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

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Motivation.

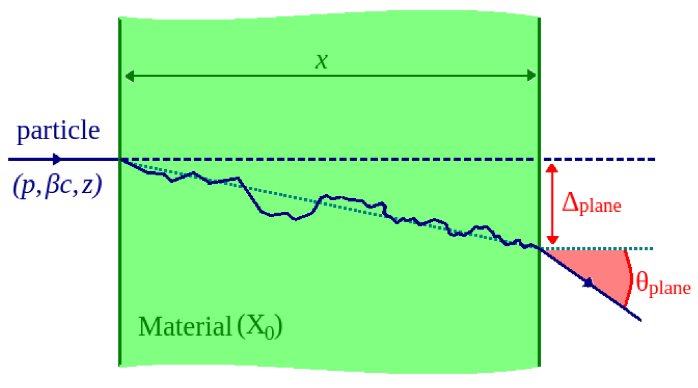
» when a charged particle traverses a material, it interacts with the nuclei's electric field and can be **deflected** via Coulomb scattering

» for a material traversal, many small-angle scatters 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** ε is defined with the **thickness x** and the material specific **radiation length** X_0 as

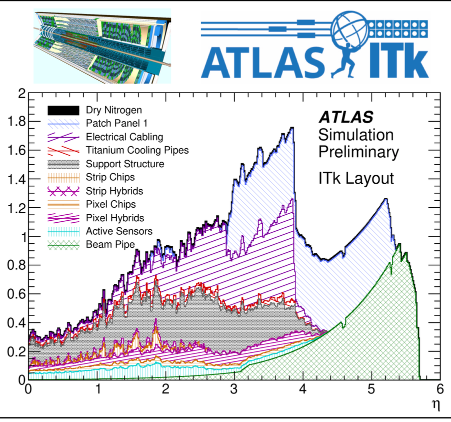
$$\epsilon := \frac{x}{X_0}$$



» 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

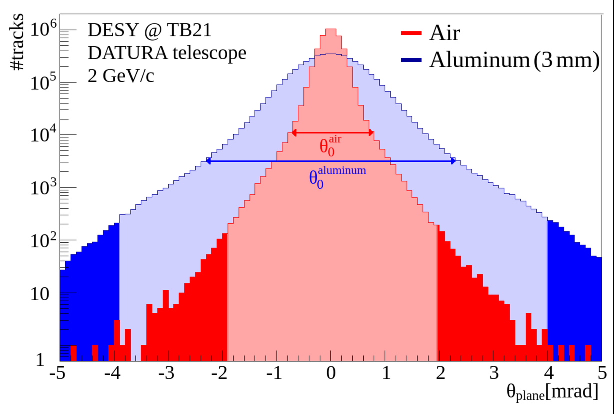


Method.

» 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 scatters

» the theoretical description of multiple Coulomb scattering was done by Molière, but the **Highland formula** serves as a good approximation:

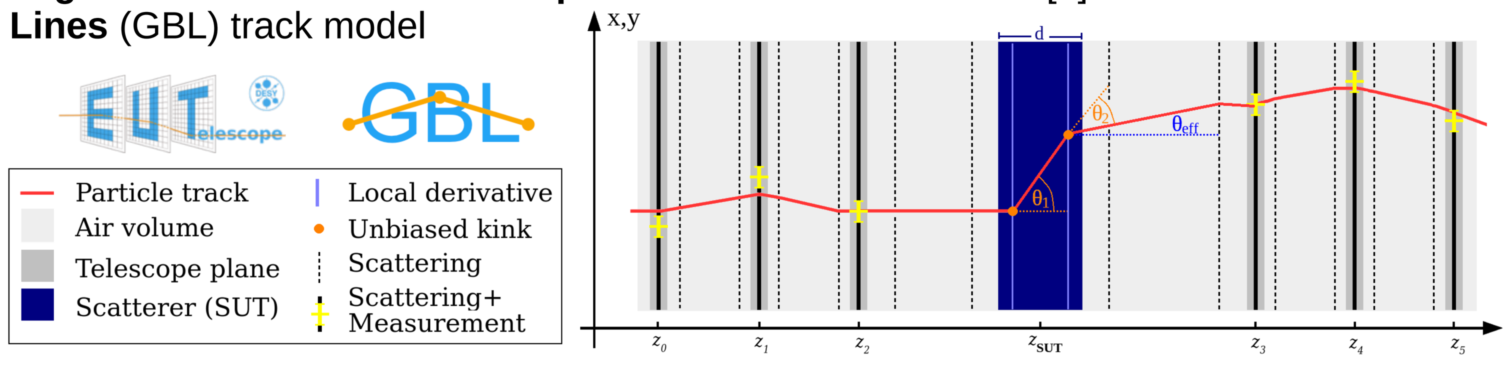
$$\theta_0 = \frac{13.6\,\mathrm{MeV}}{\beta c p} z\sqrt{\epsilon}\left(1+0.038\ln(\epsilon)\right)$$



» 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 **EUDET-type beam telescopes** [3] with track pointing 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



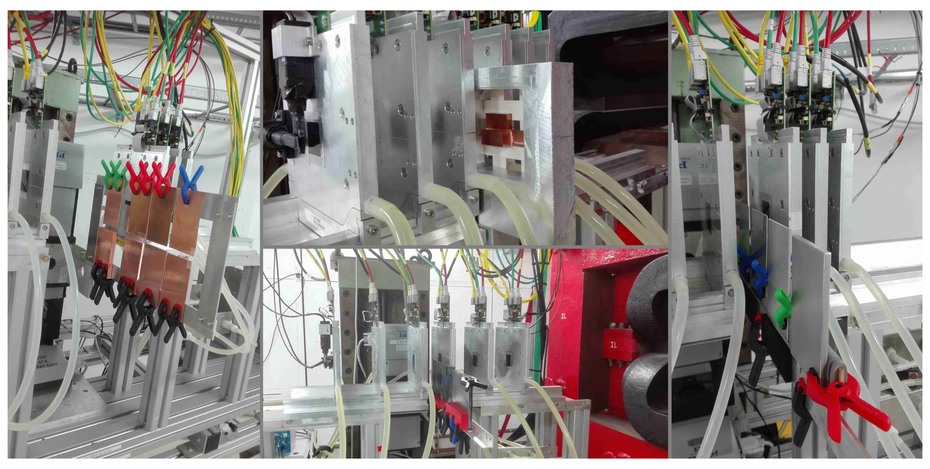
Experiment.

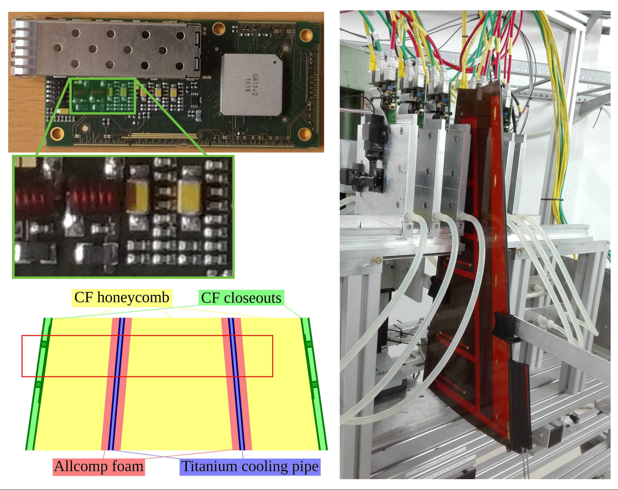
» several **test beam campaigns** on material budget studies were performed at DESY [2] using the DATURA (TB21) and DURANTA (TB22) beam telescopes [3]

» systematic testing of **beam and telescope parameters** → **momentum scan** between 1 to 6 GeV/c and variation of **telescope geometry** to optimize angular and spatial resolution

» fixed **measurement routine**:
→ choose parameter settings
→ measure **air scattering** effect
→ insert **scatterer-under-test**

» investigate **homogeneous material** samples with **known** X_0
→ types: Al, Cu, C, Ni, Fe, Sn, Ti, W
→ thickness: 0.05 to 10.0 mm
→ material budget: $3.5\cdot10^{-4}$ to 1.42



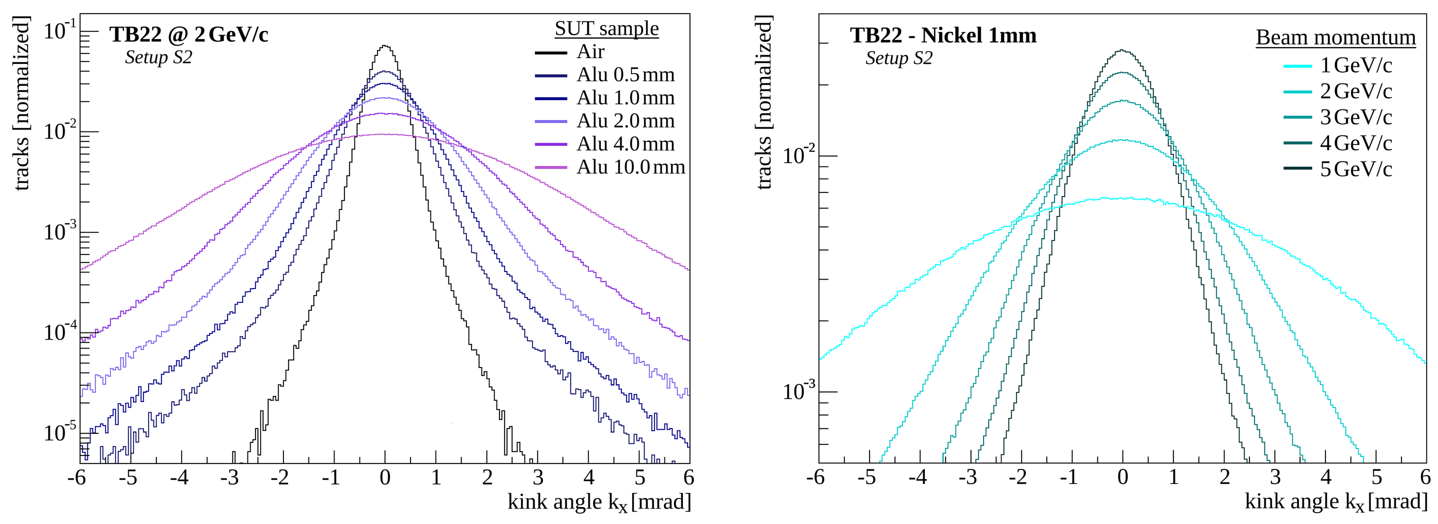


» investigate **complex structures** planned for the ATLAS ITk detector [1] with **unknown** X_0
→ **multi-layered PCB** with SMD components
→ **petal core:** CFK sandwich with embedded Ti pipe

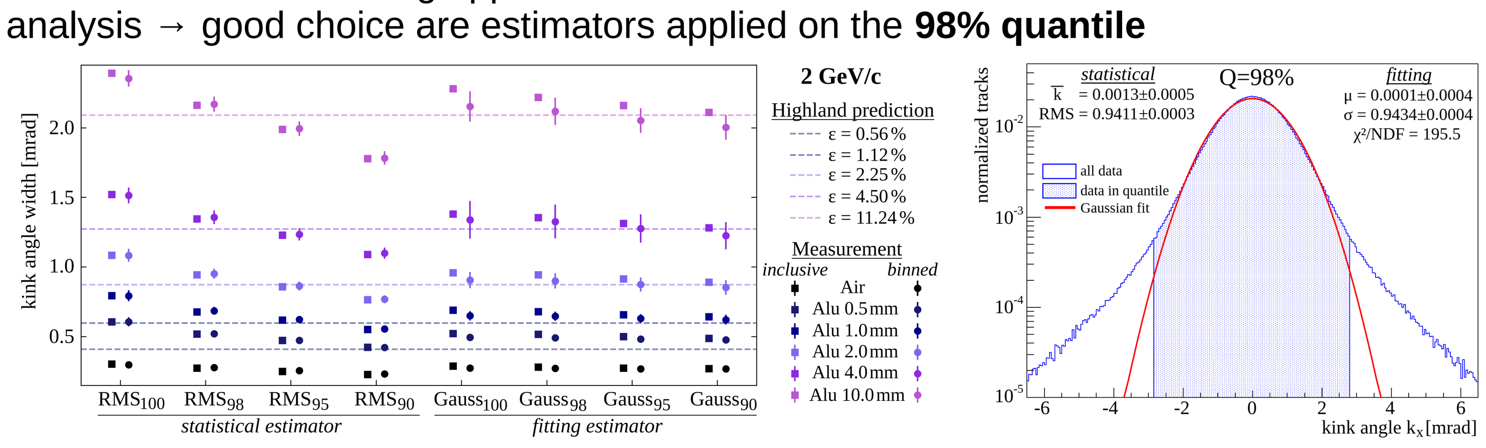
» **position-resolved** analysis of material budget distribution allows **2D imaging** of structures
→ use of **x-y translation** stages to image larger surface than **telescope acceptance** (1x2 cm²)

Analysis.

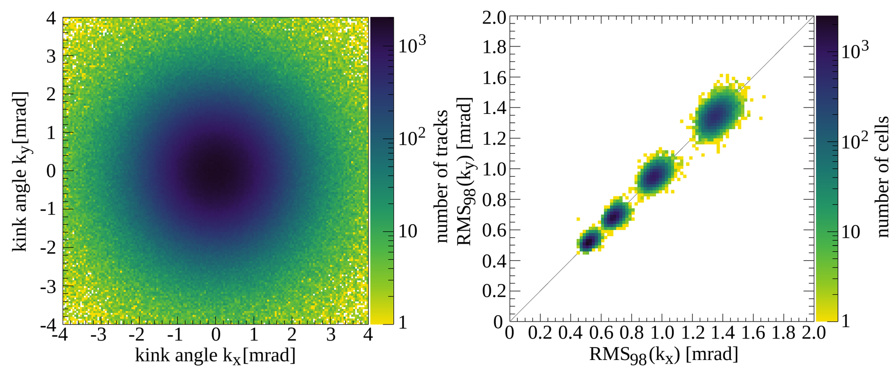
» the scattering distribution depends on the **material type and thickness** as well as the **beam momentum** → width of scattering angle distribution is changing



» 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 **98% quantile**



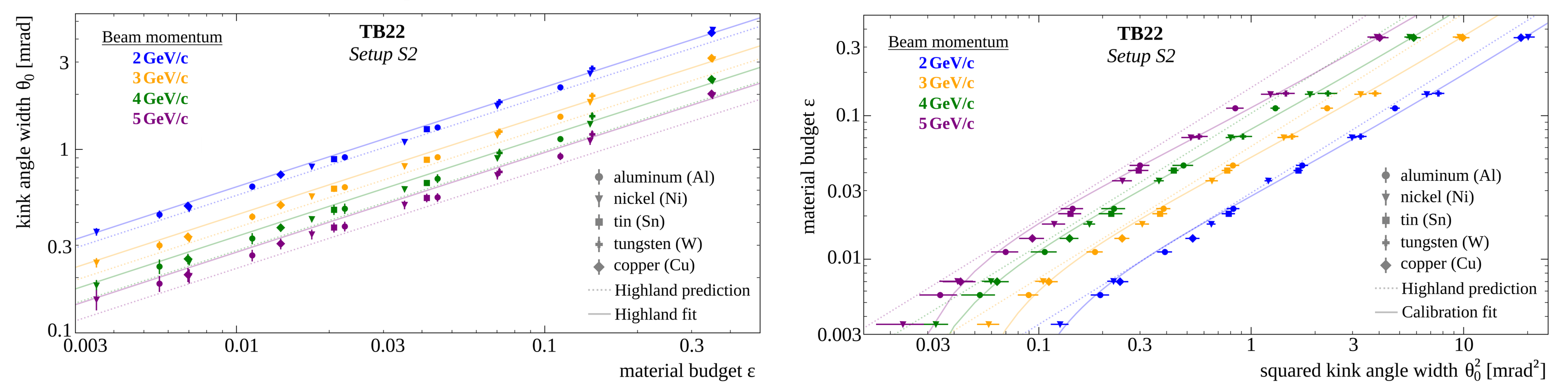
» reconstruction yields two independent measurements of deflection angle in **horizontal** and **vertical** plane
→ **kink angles are fully uncorrelated** but their estimators are **correlated**
→ **combination** k_{x+y} increase statistics

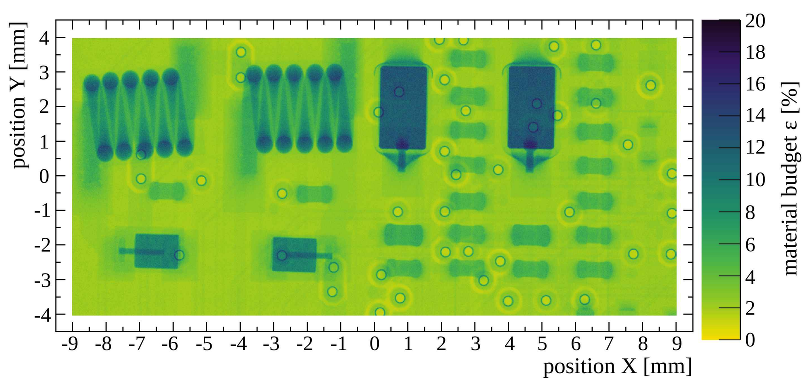


Results.

» **calibration** of the reconstructed scattering angle width after **subtracting effect of air** scattering using **samples with known material budget**
→ *model-dependent Highland calibration* and *model-independent empirical calibration*

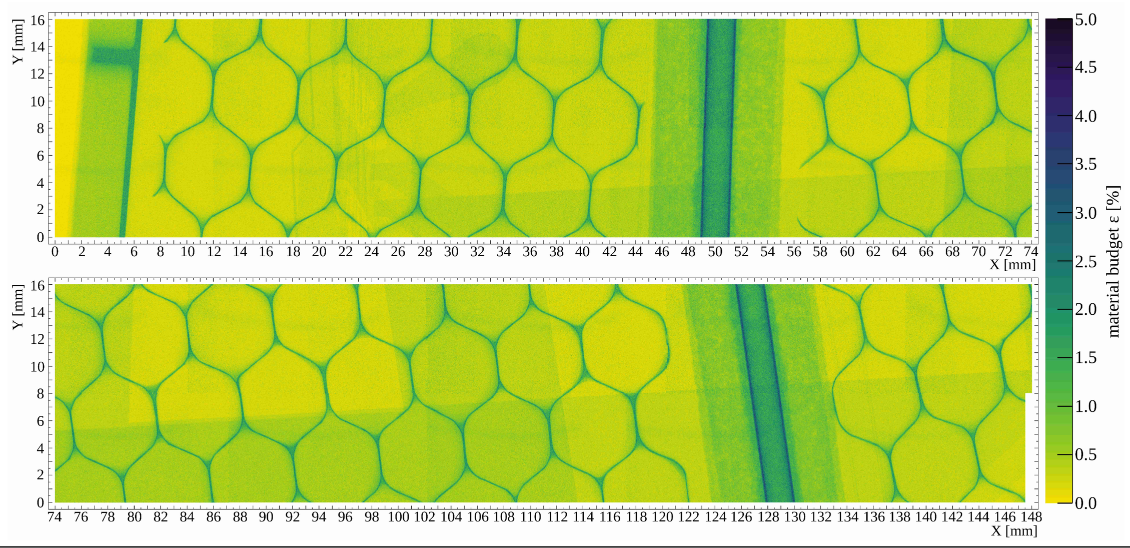
$$\theta_0 = f(\epsilon) = a\cdot\frac{13.6\,\mathrm{MeV}}{p}\sqrt{\epsilon}\left(1+0.038\ln(\epsilon)\right) \qquad \epsilon = f\left(\theta_0^2\right) = \left[p_0 + p_1\cdot\theta_0^2\right]\cdot\left[1+\left(\theta_0^2\right)^c\right]$$





» 2D material budget distribution of the **multi-layered PCB** reconstructed with an image cell size of **(10 µm)²** shows
→ internal structure of SMD components (e.g. *coils with individual windings*)
→ gold *soldering pads* with higher ε compared to background of PCB
→ *electrical vias* with size of only 500 µm

» reconstructed material budget image of **petal core** with an image cell size of **(10 µm)²** after stitching of x-y scan
→ covering a total area of (148 × 16) mm²
→ internal structure with *CF honeycomb* and *Ti pipe* surrounded by *carbon-based foam* clearly visible



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 **work flow** (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.

Outlook.

» A full overview over the **material budget imaging analysis** can be found in [5].
→ further studies on **influencing effects** and **radiation length extraction** for ITk materials
→ investigation of **energy loss** effects and first attempt with a **corrected Highland model**

» Possibility to enhance material budget imaging method into **3D tomography** [6].

» Exploring the **future potential** of this new imaging technique in various applications.
→ creation of a radiation length database of materials for (tracking) **detector developments**
→ study high-Z material assemblies (not accessible by photon CT) for **industry application**
→ use of imaging technique as electron CT method in **medical applications**

References

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[2] R. Diener *et al.*, The DESY II test beam facility, NIMA, vol. 922, pp. 265-28 (2019)

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[5] J.-H. Arling, Detection and Identification of Electrons and Photons, DESY-THESIS-2020-022 (2020)

[6] P. Schütze *et al.*, Feasibility of track-based multiple scattering tomography, APL vol.112, p.144101 (2018)

Acknowledgements

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