Building a Tracking Detector for the P2 Experiment

DPG Frühjahrstagung, Münster 2017

Marco Zimmermann
Institute for Nuclear Physics
March 28, 2017
The P2 Experiment: Overview

The Idea

Precision measurement of the weak mixing angle at low $Q^2$

Motivation

- Fundamental quantity of the Standard Model
- Sensitive for New Physics

Method

- Measure parity-violating asymmetry in electron-proton scattering
- Mainz Energy-recovery Superconducting Accelerator (MESA)
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The Weak Mixing Angle $\theta_W$ in the Standard Model (SM)

Definition

$$\tan \theta_W = \frac{g}{g'}$$

with $SU(2)_L \times U(1)_Y$ gauge couplings $g$, $g'$

Proton electric charge

$$+1$$

Proton weak charge

$$1 - 4\sin^2 \theta_W$$

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Scale dependence of $\sin^2 \theta_W$

Absorb radiative corrections into effective, scale-dependent ("running") $\sin^2 \theta_W(Q^2)$
Running $\sin^2 \theta_W$ Measurements

\[
\sin^2 \theta_W (Q)
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\[
Q_W (p)
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\[
Q_W (e)
\]

\[
Q_W (APV)
\]

\[
Q_W (eDIS)
\]

\[
Q_W (Tevatron)
\]

\[
Q_W (SLD)
\]

\[
Q_W (NuTeV)
\]

\[
Q_W (ATLAS)
\]

\[
Q_W (CMS)
\]

\[
Q [\text{GeV}]
\]

\[
\text{hs}
\]
Running $\sin^2 \theta_W$ Measurements

The figure shows a plot of $\sin^2 \theta_W$ as a function of $Q$ for various experiments and data sets.

- **QW (p)**: Proton data from LEP1 and SLD.
- **QW (e)**: Electron data from Tevatron and ATLAS.
- **QW (APV)**: Antiproton data.
- **Moller**: Møller scattering data.
- **P2@MESA**: Data from the P2@MESA experiment.
- **Qweak**: Weak charge data.
- **SOLID**: Solid state and liquid data.
- **NuTeV**: Neutrino TeV data.
- **eDIS**: DIS data.

The plot includes a range of experimental data points and error bars, illustrating the precision and variation of $\sin^2 \theta_W$ measurements across different scales of $Q$. The data sets are distributed across a wide range of $Q$ values, from approximately 0.0001 to 10000 GeV.
Measure $\sin^2 \theta_W$ via Parity Violating $ep$-Scattering
Measure $\sin^2 \theta_W$ via Parity Violating ep-Scattering

Parity violating asymmetry

- Photon exchange parity invariant
- Z-boson exchange violates parity!
- $A_{PV} \equiv \frac{N_- - N_+}{N_- + N_+}$
- Flip helicity and count!
Measure $A_{PV}$ in ep-Scattering

$A_{PV} \equiv \frac{N_- - N_+}{N_- + N_+} = \frac{G_F Q^2}{4\sqrt{2}\pi \alpha} \left( 1 - 4 \sin^2 \theta_W - F(Q^2) \right)$

- $Q^2 =$ momentum transfer
- $F(Q^2) =$ proton form factor

Need very high statistics and precise control of systematics
- 150 $\mu$A beam current, 10 000 h measuring time
- 60 cm liquid hydrogen target for high luminosity
- MESA beam
  - $E = 150$ MeV
  - Highly polarized ($\geq 85\%$), flip helicity at 2 kHz
  - Low helicity-correlated uncertainties
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- $Q^2 = \text{momentum transfer}$
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- Need very high statistics and precise control of systematics
  - 150 $\mu$A beam current, 10 000 h measuring time
  - 60 cm liquid hydrogen target for high luminosity
  - MESA beam
    - $E = 150\text{ MeV}$
    - Highly polarized ($\geq 85\%$), flip helicity at 2 kHz
    - Low helicity-correlated uncertainties $\leq 0.1 \text{ ppb}$
P2 Detector Layout

Tracking Detector

- 2 × 4 modules of plane pairs
- ~15° φ-coverage per tracking detector module
- Measure average $Q^2$
- Reconstruct individual electron tracks
- 50 μm thin silicon High Voltage Monolithic Active Pixel Sensors (HV-MAPS)
- ~50 μm thin Kapton layer
- Overlapping strips to minimise inactive area
- Less than 1% of a radiation length per tracker plane
- ~2 × 316 chips with size 2 × 2 cm² per module
- 50 μm thin silicon High Voltage Monolithic Active Pixel Sensors (HV-MAPS)
- ~ 50 μm thin Kapton layer
- Overlapping strips to minimise inactive area
- Less than 1% of a radiation length per tracker plane
- ~ 2 × 316 chips with size 2 × 2 cm² per module
Challenges for the Tracking Detector

- Very high particle rates at full beam intensity
  - $\mathcal{O}(10^{15})$ beam electrons per second
  - Large amount of background, mostly bremsstrahlung photons
Test the Detector Response to Photons

**Photon Background**

- Continuous bremsstrahlung energy spectrum
- Photoelectric Effect
- Compton Scattering
- Pair Creation

- Radioactive Sources
  - First result: $\eta \sim 29\%$ at 6 keV (Fe55)
- MAMI beamtest for higher photon energies

[Graph showing photon energy versus events per second]
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![Graph showing photon background and detector response](image-url)
Summary and Conclusions

- **P2 Experiment**
  - Measure $\sin^2 \theta_W$ at low $Q^2$ in parity violating ep-scattering
  - Start data taking around 2020
  - $A_{PV}$ measurement with integrating Cherenkov detectors

- **Tracking Detector**
  - $Q^2$ Measurement and systematic studies
  - Low material budget
  - Very high (background) particle rates
  - Detailed track finding and reconstruction studies ongoing
  - Development of mechanical layout started
Thank you for your attention.
Backup
Hooman Davoudiasl, Hye-Sung Lee, and William J. Marciano
Phys. Rev. D 89, 095006

\[ m_{\text{dark } Z} = 100 \text{ MeV} \]
\[ m_{\text{dark } Z} = 200 \text{ MeV} \]

\[ \sin^2 \Theta_W (Q^2) \] vs \[ \log_{10} Q \text{ [GeV]} \]

Anticipated sensitivities
**Beam Stability Requirements**

<table>
<thead>
<tr>
<th></th>
<th>Achieved at MAMI</th>
<th>$A_{PV}$ uncertainty</th>
<th>requirement</th>
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<tbody>
<tr>
<td>Energy fluctuation</td>
<td>0.04 eV</td>
<td>&lt; 0.1 ppb</td>
<td>ok!</td>
</tr>
<tr>
<td>Position fluctuation</td>
<td>3 nm</td>
<td>5 ppb</td>
<td>0.13 nm</td>
</tr>
<tr>
<td>Angle fluctuation</td>
<td>0.5 nrad</td>
<td>3 ppb</td>
<td>0.06 nrad</td>
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<tr>
<td>Intensity fluctuation</td>
<td>14 ppb</td>
<td>4 ppb</td>
<td>0.36 ppb</td>
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Systematic Uncertainties

\[ \Delta \sin^2 \theta_w = 3.2 \times 10^{-4} \]

Beam energy: 150 MeV
Beam current: 150 \( \mu \)A
Polarization: 85 \%
\( \Delta P \): 0.425 \%
Target length: 60 cm
Detector acceptance: 20 deg
Total rate (el e-p): 0.1 THz
Measurement time: 10000 h
\( \Delta A_{\text{app}} \): 0.1 ppb
$y/Z$-box processes uncertainty contribution

\[
y = Z - \text{box processes uncertainty contribution}
\]

\[
E (\text{GeV})
\]

\[
Re \, Re_z (E, t=0) - \text{Avg. (Model I,II)}
\]

\[
Re \, Re_z (E, t=0) \pm \Delta (\chi^2)
\]

\[
Q\text{WEAK} (E = 1.165 \text{ GeV})
\]

\[
P2
\]
Projection of Expected Electron Trajectories

- FUPI real Solenoid, $B_{\max} = 0.01 T$
- $B = 0.96 B_{\max}$
- Target center @ $z = -700$ mm
- $E_{\text{beam}} = 150.0$ MeV
- el. e-p-scattering: $\theta \in [25.00 \text{ deg}, 45.00 \text{ deg}]$
- el. e-p-scattering: $\theta \in [0.00 \text{ deg}, 90.00 \text{ deg}]$
- el. e-e-scattering: $\theta \in [5.00 \text{ deg}, 90.00 \text{ deg}]$
Expected Particle Rates on First Plane

Hit Distribution in Tracking plane 0, z = 1080

- Signal Electrons hitting ICD
- Other hard scattered electrons
- Secondary electrons
- Beam electrons (no hard scattering)
- Photons
- Positrons
- Protons
- Neutrons

Events/(s*mm²)

Events/(pixel*50ns)
Expected Particle Rates on Second Plane

Hit Distribution in Tracking plane 1, $z = 1100$

- Signal Electrons hitting ICD
- Other hard scattered electrons
- Secondary electrons
- Beam electrons (no hard scattering)
- Photons
- Positrons
- Protons
- Neutrons

Events/(s*mm$^2$)

$10^{-7}$
$10^{-6}$
$10^{-5}$
$10^{-4}$
$10^{-3}$
$10^{-2}$

Events/(pixel*50ns)

$10^{-9}$
$10^{-8}$
$10^{-7}$
$10^{-6}$

$R_{cyl}/mm$

0.6 0.7 0.8 0.9 1 1.1
Expected Particle Rates on Third Plane

Hit Distribution in Tracking plane 2, $z = 1640$

- Signal Electrons hitting ICD
- Other hard scattered electrons
- Secondary electrons
- Beam electrons (no hard scattering)
- Photons
- Positrons
- Protons
- Neutrons

Events/($s \times mm^2$) vs. $R_{cyl}/mm$
Expected Particle Rates on Fourth Plane

Hit Distribution in Tracking plane 3, z = 1660
Photon Background

- Continuous bremsstrahlung energy distribution
- Secondary electrons mainly produced by photo-effect
- Low detection rate of higher energetic photons
- Reduced rate of secondary electrons on “covered” plane
- Detailed investigation of detector response to low energy photons needed
Photon Background

- Continuous bremsstrahlung energy distribution
- Secondary electrons mainly produced by photo-effect
- Low detection rate of higher energetic photons
- Reduced rate of secondary electrons on “covered” plane
- Detailed investigation of detector response to low energy photons needed
Photon Production Processes

process encoding: $0 =$ bremsstrahlung in the target, $3 =$ bremsstrahlung in other detector parts, $5 =$ pair annihilation
Photon Vertices

Truth vertex of photons hitting Tracking plane 0, $z = 1080$
### MC Detector Response to Photons

**Detector Response to Photons**

- Detector Response to Photons
- Detector Response to Photons by Photoelectric Effect
- Detector Response to Photons by Compton Scattering
- Detector Response to Photons by Pair Creation

**Photon Energy/MeV**

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Secondary Electrons Production Processes

Process encoding: 2 = ionisation, 12 = Photoeffect, 13 = Compton Scattering, 14 = Pair creation
Background Electrons Hitting Integrating Cherenkov Detector

Production Vertices

Truth vertex of backgr. electr. hitting Integrating Detector

M. Zimmermann (Institute for Nuclear Physics) | Tracking Detector for P2 | March 28, 2017
Additional Electron Loss due to Segmented Tracker Layers

Particle rates at subsequent tracking planes normalized to the first one

- h_2nd_plane
- h_3rd_plane
- h_4th_plane

Relative particle rate vs. Coverage/deg (φ)

M. Zimmermann (Institute for Nuclear Physics)