Neutral pion production in μe scattering at MUonE

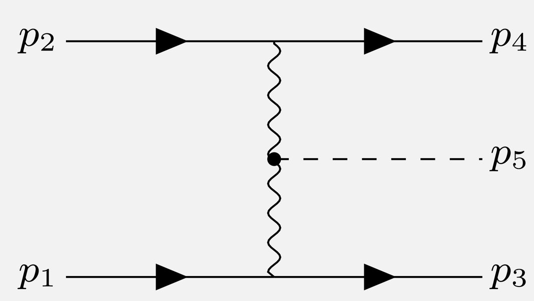
Clara Lavinia DEL PIO [a, b, *], **Ettore BUDASSI** [a, b], **Carlo Michel CARLONI CALAME** [b], **Fulvio PICCININI** [b]

(a) Dipartimento di Fisica, Università di Pavia, Italy (b) INFN, Sezione di Pavia, Italy ($*$) contact: claralavinia.delpio01@universitadipavia.it

Based on: Budassi E., Carloni Calame C. M., Del Pio C. L., Piccinini F., *Single π^0 production in μe scattering at MUonE*, Phys. Lett. B 829 (2022) 137138

Motivation and Methods

The MUonE project, recently proposed at CERN [1, 2], aims at providing a novel determination of the leading order hadronic contribution (HLO) to the muon anomalous magnetic moment, $a_\mu = (g-2)_\mu/2$, through a *space-like* approach [3], i.e. via the study of elastic muon-electron scattering at small momentum transfer [4], by making use of a relation between $a_\mu^{\rm HLO}$ and the hadronic running of the electromagnetic coupling constant α [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 $\mu - e$ 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.



The focus here is on the real emission of hadrons:

- pion pair production is negligible due to the limited available phase space at MuonE;
- single pion production is dynamically enhanced in the region of small electron and muon scattering angles, where the elastic cross section (blue curve in figure) becomes negligible 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:

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

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

$$\mathcal{L}_1 = \frac{g}{2!}\varepsilon^{\mu\nu\kappa\lambda} F_{\mu\nu} F_{\kappa\lambda} \varphi_\pi\,,$$

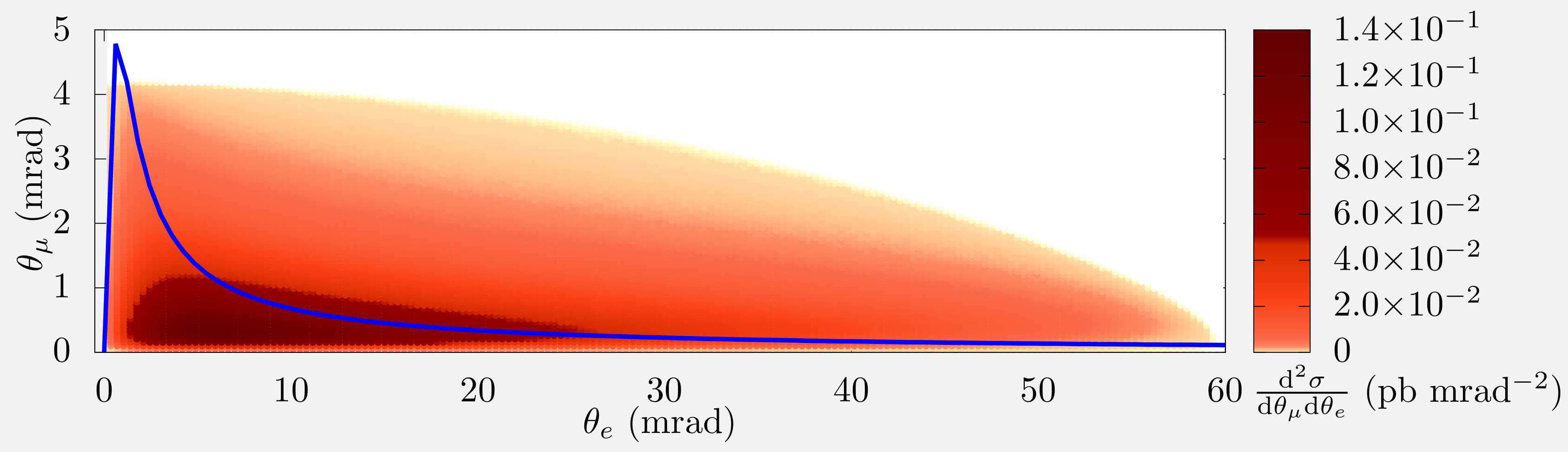
we derived the tree-level scattering amplitude, by exploiting the relation between the coupling g, the π^0 decay width and the f_π parameter [6].

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

We then multiplied the amplitude for $\mu e \to \mu e \pi^0$ by a form factor $F_{\pi^0\gamma^*\gamma^*}$, to take into account the extended structure of the pion [7].
For the phase-space parametrisation, we decomposed the three-body Lorentz-invariant phase space according to the following chain:

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

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



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:

$$\sigma_{\mu e \pi^0} = 6.53589(6)\ \text{pb}.$$

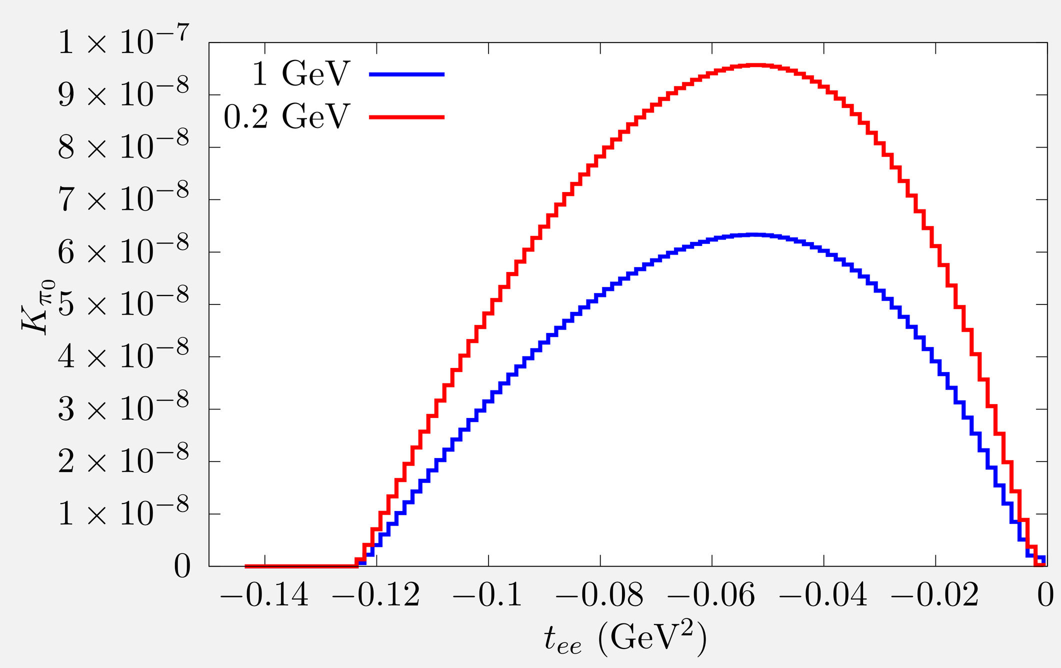
With the two different event selections:

- *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:

- $\sigma^{0.2\,\rm GeV}_{\mu e \pi^0} = 2.69836(4)$ pb w.r.t $\sigma^{0.2\,\rm GeV}_{\rm LO} \sim 1265\ \mu$b,
- $\sigma^{1\,\rm GeV}_{\mu e \pi^0} = 1.61597(3)$ pb w.r.t. $\sigma^{1\,\rm GeV}_{\rm LO} \sim 245\ \mu$b.

The differential ratio of the π^0-production cross section with the tree-level prediction, i.e. $K_{\pi^0} = d\sigma_{\mu e\pi^0}/d\sigma_{\mu e}$, plotted against the transferred momentum $t_{ee} = (p_4 - p_2)^2$, weighs at most about 10^{-7} for both the configurations with $E_e > 0.2$ GeV (red curve) and $E_e > 1$ GeV (blue line). The effects of pion production remain well below 10 ppm for all other distributions.



Background to New Physics searches

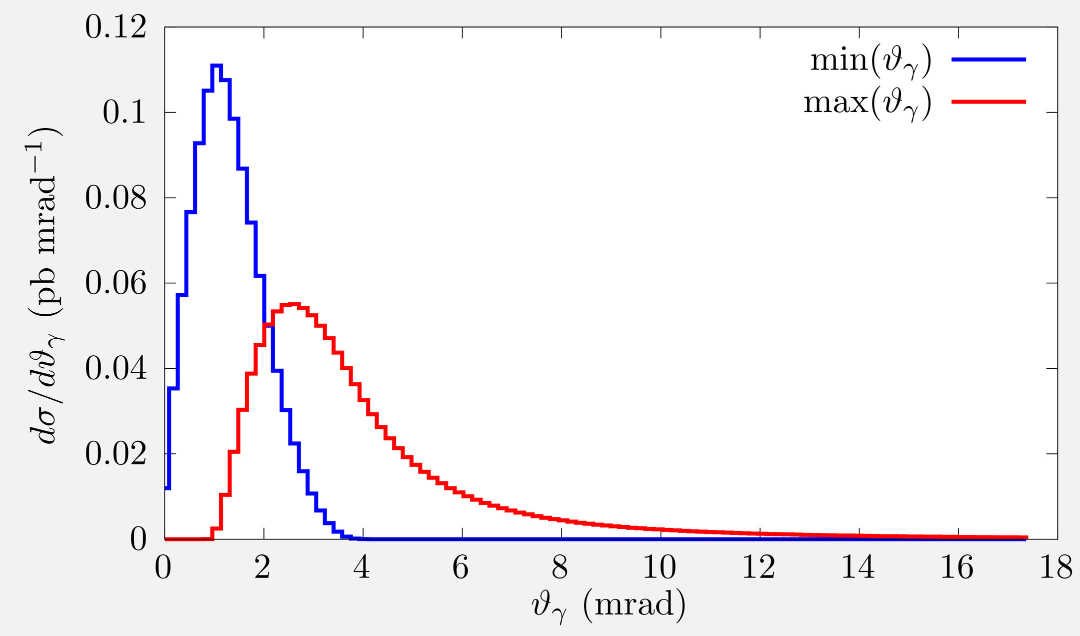
The process $\mu e \to \mu e \pi^0$ could represent a source of background for possible New Physics searches at MUonE in $2 \to 3$ processes [8, 9] e.g. within the context of a $L_\mu - L_\tau$ gauge model, through the production of a light massive Z' via the process $\mu e \to \mu e Z' \to \nu\bar{\nu}$ [8].
The considered event selection in this case is:

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

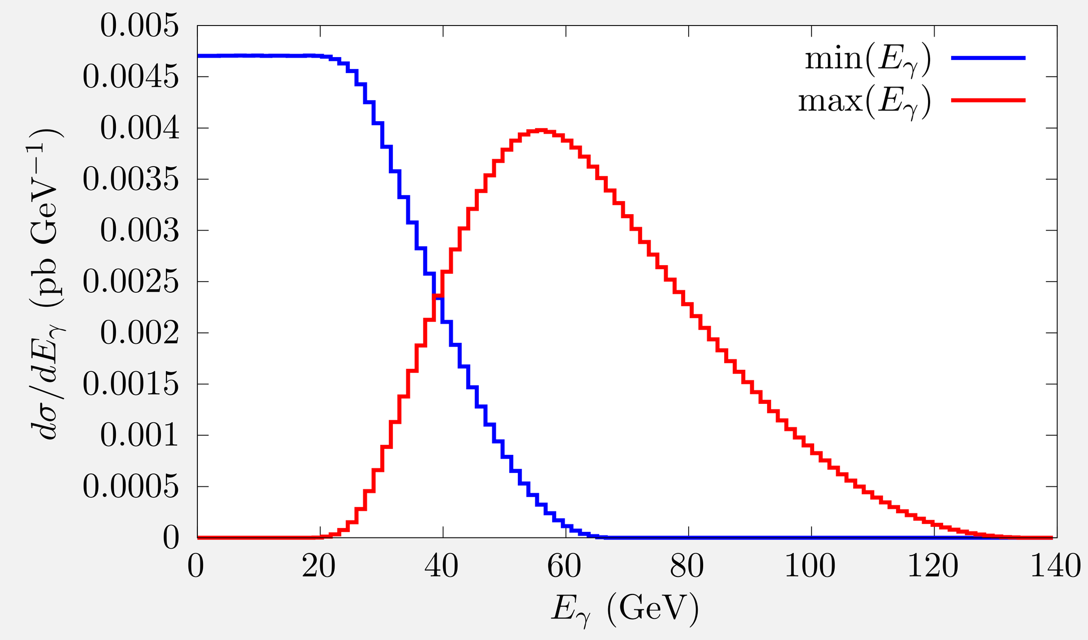
complementary to the one of interest for the $\mu e \to \mu e$ elastic process.
The integrated cross section for π^0 production results in:

$$\sigma_{\mu e \pi^0} = 0.19210(1)\ \text{pb}.$$

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 [8]. The impact of π^0 production can be reduced through a photon veto strategy.



From the differential cross section 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 the figure below, the differential cross section versus the minimum of the photon energy E_γ (in blue) in the laboratory frame remains constant at about 4.5×10^{-3} pb GeV^{-1} 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.



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, 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. We characterised some relevant distributions involving the photons from π^0 decay, to be considered for a photon veto analysis strategy.

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