Performing precision measurements and new physics searches at the HL-LHC with the upgraded CMS Level-1 Trigger

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On behalf of the CMS Collaboration

LLWI 2023

23rd February

Imperial College London

CMS

The High-Luminosity LHC (HL-LHC)

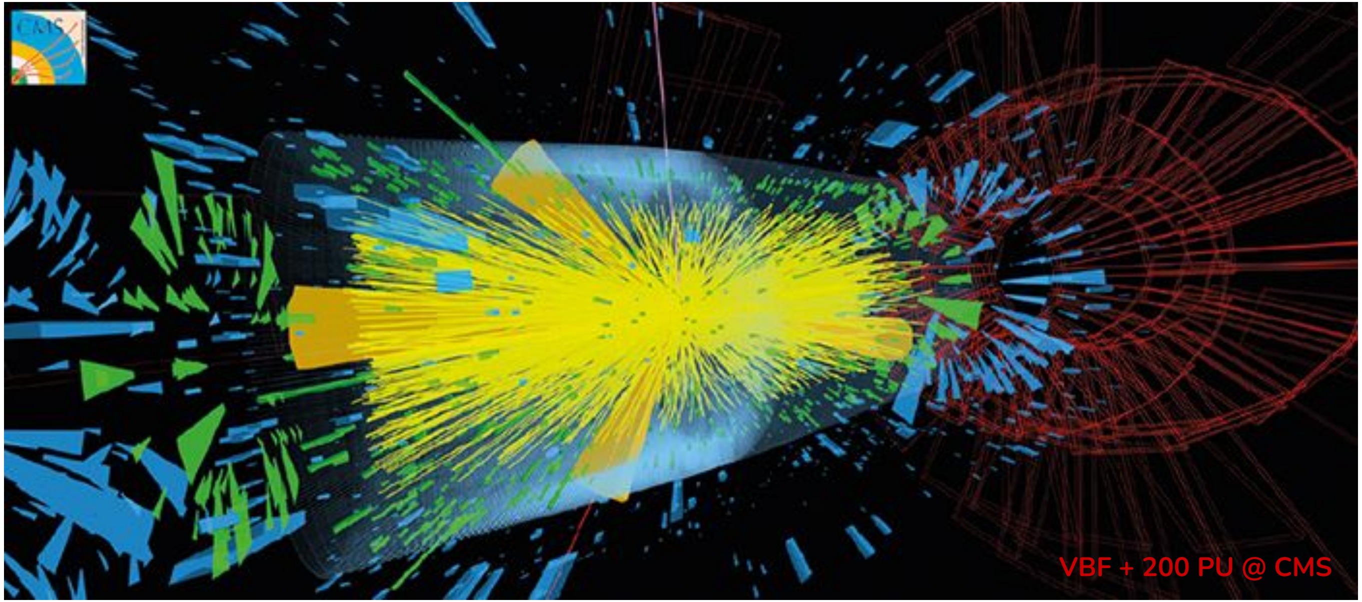
- The HL-LHC era is fast approaching: 2029-2040+
- Unprecedented statistics to probe the structure of the universe at the EWK scale
  - Precision measurements looking for small SM deviations
  - New physics searches in difficult phase space

Integrated Luminosity	*Instantaneous Luminosity*	*Pileup*
$\mathcal{L}_{\text{int}} = 4000\ \text{fb}^{-1}$	$\mathcal{L}_{\text{inst}} = 7.5 \times 10^{34}\ \text{cm}^{-2}\text{s}^{-1}$	200
(vs ~150 fb^{-1} now)	(vs ~2x10^{34} $\text{cm}^{-2}\text{s}^{-1}$ now)	(vs ~60 now)

- Efficiently collecting datasets within harsh HL-LHC collision environment will be a challenging task
- CMS is designing the data-processing hardware trigger: Phase-2 Level-1 Trigger (L1T)
- This talk will introduce Phase-2 L1T design and highlight physics performance

[L1T Technical Design Report]

An experimental challenge



- Expect up to 200 pileup (PU) interactions per bunch crossing
- Current Phase-1 L1T (allowed bandwidth = 100 kHz) operating at 200 PU → 4000 kHz for same physics acceptance
- Total allowed Phase-2 L1T bandwidth = 750 kHz
  - L1T system is upgraded to perform physics measurements and searches in this intense hadronic environment

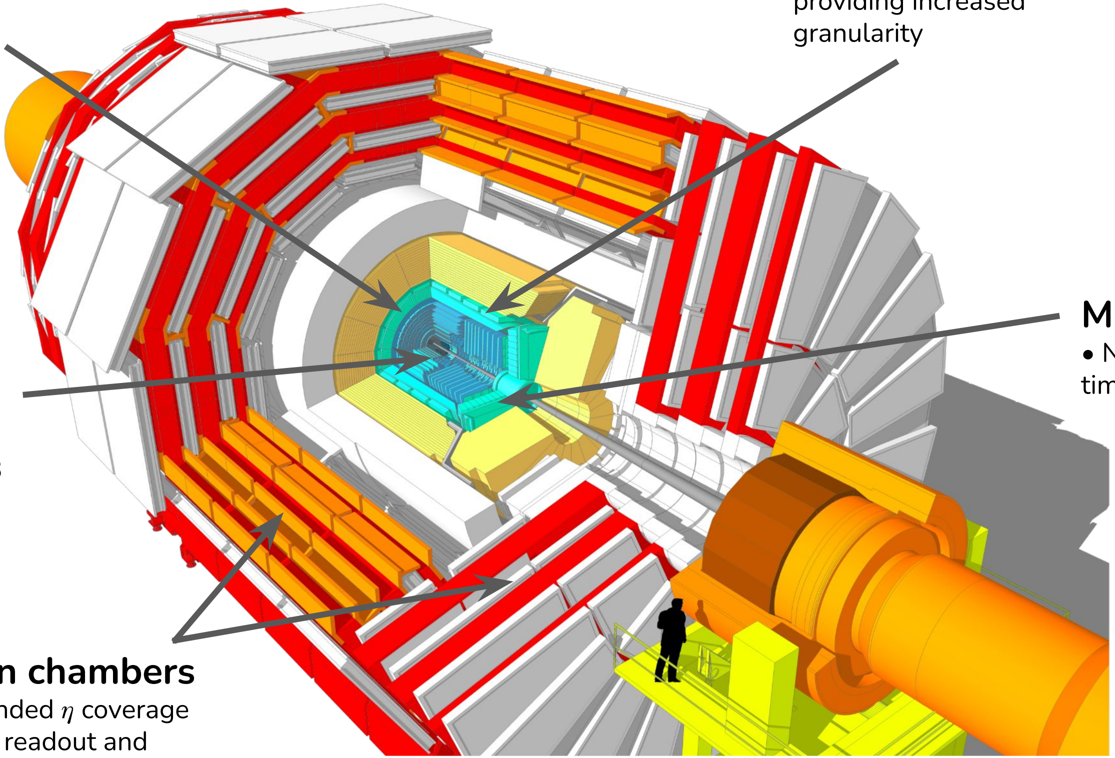
CMS Phase-2 detector

New High Granularity Calorimeter (HGCAL)

- Replacing current endcaps
- High lateral and longitudinal granularity
- Precise timing information

Barrel calorimeters

- New backend electronics providing increased granularity



MIP timing detector

- New detector offering precise timing information for PU rejection

Tracker

- Replace Si strips and pixels with increased granularity
- Extended coverage to η~3.8
- L1 track trigger

Muon chambers

- Extended η coverage
- New readout and backend electronics

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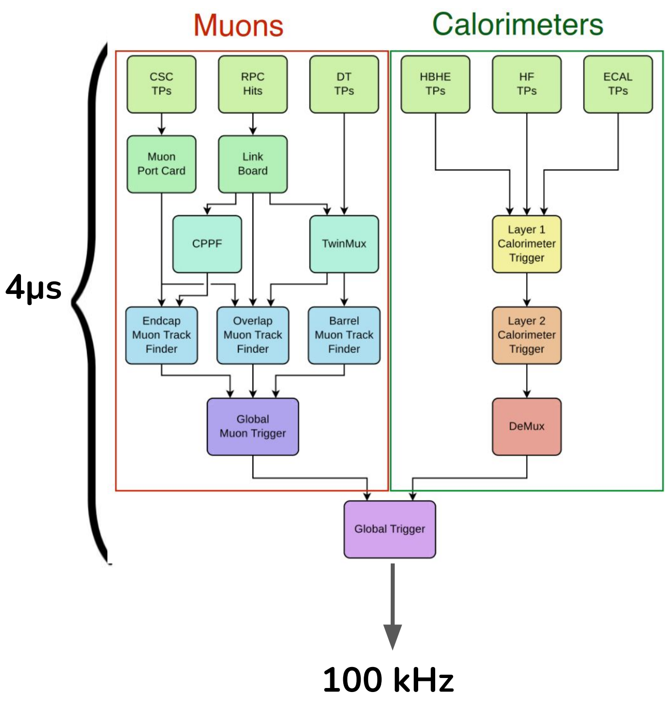
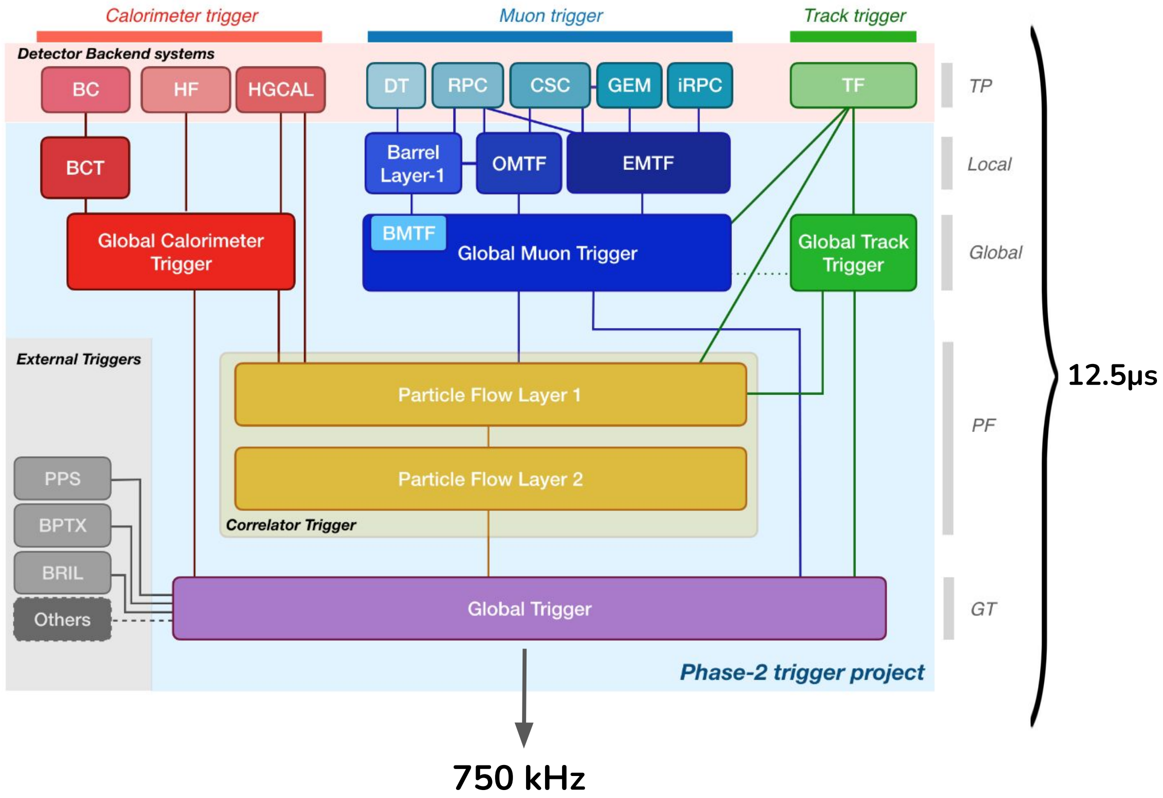
Phase-2 L1T architecture

Phase-1 (LHC Run 1, 2 & 3)



Phase-2 (HL-LHC)

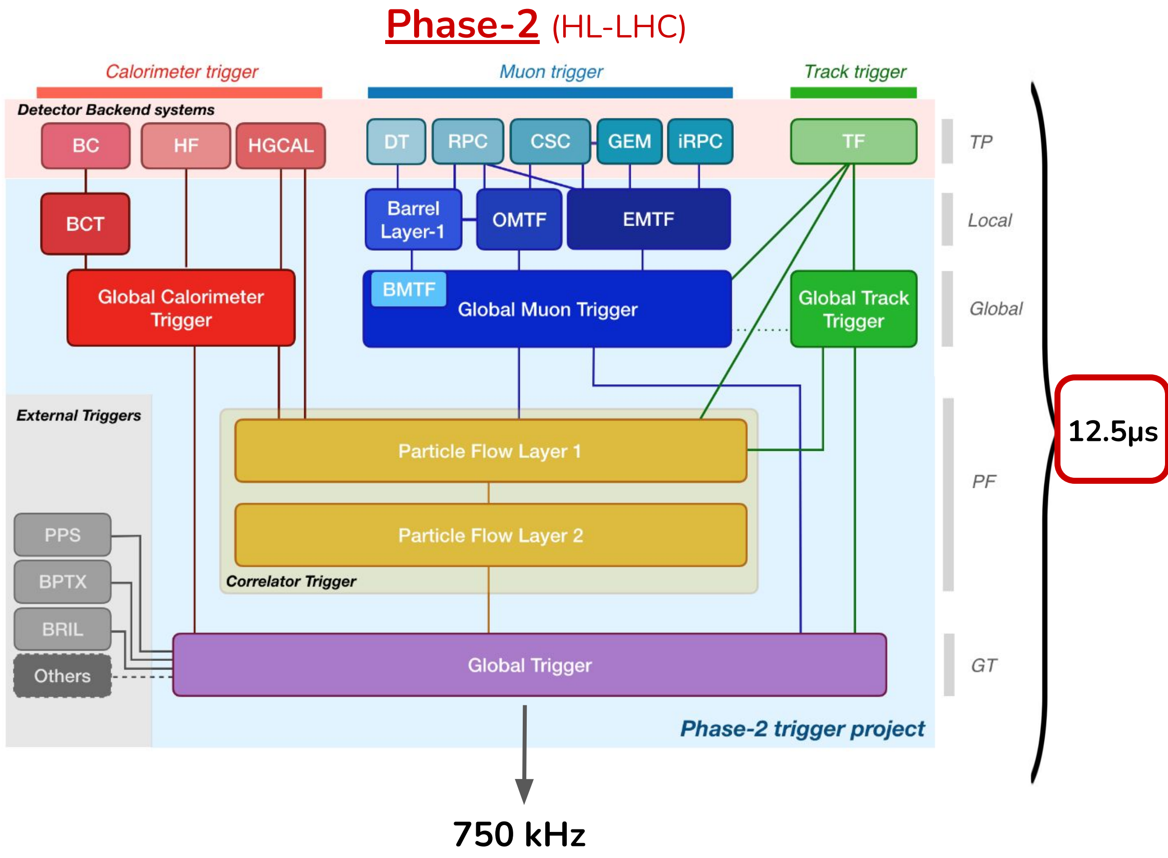


Phase-2 L1T architecture

Increased latency (12.5μs) allows us to include tracks and high-granularity information from the CMS sub-detectors!

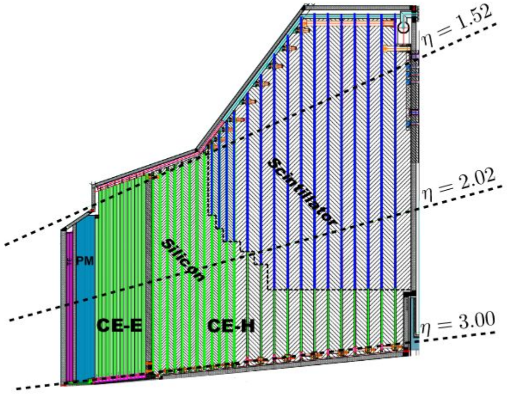
Increased bandwidth (750kHz)

State-of-the-art FPGA technology used extensively throughout



Increasing the physics acceptance

- Upgraded sub-detectors, expanded L1T architecture and improved FPGA resources
  - Technical design inspired by our experience from Phase-1 e.g. Time-Multiplexed Trigger
  - Phase-2 L1T is able to maintain the reference Run 2 + Run 3 physics acceptance even at 200 PU!
- Highly modular and flexible design enables new trigger strategies at Phase-2
  - We can extend physics acceptance and realise the full potential of HL-LHC runs
  - Both in terms of precision measurements and new physics searches
  - e.g. long-lived particle tagging using displaced objects, b tagging, ML discriminants, ...
- Rest of the talk will focus on new trigger strategies
  - Demonstrate expanded physics reach which Phase-2 L1T can achieve
  - Show expected performance using MC simulation with high PU
  - This is not an exhaustive list but a few highlights!



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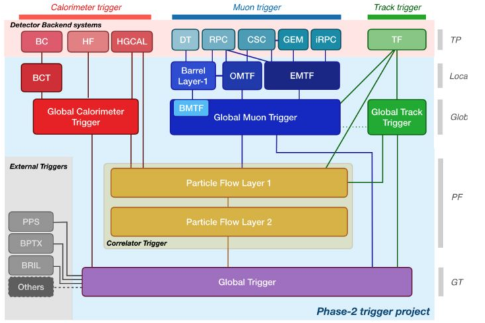
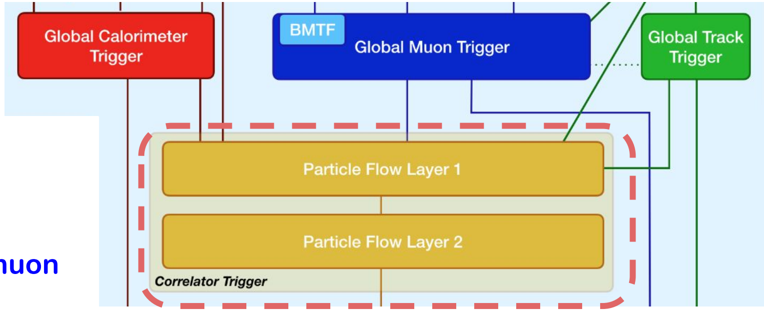
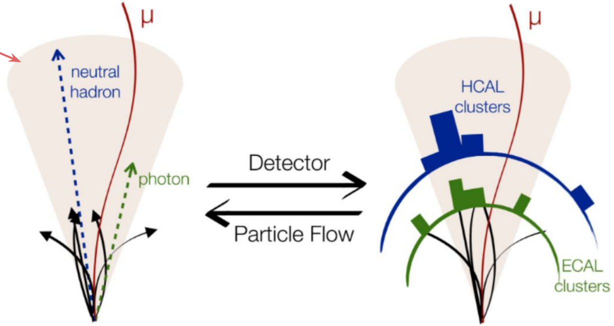
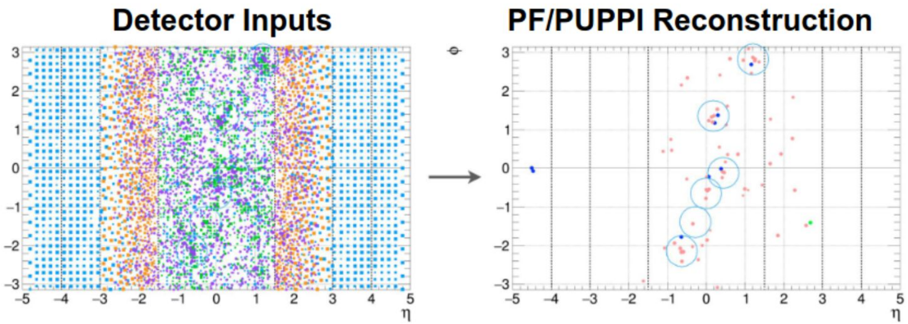


Particle flow (PF) algorithm



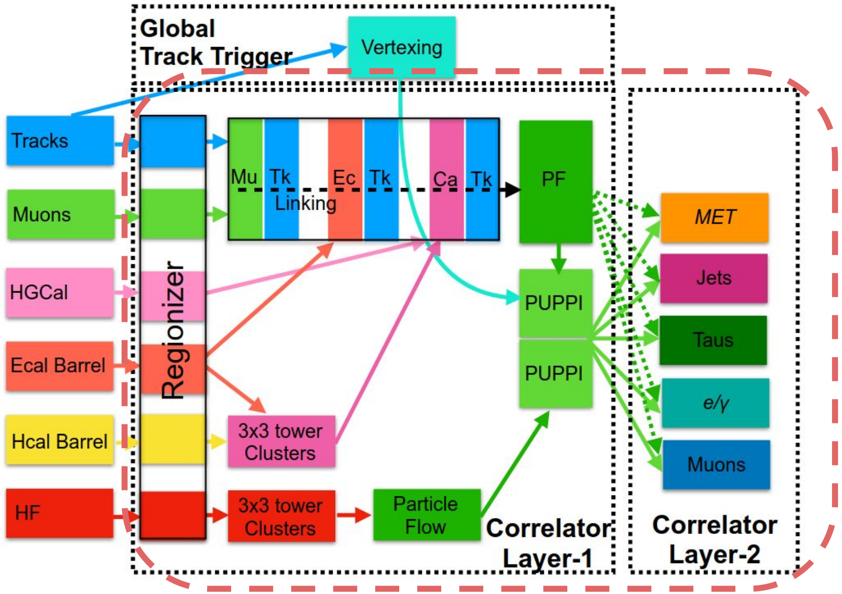
- Key aspect of Phase-2 L1T is the **Correlator Trigger**
  - Sophisticated algorithms building higher-level objects from **tracker**, **calo** + **muon**
  - Similar to algorithms used offline in Run 2 & 3
- **Layer 1: PF + PUPPI**
  - Produce PF candidates by matching calorimeter clusters and tracks
  - Pileup Per Particle Identification (PUPPI) for mitigating effect of PU
- **Layer 2**
  - Build and sort final trigger objects e.g. jets, τ_h, MET, HT, …
  - Apply additional ID and isolation

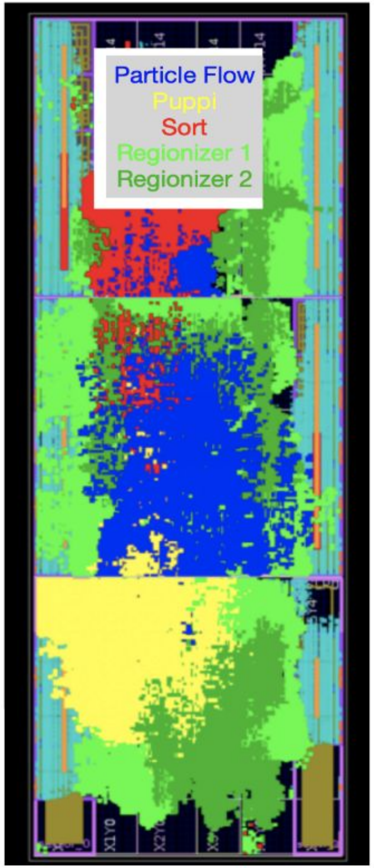




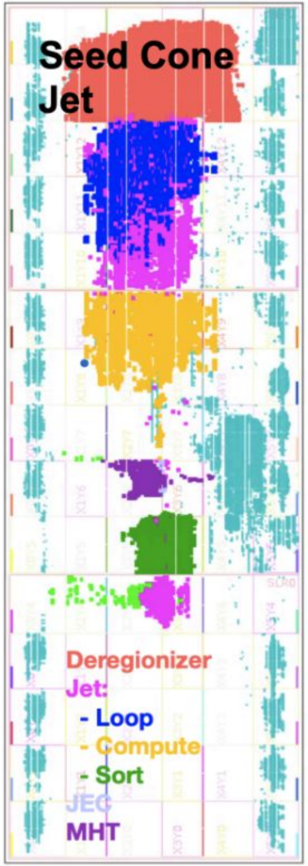
Particle flow firmware

- Algorithms have to fit within the resources of FPGAs
  - **Layer-1:** fully working PF+PUPPI on VU9P-2 which meets timing!
  - **Layer-2:** two well performing algorithms for jet finding. Also NNTaus + e/γ ID





Layer-1 Barrel

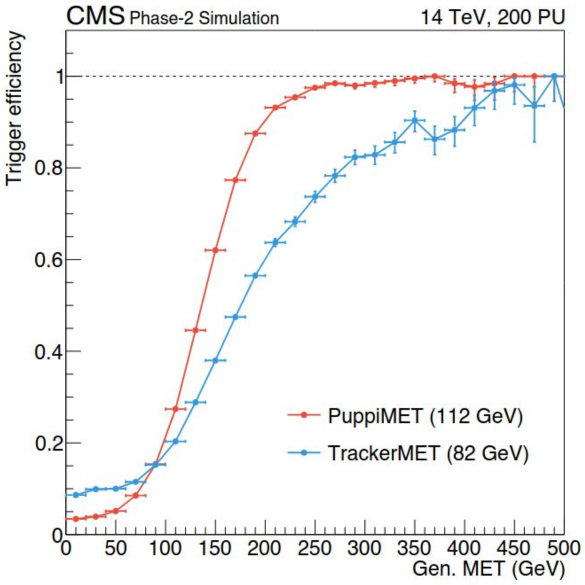


Layer-2 Jets

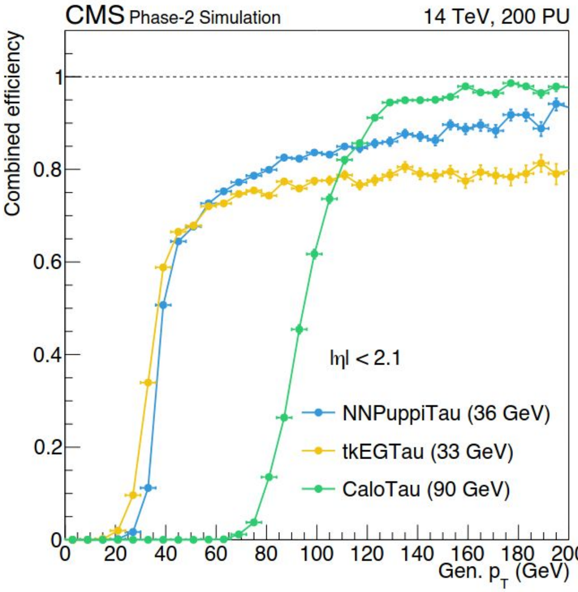
FPGA Floorplans

Particle flow impact

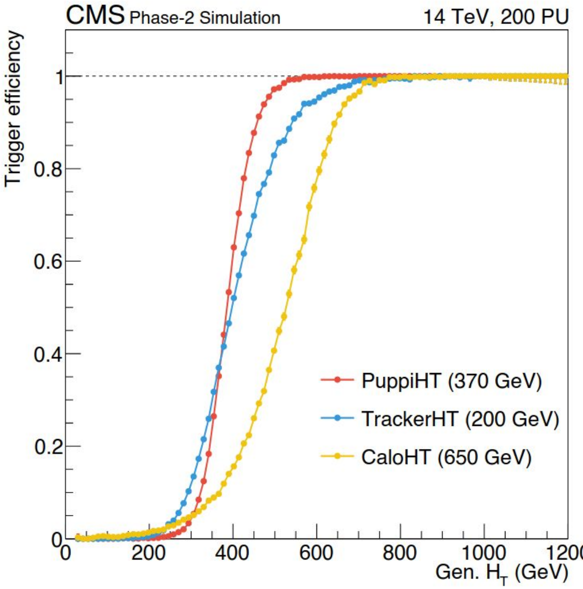
- Compare performance improvement using PF+PUPPI vs calorimeter-only/tracker-only objects



MET
(missing transverse energy)



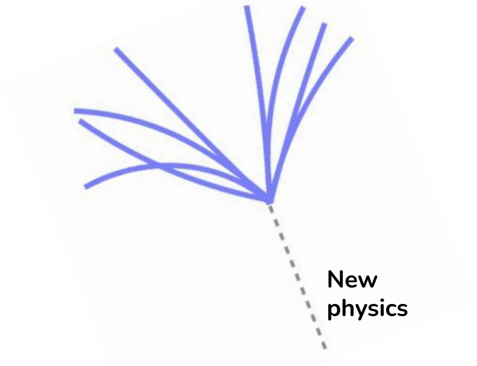
τ_h
(hadronically decaying tau-lepton)



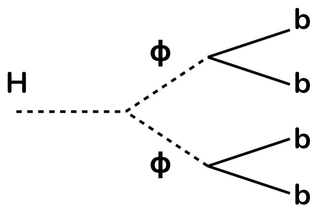
HT
(scalar sum of jet energy)

- PF+PUPPI allows for sharper and earlier turn-on curves → **Major gains in signal acceptance!**

L1 Track Trigger: long-lived particles

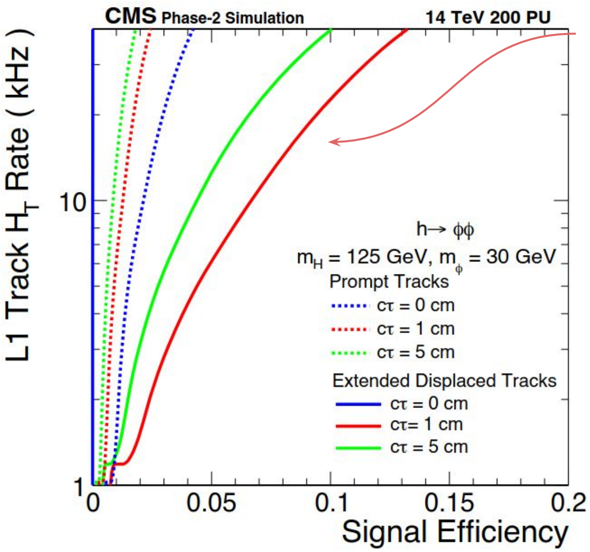


- Phase 2 L1T will introduce tracking information for the very first time
    - Target distinctive features of unconventional BSM signatures (long-lived particles)
- Extended track-trigger targets displaced tracks ~5cm from interaction vertex
- Example: **Displaced jets**

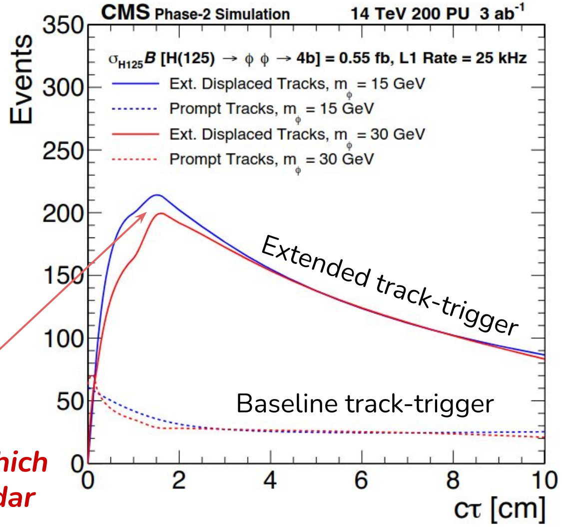


ϕ: Long-lived particle

- Lifetime, τ
- Mass, m_ϕ



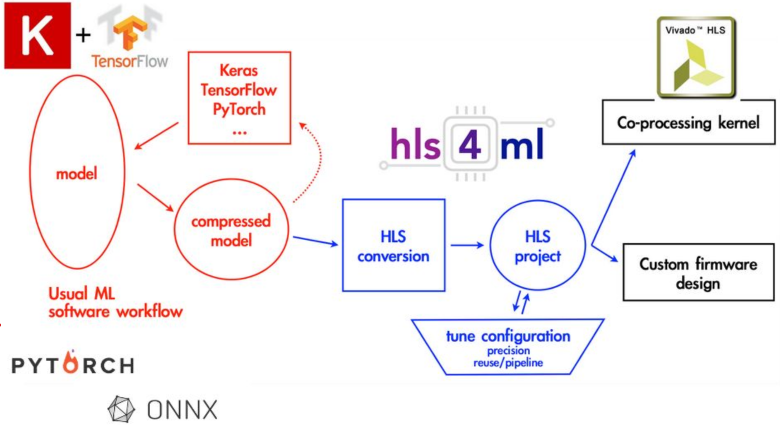
Large improvement in signal efficiency with extended track-trigger



Enough events to discover a signal which has been off our radar in Phase-1

Machine learning (ML) in the L1T

- Phase-2 L1T will use state-of-the-art FPGA boards throughout: XILINX VU13P
  - Providing 7.5x more resources than FPGAs in Phase-1 L1T
- New tools hls4ml and Conifer synthesize ML models into FPGA firmware
  - Translation packages for simple (python-based) models to HLS for use in firmware
  - Inference optimised for FPGA resources, throughput, latency
  - Enables physicists to enter world of firmware development!
- Tools have been used already to synthesize BDTs, NNs, DNNs, ...
  - Many Phase-2 L1T applications
  - e.g. PU rejection in PF clustering, vertexing, track-to-vertex association, object id, ...

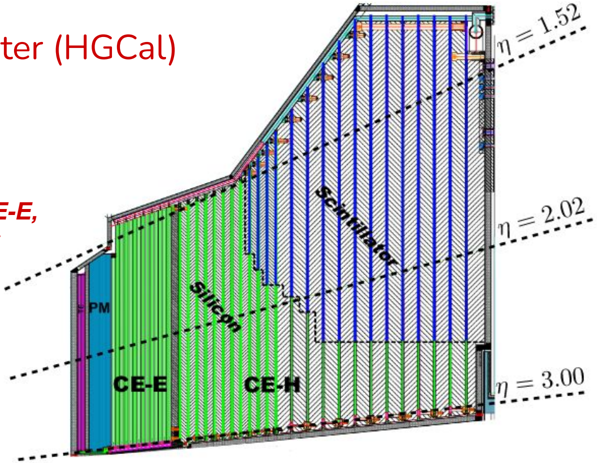


Crucial in our goal to extend our physics reach at the HL-LHC, even in the harsh 200 PU environment!

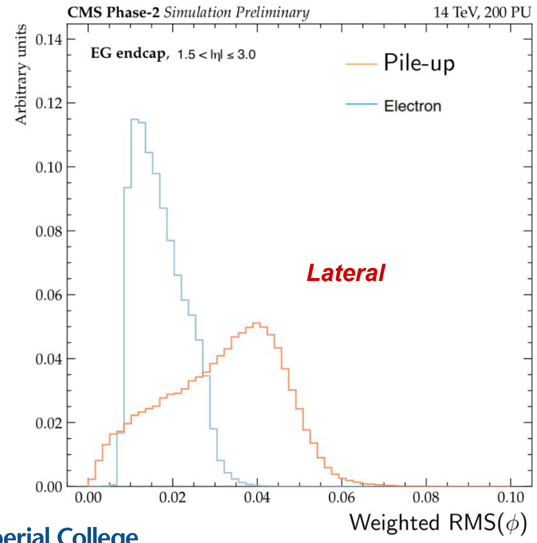
Electron/photon identification in the HGCal L1T

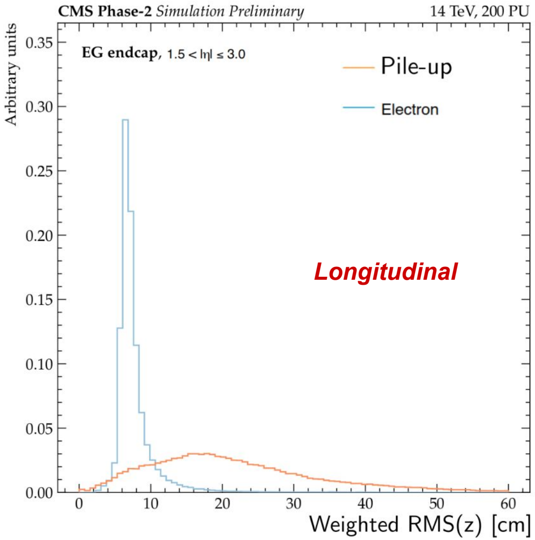
- Replace current CMS endcap calorimeters with the High Granularity Calorimeter (HGCal)
  - Excellent spatial resolution in both lateral and longitudinal dimensions
  - Use shower profiles for object identification in the L1T
  - Electron/photon vs PU
- Construct shower-shape variables in firmware using HGCAL trigger cells

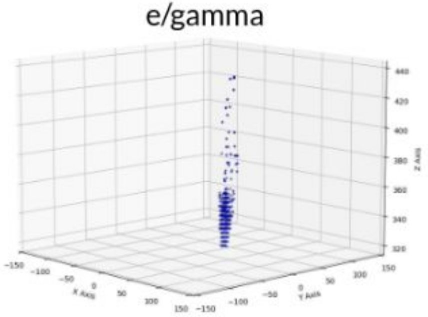
Every second layer in CE-E, with reduced granularity



[HGCal Technical Design Report]







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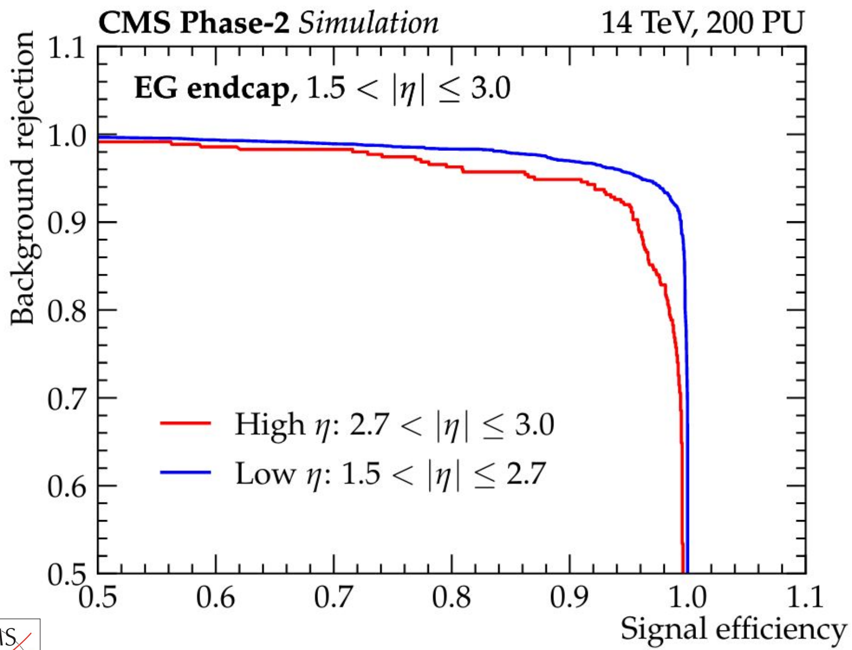
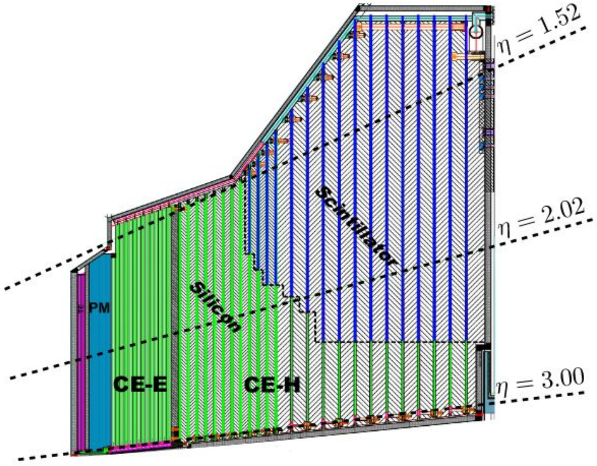
Electron/photon identification in the HGCal L1T

- Nine variables used to train a Boosted Decision Tree (BDT) classifier
  - Two η regions to account for evolution of shower shape variables vs η
  - Excellent discrimination between e/γ and PU

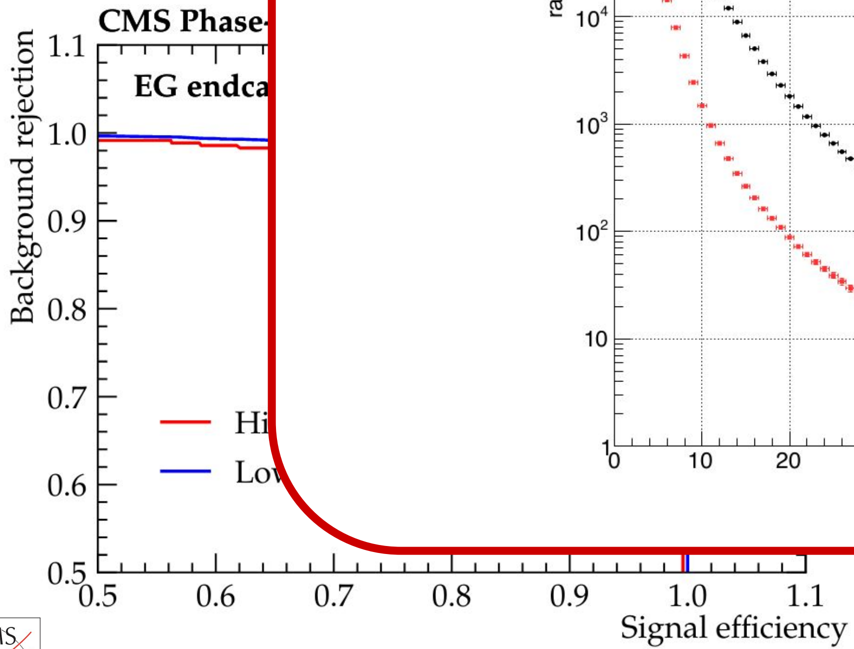




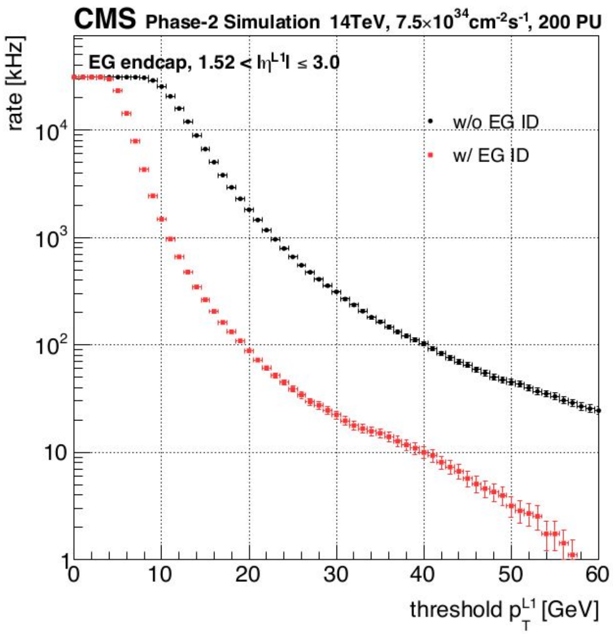
- Objects passing BDT threshold promoted to calo-only e/γ candidates
- BDT model successfully implemented in firmware

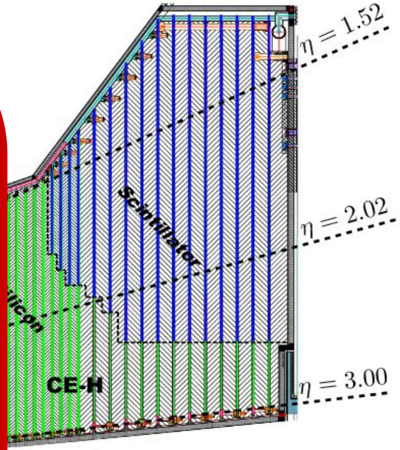
Electron/photon identification in the HGCal L1T

- Nine variables us
  - Two η reg
  - Excellent



ID BDT is crucial in reducing single e/γ trigger rates in the HGCAL!





to calo-only e/γ candidates

firmware

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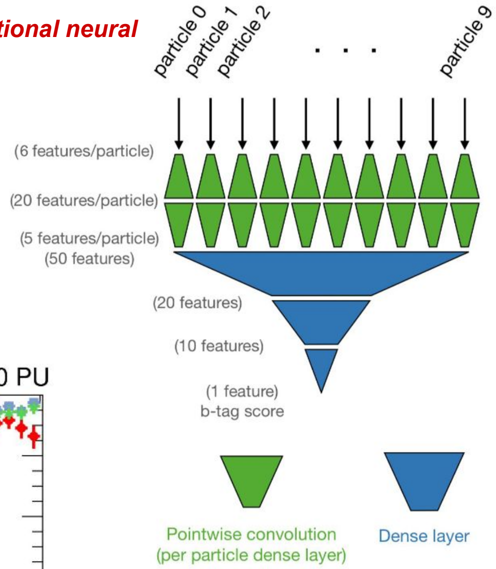
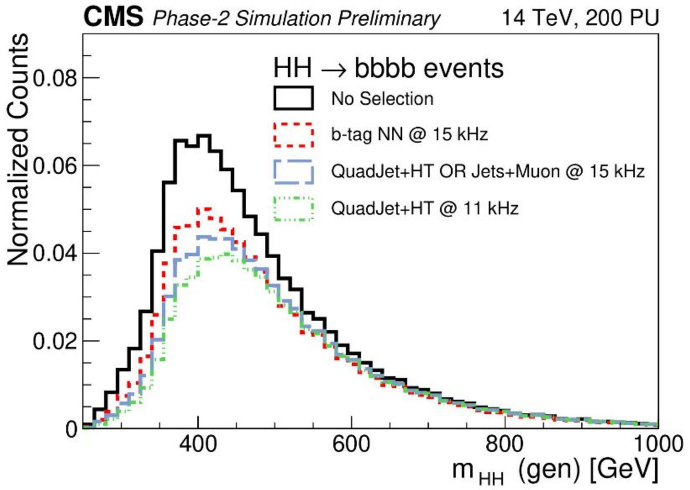
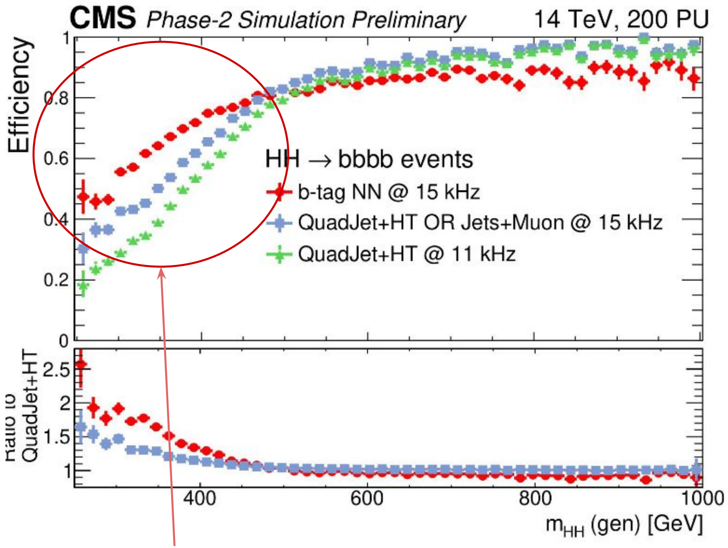
B tagging at L1T

- B tagging is made possible by PF+PUPPI algorithm in correlator trigger
  - CNN Input: 10 highest p_T PUPPI candidates within reconstructed jet
  - Tracking information (in particular d_z, d_{xy}) is crucial to identify displaced vertices
- Studied application in HH → bbbb

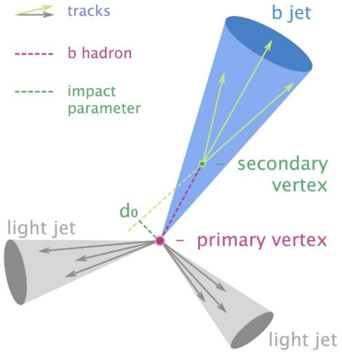
Convolutional neural network







12% signal efficiency increase over conventional triggers for m_{HH} < 500 GeV!



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[CMS DP-2022/021]

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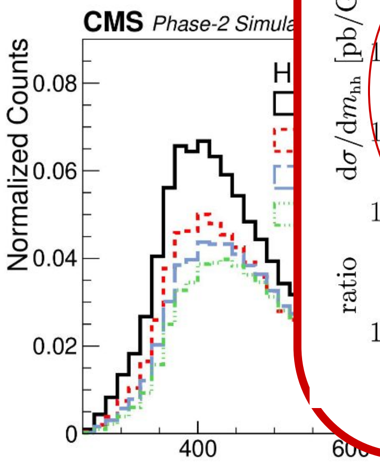
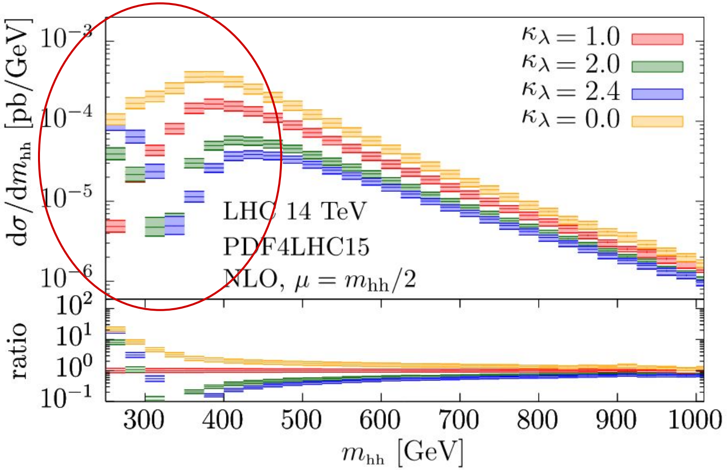
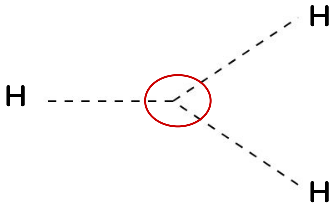
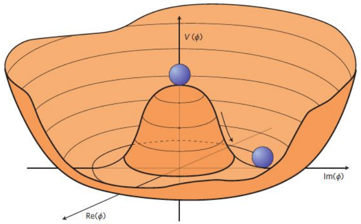


m_{HH} (gen) [GeV]

Phase space with enhanced sensitivity to Higgs boson self-coupling!







m_{HH} (gen) [GeV]

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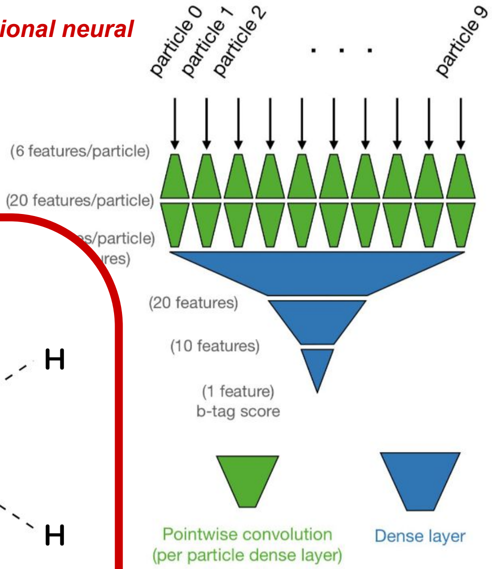
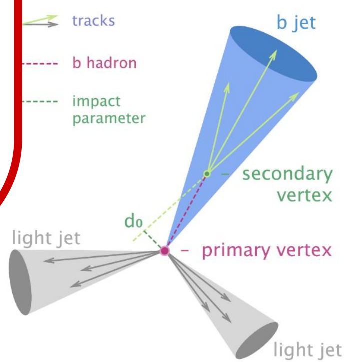
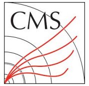
Convolutional neural network





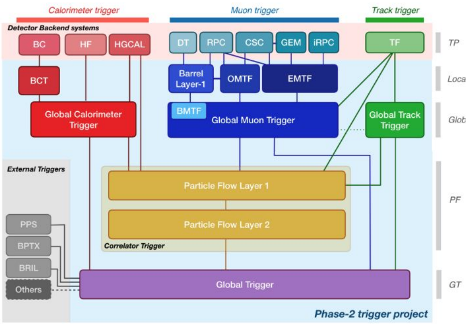


[CMS DP-2022/021]

Summary

- HL-LHC era provides exciting experimental challenge with high physics reward!
- CMS experiment will undergo a vast upgrade programme to realise HL-LHC potential
- Phase-2 L1T will increase physics acceptance with new trigger strategies
  - Benefit from additional detector information (tracker, HGCAL), expanded L1T architecture, improved FPGA resources
  - Machine learning techniques made possible due to new synthesis tools
- Presented a number of highlights:
  - Particle-flow algorithm in correlator trigger
  - Long-lived particle tagging with displaced tracks
  - Electron/photon identification in HGCAL with ML
  - B tagging using CNN
  - This is by no means an exhaustive list!

CMS will have a fruitful HL-LHC era thanks to the Phase-2 L1T!



Summary

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- CMS experiment will undergo a vast upgrade programme to realise HL-LHC potential
- Phase-2 L1T will
  - Benefit from a
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  - Machine learn
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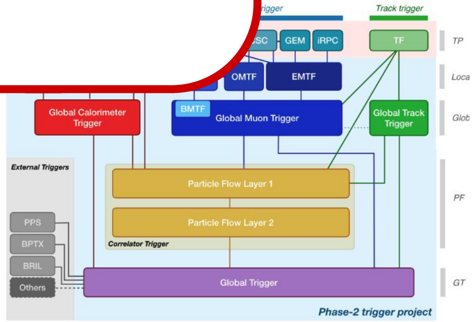
Thanks for listening!

Any questions?

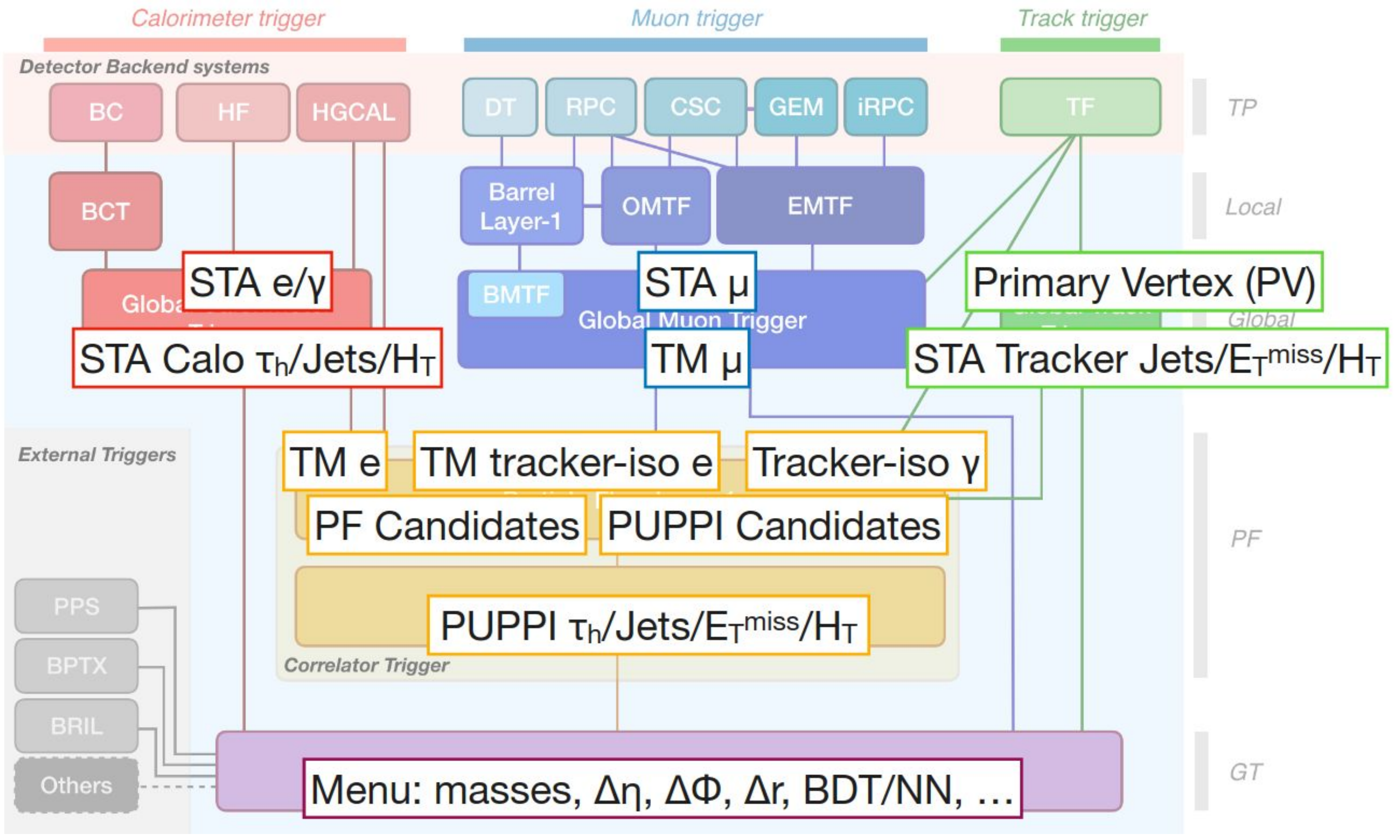
itful HL-LHC era
-2 L1T!



Back-up

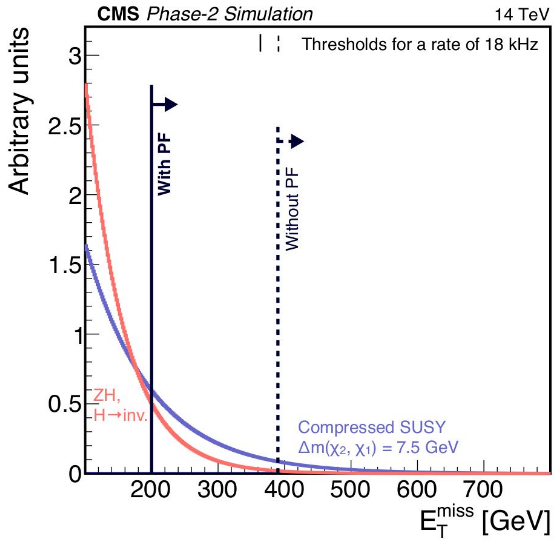
Phase-2 L1T objects

[Figure taken from B. Radburn-Smith slides at ICHEP]

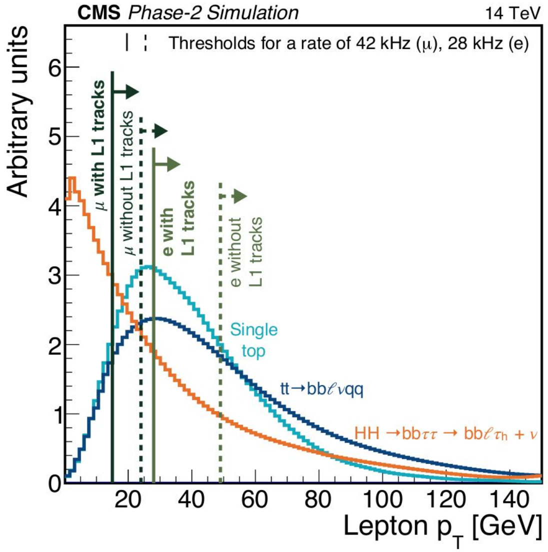


Threshold improvement with PF

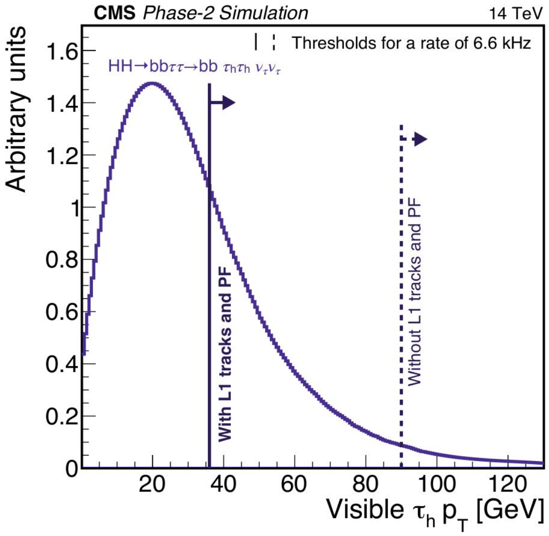
- For fixed L1T rate using PF allows us to dramatically reduced thresholds (increase signal acceptance)
  - Impact shown for benchmark signal processes



MET
(missing transverse energy)



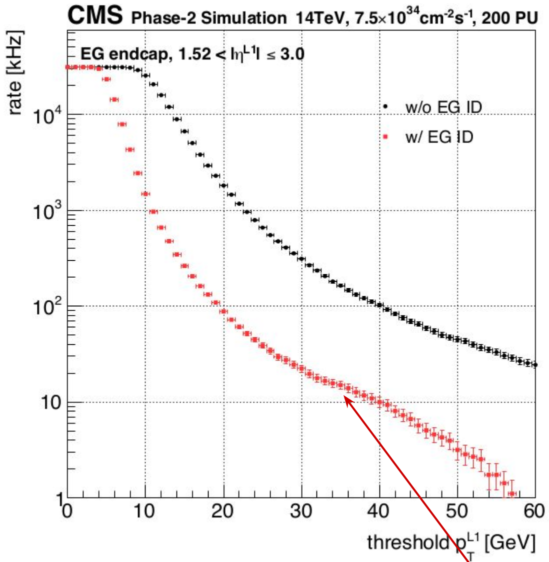
Single-lepton



Single-tau

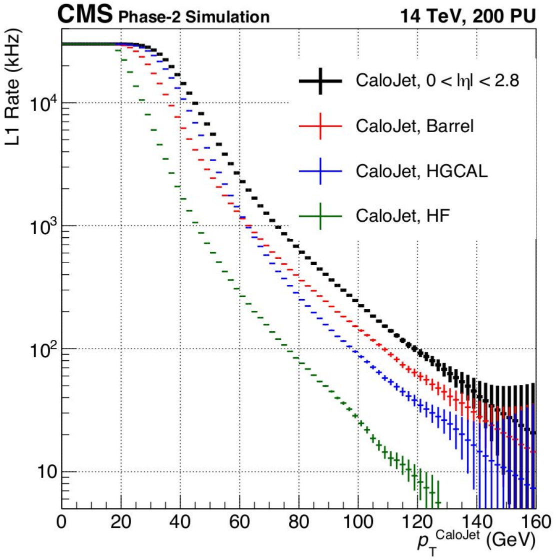
Trigger rates at Phase-2

- Total rate calculated using appropriate background MC samples with same machine conditions as signal
  - Plotted as a function of threshold applied on L1T object

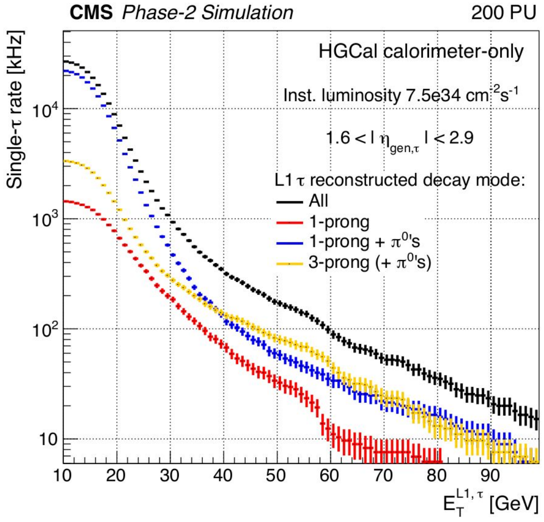


e/γ in the HGCAL

Dramatic reduction in rate when applying the e/γ ID!

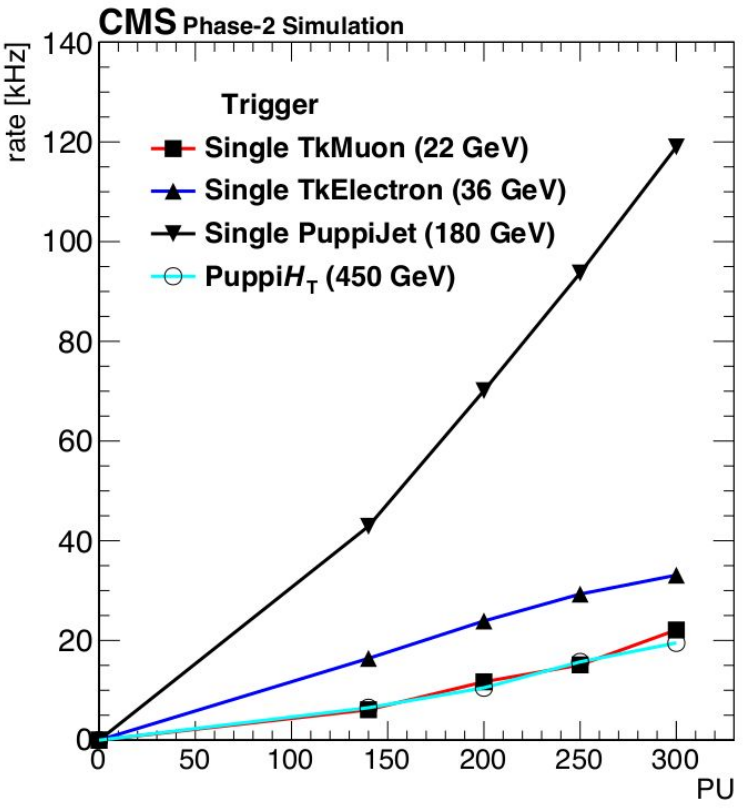


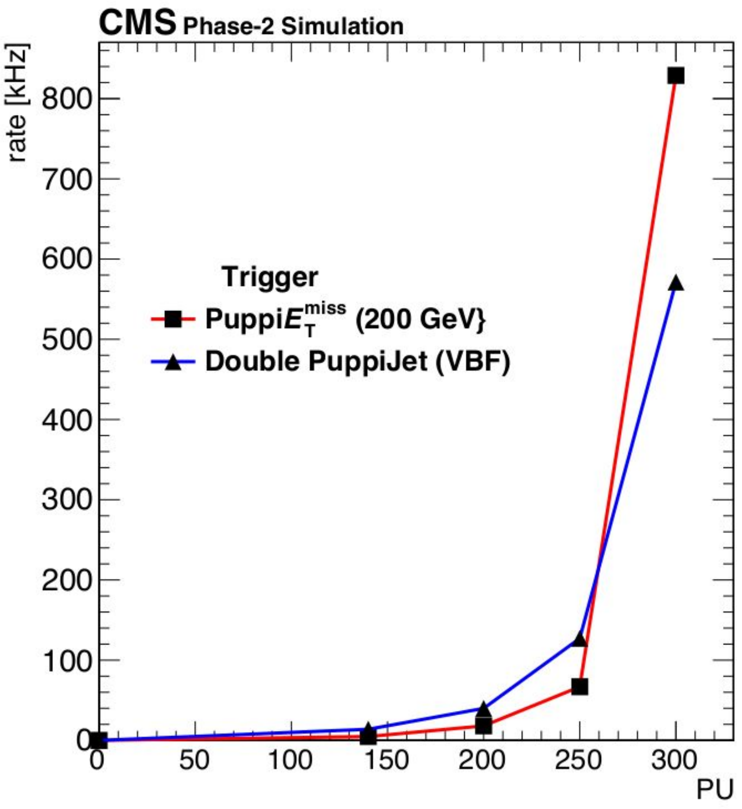
Calo-Jet



Single-tau

Trigger rate evolution with PU





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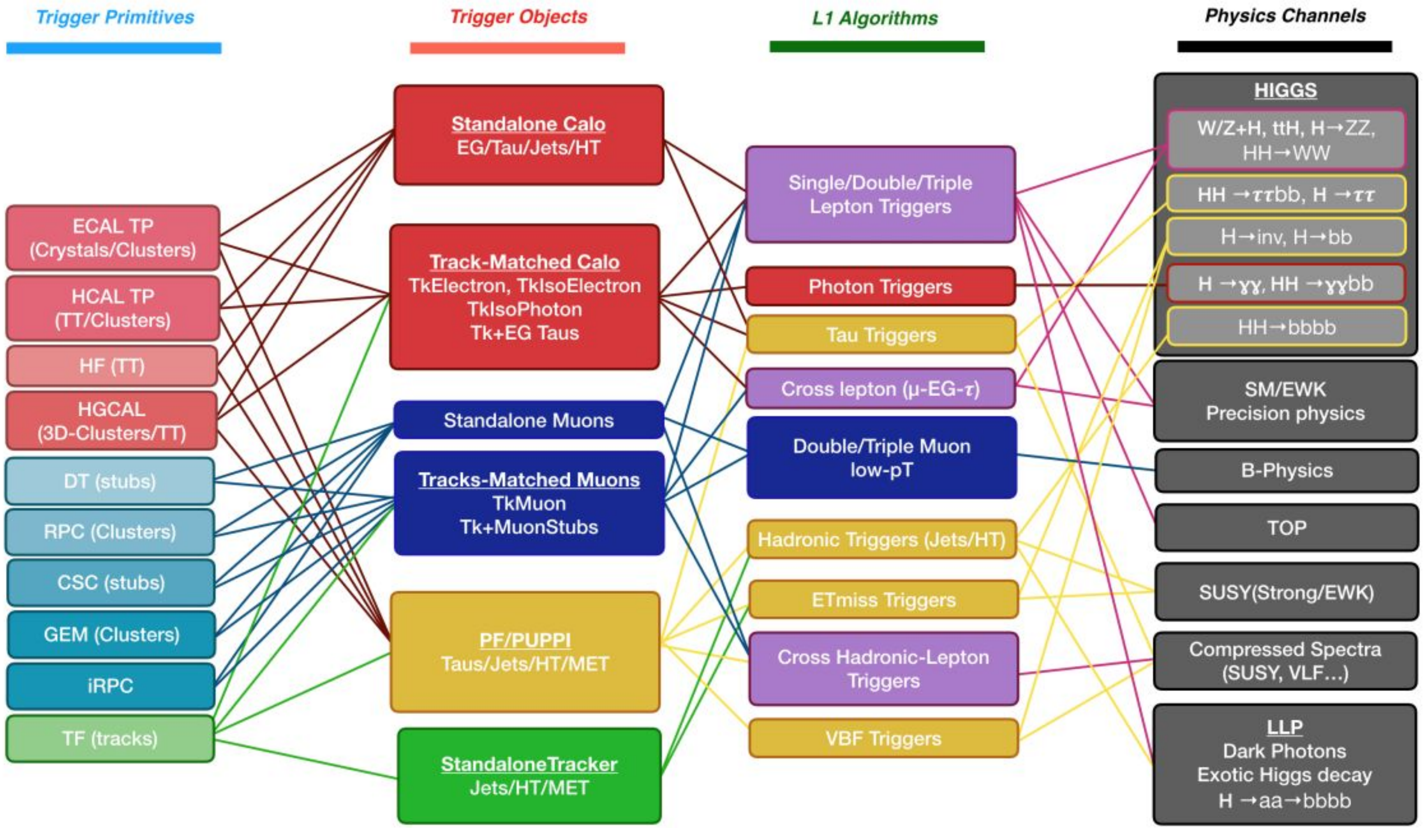
Trigger primitives to physics channels



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Phase-2 L1T menu (standard physics triggers)

L1 Trigger seeds	Offline Threshold(s) at 90% or 95% (50%) [GeV]	Rate $\langle PU \rangle = 200$ [kHz]	Additional Requirement(s) [cm, GeV]	Objects plateau efficiency [%]
Single/Double/Triple Lepton (electron, muon) seeds				
Single TkMuon	22	12	$\|\eta\| < 2.4$	95
Double TkMuon	15,7	1	$\|\eta\| < 2.4, \Delta z < 1$	95
Triple TkMuon	5,3,3	16	$\|\eta\| < 2.4, \Delta z < 1$	95
Single TkElectron	36	24	$\|\eta\| < 2.4$	93
Single TkIsoElectron	28	28	$\|\eta\| < 2.4$	93
TkIsoElectron-StaEG	22, 12	36	$\|\eta\| < 2.4$	93, 99
Double TkElectron	25, 12	4	$\|\eta\| < 2.4$	93
Single StaEG	51	25	$\|\eta\| < 2.4$	99
Double StaEG	37,24	5	$\|\eta\| < 2.4$	99
Photon seeds				
Single TkIsoPhoton	36	43	$\|\eta\| < 2.4$	97
Double TkIsoPhoton	22, 12	50	$\|\eta\| < 2.4$	97
Taus seeds				
Single CaloTau	150(119)	21	$\|\eta\| < 2.1$	99
Double CaloTau	90,90(69,69)	25	$\|\eta\| < 2.1, \Delta R > 0.5$	99
Double PuppiTau	52,52(36,36)	7	$\|\eta\| < 2.1, \Delta R > 0.5$	90
Hadronic seeds (jets, H_T)				
Single PuppiJet	180	70	$\|\eta\| < 2.4$	100
Double PuppiJet	112,112	71	$\|\eta\| < 2.4, \Delta\eta < 1.6$	100
PuppiH_T	450(377)	11	jets: $\|\eta\| < 2.4, p_T > 30$	100
QuadPuppiJets-PuppiH_T	70,55,40,40,400(328)	9	jets: $\|\eta\| < 2.4, p_T > 30$	100,100
E_T^{miss} seeds				
PuppiE_T^{miss}	200(128)	18		100
Cross Lepton seeds				
TkMuon-TkIsoElectron	7,20	1	$\|\eta\| < 2.4, \Delta z < 1$	95, 93
TkMuon-TkElectron	7,23	3	$\|\eta\| < 2.4, \Delta z < 1$	95, 93
TkElectron-TkMuon	10,20	1	$\|\eta\| < 2.4, \Delta z < 1$	93, 95
TkMuon-DoubleTkElectron	6,17,17	0.1	$\|\eta\| < 2.4, \Delta z < 1$	95, 93
DoubleTkMuon-TkElectron	5,5,9	4	$\|\eta\| < 2.4, \Delta z < 1$	95, 93
PuppiTau-TkMuon	36(27),18	2	$\|\eta\| < 2.1, \Delta z < 1$	90, 95
TkIsoElectron-PuppiTau	22,39(29)	13	$\|\eta\| < 2.1, \Delta z < 1$ $\Delta R > 0.3$	93, 90

L1 Trigger seeds	Offline Threshold(s) at 90% or 95% (50%) [GeV]	Rate $\langle PU \rangle = 200$ [kHz]	Additional Requirement(s) [cm, GeV]	Objects plateau efficiency [%]
Cross Hadronic-Lepton seeds				
TkMuon-PuppiH_T	6,320(250)	4	$\|\eta\| < 2.4, \Delta z < 1$	95,100
TkMuon-DoublePuppiJet	12,40,40	10	$\|\eta\| < 2.4, \Delta R_{j\mu} < 0.4,$ $\Delta\eta_{jj} < 1.6, \Delta z < 1$	95,100
TkMuon-PuppiJet-PuppiE_T^{miss}	3,100,120(55)	14	$\|\eta\| < 1.5, \|\eta\| < 2.4,$ $\Delta z < 1$	95,100, 100
DoubleTkMuon-PuppiJet-PuppiE_T^{miss}	3,3,60,130(64)	4	$\|\eta\| < 2.4, \Delta z < 1$	95,100, 100
DoubleTkMuon-PuppiH_T	3,3,300(231)	2	$\|\eta\| < 2.4, \Delta z < 1$	95,100
DoubleTkElectron-PuppiH_T	10,10,400(328)	0.9	$\|\eta\| < 2.4, \Delta z < 1$	93,100
TkIsoElectron-PuppiH_T	26,190(124)	9	$\|\eta\| < 2.4, \Delta z < 1$	93,100
TkElectron-PuppiJet	28,40	34	$\|\eta\| < 2.1, \|\eta\| < 2.4,$ $\Delta R > 0.3, \Delta z < 1$	93,100
PuppiTau-PuppiE_T^{miss}	55(38),190(118)	4	$\|\eta\| < 2.1$	90,100
VBF seeds				
Double PuppiJets	160,35	40	$\|\eta\| < 5, m_{jj} > 620$	100
B-physics seeds				
Double TkMuon	2,2	12	$\|\eta\| < 1.5, \Delta R < 1.4,$ $q1 * q2 < 0, \Delta z < 1$	95
Double TkMuon	4,4	21	$\|\eta\| < 2.4, \Delta R < 1.2$ $q1 * q2 < 0, \Delta z < 1$	95
Double TkMuon	4.5,4	10	$\|\eta\| < 2.0, 7 < m_{\mu\mu} < 18,$ $q1 * q2 < 0, \Delta z < 1$	95
Triple TkMuon	5,3,2	7	$0 < m_{\mu 5 \mu 3, q1*q2<0} < 9$ $\|\eta\| < 2.4, \Delta z < 1$	95
Triple TkMuon	5,3,2.5	6	$5 < m_{\mu 5 \mu 2.5, q1*q2<0} < 17$ $\|\eta\| < 2.4, \Delta z < 1$	95
Rate for above Trigger seeds				346
Total Level-1 Menu Rate (+30%)				**450**

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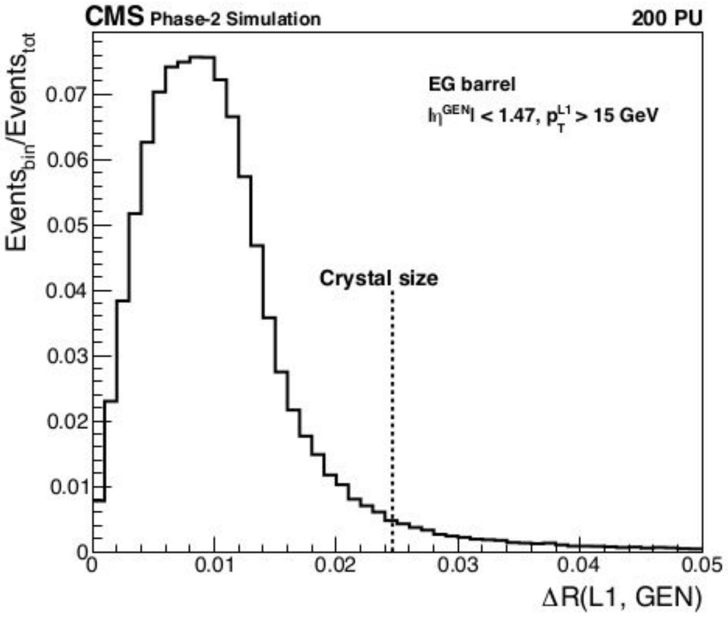
Phase-2 L1T menu (extended physics triggers)

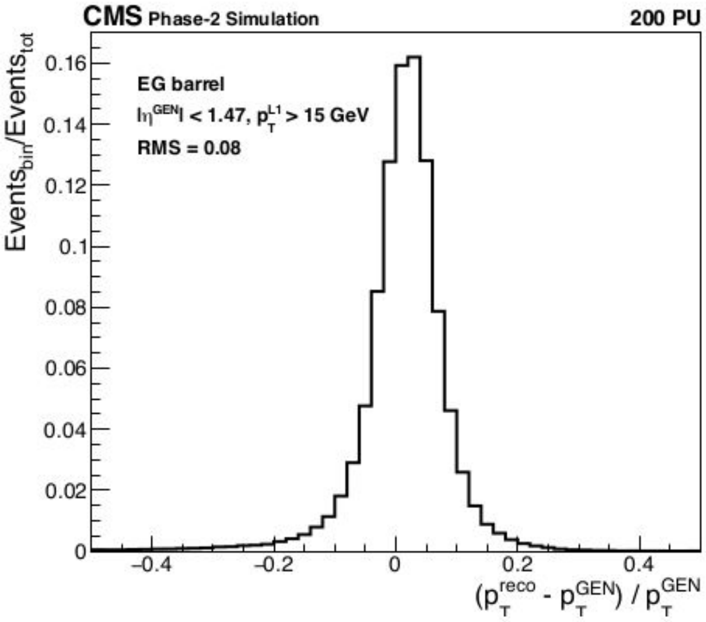
- Standard physics triggers will be supplemented with new trigger algorithms to extend physics acceptance

L1 Triggers	Online Threshold(s) (* for Offline) [GeV]	Rate $\langle PU \rangle = 200$ [kHz]	Additional Requirement(s) [cm, GeV, ns]
Single StaEG ext. eta	36 *	12	$2.4 < \lvert\eta\rvert < 3.0$
Muon-Jet (Cat0+Cat1)	2, 2, 0.5	27	$\lvert\eta\rvert < 2.4, \Delta R < 1, \Delta z < 1, m_{\mu-jet} < 3$
Tracker B_s^0	12	15	$\lvert\eta\rvert < 2.4, \Delta z < 0.6, 5.0 < m_{B_s^0} < 5.8$
Displaced Single Muon	22	14	$\lvert\eta\rvert < 0.9$ $(1.2 < \lvert\eta\rvert < 2.4)$, $d_{xy} > 75(20)$
Displaced Double Muon	20, 15	2	$\lvert\eta\rvert < 0.9$ $(1.2 < \lvert\eta\rvert < 2.4)$
Displaced Tracker H_T	248(153) *	20	jets: $\lvert\eta\rvert < 2.0, p_T > 5$
Displaced Calo-Jet	40	20	$\lvert\eta\rvert < 1.44, \Delta t > 1$
Total rate for above triggers			110 kHz

Increased granularity in the barrel calorimeter

- Increased latency of Phase-2 L1T allows for more granular information from CMS sub-detectors
  - Upgraded read-out electronics for individual crystal information in the ECAL (25x higher granularity)
  - Extremely useful for spatial resolution and PU mitigation in energy resolution of e/gamma objects



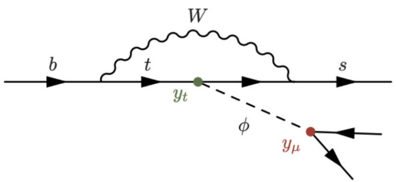


Displaced Muons

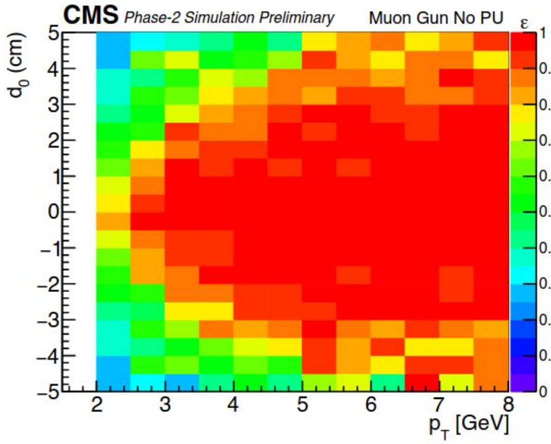
- Extended track trigger adds few modules to baseline track-trigger to target large displacements
  - E.g. adding track impact parameter information allows for good displaced track efficiency

- Another physics example is displaced muons

$$B \to X_s \phi$$
$$\hookrightarrow \mu\mu$$



Signal is displaced di-muon resonance



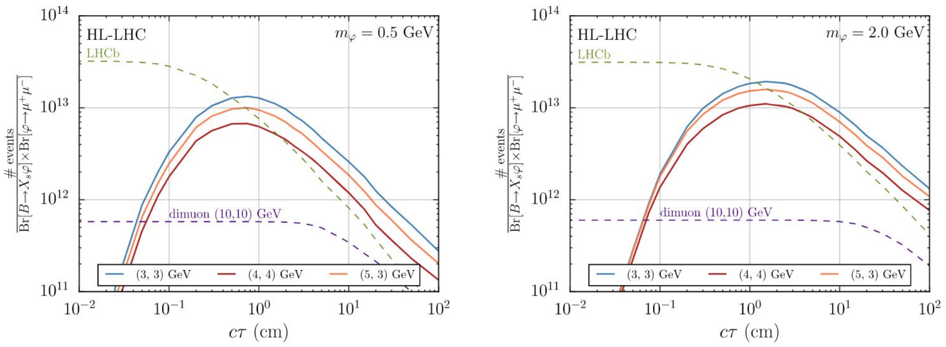


FIG. 7. Projected yield for the CMS displaced dimuon vertex trigger for three different choices of the muon p_T threshold (solid), compared with LHCb (dashed green) and a hypothetical future ATLAS/CMS trigger on two standalone muons with $p_T > 10$ GeV each (dashed purple).

[Phys Rev D 101 032003]

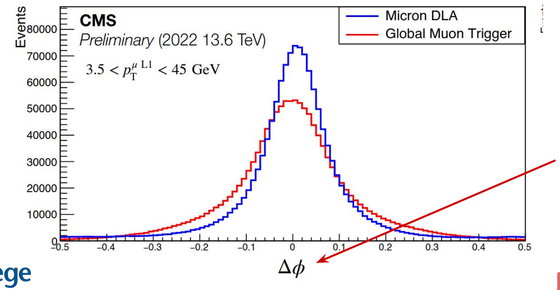
L1 scouting @ 40MHz

- Data scouting idea originated for the High-Level Trigger: event-volume reduction rather than event-filtering
- Read out L1T objects with reduced information at full bunch crossing rate (=40 MHz) and analyse!
  - Primarily can use for data monitoring, diagnostics, luminosity measurements
  - But also use to look for signatures which would evade: L1T -> HLT -> Offline chain e.g:

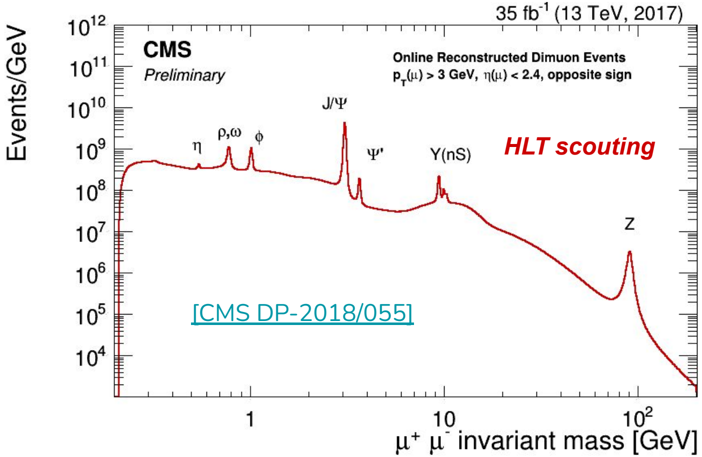
Large irreducible backgrounds	***Complex (combinatorial) signatures***	***Time-correlated signal across BX***
i.e. narrow resonances *Too frequent for nominal L1T menu*	*Algorithms do not fit within L1T latency and resource budget*	*e.g. slow or long-lived BSM*

- Dedicated scouting DAQ hardware (FPGA)
  - 40 MHz acquisition demonstrated successfully for muons (GMT) at end of Run 2, and calorimeter information in Run 3
- Sensitivity limited by quality of L1T objects e.g. resolution
  - Investigated use of ML (neural-network) to *correct* object properties

[CMS DP-2022/066]



$\Delta\Phi = \Phi_{true} - \Phi_{L1T}$



[CMS DP-2018/055]

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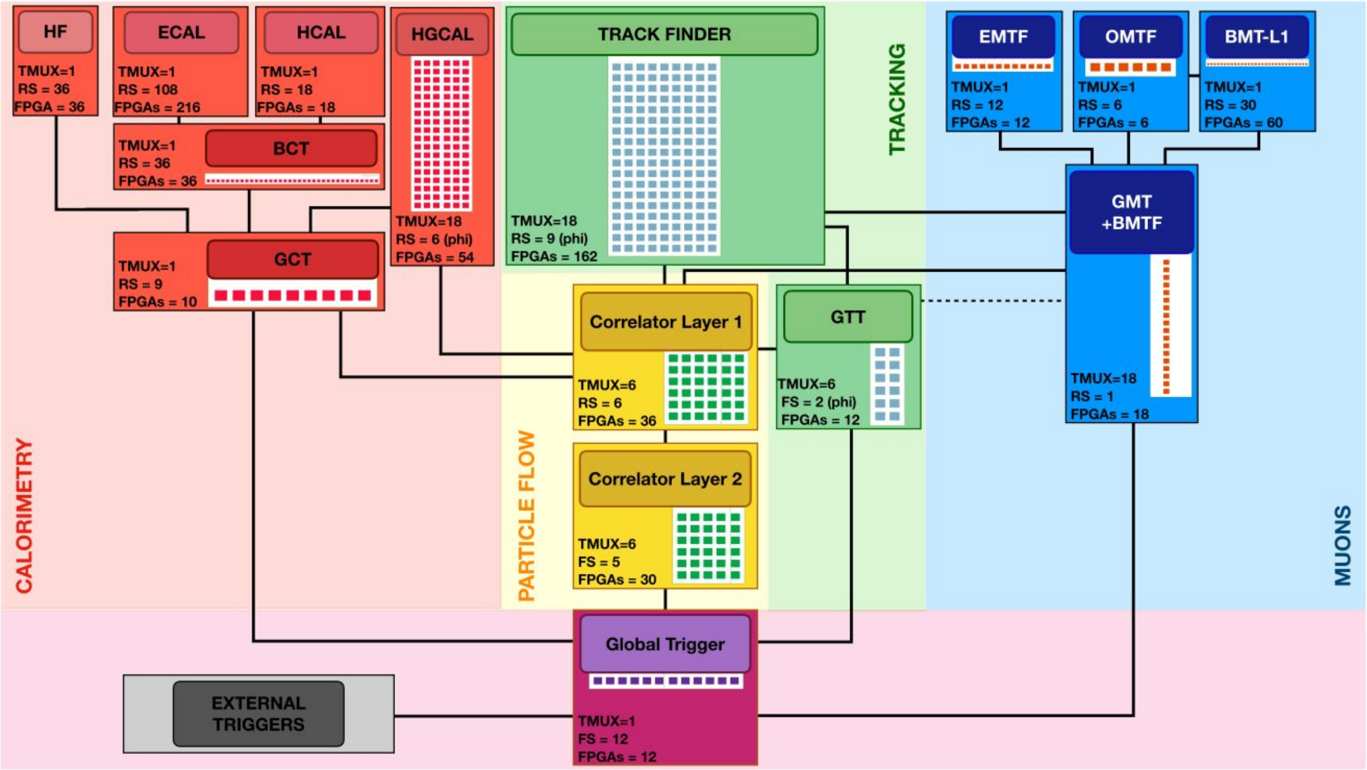
Phase-2 L1T design

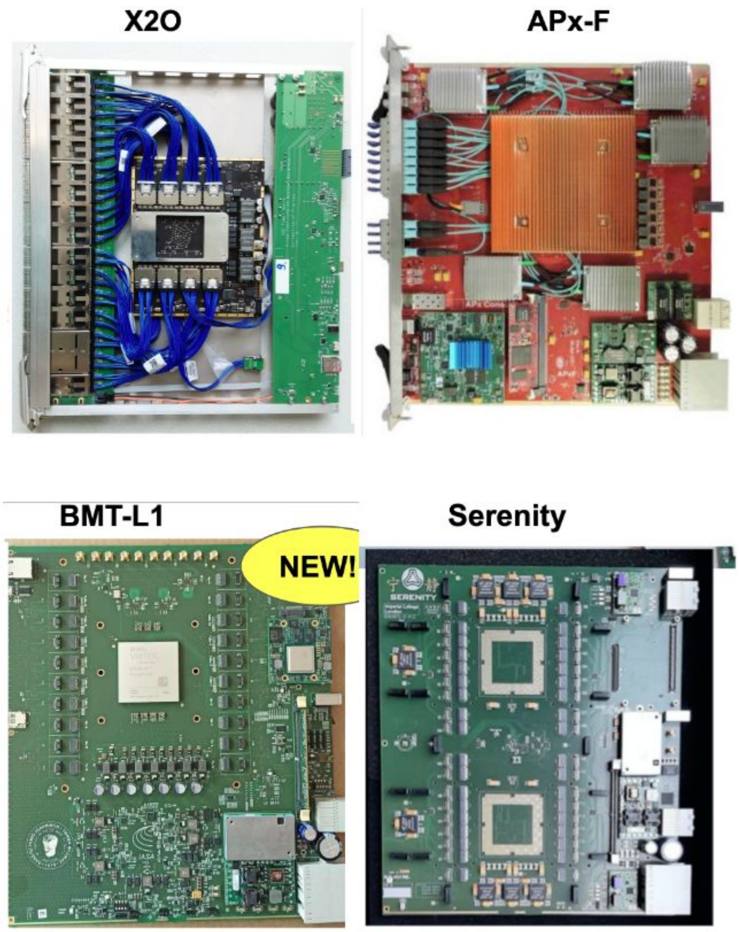
RS = regional segmentation in η or ϕ
FS = functional segmentation
TMUX = time-multiplexing period



Time-multiplexing: N processors running identical algorithms on different events (BXs). In this approach, the same data may be sent to multiple boards which run different algorithms.

Instrumentation

- All boards aim to use the same FPGA: XILINX VU13P
  - High-speed optical links, 28 Gb/s
- Different board families performing different tasks in the L1T
- Target latency is 9.5μs, allowing 20% buffer
- All pre-production hardware has been delivered
  - Extensive testing already performed on many boards



Phase-2 L1T cost (estimates from TDR)

WBS	Cost (kCHF)
1.1 Barrel Regional Calorimeter Trigger	494
1.2 Global Calorimeter Trigger	306
1.3 Infrastructure and Integration	237
1. Calorimeter Trigger	1036
2.1 Endcap Muon Trigger	686
2.2 Barrel Muon Trigger	579
2.3 Overlap Muon Trigger	231
2.4 Global Muon Trigger	500
2.5 Infrastructure and Integration	565
2. Muon Trigger	2560
3.1 GTT boards	443
3.2 Infrastructure and Integration	75
3. Global Track Trigger	518
4.1 Layer 1	940
4.2 Layer 2	876
4.3 Infrastructure and Integration	274
4. Particle Flow Trigger	2090
5.1 GT boards	414
5.2 Infrastructure and Integration	66
5. Global Trigger	480
6.1 DS boards	296
6.2 Infrastructure and Integration	78
6. Data Scouting System	374
L1 trigger upgrade total	7058