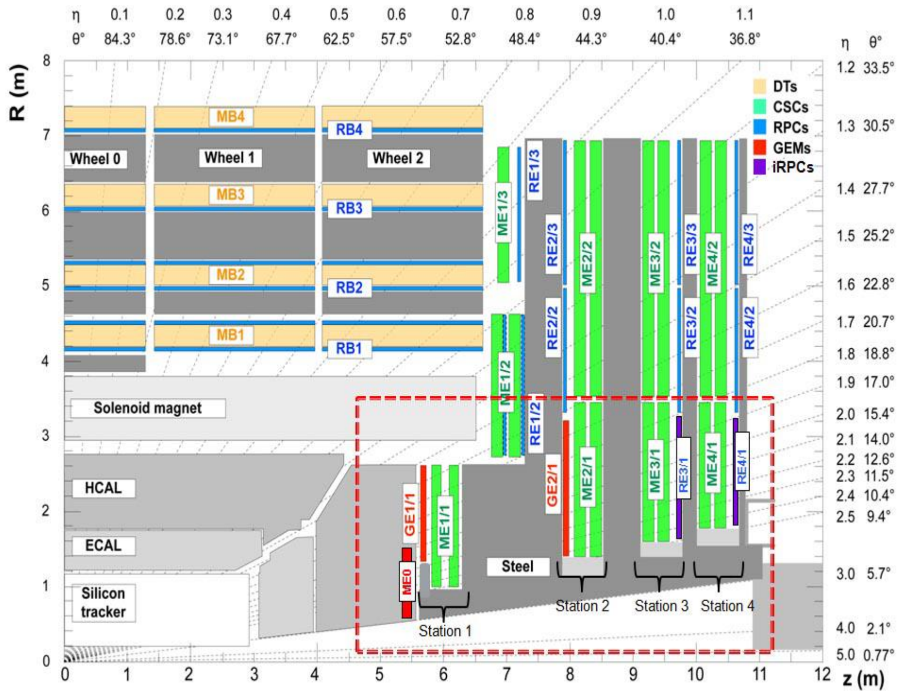
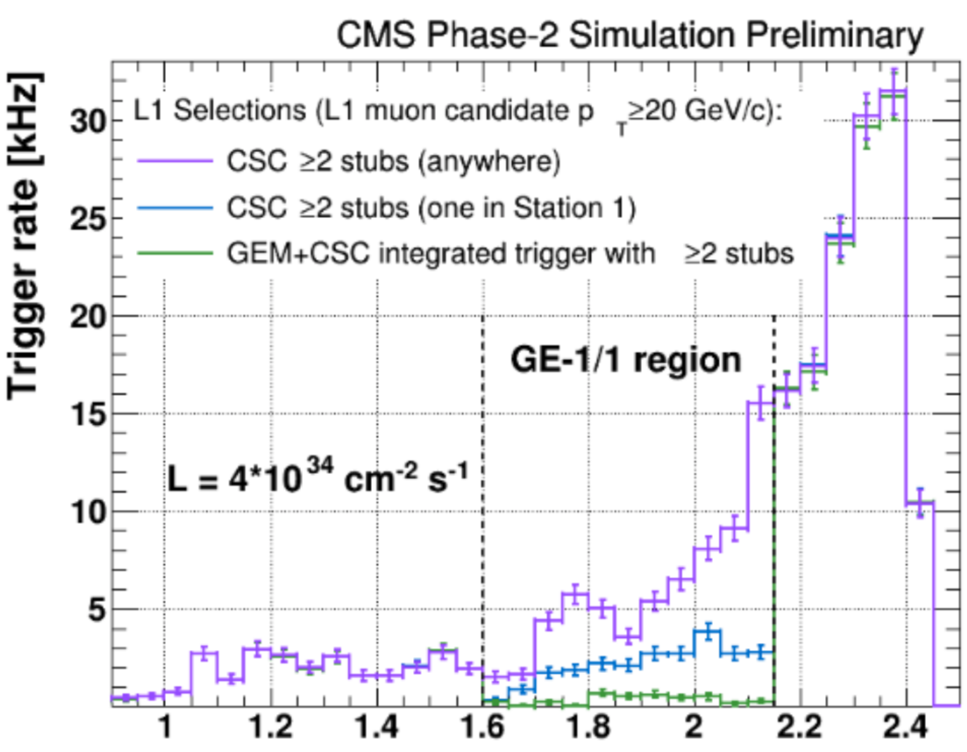
Displaced Muons Triggering

Alexei Safonov
Texas A&M University

Muon Trigger

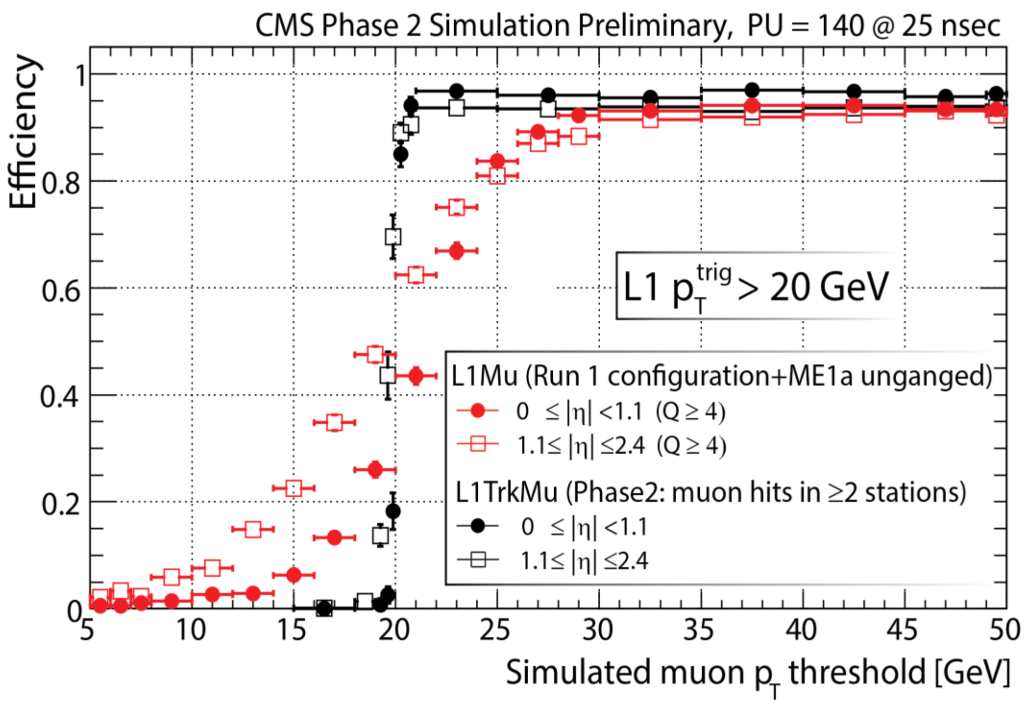
- CMS Muon System original concept is driven by the trigger redundancy considerations
- Forward system is challenging:
  - Particle rates are higher (easy to get confused)
  - Detector efficiency is lower (high occupancy, exacerbated by instrumental malfunction)
  - Momentum measurement is much worse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

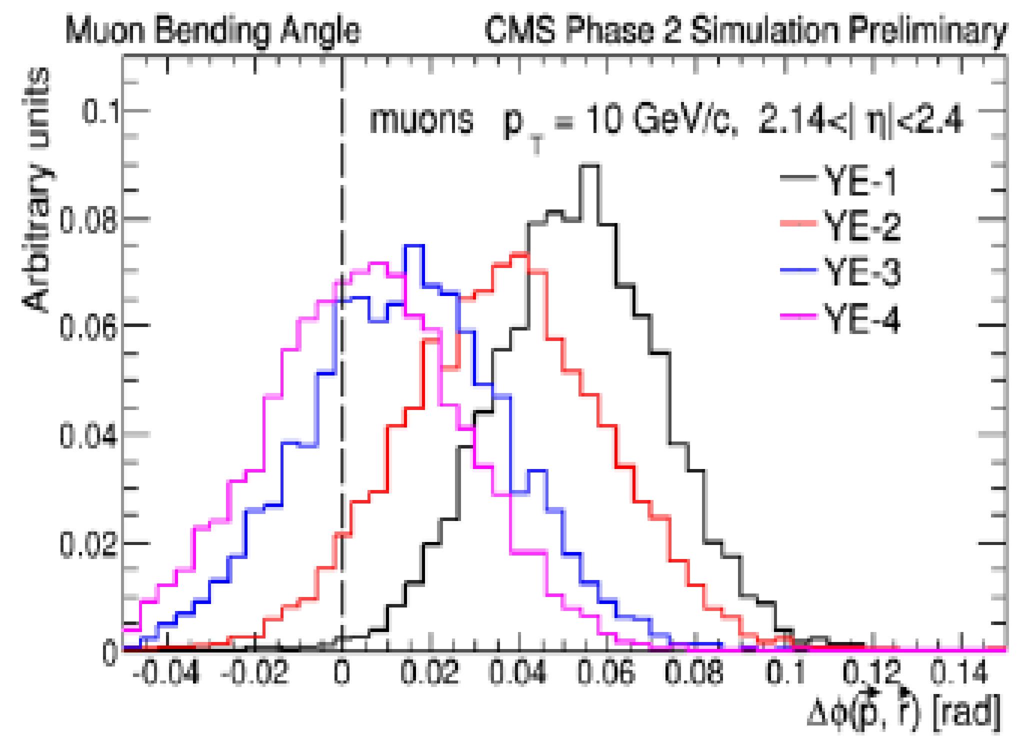




Meeting the Phase-2 Challenge

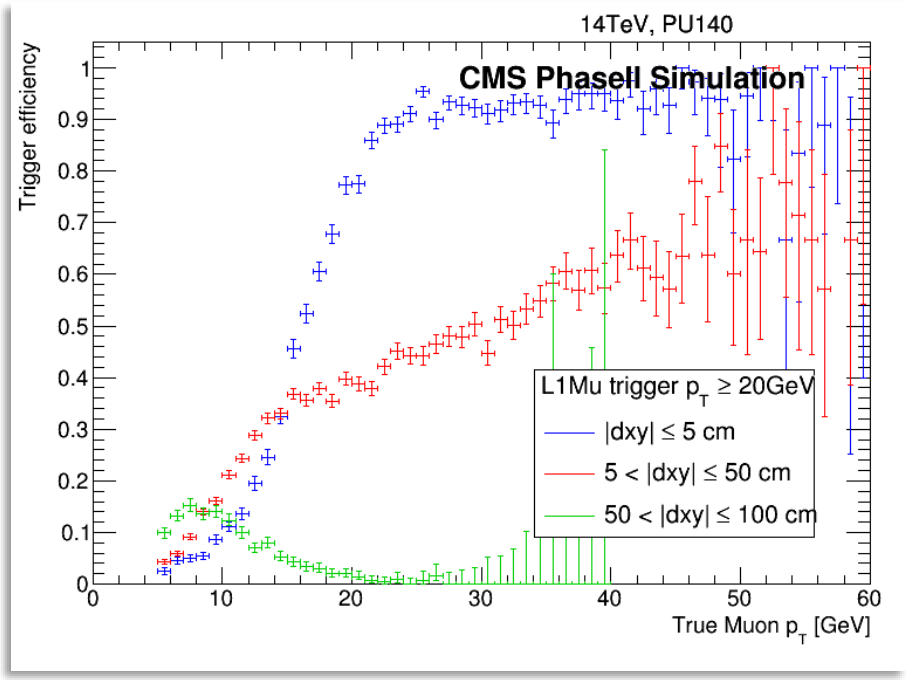
- New powerful handles for Phase-2:
  - L1 tracking greatly improves momentum resolution
    - Eliminates tails of the standalone measurement that drive trigger rate
  - Better use of muon direction measurements
    - Especially big improvement in the very forward region (new GEM detectors)
- To first 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.

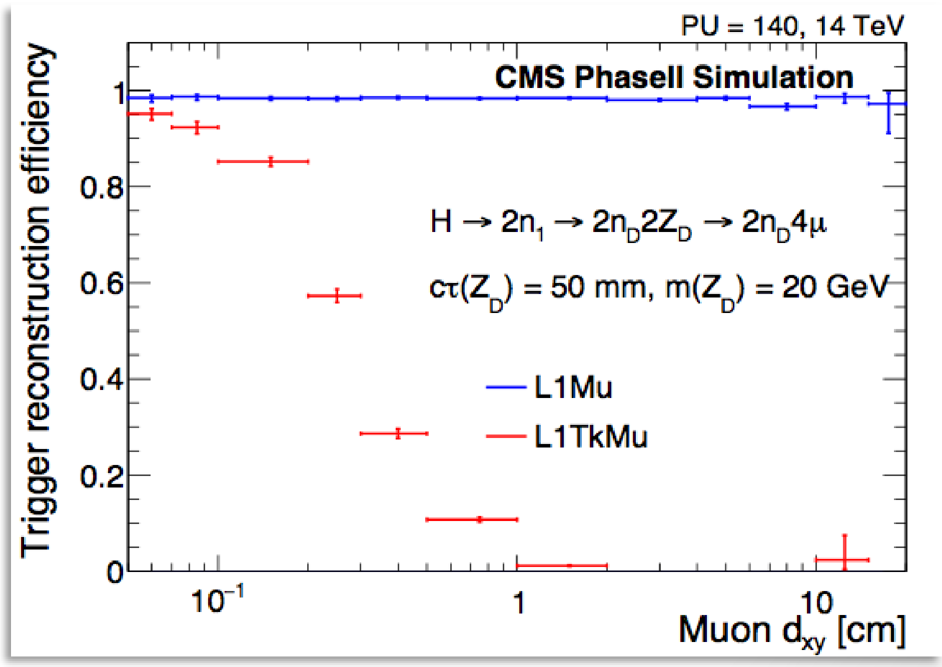




Displaced Muons: Challenge Remains

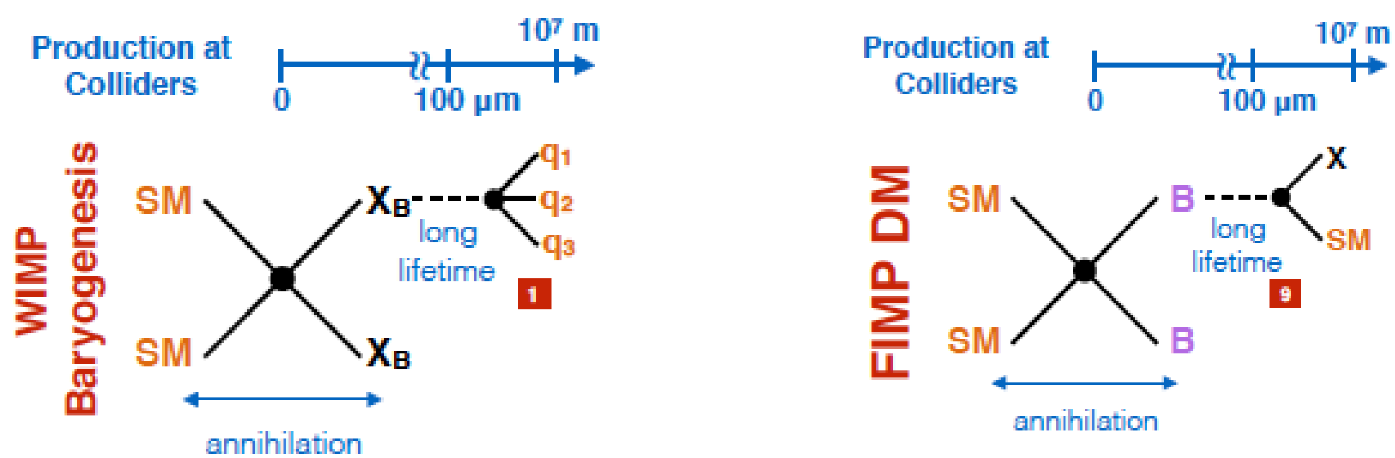
- Current CMS sensitivity to displaced muons is not ideal, but not too bad
  - L1 p_T measurement assumes that muons come from the interaction point
    - Dropping this powerful constraint reduces resolution, increases rate
  - More recently, even better performance with the deployment of Kalman filter 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



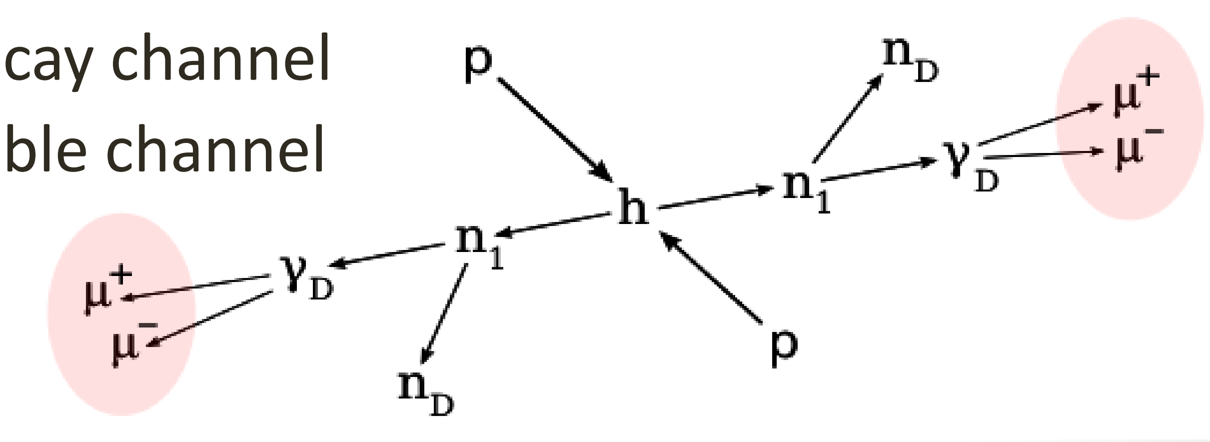


Physics with Displaced Muons

- 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

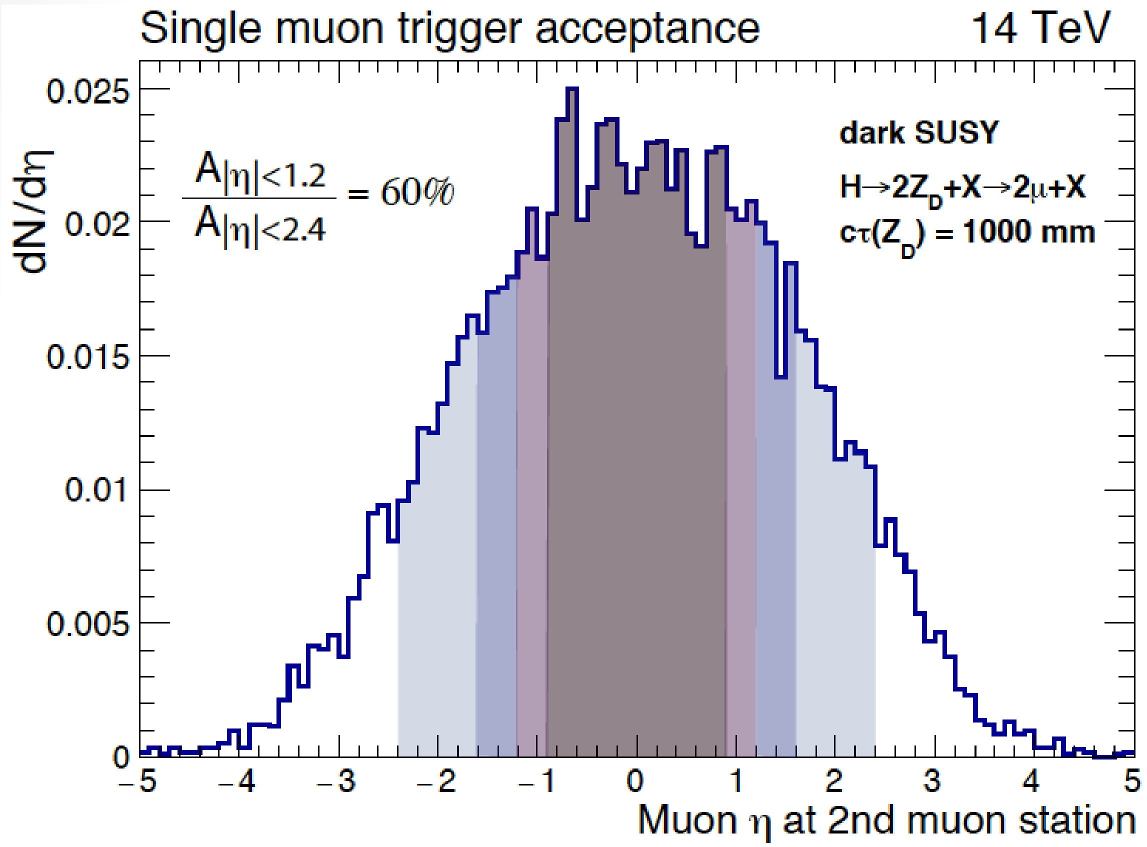


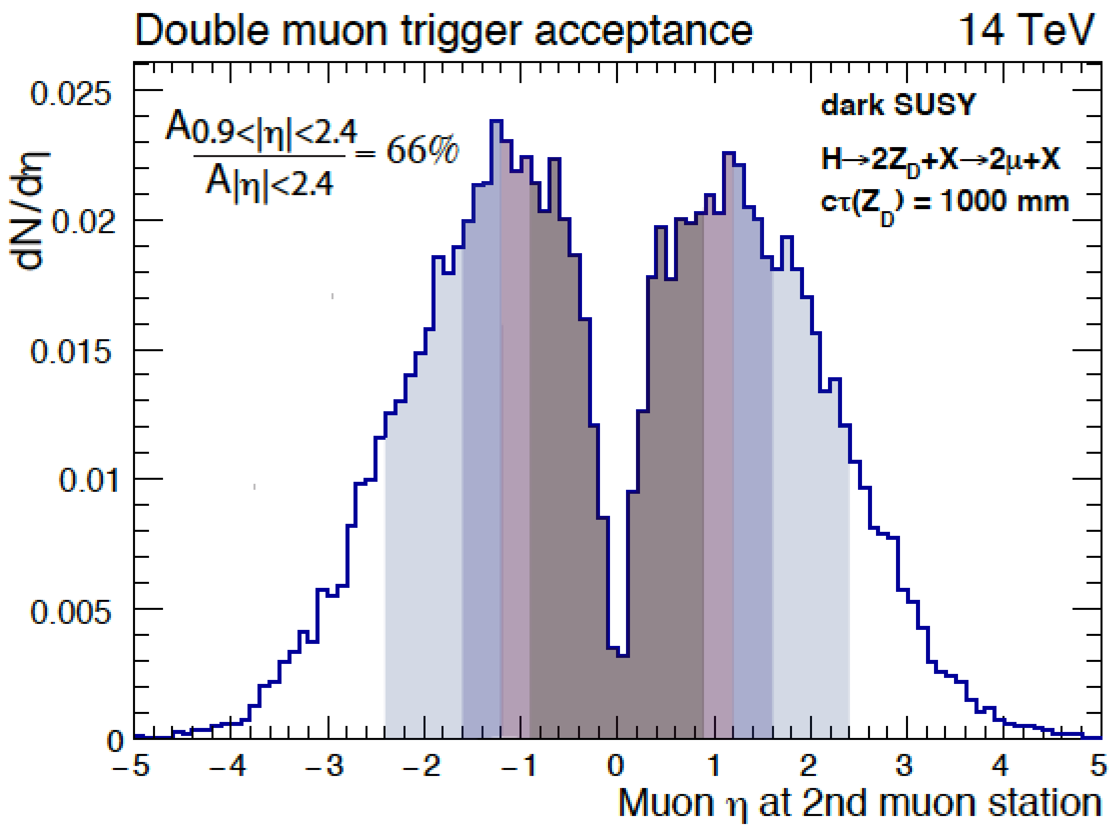
- Use simplified model to evaluate performance: dark Z/γ production followed by decay to SM particles
  - Muons may not be the only decay channel
  - Could well be the only triggerable channel
    - Or one of a handful



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

Trigger Design Considerations

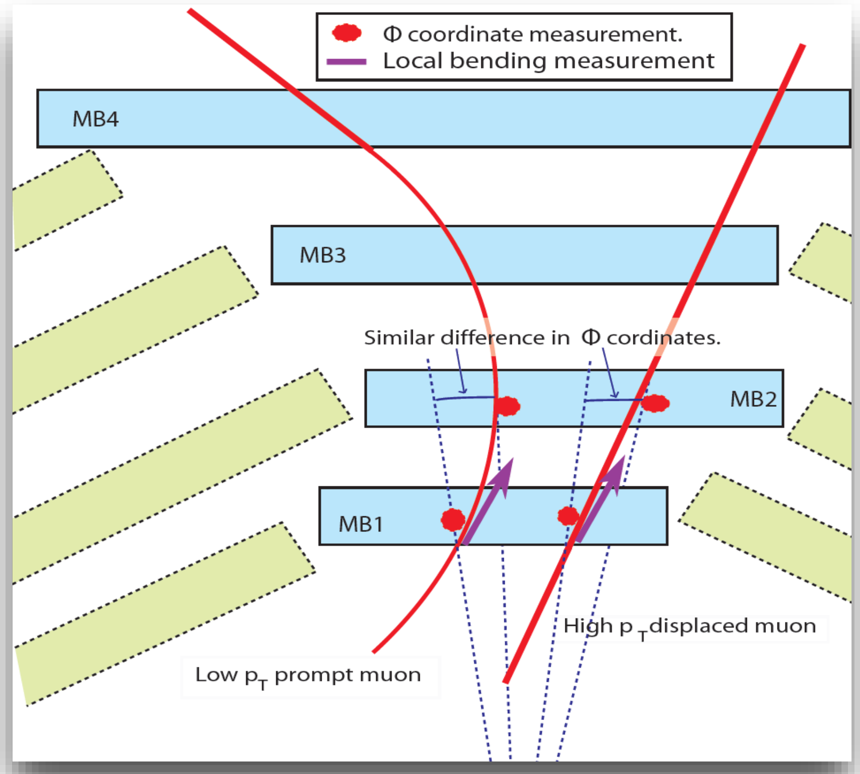


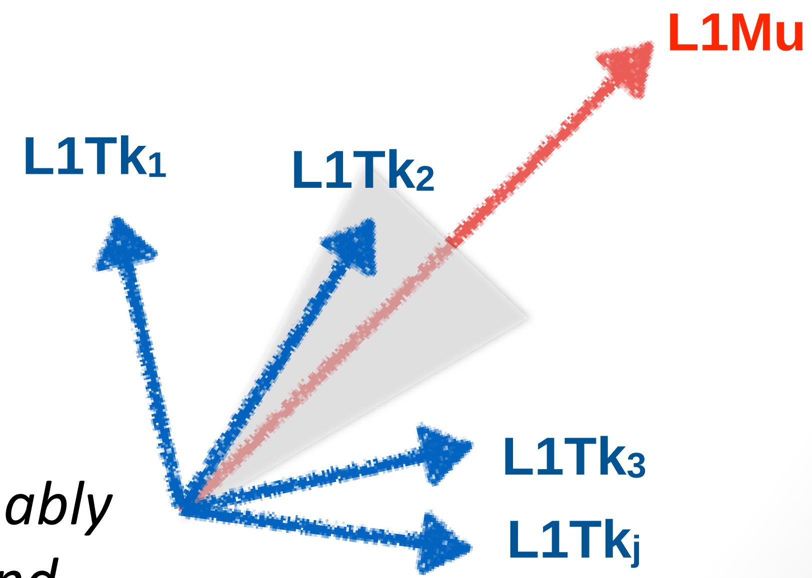


- Achieving good coverage of the range of potential signatures requires a whole family of displaced muon triggers:
  - High momentum muon signatures (heavy particle decays) can use single muon trigger – significant fraction of acceptance in the barrel region
  - Low momentum muon signatures (light-ish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

Displaced Muon Trigger Design

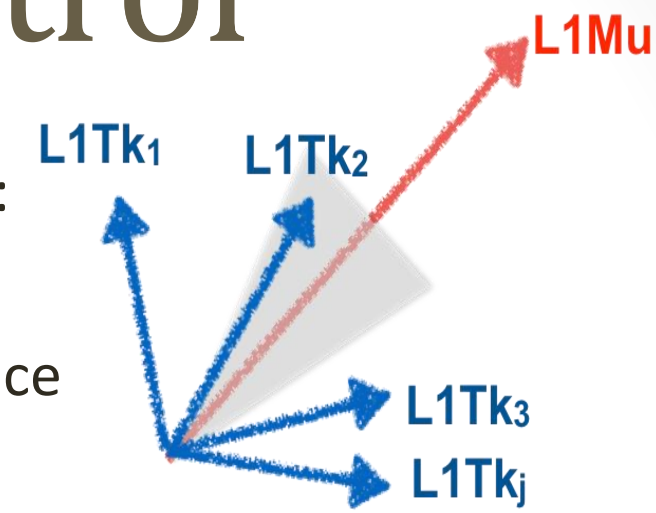
- Two main ideas:
  - A simple algorithm for better utilization of muon directions in p_T measurement*
    - For displaced muons bending angles can be large, but consistent in different stations
    - Combine with the power of the regular point-based measurement (w/o the beam constraint)
  - Track trigger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



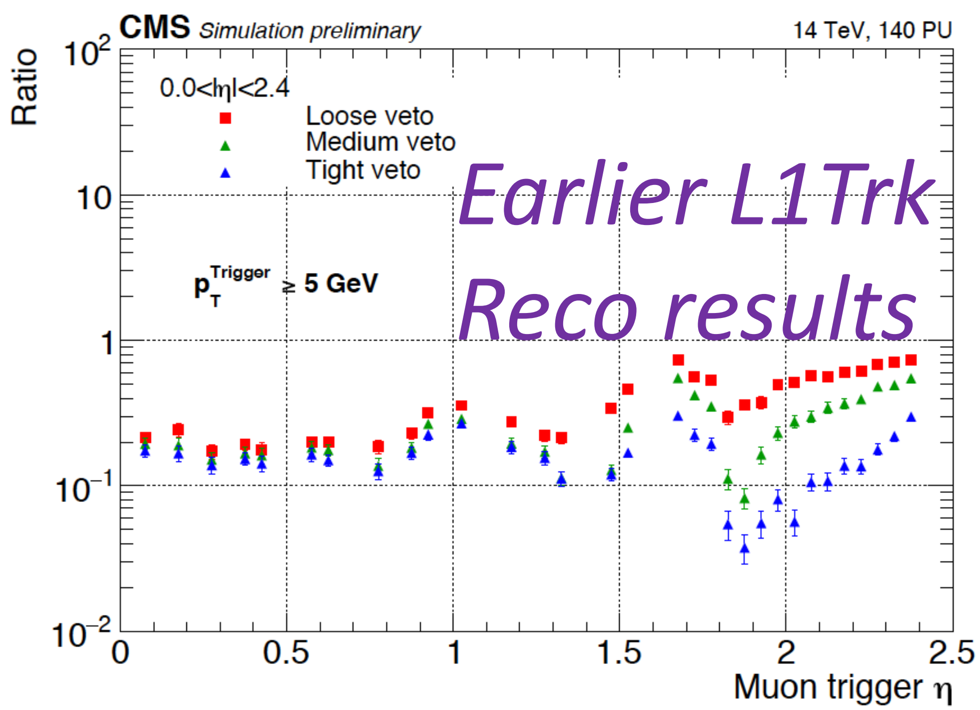


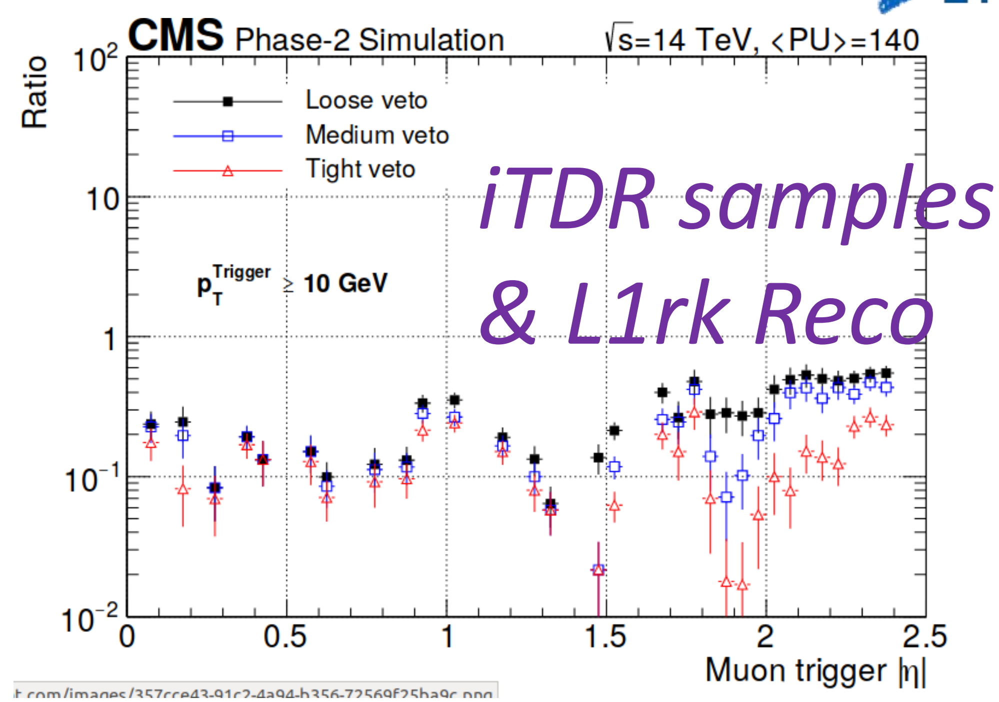
** Kalman filter implemented in L1 for the barrel is presumably doing the same thing, we should compare performance and see if there are any gains we can make from merging*

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

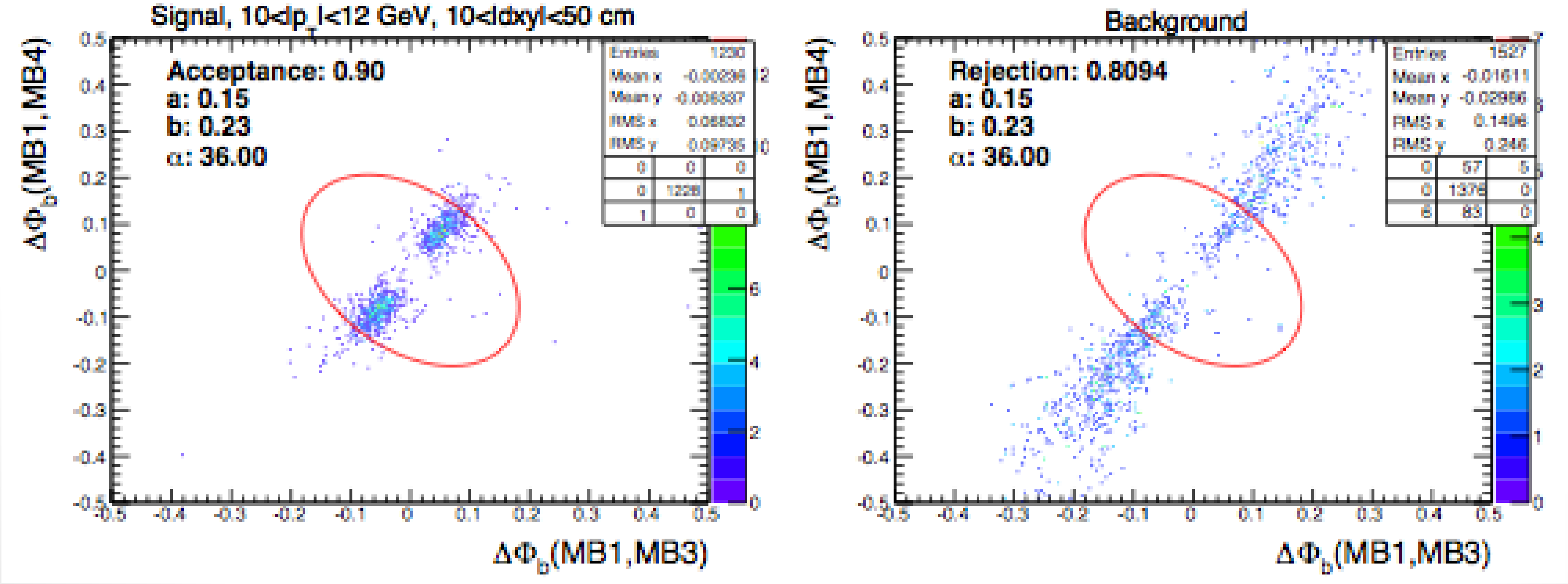




- Suppression power depends on how good the actual L1Trk trigger performs
  - A potential concern, but there is room for maneuver adjusting veto definition, especially in the forward region
  - Assuming that the main concern is the rate control, good L1Trk efficiency is the key figure to watch
    - 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.)

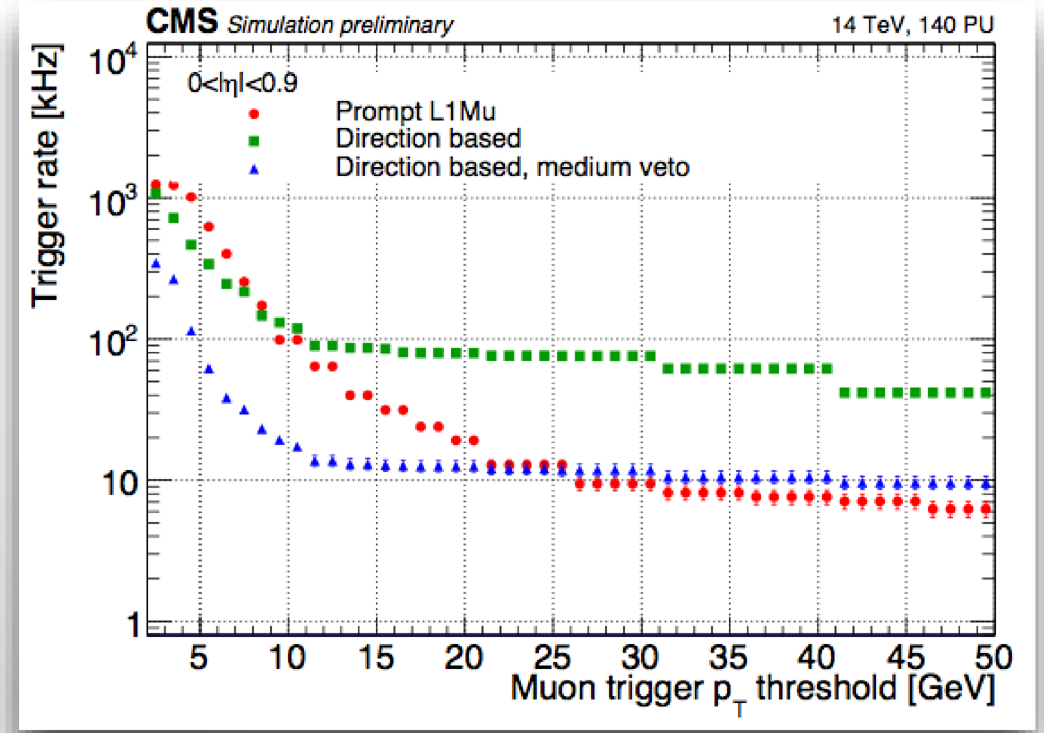
Displaced Muons in Barrel

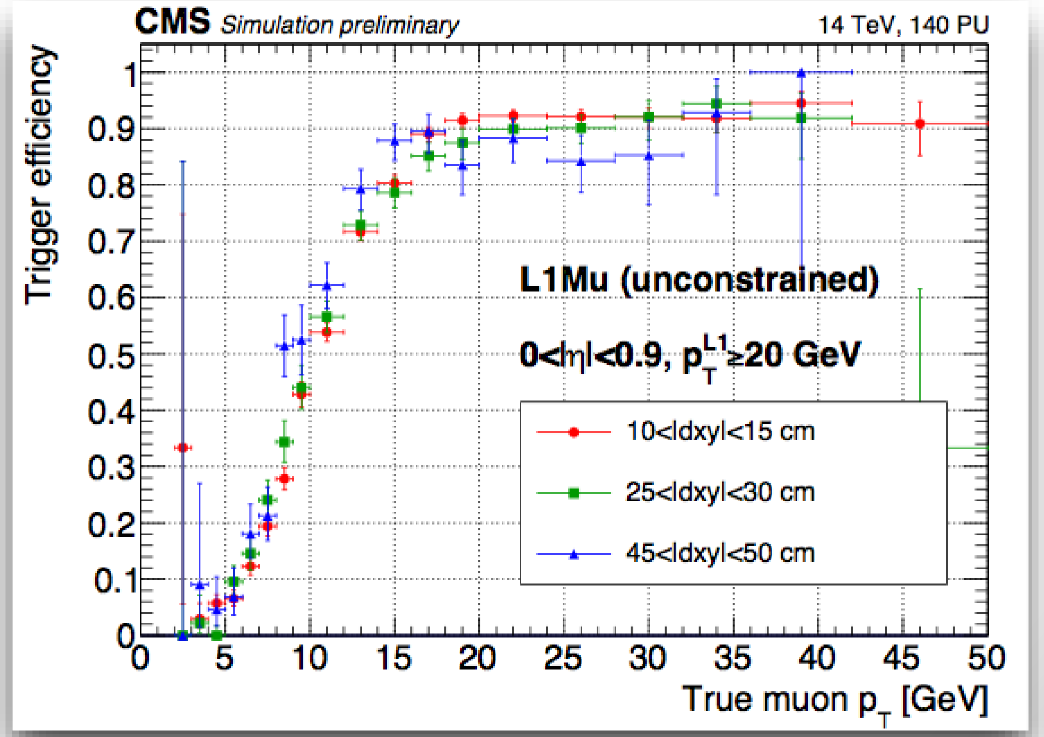
- A standalone algorithm comparing directions of stubs measured in different stations
  - A nearly literal implementation of the conceptual idea shown on slide 7: directions should be the same in all stations
- Simplified implementation: if more than two measurements are available, pick the most "powerful" 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



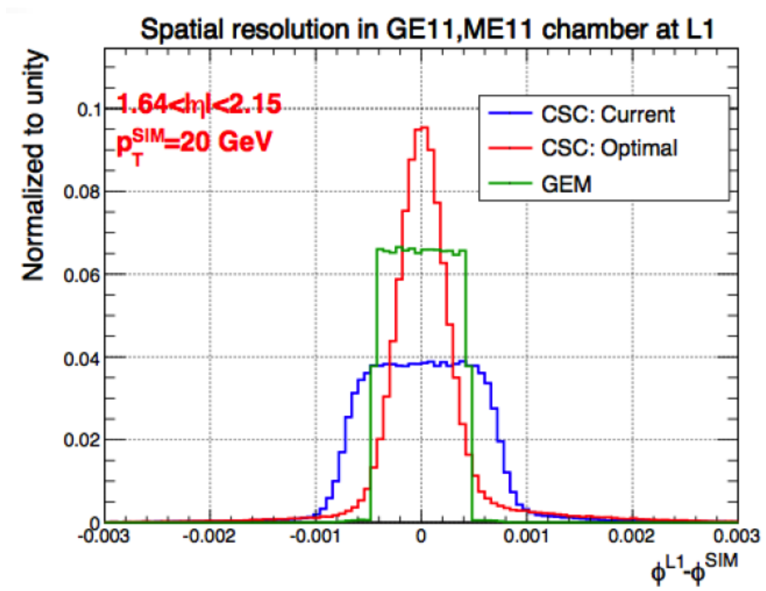


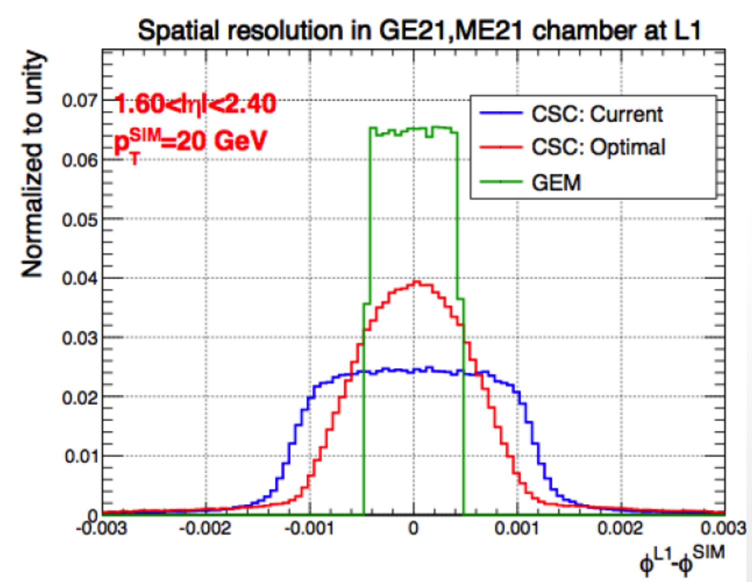
Displaced Muons in Endcap

- 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

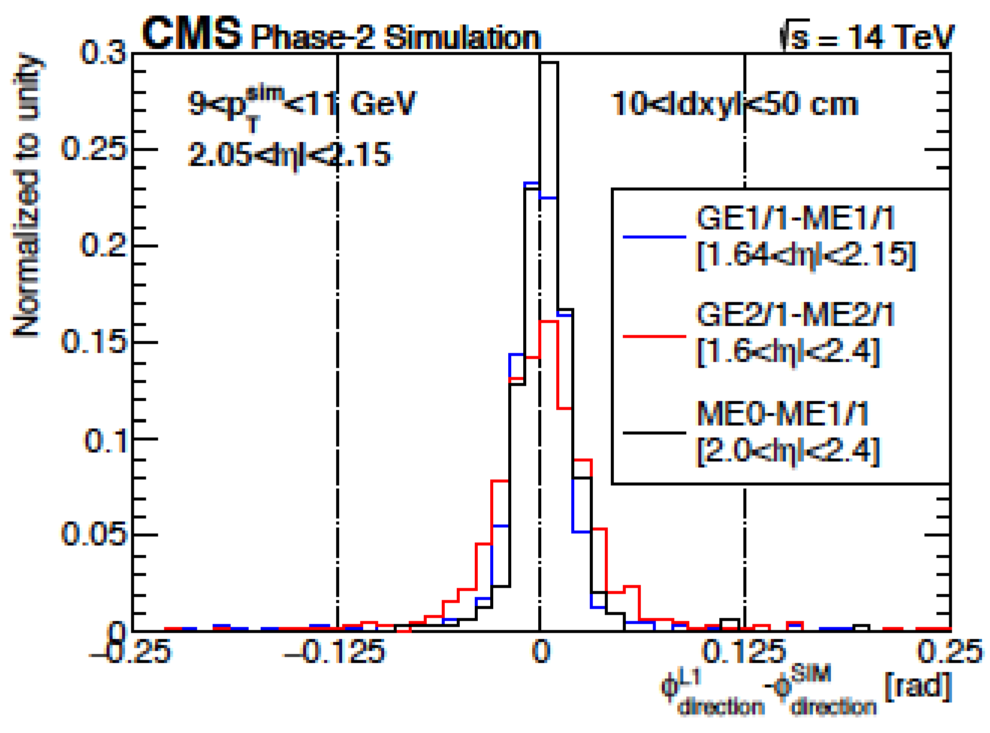
Muon Direction Measurement

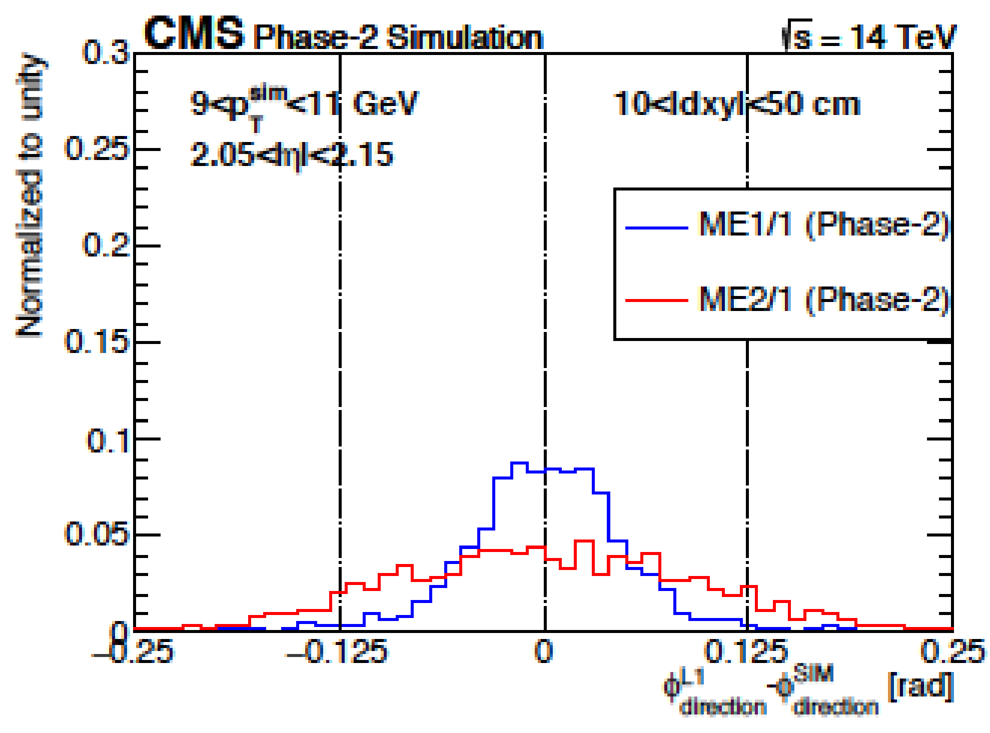
- Similar to prompt muons, forward region |η|>1.6 is the hardest
  - Good muon direction measurements are essential
    - Need at least two direction measurements to compare to each other
    - CSC or GEM standalone – too crude for this region (even soft muons bend very little)
- With GE2/1 added, GEM-CSC 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 ϕ 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 ϕ-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



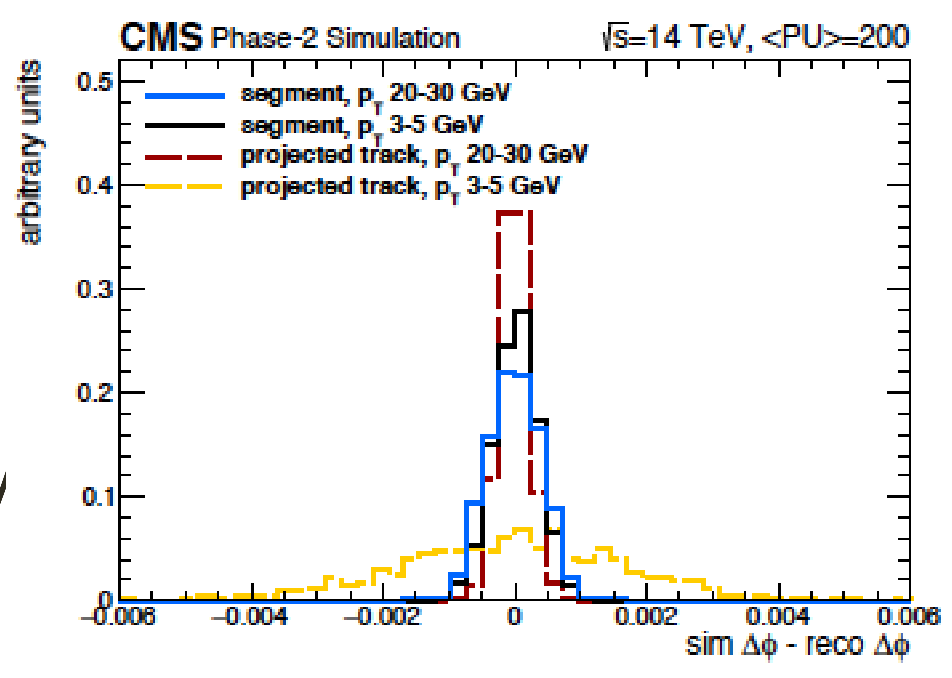


Direction Measurements



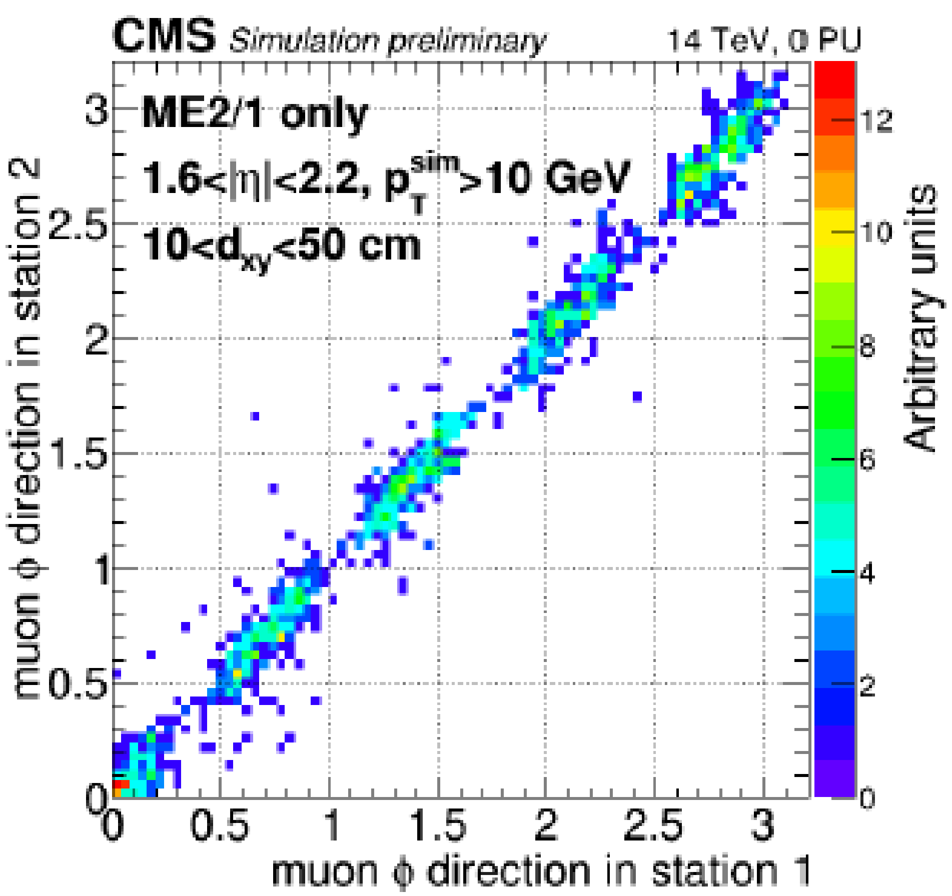


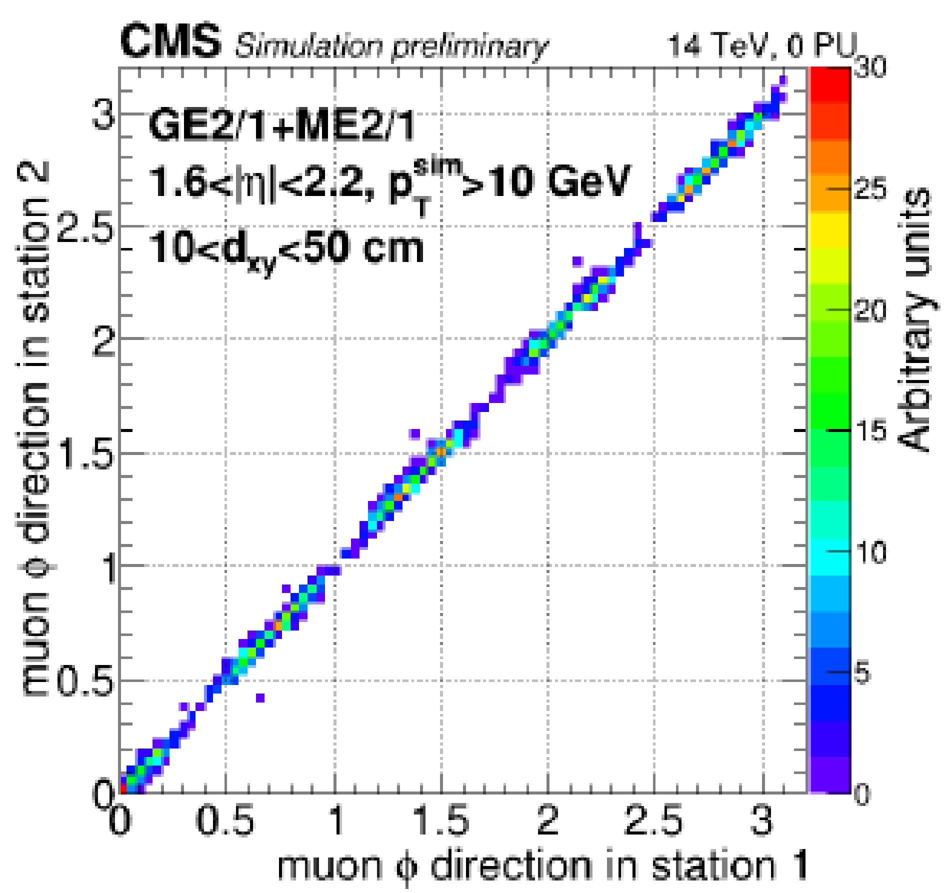
- Improved CSC L1 spatial position resolution improves measurement of the bending angle
- ME0 with its excellent resolution closes the whole in 2.1<η<2.4 left by GE1/1 not going all the way through



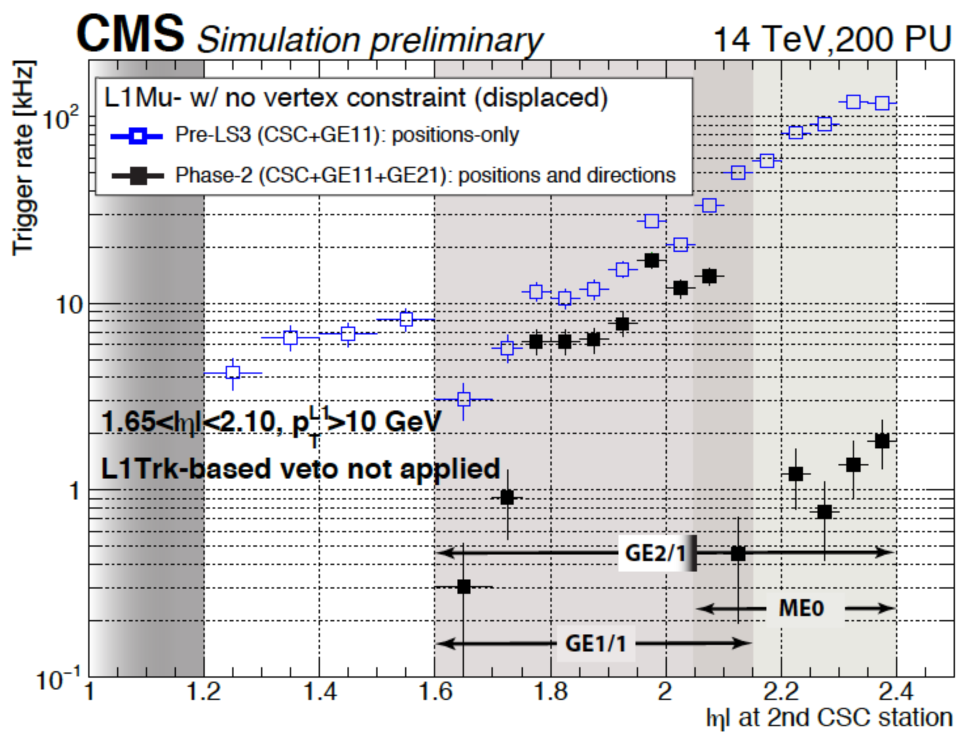
GEM-CSC Bending Angles

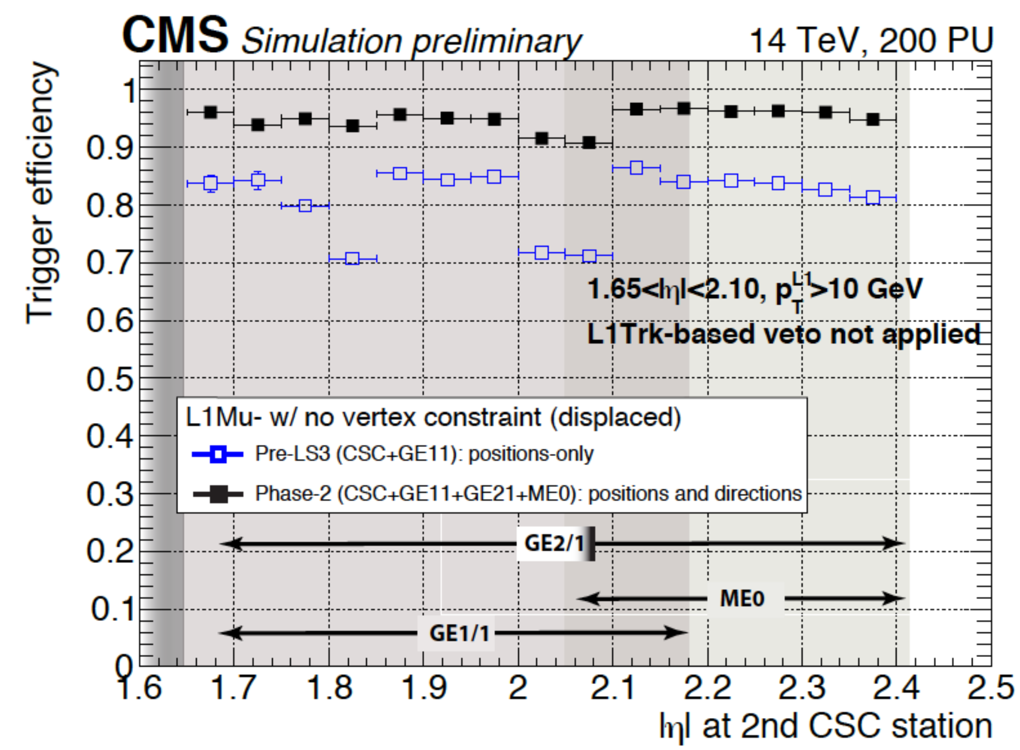
- Taking everything together, compare direction measurements in stations 1 & 2 for two scenarios:
  - Station 1: GE1/1-ME1/1 based measurement in both cases
  - Station 2: ME2/1 only in one case and GE2/1-ME2/1 in the other
- GE2/1 allows a much improved correlation of the directions
  - Pre-requisite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





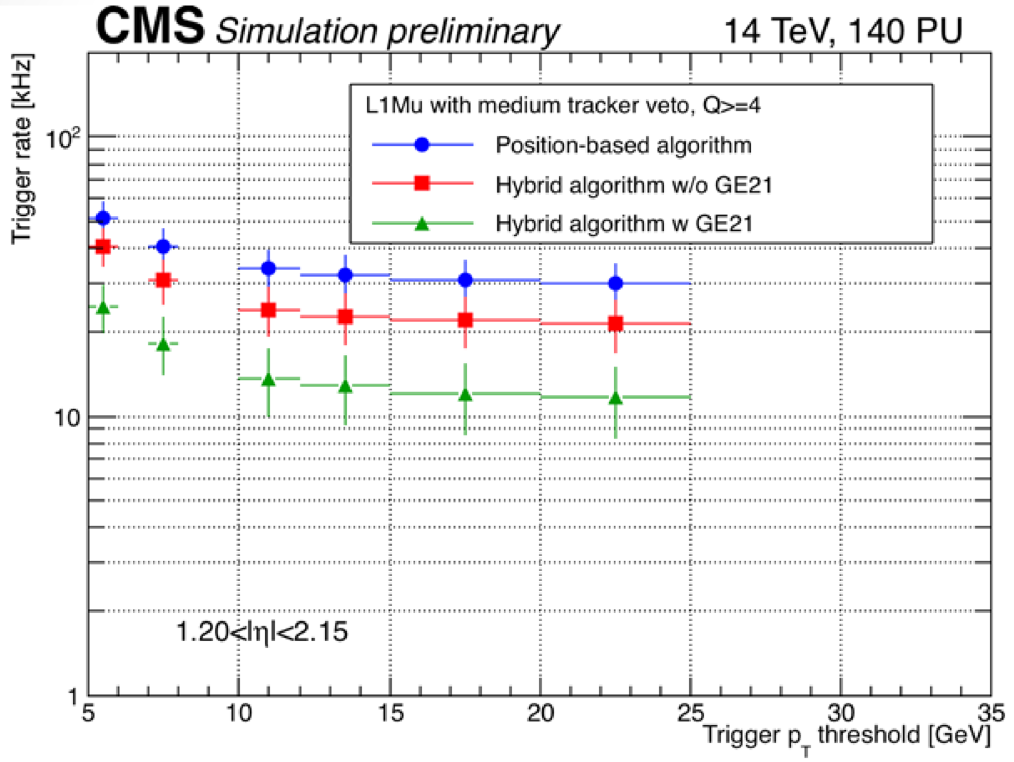
Hybrid Algorithm - Endcap

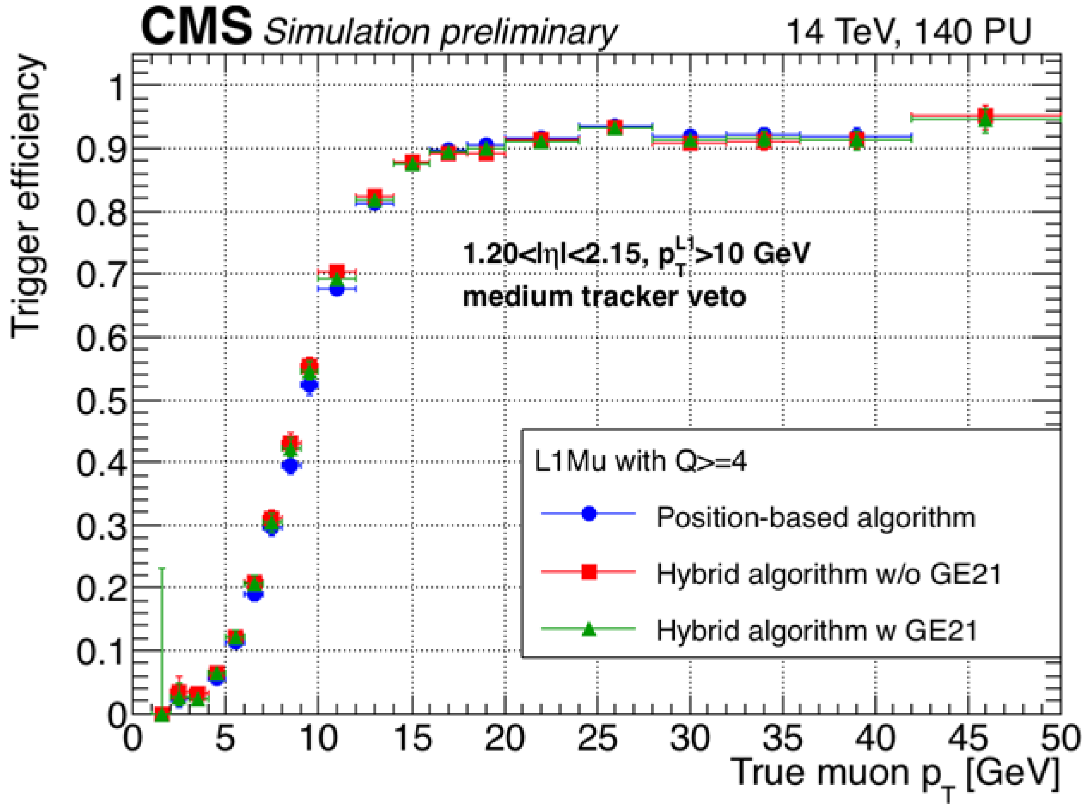




- Position-based measurement provides good rate reduction in lower eta part of the endcap; in the higher eta part, a significant improvement is obtained using both stub position and direction measurements
  - In eta<2.1: use GE1/1-ME1/1 and GE2/1-ME2/1 measurements
  - In eta>2.1: use ME0 and GE2/1-ME2/1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

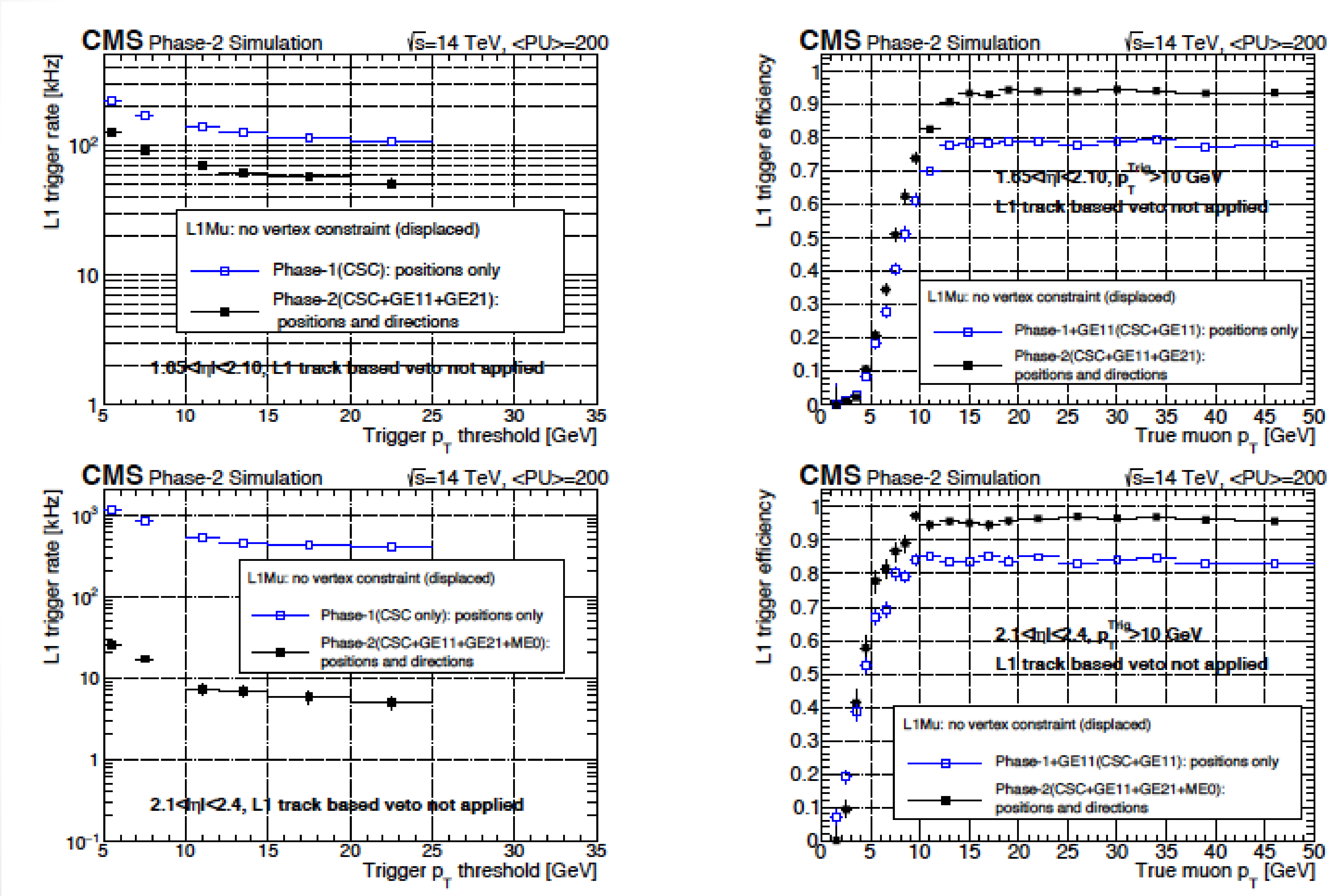
Hybrid Algorithm - Endcap





- 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



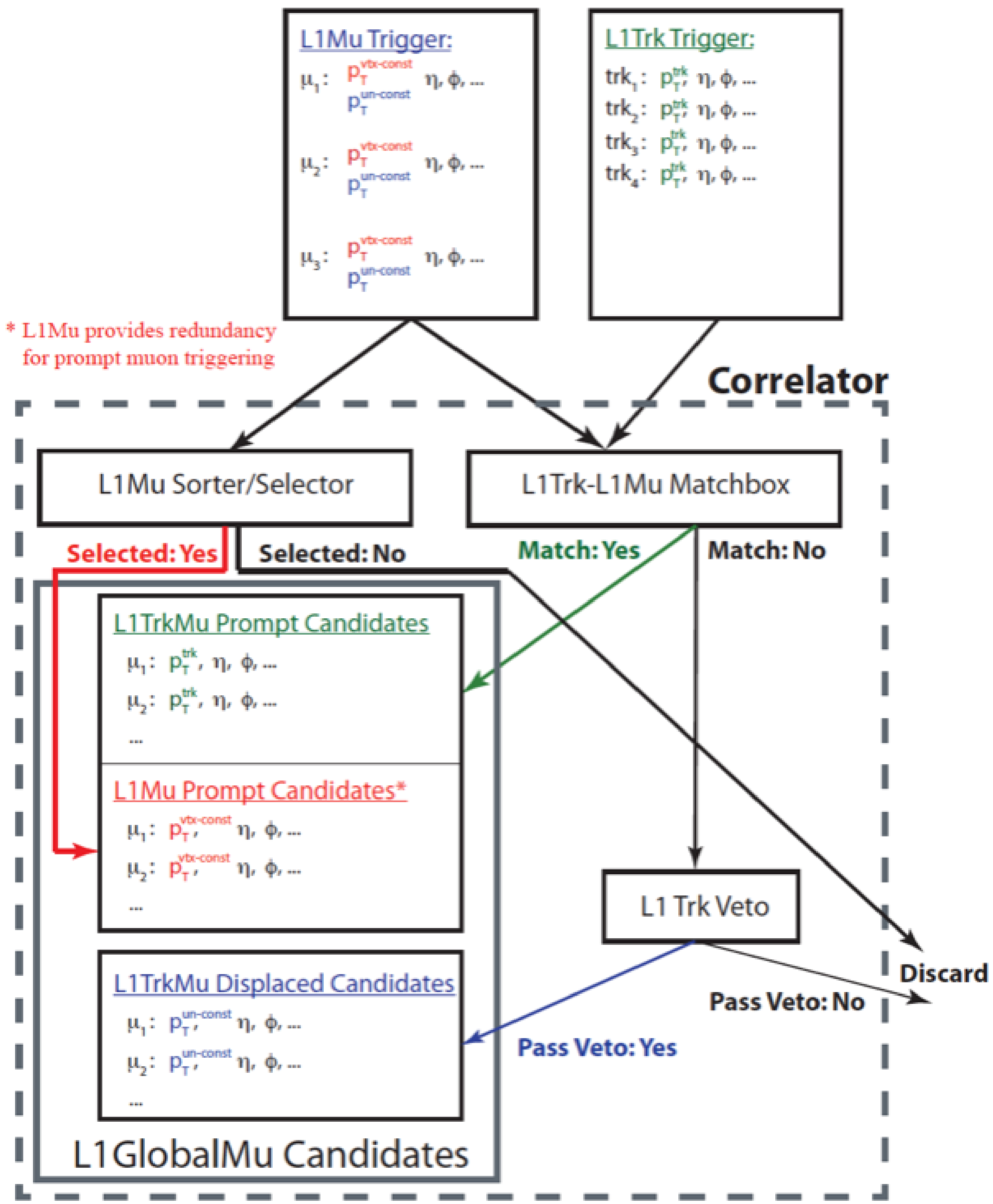
**Note track veto not applied here*

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)