Upgraded Muon Trigger Development for the CMS Experiment at the LHC

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The Standard Model of Particle Physics

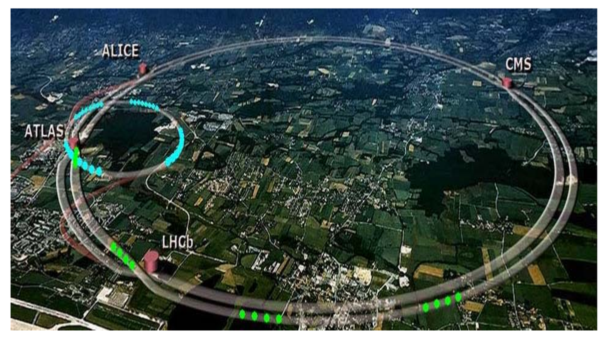
The Standard Model (SM) of particle physics describes the fundamental particles and their interactions. Despite its ability to make predictions which match experimental data with tremendous accuracy, it still has shortcomings. One of these shortcomings is its inability to explain the origin of the masses of the particles it describes. A theoretical solution is the existence of yet another particle, the Higgs boson, which interacts with the other particles of the SM and gives them their mass.

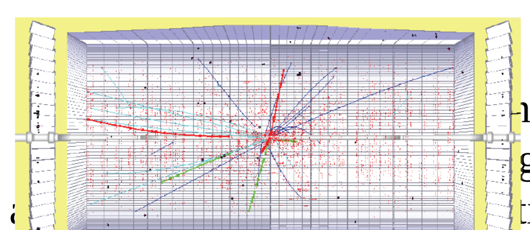
The Large Hadron Collider

The Large Hadron Collider (LHC) is the new highest energy particle accelerator, which collides high energy proton beams to explore the world at the smallest scales ever for new phenomena and interactions.

Search for Higgs Boson at LHC

It is widely expected that the collisions at the LHC will produce the Higgs boson. Discovery of the Higgs boson requires observing its signature decay products in detectors.

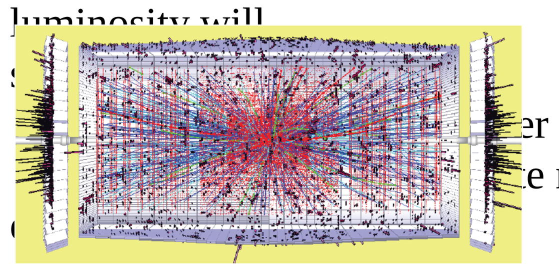




Collision reconstruction at current LHC luminosity

LHC Upgrade

…nal LHC beam luminosity may be too … gh data to discover and a… ties of the Higgs boson or other new physics in a reasonable time period. The beam luminosity will therefore be increased in the next s… years. This will greatly increase number of … er collision seen by the detector … e new challenges for …



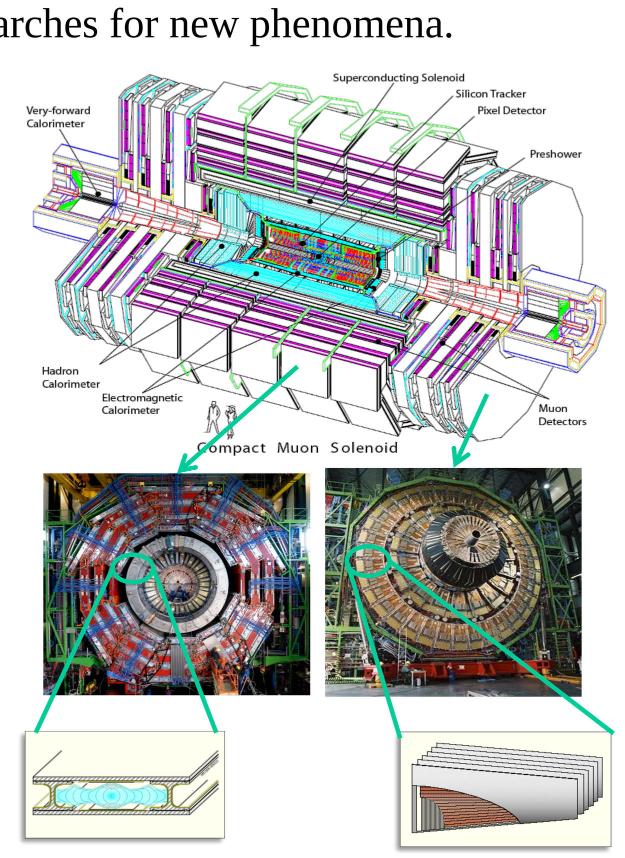
Collision reconstruction at upgraded LHC luminosity

Compact Muon Solenoid (CMS) Experiment and Muon Detection

CMS is one of two general purpose detectors at the LHC used to perform a broad range of physics measurements and searches for new phenomena.

Muon Detection

Unlike other charged particles, muons are good at penetrating material. Placing the muon sub-detector behind the other detectors (thus providing effective shielding) ensures all we see is muons. Coincidentally, muons also provide one promising search mode for discovery of the Higgs boson: $pp \rightarrow H \rightarrow ZZ \rightarrow \mu^-\mu^+\mu^-\mu^+$



Barrel and Endcap Regions

- The barrel region of the detector uses "drift tubes" (DT) to reconstruct muons
- The endcap region of the detector uses "cathode strip chambers" (CSC)

Muon Trigger

Due to the high collision rate at the LHC (every 25 ns), it is impossible to record every collision event. A "trigger" is therefore implemented in electronics to pick out and record only interesting events. To be effective, this selection process must be extremely fast, requiring state of the art electronics.

Muon Trigger Upgrade

Monte Carlo Simulation and Trigger Emulation

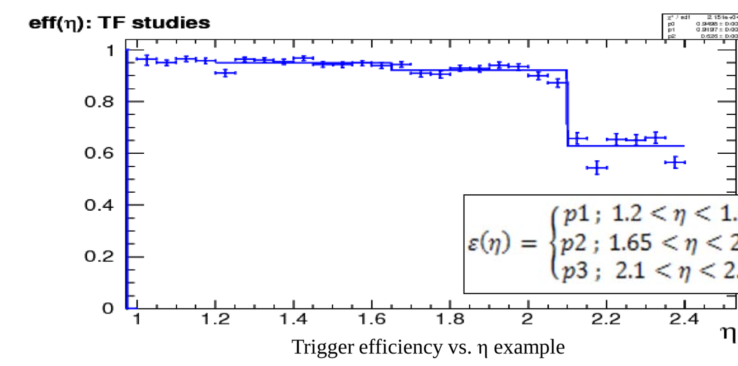
Monte Carlo software simulation is used to model the generation of collision events, passage of particles through matter, detector electronics response and trigger logic. This data is used to study the performance of the trigger in different scenarios, e.g.: low and high luminosity, current or upgraded muon trigger, different trigger p_t thresholds.

Trigger Efficiency Parameterization

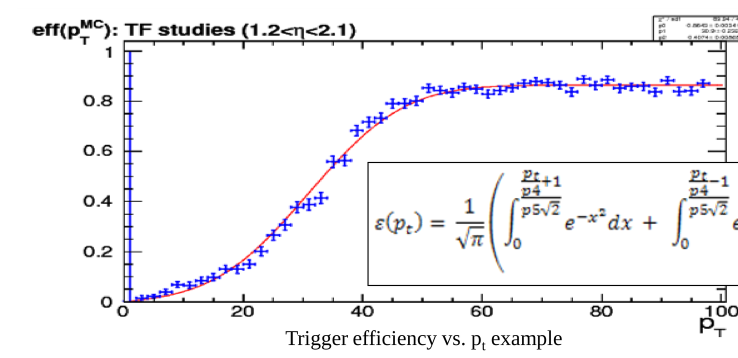
Probability that the trigger will flag and reconstruct a true muon in an event. For each scenario, efficiency depends on η (muon angle from the beam) and p_t (muon transverse momentum). We parameterize and fit each dependence to obtain the final efficiency:

$$\varepsilon_{final}(\eta, p_T) = \varepsilon(\eta; p1, p2, p3) \times \varepsilon(p_T; p4, p5)$$

A CMSSW function has been written to emulate trigger performance for physics studies with the upgraded detector.



Trigger efficiency vs. η example

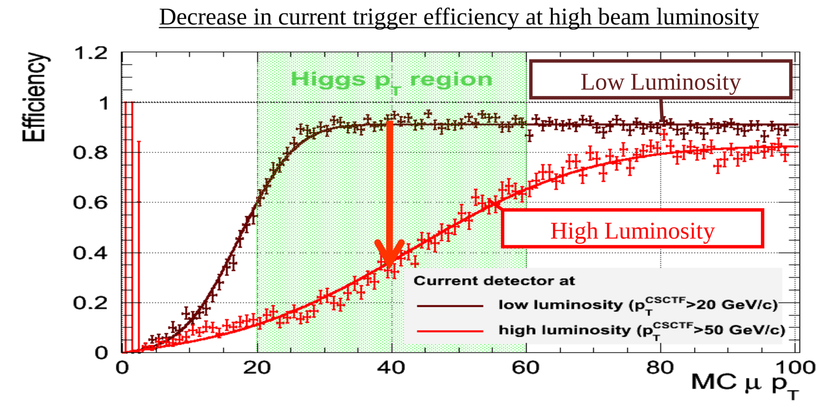


Trigger efficiency vs. p_t example

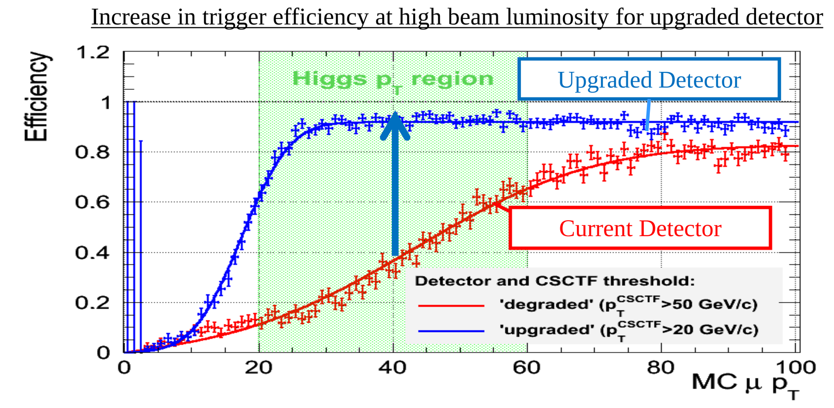
CMS Upgrade

Without an upgrade, the current trigger must enforce a high p_t threshold 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. The upgraded detector will be able to handle the higher rates while still enforcing a low p_t threshold.

Decrease in current trigger efficiency at high beam luminosity



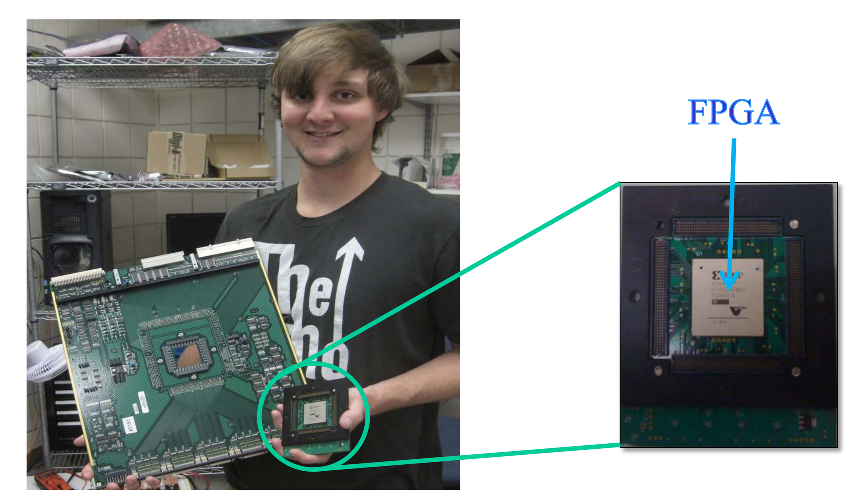
Increase in trigger efficiency at high beam luminosity for upgraded detector



Trigger MotherBoard (TMB) Upgrade

One of the critical updates is the TMB upgrade:

- High efficiency requires a more intelligent algorithm to decrease the dead time
- Need a faster, more robust FPGA (Vertex 2 → Vertex 6) and therefore a new board design

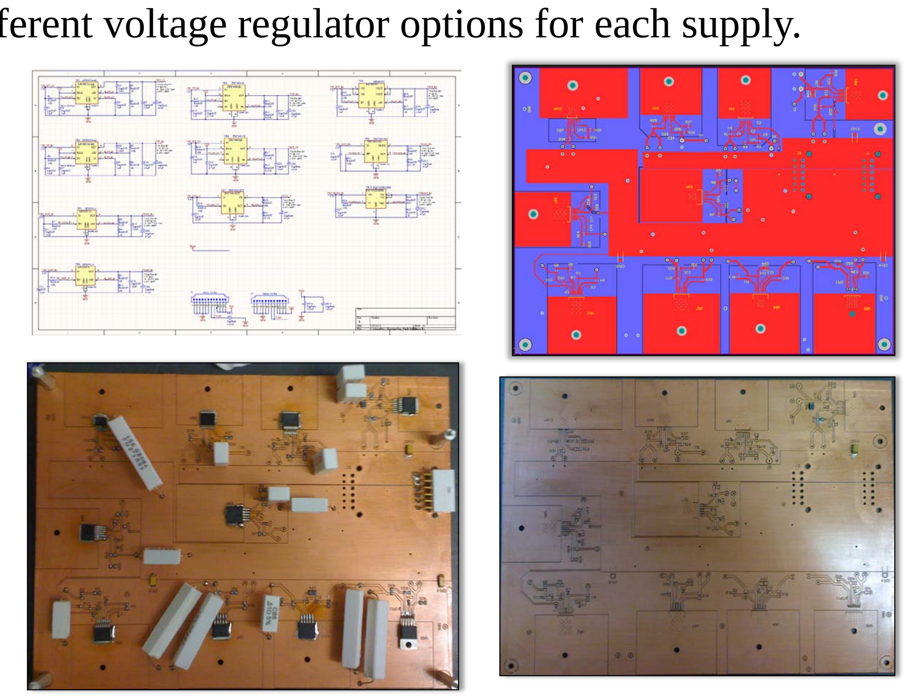


Voltage Regulator Testing: Board Design

The FPGA going on the new TMB requires 6 stable voltage inputs: 1V (x2), 1.2V, 1.8V, 2.6V, 2.9V. Boards were designed and manufactured in order to test several different voltage regulator options for each supply.

Design and Testing Steps

1) Design circuits to meet the required voltage, current, power, etc. specifications using the device datasheet
2) Schematic and Printed Circuit Board (PCB) layout using Altium Designer
3) Manufacture board in the TAMU Physics Electronics Shop: drill holes, plate with copper, etch tracks
4) Solder parts
5) Test circuits for voltage stability, operating temperature and radiation tolerance



Voltage Regulator Testing: Stability Analysis

Electronics system requires that that voltage levels into the FPGA remain stable.

Testing and Analysis

Test board was powered for extended periods of time (typically multiple 12 hour runs). Regulators were monitored periodically for instabilities in the output voltages (± 10mV).

Results

All tested regulators met stability requirements during continuous operation in the laboratory.

Voltage Regulator Testing: Thermal Analysis

All regulators used on the TMB must operate at a temperature reasonably below their manufacturer specified maximum to ensure a long lifetime for the device.

Testing

- Thermal images were taken periodically (simultaneous with the voltage stability tests) with a Flir Extech i5 Thermal Imager
- The images were analyzed using the Flir software to determine the external operating temperature of each regulator
- Several "operation modes" were used to simulate possible working conditions in the CMS cavern environment: natural convection, with and without heat sinks, with and without air flow

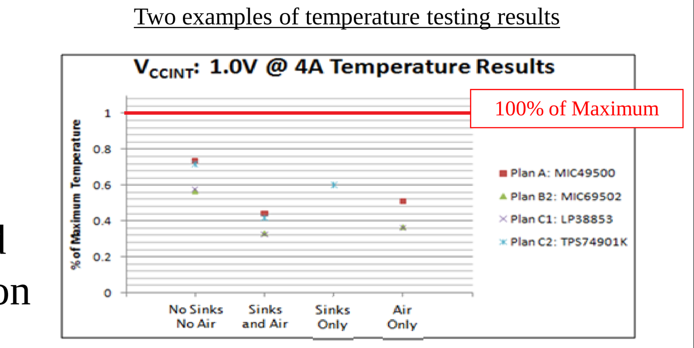
Analysis

Temperature measurements were taken on the case of the device, but the manufacturer specified maximum temperatures are given for inside chip. The measured temperature was converted to the internal silicon ("junction") temperature using the thermal resistance given by the manufacturer and the power the device is dissipating:

$$T_J = T_C + P_D \times R_{\theta JC}$$

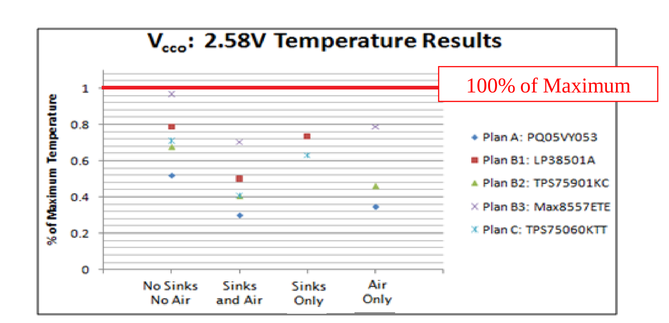
The ratio of measured temperature to specified maximum temperature was used for comparison

Two examples of temperature testing results



Results

- All operated below their maximum specified junction temperature
- Some were too close to their maximum to be considered safe for operation at LHC.



Heat dissipation methods

- Air flow was determined to be the most effective method for removing heat from the regulator circuits (~30% - 40% decrease)
- Thermal heat sinks had a much smaller effect, (~10% decrease), but could be considered as a complementary heat dissipation tool.

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