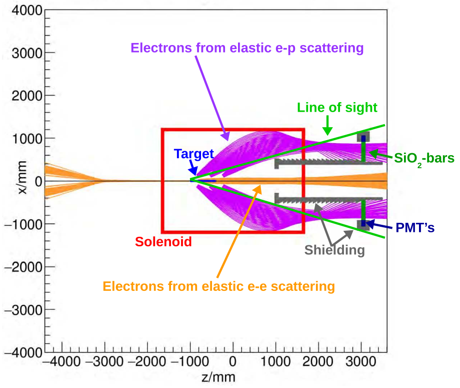
- Cross section asymmetry: A_{LR}^{exp}
  - Magnetic spectrometer
- Beam polarisation: P
  - Polarimetry
  - Different systems (5MeV-Mott, Hydro/Iron-Moller)
- Momentum transfer: Q^2
  - Tracking system
- Theory: $Q_W(p) - F(E, Q^2)$
  - QED corrections
  - Hadron structure $F(E, Q^2)$
  - Strangeness/Axial form factor
- False asymmetries: A_F
  - Control of 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 polarised beam ($150\,\mu\mathrm{A}$)
- Helicity switch with $f \sim 1\mathrm{kHz}$
- Two different beam modes
  - External beam
  - Energy recovering
- Three experiments: darkMESA, MAGIX, P2

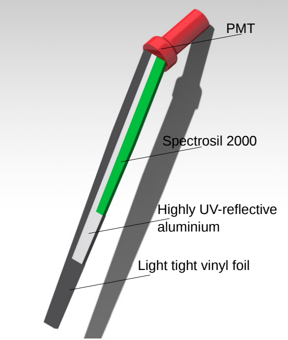


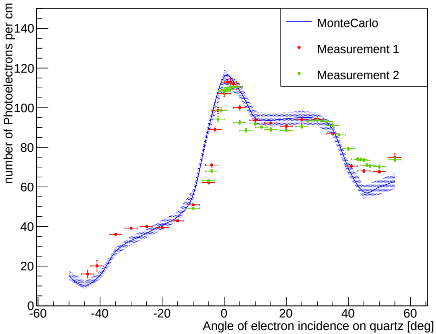




- Detect elastic e-p-scattering
- Fast and radiation-resistant detector
  - ⇒ Fused silica Cherenkov detector
  - ⇒ Liquid hydrogen target
- Measurement of Q^2
  - ⇒ Tracking detector (HV-MAPS)
- Suppress other processes
  - ⇒ Lead shielding
  - ⇒ $0.6\,\mathrm{T}$ superconducting solenoid

Cherenkov detector and electronics





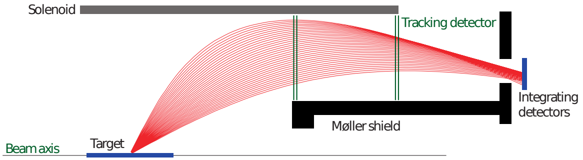
- Detector ring consisting of 72 wedged fused silica bars
- Cover angle range of 25° to 45°
- Collaboration with Manitoba
- Hit rate 10^{11} Hz
  - → Integrating measurement

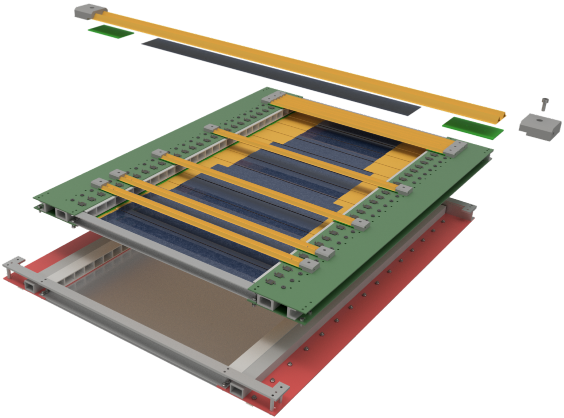
- Single event mode
  - → Special PMT base developed
- Preamplifier with line driver
- Digitised by ADC

⇒ Full chain (Quartz-PMT-Preamp-SADC) tested in beamtimes at MAMI

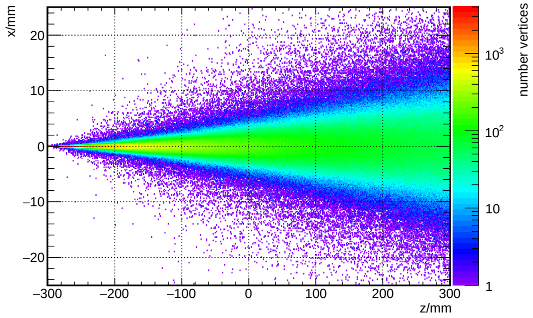
Tracking detector

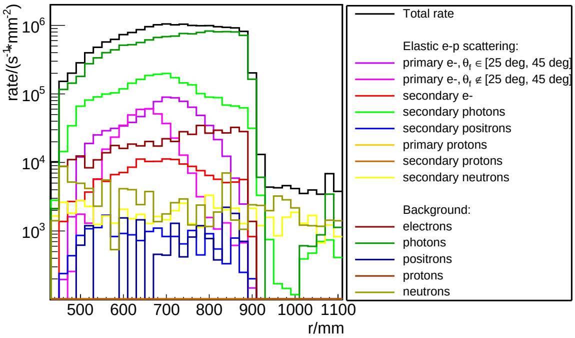
- High resolution tracking:
  - Measure $\langle Q^2 \rangle$
  - Study systematic effects
- Use in tracking mode
  - High efficiency
  - Cover at least one silica bar
  - Coincidences with Cherenkov detector possible
- 4 segments with 2 double layer detectors
- 50 $\mu\mathrm{m}$ thin HV-MAPS sensors
- Resolution for track momentum: $\sim 2\,\mathrm{MeV}/c$





Simulations of the P2 setup





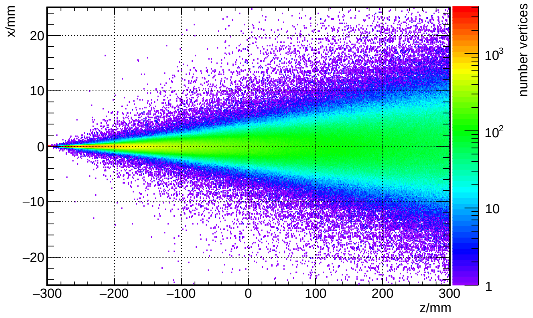
- Geant4 simulation of the P2 setup
- Beam target interaction
- Event generator for e-p scattering
- Simulation of background processes

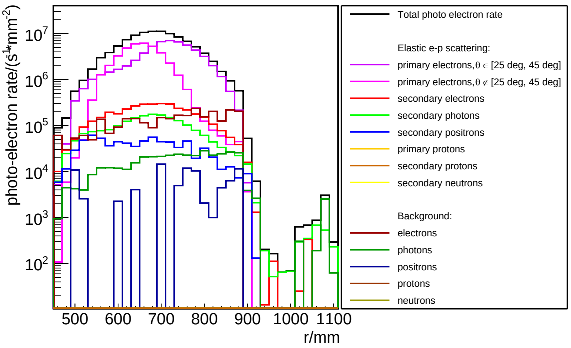
- Calculate rate distribution

  ⇒ Prediction for signal and background

- Parametrise detector response

Simulations of the P2 setup

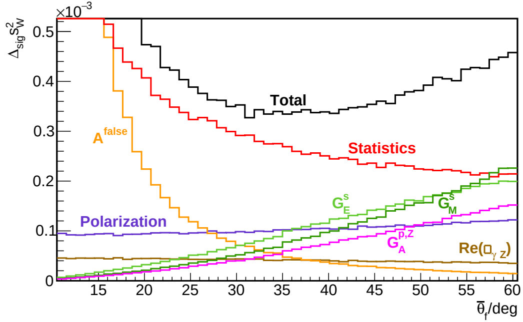




- Geant4 simulation of the P2 setup
- Beam target interaction
- Event generator for e-p scattering
- Simulation of background processes

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

Achievable precision



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

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

- 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%

Challenges form factors

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

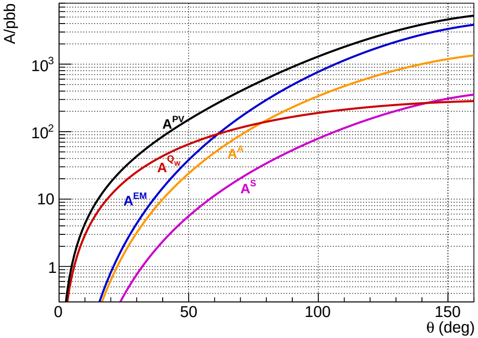
- $F(E, Q^2)$ includes form factors
- Electromagnetic form factors of the proton/neutron
  - $\rightarrow$ Precision of parametrisation OK
- Isospin breaking electromagnetic form factors
  - $\rightarrow$ Precision of parametrisation OK
- Strangeness form factor
  - $\rightarrow$ Improvement needed
- Proton axial form factor
  - $\rightarrow$ Improvement needed
- How to improve
  - Progress in lattice QCD
  - Backward angle measurement

Backward angle measurement

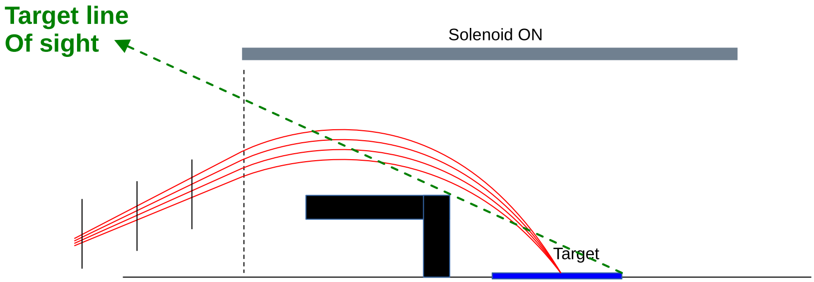
$$A_{ep}^{PV} = \frac{\sigma_{ep}^{+} - \sigma_{ep}^{-}}{\sigma_{ep}^{+} + \sigma_{ep}^{-}} = \frac{-G_F Q^2}{4\sqrt{2}\pi\alpha_{em}} \left[Q_W(p) - F(E, Q^2)\right]$$

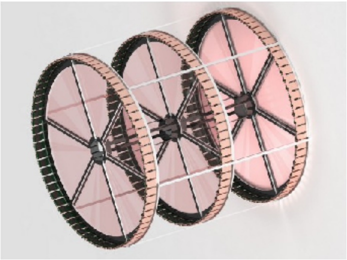
$$F(E, Q^2) = F^{EM}(E, Q^2) + F^{A}(E, Q^2) + F^{S}(E, Q^2)$$

- 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
  - Time $\sim 2000\,\mathrm{h}$
    - $\Rightarrow$ Improve Uncertainty from $\Delta(F^S + F^A)$ by a factor of 4
  - Using hydrogen and deuterium target
    - $\Rightarrow$ Separation of $G_A^{p,Z}$ and G_M^s



Setup for the backward angle measurement





- Measurement with increased magnetic field ($0.6\,\mathrm{T} \rightarrow 0.7\,\mathrm{T}$)
- Use 3 planes of Micromega detectors
- Target close to the downstream end of the vacuum chamber
- Measure position at the detector

$\rightarrow$ Determine momentum and vertex

- Cooperation with CEA Saclay
- Currently: Design/testing of the Micromegas (Successful test at MAMI one week ago)
- Parity violating asymmetry $\sim \mathrm{ppm}$
- Maybe possibility to resolve inelastic states in electron carbon scattering

Measurement with carbon

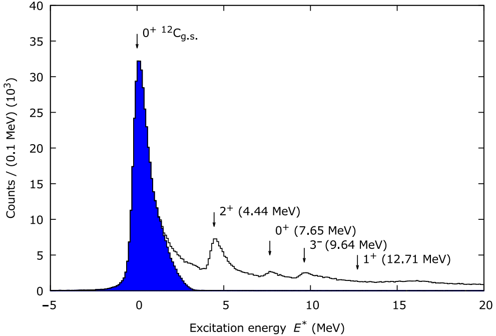
- Cross section $\frac{d\sigma}{d\Omega} \sim Z^2$
  - QED cross section 36 times larger

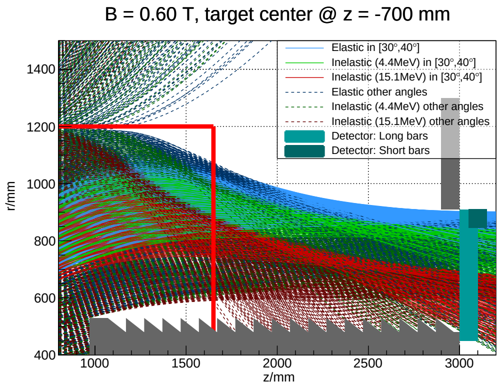
  $\Rightarrow$ Shorter measuring time
- Weak charge
  - Proton: $Q_W = 1 - 4\sin^2\theta_W \approx 0.07$
  - Carbon: $Q_W = -24\sin^2\theta_W \approx -5.51$

  $\Rightarrow$ Weak charge is 78 times larger

  $\Rightarrow$ Larger asymmetry
- Additional and complementary sensitivity to new physics models
- Weak charge of different targets expressed via Peskin-Takeuchi parameters: $(\chi = m_Z^2/m_{Z_x}^2)$

$$
\begin{aligned}
Q_W(\mathrm{e}) &= -0.0435\,(1 + 0.25\,T - 0.34\,S + 0.7\,X + 7\,\chi) \\
Q_W(\mathrm{p}) &= 0.0707\,(1 + 0.15\,T - 0.21\,S + 0.43\,X - 4.3\chi) \\
Q_W(\mathrm{C}) &= -5.510\,(1 - 0.003\,T + 0.016\,S - 0.033\,X - \chi) \\
Q_W(\mathrm{Cs}) &= \underbrace{73.24\,(1}_{\text{SM}}\;\underbrace{+\,0.011\,S - 0.023\,X - 0.9\chi)}_{\text{``New Physics''}}
\end{aligned}
$$

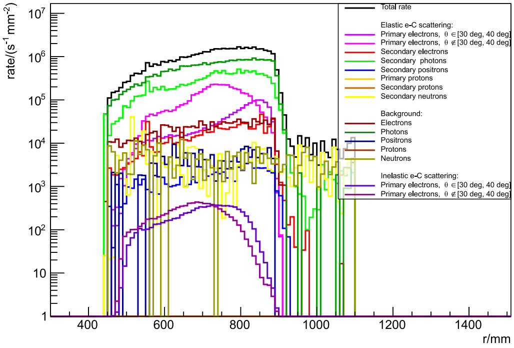


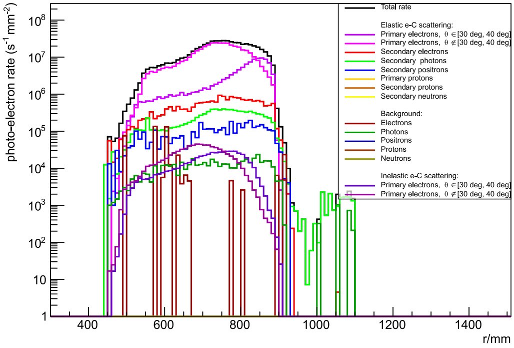


- Excited states in ^{12}C nucleus
- Visible in electron scattering (PRL **121**(2018) 022503)
- Asymmetry not known

- Raytracing simulation
  - Target centre at lH2 position
  - Using a 5-finger target

Simulations with a carbon target





- Inelastic scattered electrons
  - Sum from $4.4, 7.6, 9.6\,\mathrm{MeV}$ states
  - Strongly suppressed

- Rates on the detector
  - Hit rate dominated by photons
  - ⇒ Photoelectron rate dominated by primary electrons

Comparison with hydrogen measurement

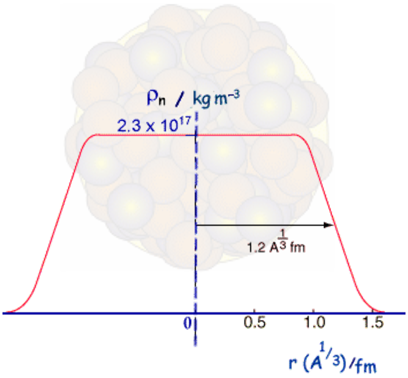
- Parity violating asymmetry for carbon
  - Only elastic scattering
  - Asymmetry for inelastic scattering not known
  - Asymmetry $A_{eC}^{PV} = -\frac{G_f Q^2}{4\sqrt{2}\pi\alpha_{em}} \frac{Q_W(C)}{6}$

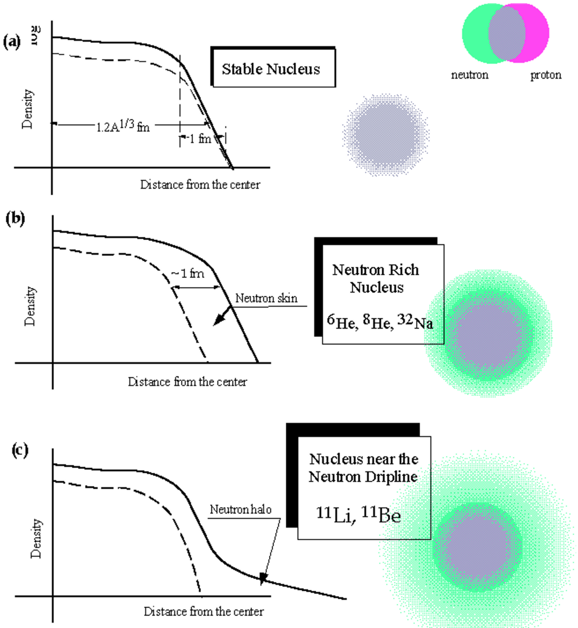
	Hydrogen	**Carbon**
$\langle Q^2 \rangle$	$4.82 \cdot 10^{-3}\,(\mathrm{GeV}/c)^2$	$4.98 \cdot 10^{-3}\,(\mathrm{GeV}/c)^2$
Measuring time	$11000\,\mathrm{h}$	$2500\,\mathrm{h}$
Asymmetry $\langle A^{\mathrm{raw}} \rangle_{\mathrm{exp}}$	$-24.03\,\mathrm{ppb}$	$353.94\,\mathrm{ppb}$
Statistical uncertainty $\Delta_{\mathrm{stat}} \langle A^{\mathrm{raw}} \rangle_{\mathrm{exp}}$	$0.50\,\mathrm{ppb}$ (2.08%)	$0.70\,\mathrm{ppb}$ (0.2%)
$\Delta \sin^2 \theta_W$	$3.1 \cdot 10^{-4}$ (0.13%)	$4.6 \cdot 10^{-4}$ (0.2%)

- Challenges
  - Same relative uncertainty on asymmetry and weak mixing angle
  - Very precise polarisation measurement needed for carbon (Aim: $\Delta P/P = 0.3\%$)
  - Systematic uncertainties need to be small

Neutron skin

- Nuclear charge radii



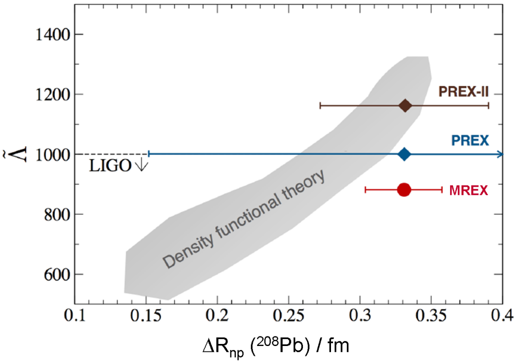


- Where do the neutron go?
- Pressure forces neutrons out against surface tension

P2 measurements: Neutron skin measurement

$$A^{PV} \approx \frac{G_F Q^2}{4\pi\alpha_{em}\sqrt{2}} \frac{F_W(Q^2)}{F_{Ch}(Q^2)}$$

- Neutron radius of ^{208}Pb
- Measurement time $\sim 1500\,\mathrm{h}$
- Weak radius measured via weak-charge density F_W
- $\frac{\Delta R_n}{R_n} = 0.52\%$ possible
- Better understanding of neutron stars



Time line

- 2023/2024: Installation of the P2 experiment in the hall
- 2023: Preparation for magnet installation/testing in the experimental hall
- Beginning 2024: Magnet installation/testing
- 2024: Commissioning with MESA beam
- 2025: First data taking with MESA beam

Summary

- P2 optimised 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
  - ^{12}C weak charge
    - Additional complementary measurement
    - Small contribution from inelastic scattering $\mathcal{O}(10^{-3})$
    - Very high precision achievable: Statistical uncertainty up to 0.2
  - ^{208}Pb neutron skin, $\frac{\Delta R_n}{R_n} = 0.5\%$ possible
  - Backward angle measurement
- More information: Eur. Phys. J. A (2018) 54, 208