MUON & CORRELATOR TRIGGER ARCHITECTURE OPTIONS

Achieving Muon Universality?

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Science Drivers and Requirements

- **Maintain sensitivity to electroweak scale physics at higher luminosity and pileup of the HL LHC**
  - Report all standalone muon coordinates and momenta in convention to facilitate **global correlation** with tracks from the **Track Trigger**
  - The tracker will have far better $P_T$ resolution for rate reduction
  - **Incorporate additional HL LHC forward muon detectors** to improve
  - Efficiency, redundancy, and improved standalone $P_T$ measurement
  - **Maintain standalone muon trigger** (without track combination) for sufficiently high $P_T$ threshold
  - HL LHC is “only” 3-4X higher lumi, and we increased the max L1 rate

- **Add sensitivity to new physics scenarios**, i.e. acceptance to displaced muons and HSCPs from long-lived particle decays
  - Additional patterns/logic (displaced tracks, timing)
  - Expanded momentum assignment (vertex constrained and not)
Comment about displaced muons in endcap

- A large source of displaced muons for the endcap regions is **beam halo**, which is **not included** in our HL LHC simulations.

- Looking at rates in 2015, the halo muon rate per bunch was measured using the CSCTF (predecessor to EMTF).

- Scaling to 2500 bunches gives ~30 kHz.

- Algorithms for displaced muons will need to consider that other background source
  - non-pointing, but **not** parallel to beamline (e.g. displaced in x-y)

(Thanks to Osvaldo Miguel Colin)
Muon-Track Matching Architectures

Original baseline

Another variant

Proposed from barrel muon trigger groups
Proposed baseline EMTF++ for Phase-2 does regional standalone (SA) track-finding in the endcaps ("Layer-1")

- 12 sectors, 6 per endcap
- Takes trigger primitives from existing or new muon detector electronics

Recent studies show that “tracker muons” (track + muon stub matches) are interesting to include for performance reasons beyond just track + SA muon

Could have EMTF++ send out muon stubs in addition to standalone muons to the Correlator for matching with tracks

- If time multiplexed, send all stubs within a time window around current BX (HSCPs, monitoring,...)
The proposed variation of this is to postpone SA muon track-finding and only send stubs from Layer-1 (concentrated to higher bandwidth links).

- Then the Correlator layer finds both standalone muons and track+muon matches
- Matches current barrel region architecture proposal
- Allows smaller/cheaper FPGAs for data concentration (or re-use old hardware)
- But adds to latency, and project cost (who does this concentration layer?)
  - One option is to use current Phase-1 EMTF as a concentrator for Phase-2
Prior assumptions, per 60° sector, with neighbor sharing (+N):

- **CSC:**
  - 3.2 Gbps links from legacy MPCs (40+9)

- **RPC endcap via CPPF/New RPC electronics:**
  - 12.5 Gbps links from LBs + RE1/3+RE2/3 (8+2)

- **iRPC forward:**
  - RE3/1: 10 Gbps links (3+1)
  - RE4/1: 10 Gbps links (3+1)

- **GEM:**
  - ME0: 10 Gbps links (3+1)
  - GE1/1: 10 Gbps links (8+2)
  - GE2/1: 10 Gbps links (9+2)

- **DT:**
  - 10 Gbps links, 1/30° for MB2/1+MB2/2 (2+1)

**Summary for Regional SA tracking:**

- 95 links per 60° sector [Includes sharing]
- 12 cards total, ~1100 total input links for ~7 Tbps bandwidth
Endcap Data Concentrator Only

- Remove neighbor inputs (and barrel) for concentrator mode (no need)

  - **CSC:**
    - 3.2 Gbps links from legacy MPCs (40)
  
  - **RPC endcap via CPPF/New RPC electronics:**
    - 12.5 Gbps links from LBs + RE1/3+RE2/3 (8)
  
  - **iRPC forward:**
    - RE3/1: 10 Gbps links (3)
    - RE4/1: 10 Gbps links (3)
  
  - **GEM:**
    - ME0: 10 Gbps links (3)
    - GE1/1: 10 Gbps links (8)
    - GE2/1: 10 Gbps links (9)

**Summary:**

- 74 links per 60° sector
- Could fit into existing EMTF system, for example
  - Optical link input limit is 84 x 10 Gbps for an MTF7 uTCA processor, and output is 24 x 10 Gbps
An Endcap Data Concentrator Layer-1

- Despite the large number of input links, the stub occupancy in the muon system is rather low even at HL LHC
  - The input links are mostly sending “zeroes”
- The first layer can zero suppress, concentrate, and time multiplex muon stub data for transmission to Layer-2
  - If this is an “intelligent” Layer-1, it also can perform standalone muon track-finding in the endcap in parallel to concentration (as currently)
- What constitutes a stub?
  - Could be a multilayer CSC LCT, or ME0 GEM stub
  - RPC and GE1/GE2 hits might need a coincidence with a CSC because of background noise rates (for now don’t include in calculations)
    - Good case for forming “super-primitives” in Concentration Layer
  - Allows for finding “tracker muons” in Correlator (TT tracks + single stub)
- Concentrator Layer-1 is essentially equivalent to a fast DAQ path, but sending data for every BX rather than on L1Accept (as current EMTF)
- How much data?

11/29/2018  Acosta - Muon Trigger Architecture
CSC LCT Occupancy from Data

ZeroBias Run 306091: BX0 vs All Chambers per Event in ME1/1

All Chambers/Event
- $C_{\text{mu}} = 2.801\times10^{-2} \pm 1.408\times10^{-2}$
- $C_{\mu} = 3.531\times10^{0} \pm 9.452\times10^{-3}$

BX0 Chambers/Event
- $C_{\text{rand}} = -3.725\times10^{-3} \pm 4.231\times10^{-3}$
- $C_{\mu} = 6.388\times10^{-1} \pm 2.682\times10^{-3}$

All BX in readout

BX0 only: 5.5X reduction

→ 6.5 stubs/BX at HL LHC

A. Aubuchon, Northeastern U

# CSC chambers with ≥1 LCT
Jia Fu Low, PU=200 sample

MC yields 5.8 CSC stubs/BX, in good agreement with data (6.5)

ME0 adds 3.7 stubs/BX for full eta region (1.7 for |\(\eta|<2.4\))

Sum is ~10 stubs/BX, or ~0.8 stubs/BX/sector

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<td>ME0</td>
<td>3.653</td>
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<tr>
<td>TOTAL</td>
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Layer-1 Output Data for Standalone Muons

- Assume up to 3 muons / sector / BX
  - Any combination of prompt or displaced muons
- Start from Phase-1 Muon Trigger Detector Note:
  - 192 bits for 3 muons \rightarrow 64 \text{ bits/μ (Phase-1)}
- To this add another $P_T$ word for displaced μ hypothesis, (+9 bits), plus more spare bits for future use
- Propose: \~100 \text{ bits/μ (a là Track-Trigger)}
  - Up to 3μ / sector/BX at 64/66 encoding \rightarrow 300 \text{ bits} \rightarrow 1 \times 16 \text{ Gbps link/sector}
  - One output link \geq 16 \text{ Gbps per sector per target destination for standalone tracks, even without longer time multiplexing latency}
- How many stubs need be sent on (perhaps) additional links?
CSC+ME0 stubs per 60° sector

- For now assume one stub takes as much data as a CSC LCT sent from the MPC: ~40 bits
  - 32 bits per correlated LCT
  - Plus additional bits [7] for labeling which CSC LCT of the possible 5*18 = 90 CSC LCTs/BX/sector

- Unassociated stubs from pileup are ~0.8/BX/sector
  - ≤ 2 @ 95% CL → 80 bits / BX / sector
  - If time-multiplexed, need to send stubs from a time window around current BX
    - Useful for HSCP trigger plus commissioning and operations monitoring to see stubs before an after in-time crossing
    - Including +/- 2 BX → ~4 unassociated stubs/sector (≤ 8 @ 95%CL)
    - → 8 stubs * 40 bits = 320 bits / 5BX / sector

- Allow stubs from up to 3 muon tracks per sector for a signal in event
  - Assume muons (and their segments) are in-time (1 BX, even if TMUX)
  - Assume each track can have 4 stubs
  - 3 tracks * 4 stubs * 40 bits ~ 500 bits
Endcap Data Bandwidth to Layer-2

- Endcap muon data to send to Layer-2, per sector
  - Tracks: 300 bits (if done in Layer-1) $\rightarrow$ 12.5 Gbps
  - Stubs: 600, 800 bits (TMUX=1, >1) $\rightarrow$ 25, 33 Gbps
  - 46 Gbps @ 64/66 encoding [33 Gbps stubs only]

- For a latency of 1 BX+serdes for transmission (e.g. TMUX=1):
  - Tracks + stubs: 3 x 16 Gbps links per sector, or 2 x 25 Gbps
  - Stubs only: 1 x 25 Gbps links, TMUX=1
    - or 2 x 16 Gbps links, TMUX>1

- For a latency of 3 BX+serdes (e.g. for TMUX ≥ 3)
  - 1 x 16 Gbps link per sector (or higher BW)
    - Or 1 x 10 Gbps (old EMTF concentrator, 8b10 encoding), 4 BX latency

- For entire endcap muon tracks + stubs to a target Layer-2 node
  - 36 x 16 Gbps @ 1 BX [24 x 16 Gbps or 12 x 25 Gbps, stubs only]
  - 12 x 16 Gbps @ 3 BX

≈1 kb of data/sector

Or even more data for longer latencies
Muon+Correlator Architecture, TMUX Model

Barrel Muon System
- 60 MB sectors

Track Trigger
- 9 regions by ~18 time slices, 2 links each

(Standalone ME Muons) + Stub Data Concentrator
- 12 ME sectors
- In ~2.5 us

Correlator layer
- 18 processors (1 per time slice)
- Take all muon and all Tracker data
- In ~5 us

Layer-1
- 18 x 1
- 9 x 2

Layer-2
- x TM

Track Finding Processor
Muon Correlator Board Inputs, TMUX Model

- **Track Trigger**
  - 18 x 25 Gbps (9 regions by 2 links per time sample)

- **Endcap Muon (New Layer-1)**
  - 12 x ≥16 Gbps for 3BX + SerDes latency (stubs, or stubs+muons)
  - or 36 x ≥16 Gbps (24 x 25 Gbps) for 1BX + SerDes latency

- **Endcap Muon (Re-use old EMTF as concentrator)**
  - 12 x 10 Gbps, stubs only

- **Barrel Muon**
  - 60 x ≥16 Gbps (60 layer-1 processors)

**Total links per Concentrator (+standlone muon) module**
- 90 links for each of 18 cards (fits in APx card)
  - Does not allow +12 more links from endcap if needed, in APx
  - Does not allow links from other subsystems for correlation

11/29/2018
Acosta - Muon Trigger Architecture
Note that latency to receive muon data should be ~2.5μs, whereas that for the Track Trigger is ~5μs

- Can receive (and buffer) all muon data for a given BX before tracks are available
- Standalone muon reconstruction can start in advance of track matching and not add to overall latency
  - But now done globally, with TMUX, and not just regionally
    - Increased logic, but also increased latency available
- Can immediately test tracks with all SA muons + stubs as tracks are received
With Dedicated Barrel Track-Finder/Concentrator

60 MB sectors

(Standalone MB Muons) + Stubs

12 MB sectors

(Standalone ME Muons) + Stubs

Track Trigger

Track Finding Processor

Correlator layer

N processors take all muon and all Tracker data

9 regions by ~18 time slices, 2 links each

Maybe even far fewer

12 ME sectors

x TM

9 x 2
Muon Correlator Board Inputs with MB Concentrator, TMUX Model

- **Track Trigger**
  - 18 x 25 Gbps

- **Endcap Muon**
  - 12 x ≥16 Gbps (or 10 Gbps)

- **Barrel Muon**
  - 12 x ≥16 Gbps (assume same as for endcap)

- **Total links per Muon Correlator time slice**
  - 42 links

- **Could fit more than one time slice per APx card:**
  - 9 cards (2 time slices) → 60 links for longer muon serdes (+3BX)
  - 6 cards (3 time slices) → 78 links for longer muon serdes (+6BX)

- **Or could fit additional subsystem inputs for same 18 cards**
Regional Track-Finding and Matching

60 MB sectors

(Standalone MB Muons) + Stubs

12 MB sectors

Maybe even far fewer

Track Trigger

Track Finding Processor

12 MB sectors

(Standalone ME Muons) + Stubs

12 ME sectors

Correlator layer

9 processors take all time slices for specific nonets

9 regions by ~18 time slices, 2 links each
Muon Correlator Board Inputs with MB Concentrator, Regional Model

- **Track Trigger**
  - 36 x 25 Gbps (18 time slices by 2 links per 40° nonet region)

- **Endcap Muon**
  - (≤) 12 x 25 Gbps (up to 12 sectors, higher bandwidth to get stubs in 1 BX without TMUX)

- **Barrel Muon**
  - (≤) 12 x 25 Gbps (assume same as for endcap)

- **Total links per Muon Correlator time slice**
  - (≤) 60 links (+12 if sending SA tracks from endcap Layer-1)

- **Target 9 APx cards (one per 40°)**

- **SA Muon Logic in Layer-2**
  - Could limit SA muon reconstruction to relevant sector around Tracker nonet → move SA muon tracking also to 40° sector?

- **Correlator logic**
  - Will need stubs from wider region of muon system (~180°), but covered by links above
  - Leaving tracker data time multiplexed implies correlator target would receive links from 9 regions per time slice

- **Could even double region to 2 nonets (80°) for 5 APx cards**
  - (≤) 96 links (one board only gets a 40° region)
Could perform standalone muon reconstruction and track matching in one layer for barrel-overlap-endcap in a set of 18 cards → unifies muon trigger

- I/O takes 90 links per card
- But need to verify logic usage in FPGA to check if logic for entire detector can fit in the FPGA resources and in the latency
- Requires rewriting EMTF algorithm from regional → global+TMUX
- Requires group(s) to contribute an endcap concentrator layer, or re-use the Phase-1 EMTF
  - Could be used to form super-primitives

Adding a BMTF Concentrator/TF Layer can reduce number of Layer-2 cards required for track matching, or accommodate additional subsystem inputs

- Requires group(s) to contribute a barrel concentrator/TF layer
Having an “intelligent Layer-1 that finds SA muons in addition to stub concentration does not significantly increase the data BW to Layer-2

- Still one output link per Correlator target
- Reduces logic resources required in Layer-2, but adds to Layer-1
- Would allow use of baseline regional EMTF++ algorithm
- But breaks barrel-endcap symmetry unless barrel region does same
  - And would need to share data across boundary

A regional approach (vs. TMUX) is also feasible for track+muon correlation

Standalone muon reconstruction can take place before Tracker Trigger tracks are available for correlation

- ~2.5 $\mu$s vs 5.0 $\mu$s, either in Layer-1 or Layer-2 (assuming SA latency ~ Phase-1 latency)