PROCEEDINGS OF SCIENCE

Neutral pion production in μe scattering at MUonE

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The value of the anomalous magnetic moment of the muon, $a_\mu = (g-2)_\mu/2$, is a fundamental quantity in particle physics. Its most precise experimental measurement yields a deviation of 4.2σ from the theoretical prediction within the Standard Model. In this context, the recently proposed MUonE experiment at CERN aims at providing a novel and independent determination of the main source of theoretical uncertainty on the muon anomaly, namely the leading order hadronic contribution a_μ^{HLO}, through the study of elastic muon-electron scattering at small momentum transfer. The anticipated accuracy of the order of 10 ppm demands for high-precision calculations of the relevant radiative corrections to μe scattering, as well as for robust quantitative estimates of all possible background processes. The contribution due to the emission of a neutral pion through the process $\mu e \to \mu e \pi^0$ is here studied as a source of reducible background for the measurement of the QED running coupling constant at MUonE, and as a background for possible New Physics searches at MUonE involving $2 \to 3$ processes, in phase space regions complementary to the ones characteristic of the elastic μe scattering. Its numerical impact is discussed by means of the Monte Carlo event generator Mesmer.

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1. Introduction

The MUonE project [1–3] aims at providing an independent determination of the main source of theoretical uncertainty on the muon anomaly a_μ, namely the leading order hadronic contribution (HLO), through a *space-like* approach [4], i.e. via the study of elastic muon-electron scattering at small momentum transfer, by making use of a dispersion relation between $a_\mu^{\rm HLO}$ and the hadronic running of the electromagnetic coupling constant α (see also [5]). In order for this determination of $a_\mu^{\rm HLO}$ to be competitive with the traditional time-like methods, the uncertainty in the measurement of the differential cross section must be of the order of 10 ppm. Robust quantitative estimates of all possible background processes to the experiment thus become crucial. Here we focus on hadronic processes, in particular on the single π^0 production in μe scattering at MUonE [6].

2. Methods

The real-emission contributions due to hadronic corrections at MUonE consist of three channels: $\mu^\pm e \to \mu^\pm e \pi^+\pi^-$, $\mu^\pm e \to \mu^\pm e \pi^0\pi^0$ and $\mu^\pm e \to \mu^\pm e \pi^0$. While pion-pair production is extremely constrained for the limited available phase space at MuonE, single pion production deserves a more detailed investigation. In fact, single pion production is dynamically enhanced in the region of small electron and muon scattering angles, where the elastic cross section becomes small and the sensitivity to the running of α reaches its maximum.

The hadronic background to $\mu - e$ scattering due to the real emission of a single pion is represented by the process:

$$\mu^\pm(p_1)\, e(p_2) \;\to\; \mu^\pm(p_3)\, e(p_4) \,+\, \pi^0(p_5) \tag{1}$$

where p_i are the four-momenta of the particles. Starting from the $\pi^0\gamma\gamma$ interaction Lagrangian density

$$\mathcal{L}_{\rm I} = \frac{g}{2!}\varepsilon^{\mu\nu\kappa\lambda} F_{\mu\nu} F_{\kappa\lambda} \varphi_\pi \,, \tag{2}$$

we derived the tree-level scattering amplitude, by exploiting the relation between the coupling g, the π^0 decay width and the f_π parameter [7]:

$$g^2 = \frac{4\pi\Gamma_{\pi^0\to\gamma\gamma}}{m_{\pi^0}^3} = \frac{4\pi}{m_{\pi^0}^3}\frac{\alpha^2 m_{\pi^0}^3}{64\pi^3 f_\pi^2}\,. \tag{3}$$

We then multiplied the amplitude for the process $\mu e \to \mu e \pi^0$ by a form factor $F_{\pi^0\gamma^*\gamma^*}$, to take into account the extended structure of the pion [8].

For the phase-space parametrisation, we decomposed the three-body Lorentz-invariant phase space according to the following chain:

$$d\Phi_3^{\rm LIPS} = (2\pi)^3 \int dQ^2 d\Phi_2(P \to p_3 + Q) \times d\Phi_2(Q \to p_4 + p_5)\,. \tag{4}$$

The leading order amplitude and the phase-space have been implemented in the Monte Carlo event generator Mesmer.

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3. Background to elastic μe scattering

The total cross section for the process $\mu e \to \mu e \pi^0$, with incoming muon energy of 150 GeV and initial-state electron at rest, is $\sigma_{\mu e \pi^0} = 6.53589(6)$ pb. By considering the two event selections:

- basic acceptance cuts: $\vartheta_\mu \lesssim 4.84$ mrad, $E_\mu \gtrsim 10.28$ GeV, $\vartheta_e < 100$ mrad and $E_e > 0.2$ GeV,
- basic acceptance cuts, but with $E_e > 1$ GeV,

we obtain $\sigma^{0.2\,\mathrm{GeV}}_{\mu e \pi^0} = 2.69836(4)$ pb, and $\sigma^{1\,\mathrm{GeV}}_{\mu e \pi^0} = 1.61597(3)$ pb, respectively. We notice that these cross sections are negligible with respect to the elastic $\mu e \to \mu e$ cross sections within the same cuts. The effects of pion production remain well below 10 ppm for all differential distributions.

4. Background to New Physics searches

The process $\mu e \to \mu e \pi^0$ could represent a source of background for possible New Physics searches at MUonE in $2 \to 3$ processes [9, 10], e.g. within the context of a $L_\mu - L_\tau$ gauge model, through the production of a light massive Z' via the process $\mu e \to \mu e Z' \to \mu e \nu \bar{\nu}$ [10].

The considered event selection in this case is:

- $\vartheta_\mu > 1.5$ mrad,
- $E_e \in [1, 25]$ GeV,

complementary to the one of interest for the $\mu e \to \mu e$ elastic process.

The integrated cross section for π^0 production results in $\sigma_{\mu e \pi^0} = 0.19210(1)$ pb. Considering an integrated luminosity for MUonE of about 15 fb^{-1}, the number of expected $\mu e \to \mu e \pi^0$ events is about 3×10^3, the same order of magnitude of the predicted Z' signal [10]. The impact of π^0 production can be reduced through a photon veto strategy, in anticipation of which it can be useful to analyse distributions involving the photons from π^0 decay. For example, from Fig. 1, where the differential cross section is plotted against the photon angle ϑ_γ, it is clear that the photons are all produced in the forward region, below ~ 10 mrad in the laboratory reference frame. In Fig. 2, the differential cross section versus the minimum of the photon energy E_γ (in blue) in the laboratory frame remains constant and then goes to zero approximately at 65 GeV, while the distribution against the maximum of E_γ (red curve) has a peak at 60 GeV.

5. Conclusions

Single π^0 production is a completely negligible reducible background to elastic μe scattering, in view of a target precision of 10 ppm. Since pion pair production is kinematically forbidden for realistic event selections, we conclude that real hadron production is negligible in μe scattering at MUonE. Neutral π^0 production could represent a background to New Physics searches at MUonE performed through $2 \to 3$ processes, e.g. within the context of a $L_\mu - L_\tau$ gauge model. We characterised some relevant distributions involving the photons from π^0 decay, to be considered for a photon veto analysis strategy.

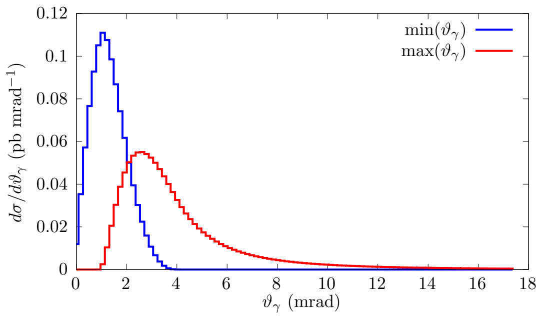

Figure 1: In blue, the differential cross section for the $\mu e \to \mu e{+}\pi^0 \to \mu e{+}\gamma\gamma$ process versus the minimum photon angle in the laboratory frame min(ϑ_γ) is plotted. The red curve represents the same quantity but w.r.t. the maximum photon angle max(ϑ_γ).

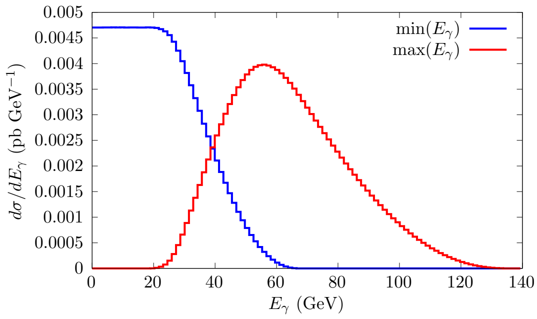

Figure 2: The same as in Fig. 1 but plotted against the minimum (blue curve) and the maximum (red curve) of the photon energy E_γ.

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