Material budget imaging with multi-GeV electrons - calibration and applications for 2D material scanning.

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Motivation.

- when a charged particle traverses a material, it interacts with the nucleus's electric field and can be deflected via Coulomb scattering
  - for a material traversal, many small-angle scatterers sum up to an effective deflection of the incident particle, called multiple Coulomb scattering
  - the deflection angle depends on the material's density and thickness
  - the material budget is defined with the thickness x and the material specific radiation length $X_e$ as
  $\epsilon = \frac{x}{X_e}$

- minimizing the material budget is important factor in the design of tracking detectors
  - e.g. the new ATLAS Inner Tracker (ITk) [1]
  - radiation length values not known for each material/component (e.g. composites, glues)
  - approximate values for detector simulations
  - idea: direct measurement of the radiation length/material budget of materials/objects

Method.

- the scattering distribution can be described in the core by a Gaussian function (central-limit theorem) plus non-Gaussian tails due to less frequent hard scatterings
  - the theoretical description of multiple Coulomb scattering was done by Molière, but the Highland formula serves as a good approximation:
    $\theta = \frac{13.6}{E_{LP}} \sqrt{\frac{1}{\epsilon} + \frac{0.036}{\epsilon^2}}$
  - exploiting the dependence between the width of the scattering distribution and the material budget in a test beam experiment - use of the DESY II test beam facility [2] with electrons between 1 and 6 GeV/c
  - measurement of the deflected particle tracks after material traversal with highly sensitive beam telescopes - use of the high resolution EUTelescope beam telescopes [3] with track resolution of ~2 μm
  - reconstruction of particle tracks and unbiased measurement of the individual scattering angles - use of the EUTelescope reconstruction framework [4] with the General Broken Lines (GBL) track model

Analysis.

- the scattering distribution depends on the material type and thickness as well as the beam momentum - width of scattering angle distribution is changing
  - evaluation of a suitable width estimator for the kink angle using a statistical approach with the RMS and a fitting approach with the Gaussian fit for the inclusive and binned analysis - good choice are estimators applied on the 99% quantile

- reconstruction yields two independent measurements of deflection angle in horizontal and vertical plane
  - kink angles are fully uncorrelated
  - their estimators are correlated
  - combination kin increases statistics

Conclusion.

- The material budget imaging technique allows to investigate experimentally in a test beam experiment the position-resolved material distribution of an object under test.
  - A fully functional workflow (test beam experiment - offline track reconstruction - analysis of scattering angle distributions) were established and analyzed in detail.
  - Several effects on the scattering distribution (correlation, acceptance, etc.) were studied.
  - A calibration procedure using the input of known material samples was implemented.
  - The reconstruction of high resolution images of the 2D material distribution of complex structures including the possibility of image stitching was demonstrated.