Imperial College London

Overview of the HL-LHC Upgrade for the CMS Level-1 Trigger

9th July 2022
ICHEP 2022

Benjamin Radburn-Smith
Imperial College London

High Luminosity Large Hadron Collider

- We need the high statistics provided by HL-LHC in order to search for New Physics at the EWK-scale
  - Small SM deviations (high stats)
  - Difficult phase space (increase acceptance)

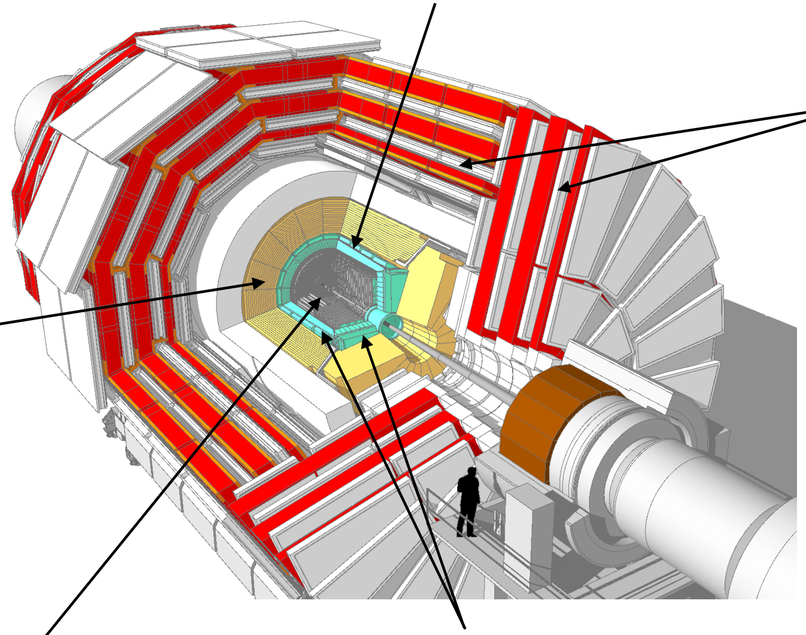
High Statistics	→	High Luminosity	→	Pile Up increase
4000 fb^{-1}		$7.5x10^{34}$ $cm^{-2}s^{-1}$		200 PU

- The Phase 1 Level-1 Trigger (L1T) system and algorithms at 200 PU = 4 MHz for the same Physics acceptance
- Total allowed Phase 2 L1T bandwidth = 750 kHz

CMS at HL-LHC

L1T and HLT/DAQ
- Tracker Tracks in L1T at 40 MHz
- PFlow selection at 750 kHz
- HLT output at 7.5 kHz
- 40 MHz Scouting: Real time analysis
- L1T latency: 4 → 12.5 μs

Barrel Calorimeters
- ECAL crystal granularity readout at 40 MHz with precise timing for e/γ at 30 GeV
- ECAL and HCAL new Back-end boards



Muon Systems
- DT & CSC new FE/BE readout
- RPC back-end electronics
- New GEM/RPC $1.6 < \eta < 2.4$

Calorimeter Endcap
- High Granularity Calorimeter (HGCAL)
- 3D showers and precise timing
- Si, Scint+SiPM in Pb/W-SS

Beam Radiation Instr. and Luminosity
- Bunch-by-bunch luminosity measurement:
- 1% offline, 2% online

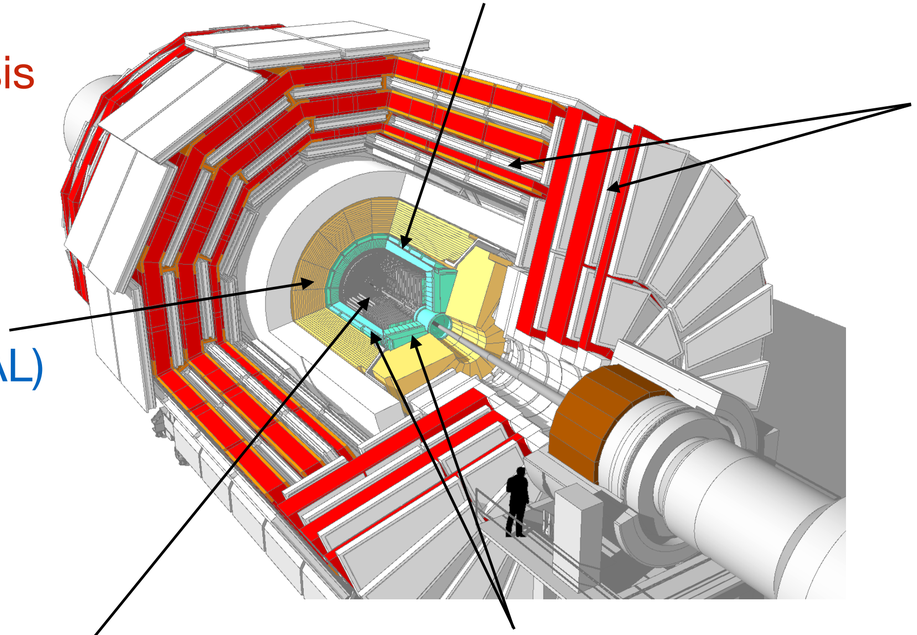
Tracker
- Si-Strip and Pixels increased granularity
- Design for tracking in L1-Trigger
- Extended coverage to $\eta \simeq 3.8$

MIP Timing Detector
- Precision timing with:
- Barrel layer: Crystals + SiPMs
- Endcap layer: Low Gain Avalanche Diodes

CMS at HL-LHC

L1T and HLT/DAQ
- Tracker Tracks in L1T at 40 MHz
- PFlow selection at 750 kHz
- HLT output at 7.5 kHz
- 40 MHz Scouting: Real time analysis
- L1T latency: 4 → 12.5 μs

Barrel Calorimeters
- ECAL crystal granularity readout at 40 MHz with precise timing for e/γ at 30 GeV
- ECAL and HCAL new Back-end boards



Muon Systems
- DT & CSC new FE/BE readout
- RPC back-end electronics
- New GEM/RPC $1.6 < \eta < 2.4$

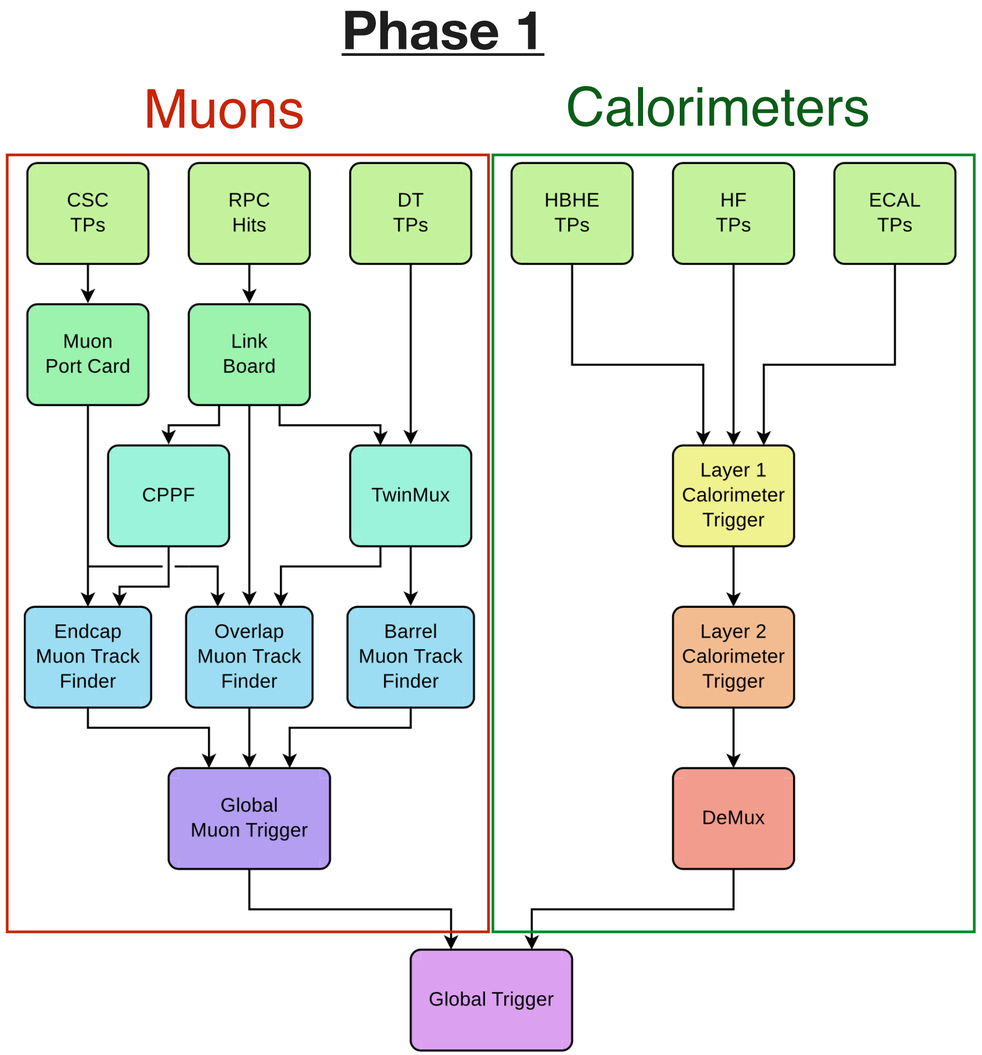
Calorimeter Endcap
- High Granularity Calorimeter (HGCAL)
- 3D showers and precise timing
- Si, Scint+SiPM in Pb/W-SS

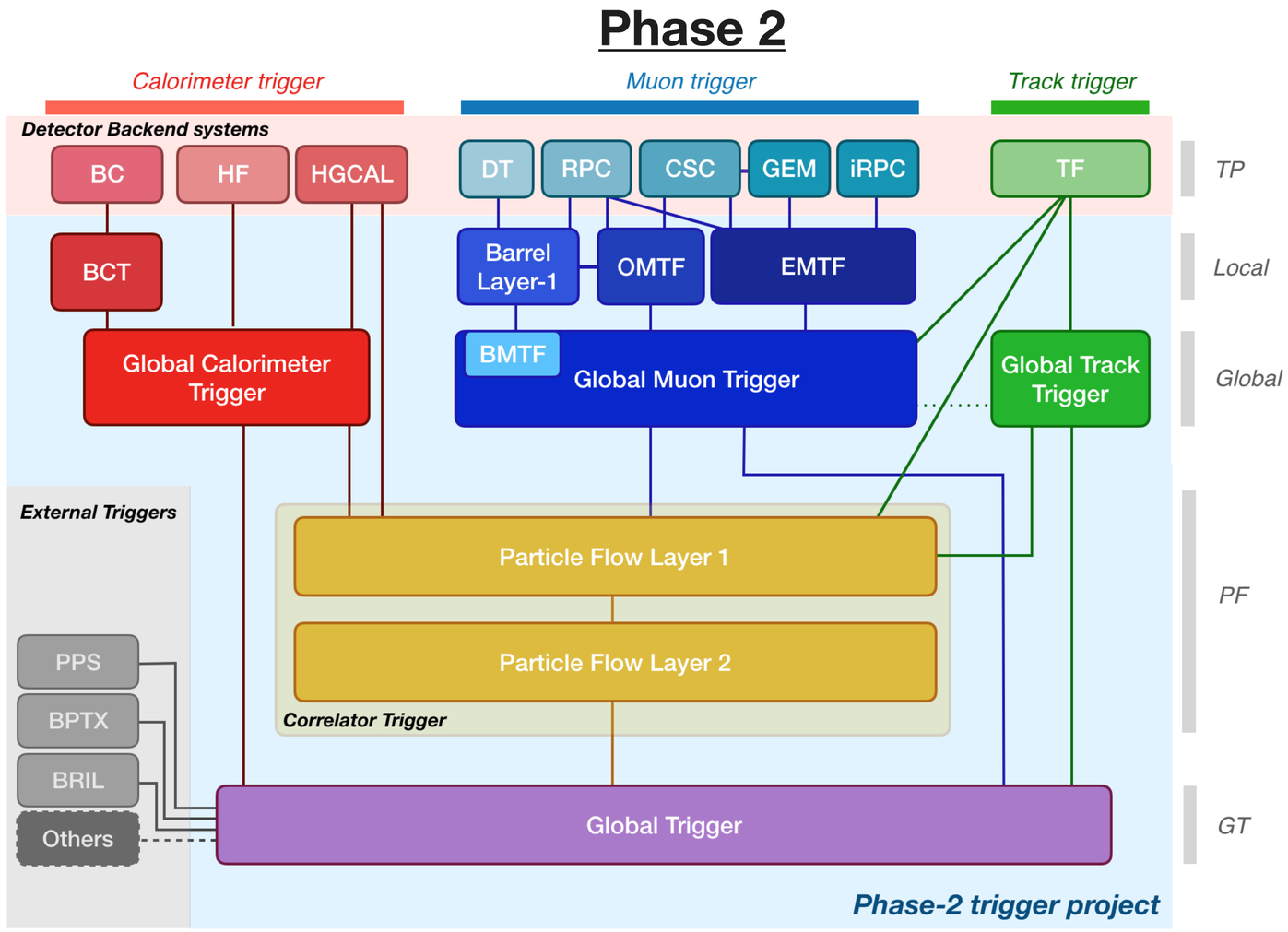
Beam Radiation Instr. and Luminosity
- Bunch-by-bunch luminosity measurement:
- 1% offline, 2% online

Tracker
- Si-Strip and Pixels increased granularity
- Design for tracking in L1-Trigger
- Extended coverage to $\eta \simeq 3.8$

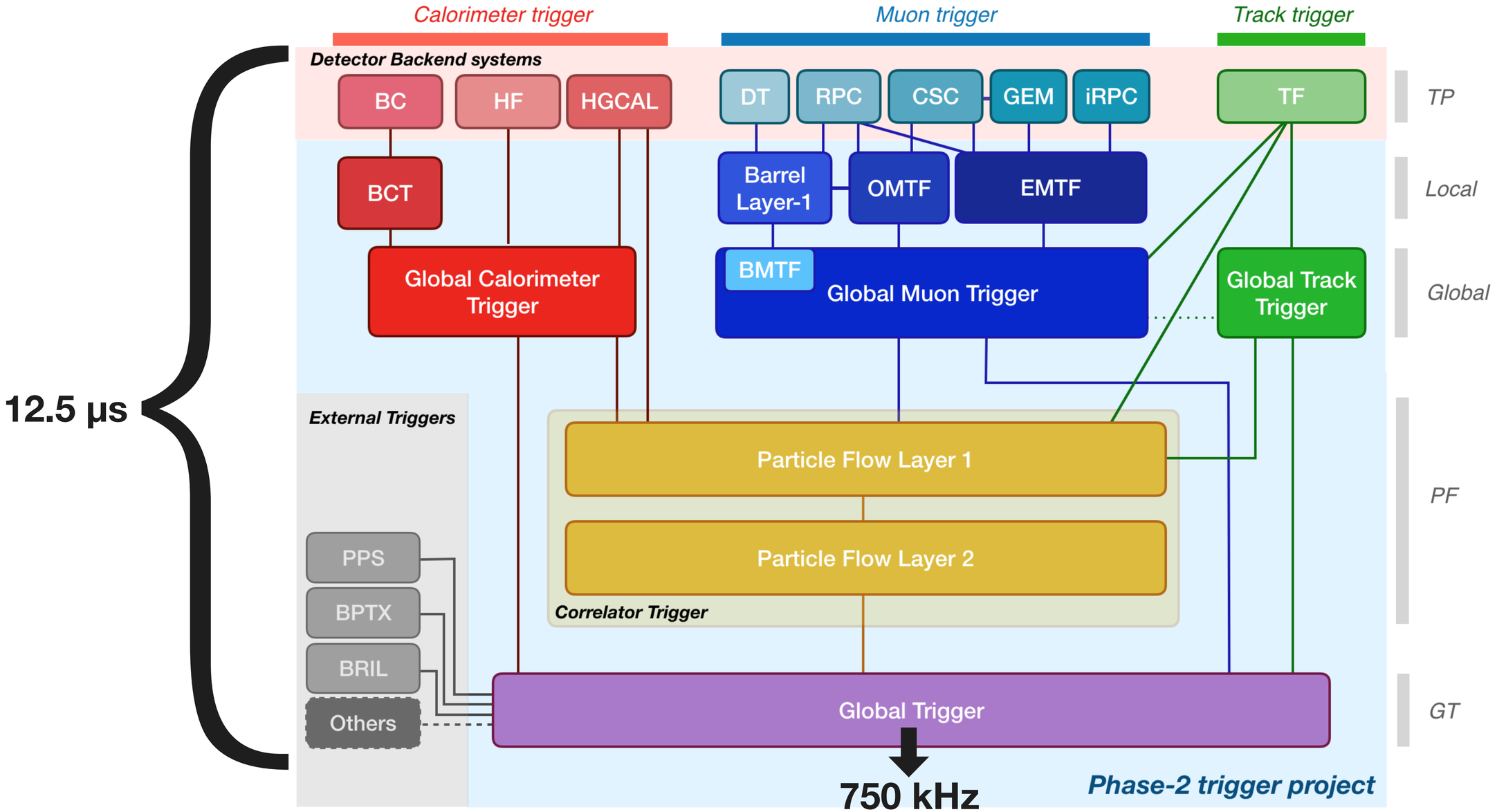
MIP Timing Detector
- Precision timing with:
- Barrel layer: Crystals + SiPMs
- Endcap layer: Low Gain Avalanche Diodes

Phase 2 L1T: Architecture



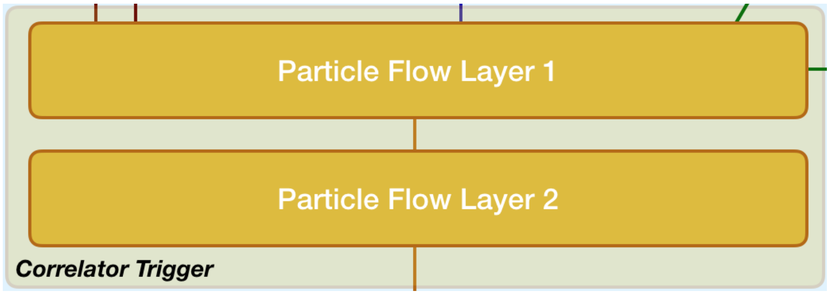


Phase 2 L1T: Architecture



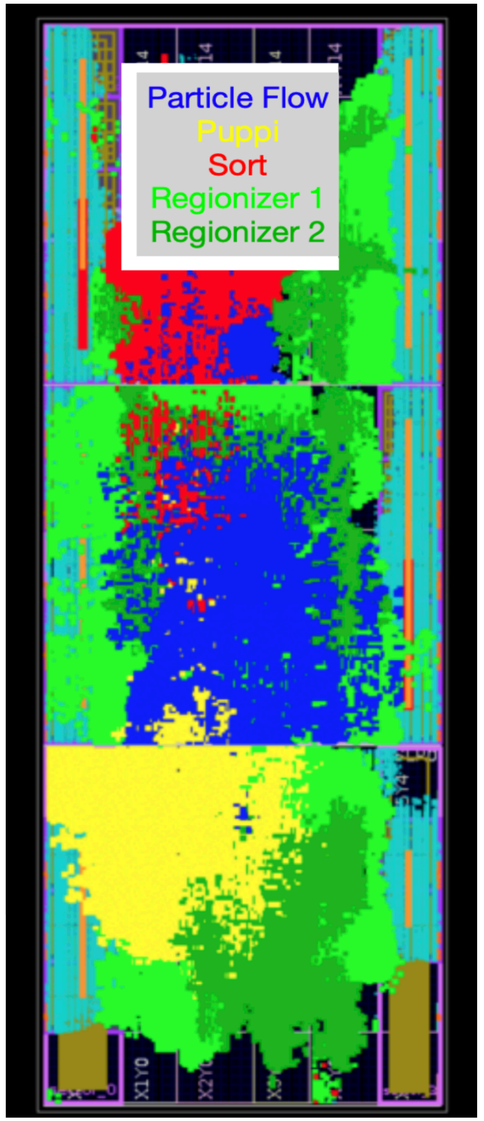
L1T Algorithms: Particle Flow

- One of the key aspects of the P2 L1T system is the Correlator Trigger, implementing sophisticated algorithms allowing for higher level objects
  - Similar algorithms have been used offline in Run 2
- Layer 1:
  - Produces particle-flow (PF) candidates; constructed from the matching of calorimeter clusters and tracks
  - Pileup Per Particle Identification (PUPPI) algorithm mitigating the degradation of the energy resolution due to PU
- Layer 2:
  - Building and sorting final trigger objects
  - Applying additional ID and Isolation
- PF+PUPPI: needed to sustain Run 2 Jets & MET thresholds

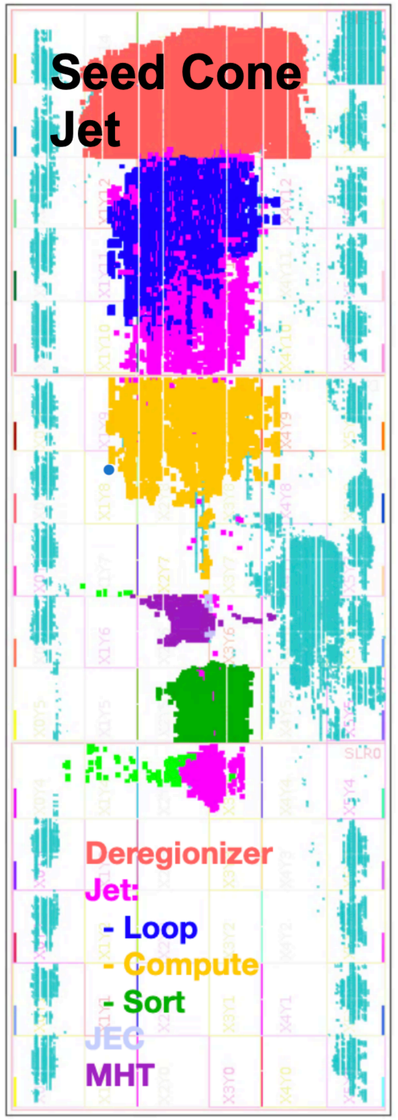


L1T Algorithms: Particle Flow

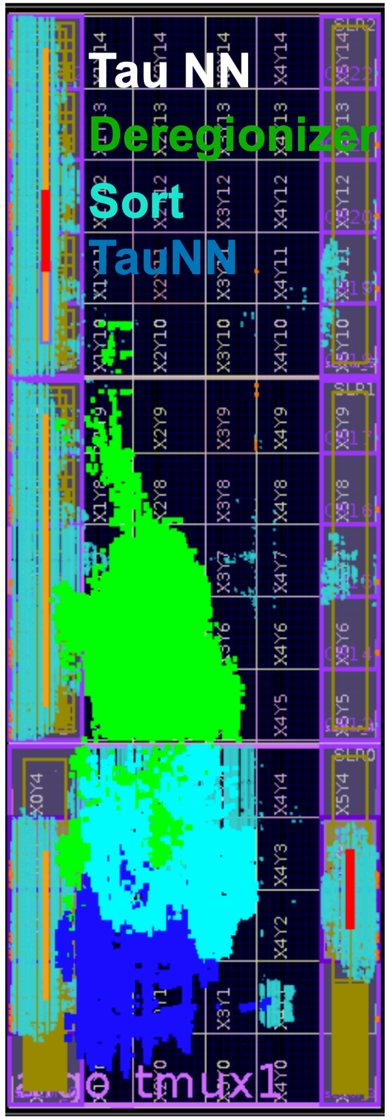
- All the algorithms have to fit within the resources of FPGAs
- For the Layer 1 we have the fully working PF+PUPPI on VU9P-2 boards and plan to then go to VU13P-2
  - Despite the complicated algorithms we still have room to expand with other algorithms
- On Layer 2 we have:
  - 2 well performing algorithms for the Jet finding: SeedCone and Histogram
  - NNTaus and e/γ ID: working to expand the scope of ID, isolation



Layer 1 Barrel

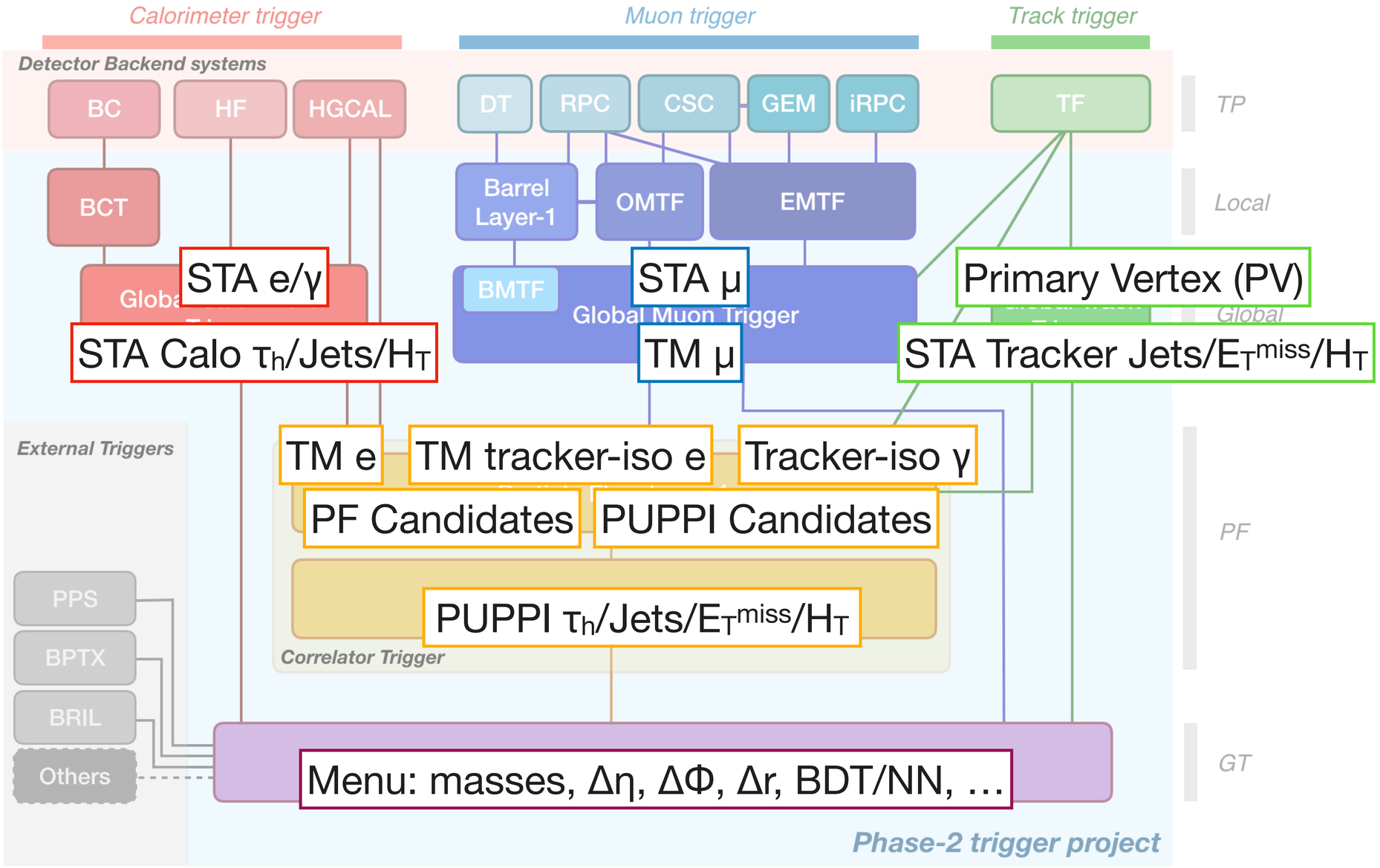


Layer 2: Jets



Layer 2: NNTau

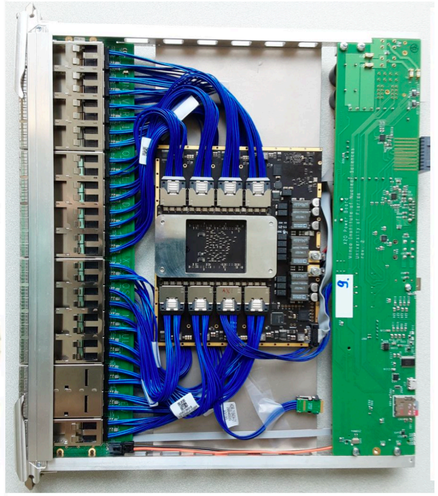
Phase 2 L1T: Objects



Phase 2 L1T: Technology

- All boards aim to use the same FPGA: XILINX VU13P
  - 100 optical links
  - 28 GB/s
- Different board families perform different functions
  - FW is different
- Latency: < 9.5μs (allowing for 20% buffer)
- All preproduction hardware has been delivered
  - Extensive testing has been performed on many of the boards

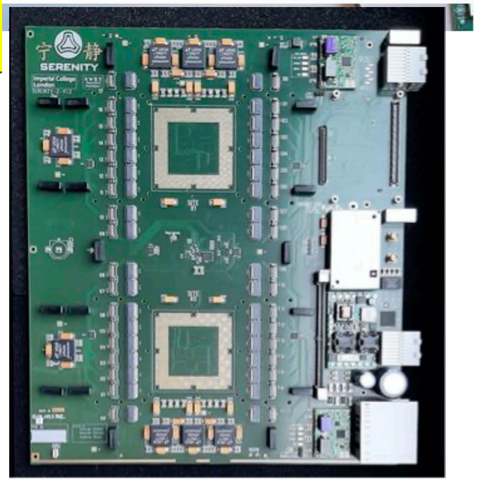
X2O



APx-F

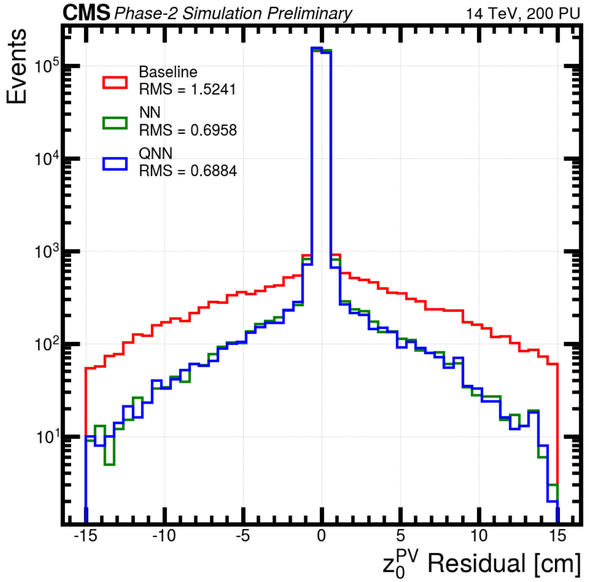
BMT-L1

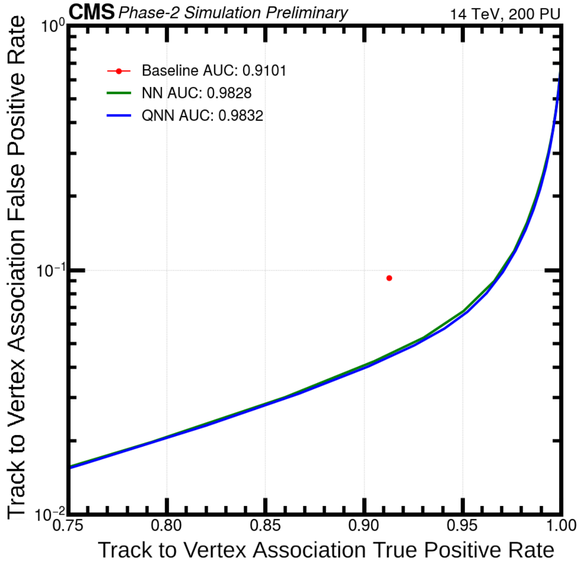
Serenity

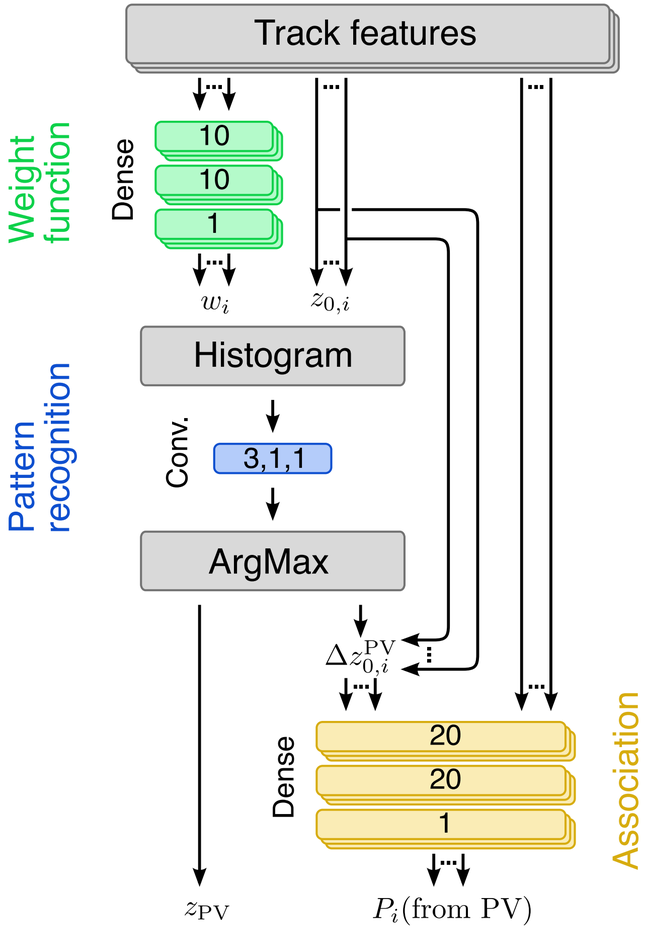


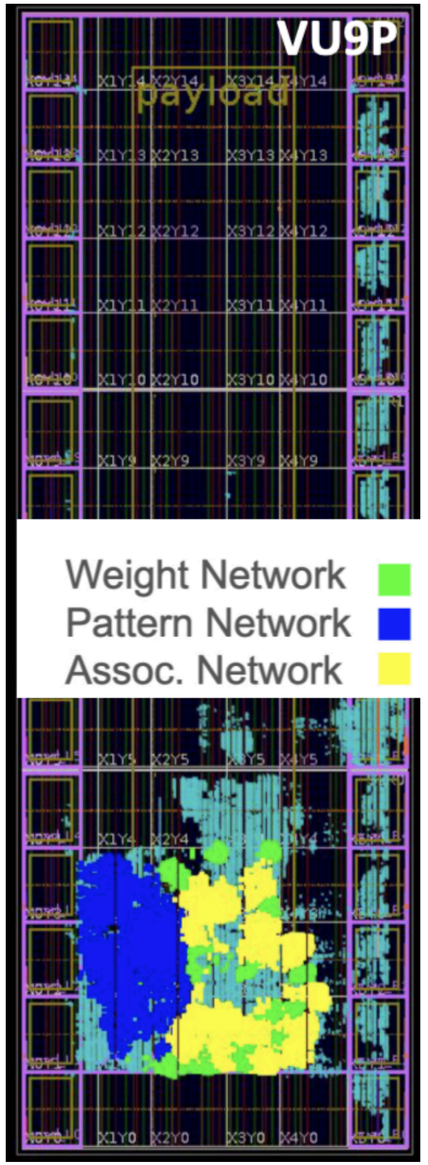
Highlight: NN Vertexing

- Using an End to End NN for Vertex finding
  - End to End: track to vertex association is optimised
  - Quantised and pruned in order to fit onto Field Programmable Gate Array (FPGA)
- Reduction in the tails of the residual
- Returns likelihood of track belonging to the vertex with a flexible threshold for downstream algorithms





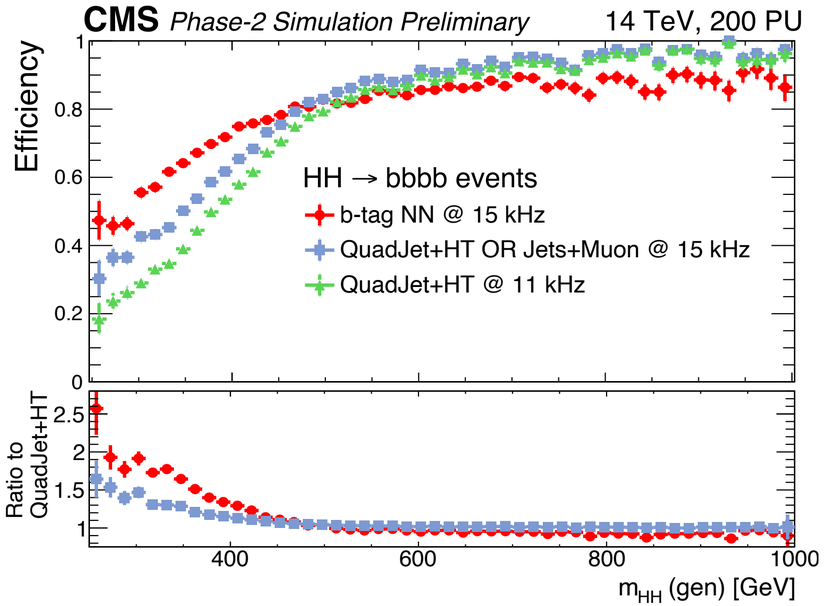


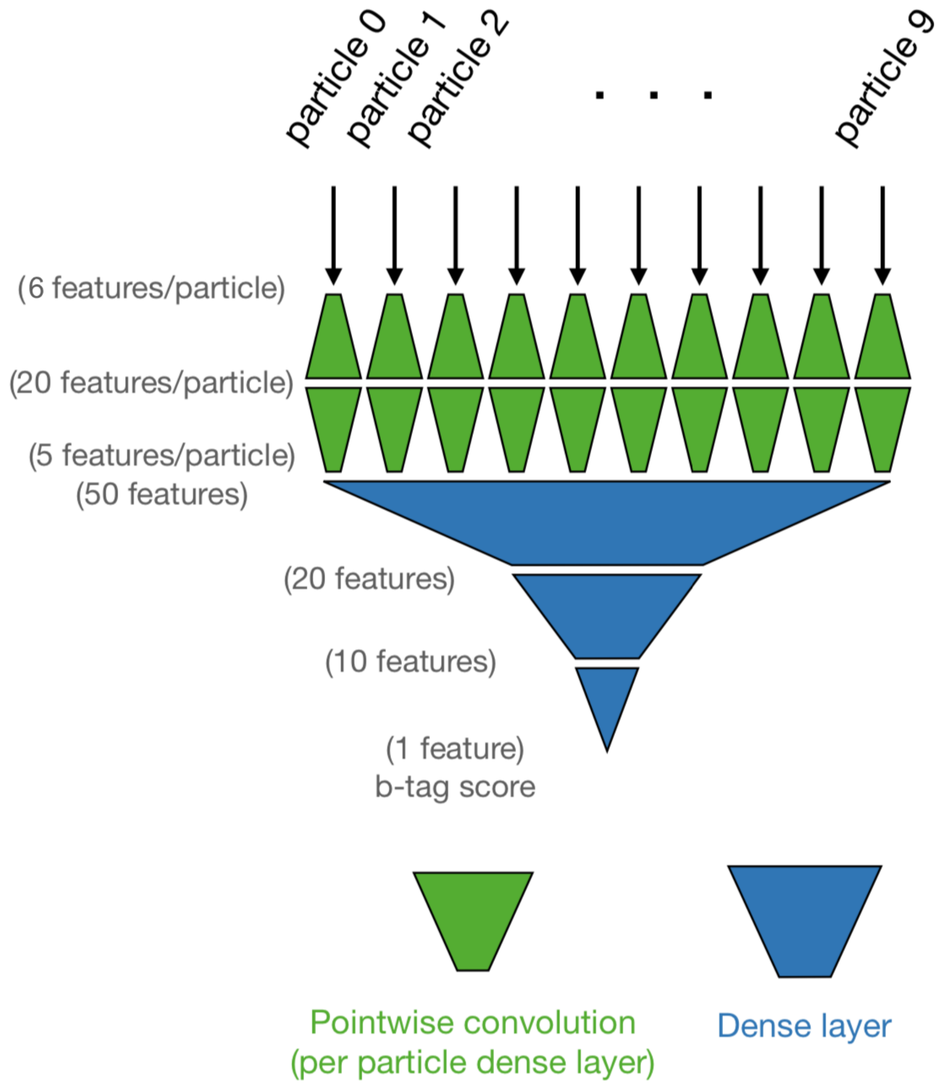


Highlight: NN ID of B-quarks

- Implement in the Correlator Layer 2 a NN to ID jets originating from b-quarks
  - Runs on the PUPPI particles in each jet and discriminates between jets originating from b quarks, and those from light quarks or gluons
  - Better performance compared to QuadJet+HT for m(HH) < 500 GeV

m(HH) < 500 GeV
- NN: 68.9%
- QJ+HT || J+μ: 53.9%
- QJ+HT: 61.4%





Impact on Physics Reach

- With the upgraded L1T system we now have:

Tracker tracks

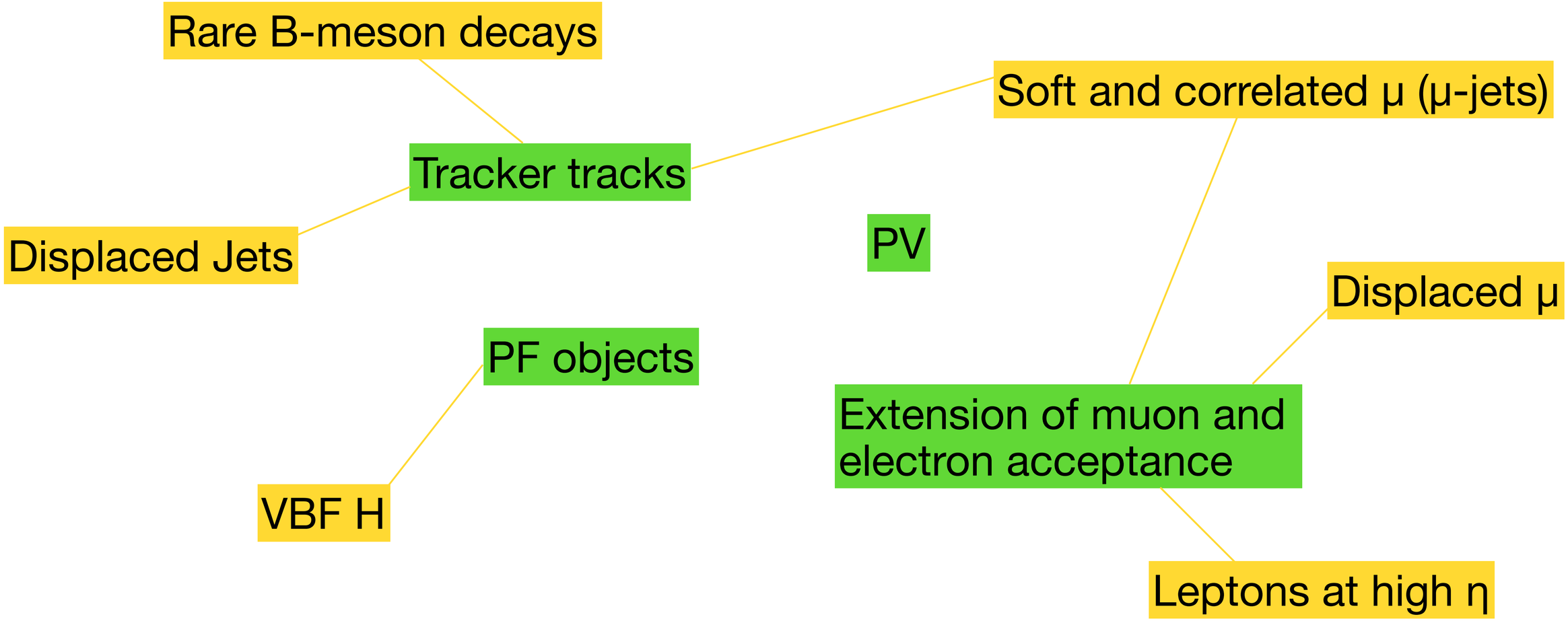
PV

PF objects

Extension of muon and electron acceptance

Impact on Physics Reach

- With the upgraded L1T system can trigger on:

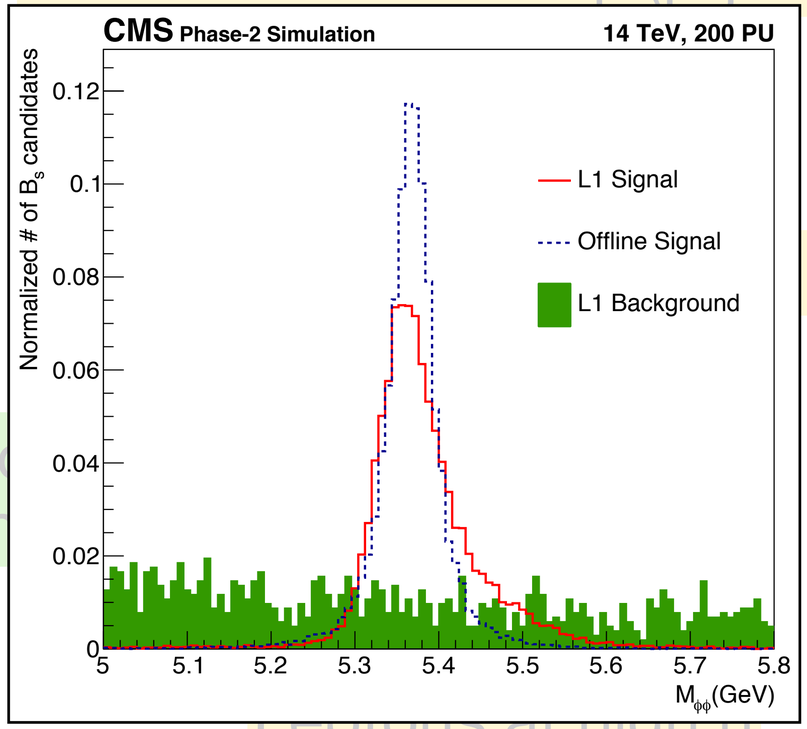


Impact on Physics Reach: Example 1

- With the upgraded L1T system can trigger on:

Rare B-meson decays

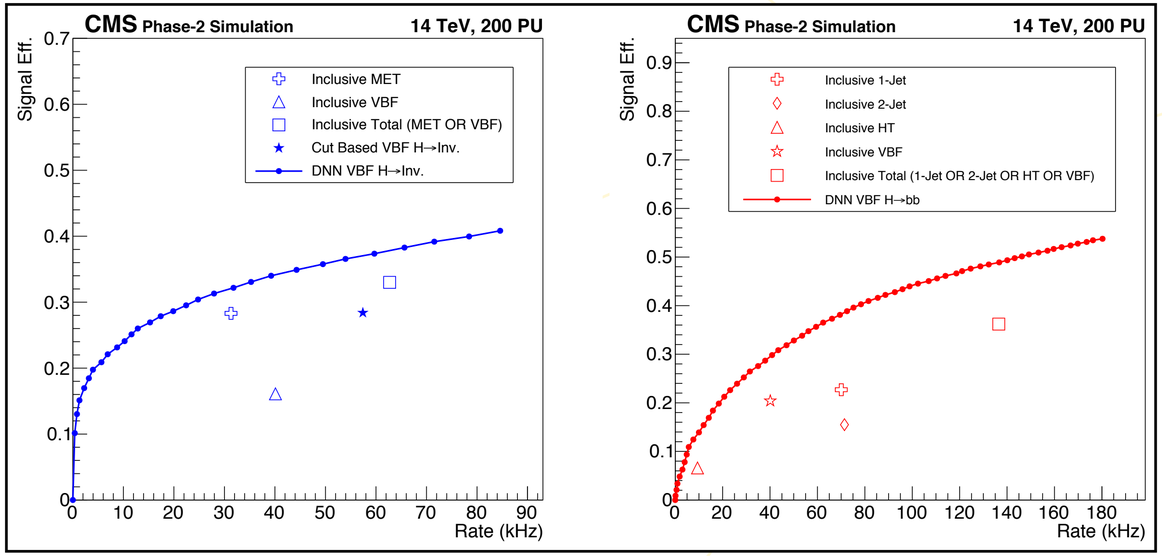
- $B_s^0 \rightarrow \Phi(K^+K^-)\Phi(K^+K^-)$
  - A rare FCNC process forbidden at the tree level in the SM
  - Trigger on the fully hadronic final state with L1 Tracks
  - Reconstruct Φ candidates using pairs of oppositely charged tracks originating from the same vertex
  - Then reconstruct B_s^0 candidates from pairs of Φ candidates originating from the same vertex



Impact on Physics Reach: Example 2

- With the upgraded L1T system can trigger on:

Rare B-meson decays



VBF H

- VBF H→invisible, VBF H→$b\bar{b}$
  - Requires the L1 PF reconstruction
  - DNN separately trained using both signals, with the minimum bias as background
  - Models were pruned to remove connections with low weights
  - The DNN outperforms the cut-based trigger algorithms
  - Larger gains in the VBF H→$b\bar{b}$ signal where MET could not be used

Leptons at high η

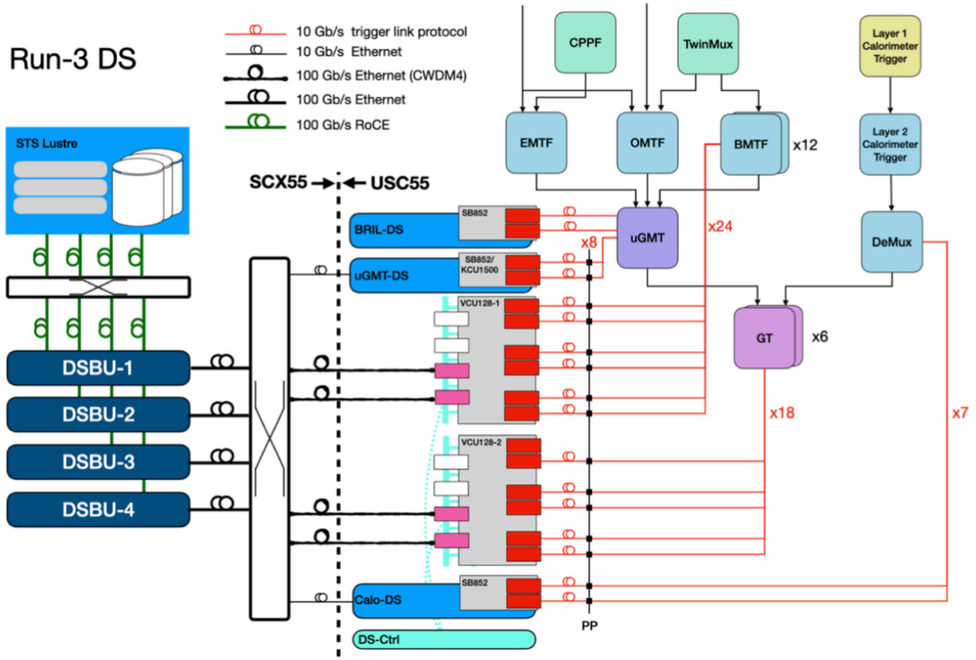
Summary

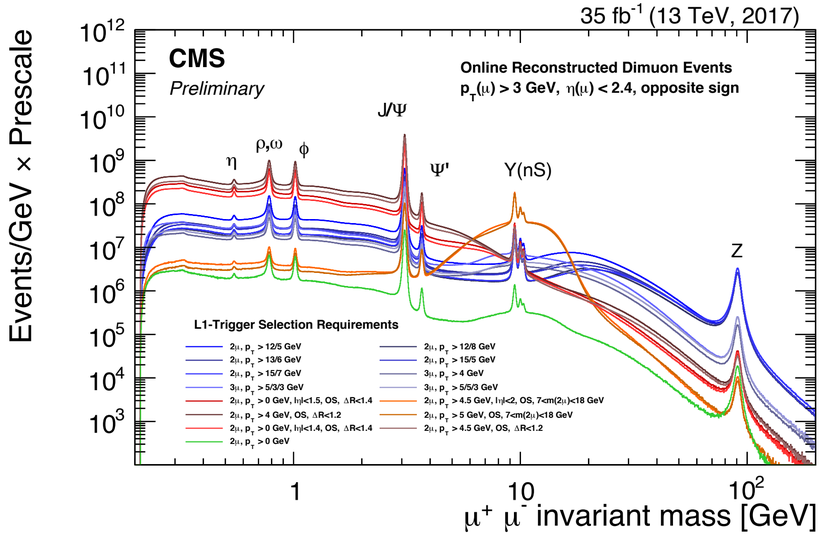
- HL-LHC is required to gain large statics for physics analyses; but comes at a price of high PU
- CMS will undergo many developments in order to capitalise on the HL-LHC
  - Including entirely new detectors
- The Level 1 Trigger will be upgraded in order to not only cope with the harsh environments provided by the HL-LHC, but also increase acceptance
- Novel triggering solutions are being developed now for Phase 2
  - Including developing Machine Learning techniques which have to fit onto the resources of the FPGAs
  - Modern ML possible due to more powerful FPGAs and tools to synthesise ML in those FPGAs such as HLS: simple algorithms → complex offline-like algorithms
- The physics reach will be extended with the upgraded L1T system
  - Benchmark channels have been studied to understand the potential improvement compared to Run 2 studies

Extra

40 MHz Scouting

- We have used scouting in Run 2, and are expanding the capabilities in Phase 2
- For Phase 2 we are planning on utilising 40 MHz scouting
- Inputs from multiple sources
- Access to μGMT muons, e/γ, jets, taus, MET, BMTF muons, μGT algorithm bits





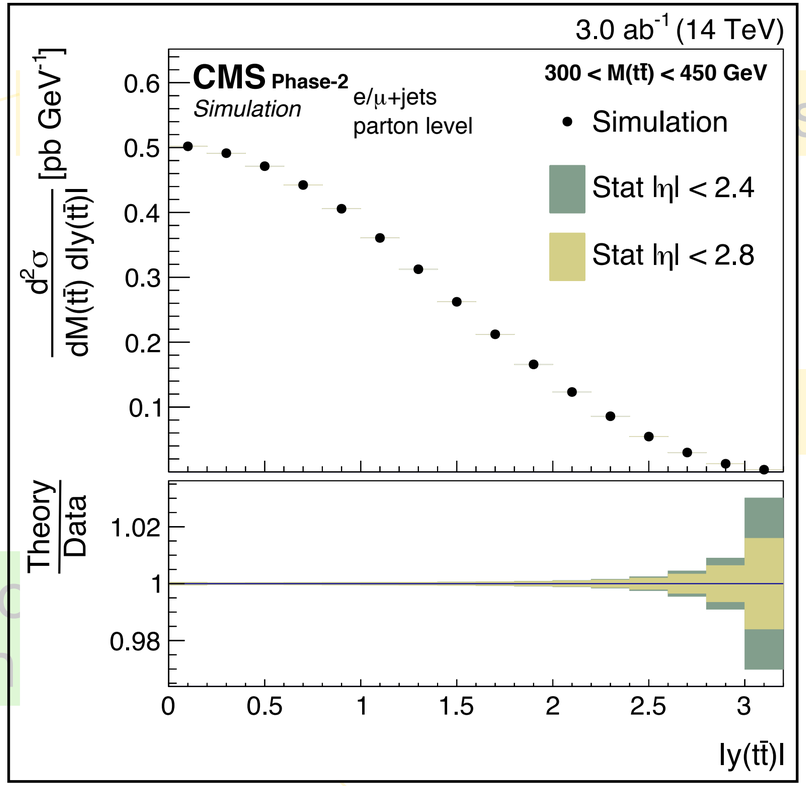
Example of online only reconstruction dimuons probing from MeV to 100s of GeV

- Autoencoder for anomaly detection
- Can be used for monitoring, diagnostics, luminosity measurements
- And for physics: accessing processes without distinctive trigger signatures (and won't fit in the L1T accept rate budget)
- μGMT muons scouting demonstrator ran at the end of Run 2

Impact on Physics Reach: Example 3

- With the upgraded L1T system can trigger on:

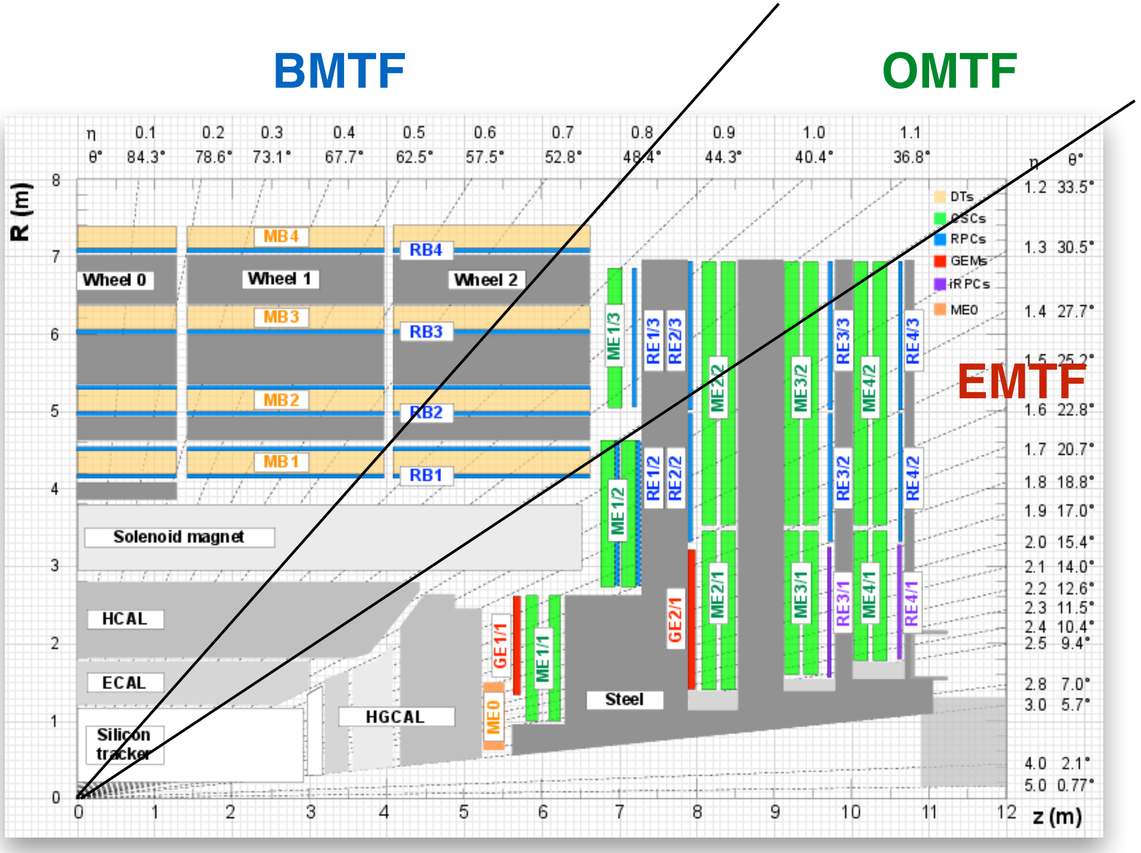
  - Differential $t\bar{t}$ production cross section
    - Constrains the PDFs; useful for all physics analyses at LHC
    - Semileptonic decays use lepton triggers
    - η coverage: 2.4 → 2.8 or 3.0
    - Reducing the statistical uncertainties in the forward region where the sensitivity of the analysis is significant



Leptons at high η

Phase 1: L1 Muon Triggers

- 3 Track Finders which:
  - Reconstruct muon track from hits or primitives
  - Assign η, ϕ, pT and quality to each candidate
- BMTF: The Barrel Muon Track Finder
  - Uses DT+RPC "super primitives" created in previous layer for track finding
  - Using Kalman BMTF for Run 3
- OMTF: The Overlap Muon Track Finder
  - Treats hits from CSCs, DTs, and RPCs on an equal footing using a Golden Pattern approach
- EMTF: The Endcap Muon Track Finder
  - Exploits look-up tables generated from BDTs to create tracks from CSC, RPC and GEM hits
- μGMT: The Global Muon Trigger
  - Receives up to 108 muon tracks from all track finders, sorts and removes duplicates



Phase 1: L1 Calorimeter Triggers

- Layer-1
  - Combines inputs from electromagnetic and hadronic calorimeters into "trigger towers"
  - Applies position- and energy-dependent calibrations
- Layer-2
  - Finds Jets, e/gamma and Tau candidates
  - For each object, applies pileup subtraction, computes isolation, applies object-based calibrations
  - Computes global quantities: transverse energy, missing energy, etc.
  - Time-multiplexed architecture
    - Array of processors that each receive the full event information for subset of events