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Chiral EFT Approach to Bremsstrahlung Corrections and Charge Asymmetry in Elastic Lepton-Proton Scattering

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We present a detailed analytic evaluation of the soft-photon bremsstrahlung radiative corrections to the unpolarized elastic lepton-proton scattering cross-section within the framework of low-energy chiral effective field theory. Our study is motivated by the precision goals of the MUSE experiment, which aims to resolve the proton radius puzzle via simultaneous measurements of $e^{\pm}p$ and $\mu^{\pm}p$ scattering at low energies. In particular, we employ SU(2) heavy baryon chiral perturbation theory (HBChPT), a model-independent approach to the pion-nuclear sector, incorporating gauge-invariant couplings to photons. All possible next-to-leading order (NLO) contributions to the $\mathcal{O}(\alpha^3/M)$ cross-section are systematically included. The infrared divergences from soft bremsstrahlung emission are isolated using dimensional regularization and are shown to cancel precisely against the divergent parts of the virtual loop corrections, following the standard Mo-Tsai procedure. A significant component of the bremsstrahlung corrections arises from the interference between lepton and proton radiation, which, together with the analytically computed NLO two-photon exchange (TPE) contributions, constitutes the charge-odd radiative effects. These corrections are particularly relevant for charge asymmetry observables extracted from elastic lepton–anti-lepton scattering off the proton. Accordingly, we also provide a theoretical analysis of the charge asymmetry at NLO accuracy. All results are derived beyond the ultra-relativistic limit by retaining finite lepton mass effects in light of the low-energy regime accessible by the MUSE experiment.

Authors: Ms DAS, Bhoomika (Department of Physics, Indian Institute of Technology Guwahati); Dr RAHA, Udit (Department of Physics, Indian Institute of Technology Guwahati)

Presenter: Ms DAS, Bhoomika (Department of Physics, Indian Institute of Technology Guwahati)

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