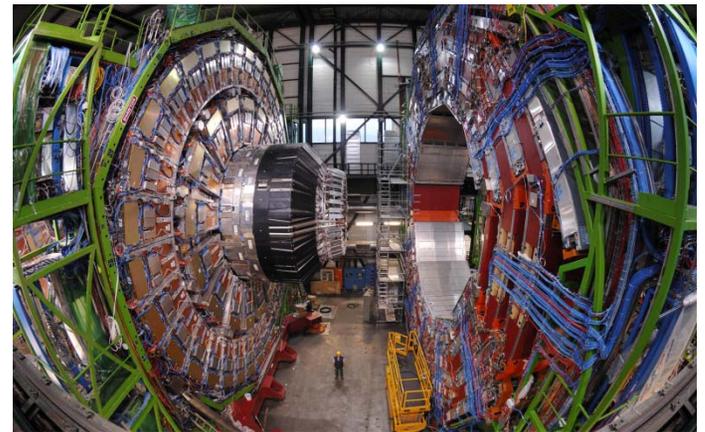


The CMS Muon Detector Upgrade

Jeffrey Roe
August 5, 2010

Overview

- ▶ The Standard Model of particle physics
- ▶ The LHC and CMS Detector
- ▶ Why Muons?
- ▶ Muon Detection at CMS
- ▶ Endcap Trigger Electronics
- ▶ LHC/CMS Upgrade
 - Motivation
 - Trigger MotherBoard upgrade



Standard Model of Particle Physics

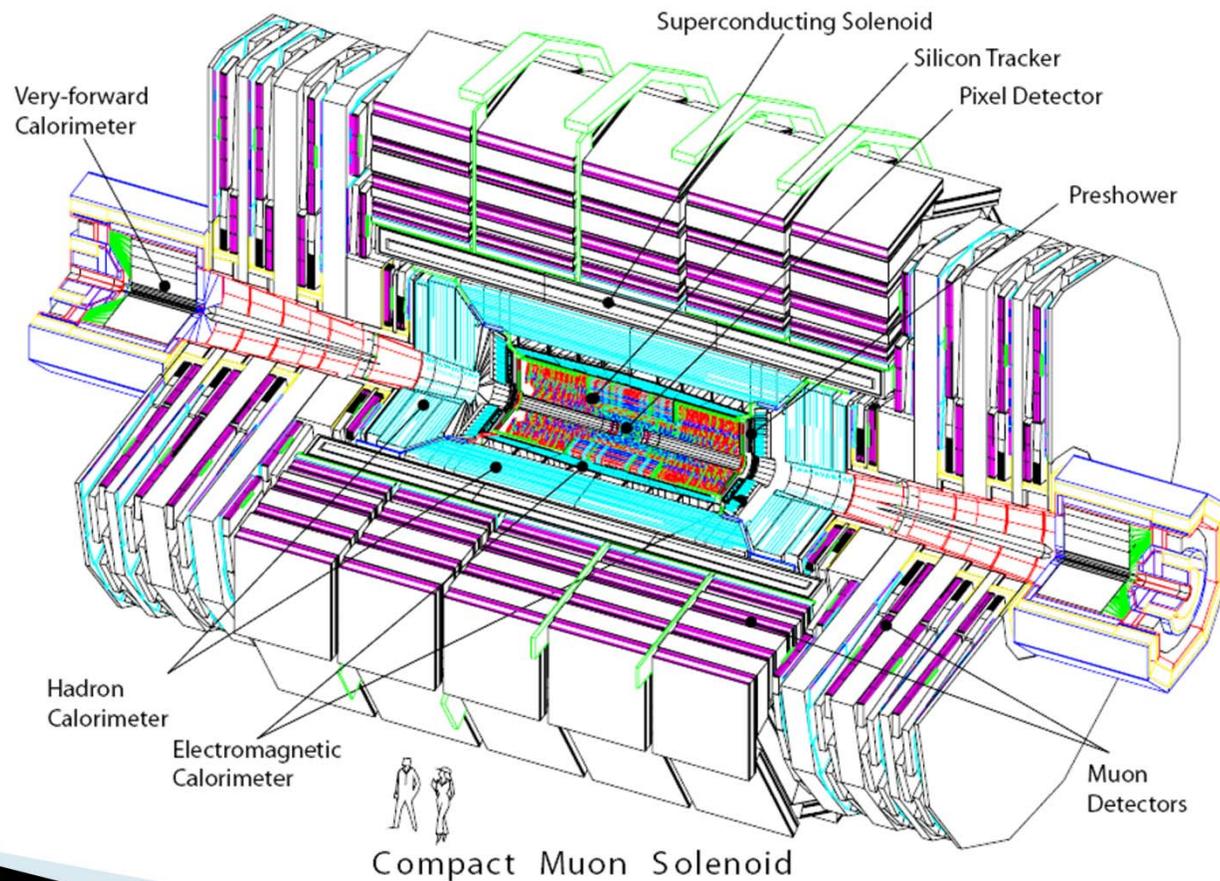
Higgs Boson

- ▶ The Standard Model describes fundamental particles and their interactions but has shortcomings
 - E.g., cannot explain the origin of particle masses
 - The “Higgs boson” provides a theoretical solution
 - A new particle, which interacts with other particles, giving them mass in the process
- ▶ Search for the Higgs boson at the Large Hadron Collider (LHC):
 - Produce Higgs bosons in high energy collision experiments
 - Search for its decay products in detectors, to prove that we have seen it



CMS Layout

The Compact Muon Solenoid (CMS) is one of two flagship detector experiments at the LHC



Why Muons?

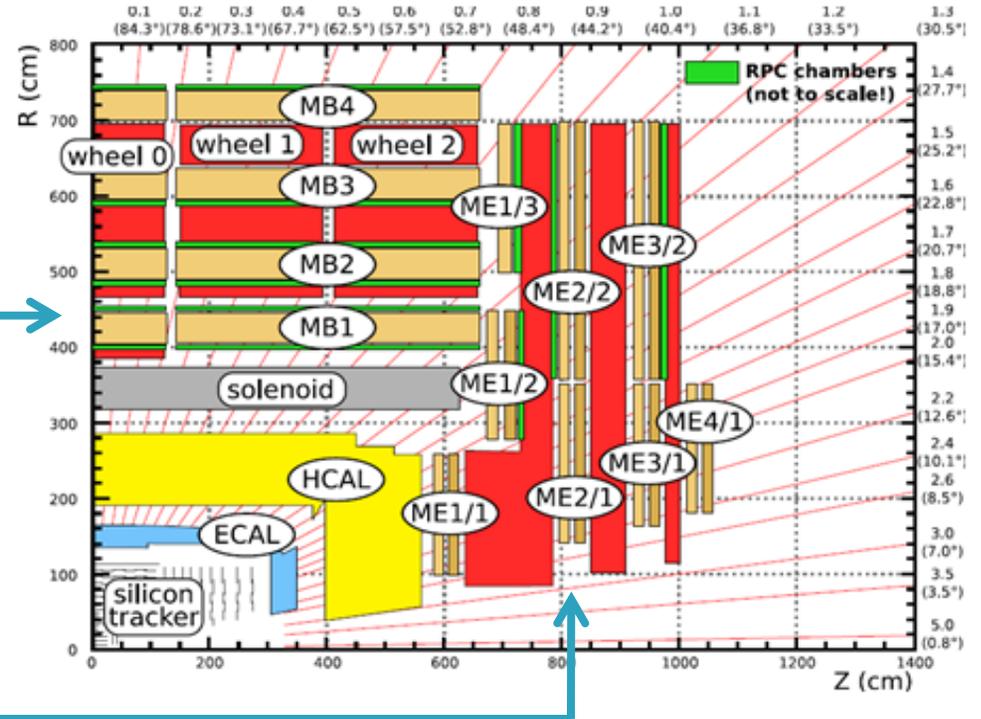
Higgs Boson and More

- ▶ Search for Higgs Boson
 - One promising decay mode: $pp \rightarrow H \rightarrow Z^0 Z^0 \rightarrow \mu^+ \mu^- \mu^+ \mu^-$
- ▶ Physics beyond the Standard Model
 - Super Symmetry (SUSY)
 - New heavy “cousins” of W and Z bosons
- ▶ Muons provide a “clean” signal to detect interesting events in messy backgrounds

Muon Detection at CMS

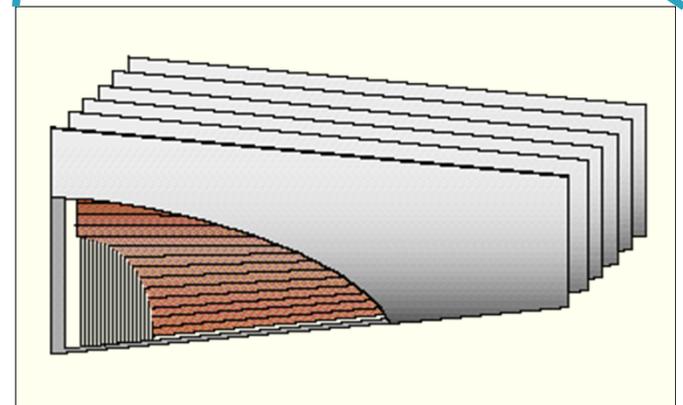
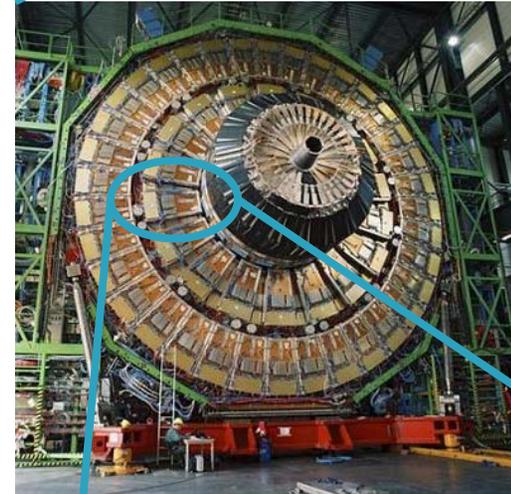
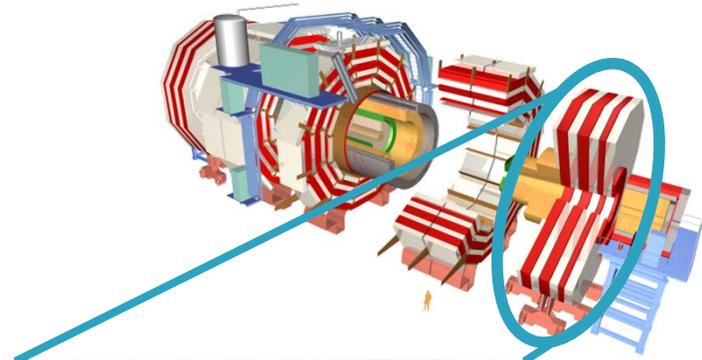
- ▶ Muons are good at penetrating material
 - No other charged particles do this
 - Muon system is the farthest sub-detector from the beam

- ▶ Muon system:
 - Barrel Region
 - Drift tubes (DTs)
 - Endcap Region:
 - Cathode Strip Chambers (CSCs)



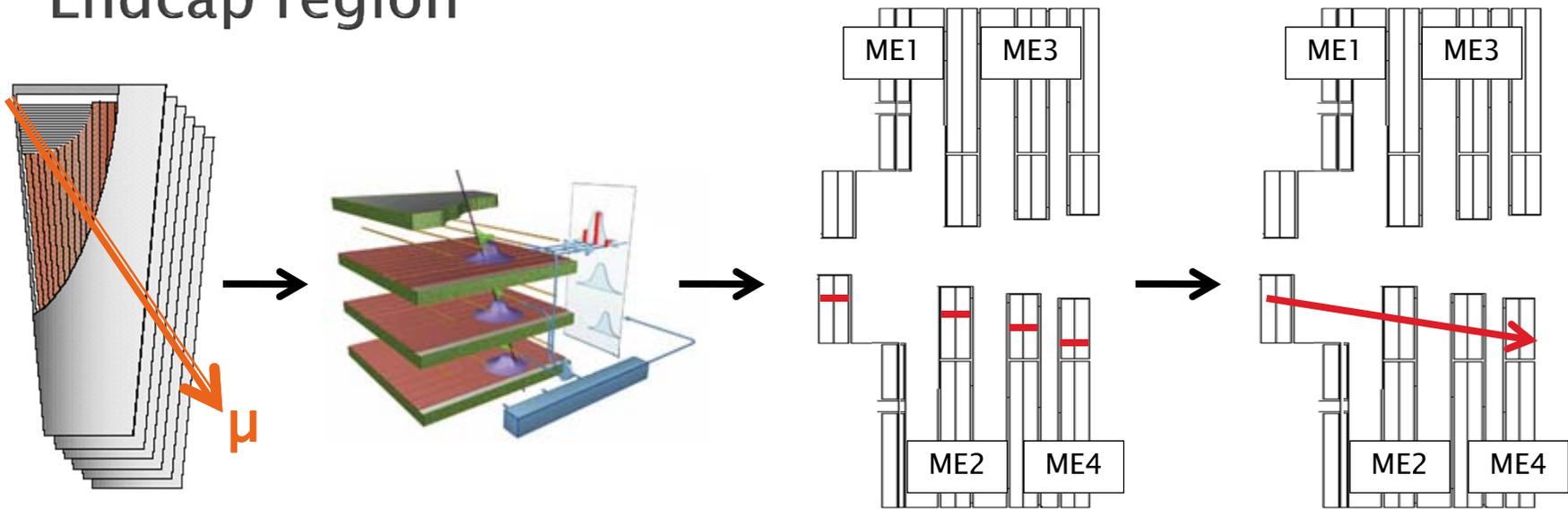
End Cap Region

- ▶ 468 trapezoidal shaped Cathode Strip Chambers (CSC) in 4 stations (ME1–ME4)
- ▶ 6 gas gaps per chamber
 - Plane of radial cathode strips
 - Plane of nearly perpendicular anode wires
- ▶ Charged particle traverses chamber which ionizes the gas in the gaps causing an electron avalanche
 - Produces a charge on an anode wire
 - Produces an image charge on cathode strip



Basics of Track Reconstruction

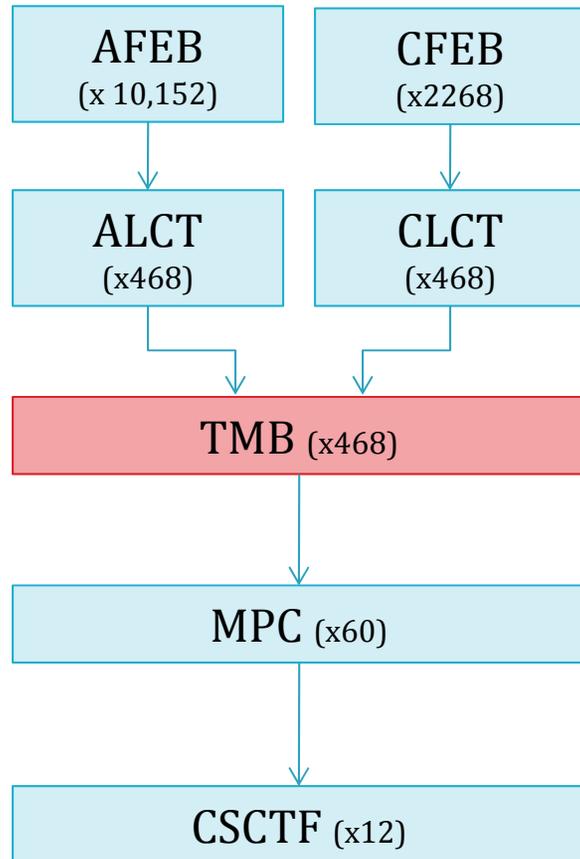
Endcap region



- ▶ You have to be able to do this in real time
 - Collisions happen every 25 nanoseconds!
- ▶ Concept of trigger:
 - Can't possibly record every event
 - Example: 1MB per 25ns means we would require a bandwidth of 312,500 Gb per sec
 - Must be selective about which events to keep and must be able to quickly pick which these are

CSC Level 1 Trigger Path

Electronics, 1st level of trigger

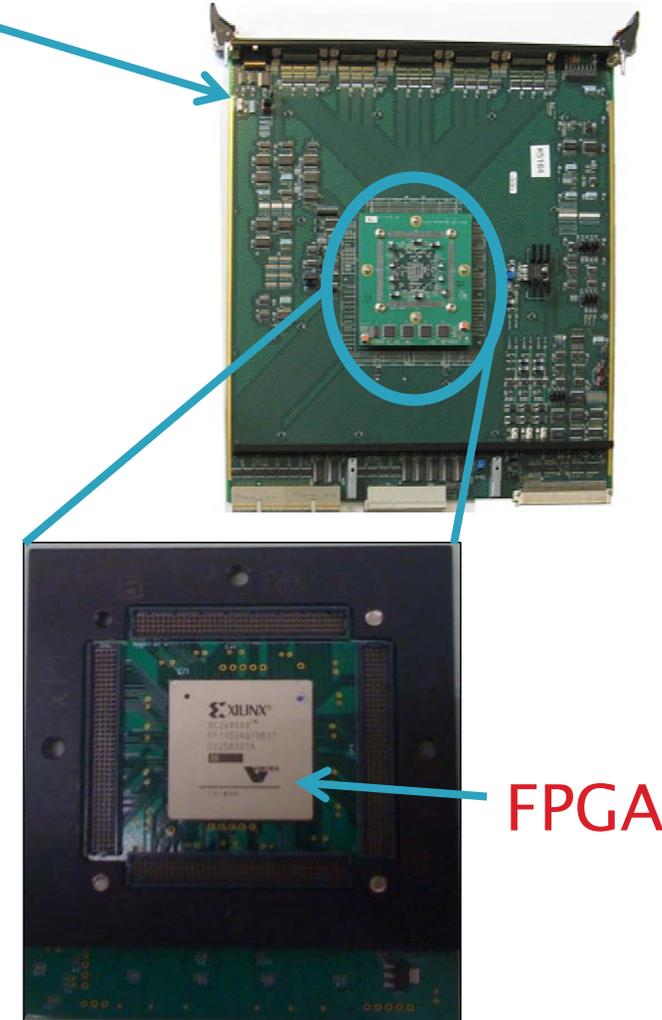
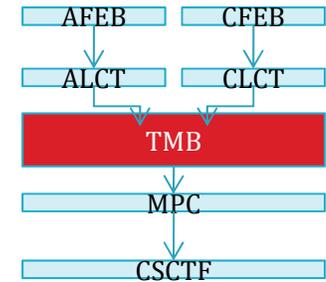


- ▶ Anode/Cathode Front End Board (AFEB/CFEB)
- ▶ Anode/Cathode Local Charge Tracks (ALCT/CLCT)
- ▶ Trigger MotherBoard (TMB)
- ▶ Muon Port Card (MPC)
- ▶ CSC Track Finder (CSCTF)

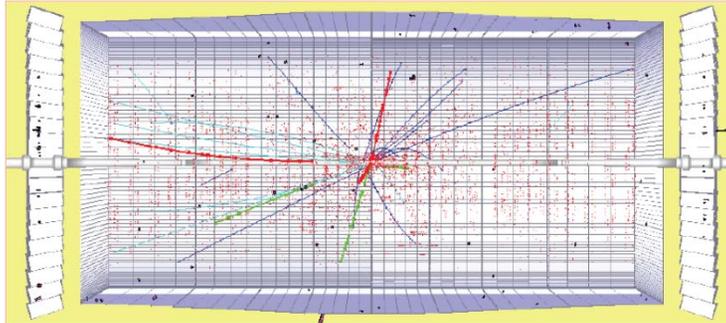
CSC Trigger Path

Trigger MotherBoard (TMB)

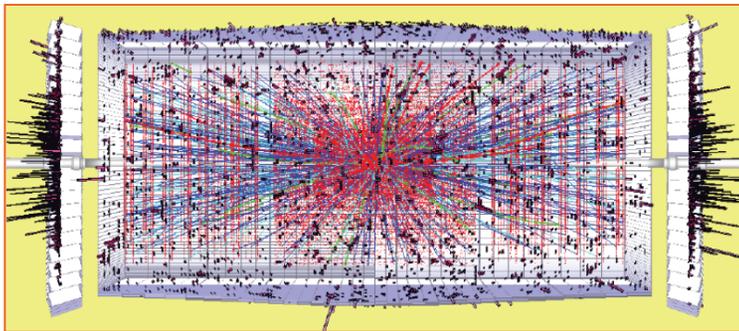
- ▶ Receives anode and cathode digitized “local charged tracks” (LCTs) separately from anode and cathode front-end electronics
- ▶ Performs a timing coincidence of the all anode and cathode LCTs in 1 chamber and forms 3D tracks (stubs)
- ▶ Selects up to 2 best stubs based on the number of layers hit, type of pattern, p_t , etc.
- ▶ Assigns vectors to the LCTs (position, direction, bunch crossing, quality)



LHC Upgrade



Collision reconstruction at current LHC intensity



Collision reconstruction at upgraded LHC intensity

- ▶ Nominal luminosity may be too low to observe new physics phenomena or measure Higgs boson properties in a reasonable time period
- ▶ Beam luminosity will be increased in the next several years
 - This will greatly increase number of particles per collision seen the in the detector
 - Could be very challenging for the detector
 - Will it even work?

Monte Carlo Simulation

Muon trigger efficiency

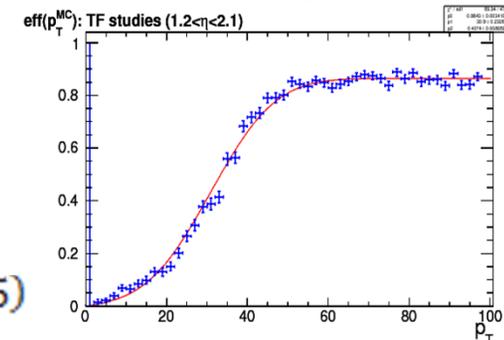
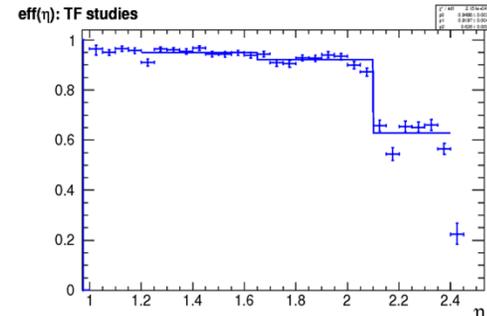
- ▶ We use Monte Carlo software simulation to model
 - Generation of collision events
 - Particles passing through matter, detector and electronics response
 - Trigger logic is emulated
- ▶ Evaluate performance for different scenarios
 - Low and high luminosity
 - Current and upgraded muon trigger
 - Several trigger p_T thresholds
- ▶ Trigger Efficiency
 - Probability that the trigger will do its job for a given Monte Carlo muon
 - $$\frac{\text{number of muons that passed trigger}}{\text{number of generated muons}}$$

Parameterization of muon trigger efficiency

- ▶ For each scenario, efficiency depends on η (muon angle to beam) and p_t (transverse momentum)
- ▶ We parameterize and fit each dependence with these functions:

$$eff(\eta) = \begin{cases} p1; & 1.2 < \eta < 1.65 \\ p2; & 1.65 < \eta < 2.1 \\ p3; & 2.1 < \eta < 2.4 \end{cases}$$

$$eff(p_t) = \frac{1}{\sqrt{\pi}} \left[\int_0^{\frac{p_t+1}{p4}} \frac{1}{p5\sqrt{2}} e^{-x^2} dx + \int_0^{\frac{p_t-1}{p4}} \frac{1}{p5\sqrt{2}} e^{-x^2} dx \right]$$



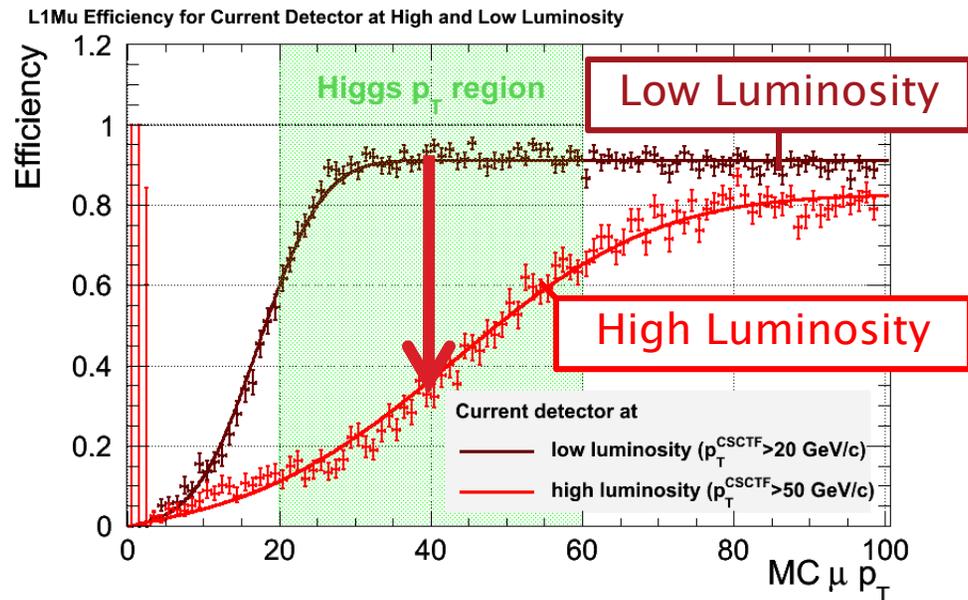
- ▶ Final efficiency function:

$$eff_{final}(\eta, p_t; p1 \dots p5) = eff(\eta; p1 \dots p3) \times eff(p_t; p4, p5)$$

- ▶ I wrote code that calculates this efficiency in certain scenarios which can be used in other physics studies for the upgrade

Current System at High Luminosity

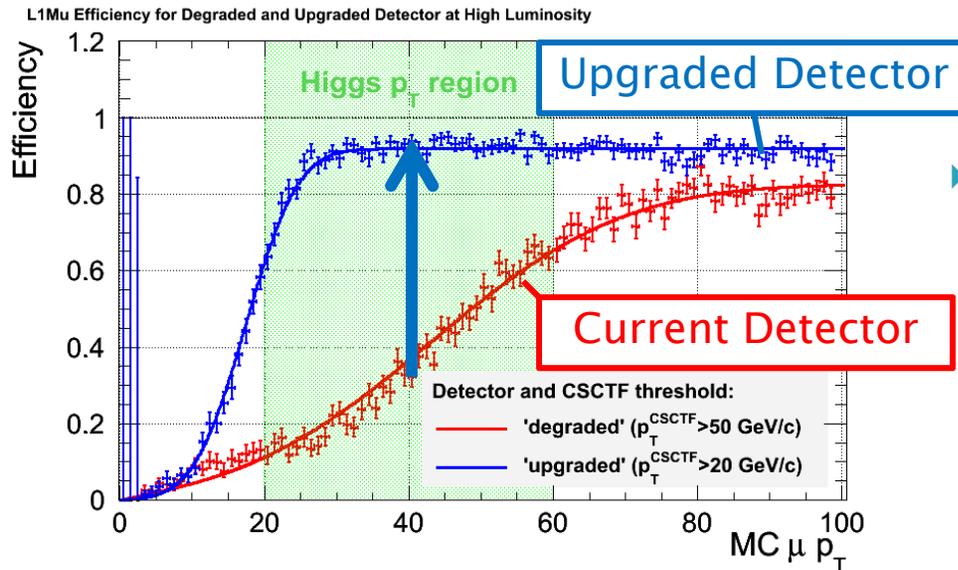
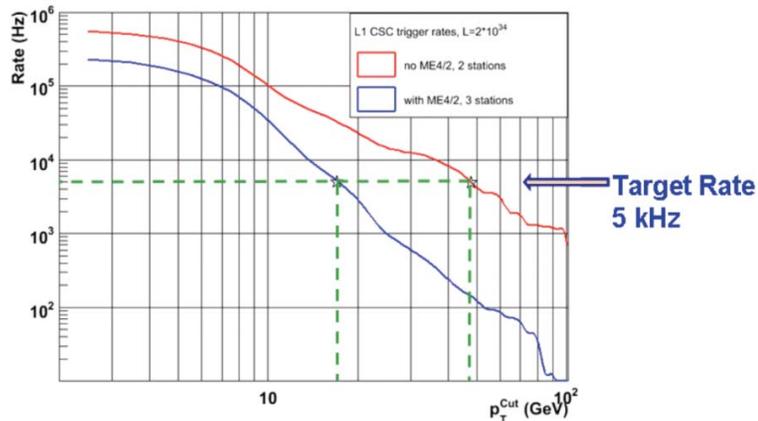
Unacceptable inefficiency



- ▶ Without an upgrade, the current trigger must enforce a higher p_T threshold (20 \rightarrow 50 GeV/c) in order to handle the higher particle rates
- ▶ This severely reduces the efficiency of the detector
 - Most notably in the region where the Higgs boson and other new physics are expected to be

Upgraded Muon Trigger

Acceptable rate and high efficiency

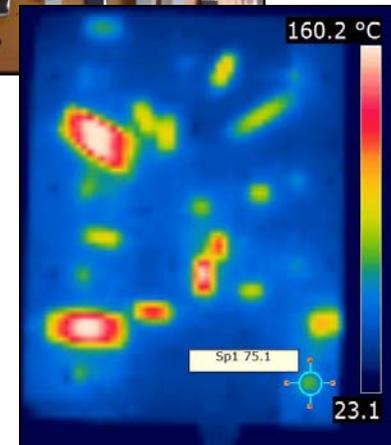
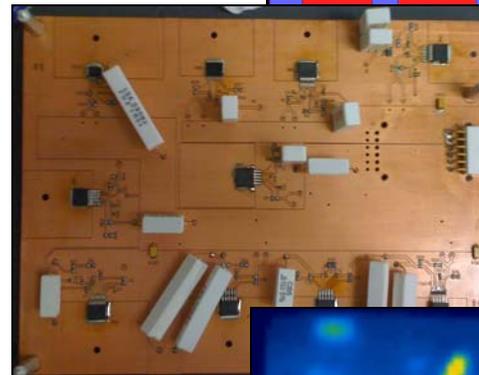
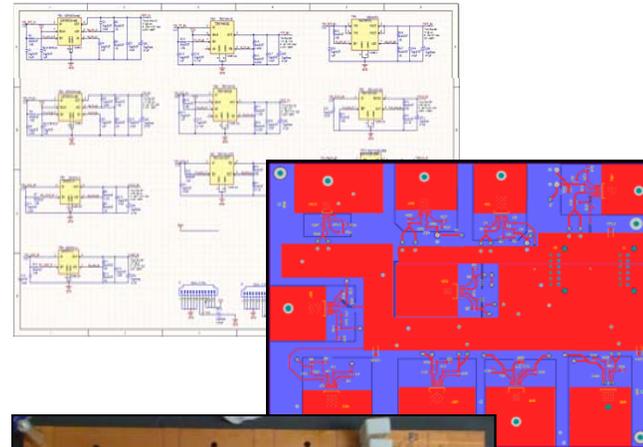


- ▶ The upgraded detector will be able to handle the higher rates while still enforcing the lower p_T threshold
- ▶ This will dramatically increase the effectiveness of the detector in the “Higgs region”
- ▶ One of the critical updates is the Trigger MotherBoard upgrade
 - Need to decrease the dead time
 - Solution requires a faster, more robust FPGA and therefore a new board design

Trigger MotherBoard Upgrade

Voltage regulator tests

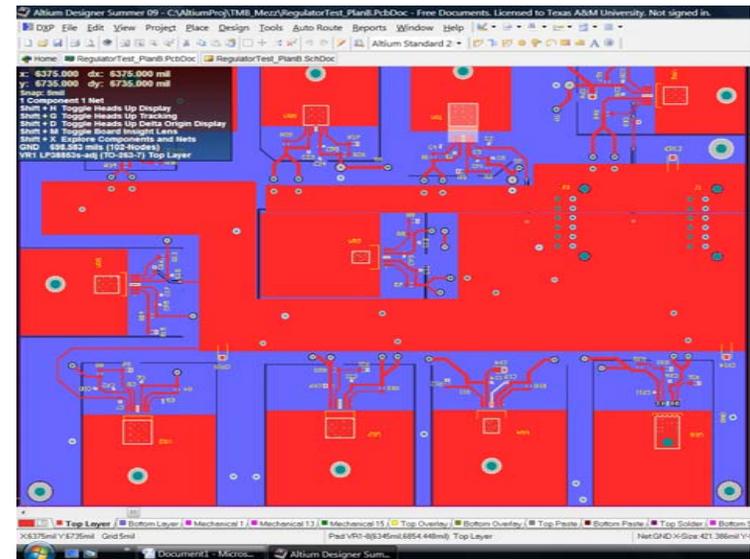
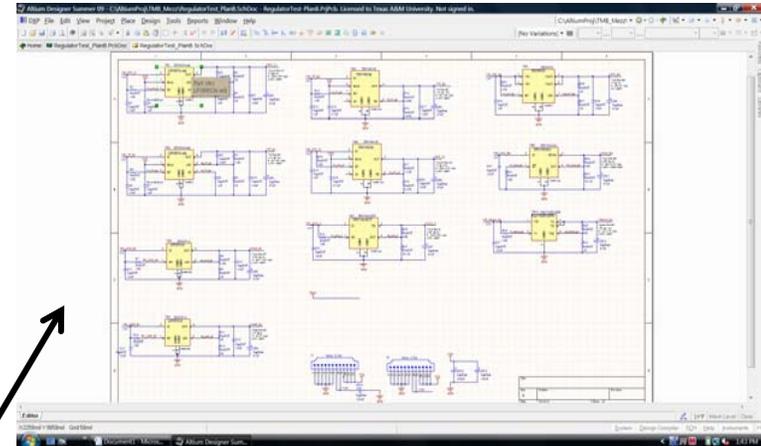
- ▶ Currently:
 - Virtex 2 FPGA
- ▶ Upgrade:
 - Virtex 6 FPGA
 - Faster (x2)
 - More logic capability (x5)
- ▶ Voltage Regulator Tests
 - FPGA requires several different input voltages (1V (x2), 1.2V, 1.8V, 2.6V, 2.9V)
 - Need to design, manufacture, and test several different regulator options for each supply
 - **Requirements:**
 - Operating voltage stability
 - Temperature
 - Radiation tolerance
 - Operation in magnetic field



Trigger MotherBoard Upgrade

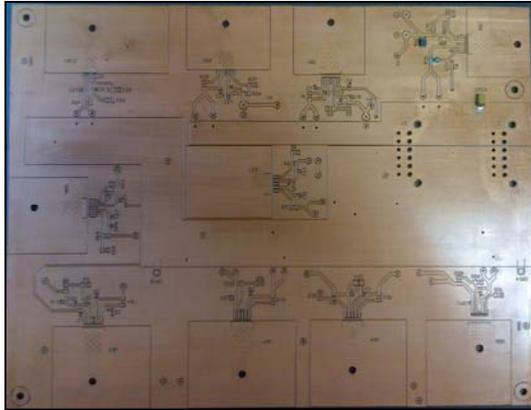
Test board design steps

- ▶ Design circuit for each regulator to achieve required behavior
 - Use device datasheets
 - Ensure all minimums and maximums are met (current, voltage drop, power, temperature estimate)
- ▶ Altium Designer
 - Schematic layout
 - Printed Circuit Board (PCB) layout



Trigger MotherBoard Upgrade

Test board design steps



←▶ Manufacture Board

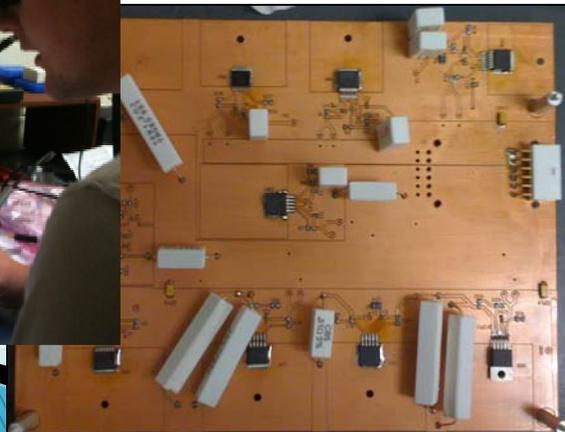
- TAMU physics electronics shop
- Drill holes
- Plate with copper
- Etch tracks and lines



←▶ Solder parts

▶ Test circuits

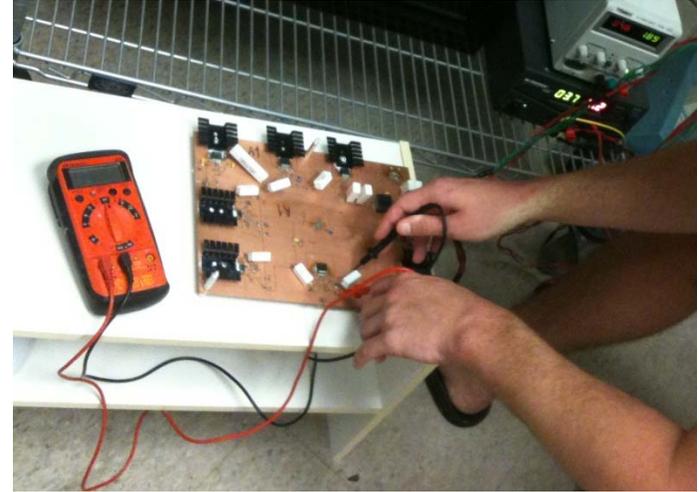
- Voltage stability
- Thermal operation
- Radiation tolerance



Voltage Regulator Tests

Voltage testing and analysis

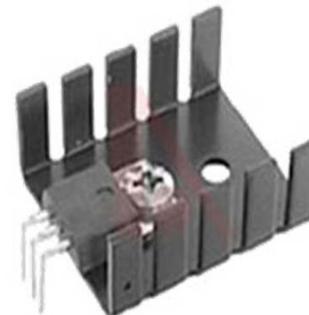
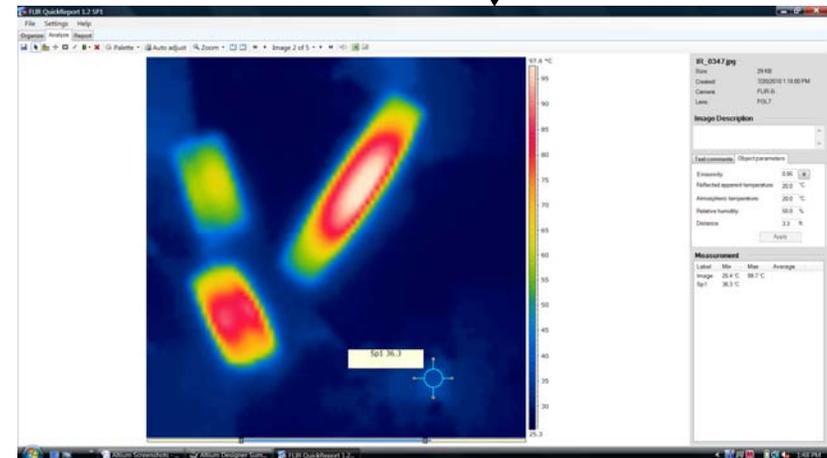
- ▶ System requires that that voltage levels into the FPGA remain stable
- ▶ Test board was powered on in the morning and the voltages of each circuit measured 3-4 times per day
 - Looked for irregularities in the measured voltages throughout the tests ($\pm 10\text{mV}$)
- ▶ **Results:** All tested regulators proved stable for several days of continuous operation in the laboratory



Voltage Regulator Tests

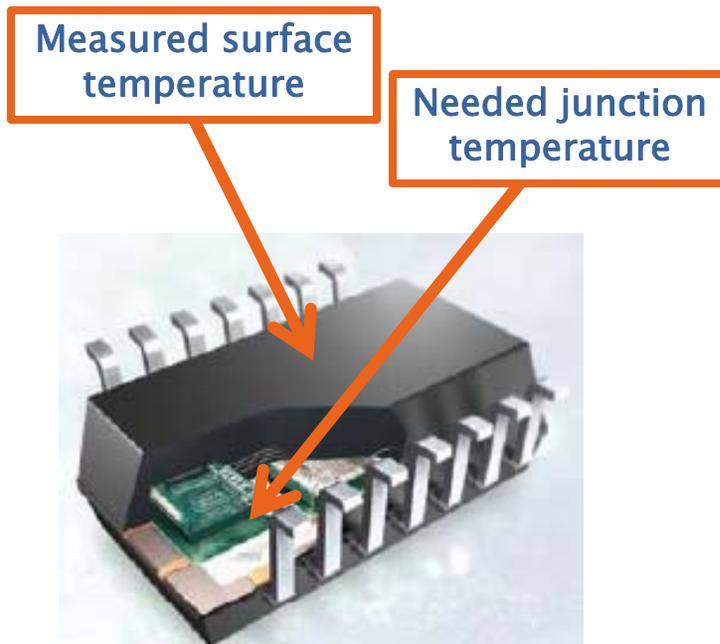
Thermal testing

- ▶ *Flir Extech i5* Thermal Imager
- ▶ Procedure
 - Thermal images taken periodically through the day
 - Several conditions were tested to simulate possible working conditions at the LHC
 - Natural convection
 - Heat sinks
 - Air flow



Voltage Regulators

Thermal Analysis

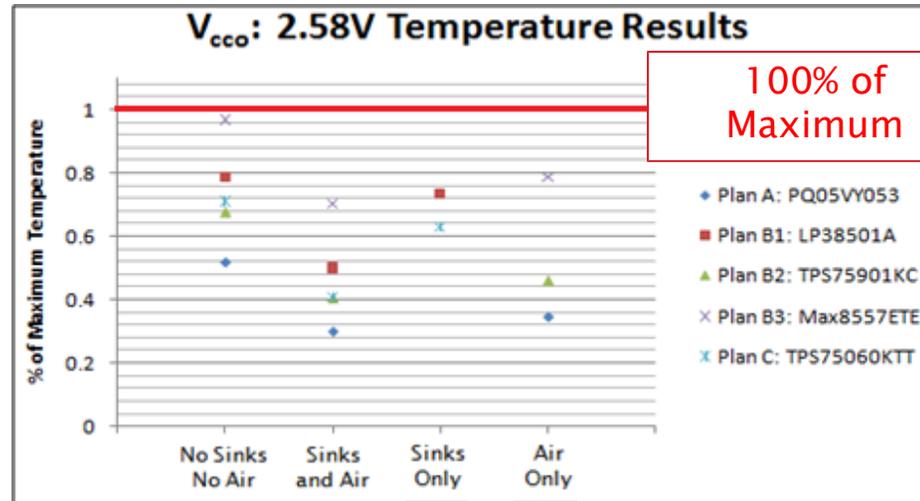


- ▶ Measurements taken on the case of the device
 - Manufacturer specified maximum temperatures are given for inside chip
- ▶ Converted measured “case” temperature to “junction” temperature
 - Junction to case thermal resistance for device is given in data sheet
 - Can calculate power the device dissipates
 - $T_J = T_C + P_D * R_{\theta JC}$
- ▶ Compared ratio of each device’s measured temperature to its specified maximum

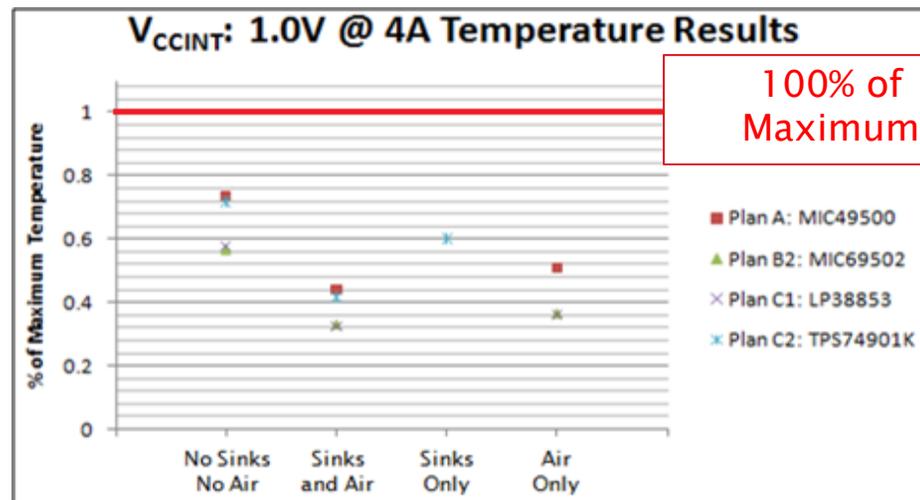
Voltage Regulators

Thermal Analysis Results

- ▶ All regulators survived the first round of thermal testing
- ▶ All operated below their maximum specified junction temperature
 - Some were too close to their maximum to be considered safe for operation at the LHC
- ▶ Heat dissipation methods:
 - Air flow was determined to have the biggest impact on the regulator temperature (~30% – 40% decrease)
 - Thermal heat sinks had a smaller effect (~10% decrease)
 - Could be a complementary tool



100% of Maximum



100% of Maximum

Voltage Regulators

Still to come...

- ▶ Radiation testing in nuclear reactor
 - Submit to neutron radiation for specified time period to and translate this to equivalent exposure time at the LHC
 - Retest circuits for voltage output and operating temperature to find which devices have been degraded by the radiation
- ▶ Choose the most appropriate regulator for each supply required by the FPGA by:
 - Radiation tolerance
 - Voltage and current stability
 - Operating temperature
 - Designer preference

Conclusion

- ▶ The anticipated discoveries of new phenomena at the LHC will require going to high intensity beams in several years
 - High rates will make detector and electronics work very challenging, likely requiring detector upgrades
- ▶ Monte Carlo simulation studies of the CMS Muon Trigger performance demonstrate a clear need for a system upgrade
 - TMB board is one of the bottlenecks
- ▶ Research and design of an upgraded TMB system is currently underway
 - Many necessary studies were completed this summer:
 - Ability of electronics components to withstand the LHC environment (heat, voltage stability)
 - Designed and built voltage regulators test boards using test components
 - The first round of exhaustive testing (voltage, operating temperature) has been completed
 - With radiation testing this Fall, the first round of testing will be completed, paving the way to building the new TMB

Questions?

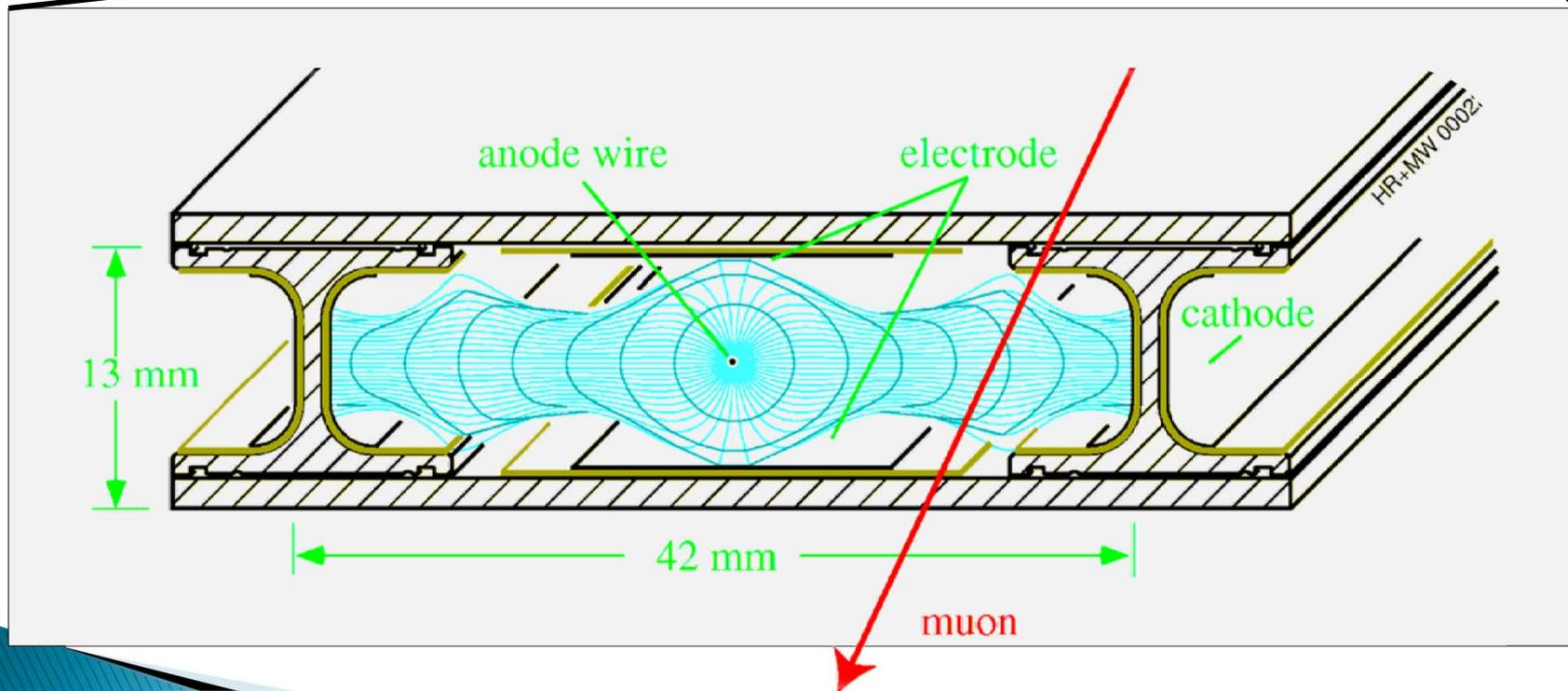


- ▶ More details



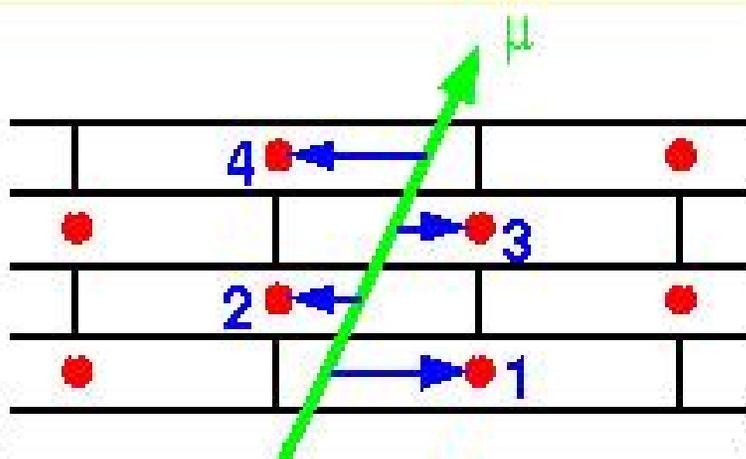
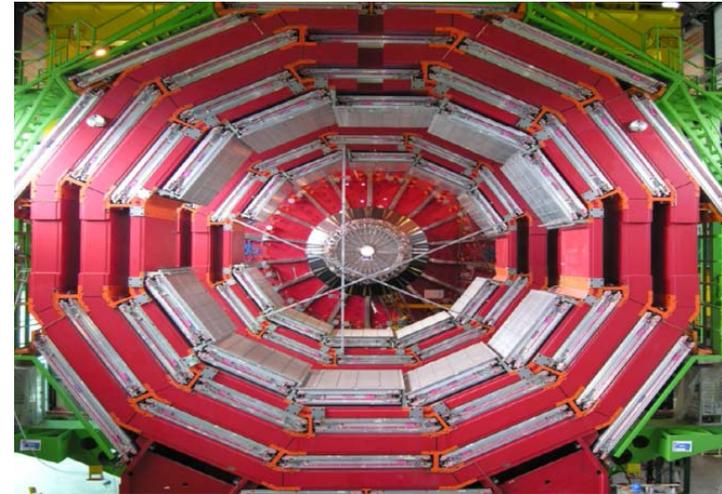
Barrel Region

Drift Tube Chambers (DTs)



Barrel Region

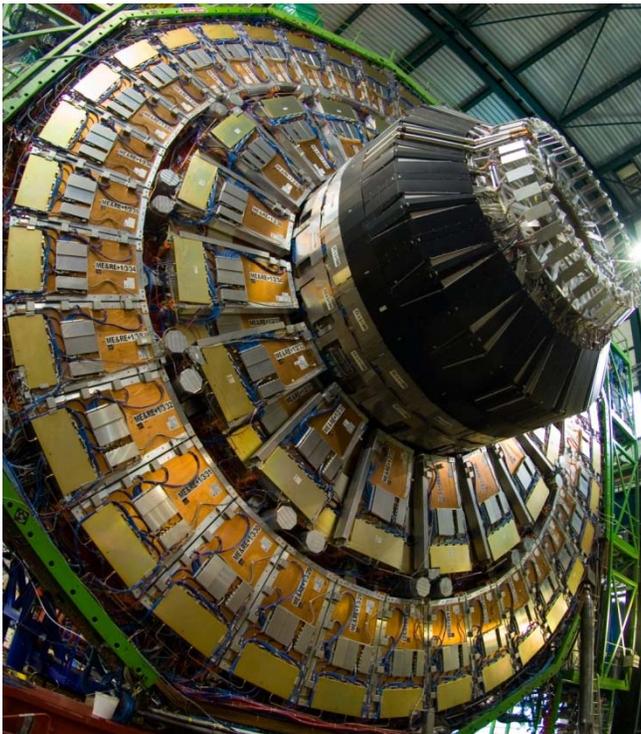
- ▶ 250 chambers organized into 4 layers
 - MB1–MB3: 5 wheels split into 12 sectors
 - MB4: 5 wheels split into 14 sectors



- ▶ MB1–MB3 Chambers:
 - 12 planes of aluminum DTs
 - Top and bottom “superlayers” have 4 planes of $r-\phi$ measuring DTs
 - Middle “superlayer” has 4 planes of z measuring tubes
- ▶ MB4 Chambers
 - 8 planes of aluminum DTs
 - All $r-\phi$ measuring tubes

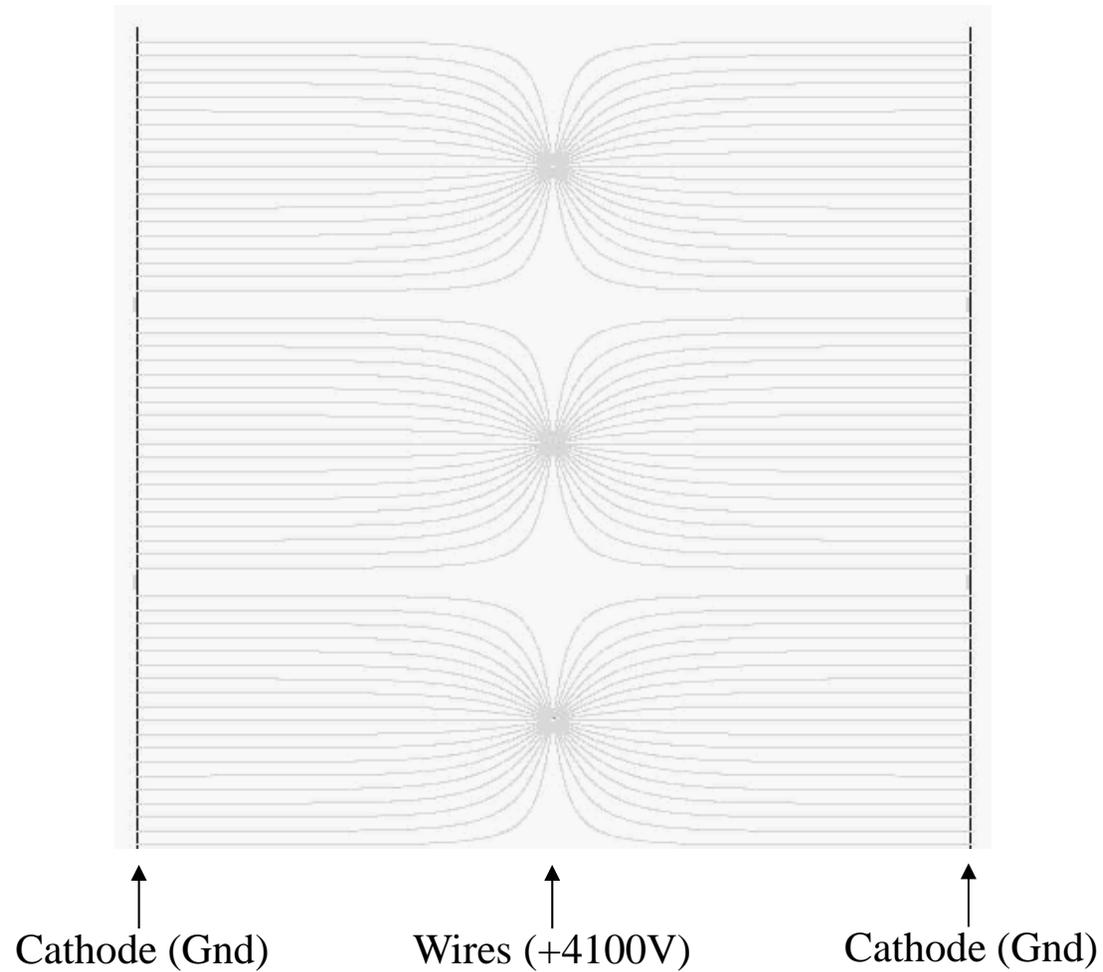
End Cap Region

Continued

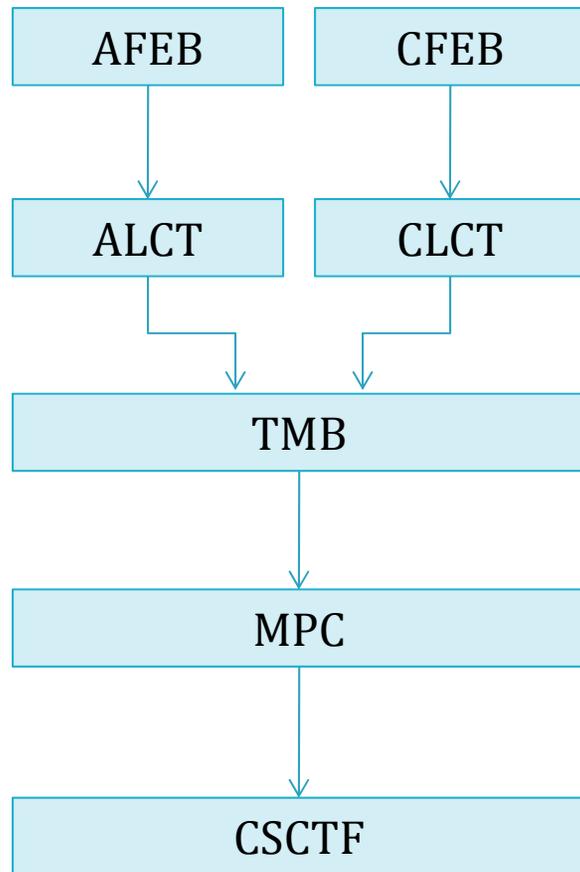


- ▶ ME1 divided into 4 rings
 - ME1 / 1a, ME1 / 1b, ME1 / 2, ME1 / 3
 - Each ring has 36 chambers covering 10° in ϕ
- ▶ ME2–ME4 divided into 2 rings
 - ME2(-4)/1, ME2(-4)/2
 - Inner rings have 12 chambers covering 20° in ϕ
 - Outer rings have 36 chambers covering 10° in ϕ

CSC Avalanche Model

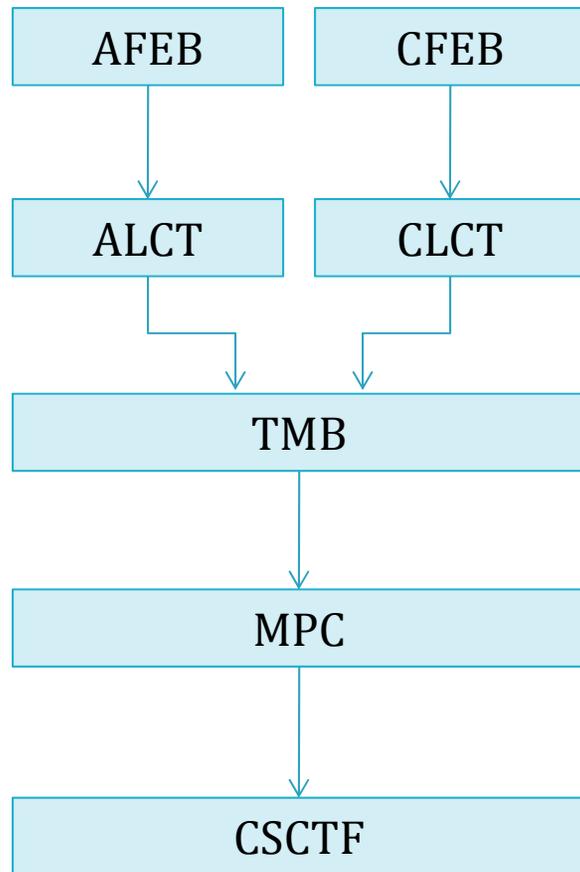


CSC Trigger Path



- ▶ Anode/Cathode Front End Board (AFEB/CFEB)
 - Report which anode wire or cathode strip groups receive hits
- ▶ Anode/Cathode Local Charge Tracks (ALCT/CLCT)
 - Find tracks in hit patterns in cathode strips and anode wires that point back toward the collision vertex
 - Up to 2 cathode LCTs and 2 anode LCTs from each chamber sent to TMB
- ▶ Trigger MotherBoard (TMB)
 - Cathode and anode projections from one chamber are combined into 3D LCTs
 - LCTs assigned vectors (position, direction, bunch crossing, quality)

CSC Trigger Path



▶ Muon Port Card (MPC)

- Receives all LCTs from one 60° sector of 1 station of ME2–ME4 or one 20° sector of ME1
- Selects the 3 best and sends them to the CSC Track Finder (CSCTF)

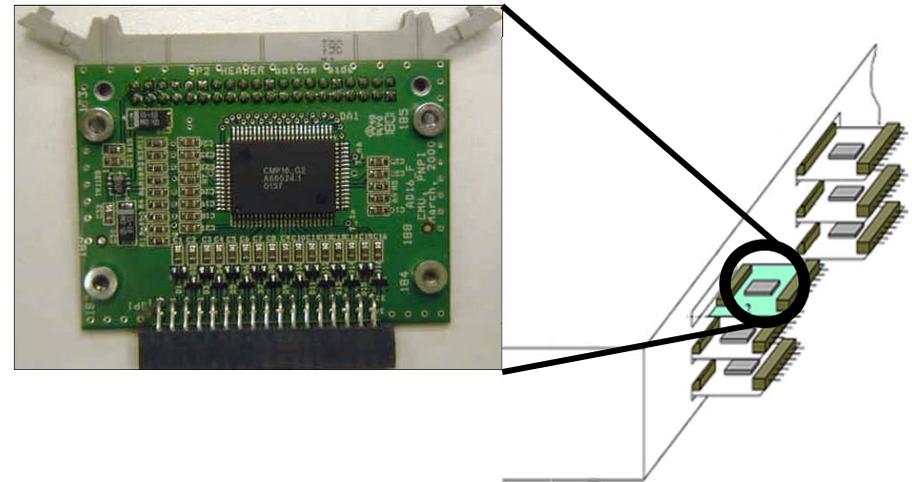
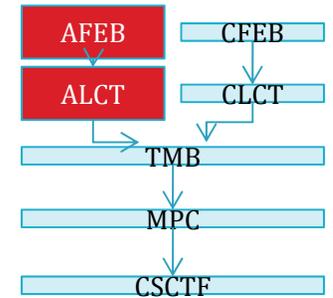
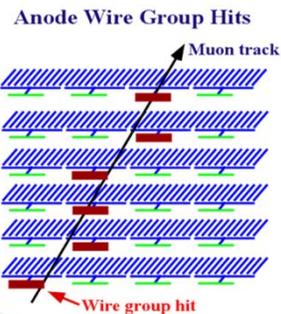
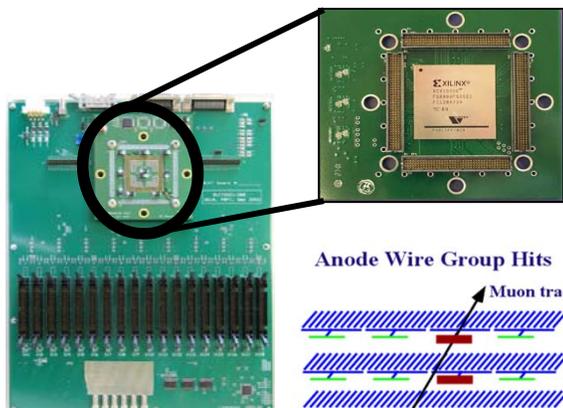
▶ CSC Track Finder (CSCTF)

- Builds tracks from LCTs from different stations compatible with a muon originating from the collision vertex
- Assigns transverse momentum value to the new muon track
- Selects the 4 best tracks in entire CSC system and forwards them to the Global Muon Trigger (GMT)

CSC Trigger Path

Anode Front End Boards (AFEB)

- ▶ Receives the signals from the anode wire groups
- ▶ Amplifies them
- ▶ Selects the signals that are over the preset threshold



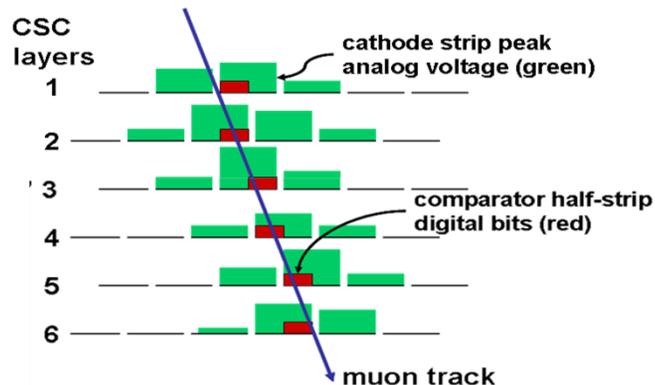
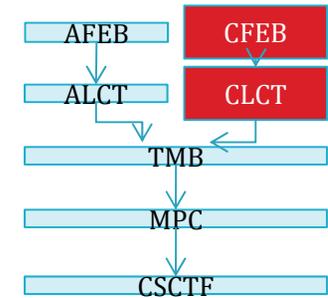
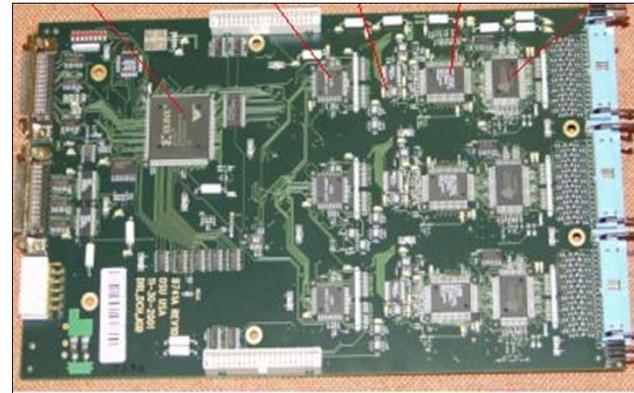
Anode Local Charged Tracks (ALCT)

- ▶ Generates 2D Anode “Local charged track” (LCT) for possible muon crossings
- ▶ Stretches the hits from the AFEB to allow for the up to 50 ns drift time in the anode wires
- ▶ Identifies the bunch crossing

CSC Trigger Path

Cathode Front End Boards (CFEB)

- ▶ Receives the signals from the cathode strips
- ▶ Amplifies signals
- ▶ Shapes them into semi-Gaussian voltage pulses
- ▶ Locates the center of the charge clusters to a $\frac{1}{2}$ strip accuracy



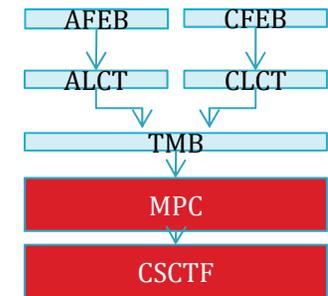
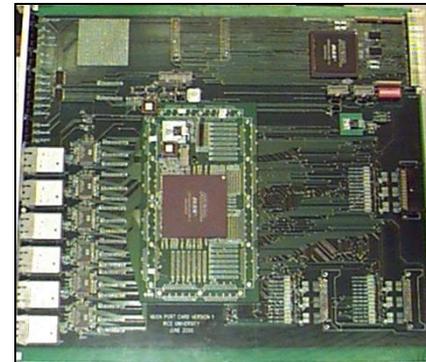
Cathode Local Charged Tracks (CLCT)

- ▶ Located on the Trigger MotherBoard
- ▶ Time-stretches the incoming hits
- ▶ Generates 2D Cathode LCTs by timing coincidence of hit patterns

CSC Trigger Path

Muon Port Card (MPC)

- ▶ Receives all LCTs from predefined groups of chambers from the same station
- ▶ Selects the 3 best and sends them via optical fiber to the CSC Track Finder (CSCTF)



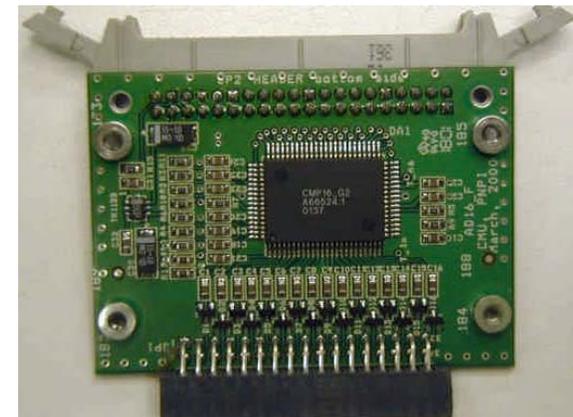
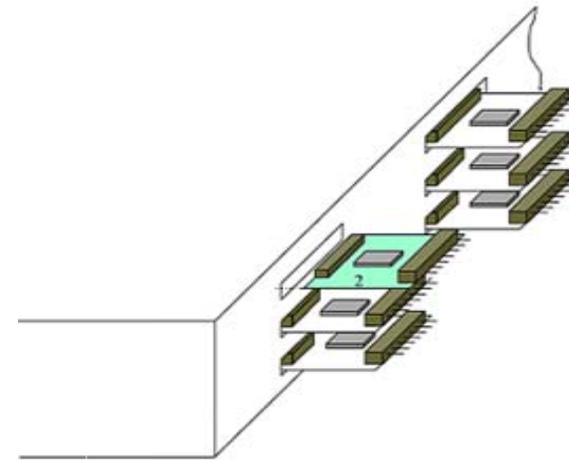
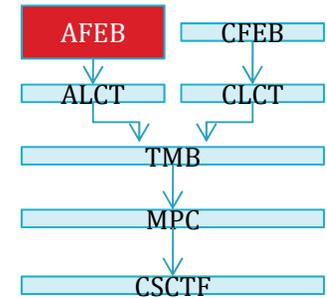
CSC Track Finder (CSCTF)

- ▶ Takes 2 LCTs from different stations and tests whether they are compatible with a muon originating from the collision (with appropriate field conditions)
- ▶ If a match is found, the CSCTF assigns a momentum value to the muon track
- ▶ Selects the 4 best muon candidates from the entire CSC system and sends them to the Global Muon Trigger

CSC Trigger Path

Anode Front End Boards (AFEB)

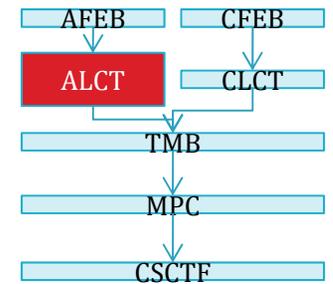
- ▶ Receives the signals from the anode wire groups
- ▶ 16 channel amplifier–shaper–discriminator ASIC
 - Amplifies them
 - Selects the signals that are over the preset threshold with precise time accuracy



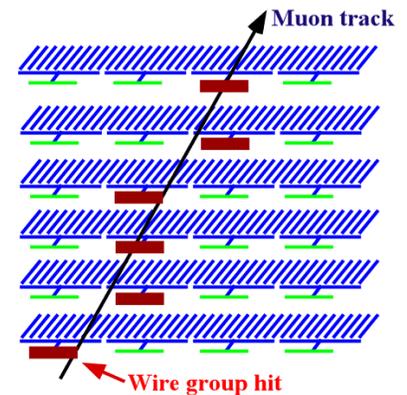
CSC Trigger Path

Anode Local Charged Tracks (ALCT)

- ▶ Stretches the hits from the AFEB to 6 bunch crossings to allow for the up to 50 ns drift time in the anode wires
- ▶ Generates 2D LCT for possible muon crossings
 - Low coincidence level used to establish timing
 - Higher coincidence level used to establish the possibility of an existing muon track
- ▶ Multilayer coincidence technique used to identify the bunch crossing

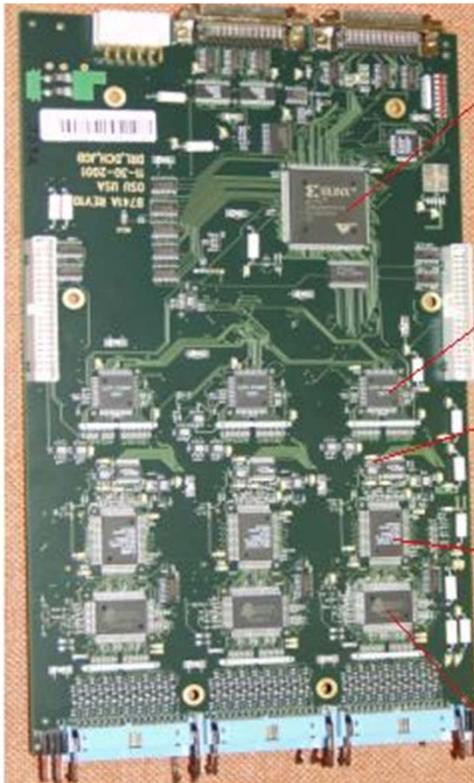
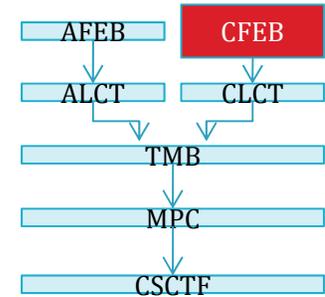


Anode Wire Group Hits



CSC Trigger Path

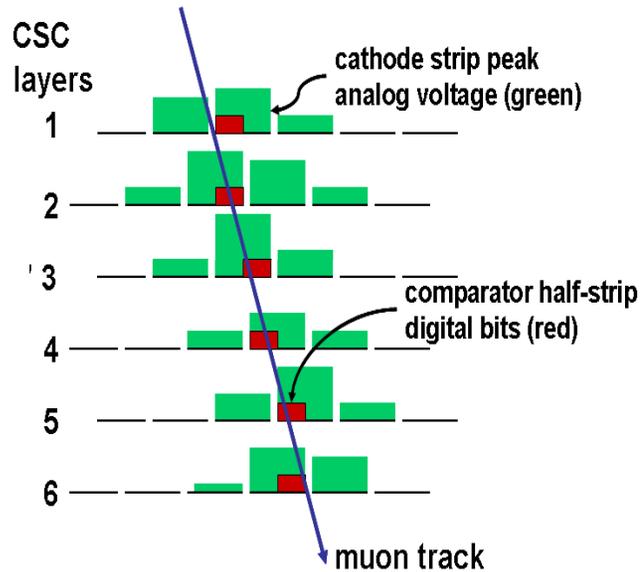
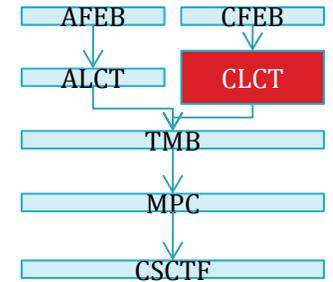
Cathode Front End Boards (CFEB)



- ▶ Receives the signals from the cathode strips
- ▶ 16 channel amplifier–shaper ASIC
 - Amplifies signals
 - Shapes them into semi–Gaussian voltage pulses
- ▶ Comparator ASIC
 - Locate the center of the charge clusters to a $\frac{1}{2}$ strip accuracy
 - Marks the time of the pulse

CSC Trigger Path

Cathode Local Charged Tracks (CLCT)



- ▶ Located on the Trigger MotherBoard
- ▶ Time-stretches the incoming hits by several bunch crossings to allow for the up to 75 ns drift time in the cathode strips
- ▶ Generates 2D LCTs by timing coincidence of hit patterns in the 6 layers of a chamber consistent with high momentum muon tracks

Electronics Challenges

- ▶ Cannot collect and reconstruct all of the events which occur during the collision
 - Must decide which events are “interesting” and should be kept and which events can be disregarded
 - Many choices to make in a short period of time in order to maintain the efficiency and integrity of the system
 - Products of interesting events can be confused with those of non-interesting events
- ▶ High radiation environment requires radiation tolerant electronics
- ▶ Large number of electronics compounds potential problems

