Systematic errors caused by imperfections of Mu2e beam line magnetic lattice

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Outline

• The Mu2e experiment
  - Signal & Background
  - Radiative pion capture background
  - Extinction

• Some accelerator physics

• Simulations
  - Check of the code
  - Misalignment of DS collimator
  - Optical errors in beam optics
The Mu2e experiment

Mu2e will search for the conversion of a muon to an electron in the field of an aluminum nucleus:

\[ \mu^- + N(Z, A) \rightarrow e^- + N(Z, A) \]

- Process allowed within the SM but at the level of $10^{-54}$
- Neutrino oscillation
- Any signal would be evidence of new physics

The experiment will measure the ratio of conversion to the usual muon capture:

\[ R_{\mu e} = \frac{\Gamma(\mu^- N(A, Z) \rightarrow e^- N(A, Z))}{\Gamma(\mu^- N(A, Z) \rightarrow \nu_\mu N'(A, Z - 1))} \]

Mu2e will achieve a SES of $3 \times 10^{-17}$ that means that if $R$ is equal to $3 \times 10^{-17}$, we will expect one event in the full dataset.
Signal & Background

• **Signal**: muon converts to an electron w/o neutrinos. The nucleus recoil in order to conserve 4-momentum $\rightarrow$ the electron is **monoenergetic** (2 bodies decay):
  $$E(e) = M(\mu) - E^{bind} - E^{rec} = 104.95 \text{ MeV}$$

• **Background**: 4 main sources
  - decay in orbit (DIO)
  - presence of antiprotons
  - cosmic rays
  - radiative pion capture

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RADIATIVE PION CAPTURE

• muons are made from protons: $pN \rightarrow \pi X \quad \pi \rightarrow \mu \nu$
• not all the pions decay before reaching the stopping target
• electron from the process $\pi N \rightarrow \gamma N' \quad \gamma N \rightarrow e^+e^-N$ could fake the signal
Avoid RPC BG: Beam Structure

- Pion lifetime: 26 ns, muon lifetime: 864 ns → in order to reduce RPC background we just need to wait → bunch structure of the beam

Bunch structure avoids the presence of protons before and during the signal window
- 3x10^7 p/bunch
- 1695 ns bunch spacing (μ lifetime)

A very small fraction of out-of-time proton is then required. This parameter is called **EXTINCTION**. Extinction is required to be <10^{-10} (10^{-11} expected)
Some accelerator physics

- level of $10^{-5}$ extinction is provided by the delivery ring
- a set of resonance dipoles (AC dipoles) and collimators will provide another $10^{-7}$ extinction

Using this coordinates the motion can be described in terms of the $\beta(s)$ function:

$$x(s) = A \sqrt{\beta(s)} \cos(\psi(s) + \delta) \quad \psi(s) = \int_0^s \frac{ds}{\beta(s)}$$

The beta function is the local wave number and defines the beam envelope

Phase advance

- Emittance: roughly the area in the phase space of the particles
- Admittance: largest value of the emittance which the system will transport w/o loss
Extinction in practice

Using this formalism, one can define a normalised angle:

\[ \delta = \frac{\theta}{\theta_0}; \text{ where } \theta_0 = \sqrt{\frac{A}{\beta_D \beta_\gamma}} \]

\[ \delta = 1 \rightarrow \text{center of beam hits edge of collimator} \]
\[ \delta = 2 \rightarrow \text{all beam hits collimator } \equiv \text{"extinction angle"} \]

- the idea is to use the AC dipole to kick the out-of-time beam against the collimator’s jaws
- the dipole system introduces an angular deflection which causes a lateral transverse deflection 90° betatron phase advance downstream
Simulations

Simulations have been carried out in order to check the transmission through the downstream collimator in different situations:

- verify that no transmission is present when $\delta > 2$
- understand the effect of the misalignment of the DS collimator
- understand the effect of optical errors (field errors) in beam optics

Tools for the simulations:

- the optic of the beam line is designed with MADX, a tool developed at CERN. It contains all the information about dipoles, quadrupoles, etc
- a Python script converts the MADX files in G4beamline scripts
- G4beamline is a GEANT4 scripting tool for particle simulations in beamlines
Simulation procedure

- Starting from MADX, a description of the entire beam line is obtained using G4beamline. It includes dipoles, quadrupoles, collimators and beam pipes.
- The description starts at the end of the Delivery Ring Enclosures. To save computer power, I have run the simulation beginning just upstream of the AC dipole using a provided mathematical model of the beam.

- Particles are “transmitted” if they are within 5 mm of the target after the DS collimator (real radius is 3 mm) → if they miss the target the won’t produce BG
- Transmission results of the simulations are given as a function of the normalised angles $\delta$
- Results will be combined with the wave function of the dipole to correlate transmission with the time (not by me)
G4beamline graphic model
Check of the code

- G4beamline produces a ROOT file with NTuples that contain information about $x$ and $y$ position of the particles and their momentum components at a given $s$

- a ROOT script takes the data contained in the last NTuples and computes the number of particles within the target
- G4beamline simulation uses 100,000,000 events (1,000,000 on 100 processor) for each value of $\delta$ going from 1.8 to 2.5 with .1 increments
- code works as expected — no transmission for $\delta \gtrsim 2$

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<tr>
<td>2.5</td>
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Misalignment of DS collimator

- Full simulations have been run with the downstream collimator tilted by 1 mr and 2 mr
- This is much more than what would actually happen

Even in this arrangement the extinction is below the limit (remember that a level of $10^{-5}$ is achieved with the delivery ring)
Optical errors in beam optics I

- This analysis starts by modifying the MADX optic file
- A random error is added to the quadrupole field
  - Gaussian error distribution with a cut at 2.5 sigma
  - Rms value of $10^{-3}$ for the quadrupole field relative error
- This is done to have an idea of the effect on extinction while waiting for more realistic errors
- 5 different runs of the simulation (they take time)

How the Betatron function varies with the $s$ coordinate for the first 4 runs of the optic simulation.
Optical errors in beam optics II

- Mathematical distribution of the beam has been regenerated in order to match the new optic. This has been done for each run.
- Once the random optic configuration is set, this has been translated in a G4beamline script in order to get transmission as a function of $\delta$
- Again, we see that extinction is not sensible to .1% error of the quadrupole magnetic field
Summary

- Understand the aim of the Mu2e experiment
- Background characterisation
- How extinction suppress background
- Prove that extinction meets the requirements even with reasonable errors caused by imperfections