Electrical signals induced in detectors by cosmic rays: a reciprocal look at electrodynamics

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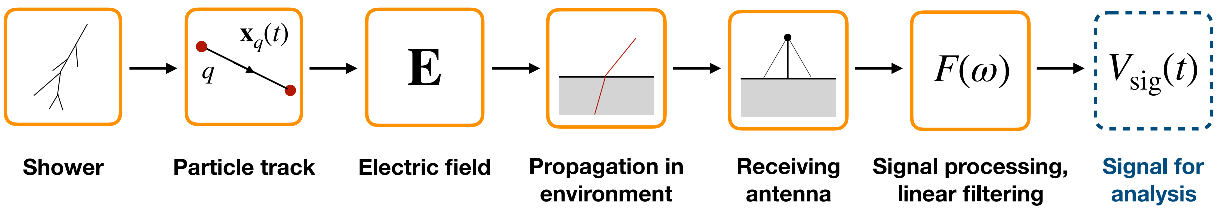
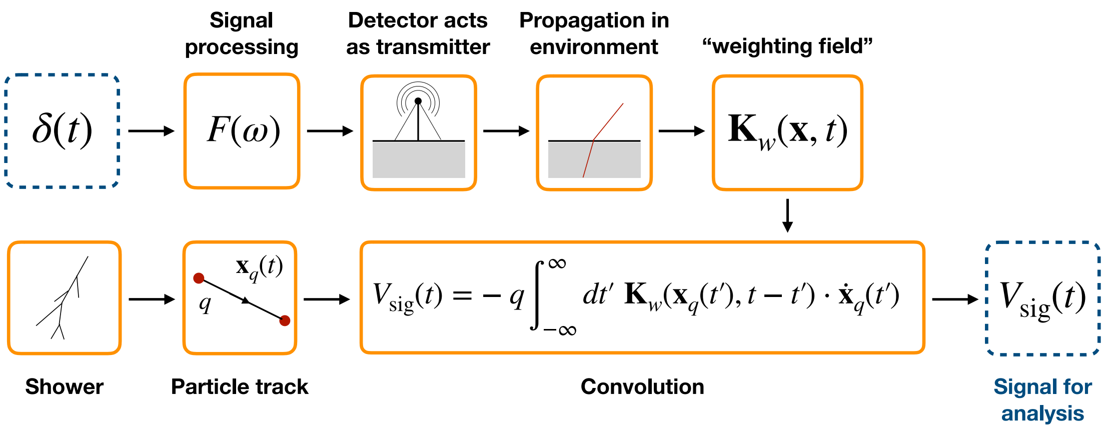
To facilitate the experimental study of radio emissions produced by cosmic ray-induced showers, high-fidelity simulations of these radio signatures have been developed over the past years. Given the trajectories $\mathbf{x}_q(t)$ of the charged particles in the shower, the computation of the signal induced in an experimental apparatus typically proceeds as shown below.



The electric field $\mathbf{E}$ generated by an isolated shower is evaluated as the superposition of the contributions effected by the individual particle track segments (which are known analytically). The radiation component is then propagated through the environment (which can be nontrivial, e.g. in the presence of varying atmospheric conditions, or ice-air transitions), the antenna of the detector, and the signal processing pipeline of the experiment. This gives rise to the filtered signal $V_{\mathrm{sig}}(t)$ which forms the starting point for event reconstruction and analysis.

In this contribution, we outline an alternative approach. We show that the signal $V_{\mathrm{sig}}(t)$ can also be computed through a convolution of the particle trajectories $\mathbf{x}_q(t)$ with a particular electric field distribution $\mathbf{K}_w(\mathbf{x}, t)$. This holds true in full generality, and the signal computed in this way automatically includes all electrodynamic effects.



The "weighting field" $\mathbf{K}_w(\mathbf{x}, t)$ effectively acts like a Green's function that encodes all properties of the detector and its environment. Using reciprocity relations inherent to classical electrodynamics, we show that $\mathbf{K}_w(\mathbf{x}, t)$ corresponds to the electric field distribution that would ensue if the detector was operated as a *transmitting* antenna. This correspondence allows the weighting field to be computed using standard numerical electrodynamic solvers (or analytically in certain simple cases).

Crucially, this (expensive) computation can be done a-priori, and the weighting field then saved to disk. At simulation time, only a numerical convolution with the shower needs to be performed, irrespective of the complexity of the environment.