CMS Reconstruction and Analysis Software

CMS Barrel Muon Workshop

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Outline

- Introduction
  - **CMS Software**
- Muon Reconstruction
  - **Local Pattern Recognition**
  - **Standalone Reconstruction**
  - **Global Reconstruction**
  - **Muon Isolation**
- Analysis
  - **DSTs**
- Summary

Introduction

CMS software is structured in projects focusing on different tasks:

- **Geometry** XML description of the CMS detector
- **COBRA** Framework: Interface to basic services
- **OSCAR** Simulation with GEANT-4
- **ORCA** Reconstruction and analysis
- **FAMOS** Fast simulation and reconstruction
- **IGUANA** Framework for visualization
- **IGUANACMS** Visualization (e.g. event display)

CMS Software

OSCAR
Detector Simulation

ORCA
Detector Reconstruction
HLT
Physics Analysis

FAMOS
Fast Simulation

IguanaCMS
CMS Visualization
Event Display

Iguana
Core Visualization
GUI and Scripting Services

COBRA
Core Framework(s)
Core Services

Mantis
G4 Simulation
Framework

DDD
Detector Description
Framework

Profound
PRS
Foundation

Generator
Interface

G3 OO
Interface

CARF
Reconstruction
Framework

Persistency
Layer

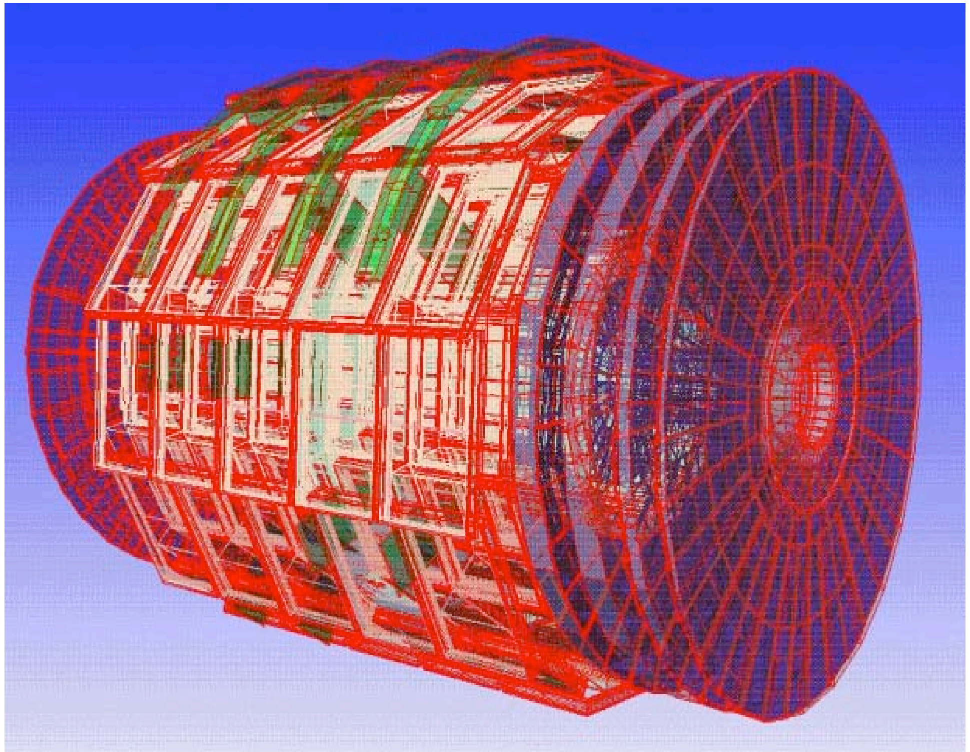
Application
Infrastructure

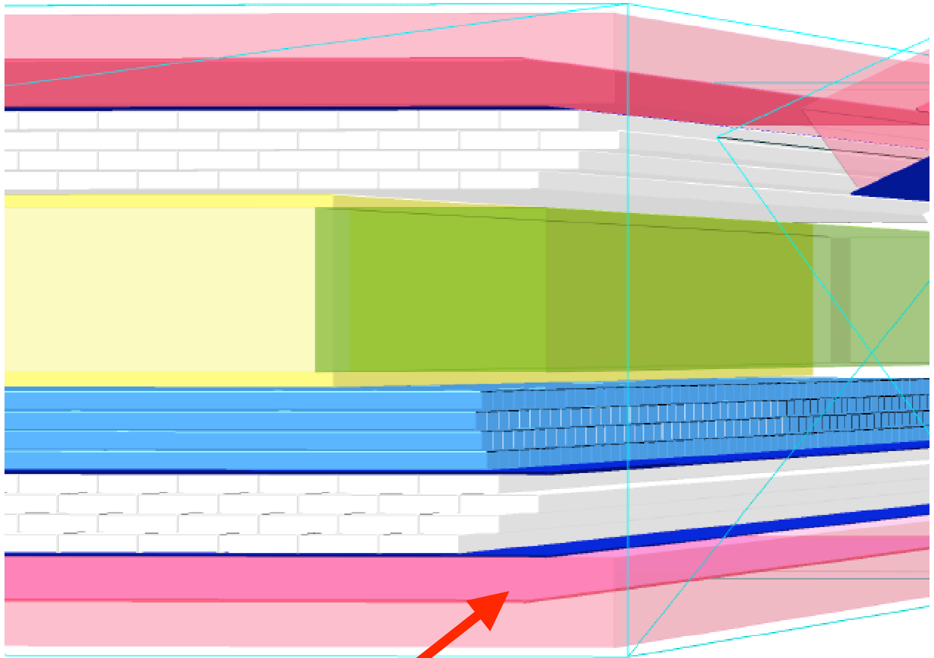
Geometry

- **Geometry description**
  - Simulation Geometry: must be detailed
    - Used for tracking
    - Includes both active and passive material
    - Currently described in XML
  - Reconstruction Geometry: must be lightweight
    - To allow fast navigation
    - Currently, includes only chambers (active material)
    - Extracted from same XML description; ORCA implementation
    - No material at all (just volumes and positions)
    - But material description is needed for global reconstruction!
    - To extrapolate track parameters through the yoke (propagation)
    - GEANE

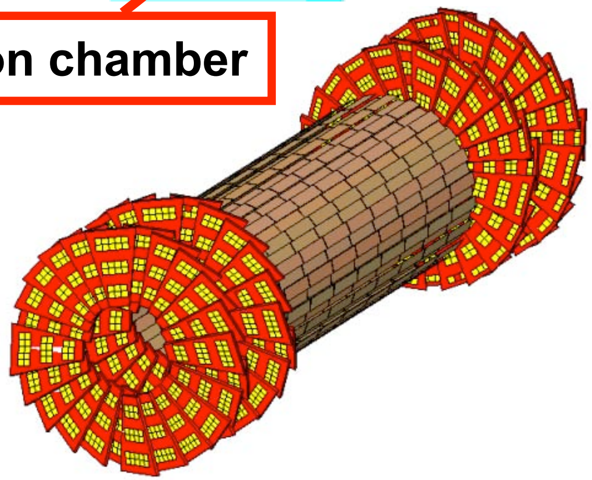
Geometry

CMS muon system





Barrel muon chamber

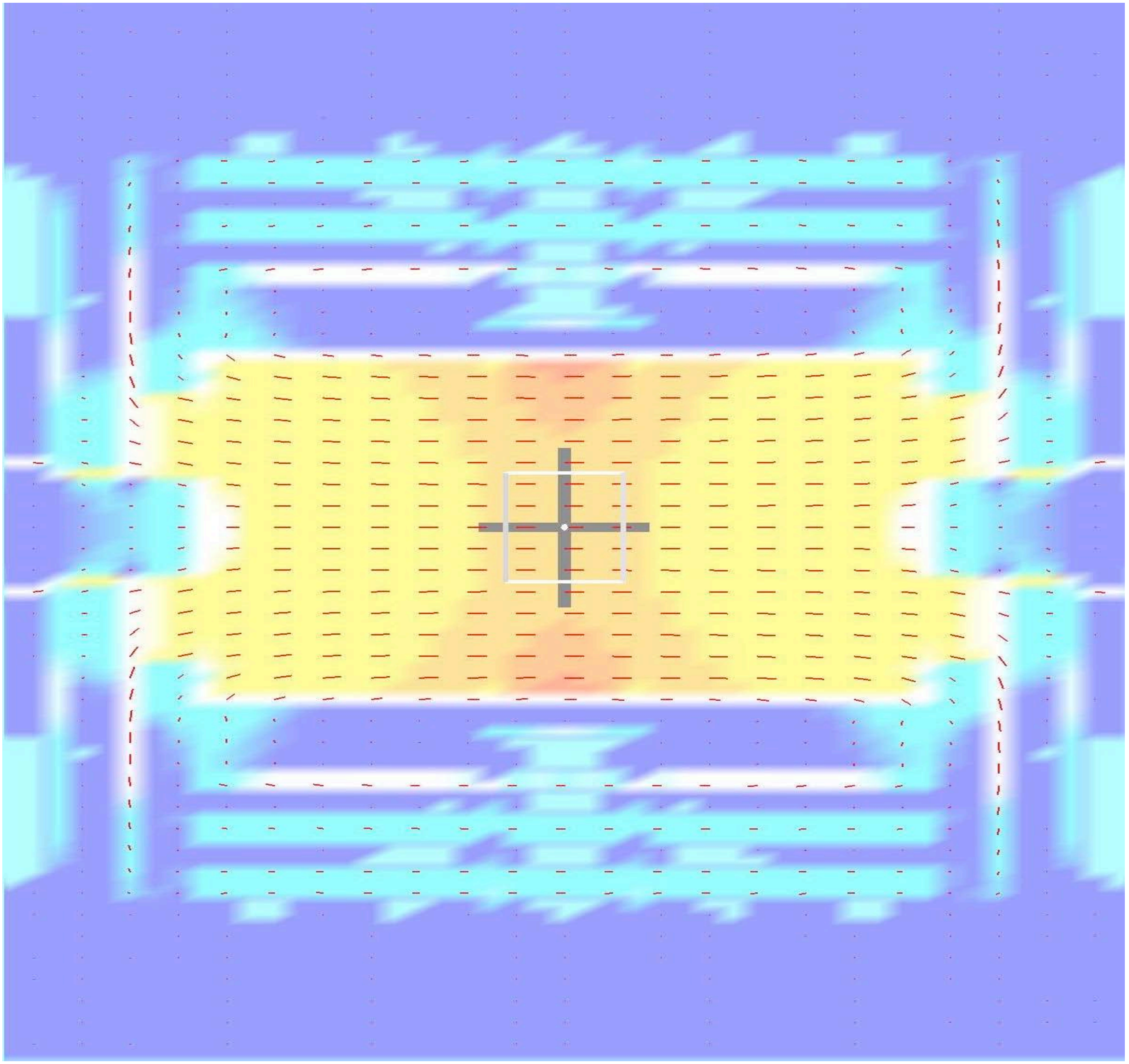


CMS pixel detector

Magnetic Field

- **Needed for simulation and reconstruction**
- **Must be known with good precision**
  - Impact on quality of reconstruction
- **Current implementation:**
  - From an independent magnetic geometry
    - 3D TOSCA field map implemented
    - Differences wrt. simulation geometry!
    - Values on a grid in *global* coordinates
- **Requirements:**
  - Current system must be replaced
  - Must be fast
    - Performance issue for simulation and reconstruction
  - Consistent with other geometries
  - Ability to introduce misalignment

Field Map



COBRA

CMS Analysis and Reconstruction Framework

- Glue it all together
- Insulate user code from services
- Manage persistent data transparently
  - Persistency based on POOL (ROOT IO)
- Manage Runs, Events, Collections, etc.
- Manage the order of reconstruction
- Ensure a uniform interface to all CMS code

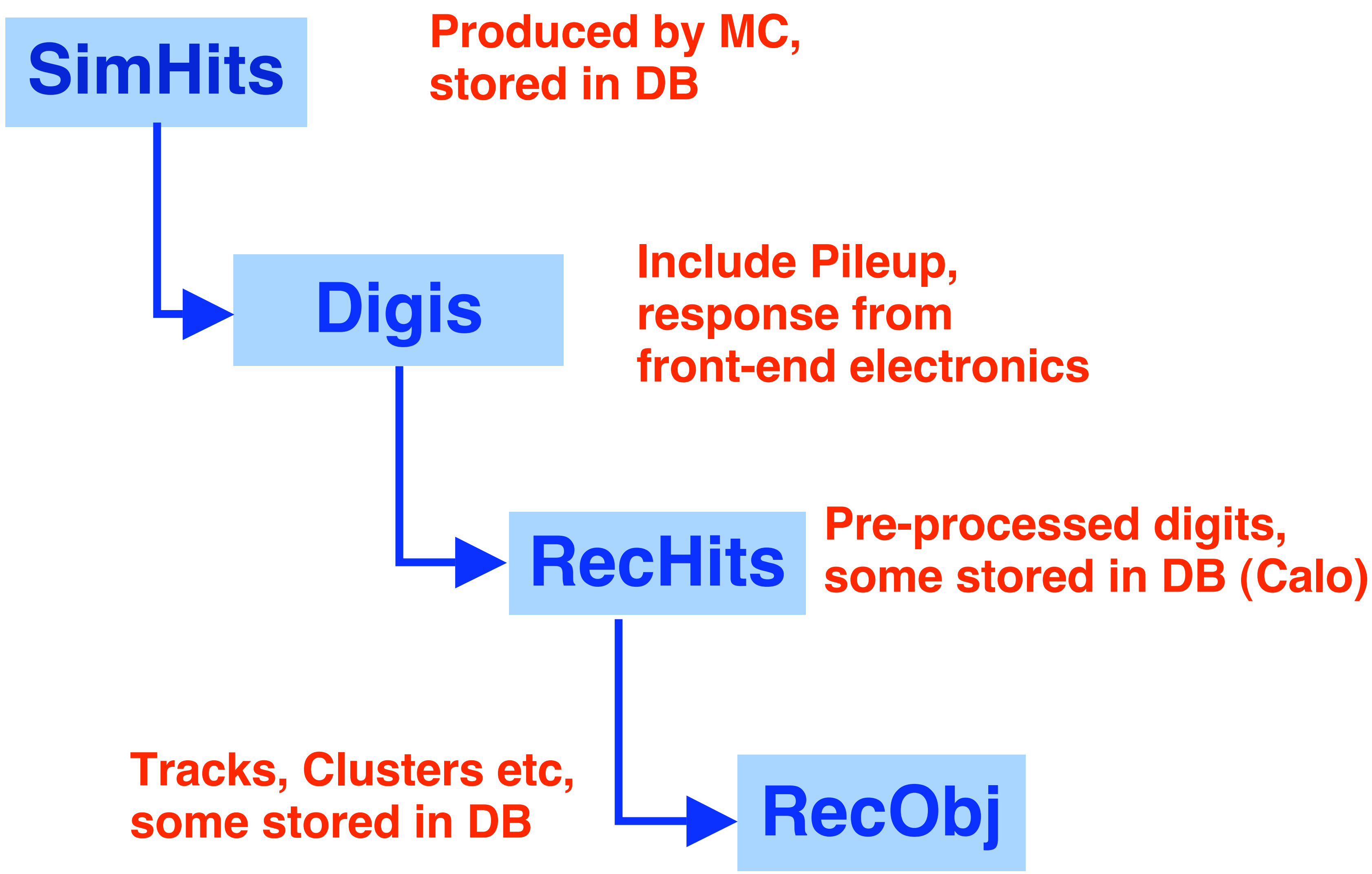
OSCAR

- Detector simulation based on GEANT 4
- Integrated with CMS software (COBRA)
  - User interface compatible with ORCA
- Interface with
  - PYTHIA ntuples
  - HEPEVT ASCII files
  - HepMC
  - **Particle gun**
- Persistency of
  - **Hits for all detectors**
  - **Primary generator particles**
  - **Selected tracks**

ORCA

- **Combination of Signal & Pile-up events**
- **Detector digitisation and reconstruction of detector objects**
  - Clusters, Hits
- **Reconstruction of physics objects**
  - Jets, Electrons, Photons, Muons, Vertices
- **Simulation of Level-1 Trigger decisions**
- **Implementation of High-Level Trigger algorithms**
- **ORCA programs are COBRA applications**

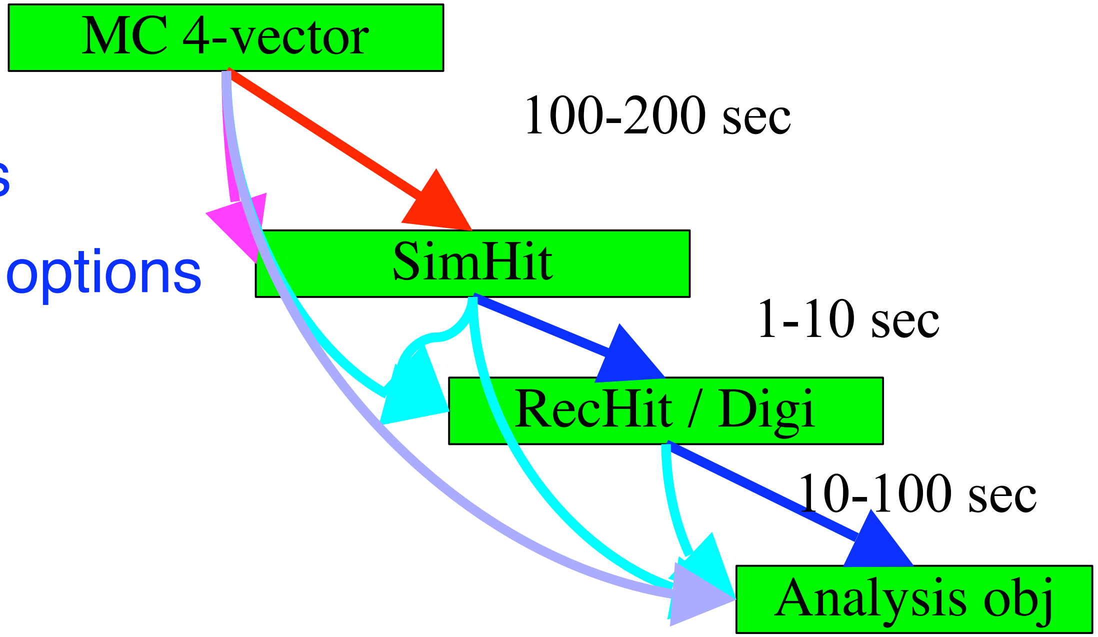
Stages of Reconstruction



FAMOS

FAst MOnte Carlo Simulation

- FAMOS for OSCAR
  - less geometry volumes
  - less detailed GEANT4 options



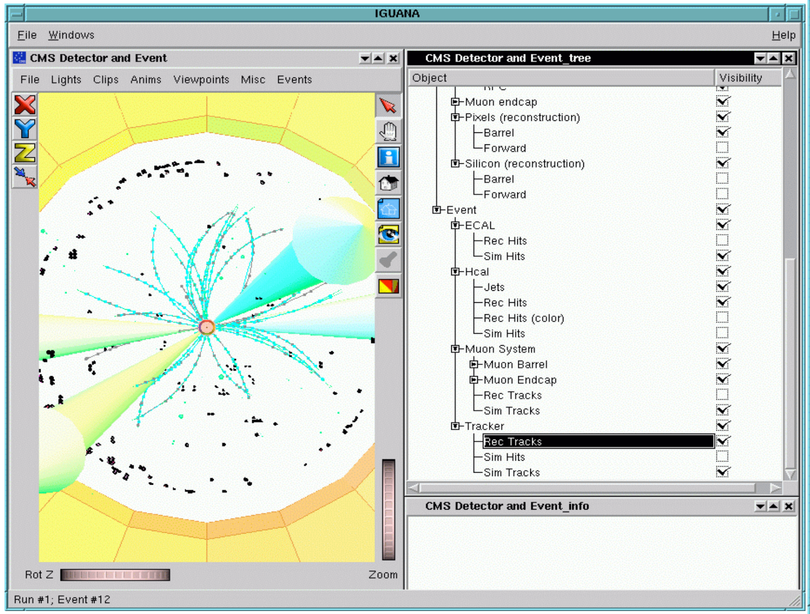
- FAMOS for ORCA
  - faster algorithms
  - simple parametrisation of resolutions & efficiencies
  - tuned to full simulation/reconstruction

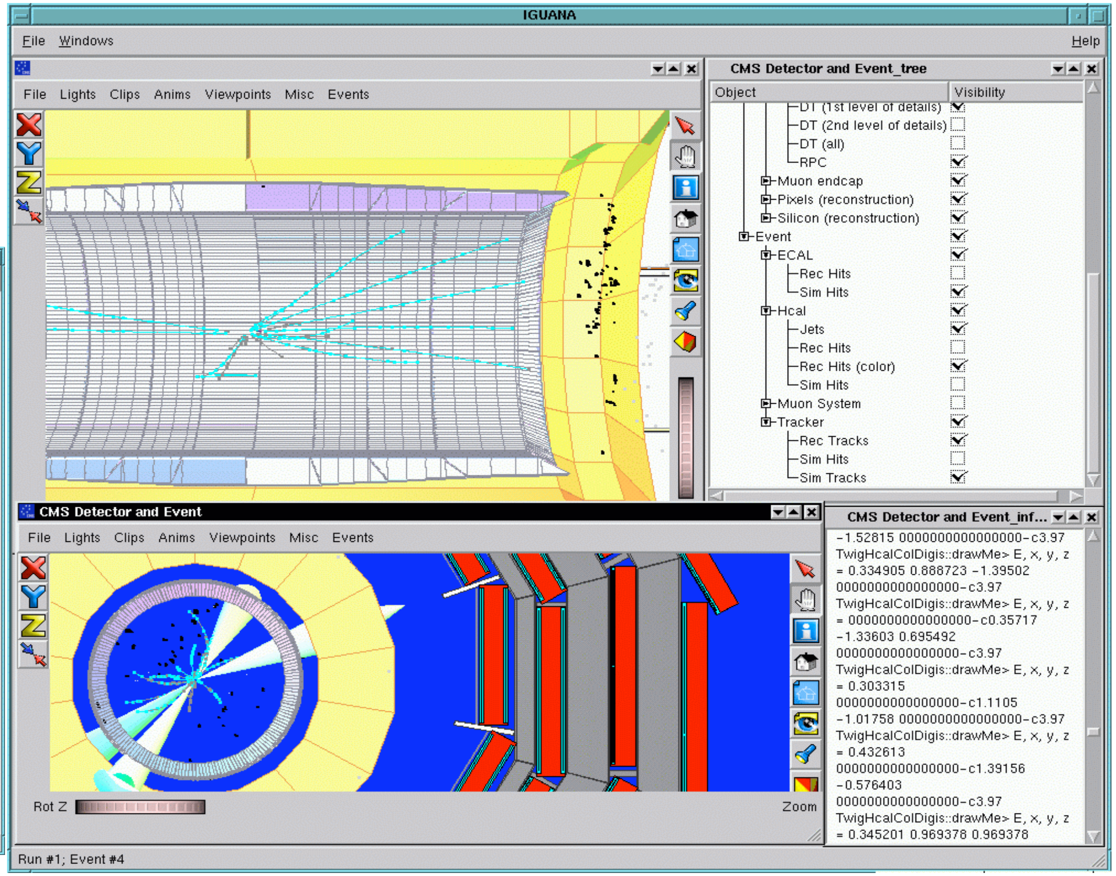
ORCA Visualization

- Interactive 3D CMS detector geometry for sensitive volumes with levels of details;
- Interactive 3D reps of reconstructed and simulated events including visualization of physics quantities such as tangent of a SimHit;
- Access event by event or automatically fetching events (no batch mode);
- Event and run number displayed.

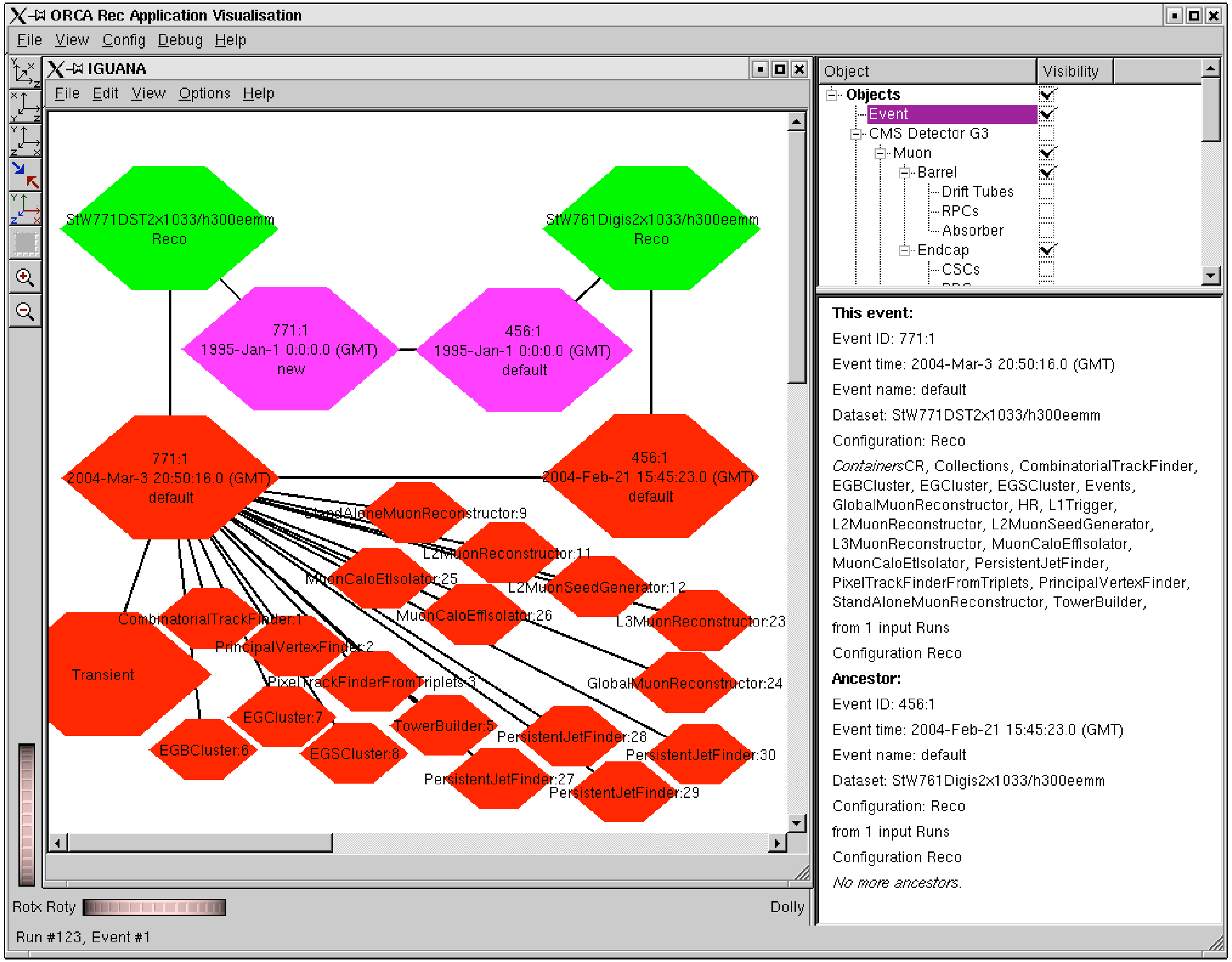
- Interactive picking;
- Correlated selection;
- Projections (a la 2D);
- Save .iv and print (jpeg, tiff, ps);

- Multiple (cloned) views;
- Slices and cuts;
- Printout for selected object;



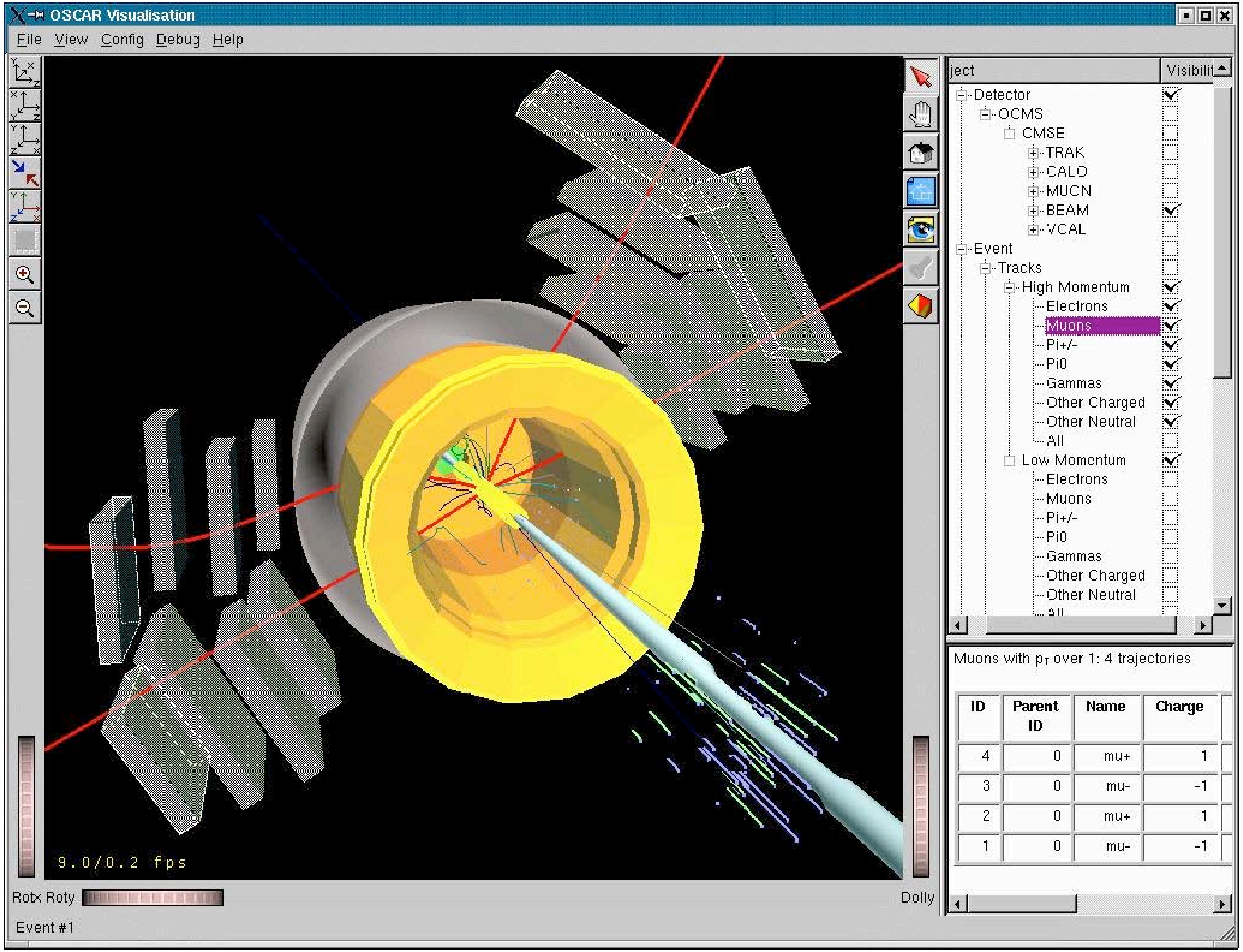


IGUANACMS

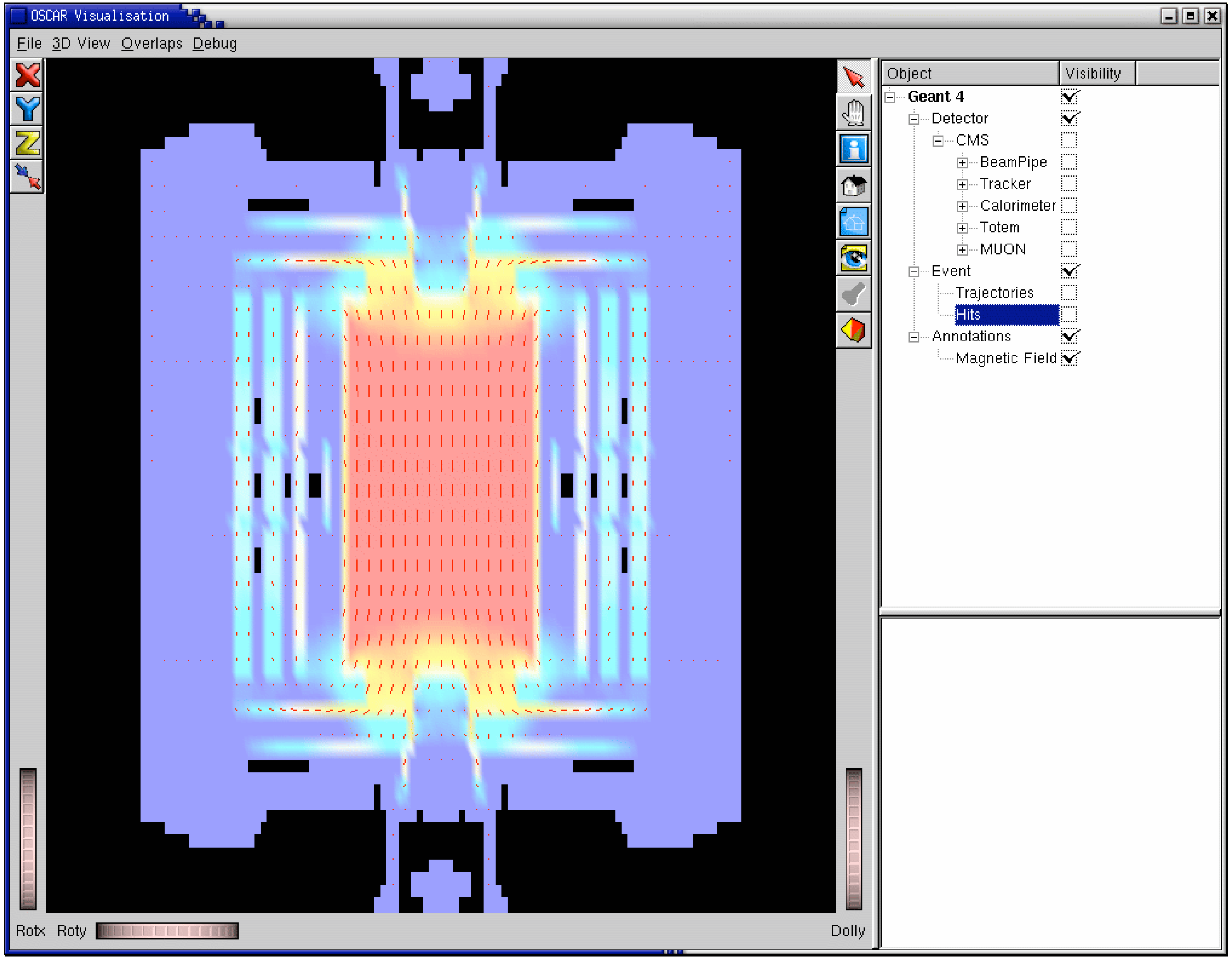


ORCA Rec Application Visualisation
File View Config Debug Help
IGUANA
File Edit View Options Help
StW771DST2x1033/h300eemm Reco
StW761Digis2x1033/h300eemm Reco
771:1 1995-Jan-1 0:0:0.0 (GMT) new
456:1 1995-Jan-1 0:0:0.0 (GMT) default
771:1 2004-Mar-3 20:50:16.0 (GMT) default
456:1 2004-Feb-21 15:45:23.0 (GMT) default
StandAloneMuonReconstructor:9
L2MuonReconstructor:11
MuonCaloEtIsolator:25
L2MuonSeedGenerator:12
MuonCaloEfIsolator:26
L3MuonReconstructor:23
CombinatorialTrackFinder:1
PrincipalVertexFinder:2
Transient
PixelTrackFinderFromTriplets:3
GlobalMuonReconstructor:24
EGCluster:7
TowerBuilder:5
PersistentJetFinder:28
EGBCluster:6
EGSCluster:8
PersistentJetFinder:30
PersistentJetFinder:27
PersistentJetFinder:29
Rotx Roty
Dolly
Run #123, Event #1
Object
Visibility
Objects
Event
CMS Detector G3
Muon
Barrel
Drift Tubes
RPCs
Absorber
Endcap
CSCs
This event:
Event ID: 771:1
Event time: 2004-Mar-3 20:50:16.0 (GMT)
Event name: default
Dataset: StW771DST2x1033/h300eemm
Configuration: Reco
ContainersCR, Collections, CombinatorialTrackFinder, EGBCluster, EGCluster, EGSCluster, Events, GlobalMuonReconstructor, HR, L1Trigger, L2MuonReconstructor, L2MuonSeedGenerator, L3MuonReconstructor, MuonCaloEfIsolator, MuonCaloEtIsolator, PersistentJetFinder, PixelTrackFinderFromTriplets, PrincipalVertexFinder, StandAloneMuonReconstructor, TowerBuilder,
from 1 input Runs
Configuration Reco
Ancestor:
Event ID: 456:1
Event time: 2004-Feb-21 15:45:23.0 (GMT)
Event name: default
Dataset: StW761Digis2x1033/h300eemm
Configuration: Reco
from 1 input Runs
Configuration Reco
No more ancestors.

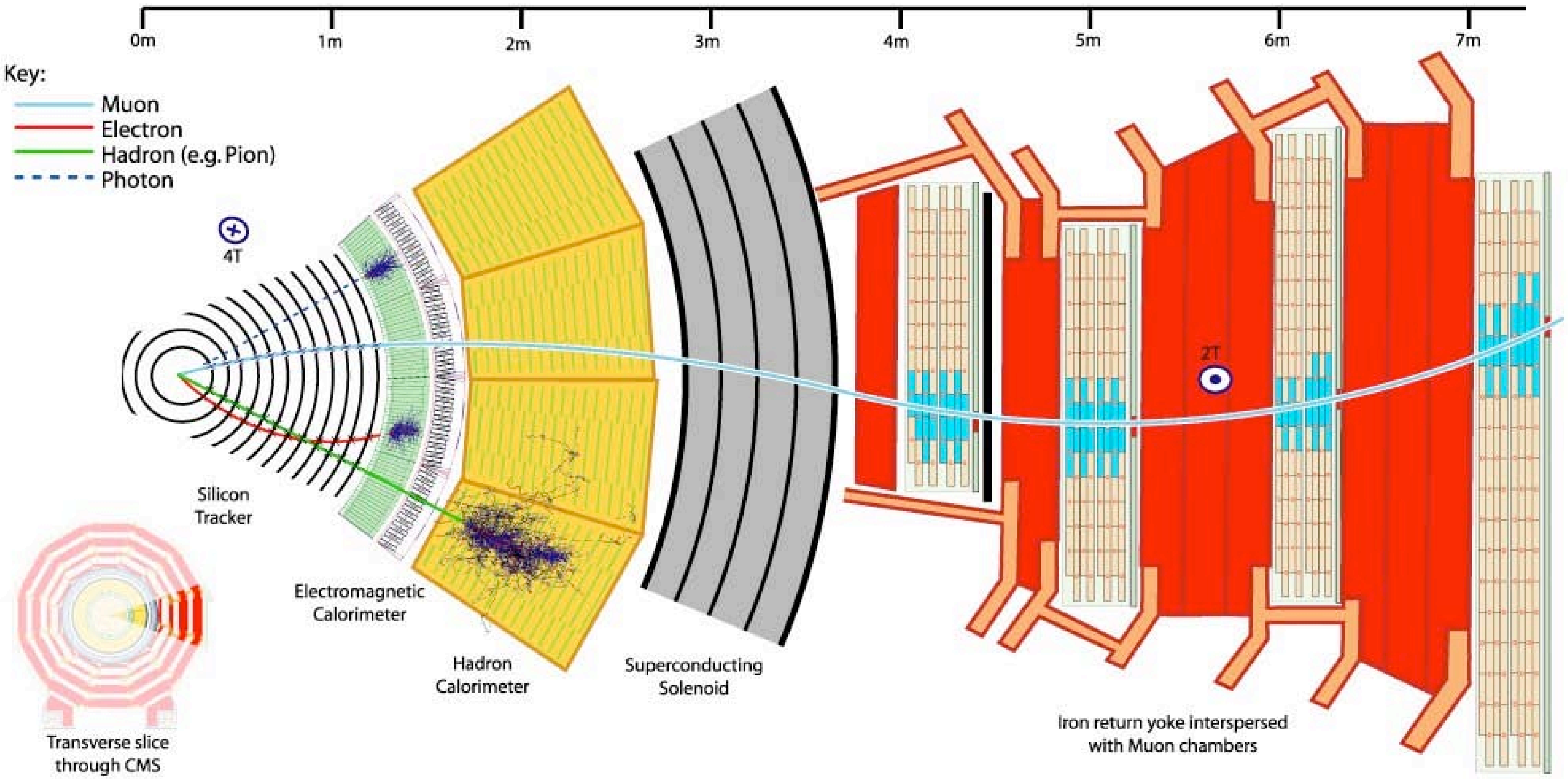
IGUANACMS


OSCAR Visualisation
File View Config Debug Help
ject
Visibilit
Detector
OCMS
CMSE
TRAK
CALO
MUON
BEAM
VCAL
Event
Tracks
High Momentum
Electrons
Muons
Pi+/-
Pi0
Gammas
Other Charged
Other Neutral
All
Low Momentum
Electrons
Muons
Pi+/-
Pi0
Gammas
Other Charged
Other Neutral
Muons with pT over 1: 4 trajectories
ID
Parent ID
Name
Charge
4 0 mu+ 1
3 0 mu- -1
2 0 mu+ 1
1 0 mu- -1
9.0/0.2 fps
Rotx Roty
Dolly
Event #1

Magnetic Field



Muon Reconstruction



Muon Reconstruction

- **Offline and High-Level Trigger**
  - Reconstruction software is designed to work for both, offline and HLT
  - Level-1 Trigger provides “seeds” (Regions of Interest) for HLT
  - Offline reconstruction makes use of complete calibration, alignment, etc.
- **Robust, high quality reconstruction software**
  - Object-Oriented design
  - Use of a common framework
- **Basic concepts:**
  - Reconstruction on demand
  - Regional reconstruction

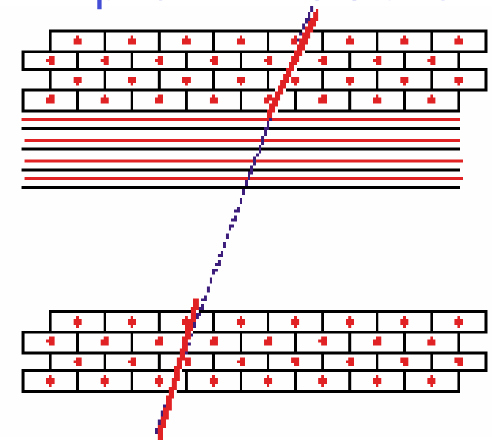
Local Pattern Recognition (I)

DT's and CSC's are multi-layer detectors:

- First step of muon reconstruction is local pattern recognition
- Reconstruct track segments in the DT and CSC detectors

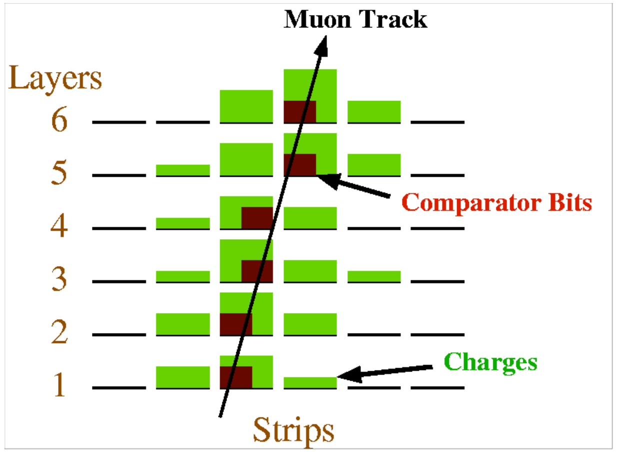
- **Barrel (DT):**
  - Reconstruct position of each channel above threshold using effective drift velocity
  - Reconstruct ϕ super-layer hits (time-space conversion)
    - Drift velocity depends on B field and impact angle
  - Cluster hits (linear fit): 2D segment
  - Fit 2D lines separately in r-ϕ and r-z through the 8+4 layer of chamber
    - L/R ambiguities solved by best χ^2
  - Combine into 3D segments, use segment position and direction for tracking
    - Resolution: 100 μm in ϕ view, direction ~1mrad
  - Apply impact angle correction on time-to-distance relation and refit
  - Calculate position (center of gravity) of the track-segment and its angle in the super-layer (+error matrix)

up to 12 hits/station

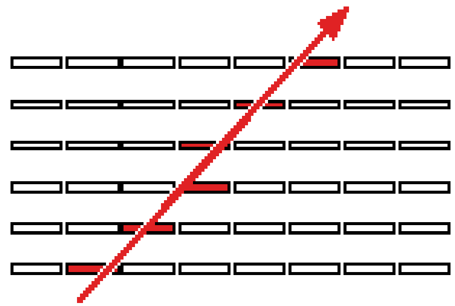


Local Pattern Recognition (II)

- **Endcaps (CSC):**
  - Reconstruct 3D hits
  - Associate hits with linear fit (only one hit per layer)
  - Fit “Gatti” function to the spatial shape of 3-strip charge distribution to determine centroid of cluster in layer
  - Associate two projections by time coincidence
  - Fit 3D segments through the collection of wire and strip clusters in chamber; linear fit
  - Resolution: 120–250 μm form bending coordinate, depending on chamber



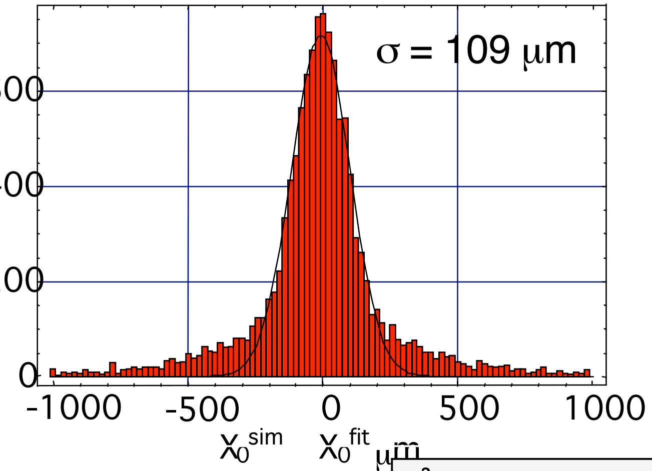
up to 6 hits/station

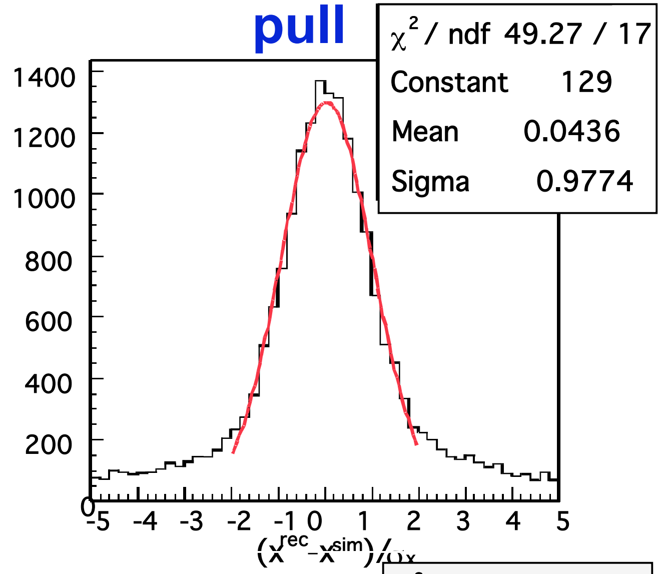


Residuals and Pulls in r-ϕ

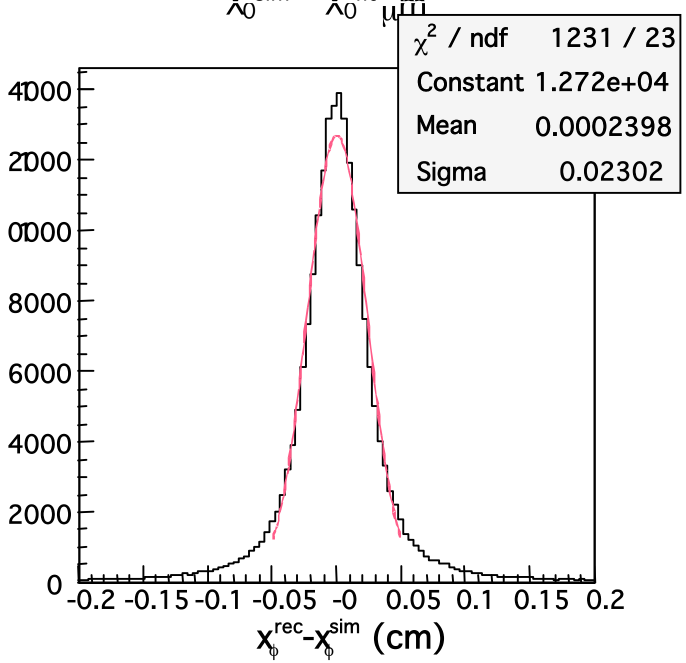
residual | **pull**

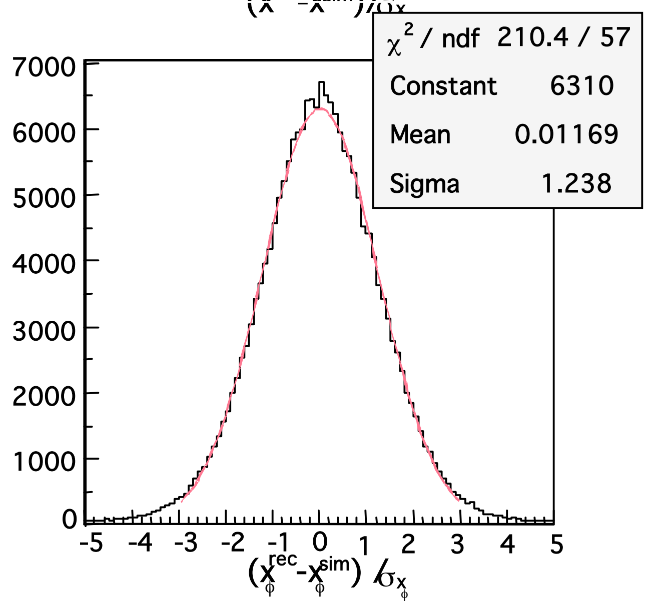
DT





CSC





Standalone Muon Reconstruction

- **All muon detectors (DTBX, CSC and RPC) are used**
- **Seed generation:**
  - **external:** Level-1 trigger (vector at 2nd station) → **Level-2 reconstruction**
  - **internal:** track segments from local pattern recognition
- **Fit:**
  - Kalman filter technique applied to DT/CSC/RPC track segments
  - Use segments in barrel and 3D hits in endcaps
  - Trajectory *building* works from inside out
  - Apply χ^2 cut to reject bad hits
  - Track *fitting* works from outside in
  - Fit track with beam constraint
- **Propagation:**
  - Non constant magnetic field
  - Iron between stations, propagation through iron (more difficult than in tracker!)
  - GEANE used for propagation through iron

Global Muon Reconstruction

Inclusion of Tracker Hits

Start from standalone reconstructed muons:

- **Seed generation**
  - Get muon trajectory at innermost muon station
  - Propagate to outer tracker surface and to interaction point
  - Open window for track reconstruction
    - define *region of interest* through tracker based on L2 track with parameters at vertex
    - fixed/dynamic region
  - Create one or more seeds for each Level-2 muon
- **Construction of trajectories for a given seed**
  - Propagate from innermost layers out, including hits in muon chambers
  - Resolve ambiguities
  - Final fit of trajectories

➢ tremendous gain in resolution

Tracking Strategy

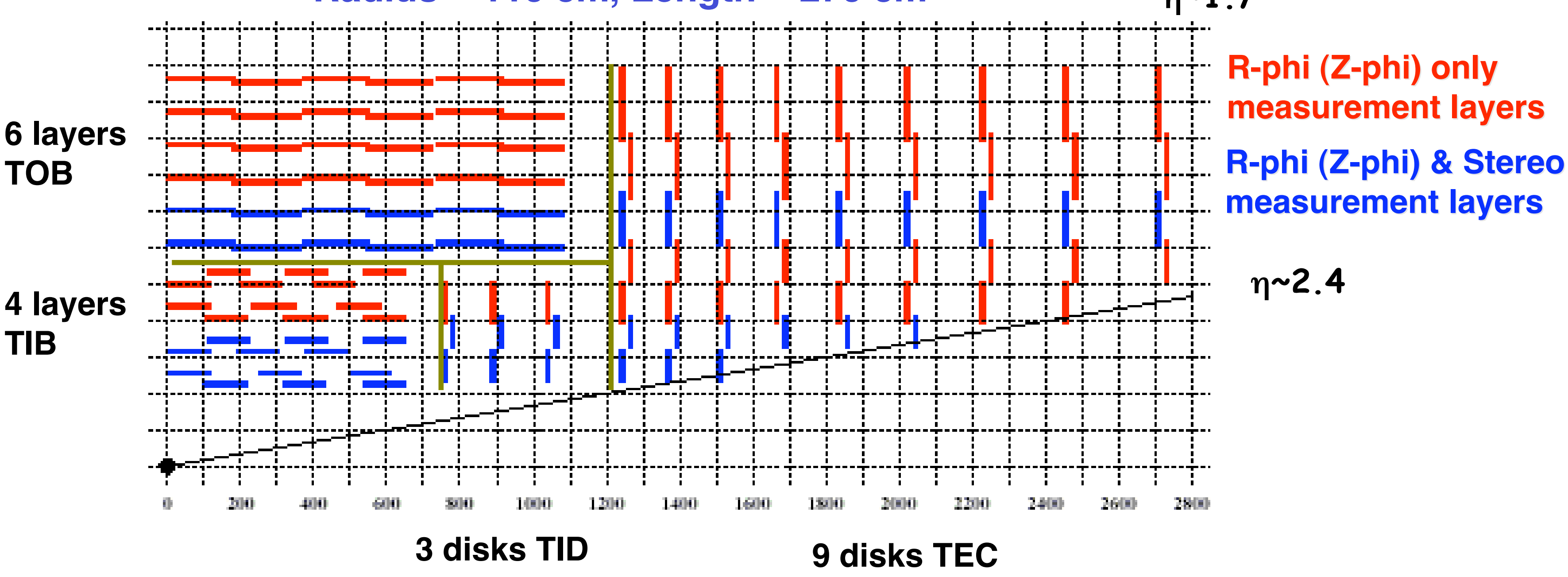
Rely on few measurement layers, each able to provide robust (clean) and precise coordinate determination

2 to 3 Silicon Pixel, and 10 to 14 Silicon Strip Measurement Layers

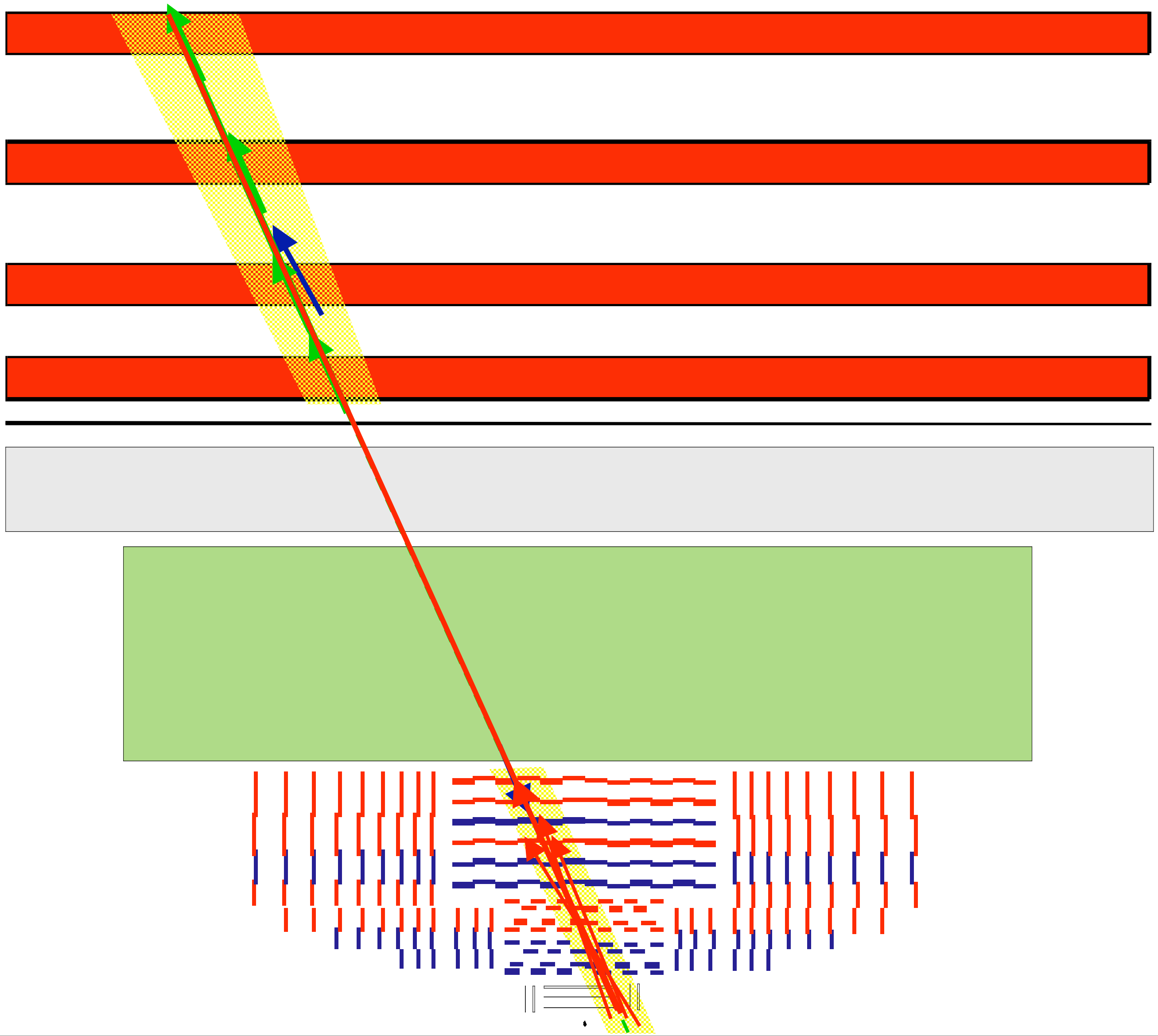
At high luminosity (~ 20 min. bias events every 25 ns):

R	=	10 cm	25 cm	60 cm
$N_{ch}/(cm^2*25ns)$	=	1.0	0.10	0.01

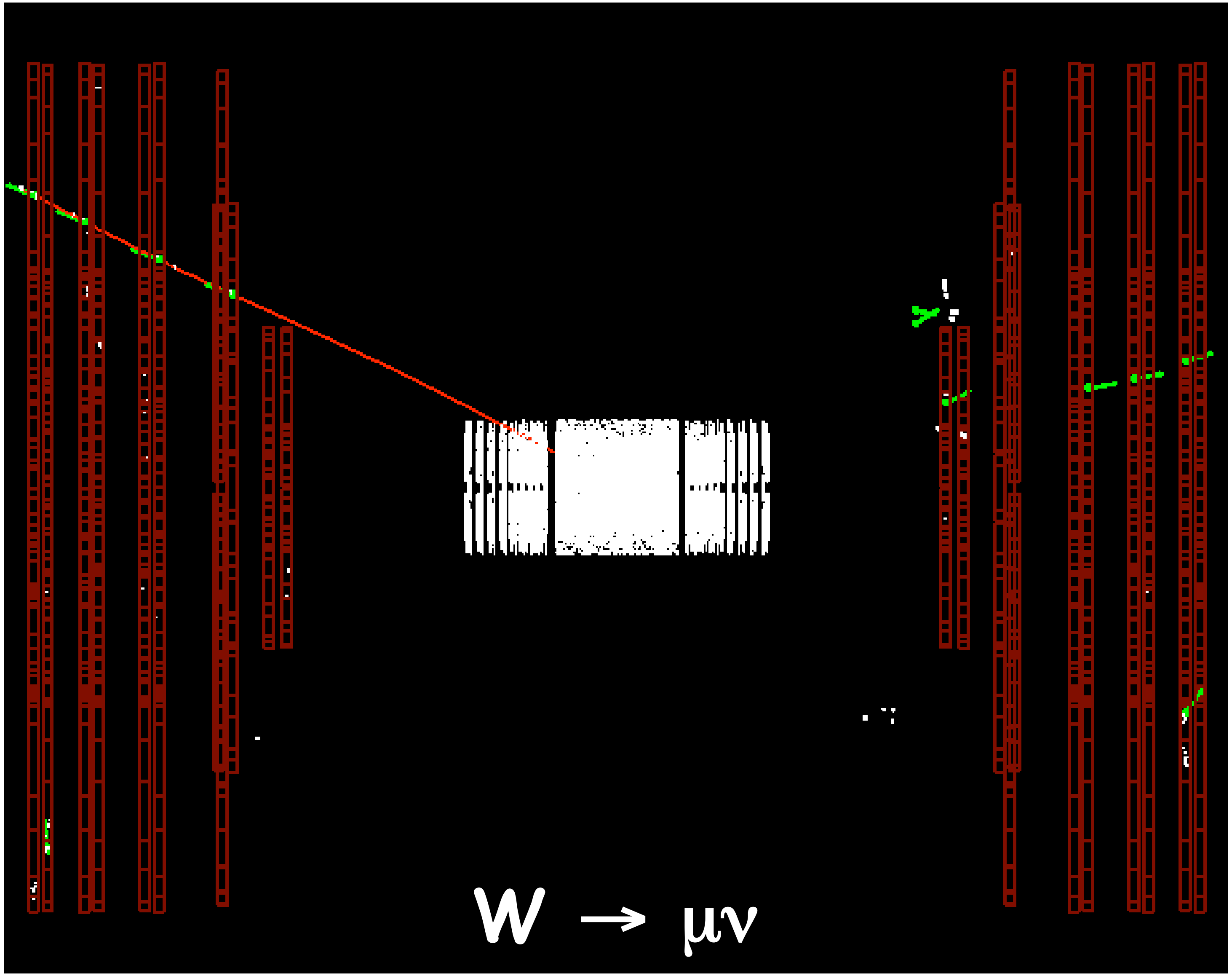
Radius ~ 110 cm, Length ~ 270 cm



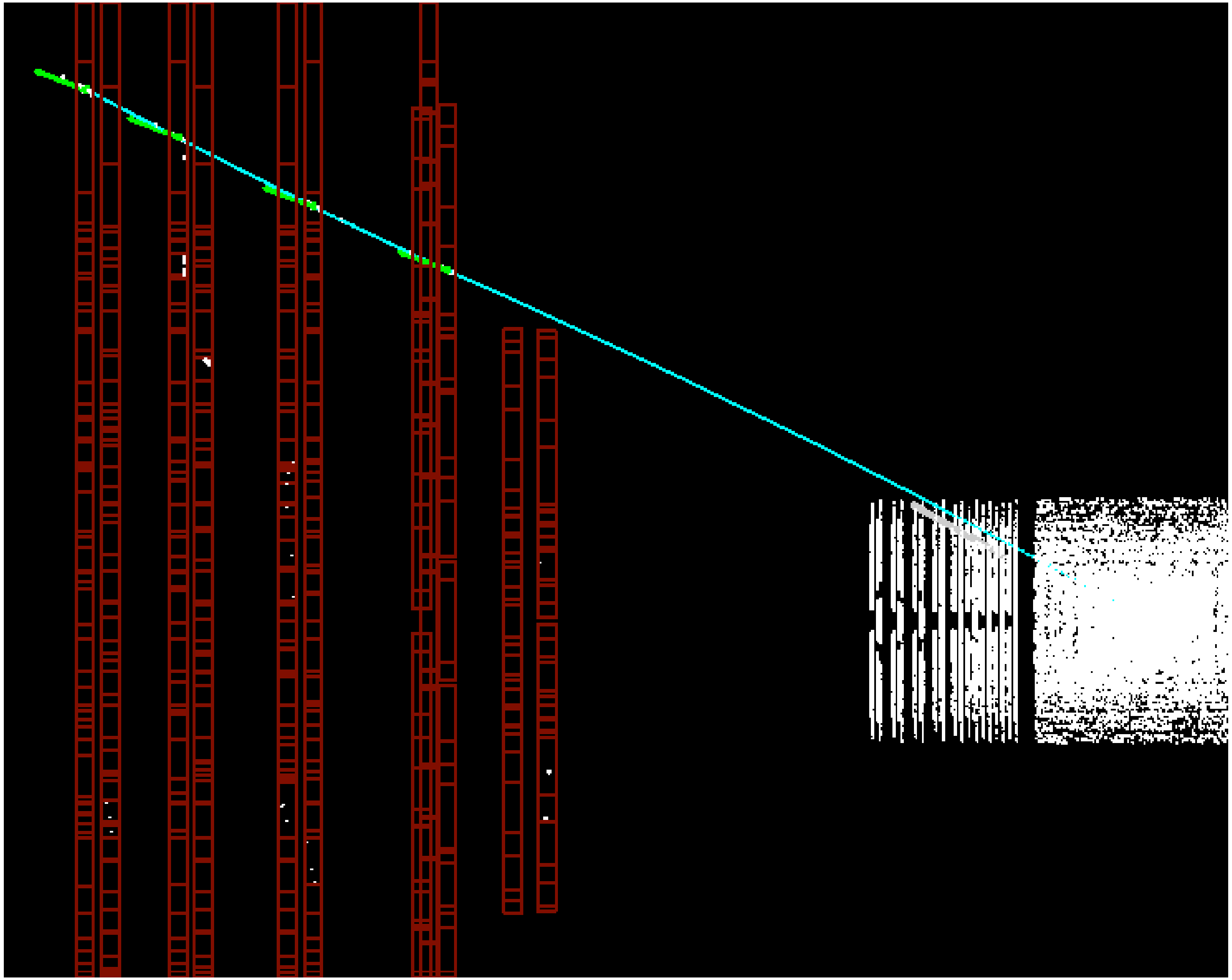
Muon Reconstruction



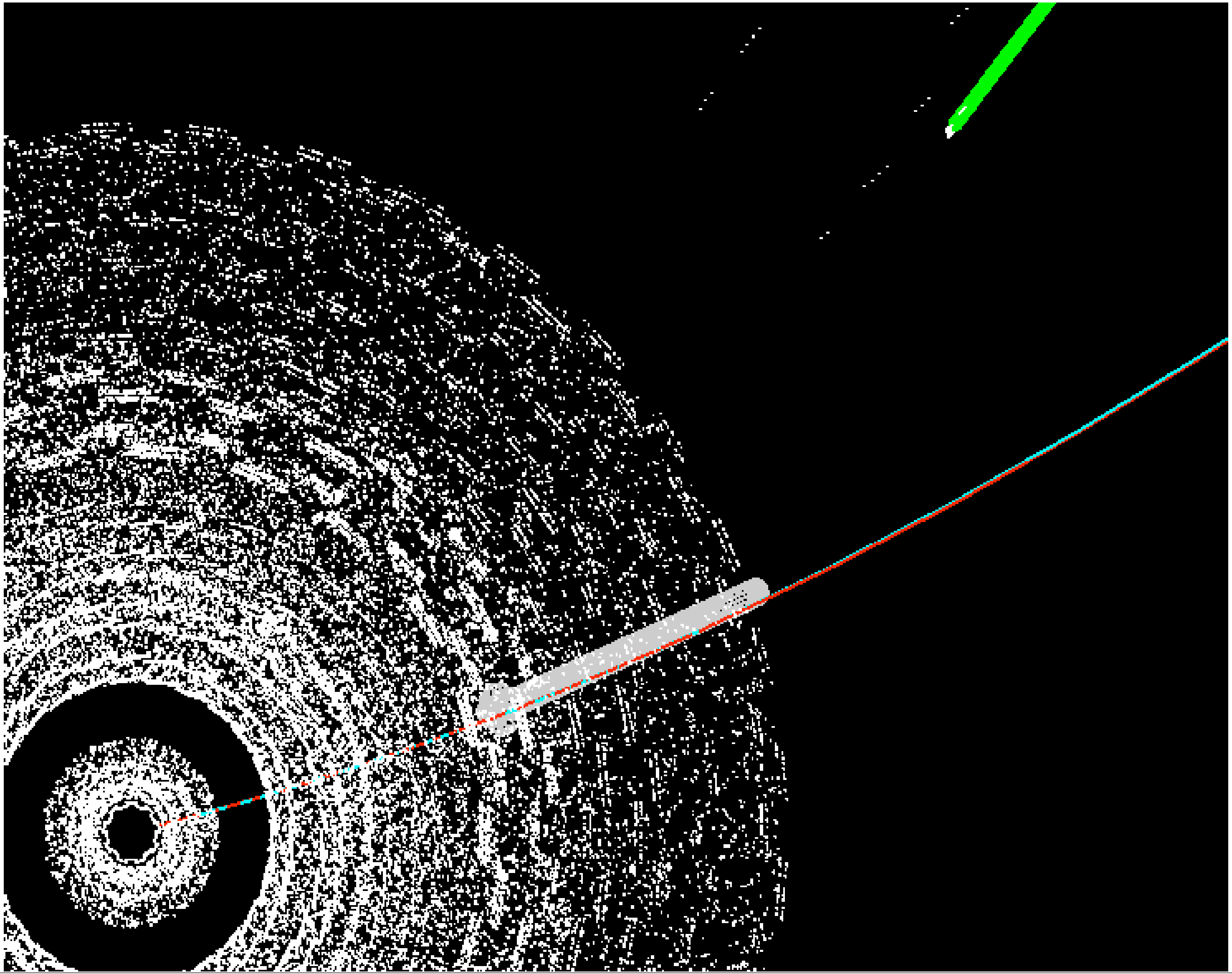
Muon Reconstruction @ high L



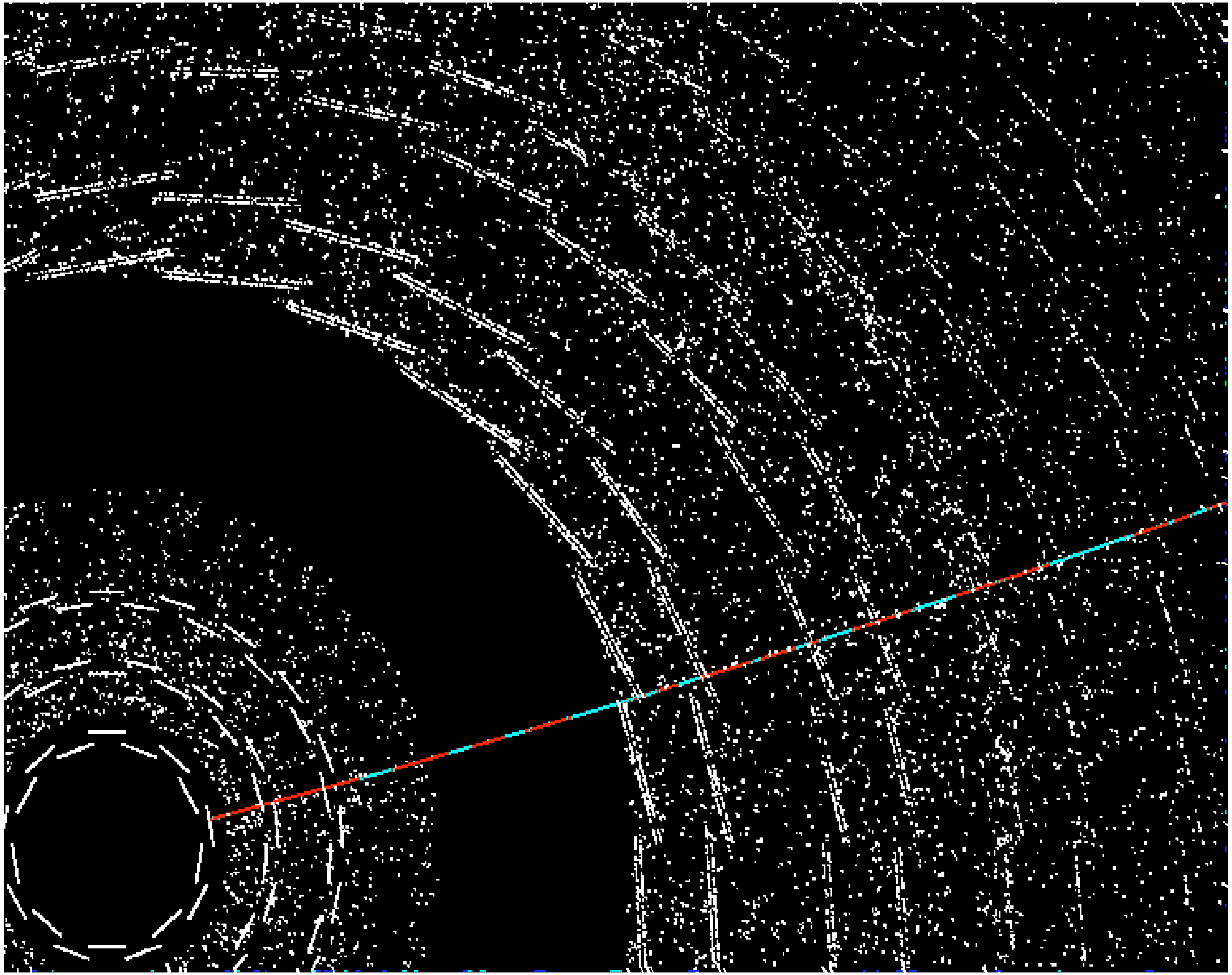
Muon Reconstruction @ high L



Muon Reconstruction @ high L



Muon Reconstruction @ high L

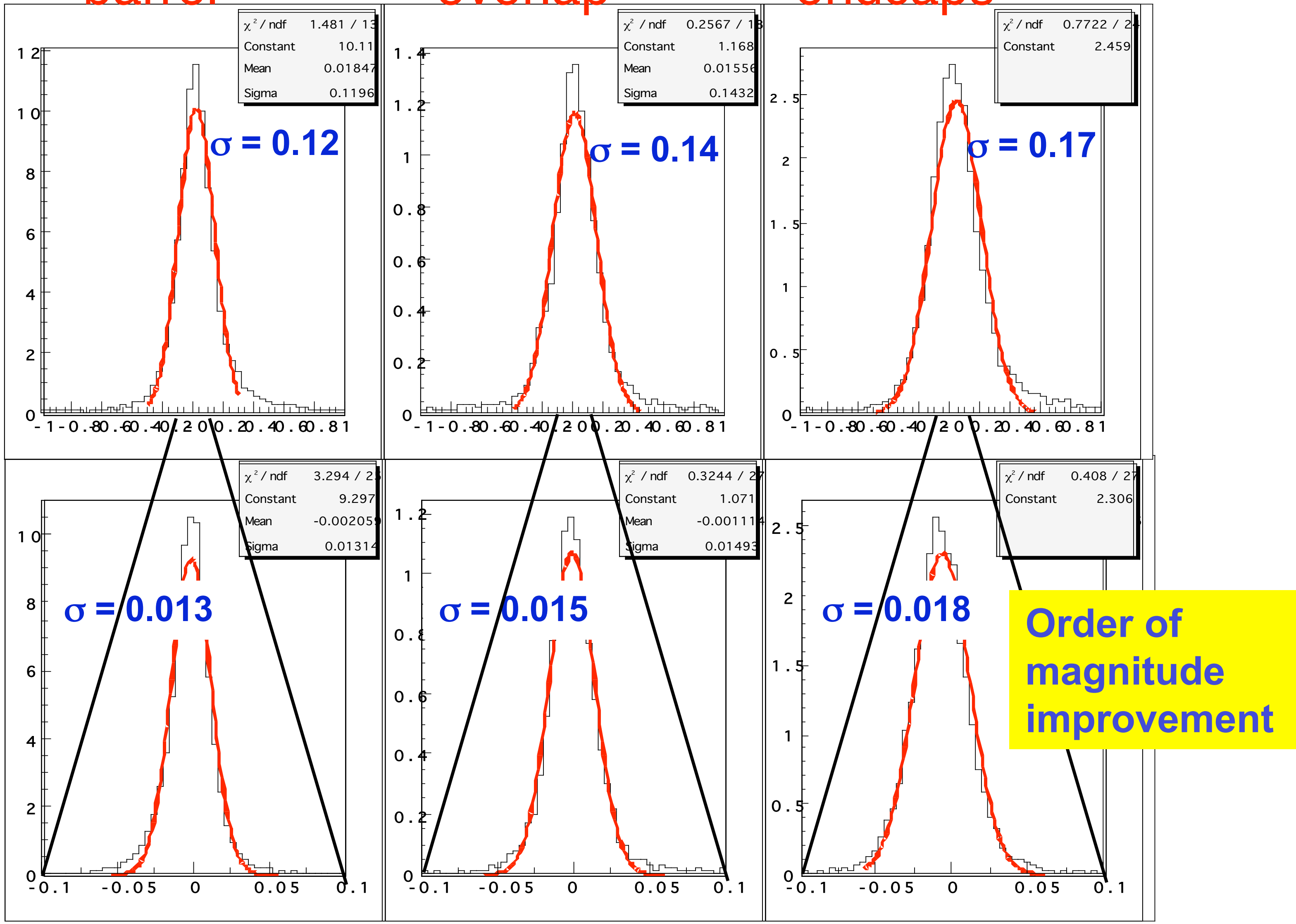


Muon p_T Resolution

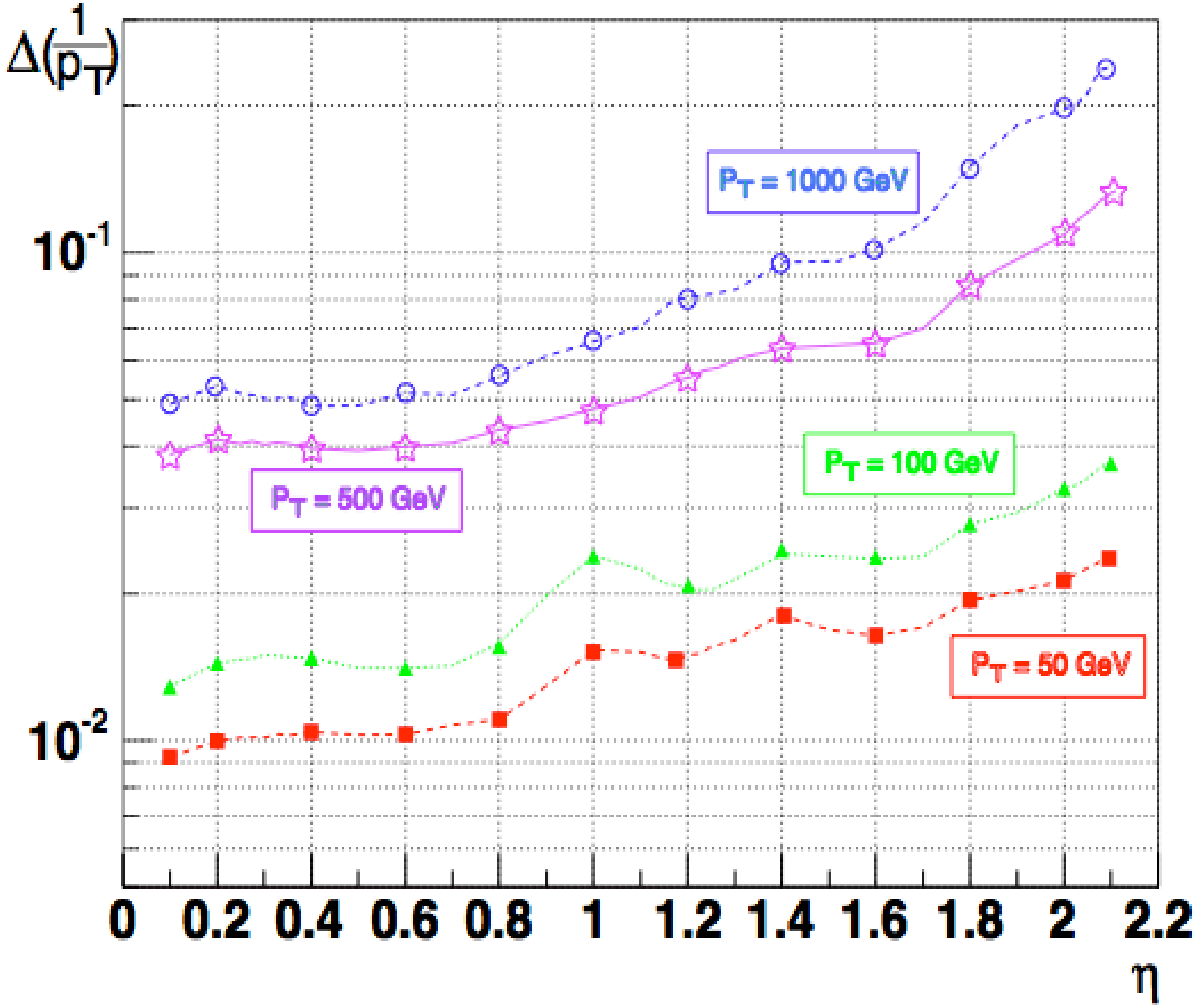
barrel overlap endcaps

Level-2:

Level-3:



Muon p_T Resolution

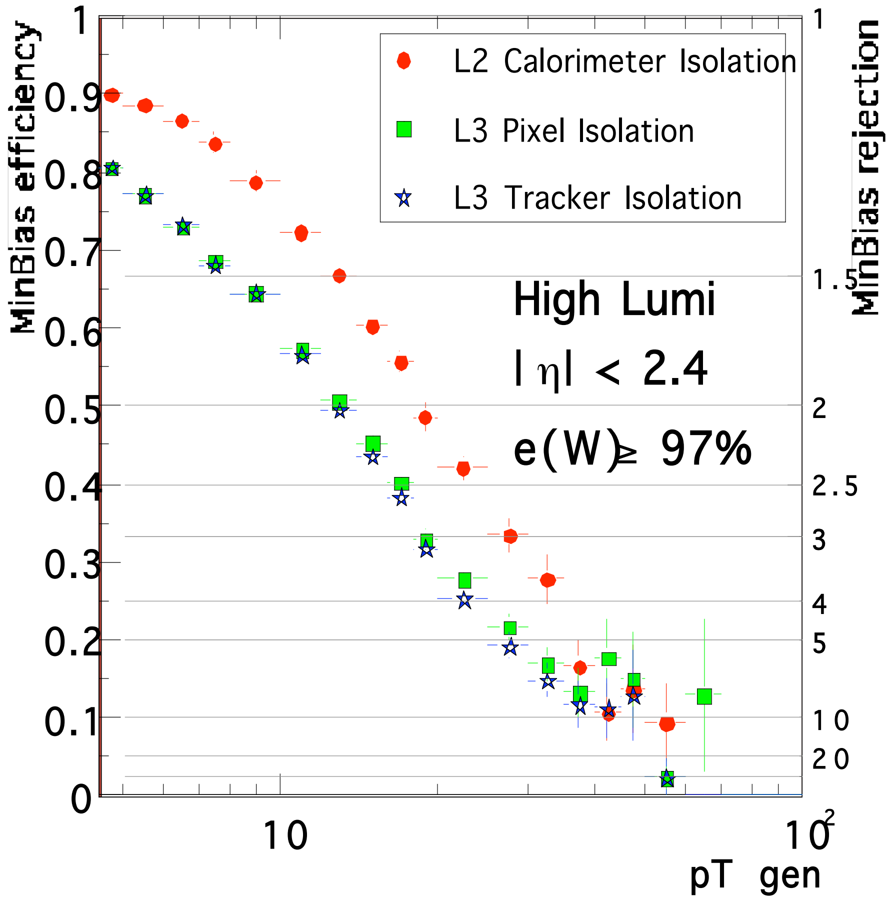


Muon Isolation

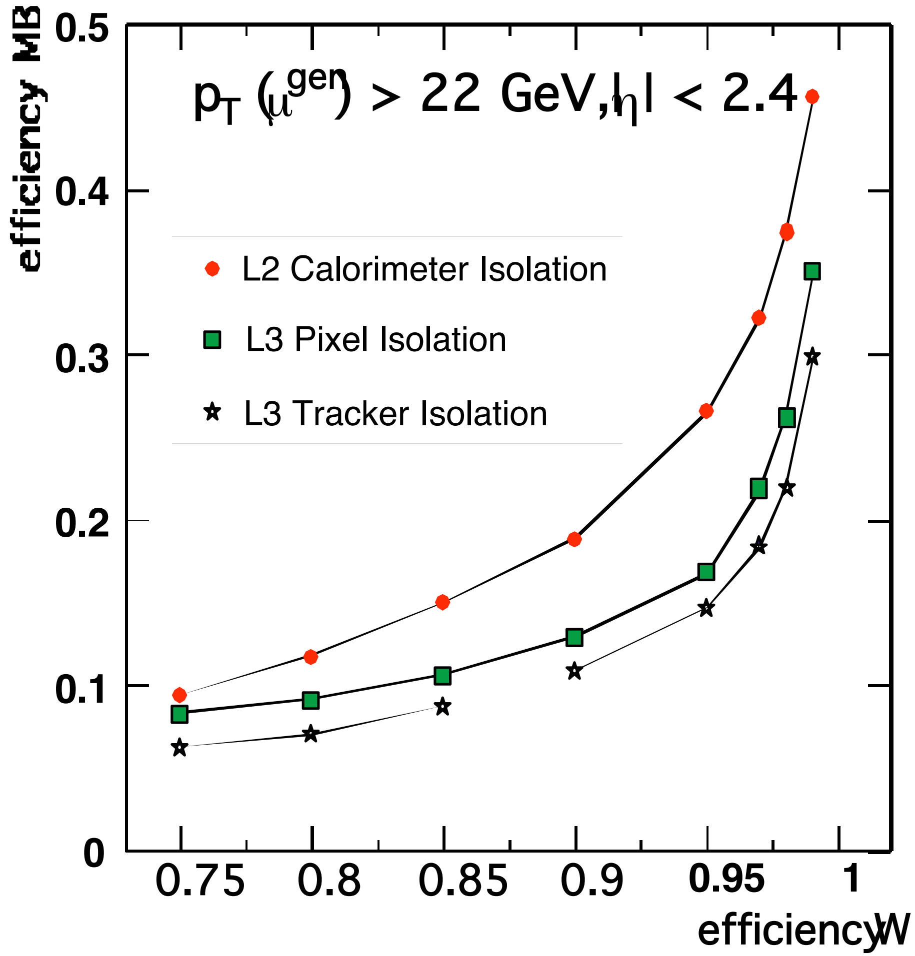
- General framework for isolation
  - Based on ΣE_T or ΣP_T measurements in cones around the muon
  - Cone sizes and thresholds are optimized
    - To get maximal rejection on "reference background" (Minimum Bias muons with P_T above the trigger threshold) for a given nominal efficiency on reference signal ($W \rightarrow \mu\nu$)
    - Optimization provides flat $\varepsilon(\eta)$ on signal by construction
- Calorimeter Isolation
  - ΣE_T from calorimeter towers in a cone around muon (sensitive to pile-up)
- Pixel Isolation
  - ΣP_T of 3-hit tracks in the pixel detector in cone around muon
  - Studies done for full pixel detector (no staging)
  - Requires that contributing tracks come from the same primary vertex as the Level-3 muon (to reduce pile-up contamination)
- Tracker Isolation
  - ΣP_T of tracks in the tracker (regional reconstruction around Level-3 muon)

Isolation Performance

Efficiency on minbias events as a function of P_T^{gen} for 97% efficiency on signal

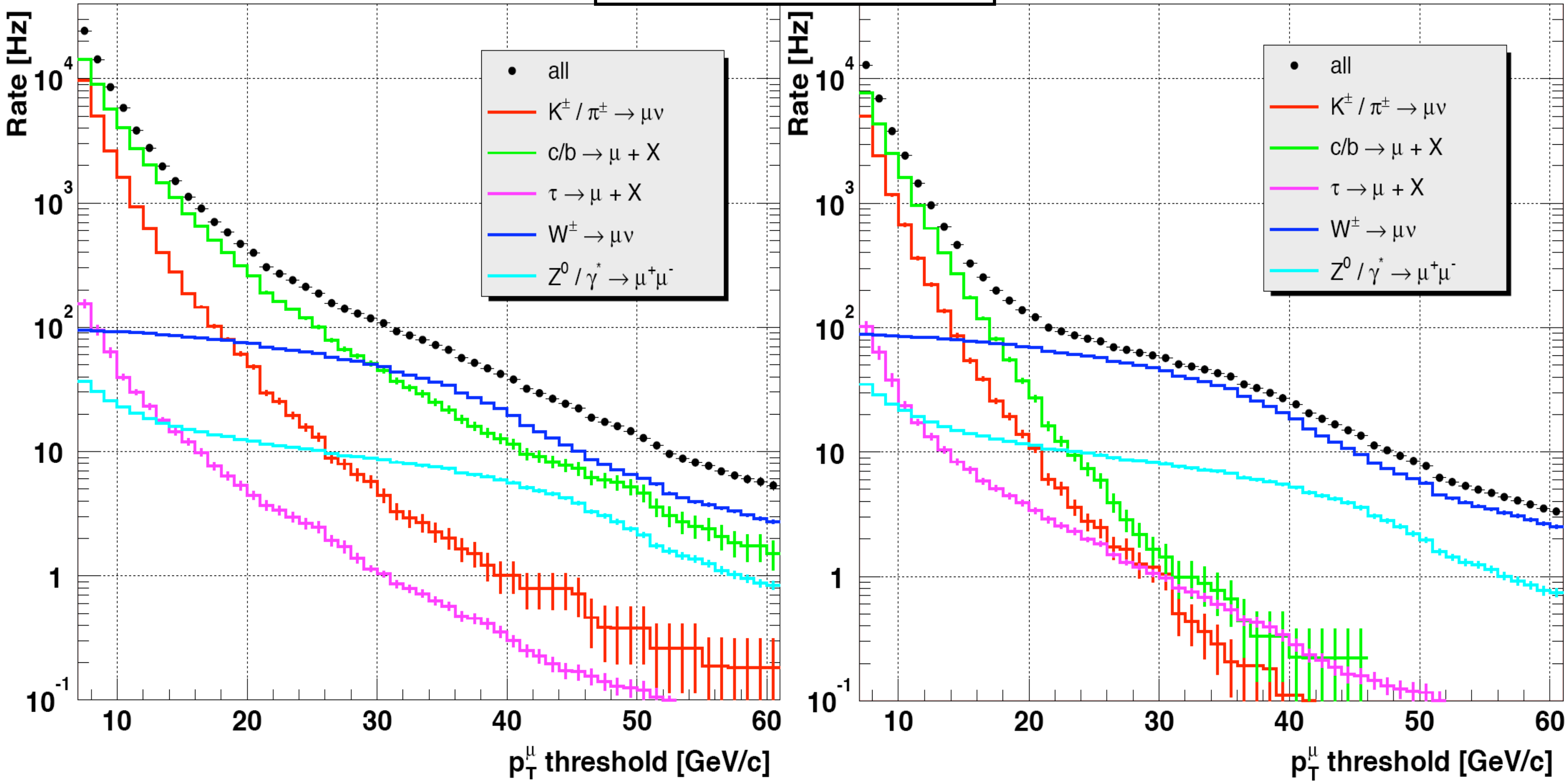


Efficiency on minbias events as a function of efficiency on W signal



Physics Content after Level-3

before isolation $L = 10^{34}\ cm^{-2}s^{-1}$ after isolation

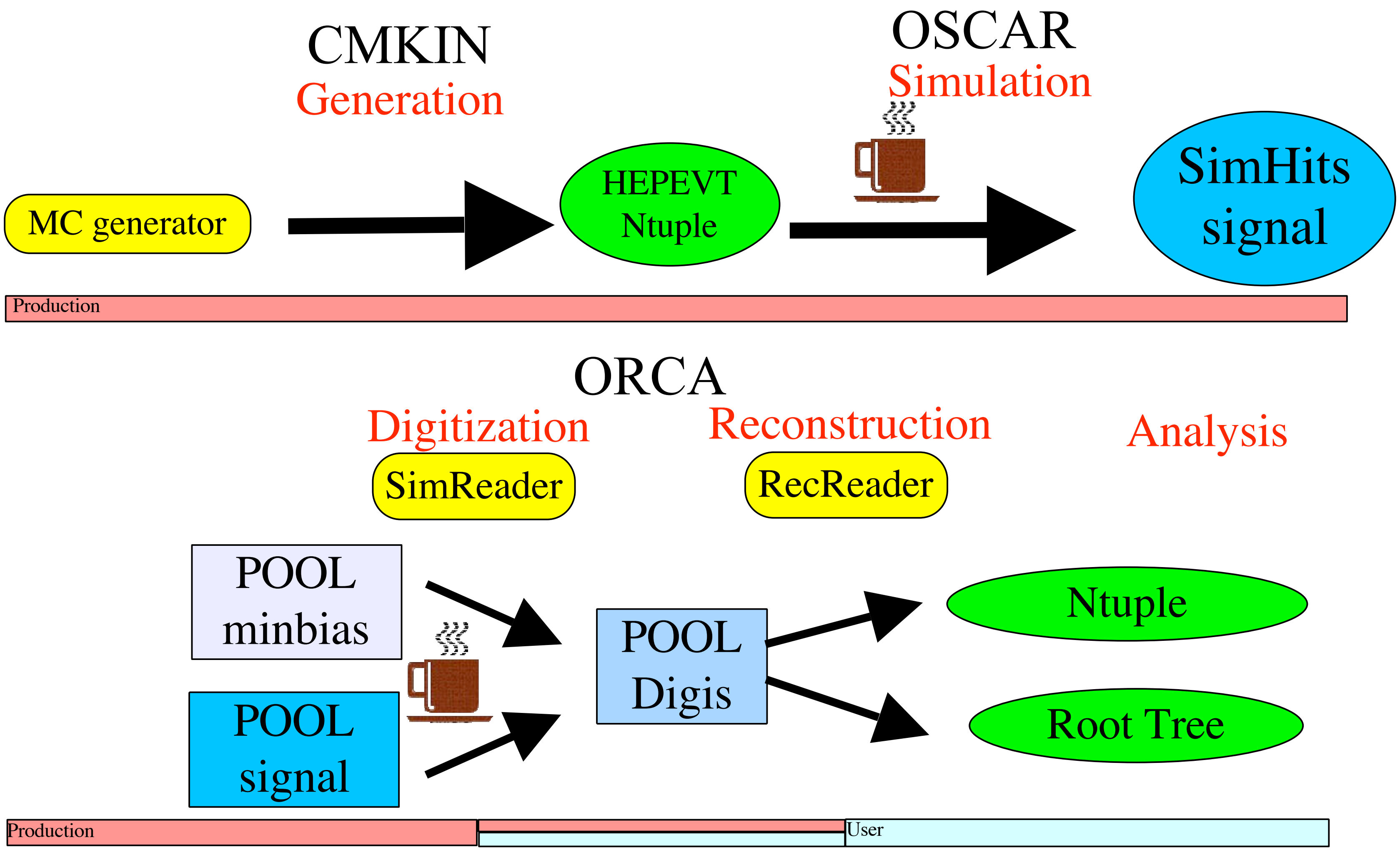


π/K/b/c strongly suppressed → dominated by W rate

Analysis

- Analysis is an iterative process:
  - Reduce data samples to more interesting subsets (selection)
  - Compute higher level information
  - Calculate statistical entities
- Several steps:
  - Run analysis job on full dataset (few times)
    - Read reconstructed objects and fill ROOT Tree
    - Save your intermediate analysis objects in the DB
    - Share them with your colleagues
  - Use interactive analysis tool to run several times on reduced dataset and make plots
- Only one part of the work can be done (*today*) with an interactive analysis tool

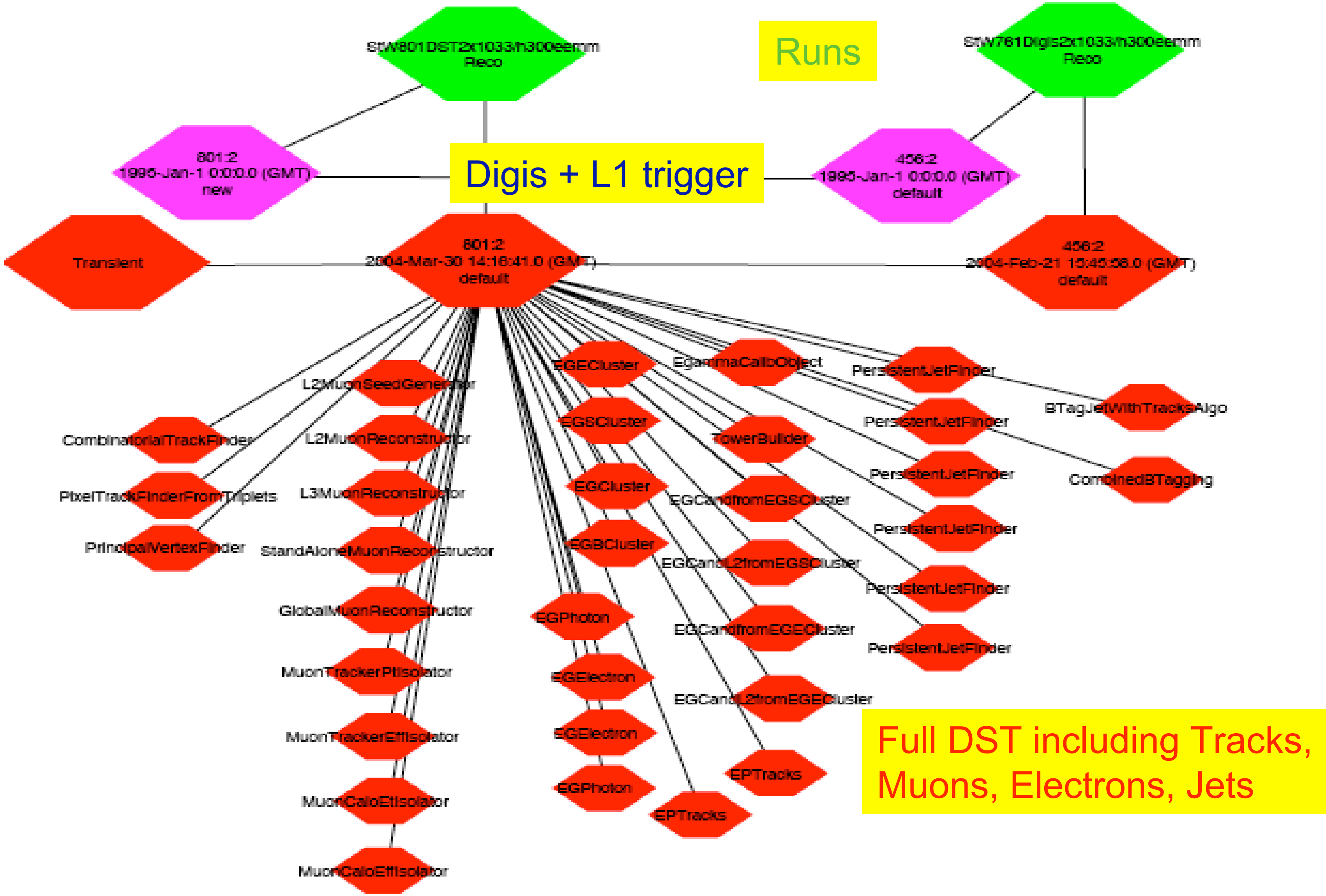
The Analysis Chain



DST

- We stored already
  - MCinfo: MC generator, SimTrack, SimVertex
  - SimHits: subdetector specific
  - Digis & Associations
- Add Level-1 Trigger info and RecHits (Calorimeter)
- DST: Store a complete record of all objects created during reconstruction (organized in collections)
- DST contains collections of reconstructed objects
  - Tracker tracks, Muons, Electrons, Jets, etc.
  - In total about 50 different RecCollections
  - Selection of what to store via orcarc

DST


StW801DST2x1033/h300eemm
Reco
Runs
StW761Digis2x1033/h300eemm
Reco
801:2
1995-Jan-1 0:0:0.0 (GMT)
new
Digis + L1 trigger
456:2
1995-Jan-1 0:0:0.0 (GMT)
default
Transient
801:2
2004-Mar-30 14:16:41.0 (GMT)
default
456:2
2004-Feb-21 15:45:58.0 (GMT)
default
EGECluster
EgammaCaloObject
PersistentJetFinder
L2MuonSeedGenerator
BTagJetWithTracksAlgo
EGSCluster
PersistentJetFinder
CombinatorialTrackFinder
L2MuonReconstructor
TowerBuilder
PersistentJetFinder
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PrincipalVertexFinder
StandAloneMuonReconstructor
EGBCluster
EGCandL2fromEGSCluster
PersistentJetFinder
GlobalMuonReconstructor
EGPhoton
EGCandfromEGECluster
PersistentJetFinder
MuonTrackerPtIsolator
EGElectron
EGCandL2fromEGECluster
MuonTrackerEtIsolator
EGElectron
EPTracks
Full DST including Tracks, Muons, Electrons, Jets
MuonCaloEtIsolator
EGPhoton
EPTracks
MuonCaloEtIsolator

DST Contents

- **DSTs contain reconstructed objects for"users"**

HLT info
Level-1 Trigger

CombinatorialTrackFinder
CombinedBTagging
PixelTrackFinderFromTriplets
PrincipalVertexFinder

EGCandL2
EGBCluster/SECluster/Cluster
EGHLTelectron/photon
EGTracks
EGcalibration
EGofflineCandidates
EGofflineElectron/Photon

METfromCaloRecHits/EPHTowers
METfromIterConeJets/KtJets
RecJet-Itercone0.5/0.7
RecJet-Ktrecom1/4
TowerBuilder

StandAloneMuonReconstructor
GlobalMuonReconstructor
L2MuonReconstructor
L3MuonReconstructor
MuonCaloEffIsolator
MuonCaloEtIsolator
MuonTkEffIsolator
MuonTkPtIsolator

Persistent Muon

- **Persistent Track data:**
  - First and last Trajectory State
  - Track quality criteria
    - Chi^2
    - Number of degrees of freedom
    - Number of hits used in the fit
    - Number of “lost” hits
  - Individual RecHits used in muon fit (possible to refit track!)
- **Persistent RecMuon data:**
  - innermost and outermost Trajectory State
  - Vertex extrapolated State (stateAtIP, stateAtVertex)
  - Track quality
  - TrajectoryState persistency as for Tracker
  - TRecRef<TTrack> muonTrack
  - TRecRef<TTrack> trackerTrack

Muon Reconstruction

- **For the time being we have four different muon reconstruction algorithms implemented:**
  - StandAloneMuonReconstructor
  - GlobalMuonReconstructor
  - L2MuonReconstructor
  - L3MuonReconstructor
- **All four algorithms are RecAlgorithm<RecMuon>**
  - inheriting from RecAlgorithm<T>
- **RecMuon inherits from TTrack (RecObj)**
- Easy access to reconstructed muons

```
RecQuery q("<Name of Reconstructor>");
RecCollection<RecMuon> theCollection(q);
for (RecCollection<RecMuon>::const_iterator
      it = theCollection.begin(); it != theCollection.end(); ++it)
cout << "RecMuon: " << (**it) << endl;
```

Muon Isolation

- **Output again a RecMuon, but with isolation info filled**
- **float RecMuon::isolation()**
- **Several isolation algorithms are available**
  - **L2MuonCaloIsolator** for HLT: uses calo
  - **L3MuonTrackerIsolator** for HLT: uses Tracker
  - **MuonCaloEtIsolator** for offline: return ΣE_T
  - **MuonCaloEffIsolator** return discriminating parameter [0,1]
  - **MuonTrackerPtIsolator** return the Σp_T
  - **MuonTrackerEffIsolator** as above

Summary

- **CMS Software**
  - Simulation, reconstruction, analysis, visualization
- **Muon reconstruction**
  - Local: pattern recognition
  - Regional: standalone muon reconstruction
  - Global: Muon system + tracker
  - Same base software for offline and HLT
- **Analysis**
  - Read DST
  - Use interactive analysis tool (ROOT)