CMS Trigger in Phase-2

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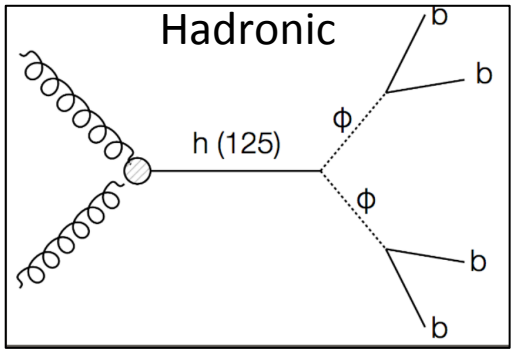
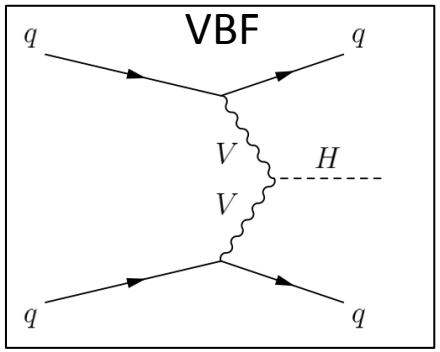
Motivations

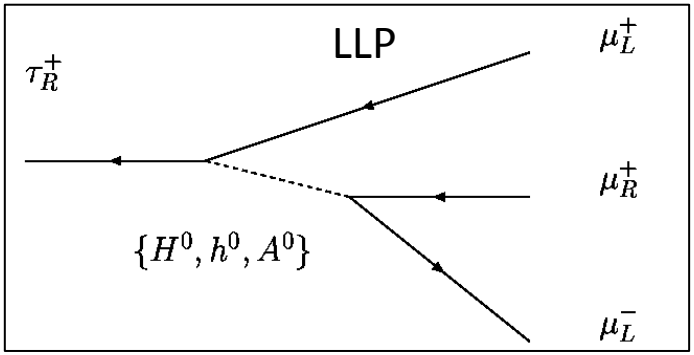
Trigger designed to target events of interest

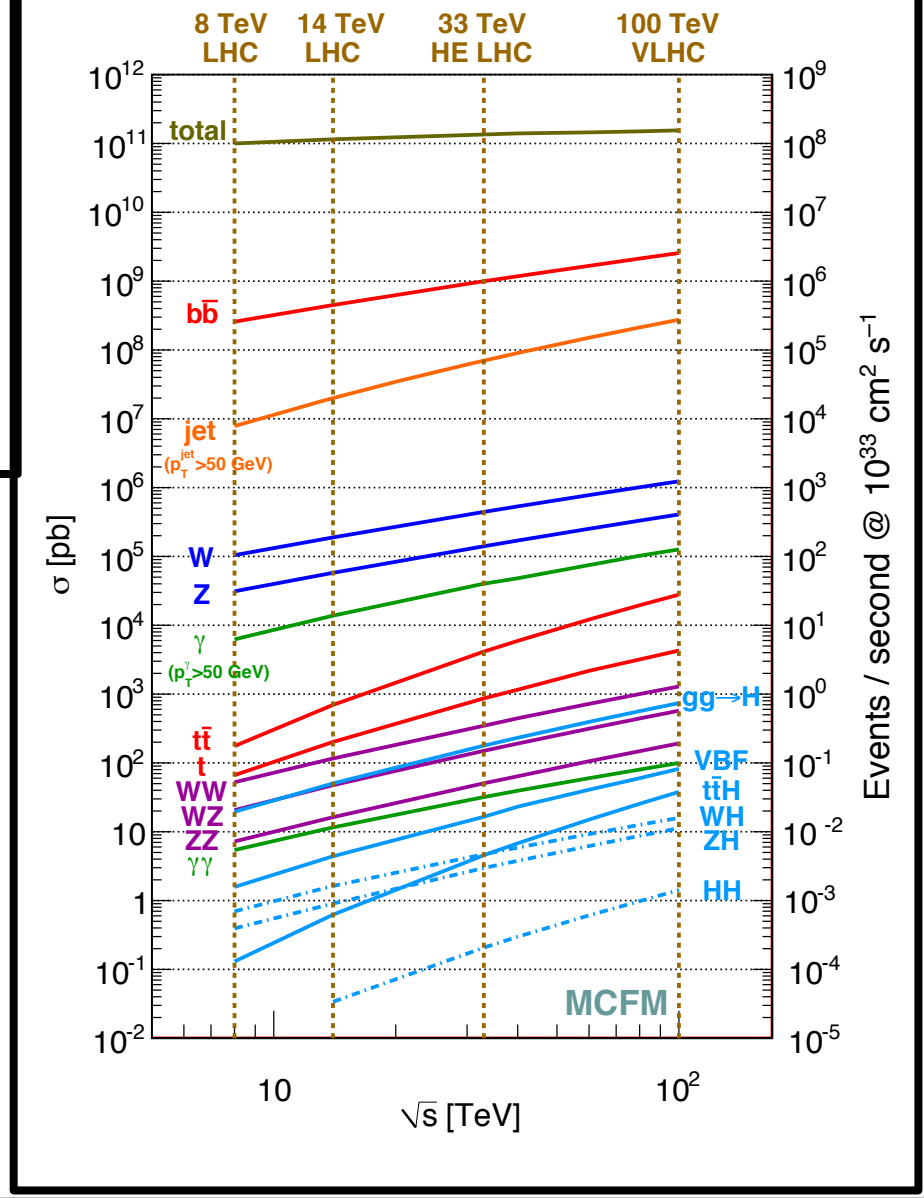
- Interested in events with small rates(xsec)
- Need accurate reconstruction of local objects
- Upgrades needed in order to maintain thresholds
- Additionally, hard work to extend our physics capabilities through the trigger

1. Forward regions (VBF)
2. LLPs (Tau→3 mu)
3. Hadronic (exotic) (Higgs→4b)





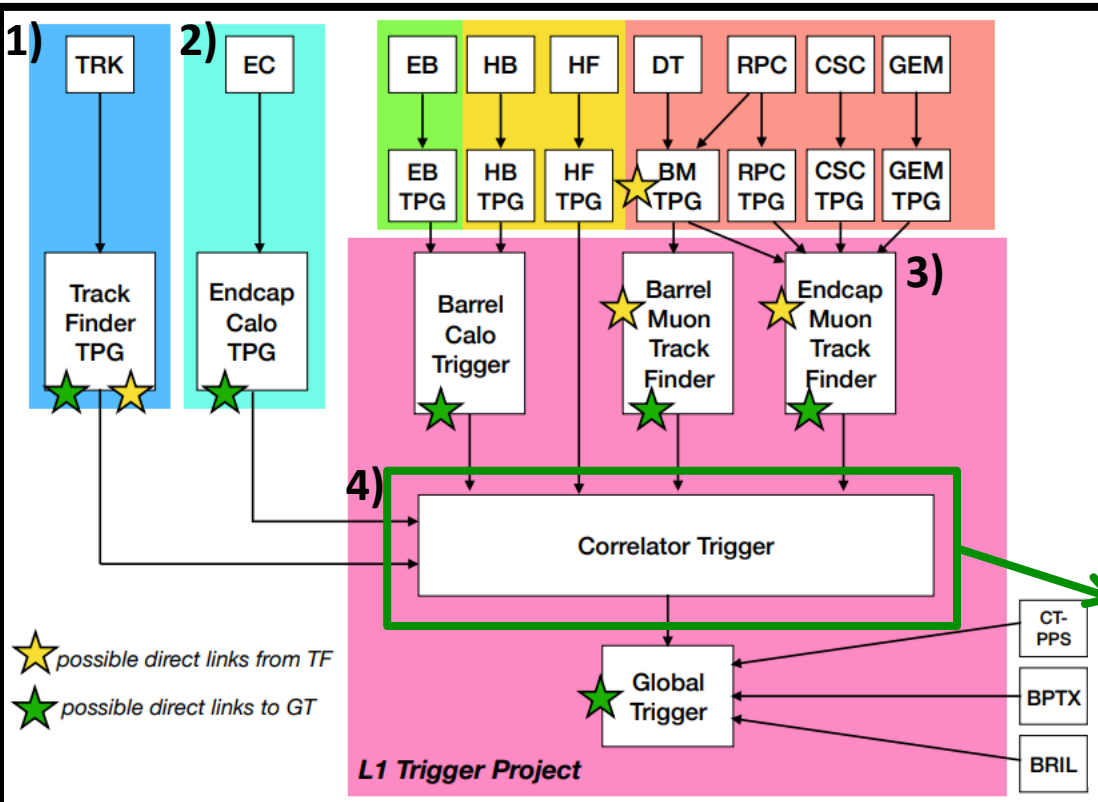




Phase-2 Changes

New Additions to Phase-2 L1 trigger:

1. Tracker will be incorporated at L1 level. (~5 μs latency)
2. New High granularity calorimeter in forward region (HGCAL) will be added to L1
3. The muon endcap will incorporate several new detectors into the L1 Muon Track Finder
   - iRPC → RPC TPG
   - GEM → GEM TPG
   - ME0 → GEM TPG
4. Correlator Trigger to implement sophisticated reconstruction algorithms like particle flow

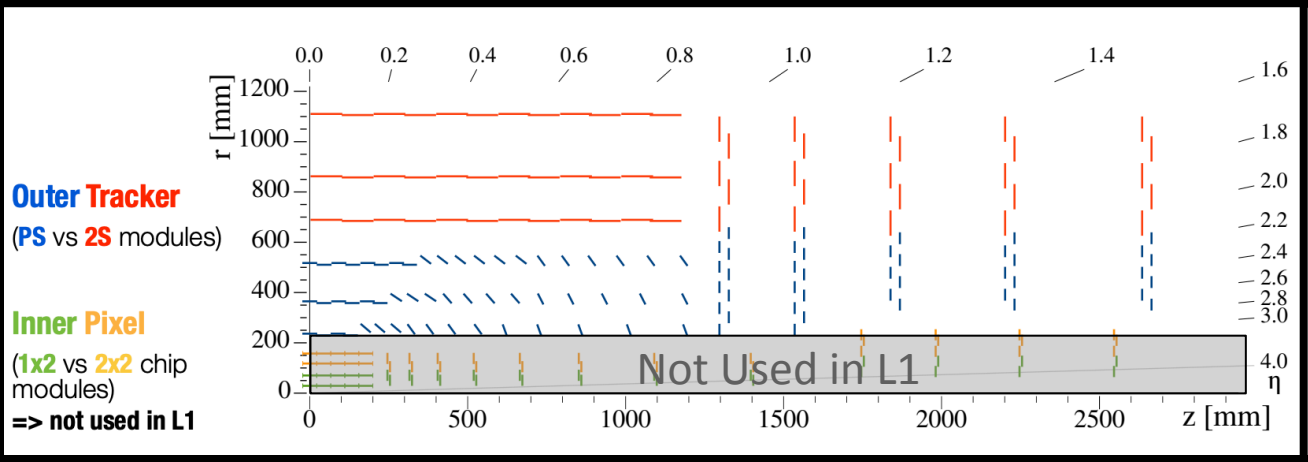


	Phase-1	Phase-2
L1 Rate	100 kHz	750 kHz
Latency	3.8 μs	12.5 μs
Bandwidth	1.8 Tb/s	50 Tb/s

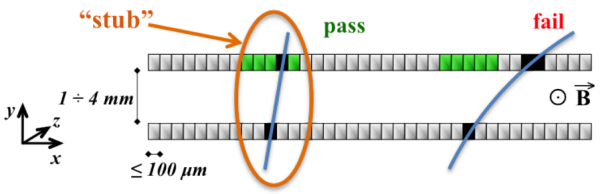
Processing step	Time (μs)
Input data received by CT	5
Trigger objects received by GT	7.5
L1A received by TCDS	8.5
L1A received by front-ends	9.5

30% contingency placed on latency

Tracker Stubs and Bend



Stubs generated if pairs of strips are consistent with high momentum particles (pT > ~2 GeV)

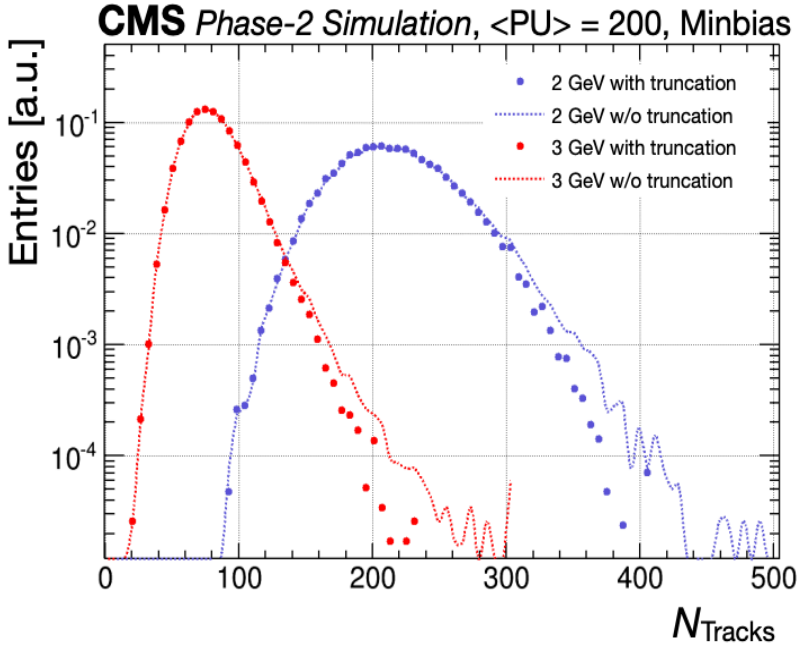


2S/PS modules:

- pT discrimination in FE electronics through hit correlations allows for triggering at L1 level
- Modules made of 2 closely-spaced silicon sensors.
- Create stubs associated with particles of 2 GeV or greater
- At <PU>=200, approximately 15,000 stubs will be sent to the backend Track Finder (TF)

Backend Track Finder:

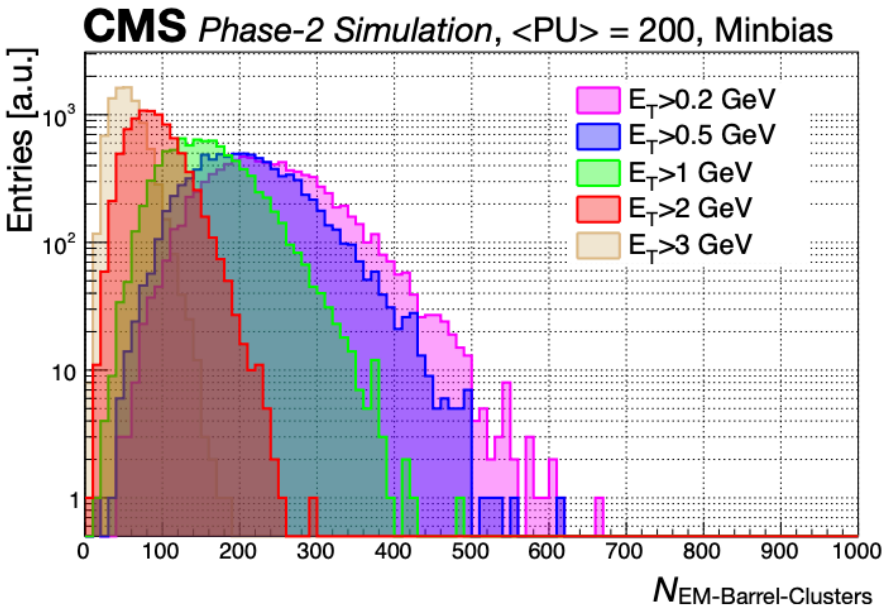
- Measured bend between modules gives rough pT measurement for tracks
- Enormous amount of data…
- However, most tracks produced have very soft pT
- 97% (99%) of tracks produced have pT<2GeV (pT<3GeV)
- At <PU>=200, an average of 200 tracks will be sent to L1 trigger correlator



ECAL and HCAL at L1

Electromagnetic Barrel Calorimeter:

- ECAL barrel trigger and readout electronics will be upgraded
- Phase-1 TP generator was located on-detector but will be moved off-detector
- Phase-2 will have single crystal granularity with 160 MHz sampling frequency
- Allows for more sophisticated clustering algorithms (under study)
- Re-optimization of spike killer algorithms (Using timing/pulse shape)

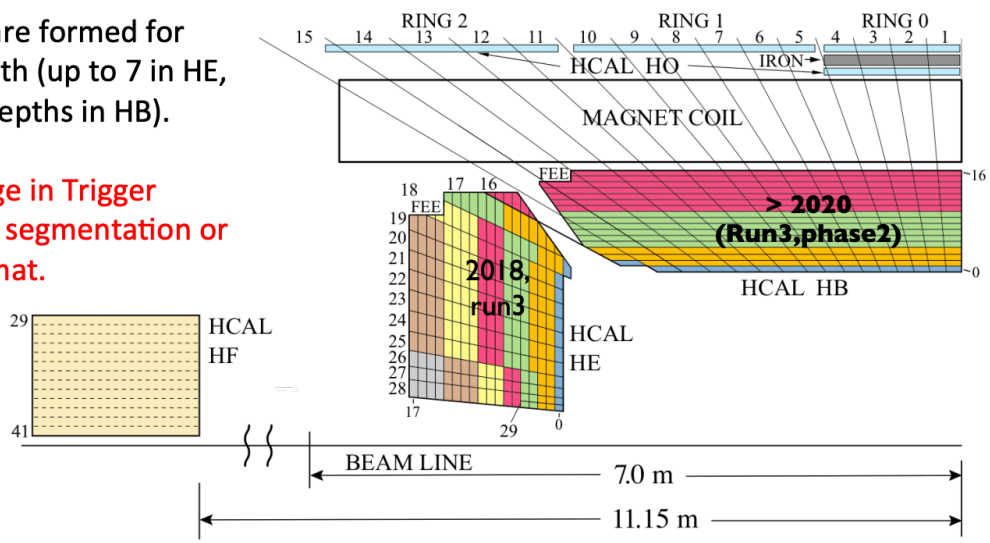


Hadron Barrel and Forward Calorimeters:

- Replacing back-end electronics and partial replacement of front layer scintillator tiles
- HCAL Towers same as Phase-1 + Depth Information (7 total)
- HF Towers same as Phase-1
- Additional feature bits available with upgraded HBHE and HF
- Ongoing studies for TP reconstructing schemes to reduce PU

RecHits are formed for each depth (up to 7 in HE, up to 4 depths in HB).

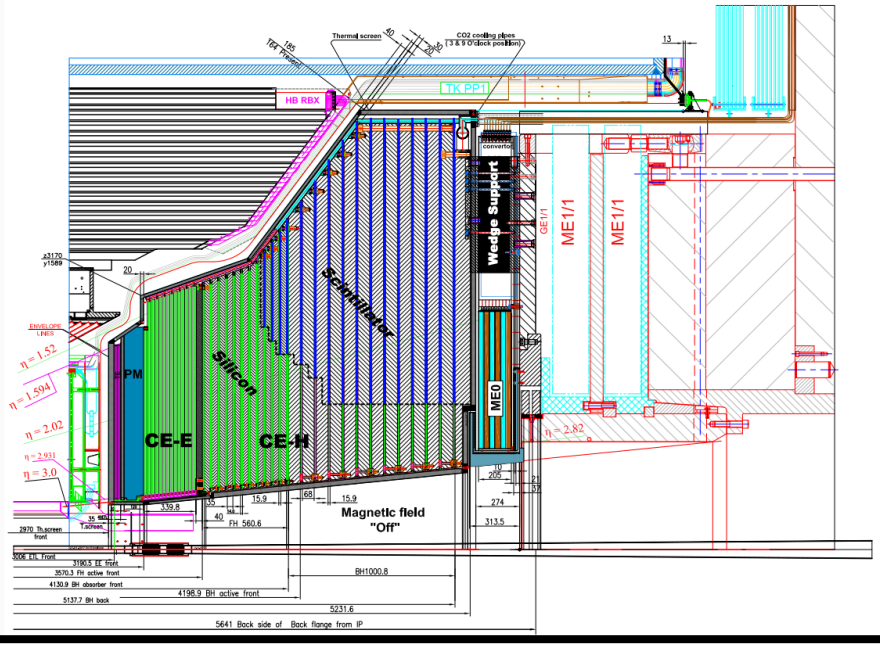
No change in Trigger Primitive segmentation or data format.



Geometry and Readout

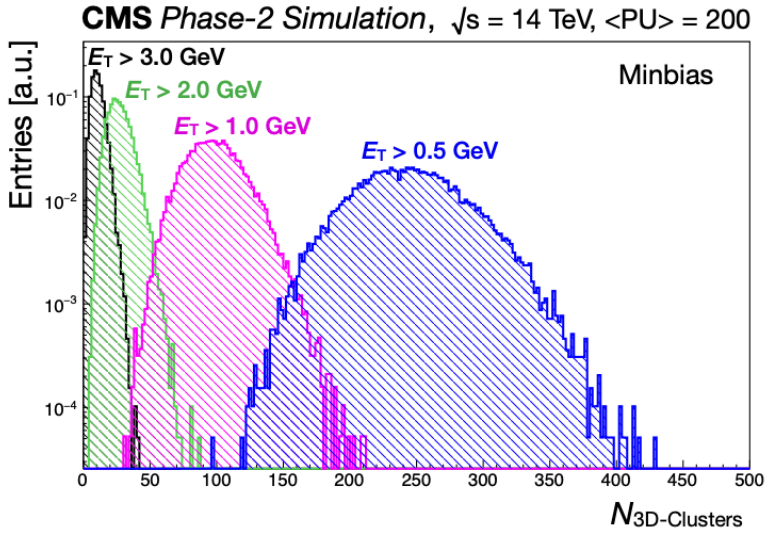
HGCAL Geometry:

- Geometry from TDR (2018) https://cds.cern.ch/record/2293646/files/CMS-TDR-019.pdf
- Sampling calorimeter
- Mix of Silicon (Green) and Scintillator (Blue) modules
- Will have 52 sensitive layers
  1. 28 in the electromagnetic section (half used for trigger)
  2. 24 in hadronic section (All used for trigger)



HGCAL L1 Readout:

- Large amount of data associated with 3D clusters
- Simple E_T cuts can reduce rate to add more cluster information
  1. Transverse energy
  2. Subdetector section fractions
  3. Shower position
  4. Quality information
- Optional information
  1. Cluster shape
  2. Transvers energy interpreted for electromagnetic shower
  3. Subclusters



Muon Triggers

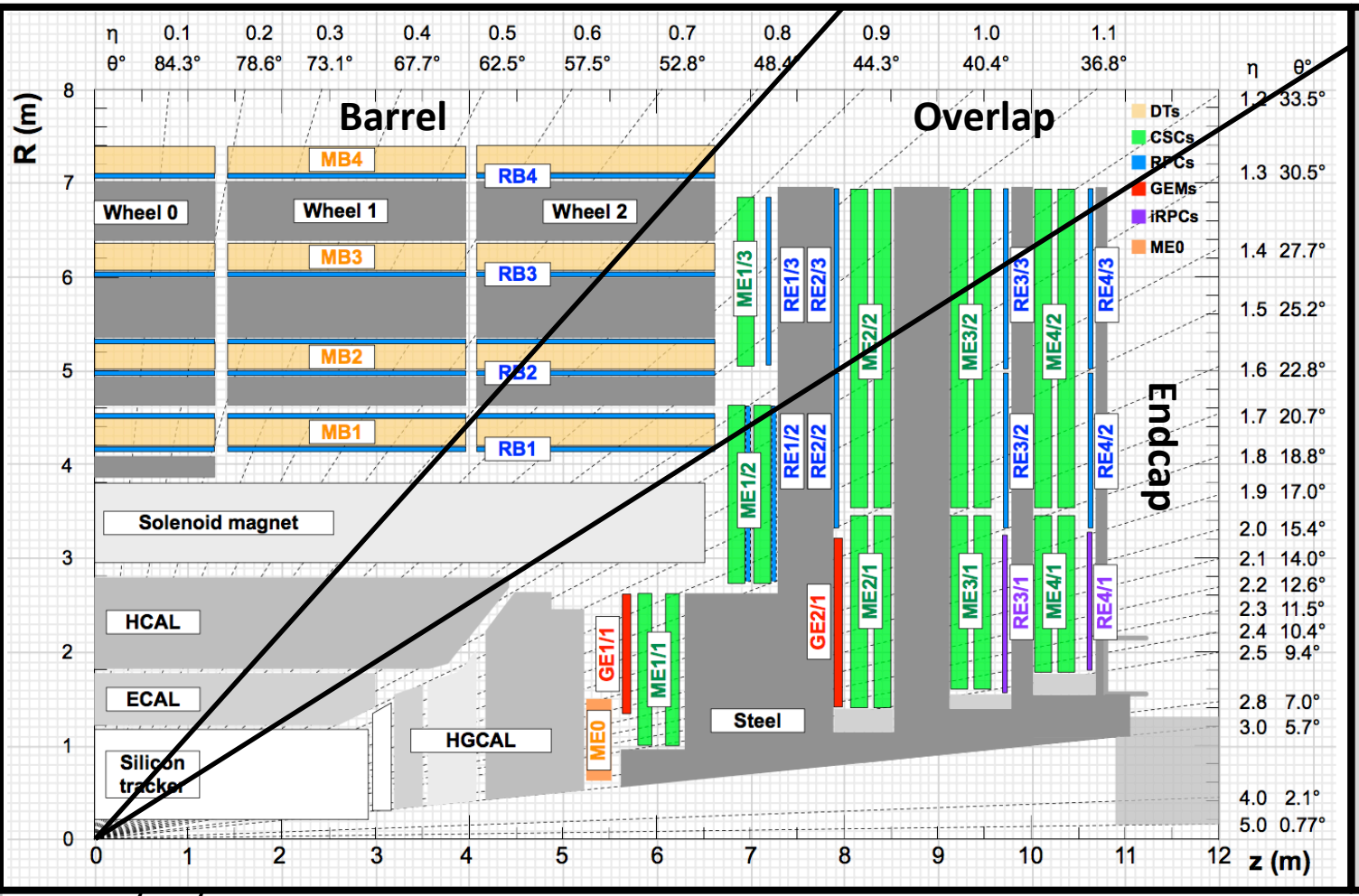
Muon Track Finders at L1:

Split into 3 different subsystems based on geometry and detector type

Barrel: DT and RPC.

Overlap: Complicated geometry utilizing DT, RPC and CSC.

Endcap: CSC and RPC plus new GEM, ME0 and iRPC detectors. New detectors needed to help with higher PU and punch through in the forward region.



KEY:

DT=Drift Tube

RPC=Resistive Plate Chamber

CSC=Cathode Strip Chamber

GEM=Gas Electron Multiplier

ME0=Based on GEM

iRPC=Based on RPC

New to Phase-2 EMTF:

ME0

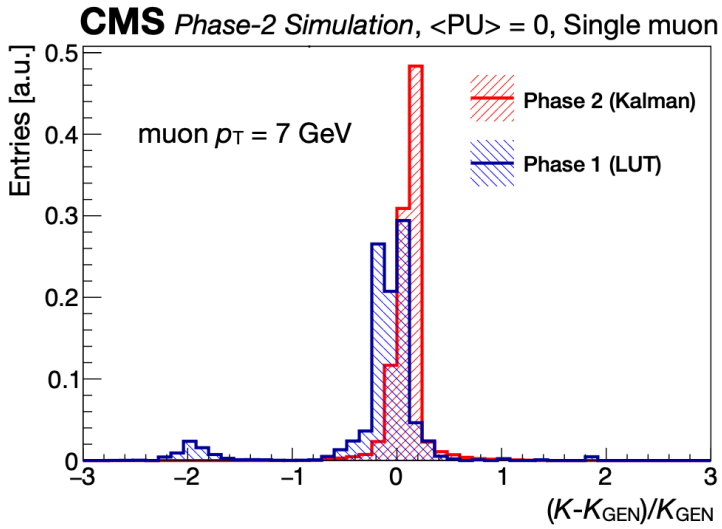
GEM (2 Stations)

iRPC (2 Stations)

Phase-2 Barrel and RPC

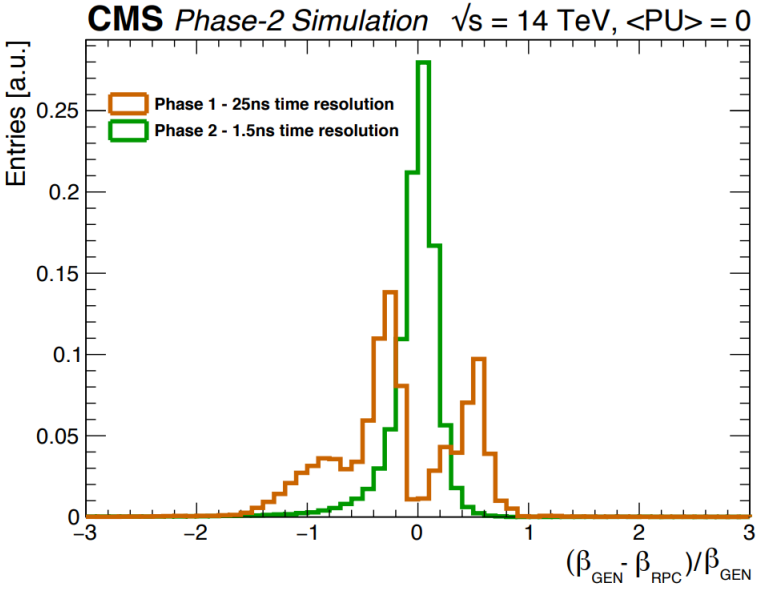
Studies for Phase-2 BMTF:

- Kalman filter algorithm fully commissioned by end of 2018
- Iterative track building algorithm starting from outer chamber and propagating to inner stations (shown in Backup)
- Can be used to trigger on displaced particles
- Tracks can be unconstrained or constrained to tracker tracks



Studies for HSCP using RPC timing:

- Slow moving particles can be identified by time-of-flight measurements
- Upgrade to RPC backend electronics will provide increased time resolution (from 25 ns to ~1.5 ns)
- HSCPs can be identified using linear fit of RPC hits in space-time (slope provides measurement β=v/c)
- Clear improvement in the resolution of the β measurement
- Clear improvement is observed in efficiency for slow moving particles β~0.5c



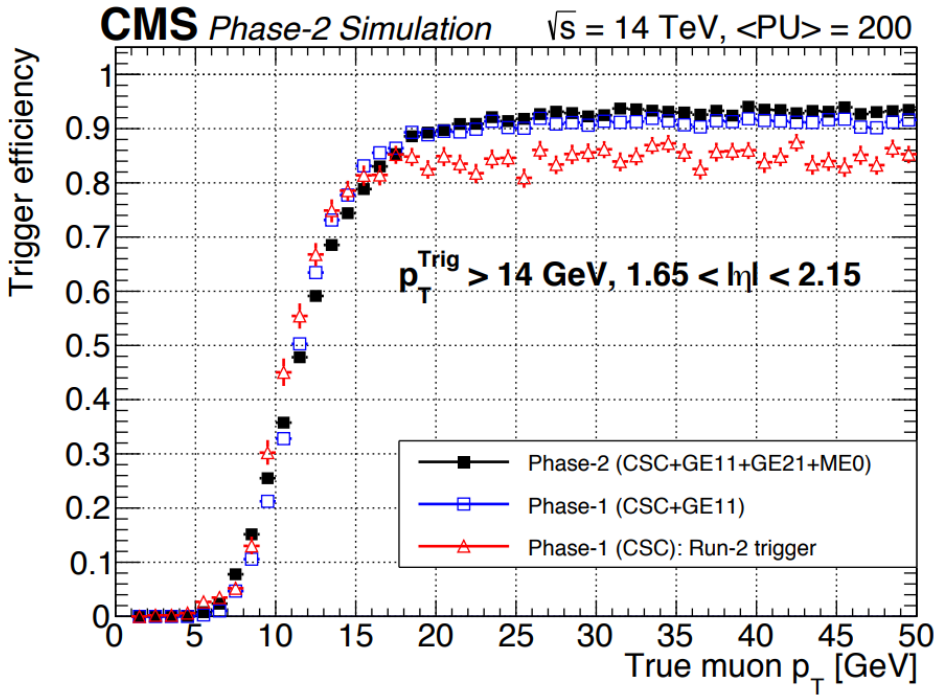
Phase-2 EMTF

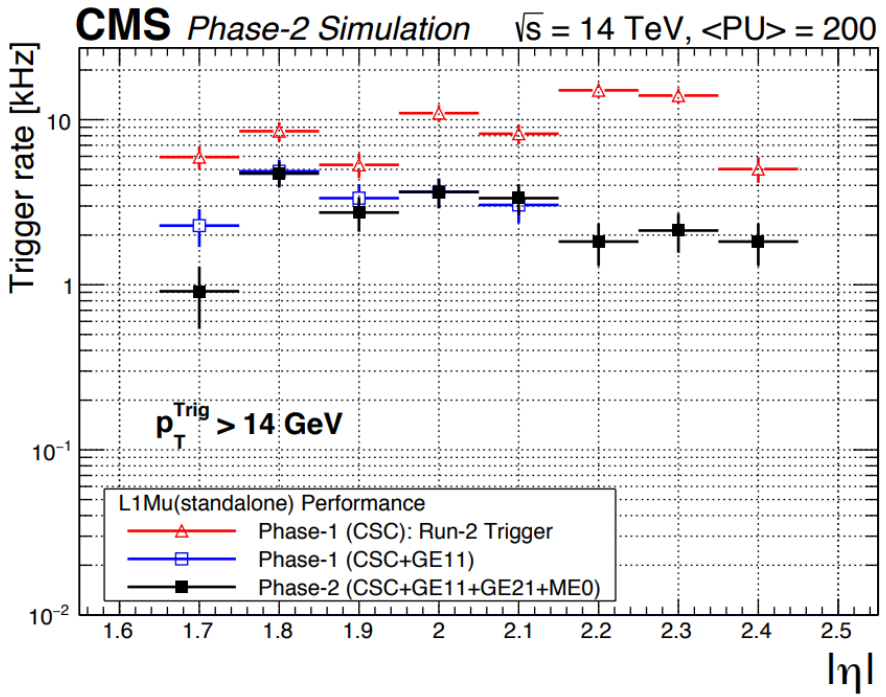
Phase-2 EMTF:

- Incorporates the new muon detectors (ME0, GE1/1 and GE2/1 shown here)
- Detectors provide more bend information to mitigate PU effects
- Sharper turn-on while reducing trigger rates

Ongoing Studies:

- Will also add iRPCs (not shown here)
- Correlating tracker tracks to endcap tracks/stubs reduces rate significantly further
- pT assignment using a NN instead of LUTs (incorporating all Phase-2 detectors)





L1 Menu

L1 Physics Menu based on the Run 2 Menu:

- Thresholds mostly consistent with Run 2 values
- L1 Menu studied for multiple PU conditions
  1. <PU>=140
  2. <PU>=200
  3. <PU>=200 rate * 1.3 (incomplete menu)
- Total rate below 500 kHz (390 kHz) out of maximum of 750 kHz
- Changes to a few thresholds but most are maintained with help of tracker information
- Will continue to integrate algorithm updates and re-evaluate rates and efficiencies
- Will add several trigger paths
- Preparing update highlighting HL-LHC physics signals

Proposed L1 Menu

$L = 5.6 \times 10^{34}\ \mathrm{cm^{-2}s^{-1}}$, $\langle PU \rangle = 140$ $L = 8.0 \times 10^{34}\ \mathrm{cm^{-2}s^{-1}}$, $\langle PU \rangle = 200$	L1 trigger with L1 tracks		
Trigger algorithm	Rate [kHz]		Offline threshold(s) [GeV]
$\langle PU \rangle$	140	200	
Single Mu (tk)	14	27	18
Double Mu (tk)	1.1	1.2	14 10
Ele* (iso tk) + Mu (tk)	0.7	0.2	19 10.5
Single Ele* (tk)	16	38	31
Single iso Ele* (tk)	13	27	27
Single γ^* (tk-iso)	31	19	31
Ele* (iso tk) + e/γ^*	11	7.3	22 16
Double γ^* (tk-iso)	17	5	22 16
Single Tau (tk)	13	38	88
Tau (tk) + Tau	32	55	56 56
Ele* (iso tk) + Tau	7.4	23	19 50
Tau (tk) + Mu (tk)	5.4	6	45 14
Single Jet	42	69	173
Double Jet (tk)	26	43	2@136
Quad Jet (tk)	12	45	4@72
Single ele* (tk) + Jet	15	15	23 66
Single Mu (tk) + Jet	8.8	12	16 66
Single ele* (tk) + $H_{\mathrm{T}}^{\mathrm{miss}}$ (tk)	10	45	23 95
Single Mu (tk) + $H_{\mathrm{T}}^{\mathrm{miss}}$ (tk)	2.7	8	16 95
H_{T} (tk)	13	24	350
Rate for above triggers*	180	305	
Est. rate (full EG eta range)		390	
Est. total L1 menu rate ($\times$ 1.3)	**260**	**500**	

Preparation for HLT at Phase-2

HLT menu preparation:

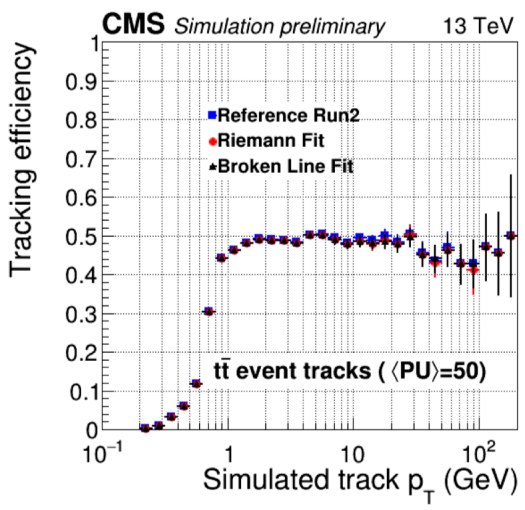
- 2019: Prepare basic menu based on simple HLT algorithms and the Phase-2 L1T menu.
- 2020: Update the HLT menu for simplified menu covering a few representative physics channels.
- Prepare tighter versions of the menu to have several reduced-rate options.

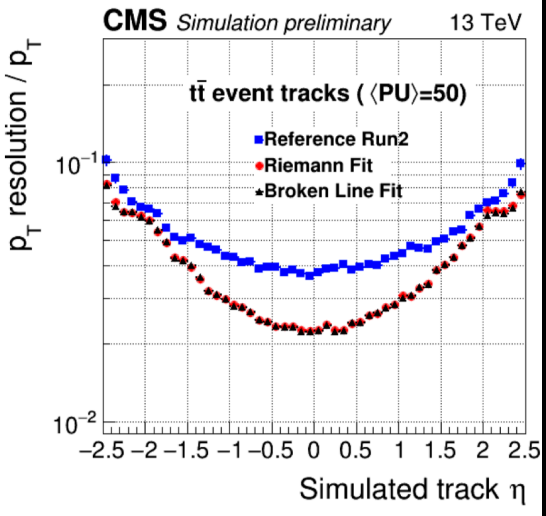
HLT reconstruction:

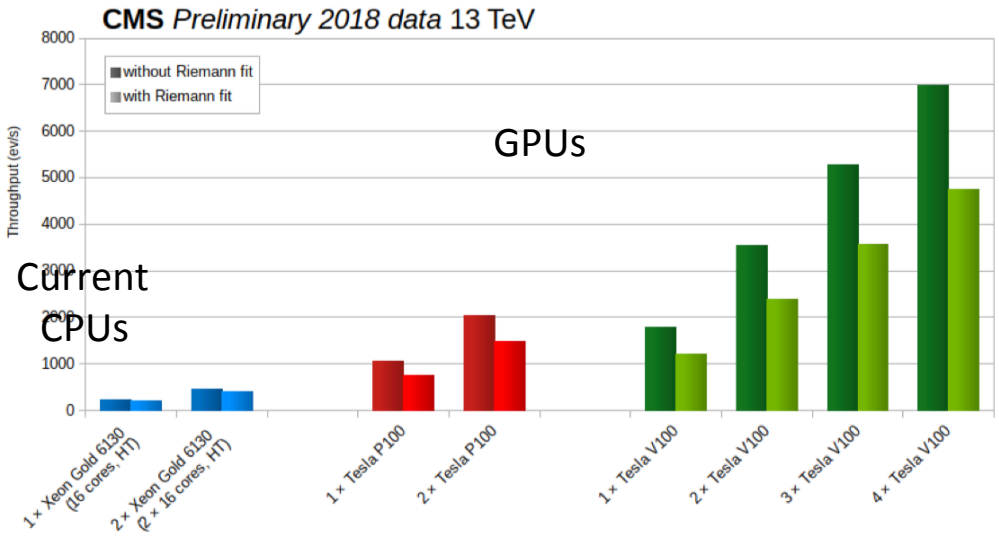
- Adapt the developing offline reconstruction code to the online environment.
- Extrapolate the resource requirements: using high pileup data and Phase-2 simulations
- Estimate impact from upgraded/new detectors (MTD, HGCAL, L1 tracking, etc).

Heterogeneous computing:

- Adapt some reconstruction algorithms (calorimeters, pixel tracking) to the use of accelerators (GPUs or FPGAs).
- Pixel tracking results: significantly larger throughput using GPUs (bottom plot); similar efficiency and better pT resolution using updated algorithms (top plots).







Summary

END

L1 trigger for Phase-2 compared to Phase-1:

- Additional detectors at the L1 trigger level:
  1. Tracker
  2. HGCAL

  } Correlator Trigger **[1]**

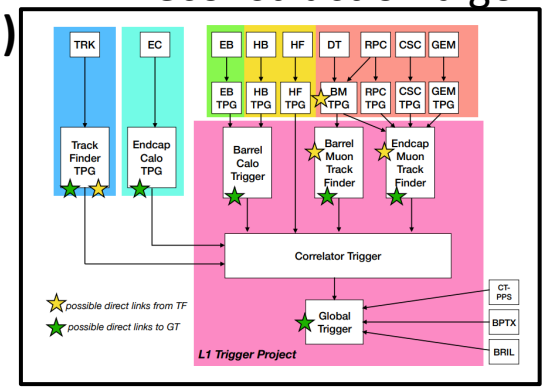
  3. ME0
  4. GEM
  5. iRPC

  } Endcap Muon Track Finder **[2]**

	Phase-1	Phase-2
L1 Rate	100 kHz	750 kHz
Latency	3.8 μs	12.5 μs
Bandwidth	1.8 Tb/s	50 Tb/s

- Increased latency to 12.5 μs (~3 times)
- Increased rate to 750 kHz (7.5 times)
- Reworking algorithms across L1 to utilize higher granularity/timing resolution associated with upgraded electronics and to take advantage of new detectors
- Correlator Trigger to incorporate tracker tracks into L1 **[1]**
- L1 Menu set with similar thresholds as Run 2 menu
- HLT menu will follow based on Run 2 menu
- HLT reconstruction algorithms have been ported to GPUs for a heterogeneous HLT farm **[3]**

1)



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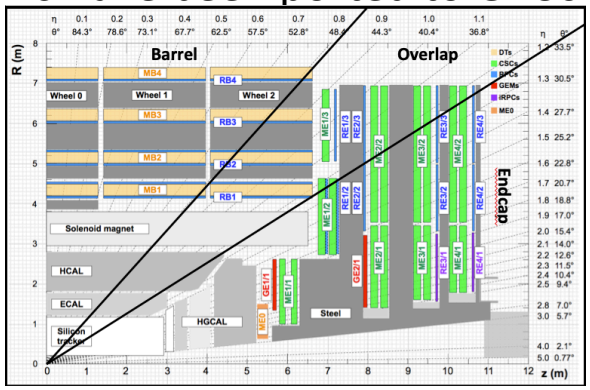
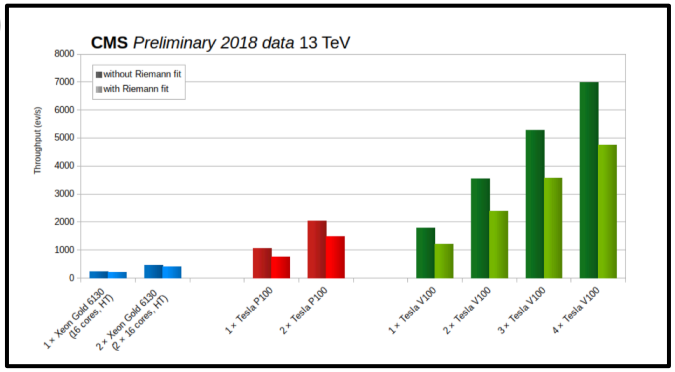


3)



Backup

END

What is the Trigger System?

Level 1 Trigger (L1T):

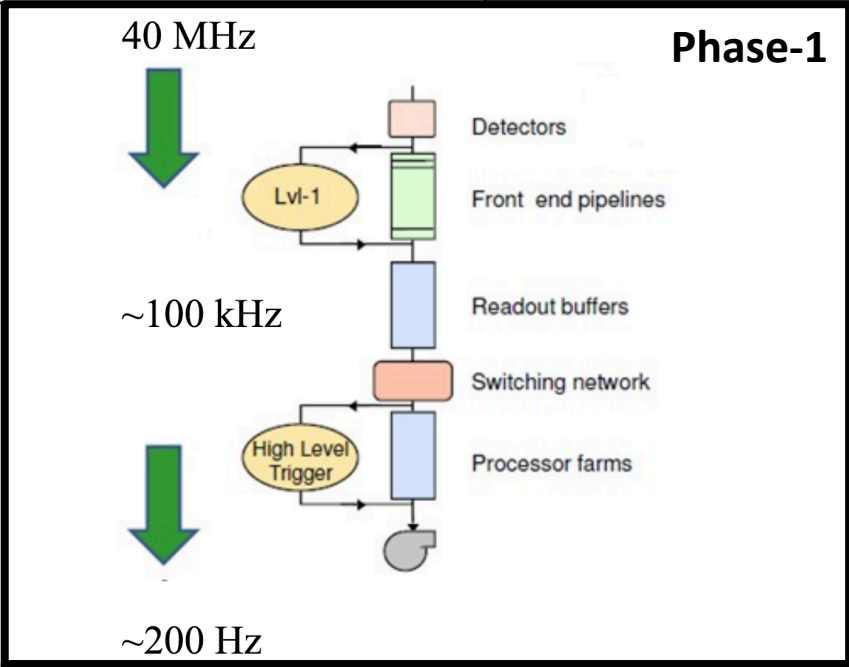
- Creates trigger primitives out of basic detector information.
- Creates local objects (primitive electrons, photons, jets and muons)
- Reduces event rate from ~40 MHz to ~ 100 kHz
- Sends events of interest to high level trigger

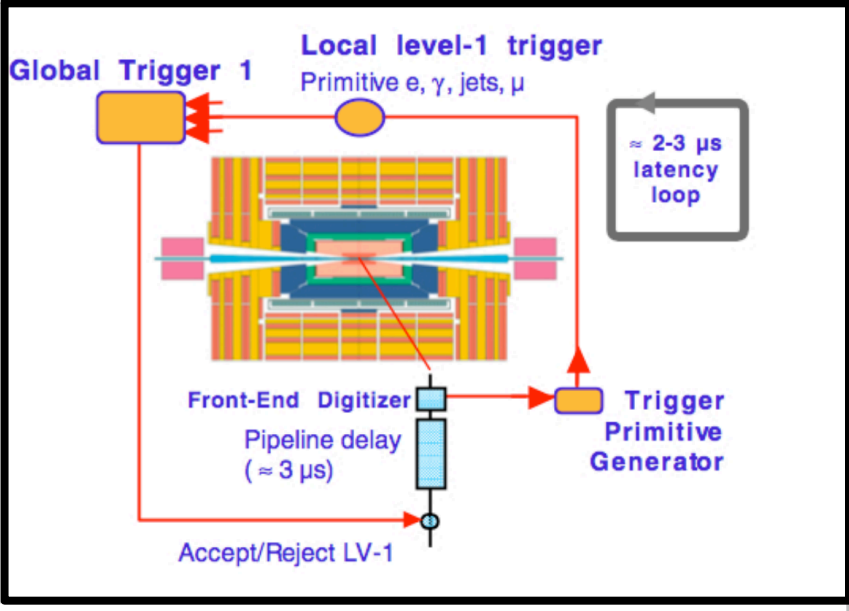
High Level Trigger (HLT):

- PC farm (~1000 units) using reconstruction software and event filters
- Looks for events likely containing "interesting" physics
- Large HLT Menu to look at a wide range of physics
- Reduces event rate from ~100 kHz to ~ 200 Hz

All done online (no chance to get events back!)

Data Rate: ~10^9 Hz W→lv Rate: ~100 Hz





2D+3D Clustering

Backup

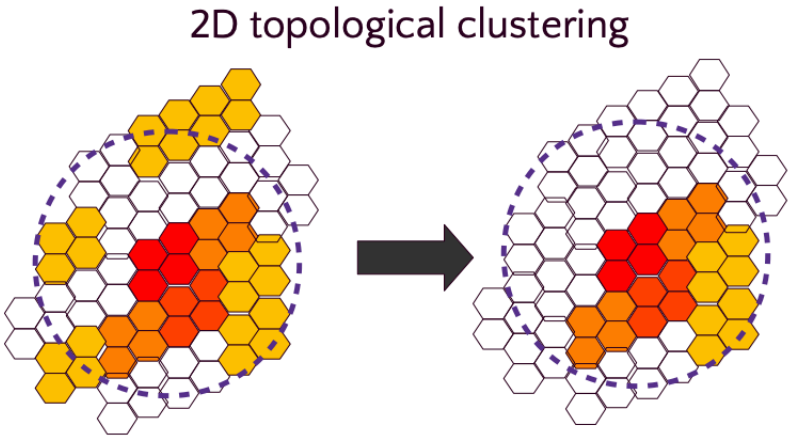
2D Clustering:

- Trigger cells are the sums of sensor cells
- 3*3 for small cells and 2*2 for large cells
- 48 trigger cells/module
- Layer-by-layer 2D clustering
- Cluster TCs around seed TC (>5mip$_T$) **[1]**

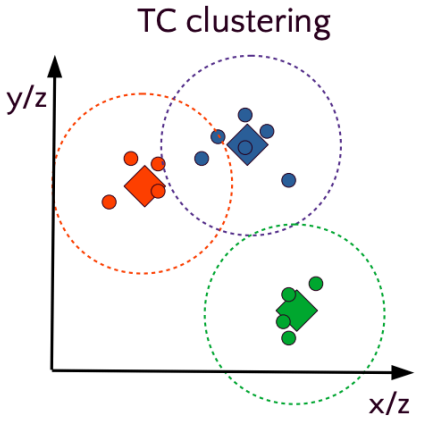
3D Clustering (TC clustering):

- Seeds and TCs in (x/z,y/z) plane **[2]**
- TC association to the closest seed within given distance
- Distance depends on the layer
- Assumed maximum of 400 clusters * 200 bits **[3]**
- Between 128 and 416 bits per cluster (200 assumed)

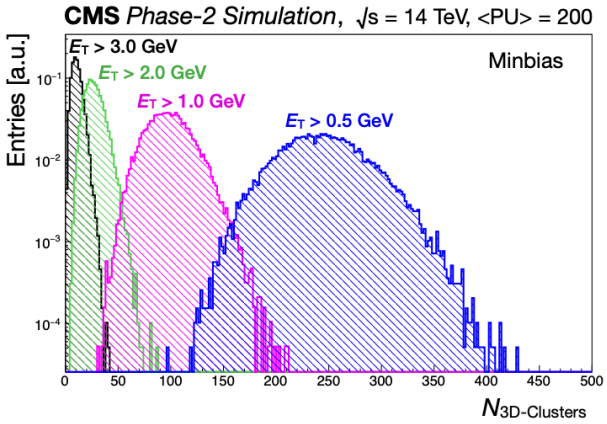
1)



2)



3)

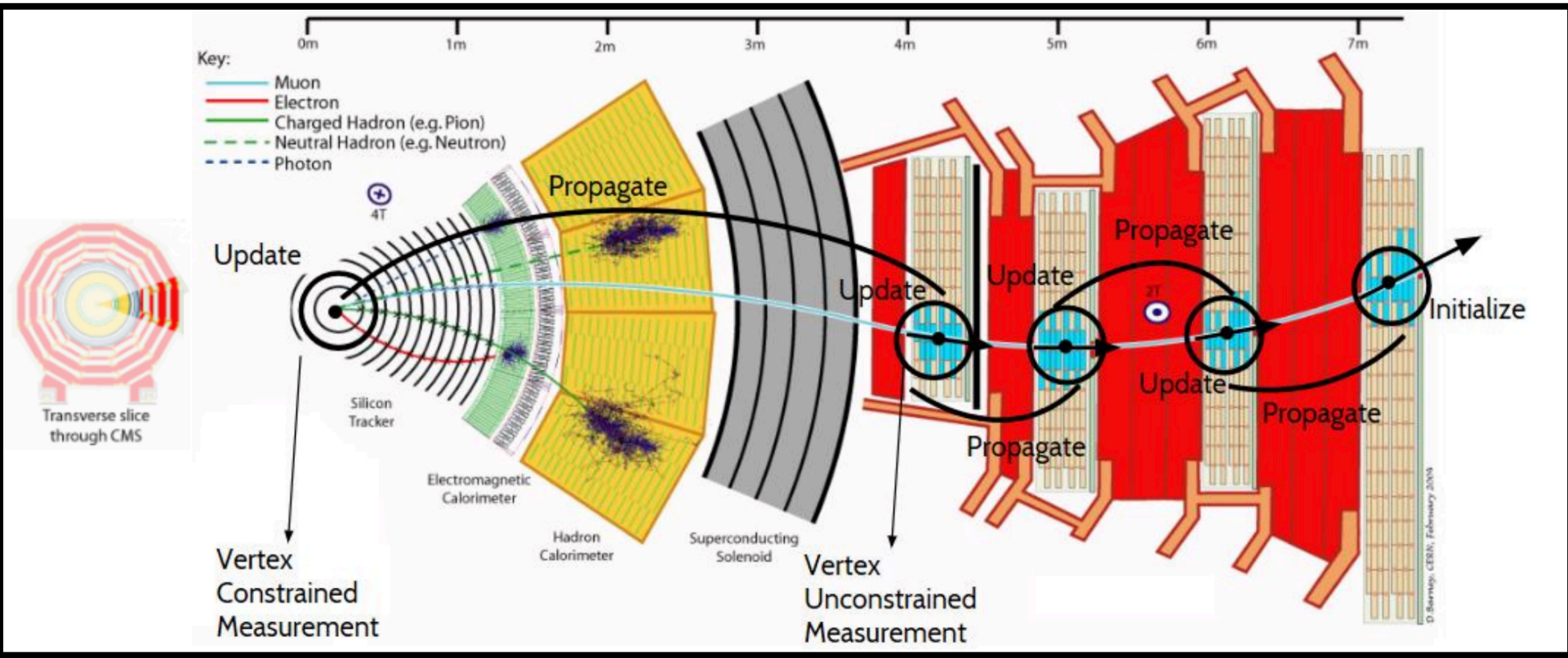


BMTF Kalman Filter

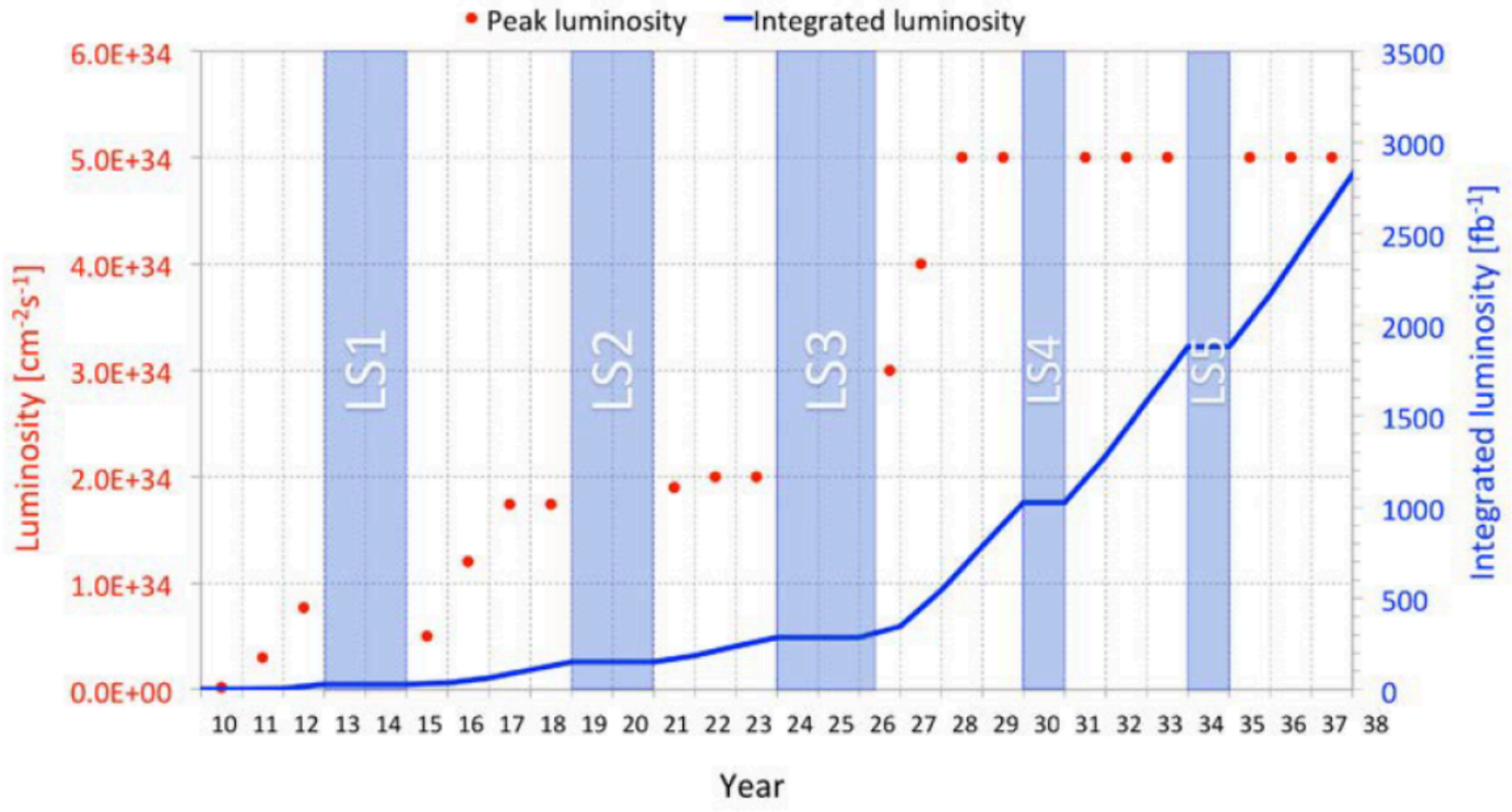
Backup

Kalman Filter:

- Iterative track finding algorithm.
- Combines Stub measurements with predictions based on phi, bend angle and curvature
- Starts from the outermost muon station and propagates inwards, updating at each station
- Provides both vertec constrained and vertex unconstrained measurements
- Can trigger on displaced particles
- Fully commissioned by the end of 2018 data taking

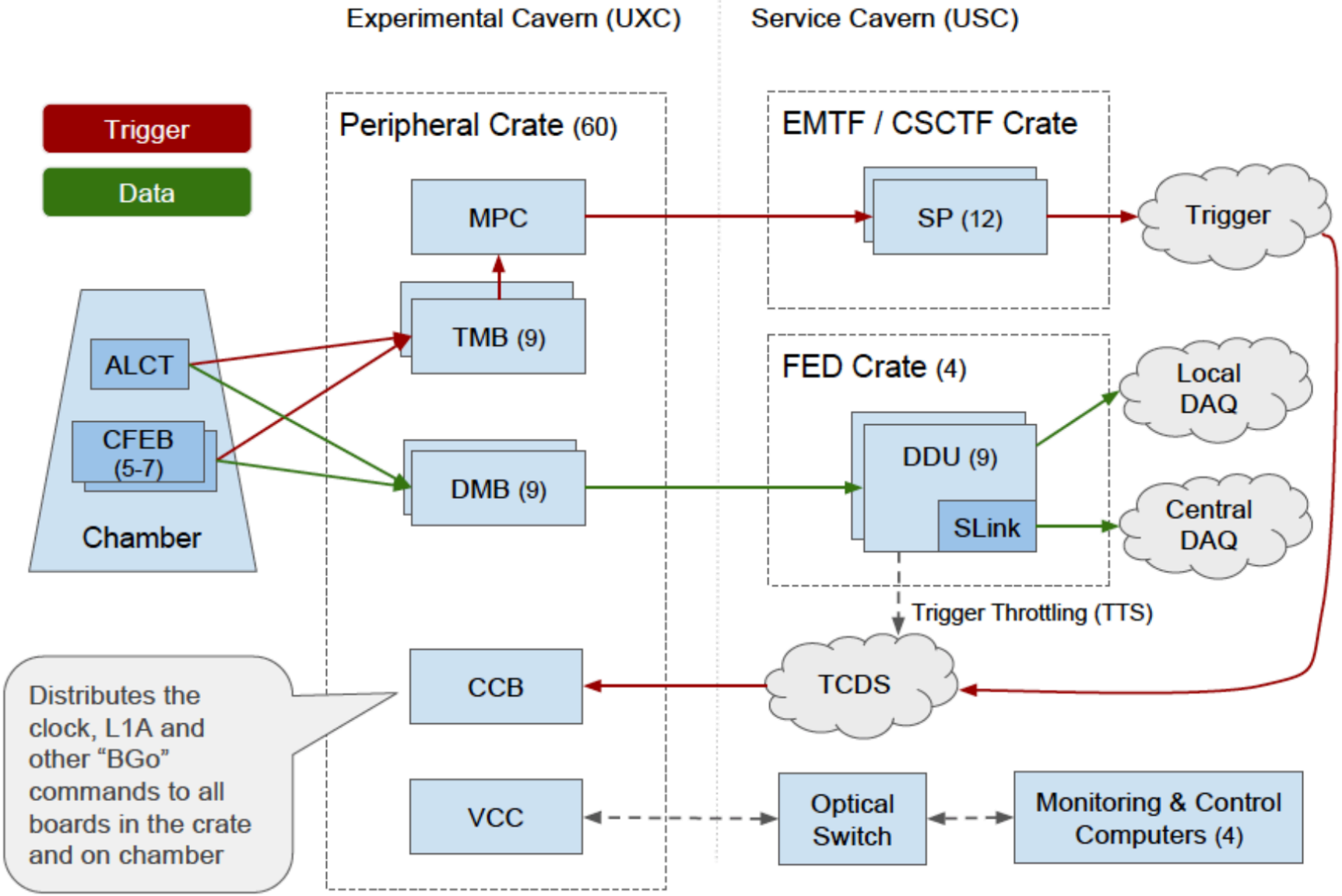


HL-LHC Plans


Peak luminosity
Integrated luminosity
6.0E+34
5.0E+34
4.0E+34
3.0E+34
2.0E+34
1.0E+34
0.0E+00
Luminosity [cm-2s-1]
3500
3000
2500
2000
1500
1000
500
0
Integrated luminosity [fb-1]
LS1
LS2
LS3
LS4
LS5
10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38
Year

Example Workflow

Backup



HLT Data Stream

Backup