CMS Level-1 Trigger Upgrade

Enrique Palencia Cortezon

(on behalf of the CMS Collaboration)

Universidad de Oviedo - ICTEA

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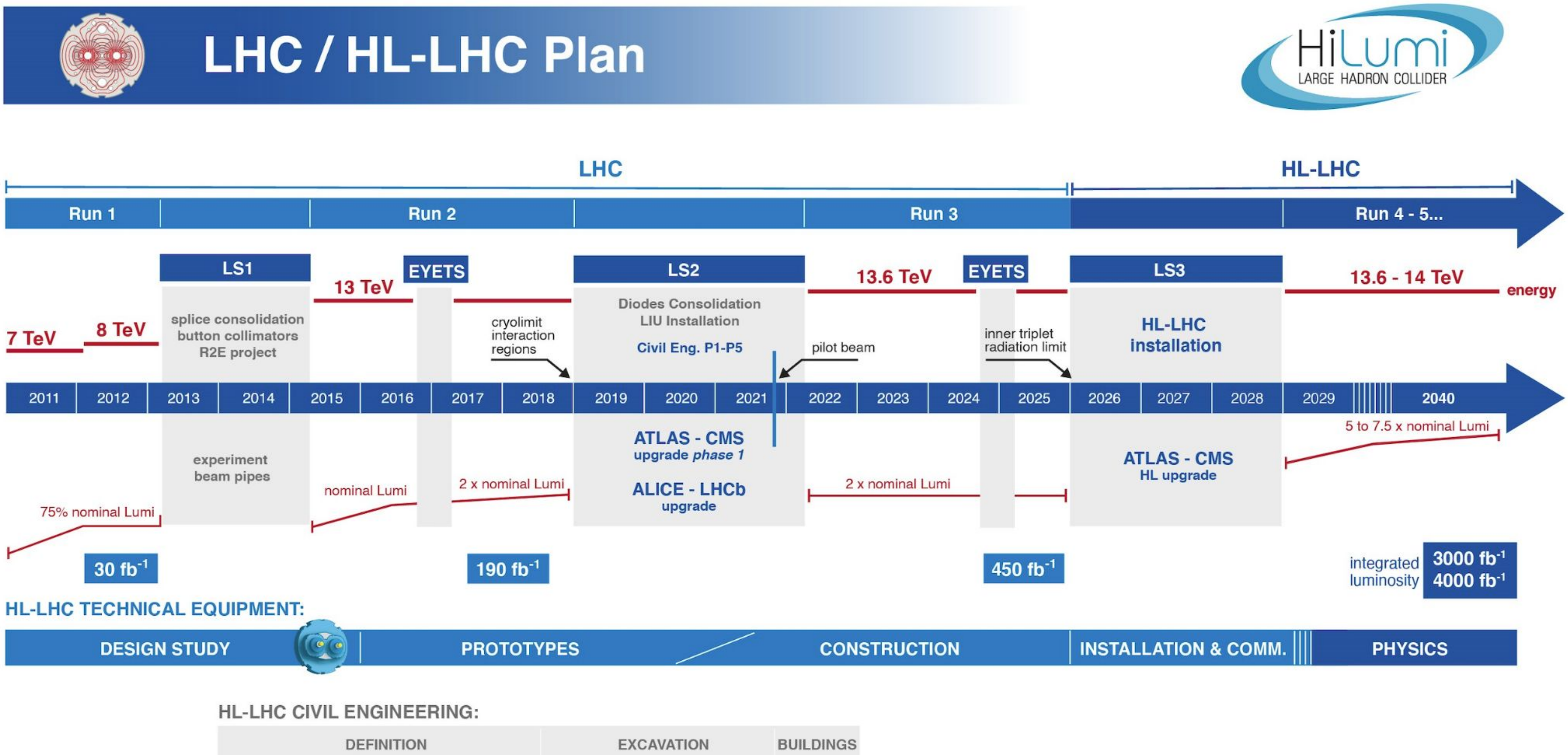
Large Hadron Collider Timeline



High Luminosity Large Hadron Collider (HL-LHC)

- **HL-LHC** presents the opportunity for a very rich and **ambitious physics program**, exploiting an integrated luminosity of **3000 fb^{-1}**

- The LHC will undergo major upgrades of its components leading to an increase of the instantaneous luminosity to **$5x10^{34}$ $cm^{-2}s^{-1}$** (x5 the original design)
  - In its ultimate configuration, peak instantaneous luminosity of **$7.5x10^{34}$ $cm^{-2}s^{-1}$**, leading to **4000 fb^{-1}** increasing the average number of proton-proton collisions per bunch crossing (pileup, PU) to around 200

- CMS will require a trigger and data acquisition system with exceptional performance to collect the required information in these challenging running conditions (**63 Tb/s**)
  - The upgrade of the trigger system will enhance the physics selectivity and maintain the performance necessary throughout the 10 year long HL-LHC program (including the trigger on **unknown signatures**)

CMS at the HL-LHC

L1T and HLT/DAQ

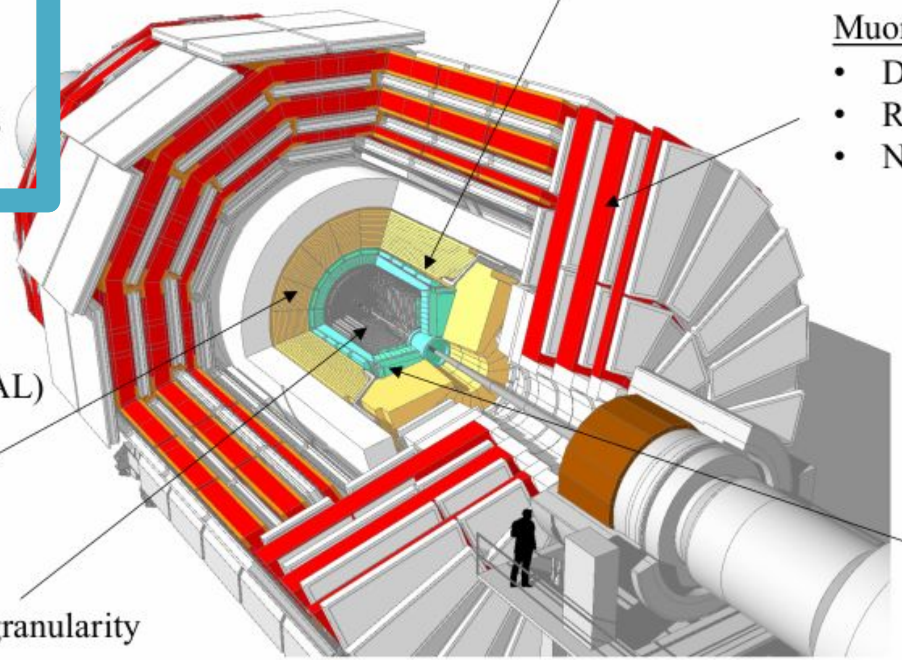
- Tracker Tracks in L1T at 40 MHz
- L1T acceptance: 100 → 750 kHz
- HLT output at 7.5 kHz
- 40 MHz Scouting: Real time analysis
- L1T latency: 4 → 12.5 μs

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

L1 Trigger (L1T) at the HL-LHC

L1T and HLT/DAQ

- Tracker Tracks in L1T at 40 MHz
- L1T acceptance: 100 → 750 kHz
- HLT output at 7.5 kHz
- 40 MHz Scouting: Real time analysis
- L1T latency: 4 → 12.5 μs

L1T and HL
- Tracker
- L1T acc
- HLT out
- 40 MHz
- L1T late

Calorimeter
- High Gra
- 3D show
- Si, Scint

Track
- Si
- D
- Extended coverage to $\eta \simeq 3.8$

out

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+ SiPMs
- Endcap layer: Low Gain Avalanche Diodes

Upgraded Phase-2 L1T

- Phase-2 upgrade of the CMS detector will provide the L1T with significantly more precise inputs, used to compute trigger objects with performance comparable to offline reconstruction
  - **Tracking** for charged particles with **p_T above 2 GeV**
  - **High Granularity** information from the calorimeter and muon detectors. In particular HGCAL in the endcap ($|\eta| > 1.5$)
  - More precision from barrel calorimeter to L1T
- Particle Flow (**PF**) will be brought to L1T for the first time
- Pile-Up Per Particle Identification (**PUPPI**) for mitigation of extremely high PU environment
- **State of the art FPGAs** (7.5x more powerful than Phase-1): enable use of Machine Learning (ML) based approach algorithms in FPGA
- Increased rate: 100 kHz (Run 3) ⇒ **750 kHz** (Run 4)

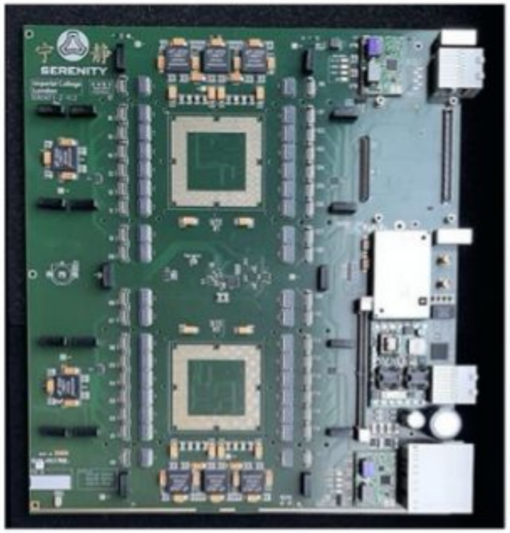
Phase-2 L1T Technology

- Same FPGA for all boards: Xilinx VU13P
  - > 100 I/O high-speed optical links: need gather data rapidly to compute global quantities or reconstruct global event content
  - 28 Gb/s
- Different board families for different functions
- Hardware: pre-production completed
- Extensive testing has been performed on many of the boards

APx

BMT

Serenity



X2O

Phase-2 L1T

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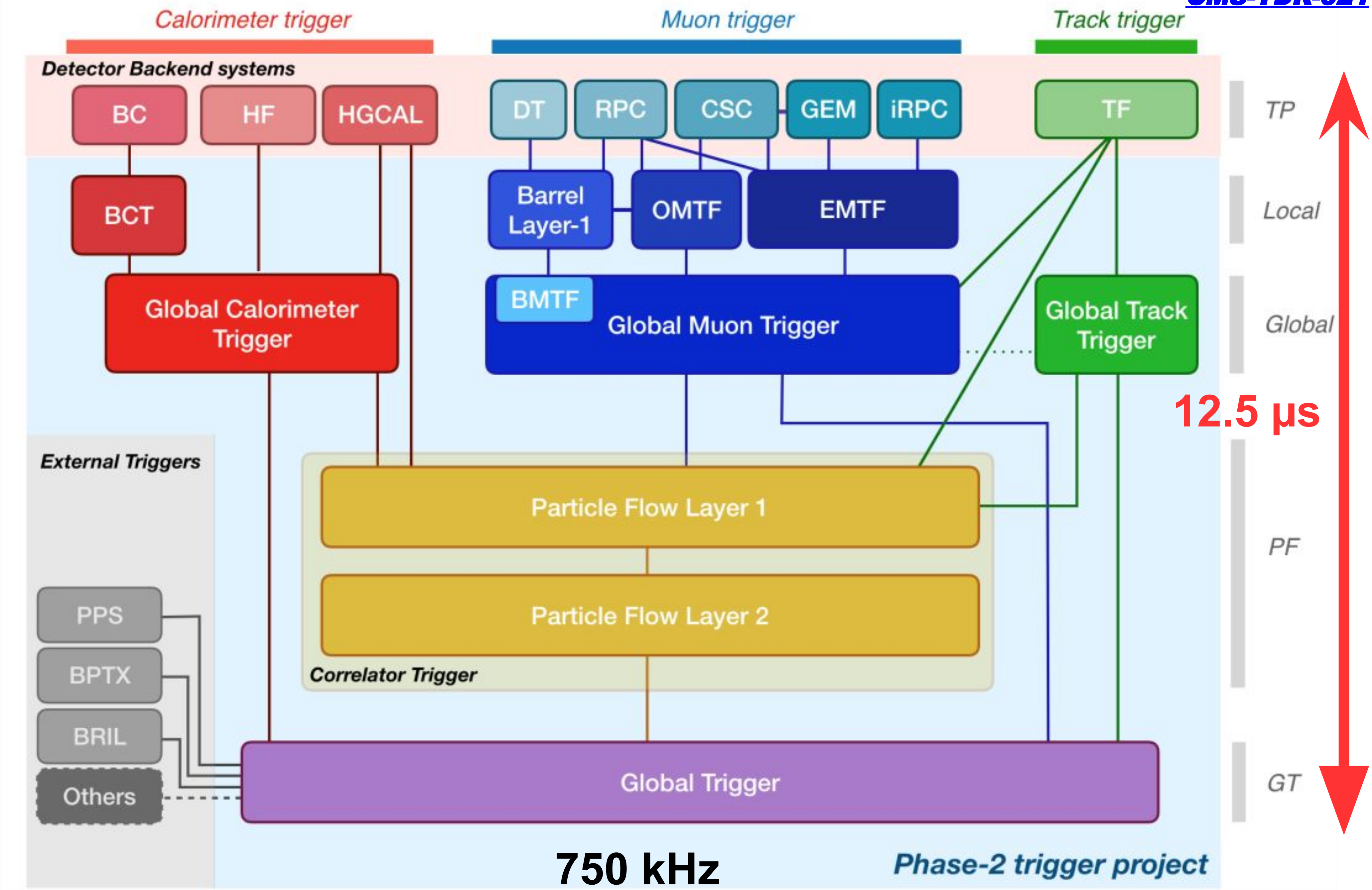
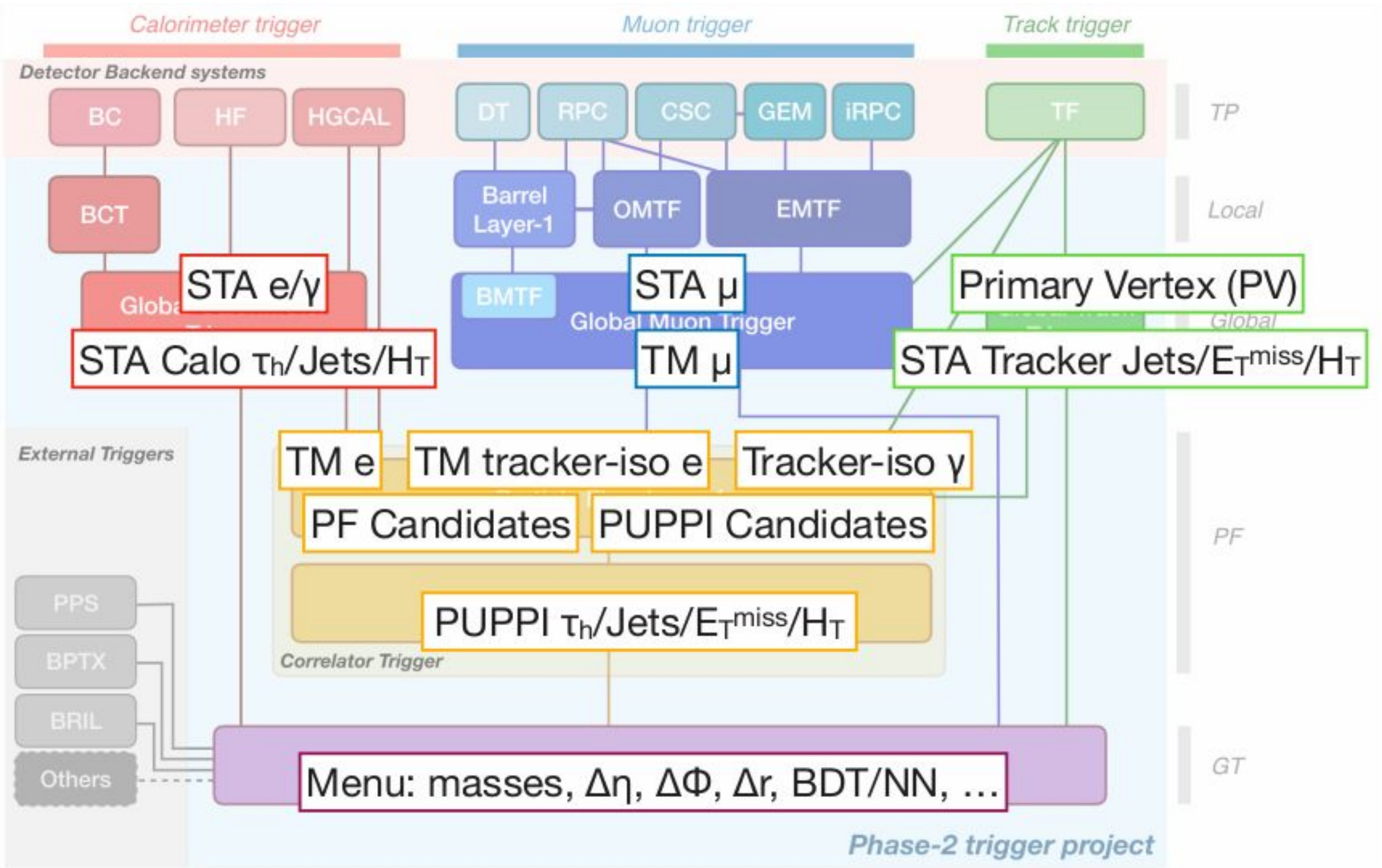


Phase-2 L1T Objects



Global Track Triggers

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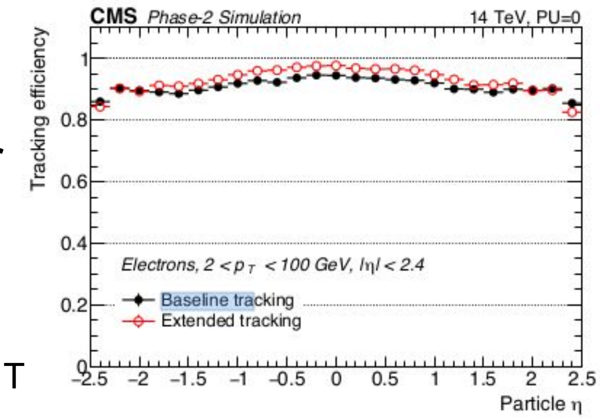
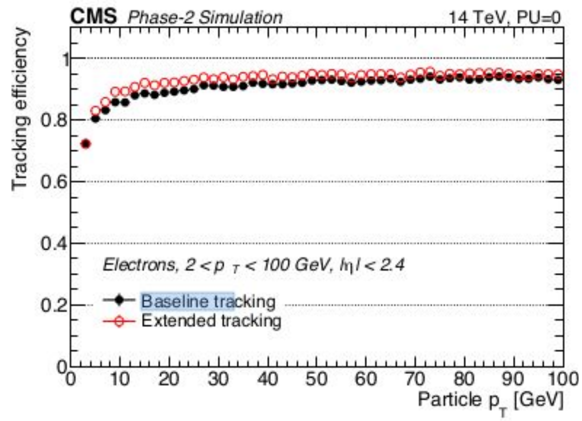
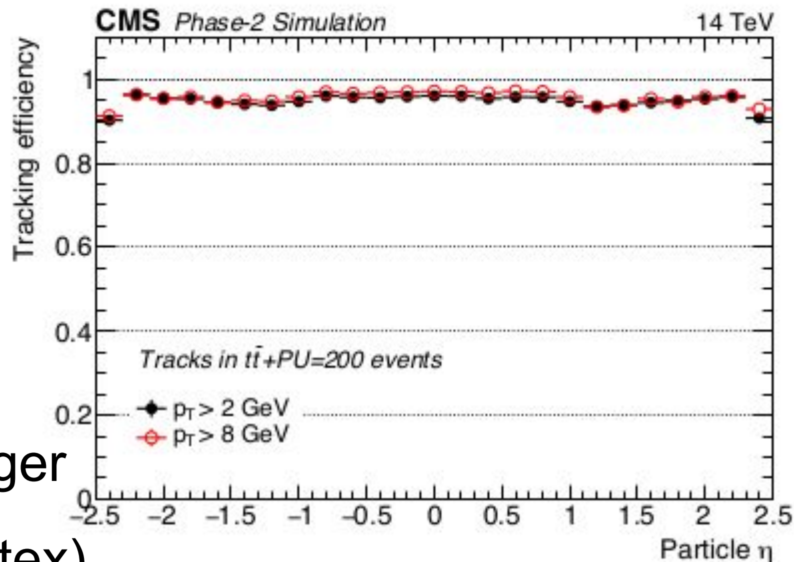
- Tracker upgrade ⇒ **tracking information included in L1T for the first time**
  - ➢ New paradigm!
  - ➢ 200 tracks with p_T>2 GeV @200 PU
- All tracker tracks from Track Finder
- Build track objects: jets, vertices, H_T





- **Huge impact on trigger object reconstruction**
  - ➢ Rate reduction and resolution improvement in essentially all possible objects
  - ➢ PF algorithms at the correlator layer
  - ➢ Displaced vertices and tracks (extended track-trigger targets displaced tracks ~5cm from interaction vertex)



Calorimeter Triggers

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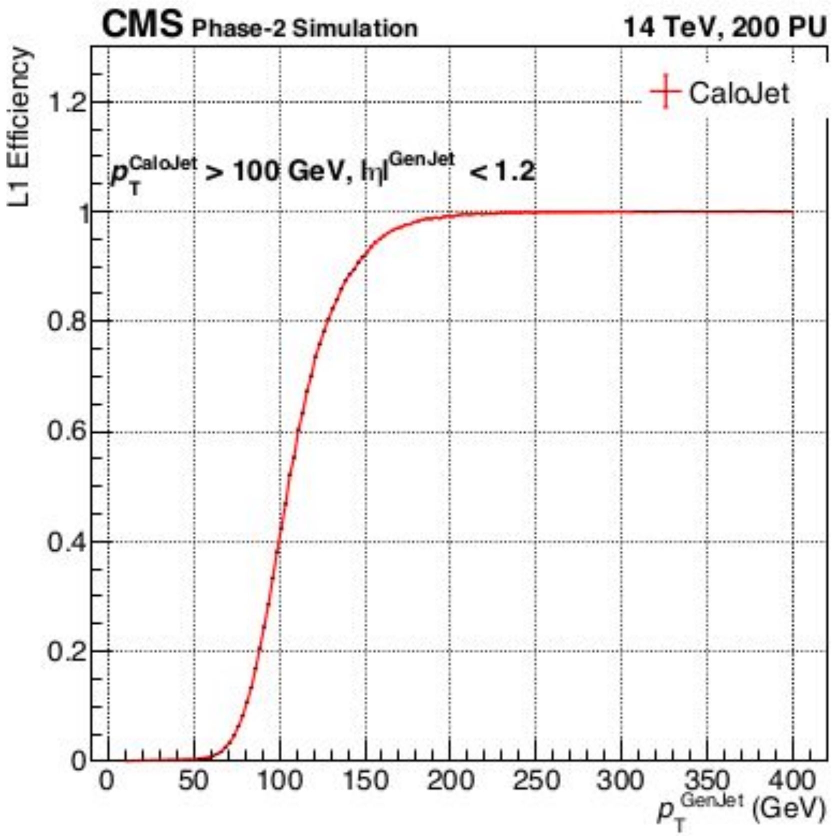
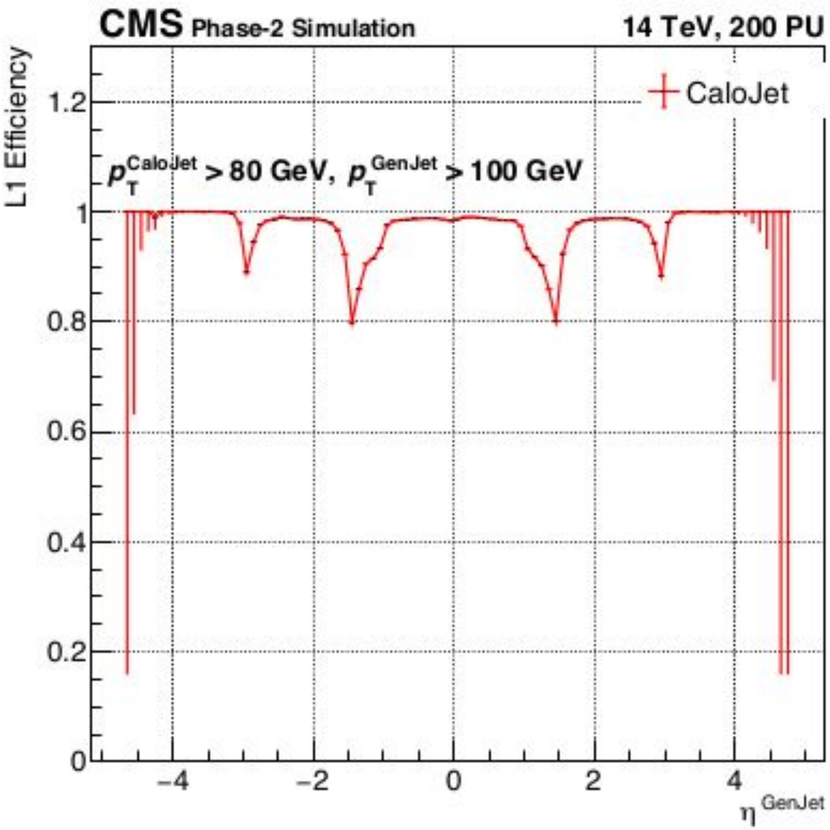
- **Higher granularity** for high-resolution clusters and identification variables
- Build electrons, photons, hadronic τ, jets, energy sums
- Jet finding efficiency





Muon Trigger

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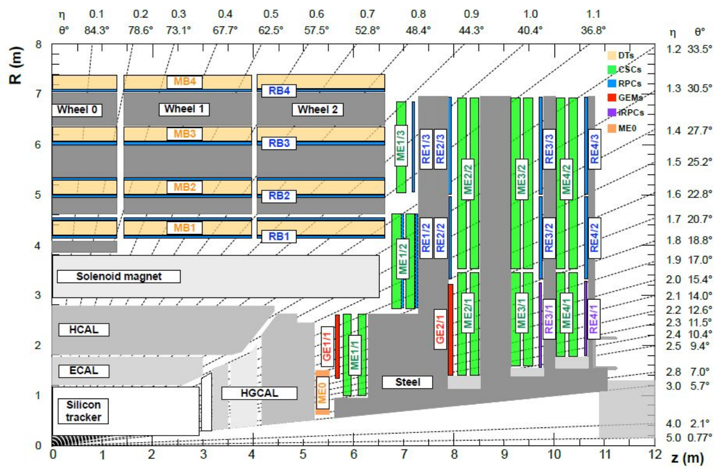
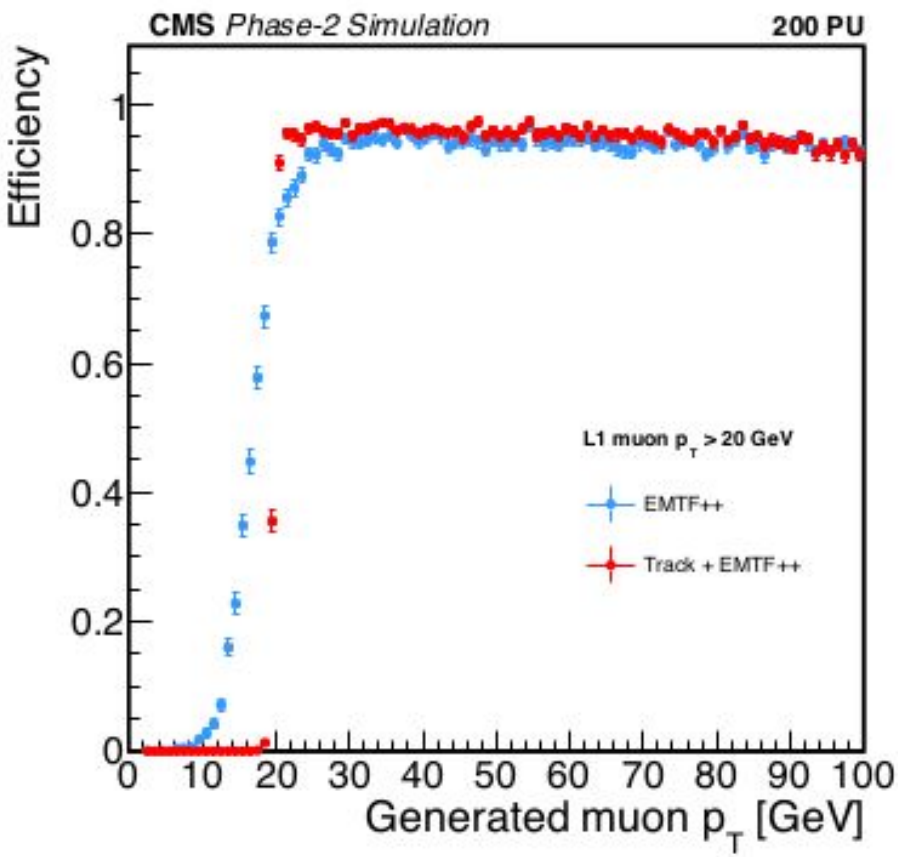
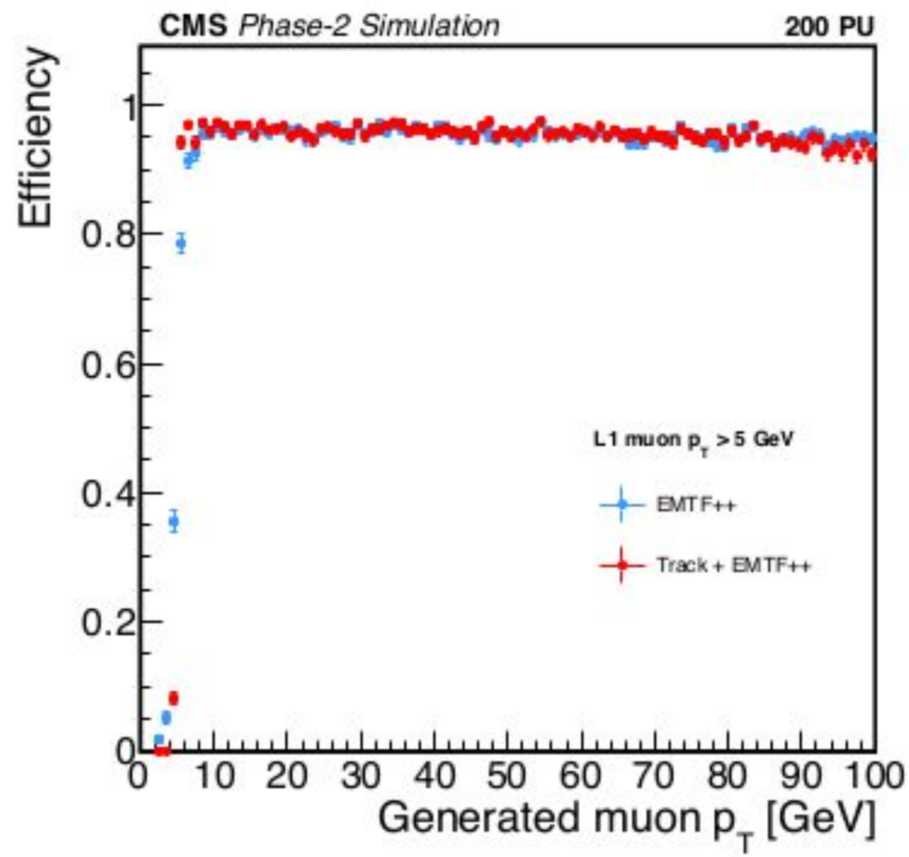
- **Extended coverage**: η < 2.4 → 2.8



- Muon track finders separated in barrel, endcap, and overlap regions

- Muon track finding efficiency





Correlator Trigger: Particle Flow

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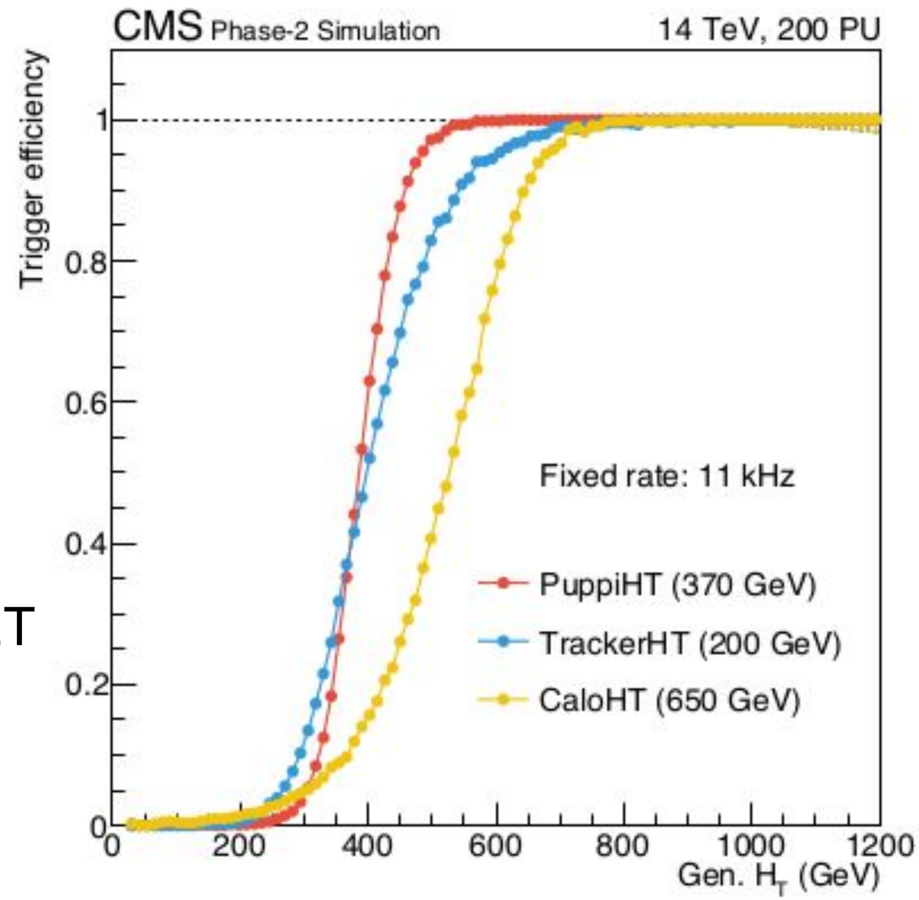
- **Key feature for Phase-2 L1T**: sophisticated algorithms for high level objects
  - As done offline in Runs 2 and 3
- Combines information coming from the muon, calorimeter and tracking triggers
- Layer 1 (VU9P-2 boards working and plan to go to VU13P-2)
  - Creates PF candidates (from calorimeter clusters matched to tracks)
  - PUPPI mitigates the degradation of the energy resolution due to PU
- Layer 2: final trigger objects, with additional ID and isolation
- PF+PUPPI: needed to sustain Run 2 Jets & MET thresholds
  - PF+Puppi **reduce the event content** keeping the core of the physics information



40 MHz Scouting

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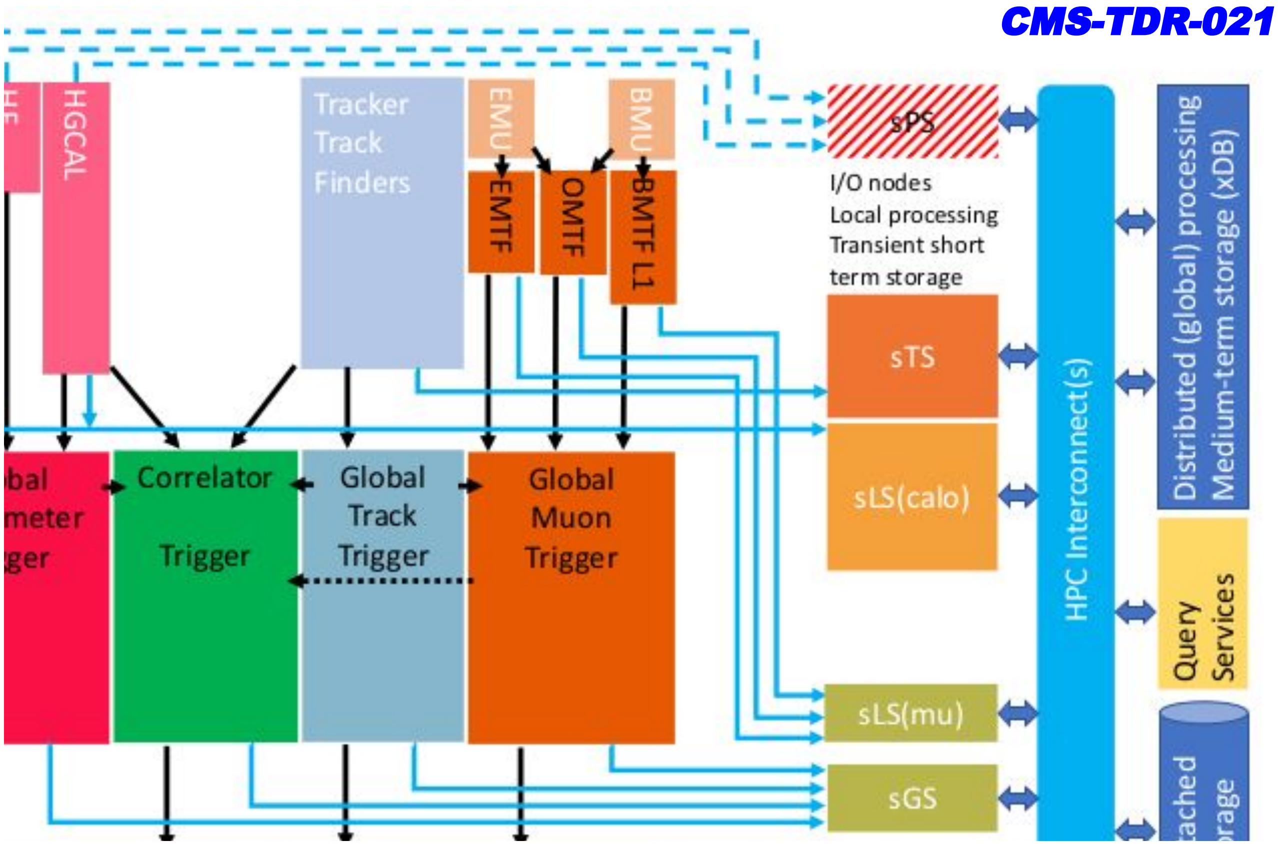
- ❖ Captures a **data** from the different trigger outputs
  - ➢ Using **spare optical outputs** of the different processing boards

- ❖ Expands the reachable phase space accessible with the standard L1T→HLT→Offline chain



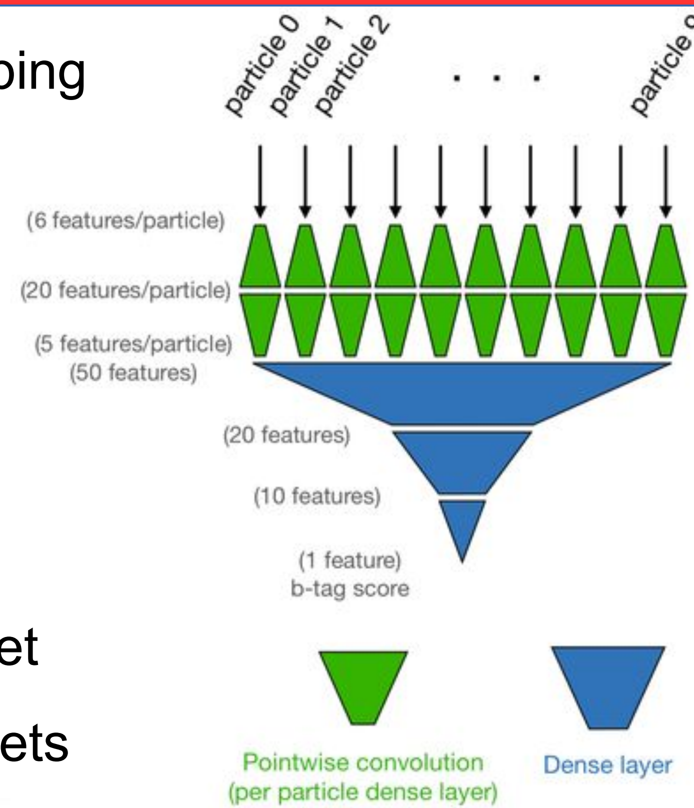
- ❖ Can be used for monitoring, diagnostics, luminosity measurements

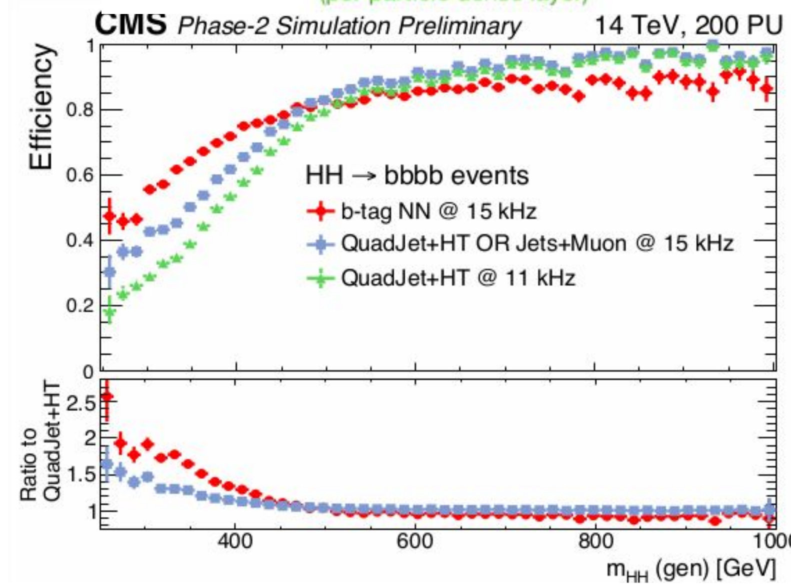
- ❖ And for physics: accessing **processes unreachable through standard triggers** (and not affecting the L1T accept rate budget): Higgs rare decays, LLPs, flavor anomalies...

- ❖ μGMT muons scouting demonstrator ran at the end of Run 2 (CMS-DP-2022-066)

NN for b-tagging - [CMS-DP-2022-021]

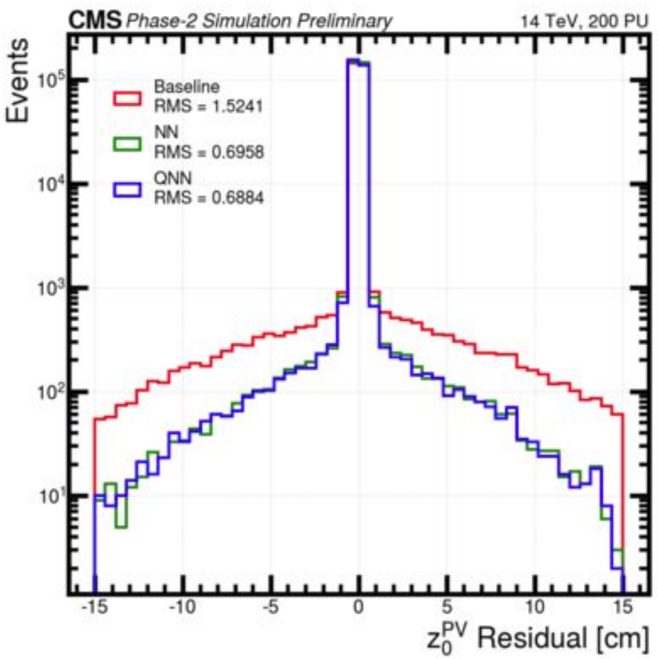
- **Including tracking** (d_z, d_{xy}) offers the chance for developing a b-tagging algorithm for the **first time in the CMS L1T**
- A NN is implemented in the Correlator Layer 2
- The algorithm runs on the PUPPI particles in each jet
  - Input: 10 highest p_T PUPPI candidates within recon. jet
  - Able to discriminate b-jets from light quarks or gluon jets
- **Better performance** with respect to QuadJet+HT for m_{HH} < 500 GeV
  - Efficiency increased for events with low m_{HH} by up to a factor of 1.5 wrt the QuadJet+HT or Jets+Muon triggers

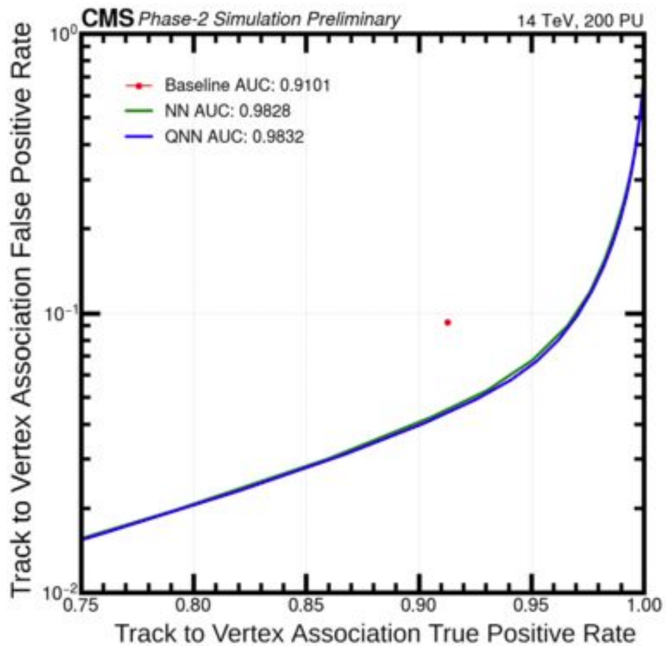


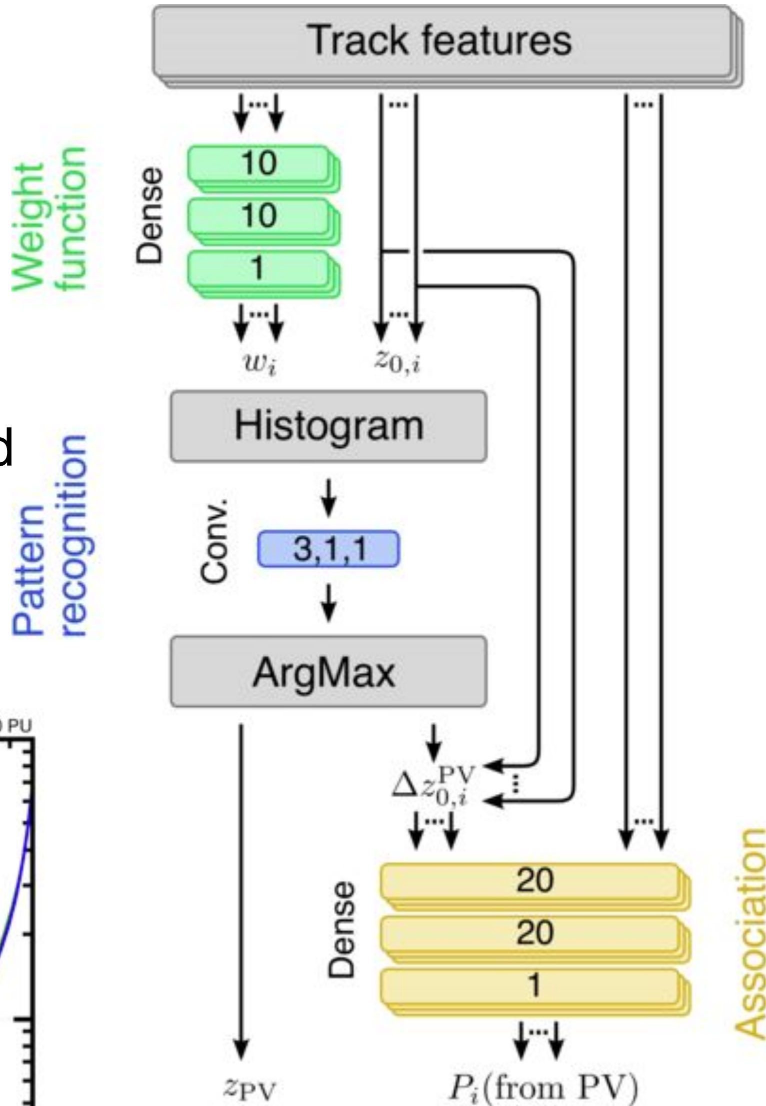


NN Vertexing - [CMS-DP-2022-018]

- End to End NN for Vertex finding
  - End to End: track to vertex association is optimised
  - Pruned in order to fit onto FPGA
- From tracker track properties, returns **likelihood of track belonging to the vertex** with a flexible threshold for downstream algorithms
- **Reduction in the tails of the residual**







Seeded Cone (SC) Algorithm - CMS-DP-2023-023

- Algorithm to reconstructing jets from PF reconstructed particles using the full available granularity

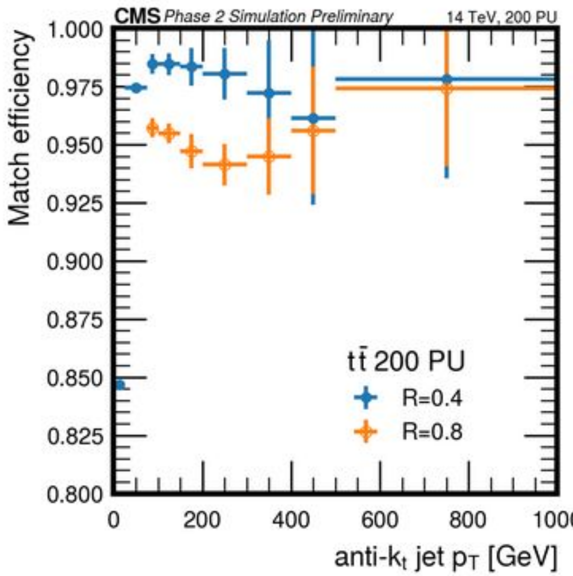
- Implemented in Xilinx VU9P FPGAs in the Correlator system

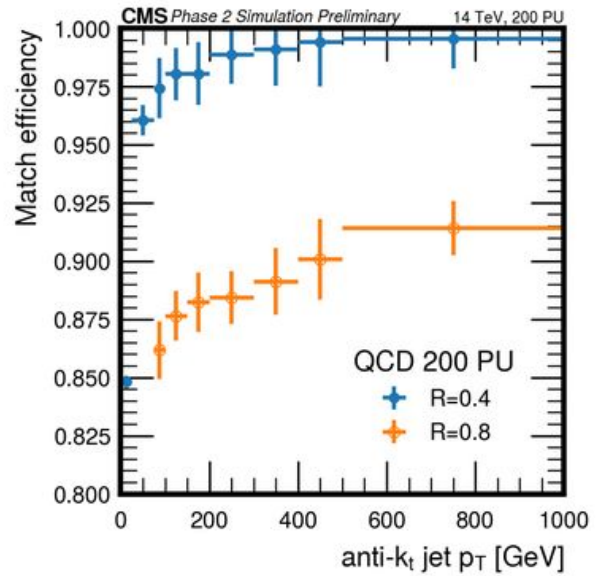
- Algorithm
  1. Find the highest p_T particle as the seed for a jet
  2. Compute distance between each particle and the seed (and whether in or out of jet radius)
  3. Compute jet axis from constituents, correct jet energy
  4. Mask seed and constituents out from event, go back to 1

- The SC4 jets, jets with R=0.4 are used for the baseline performance
  - Produce SC8 jets also for little hardware cost

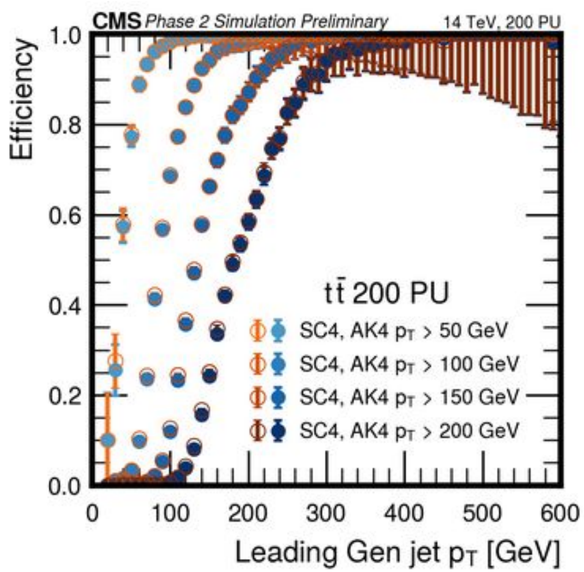
Performance SC Algorithm - CMS-DP-2023-023

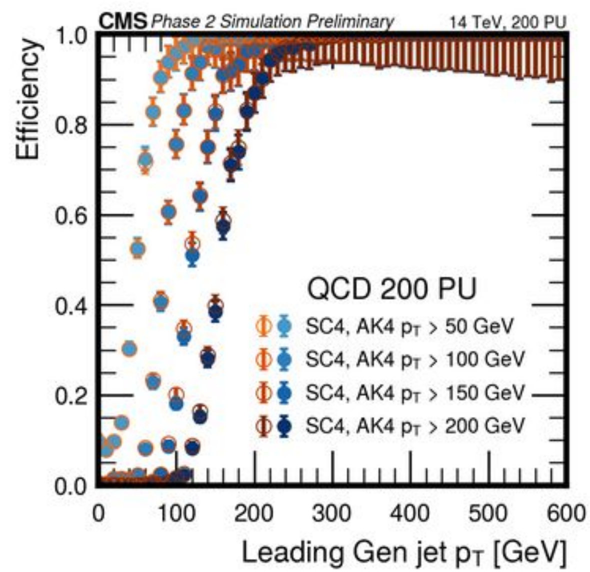
- ❖ Efficiency to match each anti-k_T jet to a SC jet within $\Delta R \leq 0.2$ and p_T within 20%
  - ➢ SC generally matches well to anti-k_T, with some mismatches where the SC jet seeding can miss some particles / sub-jet that anti-k_T captures





- ❖ Trigger efficiency as a function of simulated jet p_T for different L1T thresholds
  - ➢ Trigger turn-ons are virtually identical for SC4 and AK4

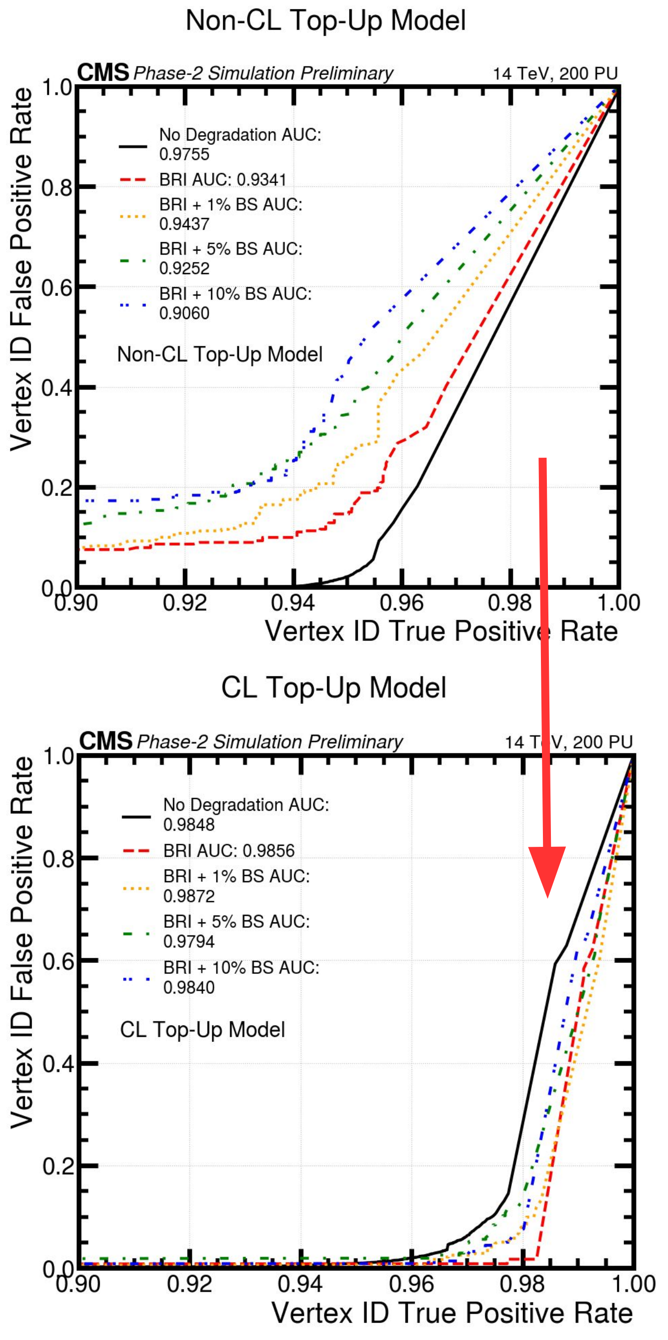




Continual Learning - CMS-DP-2023-022

- The Phase-2 L1T uses ML to make decisions: small, low-latency models
  - need to be robust to the changing detector environment
  - started investigating techniques to mitigate possible issues

- **Continual Learning**: train a model with a continuous stream of data. Learns from a sequence of partial experiences rather than all the data at once
  - Update model to changing conditions without needing large MC production campaign
  - Tested using a CNN for fake vertex identification on MC with a degraded outer tracker (up to a 10% strips removed)
  - The CL method gave better performance across degraded datasets compared to a non-CL approach



L1T Physics Reach

- Links between the trigger primitives, the trigger objects, the L1 algorithms used in the menu, and the physics channels

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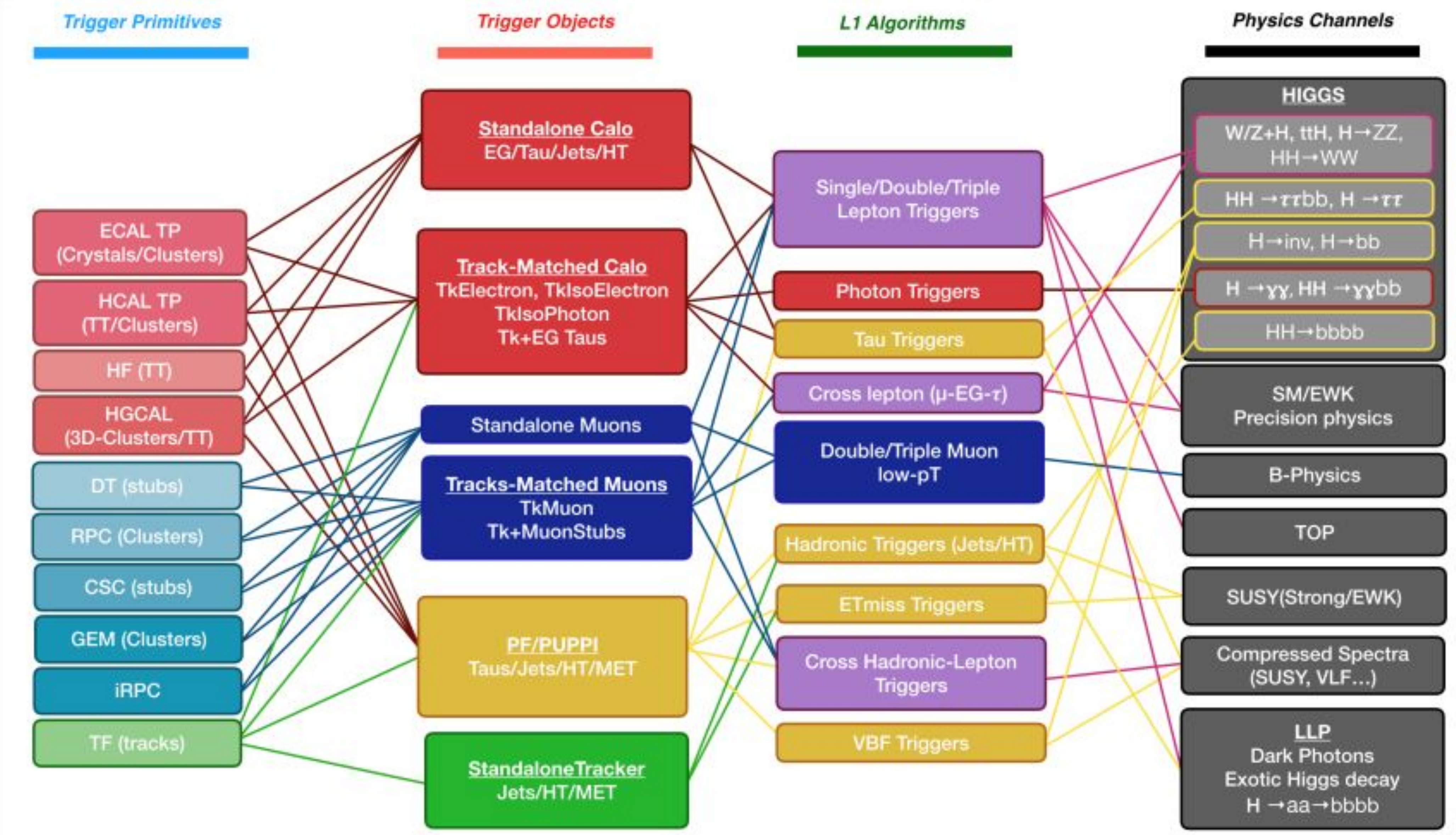
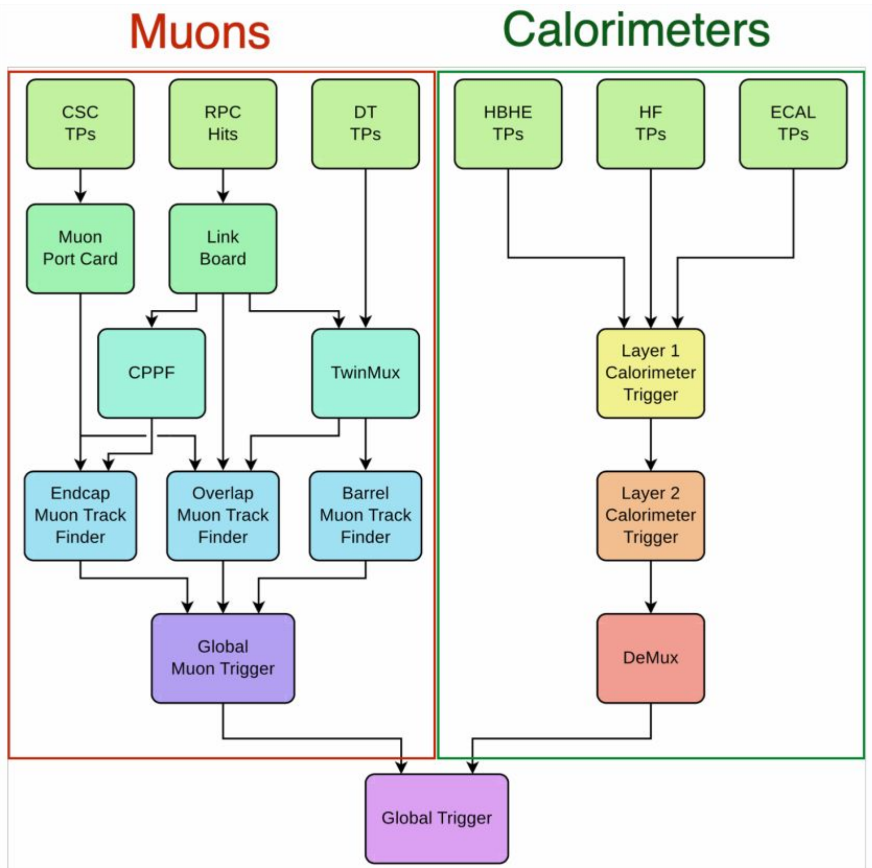


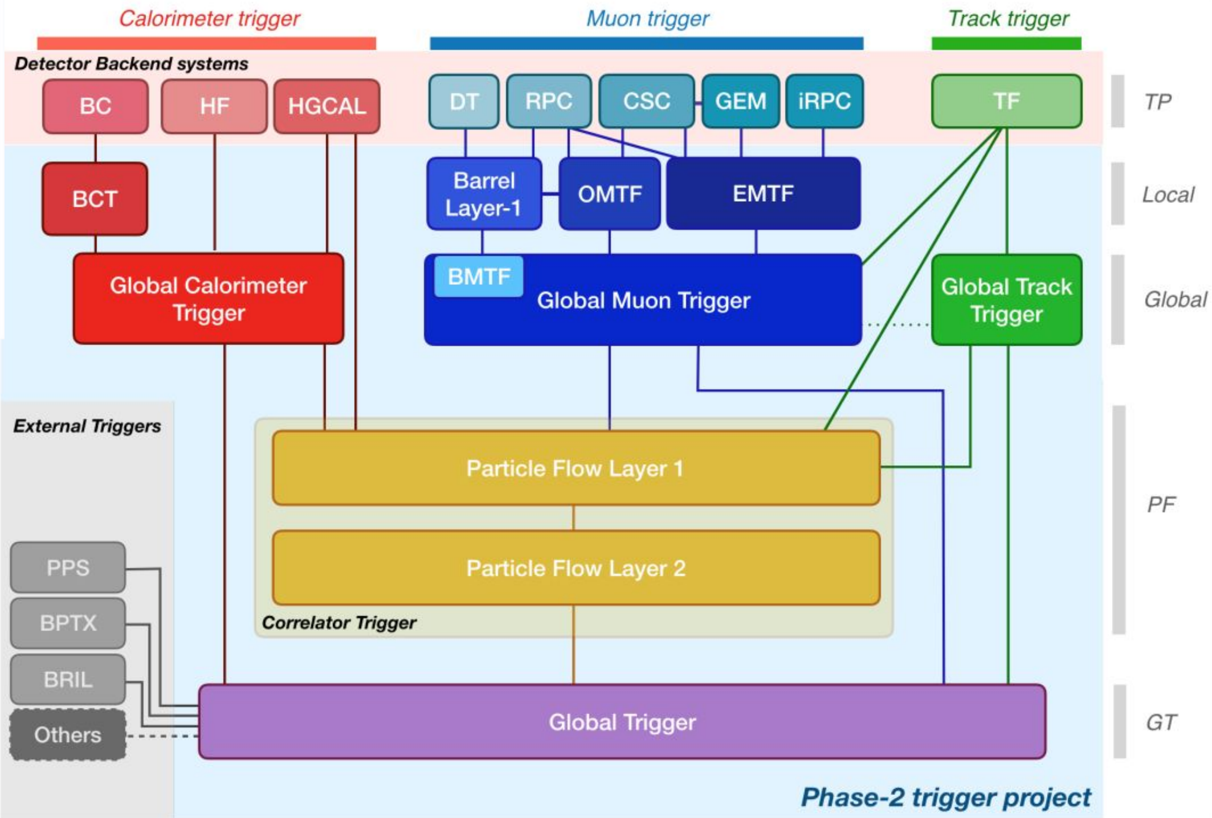
Summary

- **HL-LHC** will provide **huge statistics** for physics but comes at a price of **high PU**
- CMS will undergo many developments in order to deal with it
- In particular, **L1T will be upgraded** in order to not only cope with the harsh environment, but also to increase acceptance and expand the physics reach to unexpected new physics at the HL-LHC
- Benefit from additional detector information (tracker, HGCAL), improved inputs and granularity, expanded L1T architecture, extensive FPGA resources, redesigned algorithms, and new ML techniques
- Phase-2: **CMS L1T will meet the challenge** with an intense upgrade program:
  - Innovative trigger strategies will increase physics acceptance and improve performance even further, with algorithms getting closer to offline ones
- The **physics reach will be extended** with the upgraded L1T system

Back-up Slides

Phase-1 vs Phase-2 L1T





Phase-2 L1T Architecture

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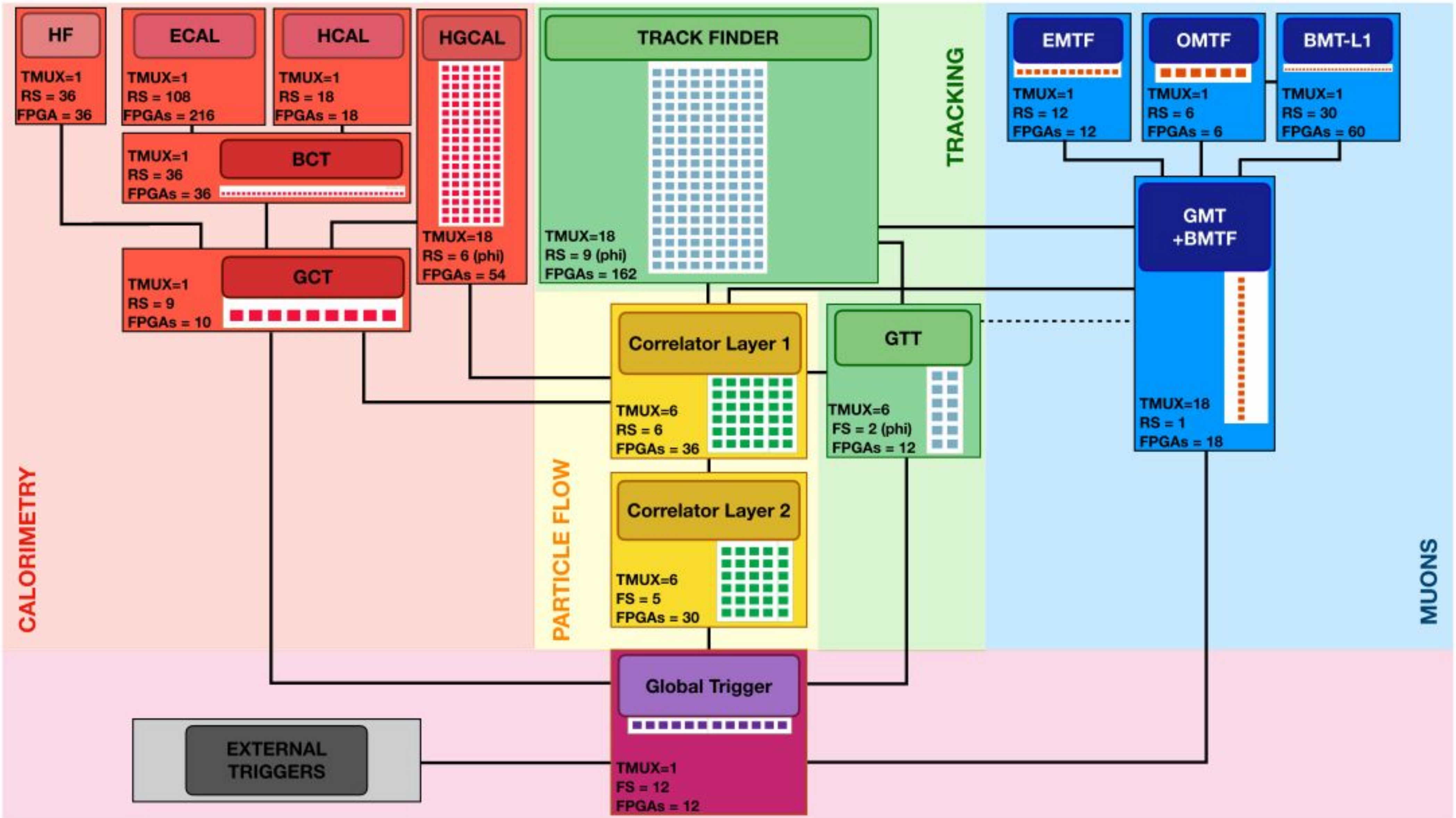

Physics Reach Example

- $h \longrightarrow \phi\phi \longrightarrow 4j$

- Benefits from L1 extended tracking that builds displaced tracks and jets