Intelligent ^ *Detector* *Design*

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SLAC

BNL Particle Physics Seminar

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Outstanding Issues in HEP

- Despite the spectacular success of the Standard Model, many questions remain, such as:
  - Pattern of particle masses; why is top so heavy?
    - Evidence for light Higgs…
  - Pattern of quark mixing? Lepton mixing?
  - Origin of CP violation? Baryogenesis?
  - Why 3 generations?
  - Unification?
  - Hierarchy
    - Why is the electroweak scale << Planck scale?
  - Dark Matter?
  - Dark Energy?
  - Quantum Gravity?

The Next Big Machine

- For precision measurements, want an e^+e^- collider to complement existing and planned hadron machines.
- There are strong theoretical reasons for wanting to achieve ~1 TeV in energy.
- Nature abhors acceleration, so we cannot build such a machine as a circular accelerator.

International Linear Collider

Why Another Machine?

Physics & Detector Workshops (LCWS)

- Saariselka, Finland - September 9 - 14, 1991
- Hawaii, USA - April 26 - 30, 1993
- Morioka, Japan - September 8 - 12, 1995
- Sitges, Spain - April 28 - May 5, 1999
- Fermilab, USA - October 24-28, 2000
- Jeju Island, Korea - August 26-30, 2002
- Paris, France - April 19-23, 2004
- Stanford, USA - March 18-21, 2005
- Bangalore India – March 9-13, 2006

Linear Collider Detector Environment

- Detectors designed to exploit the physics discovery potential of e^+e^- collisions at $\sqrt{s} \sim 1$TeV.
- Perform precision measurements of complex final states with well-defined initial state:
  - Tunable energy
  - Known quantum numbers & e^-, e^+, γ polarization
  - Possibilities for $\gamma\gamma$, γe^-, $e^- e^-$
  - Very small interaction region
  - Momentum constraints (modulo beam & bremsstrahlung)

Detector Requirements

- Desire to fully reconstruct hadronic final states
- Ability to tag heavy (light) quarks
- Excellent missing energy/mass sensitivity
- Require:
  - Exceptional momentum resolution
    - Large volume TPC or low-mass Si μ-strip tracker
  - Excellent vertexing capabilities
    - 5-Layer pixel Vertex Detector (~GigaPixel)
  - "Particle Flow" calorimetry
    - Imaging, (non-compensating) sampling calorimeter
  - Hermeticity
    - Minimal supports, on-detector readout.

Detector Design

- Perception that LC detectors are trivial to build.
- Much R&D has been done for SSC/LHC, but optimizations are different.
- Hadron colliders have large cross sections and enormous backgrounds
- LC much smaller event rates and data sizes and small backgrounds.
- Robustness vs precision.

LCD Simulation Mission Statement

- Provide full simulation capabilities for Linear Collider physics program:
  - Physics simulations
  - Detector designs
  - Reconstruction and analysis
- Need flexibility for:
  - New detector geometries/technologies
  - Different reconstruction algorithms
- Limited resources demand efficient solutions, focused effort.

Overview: Goals

- Facilitate contribution from physicists in different locations with various amounts of time available
- Use standard data formats, when possible.
- Provide a general-purpose framework for physics software development.
- Develop a suite of reconstruction and analysis algorithms and sample codes.
- Simulate benchmark physics processes on different full detector designs.

Fast Detector Response Simulation

- Covariantly smear tracks with matrices derived from geometry, materials and point resolution using Billoir's formulation.

  http://www.slac.stanford.edu/~**schumm/lcdtrk**

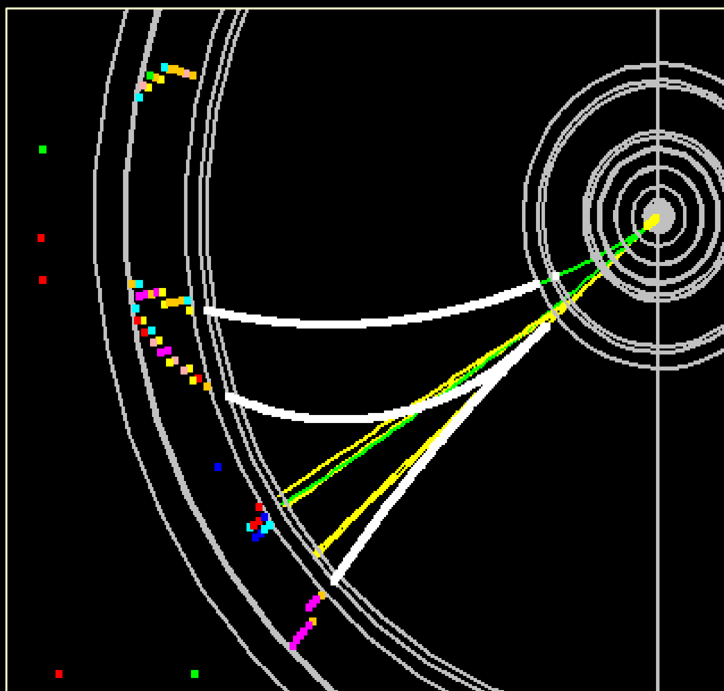
- Smear neutrals according to expected calorimeter resolution (EM for γ, HAD for neutral hadrons)
- Create reconstructed particles from tracks and clusters (γ, e, μ from MC, $\pi^{+/-}$, K^0_L for others)
- Can also dial in arbitrary effective jet energy resolution.

lelaps

- Fast detector response package.
- Handles decays in flight, multiple scattering and energy loss in trackers.
- Parameterizes particle showers in calorimeters.
- Produces lcio data at the hit level.
- Uses runtime geometry (compact.xml → godl).
- An excellent tool for designing tracking detectors!

http://lelaps.freehep.org/index.html

Lelaps: Decays, dE/dx, MCS

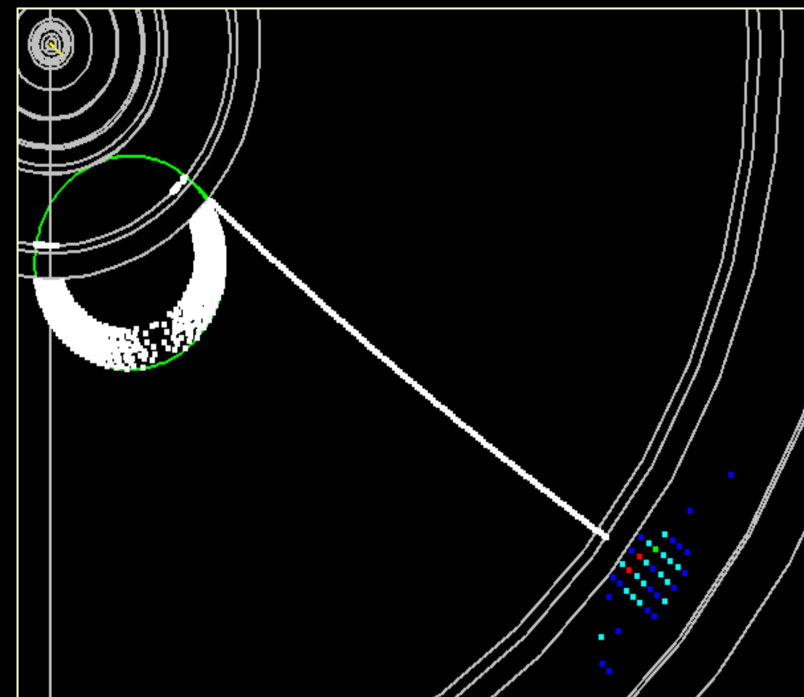


$\Omega^- \to \Xi^0 \pi^-$

$\Xi^0 \to \Lambda \pi^0$

$\Lambda \to p \pi^-$

$\pi^0 \to \gamma \gamma$ as simulated by Lelaps for the LDC model.



gamma conversion as simulated by Lelaps for the LDC model.

Note energy loss of electron.

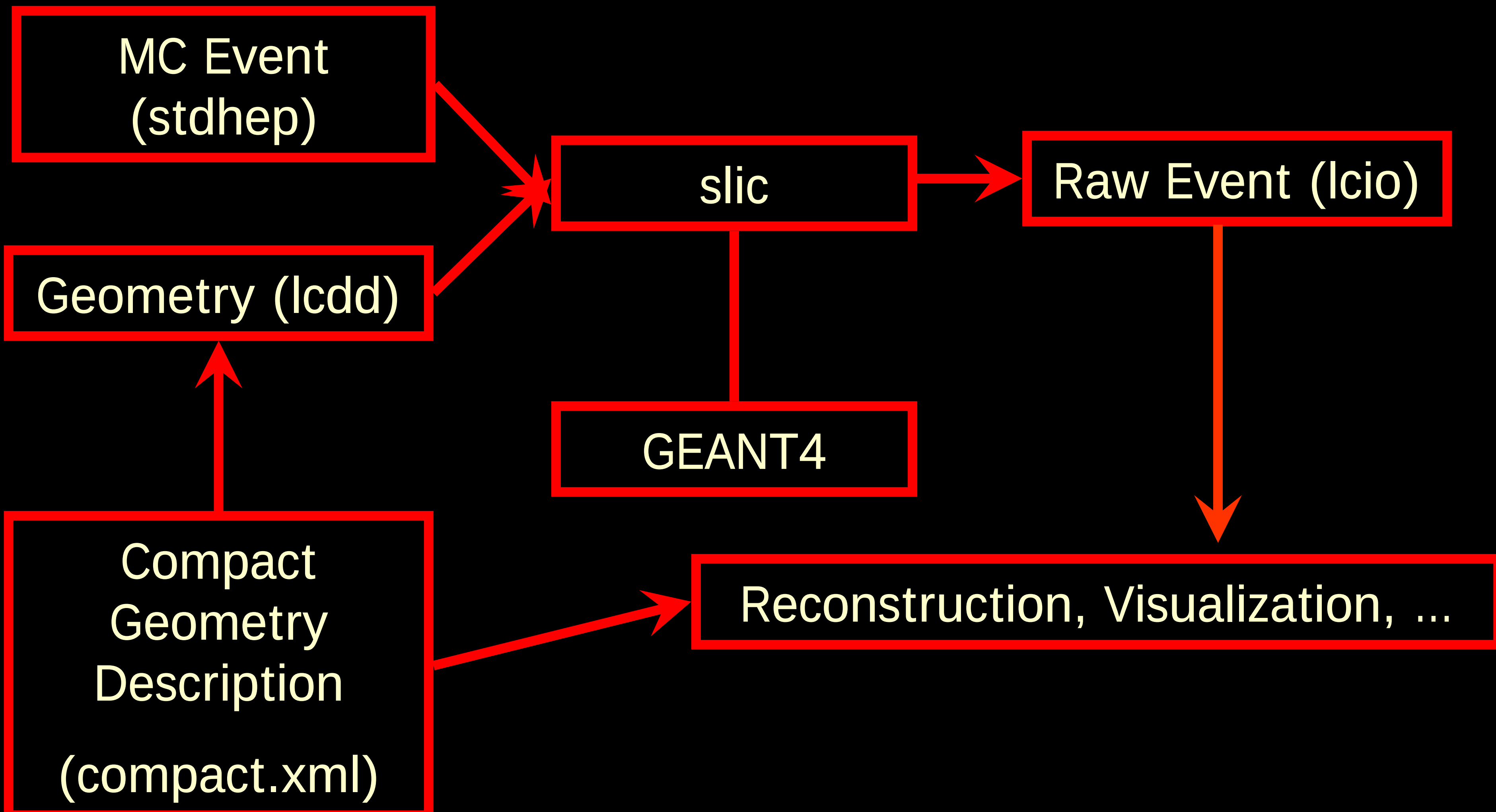
Detector Design (GEANT 4)

- Need to be able to flexibly, but believably simulate the detector response for various designs.
- GEANT is the de facto standard for HEP physics simulations.
- Use runtime configurable detector geometries
- Write out "generic" hits to digitize later.

Full Detector Response Simulation

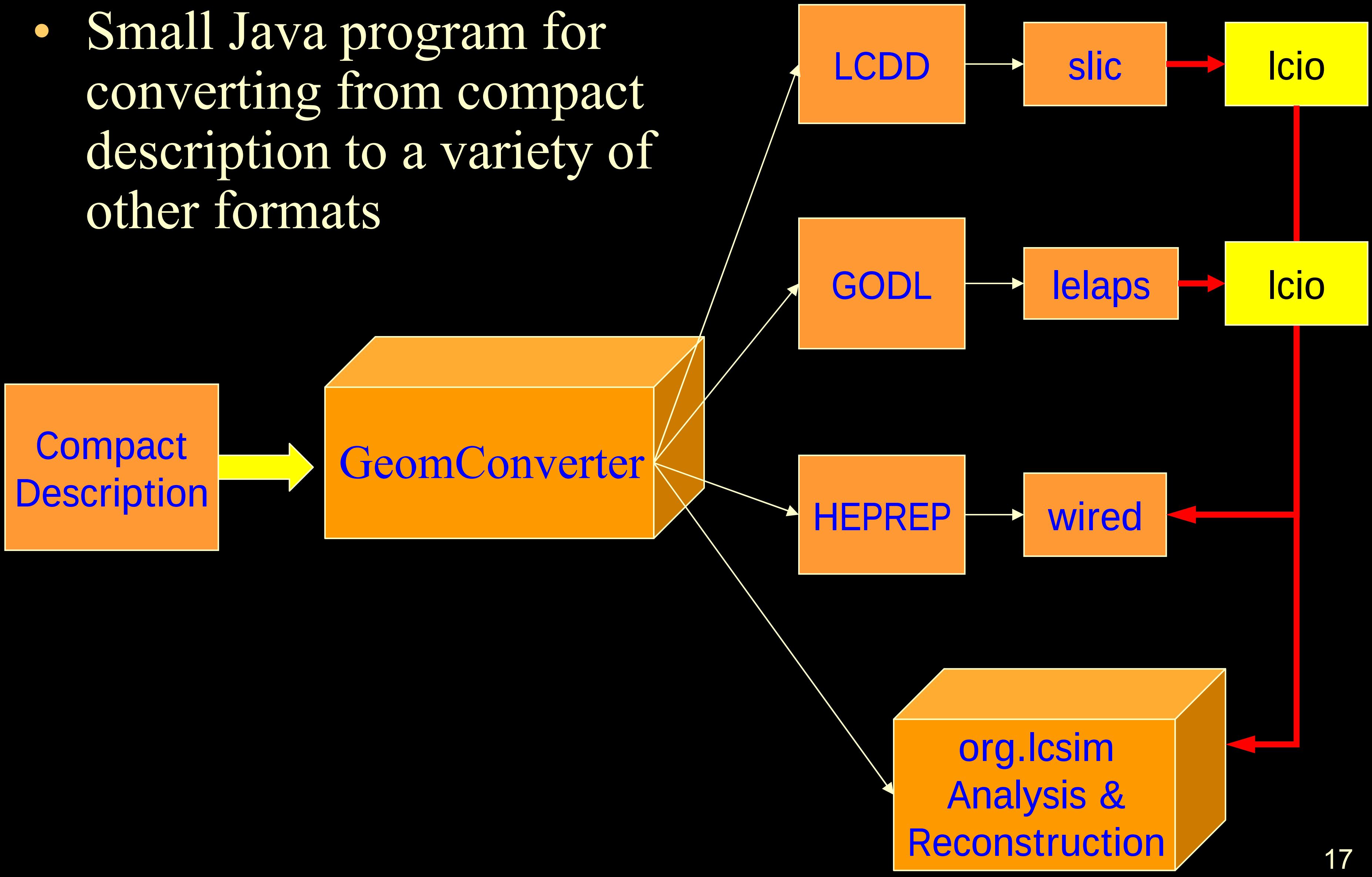
- Use Geant4 toolkit to describe interaction of particles with matter.
- Thin layer of LC-specific C++ provides access to:
  - Event Generator input (binary stdhep format)
  - Detector Geometry description (XML)
  - Detector Hits (LCIO)
- Geometries fully described at run-time!
  - In principle, as fully detailed as desired.
  - In practice, will explore detector variations with simplified approximations.

LC Detector Full Simulation



GeomConverter

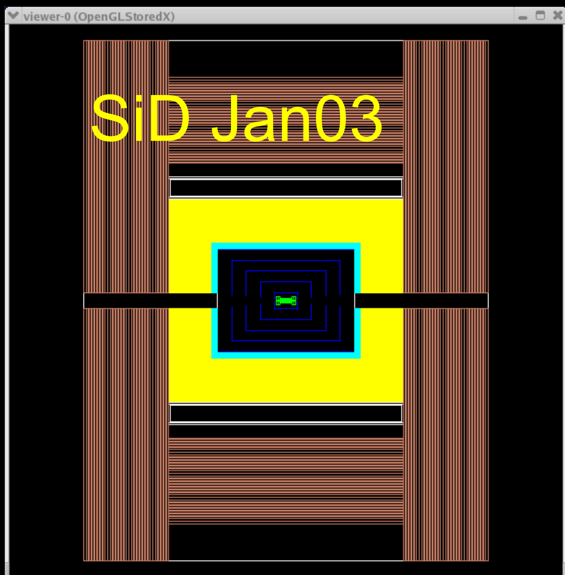
- Small Java program for converting from compact description to a variety of other formats

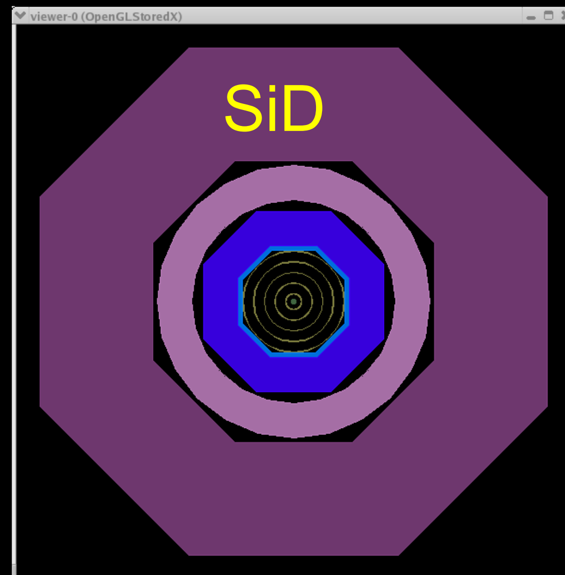


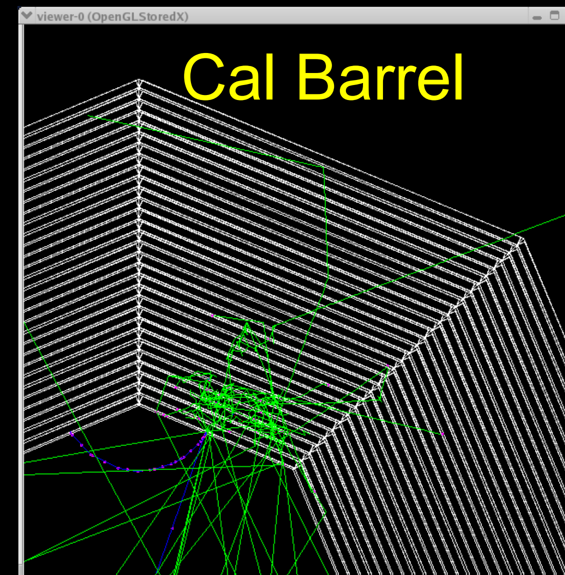
Detector Variants

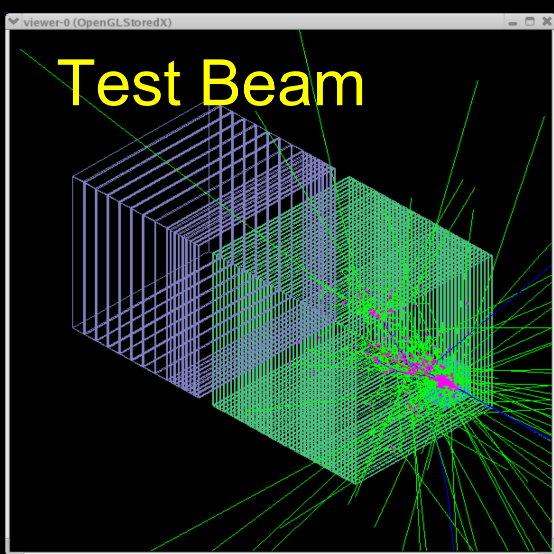
- Runtime XML format allows variations in detector geometries to be easily set up and studied:
  - Stainless Steel vs. Tungsten HCal sampling material
  - RPC vs. GEM vs. Scintillator readout
  - Layering (radii, number, composition)
  - Readout segmentation (size, projective vs. nonprojective)
  - Tracking detector technologies & topologies
    - TPC, Silicon microstrip, SIT, SET
    - “Wedding Cake” Nested Tracker vs. Barrel + Cap
  - Field strength
  - Far forward MDI variants (0, 2, 14, 20 mr)

Example Geometries

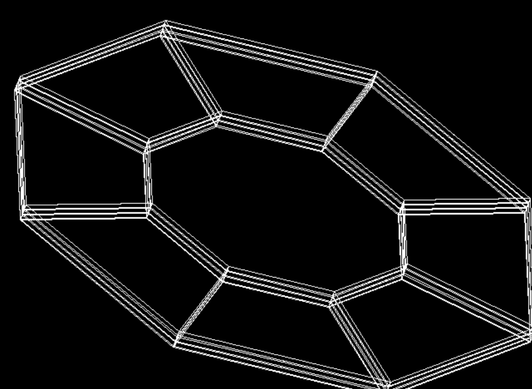




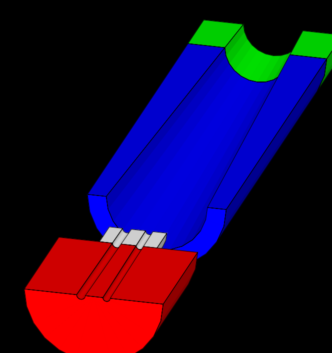




Cal Endcap

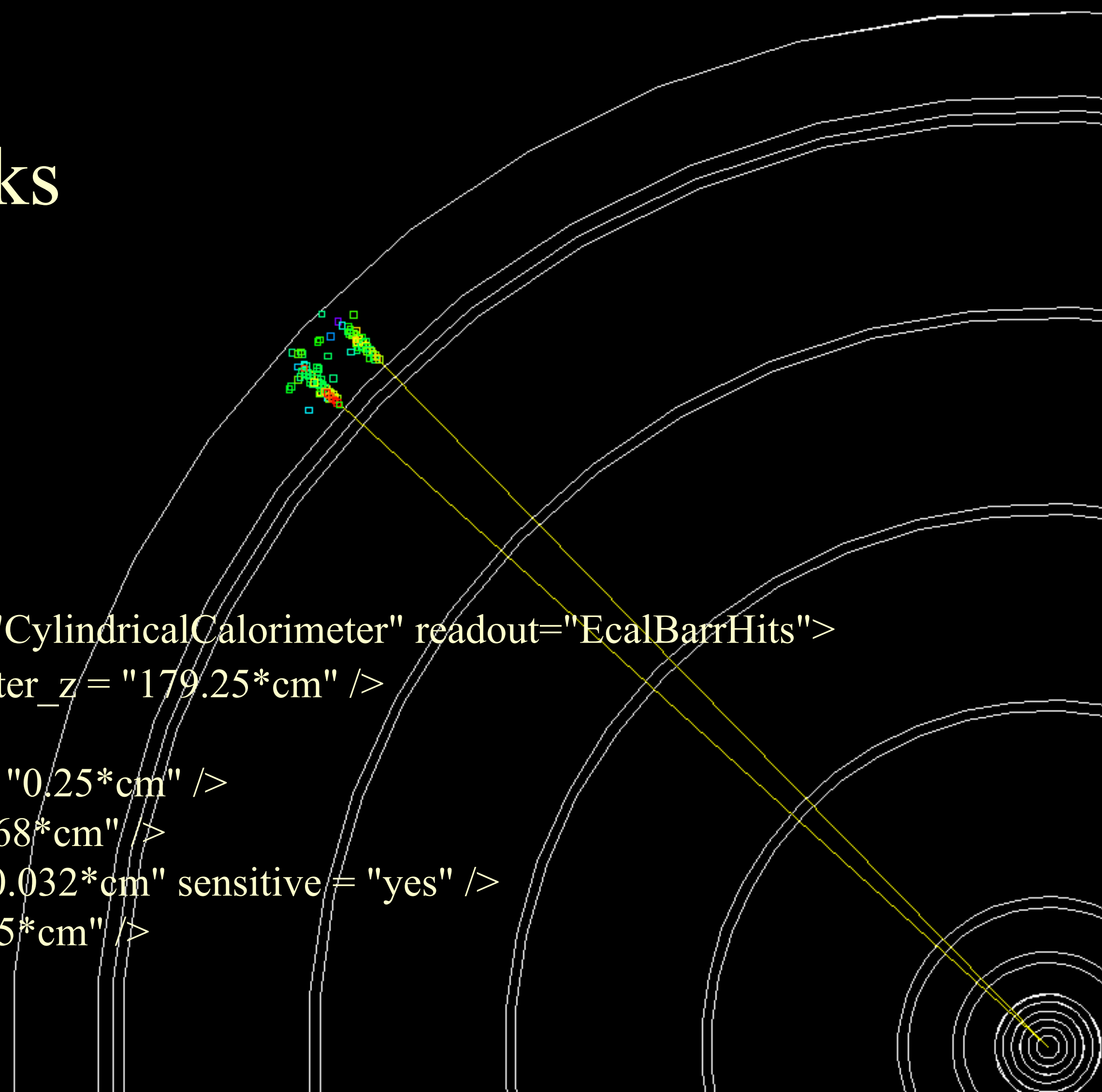


MDI-BDS



EM Calorimeter

- W-Si Sampling
- Barrel+Endcap Disks



```
<detector id=“3" name="EMBarrel" type="CylindricalCalorimeter" readout="EcalBarrHits">
    <dimensions inner_r = "127.0*cm" outer_z = "179.25*cm" />
    <layer repeat=“30">
      <slice material = "Tungsten" width = "0.25*cm" />
      <slice material = "G10" width = "0.068*cm" />
      <slice material = "Silicon" width = "0.032*cm" sensitive = "yes" />
      <slice material = "Air" width = "0.025*cm" />
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```
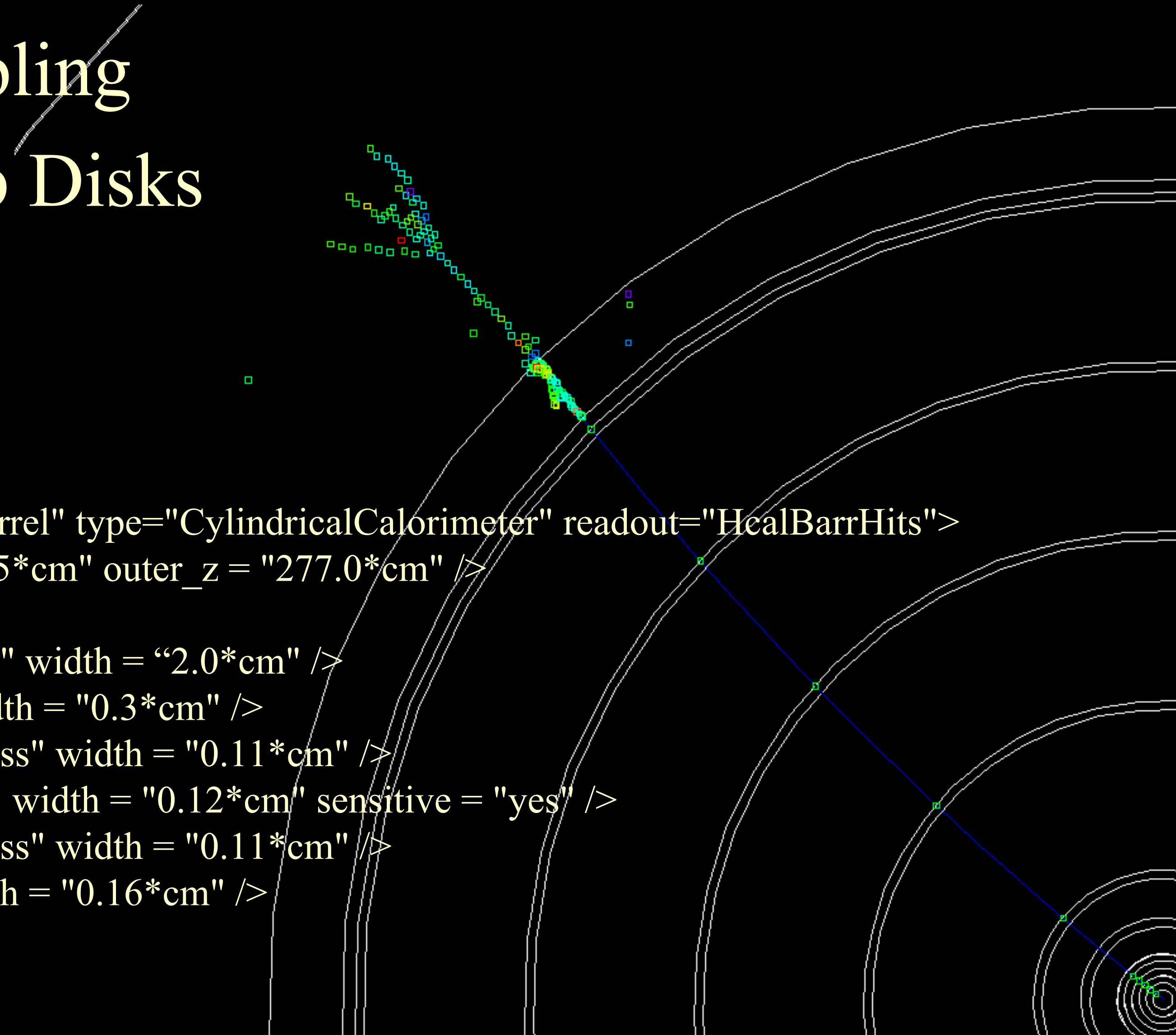

Hadronic Calorimeter

- SS+RPC Sampling
- Barrel+Endcap Disks



```
<detector id="3" name="HADBarrel" type="CylindricalCalorimeter" readout="HcalBarrHits">
      <dimensions inner_r = "138.5*cm" outer_z = "277.0*cm" />
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        <slice material = "RPCGas" width = "0.12*cm" sensitive = "yes" />
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      </layer>
  </detector>
```
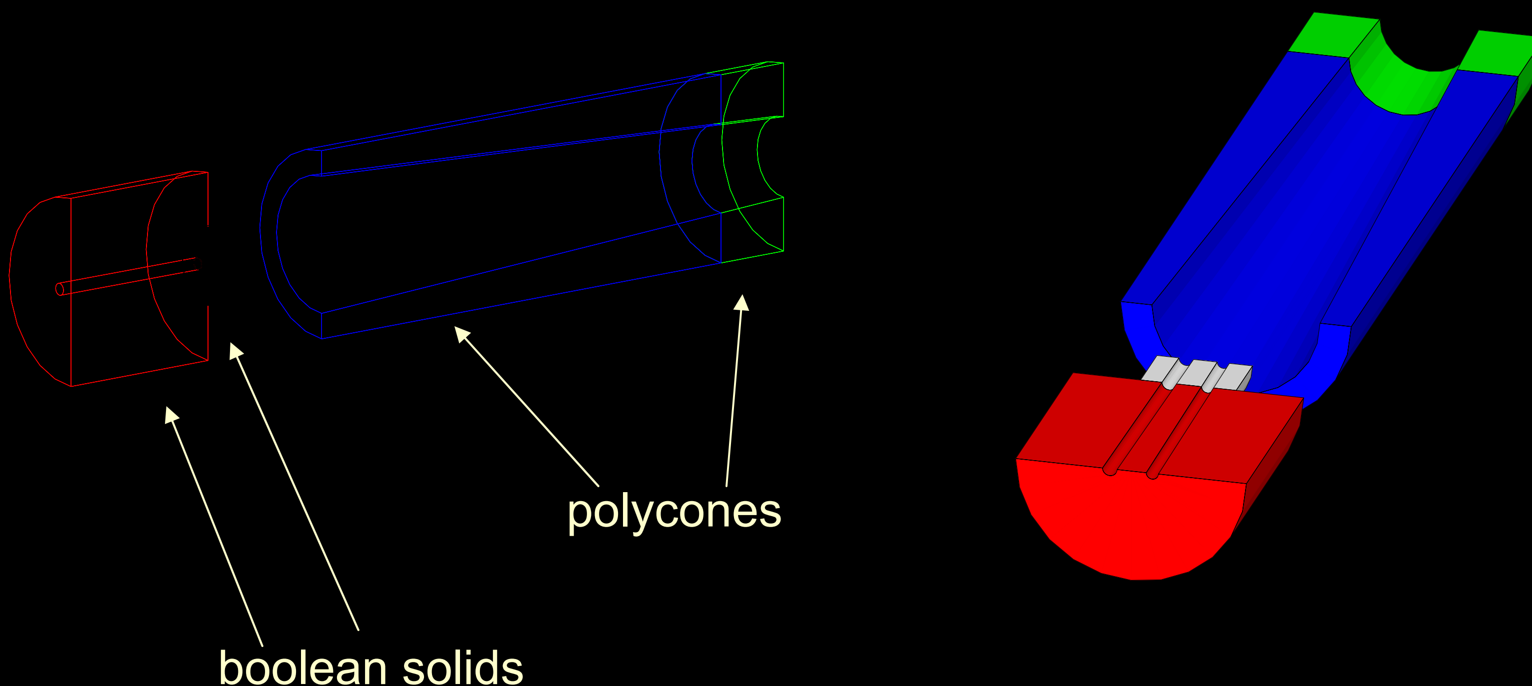
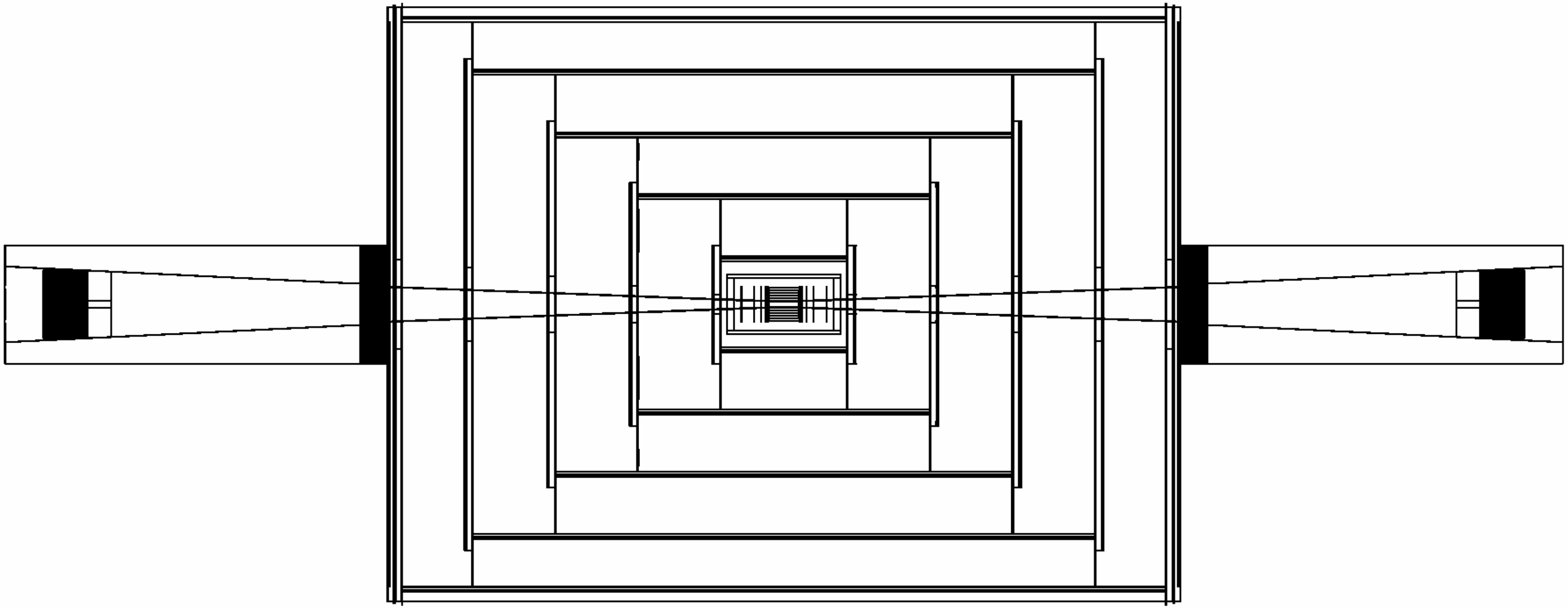

Far forward calorimetry

Machine Detector Interface and Beam Delivery System

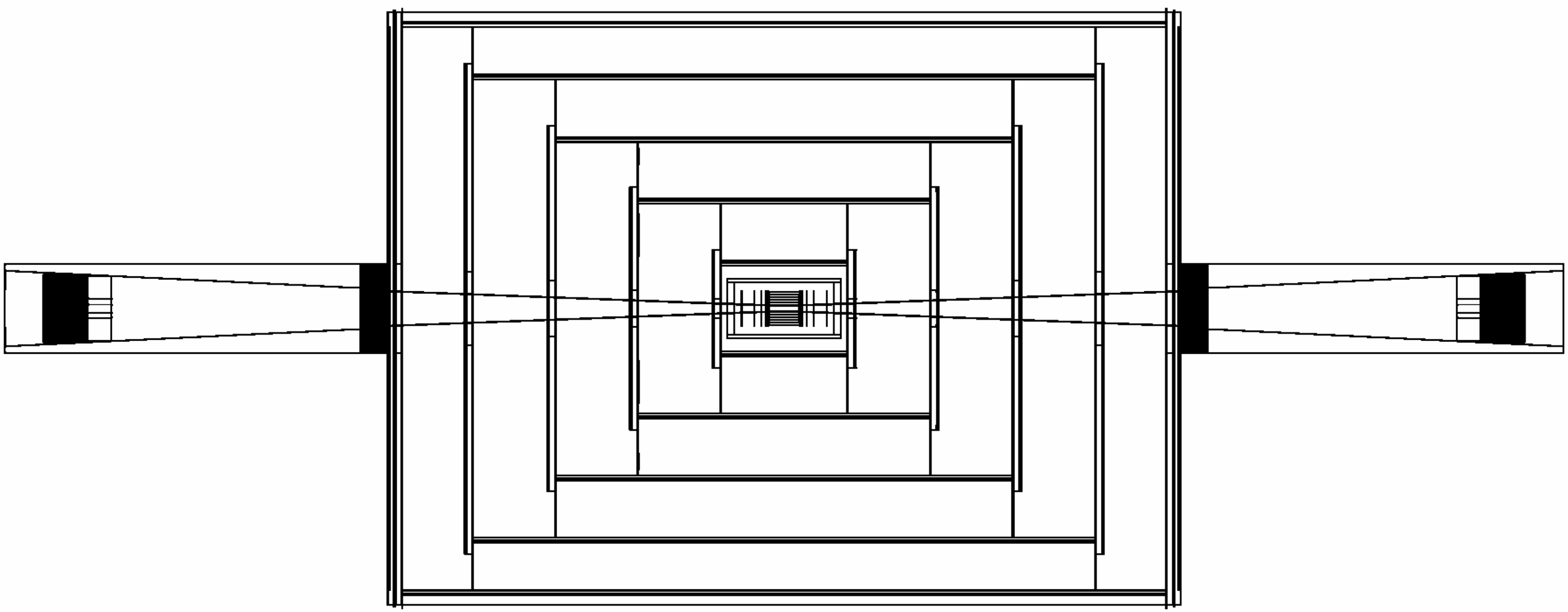


Both 2 and 20 milliradian solutions implemented.

2 mr crossing angles



20 mr crossing angles



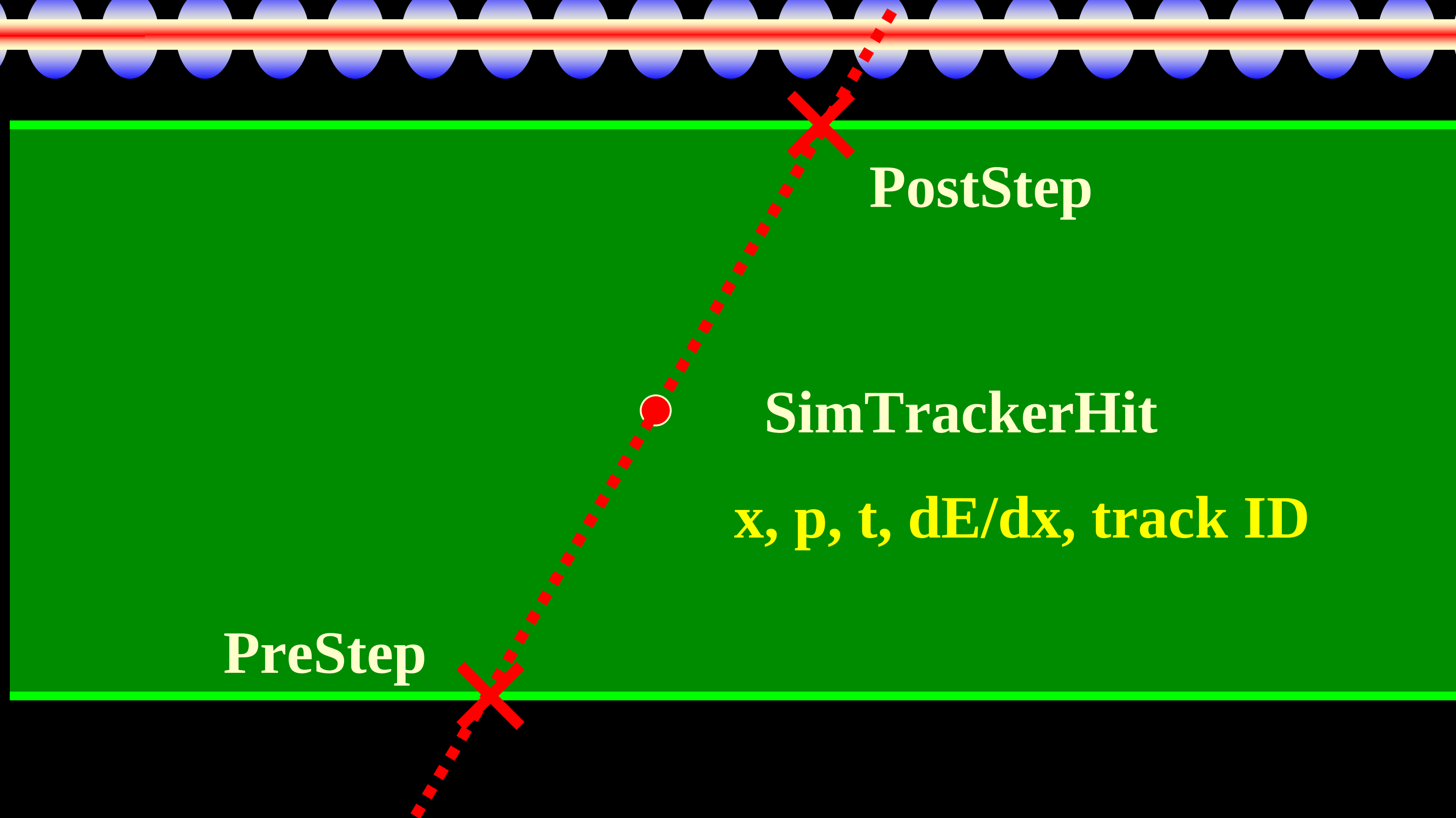
Geant4 Calorimeter Studies

- Still investing a lot of time understanding Geant4!
- Strong EM calorimeter resolution dependence on range cuts, reported several years ago, appears to be fixed in latest Geant4 release.
- Energy non-conservation in hadron showers.
  - Bugs found in GEISHA and patches provided for G4 several years ago, not all of which were adopted.
  - n and $\bar{n}$ treated with different models.
  - New hadronics coordinators appointed at last Geant4 collaboration meeting.

Geant4 Tracking Studies

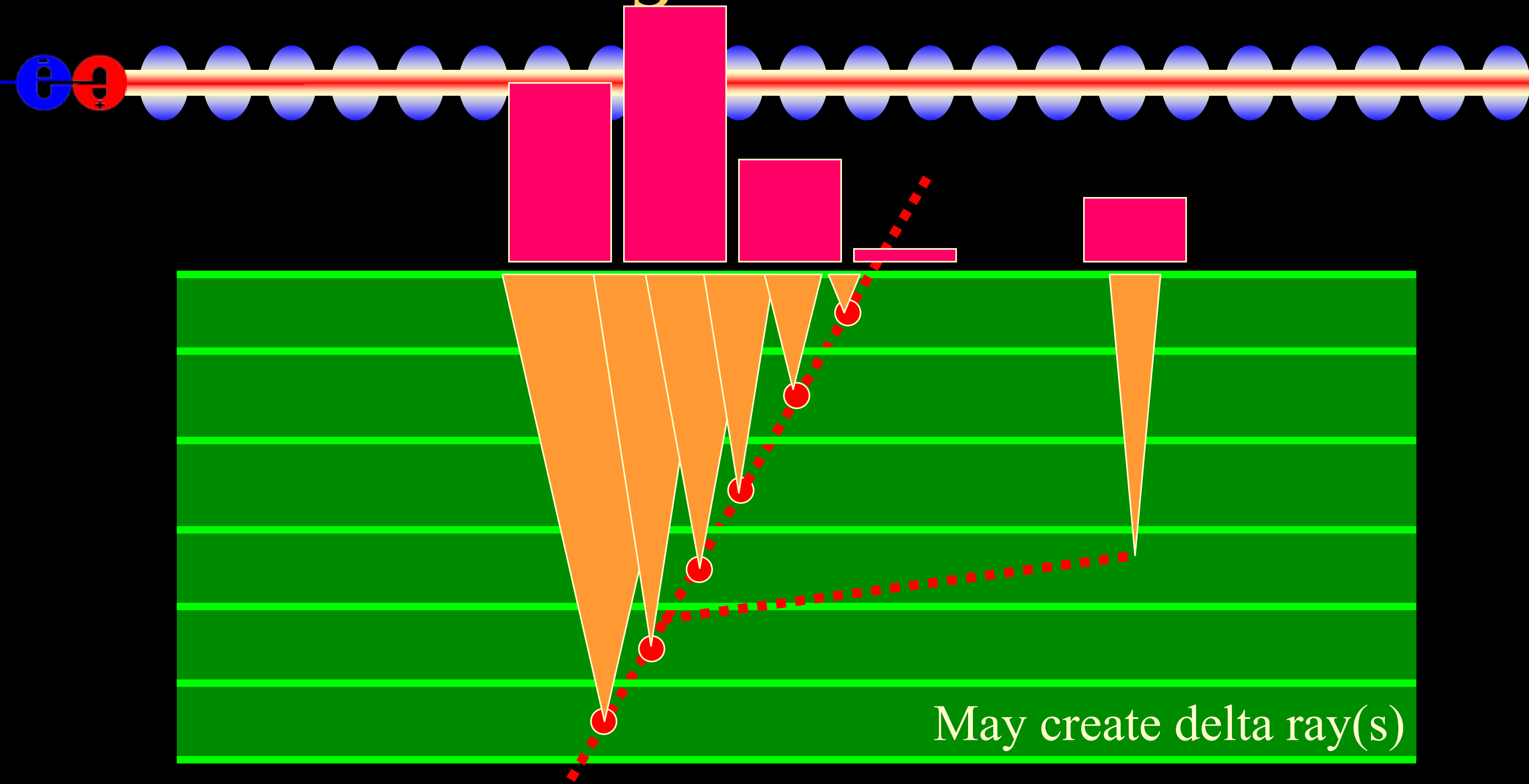
- Currently using large G4 step lengths in silicon
  - normally only one hit per layer per track
  - digitization step then subdivides energy and introduces charge diffusion and Lorentz angle effects.
- Investigating smaller range and step sizes to improve simulation at the Geant level.
  - Reducing range cuts increases number of secondaries produced and explicitly tracked.
  - MaxStepLength limits step when no other process occurs. Reducing this increases the number of hits.

Current Hit Creation



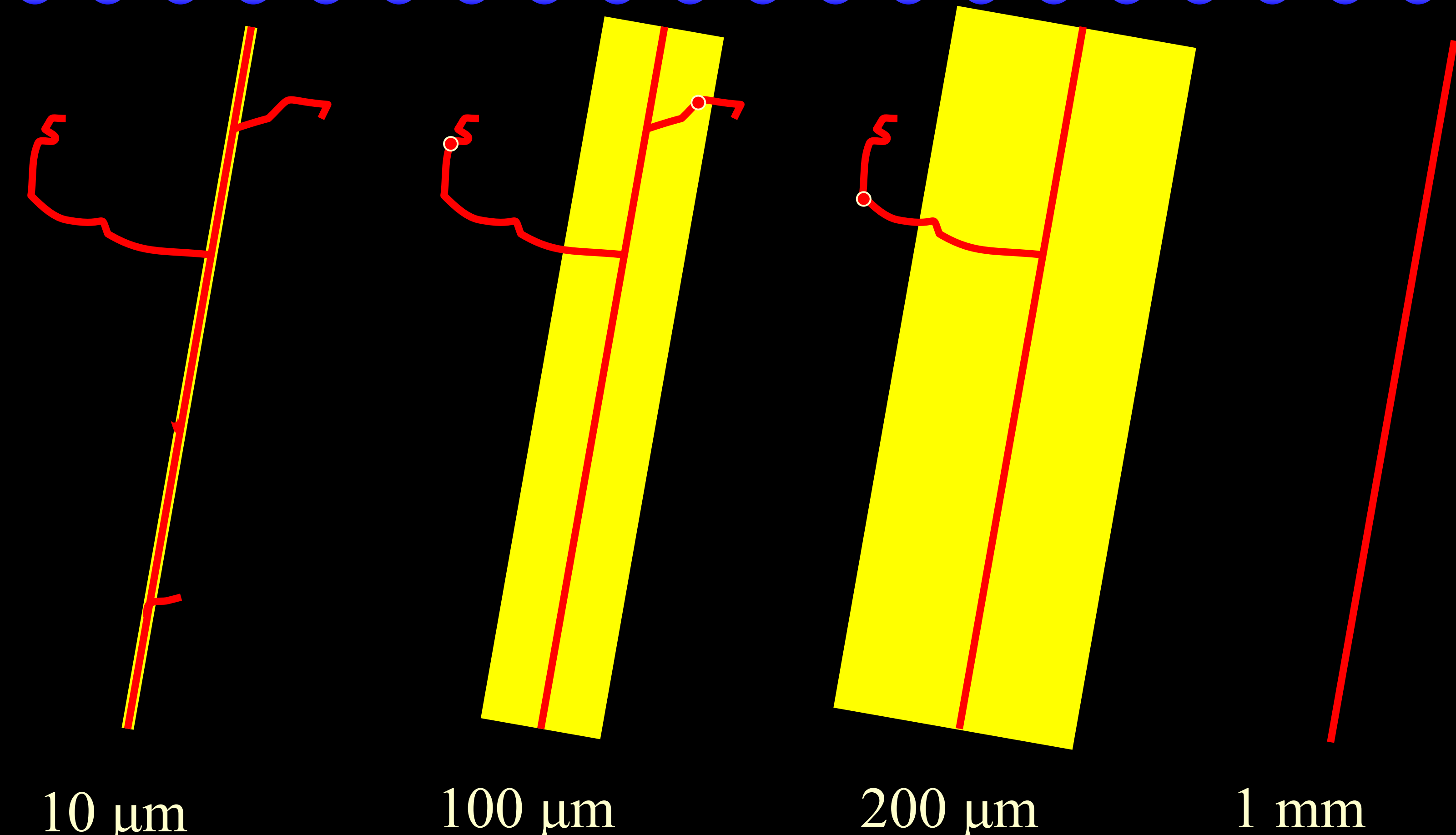
With large current step limits and range cuts in Geant4, usually get a single step in sensitive silicon, with hit placed in center of volume, and only dE/dx along path.

Digitization



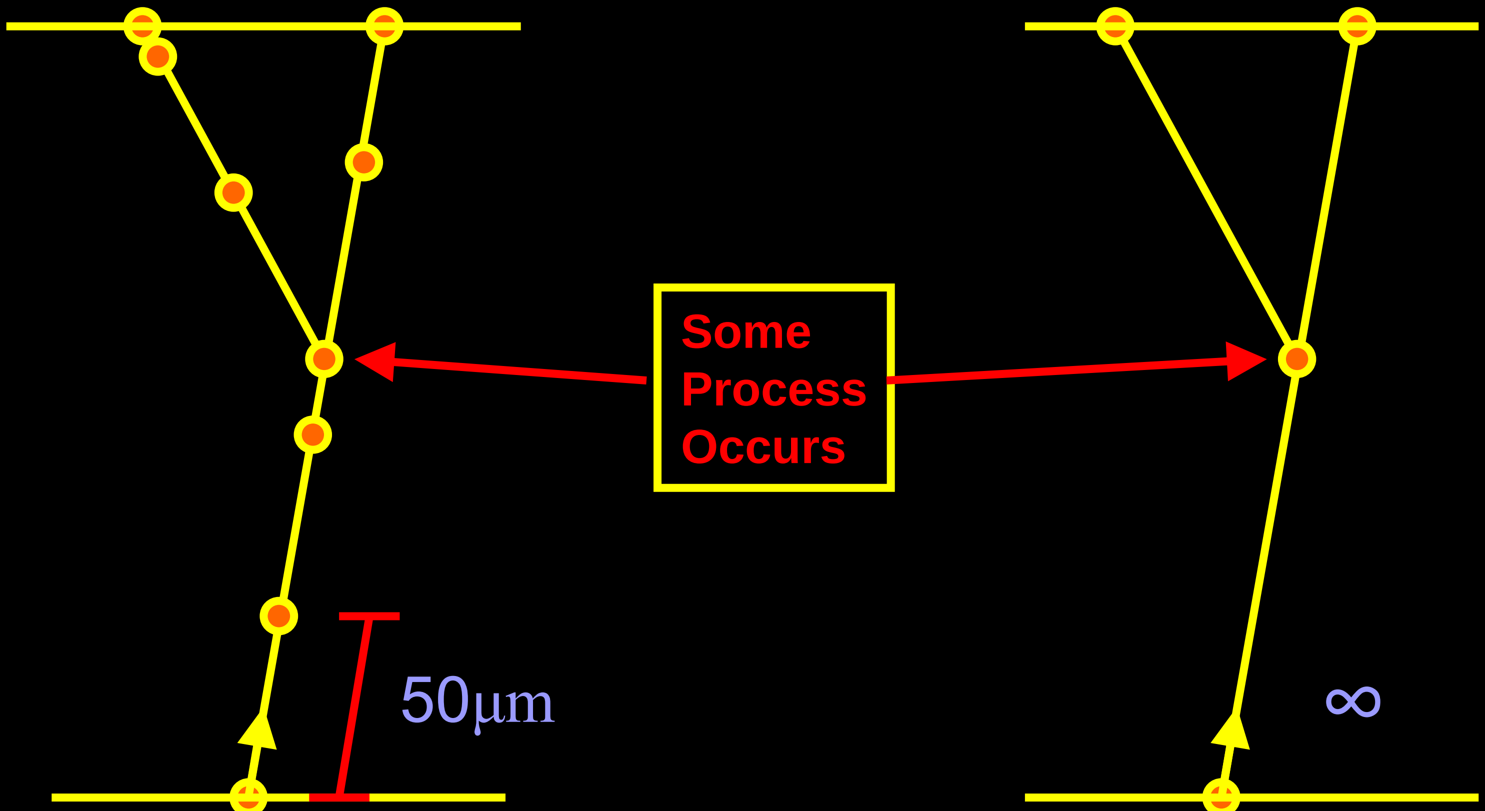
Usual digitization algorithm starts by artificially subdividing the step and distributing the deposited energy in subslices. These depositions are then drifted to the surface, with appropriate diffusion and Lorentz angle effects, to provide hits in strips.

G4 Cuts - Range Cuts



Reducing range cuts increases number of secondaries produced and explicitly tracked

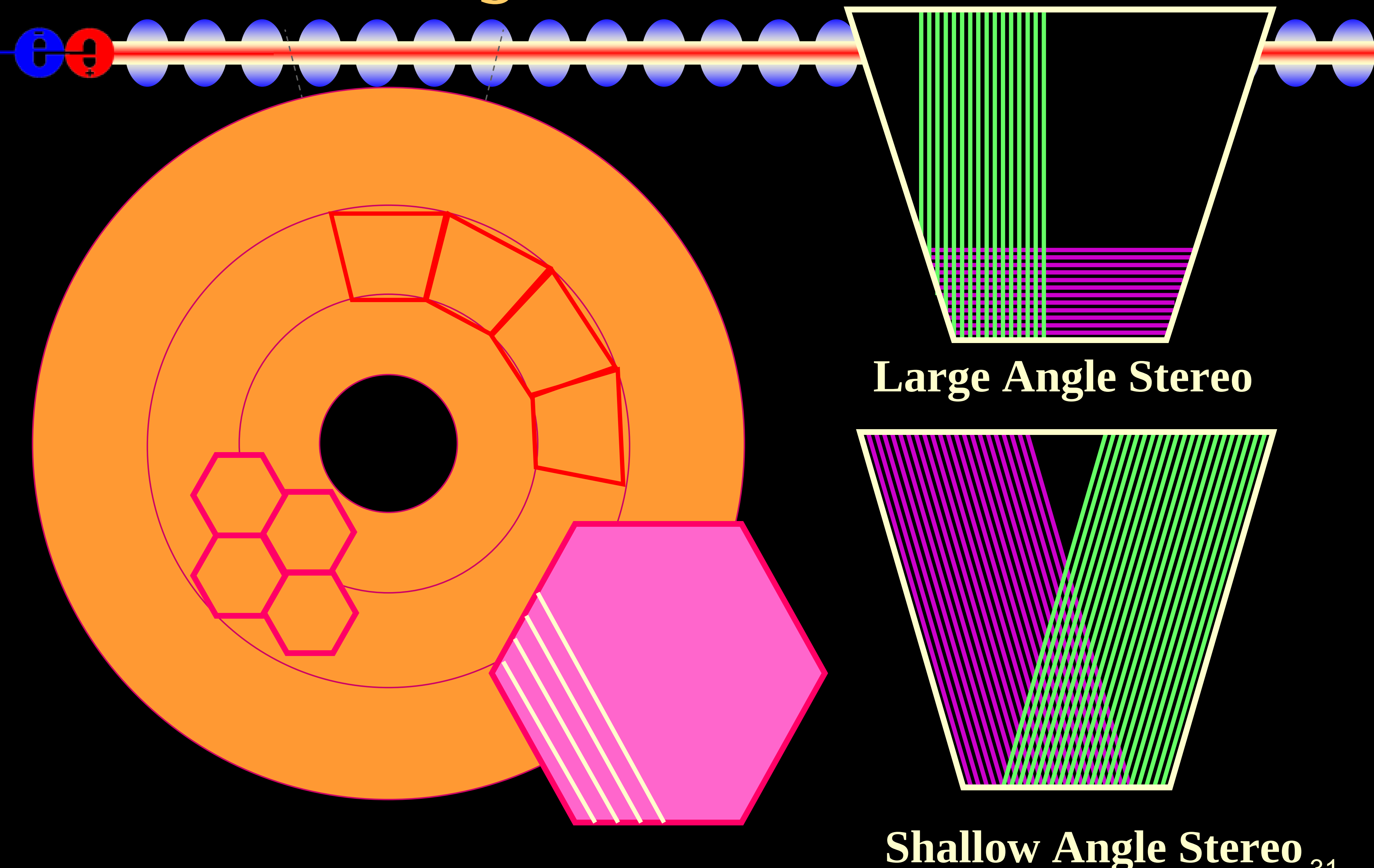
G4 Cuts - Max Step Length



Limits step when no other process occurs in that distance.

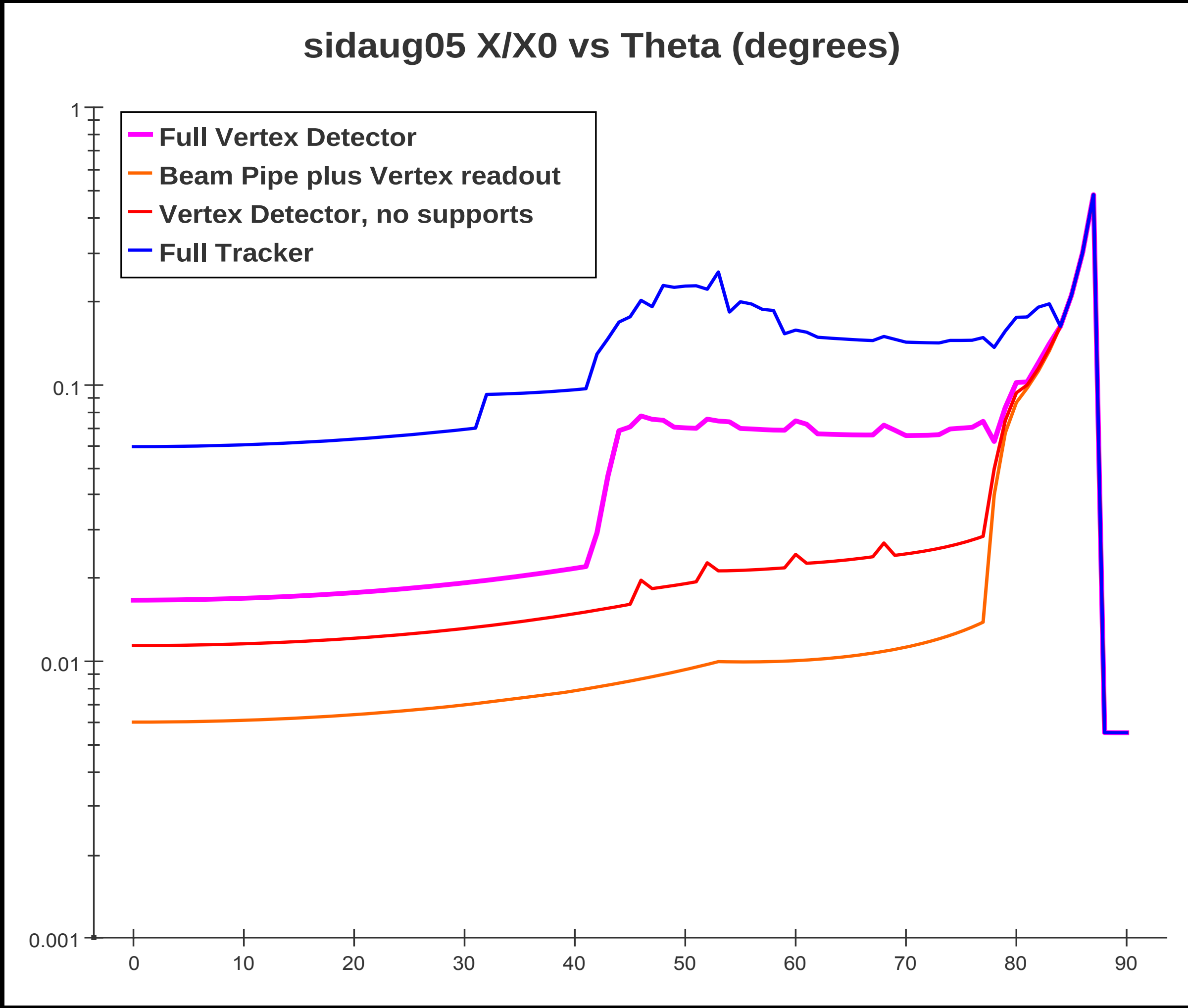
Reducing size limit increases number of hits produced.

Tiling Forward Disks



Geant4 Tracking Studies

- New tool allows plots of material budget to be easily created.
- Tracks geantino through detector and sums up radiation and interaction lengths.



“Signal” and Diagnostic Samples

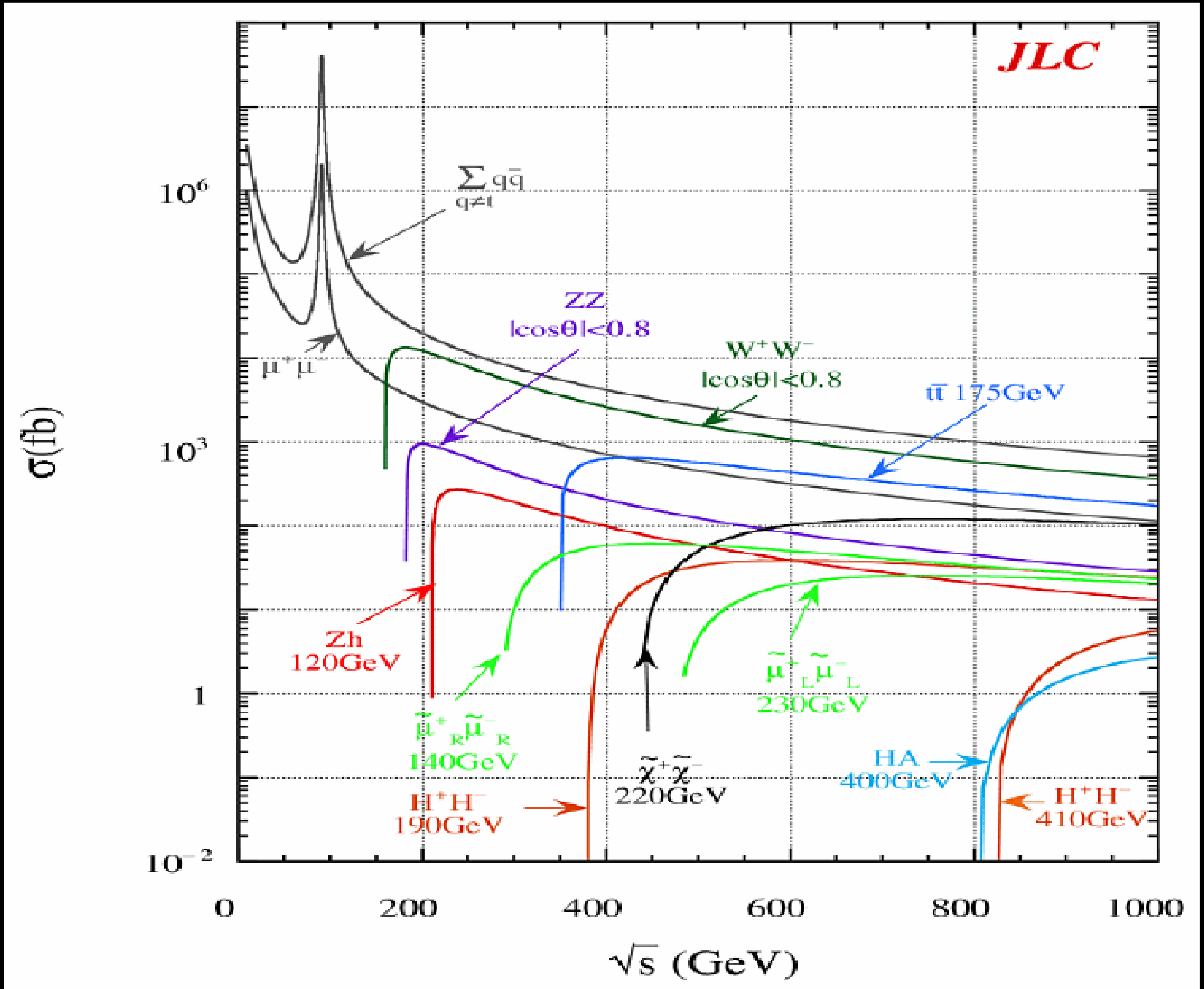
- Have generated canonical data samples and have processed them through full detector simulations.
- simple single particles: γ, μ, e, $\pi^{+/-}$, n, …
- composite single particles: π^0,ρ, K^0_S ,τ, ψ
- Z Pole events: comparison to SLD/LEP
- WW, ZZ, $t\bar{t}$, $q\bar{q}$, tau pairs, mu pairs, Zγ, Zh:
- Web accessible:

http://www.lcsim.org/datasets/ftp.html

"Standard Model Background"

- Generate an inclusive set of MC events with all SM processes + backgrounds arising from beam- and brems-strahlung photons and machine-related particles. 500 fb^{-1} @ 0.5 TeV, 2 ab^{-1} @ 1.0 TeV
  - WHIZARD Monte Carlo used to generate all 0,2,4,6-fermion and t quark dominated 8-fermion processes.
- Used for realistic analyses and represents a "standard" sample.
- Canonical background for Beyond-SM searches.
- 100% e^- and e^+ polarization used in generation. Arbitrary electron, positron polarization simulated by properly combining data sets.
- Fully fragmented MC data sets are produced. PYTHIA is used for final state QED & QCD parton showering, fragmentation, particle decay.
- 1 year's worth of stdhep files fits on one external harddrive.

“Standard Model Background”



Reconstruction/Analysis Overview

- Java based reconstruction and analysis package
  - Runs standalone or inside Java Analysis Studio (JAS)
  - Fast MC $\rightarrow$ Smeared tracks and calorimetry clusters
  - Full Event Reconstruction
    - detector readout digitization (CCD pixels & Si μ-strips)
    - *ab initio* track finding and fitting for ~arbitrary geometries
    - multiple calorimeter clustering algorithms
    - Individual Particle reconstruction (cluster-track association)
  - Analysis Tools (including WIRED event display)
  - Physics Tools (Vertex Finding, Jet Finding, Flavor Tagging)
  - Beam background overlays at detector hit level

Tracking Detector Readout

- Hits in Trackers record full MC information.
- Digitization is deferred to analysis stage.
- Nick Sinev has released a package to convert hits in silicon to CCD pixel hits.

  MC Hits → Pixels & PH → Clusters → Hits ($x \pm \delta x$)
- UCSC developed long-shaping-time μ-strip sim.

  MC Hits → Strips & PH → Clusters → Hits ($\varphi \pm \delta\varphi$)
- SLAC developing short-strip simulation.
- Needed to correctly study occupancies, overlaps, ghost hits, etc.

Track Finding

- Standalone pattern recognition code for the 2D Barrel VXD hits.
  - High efficiency, even in presence of backgrounds.
  - Efficient at low momentum.
  - Propagates tracks into Central Tracker to pick up φ hits
- Conformal-mapping pattern recognition also available, applicable also to TPC.
- Work ongoing to find MIP stubs in calorimeter and propagate inwards to tracker.

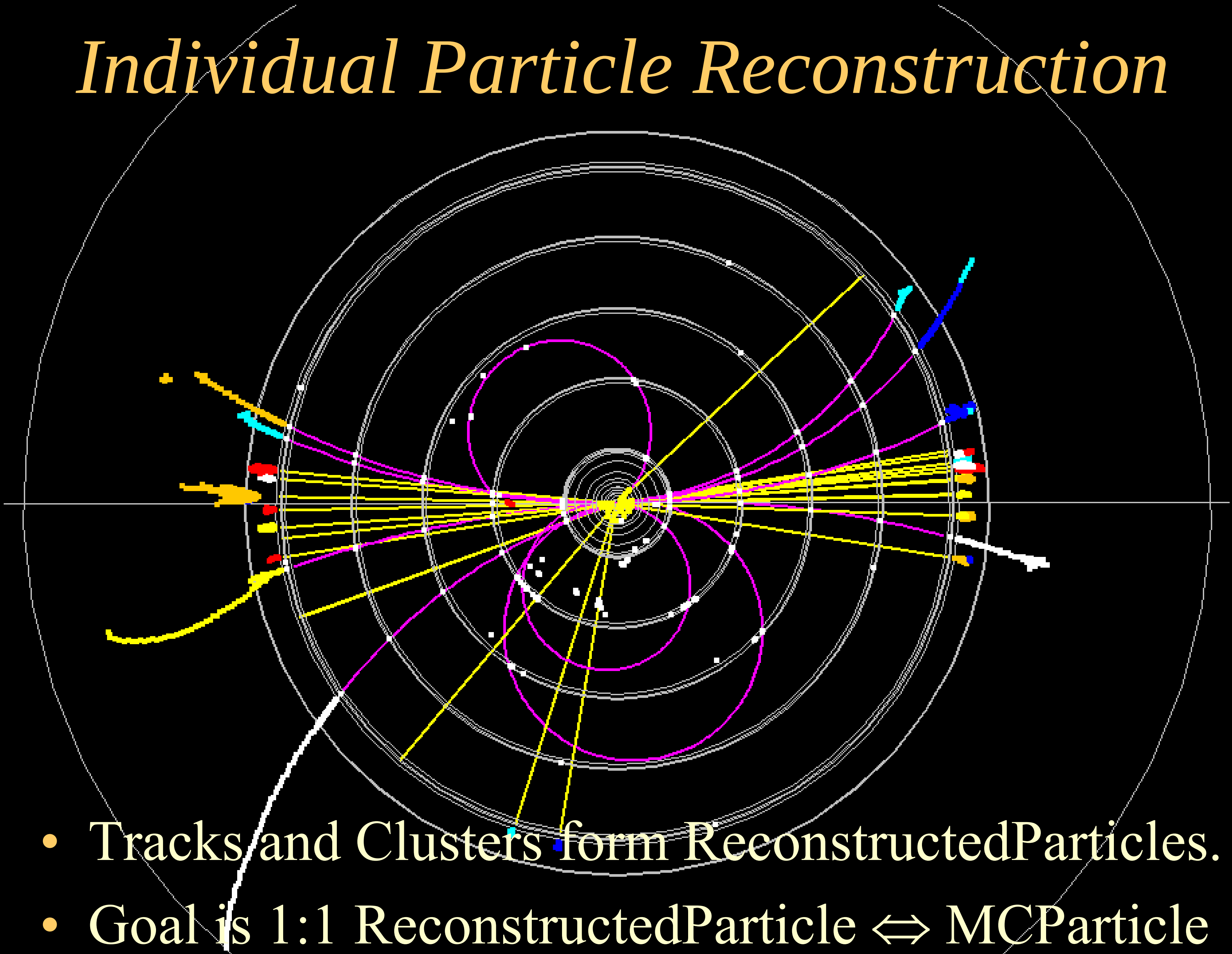
Tracking

- Analytic covariance matrices available for fast MC smearing for each detector. Uses lcdtrk.
- Track "cheater" available for studies of full detector simulation events. Assigns hits on basis of MC parentage.
- Ab initio track finding packages.
- Fitting code incorporating multiple scattering and energy loss via weight matrix or Kalman Filter available.

Particle Reconstruction

- Several groups are following different approaches towards individual particle reconstruction (“particle flow”).
- Template allows plug-and-play of different approaches.
- Have first packages for identifying photons, electrons, charged & neutral hadrons and muons.
- Being tuned and optimized for different detectors and different final states.
- Main tool for detector optimization.

Individual Particle Reconstruction



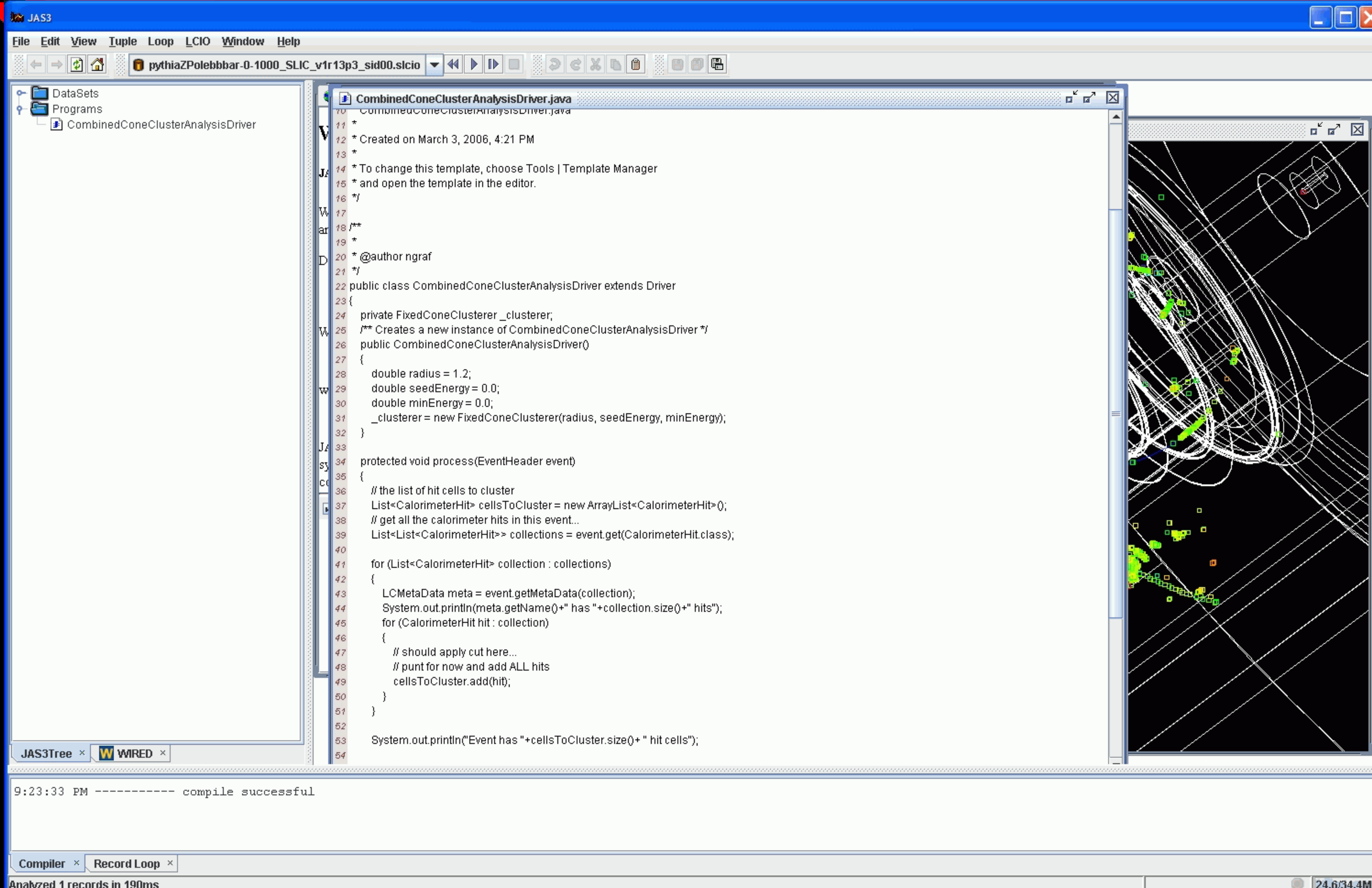
- Tracks and Clusters form ReconstructedParticles.
- Goal is 1:1 ReconstructedParticle ⇔ MCParticle

Java Analysis Studio (JAS)

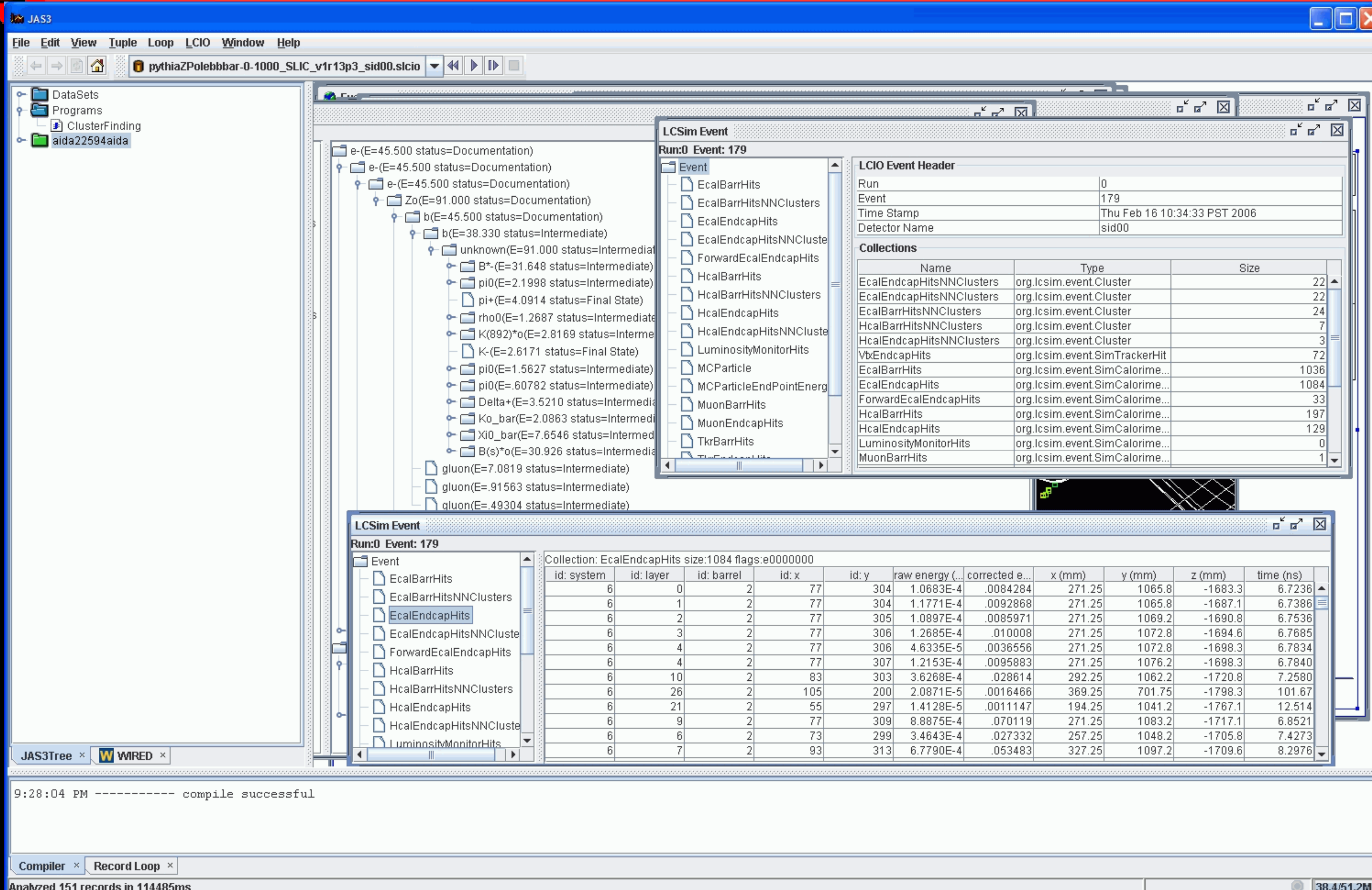
- Integrated Development Environment (editor, compiler)
- Cross-platform physics analysis environment with iterative, event-based analysis model
  - quick development, debugging, ad hoc analysis
  - additional functionality with plugins
- Dynamically load / unload Java analysis drivers
  - Supports distributed computing.
- Plotting and fitting and analysis (cuts, scripting) engine
  - 1D, 2D histograms, clouds, profiles, dynamic scaling, cuts
  - high-quality output to vector or raster formats
- Integrated event browser and event display

JAS

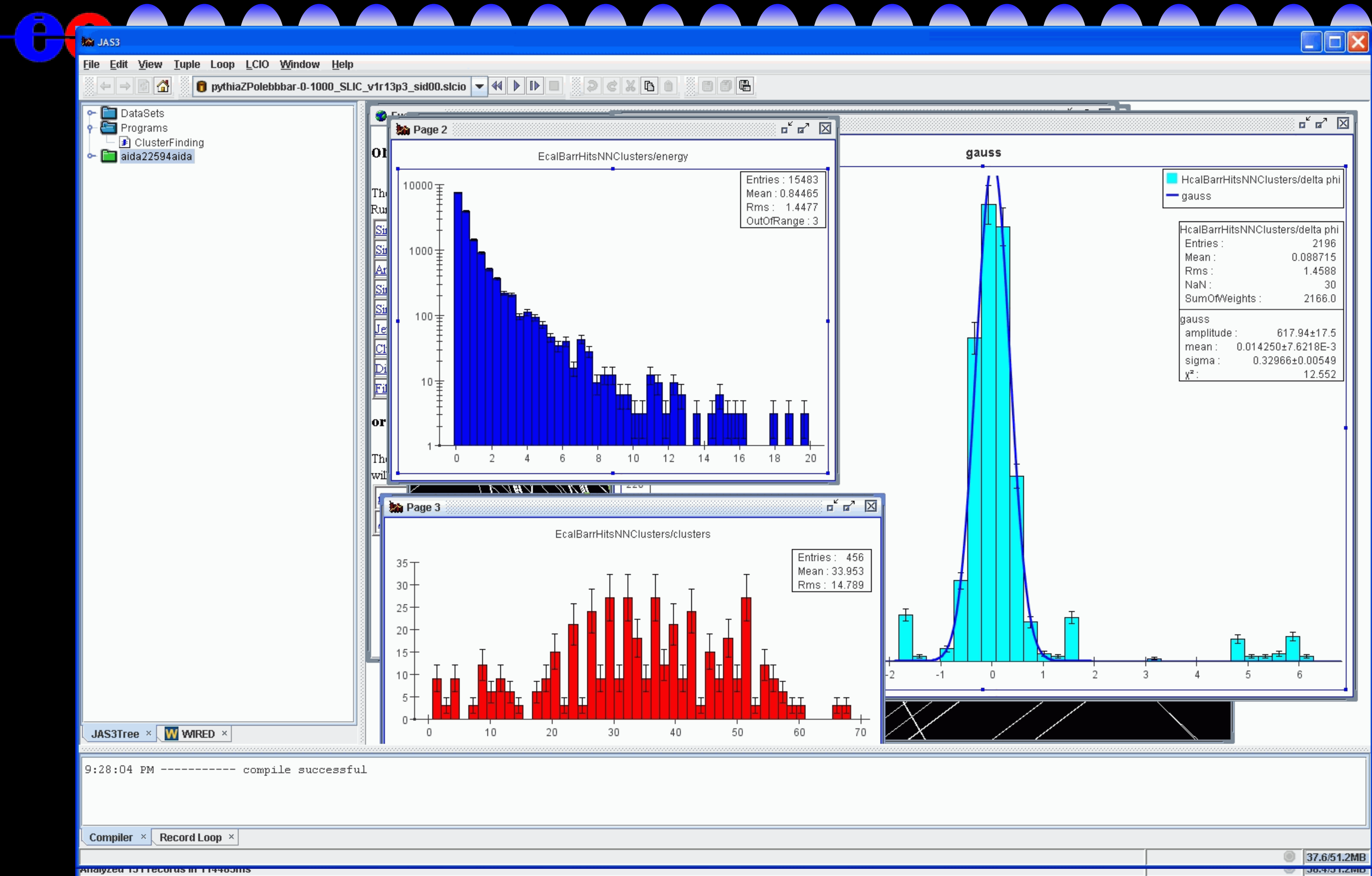
JAS editor/compiler



JAS event browser



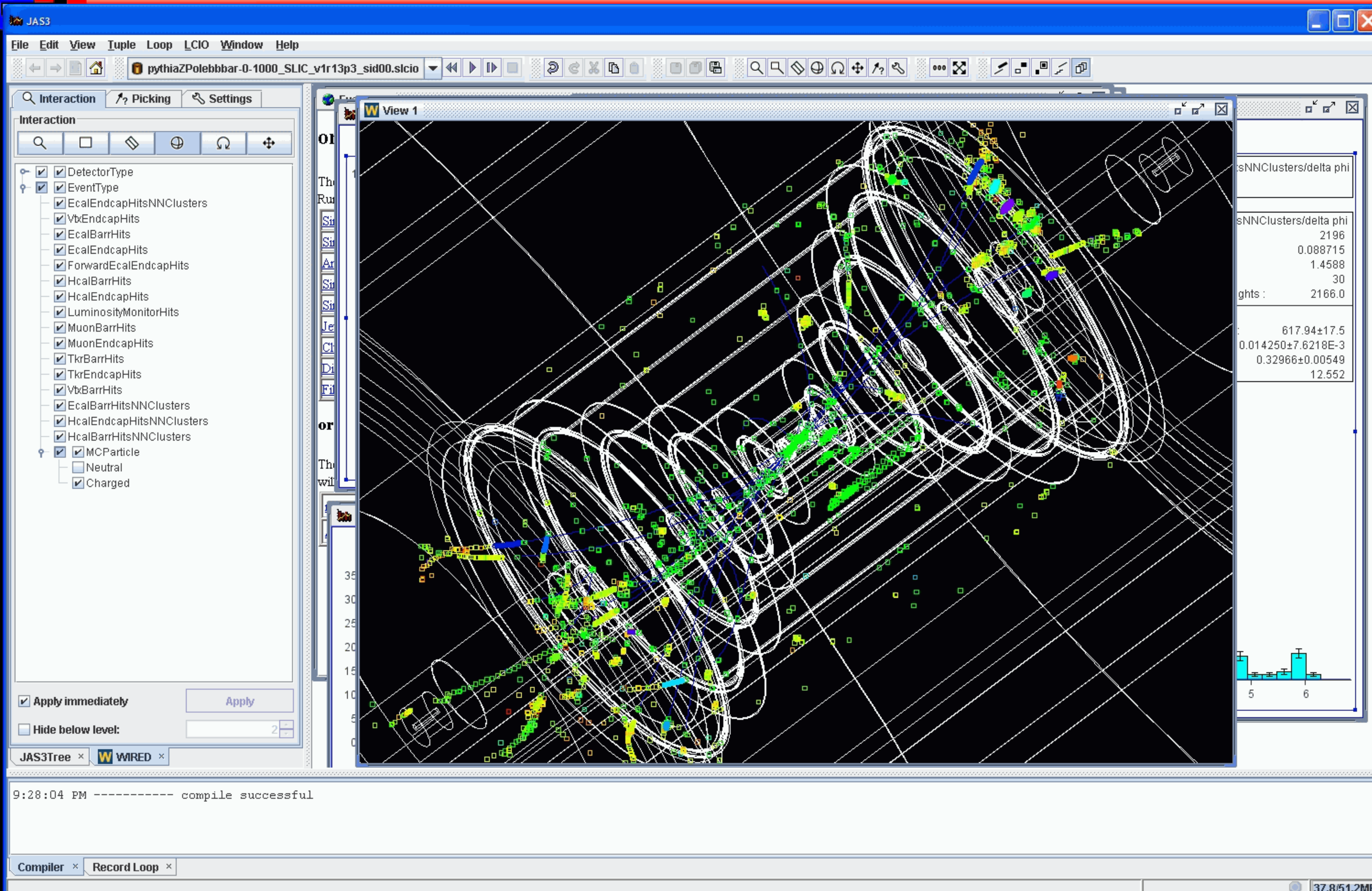
JAS histogramming/ fitting



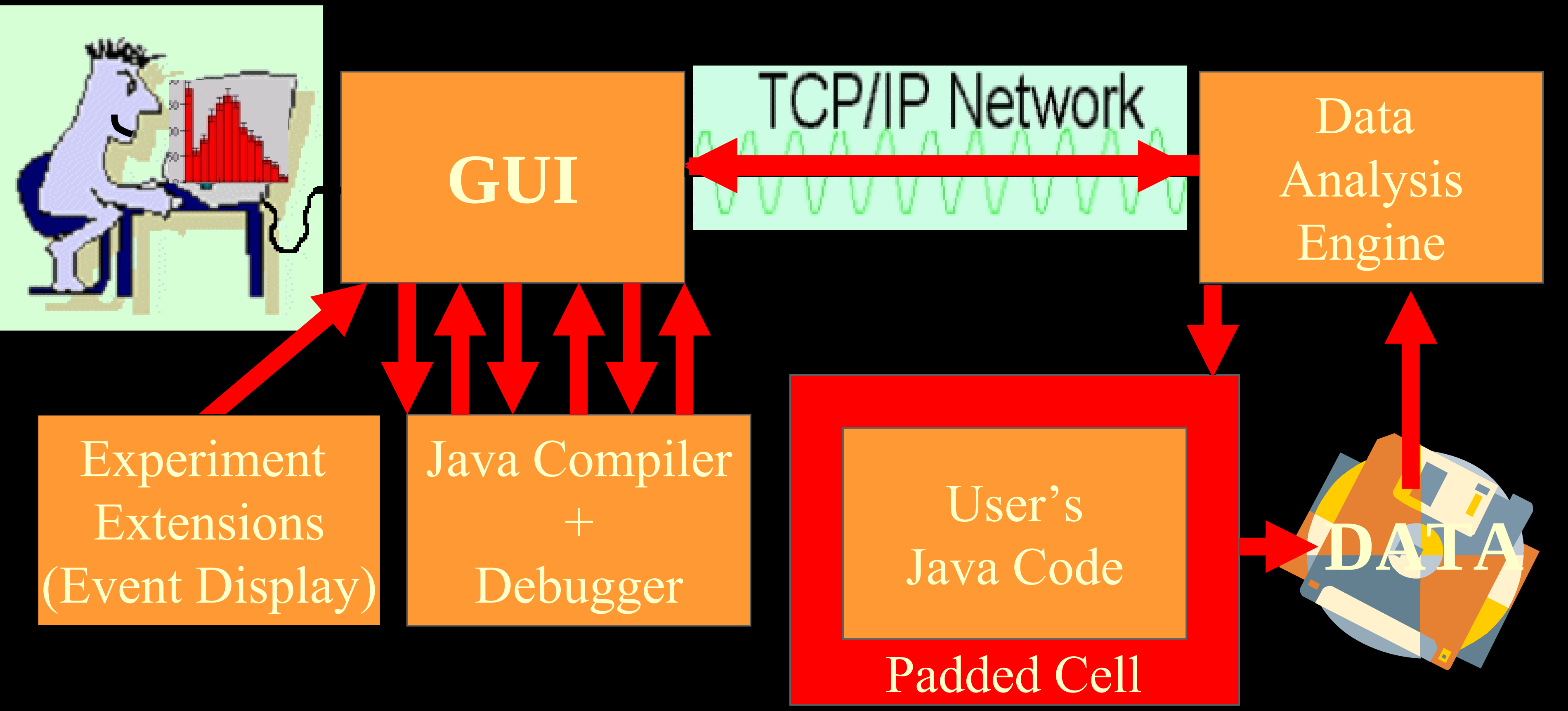
JAS LCD Physics Utilities

- Physics Utilities
  - 4-vector, 3-vector classes
  - Event shape/Thrust finder
  - Jet Finders
    - Many kT algorithms implemented (e.g. Jade and Durham)
    - Extensible to allow implementation of other algorithms
- Event Displays
  - 2D - Suitable for debugging reconstruction and analysis
  - Wired for full 3D support
- Particle Hierarchy Displays

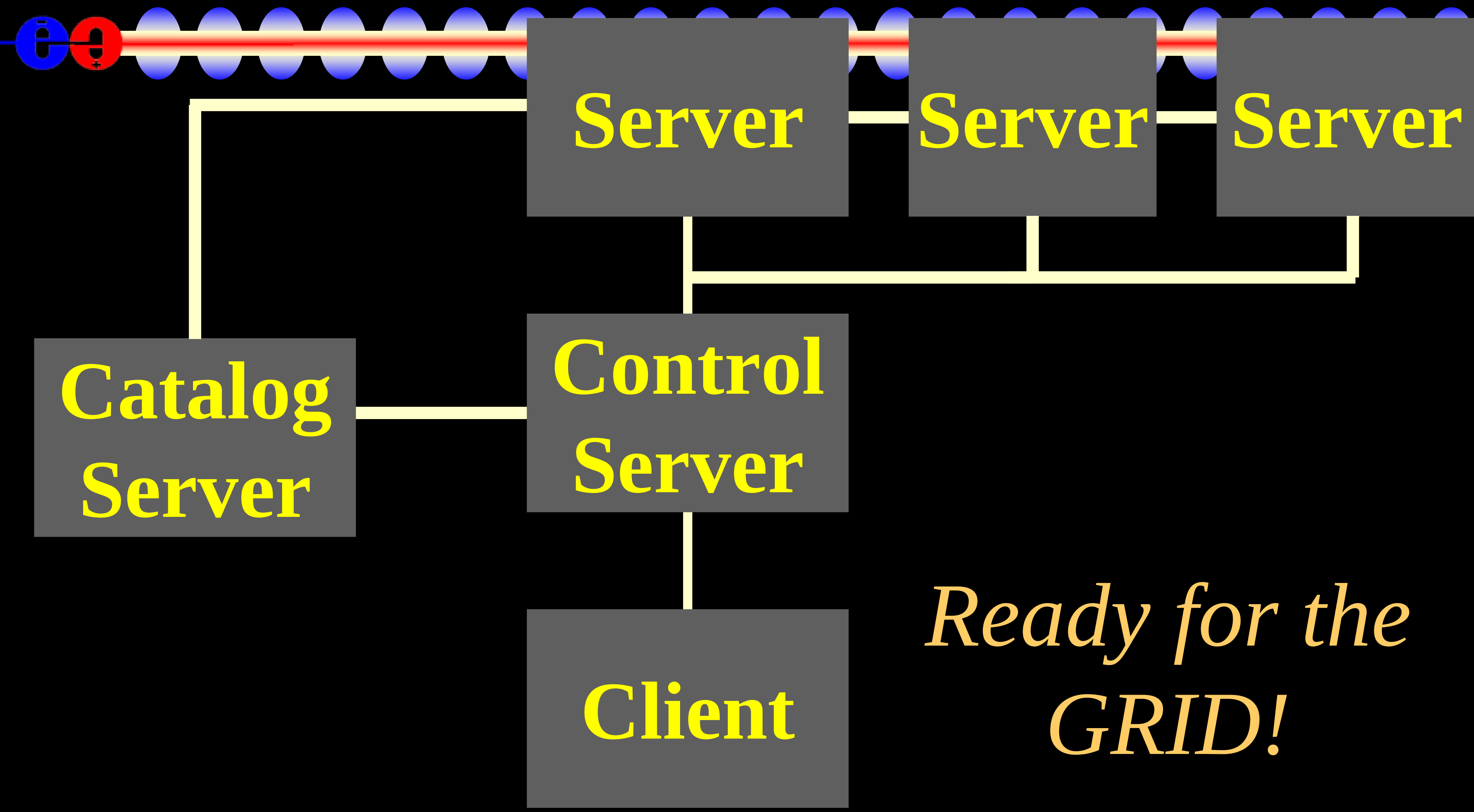
Wired LCD Event Display



JAS Remote Data Access



Distributed Analysis



Ready for the GRID!

Detector Optimization (Costing)

- Goal is to fully simulate and validate baseline design.
- Then determine the dependence of performance on detector attributes.
- Iterate to achieve balance of cost, risk, & performance

Spreadsheet

- Excel Spreadsheet demo of costing vs parameters.

Simulation Summary

- ALCPG sim/reco supports an ambitious international detector simulation effort. Goal is flexibility and interoperability.
- Provides full data samples for ILC physics studies.
- Provides a complete and flexible detector simulation package capable of simulating arbitrarily complex detectors with runtime detector description.
- Reconstruction & analysis framework exists, various algorithms implemented.
- Need to iterate and apply to various detector designs.

Additional Information

- Wiki - http://confluence.slac.stanford.edu/display/ilc/Home
- lcsim.org - http://www.lcsim.org
- org.lcsim - http://www.lcsim.org/software/lcsim
- Software Index - http://www.lcsim.org/software
- Detectors - http://www.lcsim.org/detectors
- ILC Forum - http://forum.linearcollider.org
- LCIO - http://lcio.desy.de
- SLIC - http://www.lcsim.org/software/slic
- LCDD - http://www.lcsim.org/software/lcdd
- JAS3 - http://jas.freehep.org/jas3
- AIDA - http://aida.freehep.org
- WIRED - http://wired.freehep.org