Triggering at HL-LHC with Phase-2 CMS

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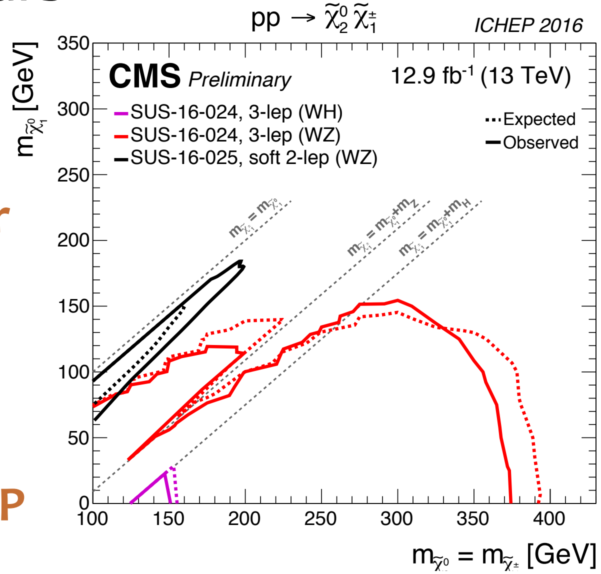
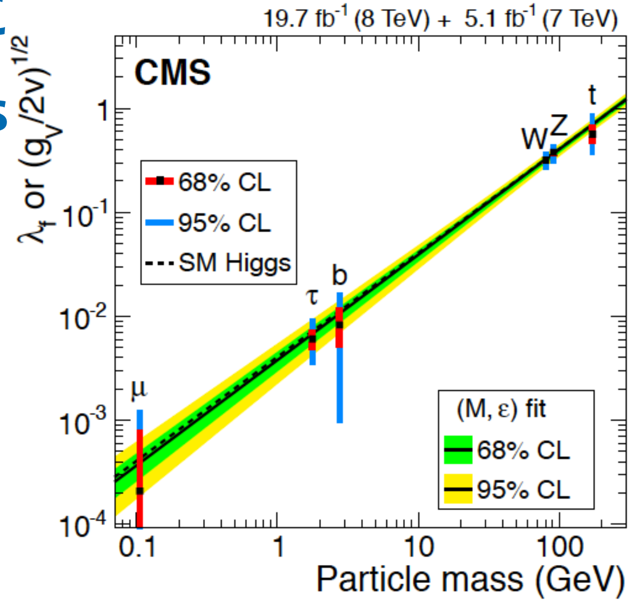
Physics guidelines

- **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**



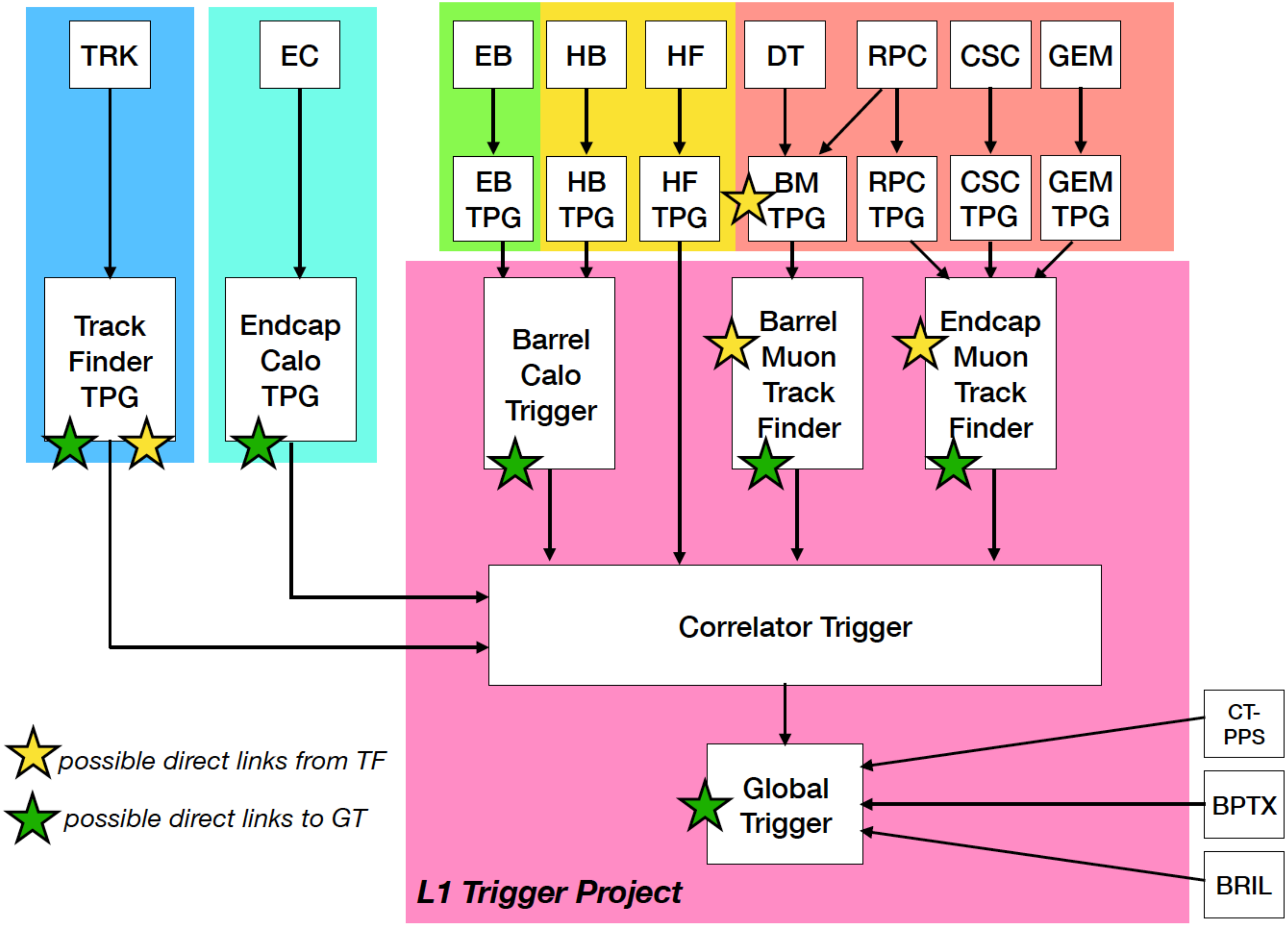
- Require the **high statistical power dataset of HL-LHC**
- CMS will have to maintain the **Phase-I overall physics acceptance** under the harsh pile-up environment: **140 - 200**
  - **efficiently trigger on low/medium p_T physics objects: leptons, photons, (b-)jets, E_T^{miss}**



Trigger upgrades for Phase-2

- **CMS Phase-1 trigger**
  - **L1 Trigger:** 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:** implemented in software, reduces the rate to **~1 KHz.**
- **CMS Phase-2 trigger**
  - same 2-level structure
  - detector readout and DAQ systems will allow L1A rate of **750 KHz** and **12.5 μs** latency
  - **inclusion of Tracking information at L1** to be combined with Calo and Muon information
  - **upgrade of Calo and Muon systems:** finer granularity
  - **upgrade of GT design** to process more information
  - with 1/100 event selection from L1 to HLT, permanent event storage of **7.5 KHz**

High Level view of the Phase-2 L1



Motivations

- **Upgrades motivated by dedicated L1 Menu studies (presented in TP)**
  - with Phase-I algorithms **1500(4000) KHz** of L1A rate for same Physics acceptance **@140(200)PU**
  - adding L1 tracking information matched to improved L1 Calo and Muon trigger objects rate substantially reduced: **260(500) KHz + 50% uncertainty**

- **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)

Motivations (2)

- **Upgrades to the L1 Calorimeter and Muon trigger systems**
  - full exploitation of the Track trigger requires **good position and energy resolution**
    - replacement of electronic systems to reach Calo crystal-level energies and full exploitation of spacial DT resolution
  - addition of new information to the trigger from **adding new detectors**
    - new endcap muon chambers
- **Upgrades to the Global Trigger (with intermediate Correlator Trigger step)**
  - to fully exploit the **increased information in the trigger objects**
    - more precise position and momentum resolution, track matching quality, calorimeter shower shape, number of tracking and muon hits
  - **more sophisticated and effective topologically-based global trigger calculations**

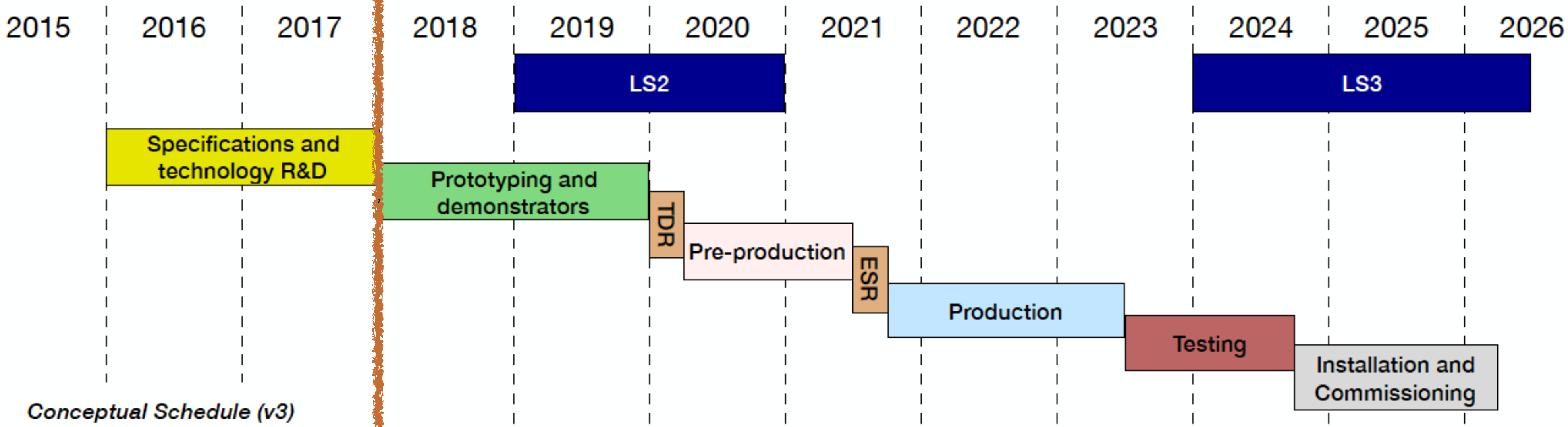
Timeline: where are we now?

2015: Technical Proposal (TP): Initial design and motivations

2016 - 2017:

- Baseline definition of trigger primitive objects, trigger algorithms and interchange requirements with subdetectors

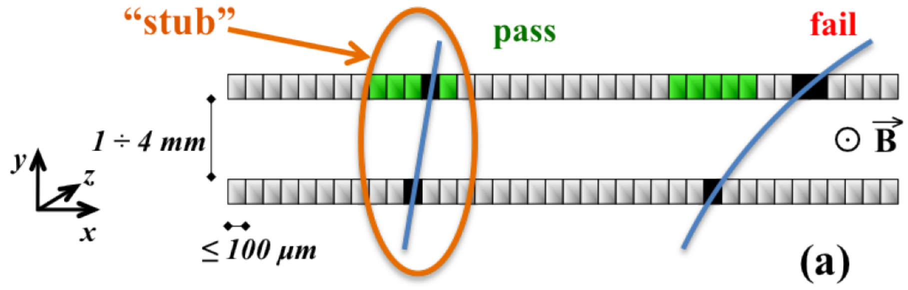
- Initial demonstration of key implementation technologies



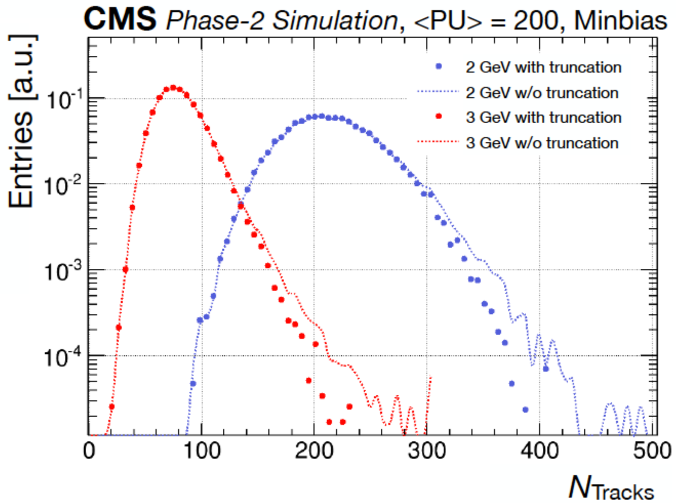
Interim Document (TDR-17-004)

Trigger Primitives: Outer Tracker

- **Readout of tracking information at an unprecedented 40 MHz data rate**
  - thanks to ability to perform p_T measurement with the detector front-end electronics: **p_T modules**
    - **readout rate reduced by a factor 10 with p_T>2 GeV selection**
      - 97% of particles created in pp interactions @ 14 TeV have pT<2 GeV:



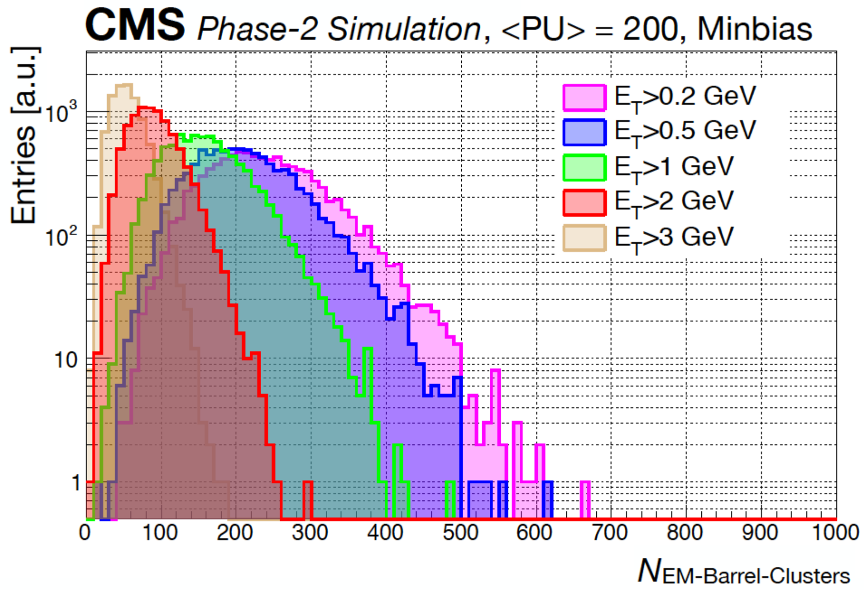
- **Trigger algo improvements require full track reconstruction**
  - @PU 200 15000 stubs sent to the **Track Finder TPG (Track Trigger)** which must reconstruct tracks within 5 µs
  - Significant challenge: 3 approaches, 3 hardware demonstrators
  - **<200> tracks** to be sent
  - **100 bits per track**
  - ~150 TF processor cards, 2 x 16 Gb/s fibres each



Quantity	N bits
p_T	16
Charge	1
ϕ_0	17
d_0	10
z_0	12
t	12
χ^2	10
Stub p_T consistency	5
Hit mask	15
Spare	2
Total	100

Trigger Primitives: Calorimeters

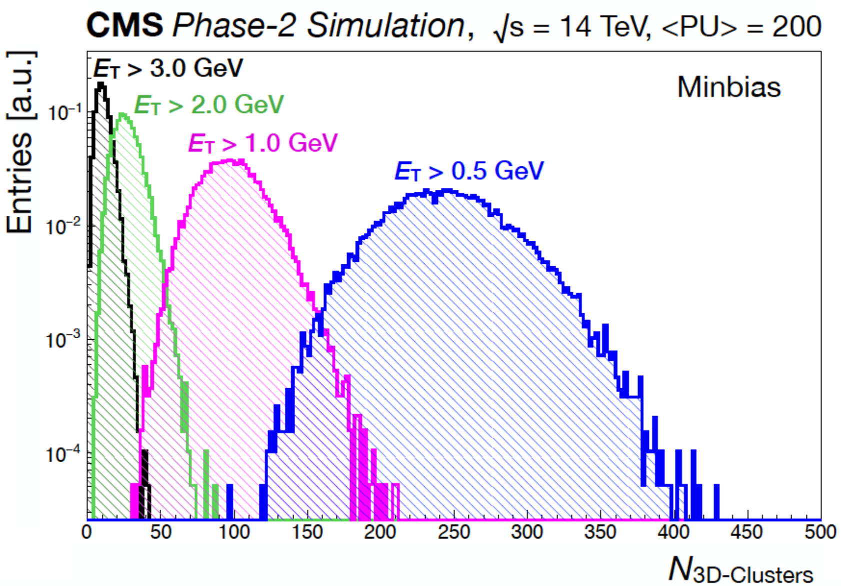
- **ECAL Barrel**
  - EB TPG (back-end electronics) will receive **crystal data** from the detector:
    - 216 card, 300 crystals each, 18 crates
  - Baseline EB TP: **single crystal 16 bit word for each of the 612000 crystals (with E_T, time, spike flag),** sent via 12 16Gb/s links per card
  - Studies of **cluster primitive word** generate by EP TPG are on-going



- **HCAL Barrel**
  - Number of readout channels for transverse segmentation, longitudinal readout depths as after LS2 upgrade
  - the depths samples for each tower (2304) are summed and a peak detection algo is applied
  - **HB TP: tower E_T and longitudinal shower profile data**

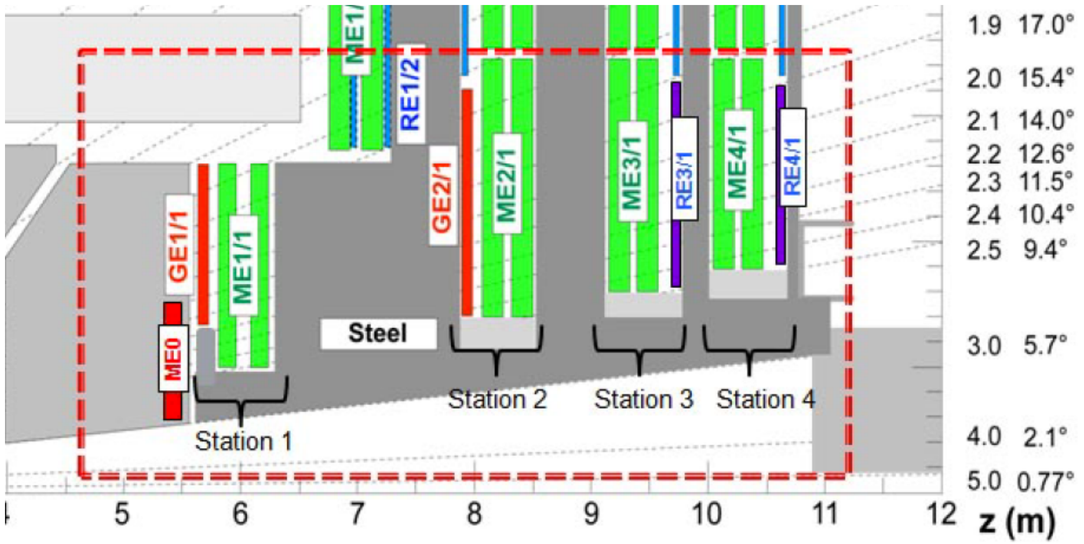
Trigger Primitives: Calorimeters

- **HGCAL**
  - Each EM or HD trigger layer provide **"trigger cells"** (sums over individual channels, ~ 4cm² in the silicon layers) with front-end electronic E_T threshold
  - **The TPG proceed in two stages**
    - for each layer: **2D clusters from trigger cells**, sum tower data into a single η-φ grid.
    - combine the 2D clusters in depth to form **3D clusters**, combine all the single-layer tower map data into the **complete transverse energy tower map**
    - Time-multiplexing to transfer all the 2D clusters and tower maps into one FPGA for 3D mapping; preliminary **firmware implementations indicate TPG within 5 μs**
  - **E_T threshold on 3D clusters** is needed
    - to match the needs of the PF@L1 **E_T>1 GeV seems appropriate**
    - 400 clusters per bunch crossing, total bandwidth of 120 kb, 300 links running at 16 Gb/s



Trigger Primitives: Muons

- **Barrel**
  - **DT TPG and RPC link board system will be replaced to exploit DT system 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
    - under study: **include hits position to allow full fit in BMTF**
    - under study: **TPG that combines both DT and RPC primitives**
    - under study: **receive stubs from Outer Tracker via TF (for tracks from displaced vertices)**
- **Endcap**
  - **TP for existing detectors will not change**
  - The Phase-2 coverage will be extended by the addition of **iRPC and GEM which will all provide TPs to the L1 trigger**
  - GEM TPs clusters from hits in each GEM layer, transmitted on 252 10 Gb/s links
  - GEM-CMS integrated local trigger to improve local reconstruction: new data format for CSC TPs
  - iRPC TPs transmitted on 48 10 Gb/s links



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

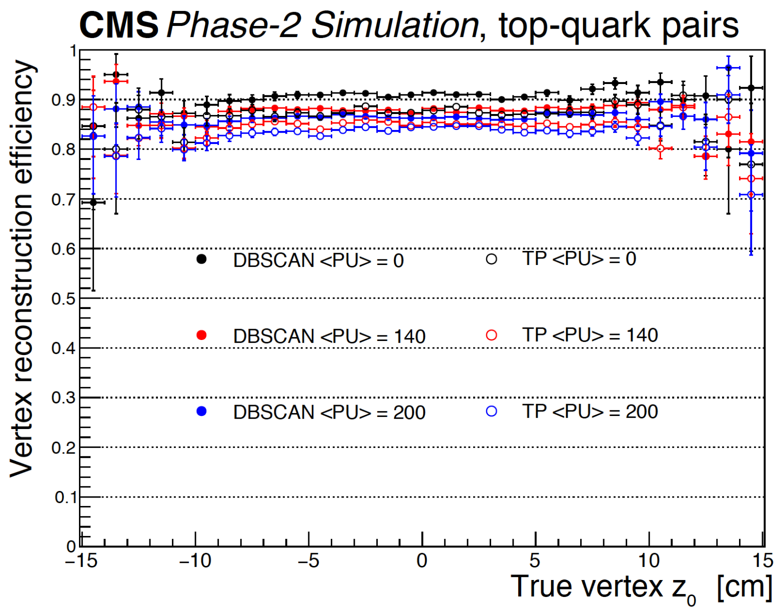
Trigger Algorithms

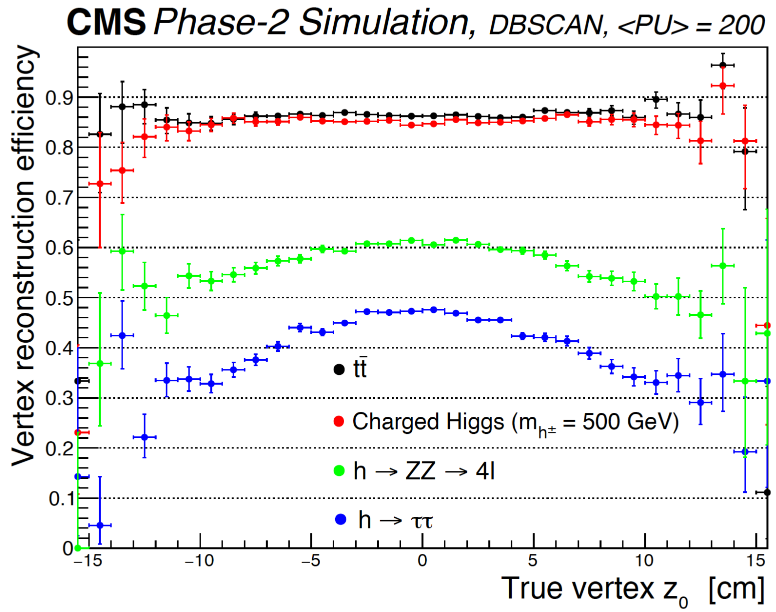
- **Already proven (2015 TP) that to maintain Phase-1 trigger thresholds it's crucial:**
  - **identify the PV to mitigate PU effects**
  - **match the performance of offline algo** with extensive use of tracking information: well match algo provide **sharpened turn-on of the efficiency, reducing rate, 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, does not require pre-sorting, **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**

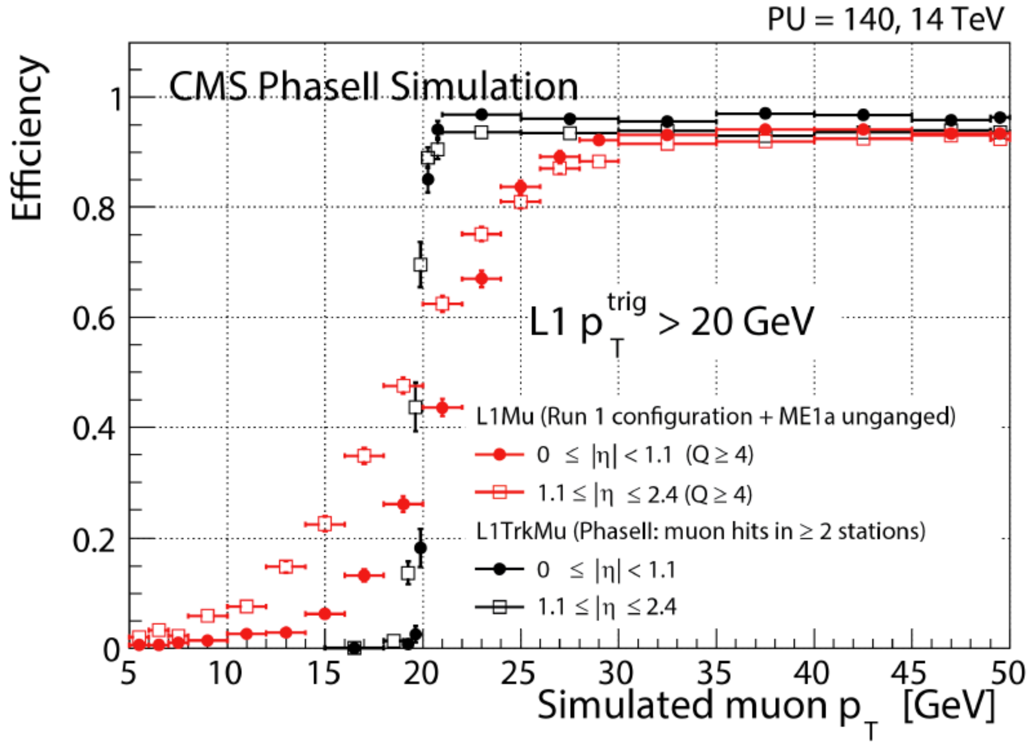




Muons (tracked-matched)

- 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 $p_T > 20$

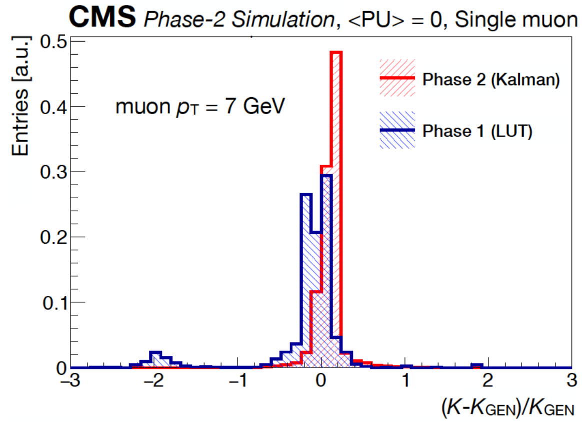
- **Matching with L1 Tracks provides a major improvement**
  - Studied at TP time with RunI L1Muon algo in input
  - Inside-out and outside-in matching algo (same performance)
  - **Efficiency > 95%, online-offline offset negligible, factor 6 to 10 of rate reduction for SingleMu $p_T > 20$ GeV**
  - Rate reduction in DoubleMu trigger thanks to $dz_0 < 1$cm

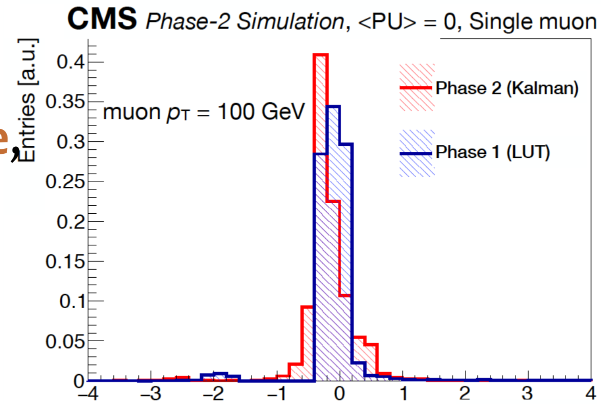


still valid also at PU 200

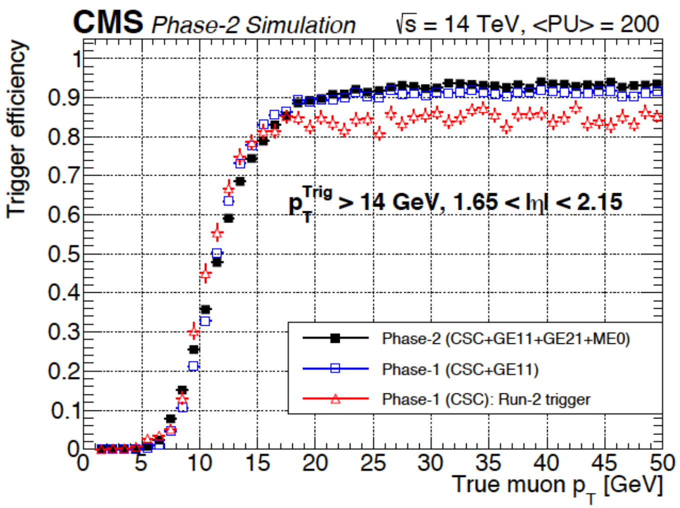
Muons (stand-alone)

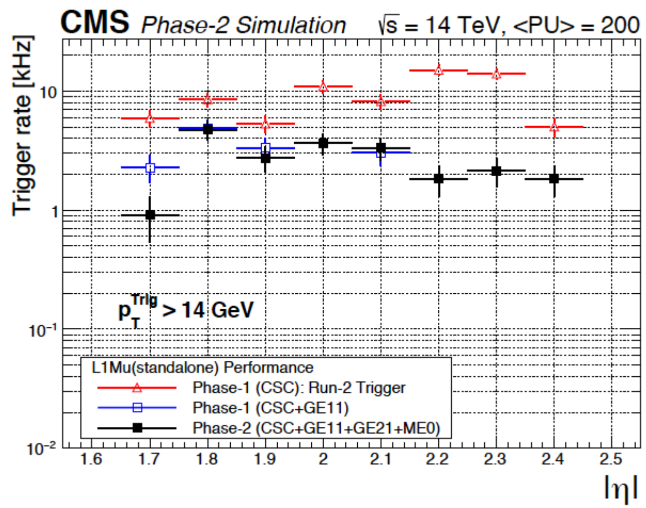
- **Improvements in barrel stand-alone momentum resolution (Phase-2 vs -1)**
  - Exploitation of **DT full spacial resolution** thanks to electronic upgrade
  - **Use of advanced FPGAs** with large number of DSP cores, large numbers of LUTs, and can operate at high clock frequency, is essential to develop 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**





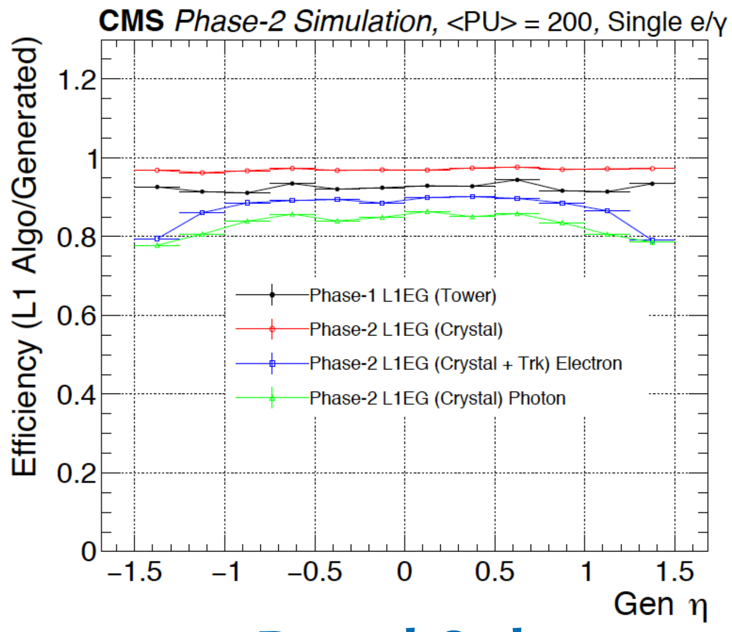
- **Improvements in Muon Endcap trigger efficiency and rate reduction thanks to new chambers**





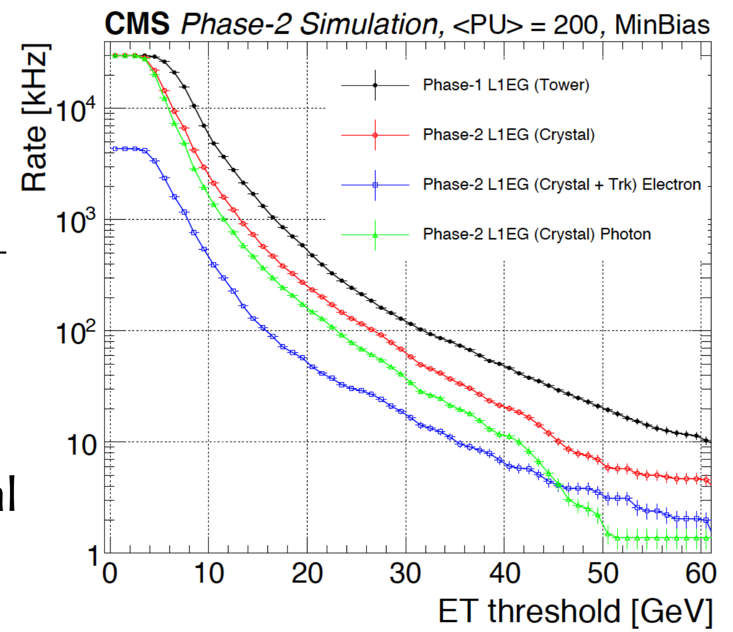
Electrons and Photons

- **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**



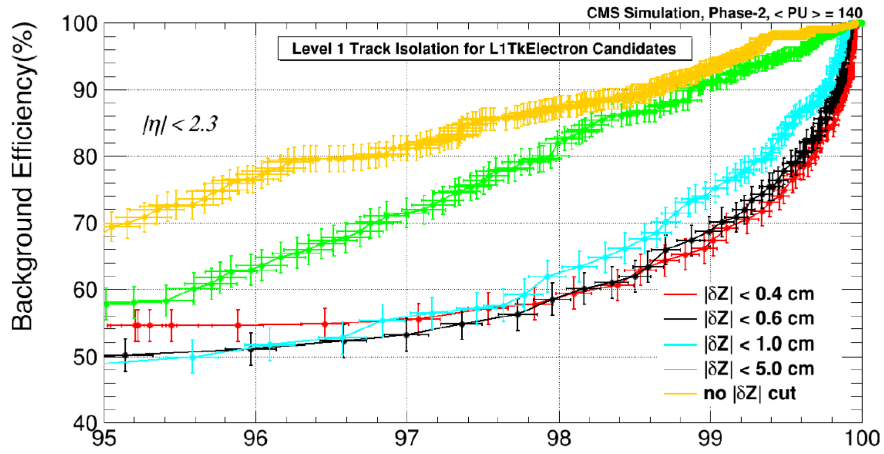
Barrel Only

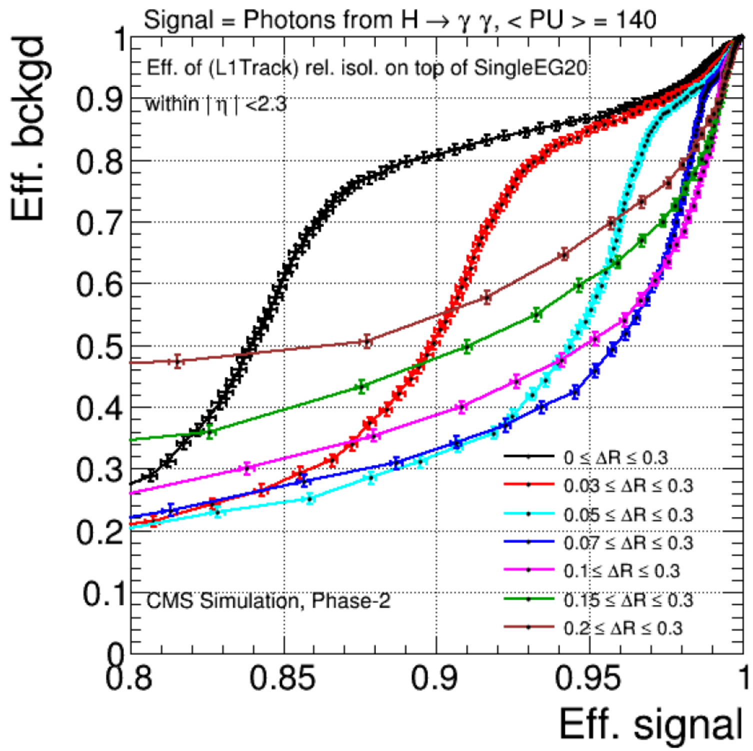
- **Track matching: rate reduction**
  - L1 Tracks are extrapolated to the ECAL surface and matched to EM clusters.
  - **To maximise electron reconstruction efficiency:**
    - looser matching windows in tracking algo and track p_T determination only with innermost hits
    - track selection and matching 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





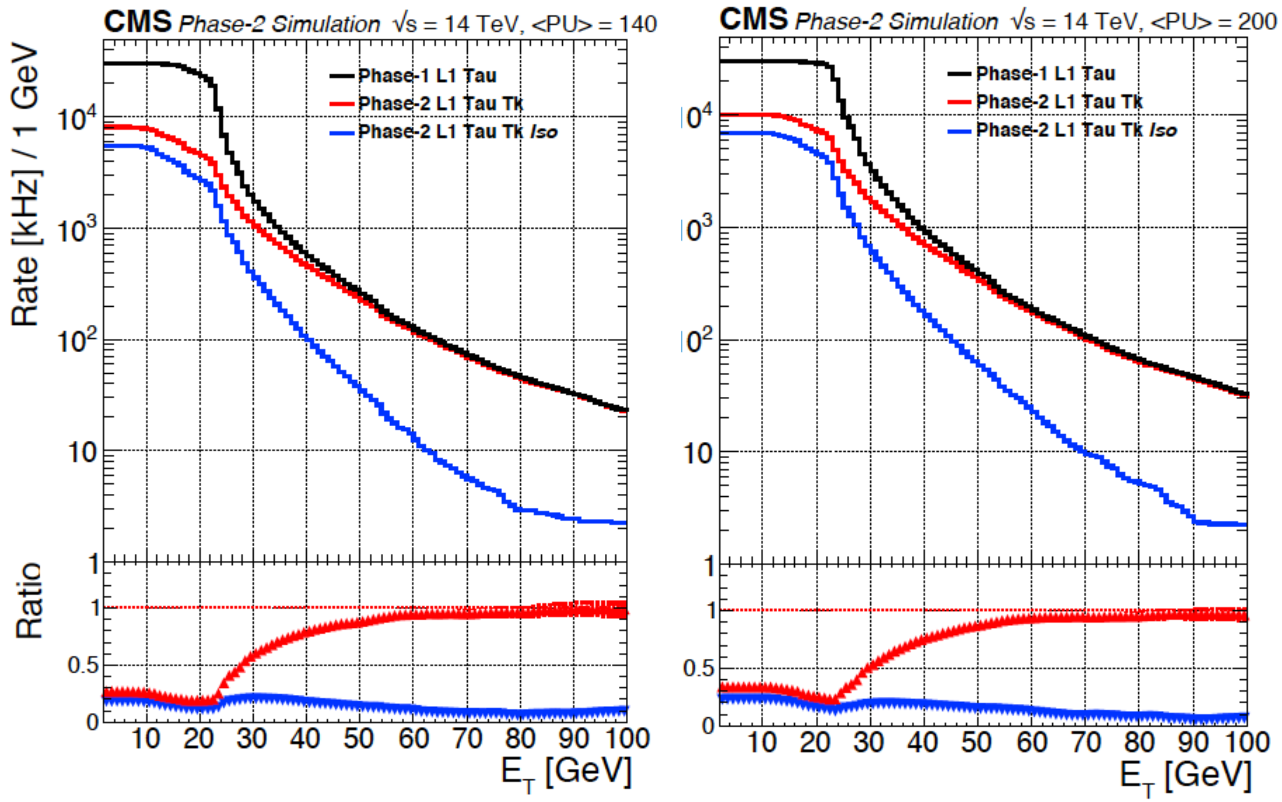
Factor 2 in bkg reduction for 95% signal efficiency

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**)

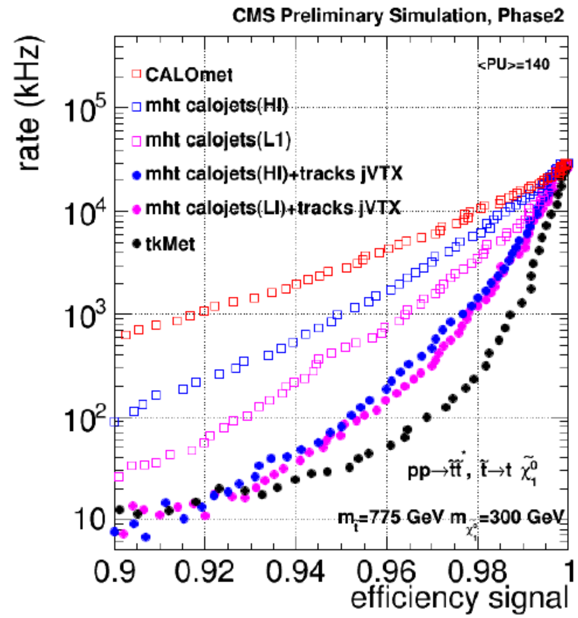
- **Single Tau trigger**
  - 50 kHz at PU200(140) with thresholds: **90(78),90(78), 52(46) GeV**

- **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**

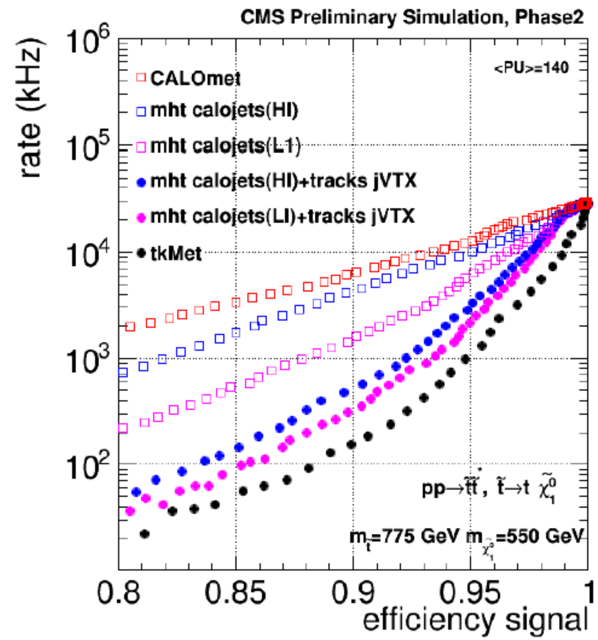


Jets, H_T, MH_T, E_T^{miss}

- **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

New algorithms: PF@L1

- With L1 Tracking new opportunities for algo more closely matching offline and HLT: great benefits from **combining the complete detector information using the Particle-Flow algorithm**

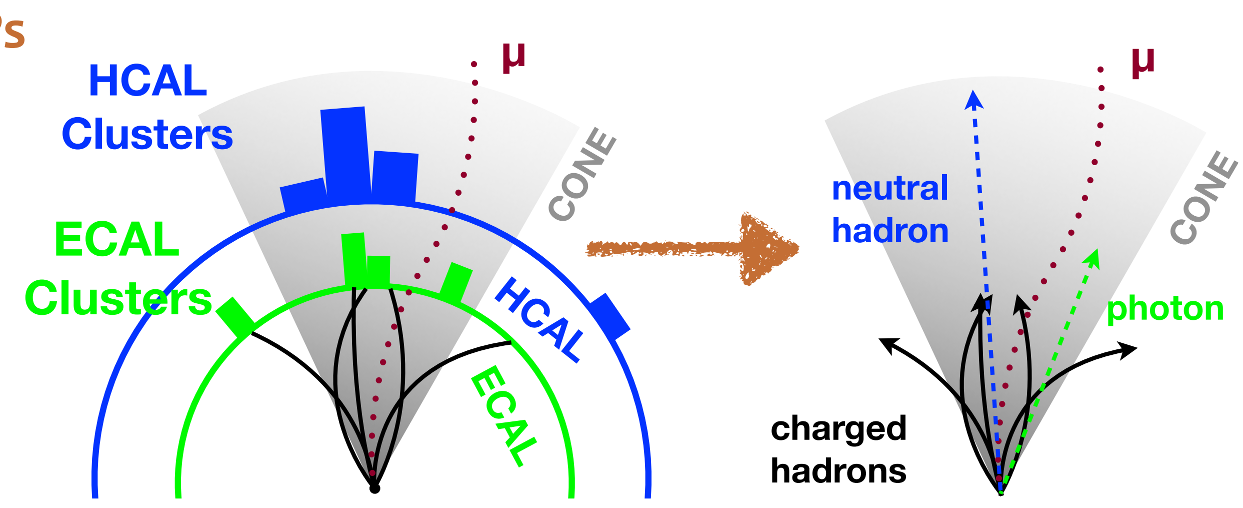
Calorimeter, Muon, Tracker TPs

↓

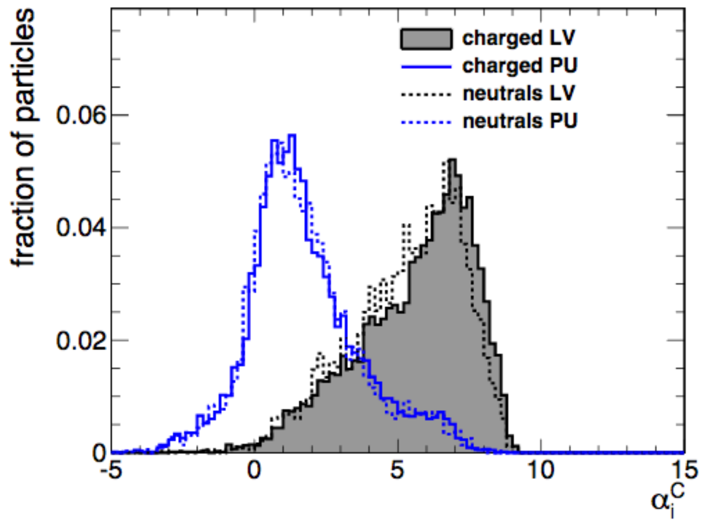
Charged and neutral hadrons, photons, muons, electrons

↓

E_T^{miss}, H_T, jets, prompt muons, electrons, τ_h, photons

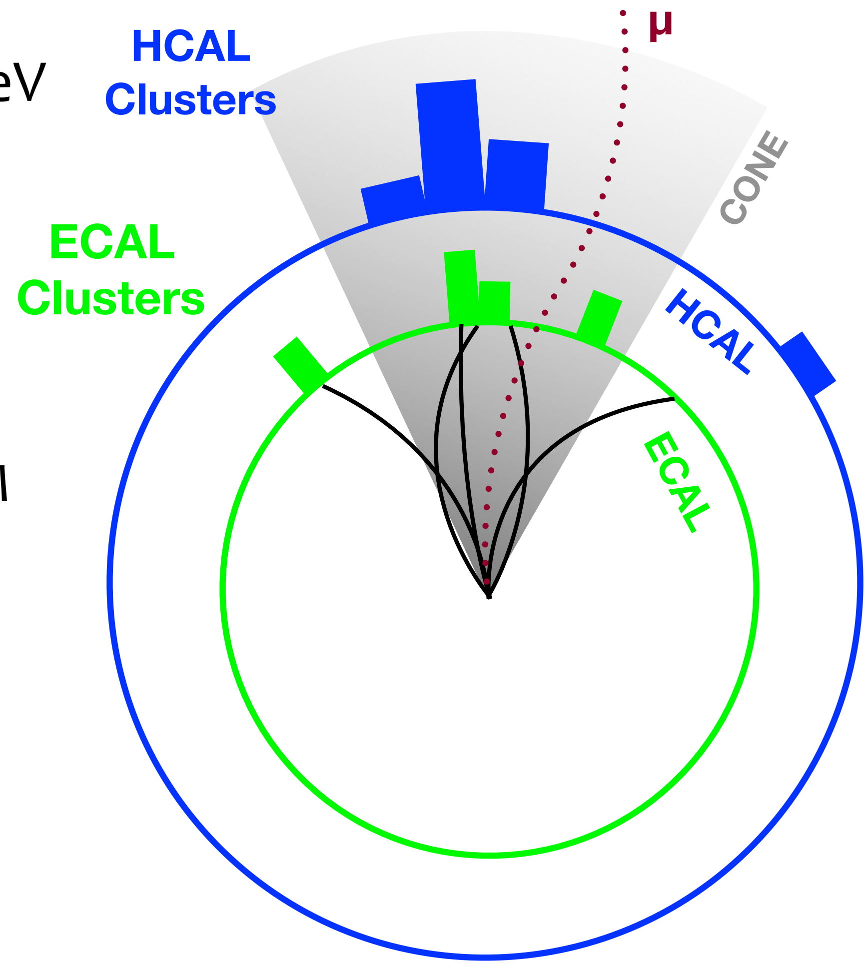


- **Pile-Up-Per-Particle-Identification (PUPPI)** on PF candidates greatly mitigate PU effects
  - uses **vertexing info from tracks and QCQ-based ansatz function** to define a particle weight



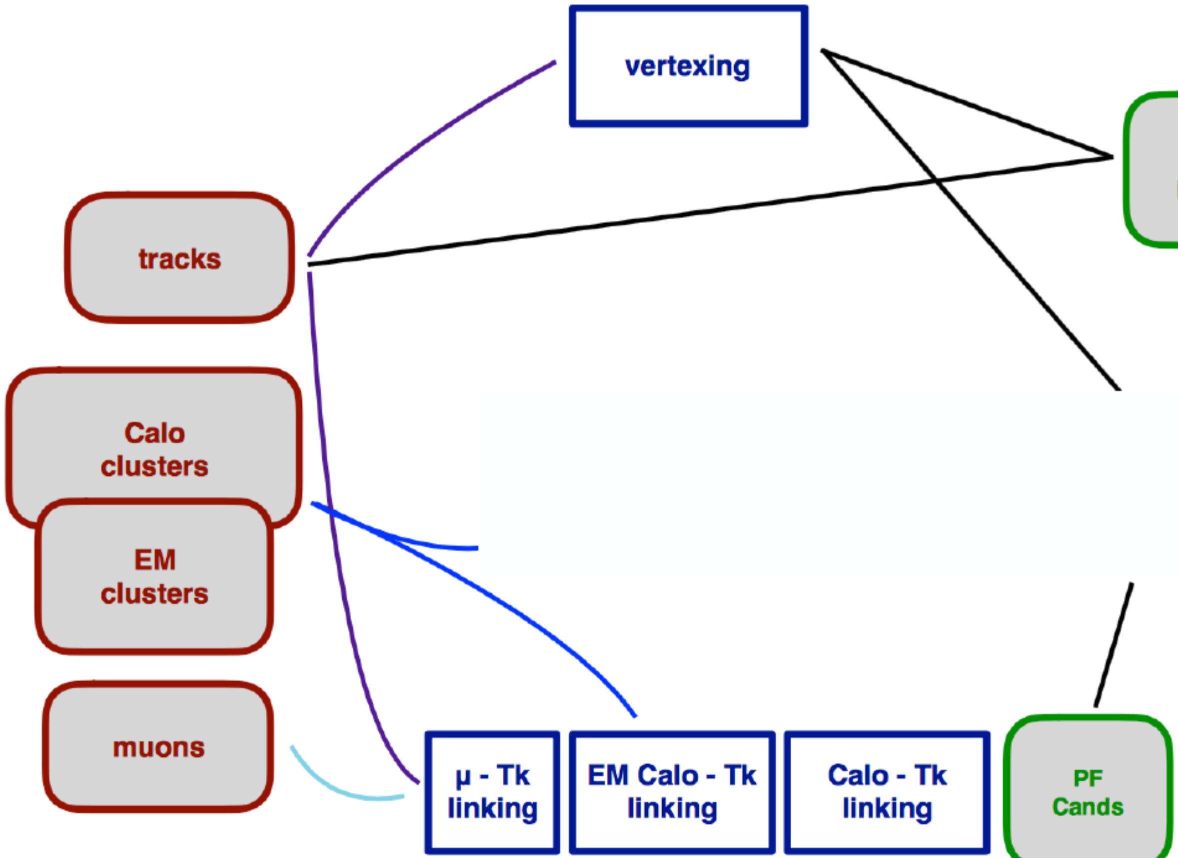
PF Inputs

- **Details of trigger primitive inputs to the PF (92X simulation)**
  - **Tracks:** tracklet objects from L1 TF $p_T > 2$ GeV
  - **EM Clusters:** use finest granularity
    - barrel: 3x5 clusters TPs
    - endcap: EM part of HGCal 3D Clusters
  - **Calo (EM+HAD) Clusters:** still coarse
    - for each trigger tower (Phase-1) sum of EM Clusters, HCAL towers, HGCAL FH trigger cells, HGCAL BH offline rechits (not yet available in simulation)
    - old 3x3 tower clustering algorithm: linking can assume one cluster per particle
  - **Muons:** stand-alone muon TPs



PF+PUPPI algo

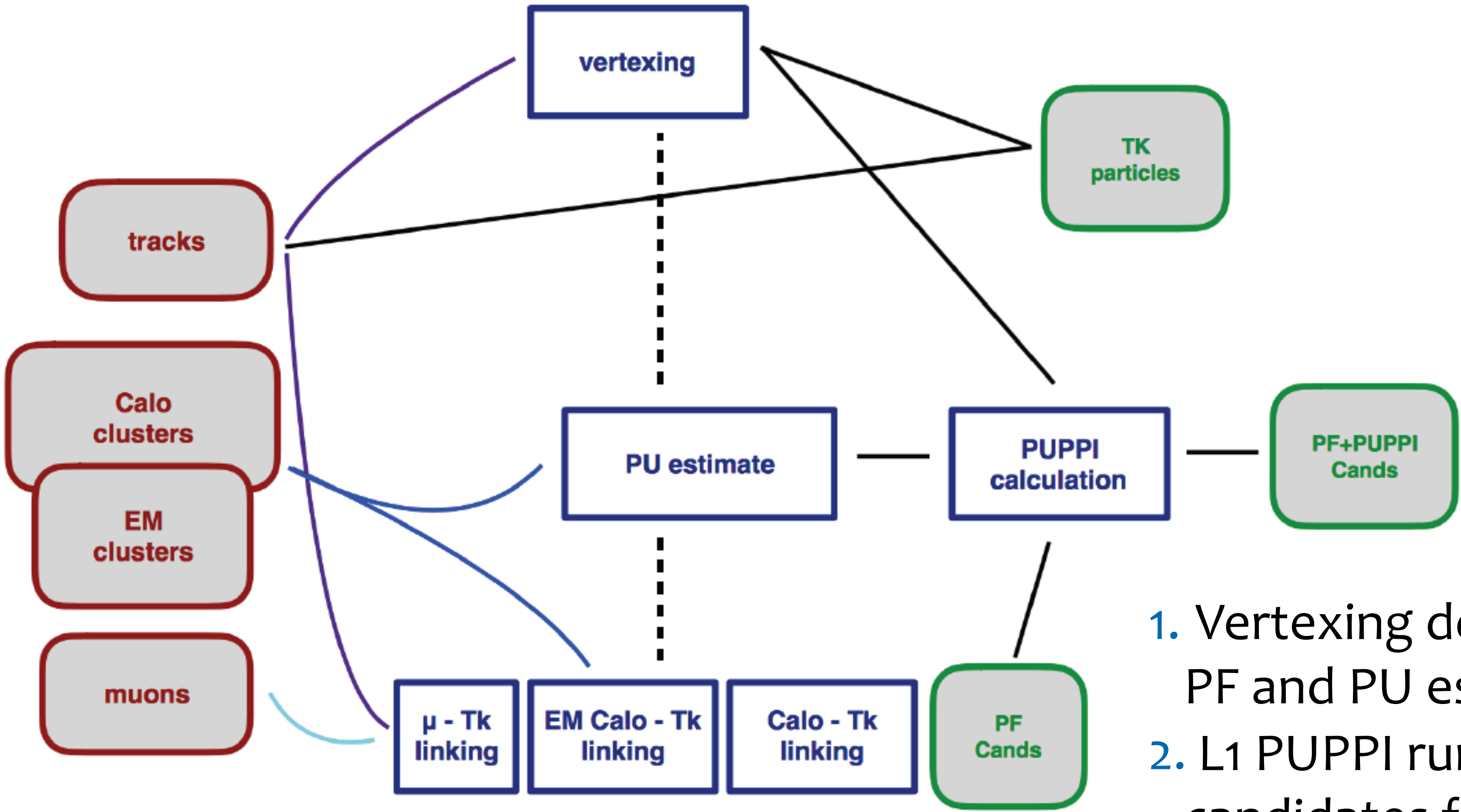
- Algo complexity reduced wrt offline-software (integer operations)
- **Basic PF Algo steps:**



1. Link tracks to EMClusters/Muons > **Muons**
2. Process EM clusters
   - no tracks: EM > **Photons**
   - tk p_T < EM p_T: EM > **Electrons**
   - tk p_T > EM p_T: likely hadronic activity from $\pi^{\pm}$, ignore EM cluster and rely on Calo clusters
3. Remove electrons and photons from Calo clusters
4. Reconstruct **hadrons** from Calo+Tracks

PF+PUPPI algo

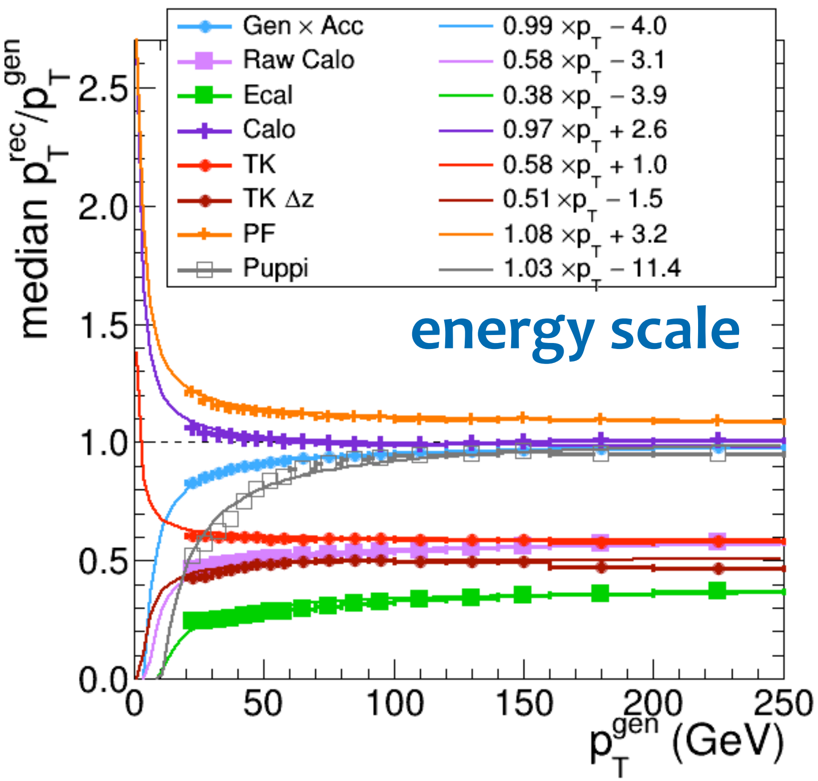
- Algo complexity reduced wrt offline-software (integer operations)
- **Basic PF+PUPPI Algo steps:**



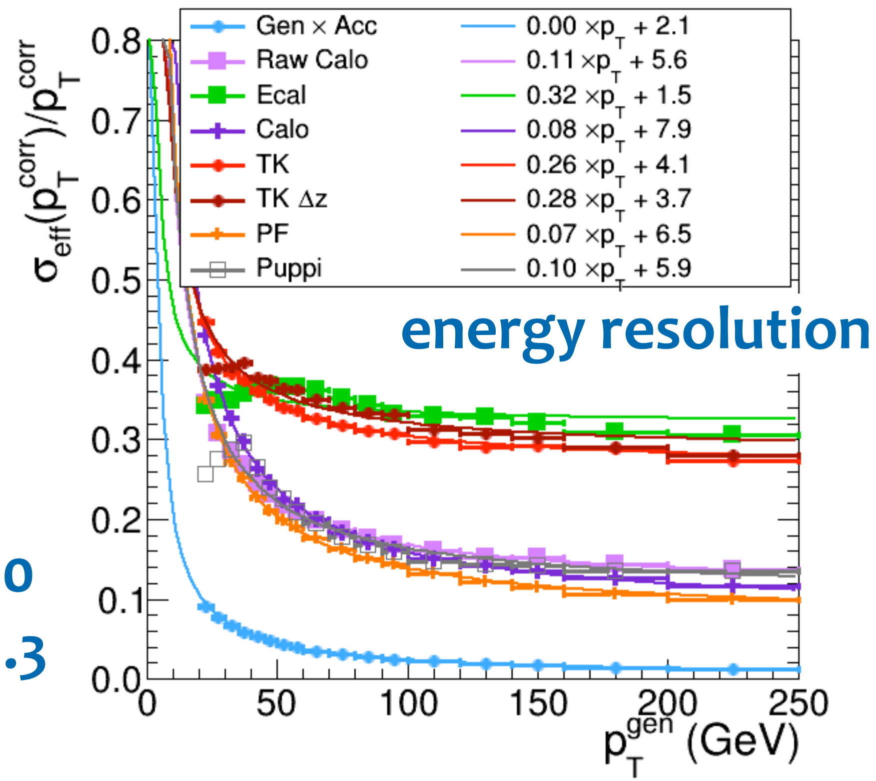
1. Vertexing done in parallel w/ PF and PU estimate
2. L1 PUPPI runs on global list of candidates from PF step
3. Output vertex-filtered list used for RECO/ID **> Prompt physics objects**

Jets response

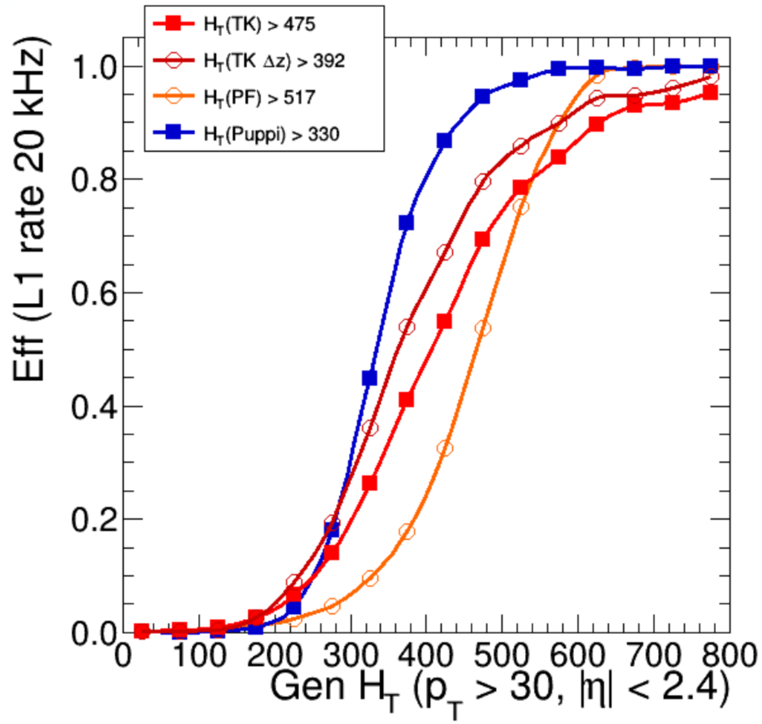
- **Derive energy scale and resolution calibrations for PF inputs from single particle response**
  - Energy scale and resolution response
    - EM Clusters: calibrated for π^0
    - Calo Clusters: calibrated for $\pi^\pm$ in bins of ECAL/(HCAL+ECAL)
  - Energy resolution response for tracks calibrated for $\pi^\pm$
- **Derive energy scale and resolution calibrations for jets after applying calibrations for single particle response**

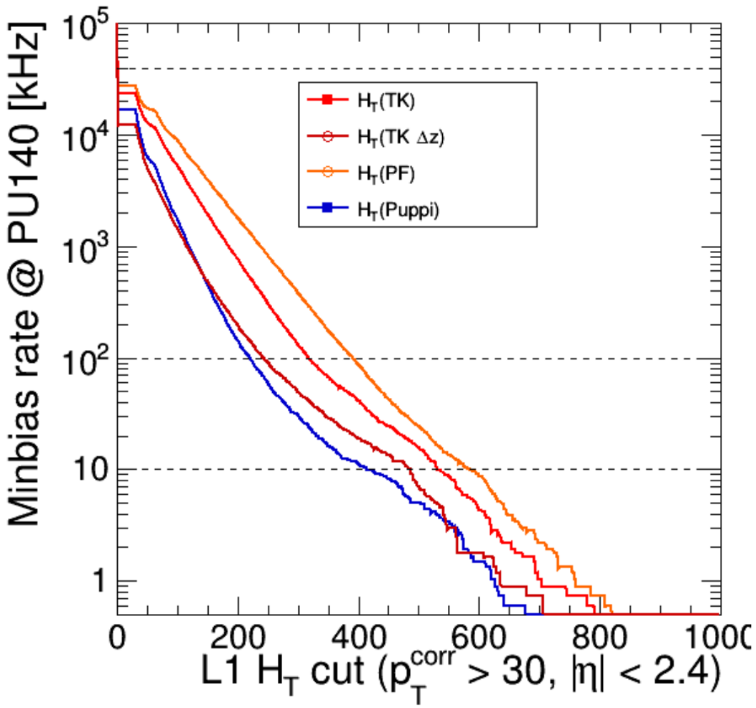


ttbar
PU 140
|η| < 1.3



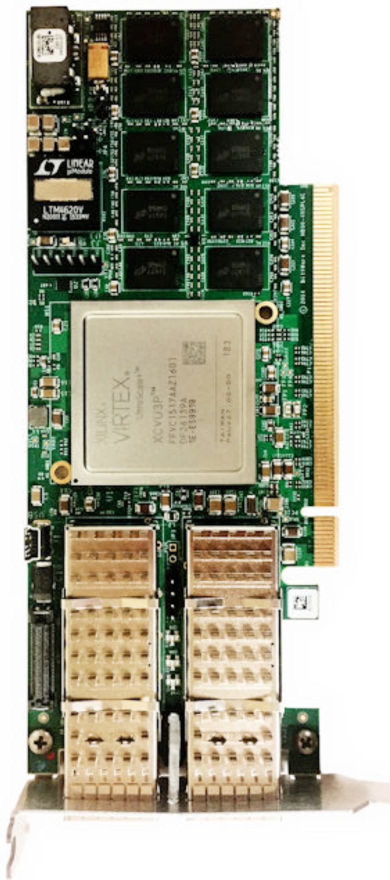
H_T trigger performance and more



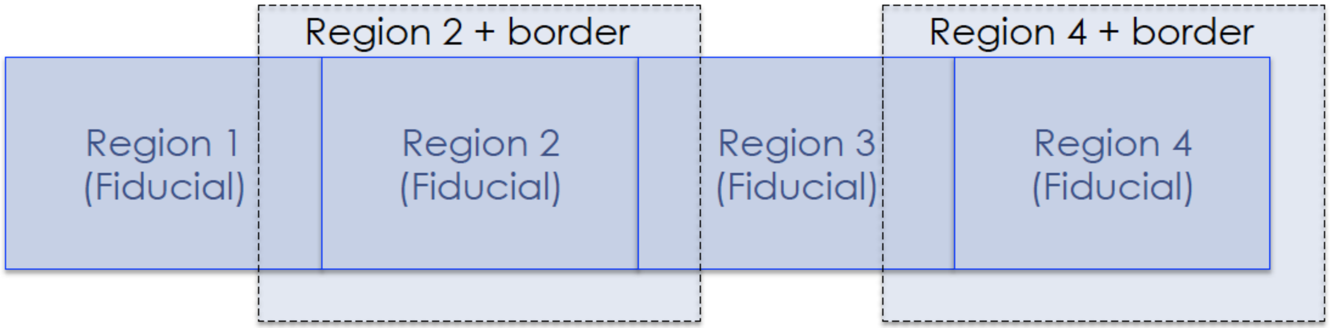


- **Comparing H_T trigger performance from PF-jets and Track-based jets**
  - Different quality cuts applied on L1 tracks (looser for PF), jets $p_T > 30$ GeV
  - PUPPI performance depend on PV to be properly reconstructed: easy in events with large high p_T tracks multiplicity (ttbar)
  - **PF+PUPPI 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**

Hardware implementation



- In addition to algorithm R&D activities, **started to develop PF and PUPPI in firmware** to optimise their total resources usage, within latency allocated for TC
  - **First early test using Vivado HLS demonstrates feasibility:** High-particle-density (25 tracks and 20 clusters) detector region ($\eta x \varphi$=0.55x0.55)
    - 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**
  - **Regions definition to be studied**
    - linking requires borders around them
    - duplicates can be removed after PF candidates generation



Other possible developments

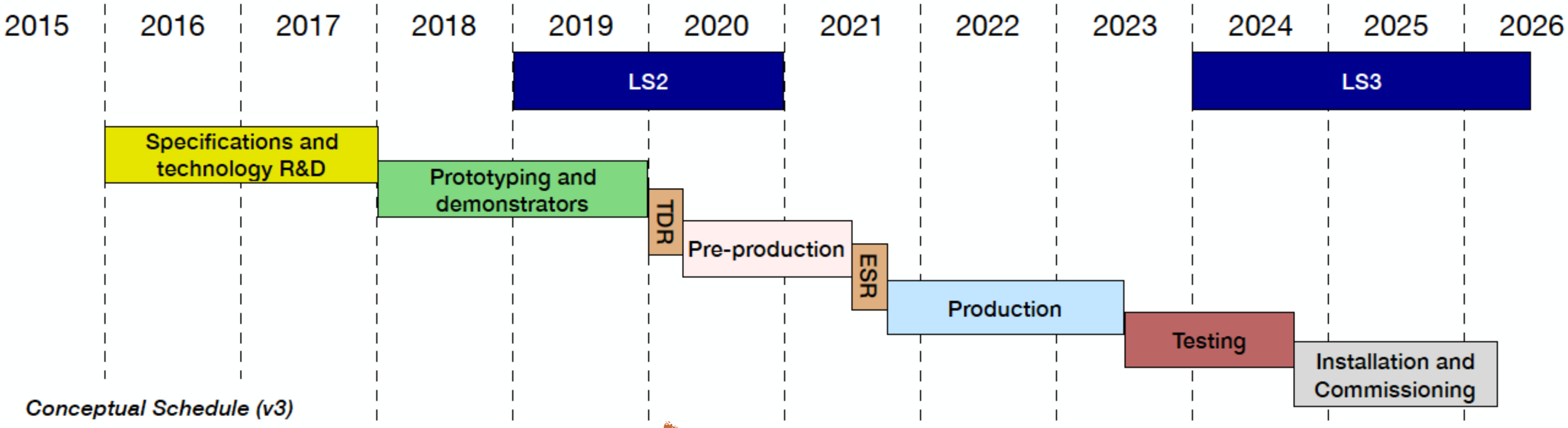
- The use of advanced FPGAs with ever greater processing resources will allow **a range of global algorithms, which will be extremely powerful thanks to the improved object position resolution** of Phase-2 TPs
  - Inter-object correlation (Run 1 L1 trigger for soft muon b-tagging of jets)
  - Invariant 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

[. . .]

List of institutions

Vienna	Institut für Hochenergiephysik, Wien, Austria
Beijing	Institute of High Energy Physics, Beijing, China
Cyprus	University of Cyprus, Nicosia, Cyprus
Tallinn	National Institute of Chemical Physics and Biophysics, Tallinn, Estonia
LLR	Laboratoire Leprince-Ringuet, Ecole polytechnique, CNRS/IN2P3, Universite Paris-Saclay, Palaiseau, France
NKUA	National and Kapodistrian University of Athens, Athens, Greece
Ioannina	University of Ioannina, Ioannina, Greece
TIFR	Tata Institute of Fundamental Research-B, Mumbai, India
Bologna	INFN Sezione di Bologna, Universit di Bologna, Bologna, Italy
Padova	INFN Sezione di Padova, Universita di Padova, Padova, Italy
Warsaw-IEP	Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland
Warsaw-INS	National Centre for Nuclear Research, Warsaw, Poland
CIEMAT	Centro de Investigaciones Energeticas Medioambientales y Tecnologicas, Madrid, Spain
CERN	CERN, European Organization for Nuclear Research, Geneva, Switzerland
Bristol	University of Bristol, Bristol, United Kingdom
RAL	Rutherford Appleton Laboratory, Didcot, United Kingdom
Imperial College	Imperial College, London, United Kingdom
FNAL	Fermi National Accelerator Laboratory, Batavia, USA
Boulder	University of Colorado at Boulder, Boulder, USA
Boston	Boston University, Boston, USA
MIT	Massachusetts Institute of Technology, Cambridge, USA
UIC	University of Illinois at Chicago, Chicago, USA
TAMU	Texas A&M University, College Station, USA
Davis	University of California, Davis, Davis, USA
Northwestern	Northwestern University, Evanston, USA
Florida	University of Florida, Gainesville, USA
Rice	Rice University, Houston, USA
UCLA	University of California, Los Angeles, USA
Wisconsin	University of Wisconsin - Madison, Madison, USA
Rutgers	Rutgers, The State University of New Jersey, Piscataway, USA
Princeton	Princeton University, Princeton, USA

Next steps towards TDR



2018 - *Software emulator demonstrates implementation of core Phase-2* ***trigger menu with prototype trigger algo;***

- ***Benchmark performance baselines*** *for representative sample of core trigger algorithms*
- ***Definition of hardware technology implementation baseline***
- ***Test setups*** *of 1st-generation demonstration processors; allows local comparisons with emulators;*

2019 - ***Benchmark performance baselines*** *for all core triggers algo;*

- ***Test setups*** *of 2nd-generation demonstrators show integration and scaling; allows global / full chain comparisons with emulator;*

2020 - ***Phase-2 Trigger Technical Design Report (TDR).***