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Systematic errors caused by imperfections of Mu2e beam line magnetic lattice

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Mu2e

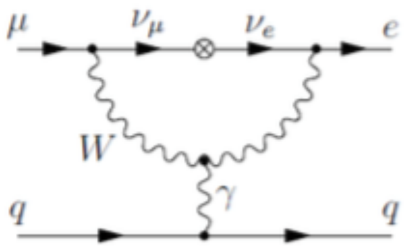
Outline

- 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:

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

Mu2e will achieve a SES of $3\text{x}10^{-17}$ that means that if R is equal to $3\text{x}10^{-17}$, 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 $\longrightarrow$ the electron is monoenergetic (2 bodies decay):

$$E(e) = M(\mu) - E^{bind} - E^{rec} = 104.95 \text{ MeV}$$

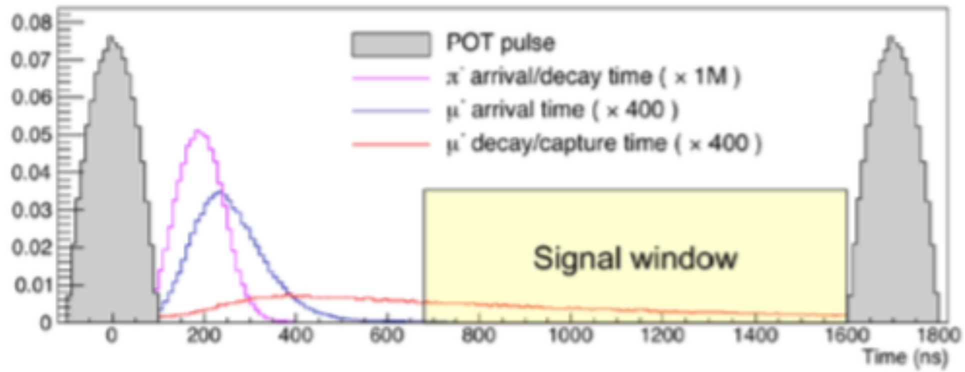
- Background: 4 main sources
  - decay in orbit (DIO)
  - presence of antiprotons
  - cosmic rays
  - radiative pion capture

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 $\longrightarrow$ in order to reduce RPC background we just need to wait $\longrightarrow$ bunch structure of the beam

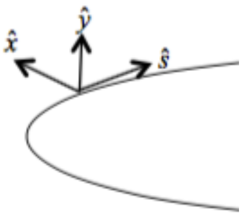


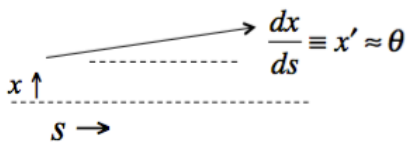
Bunch structure avoids the presence of protons before and during the signal window
- 3×10^7 p/bunch
- 1695 ns bunch spacing (μ lifetime)

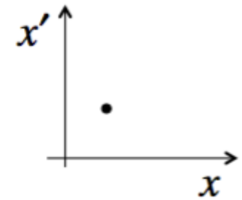
A very small fraction of out-of-time proton is then required. This parameter is called EXTINCTION. Extinction is required to be $<10^{-10}$ (10^{-11} expected)

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 β(s) function:

$$x(s) = A\sqrt{\beta(s)}\cos(\psi(s) + \delta)$$

$$\psi(s) = \int_0^s \frac{ds}{\beta(s)}$$

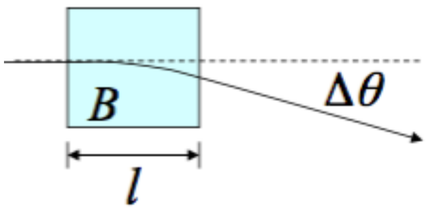
The beta function is the local wave number and defines the beam envelope

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:



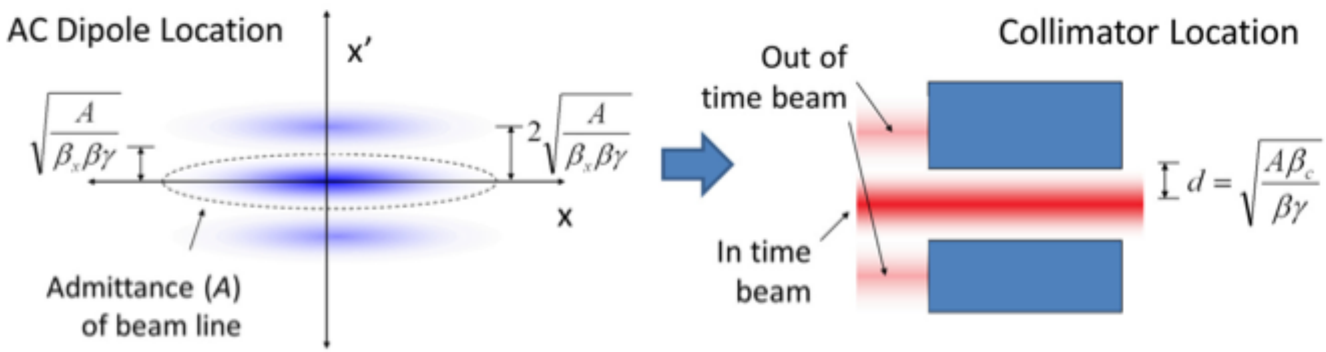
$$\delta \equiv \frac{\theta}{\theta_0}; \quad \text{where } \theta_0 \equiv \sqrt{\frac{A}{\beta_D \beta\gamma}}$$

Admittance of the collimator

β(s) evaluated at the AC dipole

$\delta = 1 \rightarrow$ center of beam hits edge of collimator

$\delta = 2 \rightarrow$ all beam hits collimator ≡ "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:

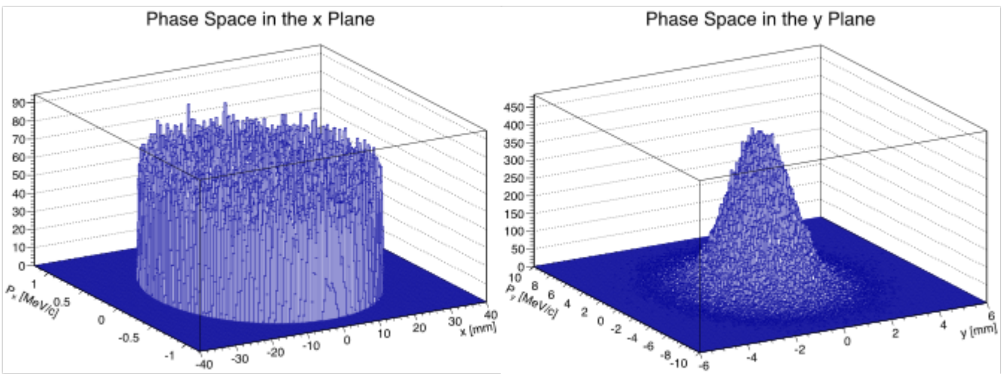
➡ the optic of the beam line is designed with MADX, a tool developed at CERN. It contains all the information about dipoles, quadrupoles, etc

➡ a Python script converts the MADX files in G4beamline scripts

➡ G4beamline is a GEANT4 scripting tool for particle simulations in beamlines

Simulation procedure

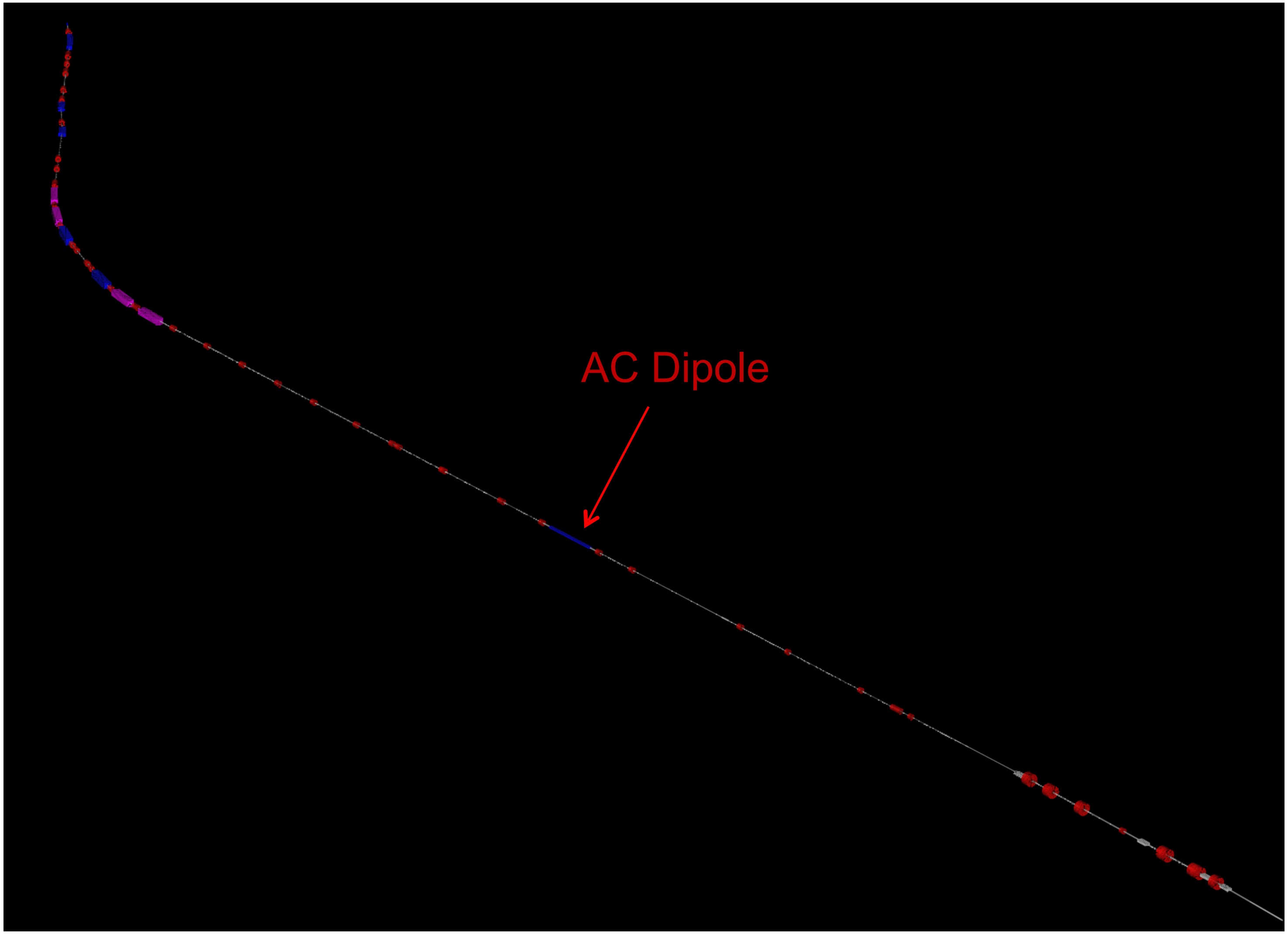
- Starting from MADX, a description of the entire beam line is obtained using G4beamline. It includes dipoles, quadrupoles, collimators and beam pipes.
- The description starts at the end of the Delivery Ring Enclosures. To save computer power, I have run the simulation beginning just upstream of the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



- Full emittance in bend plane (x-plane)
- Gaussian emittance in the y-plane

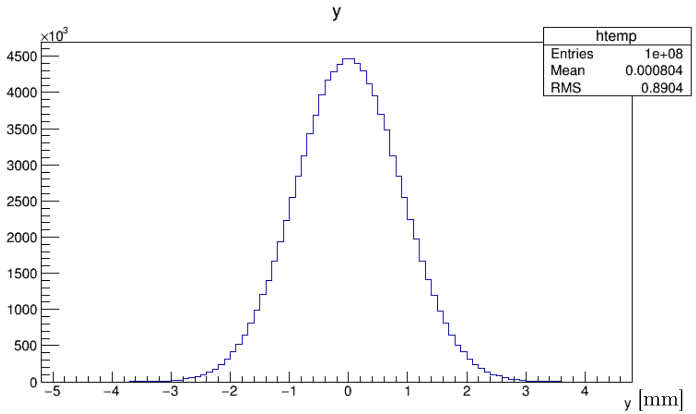
- Particles are "transmitted" if they are within 5 mm of the target after the DS collimator (real radius is 3 mm) ⟶ if they miss the target the won't produce BG
- Transmission results of the simulations are given as a function of the normalised angles δ
- Results will be combined with the wave function of the dipole to correlate transmission with the time (not by me)

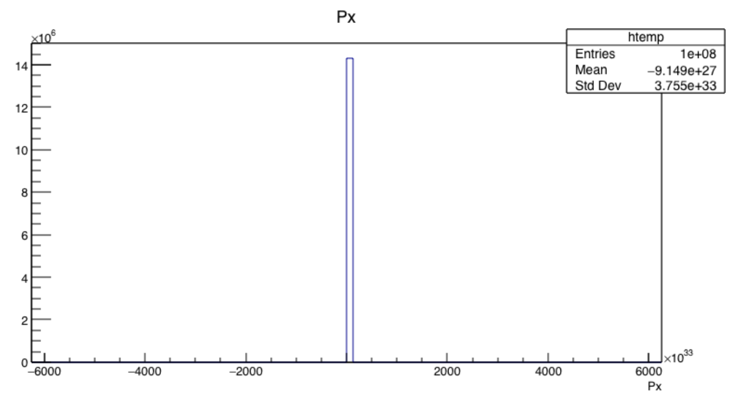
G4beamline graphic model



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



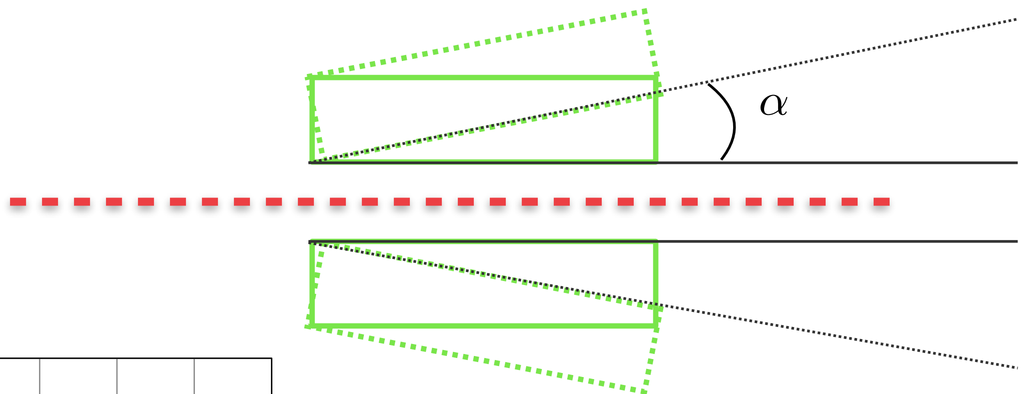


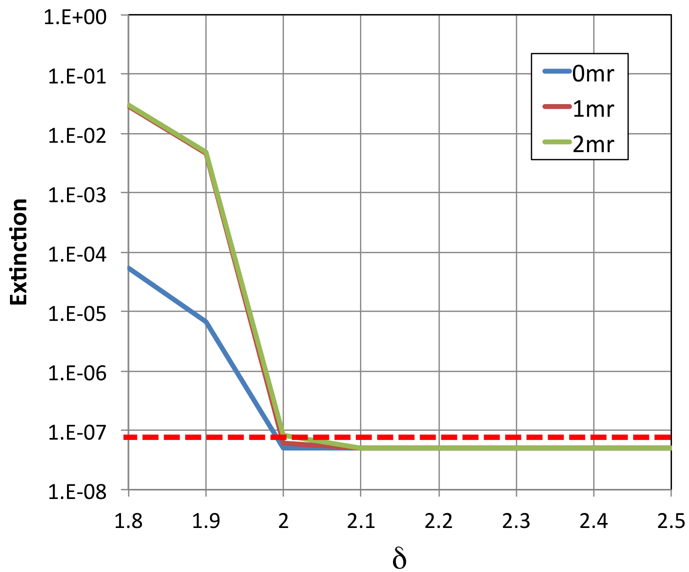
- a ROOT script takes the data contained in the last NTuples and computes the number of particles within the target
- G4beamline simulation uses 100,000,000 events (1,000,000 on 100 processor) for each value of δ going from 1.8 to 2.5 with .1 increments
- code works as expected $\longrightarrow$ no transmission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

δ	End	Hit
1.8	177890	5309
1.9	35755	667
2.0	2841	1
2.1	869	0
2.2	359	0
2.3	147	0
2.4	76	0
2.5	33	0

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

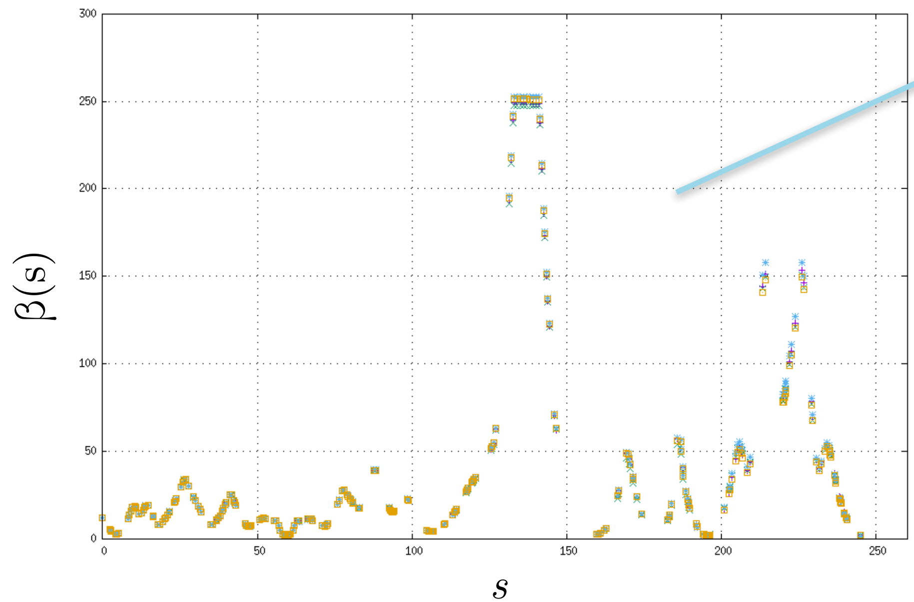




Even in this arrangement the extinction is below the limit (remember that a level of 10^{-5} is achieved with the delivery ring)

Optical errors in beam optics I

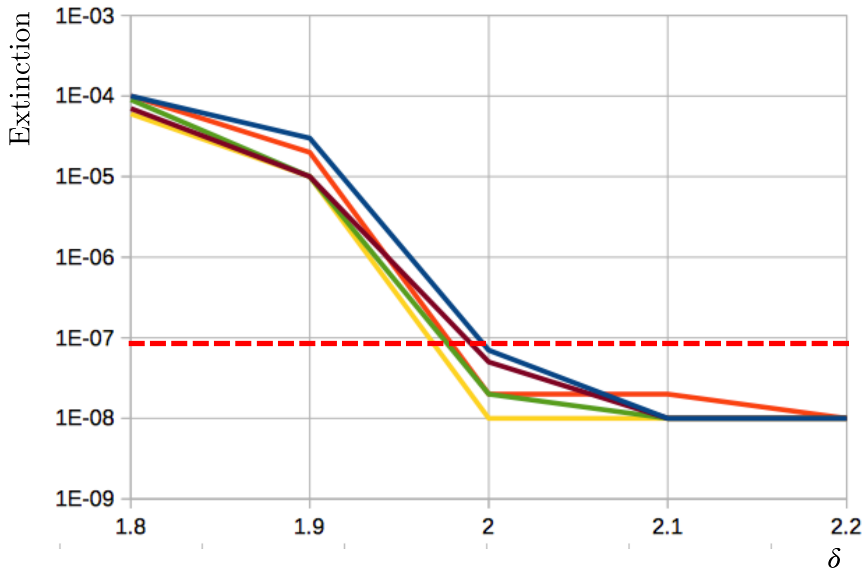
- This analysis starts by modifying the MADX optic file
- A random error is added to the quadrupole field
  - gaussian error distribution with a cut at 2.5 sigma
  - rms value of 10^{-3} for the quadrupole field relative error
- This is done to have an idea of the effect on extinction while waiting for 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 δ
- 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