Monte Carlo Programs for Muon Decays at NLO

Yannick Ulrich[1,2], **Gionata Luisoni**[3], **Giovanni Marco Pruna**[1], **Adrian Signer**[1,2]

[1] Laboratory for Particle Physics, Paul Scherrer Institut, CH-5232 Villigen PSI, Switzerland
[2] Physik-Institut, Universität Zürich, Winterthurerstrasse 190, CH-8057 Zürich, Switzerland
[3] Theoretical Physics Department, CERN, Geneva, Switzerland

Abstract

Using the amplitude provided by GoSam, a tool for the automated generation of tree level and one-loop amplitudes, fully differential next-to-leading order (NLO) corrections were obtained for the three decay channels of the muon: The Michel decay, the radiative decay $\mu \to \nu\bar\nu e\gamma$ and the rare decay $\mu \to \nu\bar\nu eee$. Especially the latter two are important Standard Model backgrounds to searches for Lepton Flavour Violation at the PSI experiments MEG and Mu3e as they become indistinguishable when the neutrinos carry little energy. With the present NLO program we are able to compute custom tailored observables for the experiments.

Methodology

We compute quantum electrodynamical corrections to the fierzed 4-Fermi Lagrangian describing Fermi's $V-A$ theory of the muon decay

$$\mathcal{L} = \mathcal{L}_{\rm QED} + \frac{4G_F}{\sqrt{2}} \left(\bar\psi_\mu\, \gamma^\mu P_L\, \psi_e\right) \left(\bar\psi_{\nu_\mu}\, \gamma_\mu P_L\, \psi_{\nu_e}\right).$$

The present computations are done using the following recipe:

1. Virtual and real amplitudes generated using the automated tool GoSam.
2. Infrared divergences handled through FKS subtraction with a custom phase space generator for increased stability.
3. Numerical integration using the Monte Carlo integrator VEGAS.

The radiative decay $\mu \to \nu\bar\nu e\gamma$

MEG needs precise predictions, preferably tailored to the detector. In figure 1 the kinematic and geometric cuts mimicking the MEG detector are shown.

Kinematic cuts

$|\cos\theta_\gamma| < 0.35$ $\quad E_\gamma > 40\,\mathrm{MeV}$

$120° < \phi_\gamma < 240°$ $\quad E_e > 45\,\mathrm{MeV}$

no second photon in detector with $E_\gamma > 2\,\mathrm{MeV}$

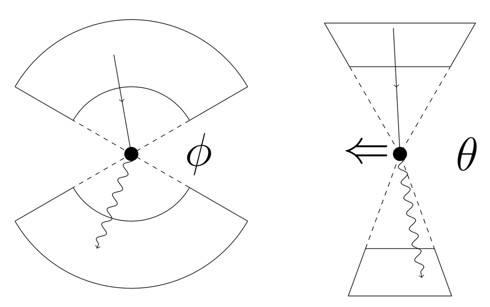

Fig. 1: The kinematic and geometric cuts mimicking the MEG detector

In our event generator, we can easily implement cuts and create arbitrary distribution such as the missing energy of the event $E_{\rm inv}$ as shown in figure 2.

Invisible energy spectrum for MEG

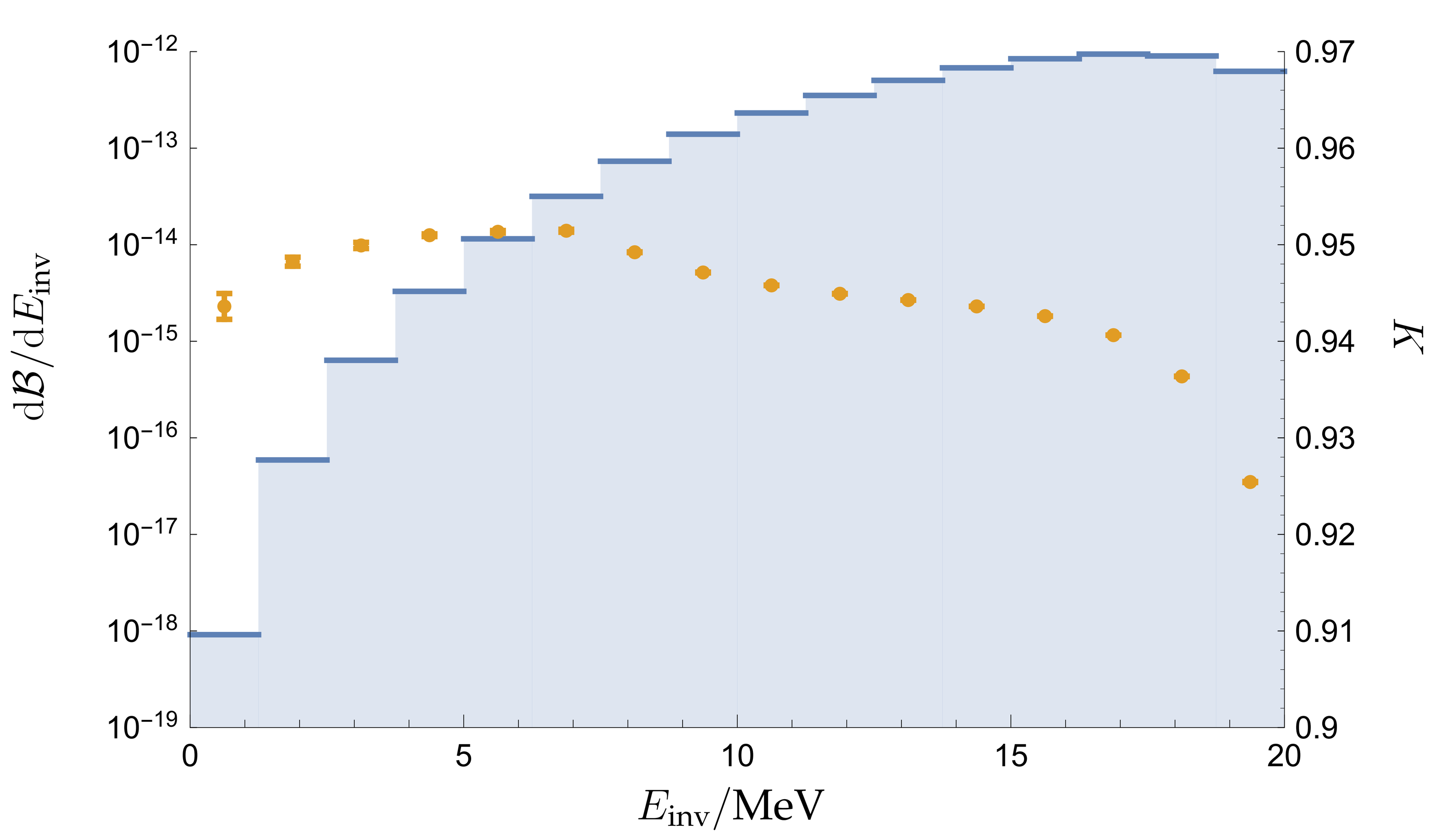

Fig. 2: The differential decay distribution w.r.t. $E_{\nu\bar\nu}$ at NLO and the K factor NLO/LO.

Additionally to single differential distributions like $\mathrm{d}\mathcal{B}/\mathrm{d}E_{\rm inv}$ one can also compute double differential distributions. As an example the distribution $\mathrm{d}^2\mathcal{B}/\mathrm{d}E_e\mathrm{d}E_\gamma$ is shown in figure 3.

MEG LEGO plot

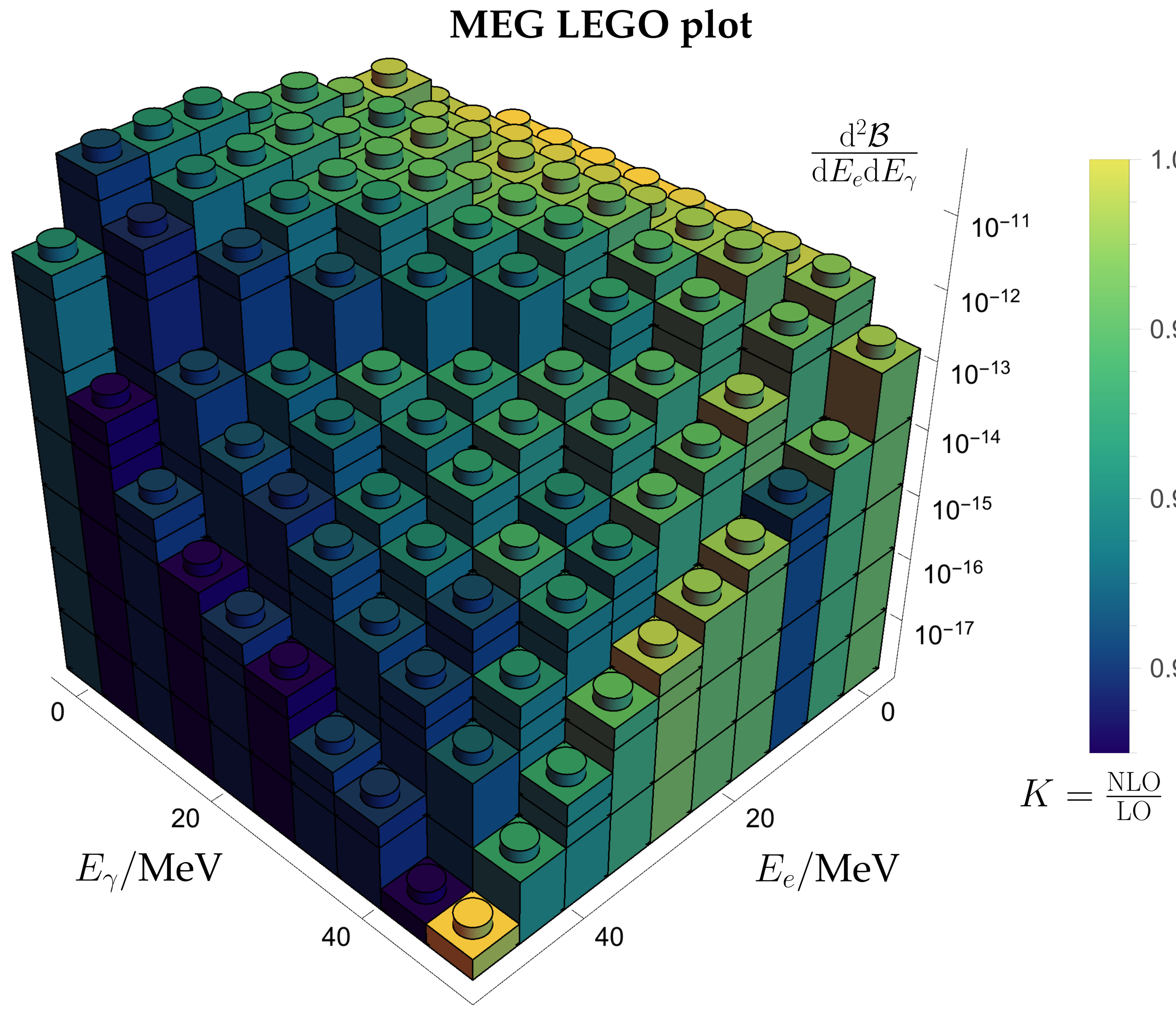

Fig. 3: The double differential distribution $\mathrm{d}^2\mathcal{B}/\mathrm{d}E_e\mathrm{d}E_\gamma$. The K factor is shown through the colouring. A hard cut of $E_\gamma \geq 2\,\mathrm{MeV}$ was imposed on the visible photon.

The rare decay $\mu \to \nu\bar\nu eee$

Branching 1002.183ptratio, with and without cut $E_{\rm inv} = m_\mu - E_{e^-} - E_{e_1^+} - E_{e_2^+} < 10 \cdot m_e$ in the on-shell scheme.

$\mathcal{B}$	LO	NLO only	rel. corr.
no cuts	3.589×10^{-5}	-0.0066×10^{-5}	$-0.18\,\%$
$E_{\rm inv} > 10 \cdot m_e$	3.057×10^{-13}	-0.403×10^{-13}	$-13.2\,\%$

Similarly to MEG, Mu3e needs precise predictions, preferably tailored to its polarisation ($p = -0.85\mathbf{e}_z$) and kinematic cuts

$$E_{e^\pm} > 10\,\mathrm{MeV} \qquad |\cos\sphericalangle(\mathbf{p}_{e^\pm}, \mathbf{e}_z)| \equiv |\cos\theta_{e^\pm}| < 0.8\,.$$

Invisible energy spectrum for Mu3e

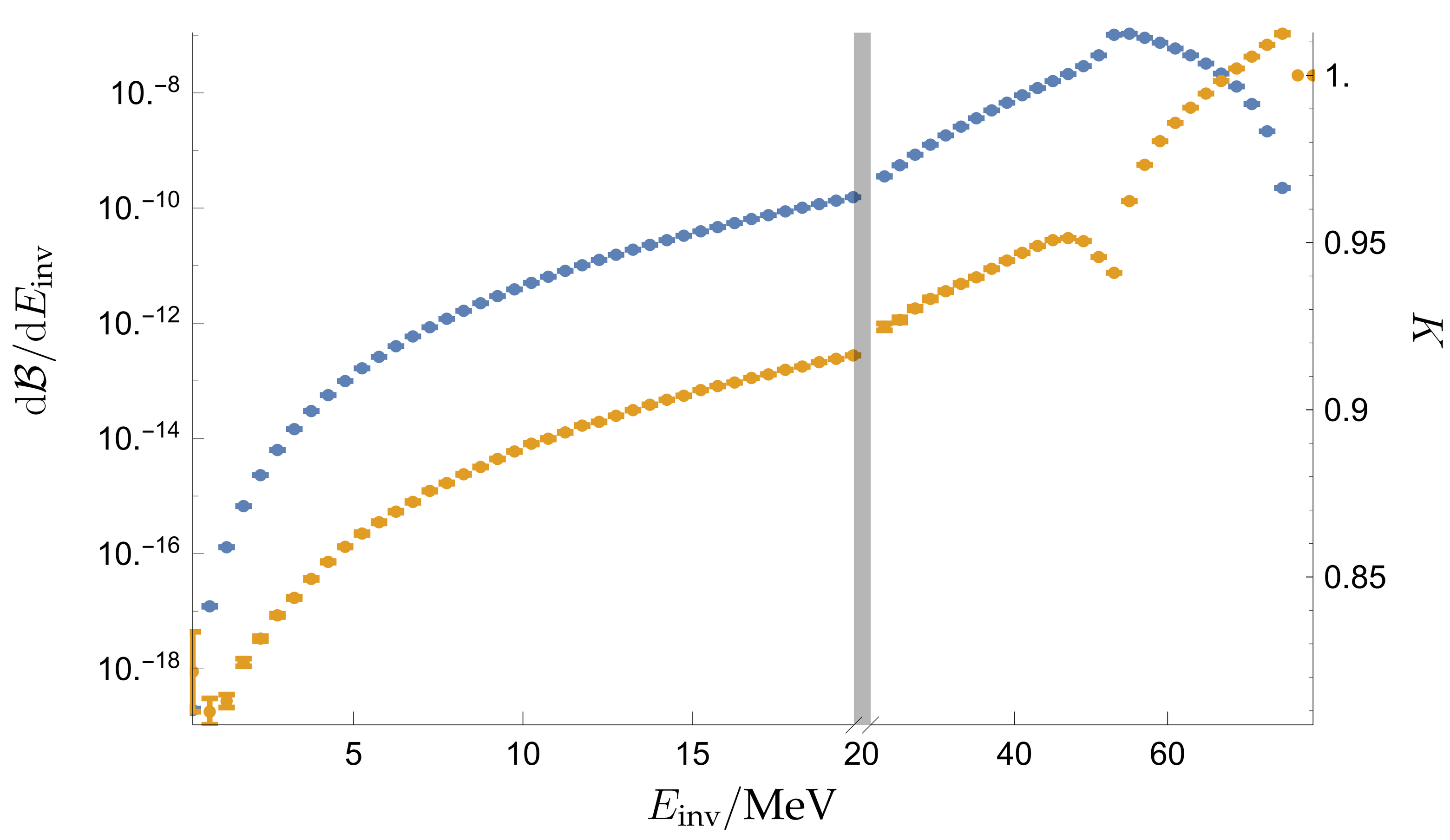

Fig. 4: The differential decay distribution w.r.t. $E_{\rm inv}$ at NLO and the K factor NLO/LO.

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Contact: Yannick.Ulrich@psi.ch