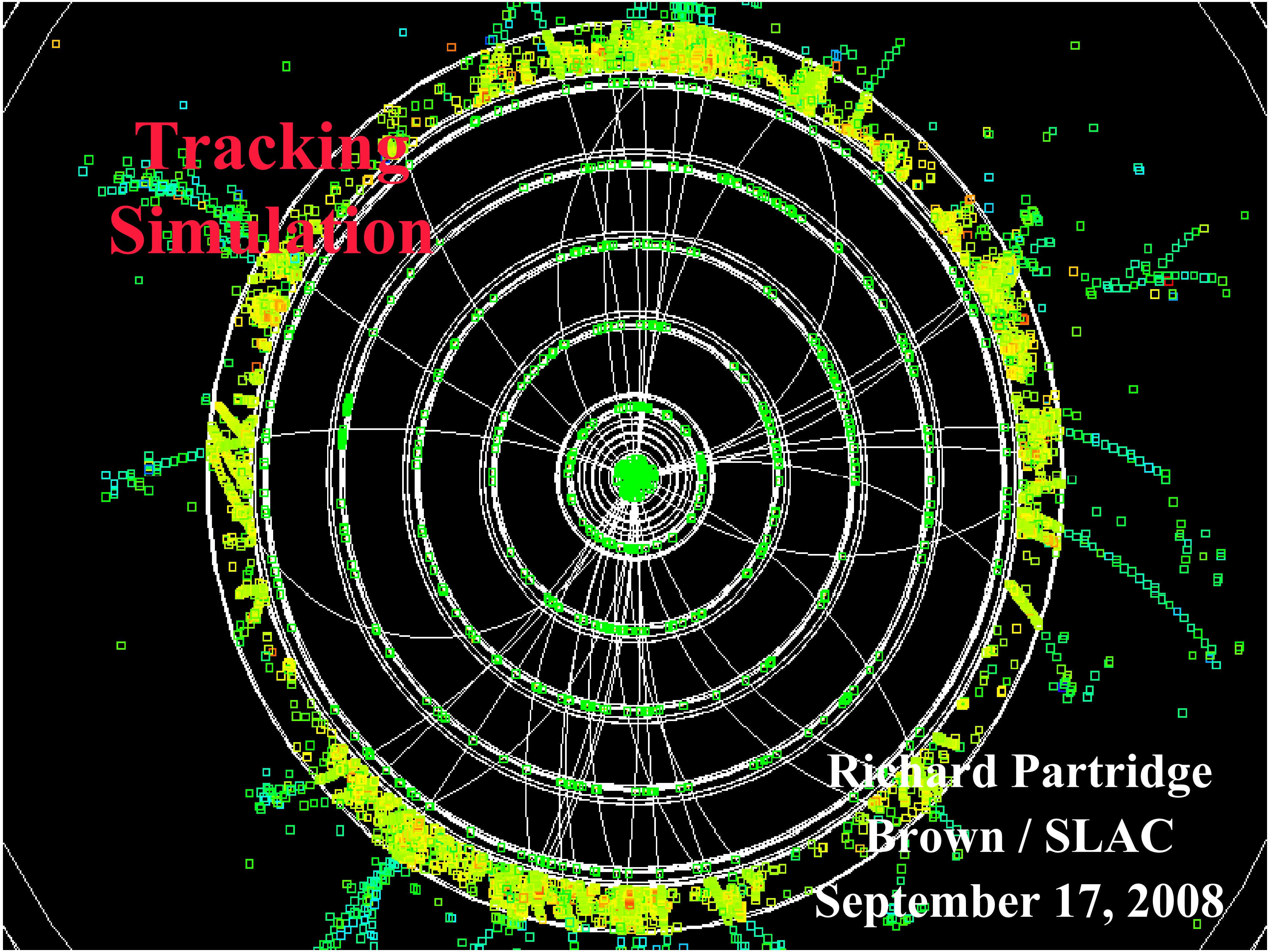
Tracking Simulation



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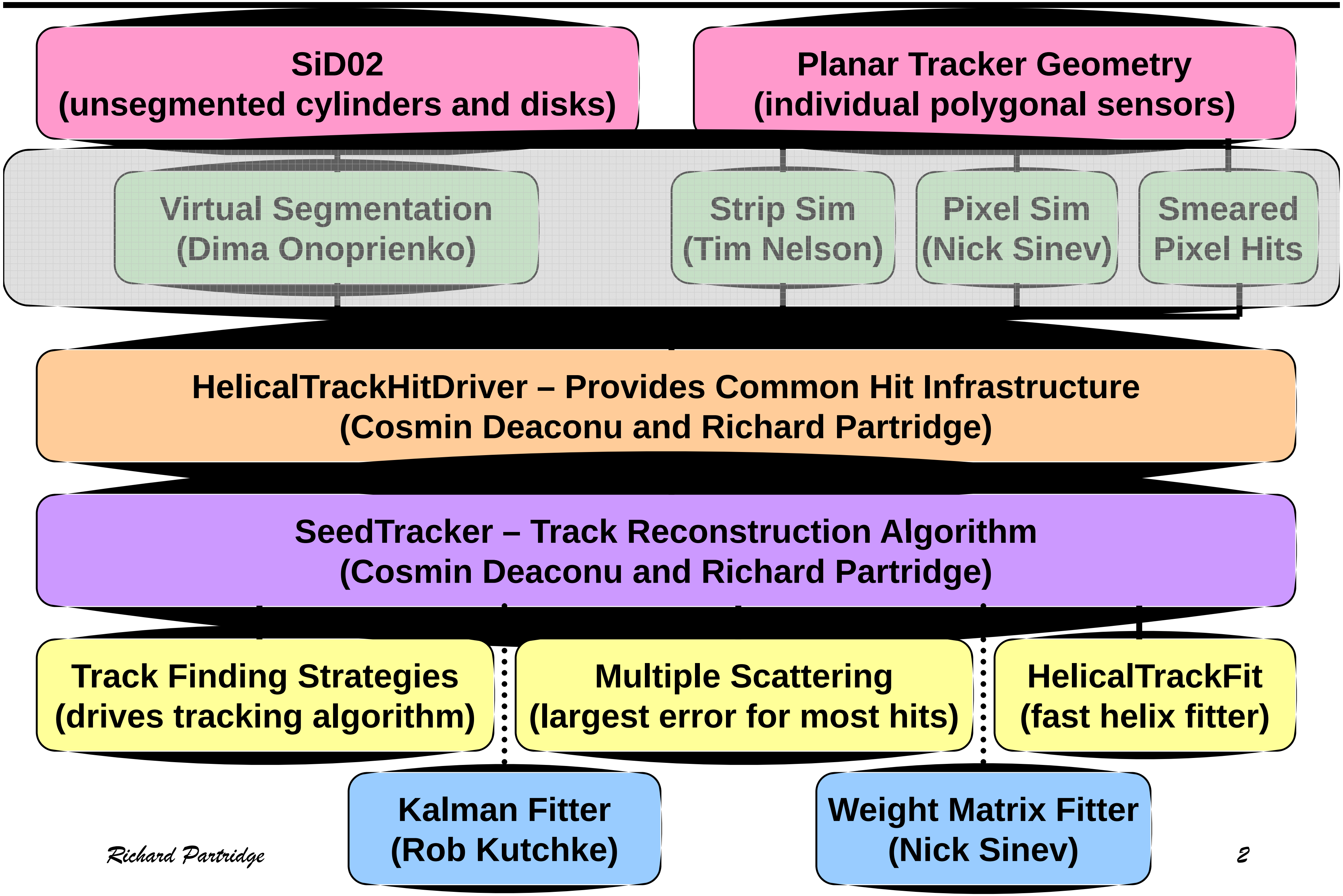
Brown / SLAC
September 17, 2008

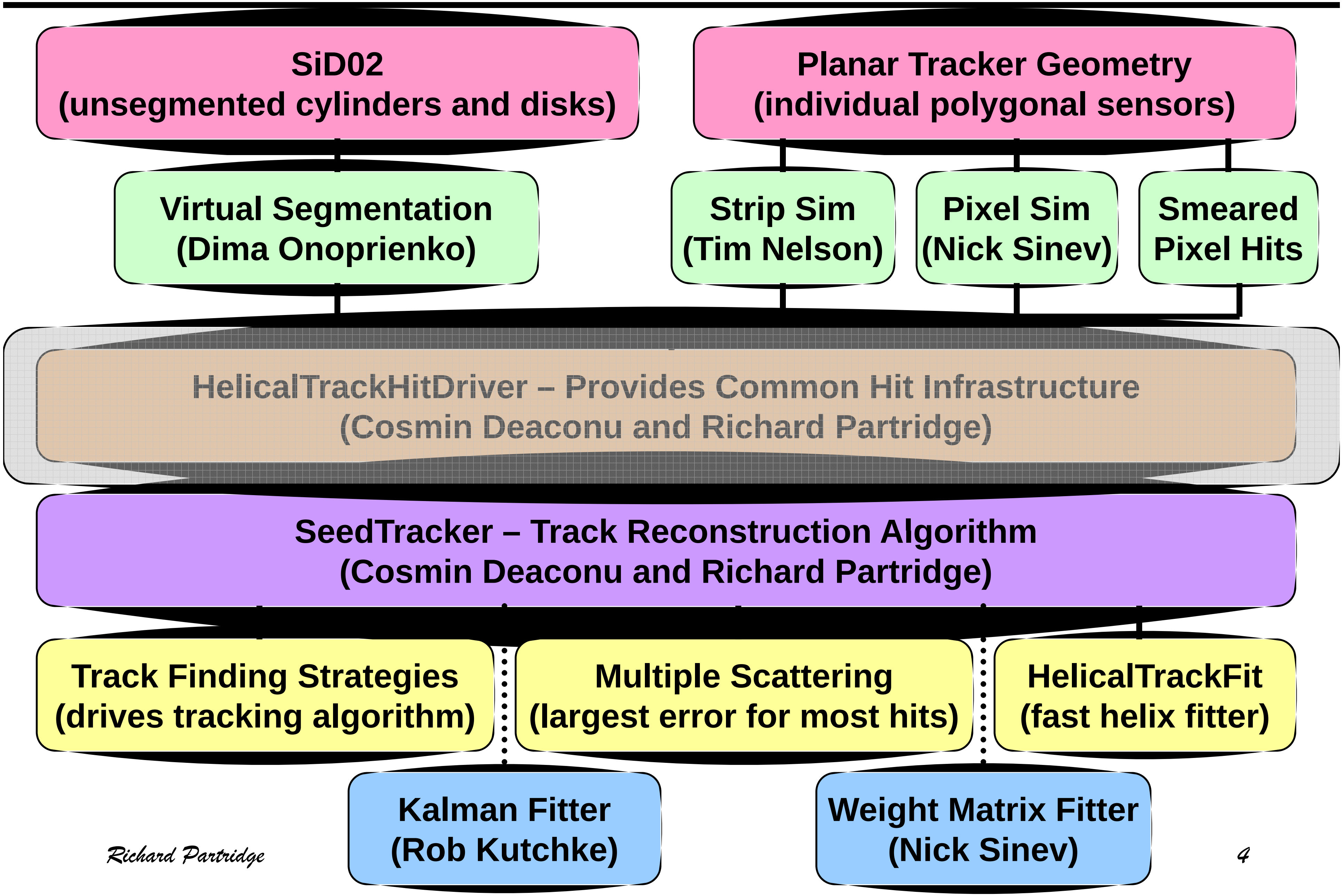
Track Reconstruction Flow Chart



Hit Digitization

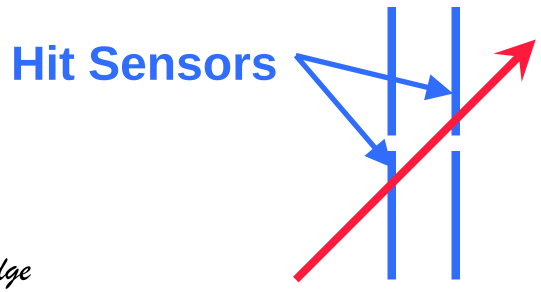
- Hit digitization turns GEANT energy deposits into tracker hits
- Several digitization packages are available:
  - Virtual segmentation divides cylinders / disks into virtual sensors allowing different segmentation schemes to be compared without re-running GEANT
  - Strip digitization provides detailed simulation of charge collection, digitization, and clustering of strips
  - Pixel digitization provides similar functionality as the strip digitization, and includes the ability to derive charge collection from pixel field maps
  - Pixel smearing allows Gaussian smearing of pixel hits – mostly used before the pixel digitization code was integrated into tracking
- Track reconstruction code works with either virtual segmentation or full digitization packages

Track Reconstruction Flow Chart



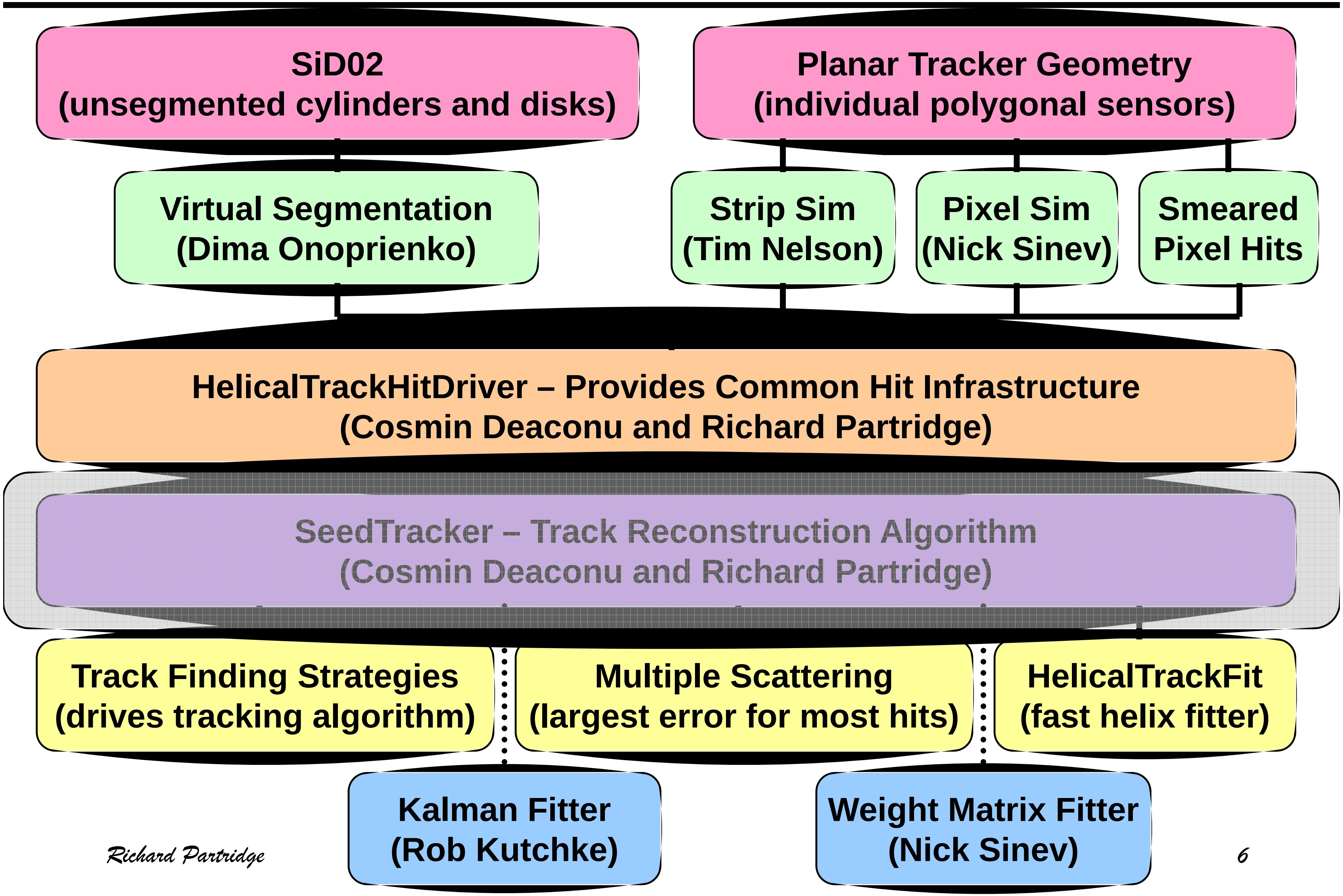
Common Hit Infrastructure

- Tracker hit infrastructure is rather weak in LCIO
  - Key features (e.g. sensor orientation and endpoints of a strip) hit are missing
  - Hit errors are represented by a 3x3 covariance matrix, which is intrinsically singular for 1 coordinate (strip) or 2 coordinate (pixel) measurements
- Virtual segmentation and full digitization algorithms extend LCIO conventions, but take different approaches
- Common hit infrastructure developed to shield the tracking code from the details (and changes) in the hit digitization
- Infrastructure also provides extensive support for stereo hits
  - Forms stereo hits (and ghost hits) from nearby non-parallel strips
  - Adjusts hit position for track direction
  - Uncertainty in hit position includes uncertainty in the track direction



Common Hit Infrastructure provides robust handling of stereo hits, including cases like the one show here

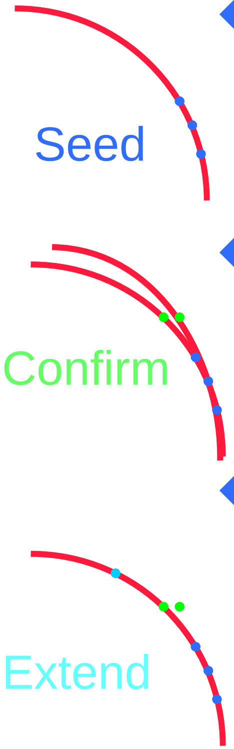
Track Reconstruction Flow Chart



SeedTracker Philosophy

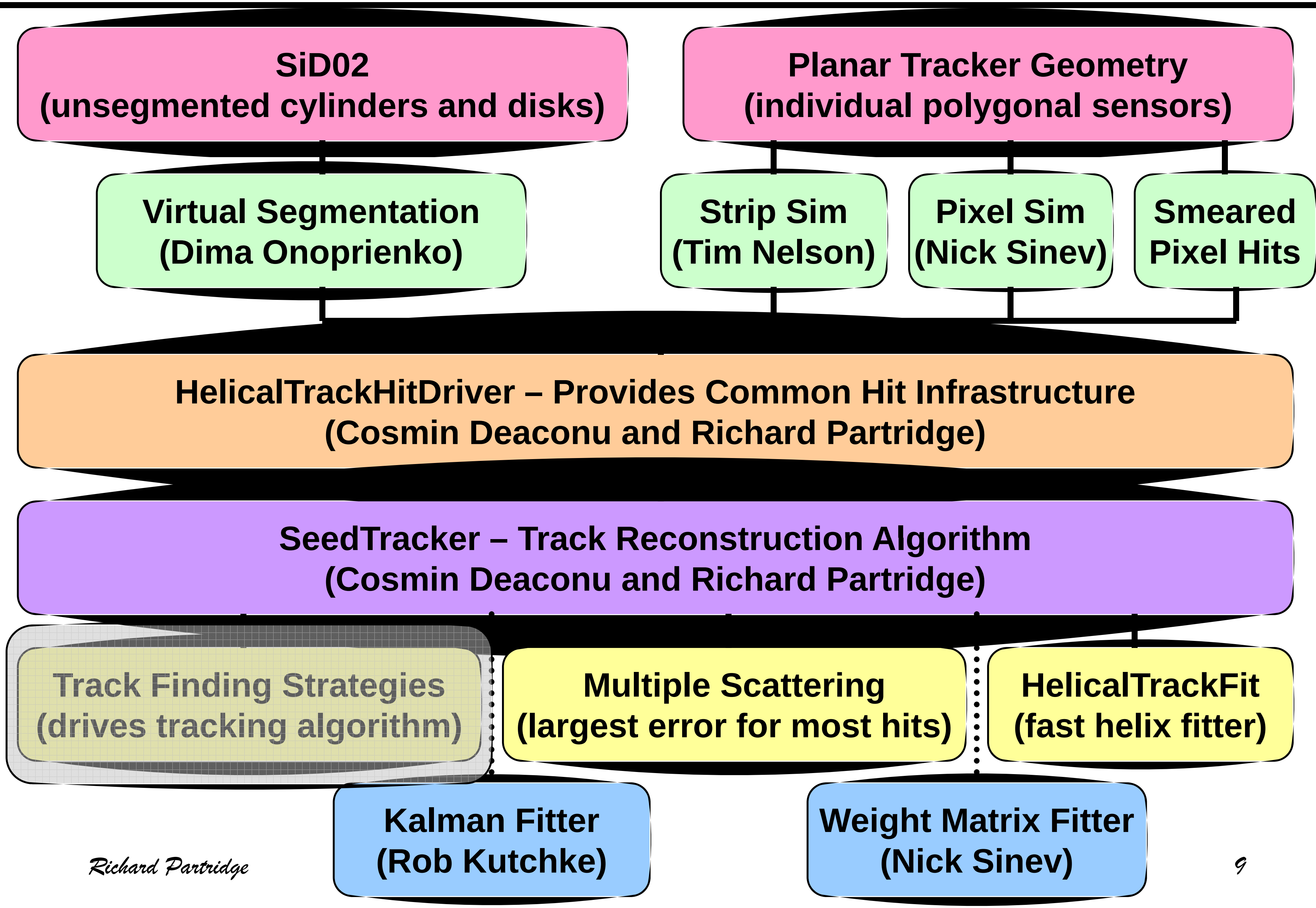
- Track finding is guided by a set of user defined "Strategies"
  - A strategy defines layers to be used, their roles, and constraints (e.g. $p_T > x$)
- All pattern recognition code is agnostic as to the type of hit
  - No differentiation between pixel or strip, barrel or forward sensors
- Multiple Scattering must be accounted for in track finding
  - Superb intrinsic pixel/strip resolution $\Rightarrow$ MS errors will typically be dominant
- A fast helix fitter, HelicalTrackFitter, plays a central role
  - This is the only piece of code that needs to understand the differences between pixels and strips, barrels and disks, etc.
- All decisions based on a global χ^2 from fits, constraints, etc.
  - No internal parameters or tuning is required if tracker geometry changes
  - Constraint example: if $(|z_0| > z_0^{max})$ $\chi^2 = \chi^2 + (|z0| - z_0^{max})^2 / \sigma^2(z_0)$
- Maximize flexibility for detector design optimization
  - No aspect of the detector geometry is hard coded
  - High efficiency and robust track finding achieved by brute force

SeedTracker Algorithm



- Track finding begins by forming all possible 3 hit track seeds in the three “Seed Layers” (specified in the strategy)
  - Brute force approach to finding all possible track seeds
- Typically require the presence of a hit in a “Confirmation Layer” (specified in the strategy)
  - Significantly reduces the number of candidate tracks to be investigated
- Add hits to the track candidate using hits on the “Extension Layers” (specified in the strategy)
  - Discard track candidates that have fewer that the minimum number of hits specified in the strategy
  - If two track candidates share more than one hit, best candidate is selected
- Upon each attempt to add a hit to a track candidate, a helix fit is performed and a global χ^2 is used to determine if the new track candidate is viable

Track Reconstruction Flow Chart



Track Finding Strategy

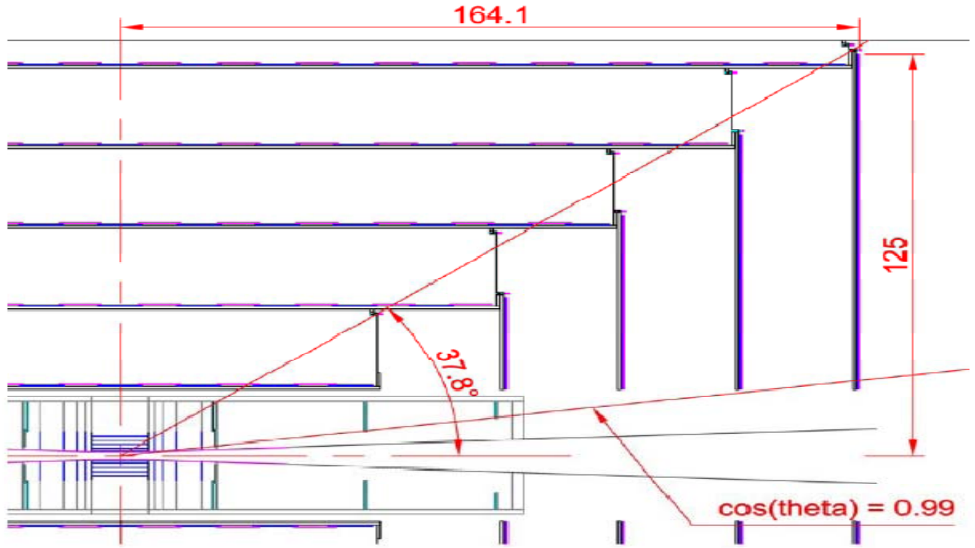
- The user interacts with the track reconstruction program by specifying one or more "strategies"
- Strategies identify:
  - Layers to be used in track finding
  - Role of each layer (seed, confirm, extend)
  - "Cutoffs" on helix parameters (p_T, d_0, z_0) where a χ^2 penalty is introduced
  - Minimum number of confirmed hits and total hits
  - Cut on global χ^2
  - "Bad Hit χ^2" – a χ^2 increase exceeding this amount will flag hit as suspect
- Tracking code processes all strategies sequentially
  - Final list of tracks is the union of all distinct tracks
- Strategies can most easily specified using an xml file, but may be hard coded if desired

Example xml Strategy File

```xml
<?xml version="1.0" encoding="UTF-8"?>
<StrategyList>
  <Strategy name="OutsideInBarrel">
    <!--Cutoffs-->
    <MinPT>1.0</MinPT>
    <MinHits>7</MinHits>
    <MinConfirm>1</MinConfirm>
    <MaxDCA>10.0</MaxDCA>
    <MaxZ0>10.0</MaxZ0>
    <MaxChisq>50.0</MaxChisq>
    <BadHitChisq>15.0</BadHitChisq>
    <!--Layers-->
    <Layer type="Extend" layer_number="1" detector_name="SiVertexBarrel" be_flag="BARREL" />
    <Layer type="Extend" layer_number="2" detector_name="SiVertexBarrel" be_flag="BARREL" />
    <Layer type="Extend" layer_number="3" detector_name="SiVertexBarrel" be_flag="BARREL" />

    ...

    <Layer type="Confirm" layer_number="2" detector_name="SiTrackerBarrel" be_flag="BARREL" />
    <Layer type="Seed" layer_number="3" detector_name="SiTrackerBarrel" be_flag="BARREL" />
    <Layer type="Seed" layer_number="4" detector_name="SiTrackerBarrel" be_flag="BARREL" />
    <Layer type="Seed" layer_number="5" detector_name="SiTrackerBarrel" be_flag="BARREL" />
  </Strategy>
  <Strategy name="OutsideInEndcap">

    ...

  </Strategy>

...
</StrategyList>
```

Strategy Builder

- Finding an optimal set of strategies that provides complete coverage turns out not to be so easy
  - Many distinct sets of layers are required, especially in the forward region
  - Requires carefully examining possible track paths looking for coverage holes
  - Typically need ~20 strategies to have full coverage for baseline tracker design to find ≥7 hit tracks with p_T > 1.0 GeV for 100% detector efficiency
- Strategy list needs to be re-optimized whenever:
  - Change detector geometry
  - Change helix cutoffs
  - Change number of hits required

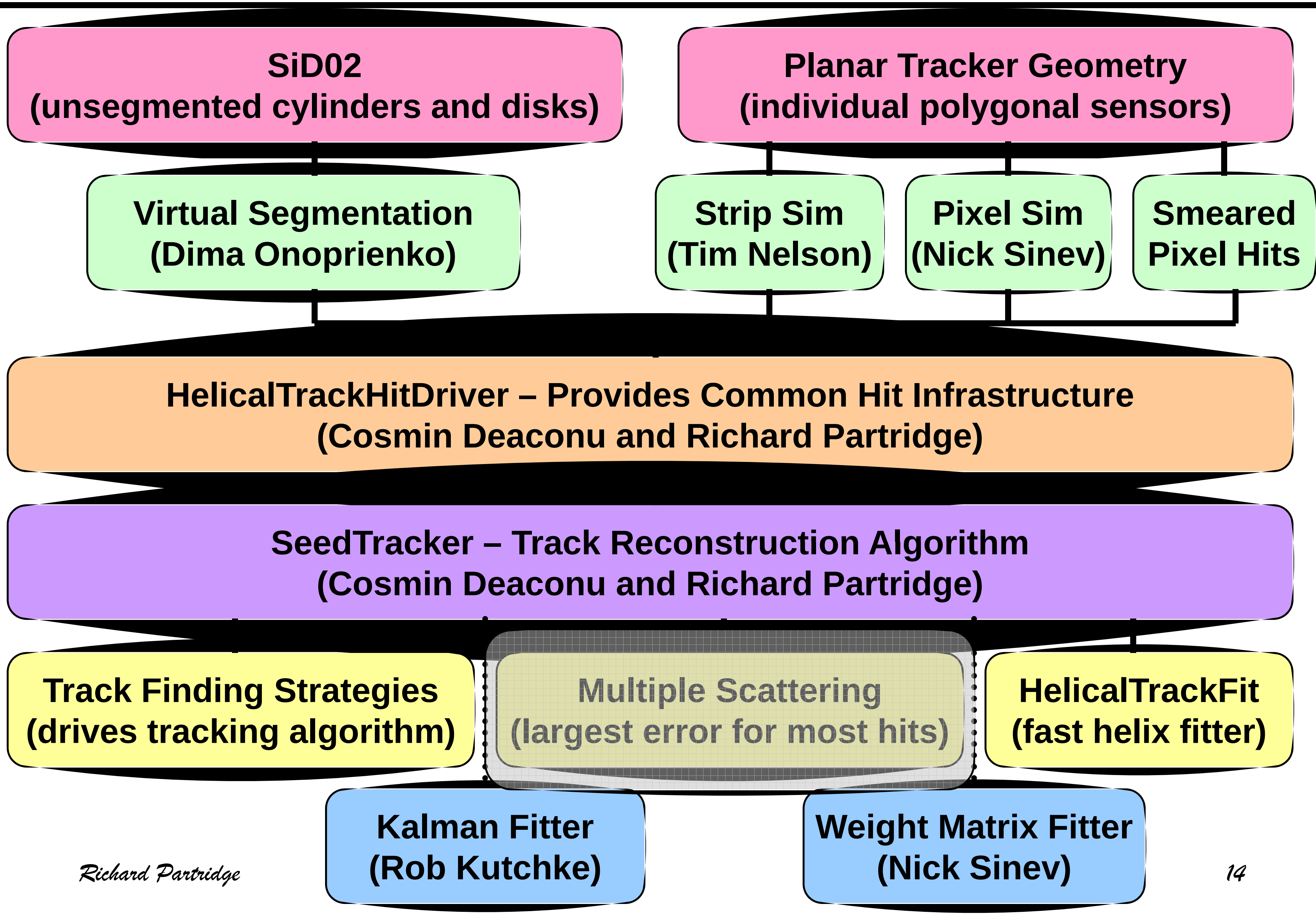


- Strategy Builder automates creation of optimized strategy list

Strategy Builder Algorithm

- Starting point is a file of simulated events that you want to use for optimization
  - Simulated top events would be a good choice since they have a wide variety of particles in them
- Findable MC particles are identified based on helix cutoffs and minimum hit requirements
- All potential combinations of seed / confirm layers are identified and ranked by a weighted frequency of occurrence
  - Weighting can favor / disfavor using particular layers
  - Weighting can also favor combinations with greater adjacency between layers
  - Can optionally randomly discard MC hits to simulate detector inefficiency
- Strategy builder chooses the highest ranked strategy
  - Remove MC Particles from top ranked strategy and re-do ranking
  - Iterate until desired track finding efficiency is achieved

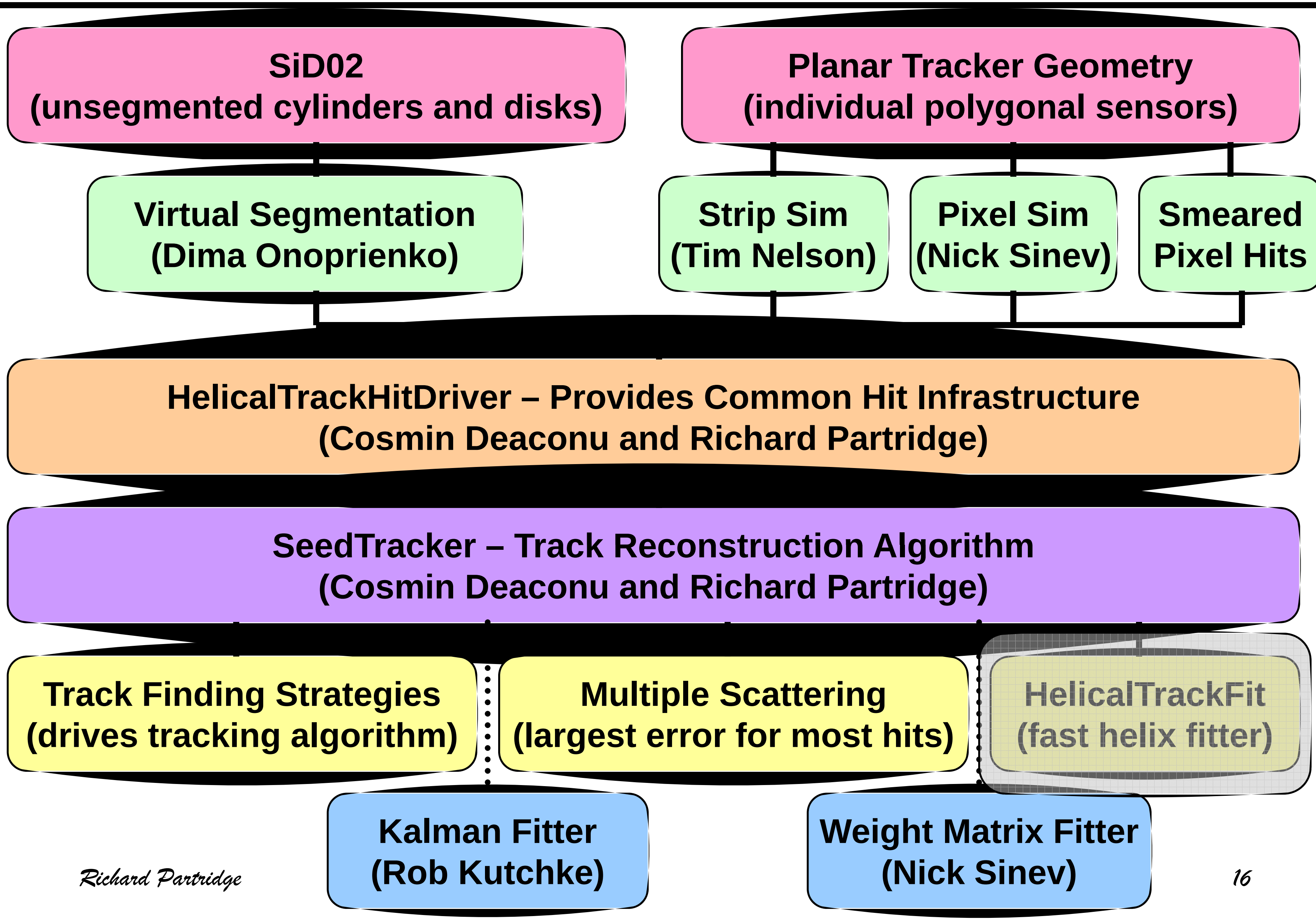
Track Reconstruction Flow Chart



Multiple Scattering

- Multiple scattering errors dominate for most tracks, so having a reasonable estimate of these errors is critical to form a sensible χ^2 discriminator
- SeedTracker constructs a model of the tracker material
  - All material that derives from a common element in the compact.xml description is lumped together
  - Material is modeled as either a cylinder or disk depending on aspect ratio as seen from the origin
- Multiple scattering errors are assigned to each hit
  - Tracks are assumed to originate from it's point of closest approach
  - For a given hit, the multiple scattering error is the cumulative error from all the material crossed in getting from the point of closest approach to the hit
- Multiple scattering correlations are ignored for track finding
  - This isn't really true - a given multiple scattering will systematically affect all subsequent hits – but shouldn't have a big effect on track finding

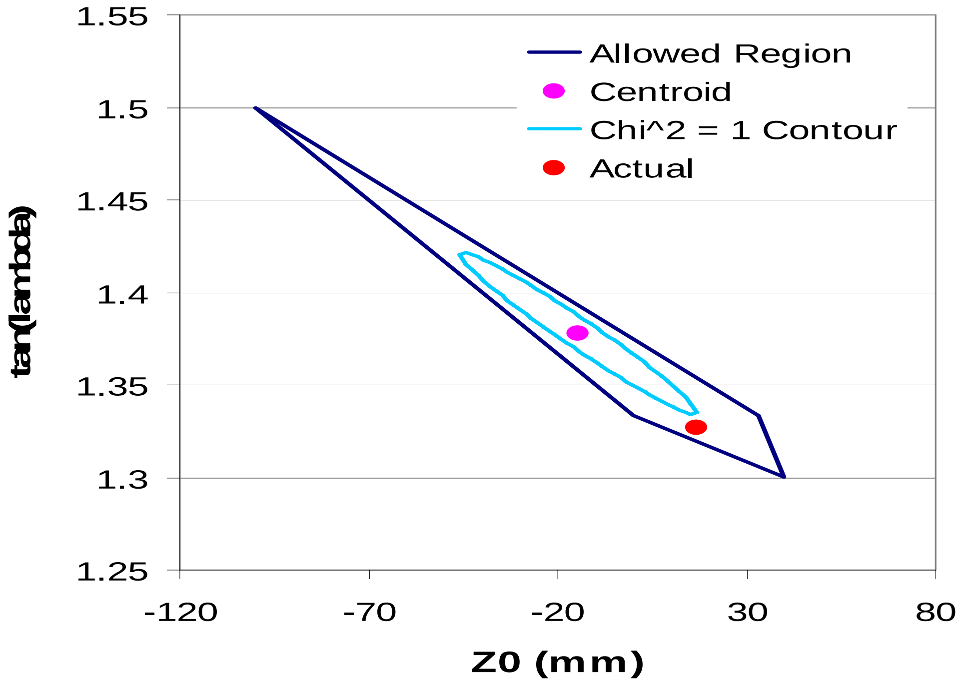
Track Reconstruction Flow Chart



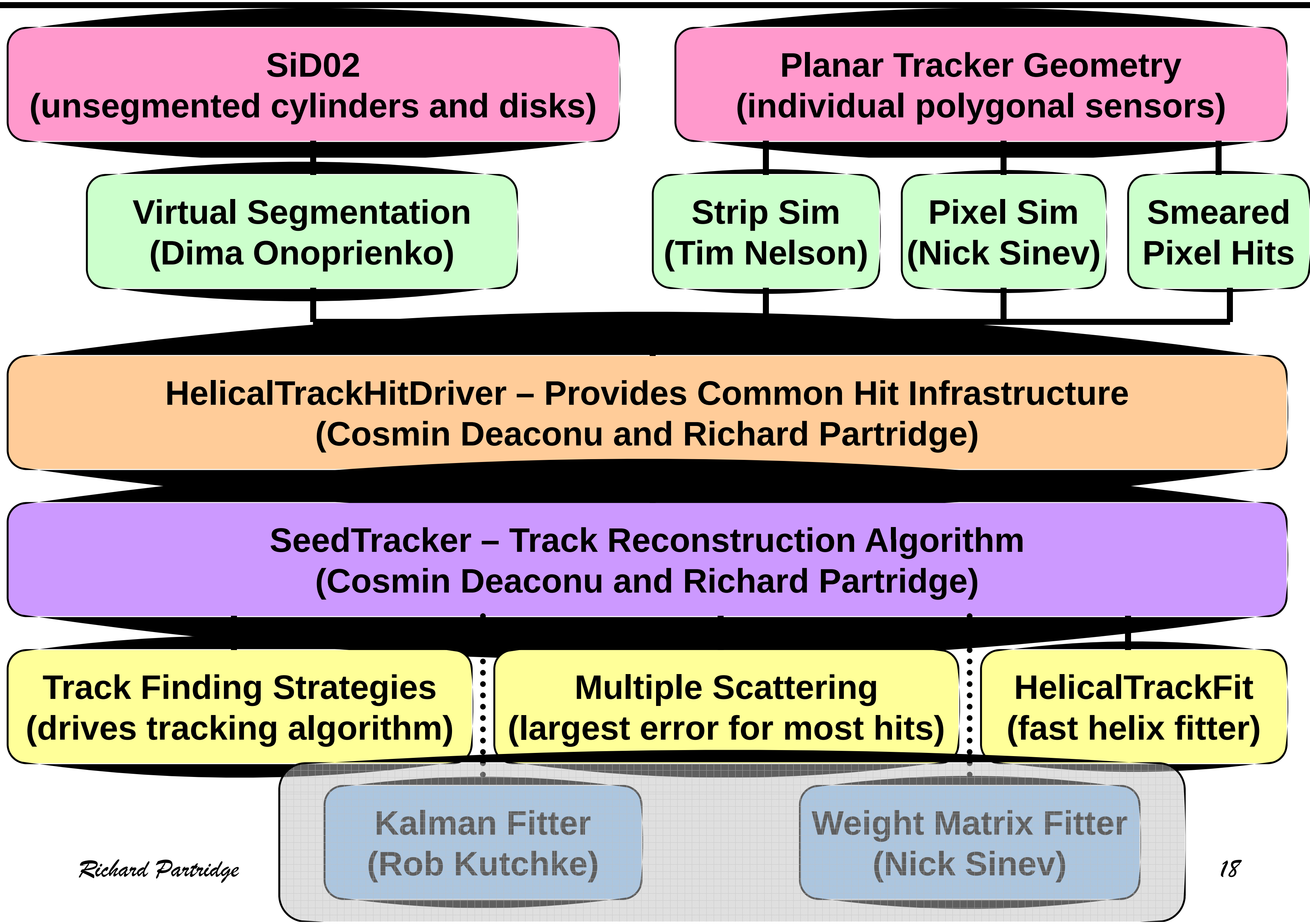
Fast Helix Fitting

- Approximate helix by fitting a circle in x – y and a line in s – z
- Circle fit uses Kariaki algorithm to determine the track parameters $\omega \equiv 1/R$, d_0, and ϕ_0
- Determine the z_0 and $\tan(\lambda)$ track parameters: $z = z_0 + s \tan(\lambda)$
  - If there are >1 pixel hits, do a straight-line fit using only the pixel hits
  - If there are 0 pixel hits, do a ZSegment fit using all strip hits
  - If there is 1 pixel hit, treat the pixel hit as a short strip and do a ZSegment fit

The ZSegment fitter uses the observation that for ≥2 strip hits, there is a polygonal allowed region in the $z_0 - \tan(\lambda)$ plane (in some cases there is no allowed region)



Track Reconstruction Flow Chart

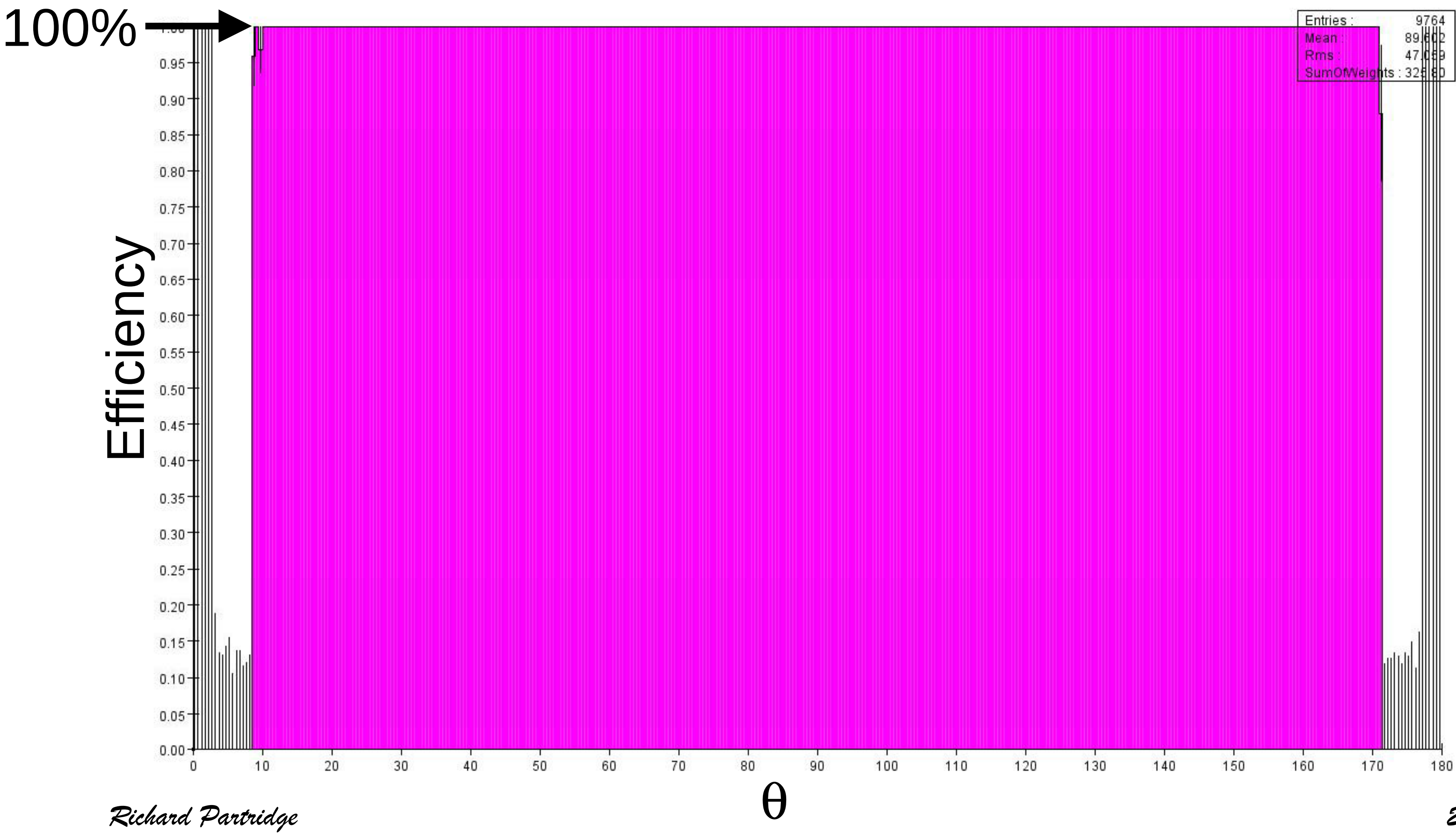


Track Fitting

- Reconstructed tracks are saved into the event with helix parameters and covariance matrices obtained from the fast helix fitter
- These fits are not true helix fits
  - Separate circle / line fits instead of a true helix fit
  - Multiple scattering correlations not included
- Two track fitting approaches have been pursued in SiD
  - Kalman filter track fitter
  - Weight matrix track fitter
- Additional work is required before we can perform true helix fits on the reconstructed tracks
- Goal is to have at least one helix fitter running by the time the LOI is submitted

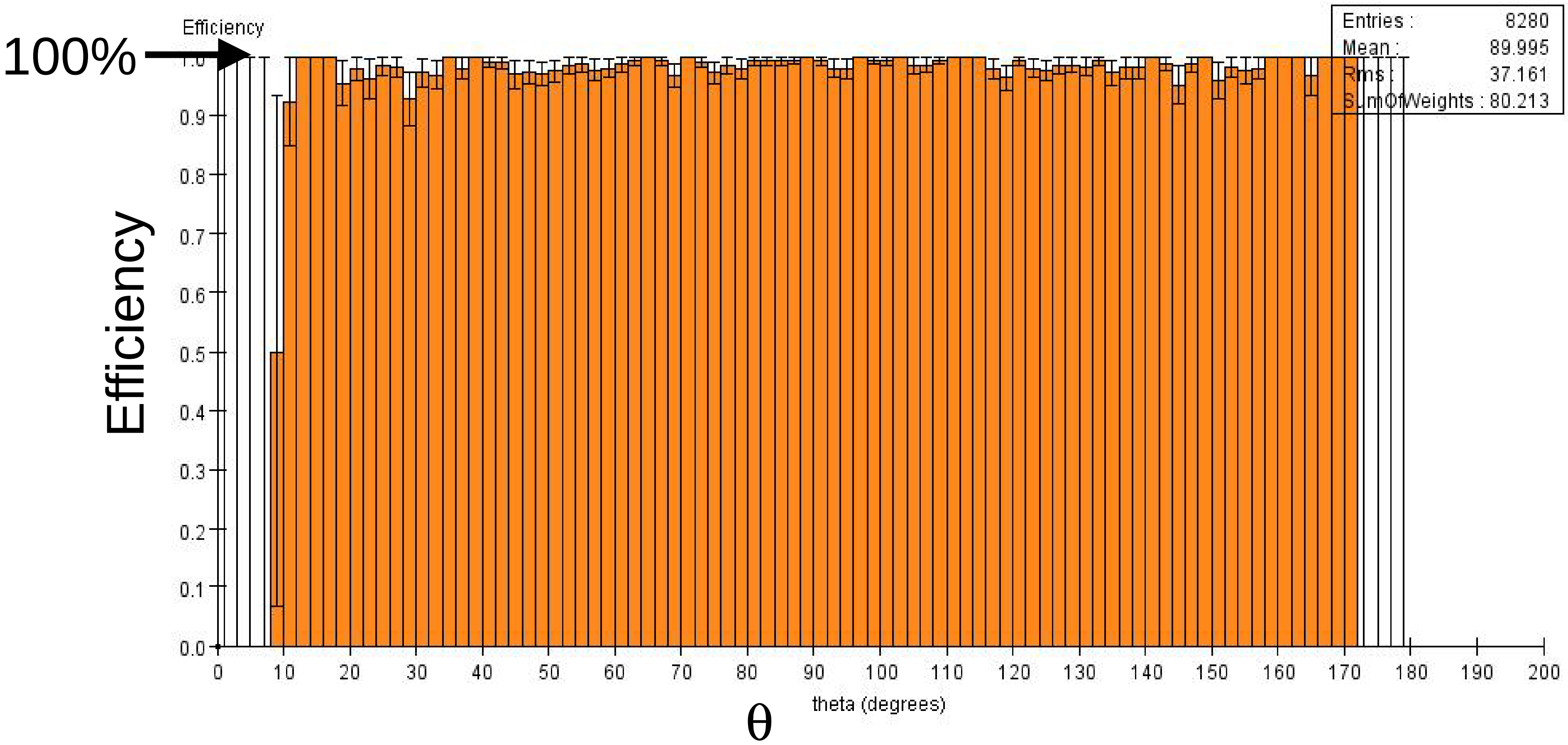
Tracking Results - Coverage

- Look at single muon events in the SiD02 detector
- 100% tracking efficiency for |cosθ| < 0.99 (~8° from beam axis)



Efficiency for ZPole Events

- Calculate efficiency for "findable" MC Particles events
  - $p_T > 1$ GeV, $|d_0| < 10$ mm, $|z_0| < 10$ mm, ≥ 7 hits
  - Find efficiency of $98.6 \pm 0.1\%$ for findable tracks



Track Purity

- Track purity is the fraction of hits on the track from the MC particle associated with the track
  - Purity = 1 if all hits are from the same MC particle

From RAL Meeting →
$e^+e^- \to t\bar{t} \to 6$ Jets

Hits	Fraction	Ave Purity
7	1.3%	76.3%
8	0.2%	96.9%
9	7.7%	99.6%
10	90.9%	99.7%
All	100%	99.4%

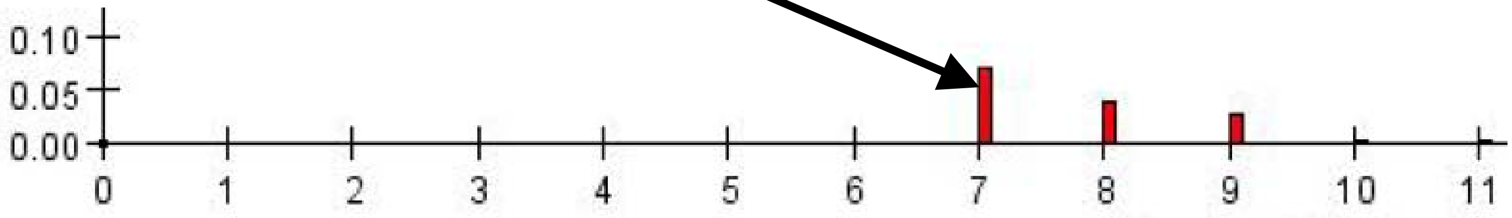
Summer study of Z Pole Events

96.4% of Tracks have Purity = 1

~93% Purity for 7 hit tracks

Fake rate of 0.01% (purity < 50%)

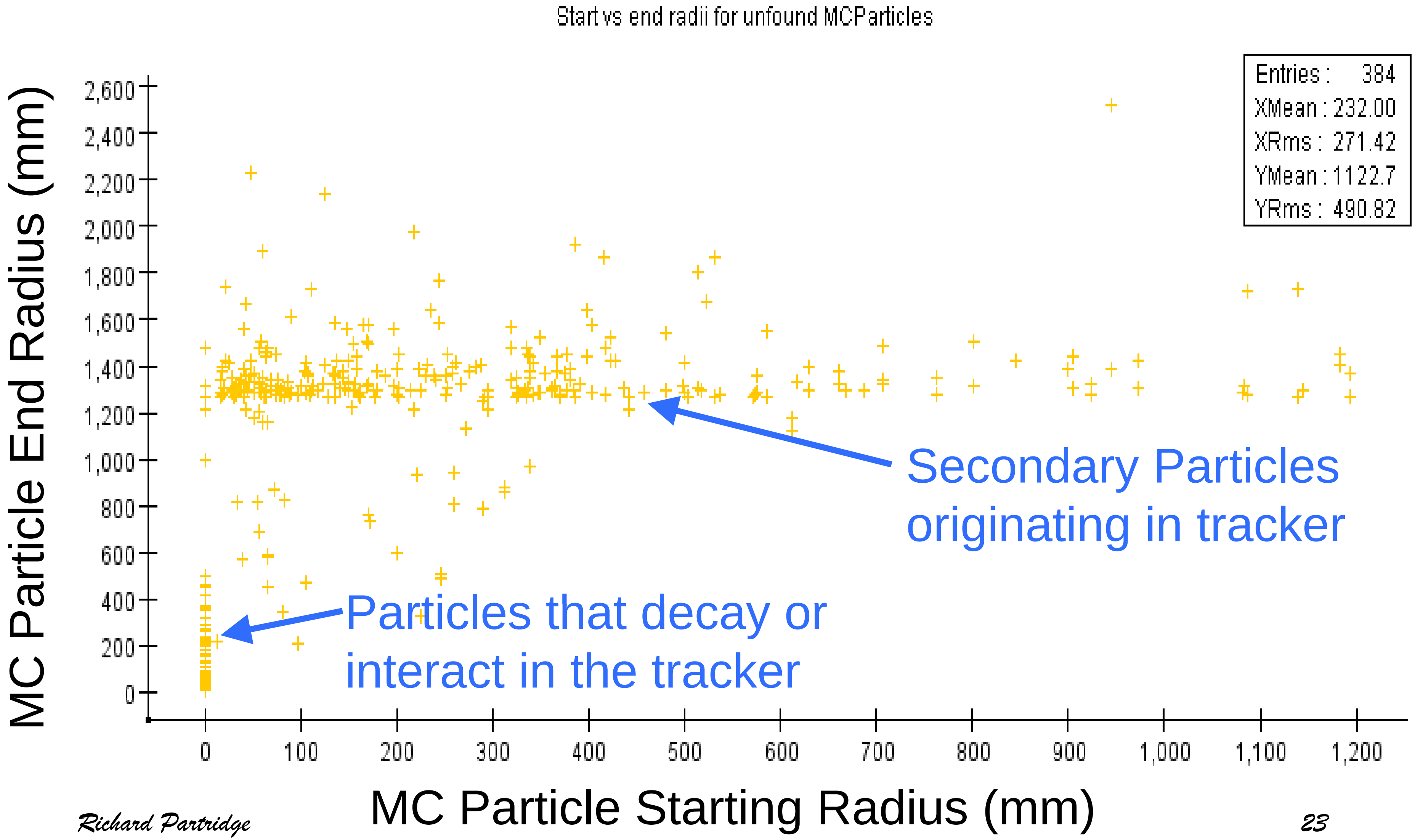
1 - Purity



Hits

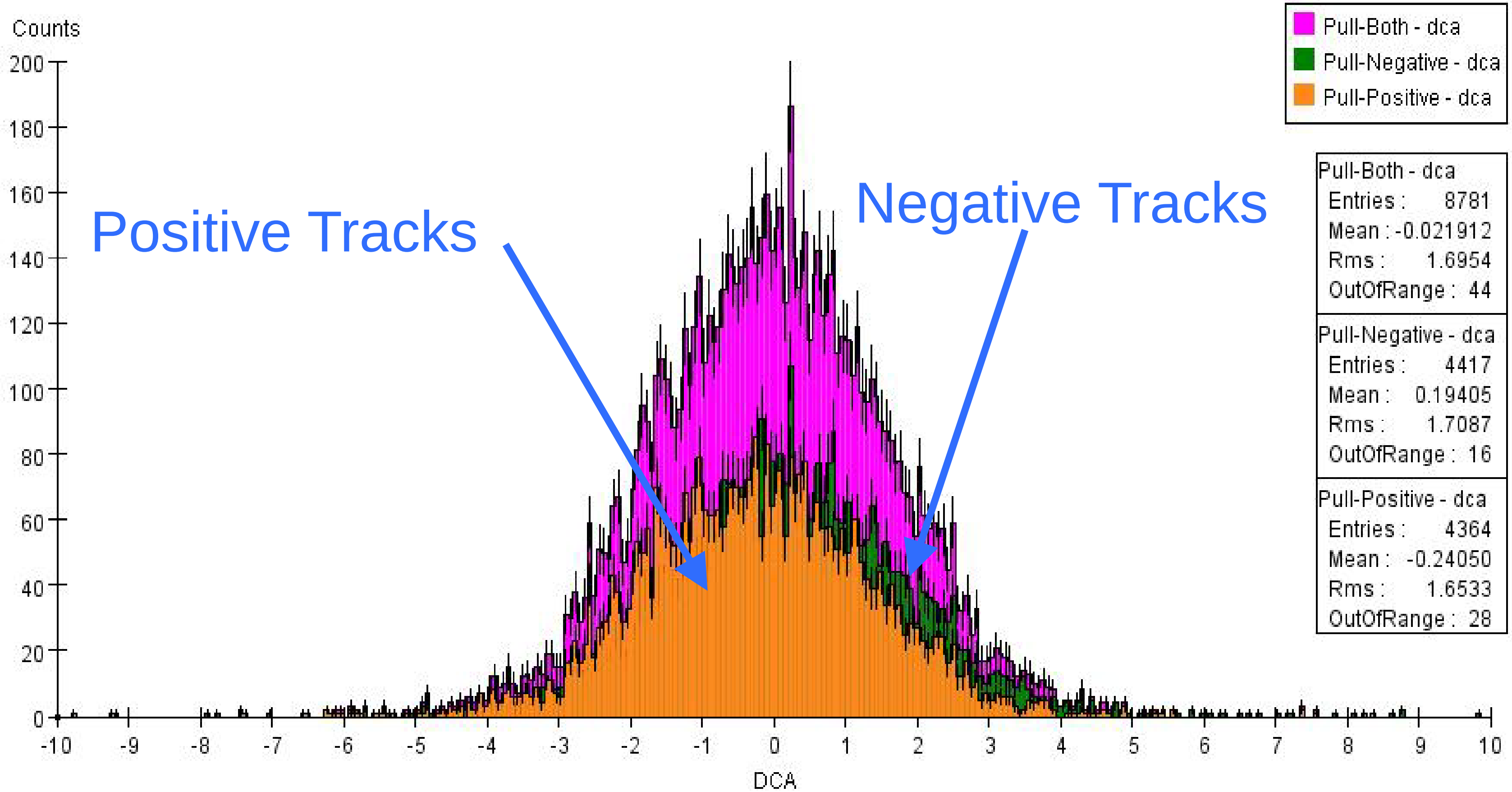
What Tracks are Not Found?

- Tracks with $p_T < 1$ GeV – near term goal to push lower in p_T



Helix Parameter Pulls

- Look at pull distributions from fast track fits
- Example: d_0 – distance of closest approach in x-y plane
  - Small charge asymmetry – probably due to not correcting for energy loss



Pull Summary Table

- RMS of pull distributions are consistently >1
- Track fit errors are underestimated by a factor of ~2
- Not all that bad given the approximations in the fast helix fitter
  - No correlations in multiple scattering errors
  - No propagation of circle fit uncertainties into s – z line fits (or vice versa)
  - Approximations made to include disks in s – z line fits
  - No energy loss corrections

Helix Parameter	RMS Pull
ω	2.07
δ	1.70
φ_0	2.15
$\tan(\lambda)$	1.80
z_0	2.32

Track Reconstruction Summary

- Track reconstruction algorithm seems to be working as advertised
  - Full coverage with high efficiency for findable tracks
  - Tracks have high purity with very small fake rate
  - Fast helix fits are usable, but lack precision of a full helix fit
- Real tracking is being incorporated into Matt's PFA algorithm
  - So far, only one bug that required fixing
- A number of areas for future work
  - Push to lower p_T
  - Integrate with calorimeter assisted tracking to pick up secondaries
  - True helix fits using Kalman and weight matrix fitters
  - Study effect of machine backgrounds on tracking performance
  - Apply tracking code to the task of detector optimization