Tracking Simulation Infrastructure

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Problem Statement

- **The tracking system is tasked with finding and reconstructing the trajectories of charged particles with high efficiency and precision.**

What is a track?

- ❖ **Ordered association of digits, clusters or hits**
  - **Digit = data read from a detector channel**
  - **Cluster = collection of digits**
  - **Hit = Cluster (or digit) + calibration + geometry**
    - **Provides a measurement suitable to fit a track**
    - **E.g. a 1D or 2D spatial measurement on a plane**
- ❖ **Trajectory through space**
  - **Space = 6D track parameter space**
    - **3 position + 2 direction + 1 curvature**
  - **5 parameters and error matrix at any surface**

Requirements

- **Track provides access to ordered**
  - **Hits, their digits and clusters if relevant**
  - **Fits with fit quality (chi-square)**
    - **Fit = surface + 5D track vector + error matrix**
  - **Misses**
    - **Active surface crossed without adding a hit**
    - **Miss probability: individual and/or summary**
  - **Kinks**
    - **Change in direction and/or curvature**

Requirements (cont)

- **Following services to be provided for any track**
  - **Fit (and refit)**
  - **Return a fit at any (?) intersected surface**
    - **5-vector and error matrix**
  - **Persistence**
    - **Capture and restore state**

Infrastructure components

- **Hit**
  - Surface
  - Measurement and error
  - Mechanism to predict measurement from a track fit
  - Access to underlying cluster and/or digits
- **Miss**
  - Surface
  - Miss probability calculated from track fit

Infrastructure components (cont)

- **Propagator**
  - **Generic interface**
  - **Propagates a track fit to a new surface**
  - **Does not handle measurements or kinks**
  - **May include material effects**
  - **Expect multiple versions**

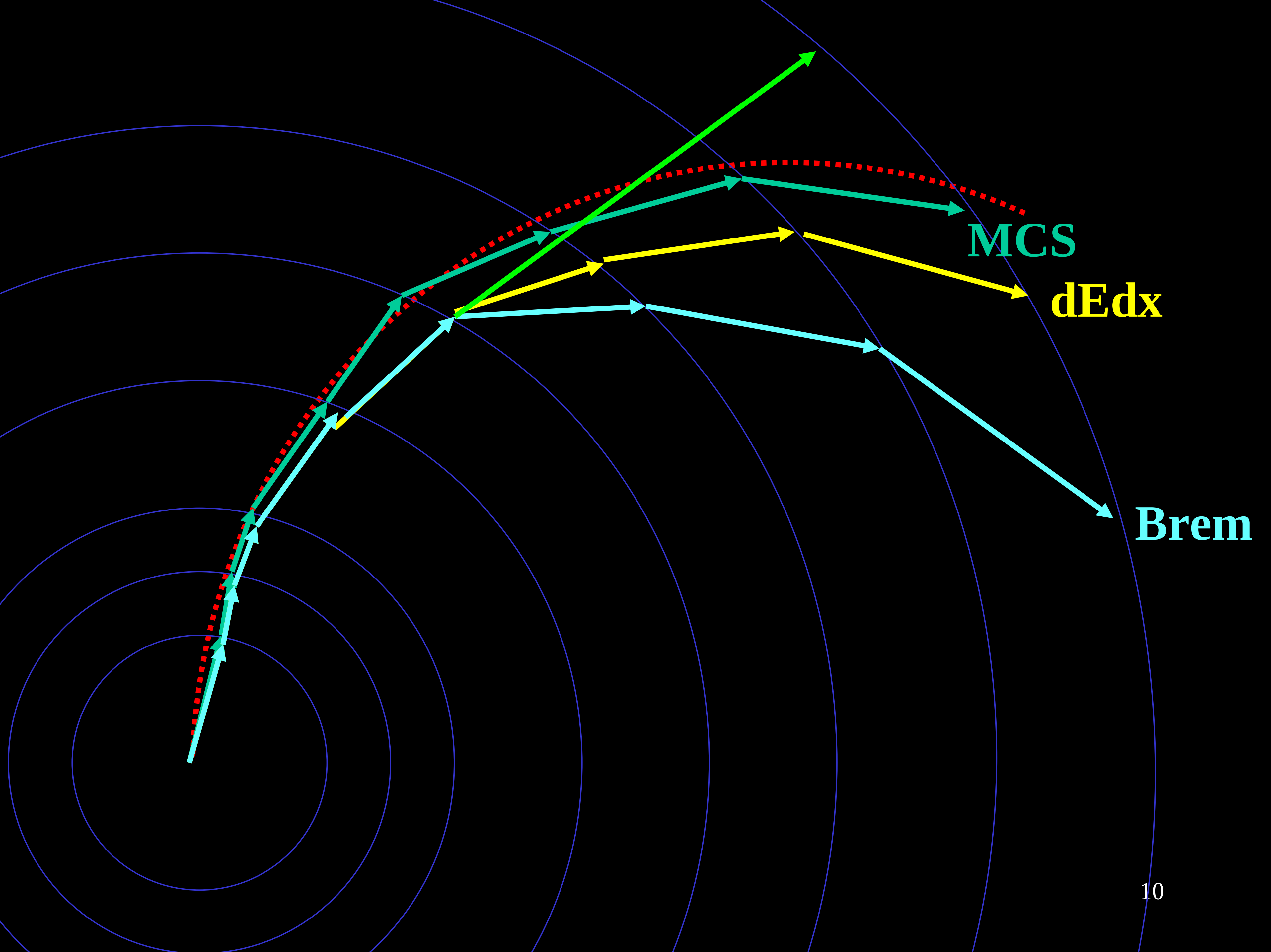
Infrastructure components (cont)

❖ **Fitter**

- **Generic interface**
- **Adds or updates the fits on a track**
- **In Kalman world, it is natural to add a fit at the surface associated with each hit**
- **Expect multiple versions**

Track Definition

- **Six parameters are required to determine a charged particle's path in a magnetic field.**
- **However, knowing these parameters at a single point (*e.g.* the distance of closest approach to the beam,** dca**) is insufficient for precision fits due to material effects (dE/dx, MCS, bremsstrahlung) and field inhomogeneities.**
  - **No global functional form for the fit.**


MCS
dEdx
Brem

Track Definition

- **We define a track as an ordered list of hits (or misses) at measurement surfaces along with the best fit at that surface (**TrackStates**).**
- **The track fit consists of five parameters appropriate to the surface plus one parameter which is provided by the constraint that the track lie on the surface.**

Surfaces

- **Surfaces generally correspond to geometric shapes representing detector devices.**
- **They provide a basis for tracks, and constrain one of the track parameters.**
- **The track vector at a surface is expressed in parameters which are "natural" for that surface.**

Cylinder

- **Surface defined coaxial with z, therefore specified by a single parameter r.**
- **Track Parameters: (ϕ, z, α, tanλ, q/p_T)**
- **Bounded surface adds z_{min} and z_{max}.**
- **Supports 1D and 2D hits:**
  - **1D Axial: ϕ**
  - **1D Stereo: $\phi+\kappa z$**
  - **2D Combined: (ϕ, z)**

XY Plane

- ❖ **Surface defined parallel with z, therefore specified by distance u from the z axis and an angle ϕ of the normal with respect to x axis.**
- ❖ **Track Parameters: (v, z, dv/du, dz/du, q/p)**
- ❖ **Bounded surface adds rectangular boundaries.**
- ❖ **Supports 1D and 2D hits:**
  - **1D Stereo: w_v*v + w_z*z**
  - **2D Combined: (v, z)**

Z Plane

- **Surface defined perpendicular to z, therefore specified by single parameter z.**
- **Track Parameters: (x, y, dx/dz, dy/dz, q/p)**
- **Bounded surface adds polygonal boundaries.**
- **Supports 1D and 2D hits:**
  - **1D Stereo: $w_x*x + w_y*y$**
  - **2D Combined: (x,y)**

Distance of Closest Approach

- **DCA is also a 5D** Surface **in the 6 parameter space of points along a track.**
- **It is** not **a 2D surface in 3D space.**
- **Characterized by the track direction and position in the (x,y) plane being normal;** $\alpha=\pi/2$.
- **Track Parameters: $(r, z, \phi_{dir}, \tan\lambda, q/p_T)$**

Detector

- **A** Detector **describes a collection of** Layers **which are organized in a hierarchy of detectors.**
- Layers **describe the geometry of the detector by holding** Surfaces**, either directly or through sub** Layers

Propagators

- Propagators **propagate a track (with or without covariance matrix) to a new surface.**
  - Propagators **to and from all the surfaces are defined, *e.g.***
    - **PropCylCyl**
    - **PropDcaCyl**
    - **PropXYZ**
  - **Conversion of track parameters to those natural for the surface propagated to.**
- **Currently defined for homogeneous fields.**
  - **Straightforward (but CPU intensive) to add RK.**

Interactions with Material

- **Interactions with material affect the track state by perturbing the track covariance matrix (*e.g.* stochastic processes such as MCS) or the track vector itself (dE/dx).**
- **This behavior is encapsulated in an abstract** Interactor
  - **Specific instances inherit from this, such as** ThinCylMs.
  - **Energy loss is handled by abstract** DeDX
    - DeDxBethe or DeDxFixed

Interactors

- **Thin material scattering affects only direction covariance matrix elements.**
- **Thick material scattering affects both direction and position covariance matrix elements.**
- **Energy loss interface defined, simple Bethe-Bloch implementation available.**

Tracking Detector

- **Sensitive detector elements which handle hits, misses and interactors.**
- **Support material which handles interactors.**
- **Driven by compact detector description + auxiliary files.**

Track Fitting

- ❖ **Need to provide best possible fit to the track parameters and also their uncertainties.**
  - **Vertex pattern recognition and Least-Squares fitting are very sensitive to track uncertainties.**
  - **Tight matching of track momentum and direction with calorimeter cluster energy and position necessary for optimal jet energy resolutions.**
- ❖ **Requiring best fit at both ends of track logically leads to a local track fitting strategy.**

Track Fitting

- **Can be combined with track finding to accomplish both tasks at once.**
- **Can also fit hits which have been identified as constituents of a track by a separate pattern recognition package.**

Track Fitting

- Pattern recognition program delivers a list of hits and an estimate of the global track parameters.
- Track Fit uses the Kalman Filter algorithm to reconcile the track hypothesis with the hit measurements in an iterative manner.
- After fitting each hit, the track covariance matrix is updated to account for the effects of MCS, and the track vector is modified to account for dE/dx.
- The track is then propagated to the next surface.

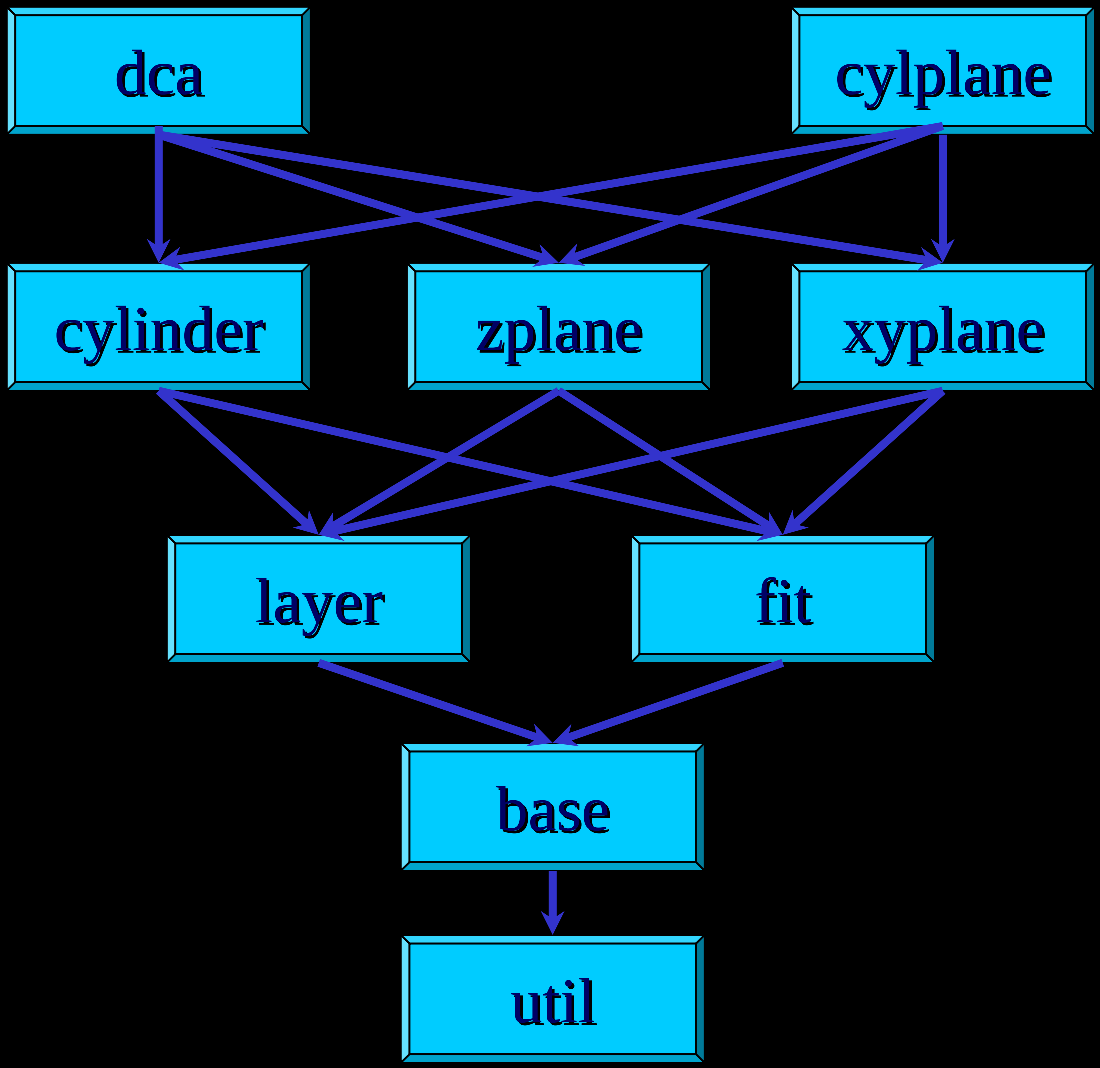
Track Fitting

- χ^2 at each surface can be used to reject outliers or search for kinks caused by decays in flight or bremsstrahlung.
- Misses are added with a probability which reflects the efficiency of the detector
  - Cut on combined probability, not number of misses.
- End up with the best fit at the extrema of the track, project to vertex or calorimeter.
  - Smoothing gives the best fit at all points.

Simulations

- Simulators are provided to generate hits and account for MCS and energy loss.
- Can be used for fast simulation:
  - Particles from MC event are propagated to each detector element.
  - The appropriate hit is generated from the intersection of the track with the surface.
  - Track vector is smeared for MCS and modified for energy loss, then propagated to next element.
- Primarily used for internal component tests.
- Lelaps and slic are primary simulation engines.

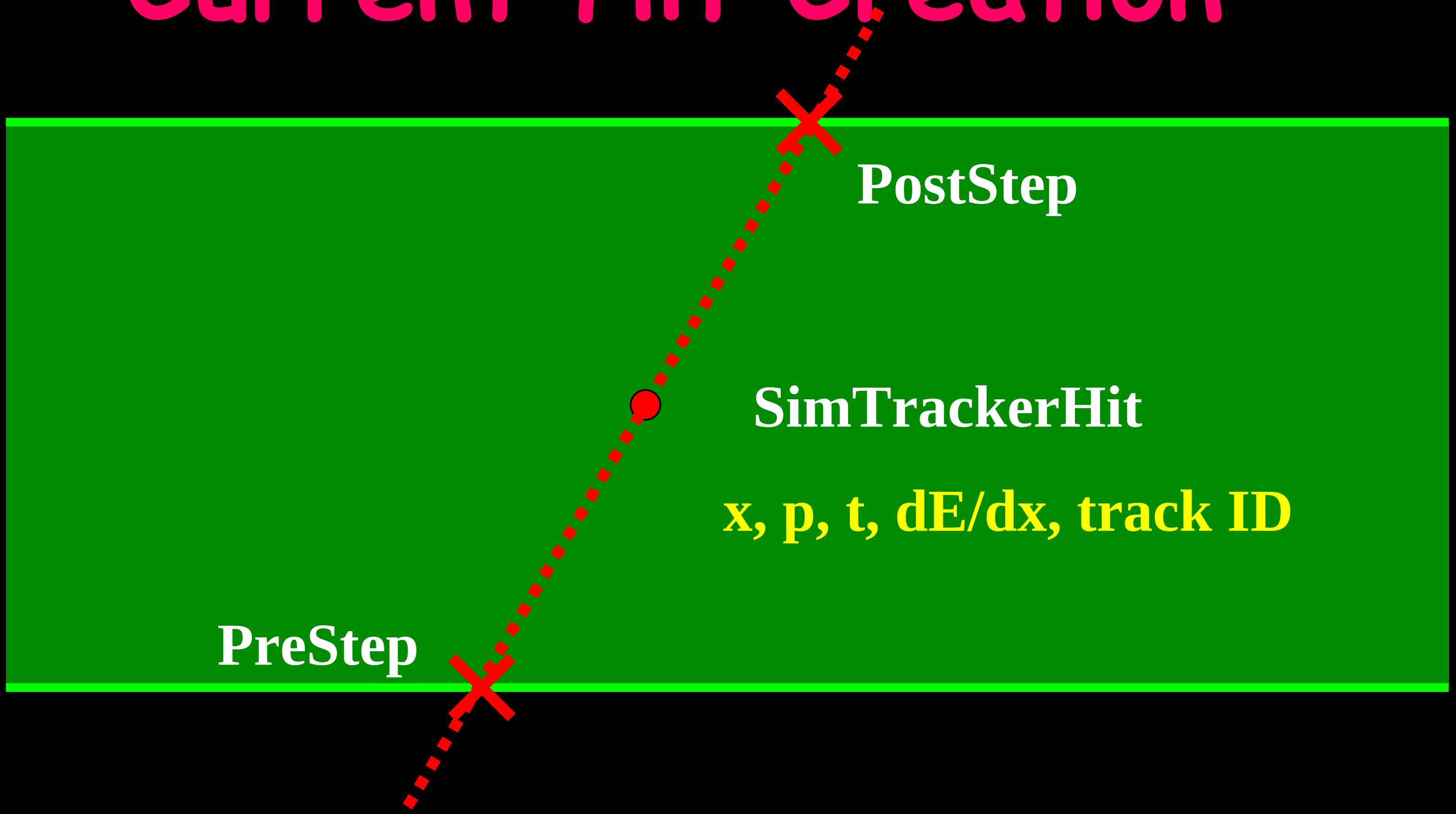
Base Package Dependencies



From SimTrackerHit to Track

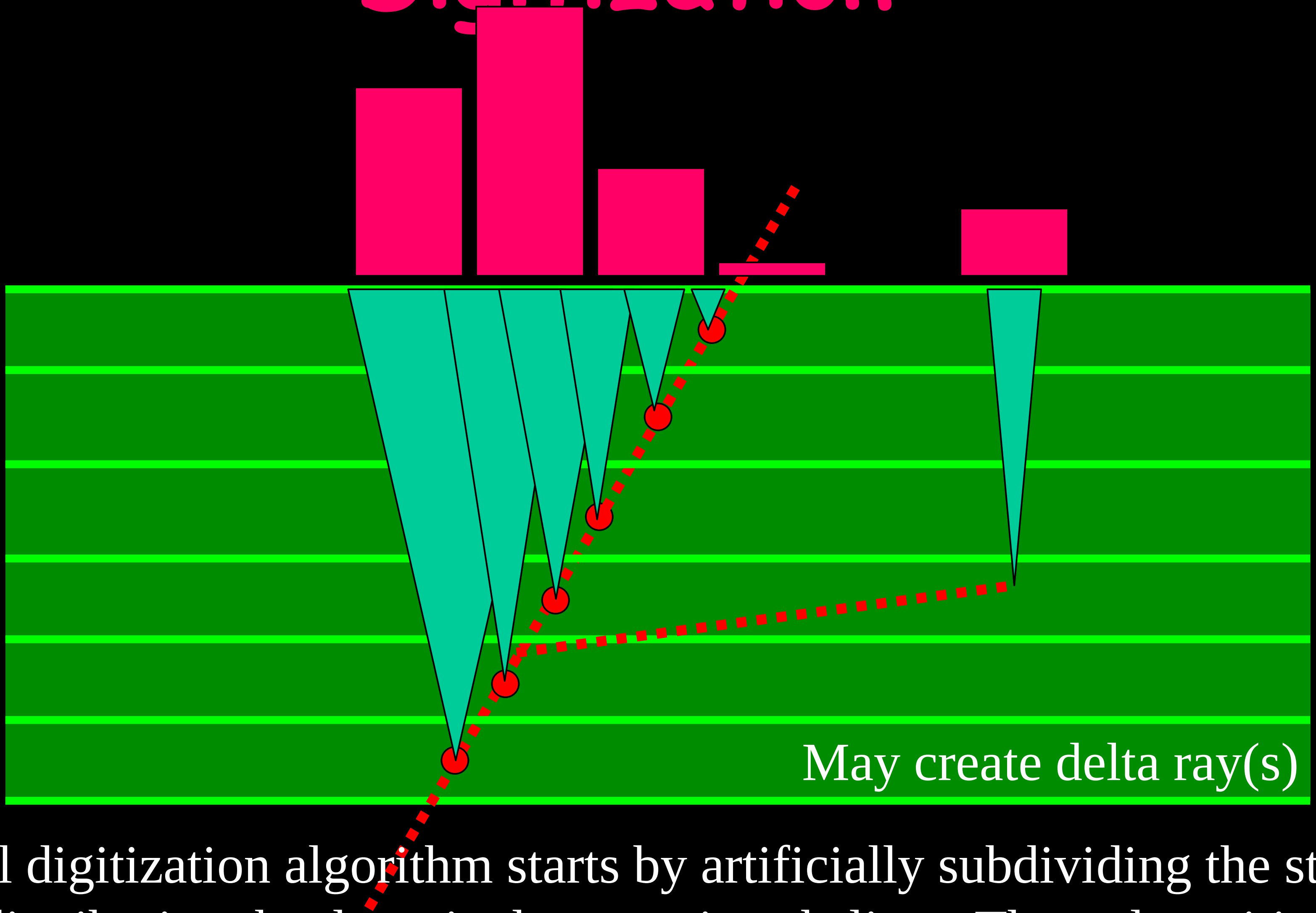
- **SimTrackerHit includes all the MC information about a particular energy deposition in a sensitive volume element.**
- **Digitization creates equivalent to raw data, e.g. channel address, ADC, time.**
- **Clustering of digitization provides clusters.**
- **Clusters can provide hits which are used in track finding and fitting.**

Current Hit Creation



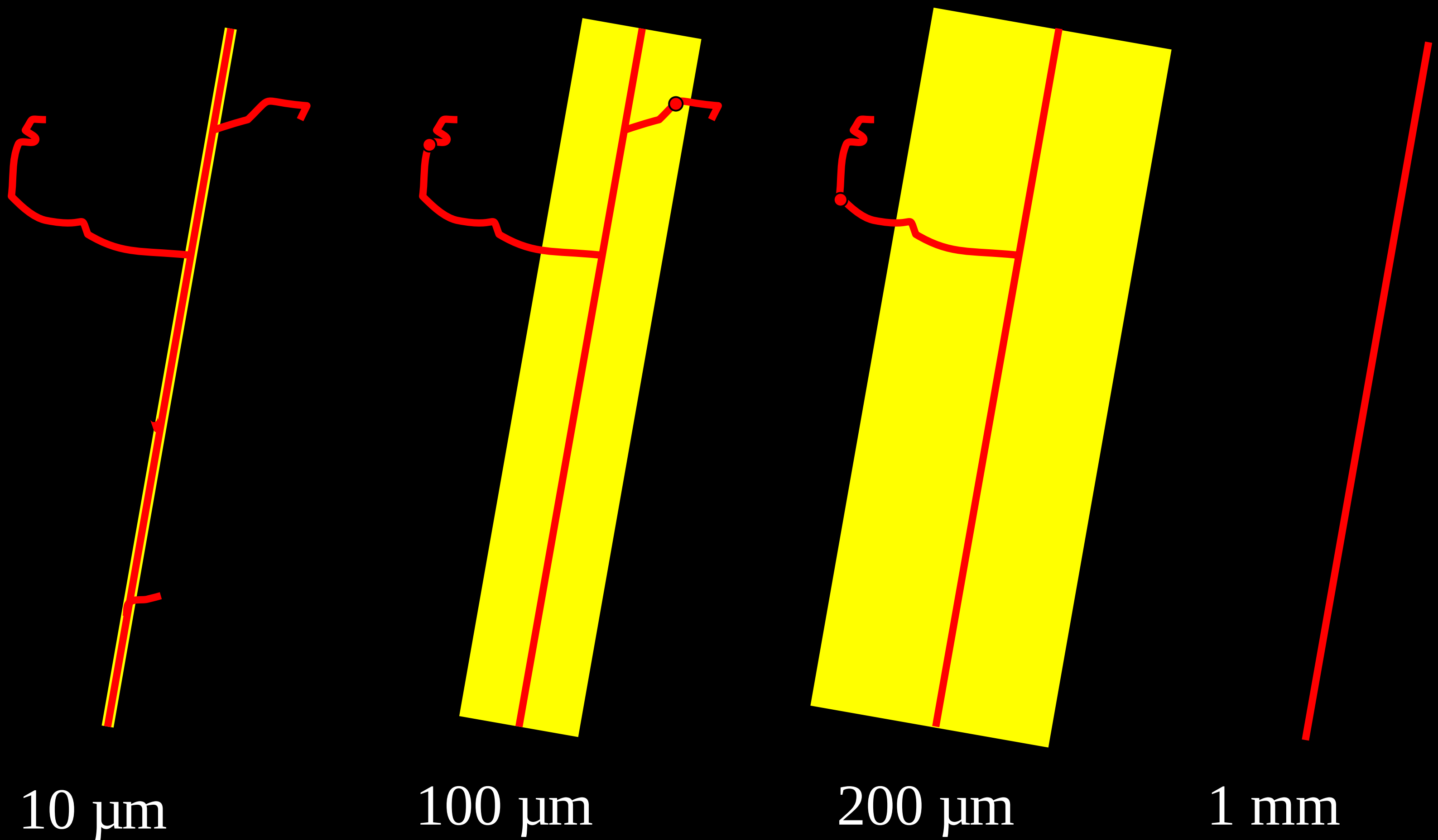
With large current step limits and range cuts in Geant4, usually get a single step in sensitive silicon, with hit placed in center of volume, and only dE/dx along path.

Digitization



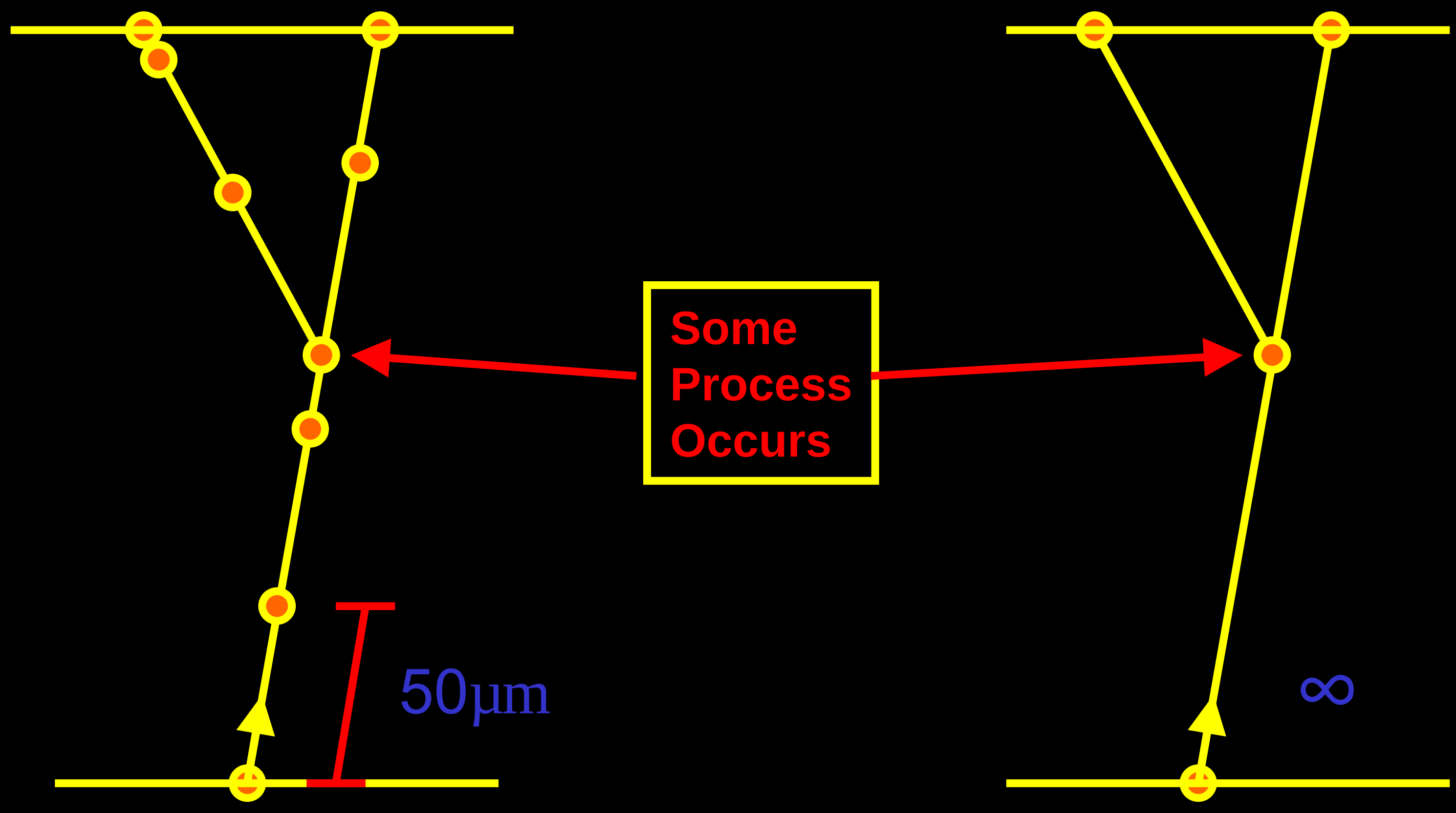
Usual digitization algorithm starts by artificially subdividing the step and distributing the deposited energy in subslices. These depositions are then drifted to the surface, with appropriate diffusion and Lorentz angle effects, to provide hits in strips.

G4 Cuts – Range Cuts



Reducing range cuts increases number of secondaries produced and explicitly tracked

G4 Cuts - Max Step Length



Limits step when no other process occurs in that distance.

Reducing size limit increases number of hits produced.

Tuning

- **Have begun investigating effects of step and range cuts on the size of the output event. Do not have data to compare to, but expect this will improve realism of the digitization process.**

Digitization

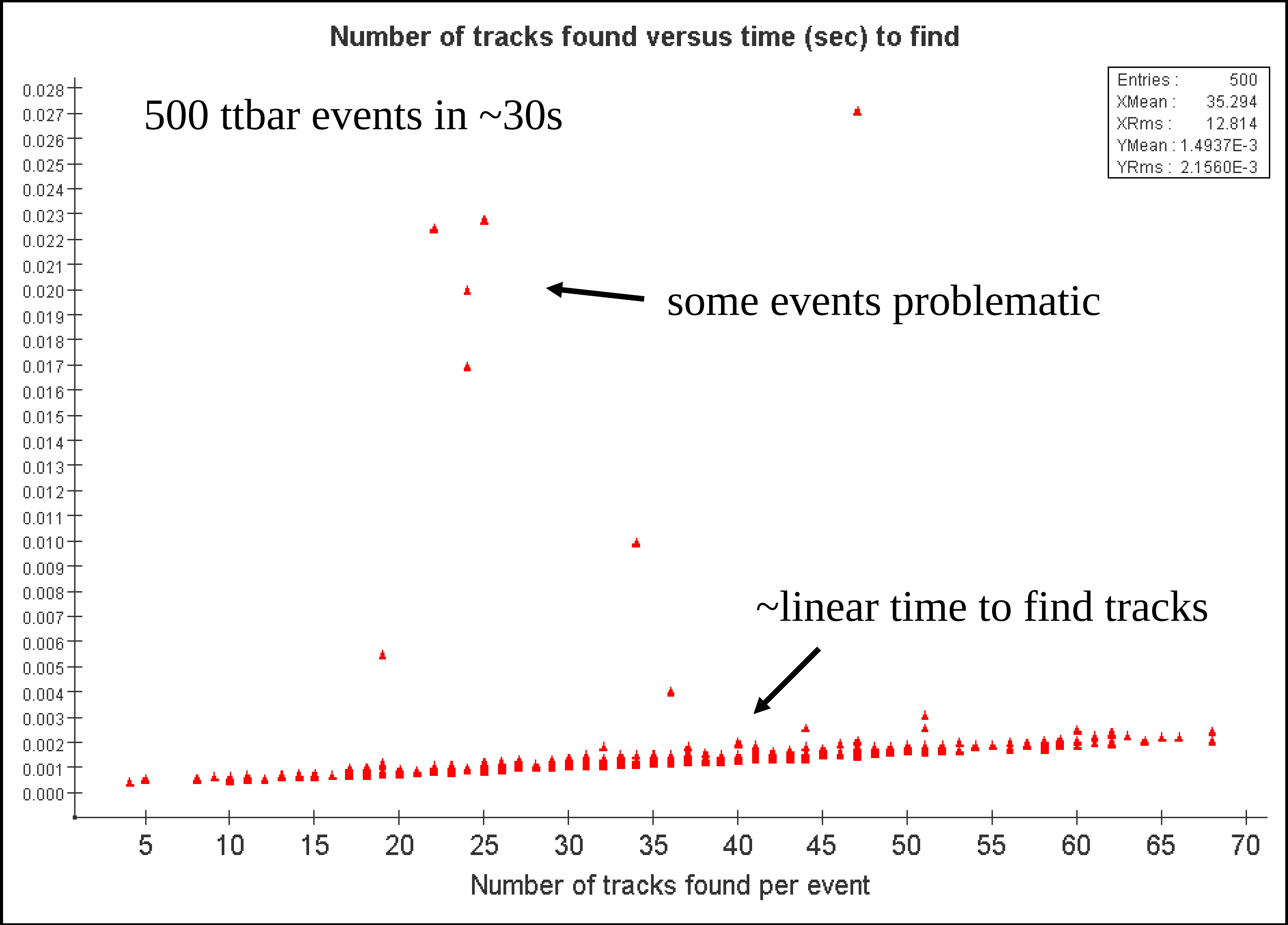
- **Have had fruitful discussions on digitization chain which takes us from SimTrackerHits to TrackerHits via readout channels.**
- **Digisim package available for handling cross-talk, noisy & dead channels.**
- **Pixel digitization for CCD done for quite some time. Has very flexible interface to study effects of pixel size, depletion thickness, etc.**
- **Working on Si strip package for January workshop.**

Track Finding

- **Once we have digitized hits, can start finding tracks.**
- **One technique for track-finding using 3D hits, or 2D measurements on surfaces has been implemented.**
- **Uses conformal mapping technique to map curved tracks to straight lines. Pattern recognition is then straightforward (or backward).**

Fast Track Finding (ftf)

- **Have applied hep.lcd ftf algorithm to hits derived from undigitized, unsmeared SimTrackerHits in org.lcsim.**
- **Run on ttbar events using only hits in vertex detector.**
- **Runs very fast, results look reasonable in event display.**
- **Have not characterized efficiency or resolution.**


Number of tracks found versus time (sec) to find
500 ttbar events in ~30s
some events problematic
~linear time to find tracks
Entries : 500
XMean : 35.294
XRms : 12.814
YMean : 1.4937E-3
YRms : 2.1560E-3
0.028
0.027
0.026
0.025
0.024
0.023
0.022
0.021
0.020
0.019
0.018
0.017
0.016
0.015
0.014
0.013
0.012
0.011
0.010
0.009
0.008
0.007
0.006
0.005
0.004
0.003
0.002
0.001
0.000
5
10
15
20
25
30
35
40
45
50
55
60
65
70
Number of tracks found per event

Track Finding

❖ **Additional strategies also implemented:**

- **Exhaustive 3-point algorithm**
  - **3D (r,φ,z) space-points, 5 or 6 layer CCD VXD**
  - **inside → out**
- **Exhaustive 3-point algorithm**
  - **2D (r,φ) space-points, 5 layer outer barrel tracker**
- **Calorimeter-seeded**
  - **outside → in**
  - **Start with MIP traces in calorimeter**
  - **Add on 2D or 3D spacepoints**
- **Aim for significant progress at sim/reco workshop**

Status

- Most of the tracking infrastructure is in place.
- Need to interface to geometry description to have automatic generation of surfaces, propagators and interactors.
- Work ongoing to define digitization chain.
- Analyzing effects of varying GEANT4 limits.
- Track fitting, including material effects, is available.
- Track finding strategies are very detector specific, await concept adoption and implementation, but some are available now.

Additional Information

Simulation & Reconstruction miniworkshop

- **http://www-hep.colorado.edu/cuilc/sim-workshop.html**
  - **January 9-11, Boulder, CO**

Simulation & Reconstruction Wiki

- **http://confluence.slac.stanford.edu/display/ilc/Home**

Linear Collider Physics and Detector Simulations

- **http://www.lcsim.org**

Discussion Forums

- **http://forum.linearcollider.org**