MUON DECAY IN ORBIT AND ITS ROLE IN NEW PHYSICS SEARCHES

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OUTLINE



- Introduction: Muon Decay In Orbit (DIO)
- Muon electron conversion
- DIO spectrum
- Summary

MUON DECAY IN ORBIT

- Muon DIO: standard muon decay into an electron and two neutrinos, with the muon and a nucleus forming bound state
- For a free muon energy and momentum conservation restricts electron spectrum to $E_e < \frac{m_{\mu}}{2}$
- For DIO momentum can be exchanged between the nucleus and both the muon and the electron



MUON ELECTRON CONVERSION





Muon converts to electron without emitting neutrinos Lepton family number not conserved



MUON

•	Muon decay spectrum Michel parameters	m - Free muon spectrum — known to NNLO	n up
•	Total Lifetime, spin asymmetry		
	Muon g-2	g-2:Theory / SM Persistent 3~4 sigma discrepancy	
-	Exotic decays		
-	Muonic atoms	Proton radius puzzle	

NEW PHYSICS?

- Similar type of operators may contribute to g-2 and Charged Lepton Flavour Violation (CLFV)
- CLFV is suppressed in SM
- Three interesting CLFV processes
 - $\mu \to e\gamma$
 - muon electron conversion
 - $\mu \rightarrow eee$



MUON ELECTRON CONVERSION

- Clean experimental signature mono-energetic electron
- Current limit on the ratio R of the conversion to the capture

 $R < 7 \times 10^{-13}$

- Planned experiments expect to improve R by ~4 orders of magnitude, this is equivalent to probing New Physics scale up to 10 000 TeV!
- Conversion can probe larger class of operators than $\mu \to e \gamma$



HOW TO CALCULATE DIO SPECTRUM?

 Spectrum has to be calculated including effects of external (classical) electromagnetic field to all orders



- RC to free muon decay spectrum are well known
- We need also RC for muon DIO spectrum!
- Some simplification can be obtained in different regions of the spectrum

CENTRAL REGION

$$m_{\mu} Z \alpha \ll E_e \lesssim \frac{m_{\mu}}{2}$$

- Typical momentum transfer between nucleus and muon is of the order of $m_{\mu}Z\alpha$
- External field effects have to be resumed
- Dominant effect muon motion in the initial state



HQEFT & MUONIC ATOM

- Similar problems appear for semileptonic $B \to X l \nu$ decays of mesons containing Heavy Quarks
- Heavy Quarks in QCD: scale separation $M \gg \Lambda_{QCD}$
- Muonic atom: $m_{\mu} \gg m_{\mu} Z \alpha$

M. Neubert 94 I. Bigi et al. 94

- HQEFT solution: shape function, a non-perturbative object
- QED solution: we can define an analog of the shape function and, what is more important, we can calculate it!

QED SHAPE FUNCTION

Electron propagator in the external field

Electron is almost on-shell

We are interested only in the leading corrections

KINEMATICS

- Electron is off-shell $p_e^2 \sim m_\mu^2 Z \alpha$
- so p_e can be written in terms of a light-like $n^2 = 0$ vector

$$p_e^{\mu} = E_e n^{\mu} + \delta p_e^{\mu}$$

$$\delta p_e \sim m_\mu Z \alpha$$

- This justifies resummation $p_e^2 \sim p \cdot \pi$

•
$$\delta\left(p_e^2 + 2p_e \cdot \pi\right) = \delta\left(p_e^2 + 2E_e n \cdot \pi\right)$$

QED SHAPE FUNCTION

Shape function is defined as an expectation value: $S(\lambda) = \int d^3x \psi^*(x) \delta(\lambda - n \cdot \pi) \psi(x)$

$$S(\lambda) = \int \frac{d^3k}{(2\pi)^3} |\psi_{l.c.}(k)|^2 \,\delta(\lambda + \vec{n} \cdot \vec{k})$$

• Normalization:
$$\int_{-\infty}^{\infty} d\lambda S(\lambda) = 1$$

POWER COUNTING

 $\lambda \sim \frac{p_e^2}{2E_e} \sim m_\mu Z\alpha$ (muon momentum in an atom)
Shape function behaves as $S(\lambda) \sim \frac{1}{Z\alpha}$ First moment is zero in the leading order $\int d\lambda \lambda S(\lambda) \sim (Z\alpha)^2$ Second moment $\int d\lambda \lambda^2 S(\lambda) = \frac{1}{3} (m_\mu Z\alpha)^2$

QED SHAPE FUNCTION





END POINT REGION $E_e \sim m_\mu$

- Typical momentum transfer between the nucleus and the muon is of the order of the muon mass
- Both wave functions and propagators can be expanded in powers of $Z\alpha$



END POINT REGION



SUMMARY

- Searches for rare decays require accurate predictions for the SM background
- TWIST measurement of the DIO spectrum is sensitive to RC
- Muon DIO spectrum:
 - We have expansion in different regions
 - Ultimate goal is a correction to spectrum in the whole energy range
- DIO spectrum not yet fully understood, but the RC can be approximately calculated

