Simulating Multiple Targets in MUonE

Niels Vestergaard - 2nd year Ph.D presentation - HEP meeting 22/5 2025
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The MUonE experiment

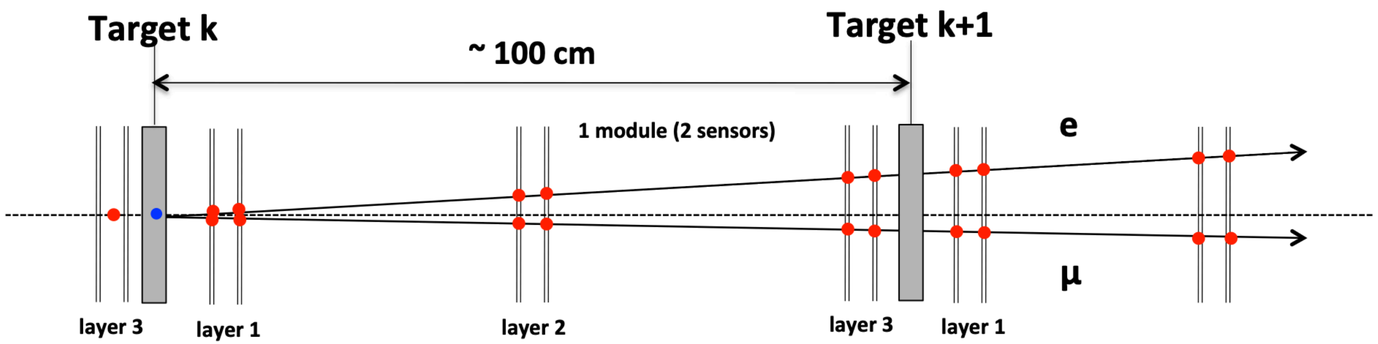
- Provide independent evaluation of the hadronic vacuum polarisation contribution at leading order to the anomalous magnetic moment of the muon a_μ^{HLO}
- High intensity muons with an energy of 160 GeV from the M2 beam line at CERN, collide with a fixed target, causing scattering of the atomic electrons
- a_μ^{HLO} is calculated from $\Delta\alpha_{had}(t)$ given by

$$a_\mu^{\mathrm{HLO}} = \frac{\alpha}{\pi}\int_0^1 dx(1-x)\Delta\alpha_{had}[t(x)]$$

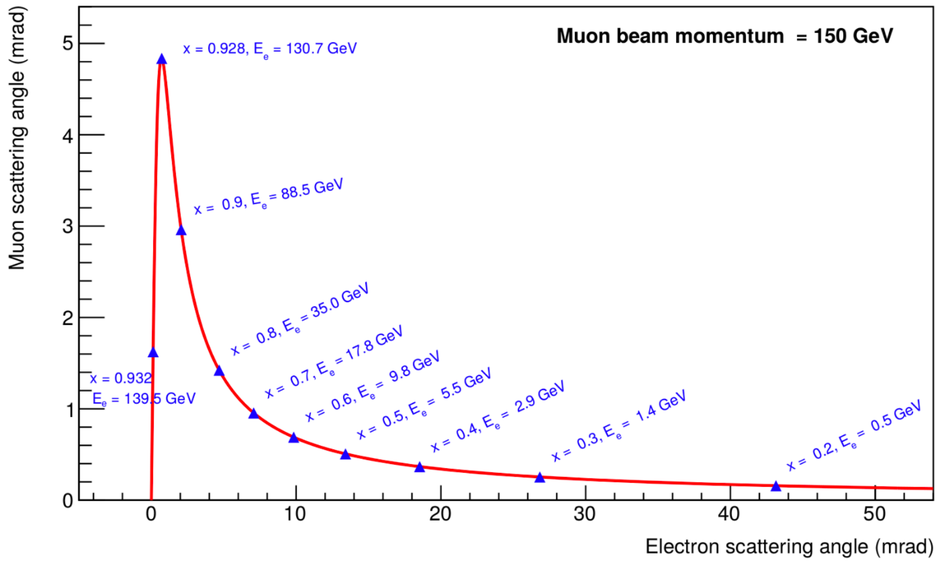
- $\Delta\alpha_{had}(t)$ is extracted from the shape of the differential cross section of elastic scattering of $\mu^+e^- \to \mu^+e^-$

Current setup

The current setup in MUonE consists of a single target of 2 cm.



[1]



[2]

The modelisation of multiple scattering effects is a major source of systematic error in the experiment, as they break the kinematic correlation between the muon and electron angles

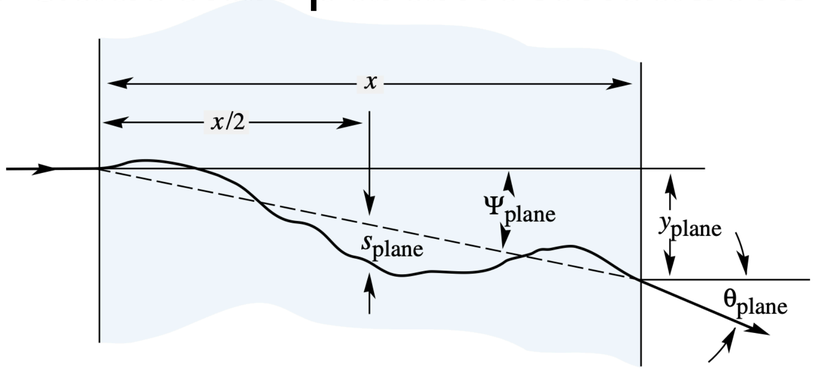
[1] G. Abbiendi et al. [MUonE Collaboration]. *Letter of Intent: the MUonE project*.

[2] G. Abbiendi et al. *Measuring the leading hadronic contribution to the muon g-2 via μe scattering*.

Modeling multiple scattering

When particles pass through the material of the detector, collisions will occur, causing a deflection of the angle.

We can model the contribution from multiple scattering effects according to a Gaussian parameterisation:



[3]

$$\theta_0 = \frac{13.6\ \text{[MeV]}}{p\beta c} z \sqrt{\frac{x}{X_0}} \left[1 + 0.038\ \ln\left(\frac{x}{X_0} \right) \right]$$

where p is the momentum in GeV, βc is the velocity, z is the charge, x is the target thickness and X_0 is the radiation length.

[3] S. Navas et al. (Particle Data Group), Phys. Rev. D 110, 030001 (2024)

Motivation behind multiple targets

To improve our estimate of the amount of material traversed, we propose replacing the single thick target with a series of thinner ones.

With a 2 cm target, we currently estimate material based on the z-vertex position, determined by the distance of closest approach of the three tracks.

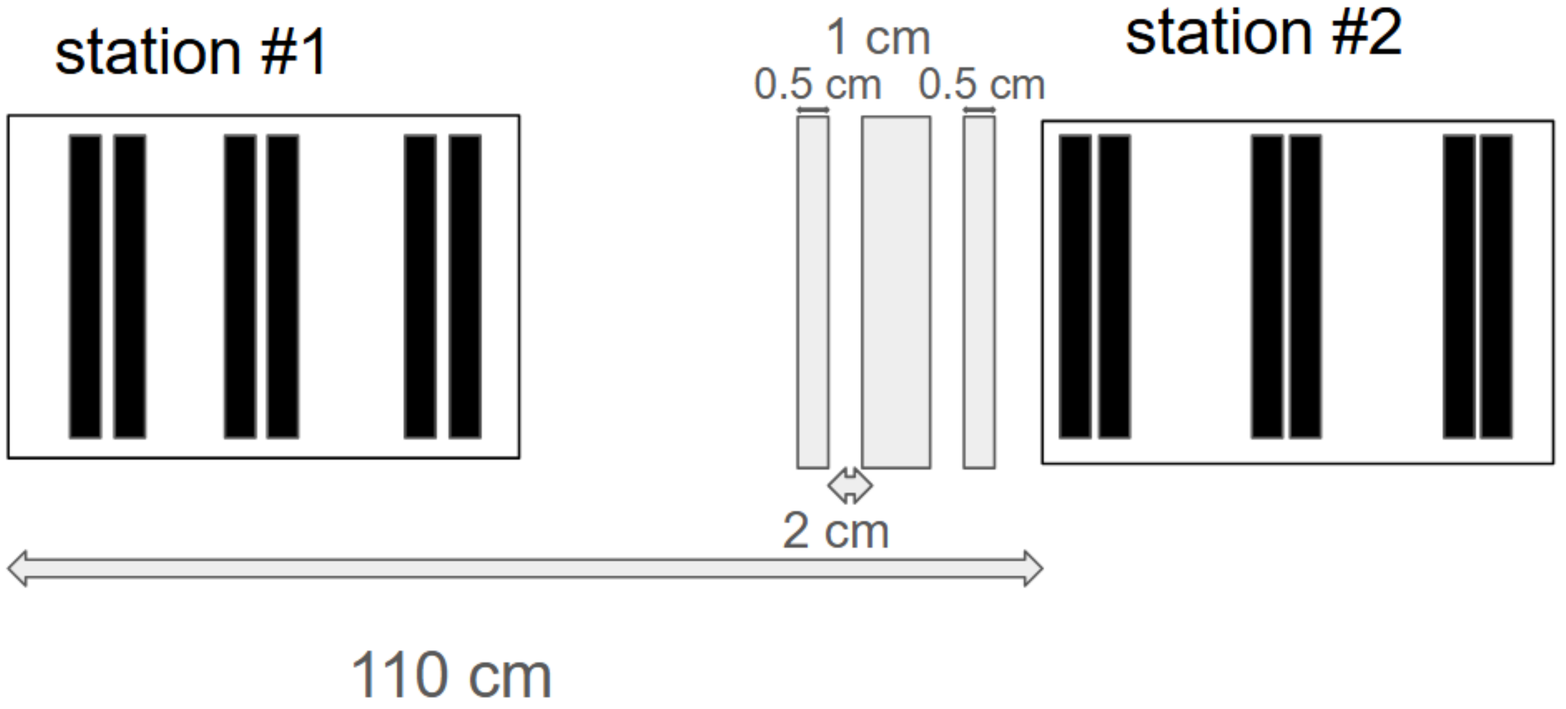
By using multiple thin targets spaced farther apart than our vertex resolution (and each thinner than the resolution), we can instead use the known target positions, measured with better than 100 μm precision via laser surveys, to more accurately constrain the z-position.

This leads to a more realistic estimate of the traversed material and better modelisation of multiple scattering.

Will be used to check that this idea is indeed improving our resolution and to optimize the multi-target geometry in view of the final version of MUonE, after the long shutdown.

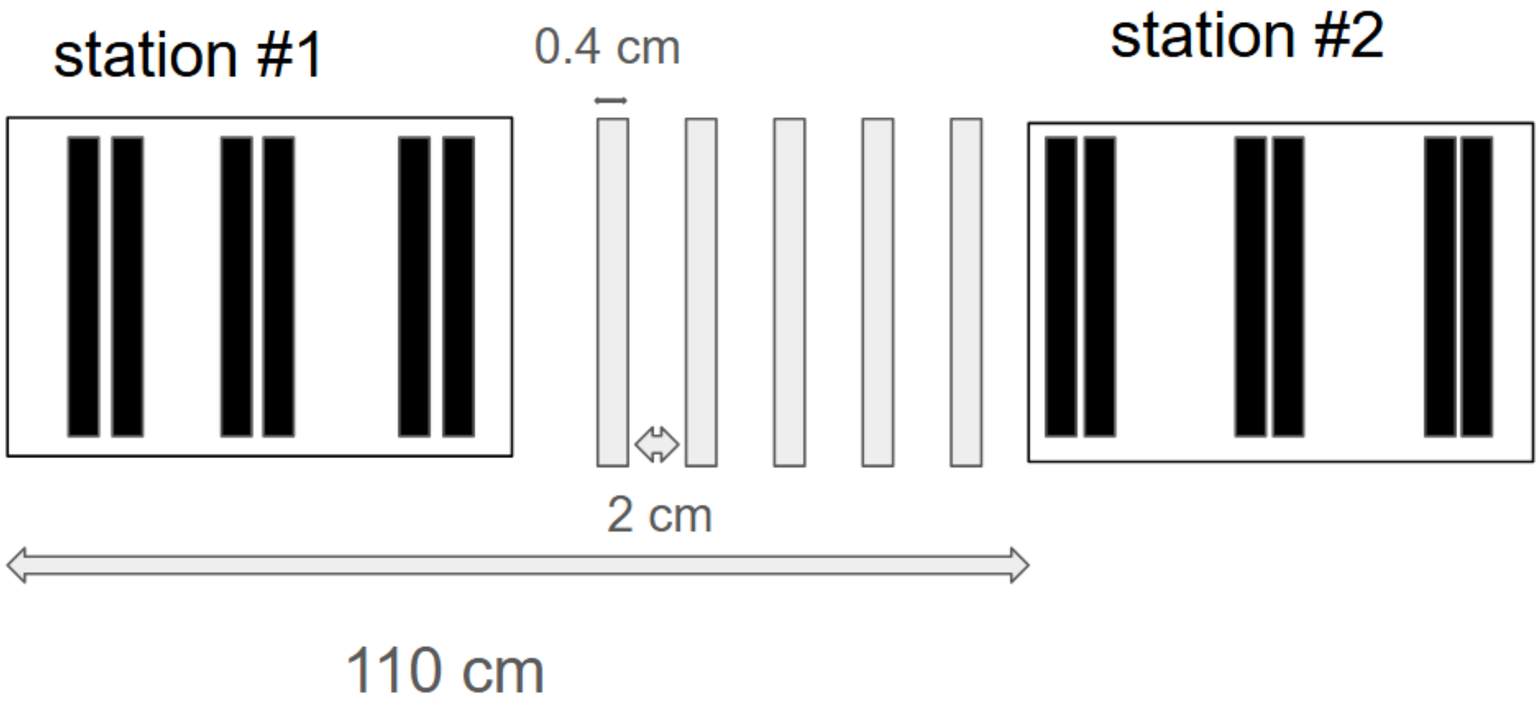
Two proposed multi target setups

Example 1 (already built and ready to test):
3 targets where:
Target 1: 0.5 cm Target 2: 1.0 cm Target 3: 0.5 cm with a spacing of 2 cm



Two proposed multi target setups

Example 2:
5 targets of 4 mm thickness, spaced 2 cm apart



Target resolution fit

z-vertex position is fitted with a convolution of the Heaviside step function and a Gaussian, in order to extract the resolution

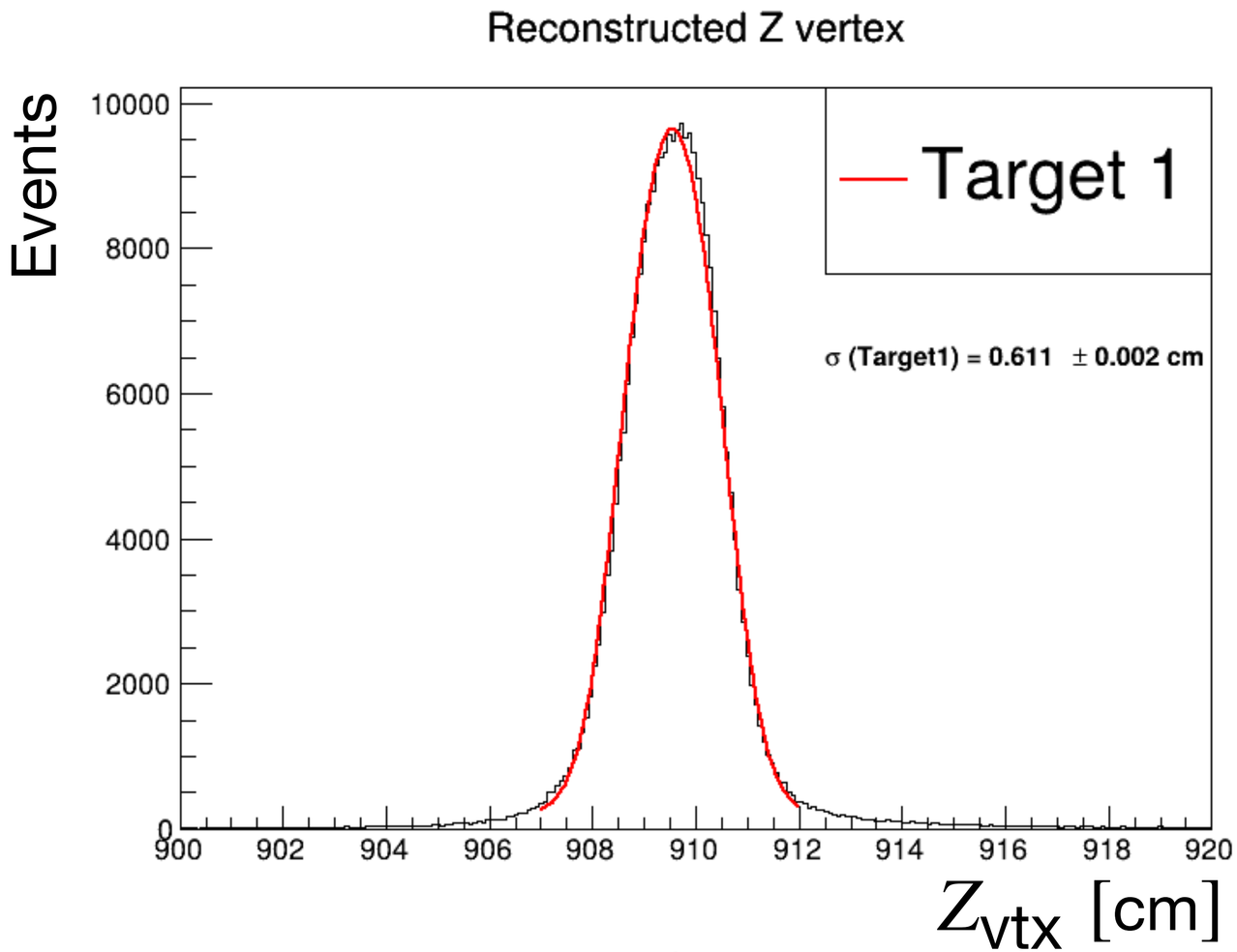
$$P_{\text{res}}(z) = \int_{-\infty}^{\infty} \left[\Theta\left(t + \frac{w}{2}\right) - \Theta\left(t - \frac{w}{2}\right)\right] \cdot \frac{1}{\sqrt{2\pi\sigma_t^2}} \exp\left(-\frac{(t-z)^2}{2\sigma_t^2}\right) dt$$

$$= \frac{1}{2}\left[\text{erf}\left(\frac{z + \frac{w}{2}}{\sqrt{2\sigma_t^2}}\right) - \text{erf}\left(\frac{z - \frac{w}{2}}{\sqrt{2\sigma_t^2}}\right)\right]$$

where z is the position in the z-axis, w is the target thickness and σ_t is the resolution. w is fixed in the fit and z and σ_t are free parameters.

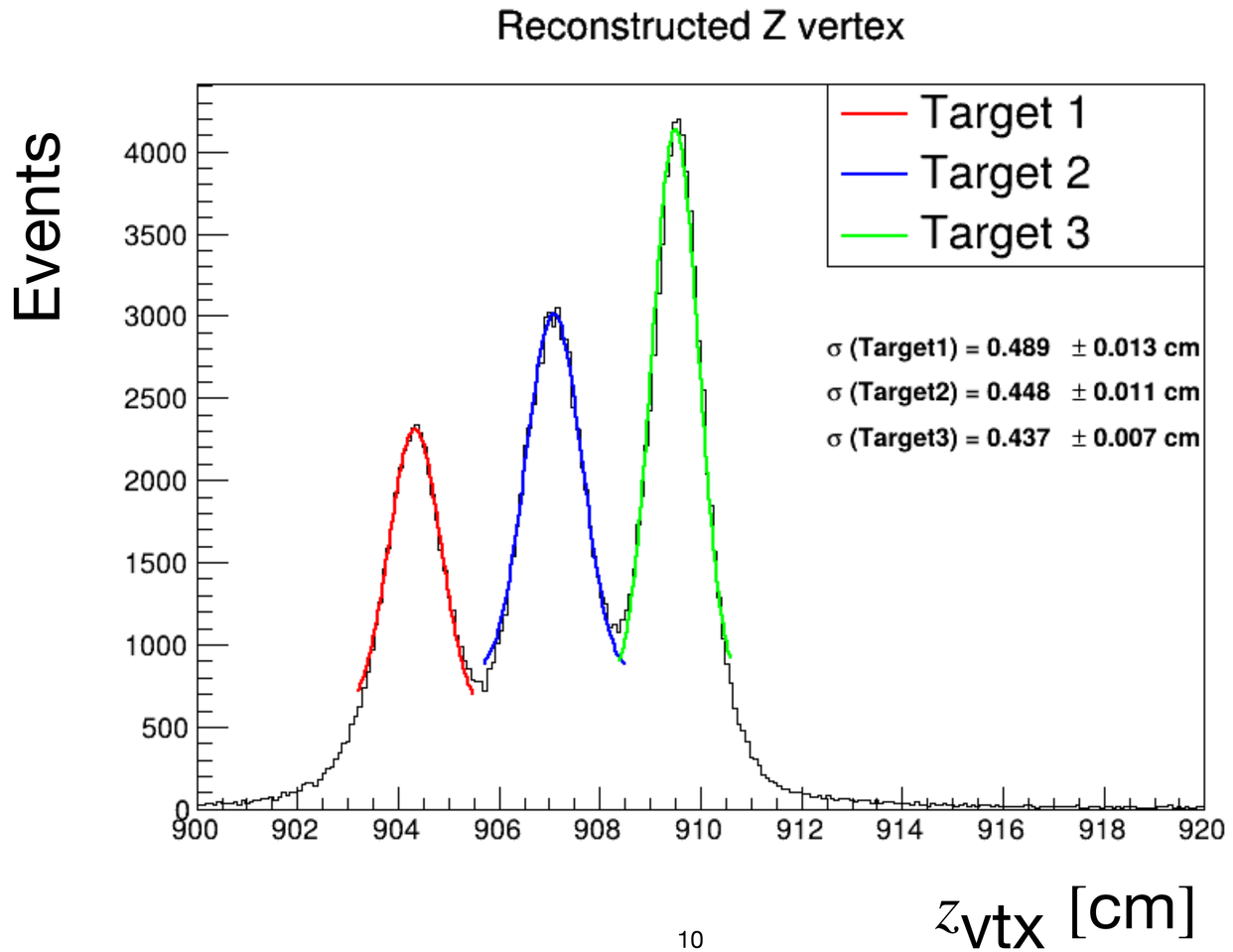
Vertex resolution of current setup

GEANT4 simulation of single target of 2.0 cm thickness



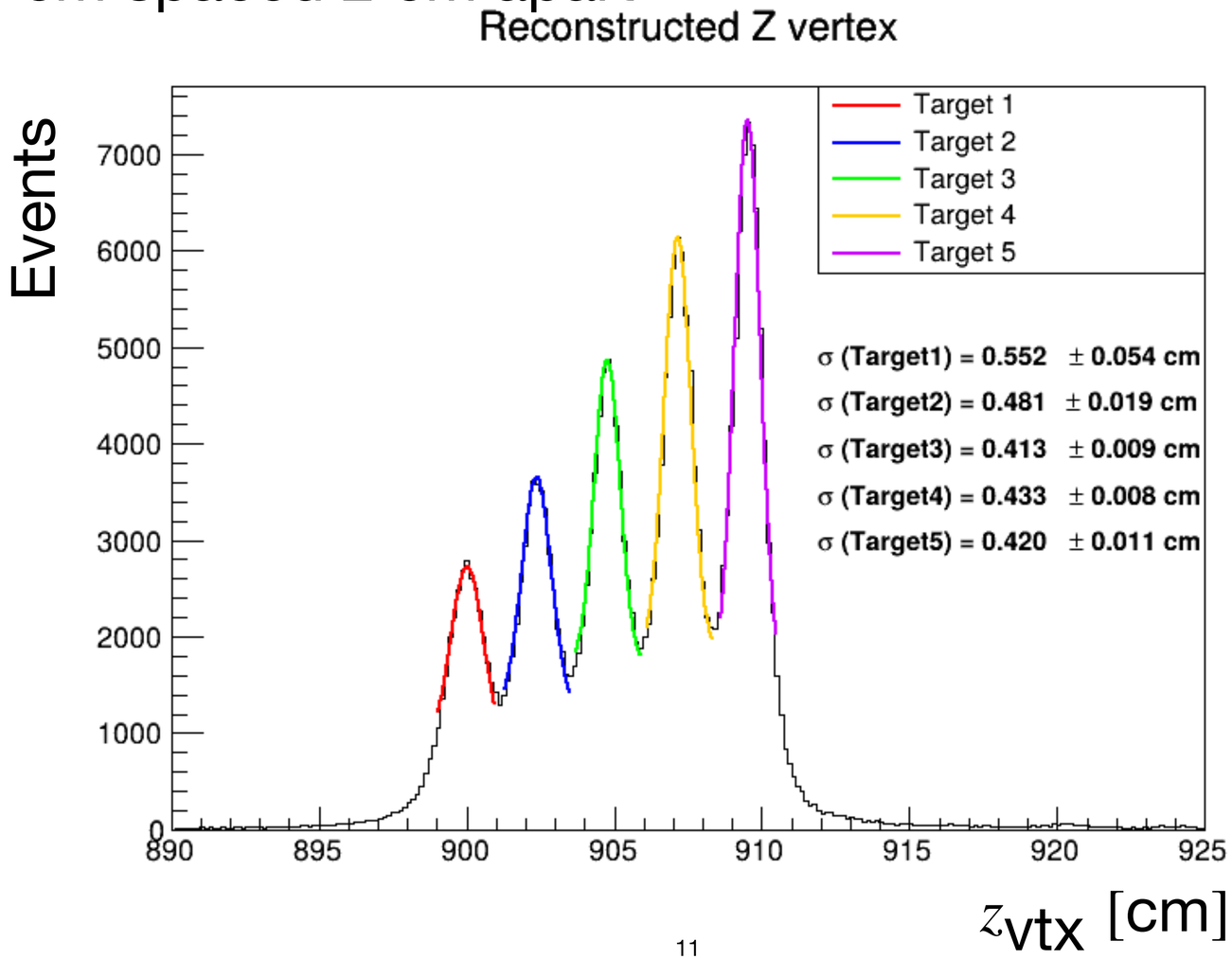
Vertex resolution of example setup 1

GEANT4 simulation of example setup 1
Target 1: 0.5 cm Target 2: 1.0 cm Target 3: 0.5 cm with a spacing of 2.0 cm



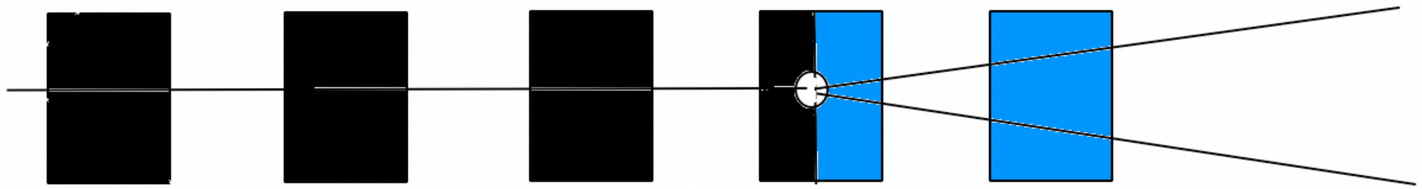
Vertex resolution of example setup 2

GEANT4 simulation of example setup 2
5 targets of 0.4 cm spaced 2 cm apart



Next step: Modify reconstruction code to account for multiple targets

After determining the specific target the vertex occurred, the contributions from the previous targets are added to the incoming track, and the contributions from the following targets are added to the outgoing tracks



Black: Multiple scattering effects to include for the incoming track

Blue: Multiple scattering effects to include for the outgoing tracks

Conclusion

- Multiple scattering represents one of the largest systematic uncertainties in MUonE, and precise modelisation is therefore vital
- Replacing the current single target setup with a series of thinner targets is a proposed way of reducing the systematic error associated with multiple scattering effects
- Ultimately, the angular resolutions of the outgoing muon and electron is the figure of merit
- Multiple target setup to be tested at the ongoing test run at CERN