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Simulation and Analysis Framework of the muEDM Experiment at PSI

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The muEDM experiment at the Paul Scherrer Institute (PSI) aims to measure the muon electric dipole moment (EDM) - a charge-parity (CP) violating observable - with an unprecedented final sensitivity of $\lesssim 6 \times 10^{-23} \text{ e cm}$ using the frozen-spin technique. This sensitivity, an improvement of over three orders of magnitude compared to the current limit, would probe beyond-Standard Model new physics and provide insights towards the matter-antimatter asymmetry of the Universe.

We present the comprehensive physics simulation framework developed for the muEDM experiment, built upon Geant4-based simulation toolkits. The framework simulates the full spin dynamics of muons in the storage region, incorporating the muon anomalous magnetic moment and EDM effects in the presence of electric and magnetic fields. The simulation includes the three-dimensional field maps of the storage solenoid, correction coils, weakly focusing fields, and the frozen-spin electric field, enabling detailed studies of spin precession and storage efficiency. The core deliverable of the framework is a robust conversion factor that relates the measured time-dependent asymmetry of decay positrons to the underlying EDM signal. This conversion factor can be applied to study various physics effects, including systematic uncertainties from field imperfections, detector asymmetries, and beam dynamics, as well as to evaluate the sensitivity to potential new physics signatures beyond the Standard Model.

The analysis framework demonstrates the functionality of the reconstruction chain using truth-level studies, extracting the EDM from the time-dependent asymmetry in the decay positron distribution. Validation against beam test data confirms the reliability of the simulation. The framework enables systematic studies of the experiment's sensitivity, evaluation of false EDM effects from field imperfections and detector asymmetries, optimisation of the frozen-spin condition for Phase-I, and to study the sensitivity to new physics signatures beyond the Standard Model.

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