Momentum transfer reconstruction for the P2 Experiment

Alexey Tyukin

Mainz Institute for Nuclear Physics
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Motivation for measuring $\theta_W$ at low $Q^2$

- The Weinberg (Weak Mixing) angle $\theta_W \approx 28.75^\circ$ is a fundamental parameter of GWS theory of electroweak unification.

\[
\begin{pmatrix} \gamma \\ Z^0 \end{pmatrix} = \begin{pmatrix} \cos(\theta_W) & \sin(\theta_W) \\ -\sin(\theta_W) & \cos(\theta_W) \end{pmatrix} \cdot \begin{pmatrix} B^0 \\ W^0 \end{pmatrix}
\]

\[
\sin^2(\theta_W) = \frac{g_e^2}{g_w^2} \approx 0.2314
\]

- $\theta_W$ is a free parameter of SM which is related to many other quantities.
- Precise determination of $\sin^2(\theta_W)$ would verify SM or provide new physics.
- Inconsistent results of previous measurements must be resolved.
Measurements of $\sin^2(\theta_W)$

- Running of $\sin^2(\theta_W)$ due to radiative corrections
- From $Z^0$ pole at 91 GeV to low energies a 3% shift is expected
- P2 Experiment: at $Q = 0.07$ GeV with 0.13% precision

- Atomic Parity Violation
- Moeller scattering
- Neutrino scattering
- pp collisions
- $e^+ e^-$ collisions
- Deep inelastic $e^-$ scattering
- Parity violating $e^-$ scattering
Parity violating electron scattering

- Scattering of longitudinally polarized electrons on a proton target.
- EM-cross section dominates: $\sigma_\gamma \gg \sigma_Z$.
- $Z^0$ cross section depends on helicity of electron: $\sigma_Z^R \neq \sigma_Z^L$.
- Parity-violating asymmetry can be calculated from scattering rates:

$$A^{PV} = \frac{\sigma^L - \sigma^R}{\sigma^L + \sigma^R} = \frac{G_f Q^2}{4\pi\alpha \sqrt{2}} \cdot \left(1 - 4\sin^2\theta_W + F(Q^2)\right)$$
Kinematics

Choice of energy and scattering angle to minimize $\Delta \sin^2(\theta_W)$:
At lower $Q^2$ cross section gets higher, but asymmetry smaller

Beam : $E_{\text{beam}} = 155\text{ MeV}$, $I_{\text{beam}} = 150\text{ }\mu\text{A} = 10^{15} \text{ e}^-/\text{s}$,
Target : 60 cm liquid hydrogen , $L = 2.4 \cdot 10^{39} \text{s}^{-1}\text{cm}^{-2}$
Experiment : $\theta_{\text{scattering}} = 35^\circ$, observing $10^{11}$ electrons per second
Asymmetry : $A_{PV} = 33\text{ ppb}$, $\Delta A_{PV} = 1.5\% = 0.44\text{ ppb}$
Weinberg angle : $\Delta \sin^2(\theta_W) = 0.13\%$ after 10000 h
A new electron accelerator is being built in Mainz which will allow a next generation parity violation experiment.

- High Intensity, 85% polarisation
- 155 MeV energy
- High stability of position, energy and intensity
- 60 cm $\text{IH}_2$ target, magnetic field, 2 detector systems
Tracking Planes

- Four tracking planes in 2 pairs inside the magnet
- Track the electrons before they reach the counting detector
- Tracking planes partially not shielded from photons
- No full azimuthal coverage necessary, very high electron rates
Tracking Planes

- MuPix chips
  (HV-MAPS, designed for Mu3e Experiment)
- Pixel size $80 \times 80 \, \mu m$, chip size $2 \times 2 \, cm^2$
- Only $50 \, \mu m$ thickness, fast response

- 8 modules covering large area ($15^\circ$ each)
- Double layers of $>300$ MuPix chips
- Operation in high background environment
- Cooling required
- Track finding (next talk) and track fitting problem
- Reconstruct track from one hit in each detection plane
- Approximate momentum transfer in target
- Inhomogeneous magnetic field and helium gas between planes
- Energy loss and scattering in planes
Track reconstruction - fitting

- Approximate seed momentum on the first plane
- Propagate seed momentum (Runge-Kutta-Nystroem)
- Calculate Jacobian matrix for the propagation (Bugge-Myrheim)
- Fit by minimizing the $\chi^2$ (General Broken Lines, GBL)
- Refit until fit converges and extract the resulting fitted momentum
Track reconstruction - performance

Reconstruction of momentum magnitude from Geant4 simulation:

\[ P_{\text{reco}} \text{ and } P_{\text{true}} : \]

\[ \frac{P_{\text{reco}} - P_{\text{true}}}{P_{\text{true}}} : \]

- The fit can never be perfect due to pixelsize, scattering, energy losses
Momentum transfer requires the kinematics of the event

\[ Q^2 = 4 \cdot P \cdot P' \cdot \sin^2(\theta/2) \]

- Need to estimate \( P, P', \theta \)
- Propagate fit result back to the target
- Estimate vertex as point of closest approach to target center
- Energy loss in target before and after scattering
Momentum transfer $Q^2$ reconstruction

**Reconstructed $Q^2$**

Gbl RKN Fit with 2PT Seed: reconstructed $Q^2$

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**Reconstructed $Q^2$ Residual**

Gbl RKN Fit with 2PT Seed: reconstructed $Q^2$ residuals

- Get reconstruction quality by comparing with Monte-Carlo simulation value
- Residual width of 0.00028 GeV$^2$/c$^2$ is an average resolution of 4.2%.
The P2 Experiment is planning a measurement of $\sin^2(\theta_W)$ with 0.13% precision.

A new accelerator will be built to make it possible.

The P2 Spectrometer will measure $A_{PV}$ of 100 GHz elastically scattered electrons on liquid hydrogen.

Silicon pixel tracking planes will measure average $Q^2$. 
Backup: Future measurements
$m_{\text{dark Z}} = 100$ MeV
$m_{\text{dark Z}} = 200$ MeV
Backup: $\Delta \sin^2(\theta_W)$ optimization

<table>
<thead>
<tr>
<th>Beam energy:</th>
<th>150 MeV</th>
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<tbody>
<tr>
<td>Beam current</td>
<td>150 $\mu$A</td>
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<tr>
<td>Polarization:</td>
<td>85 %</td>
</tr>
<tr>
<td>$\Delta P$:</td>
<td>0.425 %</td>
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<tr>
<td>Target length:</td>
<td>60 cm</td>
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<tr>
<td>Detector acceptance:</td>
<td>20 deg</td>
</tr>
<tr>
<td>Total rate (el e-p):</td>
<td>0.1 THz</td>
</tr>
<tr>
<td>Measurement time:</td>
<td>100000 h</td>
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<tr>
<td>$\Delta A^{app}$:</td>
<td>0.1 ppb</td>
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\[ \Delta \sin^2 \theta_W = 3.2 \cdot 10^{-4} \]
MESA lattice in new hall at Institut für Kernphysik, Uni-Mainz

- Beam dump building used
- BDX ideal
- More space for MESA!
- Hall-4 available for future experiments...

# = hall number

NEW (u-CFP) OLD
Backup: Angle reconstruction

reconstructed theta

- θ reco
- θ true

4Pglfit_fHThetaReco
- Entries: 92572
- Mean: 32.74
- RMS: 5.156
- Underflow: 4
- Overflow: 0
Backup: Momentum reconstruction

reconstructed absolute momentum

<table>
<thead>
<tr>
<th>fitted tracks</th>
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<tbody>
<tr>
<td>2500</td>
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<tr>
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<td>100</td>
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<tr>
<td>50</td>
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<tr>
<td>0</td>
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</tbody>
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Graph:
- Red line: \( |p| \text{ reco} \)
- Gray line: \( |p| \text{ true} \)

Statistics:
- Entries: 92572
- Mean: 140.6
- RMS: 7.612
- Underflow: 116
- Overflow: 23

Legend:
- \(|p|\text{fit}_fHMomentumAbsReco\)