K^+ Production at MINERvA

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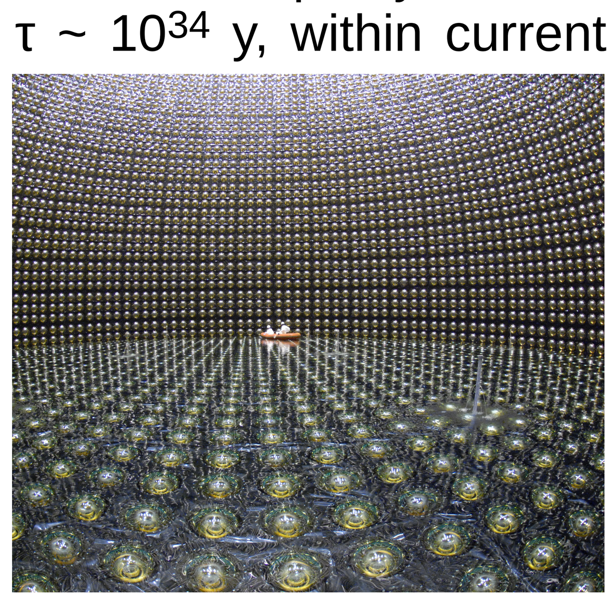
Proton Decay

Proton decay is a common feature of Grand Unification Theories (GUTs). Baryon number (B) and lepton number (L) are not independently conserved in these theories, only B-L. This allows for proton decay to a meson and an antilepton.

The simplest GUTs predict $p \rightarrow e^+ \pi^0$ with $\tau \sim 10^{30}$ y, and have been excluded by direct searches at Super-Kamiokande. Supersymmetric (SUSY) GUT models predict $p \rightarrow K^+ \bar{\nu}$ with $\tau \sim 10^{34}$ y, within current experimental constraints.

$^{16}O \rightarrow {}^{15}N + \bar{\nu} + K^+$, $K^+ \rightarrow \mu^+ + \nu_\mu$

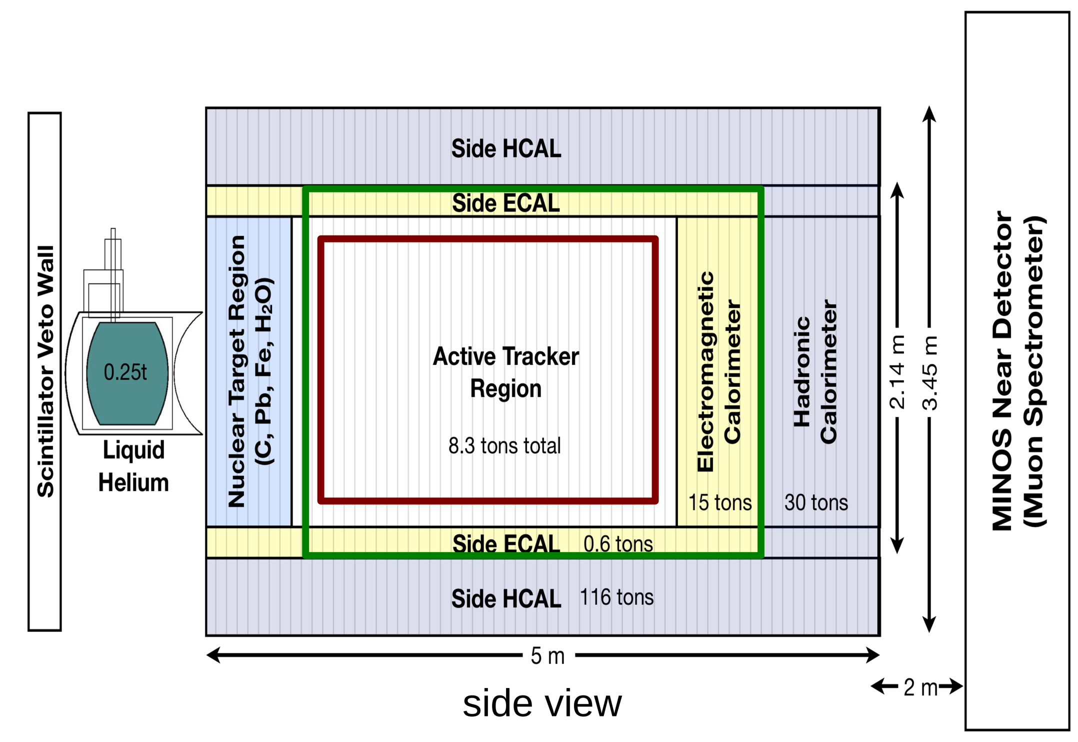
$\nu_\mu + {}^{16}O \longrightarrow {}^{15}N + K^+ + \Sigma^- + \nu_\mu$



Besides a de-excitation photon, proton decay products are **invisible** to a water Cherenkov detector. Only 152 MeV μ^+ from K^+ decay is detected.

K^+ production by atmospheric neutrinos form a background for proton decay searches when all other final-state particles are below threshold. MINERvA plans to measure K^+ production by neutrinos and produce a background constraint for searches for $p \rightarrow K^+ \bar{\nu}$.

MINERvA Detector



side view

front view

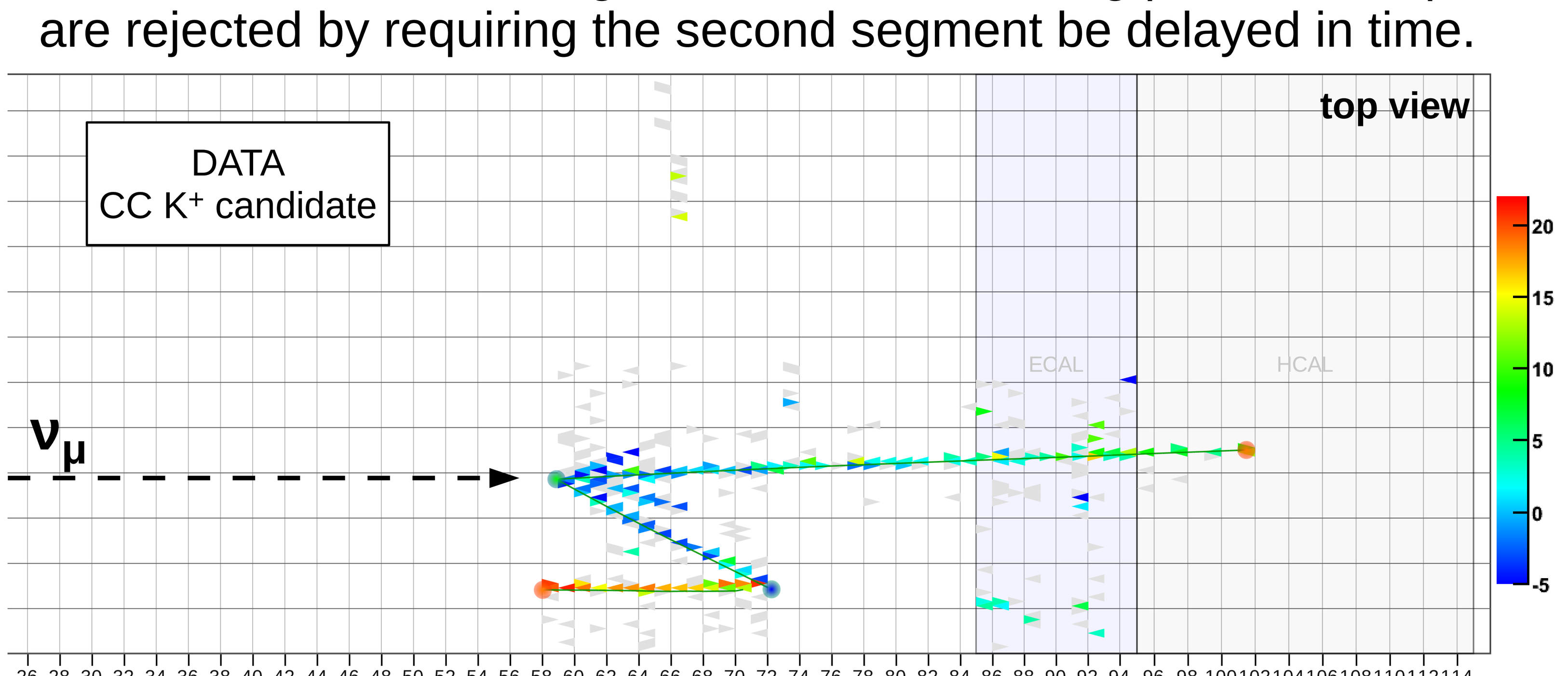
The MINERvA central tracker is fully active, composed of polystyrene scintillator (CH). Muons and high-momentum hadrons can exit the tracker and enter the side or downstream hadronic calorimeter. We require an interaction vertex in the red volume, and that the kaon endpoint be in the green volume. The upstream nuclear targets and the downstream MINOS near detector are not used for this analysis.

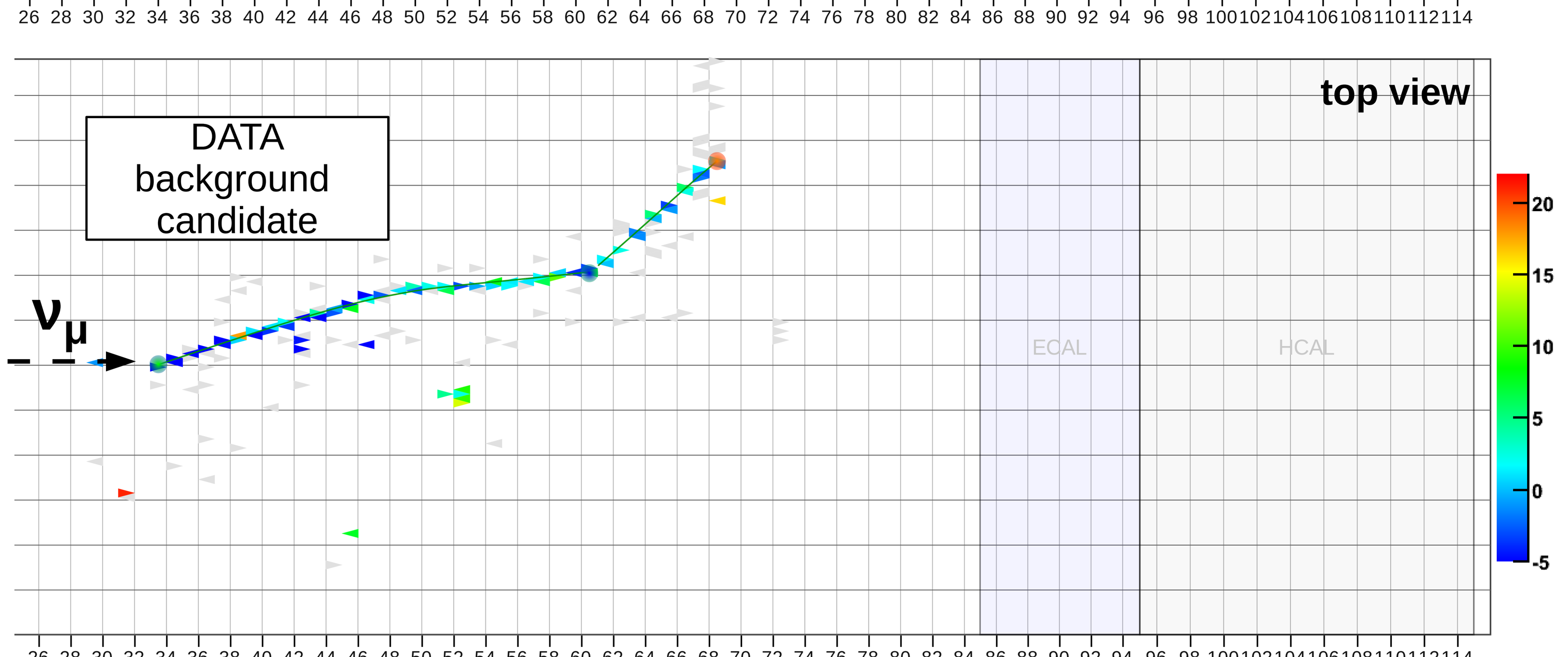
$\nu_\mu + {}^{16}O \longrightarrow {}^{15}N + K^+ + \Sigma^- + \nu_\mu$, $K^+ \rightarrow \mu^+ + \nu_\mu$, $\Sigma^- \rightarrow \pi^- + n$

MINERvA can detect kaons below water Cherenkov threshold and reconstruct this event.

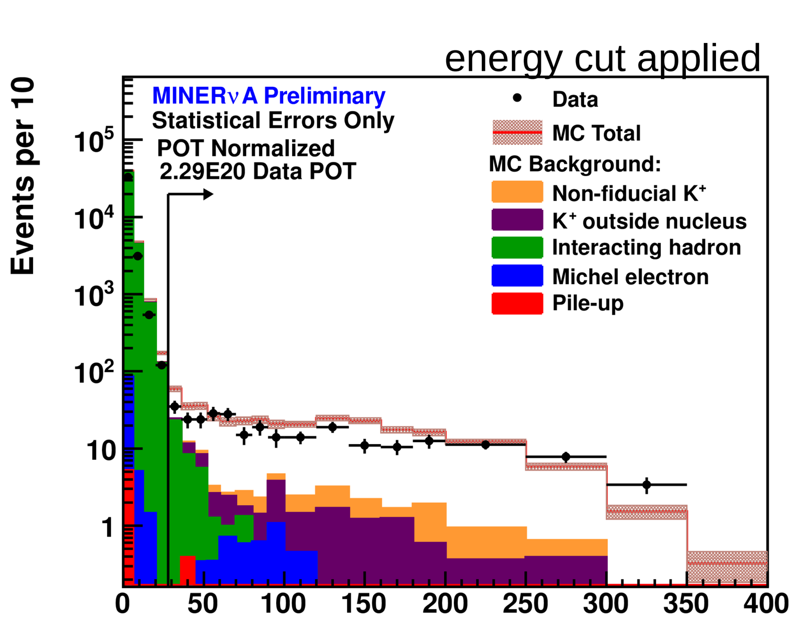
Kinked Track Reconstruction

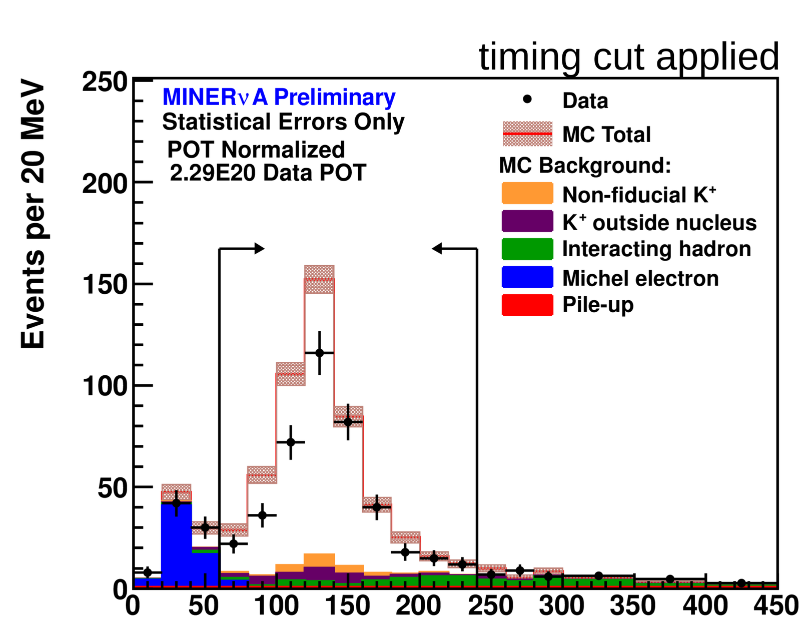
A kinked track is a signature of $K^+ \rightarrow \mu^+ \nu_\mu$ decay at rest, with a lifetime of 12.4 ns. Backgrounds from interacting protons and pions are rejected by requiring the second segment be delayed in time.





The hit times of the kinked tracks are fit under two hypotheses: 1) the true times of the segments are the same, and 2) the second segment is delayed. Interacting hadrons are fit equally well under each hypothesis, while a $K^+ \rightarrow \mu^+ \nu_\mu$ decay at rest will strongly prefer hypothesis 2 when the decay time is large. The log-likelihood ratio of the two hypotheses is used as a discriminating variable.



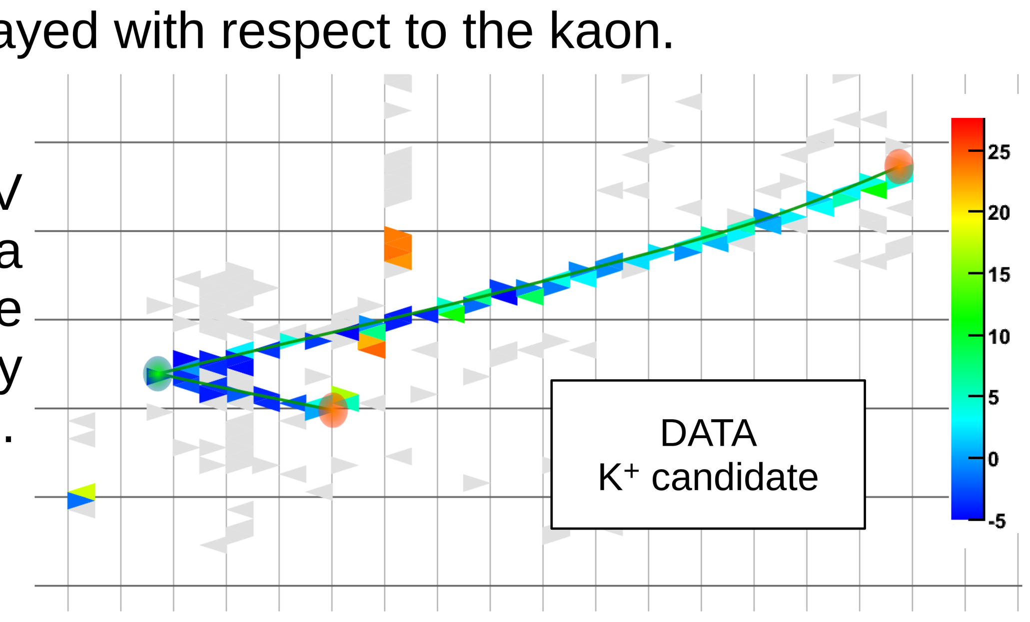


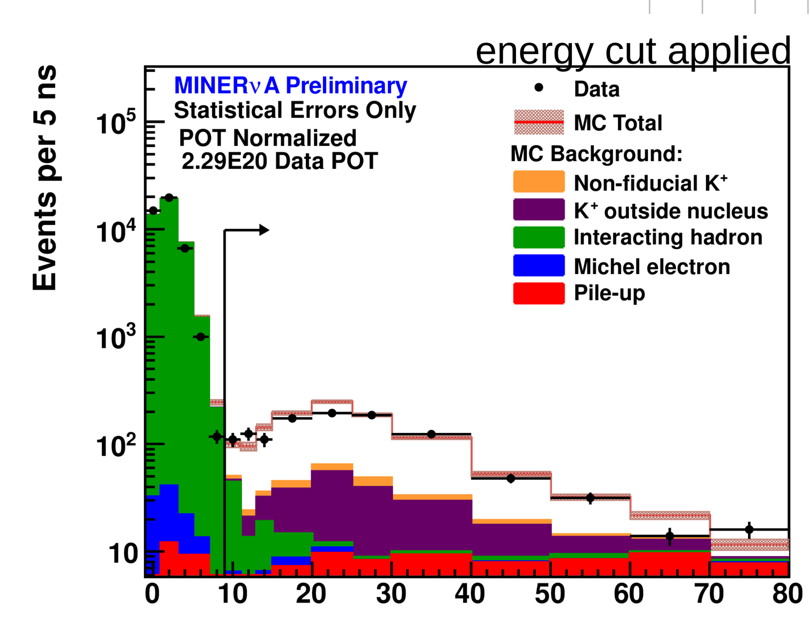
Left: The log-likelihood ratio of the two timing fits separates kaon decays at rest from the interacting hadron background.
Right: Michel electrons from $\pi^+ \rightarrow \mu^+ \rightarrow e^+$ will pass the timing cut, but can be rejected because the energy of the muon from $K^+ \rightarrow \mu^+ \nu_\mu$ is larger than the Michel electron energy.

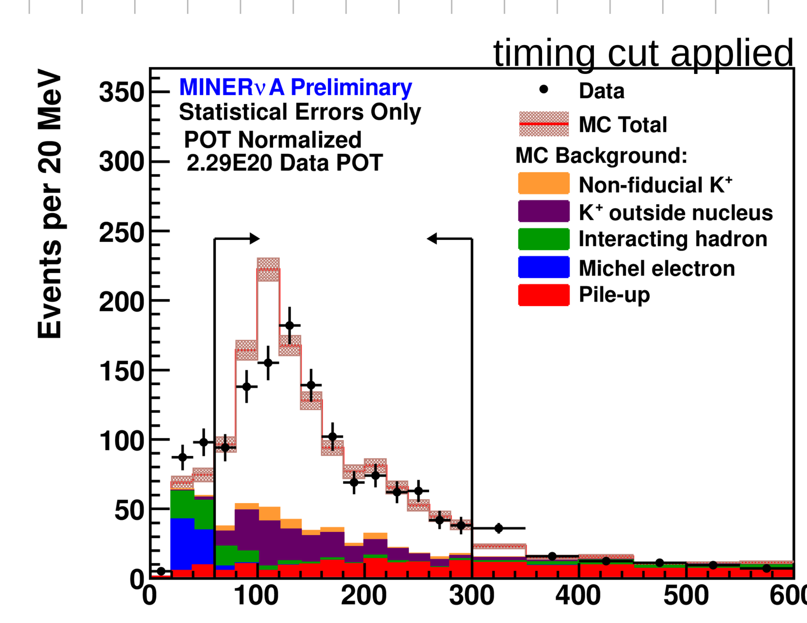
"Time Sliver" Reconstruction

The muon from $K^+ \rightarrow \mu^+ \nu_\mu$ is isotropic, and MINERvA's tracking efficiency is poor at high angles. Tracks are rarely found for $K^+ \rightarrow \pi^+ \pi^0$. When no kinked track is found, we look for hits in a narrow "time sliver," delayed with respect to the kaon.

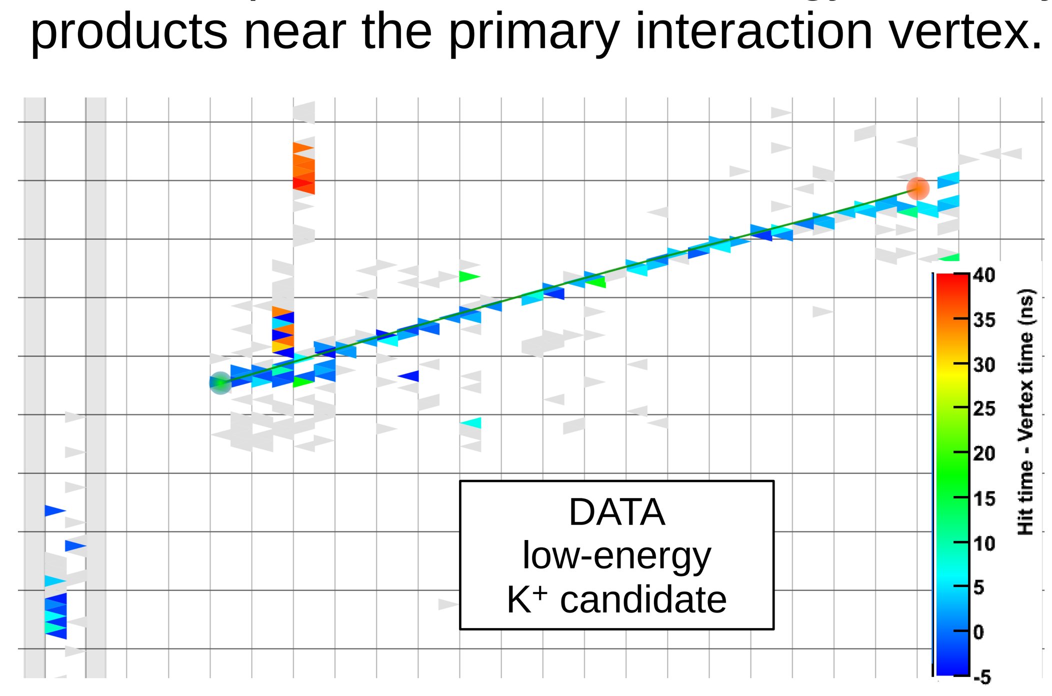
In this event, 138 MeV of energy is found in a time sliver near the endpoint of a primary track, 23 ns later in time.







Kaons below 150 MeV of kinetic energy cannot be tracked. We can infer the presence of a low-energy kaon by looking for the decay products near the primary interaction vertex.



In this event, no K^+ track is found. The event is accepted because 132 MeV of energy is found near the pirmary vertex 39 ns after the reconstructed vertex time.