Displaced Muons Triggering

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Muon Trigger

- CMS Muon System original concept is driven by the trigger redundancy considerations
- Forward system is challenging:
  - Particle rates are higher (easy to get confused)
  - Detector efficiency is lower (high occupancy, exacerbated by instrumental malfunction)
  - Momentum measurement is much worse
- LS1/2 upgrades: added ME4/2, RE4/2+RE4/3, GE1/1
- Phase 2 challenge: improve performance to offset rate increases
Meeting the Phase-2 Challenge

- New powerful handles for Phase-2:
  - L1 tracking greatly improves momentum resolution
    - Eliminates tails of the standalone measurement that drive trigger rate
  - Better use of muon direction measurements
    - Especially big improvement in the very forward region (new GEM detectors)
  - To first order, the problem is solved
    - A simple algorithm: Loose L1Mu matched to L1 Track trigger candidates
    - Good results already at the TP times
      - Very little optimization done at the time as the results were clearly meeting the goals set at the time
  - Further good ideas to perfect the performance and increase redundancy against system aging and ops failures
    - E.g. stubs+tracks, CSC stub recovery with GEMs/RPCs, integrated triggering (“super-stubs”) etc.
Displaced Muons: Challenge Remains

- Current CMS sensitivity to displaced muons is not ideal, but not too bad.
  - $L_1 p_T$ measurement assumes that muons come from the interaction point.
    - Dropping this powerful constraint reduces resolution, increases rate.
  - More recently, even better performance with the deployment of Kalman filter from UCLA.
- Expect complete loss of sensitivity in Phase-2 with straight L1Track-centric approach:
  - L1 Track Trigger cannot reconstruct displaced tracks.
  - Need to get performance improvements from elsewhere.
Physics with Displaced Muons

• Is plentiful:
  • Many new physics models predict existence of new light particles with potentially considerable lifetime
    • Feebly interactive massive particles, neutral naturalness, Hidden sectors, Dark SUSY, WIMP Baryogenesis

• Use simplified model to evaluate performance: dark $Z/\gamma$ production followed by decay to SM particles
  • Muons may not be the only decay channel
  • Could well be the only triggerable channel
    • Or one of a handful

For a recent review see e.g. D. Curtin and R. Sundrum, arxiv:1702.02524
Trigger Design Considerations

- Achieving good coverage of the range of potential signatures requires a whole family of displaced muon triggers:
  - High momentum muon signatures (heavy particle decays) can use single muon trigger – significant fraction of acceptance in the barrel region
  - Low momentum muon signatures (light-ish particle decays) will require a dimuon trigger to get low enough thresholds
    - Endcap region becomes very important
Displaced Muon Trigger Design

- Two main ideas:
  - A simple algorithm for better utilization of muon directions in $p_T$ measurement*
    - For displaced muons bending angles can be large, but consistent in different stations
    - Combine with the power of the regular point-based measurement (w/o the beam constraint)
  - Track trigger veto:
    - Turn L1TT’s “weakness” into a strength: if no L1TT track nearby, it’s likely a displaced muon!
  - Endcap more difficult as always...

* Kalman filter implemented in L1 for the barrel is presumably doing the same thing, we should compare performance and see if there are any gains we can make from merging
Track Veto For Rate Control

- Use L1 Track trigger as a veto for background suppression:
  - Require no L1 tracks around L1Mu direction
  - Veto tightness can be adjusted for optimal performance

Suppression power depends on how good the actual L1Trk trigger performs
- A potential concern, but there is room for maneuver adjusting veto definition, especially in the forward region
- Assuming that the main concern is the rate control, good L1Trk efficiency is the key figure to watch
  - L1Trk fake rate affects displaced muon efficiency and we will likely be given some handles there to tweak the performance as needed ($\chi^2$, track quality etc.)
Displaced Muons in Barrel

- A standalone algorithm comparing directions of stubs measured in different stations
  - A nearly literal implementation of the conceptual idea shown on slide 7: directions should be the same in all stations
- Simplified implementation: if more than two measurements are available, pick the most “powerful” pair
  - We felt it was good enough as a proof of concept, actual algorithm will need to be more complex
Displaced Muons in Barrel

- Good performance for displaced muons even with this simple algorithm
  - High efficiency independent of the displacement
  - Good trigger rate control with the directions alone up until 10 GeV
  - Track veto completes the job of rate control rate reduction
    - Veto power is adjustable
- Plenty of room for potential improvements
  - A more elaborate use of muon directions and position measurements (a la hybrid in the endcap – see later slides) will allow better efficiency vs rate optimization
  - Need to understand synergies/overlap with Kalman filter performance
Displaced Muons in Endcap

• Substantially more challenging:
  • CSCs are much thinner than DT chambers
  • L1 trigger measurement of stub directions is available, but coarse
  • Much weaker magnetic field, especially in the very forward region
  • With current detectors (counting GE1/1), only one good direction measurement using GE1/1-ME1/1
    • Need at least two!

• Explore the following scenario:
  • Improve CSC L1 stub position & direction measurement as much as possible
    • Assume only firmware modifications
  • Design “hybrid” algorithm to combine the power of the direction- and position-based \( p_T \) measurements
  • Add GE2/1 detector to form the second good measurement of muon direction
  • Utilize L1 track trigger veto
Muon Direction Measurement

• Similar to prompt muons, forward region $|\eta| > 1.6$ is the hardest
  • Good muon direction measurements are essential
    • Need at least two direction measurements to compare to each other
    • CSC or GEM standalone – too crude for this region (even soft muons bend very little)

• With GE2/1 added, GEM-CSC super-stubs in stations 1 and 2 can be compared
  • To be effective, resolutions in station 2 need to be sufficient

• GEM-CSC super-stub direction measurement
  • Essentially a difference of $\phi$ measurements in GEM and in CSC
    • The lever arm helps as the same muon bends more with larger lever arm, can compensates for lower resolution
  • In both stations 1 and 2, bending angle (direction) measurement performance is limited by the CSC position resolution
  • Can improve CSC $\phi$-position resolution (only firmware improvements required)
    • Can also do better direction measurement, but it’s still not nearly competitive to GEM-CSC combined measurement
      • It is however useful for ME1/2 where GEMs are not available
Direction Measurements

- Improved CSC L1 spatial position resolution improves measurement of the bending angle.
- ME0 with its excellent resolution closes the whole in 2.1<\eta<2.4 left by GE1/1 not going all the way through.
GEM-CSC Bending Angles

- Taking everything together, compare direction measurements in stations 1 & 2 for two scenarios:
  - Station 1: GE1/1-ME1/1 based measurement in both cases
  - Station 2: ME2/1 only in one case and GE2/1-ME2/1 in the other
- GE2/1 allows a much improved correlation of the directions
  - Pre-requisite for developing the direction-based algorithm
Hybrid Algorithm - Endcap

- Position-based measurement provides good rate reduction in lower eta part of the endcap; in the higher eta part, a significant improvement is obtained using both stub position and direction measurements
  - In eta<2.1: use GE1/1-ME1/1 and GE2/1-ME2/1 measurements
  - In eta>2.1: use ME0 and GE2/1-ME2/1 measurements
Hybrid Algorithm - Endcap

- Bring everything together, including track veto:
  - In low eta part of the endcap (much higher B), use improved L1 CSC stub position and direction
    - Seems sufficient to achieve reasonable performance, only firmware modifications needed (still has to be checked as these are old TMB boards with very full FPGAs)
  - Clearly acceptable trigger rate
    - Tighter L1 track trigger veto allows further reduction, but at a cost to efficiency, further algorithm improvements likely to allow further improvements
Full Forward Endcap

*Note track veto not applied here
Trigger Design Considerations

• Critical items for displaced muon trigger:
  • **Must** make sure we have both the beam constrained and unconstrained $p_T$ measurement
    • As early on we may not know if a particular muon candidate becomes a prompt or displaced candidate – critical to make both $p_T$ measurements and to keep them for as long as necessary
  • **Must** maintain access to low $p_T$ L1trk tracks to be able to apply veto
    • Without veto, rates will be sky high
Trigger Design

- Includes prompt and displaced muons
- Compatible with the iTDR baseline design
  - Can be extended to include stubs (e.g. L1Mu here can be a mix of standalone muons plus unassigned stubs)
- Demonstration that the minimal scenario (no stubs) can work is nearly complete
  - See yesterday Sven’s presentation, we just need to implement a few tweaks to fit the algorithm for a full sector into a single ultrascale FPGA board, many options for further improvements to reduce resource usage, latency is small
- Full results on a scale of weeks
Summary and Thoughts

- Displaced muons are clearly doable
- Work remains to be done on algorithm development
  - Overlap region has not been explored yet
  - Getting Kalman fitter in forward region would be very interesting
    - Compare to our simplistic stub-alignment algorithm, see if there are non-overlapping strengths that could be merged together
  - Working out the available phase space for the track veto
- On implementability:
  - Need to verify that ME1/2 TMB FPGA can fit a better measurement of directions
  - Come up with data formats that provide needed resolution of the position/direction measurements
    - May require different formats in different CSC types
      - E.g. pass precise position for ME1/2, 2/1, pass precise direction for ME2/1, ME2/2
- On design:
  - Complete demonstrator performance benchmarking and validation with hardware setup for minimal scenario
  - Look into more evolved options proposed (e.g. add stubs)