Upgrade
of the L1 Muon Trigger
for CMS

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Motivation and Requirements

Current design for: 25 ns, L ≤ 1 x 10▲34, PU ~ 25

After LS1	# bunches	Luminosity (L) Hz/cm^2	Pile-up (PU)
25 ns	2760	9.2 × 10▲33	21
25 ns low emit	2320	1.6 × 10▲34	43
50 ns	1380	0.9–1.7 × 10▲34	40–76
50 ns low emit	1260	2.2 × 10▲34	108

Requirement after LS1: L > 2 x 10▲34, PU > 50

Constraint: Max L1 rate: ≤ 100 kHz (< 1kHz logging)

Expect 6x trigger rate (3x – Lu and 2x - energy) increase after LS1 (same thresholds)

Rising trigger thresholds (2x for Single Muon) to retain trigger rate will results in a detrimental impact on the physics acceptance.

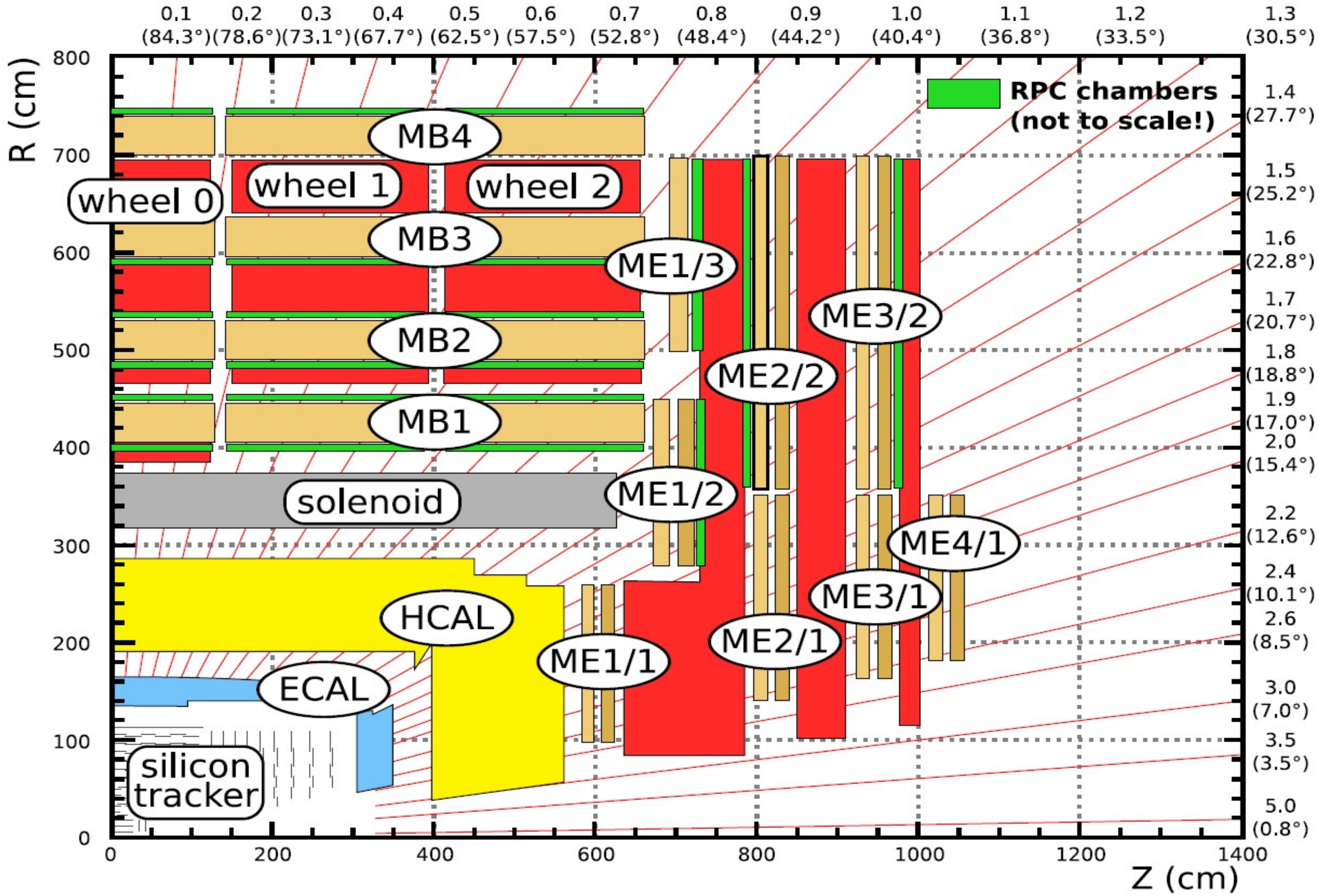
After LS3: L= 5 x 10▲34, Max L1 rate ≤ 1 MHz (10 kHz logging)

Strategy

Improve rate reduction capability without affecting efficiency

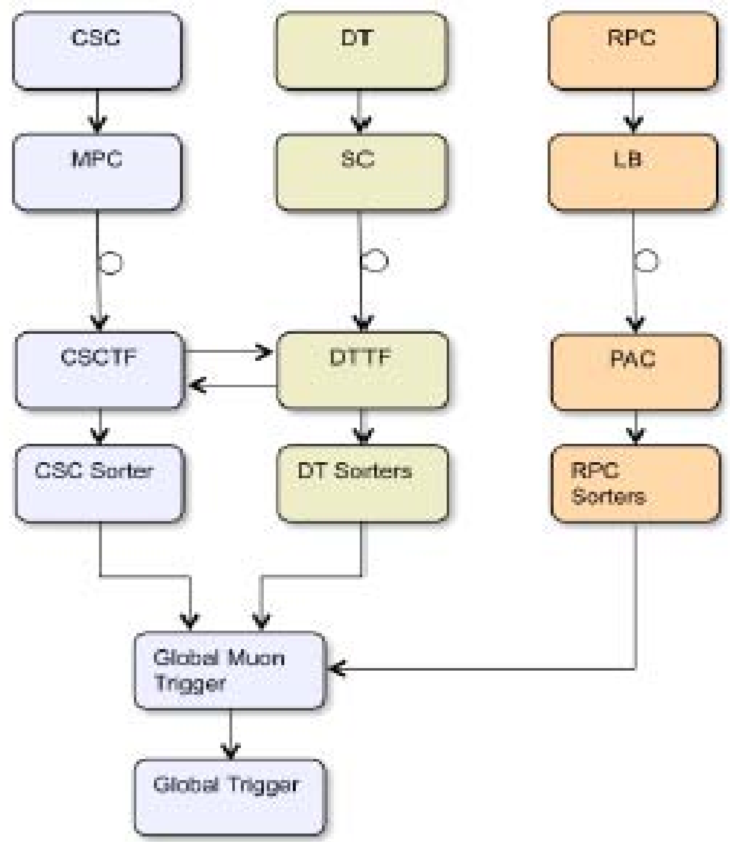
Present CMS Muon System

DT (MB) < 1.2 **RPC (RE, RB) < 1.6** **0.9 < CSC (ME) < 2.4**



0.9 < CSC-DT Overlap < 1.25

Present Muon Trigger System



Preserves the complementarity and redundancy of the three separate muon detection systems until they are combined at the GT input

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CSCTF <= MPC track segments
DTTF <= SC track segments
PAC <= LB hits

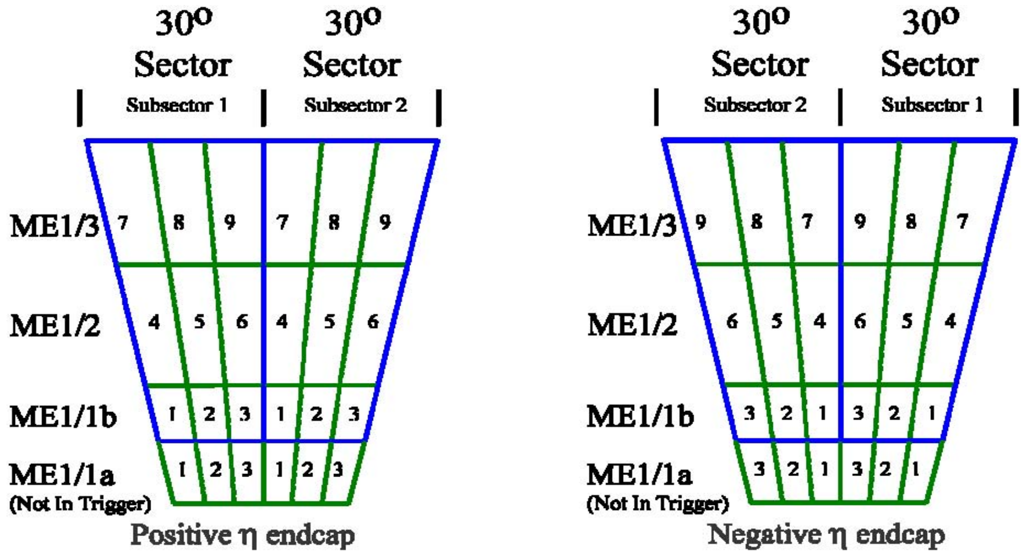
CSCTF => up to 4 candidates
DTTF => up to 4 candidates
PAC => up to 4+4 candidates

Each candidate <= {p_T, $\varphi(0.05)$, η, Q}

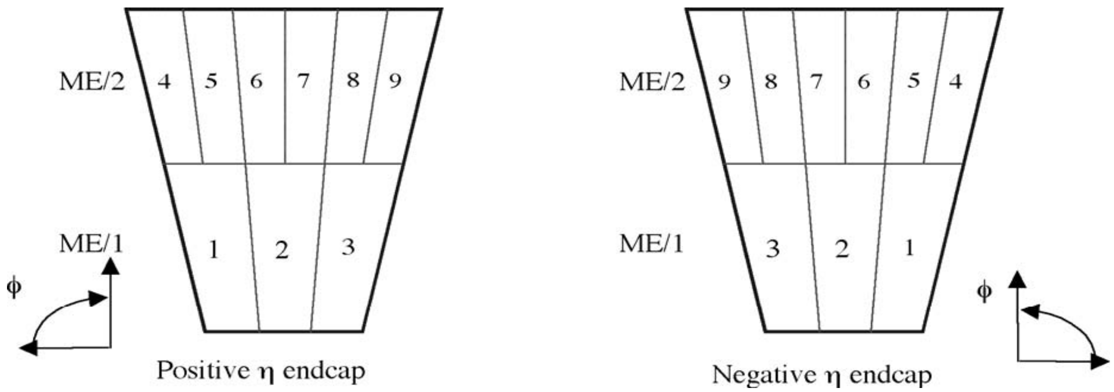
GMT merges candidates to eliminate fake muons, assigns p_T

TF – Track-Finder
PAC – PAttern Comparator
MPC – Muon Port Card
SC – Sector Collector
LB – Link Box

Cathode Strip Chambers

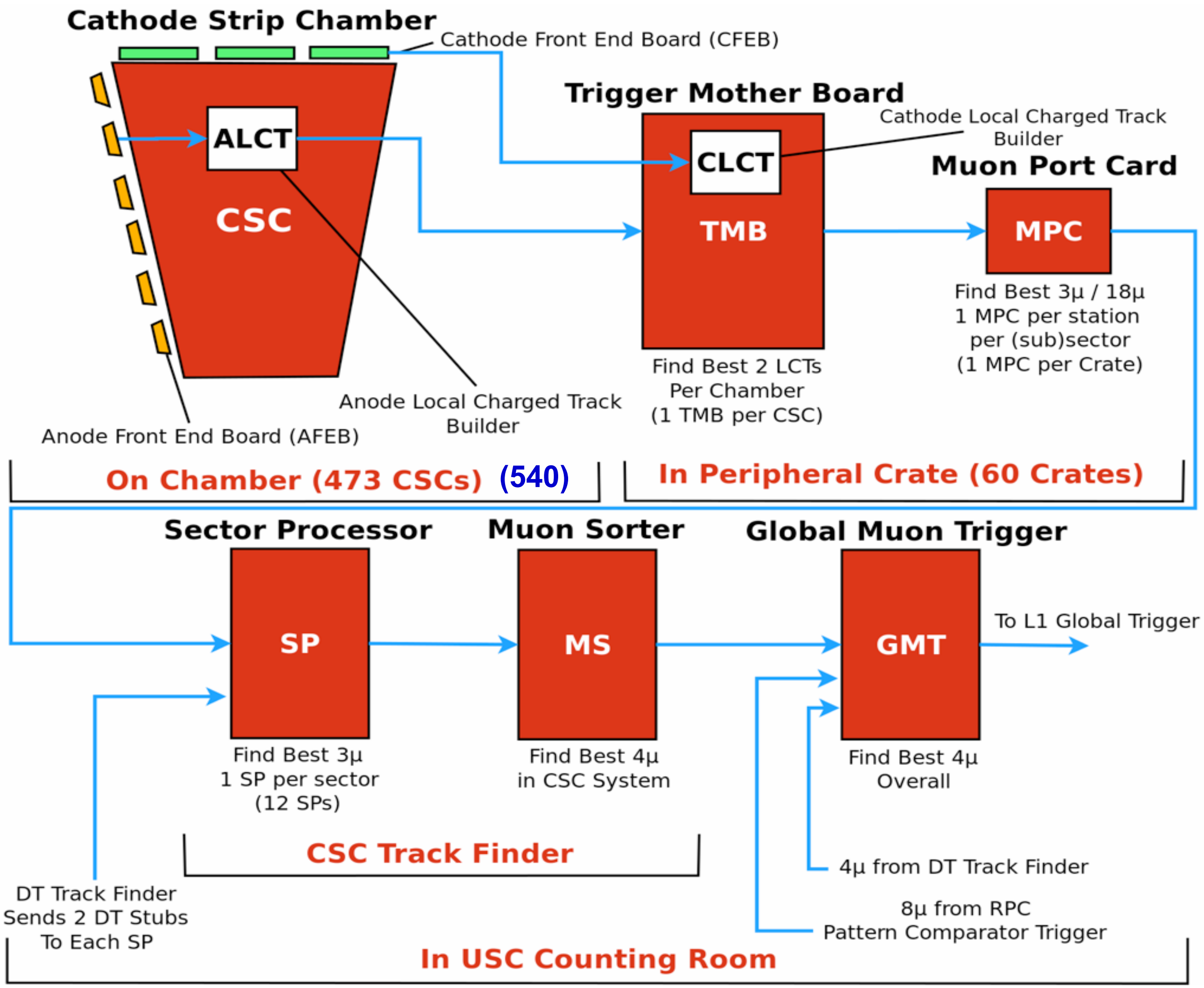


ME1

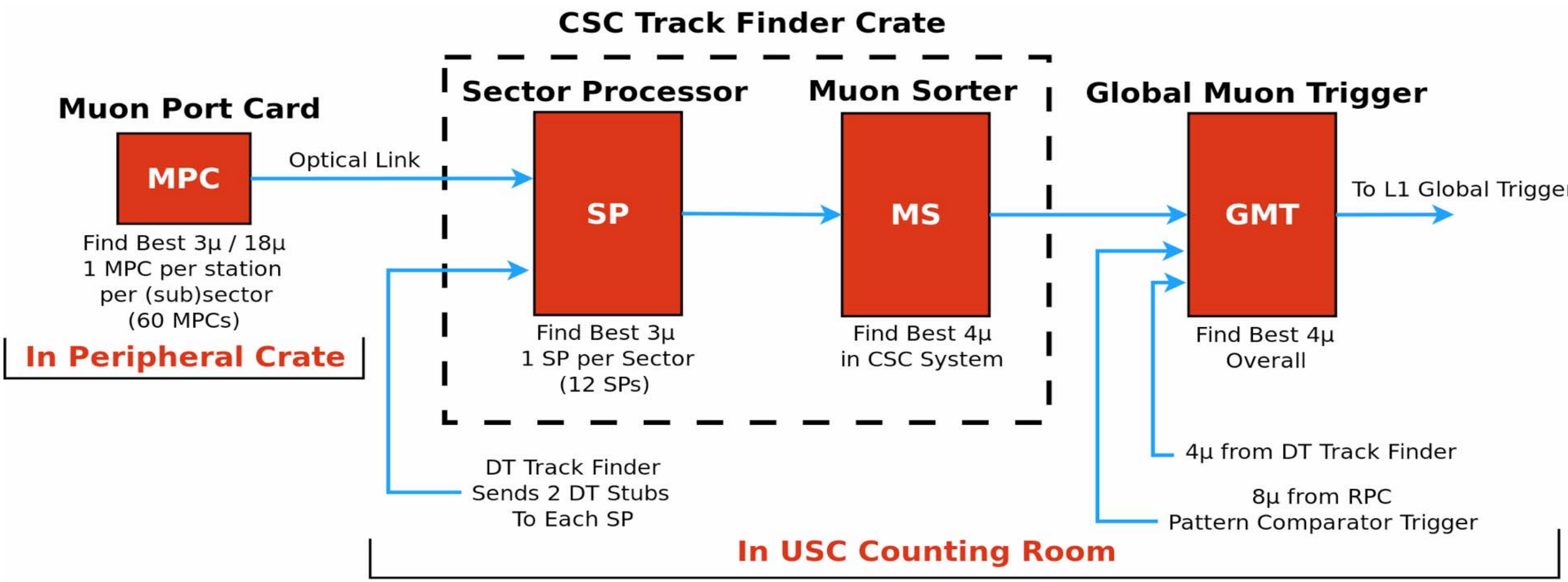


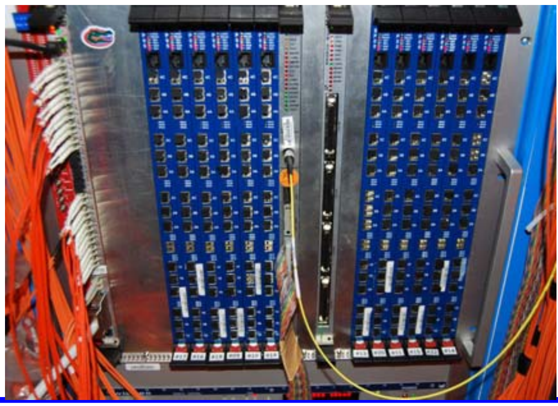
ME2
ME3
ME4

CSC Electronics



Present CSC Track-Finder



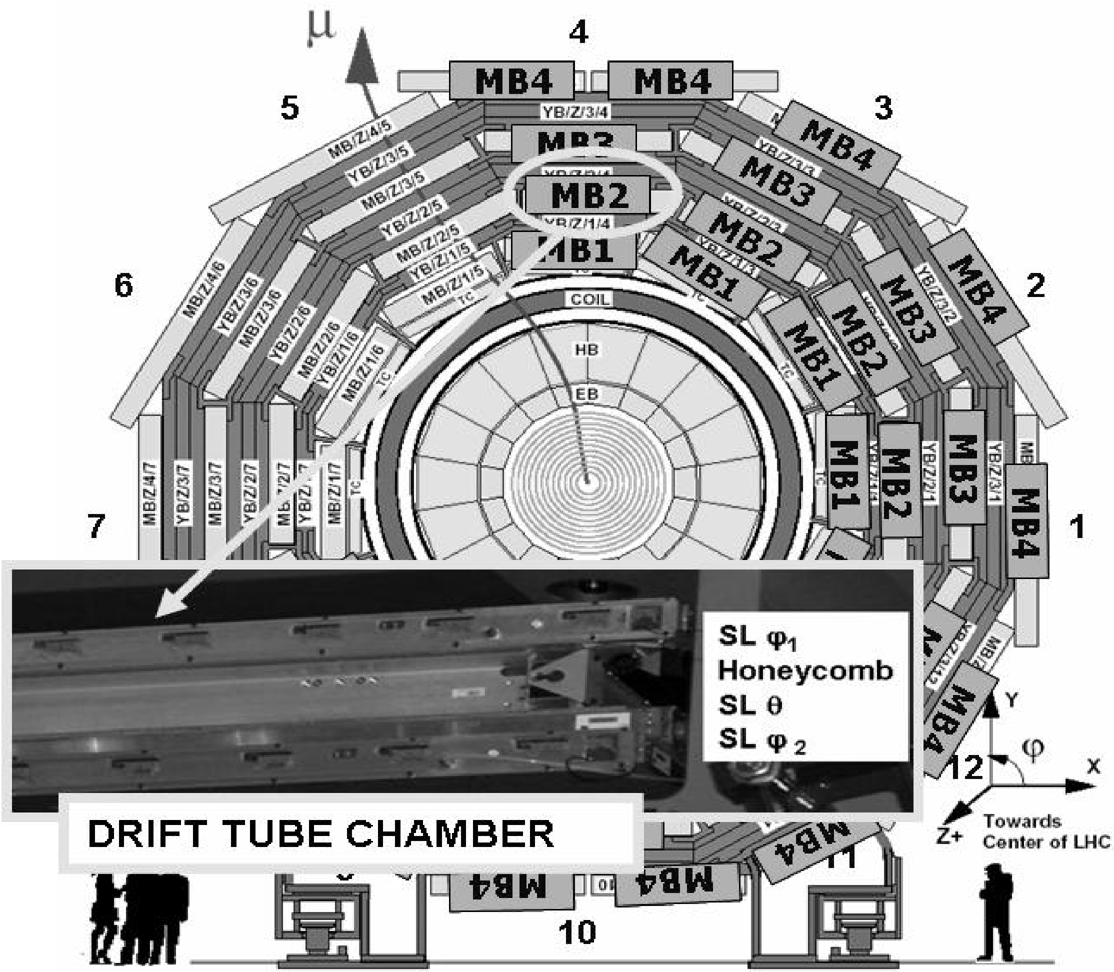


CSCTF Algorithm

Track reconstruction in Sector Processor

1) conversion of trigger primitives into geometrical parameters {η,φ} .
2) multiple Bunch Crossing Analysis (BXA) => (+2BX)
3) Extrapolation Units (EUs) in η and φ => up to 210
4) Track Assembly Units (TAUs) – (12 collision + 6 halo)
5) Transverse Momentum (Pt) Assignment Units (PAU) (η, φ, Δφ)
6) Final Selection Unit (FSU) (with ghost cancellation)
7) Output Multiplexer (OM) (priority of collision over halo)
8) BX Correction Unit (BXC) (to second trigger primitive)
9) Pt Assignment Lookup Table (Pt LUT)
(outputs encoded 5-bit Pt and 2-bit track quality (value)

Drift Tube Chambers



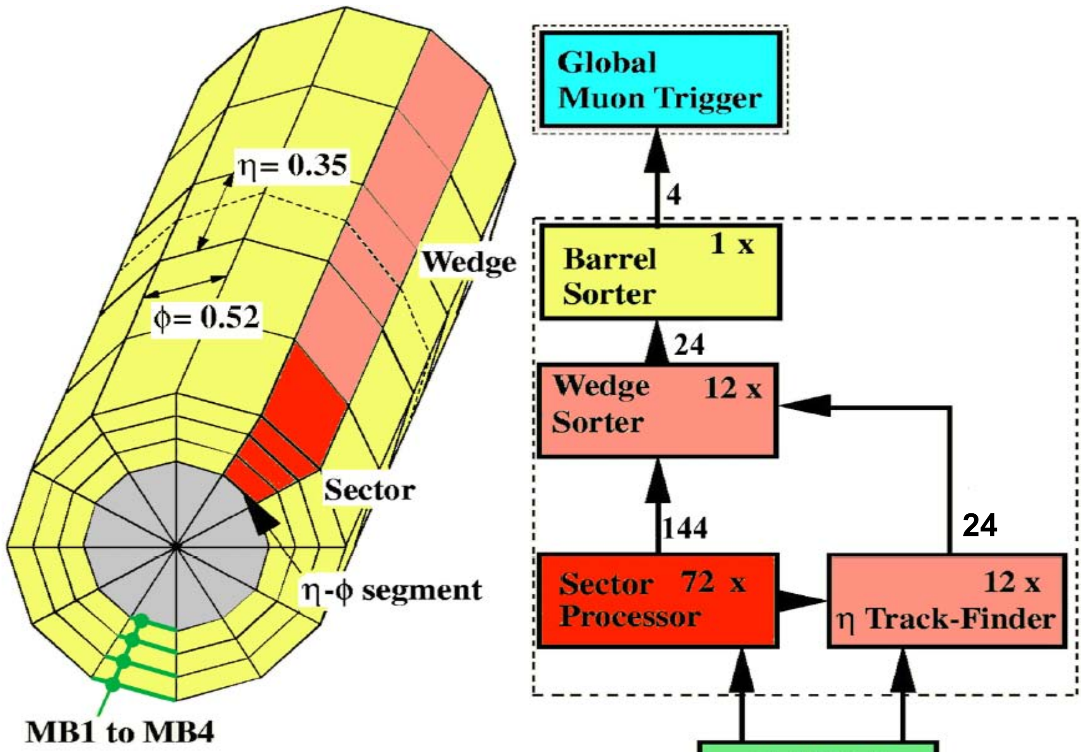
Z = -2, -1, 0, 1, 2 according to the Barrel wheel concerned

Present DT Track-Finder

PHTF in r-φ plane consists of
72 SPs in 6 crates

Each SP delivers 2 candidates per BX

72 = 12 wedges (30°) x 6 sectors



12 ETTF in r-z plane
(one per wedge)

MB1-MB3 data only,
delivers up to 2 candidates per

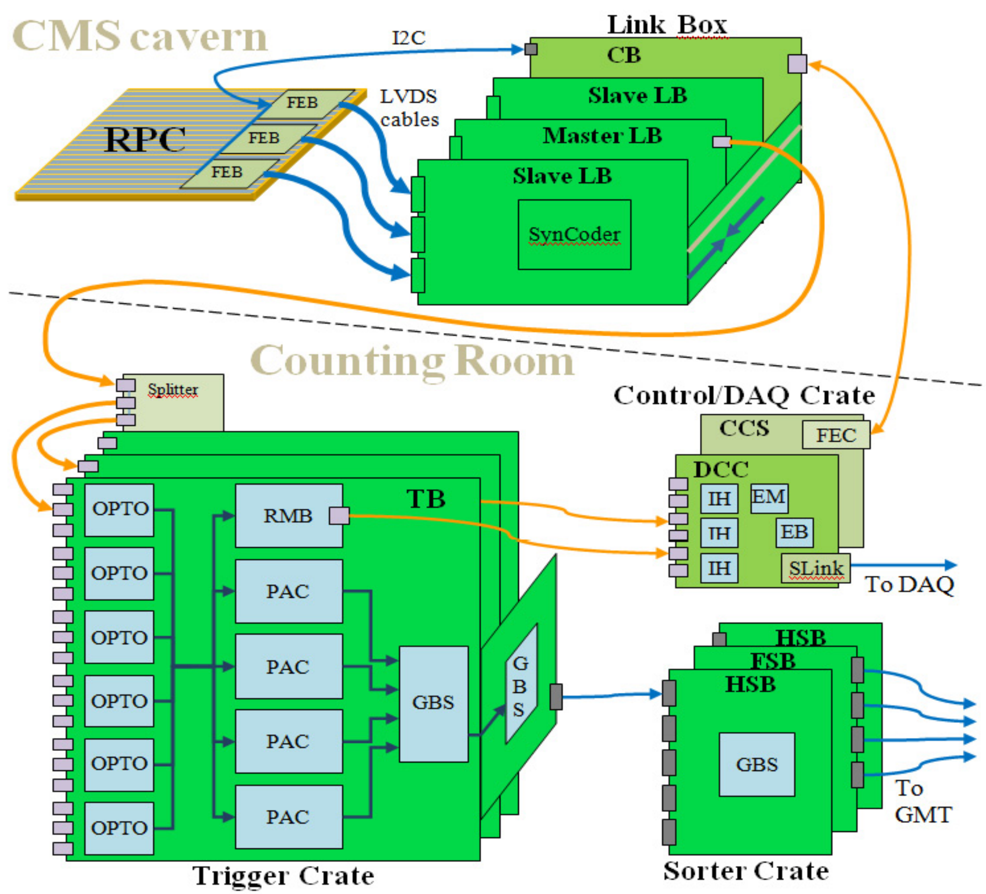
Present RPC Trigger

RPC – double gap chambers
operated in avalanche mode
RB – 4 stations, 6 layers each
RE – 4 stations, 3 layers each
25 towers in eta,
each subdivided into 144 segments
in phi

444 Fibers

Pattern matching algorithm
in 12 trigger crates,
getting hits from 84 Link Boards to
84 Trigger Boards (up to 4
candidates per BX)

PAC has > 2 000 000 patterns
preloaded



Areas to Improve

The Muon Level-1 Trigger is identified as an area which may be improved to meet requirements

- Muon trigger measures the momentum of muons using the magnetic field in the steel yoke of the CMS solenoid;
- Its resolution degrades with increasing momentum.
- This can be improved
  - by maximizing the number of chamber hits along a muon trajectory
  - by improving the precision and number of position and angular measurements participating in the track fit applied in the trigger logic.
- Isolation criteria can be applied using the energy deposits in the calorimeter in order to further reduce the rate of muons from heavy flavor jets.

Constraint:

CMS data-taking must never be put at risk!

Upgrade Strategy

~~**Present Muon Trigger:**~~
~~**Preserves the complementarity and redundancy of the three separate muon detection systems until they are combined at the GT input**~~

Utilize the redundancy of the three muon detection systems earlier in the trigger processing chain

Combine muon hits at the input stage to the Muon Track-Finder layer rather than at its output

This new Muon Track-Finder will ultimately replace the separate track-finders for the Drift-Tube (DT) and Cathode Strip Chamber (CSC) muon triggers as well as the Resistive Plate Chamber (RPC) pattern comparator trigger.

Feasibility of the Muon Trigger Upgrade

Great progress in industry since 2000

Fiber links => 5x, 10x
Serial links => 10 Gb/s
FPGA => high speed, capacity, integration with serial links

Increase of flexibility

- High bandwidth optical links between trigger cards
- Latest Xilinx FPGAs (series 6, 7) with large logic resources
- Latest Xilinx FPGAs (series 6, 7) with up to 80 GTH Transceivers
- Large memory resources (for tabular calculations - LUTs)

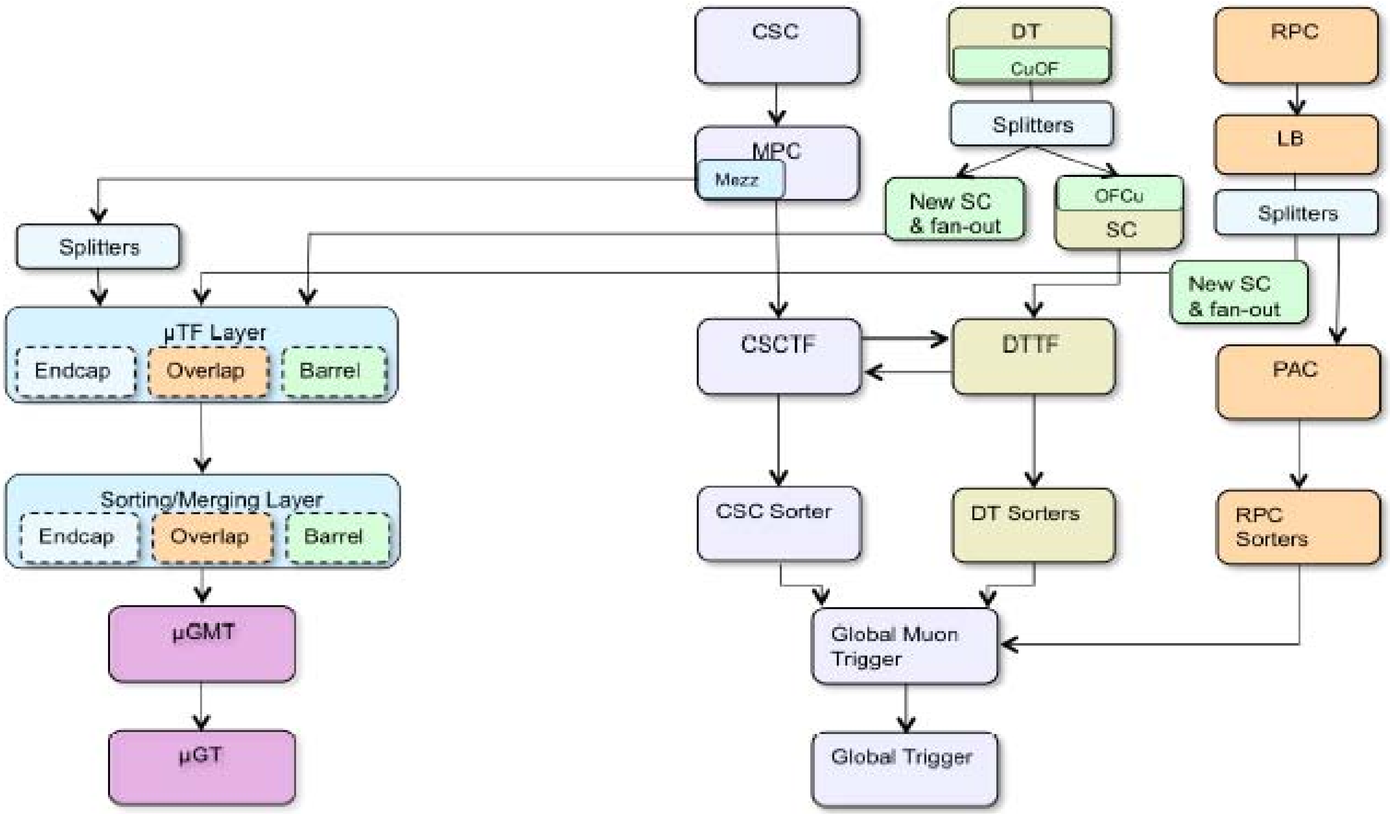
Base upgrade on small number of general purpose custom cards (vs current diversity)

Same on the software side

Implement cards in a telecommunication standard μTCA - 2006 (currently in VME64 – 1994/1997)

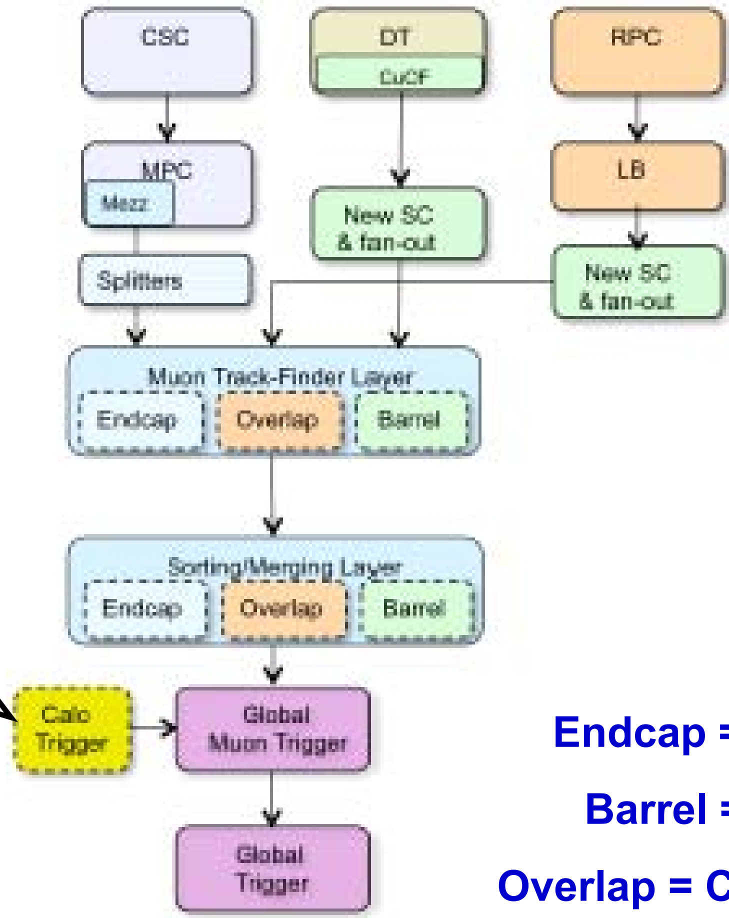
Commission (whole or slice) in parallel with the current trigger

Upgraded and Present Muon Trigger



CMS data-taking must never be put at risk!
When commissioning updated muon trigger

Upgraded Muon Trigger



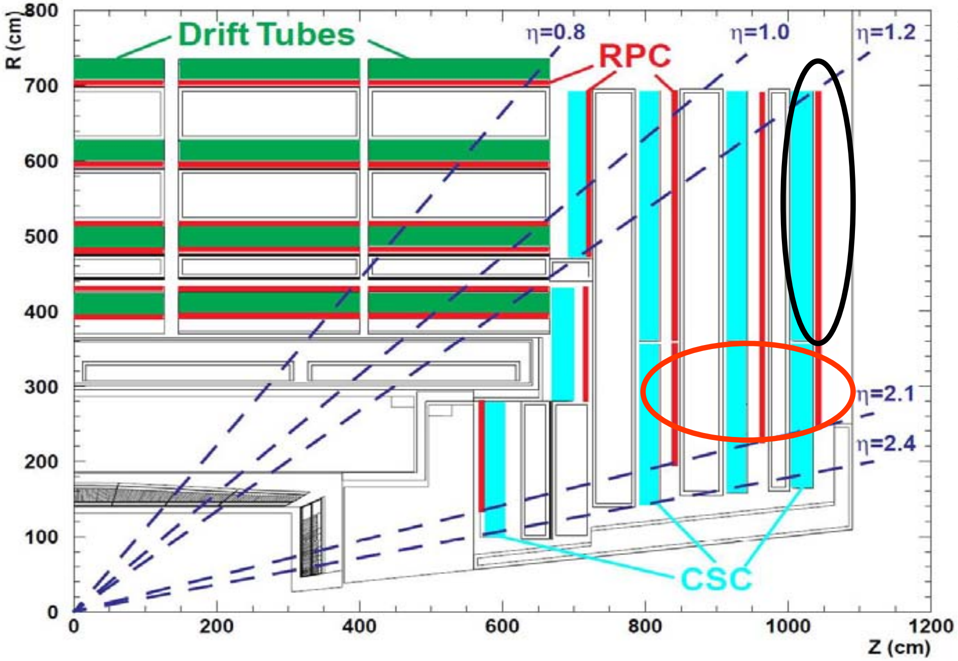
Isolation criteria can be applied using the energy deposits in the calorimeter in order to further reduce the rate of muons from heavy flavor jets.

Endcap = CSC + RPC

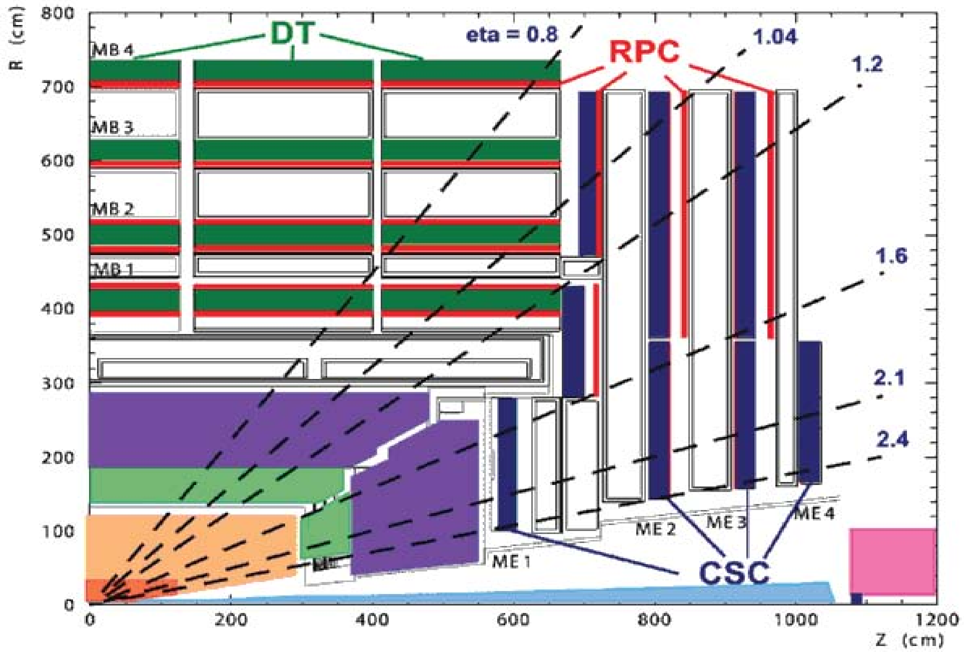
Barrel = DT + RPC

Overlap = CSC + DT + RPC

Compare CMS Muon Systems 2000⇔2013



CMS-2000



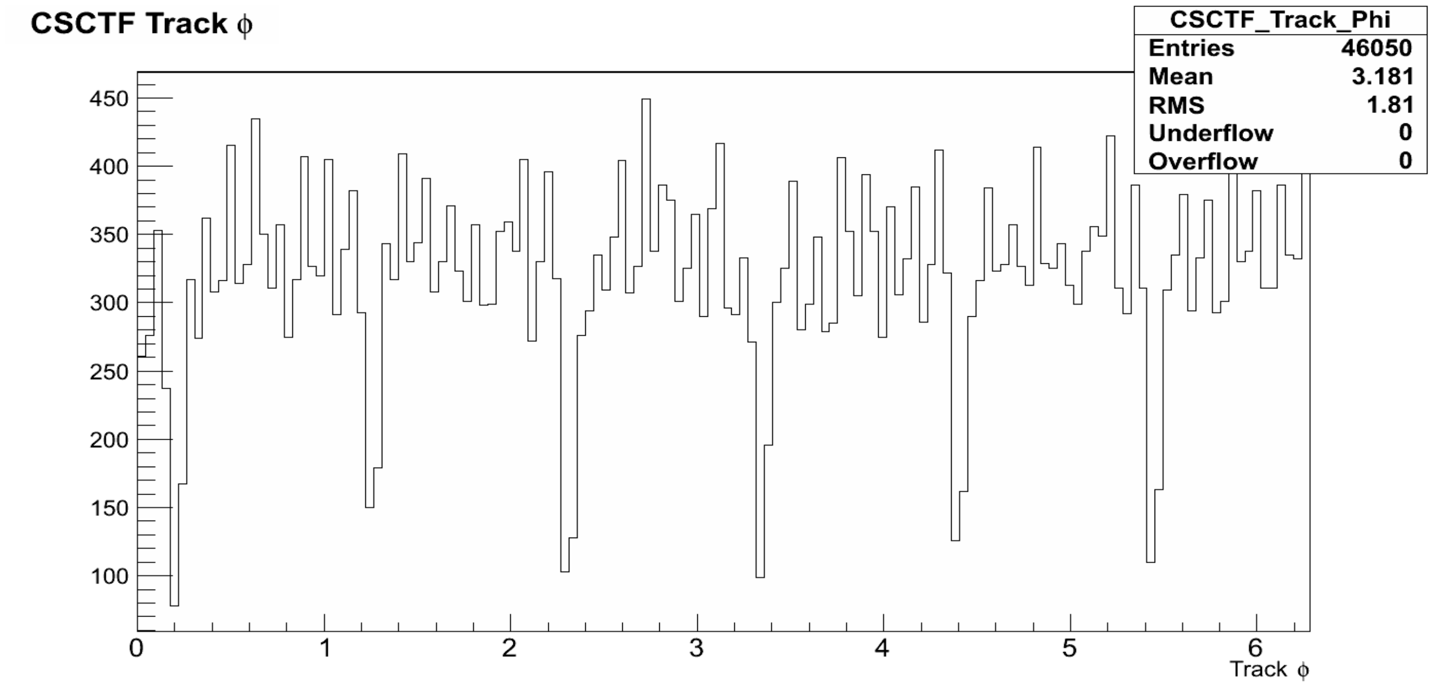
CMS-2013

CSCTF Issues

The CSC Sector Processor and Muon Port Card systems will be upgraded to address four issues:

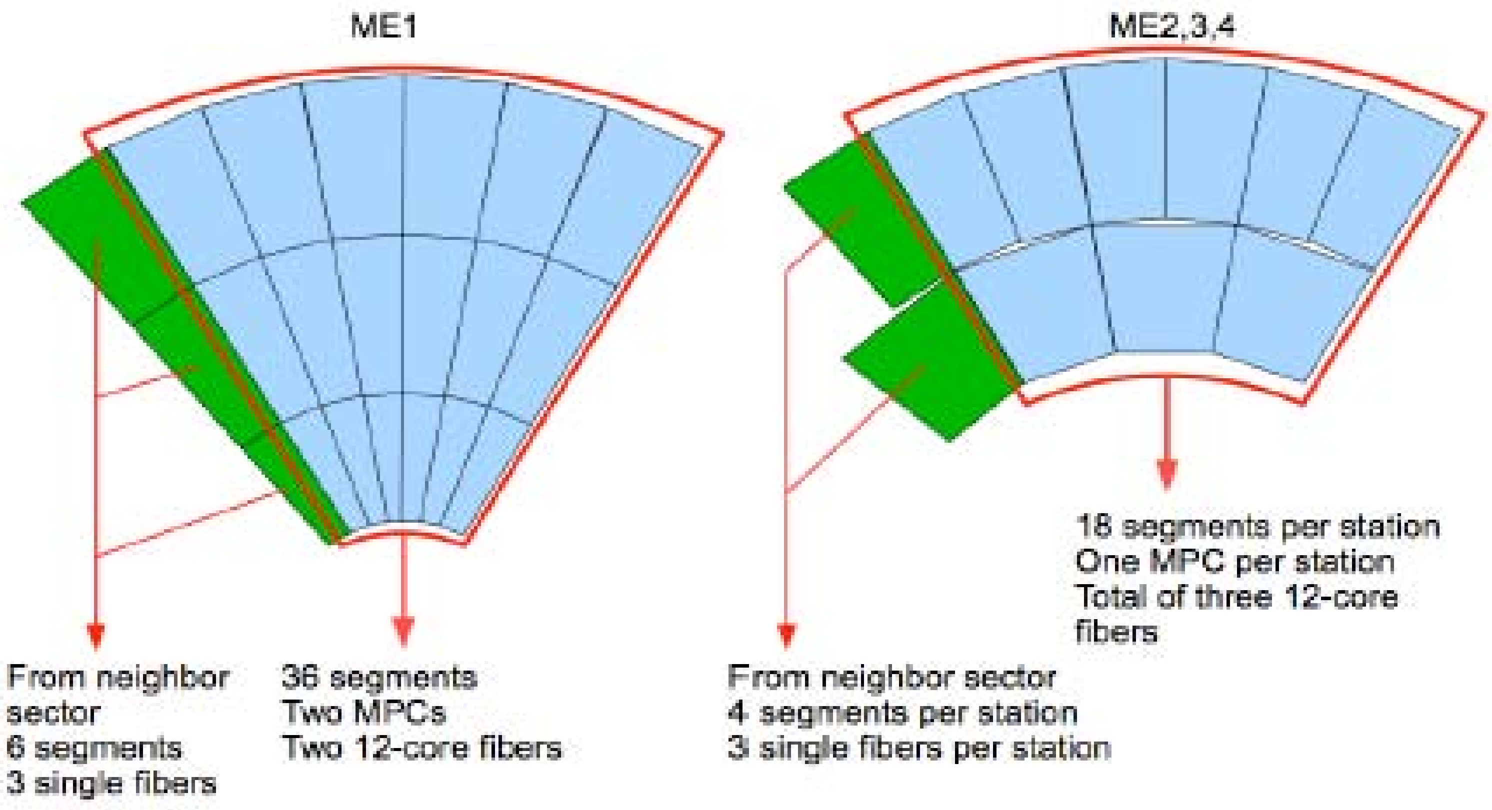
1. completing the φ coverage of the track finding system,
2. restoring sensitivity to muon jet signatures with no MPC sorting, 2 track segment per chamber (3 => 18),
3. momentum resolution improvement (Larger PT LUT),
4. providing a list of muons to the calorimetry system for isolation calculation and b-jet tagging
(MT to CT interconnection)

CSCTF Issue 1: Coverage in φ

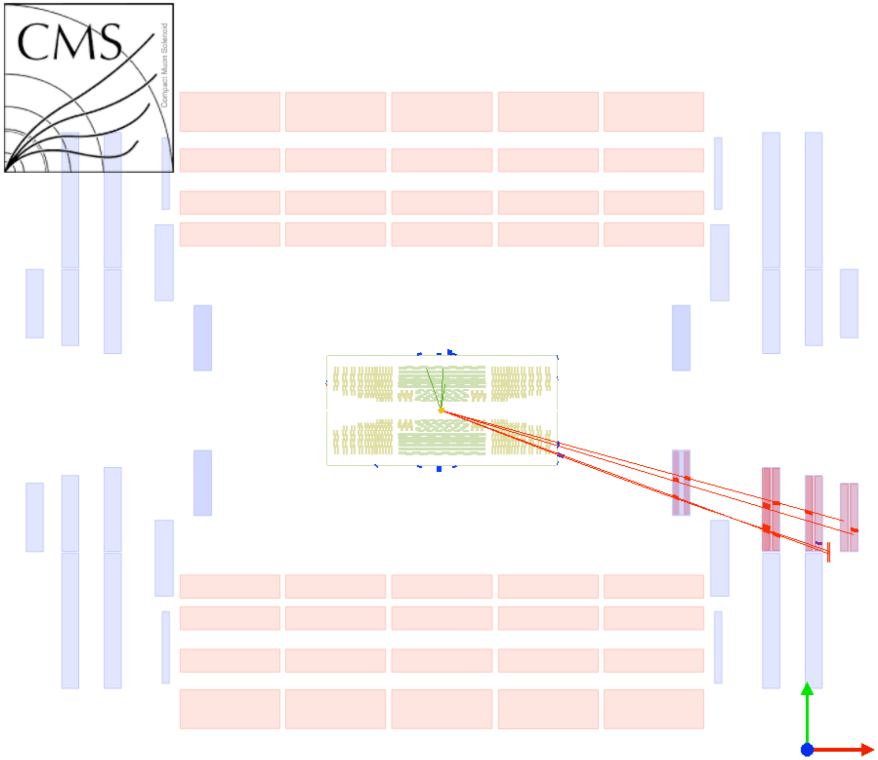


- no cross-talk between sectors in current CSCTF
- muons are lost at the edges of sector phi coverage
- estimate about 5% efficiency loss

CSC φ Cross-Talk Scheme



CSCTF Issue 2: Muon Jets (2 nearby Muons)



Trigger by requiring 2 nearby muons with PT>10..15 GeV

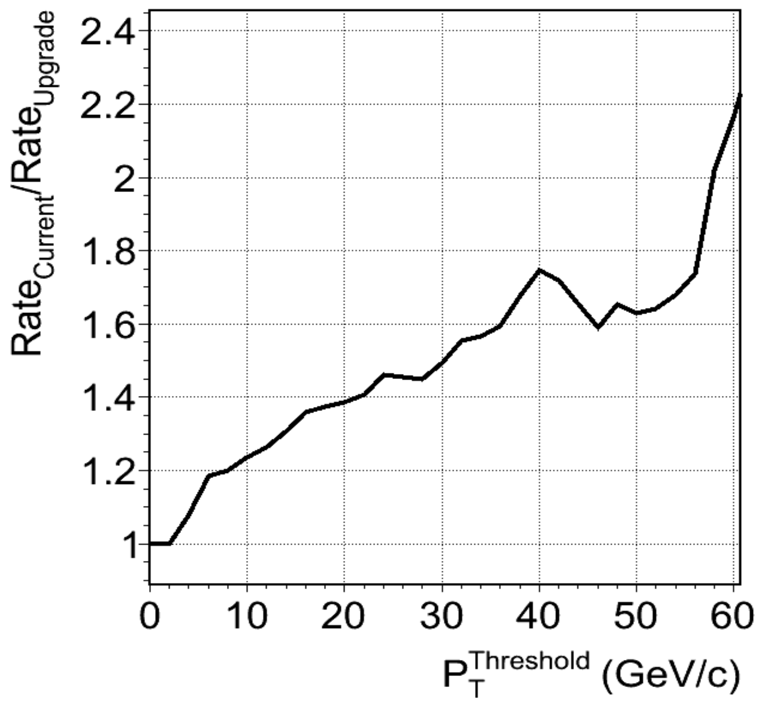
If some of the stubs are lost before the Track Finder, TF may not have enough stubs to build a muon track

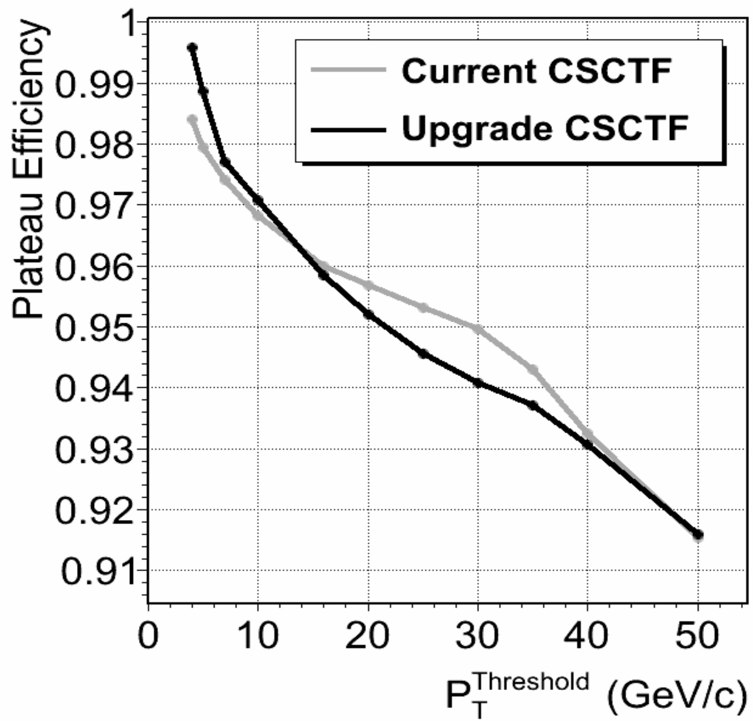
Efficiency for:	MPC ≤ 3 stubs	no MPC limit
muon jet of 4 muons	0.83	0.92
muon jet of 8 muons	0.45	0.91

CSCTF Issue 3: Pt LUT size

Current – pT assignment information
Upgrade – full information available at SP
φ => (0.05 vs 0.015)   LUT: 2M x 16 => 1G x 18

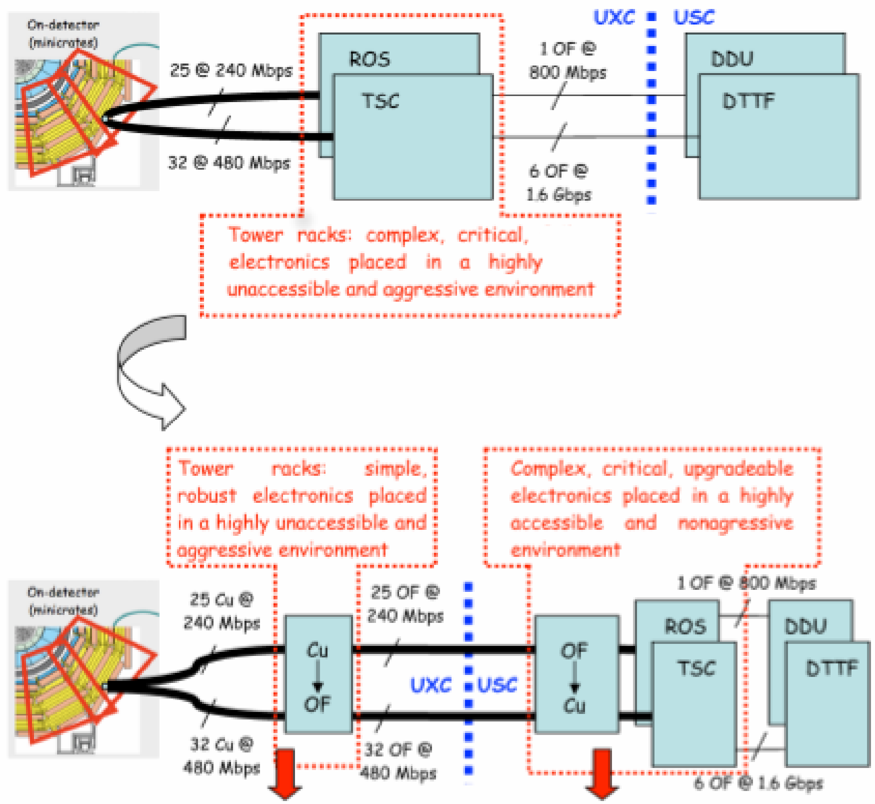
The larger LUTs the better rate reduction



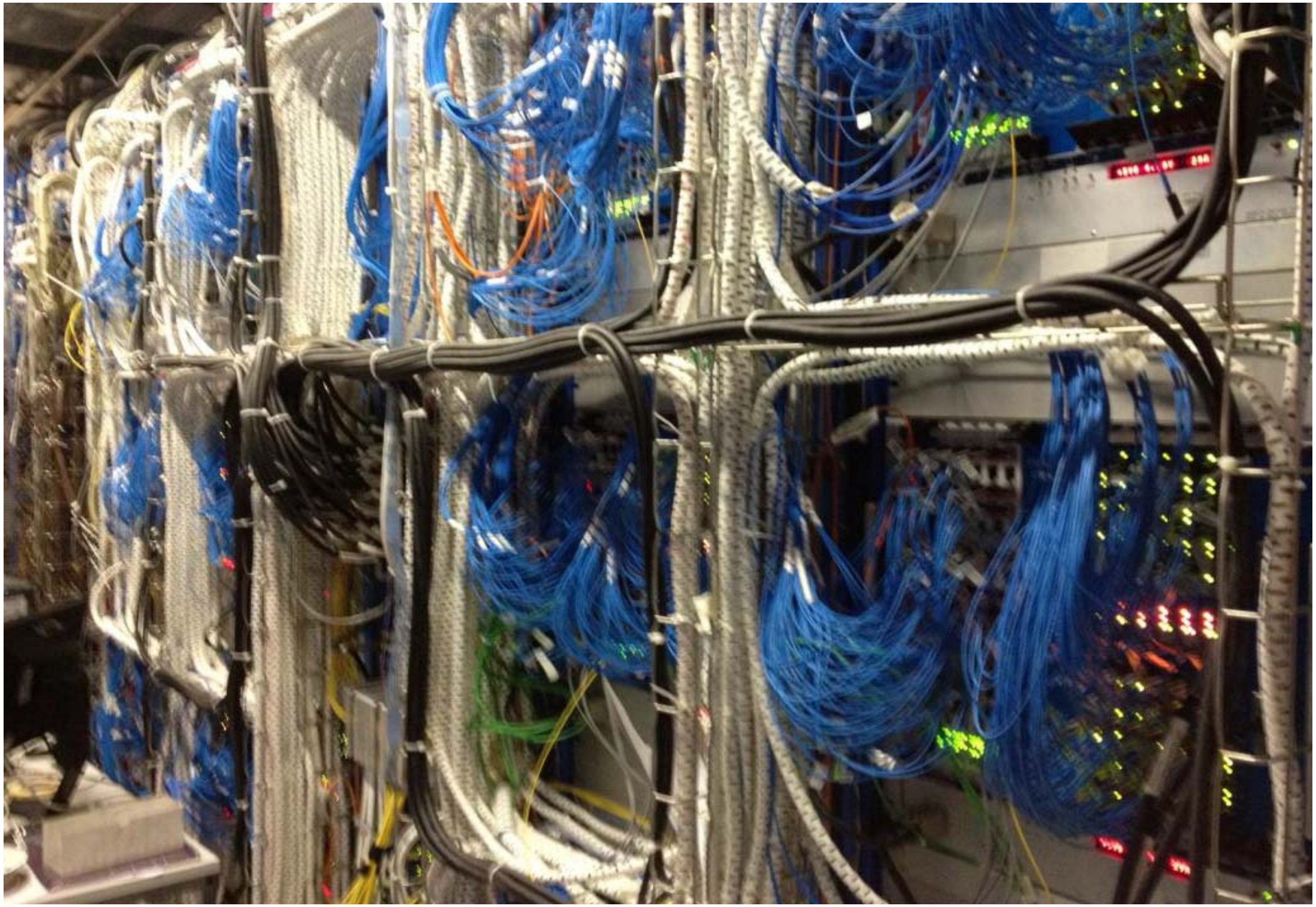


DTTF Issues

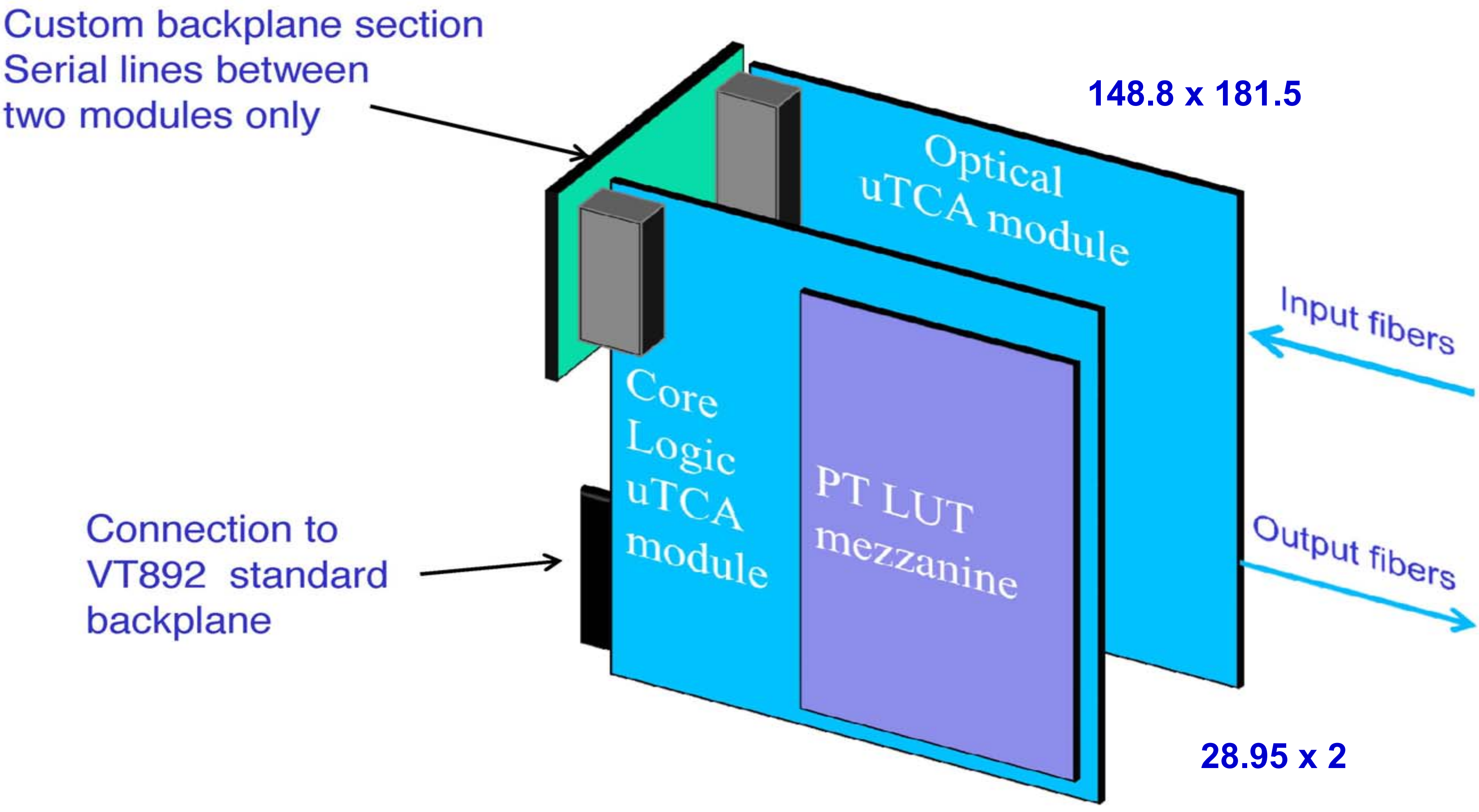
1. TSCs are located in aggressive environment => relocate to USC,
2. Flat cable connection are unreliable (green salad) => go to serial



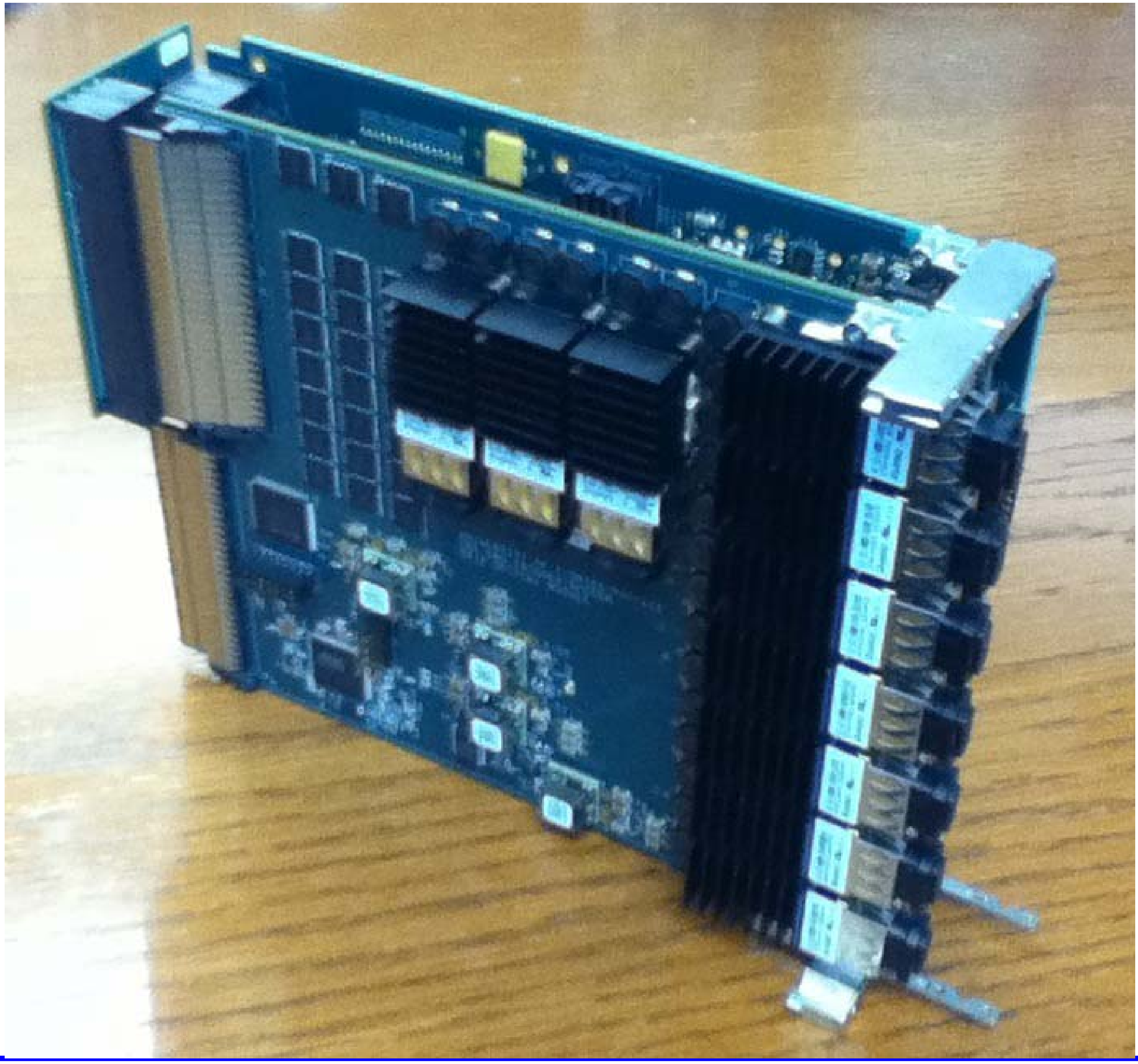
RPC Electronics



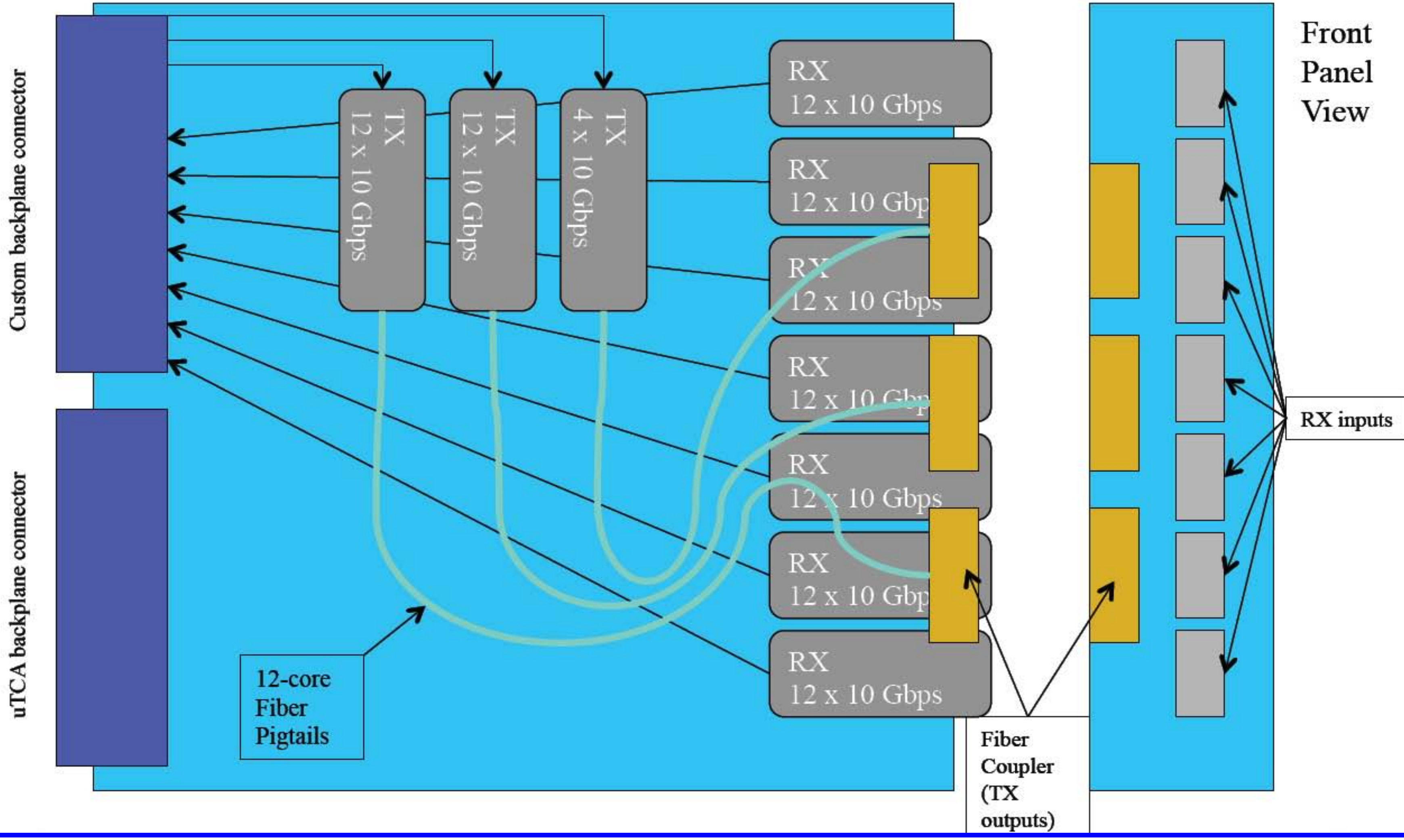
CSCTF (MTF7) Prototype



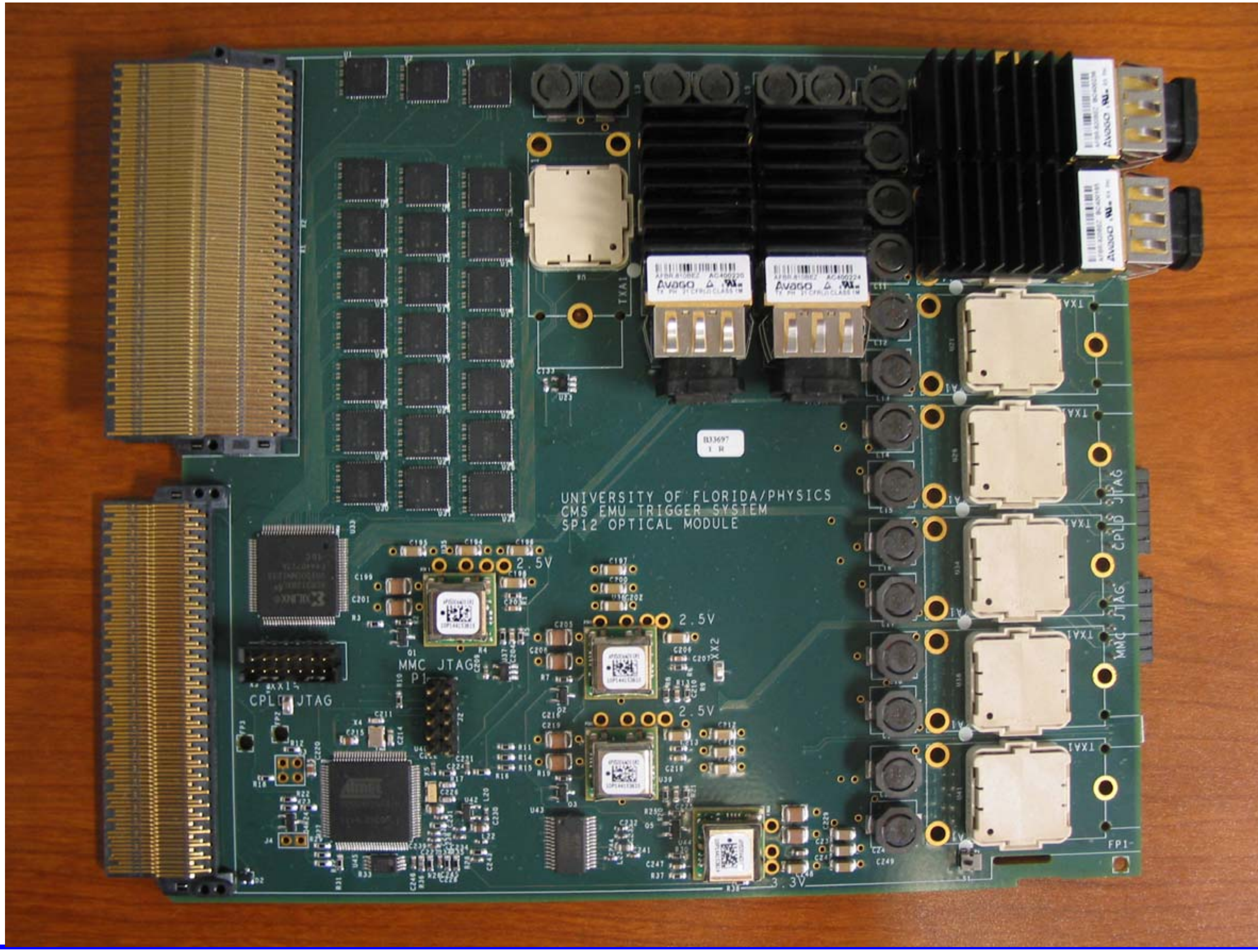
CSCTF (MTF7) Prototype



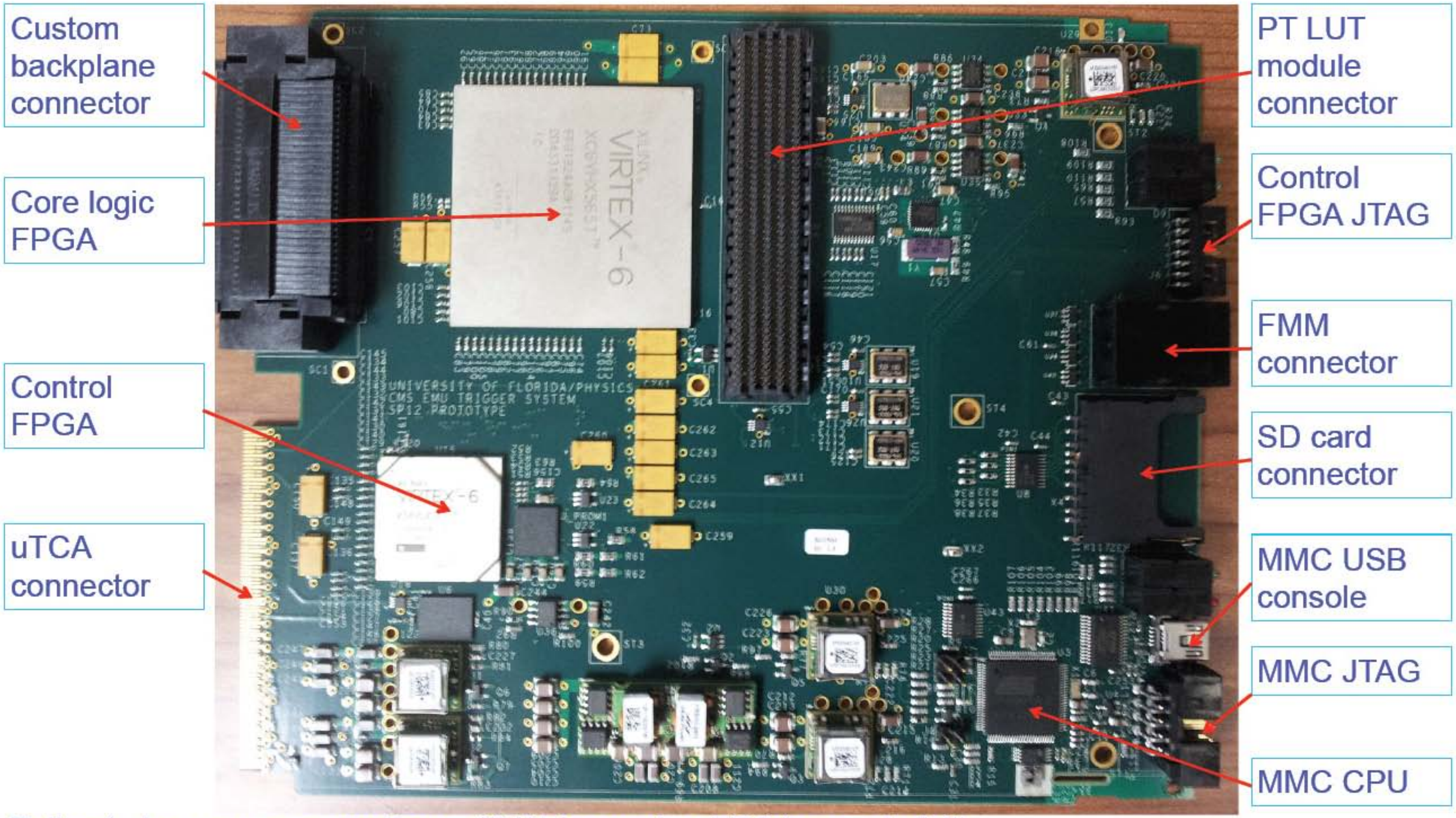
Optical AMC Prototype



Optical AMC Prototype

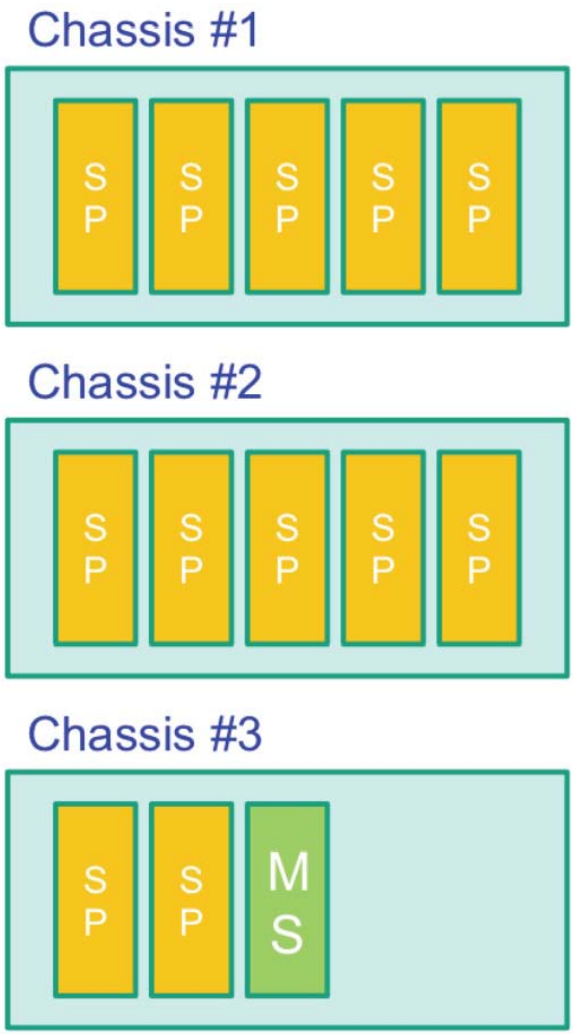


Core AMC Prototype



Estimated power consumption: ~40 W (assuming FPGAs nearly full)
PT LUT mezzanine not included

CSCTF µTCA Layout



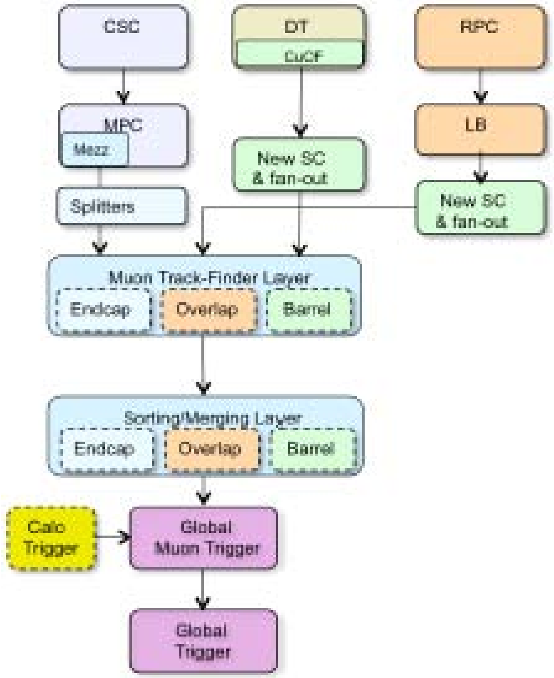
Possible layout of the endcap muon track-finding processors and corresponding muon sorter into three µTCA crates.

All hardware modules are identical and occupy 2 slots.

The MCH and AMC13 in each crate are not shown.

MTF Algorithms and Data Formats

- **Develop more sophisticated algorithms for MTF**
- **Possibly switch from extrapolation to pattern matching (à la RPC PAC)**
  - ➔ **Extrapolation not well scalable with encreasing number of input track segments (6x !)**
- **Negotiate and set up interfaces between muon systems**
  - ➔ **Ideally all muon systems (CSC, DT, RPC) should provide track segments in compatible formats**
- **Agree upon interface between TF layers and Sorting and Merging Layer**
- **…..**



Participating Institutions

Institution	Areas of interest
HEPHY Vienna (AT)	Global Trigger and Muon Trigger
University of Athens (GR)	Muon Trigger
University of Ioannina (GR)	Muon Trigger
INFN Padova (IT)	Muon Trigger
University of Warsaw (PL)	Muon Trigger
National Centre for Nuclear Research,Warsaw (PL)	Muon Trigger
Warsaw University of Technology (PL)	Muon Trigger
CERN (Switzerland)	Trigger Control and Distribution System
Ohio State University (USA)	Global Trigger
Rice University (USA)	Muon Trigger
University of California, San Diego (USA)	Muon Trigger
University of Florida (USA)	Muon Trigger
PNPI (Russia)	Muon Trigger ??????

CSCTF Cost Estimates

Date	Module/component	Stage	Cost
2012-09	Core logic module	prototype	$29,130
2012-11	Optical module + backplane	prototype	$19,250
2013-03	PT LUT module	prototype	$16,800
2013-10	All modules	pre-prod	$63,630
2014-05	All modules	production	$317,760
2014-09	uTCA chassis, optical parts	COTS	$102,136
		Total	$548,706

L1 Trigger Upgrade Costs

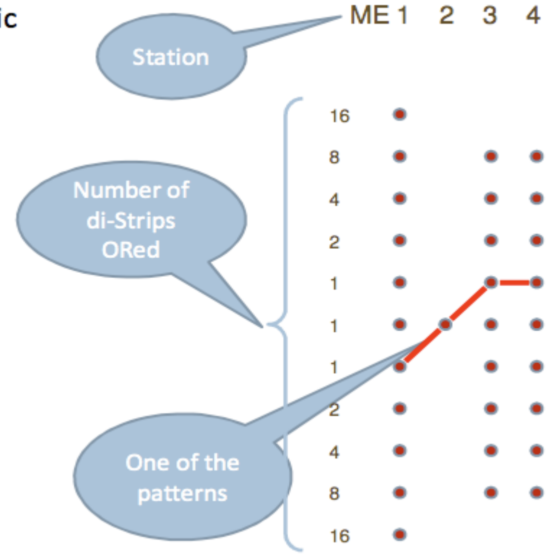
Area	Total cost (kCHF)
Calorimeter Trigger	2,527
Endcap Muon Track Finder	963
Barrel Muon Track Finder	883
Overlap Muon Track Finder	593
Global Trigger and GMT	628
Total cost	5,593

Back up slides

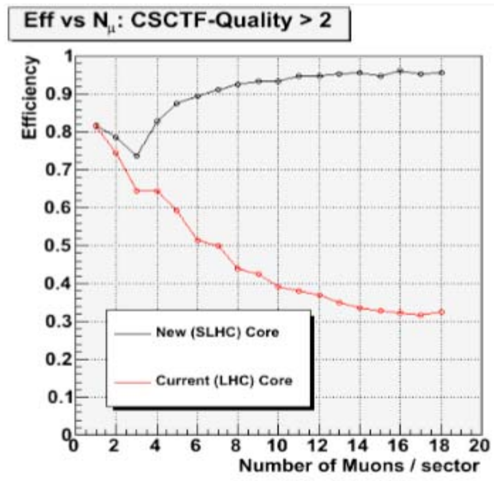
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
CMS Phase 1 Trigger Upgrade Project
LHC Operation
2012 Run
2012 Year End Technical Stop
2013 Run
Long Shutdown 1
2015 Run
2015 Year End Technical Stop
2016 Run
2016 Year End Technical Stop
2017 Run
Long Shutdown 2
DAQ & Services
No DAQ
DAQ2 available
Cooling Intervention
Cooling Intervention
Calorimeter Trigger
Base infrastructure
MP7 base fw
MP7 base sw
Local DAQ fw/sw
IPbus / uHAL updates
uTCA infrastructure test
AMC13 integration
Project milestones
M1: Stage-1 intg test
M2: TMT demonstrator
M2b: Calo dataflow test
M3: Stage-1 install
M4: Stage-2 intg test 1
M5: Stage-2 intg test 2
M6: Stage-2 install
Start of running
External constraints
oSLB / uHTR available
oRSC available
Final oRSC available
CTP7 available
Final CTP7 available
HCAL
HF back-end electronics
Trigger integration in P5
HF back-end electronics ready for operation
HB/HE back-end electronics
Trigger integration in P5 Phase 1
Trigger integration in P5 Phase 2
Trigger integration in P5 Phase 3
HB/HE back-end electronics ready for operation
oSLB/oRM
oSLB design and prototyping
oSLB production
oRM design and prototyping
oRM production
oSLB/oRM testing in 904
Remove cables and install fibres at P5
oSLB/oRM installation at P5
oSLB/oRM testing at P5
oSLB/oRM comissioned
Stage 1
Layer 1
Design and algorithms
Simulation studies
Final Firmware
System validation and shipping to CERN
Software for P5
Deployment in P5
Testing in P5
Integration with Layer 2 at P5
oRSC
oRSC design
oRSC construction
ORSC core firmware
oRSC testing in Madison
oRSC-CTP6 Demonstrator Setup
oRSC validation and shipping to CERN
oRSC-MP7 integration test at CERN
oRSC Rev B design
oRSC Rev B manufacture
oRSC Rev B Testing in Madison
oRSC validation and shipping to CERN
oRSC Testing in 904
oRSC Installation at P5
oRSC Testing at P5
CTP
CTP Core Firmware
CTP6 3-to-1 Stage-1 Demonstrator
CTP6 + oRSC Stage-1 Demonstrator
CTP6 Cluster Firmware (CTP-HF), (CTP-ECAL)
CTP6 Validation and Shipping to CERN
CTP6 - oRSC/RCT Integration Test @ CERN
CTP6 - oRSC-oRM/RCT - oSLB/TCC Integration Test
CTP6 - oRSC-oRM/RCT - oSLB/TCC - uHTR Integration Test
CTP6 - MP7 Integration test at CERN
CTP7 Design
CTP7 Manufacture
CPT7 Core Firmware
CTP7 Testing in Madison
CTP7 Validation and shipping to CERN
CTP7 Rev B design
CTP7 Rev B construction
CTP7 Rev B testing in Madison
Core software
Layer 2
MP7
Base fw
Base online sw
Algo fw
Emulator / offline sw
Stage 2
Layer 1
Design and algorithms
Simulation studies
Core Firmware
Firmware
Core software
System validation and shipping to CERN
Installation in P5
Integration with Layer 2 in P5
Commissioning
Layer 2
Base TMT fw
Base TMT sw
Stage-2 algo fw
Stage-2 emulator / offline sw
Integration / commissioning
CTP6/MP7 tests
Stage-1 integration test
Calo dataflow test support
TMT demonstration
Stage-1 installation
Stage-2 integration test
Stage-2 full test
Stage-2 installation
Global Trigger
Firmware
IPBus firmware based Virtex-7
Object structure max
Target card decision
First draft firmware complete
Testing at Vienna complete
Testing readout complete
Installation at CERN complete
Start testing with GCT
Software
HW access layer, TS services, GUI
Testing and configuration
Testing
Testing of GCT datastream complete
Testing of readout complete
Alarms and status monitoring complete
Long term tests complete
Trigger Control and Distribution System
Specification of new system
Development of demonstrator system hardware and software
Production of final hardware
Final software development
Final hardware and software completed
Installation and commissioning at P5
System ready for CMS running
Global Muon Trigger
Muon data format defined
Muon logic implemented
uTCA crate for GMT @CERN
Isolation logic implemented
First version of uGMT complete
Tests GT/TFs-GMT completed
Parallel running
Software
Common software for 904
Trigger Supervisor Integration into CMSOS
L1 Page Integration into CMSOS
Integration of configuration setups into XaaS
uHAL library, Controhub, and IPBus Firmware (UDP)
Integration of uHAL in CMSOS
uHAL GUI for Hardware Development
Common configuration database schema and library
Common Firmware upload method and associated Software
Common data format document
Library for common Packing, unpacking, and reconstruction of...
Library to generate input and output patterns
Central Cell Changes for parallel running
O2O migration to CMSSW 5 or 6
Common software for P5
Address Assignment Firmware and Software
Common Emulator library
Common DQM library
Subsystem specific software for 904
IPBus Firmware for TCP/IP
PCIe Hardware Access Firmware, kernel module, and uHAL exten...
Throw away scripts and tools for hardware development
Software to automatically generate VHDL
Abstractions for crate, board, and chip
Configuration Service and Configuration database
Test Service and pattern generation utilities
Packer, unpacker, and object reconstruction
Integration of Subsystem Online Software into CMSOS
Subsystem specific software for P5
Monitoring and its Graphical User Interfaces
Alarms
O2O customization
DQM modules
Emulator modules
Drift Tube Track Finder
Cathode Strip Chamber Track Finder
Muon Port Card Mezzanine
Design of Spartan 6 Prototype
Prototype testing at Rice and UF
Design and production of final prototype
Production prototype completed
Integration testing with SP
Integration testing completed
Production and testing of MPC mezzanine cards
Ship to CERN
Installation at P5
Installation completed
Fibres installed from UXC55 to USC55
Sector Processor & Muon Sorter
Prototype firmware testing
Integration testing with MPC
Investigate uTCA integration
uTCA prototype design & production
uTCA prototype testing
uTCA prototype DT integration
Pre-production and testing
Full production and testing
Installation and commissioning at P5
Parasitic running at P5

Pattern Matching Algorithm

- Phi pattern detection is in double strips, to save logic
  - Detection precision seems to be sufficient
  - Full 12-bit phi will be assigned to the best tracks
- Phi patterns are constructed so that:
  - They accommodate max 10 degree bending (ME1-ME2)
  - High-PT (straightest) tracks are detected most precisely
  - As bending increases, the precision becomes worse
  - Minimum two layers must be hit
- Quality code:
  - The more layers – the better
  - Patterns with ME1 hit have priority
- Theta patterns are similar but simpler
  - No bending in theta direction



Possible φ pattern envelope structure



SP upgrade - track finding

- current design - φ comparisons, does not scale well
- switch to pattern matching system for upgrade

Schedule Estimation	Project Stage	Project Materials	Project Labor
05.2013 12.2013	Prototype Development	μTCA Crate assembled AMC13 module, Core and Optical modules, MPC Port Card Prototype	Track Finder Prototype Simulation and Test Software Interface Prototype Development Firmware Prototype Development
01.2014 09.2014	Track Finder Production and Testing	Track Finder Modules and Firmware	Track Finder Modules Debugging and Testing

Schedule Estimation	Project Stage	PNPI Project Manpower	Cost Estimation
05.2013 - 12.2013	Prototype Development	4 Electronics Engineers 2 Software Engineer	200 KCHF
01.2014 - 09.2014	Track Finder Production and Testing	4 Electronics Engineers 2 Software Engineer	393 KCHF