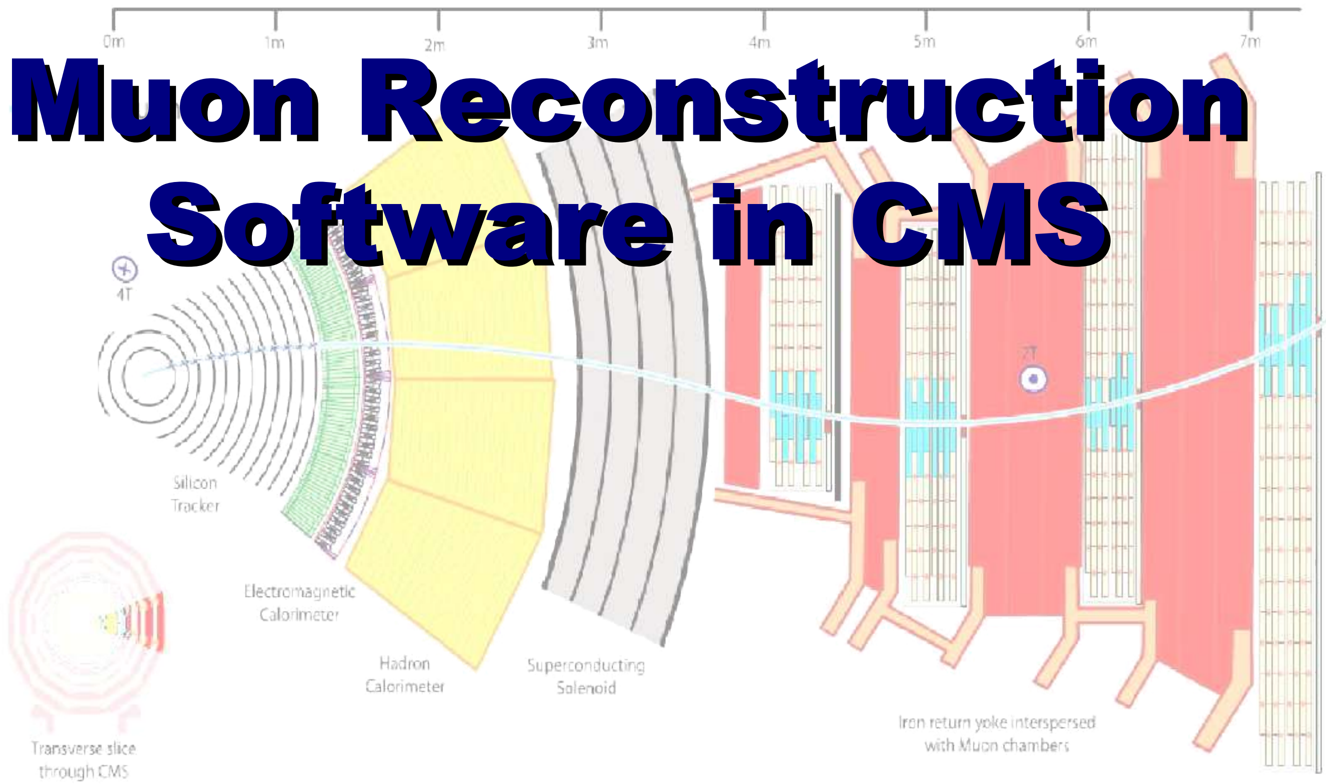
Frontier Science 2005

Muon Reconstruction Software in CMS



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Overview

- The Compact Muon Solenoid experiment:
  - muon system
  - trigger design
- Muon reconstruction software
  - HLT design (Level-2 and Level-3 trigger)
  - Local Reconstruction in DTs, CSCs and RPCs
  - Track reconstruction
    - Level-2 (standalone) reconstruction
    - Level-3 (global) reconstruction
- Performance
  - efficiency
  - resolution
- Summary

The CMS Muon System

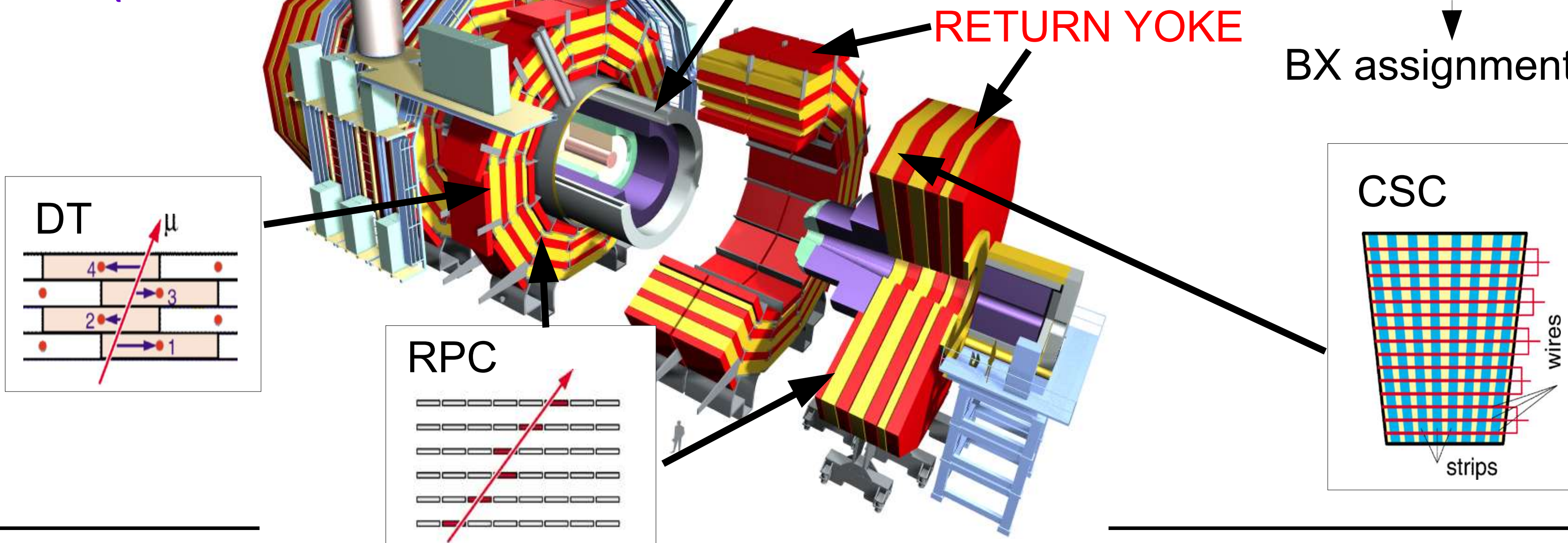
Three types of muon gas detectors with trigger capabilities:

- Drift Tubes (DT) in the central barrel region ($|\eta| < 1.2$)
  - $\sigma_x \approx 200\mu m$ / layer
- Cathode Strip Chambers (CSC) in the endcaps ($|\eta| < 2.4$)
  - $\sigma_x \approx 100 – 240\mu m$ / layer

] precise position measurement → p_T resolution

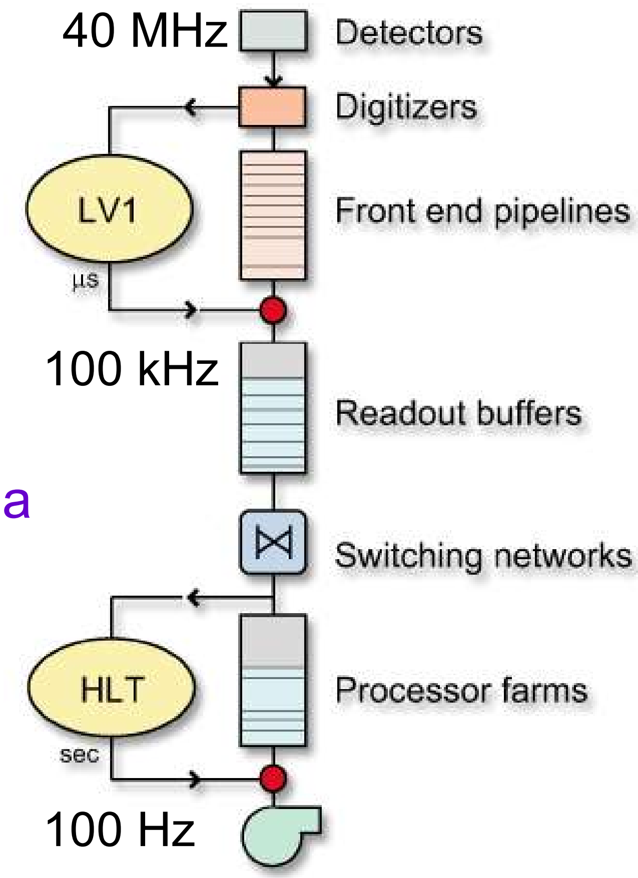
- Resistive Plate Chambers (RPC) both in barrel and endcaps
  - $\sigma_t \approx 2$ ns

good time resolution → BX assignment



CMS Trigger Design

- Innovative (No Level-2 dedicated hardware) multilevel trigger design:
  - Level-1 Trigger: implemented on dedicated hardware
    - Calorimeter and muon data (coarse granularity)
    - Dedicated hardware → minimum dead time
      - Input from detector: 40 MHz
      - Output to DAQ: ~100 kHz
  - High Level Trigger (HLT): software running on a farm of commercial processors
    - Uses as much as possible “off-line quality” data
      - Output: max rate for storage O(100) Hz
        1 event ~ 1MB



General selection tool: p_T thresholds on particles

μ Reconstruction Software

- Almost same algorithms for HLT and off-line reconstruction

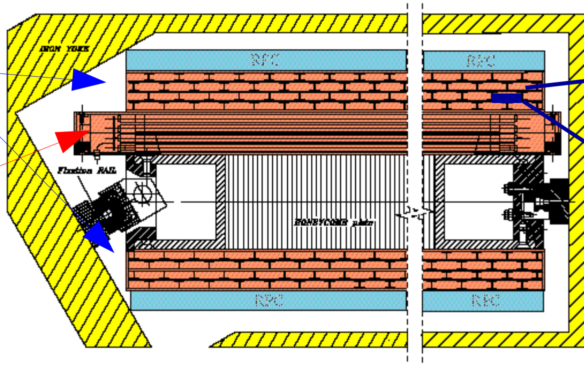
- HLT muon reconstruction performed in two logical steps (goal: reject events as soon as possible):
  - Level-2: uses the muon system data only
  - Level-3: uses data from muon system + tracker hits

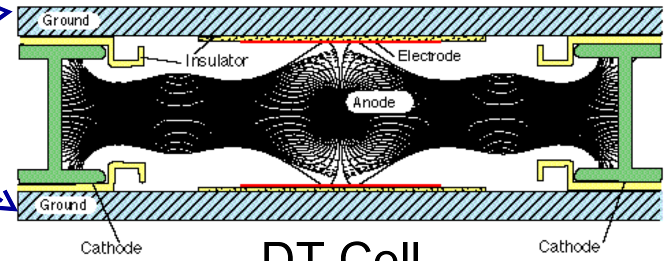
- Track reconstruction using Kalman Filter
  - off-line vs HLT → different seeds for Kalman Filter and access to calibration data
  - Base ingredients for reconstruction:
    - objects locally reconstructed in the detectors (RecHits)
    - reconstruction "on demand" in a *region of interest* defined from the track extrapolation

Local Reconstruction in the DTs

2 r-Φ superlayers

1 r-z superlayer



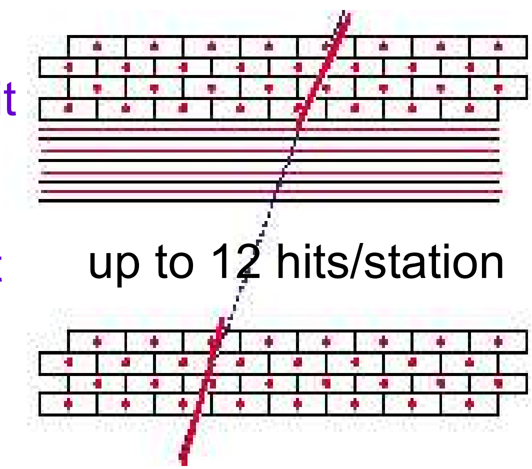


DT Cell

- Hit position in the cell estimated from TDC measurement
  - time-to-distance relation within the cell parametrized with GARFIELD:

$$x(t) = f(t, \theta, B_{wire}, B_{norm})$$

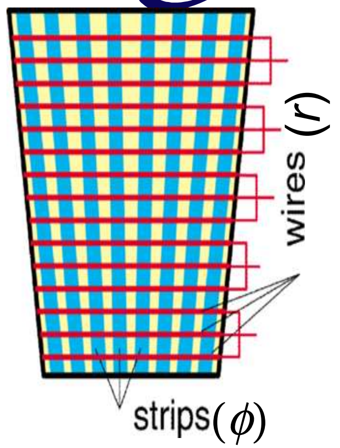
- Fit 2D segments separately in r-Φ (8 layers) and r-z SLs (4 layers)
  - L/R ambiguities solved by best χ^2
  - Update x(t) using information on impact angle θ and refit
- Combine r-Φ and r-z 2D segments in a 3D segment
  - Update x(t) using best knowledge on B_{wire}, B_{norm} and refit
  - Resolution in r-Φ plane: position ~ 100 µm, direction ~1mrad

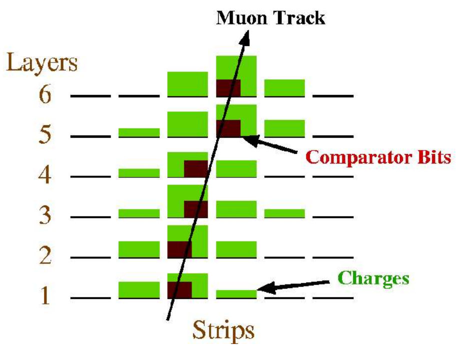


up to 12 hits/station

Local Reconstruction in the CSCs and RPCs

- Cathode Strip Chambers:
  - ϕ coordinate measured by strips
    - charge distribution on a cluster of adjacent strips fitted with “Gatti” function to determine the centroid
  - r coordinate measured by wires
    - read out in bunches to limit number of channels → limited precision
  - Use the measured points to fit a 3D linear segment
    - Resolution: 120 – 250 μm for the bending coordinate

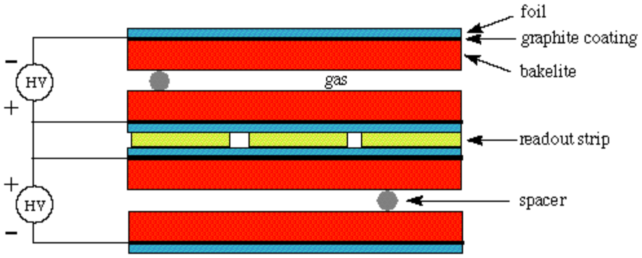




up to 6 hit/station

- Resistive Plate Chambers:
  - Measure 3D points clustering the strips:
    - up to 6 points in the barrel and 4 in the endcaps
    - Uncertainties: L / √12

L_Φ ~ O(1 cm) and L_z ~O(100 cm)



Track Reconstruction

- Track reconstruction with a Kalman Filter
  - recursive method to fit a discrete set of data independently of the number of measurements available
  - determine a generic state vector (= position and momentum + covariance matrix)

- Kalman Filter → initial seed:
  - HLT reconstruction: seeded by L1-trigger candidates (*external* seeding: faster)
    - 4 best muons from the Global Trigger:
      - p_T, position, angle, BX and quality
      - L1 p_T resolution: 17 – 22 % depending on η.
      - Efficiency: ~ 97 %
  - Off-line reconstruction: seeded by local segment reconstruction (*internal* seeding: no dependency on L1)

Level-2 Reconstruction (Standalone)

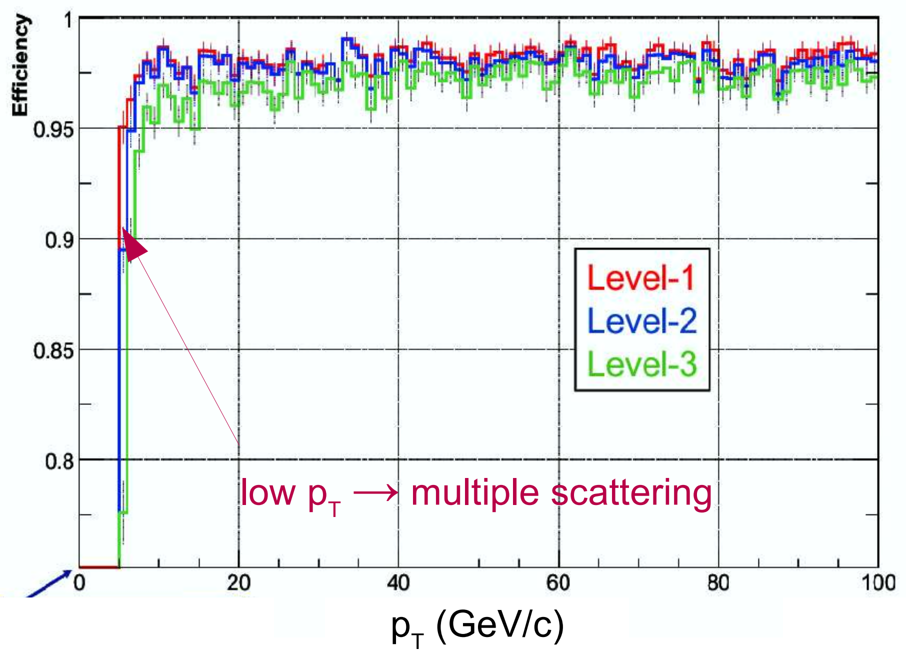
- Initial state extrapolated from track seed
- Hits to be included in the fit are looked for iteratively inside-out, at each step:
  - extrapolate the trajectory to next layer of chambers
  - perform local reconstruction in the chambers on the path
  - if RecHits are compatible (χ^2 test) update the state vector using the Kalman filter
    - DTs: 3D segments are used for the fit
    - CSCs, RPCs: 3D hits are used (inhomogeneous magnetic field)
- The obtained state (at the last station) is used to perform the actual fit going outside-in.
  - Final estimate at the innermost muon station
- Trajectory cleaning, ghosts suppression and "smoothing"
- Vertex extrapolation and constraint
  - Extrapolate the track to the point of closest approach to the beam including the nominal interaction point with its spread (σ = 20 μm) in the fit

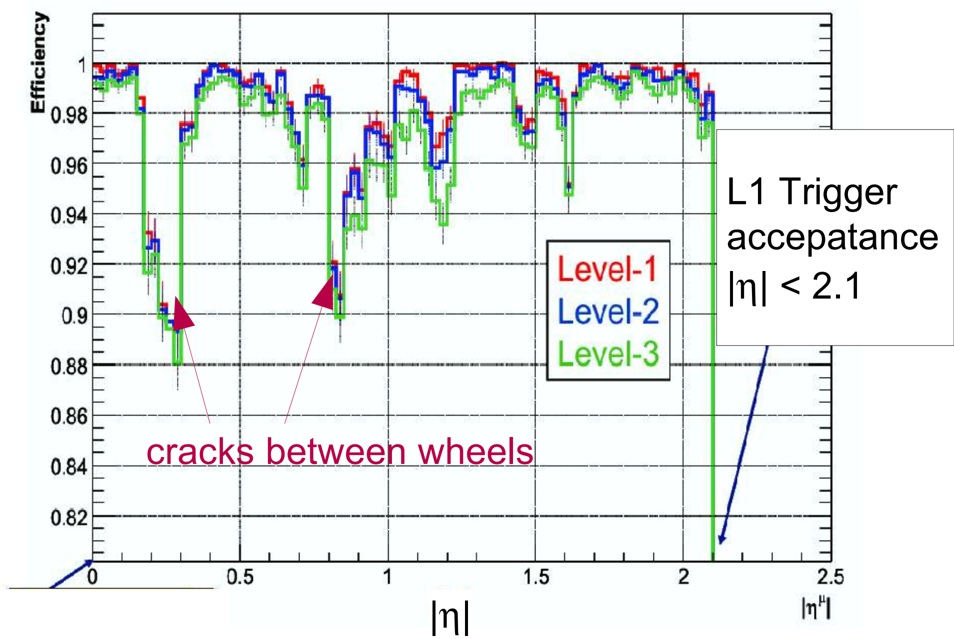
Level-3 Reconstruction (Global)

- Start defining a Region of Interest (ROI) in the tracker using standalone (Level-2) track (with vertex constraint)
  - efficiency and performance crucially depend on Level-2 reconstruction
- Regional reconstruction performed in the ROI
  - Seeds generated from pixels or double sided μ-strip detectors + vertex constraint
  - Again Kalman filter (inside-out)
    - up to 30 tracks grown in parallel
    - tracks are discarded if no hit in more than 4 consecutive layers
  - Trajectories which share more than half of the hits are selected on the basis of their χ^2.
- Tracks are fitted using also “standalone” reconstructed muons in the spectrometer.
- Great improvement in resolution with respect to “standalone” reconstruction

HLT Performance: Efficiency

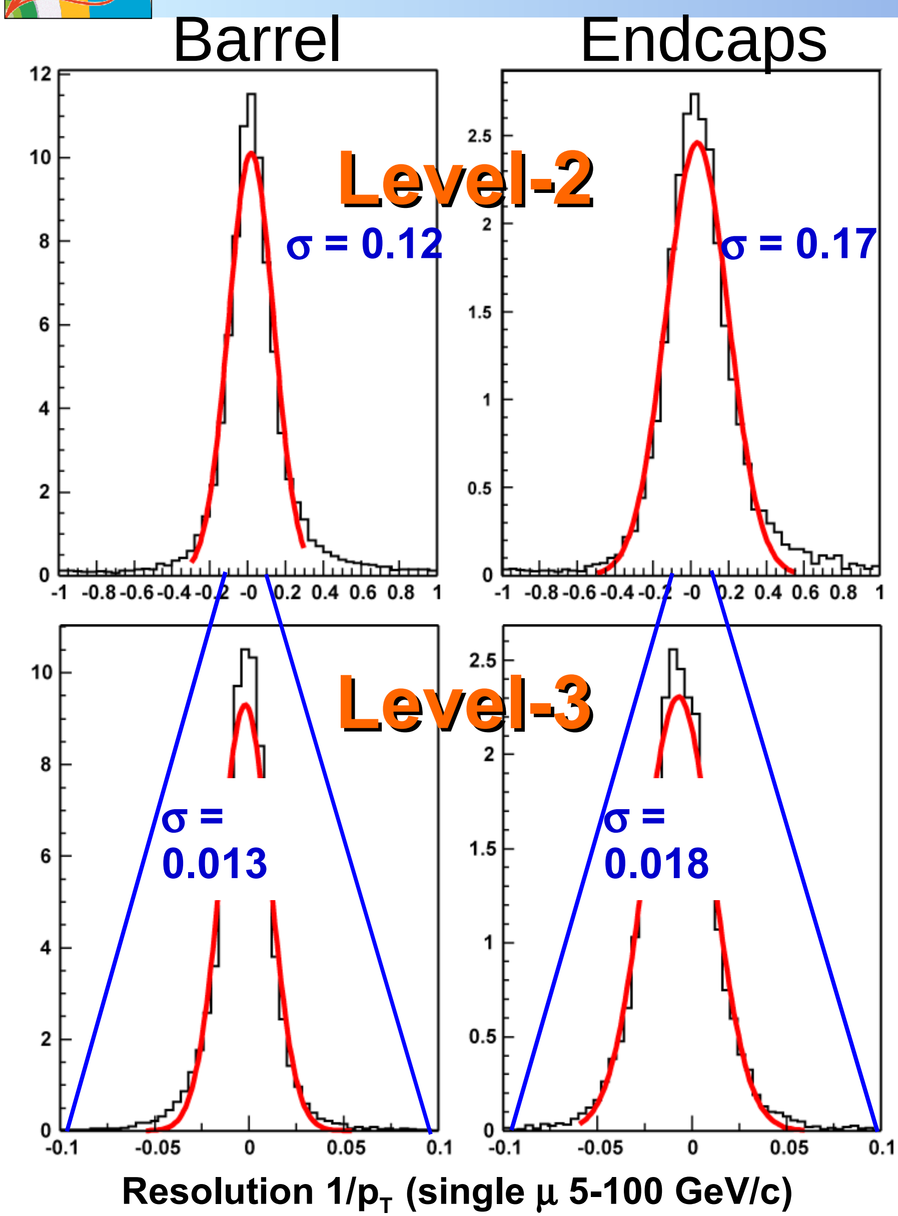
- HLT efficiency for muons with p_T = 5 - 100 GeV/c





- Overall efficiency ~ 96 %
  - Low energy muons → low efficiency because of large multiple scattering
  - Efficiency drops (~90%) in the cracks between wheels
- HLT acceptance is limited to $|\eta| < 2.1$ because no L1 trigger electronics on ME 1/1

HLT Performance: Resolution



- Good resolution
- Tails under control

  (very important for trigger rates)

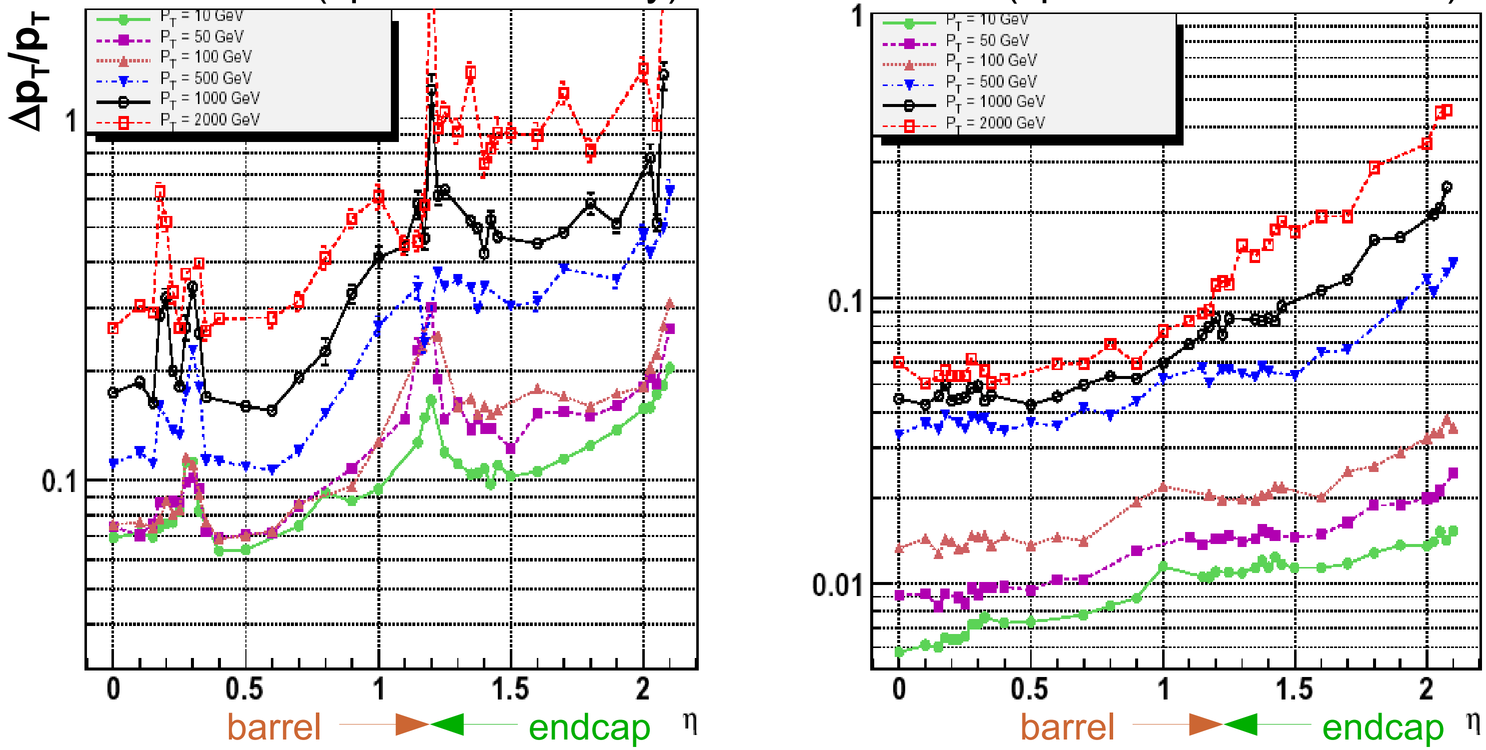
  Level-2

  resolution x 10

  Level-3
- Big improvement using tracker hits

Off-line Performance: Resolution

Standalone (spectrometer only) Global (spectrometer + tracker)



- η dependency due to solenoidal B field
- High p_T muons (~1TeV):
  - showering in the chambers → difficult Local Reconstruction
  - energy loss → bias

New reconstruction strategies under study

Summary

- HLT design allows:
  - great flexibility of the algorithms
  - benefits from continuous improvements of the reconstruction software

- Performance of muon reconstruction software must fulfil HLT requirements:
  - maximum reconstruction efficiency
  - good resolution (tails under control) for efficient selection with p_T cuts

- Muon reconstruction software is already robust and well-performing but there is still place for further developments:
  - local reconstruction of high-p_T muons

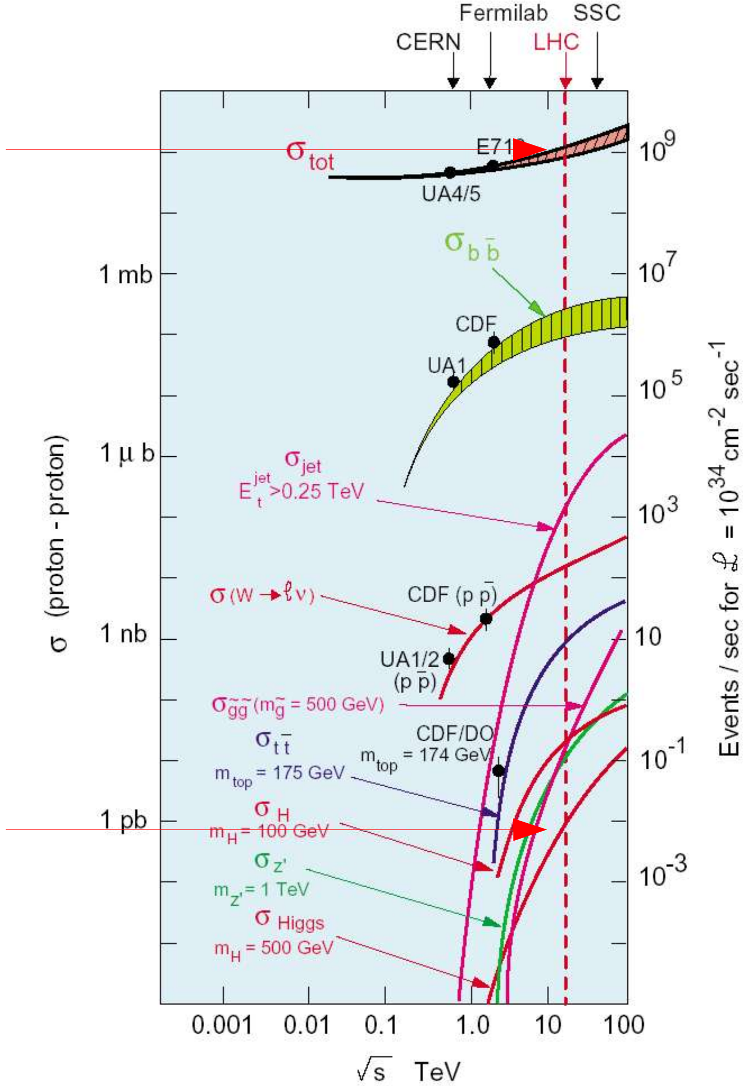
Backup Slides

LHC Environment

- LHC environment is extremely demanding for trigger system
  - High luminosity
    - High Luminosity: L=10^{34} cm^{-2} s^{-1}
  - High background rates
    - total σ_{inel}^{pp} ~ 55 mb -> Event rate O(1) GHz
  - Pile-up (PU) of several events in the same Bunch Crossing (BX)
    - ~ 17.3 minimum bias events in the same BX
  - High Bunch Crossing frequency
    - f = 40 Mhz -> 1 BX every 25 ns
- Huge selection needed
  - Rejection factor ~ 10^{10} - 10^{11}

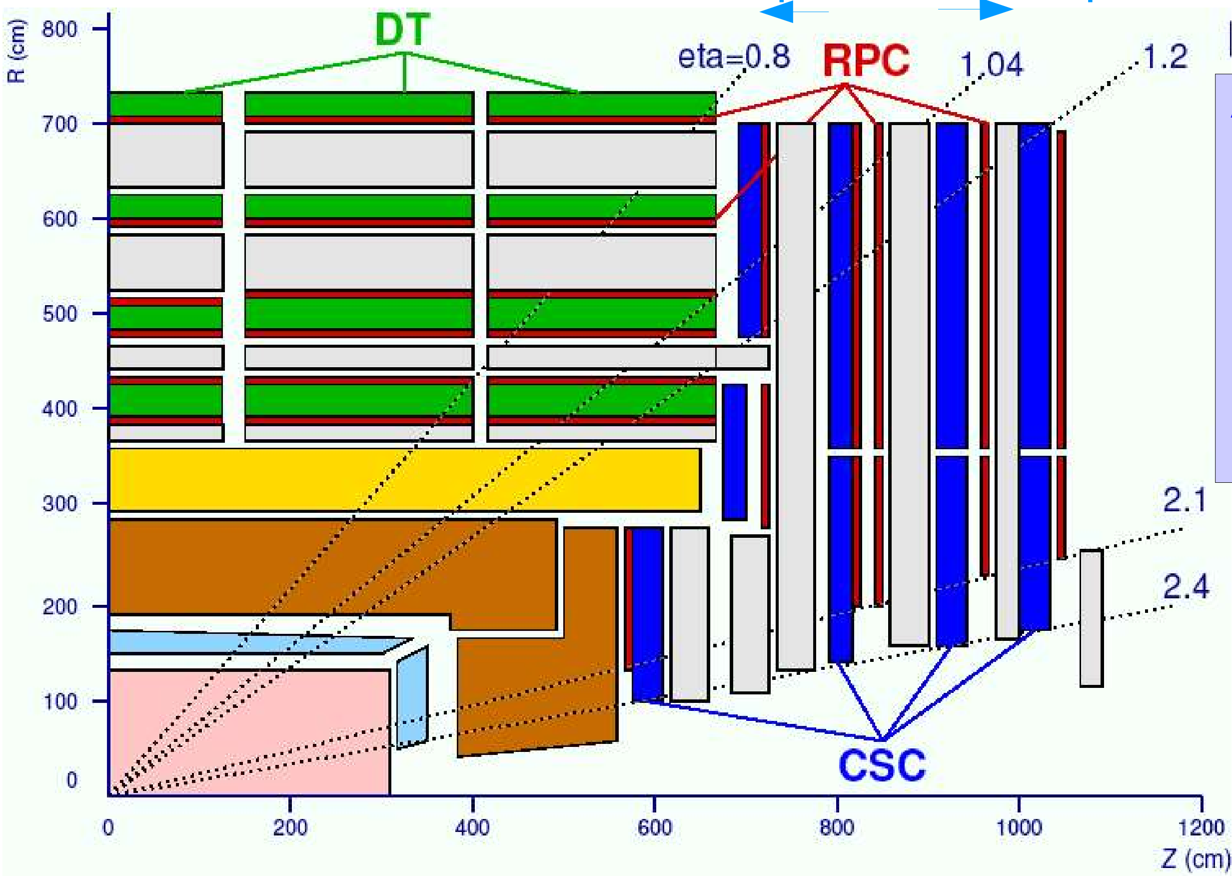
    Total MB Rate O(1) GHz

    Interesting Physics O(10-10^{-2}) Hz



The CMS Muon System

overlap barrel/endcap



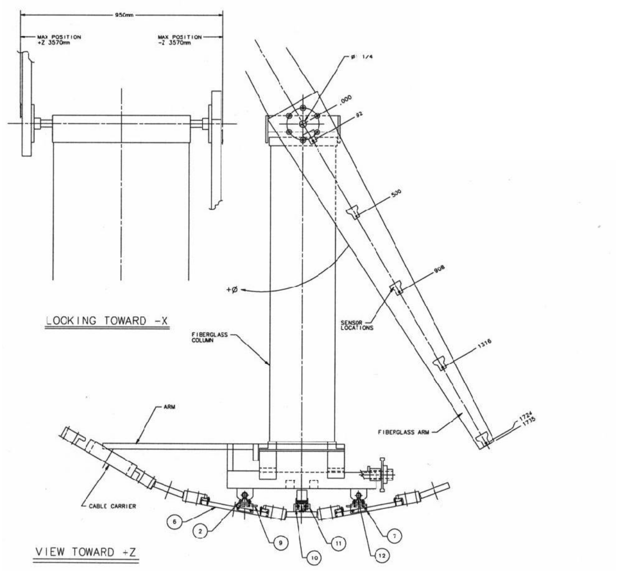
At Startup:

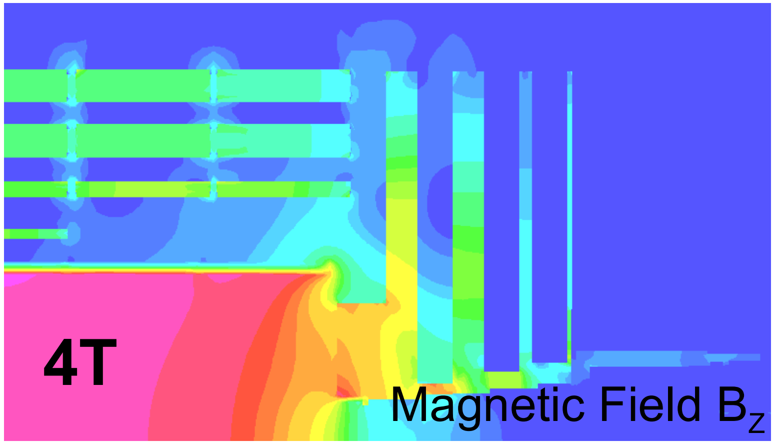
- No ME 4/2
- No trigger electronic on ME1/1
  → trigger |η| < 2.1
- RPC |η| < 1.6

- DT: 4 stations x 3 superlayers x 4 layers (|η| < 1.2)
- CSC: 4 stations x 6 layers (0.8 < |η| < 1.2)
- RPC: 6 stations in barrel + 4 stations in endcaps (|η| < 1.6)

Magnetic Field

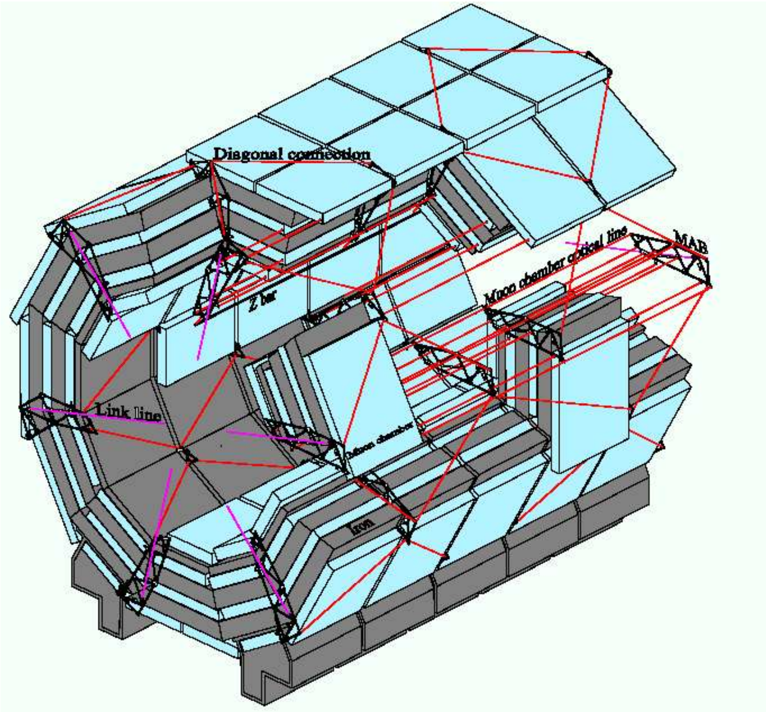
- Superconducting Solenoid
  - r = 3m, L=14m
  - B = 14T within the solenoid
  - B ~ 1.8T in the iron return yoke
- Great bending power
- Independent measurement inside / outside
- A lot of material within chambers
- Field measurement:
  - During Magnet Test (2006)
    - Rotating arm instrumented with Hall and NMR probes:
      - Δr = 20 cm, Δz = 5 cm
  - NMR probes inside the solenoid for on-line monitoring

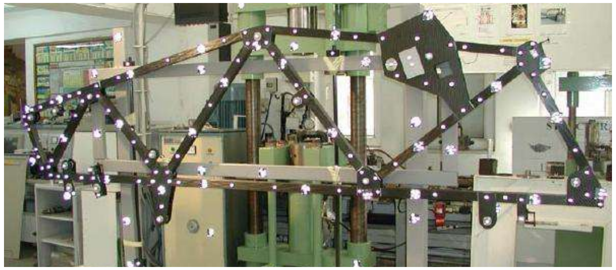




Muon System Alignment

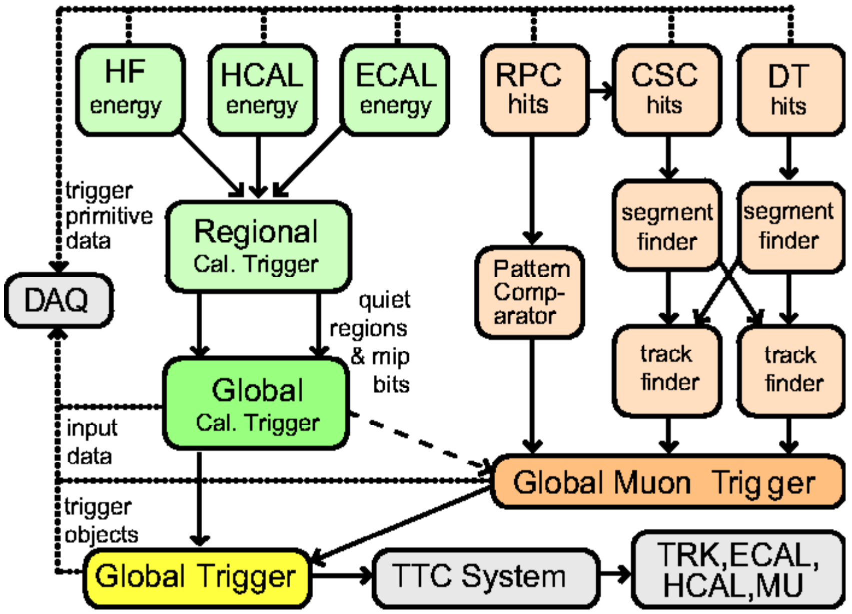
- Chamber alignment is fundamental
  - chamber resolution ~100 μm
  - movements due to B_{on}/B_{off} : O(1cm)!
- Optical alignment system
  - rigid structures + optical links (LED, laser, CCD)
  - link system for alignment with tracker
  - performance:
    - $\sigma_{r\phi}$ ~150 μm (same sector)
    - $\sigma_{r\phi}$ ~210 μm (between sectors)
- Alignment with tracks
  - Problem: knowledge of material and magnetic field
    - Only muons with p_T > ~50 GeV/c are usefull





L1 Trigger General Design

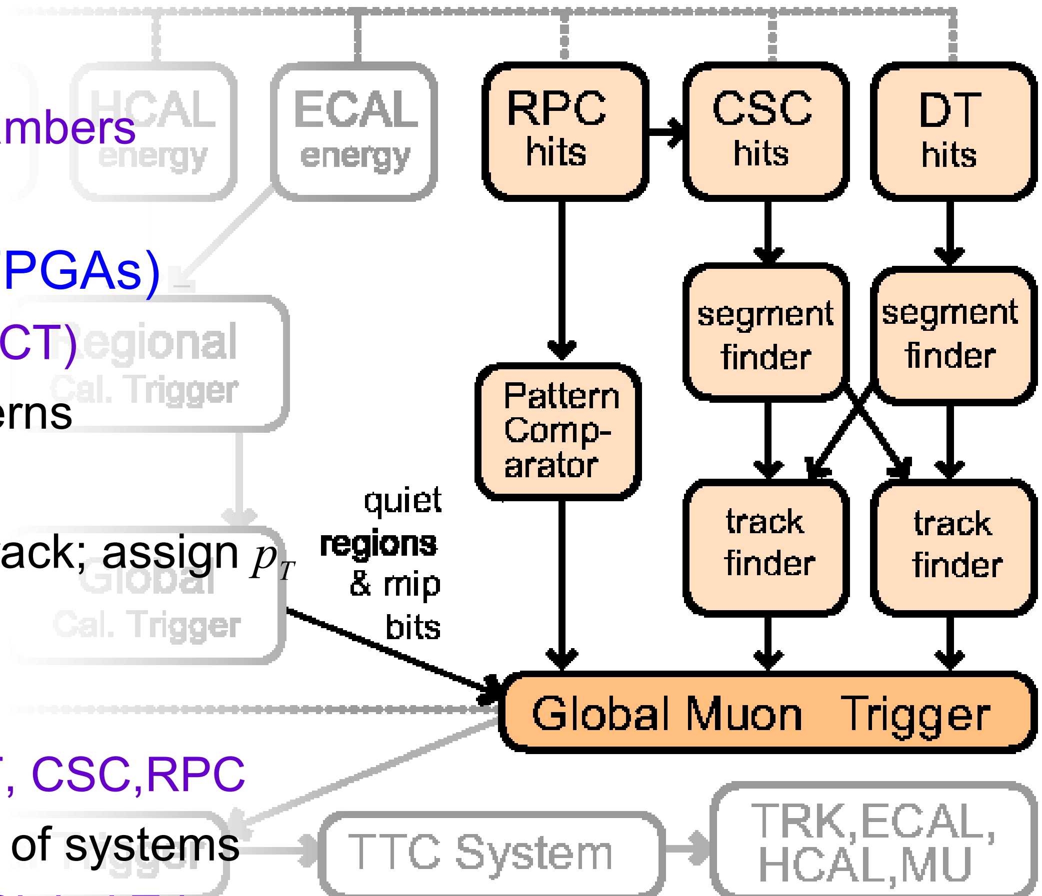
- Implemented on custom hardware
  - minimal dead time
- Synchronous, pipelined (25 ns)
  - delayed by 3.2 µs = 128 BX including propagation (~1-2 µs)
- Max output ≡ max DAQ input
  - Design: **100 kHz**; at startup: 50 kHz
- 2 Subsystems
  - **Calorimeter Trigger**
  - **Muon Trigger**
  - Result: jet, e/γ, µ, τ jet candidates; E_T^{miss}, ΣE_T



- No local decisions; selection by the "**Global Trigger**"
  - 128 simultaneous, programmable algorithms, each allowing:
    - Thresholds on single and multiple objects of different type
    - Correlations, topological conditions, Prescaling

L1 Muon Trigger

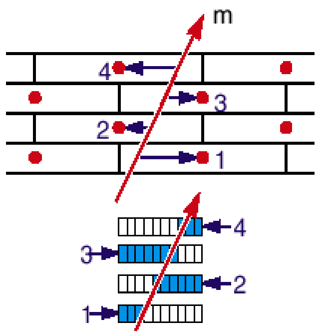
- Local" (chamber) level (ASICs)
  - Find segments in DT/CSC chambers
- "Regional" (subsystem) level (FPGAs)
  - RPC: Pattern Comparator (PACT)
    - looks for predefined patterns
  - DT/CSC Track Finders
    - combine segments into track; assign p_T
- Global Muon Trigger
  - Combines candidates from DT, CSC,RPC
    - Exploits complementarity of systems
  - Delivers 4 best muons to the Global Trigger
    - Each with p_T, position, angle, BX, quality
  - Efficiency: ~97%
  - p_T resolution: 17-22% depending on η (muons from W decays)



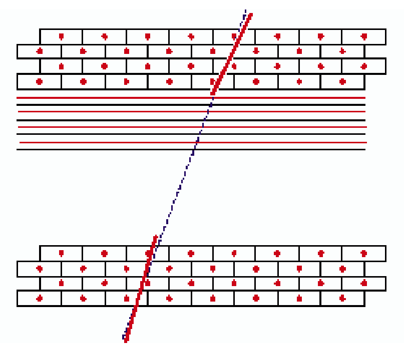
DTs, CSCs and RPCs L1 Trigger

Local Trigger: build segments

DT

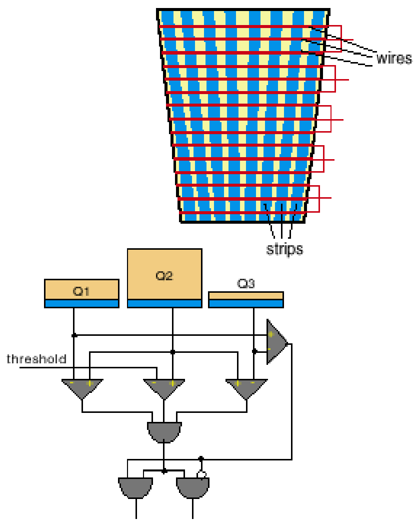


Meantimers recognize tracks and form vector / quartet.

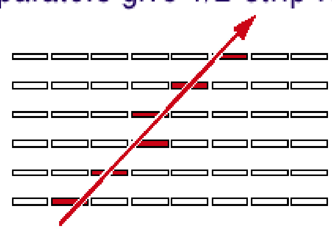


Correlator combines them into one vector / station.

CSC (strips)



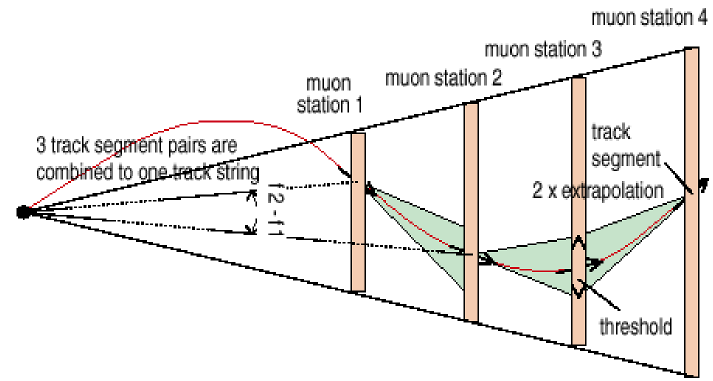
Comparators give 1/2-strip resol.



Hit strips of 6 layers form a vector.

ASICs on detector or peripheral crates

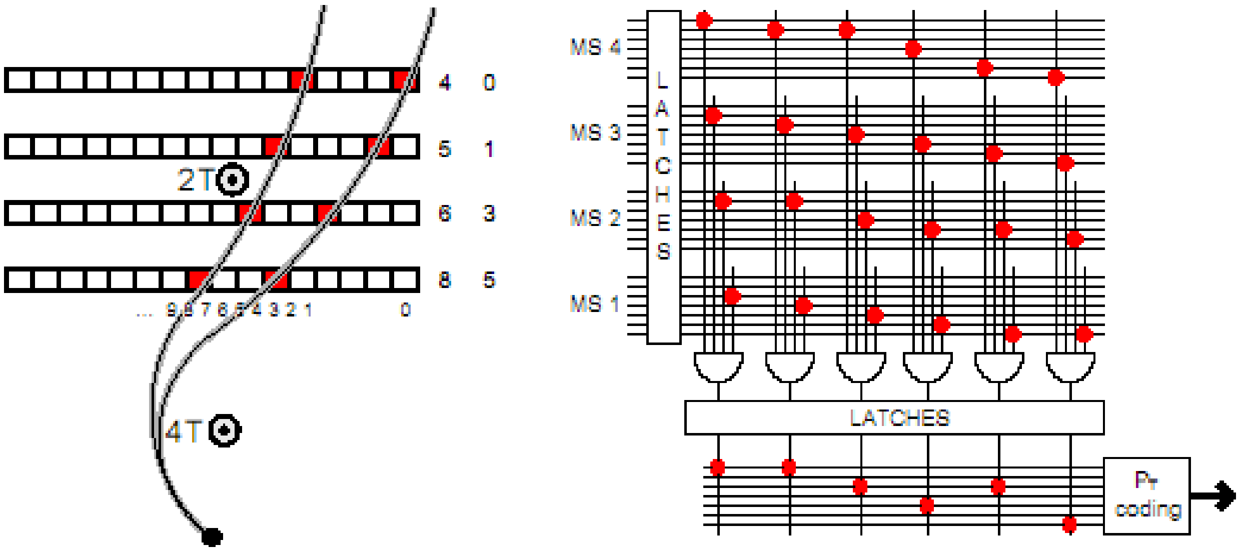
Regional Trigger: DT/CSC Track Finders



- Extrapolation Unit
  - Link segments using look-up tables
- Track Assembler:
  - link segment pairs to tracks
  - cancel fakes
- Assignment Units
  - p_T, charge, η, ϕ, quality

FPGAs in the control room

RPC Level-1 Trigger



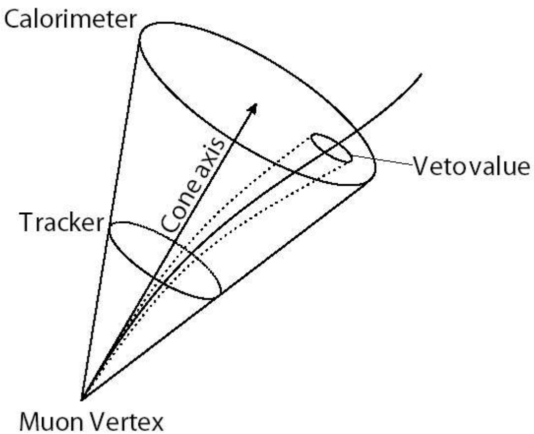
- Based on Pattern Comparator (PACT)
  - Look for predefined hit patterns in time coincidence
    - At least 3 hits out of 4 stations
    - 2 different groups of 4 stations in the barrel (6 stations in total)
  - Each hit pattern corresponds to a p_T value
  - Hardware: ASICs
    - Located in the counting room

The Kalman Filter

- Kalman Filter is a recursive method for the fit of a discrete set of data
  - Provides track fitting independent of the number of measurement available
- PROBLEM: Determination of a generic state vector **x** (= position + momentum to a given surface) given a set of measurement $\mathbf{z}_k$.
- METHOD:
  - Start from a seed (= initial state vector + covariance matrix)
  - Each step k consists of two phases:
    - *propagation*: predict an a priori state $\mathbf{x}_k^-$ obtained by projecting the previous state with its covariant matrix
    - *update*: use the information from all measurement to update the state $\mathbf{x}_k$ and the covariance matrix
- RESULT:
  - the result is the state on the surface of the last measurement station
- SMOOTHING:
  - Update the trajectory parameters of previous steps using all the measurement at every measured surface.

Isolation

- K, π, b, c → μ decays are accompanied by jets
  - Discard muons with high "activity" in their neighborhood
  - Based on ΣE_T or ΣP_T in cones around the muon
  - Cone sizes and thresholds are optimized
    - To get maximal rejection on background muons for a given efficiency on reference signal ($W \to \mu\nu$)
    - flat $\varepsilon(\eta)$ on signal by construction



- Calorimeter Isolation

  ΣE_T from calorimeter towers in a cone around muon
  - Can be applied already at L2
  - Sensitive to pile-up
- Tracker Isolation

  ΣP_T of tracks in a cone around L3 muon, exploiting:
    - Regional reconstruction in the tracker
    - Conditional tracking

Navigation in the Muon Detectors

- Navigation
  - find the next detector crossed by one trajectory, given its parameters at a given point
  - extrapolate state vector and errors for the fit
- Navigation must be optimized to cope with trigger timing
  - requires a lot of CPU time
  - extrapolation though the iron with inhomogeneous magnetic field
  - available tool: GEANE (based on ZEBRA/G3 geometry)
- Optimization through organization of the detectors in a hierarchical structure
  - minimize the number of extrapolation steps

Trigger Rate

$\mathscr{L} = 10^{34}\ \mathrm{cm^{-2}s^{-1}}$