TPC Detector Response Simulation and Track Reconstruction

Physics goals at the Linear Collider drive the performance goals for charged particle tracks :

reconstruction resolution: $\delta(1/p) = \sim 4 \times 10^{-5}$ /GeV

reconstruction efficiency: 100% within jets for energy flow measurements

Simple simulations, which represent the detector response as smeared space points, show that the track reconstruction resolution goal can be achieved with the NA "Large Detector".

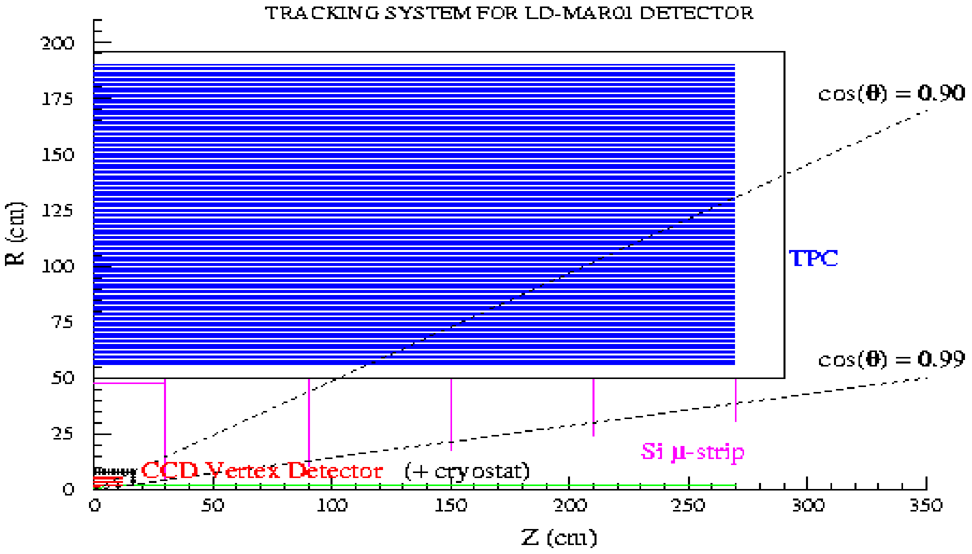
For example:

TPC:
2.0 m O.R., 0.5 m I.R., 150 μm spatial res.

Vertex Detector:
5 layer, 10 μm spatial resolution

Intermediate Tracking Device:
2 layer, r =0.45 m, 10 μm spatial res.

→ $\delta(1/p) = 4.2 \times 10^{-5}$ /GeV



Reconstruction Efficiency

Reconstruction efficiency cannot be easily estimated in the event environment of the Linear Collider, it is dependent on the **non-Gaussian smearing effects: noise and track overlap**.

While reconstruction efficiency is difficult to estimate,

one could achieve the **maximum efficiency** using the **maximum segmentation** possible with a GEM or MicroMegas amplification TPC.

However, the channel count would be excessive (and expensive). For example….

(North American) [2 x 11.8 m^2 instrumented area] / [0.2 cm^2 / channel] → 1.2 x 10^6 multi-hit channels
(Tesla) [2 x 7.9 m^2 instrumented area] / [0.12 cm^2 / channel] → 1.3 x 10^6 multi-hit channels

A TPC design can be simpler if it is established that larger pads are sufficient to provide the “full” efficiency of the smaller pad while still meeting the resolution goal.

Goals

The goal of this work is to measure the reconstruction efficiency and thereby

optimize the design for a TPC in the "Large Detector" design,

for complicated events simulating Linear Collider processes,

incorporating as many real detector effects as possible
(pad size,
charge spreading,
inefficient pads,
noise, and
track overlap)

and using pattern recognition that starts with pad level information (not space points) .

A further goal is to use the measured reconstruction efficiency as a

basis for comparing

a full detector design incorporating a large TPC for tracking
with
a full detector design using a silicon based tracking system.

Complicated event simulating a Linear Collider Process

A sample event, $e^+ e^- \rightarrow ZH$, from LCD simulation illustrates the level of overlapping tracks.

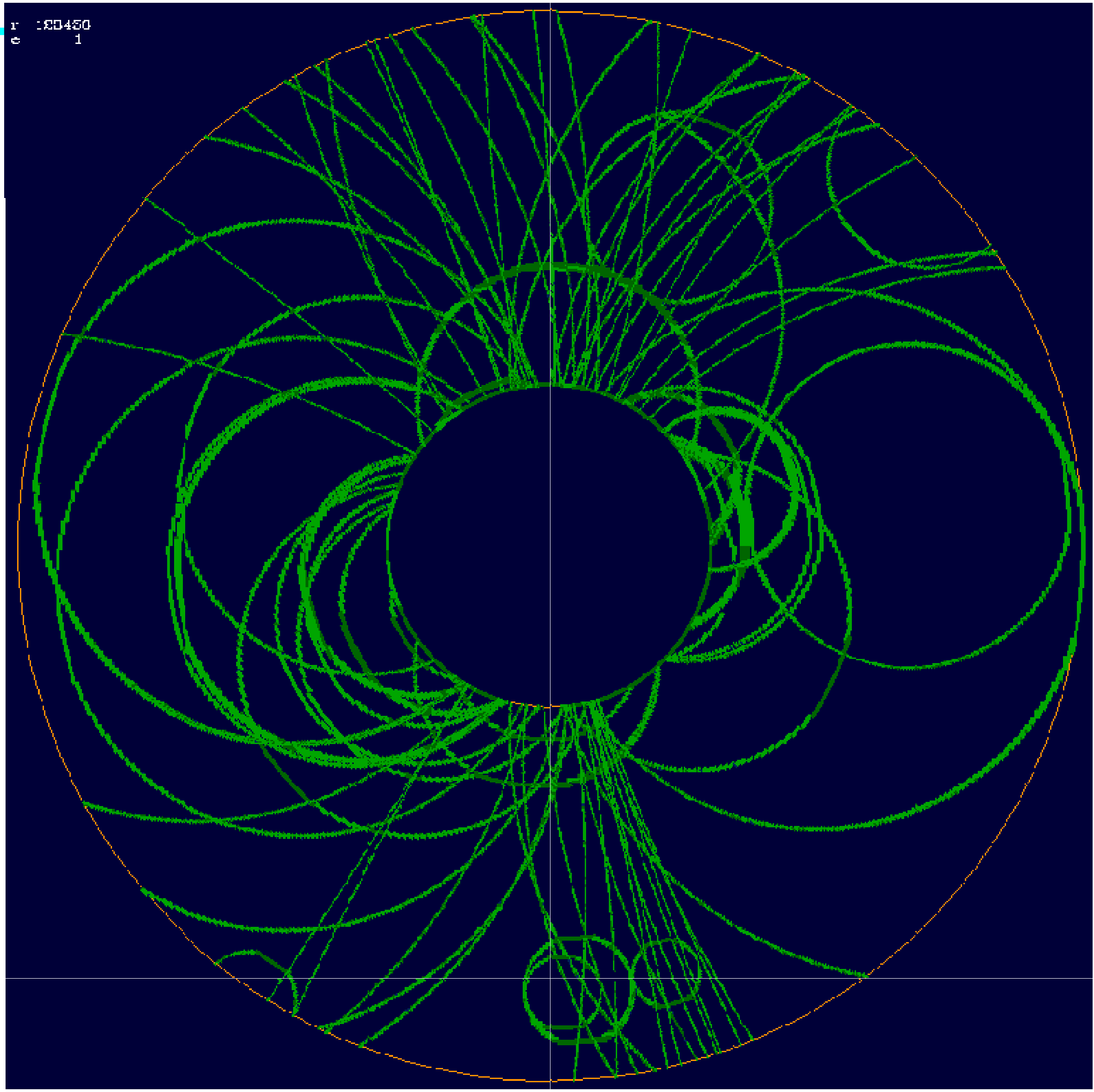
(All hits are are projected onto one endplate.)

143 layers from 56cm to 200 cm

2 mm wide pads, 1cm radial “height”
(number of pads in layer is multiple of 8)

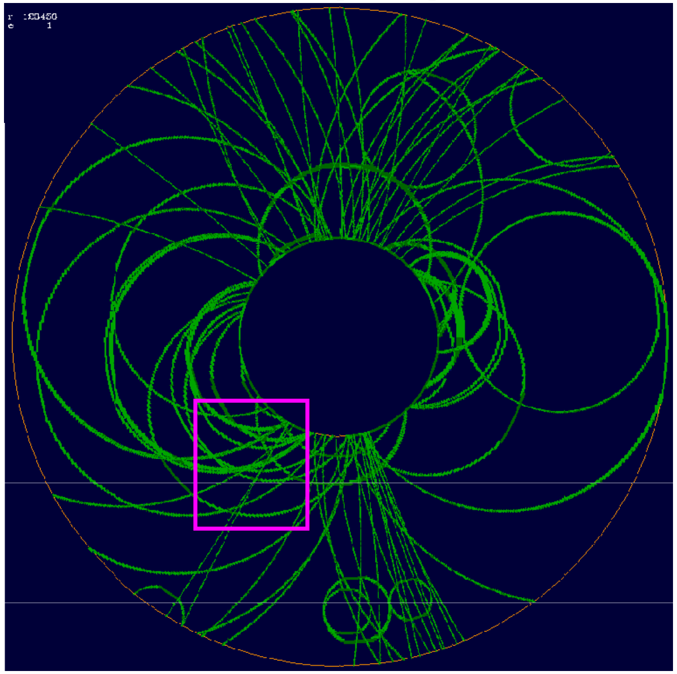
charge spread is minimal
no noise

While the overlap can be reduced by taking advantage of z separation, it is not clear from this simple picture if the separation would be sufficient.



Remaining track overlap when taking advantage of Z separation

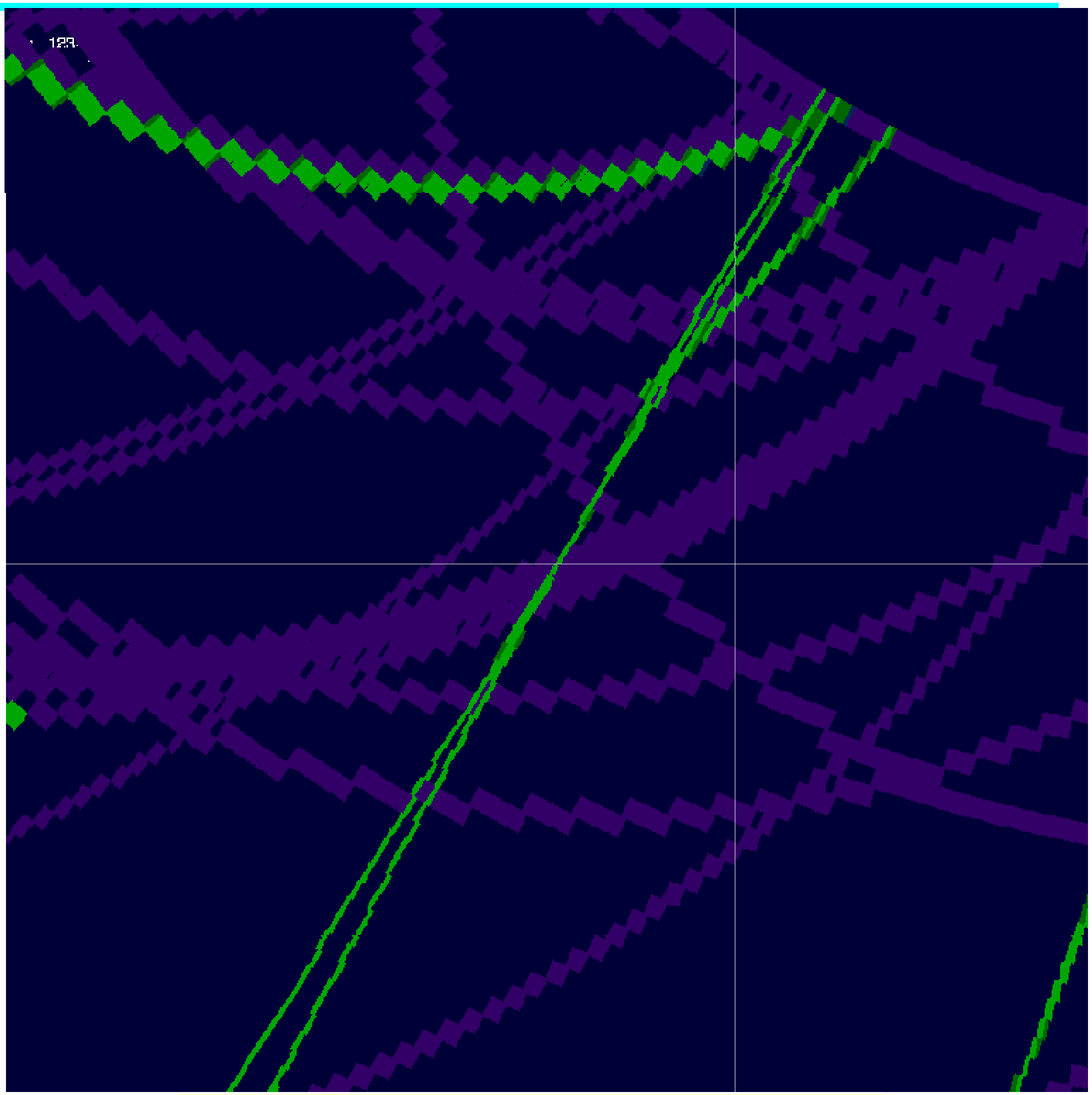
(Same event, same pad response)



The z separation is often
too small to provide track separation.

crossing tracks in r-f,   and
z-separation = **1 mm** .

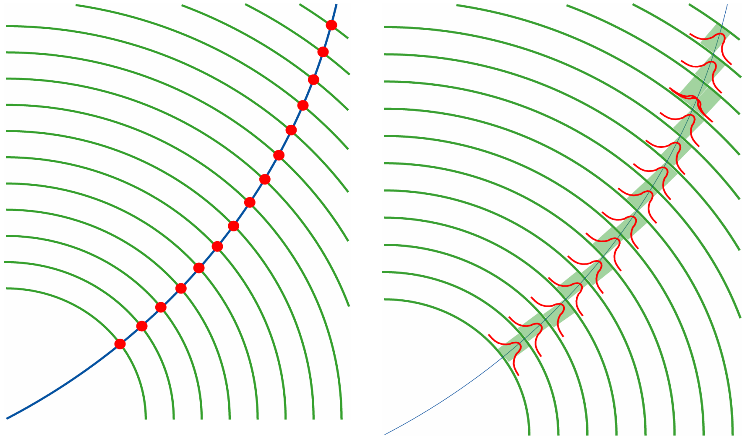
But, track reconstruction can be efficient for very close tracks by using information from regions where the tracks are isolated. This is an advantage of the pat. rec. used in this study.



Active cone: Z=[r * (-6 / 40)] +/- 4.7 cm

Detector Simulation: Pad Response

The LCD simulation provides only crossing points; extensions to the simulation are created within the CLEO reconstruction program.

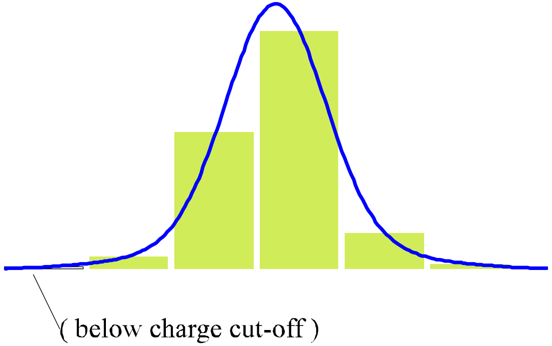


144 crossing points are treated as entries & exits for 143 layers.
143 layers are segmented into pads.

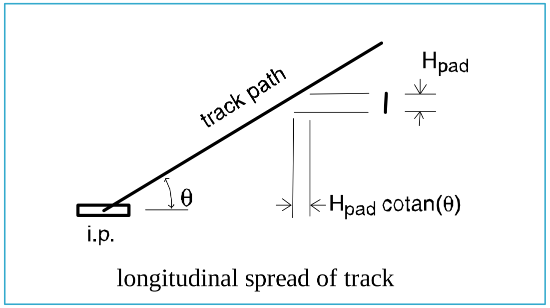
create hits, with time and pulse height,
centered on the average position in the cell

Charge spreading on the pads:

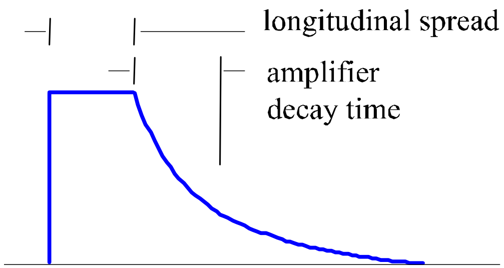
Gaussian width, cut-off (~ .002 of min.ion.),
maximum total-number-pads in the the distribution,
charge is renormalized to provide a **total of min. ion.**



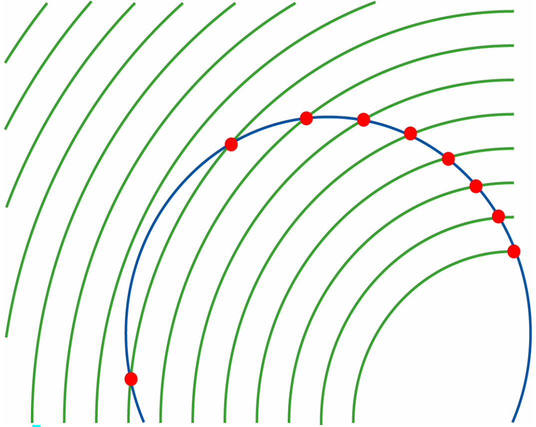
Wave Form to
simulate time (= Z) response

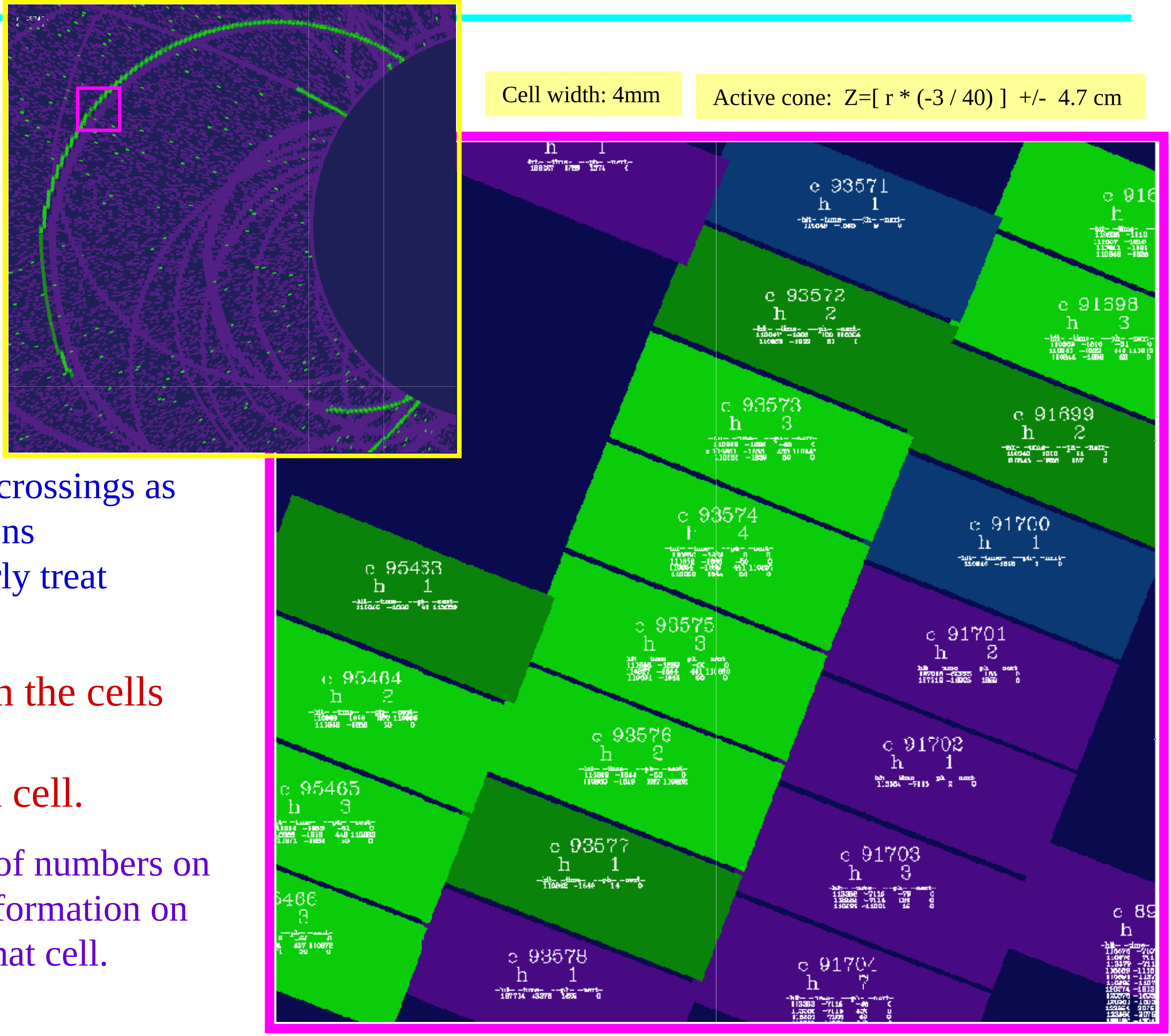


longitudinal spread of track



Ionization distribution for large entrance angle





Cell width: 4mm

Active cone: Z=[r * (-3 / 40)] +/- 4.7 cm

With treating the cylinder crossings as layer entry and exit positions comes the ability to properly treat multiple cell crossings.

Ionization is deposited in the cells depending on the path length in each cell.

Also shown: The table of numbers on each cell provides information on the hits assigned to that cell.

Detector Response: Merging Overlapping Hits and Time Pattern Recognition

After signals are generated on pads as described in the previous 2 slides,
pads may have overlapping signals that would be merged in the hardware readout.

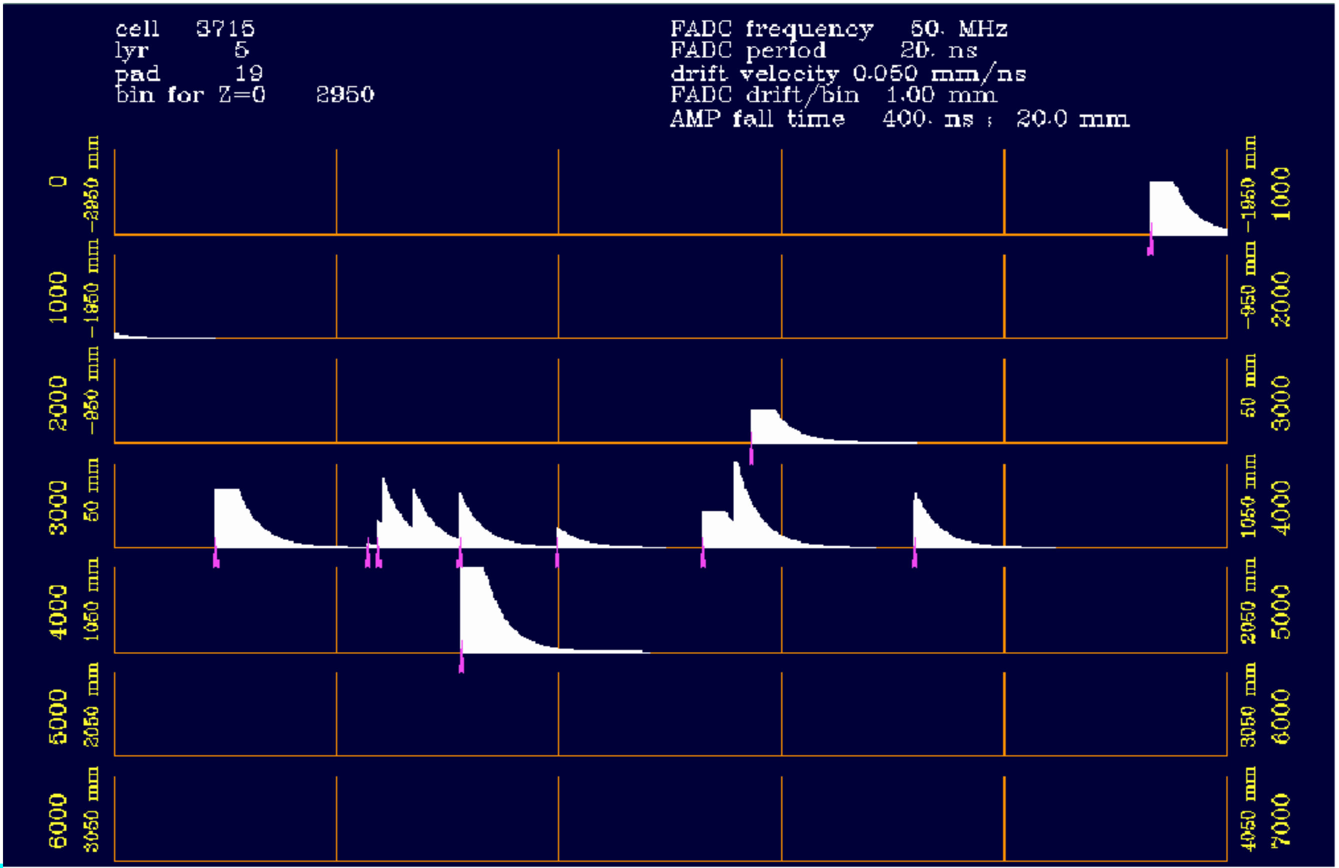
Each signal, **including noise hits**, is described by a pulse height, time, and duration at max. pulse height.

This information is used to simulate a FADC response in which overlapping signals add.

The FADC response is then analyzed to determine the unambiguous threshold crossings

indicated by (▲).

Threshold crossings found in this procedure replace the original pad signals.

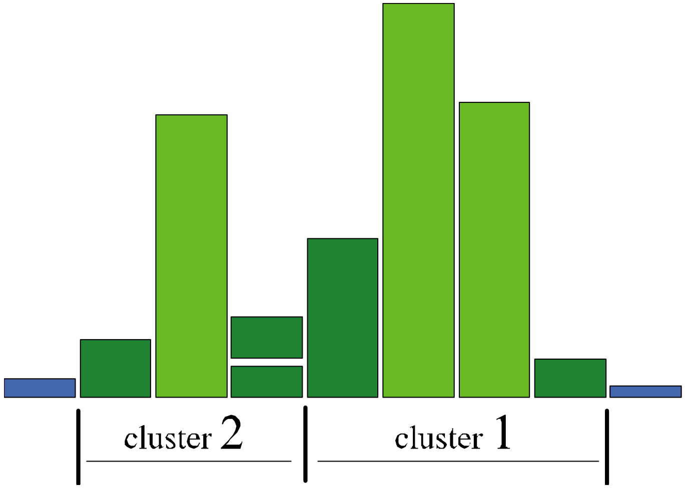


Event reconstruction: Pad Clustering

Previous slides have described how the
generator track crossing of ideal concentric cylinders
are converted to FADC signals.

The FADC signals were then processed to recognize
“unambiguous” threshold crossings – single pad hits.

Now these single pad hits are clustered
to locate the significant centers of ionization
that can be used by the pattern recognition.



Pads with > 0.51 of the maximum are treated as “core pads”.
(a detail of the primary pattern recognition)

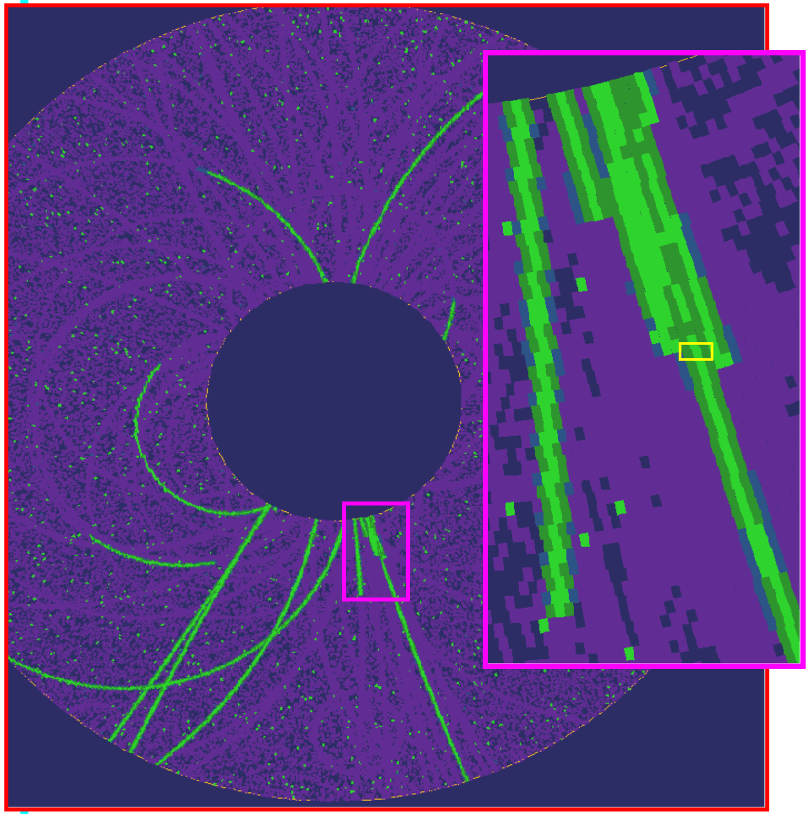
Clustering in r-ϕ

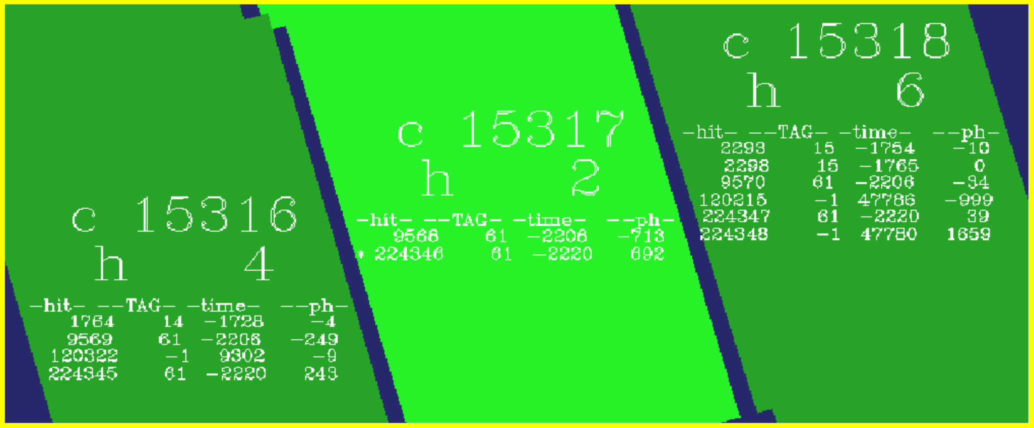
A local maximum, above a threshold, defines a **central pad**.
Adjacent pads, above a lesser threshold are added to the cluster.
Difference in Z of adjacent pads is required to be less than a threshold.
Clusters are **Split** at local minima, less than a fraction of the lesser peak.

Splitting of overlapping cluster **is not precise**.

A pad, which may have contributions from 2 (or more) sources, is assigned to the larger neighbor as shown.
This may lead to non-gaussian smearing of the central position.

Projected hits for event, after detector response simulation and clustering

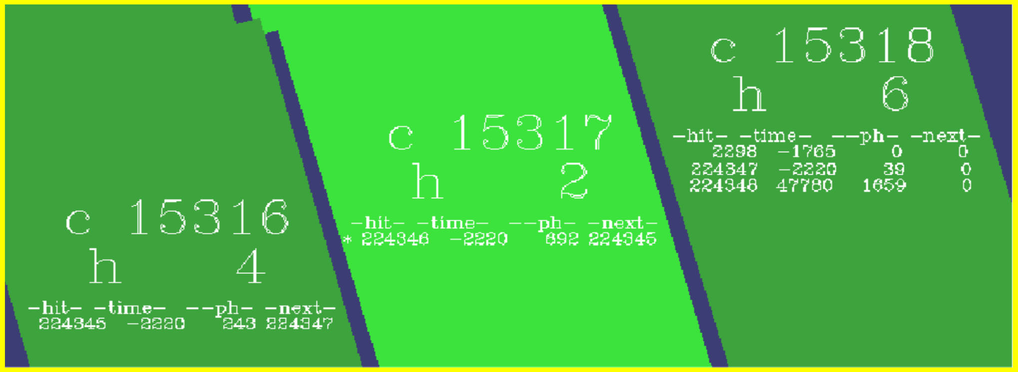




```
c 15316
h       4
-hit-  --TAG- -time-   --ph-
  1764     14  -1728      -4
  9569     61  -2206    -249
120322     -1   9302      -9
224345     61  -2220     243
```

```
c 15317
h       2
 -hit-  --TAG- -time-   --ph-
  9568     61  -2206    -713
* 224346   61  -2220     692
```

```
c 15318
h       6
-hit-  --TAG- -time-   --ph-
  2293     15  -1754     -10
  2298     15  -1765       0
  9570     61  -2206     -34
120215     -1  47786    -999
224347     61  -2220      39
224348     -1  47780    1659
```



```
c 15316
h       4
-hit-  -time-   --ph- -next-
224345  -2220    243 224347
```

```
c 15317
h       2
 -hit-  -time-   --ph- -next-
* 224346  -2220    692 224345
```

```
c 15318
h       6
-hit-  -time-   --ph- -next-
  2298  -1765      0      0
224347  -2220     39      0
224348  47780   1659      0
```

Active cone: Z=[r * (-7 / 40)] +/- 4.7 cm

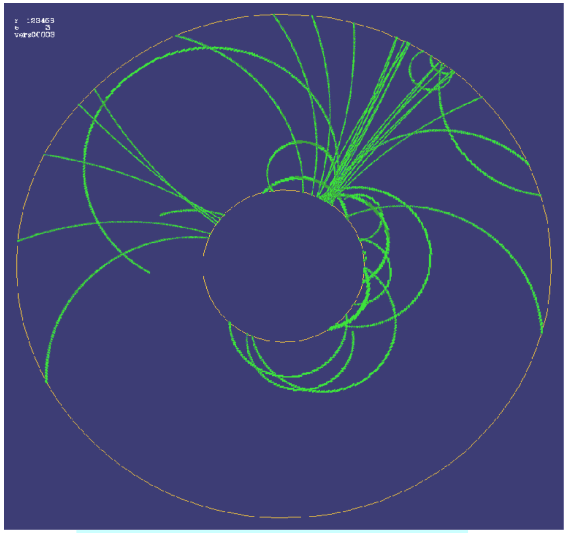
Active hits in green

Ignored hits in purple

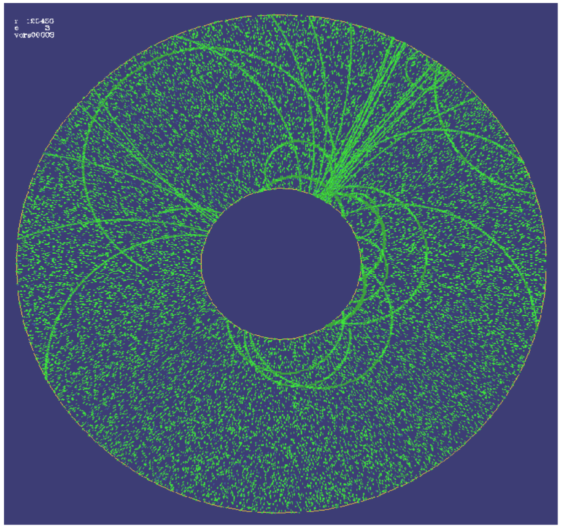
This is the information input to the pattern recognition.

- The pad response includes merged hits with time and pulse height information.
- Simple, pre-merged, hits have been “hidden”.
- Clustering has been completed for the initial pattern recognition.

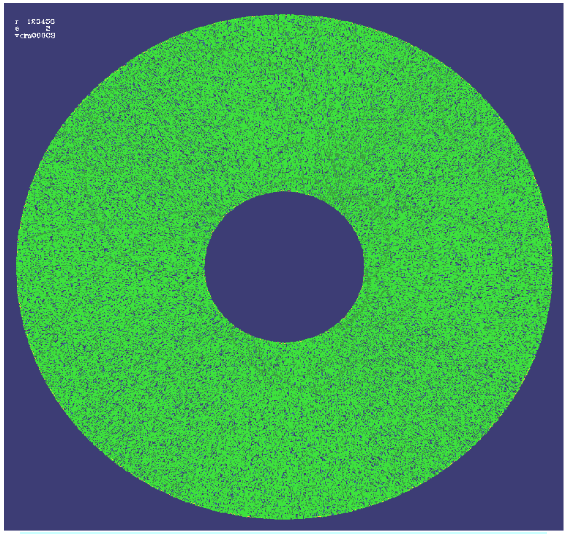
Random Noise, details



2 mm cells, no noise



2 mm cells, 30 K noise hits



2 mm cells, 300 K noise hits

Noise is added on isolated pads, in random locations.
The time structure has a 2 cm/vel duration plus a tail with 2 cm/vel time constant.
The number of noise hits is constant; the volume fraction occupied by noise is pad size dependent.

occupied volume: (# noise hits / # pads) x (noise hit length { 4 cm } / chamber length)

pad size	*occupancy with 300 K hits*	*affected signals* (signals spread over 3 cells)
2 mm	0.0046	0.014
4 mm	0.009	0.028
6 mm	0.014	0.042
10 mm	0.023	0.069

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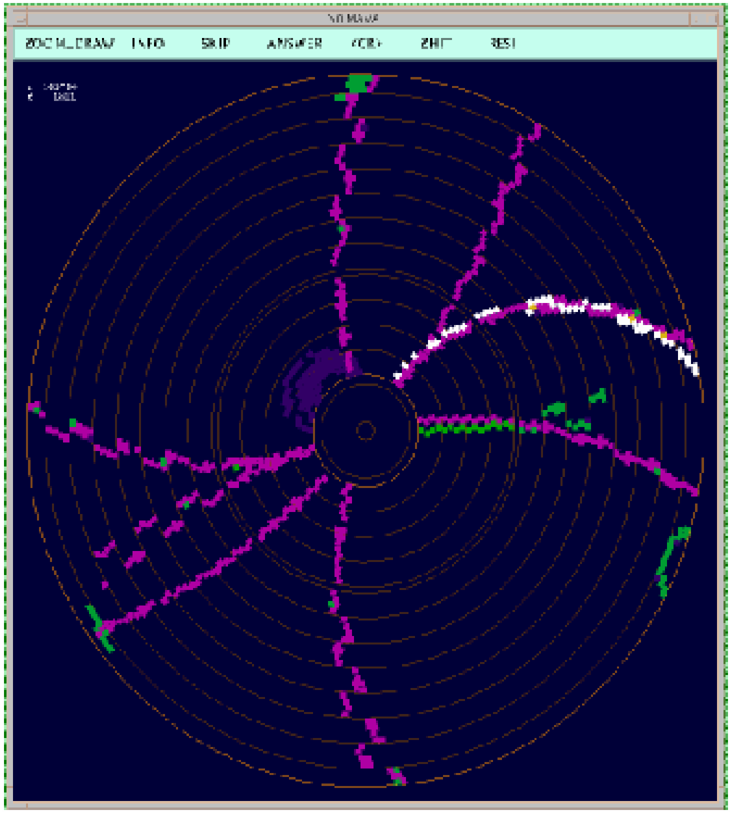
Track Reconstruction

With a goal of accurately measuring the TPC pad size and spreading that will provide the "full" reconstruction efficiency in Linear Collider physics events, it becomes important to know what is being measured -

inherent reconstruction efficiency,
limited by the track overlap and hit distortion,
or an efficiency that is limited by the algorithm.

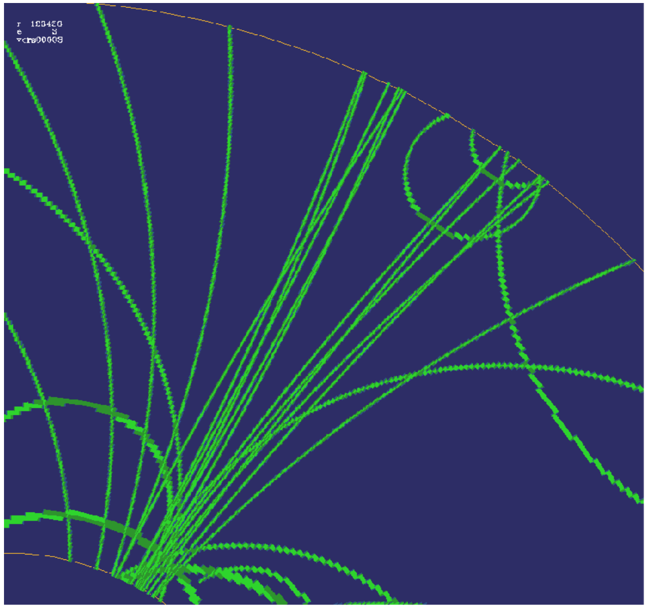
This requires a means to independently determine the root cause of reconstruction failures.

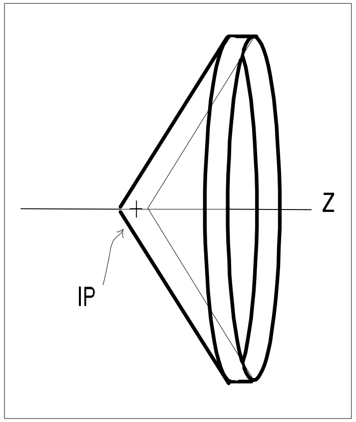


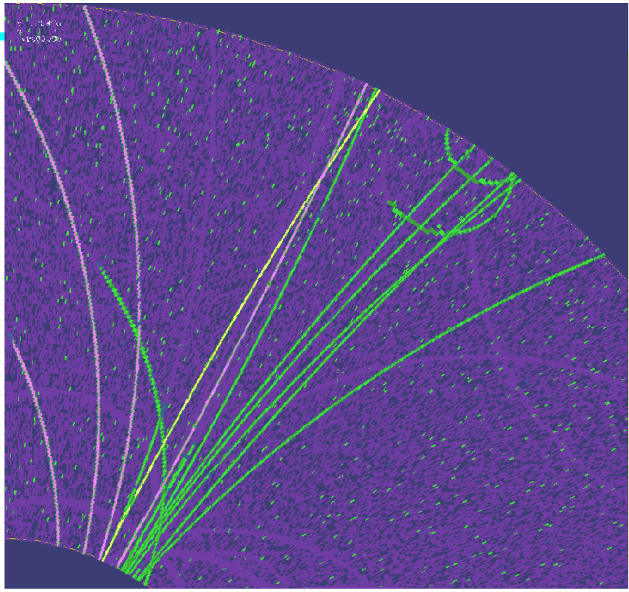
The CLEO reconstruction program is optimized to separate overlapping tracks.
More importantly, it includes a diagnostics package that provides
internal hit information and
a graphics interface to the hit assignments,
at intermediate stages in the programs.

This allows
rapid determination the root cause of reconstruction failures (on single tracks) and algorithm development.

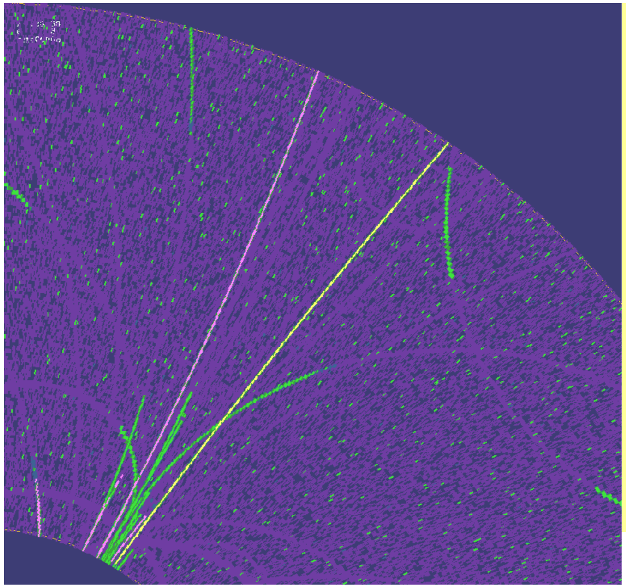
CLEO pattern recognition is modified for use with a 3-dimensional TPC.







Active cone: Z=[r * (-24 / 40)] +/- 4.7 cm



Active cone: Z=[r * (-28 / 40)] +/- 4.7 cm

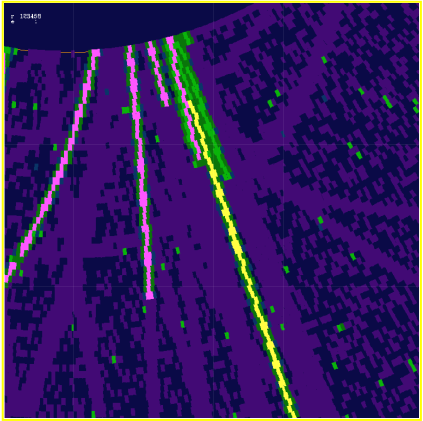
Hits are pre-selected to be in cones projected to the IP (as already seen in previous slides).

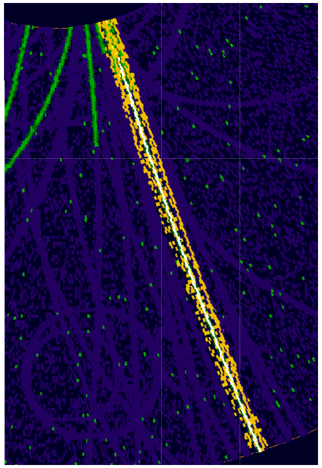
The cones provide a means of isolating tracks in dense jets (as shown at right).

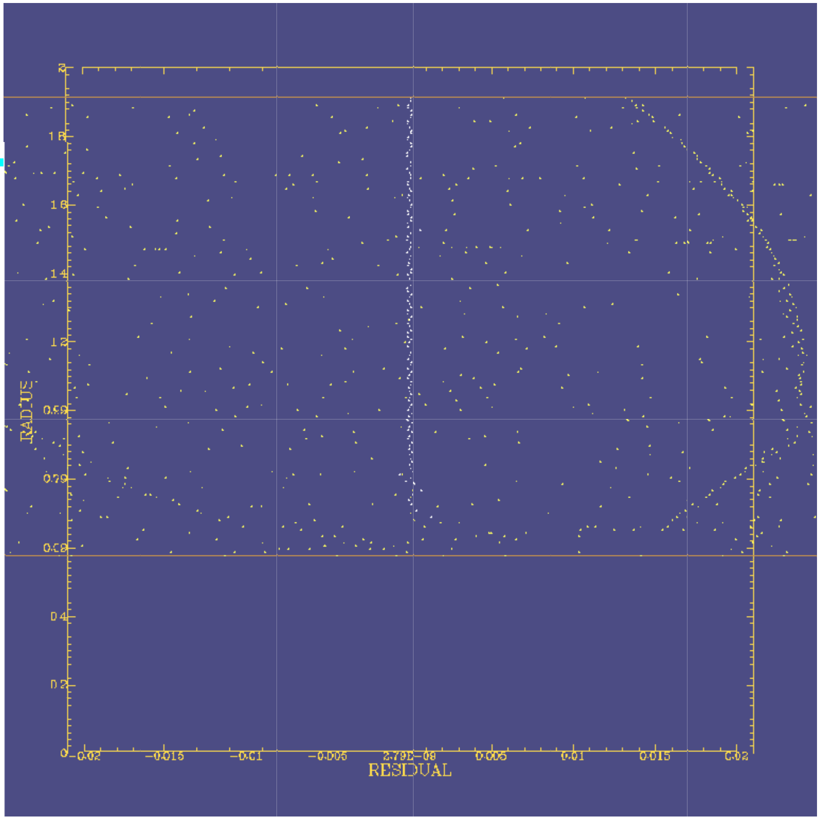
Isolated, clean, track segments are the basis for the FIRST level of pattern recognition. This uses only cell positions.

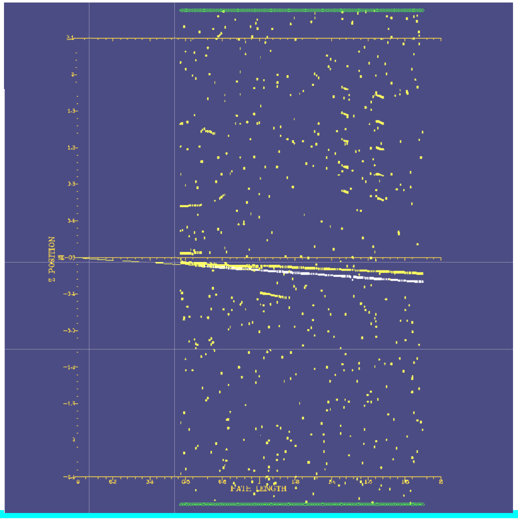
Selected track segments from all cones are collected and prioritized for further processing.

Using precision information in the track finding









After locating isolated track segments,

a road is defined around the input segment.

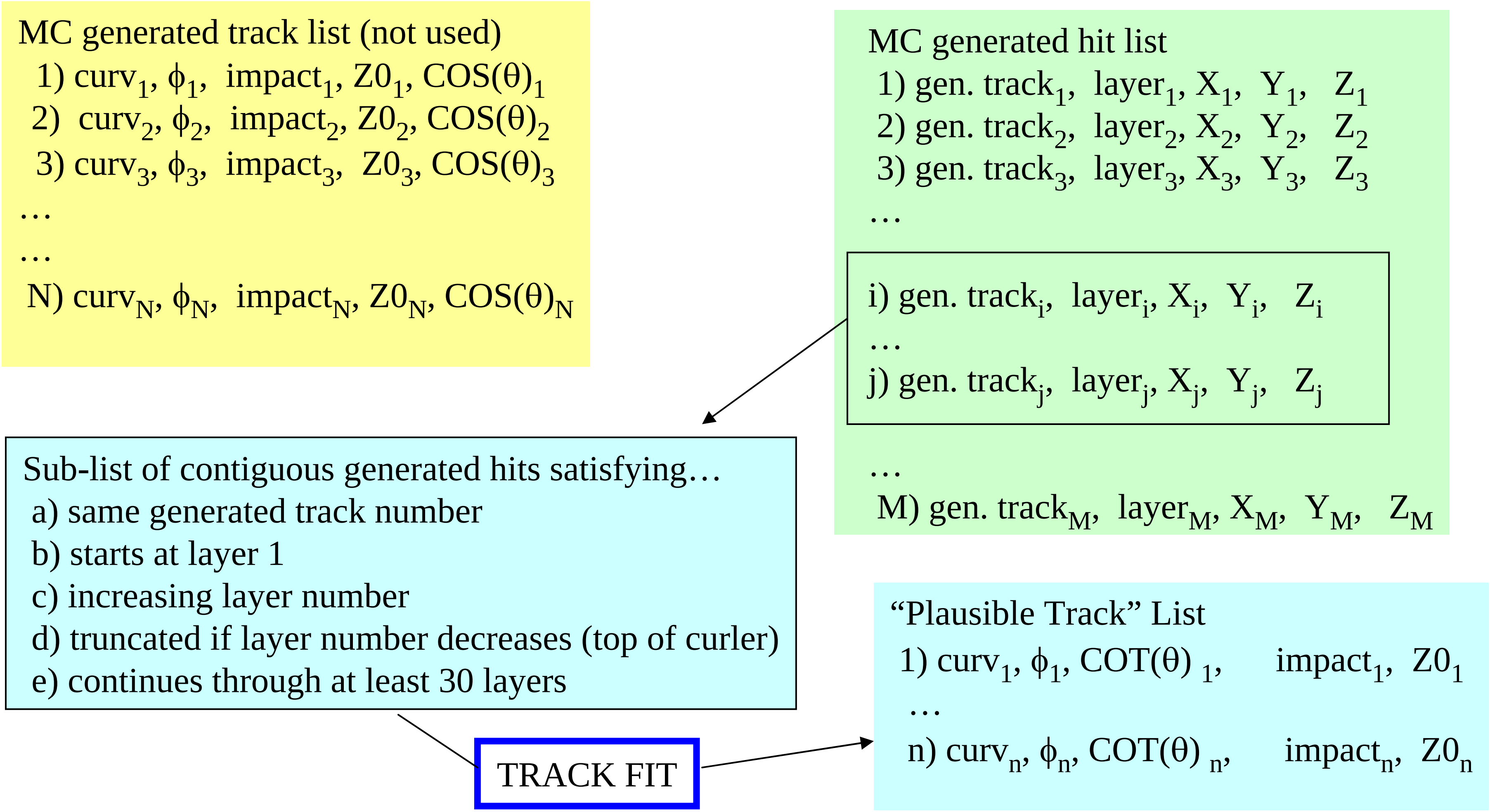
Pad responses are re-clustered within the road
and within a time correlation (~ 4cm).

Local ambiguity resolution is uses to select precision hits
within (somewhat arbitrarily) defined layer groups.

Hits are required to have consistent residuals,
relative to the "current fit".
The average residual within a layer group is less important.

The process of selecting hits is iterated.

MC tracks selected for efficiency studies



MC generated track list (not used)

1) curv$_1$, ϕ_1, impact$_1$, Z0$_1$, COS$(\theta)_1$
2) curv$_2$, ϕ_2, impact$_2$, Z0$_2$, COS$(\theta)_2$
3) curv$_3$, ϕ_3, impact$_3$, Z0$_3$, COS$(\theta)_3$

…

…

N) curv$_N$, ϕ_N, impact$_N$, Z0$_N$, COS$(\theta)_N$

MC generated hit list

1) gen. track$_1$, layer$_1$, X$_1$, Y$_1$, Z$_1$
2) gen. track$_2$, layer$_2$, X$_2$, Y$_2$, Z$_2$
3) gen. track$_3$, layer$_3$, X$_3$, Y$_3$, Z$_3$

…

i) gen. track$_i$, layer$_i$, X$_i$, Y$_i$, Z$_i$

…

j) gen. track$_j$, layer$_j$, X$_j$, Y$_j$, Z$_j$

…

M) gen. track$_M$, layer$_M$, X$_M$, Y$_M$, Z$_M$

Sub-list of contiguous generated hits satisfying…

a) same generated track number
b) starts at layer 1
c) increasing layer number
d) truncated if layer number decreases (top of curler)
e) continues through at least 30 layers

TRACK FIT

“Plausible Track” List

1) curv$_1$, ϕ_1, COT(θ) $_1$, impact$_1$, Z0$_1$

…

n) curv$_n$, ϕ_n, COT(θ) $_n$, impact$_n$, Z0$_n$

Match $\chi^2 = (\Delta C/.002)^2+(\Delta\phi/.003)^2+(\Delta COT/.002)^2$

Track finding efficiency dependence on pad width and track “curvature”.

Require χ < 25 (defined on previous slide.)

Low curvature tracks are defined to NOT curl within the TPC.

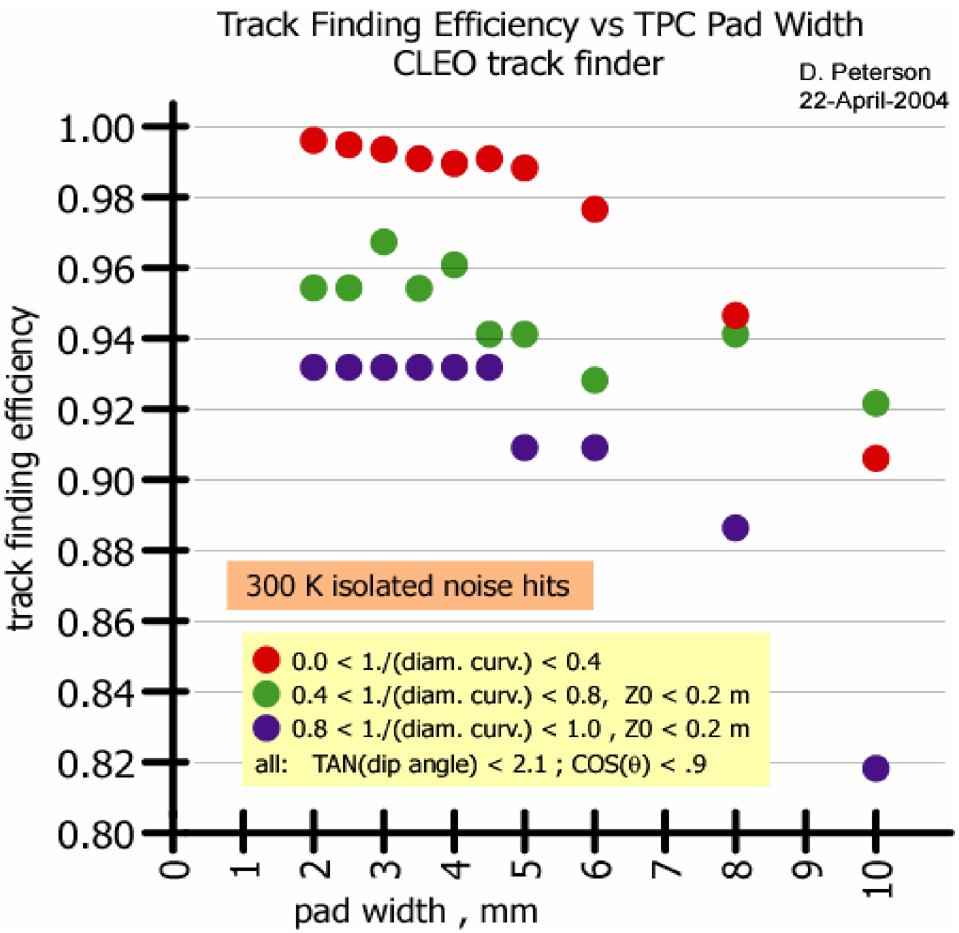
Medium curvature tracks have a curl-over radius of 1.2 to 2.5 meters. Z0 < 0.2 m.

High Curvature tracks have a curl-over radius of 1.0 to 1.2 meters. Z0 < 0.2 m. (The inner radius of the chamber is 0.56 m.)

Medium and high curvature tracks are spread outside the jets.

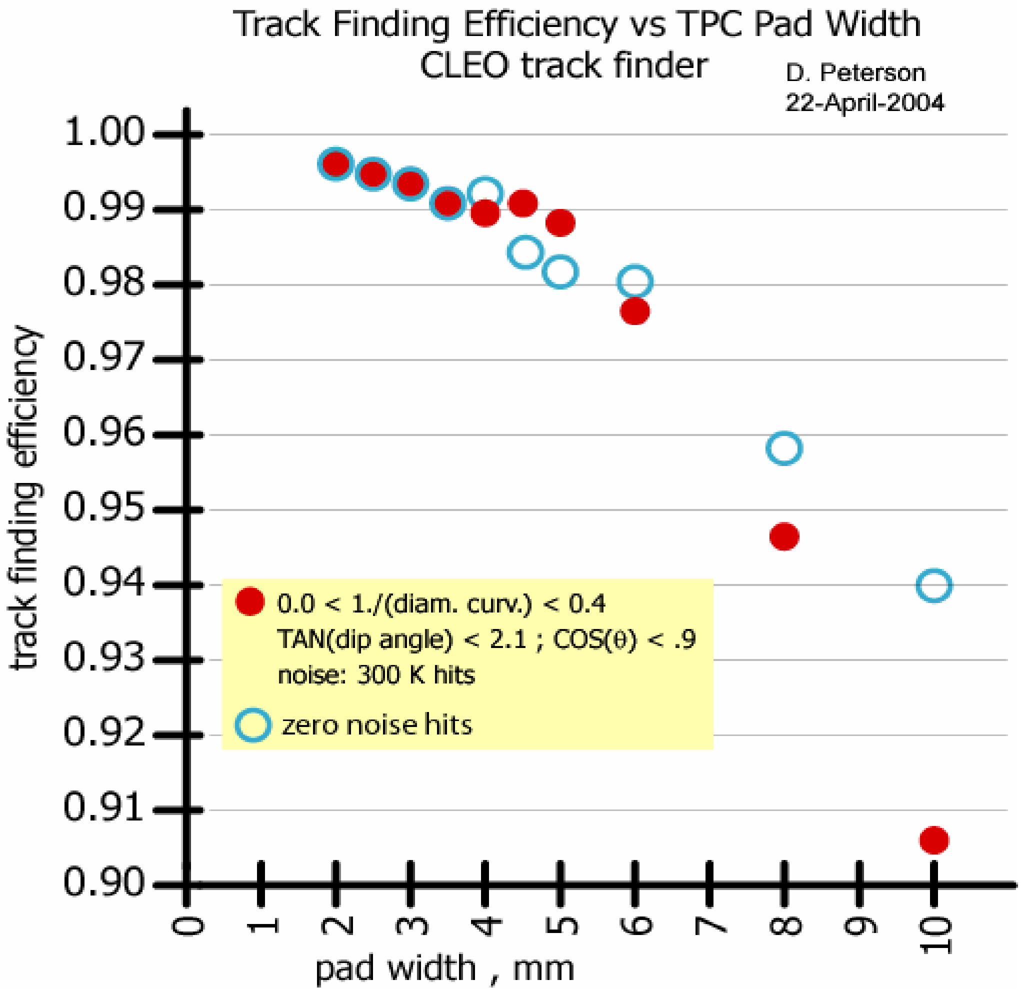
The efficiency for MEDIUM curvature tracks is largely independent of pad size.

The efficiency for HIGH curvature tracks decreases with pad size above 4 mm.



The distribution for LOW curvature is expanded on the next slide.

Efficiency dependency on noise



The efficiency for low curvature tracks is above 99% and has only a small variation below 4mm pad width.

The efficiency has little dependence on the noise rate for a pad size of 4mm (or less).

(The noise occupancy is ~1% for 4 mm pad size.)

(Surprisingly,
the points at pad width = 4.5mm and 5mm have better efficiency *with* the noise.
The discrepancy is consistent with the tolerance at that pad size.)

The efficiency for medium and high curvature tracks has insignificant dependence on noise at the levels tested.

Low curvature : 2 tracks that are never “found”

These are decays-in-flight.

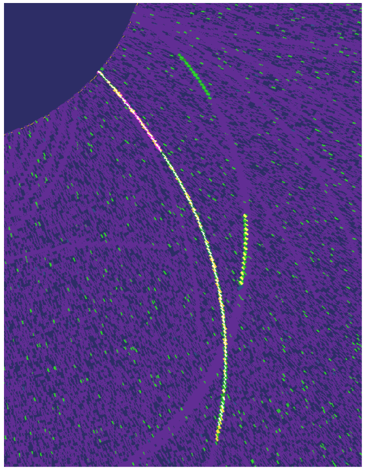
The sample is small; there are only 766 tracks in the low curvature (straight tracks) sample.

With 2 mm pad size,
only 3 tracks are lost,
of which 2 are lost
due to decay in flight.

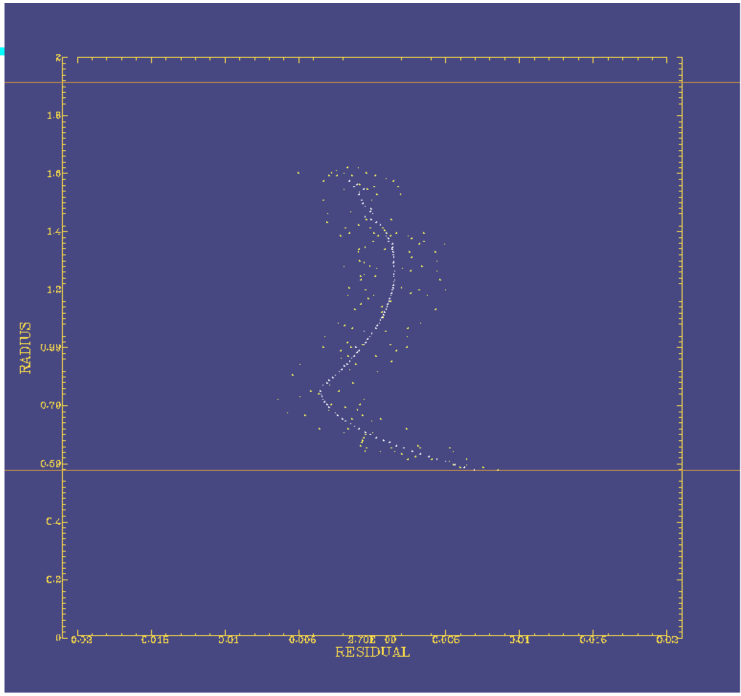
(The change in generator ID number indicates that this is decay rather than hard scatter.)

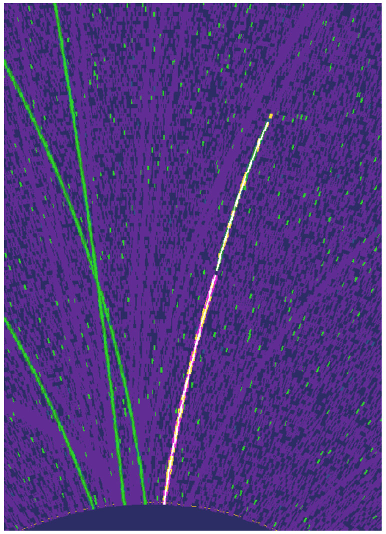
The CLEO reconstruction includes a procedure for recognizing decay-in-flight.

This is not yet implemented.

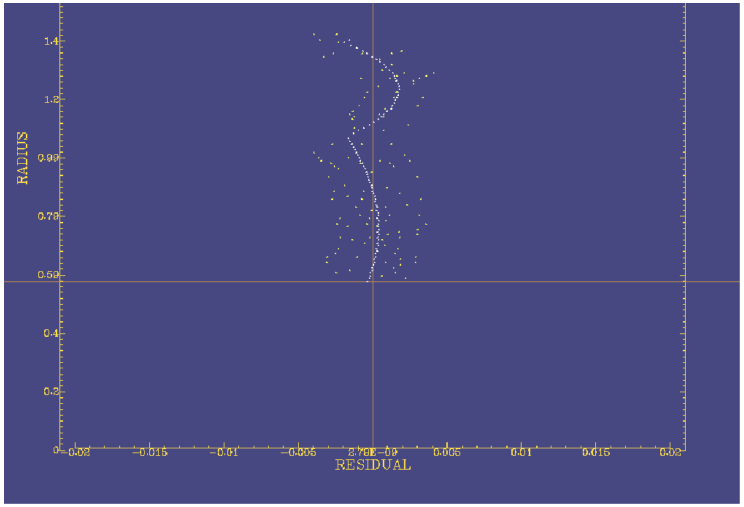


Active cone: Z=[r * (+31 / 40)] +/- 4.7 cm

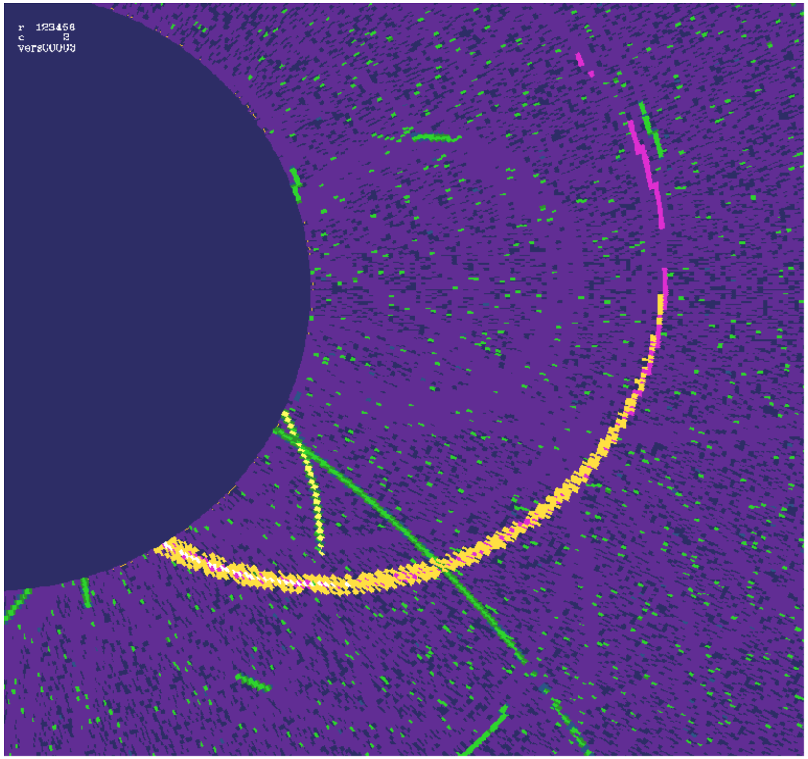


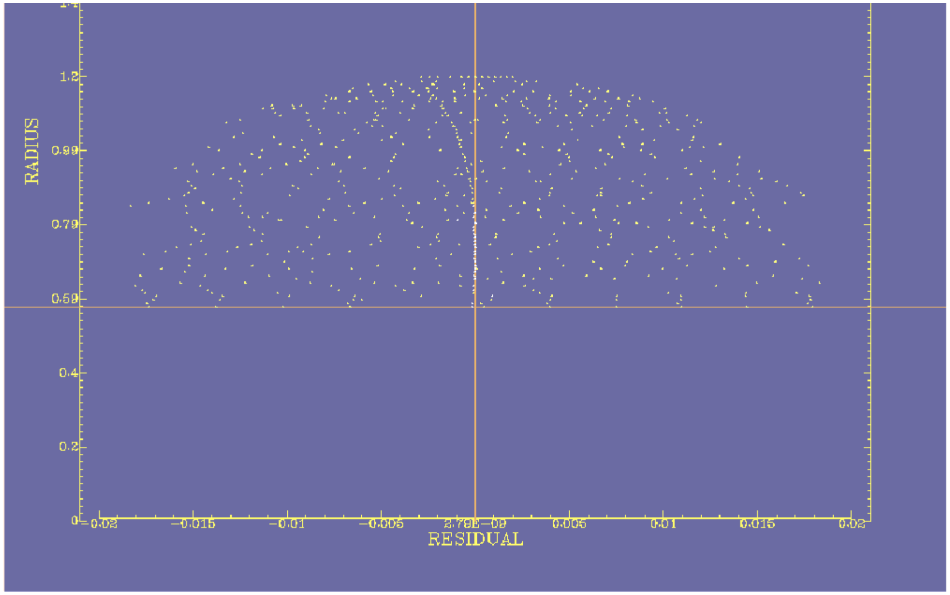


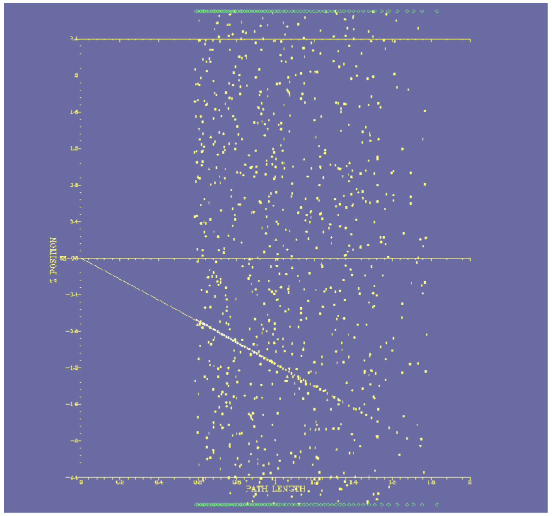
Active cone: Z=[r * (+30 / 40)] +/- 4.7 cm



Example of Inefficiency in High Curvature Tracks





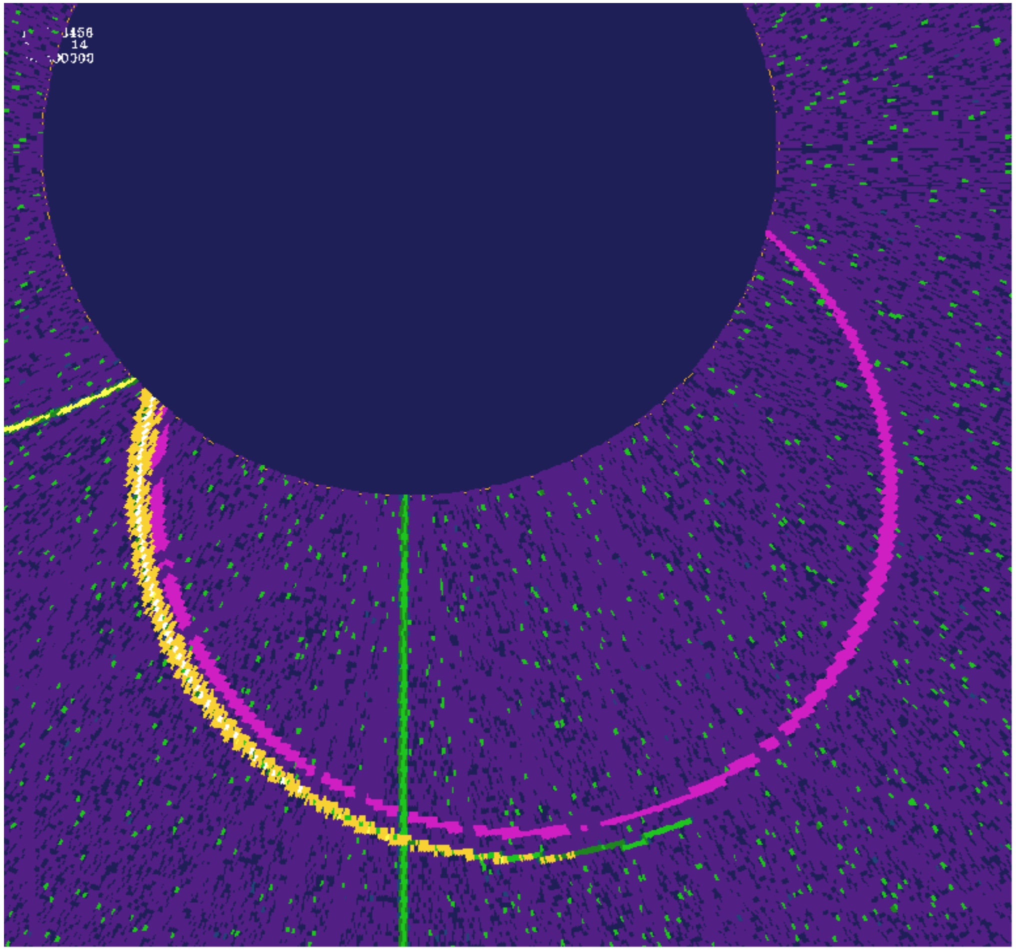


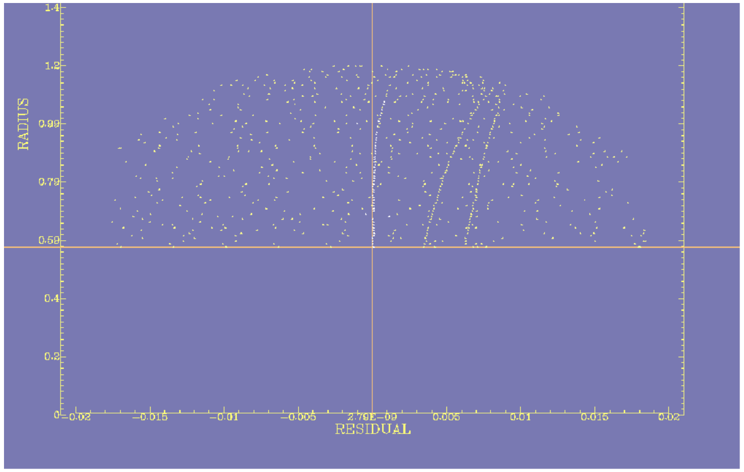
The particle, ~ 450 MeV/c, suffered energy loss after about 25 cm.
The track in reconstructed only to the radius of energy loss.

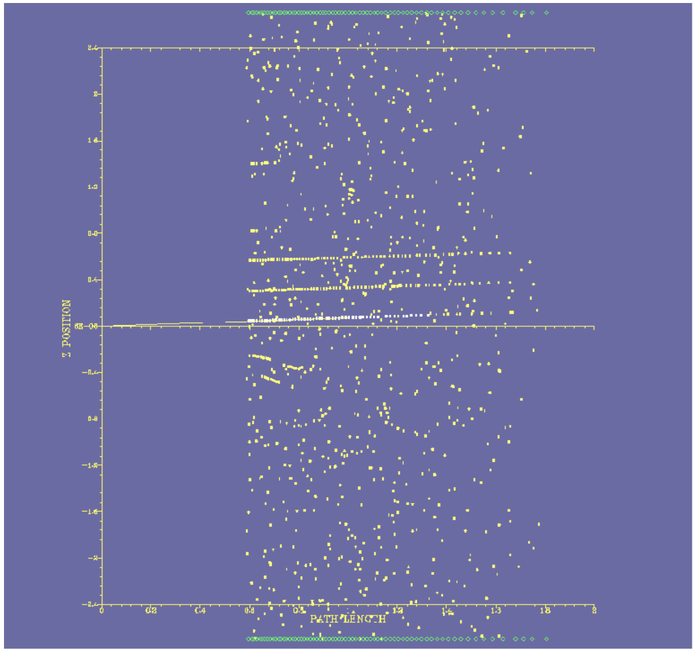
The 3rd stage of the CLEO pattern recognition (not implemented) would extend the hit recognition to the curl-over radius.

Ironically, the found track represents the initial track parameters but not do not match the defined track parameters (slide 16).

Multiple Loops







Summary, Outlook

“Complete” at the Paris 2004 LCWS meeting:

- interface to the LCD physics simulation through .sio file (Mike Ronan)
- implementation of a TPC geometry, data structure, and detector response simulation
  - including FADC response simulation
- upgrade the Cornell/CLEO reconstruction to handle multi-hit electronics
- procedure for scanning multiple I.P. pointing cones and sorting tracks (now used in CLEO)

Results:

- TPC reconstruction efficiency above 99% for pad size 4 mm and less
  - for non curling tracks
  - within the search volume.
- TPC reconstruction efficiency is unaffected by noise , up to 1% occupancy.

Possible improvements to the study:

- Higher noise, Clustered noise, Track background
- Extend the (existing) decay-in-flight pattern recognition to the TPC.
- Investigate dependence on signal spreading. This could be relevant to, *e.g.*, resistive spreading.
- Investigate dependence on a parameterization of track isolation.
- Quantify the rate of non-removable spurious “found” tracks; this is equally important to energy flow.

Future:

Mike Ronan and Norman Graf will incorporate the response simulation into the LCD simulation and provide F77 access to simulated hits. Waiting for me to provide the specifications.