A Geant4-based simulation study of a preliminary setup of the MUonE experiment

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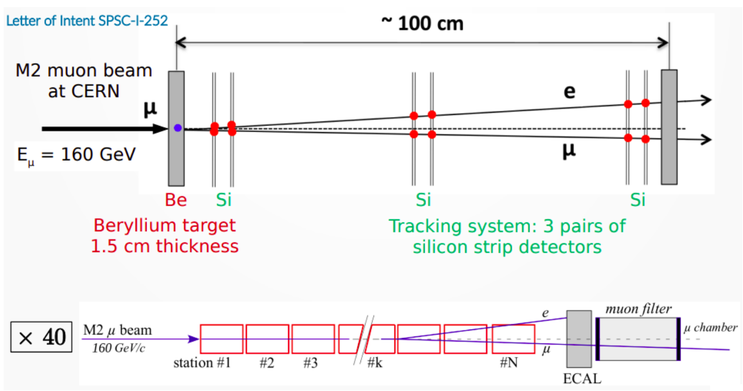
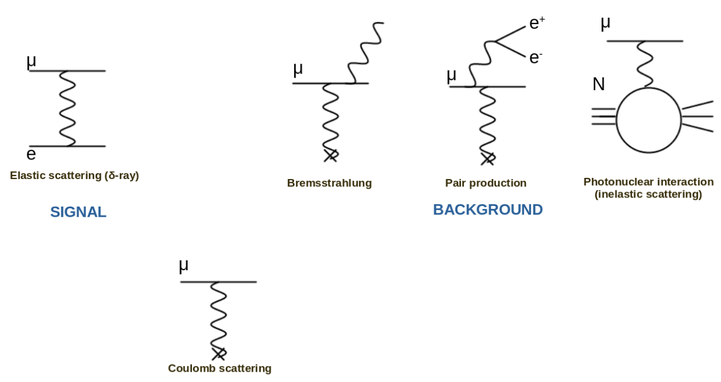
The MUonE experiment

- Muon magnetic moment anomaly a_μ: the recent FNAL measurement [1] confirmed the previous result → Data-SM prediction: 4.2σ
- Dominant theory uncertainty from the LO contribution of hadronic vacuum polarization [2]
- However, a recent Lattice QCD result [3] is closer to data, in tension with the usual dispersive calculation
- MUonE: an experiment aiming at an independent determination of the leading hadronic contribution to a_μ by a new method, from a precise measurement of the hadronic running of $\alpha(t)$ in $\mu e \to \mu e$ elastic scattering, by using the CERN muon beam ($E = 160$ GeV) on a fixed target [4, 5]

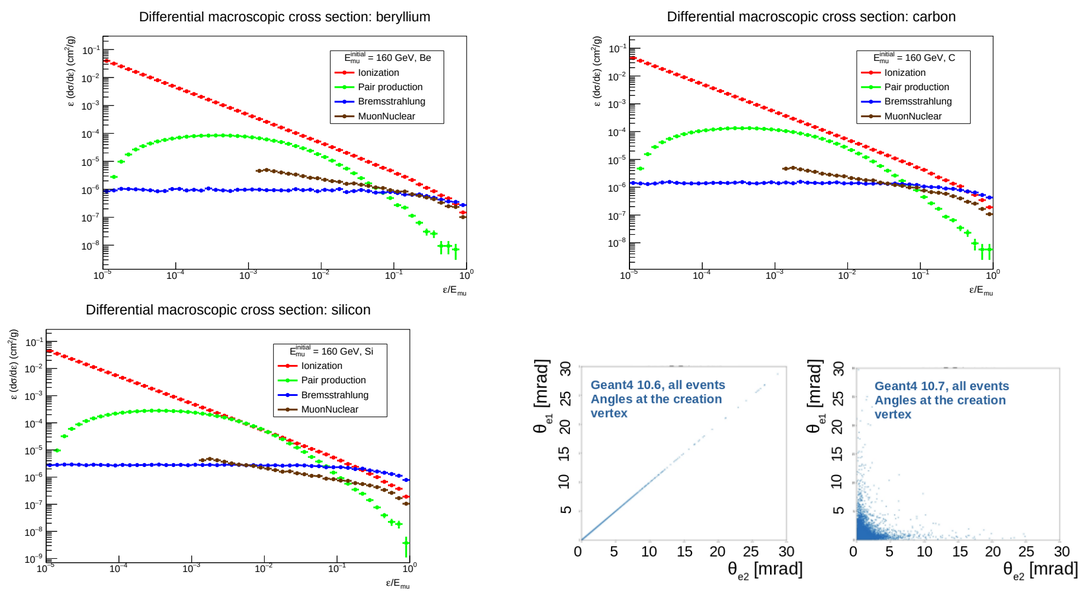


- 40 tracking stations with thin (to limit multiple scattering) low-Z target and 6 silicon CMS Outer Tracker 2S modules [6] each, followed by an electromagnetic calorimeter (ECAL) and a muon detector at the end, to help the identification and the selection
- signal: δ-rays from ionization i.e. elastic scattering; main background: pair production



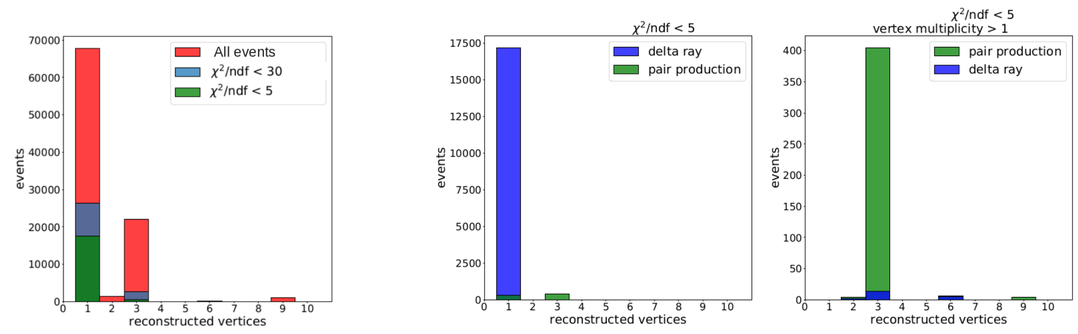
MUonESim and standalone Geant4 tests

- Standalone Geant4 [7] tests with $MUonESim$ application to determine the appropriate physics lists, models and Geant4 versions before the level of reconstruction
- Estimating for the components of the MUonE preliminary setup: angular correlation plots, contribution of interaction processes to the total energy loss
- Calculating the transferred energy from the incoming muon at every step ε
- Calculating the macroscopic differential cross section $d\sigma/d\varepsilon$, where the macroscopic cross section σ is related to the microscopic atomic cross section σ_A by $\sigma = \sigma_A n_A/\rho_A$, where n_A is the density of atoms per unit volume and ρ_A is the material density (in g/cm^3)
- Observations: Optimal physics list: FTFP-BERT, electromagnetic standard option 4 (containing the most accurate standard and low-energy models), default model for muon nuclear interactions
- The latest Geant4 versions (from 10.7 and onward) introduce an improved simulation of the angular distribution of e^+e^- pairs

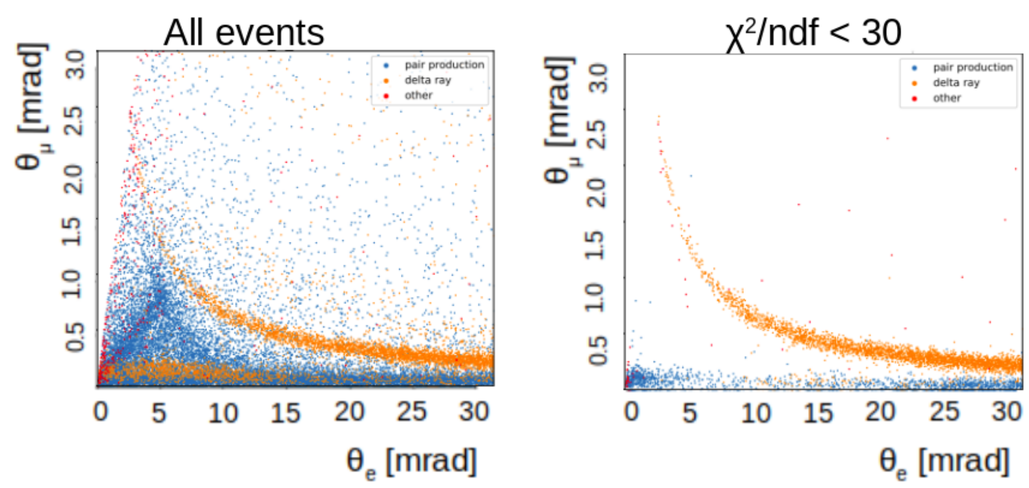


Simulation using FairMUonE

- $FairMUonE$: Official MUonE software (using the FairRoot framework [8]) for generation, simulation and offline reconstruction of events
- Interfaces the MESMER Monte Carlo generator [9, 10] and allows for production of LO and NLO elastic signal samples with an accurate beam profile
- Interaction with detector material simulated using Geant4, full tracker digitization implemented
- Scattering vertex reconstruction based on a linear χ^2 fit of an incoming and two outgoing tracks constrained to a common vertex position
- All selection requirements imposed on the best vertex in an event (lowest χ^2/ndf)
- A significant portion of pair production events produces 3 vertices (3 combinations of outgoing μ and e^+e^- pair tracks); a requirement of a single reconstructed vertex with relatively low χ^2/ndf provides an effective veto against the most important background



- Simulation output: kinematic correlation for signal (δ-ray), pair production and other background processes; muon track is always assumed to have a lower scattering angle, causing the misidentification visible on the left side of the left plot below, which will be mitigated by introducing muon chambers and ECAL in the future



- The physical origin of an event is taken to be the process that created the Monte Carlo track linked to the reconstructed electron

Conclusions

- MUonESim application developed for the evaluation of different Geant4 versions and physics configurations: estimation of the multiplicity of secondary particles per run due to different muon processes, energy loss, angular correlations
- FairMUonE introduced as the official MUonE software and ready for the full simulation and reconstruction for both the upcoming test run and the final detector
- Future plans: improved generator of pair production events to better estimate background contributions; a custom MUonE physics list for Geant4; study of the data collected during the upcoming test run using NLO signal and pair production Monte Carlo samples

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