Intensity Frontier Fellowship Final Report

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In my proposal I planned to deliver two theoretical predictions: the spectrum of the electron created in the muon-electron conversion and the spectrum of the main background to the conversion searches, due to the muon decay in orbit (DIO). I managed to achieve both goals during my work at Fermilab.

The DIO spectrum is the dominant source of non-reducible background for the Mu2e experiment. I discovered that calculation of the high-energy part of the spectrum ($E_e \sim m_\mu$, with E_e representing electron energy and m_μ muon mass) requires expansion of the muon and electron wave-function in $Z\alpha$ with relativistic corrections included. This approach allowed me to calculate the radiative corrections near the DIO endpoint. The results have been published in [1]. Radiative corrections near the endpoint are enhanced by soft and collinear photon emissions that reduce the background by about 15%. Also, my method of expansion constitutes the basis for future development of effective field theory that can facilitate systematic treatment of higher order terms and further reduction of theoretical error of the DIO endpoint prediction.

The corrections to the DIO spectrum near the free muon endpoint (for electron energies close to $E_e \sim \frac{m_\mu}{2}$) have been previously obtained in [2] using the shape function formalism. This approach relies on the QCD factorization theorems applied to QED bound states. In the case of QED, the muon dynamics is described by the quantum-mechanical wave function. Using a point-like model of a nucleus I derived analytical form of the QED shape function [3].

Recently, using an approach based on the hard-collinear factorization I managed to obtain the leading corrections to the DIO spectrum in the whole energy range [4]. The knowledge of the full DIO spectrum may help in energy calibration of the conversion experiments. The leading corrections have two sources: the emission of collinear photons and the vacuum polarization. Both corrections are shown in Fig.1. Additionally, reference [4] discusses the effect of the nuclear charge distribution uncertainty on the DIO spectrum and possibility of lowering it using the DIO spectrum measured by the Mu2e experiment. If the DIO spectrum is measured precisely enough then my calculation can provide conversion experiments with opportunities to independently measure the nuclear charge distribution. This measurement requires a precise calculation of the muon binding energy. Hence, I have also evaluated the vacuum polarization correction to the binding energy in aluminum, $\Delta E_b = -2.7\text{keV}$.

The radiative corrections modify also the spectrum of electrons emerging from the conversion. This effect is large and lowers the sensitivity of the conversion searches by about 10%. The first order correction to the spectrum of the electrons in conversion reads

$$\frac{m_\mu}{\Gamma_0}\frac{\mathrm{d}\Gamma}{\mathrm{d}E_e} = \frac{\alpha}{2\pi}\left[\left(\ln\frac{4E_{\mathrm{max}}^2}{m_e^2} - 2\right)\frac{E_e^2 + m_\mu^2}{m_\mu\left(E_{\mathrm{max}} - E_e\right)} + W\left(E_e\right)\right]_+ , \tag{1}$$

where E_{max} is the DIO endpoint energy and m_e is the electron mass. The first term is the model independent part of the correction, W is a polynomial in electron energy whose form depends on the details of the new physics model that is responsible for the conversion. A paper about these corrections is currently being prepared.

During my Intensity Frontier Fellowship, I gave several seminars and I participated in multiple conferences where I presented my results.

Conferences and workshops:

- June 2016, CLFV2016, Charlottesville, USA, "Decay of a bound muon”
- May 2016, Continuous Advances in QCD, Minneapolis, USA, “Decay of a bound muon”
- May 2016, Precision Radiative Corrections for Next Generation Experiments, JLab, USA “Radiative Corrections for Muon Physics”

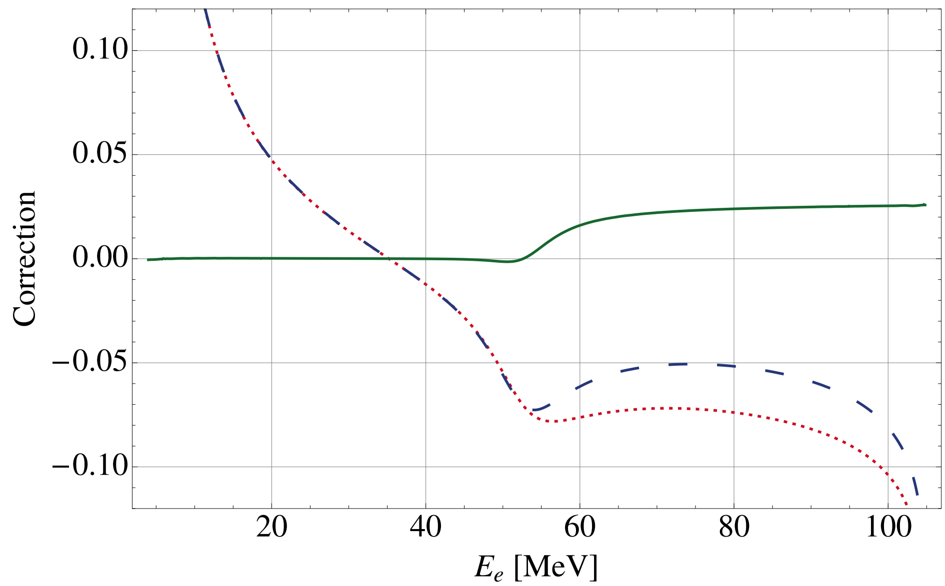

Figure 1: The leading corrections to the bound muon spectrum. The correction due to the vacuum polarization is shown in green. The red line shows the effect of collinear emission. Both corrections combined are represented by a blue line.

- September 2015, Matter to the Deepest, Ustroń, Poland, September, “Muon decay in orbit”
- June 2015, Radcor-Loopfest, Los Angeles, USA, "Muon decay in orbit and its role in new physics searches”

Invited seminars:

- Mu2e general meeting, Fermilab, 9 October 2015, “Muon decay in orbit spectrum – recent progress”
- Fermilab Theory Seminar, 16 July 2015, “Radiative corrections to muon decay in orbit spectrum”
- University of Silesia, Poland, 28 April 2015, “Muons at the intensity frontier”
- TRIUMF, Canada, 10 March 2015, “Muons at the intensity frontier”

I also gave a number of talks at the Mu2e weekly meetings.

While I was staying at Fermilab I had an opportunity to interact with multiple members of the Mu2e collaboration and the Muon Department. This was a very valuable experience for me. It allowed me to understand what kind of theoretical predictions are desired by the experimental community and accordingly prepare results that will hopefully help to discover first signals of new physics using bound muons. On the theory side, my research opens possibilities to develop an effective field theory approach to the bound muon decay.

References

[1] Robert Szafron and Andrzej Czarnecki. High-energy electrons from the muon decay in orbit: radiative corrections. *Phys.Lett.*, B753:61–64, 2016. arXiv:1505.05237.

[2] Andrzej Czarnecki, Matthew Dowling, Xavier Garcia i Tormo, William J. Marciano, and Robert Szafron. Michel decay spectrum for a muon bound to a nucleus. *Phys.Rev.*, D90(9):093002, 2014.

[3] Robert Szafron and Andrzej Czarnecki. Shape function in QED and bound muon decays. *Phys.Rev.*, D92(5):053004, 2015.

[4] Robert Szafron and Andrzej Czarnecki. Bound muon decay spectrum in the leading logarithmic accuracy. *Phys. Rev. D, Rapid. Comm. [Accepted]*, 2016.