Simulation and Reconstruction of Charged Particle Trajectories in a Time Projection Chamber with Orthogonal Fields

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Outline

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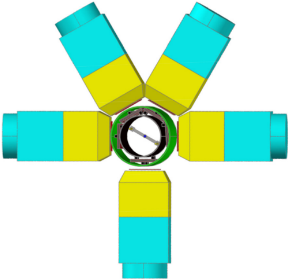
1. Motivation
2. Track Simulation
3. Track Reconstruction
4. Energy Reconstruction
5. Summary & Future

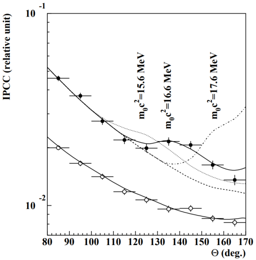
Motivation: ATOMKI Measurements

- Measurement of anomalies in the angular correlation of an electron-positron pair internally produced in excited ^{8}Be and ^{4}He

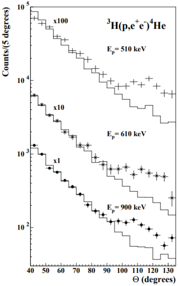


ATOMKI spectrometer. [**atomki_det**]

Beam pipe (black), MWPC, ΔE det. (red), E scintillators (yellow), light guides (blue)

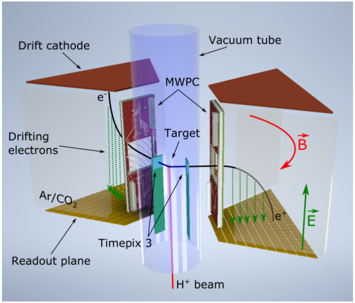


^{8}Be, e^+e^- pair angular correlation. [**atomki_be**]

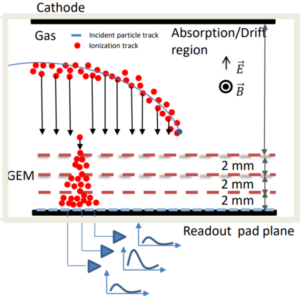


^{4}He, e^+e^- pair angular correlation. [**atomki_he**]

- Time Projection Chamber with Orthogonal Fields (OFTPC) – electric and magnetic field perpendicular (gas mixture Ar/CO_2 – 70/30)

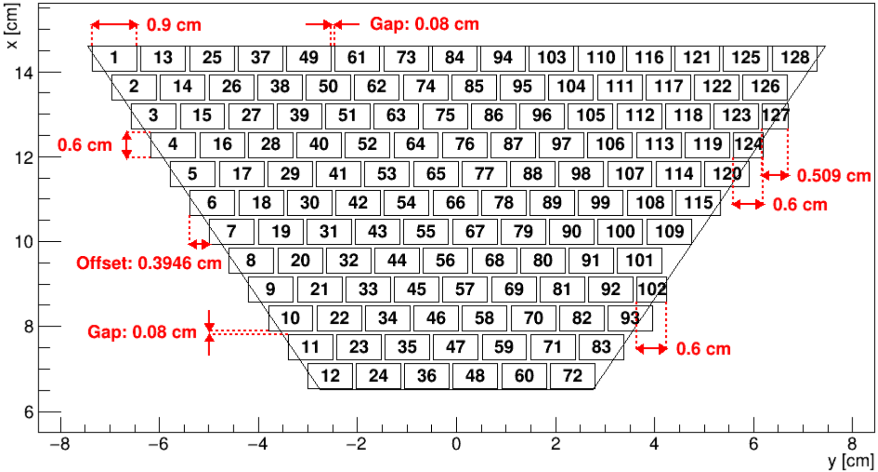


Two out of the six OFTPC chambers. **[x17_utef]**



OFTPC with a triple gas electron multiplier (GEM) readout. **[x17_utef]**

OFTPC: Pad layout

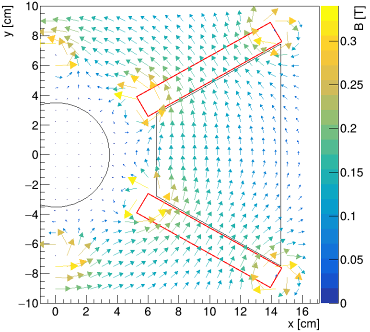


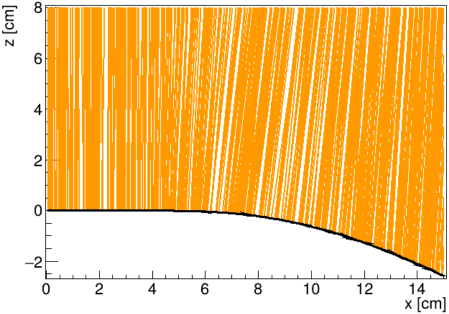
OFTPC: Reasons for Orthogonal Fields

- No solenoid – permanent magnets used to generate the field
  - Parallel fields difficult to create with permanent magnets
- Space constraints – granularity of the TPC readout limited in order to fit one SAMPA/SRS hybrid in each of the six sectors
  - Parallel fields would bend particles parallel to readout, requiring much larger number of pads
  - These trajectories would extend to more than one sector, requiring alternative architecture of the detector
- We will show a similar resolution for significantly lower cost

OFTPC: Complications

Inhomogeneous magnetic field (simulated using Maxwell [**ansys_maxwell**])





- The field interferes with the direction of the drift of ionization electrons
- Curvature of the track is not constant in this field (deviation from a circle)

Outline

Track Simulation

- Garfield++ used for track simulation
  - Primary relativistic particle simulated using the HEED program [**HEED**]
  - Secondary ionization electrons simulated using microscopic tracking (uses equations of motion)
    - Relatively slow (typically 5-30 CPU hours per track), very precise, especially for small structures.
- Five batches of 9702 tracks with different initial parameters simulated on a grid (MetaCentrum [**metacentrum**])
  - Electrons and positrons
  - 11 different energies from 3 MeV to 13 MeV (covers range for ^{8}Be)
  - 21 different angles φ and 21 different angles θ (next slide)

Track Simulation

Spherical angles (θ,φ) with respect to z
θ taken from the equatorial plane xy

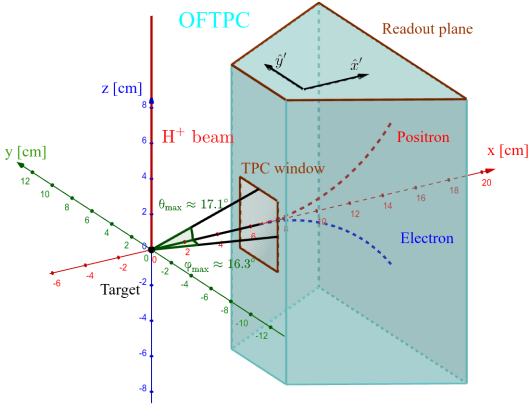
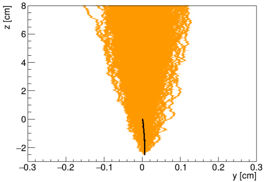


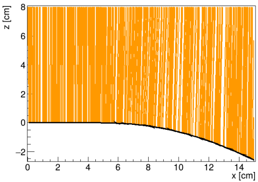
Diagram of the batch simulation parameters:
$\theta \in [-17.1°, 17.1°]$, $\varphi \in [-16.3°, 16.3°]$, $E_{kin.} \in [3, 13]$ MeV.

Simulated Track Example (microscopic tracking)

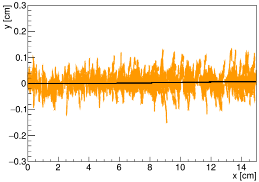
- Electron track with kinetic energy 8 MeV, $\theta = 0^\circ$ and $\varphi = 0^\circ$
- Diffusion less than 1.5 mm in both directions



Diffusion front view



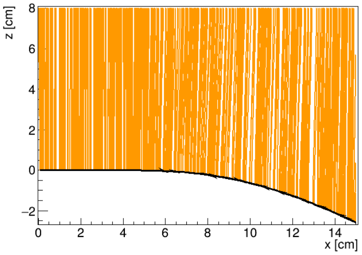
Electron drift



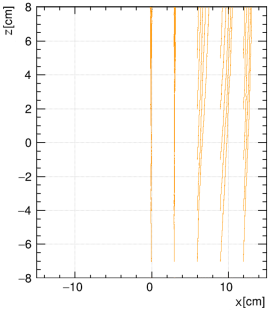
Diffusion top view

Ionization Electron Map Simulation

- We want an unambiguous map of the drift of ionization electrons for the reconstruction
- We can use a simulation of evenly spaced electrons
  - Current spacing 5 mm, 100 electrons simulated in each location with 0.1 eV energy in a random direction



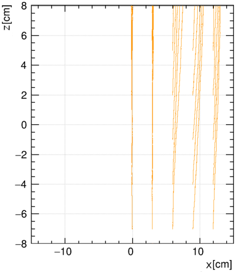
Electron drift



Partial simulation of the map

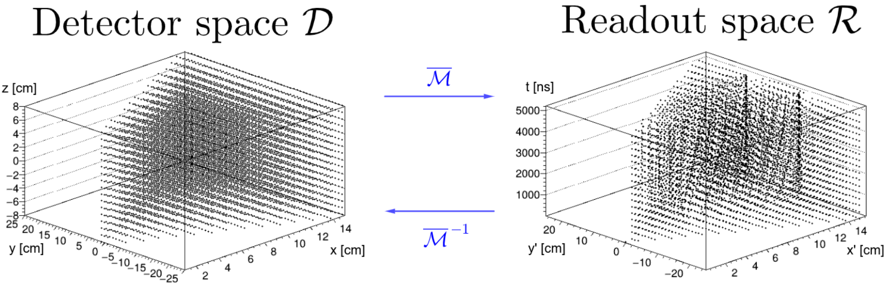
Ionization Electron Map Simulation

- As a result we get an approximation of a mapping from initial coordinates of the electrons (x, y, z) to the readout coordinates (x', y', t)
- By interpolating we can get the inverse map
- We can use the inverse map to finally create mapping from our discrete readout values (channel number, time) to voxels of the primary track



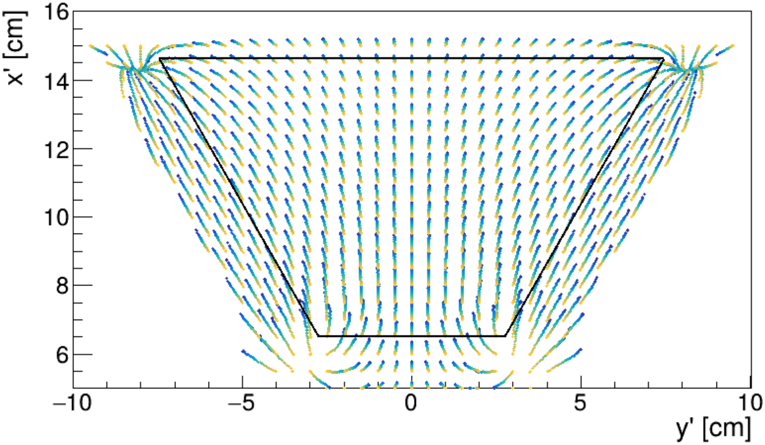
Partial simulation of the map

Ionization Electron Map Simulation



3D visualization of the simulated mapping $\overline{\mathcal{M}}$ and the inverse mapping $\overline{\mathcal{M}}^{-1}$.

Ionization Electron Map Simulation

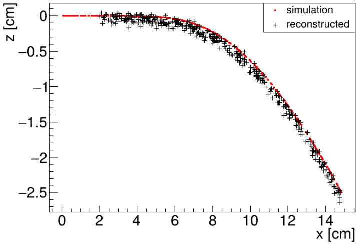


x and y coordinate distortion at different z values (denoted by colors).

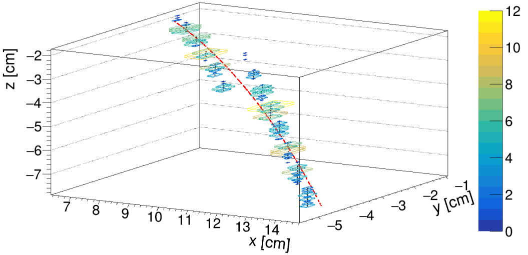
Outline

Track Reconstruction

- At first using only the inverse map (not accounting for readout pads)
- Later simple reconstruction with pads and time bins, counting the number of electrons in each bin

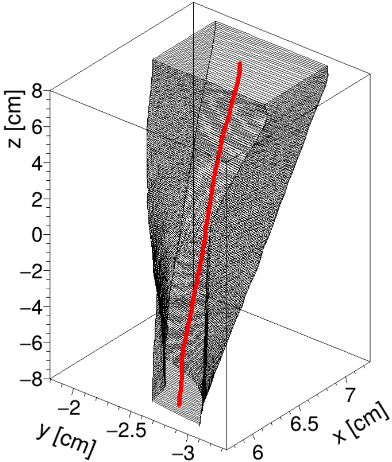


Original and reconstructed interaction points on the simulated track

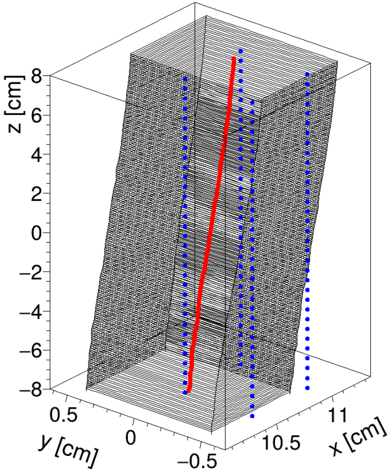


Reconstruction with pads

Inverse Mapping of Pads



Pad 12 (near the magnet pole)

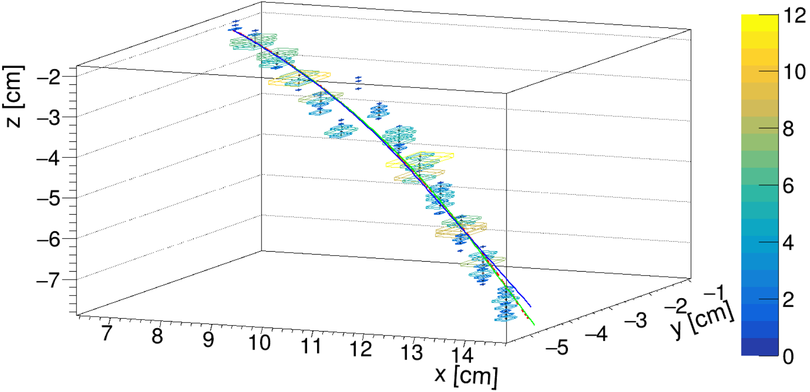


Pad 66

Outline

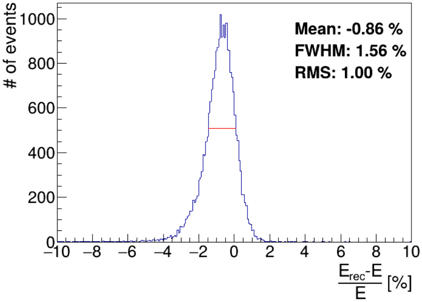
Energy Reconstruction

- Prefit with circle with smoothly attached lines
- Kinetic energy fit using 4^{th} order Runge-Kutta
- Known initial position and direction of the particle assumed
- Currently cca 0.3 CPU seconds per track

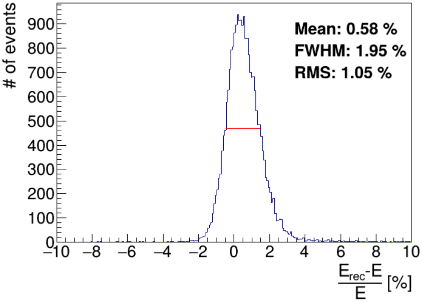


Energy Reconstruction Precision

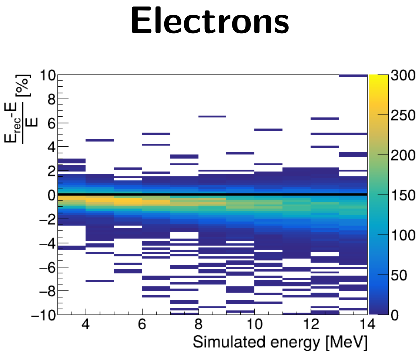
Electrons

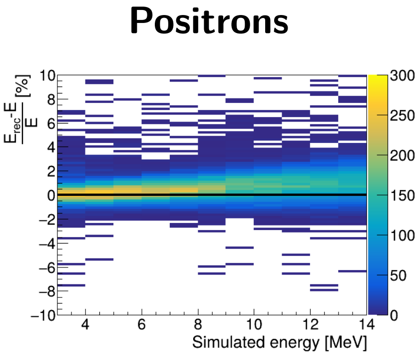


Positrons



Relative reconstruction deviation of the kinetic energy of electron and positron tracks (cca 24 000 of each simulated).





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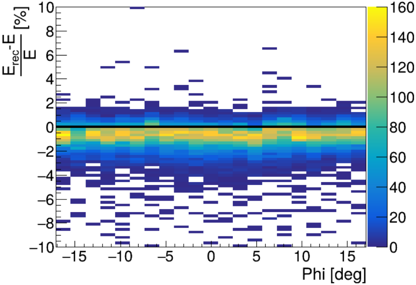
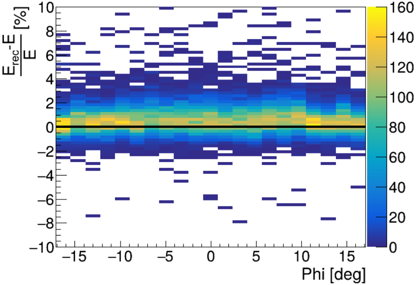


Positrons



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Energy Reconstruction Precision

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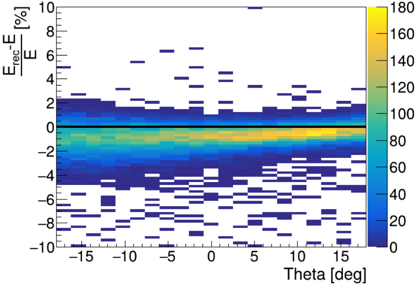
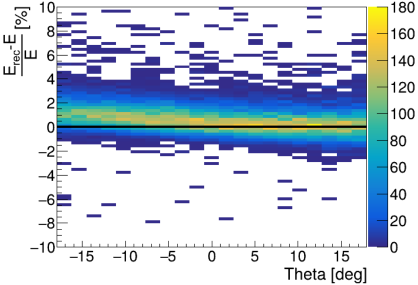


Positrons



Relative reconstruction deviation of the kinetic energy of electron and positron tracks (cca 24 000 of each simulated).

Outline

Summary

- Several batches of tracks have been simulated for testing purposes.
  - $\theta \in [-17.1^\circ, 17.1^\circ]$, $\varphi \in [-16.3^\circ, 16.3^\circ]$, $E_k \in [3, 13]$ MeV
- The map of secondary electron positions and drift times has been generated.
- The map has been tested by the track reconstruction.
- The results suggest that:
  - Current energy resolution (FWHM) is 1.6 % for electrons and 2.0 % for positrons.
  - OFTPC works well on a simulation level.
  - Some of the systematic errors can be corrected.

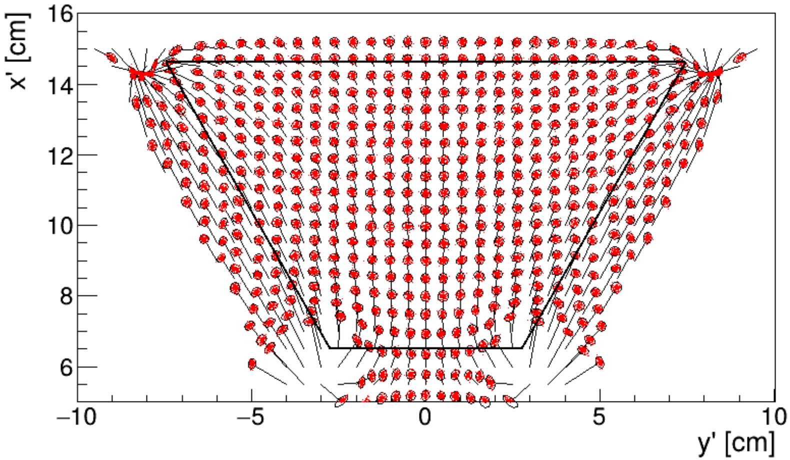
Future Steps

- Account for parasitic tracks caused by high energy secondary electrons
- Account for GEM in the simulation, charge distribution between pads
- Account for noise (denoising using a convolutional neural network — M. Gajdoš [**Gajdoš_2025**])
- Optimize Runge-Kutta integration fit with likelihood approach (instead of least squares) if needed
- Implement a faster simulation method for ionization electrons using the map
- Test different geometries
- Make a better simulation of magnetic and electric fields, compare with measurements

Thank you for your attention.

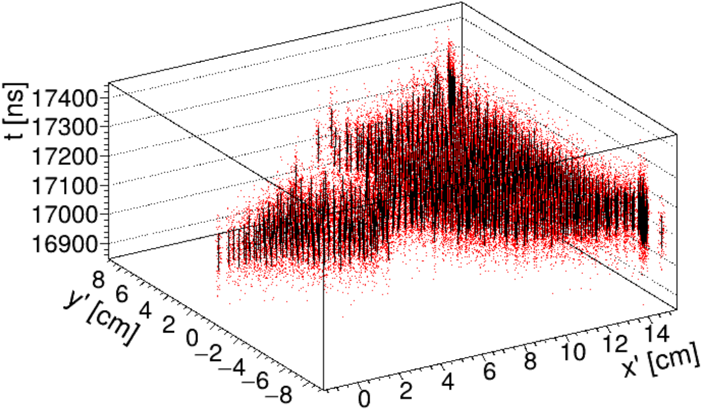
References I

Ionization Electron Map Simulation



Worst case x and y coordinate distortion for maximal initial distance from readout. Ellipses with 95 % confidence are shown for each starting position.

Ionization Electron Map Simulation

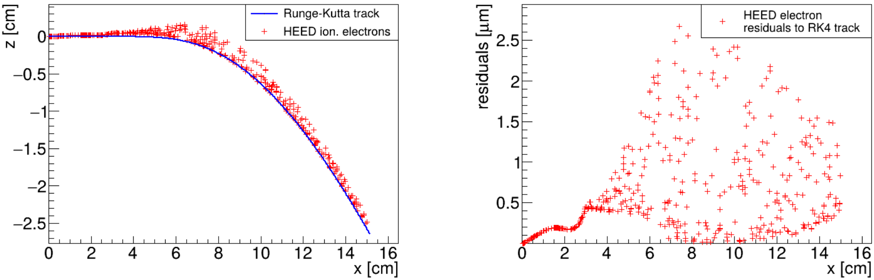


Mapping of the layer furthest from the OFTPC readout.

Reconstruction Testing Summary

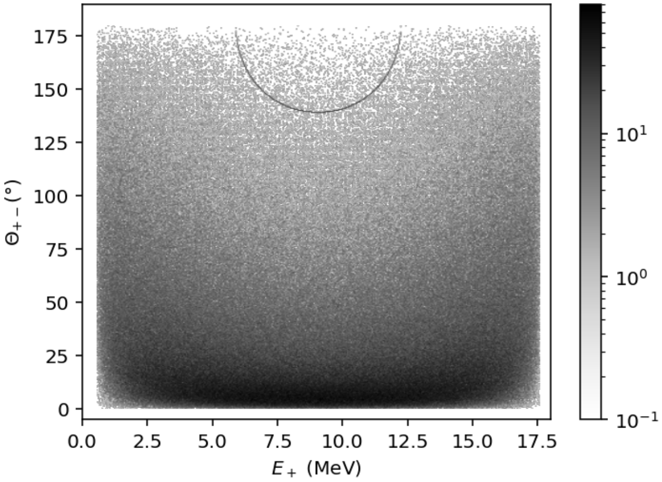
1. Ionization electron map simulation of secondary electrons in the entire volume of the OFTPC
2. Track(s) simulated using HEED and microscopic tracking
3. Counting the number of secondaries in each pad and time bin of the readout
4. Using the map to reconstruct the position of centers of pads for given centers of time bins
5. Fitting of the reconstructed points with circle and lines fit using least squares weighted by the number of secondaries in each point
6. Using the magnetic field in the middle of the track to get first energy estimate
7. Using the 4^{th} order Runge-Kutta fit with least squares to refine the energy estimate

Figure 3.3



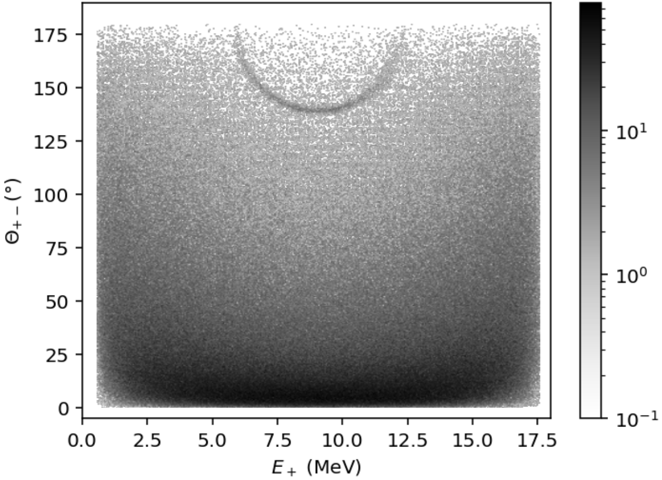
A comparison of the HEED track from the microscopic simulation in Sec. 3.1.1 with a Runge-Kutta track with the same initial parameters and $\tau_{\mathrm{step}} = 0.1$ ps (reducing the step further doesn't make a visible difference). In the view of the tracks on the left, the distance of the HEED ionization electrons from the RK4 track is exaggerated $1000\times$. On the right, the dependence of the HEED electrons residuals (i.e., their shortest distance to the RK4 track) on their z-coordinate is shown.

Electron-Positron Internal Pair Creation



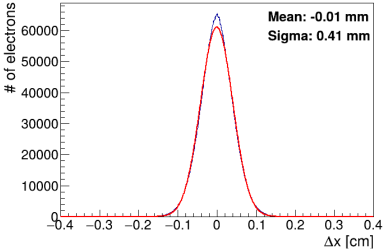
Histogram of e^+e^- pair angle and positron energy produced by standard IPC and by the decay of a hypothetical boson X17 (branching ratio $3 \cdot 10^{-3}$).

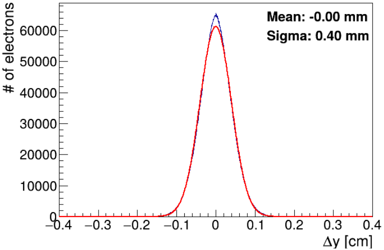
Electron-Positron Internal Pair Creation

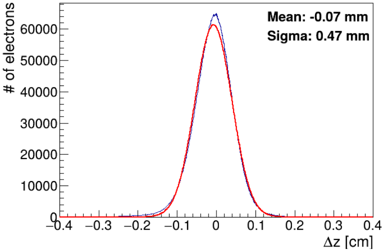


The same histogram after accounting for predicted reconstruction errors.

Ionization Electron Map Reconstruction Residuals







Track Simulation – TPC Window