High-precision theoretical predictions for the MUonE experiment

Ettore BUDASSI, Carlo Michel CARLONI CALAME[a,b], Mauro CHIESA[a,b], Clara Lavinia DEL PIO[c], Andrea GURGONE[d,e], Guido MONTAGNA[a,b], Oreste NICROSINI[a,b], Fulvio PICCININI[a,b]

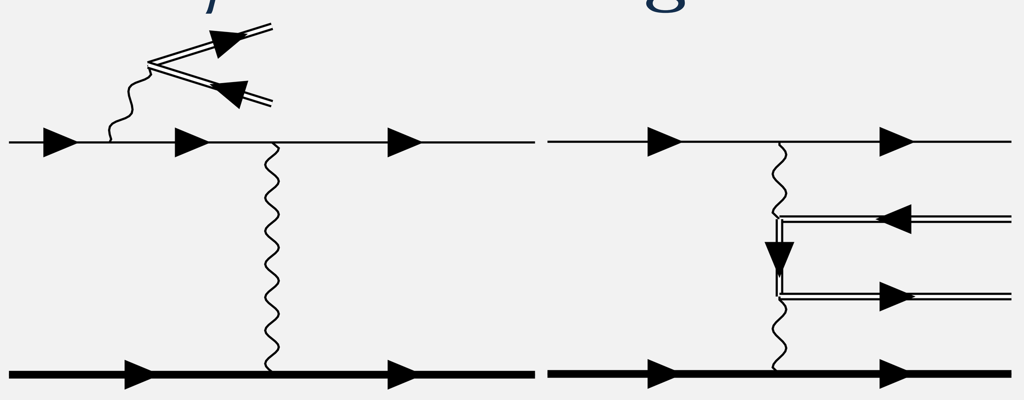
a Dipartimento di Fisica "A. Volta", Università di Pavia
b INFN — Sezione di Pavia
c High Energy Theory Group, Physics Department, BNL, Upton, NY 11973, USA
d Dipartimento di Fisica, Università di Pisa
e INFN — Sezione di Pisa

Based on: E. Budassi, C. M. Carloni Calame, M. Chiesa, C. L. Del Pio, S. M. Hasan, G. Montagna, O. Nicrosini and F. Piccinini, JHEP 11 (2021).
E. Budassi, C. M. Carloni Calame, C. L. Del Pio and F. Piccinini, Phys.Lett.B 829 (2022) 137138.
G. Abbiendi, E. Budassi, C. M. Carloni Calame, A. Gurgone and F. Piccinini, Phys.Lett.B 854 (2024), 138720.

Motivation

The MUonE project [1], recently proposed at CERN, aims at providing a novel determination of the leading order hadronic contribution (HLO) to the muon anomalous magnetic moment, $a_\mu = (g_\mu - 2)/2$ [2], through a *space-like* approach, *i.e.* via the study of elastic muon-electron scattering at small momentum transfer, by making use of a relation between a_μ^{HLO} and the hadronic running of the electromagnetic coupling constant α [3,4]. In order for this determination of a_μ^{HLO} to be competitive with the traditional *time-like* methods, the uncertainty in the measurement of the μe differential cross section must be of the order of 10 ppm [5,6]. Such calculations are included in the **MESMER** event generator, a fully differential and fully exclusive Monte Carlo code used for theoretical predictions and data analysis.

Lepton pair production from μe scattering

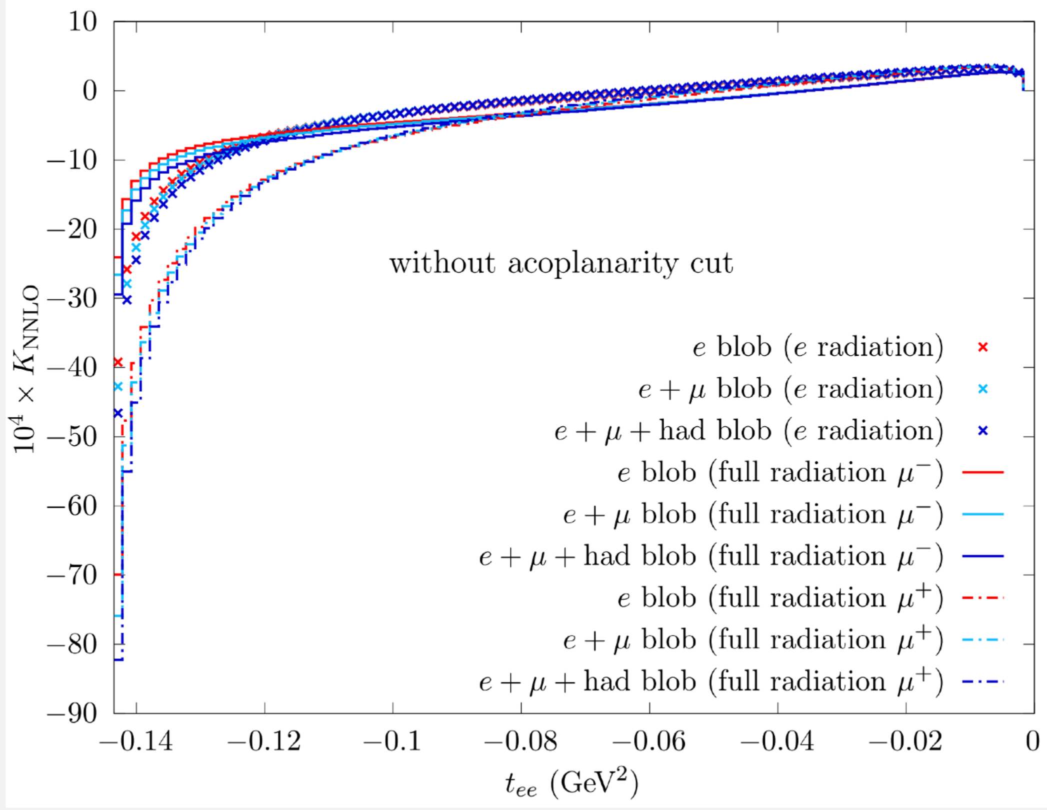


To reach MUonE's 10 ppm precision goal, NNLO QED corrections with the production of one lepton pair must be included [7].

These NNLO leptonic corrections comprise both **virtual** and **real** contributions, summing over all lepton flavors. Virtual corrections include electron and muon loops, as well as hadronic insertions, and have been calculated using dispersion relation techniques and exact analytical formulae, retaining full mass dependence. Real pair emission processes are computed with exact tree-level matrix elements, including all finite mass effects.
Virtual contributions dominate, reaching the 1% level relative to the LO cross section, while vacuum polarization, vertex, and factorized contributions affect differential distributions at the 10^{-3} level.

Real pair emission can mimic elastic events if only two tracks are observed. Peripheral diagrams introduce very large corrections, so event selection cuts — minimum scattering angles and acoplanarity cuts — are necessary to control backgrounds. After cuts, the net effect of real pair emission remains below 10^{-5}.

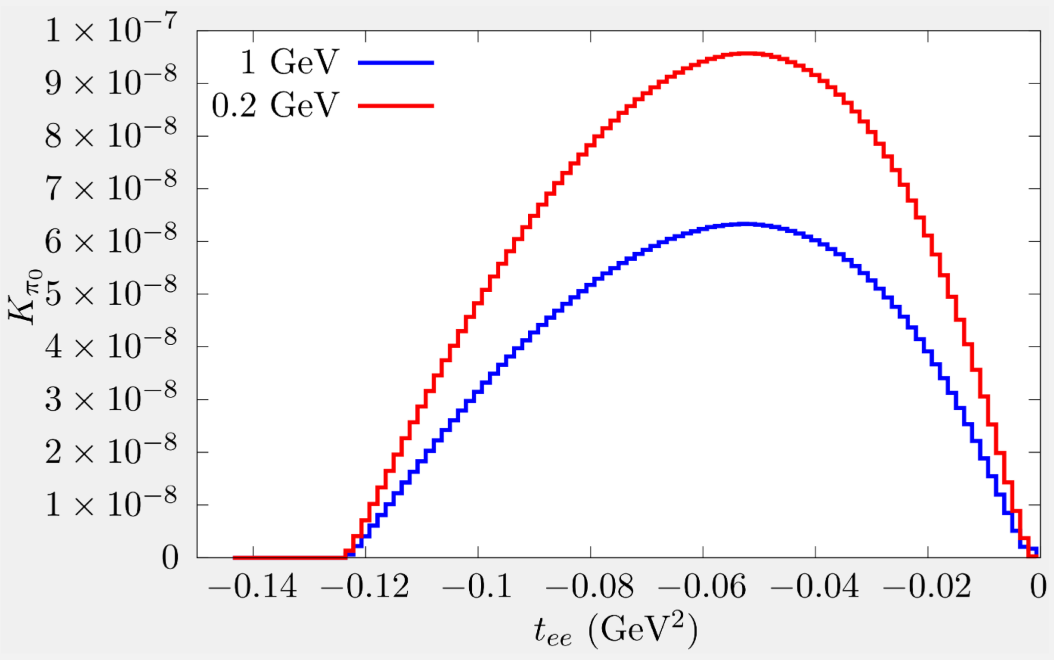
All NNLO leptonic corrections have been implemented in **MESMER**, matched to multiple photon radiation, allowing MUonE to reliably extract $\Delta\alpha_{\text{had}}(t)$ and the leading-order hadronic contribution to a_μ.



Neutral pion production from μe scattering

We investigate real hadronic radiation in μe scattering, focusing on the process $\mu^\pm e^- \to \mu^\pm e^- \pi^0$. While pion-pair production channels are strongly suppressed by the limited phase space, single π^0 emission requires a dedicated study [8].

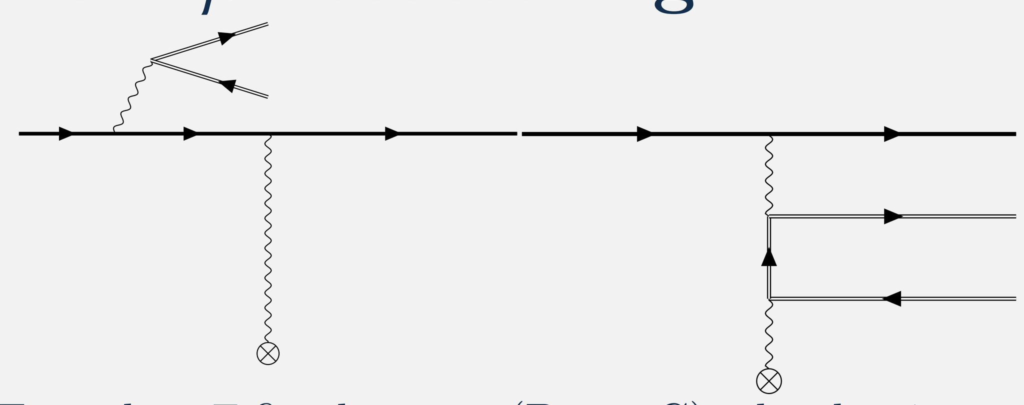
Although dimensionally suppressed with respect to elastic scattering, π^0 production is dynamically enhanced at small electron and muon scattering angles, where the sensitivity to $\Delta\alpha_{\text{had}}(t)$ is maximal there. Moreover, because the experimental setup primarily reconstructs charged tracks, the two photons from π^0 decay are not detected. Thus, the $\mu^\pm e^- \to \mu^\pm e^- \pi^0$ signature can mimic the elastic $\mu^\pm e^- \to \mu^\pm e^-$ process, making it a potential reducible background. The exact tree-level matrix element and full phase-space integration have been implemented as an additional channel in the Monte Carlo generator **MESMER**, allowing for realistic event selection studies. Differential distributions were analysed under typical MUonE running conditions, with particular attention to observables entering the extraction of $\Delta\alpha_{\text{had}}(t)$.



Our numerical results show that π^0 production constitutes a negligible background for MUonE. After realistic selection cuts, its impact on the differential cross sections is well below the experimental sensitivity.

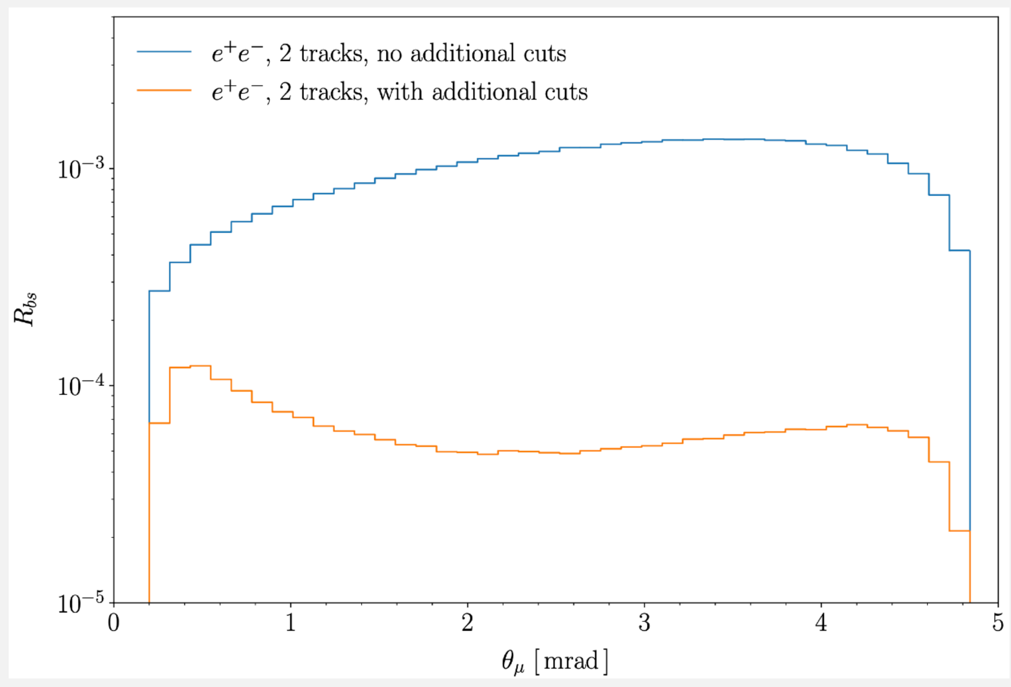
[1] MuonE Collaboration, CERN-SPSC-2019-026/SPSC-I-252.
[2] R. Aliberti, *et al.*, Phys.Rept. 1143 (2025), 1-158.
[3] C. M. Carloni Calame, *et al.*, Phys. Lett. B 746 (2015) 325-329.
[4] B. E. Lautrup, *et al.*, Phys. Rept. 3 (1972) 193-259.
[5] G. Abbiendi, *et al.*, Eur. Phys. J. C77 (3) (2017) 139.
[6] G. Abbiendi, 2022 Phys. Scr. 97 054007.
[7] E. Budassi, *et al.*, JHEP 11 (2021).
[8] E. Budassi, *et al.*, Phys.Lett.B 829 (2022) 137138.
[9] G. Abbiendi, *et al.*, Phys.Lett.B 854 (2024), 138720.

Lepton pair production from μX scattering



For a low-Z fixed target (Be or C), the dominant experimental background to elastic μe scattering originates from muon–nucleus interactions [9]. While the elastic signal scales as Z, the muon–nucleus cross section scales as Z^2, making it parametrically enhanced. We focus on the process $\mu^\pm X \to \mu^\pm X \ell^+ \ell^-$ with $\ell = e, \mu$, which represents the most relevant reducible background for MUonE. This channel is particularly critical because it can mimic elastic μe events if one of the final leptons is not reconstructed. Existing implementations in Geant4 neglect the outgoing muon scattering angle, where the typical muon deflection at MUonE is $O(m_\mu/E_\mu) \sim 0.6$ mrad, well above the detector angular resolution (20–30 μrad).

The calculation of the differential cross section is performed, retaining complete kinematic dependence and finite fermion mass effects. The nucleus is treated as an external electromagnetic field, with its finite size described by nuclear form factors. The full phase-space integration has been implemented in **MESMER**, enabling realistic event selection studies.



In contrast, e^+e^- production can reach the 10^{-3} level under basic cuts and therefore requires dedicated suppression strategies. Acoplanarity and elasticity cuts reduce the background-to-signal ratio to the 10^{-4} level, compatible with the MUonE precision goal. Comparisons among different nuclear form factor models show sub-percent differences in differential distributions, supporting a reliable Monte Carlo–based background subtraction.