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

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High Luminosity Large Hadron Collider

- Increase statistics to search for new and rare physics

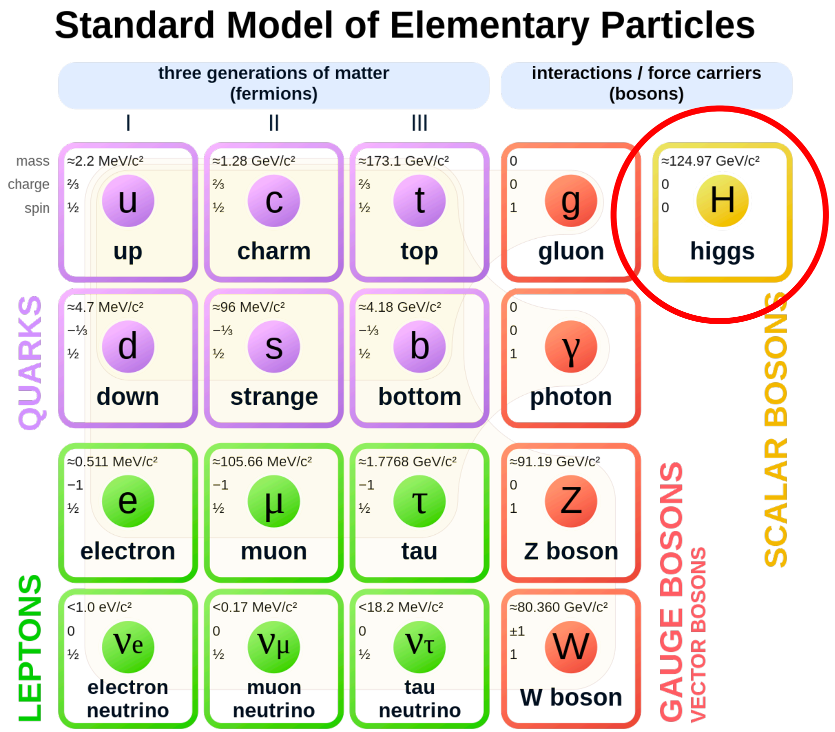
High statistics
(4000 fb^{-1})

↓

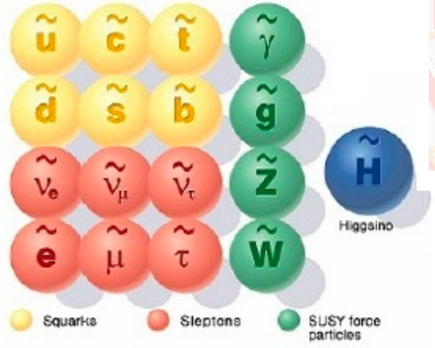
High luminosity
(7.5 x 10^{34} $cm^{-2}s^{-1}$)

↓

Pile-up increase
200 PU

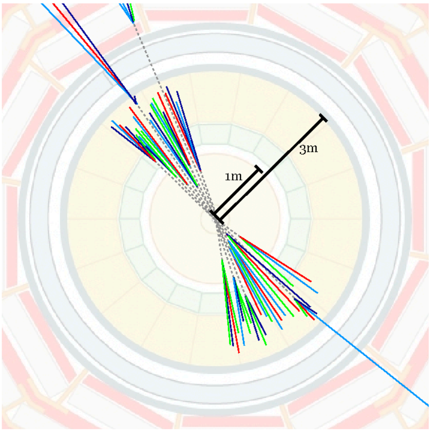


>15 million
per year

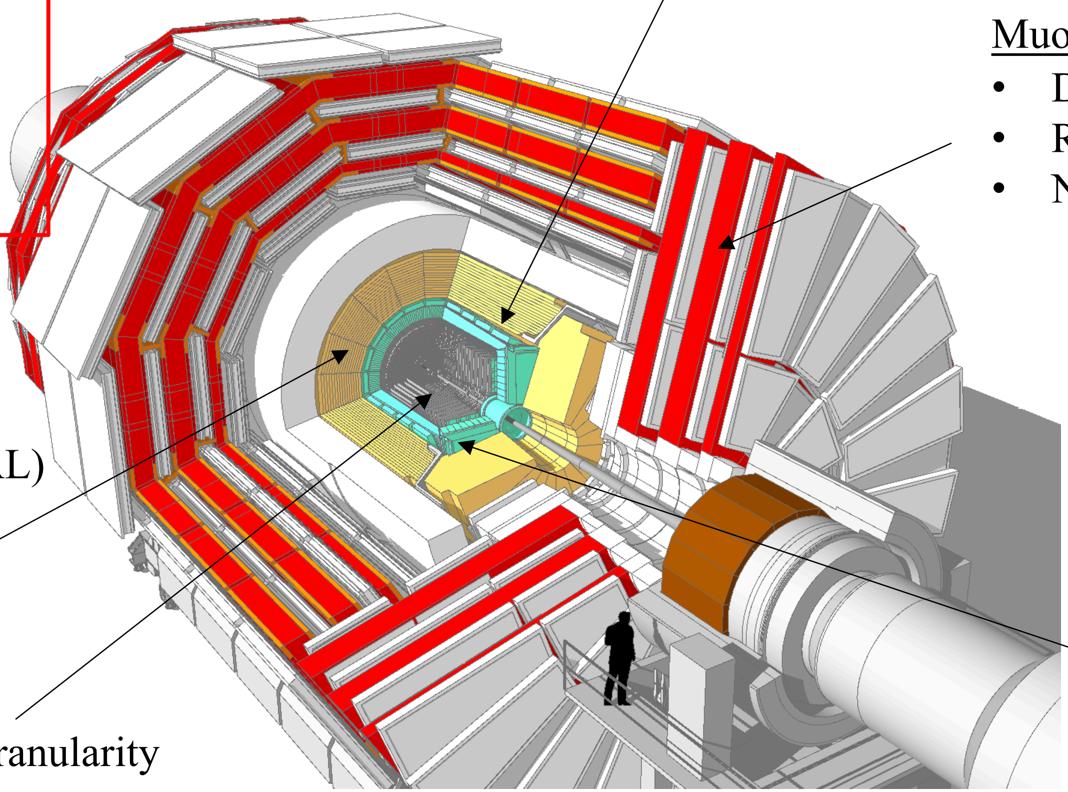


SUSY particles

Dark matter signals
(Emerging Jets)



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 $1.6 < \eta < 2.4$

Beam Radiation Instr. and Luminosity

- Bunch-by-bunch luminosity measurement:
- 1% offline, 2% online

Calorimeter Endcap

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

Tracker

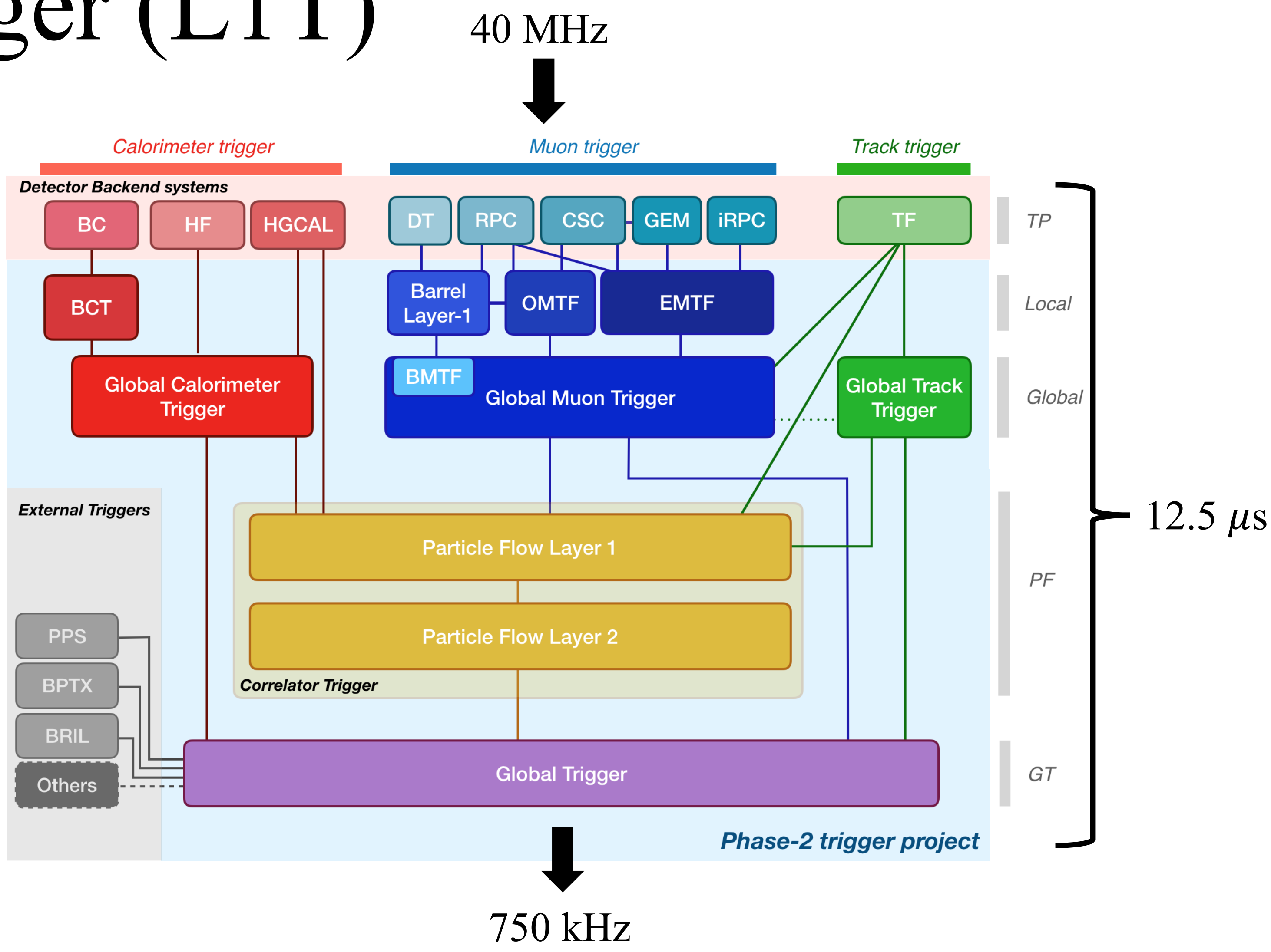
- Si-Strip and Pixels increased granularity
- Design for tracking in L1-Trigger
- Extended coverage to $\eta \simeq 3.8$

MIP Timing Detector

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

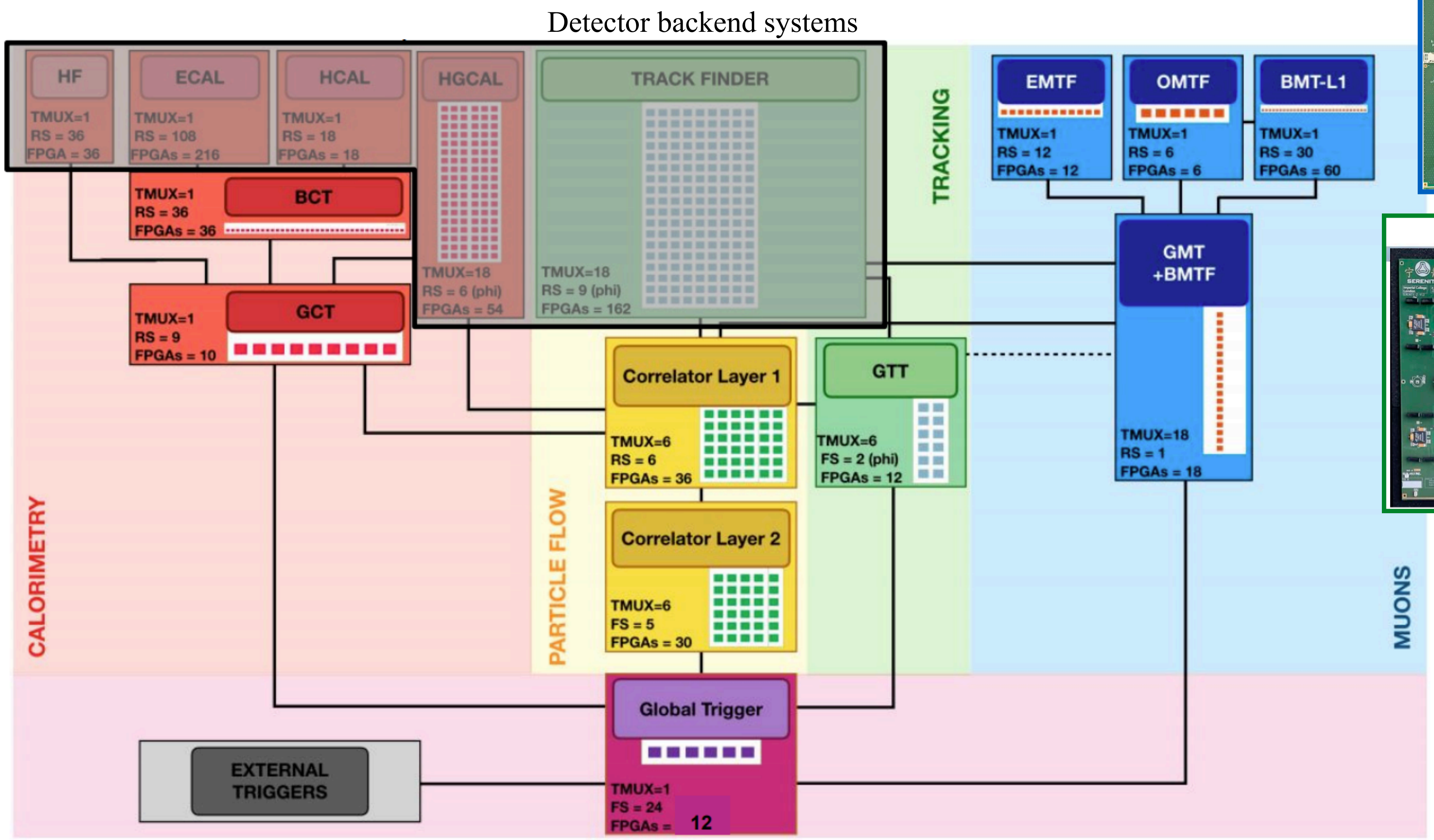
CMS Level-1 Trigger (L1T)

- Initial event selection in real time
- Reconstruction of physics objects
- FPGA-based hardware
- Goals:
  - Maintain current physics reach with 200PU
  - Extend to new signatures with advanced techniques
    - Ex: machine learning



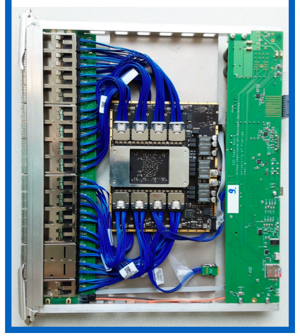
CMS-TDR-021

L1T Architecture

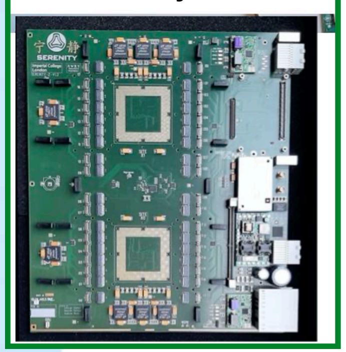


BMT-L1

X2O



Serenity

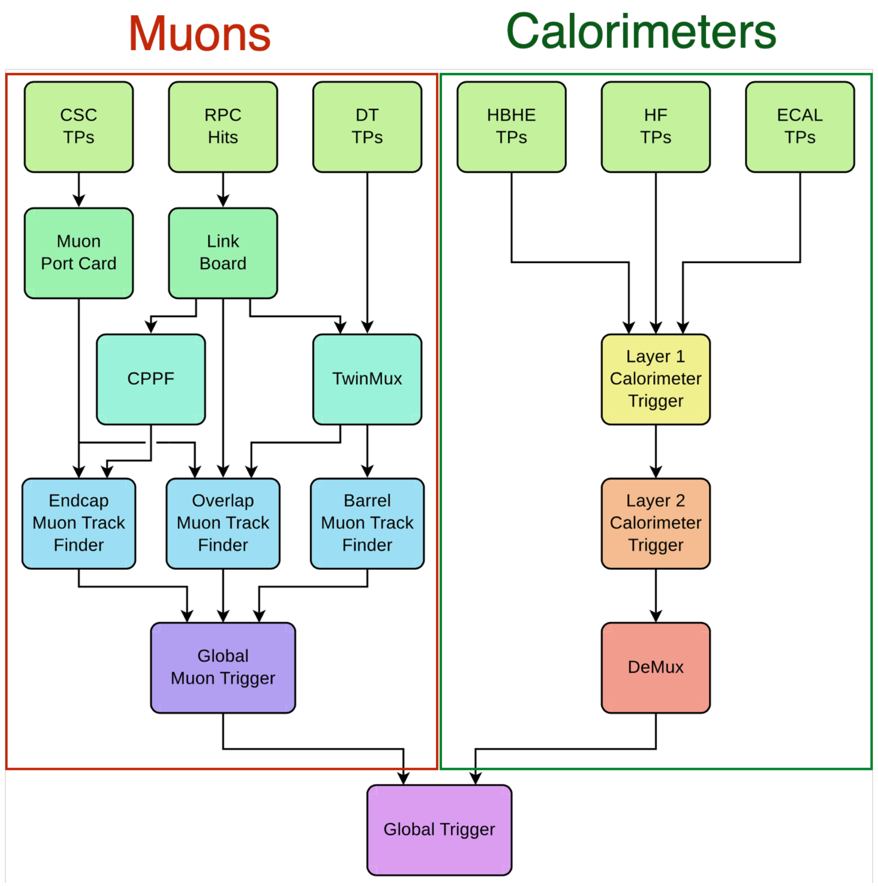


APx-F

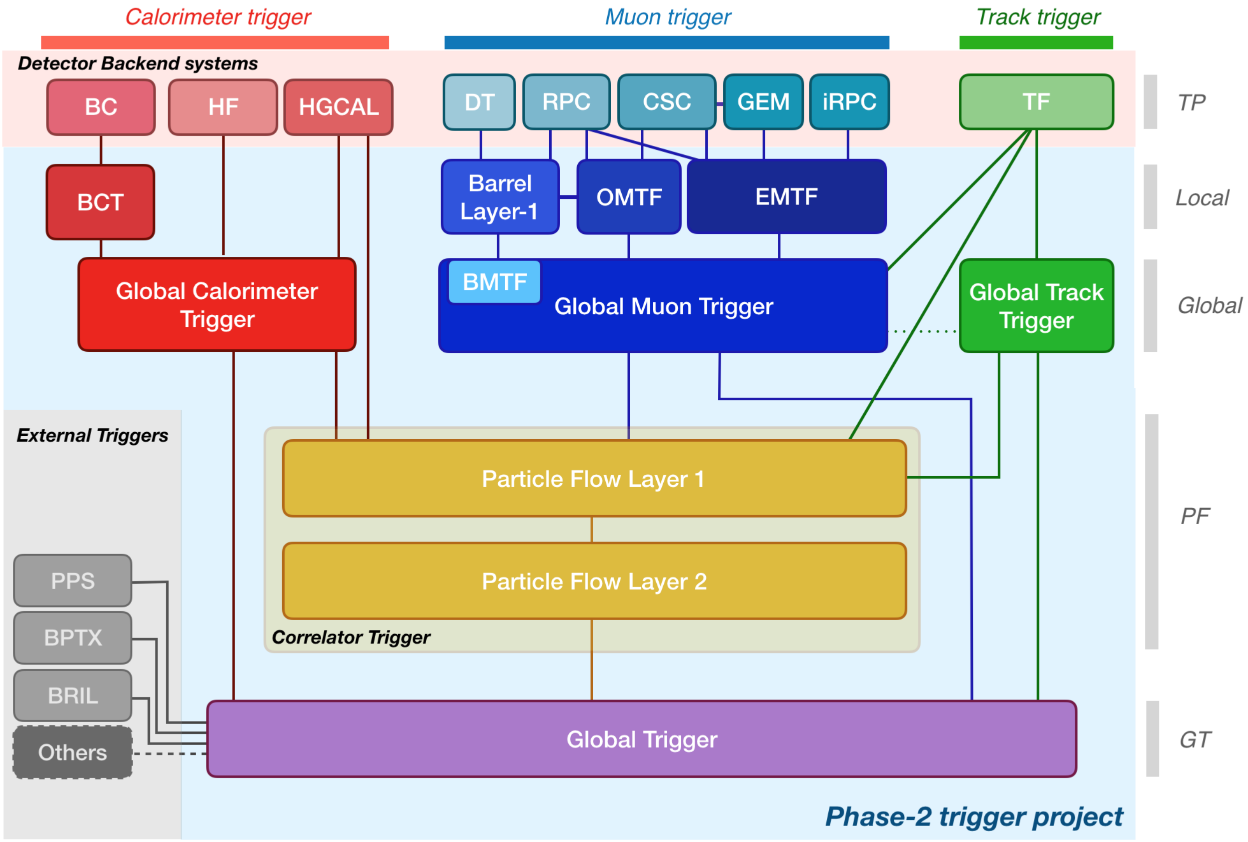
- ATCA form factor PCBs
- Xilinx VU13P FPGAs
- 25 Gb/s optical fibers

L1T Upgrades

Phase 1



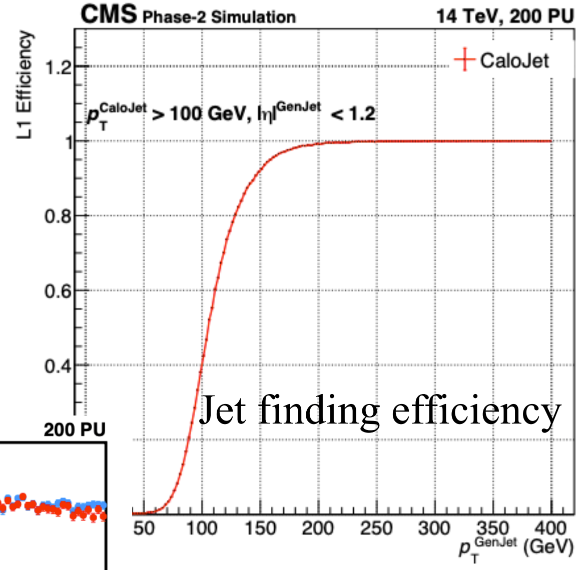
Phase 2



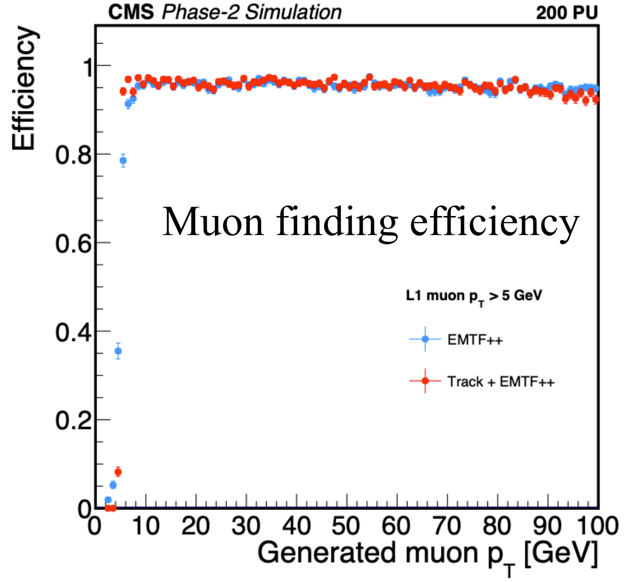
L1T Upgrades: Calorimeter and Muon Triggers

- Calorimeter trigger:
  - Higher granularity for high-resolution clusters and identification variables
  - Build e/γ, τ_h, jets, energy sums

- Muon trigger:
  - Extended coverage $|\eta| < 2.4 \rightarrow 2.8$
  - Muon track finders separated in barrel, endcap, and overlap regions



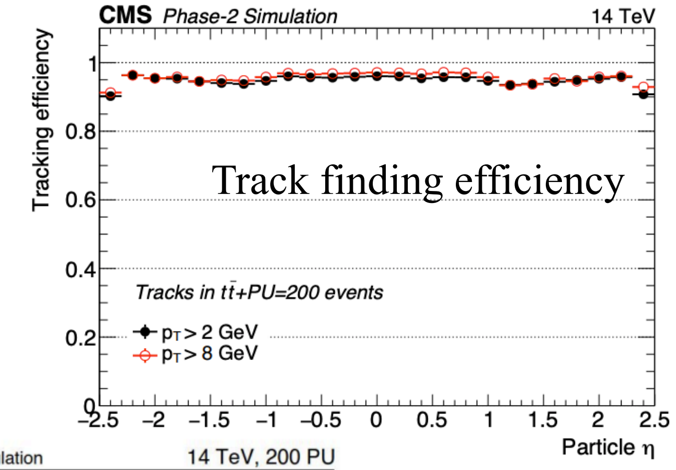
Jet finding efficiency



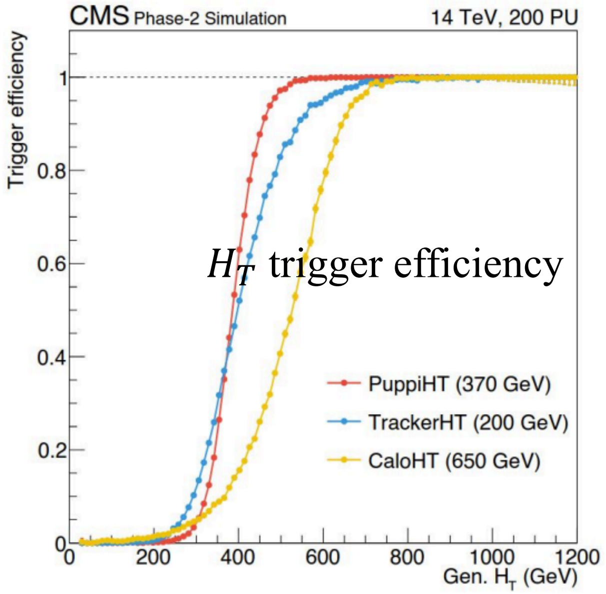
Muon finding efficiency

L1T Upgrades: Correlator and Track Triggers

- Global track trigger:
  - Gets full tracker tracks from Track Finder
  - Build track objects: jets, vertices, H_T



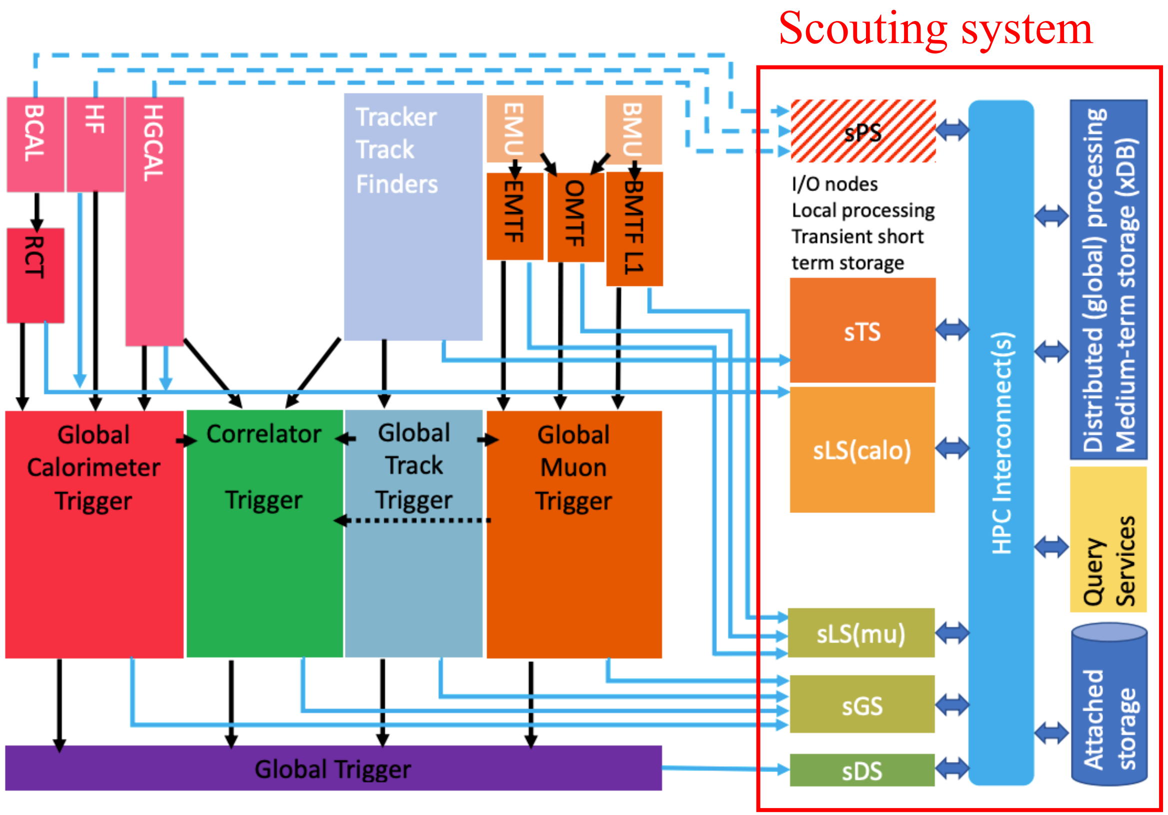
- Correlator trigger (Particle Flow):*
  - Particle Flow identifies and reconstructs all particles with sub-detectors info
  - Pileup Per Particle Identification (PUPPI) used to mitigate PU effects
  - Reconstructs hadronic jets, E_T^{miss}, τ_h, H_T, …



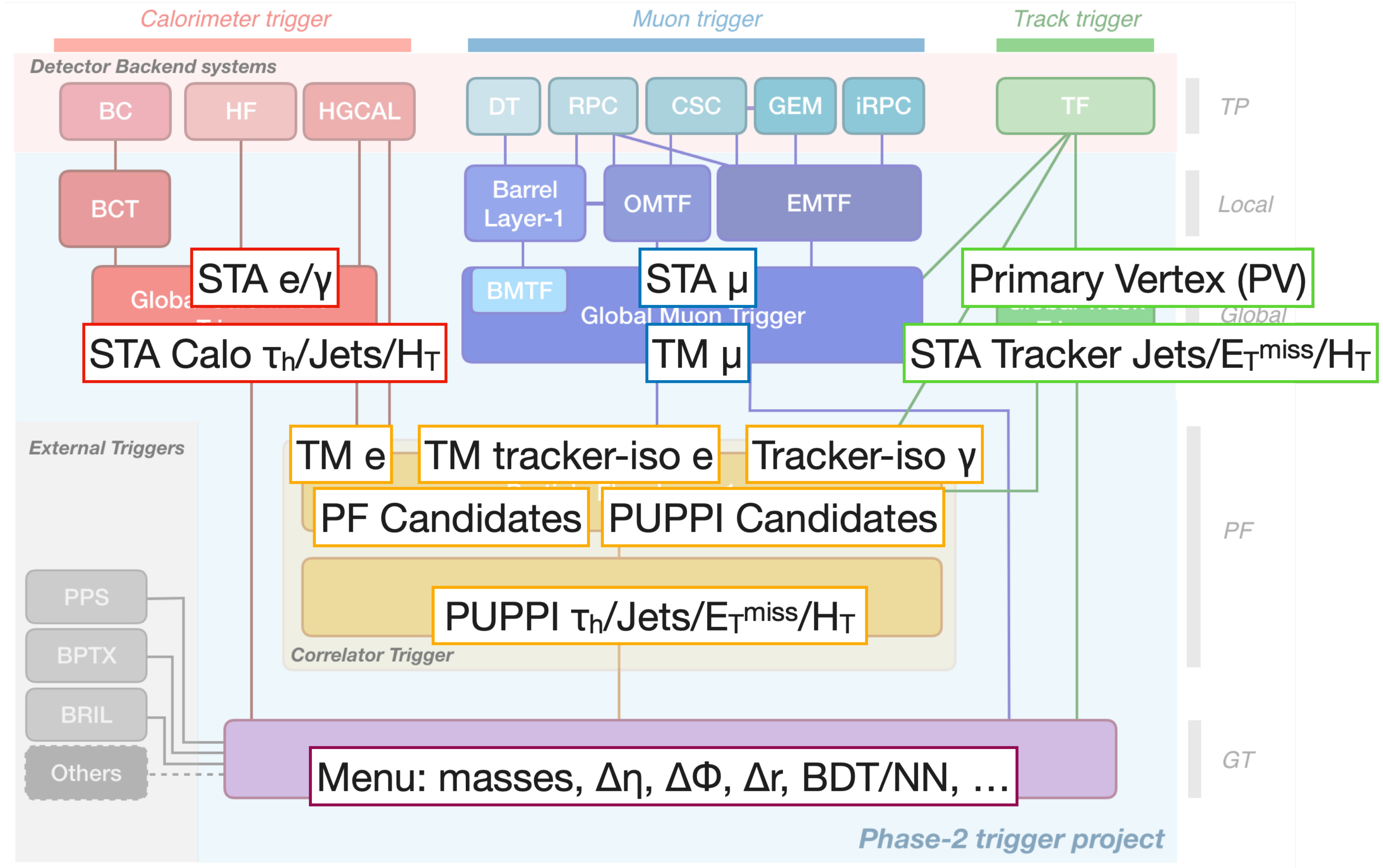
*See Sioni Summers talk on Particle Flow

L1T Upgrades: 40 MHz Scouting

- Collects subset of trigger primitives and objects through spare optical links
- Uses:
  - Monitoring, diagnosis, lumi measurements
  - Find correlations among contiguous BX
  - Analyze signatures unreachable through standard triggers

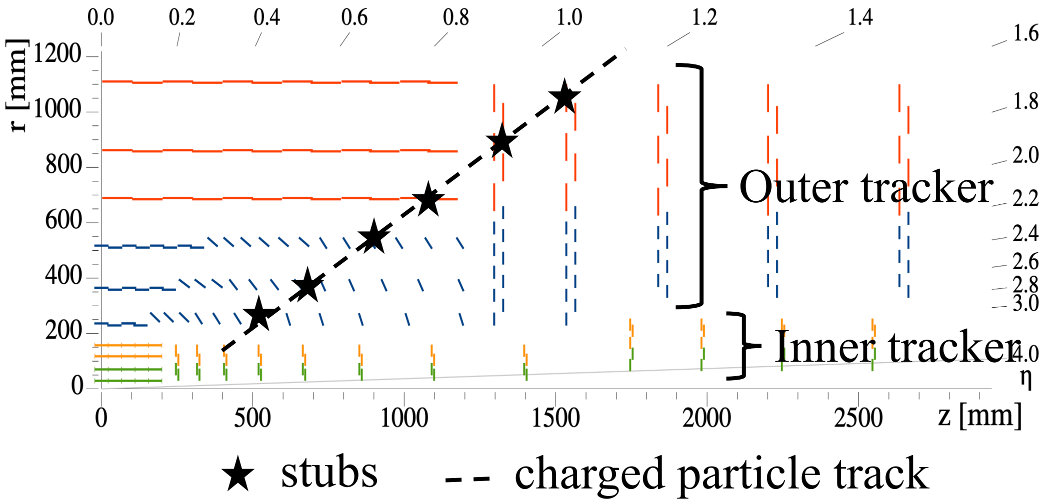


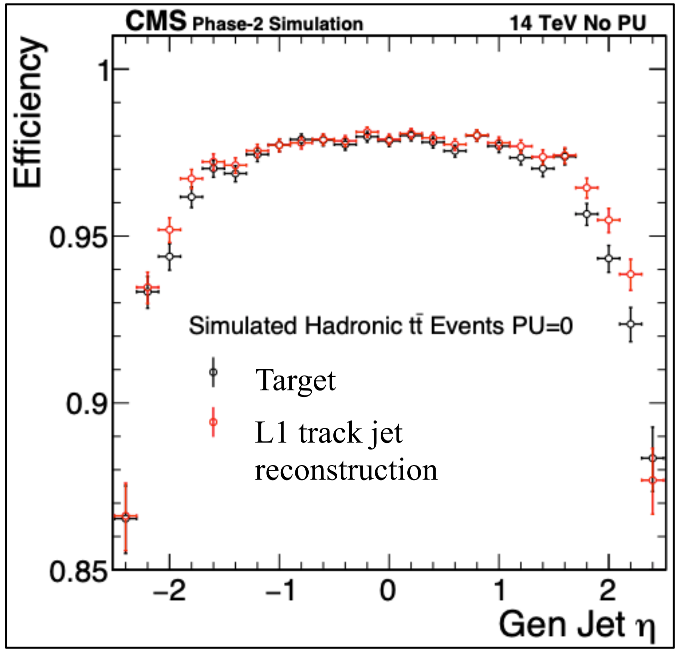
L1T Objects

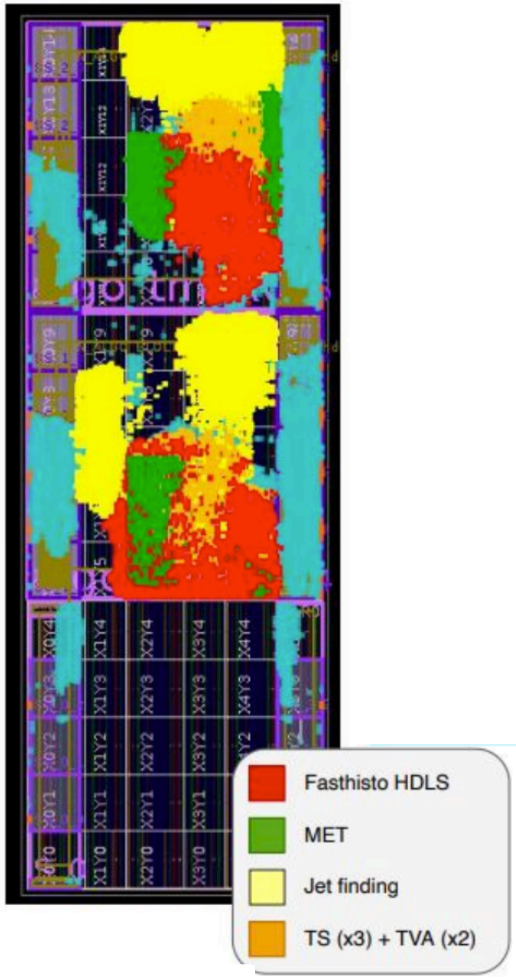

Calorimeter trigger
Muon trigger
Track trigger
Detector Backend systems
BC
HF
HGCAL
DT
RPC
CSC
GEM
iRPC
TF
TP
BCT
Barrel Layer-1
OMTF
EMTF
Local
STA e/γ
STA μ
Primary Vertex (PV)
BMTF
Global Muon Trigger
Global
STA Calo τ_h/Jets/H_T
TM μ
STA Tracker Jets/E_T^{miss}/H_T
External Triggers
TM e
TM tracker-iso e
Tracker-iso γ
PF Candidates
PUPPI Candidates
PF
PPS
PUPPI τ_h/Jets/E_T^{miss}/H_T
BPTX
Correlator Trigger
BRIL
Others
Menu: masses, Δη, ΔΦ, Δr, BDT/NN, …
GT
Phase-2 trigger project

Sub-Detector Example: GTT

- Track inputs: $\{\frac{q}{R}, \phi, \tan(\lambda), z_0, n_{stub}, \text{quality} \ldots\}$
- Global Track Trigger (GTT) builds track objects
  - H_T, E_T^{miss}, primary vertex, jets



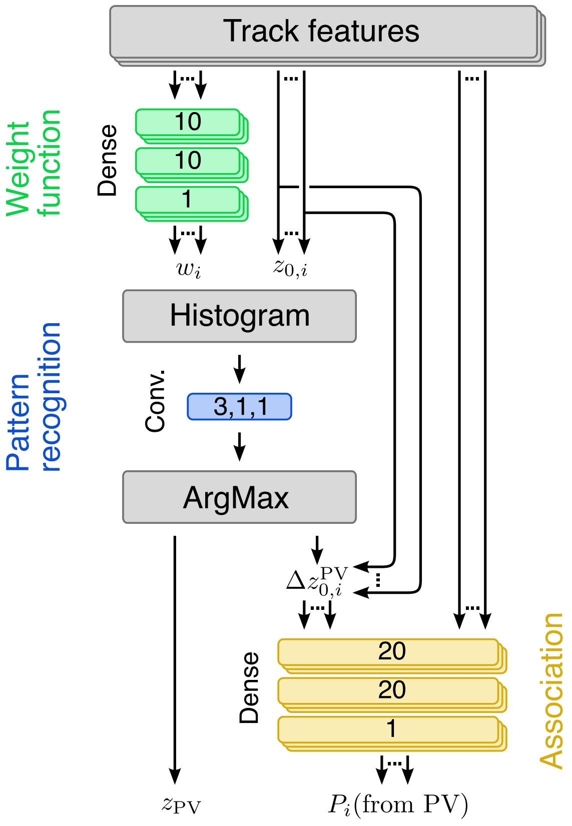




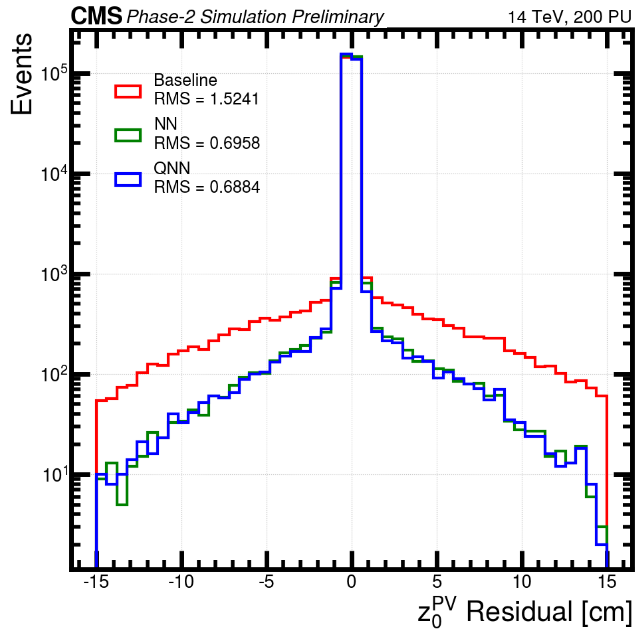
GTT floor plan:

~15% LUT, ~20% FF, ~25% BRAM, ~3% DSP

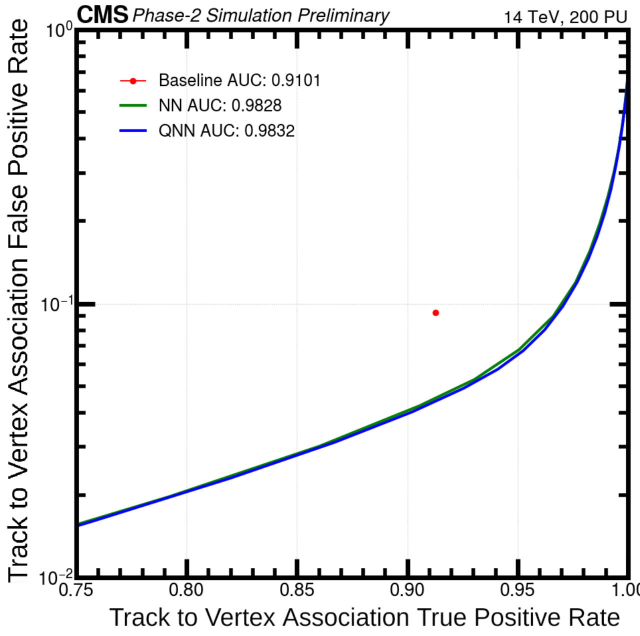
Algorithm Example: NN Vertexing

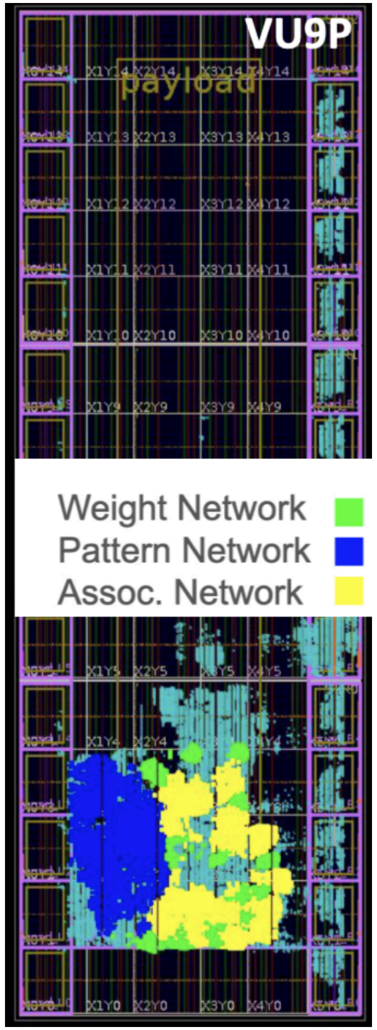


In: tracker track properties



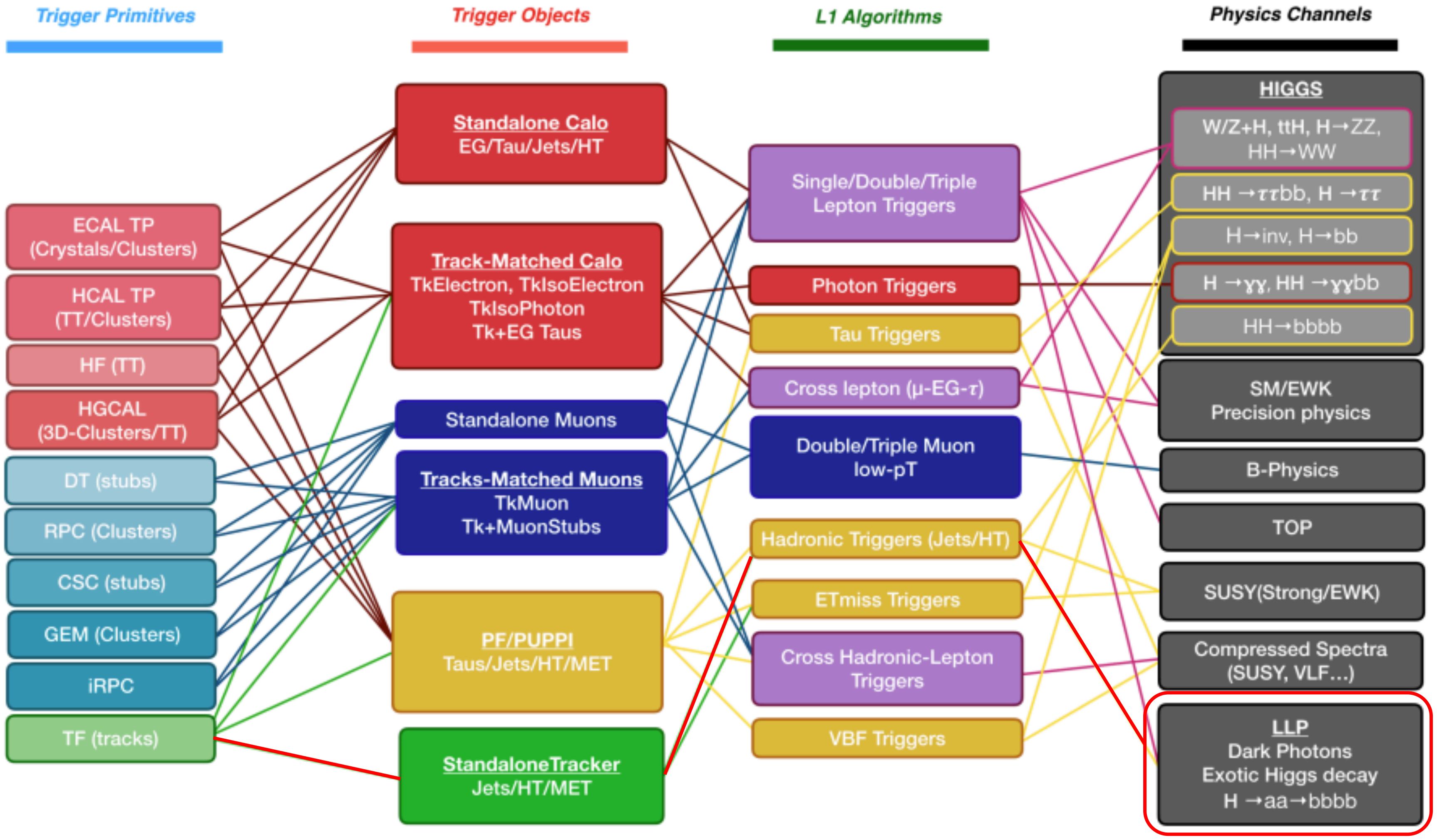
Out: likelihood track belongs to primary vertex





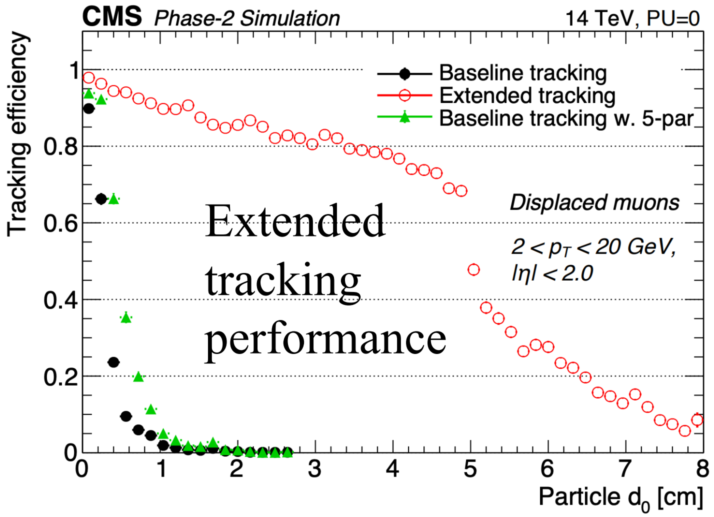
Useful for pile-up mitigation, important for Particle Flow

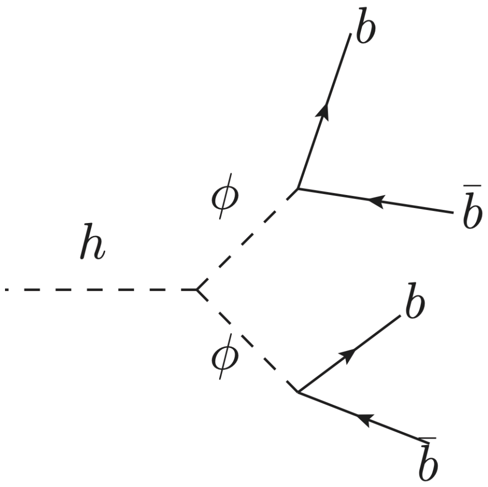
L1T Physics Reach

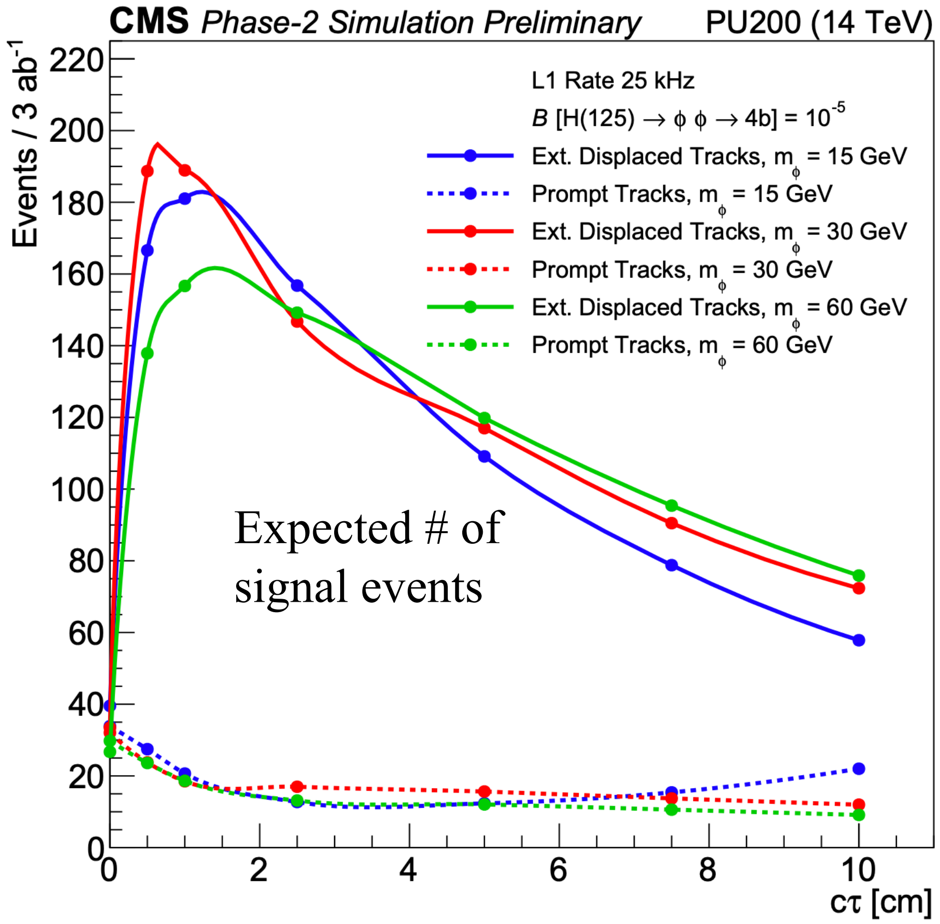


Physics Reach Example: Exotic Higgs

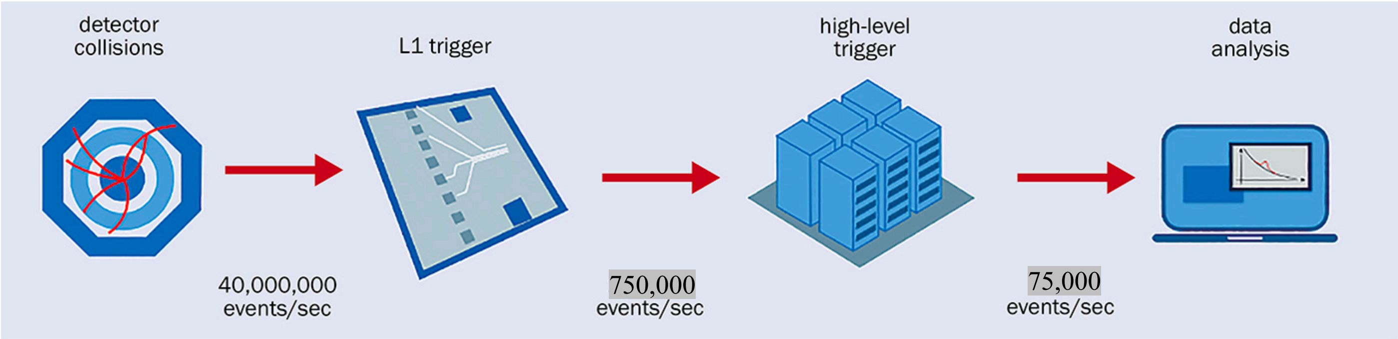
- h → $\phi\phi$ → $4j$, LLP
- L1 extended tracking builds displaced tracks and jets
  - Also calo timing, displaced STA muons, etc.
- Phase 2, H_T trigger rate



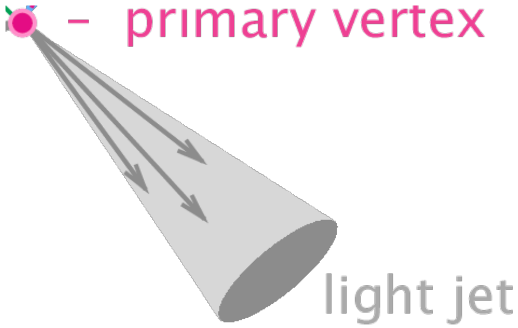




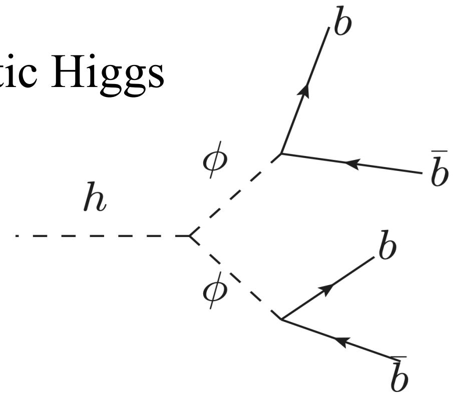
Summary



- HL-LHC increases statistics, increases pile-up
- L1-Trigger upgraded for more complicated events/increase acceptance
- Upgrades allow reconstruction of more sophisticated, offline-like, objects to improve triggering
- Physics reach extended with better triggering algorithms



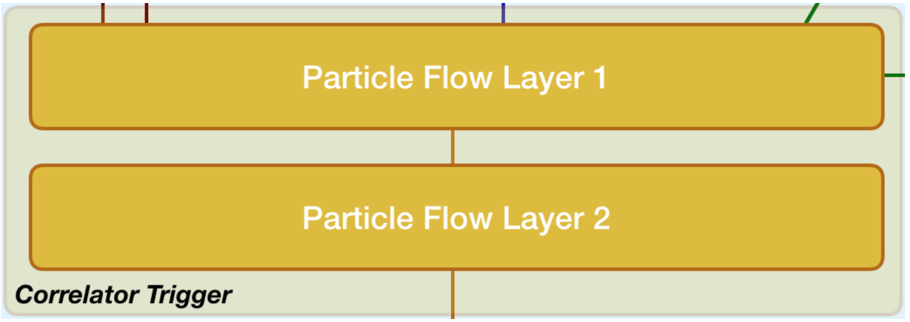
Exotic Higgs



Backup

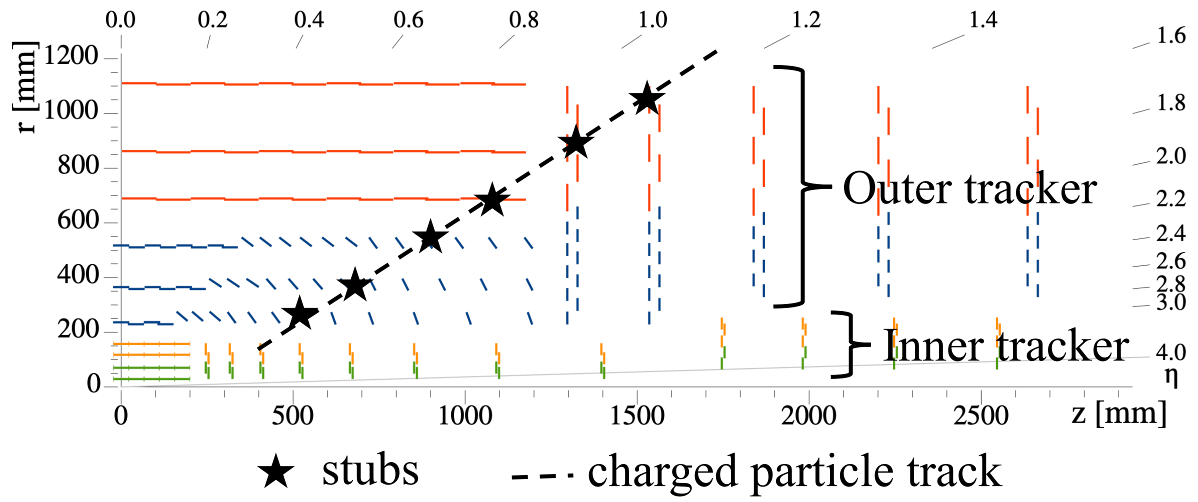
L1T Upgrades: Particle Flow

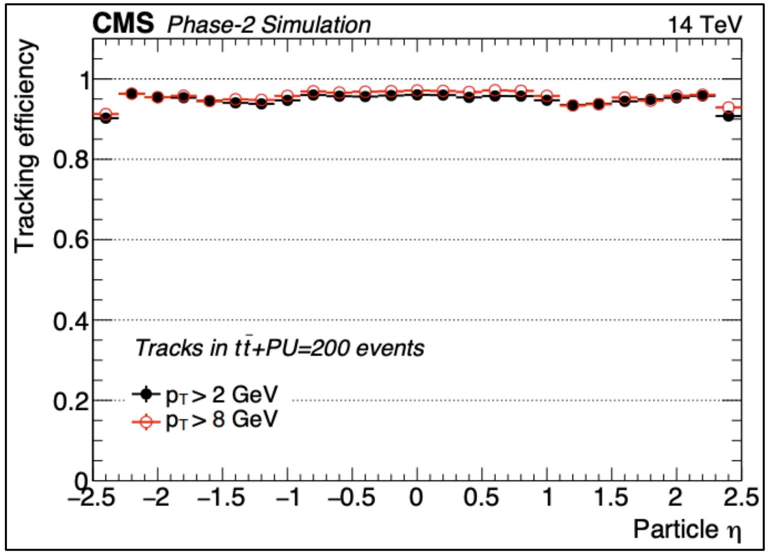
- Layer 1
  - Produces particle-flow (PF) candidates; constructed from the matching of calorimeter clusters and tracks
  - Pileup Per Particle Identification (PUPPI) algorithm mitigating the degradation of the energy resolution due to PU
- Layer 2
  - Building and sorting final trigger objects
  - Applying additional ID and Isolation
- PF+PUPPI: needed to sustain Run 2 Jets & MET thresholds

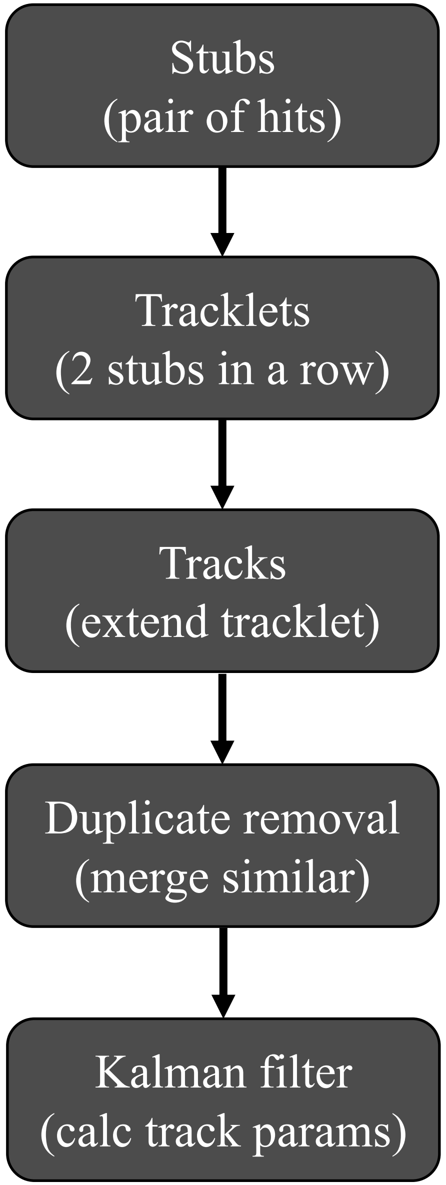


L1T Upgrades: Track Finder

- Reconstruction of tracker tracks at 40 MHz
  - $\frac{q}{R}, \phi, \tan(\lambda), z_0, n_{stub}$, quality…

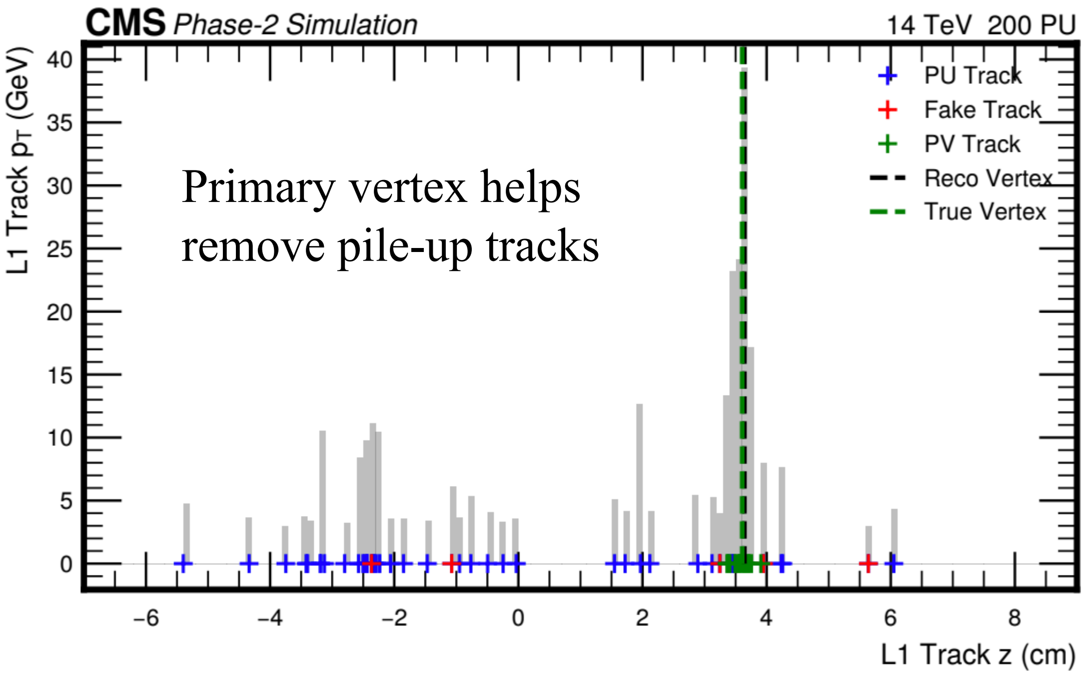


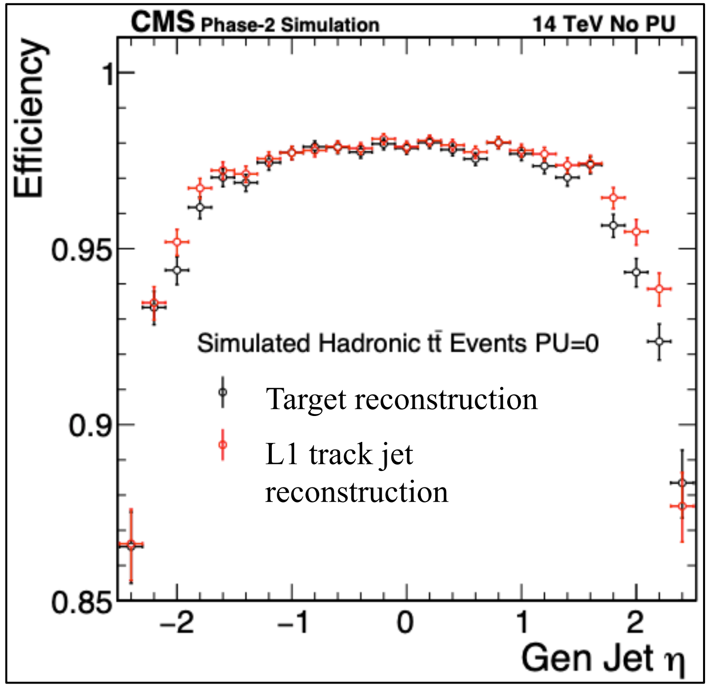


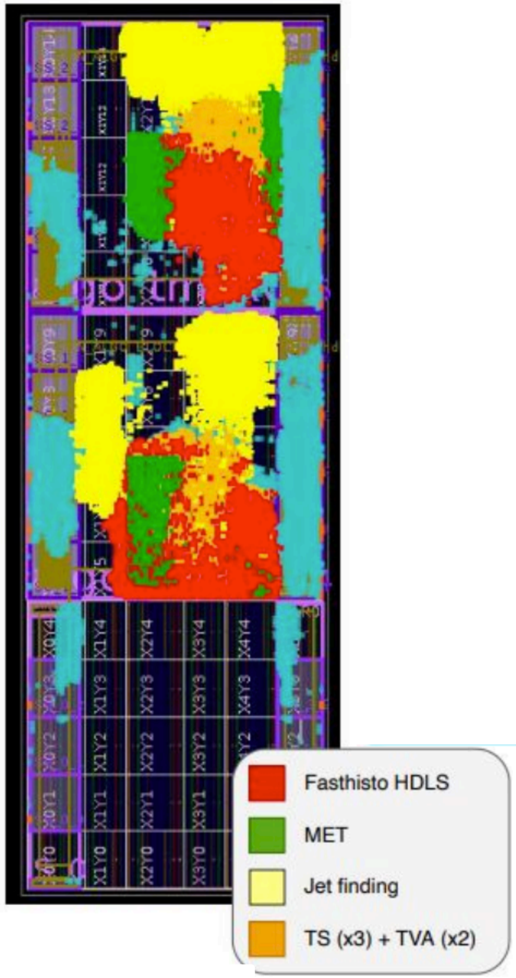


L1T Upgrades: Global Track Trigger

- Takes in tracker tracks, builds high-level physics objects
  - H_T, E_T^{miss}, primary vertex





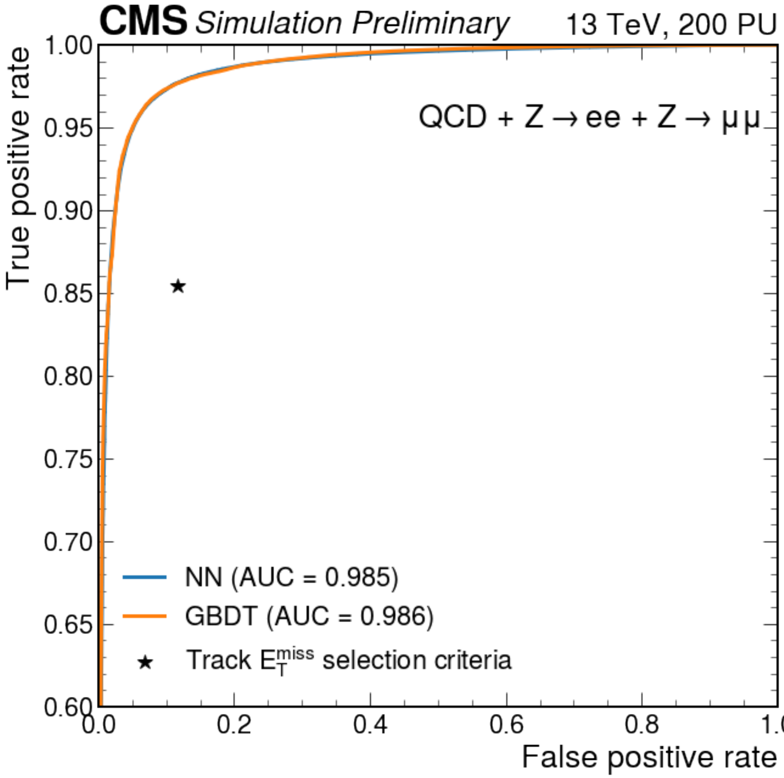


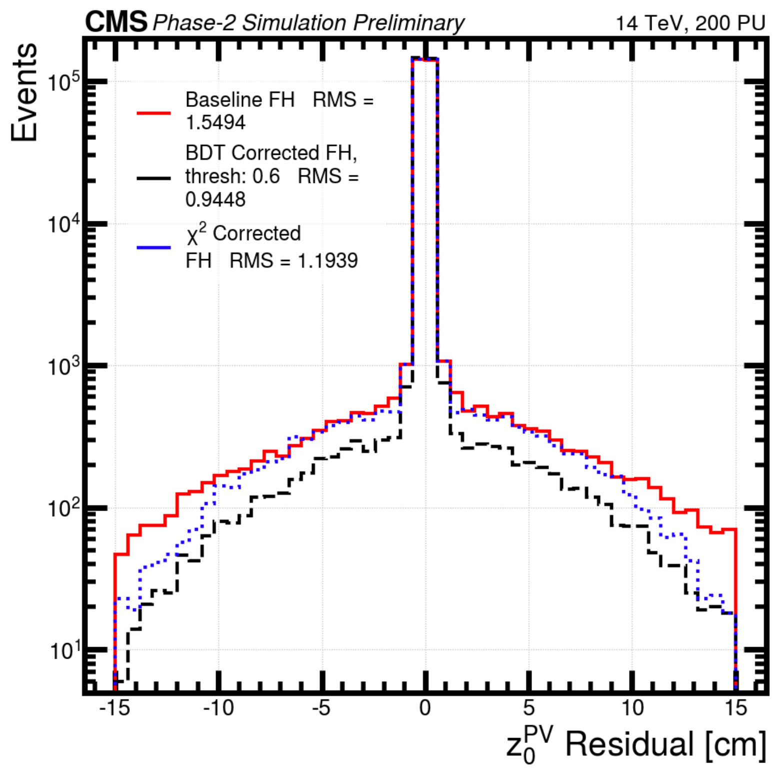
GTT floor plan

L1T Upgrades: Track Quality GBDT

In: tracker track properties

Out: likelihood track originated from true particle





Model	Python AUC	HLS AUC	Latency (clk)	LUT %	FF %	DSP %
NN	0.985	0.982	8	0.104	0.029	0.292
GBDT	0.986	0.981	3	0.140	0.027	0.0

VU9P
240 MHz

L1T Physics Reach: 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