Multi-track reconstruction algorithm in the Mu2e experiment

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The Mu2e experiment

Production Solenoid

- 8 GeV pulsed proton beam collides with a tungsten target producing π's and K's that decay in μ's.

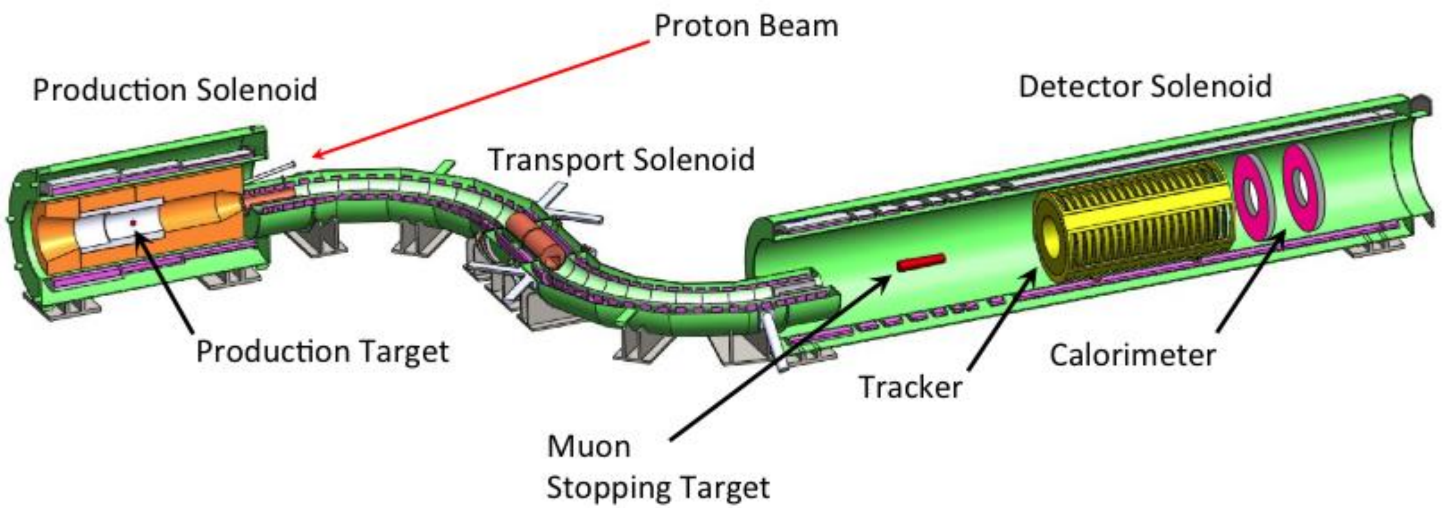
Transport Solenoid

- It selects μ's with $p < 100$ MeV/c.
- A rotating collimator selects the μ^+ or μ^- beam.

Detector Solenoid

- μ^- stop in the Al Stopping Target.
- Straw-tube tracker and crystal calorimeter detect the conversion e^-.

- Goal: Search for neutrino-less $\mu^- N \rightarrow e^- N$ coherent conversion in the field of Al nucleus, a charged lepton flavor violation (CLFV).
- Signature: almost monochromatic e^- of ~ 105 MeV/c, i.e., an event with single track.
- Sensitivity: $\Gamma_{\mu e}/\Gamma_{\mu\ capture} \sim 10^{-17}$, four-order of magnitude better than the current limit set by SINDRUM II.



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1. To constrain the background generated by $p\bar{p}$-annihilation in Al target.
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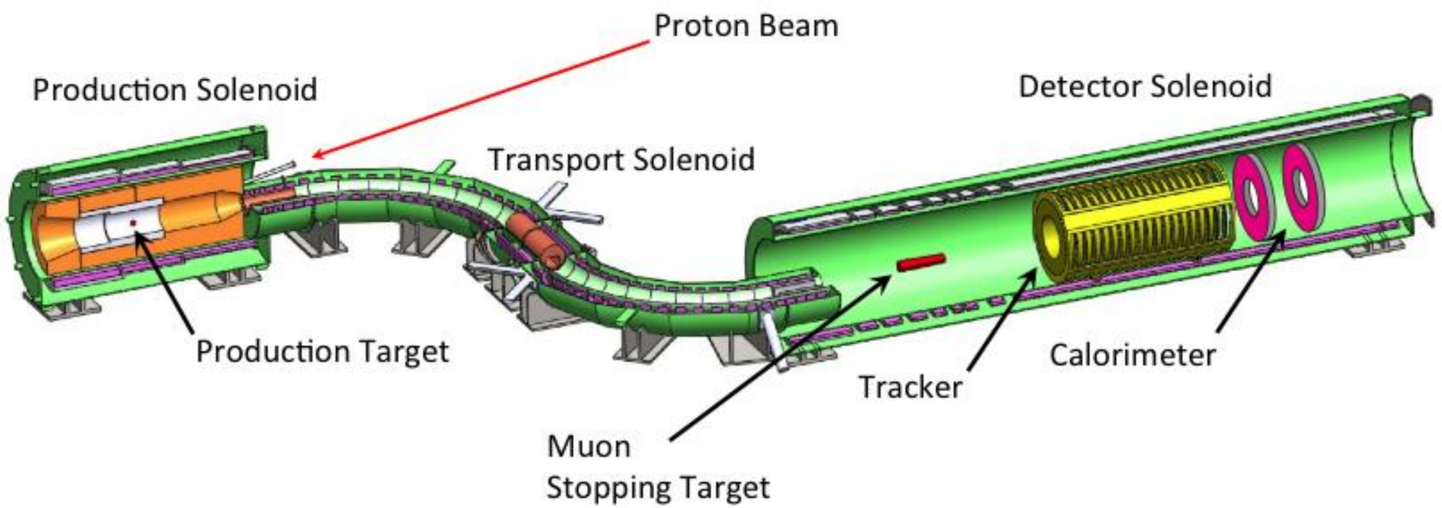
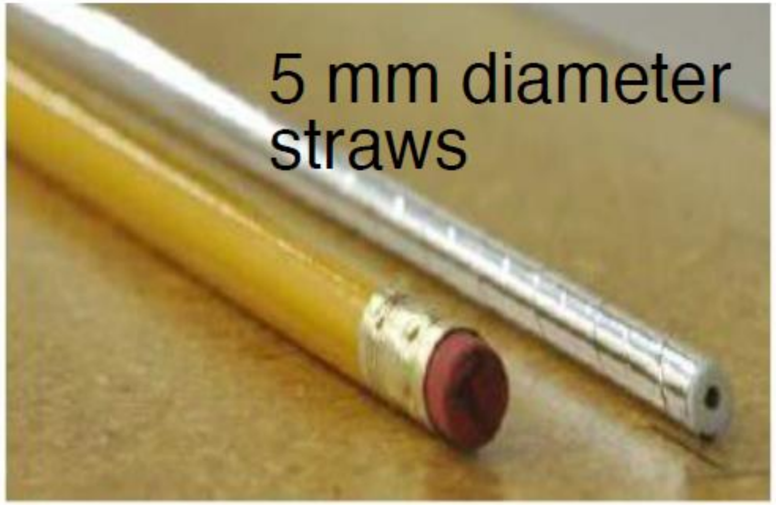
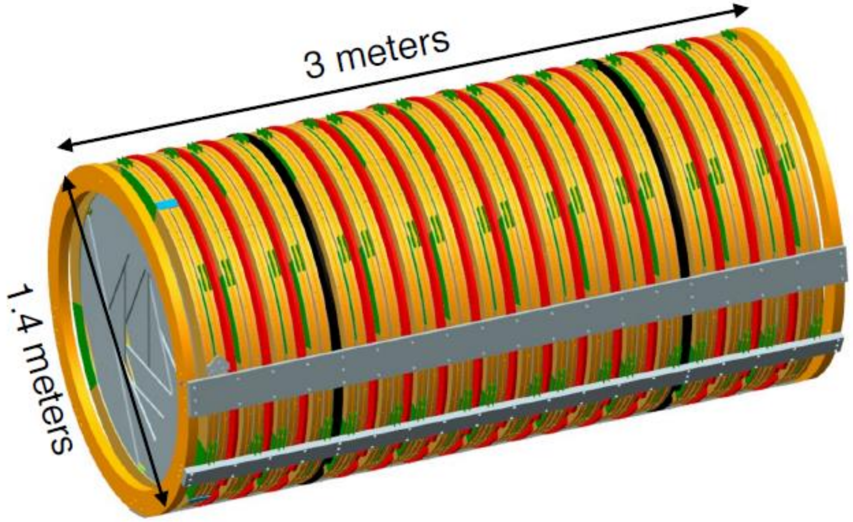
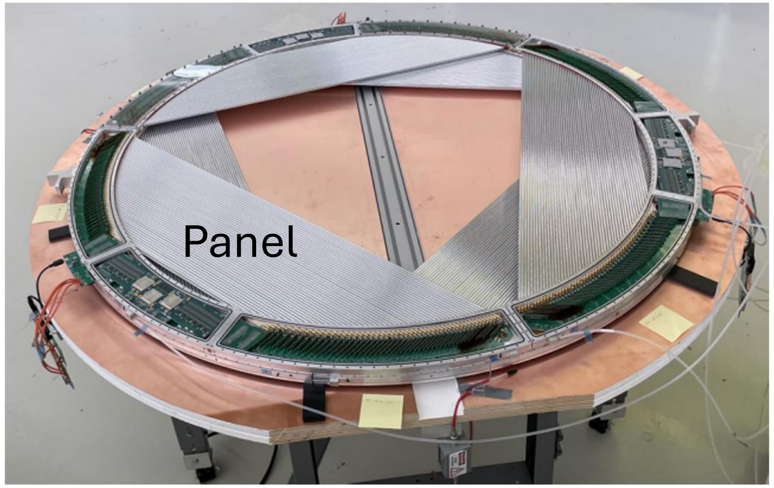


The straw-tube tracker

- It is in a 1T uniform magnetic field ⇒ helicoidal particle trajectories.
- It consists of 18 tracking stations with 1152 straws per station.
- The straws are filled with $80\%: 20\%\ Ar: CO_2$ mixture.
- The central hole reduces the number of straw hits produced from low-momentum particles.







Plane: 6 panels form a plane, 2 planes form a station.

Track reconstruction sequence

- The track reconstruction is divided in 4 sequential stages:

1) Hit Reconstruction: raw signals are converted into position and time coordinates (straw hits).

2) Time Clustering: hits close in time to each other are grouped together to create time clusters.

3) Helix Finding: within each time cluster, hits consistent with a helix are grouped into helix seeds.

4) Track Fit: the helix seeds are processed by a Kalman filter fit.

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   - It must be run with different configurations and trained each time for different physics searches ⇒ farraginous and time consuming.

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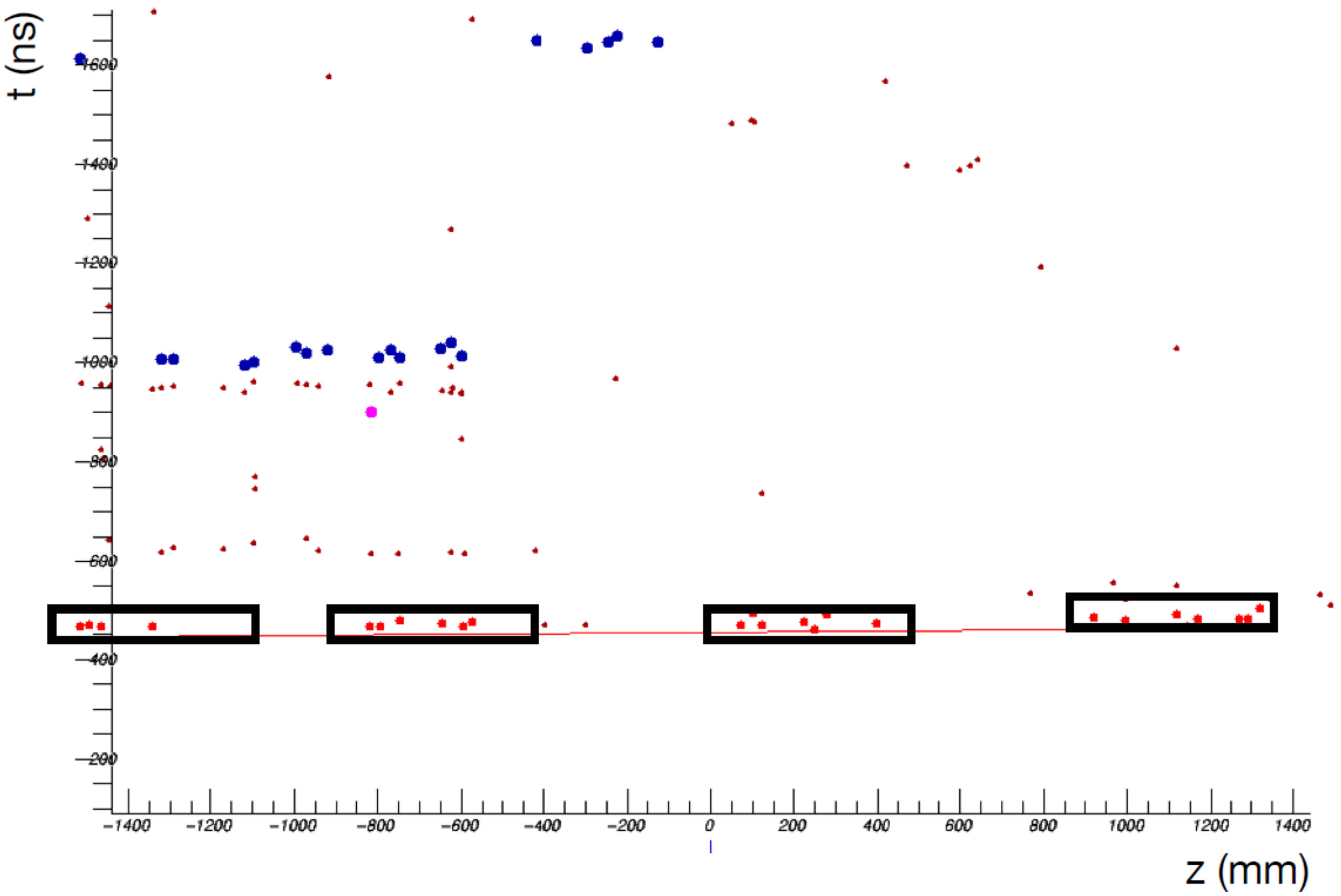

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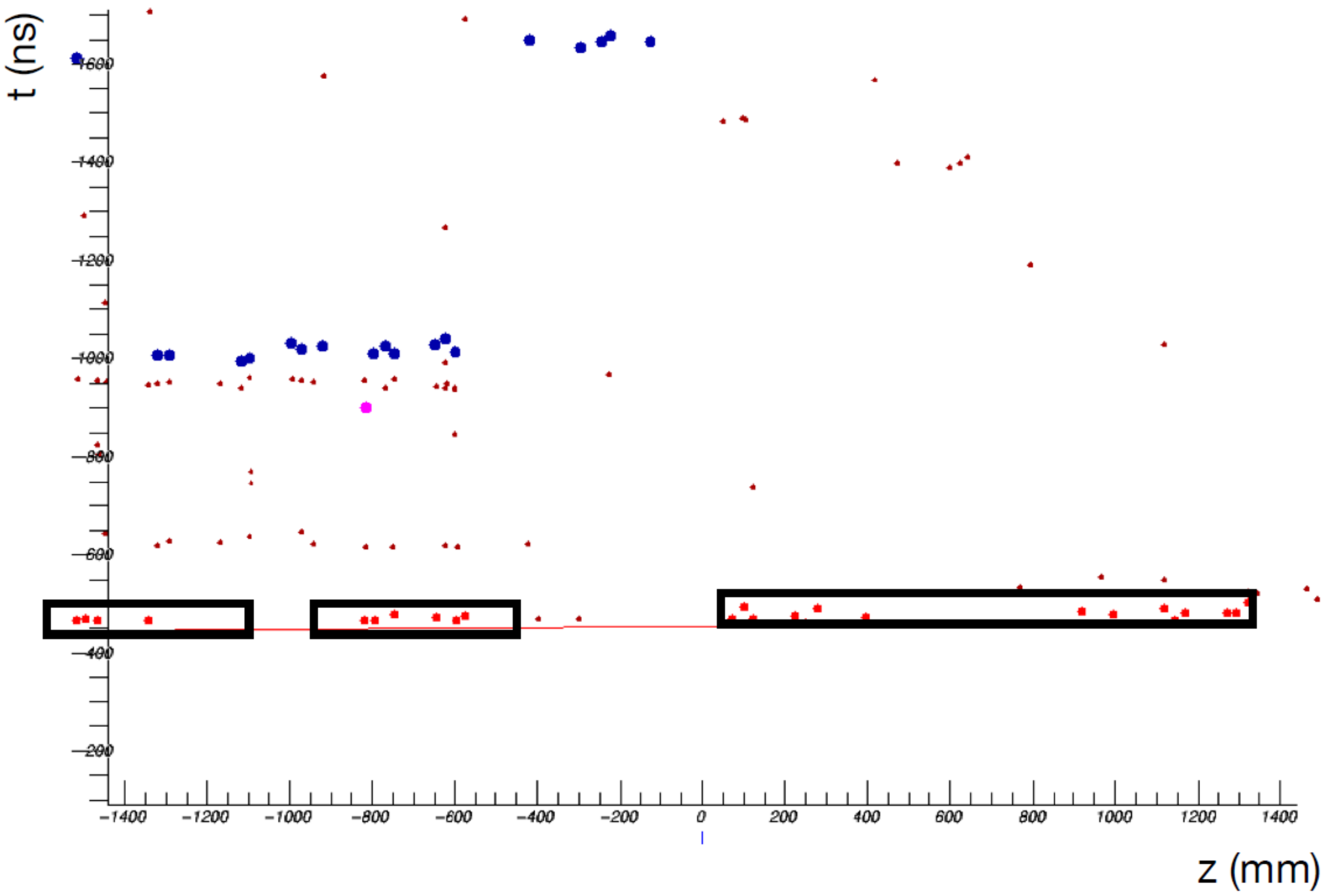

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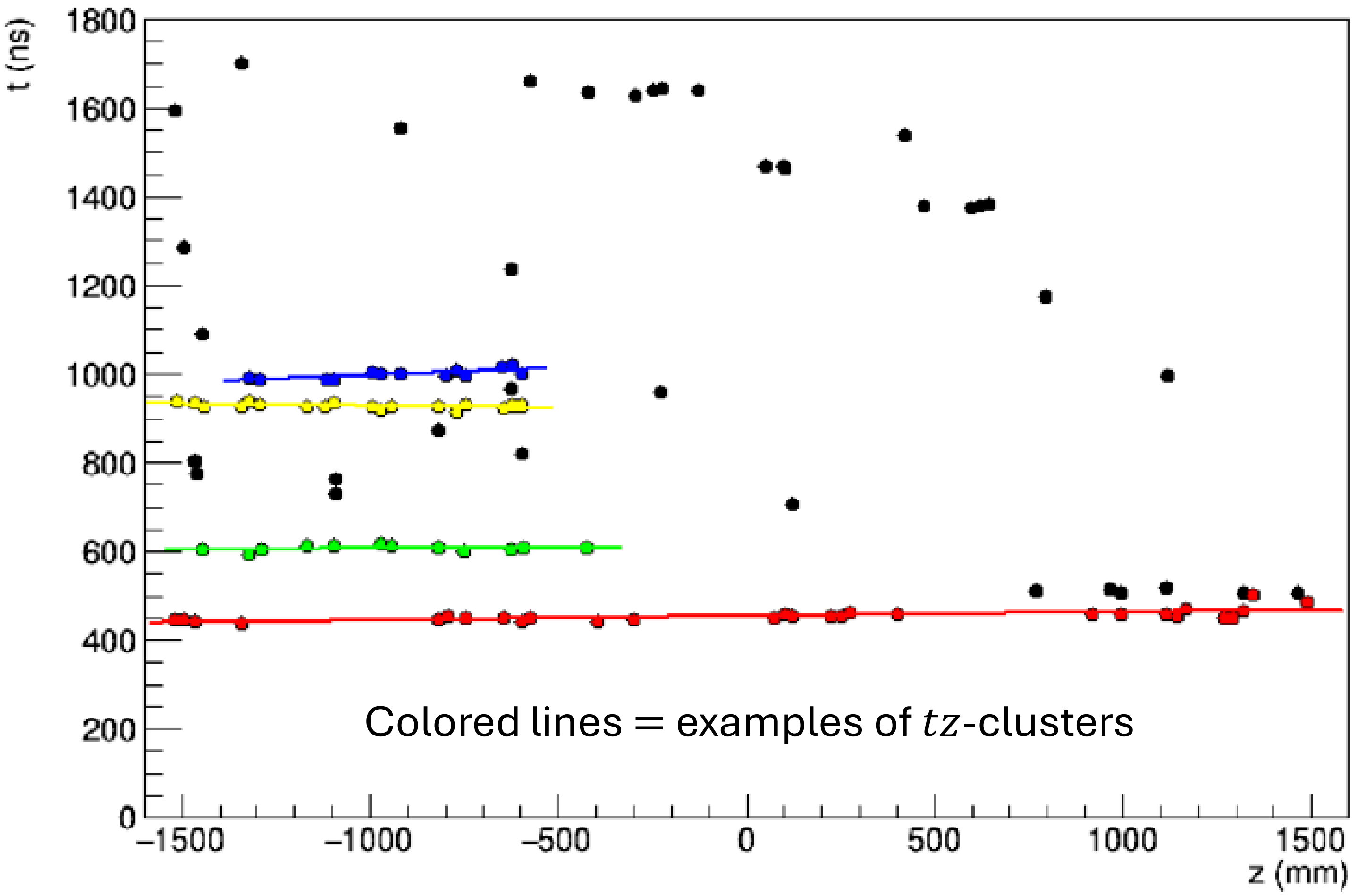
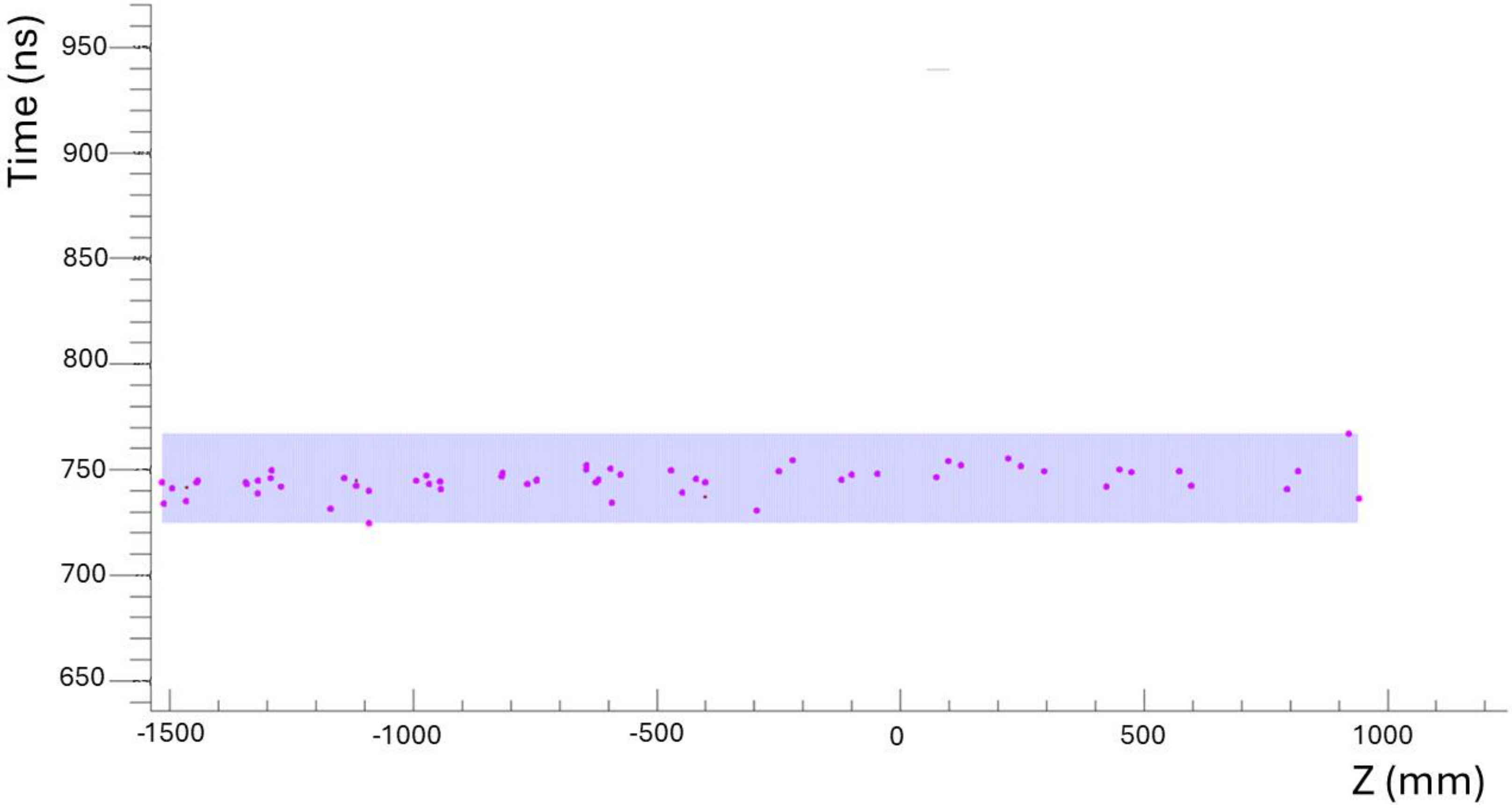
    3. Hits that have been missed but are within 30 ns of line fit of the pre-cluster are recovered.
    4. The obtained pre-cluster is considered a tz-cluster.



Shortcomings of the simple t-z clustering

- The tz-clusters are inhomogeneous and contain hits of different particles.
- In many cases, they do not result in a reconstructed track.
- The hits produced by different particles with the same initial time and longitudinal speed overlap in the tz-plane. Hence, if the tracks are simultaneous, the tz-plane is not sufficient to disentangle them.

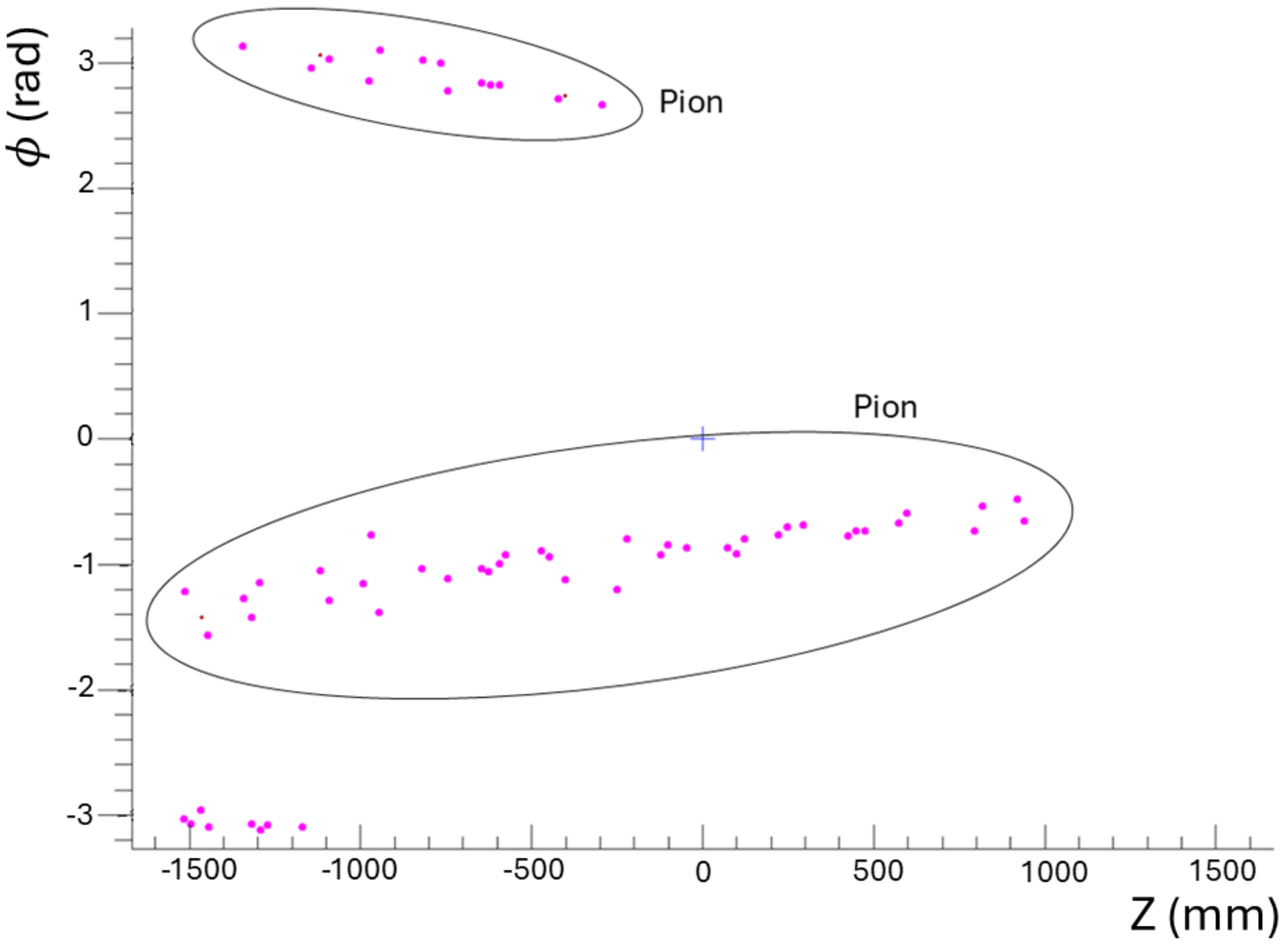


Example of event in which the hits coming from two π's produced from a $p\bar{p}$-annihilation can not be adequately distinguished in tz-plane.

Solution in the ϕz-plane

- Additional information is provided by the hit azimuthal angle:
$$\phi = \tan^{-1}\frac{y}{x}$$

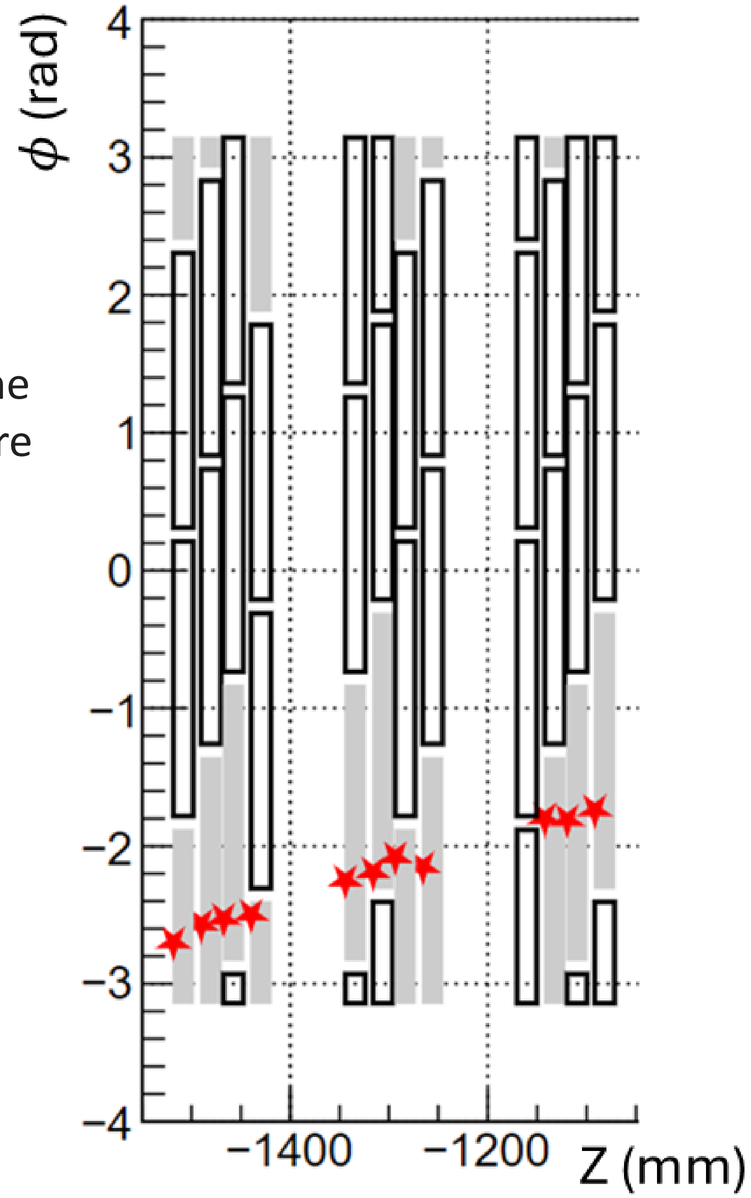
- Hits produced by synchronous particles having different angular velocity or initial azimuthal angle (ϕ_0) look well separated in the ϕz-plane.



From tz-cluster to ϕz-cluster

- The algorithm then rejects the tz-clusters that cannot do not correspond to a track:

Hits belonging to the same tz-cluster. Boxes indicate the tracker panels. Straw hits are indicated by the stars.



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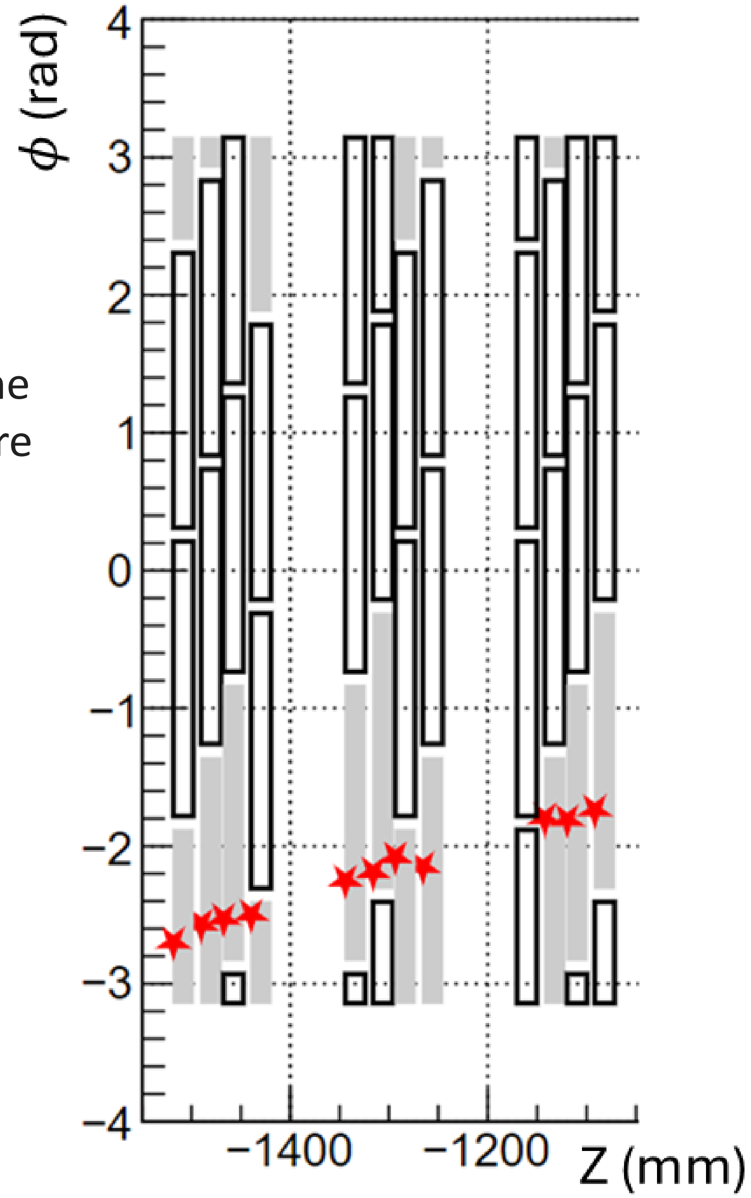

From tz-cluster to ϕz-cluster

- The algorithm then rejects the tz-clusters that cannot do not correspond to a track:
    1. Select the pairs of neighboring stations with at least 2 straw hits per station.
    2. For each station of the pair, using each straw hit as center, search a “rectangle” containing at least 2 hits in the ϕZ-plane.

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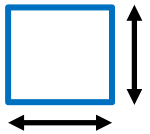
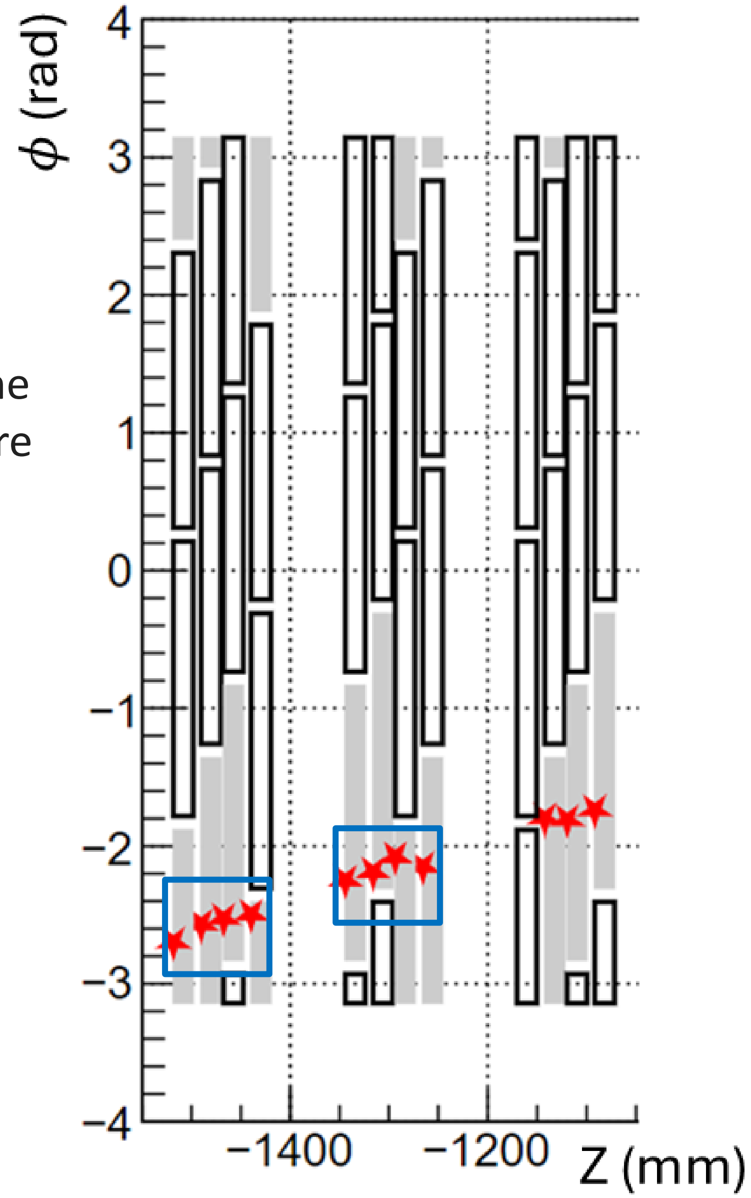


$\Delta\phi_1 = 0.4\ rad$

$\Delta z = station\ thickness$



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  3. Check if the angular distance between the centers of the rectangles $\Delta\phi_2 \leq 0.6$ rad.

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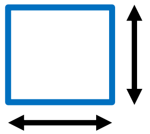

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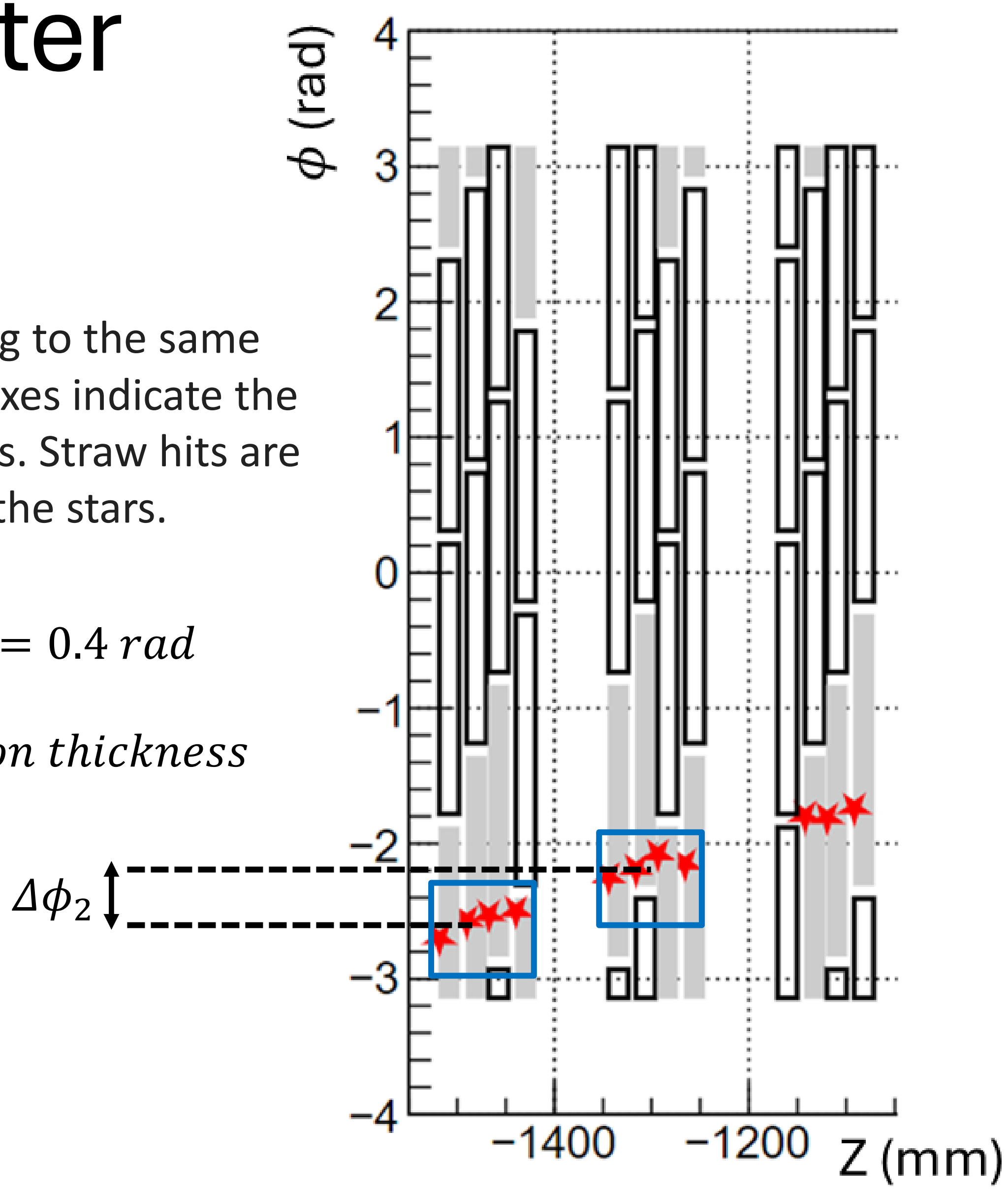

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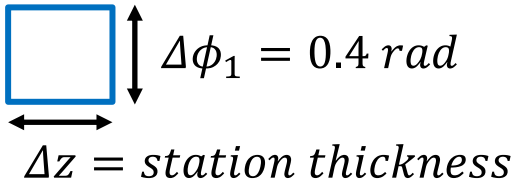
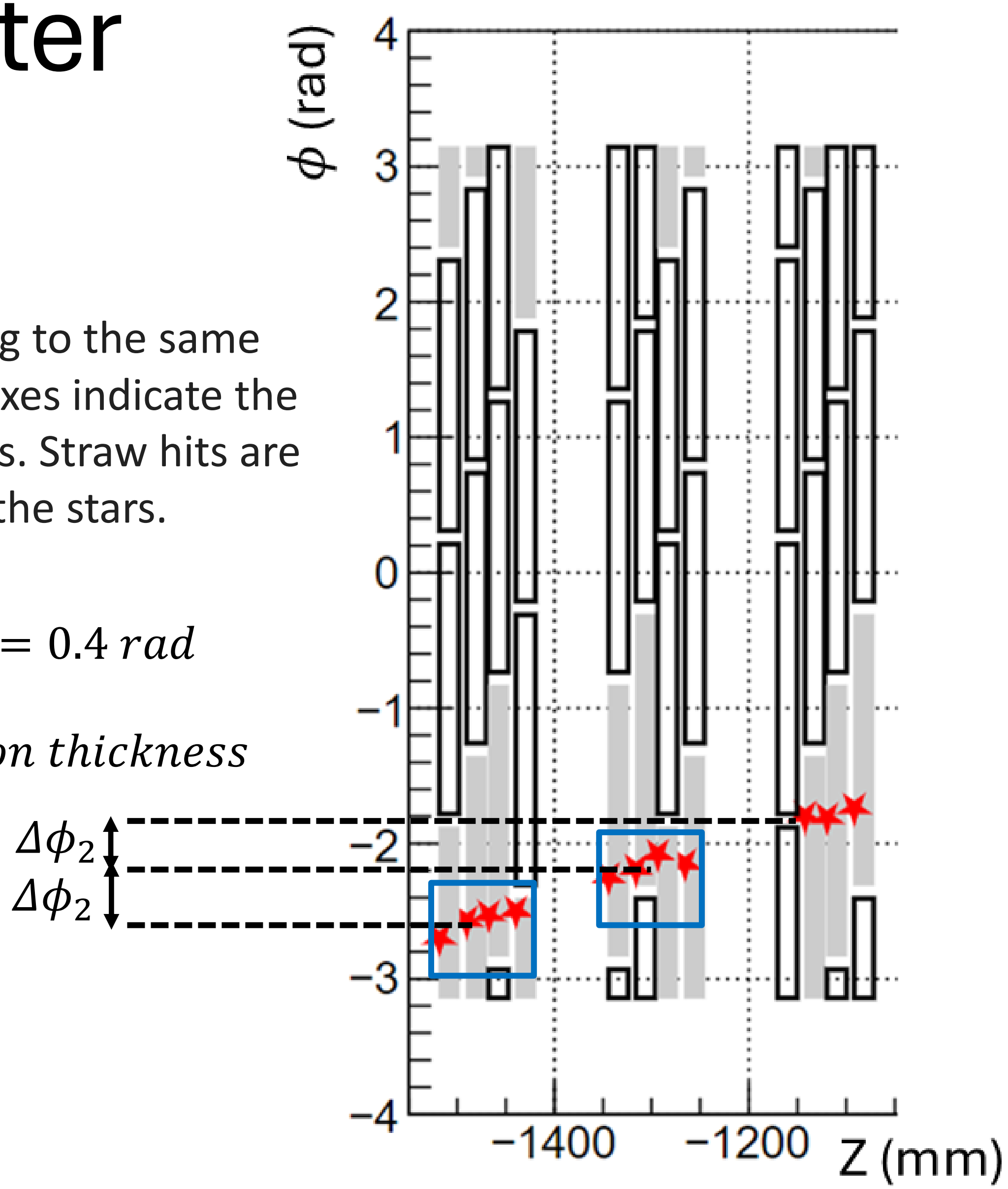
  2. For each station of the pair, using each straw hit as center, search a “rectangle” containing at least 2 hits in the ϕZ-plane.
  3. Check if the angular distance between the centers of the rectangles $\Delta\phi_2 \leq 0.6$ rad.
  4. Searches for a third station near the pair of neighboring stations with at least one hit within $\Delta\phi_2$.
- tz-clusters with less than 3 stations so connected are rejected.

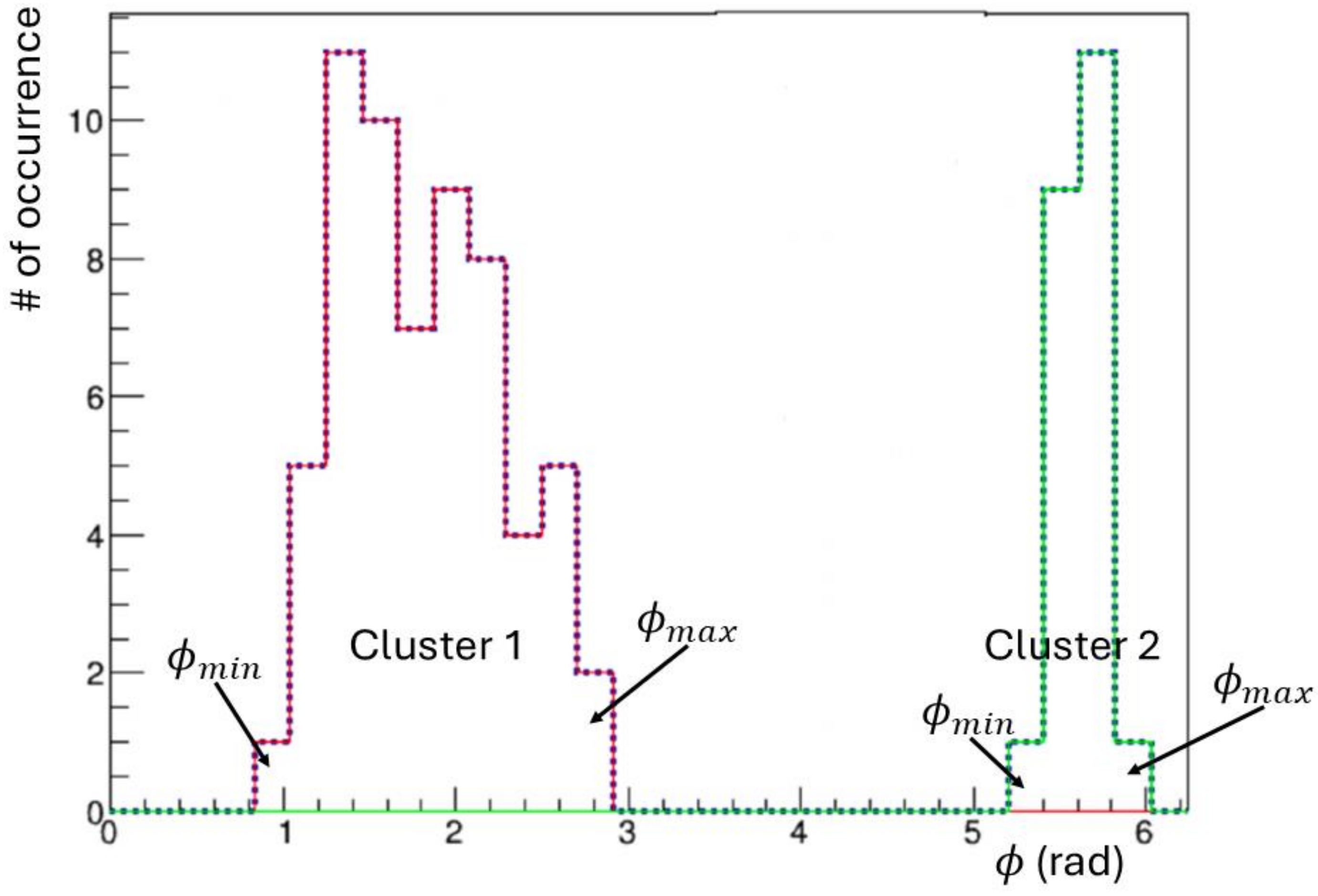
Hits belonging to the same tz-cluster. Boxes indicate the tracker panels. Straw hits are indicated by the stars.





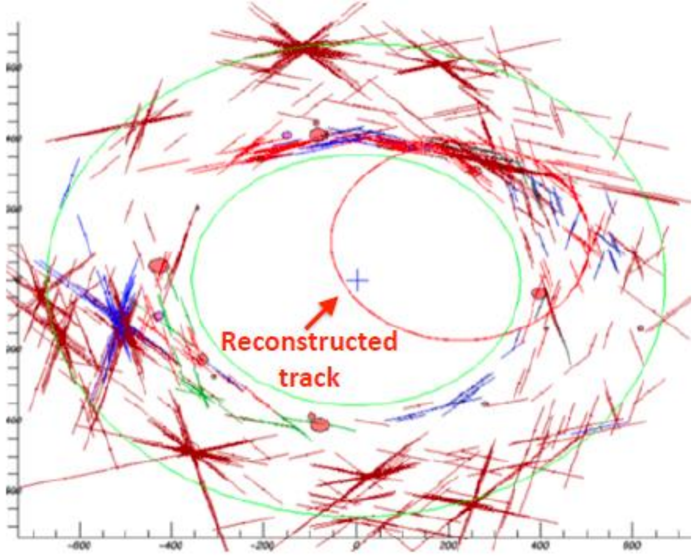
From tz-cluster to ϕz-cluster

- The algorithm recognizes the clusters that contain more tracks and split them in ϕz-clusters:
  1. Project the tz-cluster hits in the ϕ coordinate on a histogram.
  2. Find the peak bin and goes through the bins around it with content > 1.
  3. This gives ϕ_{min} and ϕ_{max} for a pre-cluster.
  4. Put the hits with ϕ between ϕ_{min} and ϕ_{max} in the pre-cluster.
  5. If the pre-cluster has > 10 straw hits, it is considered a ϕz-cluster.
  6. Repeat the above procedure for the rest of the hits in the tz-cluster.

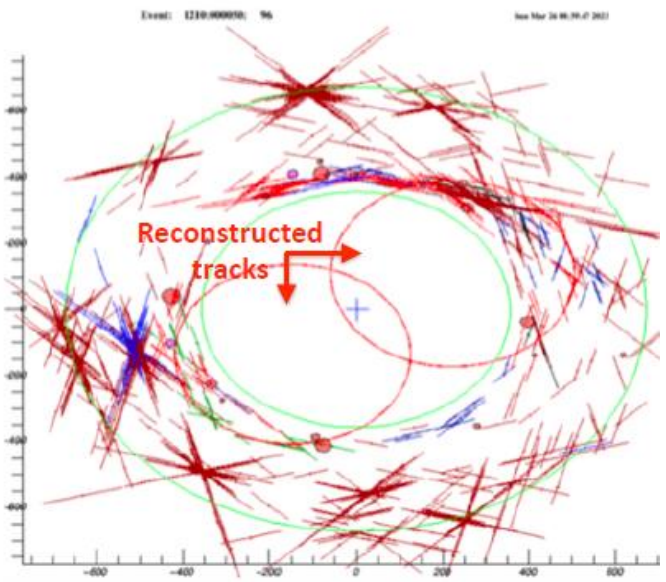


Results

- When the multi-track clustering algorithm is applied to simulated $\mu^- \rightarrow e^-$ events with beam pile-up, it selects the 99.2% of tz-clusters containing hits of the conversion e^-.
- When it is applied to $p\bar{p}$-annihilations simulated with beam pile-up, it selects 90% of the tz-clusters produced by the $p\bar{p}$-annihilation products.
- It rejects 77% of the tz-clusters that do not contain these processes.
- It reconstructs about 42% of the multi-track events from $p\bar{p}$-annihilation, where each track has a total momentum > 80 MeV/c and makes at least 20 hits in the tracker. Compared to the default reconstruction, the number of multi-track events increased by 2.1 times.
- The illustration depicts an event of $p\bar{p}$-annihilation, where the single-track optimized algorithm fails to reconstruct one of the two tracks, whereas the multi-track algorithm successfully reconstructs both.



Single-track algorithm



Multi-track algorithm

Conclusions

- The Mu2e experiment will search for neutrino-less $\mu^- N \rightarrow e^- N$ coherent conversion in the field of Al nucleus, a charged lepton flavor violation (CLFV).
- The signature is a monochromatic e^- of ~ 105 MeV/c, i.e., an event with single track.
- There are motivations to develop an efficient tracking algorithm for reconstructing more simultaneous tracks:
    1. To constrain the background generated by $\mathrm{p\bar{p}}$-annihilation in Al target.
    2. To search for Beyond the Standard Model processes.
- The default Mu2e algorithm forms time clusters using a NN trained to efficiently search for a conversion e^-, but that removes a large fraction of π and μ hits.
- The new clustering algorithms form the hit clusters searching for the straight lines in both the tz- and the ϕz-coordinate spaces.
- When the ϕz-clusters are used to feed the track reconstruction algorithm, the number of multi-track reconstructed events increases by 2.1 times.

Backup

Goal of the Mu2e experiment

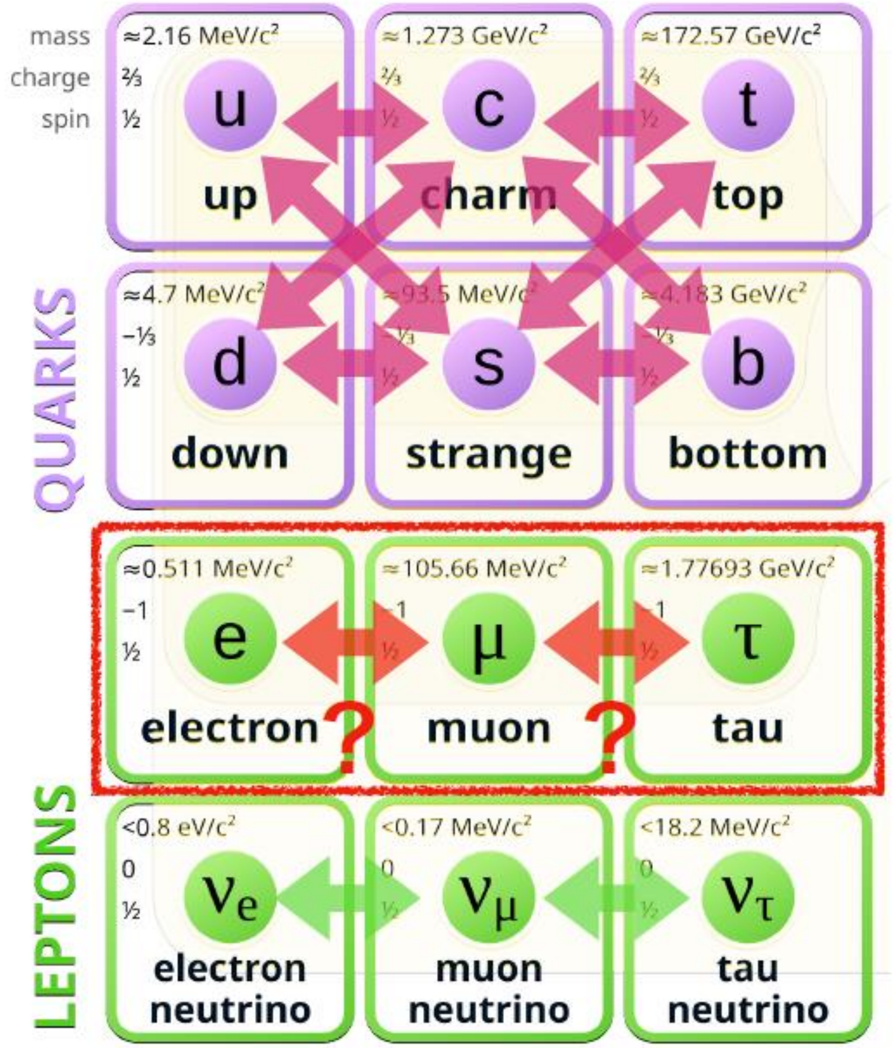
- Search for neutrino-less $\mu^- N \rightarrow e^- N$ coherent conversion in the field of Al nucleus, a charged lepton flavor violation (CLFV).

- The conversion probability is given by the ratio between the $\mu^- \rightarrow e^-$ conversion rate and the nuclear capture rate:

$$R_{\mu e} = \frac{\Gamma\big(\mu^- + N(Z,A) \rightarrow e^- + N(Z,A)\big)}{\Gamma\big(\mu^- + N(Z,A) \rightarrow \nu^- + N(Z-1,A)\big)}$$

- Signature: monochromatic e^- of 104.97 MeV/c.

- If no signal is observed, the upper limit will be $R_{\mu e} < 8 \times 10^{-17}$ at 90% CL, a four-order of magnitude improvement over the current limit set by SINDRUM II experiment.



Default time clustering algorithm

- Time clustering sequence:
  1. Find peaks in the hit time distribution.
  2. Associate hits to “time peaks”, hits must be within few nanoseconds of the time peak.
  3. Use a MVA (NN) to remove pile-up hits from the time cluster.
  4. Use another MVA (NN) to recover hits that were slightly outside the time peak window.

- Issues with the multi-track reconstruction:
  - It can not reconstruct several tracks within the same time peak (simultaneous tracks).
  - It forms time clusters using a NN trained to efficiently search for a conversion e^-, but that accidentally removes a large fraction of π and μ hits.
  - In some instances, NN reduce the speed of the reconstruction. In some instances, all hits that were removed by the first NN were added back by the second NN.
  - It must be run with different configurations and trained each time for different physics searches ⇒ farraginous and time consuming.