Overview of the High-Luminosity Upgrade for the CMS Level-1 Trigger

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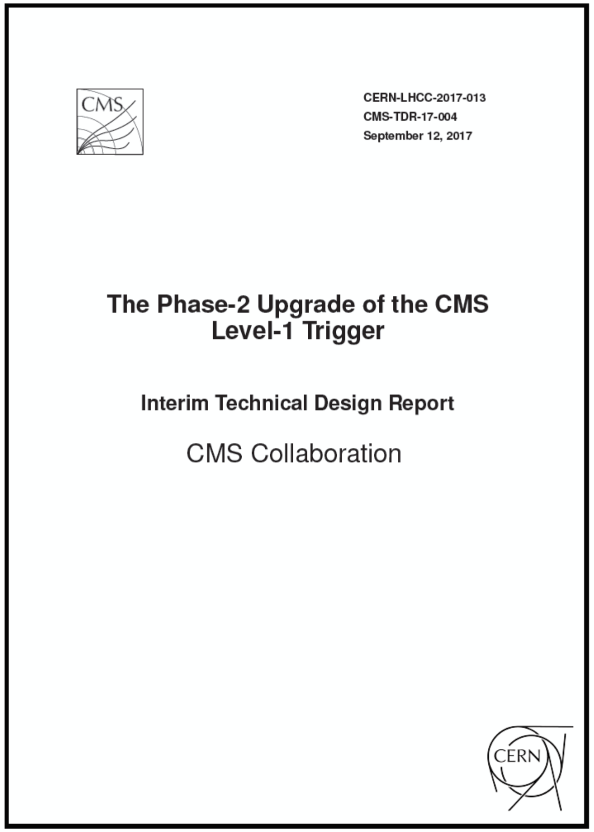
'Triggering on new Physics at HL-LHC'

Princeton Center for Theoretical Science. January 15th - 17th 2018.

Outline

- **This workshop focus:** discuss new physics signatures, trigger strategies and algorithms with phenomenologists to **motivate future developments and implementations of the trigger system for the detectors of HL-LHC**
- **The Interim TDR for the Phase-2 Upgrade of the CMS Level-1 Trigger** has been recently reviewed by the LHCC and published
  - it documents the current and planned research and development
  - baseline definition of **trigger primitive objects**, **trigger algorithms** and **interchange requirements with subdetectors**
  - Initial demonstration of key implementation technologies
  - a roadmap to the preparation of a future TDR


CERN-LHCC-2017-013
CMS-TDR-17-004
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The Phase-2 Upgrade of the CMS Level-1 Trigger

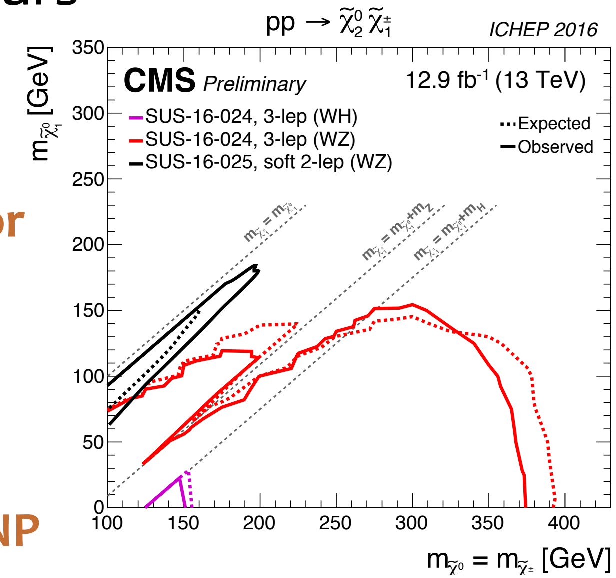
Interim Technical Design Report

CMS Collaboration

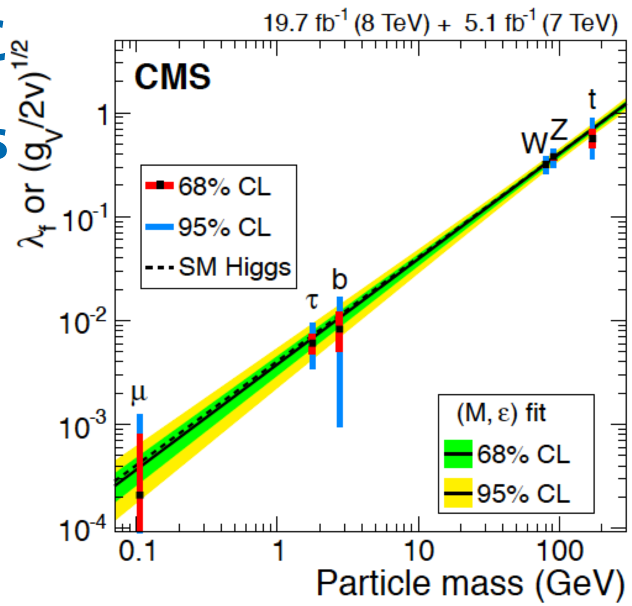
- **In this talk:** will briefly describe the **general physics guidelines** and will present an **overview of the conceptual design** that enter the ITDR

Physics guidelines

- **New Physics at the weak-scale** could be hiding in the difficult corners of the phase space, or in small deviations of the SM behaviours
  - **direct searches more sensitive to hard to identify configuration**
    - **ex. exploit low momentum lepton signatures to search for Compressed Spectra or Displaced Dark Matter**
  - **indirect searches through small deviations of the SM properties**
    - **SM Higgs boson properties, ~1% on coupling to access 1TeV NP**

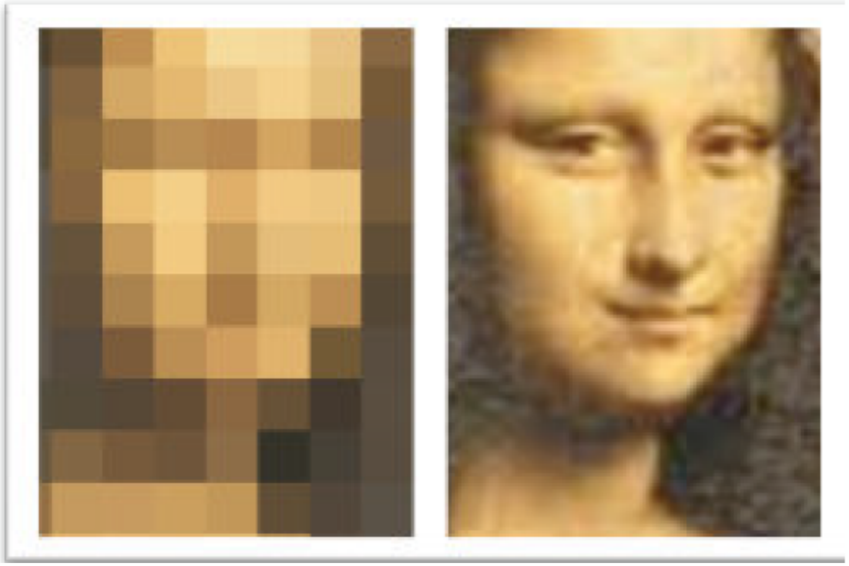


- Require the **high statistical power dataset of HL-LHC**
- CMS will have to maintain the **Phase-I overall physics acceptance** under the harsh pile-up environment: **140(200) for L = 5(8)*10^{34} cm^{-2}s^{-1}**
  - **efficiently trigger on low/medium p_T physics objects: leptons, photons, (b-)jets, E_T^{miss}**
  - **maintain flexibility to anomalous signatures**

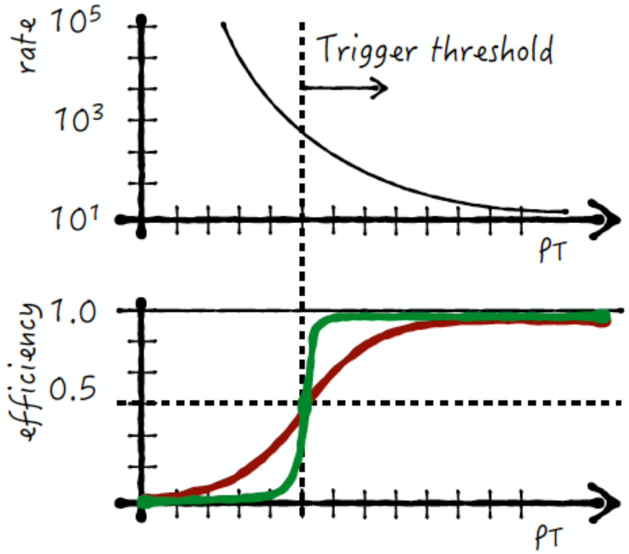


CMS Phase 1 trigger

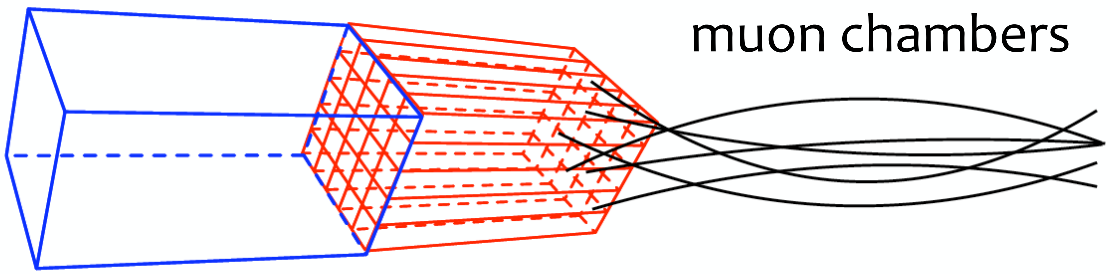
- **Level 1 (L1):** custom hardware processors that receive data from Calo and Muon systems, L1A signal within **3 μs**, max rate **100 KHz**. At each L1A, full detector is read out.
- **High Level Trigger (HLT):** implemented in software, reduces the rate to **~1 KHz**
- With Phase-I algorithms **1500(4000) KHz** of L1A rate for same Physics acceptance **@140(200)PU: beyond technical feasibility.**
- **Important lessons from RunI and RunII:**
  - **Offline particle flow (PF)** event reconstruction: brought significant resolution improvement
  - **High Level Trigger (HLT):** PF pushed into HLT, similar Offline vs HLT objects
  - **Level 1 (L1):** Final limitation: no tracking available, dissimilar HLT vs L1 objects



Major foreseen upgrades



- **CMS is investing in providing more and better information for L1**
  - Enable similar HLT vs L1 objects: **better turn-on curves, lower rates for same thresholds**
- **Increased input data compared with Phase-1**
  - **Inclusion of Tracking information at L1** to be combined with Calo and Muon
  - **Upgrades to the L1 Calorimeter and Muon trigger systems**
    - full exploitation of the Track trigger requires **good position and energy resolution**
      - **Barrel:** replacement of electronic systems to reach ECAL crystal-level energies (25x increase over current input data) and full exploitation of spacial DT resolution
      - **Endcap:** 3D High Granularity calorimeter, new endcap muon chambers



Major foreseen upgrades

- **Increased processing compared with Phase-1**
  - **Upgrade of the Global Trigger (GT) with intermediate Correlator Trigger (CT)**
    - to fully exploit the **increased information in the trigger objects**
      - more precise position and momentum resolution, calorimeter shower shape, number of tracking and muon hits …
    - **match** tracking info with fine grain calo info
    - **fit** muon and track data together
    - **more sophisticated and effective topologically-based global trigger calculations**

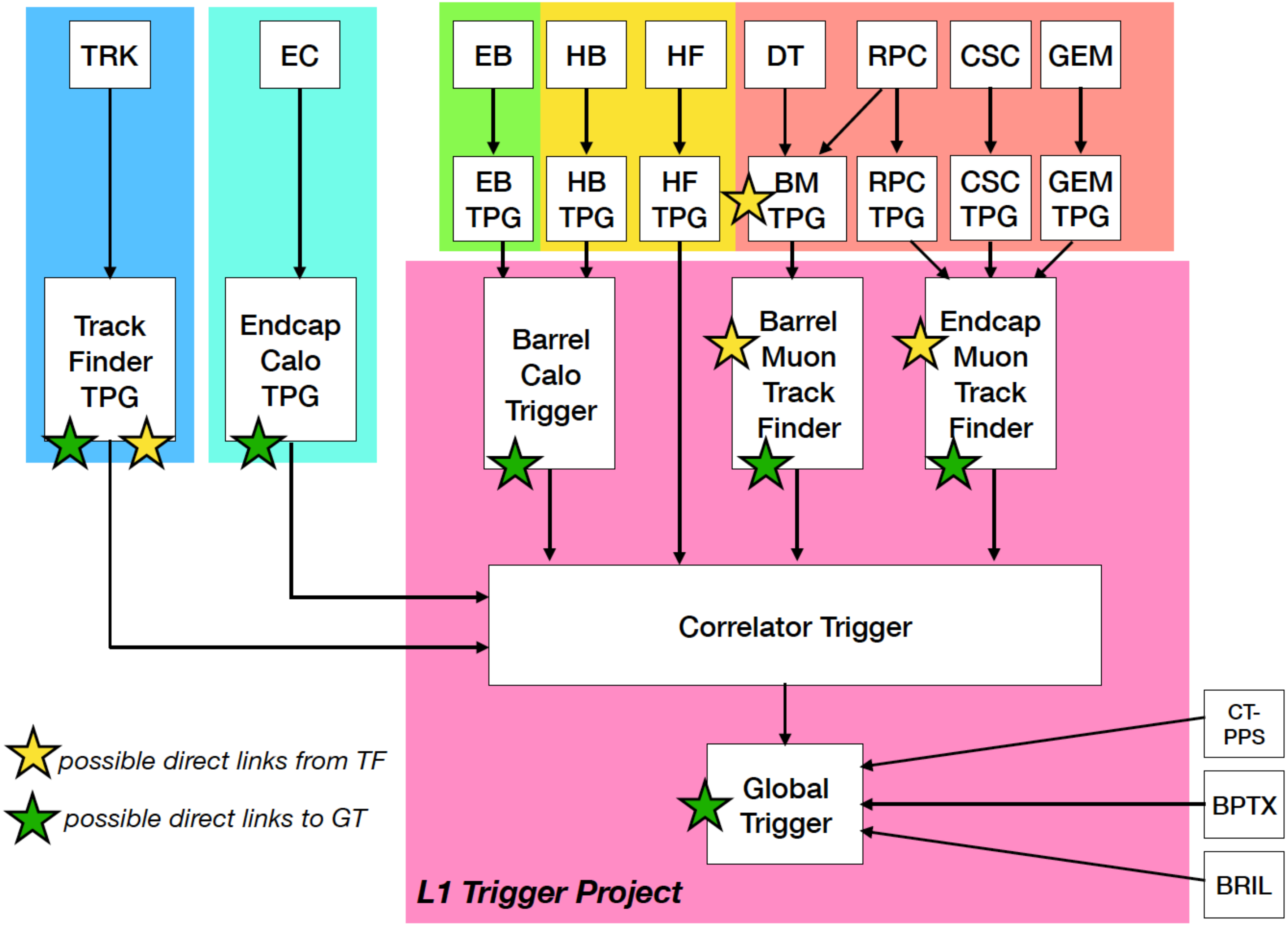
- **Input data and algorithm processing driving design and HW choices**
  - taking full advantage of Field Programmable Gate Array **(FPGA)** and **optical link technologies** as well as their maturation expected over the coming years

Major foreseen upgrades

- **Detector readout and DAQ systems will allow 12.5 µs latency**
  - Tracking information for the L1 trigger require increase in L1 latency
    - **Input data received by CT: 5 µs** (needed by L1 track trigger)
    - **Trigger objects received by GT: 7.5 µs** (tracks processed to find the PV, associated to PV, matched with Calo and Muon objects, used to compute isolation …)
    - **L1A received by TCDS: 8.5 µs** (global sums, kinematic calculations, trigger decision logic…)
    - **L1A received by front-ends: 9.5 µs (plus 30% of safety factor)**

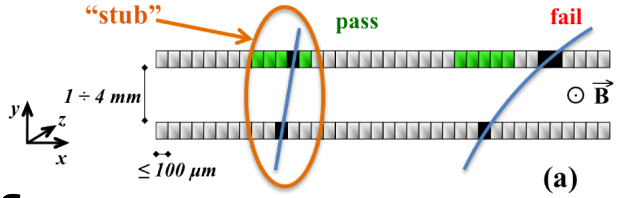
- **Detector readout and DAQ systems will allow L1A rate of 750 KHz**
  - adding L1 tracking information matched to improved L1 Calo and Muon trigger objects rate substantially reduced:
    - from L1 Menu studies **260(500) KHz @PU140(200) + 50% uncertainty**

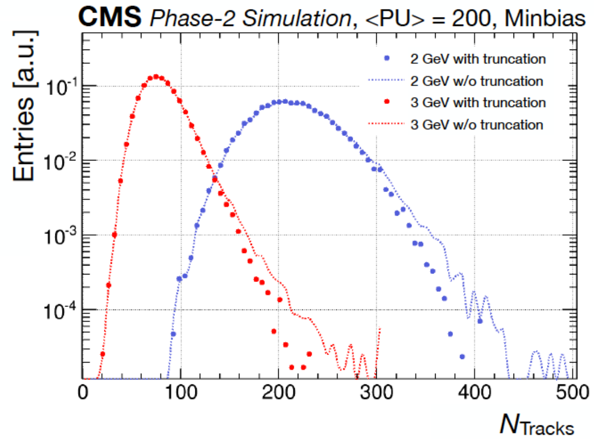
High Level view of the Phase-2 L1



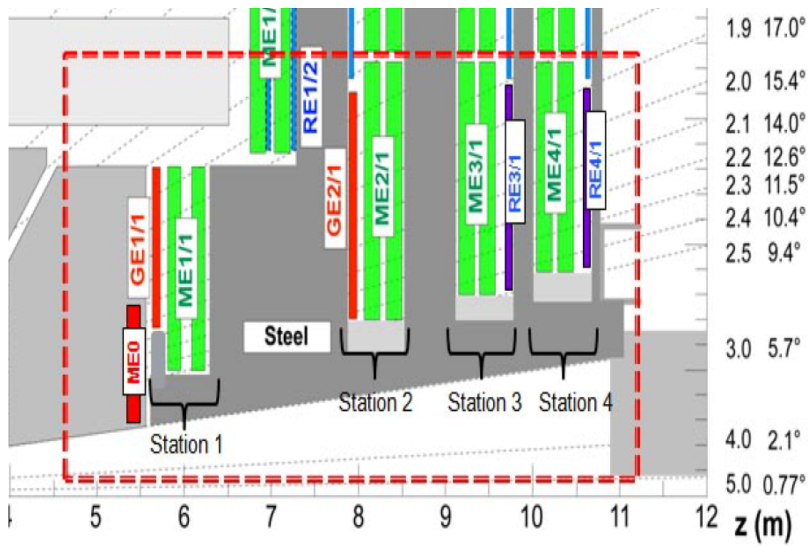
Trigger Primitives overview

- **Outer Tracker:**
  - readout at 40 MHz thanks to ability to perform p_T measurement with front-end electronics: **p_T modules**
    - **rate reduced by a factor 10 with p_T>2 GeV selection**
  - trigger require full track reconstruction
    - @PU 200 15000 stubs sent to the **Track Finder TPG** which must reconstruct tracks within 5 µs
    - **<200> tracks** to be sent, **100 bits per track**



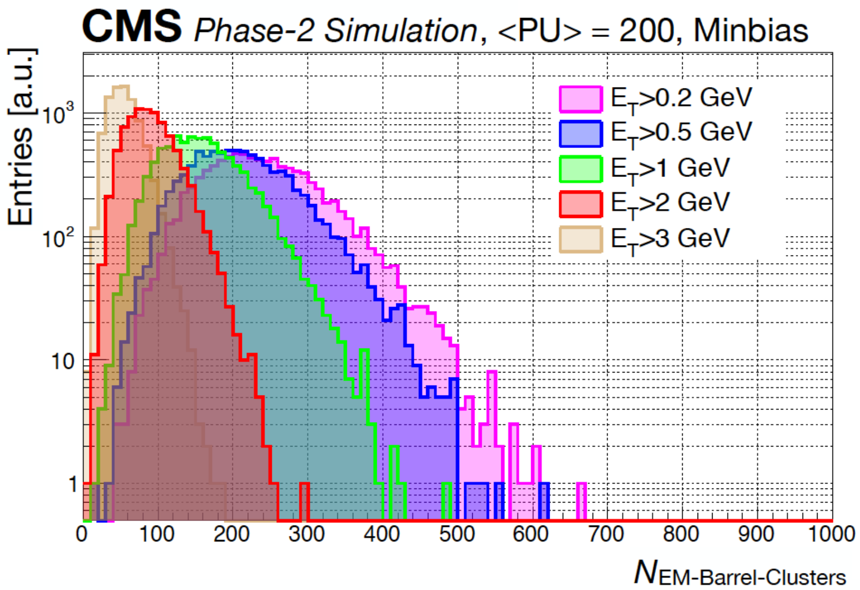


- **Muon system:**
  - **Barrel:** DT TPG and RPC link board system replaced to **exploit DT full spatial resolution, improve time resolution of RPC clusters from 25 to 1 ns**
    - new DT stub identification algorithms and proposals for new DT, RPC words
  - **Endcap:** coverage will be extended by the addition of **iRPC and GEM which will all provide TPs to the L1 trigger**

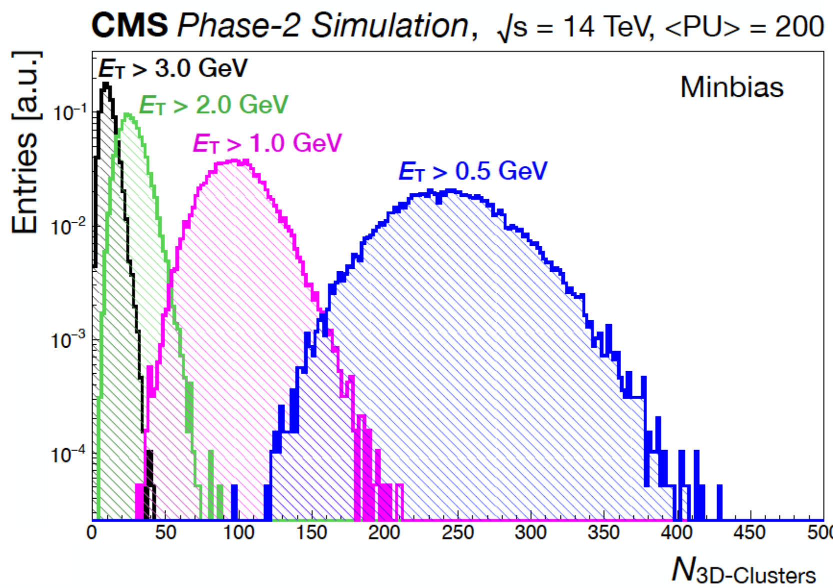


Trigger Primitives: Calorimeters

- **ECAL Barrel**
  - EB TPG (back-end electronics) will receive **crystal data** from the detector
  - Studies of **cluster primitive word** generate by EB TPG are on-going



- **HGCAL**
  - Each trigger layer provide **"trigger cells"** (sums over individual channels) with front-end electronic E_T threshold
  - TPG: for each layer **2D clusters from trigger cells then** combine the 2D clusters in depth to form **3D clusters**
  - Time-multiplexing to transfer all the 2D clusters into one FPGA for 3D mapping; preliminary **firmware implementations indicate TPG within 5 μs**



3D Cluster E_T>1 GeV

Trigger Primitive Summary

Table 2.1: Summary of the logical input data to the Phase-2 L1 trigger.

Detector	Object	N bits/object	N objects	N bits/BX	Required BW (Gb/s)
TRK	Track	100	400	40 000	1 600
EB	Crystal	16	61 200	979 200	39 168
HB	Tower	16	2 304	36 864	1 475
HF	Tower	10	1 440	13 824	553
EC	Cluster	200	400	80 000	3 200
EC	Tower	16	2 400	38 400	1 536
MB DT	Stub	70	240	33 600	1 344
MB RPC	Cluster	15	3 200	48 000	1 902
ME CSC	Stub	32	1 080	34 560	1 382
ME RPC	Cluster	15	2 304	34 560	1 382
ME iRPC	Cluster	41	288	11 808	472
ME GEM	Cluster	14	2 304	32 256	1 290
ME0 GEM	Stub	24	288	6 912	276
Total	-	-	-	-	53 980

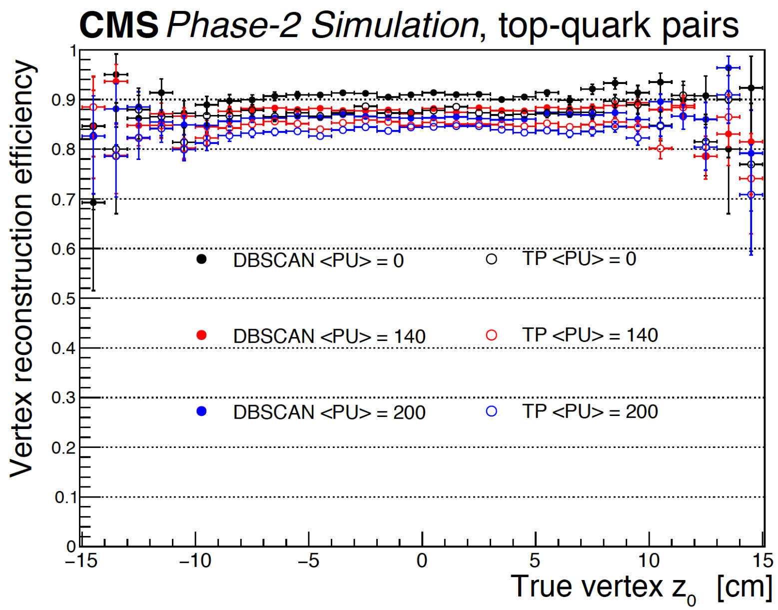
The L1 Trigger receives > 50 Tb/s

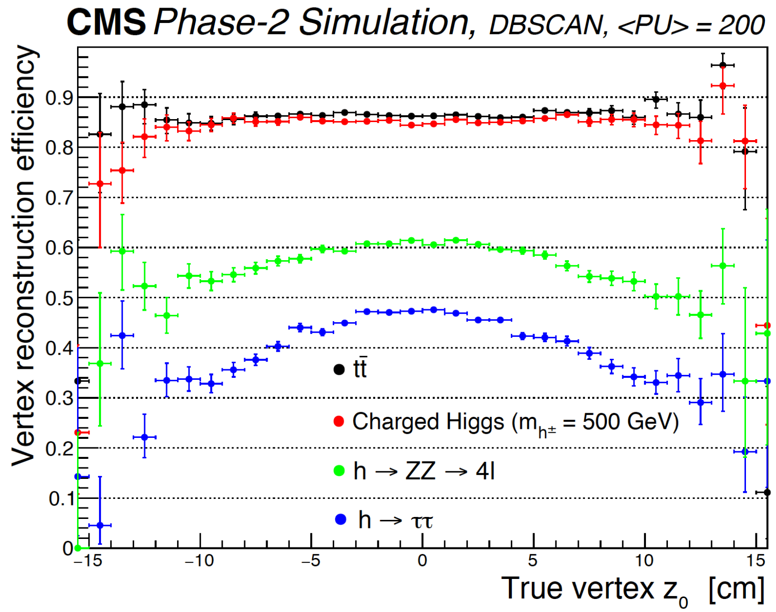
Trigger Algorithms

- **To maintain Phase-1 trigger thresholds it's crucial:**
  - **identify the PV to mitigate PU effects**
  - **match the performance of offline algo** with extensive use of tracking information: well match algo provide **sharpened turn-on of the efficiency, reducing rate, naming lower thresholds**
- **R&D strategy employed in the past two years:**
  - ***stand-alone objects:*** robust triggers based on independent sub-det, reference to compare improvements
  - ***track-matched objects:*** tracking used to confirm standalone Muon and Calo objects, significant improvement with simple design
  - ***particle-flow (PF) objects:*** ultimate performance improvement, combine all information and match offline algo, require most processing time and resources for calculation
- **Complete suite of Phase-2 triggers is expected to be rich**

Vertex reconstruction

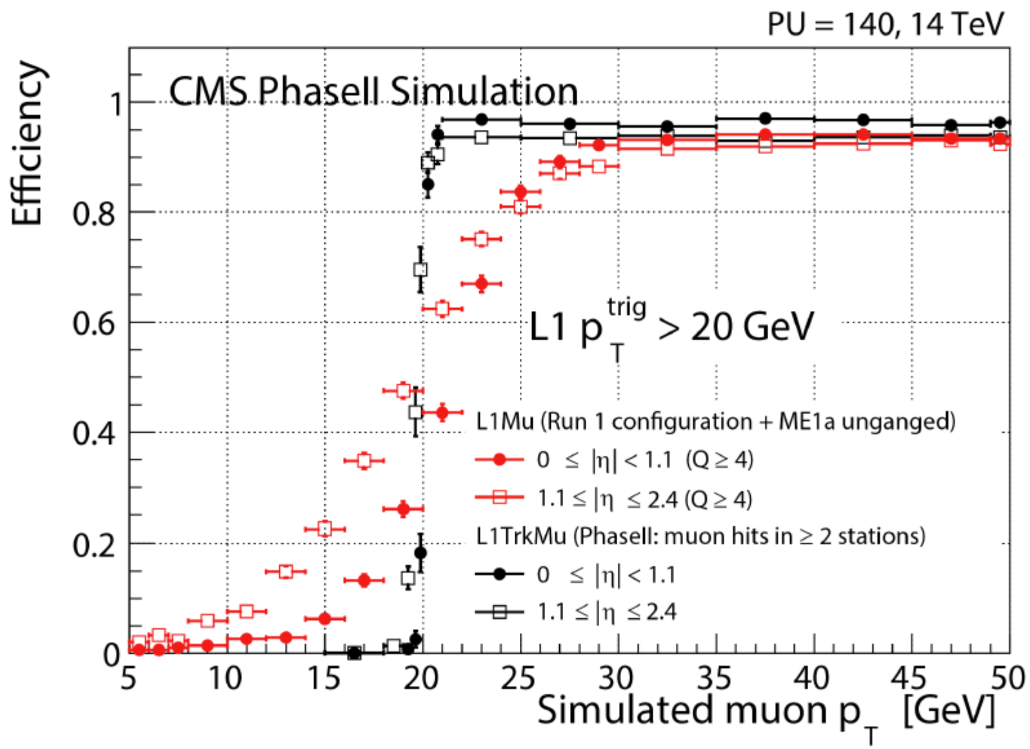
- **Several algorithms have been tested**
  - Simple: ***Histogramming method***
    - z_0 histogram of all the L1 tracks weighted with p_T, PV obtained maximising the total scalar p_T in 3 consecutive z bins.
  - Best performing: ***density based spatial clustering of application with noise (BDSCAN)***
    - good vertex reconstruction efficiency, excellent tolerance for fake tracks, **already implemented in FPGA**
- **86% reconstruction efficiency** (within 1.5 mm from true vertex) in ttbar events for 200 PU
  - much less in signal processes with less high-pT tracks: **but lepton/photon triggers can do**





Muons (tracked-matched)

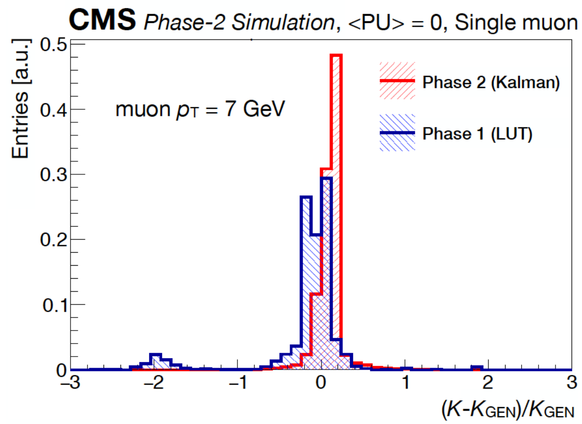
- L1 Muon trigger always provided candidates (p_T~20GeV) with high purity, **but too high rate due to the poor p_T accuracy**
  - **Core momentum resolution** require L1 thresholds lower than offline, bad turn-on
  - **Non-negligible tails of momentum resolution,** flattening of the rate for p_T > 20
- **Matching with L1 Tracks provides a major improvement**
  - Inside-out and outside-in matching algo (same performance)
  - **Efficiency > 95%, online-offline offset negligible, factor 6 to 10 of rate reduction for SingleMu p_T > 20 GeV**
  - Rate reduction in DoubleMu trigger thanks to dz_0 < 1cm

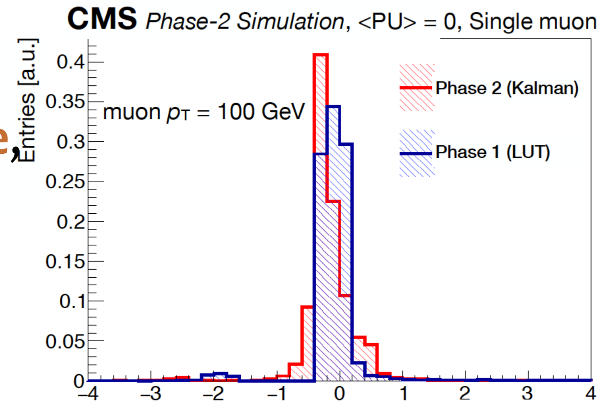


still valid also at PU 200

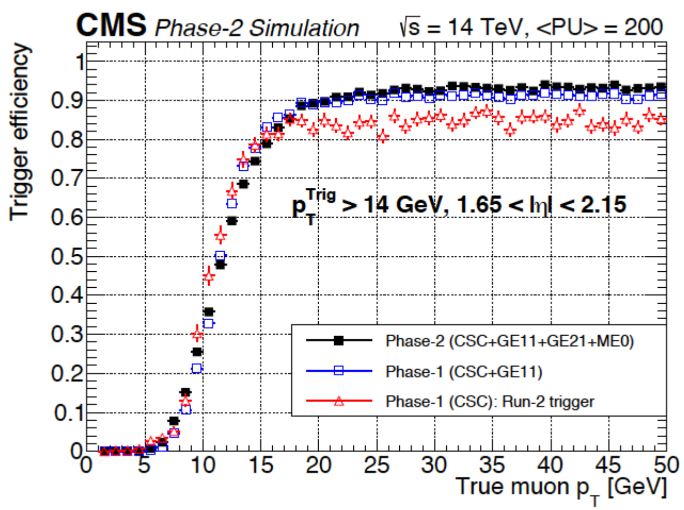
Muons (stand-alone)

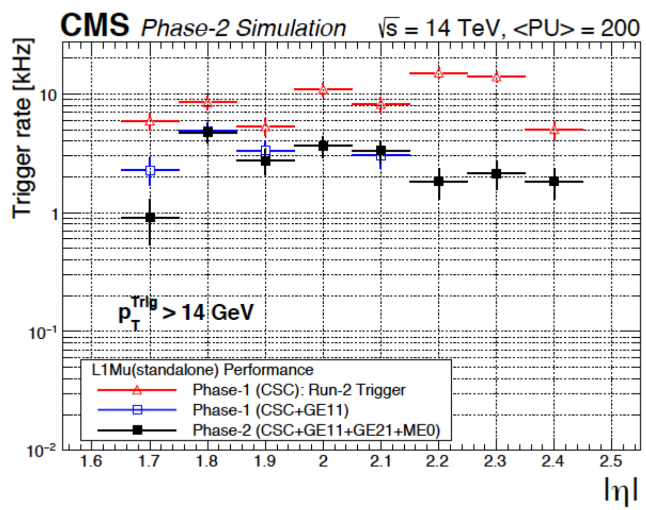
- **Improvements in barrel stand-alone momentum resolution (Phase-2 vs -1)**
  - Exploitation of **DT full spacial resolution** thanks to electronic upgrade
  - **Use of advanced FPGAs** with large number of DSP cores, large numbers of LUTs, and can operate at high clock frequency, is essential to develop new algorithms
  - Development of **Kalman filter approach in trigger hardware**, to take into account the energy loss and multiple scattering
    - **First implementation in Vivado HLS looks promising**





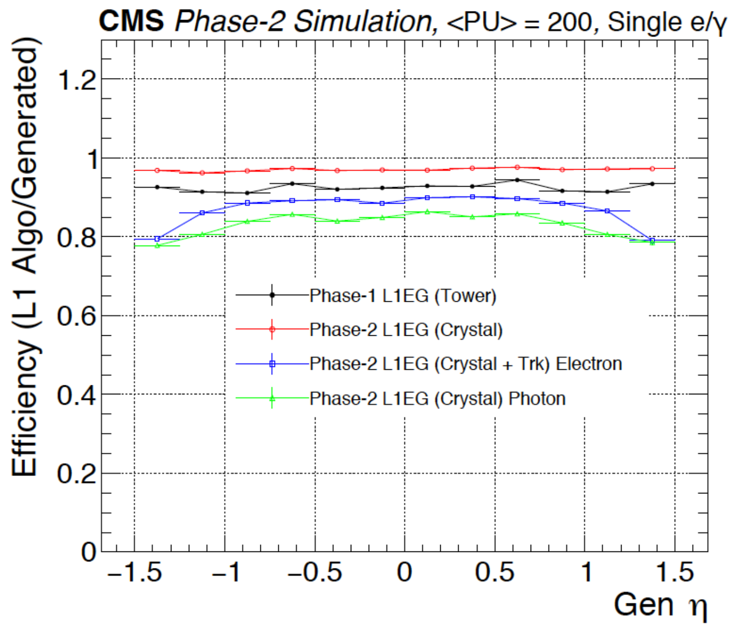
- **Improvements in Muon Endcap trigger efficiency and rate reduction thanks to new chambers**





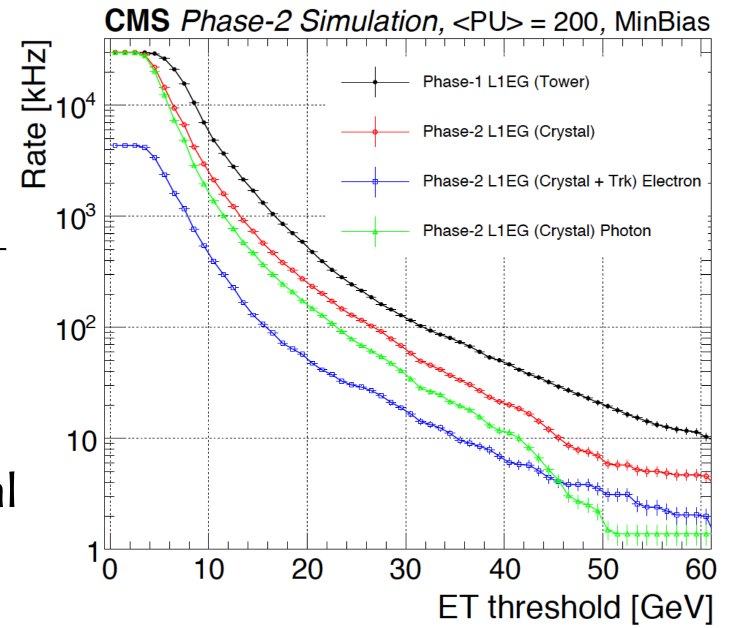
Electrons and Photons

- **Stand-alone: must provide high efficiency especially for high-p_T objects**
  - the digitised response of every crystal of the ECAL barrel will provide **crystal-level energy measurements**
    - **improved position resolution of the EM clustering algorithms (similar to offline)**
  - New trigger design improve rates, efficiency for EGM clusters is kept up to **~99% at plateau**



Barrel Only

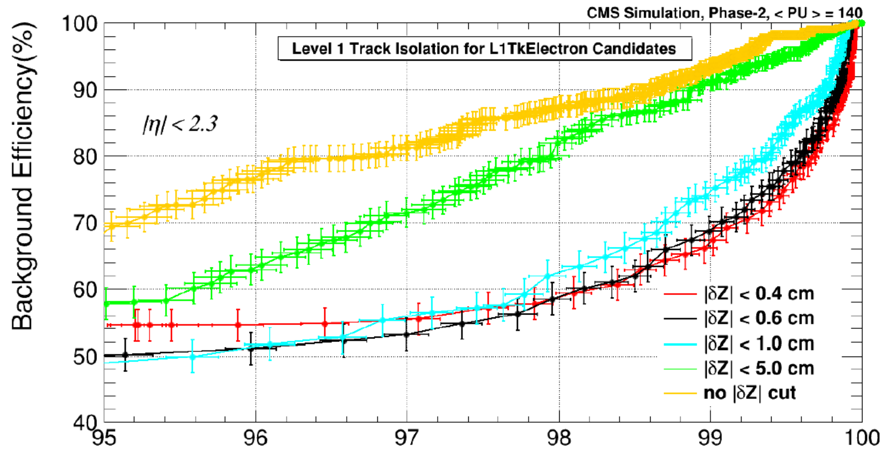
- **Track matching: rate reduction**
  - L1 Tracks are extrapolated to the ECAL surface and matched to EM clusters.
  - **To maximise electron reconstruction efficiency:**
    - looser matching windows in tracking algo and track p_T determination only with innermost hits
    - track selection and matching criteria different for low vs high momentum electrons
  - Track-matched electron object ~90% efficiency in central barrel, trigger rate reduction by a factor 5

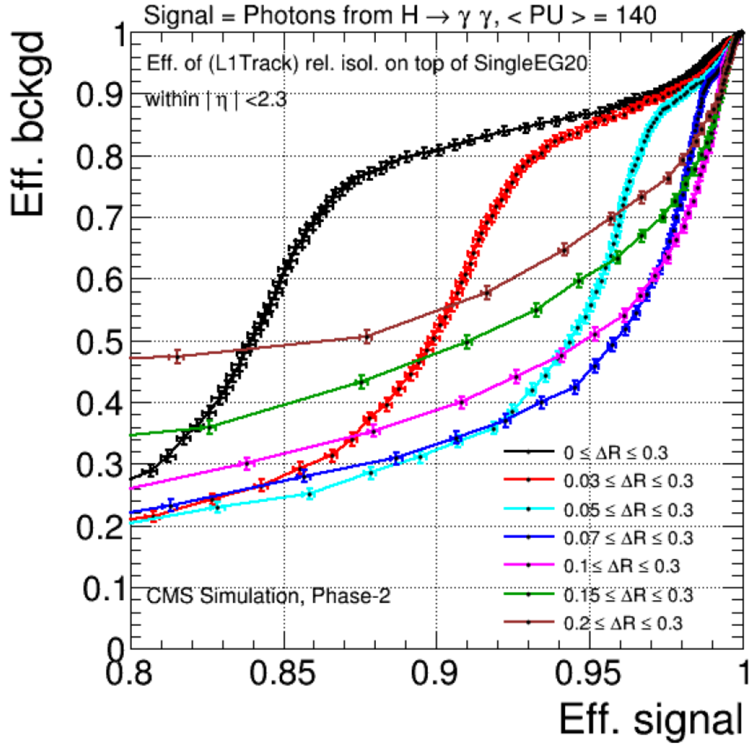


Tracker Isolation

- **Isolation requirement: efficient handle to increase the purity of the lepton/photon sample**
  - **track isolation more robust to PU wrt calorimeter-based isolation**
- **Muons and Electrons**
  - scalar sum of the L1 Tracks p_T in ΔR (0.2-0.3) around the lepton track (footprint removal for electrons) divided by lepton p_T
  - tracks must pass quality requirements and have z_0 consistent with the lepton: $|z_0 - z_{lepton}| < \Delta z_{max}$
- **Photons**
  - all tracks in $\Delta R_{min} < \Delta R < \Delta R_{max}$ irrespective of z_0
  - ΔR computed with η, φ of the L1 EM cluster

Factor 2 in bkg reduction for 95% signal efficiency



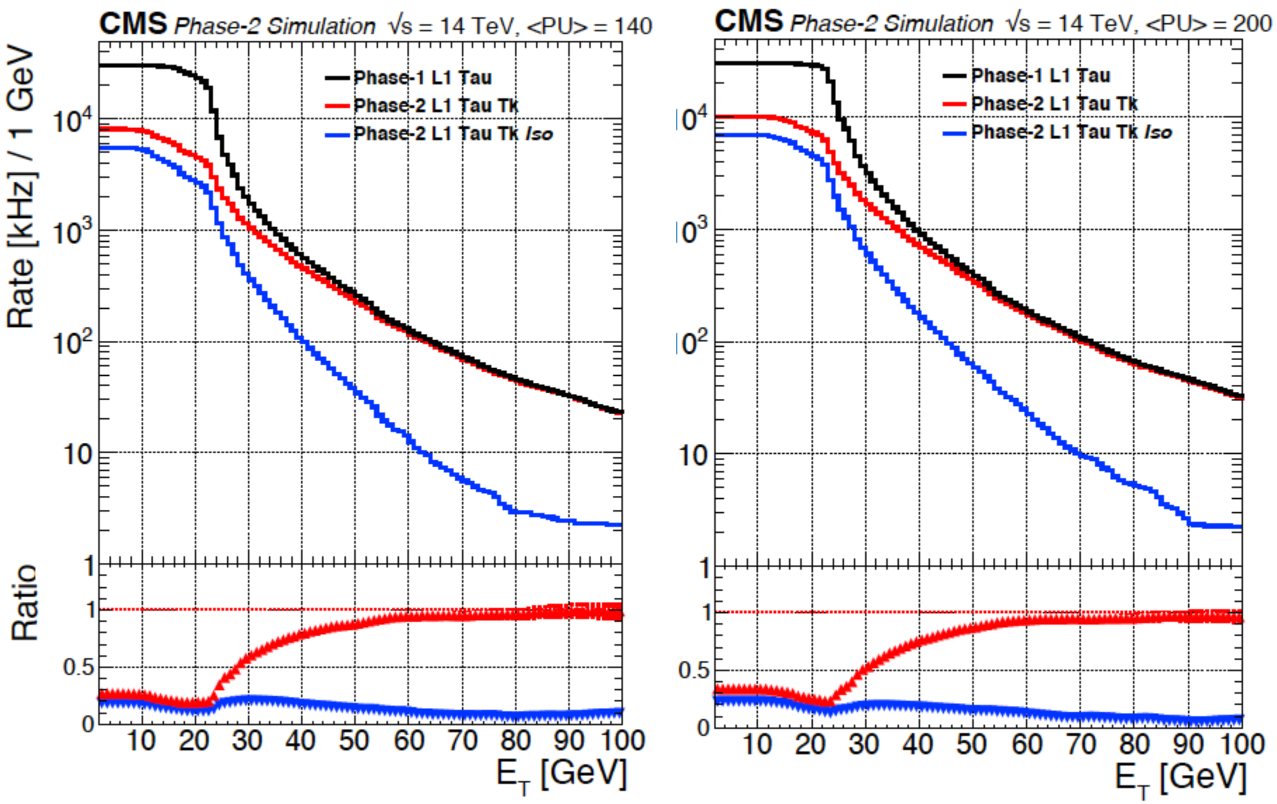


Taus

- **Identification of τ_h : challenging, usage of tracking becomes critical**
  - Phase-1 algorithms to select τ_h candidates from isolated Calo Clusters (**Phase-1 L1 Taus** from Phase-2 TPs)
  - High p_T L1 tracks matched to Phase-1 L1 Taus (**Phase-2 L1 TauTk**)
  - L1 track-based isolation requirement is applied (**Phase-2 L1 TauTkIso**)

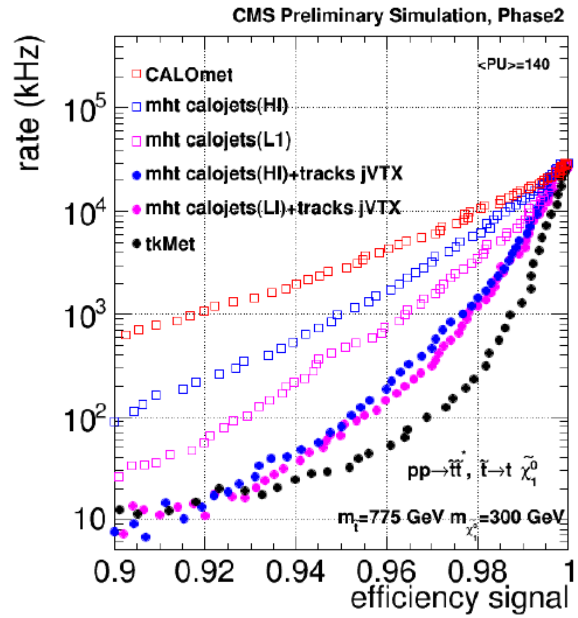
- **Single Tau trigger**
  - 50 kHz at PU200(140) with thresholds: **90(78),90(78), 52(46) GeV**

- **Double Tau trigger**
  - **τ_h are required to come from the same vertex (Δz<1 cm)**
  - 50 kHz at PU200(140) with thresholds: **46(42),40(36), 25(22) GeV**

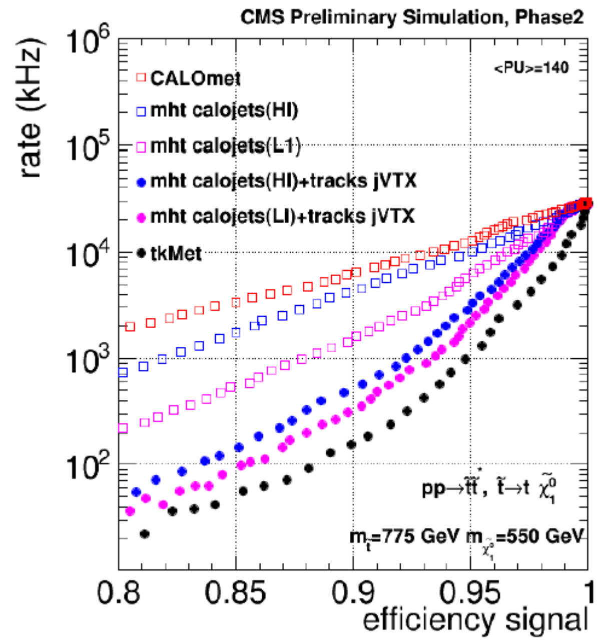


Jets, H_T, MH_T, E_T^{miss}

- **Multi-object triggers very sensitive to PU**
  - **H_T, MH_T, multi-jets:** reduce the PU dependency requiring **jets from same vertex**
    - L1 calorimeter jets are matched to L1 tracks in a η-φ cone around the jet
    - **z0 position of jet vertex determined with p_T weighted average of the tracks z0**
      - **1 mm resolution, 95% efficiency** to reconstruct the vertex within 1cm from the true vertex in ttbar events (jet p_T> 70 GeV)
    - **The leading jet used to set the z-vertex reference**
  - **Tracking based E_T^{miss}:** vectorial sum of all the **tracks p_T that come from the PV** (z0 consistent with PV within ~1 cm)
    - track quality cuts to reduce mismeasurements



E_T^{miss} ~ 300 GeV



E_T^{miss} ~ 200 GeV

Trigger Menu

- **Simplified menu similar to the one developed for Phase-I TDR:**
  - it includes **20 major trigger paths** that capture key physics signals
  - it covers **~70% of the total L1 rate** that would be needed for a full menu
    - remaining ~30% for specific physics targets, high |η|, diagnostic and prescaled triggers, etc…
  - it provides an estimate of the individual trigger rates and the total L1 bandwidth required **to maintain the physics acceptance as indicated in the Phase-1 TDR (threshold O(20-50) GeV)**
  - It shows the power of the L1 tracking when made in conjunction with an upgrade to the total L1 bandwidth: **it is not an optimised L1 menu**
- **Trigger primitives are not all up to date!**
  - phase-2 outer tracker, phase-1 pixel, phase-0 (i.e. post LS1) calorimeters (ECAL barrel rechits are used to apply 'phase-2' clustering) post LS1 CSC upgrades muons.

Trigger Menu

- **Thresholds scaled from online to offline values**
  - scaling chosen such that the trigger object is **95% (85% for taus) of the plateau efficiency for an offline cut at the threshold**
- **Single lepton triggers** include tracking requirements
- γ/e have to be kept separate: **inclusion of single and double γ paths**
- **Isolated e/γ** use tracking isolation
- **Dilepton triggers** make use of tracking info on first leg, and sometimes also on second leg
  - if both legs have a L1-Track **‘same-vertex’ requirement ($\Delta z \leq 1$ cm)**
- **Multijets, H_T and H_T^{miss} triggers** use collections of jets that are consistent with coming from the event-vertex, $|z - z_{PV}| < 1$ cm

Trigger algorithm (L1 tracks (pT > 2 GeV) correlated with object)	Rate [kHz]	Offline threshold(s) [GeV]
$\langle PU \rangle$	200	
Single Mu (tk)	27	18
Double Mu (tk)	1.2	14 10
Ele* (iso tk) + Mu (tk)	0.2	19 10.5
Single Ele* (tk)	38	31
Single iso Ele* (tk)	27	27
Single $\gamma^\star$ (tk-iso)	19	31
Ele* (iso tk) + $e/\gamma^\star$	7.3	22 16
Double $\gamma^\star$ (tk-iso)	5	22 16
Single Tau (tk)	38	88
Tau (tk) + Tau	55	56 56
Ele* (iso tk) + Tau	23	19 50
Tau (tk) + Mu (tk)	6	45 14
Single Jet	69	173
Double Jet (tk)	43	2@136
Quad Jet (tk)	45	4@72
Single ele* (tk) + Jet	15	23 66
Single Mu (tk) + Jet	12	16 66
Single ele* (tk) + H_T^{miss} (tk)	45	23 95
Single Mu (tk) + H_T^{miss} (tk)	8	16 95
H_T (tk)	24	350
Rate for above triggers*	305	
Est. rate (full EG eta range)	390	
Est. total L1 menu rate (× 1.3)	**500**	

- HL-LHC 200 pile-up events per beam crossing
  - No tracking at L1: rate ~ 4 000 kHz
  - **Tracking at L1: rate ~ 500 kHz**
- No uncertainties on actual detector performance, and detector readout electronics
  - allow 50% margin
  - max design rate 750 kHz
- **Light lepton, Photon HL-LHC thresholds are comparable with RunI, Phase-1**
- **Hadronic algos need more work to be comparable with RunI, Phase-1**
  - **how to improve further?**

(*) paths where electron and photons are restricted to the barrel

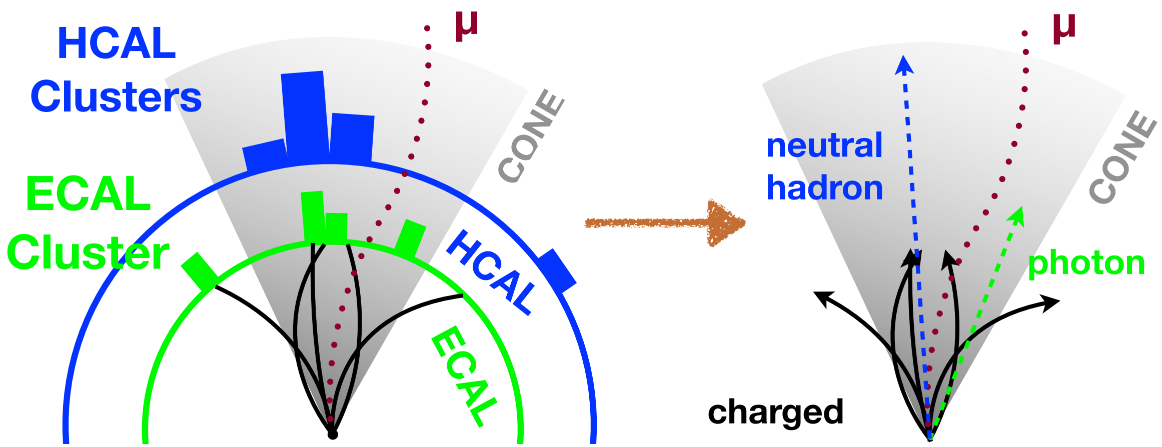
New algorithms: PF@L1

- From **combining the complete detector information using the Particle-Flow algorithm** closely matching offline and HLT:

EM Clusters (from ECAL and HGCAL EM Clusters TPs),
Calo Clusters (from EM Clusters + HCAL Towers + HGCAL Hadronic trigger cells),
Tracks (from L1TF),
Stand Alone Muons TPs

↓

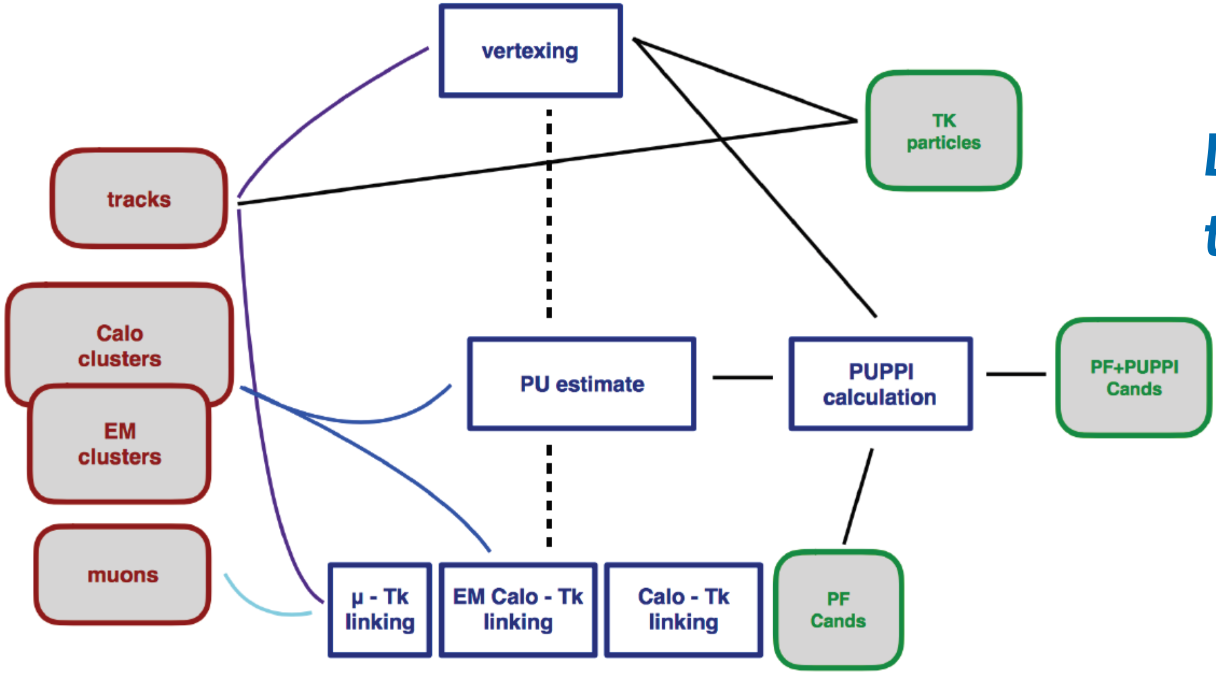
L1 PF Candidates: Charged and neutral hadrons, photons, muons, electrons



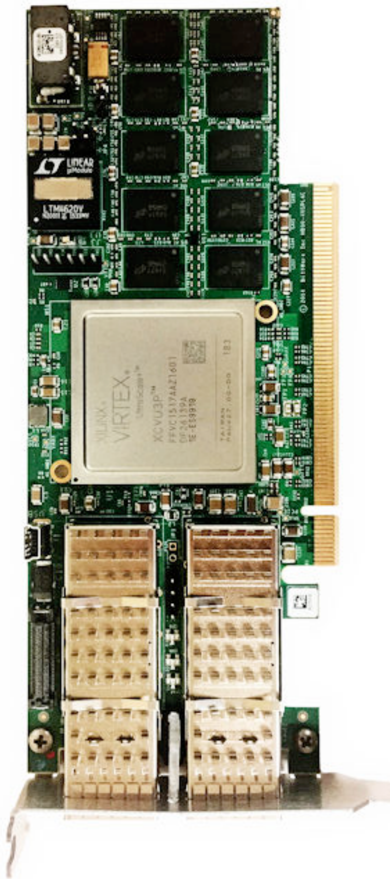
- **Pile-Up-Per-Particle-Identification (PUPPI)** on PF candidates greatly mitigate PU effects
  - uses **vertexing info from tracks and QCQ-based ansatz function** to define a particle weight
  - vertexing done in parallel w/PF and PU estimate
  - L1 PUPPI runs on global list of candidates from PF step and **select prompt physics objects**

→ **E_T^{miss}, H_T, jets, prompt μ, electrons, τ_h, photons**

PF+PUPPI algo & Firmware

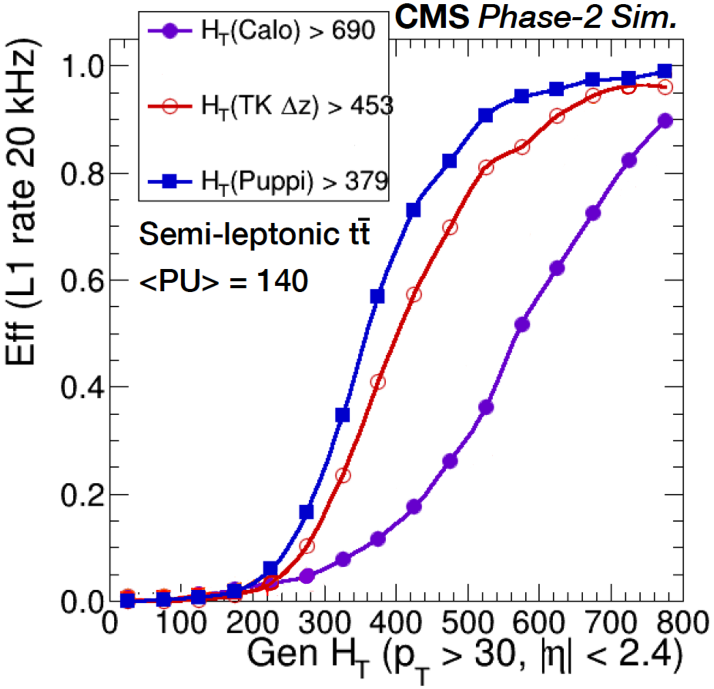


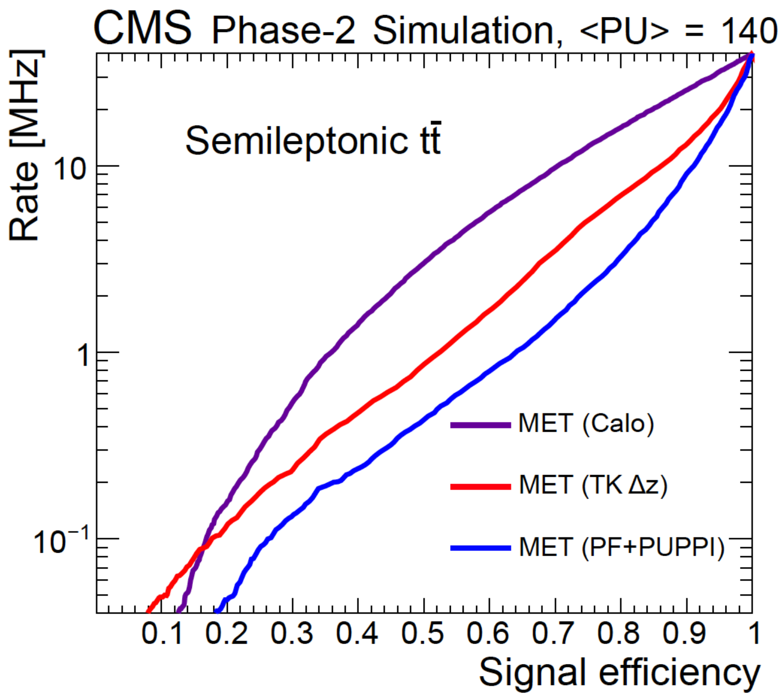
Dedicated talk by Giovanni P. to discover all the details



- Algorithms with highest complexity: **started to develop PF and PUPPI in firmware** to optimise their total resources usage, within latency allocated for CT
  - **First early test using Vivado HLS demonstrates feasibility:** High-particle-density (25 tracks and 20 clusters) detector region
    - PF candidates generated in 4 regions with **0.5 μs latency, 40% resources** of a Xilinx Ultrascale+ VU9P FPGA
    - PUPPI run with **0.1 μs latency, 3% of same resources**

H_T trigger performance and more





- **Comparing H_T trigger performance from PF-jets and Track-based jets**
  - Different quality cuts applied on L1 tracks (looser for PF), jets p_T > 30 GeV
  - PUPPI performance depend on PV to be properly reconstructed: easy in events with large high p_T tracks multiplicity (ttbar)
  - **PF+PUPPI more robust against fakes than track-only observables**
    - **higher signal efficiency, lower rates, lower thresholds**
- **H_T as early proxy for showing potential gain, much more to be developed:**
  - **jet substructure for heavy-particle tagging, lepton isolation, τh reconstruction**

Other possible developments

- The use of advanced FPGAs with ever greater processing resources will allow **a range of global algorithms, which will be extremely powerful thanks to the improved object position resolution** of Phase-2 TPs
  - Inter-object correlation (Run 1 L1 trigger for soft muon b-tagging of jets)
  - Invariant mass calculation (introduced in Phase-1 GT, used for VBF jet pairs)
  - event-level discrimination variables based on full event reconstruction (MT2…)
- **Machine learning techniques in the correlator for advanced object identification algorithms**
  - increased bandwidth may allow the object ID variables sent to the CT/GT to be greatly extended
- **Design of triggers for specific signal configurations: ex. displaced muon trigger**
  - track from the track triggers cannot be reconstructed for muons with |dxy| > 1 cm and beam-spot constraint in the stand-alone muon p_T assignment
    - prototype algo drops the beam-spot constraint, requires precision measurements of the muon direction in at least two stations, applies a veto of the tracks from the track trigger extrapolated to the second muon stations

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Conclusions

- CMS is designing a L1 Trigger for HL-LHC that will enable **unprecedented exploration of the weak-scale physics frontier**
- Moreover the trigger is being designed trying to guarantee enough **flexibility for the implementation of algorithms dedicated to new signal topologies**
- Good moment to discuss with phenomenologists: the current algorithm and hardware R&D phase will have to **converge to baseline definitions during the next two years**, given the TDR is expected by the end of 2019.