Future Measurement of the Proton Radius at the M2 beamline

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scattering experiments

\[ d\sigma \frac{dQ^2}{dQ^2} = \frac{\pi \alpha^2}{Q^4 m_p^2 \bar{p}_\mu^2} \left[ \left( G_E^2 + \tau G_M^2 \right) \frac{4E^2 m_p^2 - Q^2 (s - m^2)}{1 + \tau} - G_M^2 \frac{2m^2 Q^2 - Q^4}{2} \right] \]

with \( \tau = Q^2/(4m_p^2) \)

mean squared charge-radius

\[ \langle r_E^2 \rangle = -6\hbar^2 \left. \frac{dG_E(Q^2)}{dQ^2} \right|_{Q^2 \to 0} \]
scattering experiments

\[ G_E(Q^2) \approx G_M(Q^2) / \mu_p \approx \]
\[ G_D(Q^2) = (1 + Q^2 / a^2)^{-2} \]

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proton radius at M2 beamline

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opportunity for new generation experiment at M2 beam line

- scatter muon beam off proton target
- measure cross-section dependence on $Q^2$
- obtain combination of electric and magnetic form factor $G_E^2 + \tau G_M^2$
  - form factors cannot be separated due to high beam energy
Since there are two identical particles in the final state, the physical region is restricted to $0 < \theta \text{ cm} \leq 90^\circ$.

- The advantage of working with the dimensionless variables $(t, u)$ shows already when $s = 4m^2$, which originates from the exchange of two identical fermions, is already included in the interference term.

- Evaluating the Born terms. The two tree diagrams in figure 1 lead to the following simple polynomial expressions:

$$d\sigma = d\sigma_{1\gamma} (1 + \delta)$$

- Compared to $e^- \text{ beam}$: smaller radiative corrections for $\mu$ beam.
Figure D. Tree diagrams

Figure E. One-photon diagrams

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- compared to $e^-$ beam: smaller radiative corrections for $\mu$ beam
- measuring recoil proton will integrate over radiative tails
- uncertainty on remaining corrections
- will not reduce impact on overall cross-section measurement
advantage of high-energy $\mu$ beam

Coulomb corrections

- required corrections depend on scattering angle

$$\delta = Z\alpha\pi \frac{\sin \frac{\theta}{2} - \sin^2 \frac{\theta}{2}}{\cos^2 \frac{\theta}{2}}$$

- smaller scattering angle at higher energies compared to $\mu$ beam at low energies: smaller corrections
requirements for measurement

assuming one year of data taking

- goal: uncertainty on $\sqrt{\langle r_E^2 \rangle} \approx 0.01$ fm

- systematics: $Q^2 \gtrapprox 1 \cdot 10^{-3}$ (GeV/c)$^2$

- uncertainty on $G_M$: $Q^2 \gtrapprox 0.2$ (GeV/c)$^2$
experimental challenges

identify elastic reactions

- measurement of recoil proton
- measurement of scattering angle of muon
measurement of recoil proton

- high-pressure hydrogen target
- wide range of recoil energies $O(100 \text{ keV})$ to $O(100 \text{ MeV})$
- required energy resolution $O(50 \text{ keV})$
measurement of recoil proton

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- wide range of recoil energies $\mathcal{O}(100 \text{ keV})$ to $\mathcal{O}(100 \text{ MeV})$
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TPC as active target

- high luminosity requires long target
  - long drift time might be an issue
- not all protons might be stopped inside TPC

The HV will be known with 0.01% absolute precision.

H$_2$ gas purity

In order to avoid the losses of the ionization electrons during the drift time, the contamination of the H$_2$ gas by any electronegative gas (O$_2$, H$_2$O) should be reduced to a level below 1 ppm. This will be achieved by continuous H$_2$ purification with a special gas purification system, similar to that described in [5], which eliminates gas impurities down to <0.1 ppm.

H$_2$ atomic density

The number of protons per cm$^3$, $n$, in hydrogen gas as a function of pressure, $P_{\text{tech}}$, and temperature, $t_0$, is given by the following expression:

$$n = 5.2005 \times 10^{19} \cdot P_{\text{tech}} \cdot 273.16 / (1 + 0.000524 P_{\text{tech}}) (273.16 + t_0),$$

where $P_{\text{tech}} = 735.552$ mmHg.

In our experiment, pressure will be controlled to 0.01% absolute precision and temperature will be kept constant with $\pm 0.05^\circ$ (0.014% absolute precision). This determines the proton density with 0.025% absolute precision.

Fig. 9. Tentative design of the combined TPC & FT detector.

Fig. 10. TPC anode structure: 10 mm in diameter circle surrounded by 7 rings (Left panel). Proton range-energy plots for H$_2$ gas (20 bar and 4 bar) and for CH$_4$ (20 bar) (Right panel).
measurement of scattering angle of muon

position detectors
- small scattering angles $\mathcal{O}(100 \, \mu\text{rad})$
  - excellent spatial resolution required
- high intensity
  - fast detectors
measurement of scattering angle of muon

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silicon tracking detectors
- strip
  - for current silicon detectors required performance has been shown
- pixel
proposed set-up

- hydrogen TPC acting as active target
  - measurement of energy of recoil proton
  - between 0.5 and 100 MeV
  - required resolution: $\Delta \approx 60$ keV

- silicon telescopes up- and downstream of target
  - measurement of muon scattering angles
  - $300 \, \mu\text{rad at } Q^2 \approx 10^{-3} \, (\text{GeV}/c)^2$
  - required resolution $\sigma \lesssim 100 \, \mu\text{rad}$
combination of TPC and silicon detectors

- in simulation: required resolution achieved down to small $Q^2$
combination of TPC and silicon detectors

- in simulation: required resolution achieved down to small $Q^2$
- test beam this year
test beam set-up

- performance of TPC in muon beam
test beam set-up

- performance of TPC in muon beam
- performance of TPC in muon beam
- correlate events in silicon detectors with events in TPC
proposed set-up

- trigger on recoil proton signal
  - drift time in TPC $\mathcal{O}(100\,\mu s)$
  - trigger-less readout of all detectors
  - online event reconstruction to correlate proton and muon signals
proposed set-up

- trigger on recoil proton signal
  - drift time in TPC $\mathcal{O}(100 \mu s)$
  - trigger-less readout of all detectors
  - online event reconstruction to correlate proton and muon signals

- trigger on small kink in muon track
higher $Q^2$

- recoil protons not stopped inside hydrogen volume
- replace hydrogen TPC by hydrogen volume surrounded by scintillator barrel

- stop protons in layers
- measure energy via Bragg peak
- faster trigger decision
- measurement of proton charge-radius with high-energy muon beam
  - unique opportunity to verify results from electron scattering
  - smaller corrections required

- first test measurement this year
  - compatibility of TPC with “broad” muon beam
  - correlation of proton and muon signals