Combining information from the tracker, calorimeter and muon systems at L1 in CMS phase-2

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Overview of the simulation results presented in the CMS phase-2 Technical Proposal :
CERN-LHCC-2015-010
https://cds.cern.ch/record/2020886

HL-LHC : challenges for the L1 trigger

- To fully explore the EW scale : trigger thresholds should remain comparable to what they are at Run-2
  - but with an instantaneous luminosity up to O(10x) larger than seen so far
  - and 3-4x larger than phase-1
  - that comes with a much higher pile-up : up to PU = 200 (w.r.t. 50 at φ1)

- That is challenging for the L1 trigger since
  - Higher rates
  - hadronic triggers : rate blow up with increasing PU
  - usual isolation criteria for leptons (calorimeter-based) heavily affected by PU

For the desired thresholds (L1TDR for phase-1 upgrades) : the phase-1 trigger system would give a L1 rate of >>> 100 kHz (current L1 bandwidth).

HL-LHC : planned improvements to the L1 system

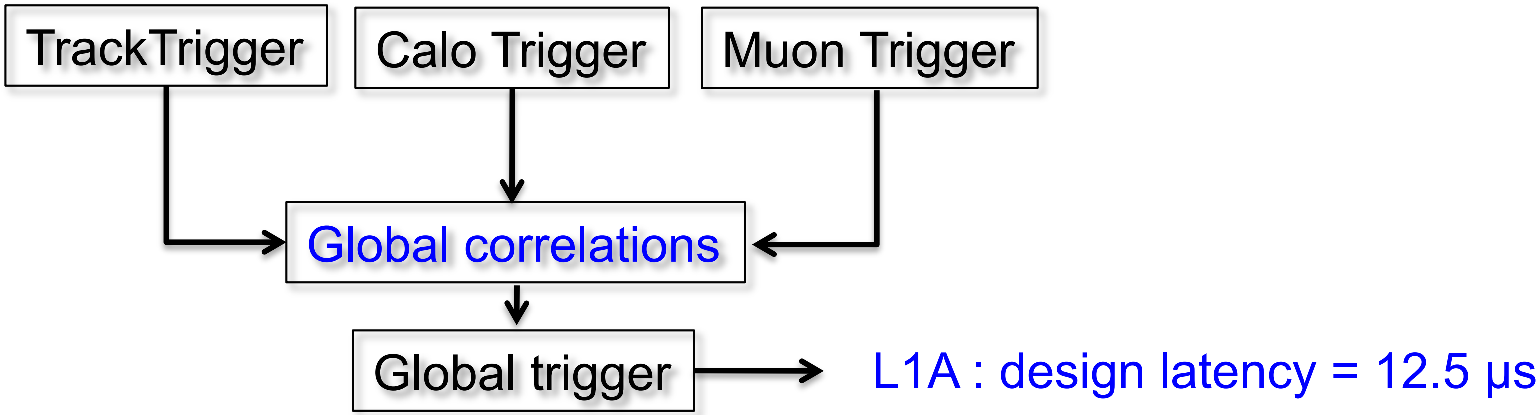
- Muon rates in the fwd region further reduced by the addition of new detectors

- HGCal calorimeter in endcap: High granularity + long. segmentation at trigger level
  - offers additional handles to electron, jets, tau ID

- Barrel ECAL : crystal-level granularity available at L1 (instead of 5x5 crystals currently)
  - improves the rejection of spikes, reduces rates of e/γ objects by O (2)

- L1 bandwidth increased (currently limit = 100 kHz)
  - In a first step to 300 kHz (HLT CPU), ultimately up to 750 kHz

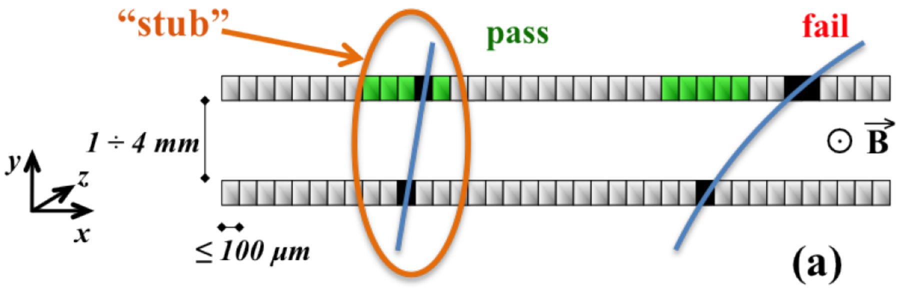
- Tracks from the outer-tracker will be available at L1 (cf HLT)
  - Object identification at L1 combines calo / muon and tracker information



CMS L1Track trigger

See dedicated session on Tuesday

Tracker layers / disks made of two closely spaced sensor layers.
Hit correlations provide pT discrimination :
“stub” = consistent with pT > (say) 2 GeV



- Stubs determined in the FE electronics
- Pattern reco / fit done in the BE, inputs = the stubs.
    - several approaches being considered

Self-seeded system (“push design”) :

- all stubs are sent to the BE : O (10k) stubs / BX = O (50) Tbps
- L1Tracking run in the whole detector (no “regions of interest”)
- O (100) L1Tracks (pT > 2 GeV) per BX (5x lower for pT > 5 GeV)

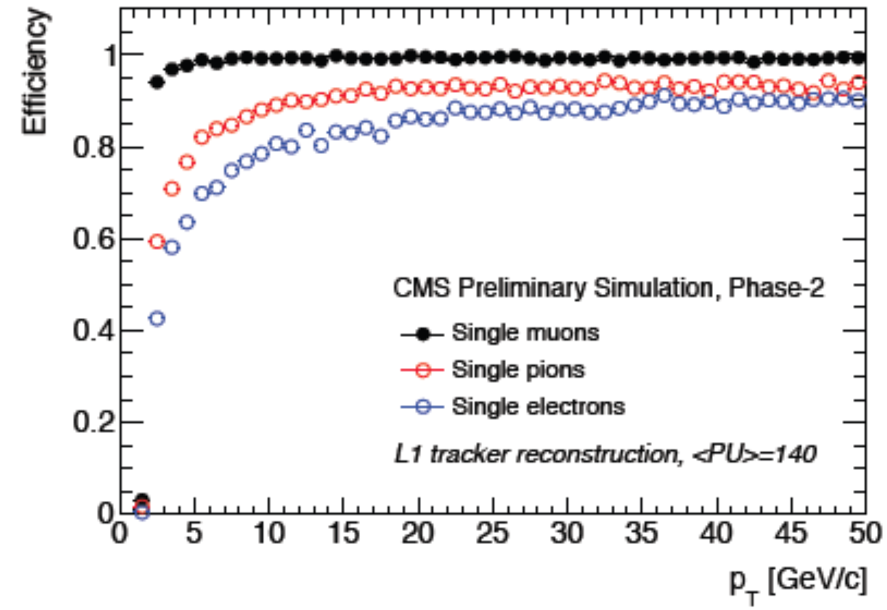
Trigger algorithms make use of these L1Tracks :

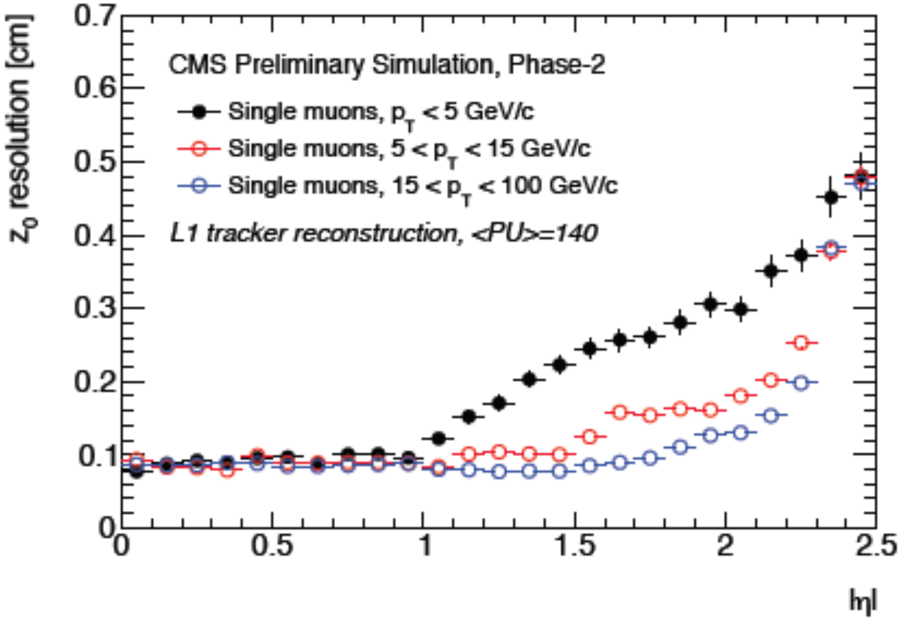
- track parameters at the IP, esp. pT, η, φ, z0, (d0)
- track quality criteria (e.g. number of stubs, ~ chi2 of the track fit)
- first estimations: O(100 bits) per L1Track

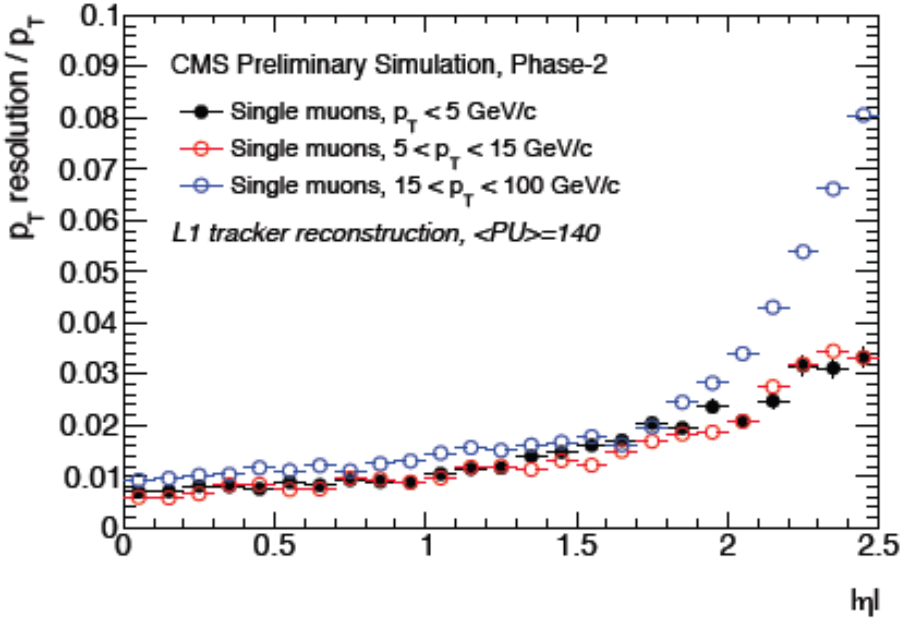
L1 Tracking Performance

C++ simulation of L1Tracking (“tracklets”) fully implemented in our standard simulation chain.

- Examples of expected L1 tracking performance from simulation
  - Efficiency: >99% (90%) for μ (e) in plateau region
  - Resolutions: $\sigma(z_0)$~1mm and $\sigma(p_T)/p_T$ ~ 1% at central eta







How L1 tracks help in a nutshell

- Muons : improve the pT determination

- Electrons : match a L1Track with a calorimeter e/γ candidate : helps ID

- Muons / electrons : tracker-based isolation
    - Can also be used for photons

- Taus : track + calo improves the tau identification

- Multi-object triggers : require that the objects come from the same vertex
    - Especially useful for multi-jet triggers
        - L1Tracks allow the "jet vertex" to be reco'ed
    - and triggers based on HT (= Σ pT of all jets) or Missing-HT (= Vec-Σ pT of jets)

- Track-based missing ET can be reconstructed
    - Once we reconstruct the primary vertex

Framework for the simulation studies

L1Tracks simulation : tracklet approach used here (fully implemented in standard sim)

L1 objects reconstructed from the calorimeter trigger :
- use the current calorimeter
- e / γ : mostly the algorithms that will be run in 2016 [unless stated otherwise]
- jets : algorithm quite similar to L1 phase-1 TDR, retuned for higher PU
  - studies limited to | η(jet) | < 2.2

L1 muons :
- basically the 2015 configuration and algorithm

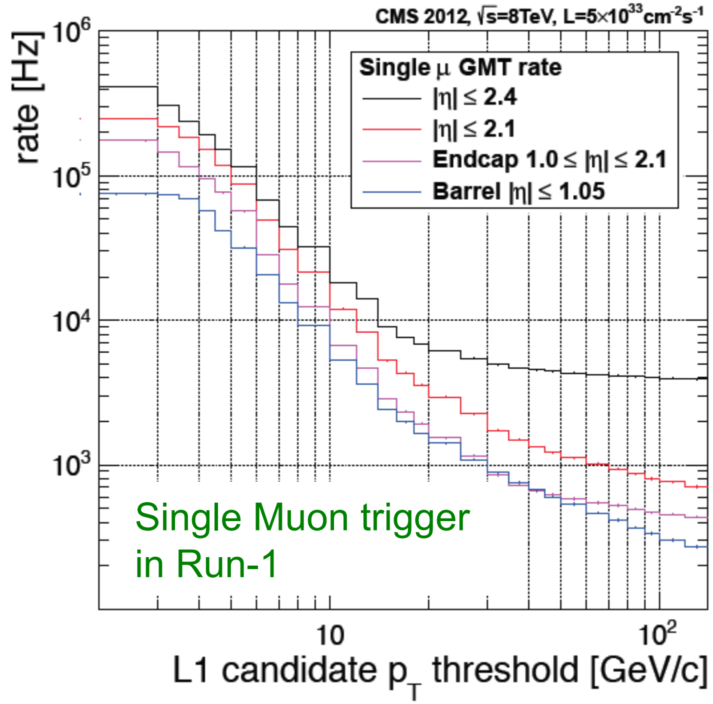
Rates: determined over a Monte-Carlo sample obtained by overlaying 140 Minimum Bias events, 14 TeV (case PU=200 also studied).

Performance of a trigger condition:
- trigger rate vs trigger threshold
- target rate for a single trigger : O (10 – 50 kHz)
  - could devote O(10%) of the L1 bandwidth to important / widely used triggers
- “ROC curves” : rate vs efficiency (e.g. over benchmark process)

Muon Trigger

Current single-Muon trigger : rate driven by the limited resolution of the L1Muon system, especially tails: low pT muons seen as high pT at L1

→ trigger rate flattens out at high pT



Phase-1 upgrades will improve the pT determination, esp. in fwd region.

Phase-2: much improved pT determination will come from matching stand-alone L1muons to L1Tracks, and assigning pT(muon) = pT(L1Track).

Two algorithms have been implemented :

- inside-out : seed = L1Tracks, extrapolated to the muon stations using the parameters of the L1Track
- outside-in (for central muons) : seed = stand-alone L1Muons, extrapolate the traj to the beamline using the bending angle measured in the muon station.

In each case: search for a match (a L1Muon, or a L1Track) within predefined windows in (Δη, Δφ). Comparable performances.

Muon trigger

Much better pT determination brought by the tracker leads to much sharper turn-on…

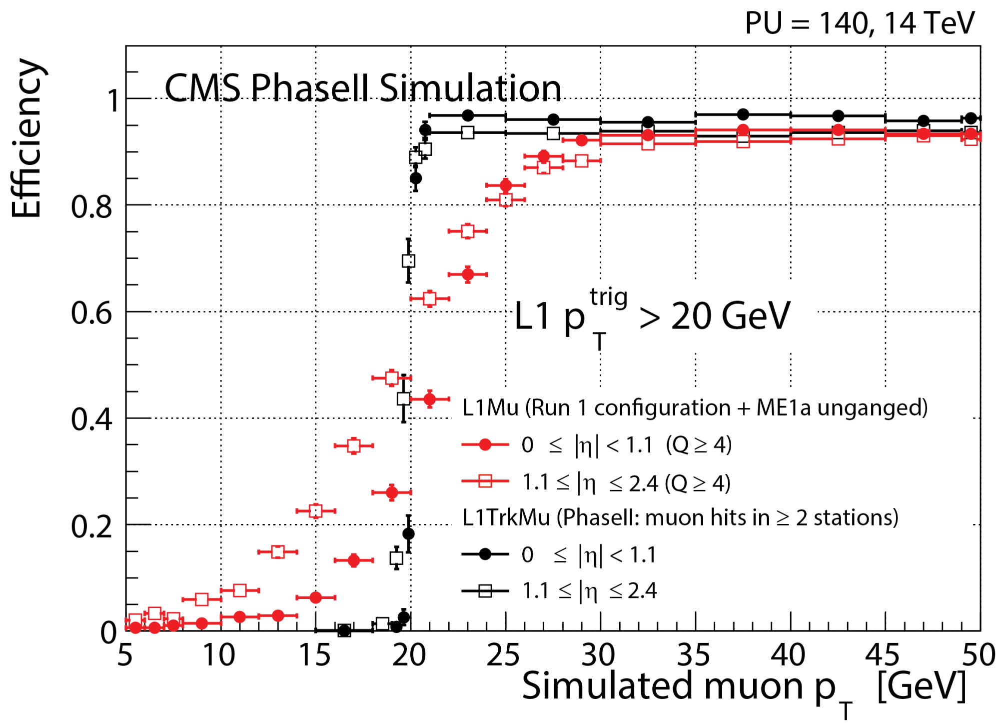
PT resolution improves from O(20%) to O(1-2 %)

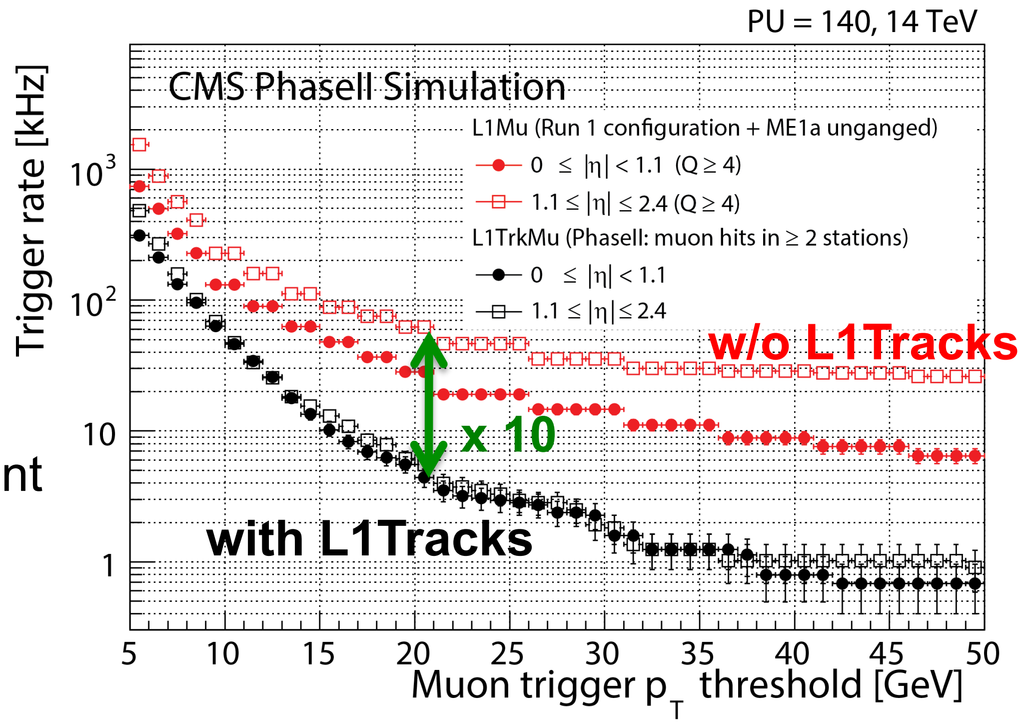
…which results in much lower rates (contribution from mismeasured low PT muons much reduced).

For a pT threshold of 20 GeV: rate is reduced by O(10) w.r.t. Run-1 like (*) L1Muons

(*) combined simulation of L1Tracks with phase-1 L1Muons not available yet

Genuine rate still O(4 -5) lower. Better stand-alone pT measurement will lower the rate further.





Electron trigger

Start from calorimeter L1EG (e / γ) candidates.

- main results shown here use the phase-1 calorimeter, 2016 L1EG algorithm, based on trigger towers (5x5 crystals)

Simple matching of the L1EG object with a L1Track : Δφ and ΔR cuts

- track extrapolated to the calorimeter and Δφ with L1EG
- in Δη, η(L1EG) is corrected for the vertex position using the z0 of the track

The ET of the matched object is given by the calorimeter ET.

Separate optimizations for high ET and lower ET L1EG

- for L1EG with ET > (<) 20 GeV, match to tracks with pT > 10 GeV (3 GeV)

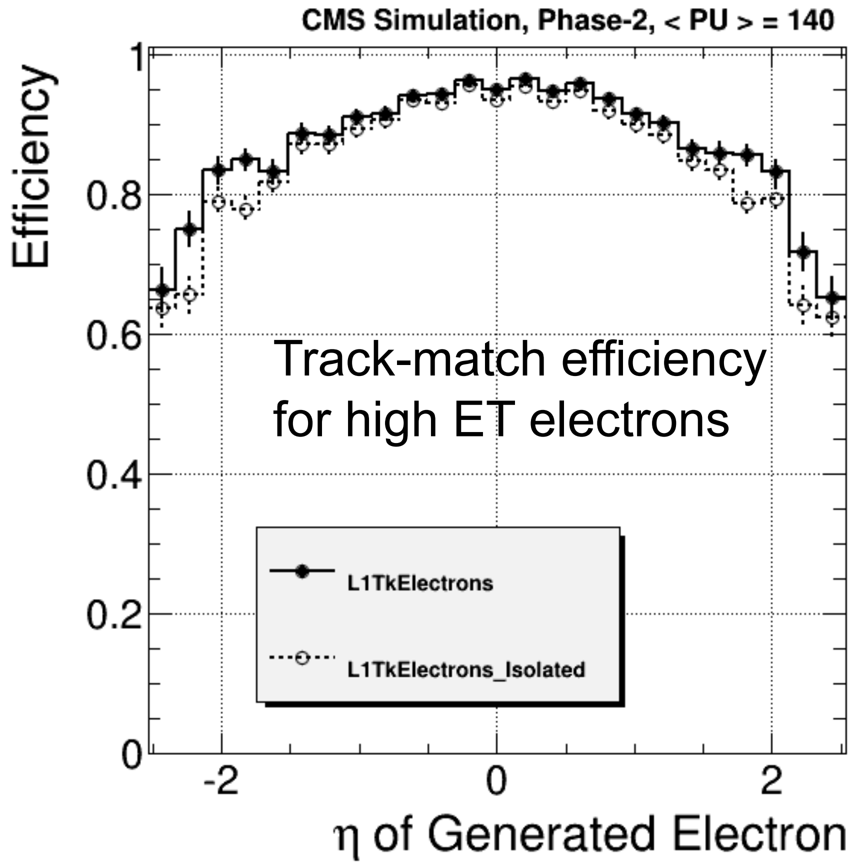
Note : matching the L1EG objects with stubs in the tracker layers has also been considered

- but more complicated implementation, and performances not better

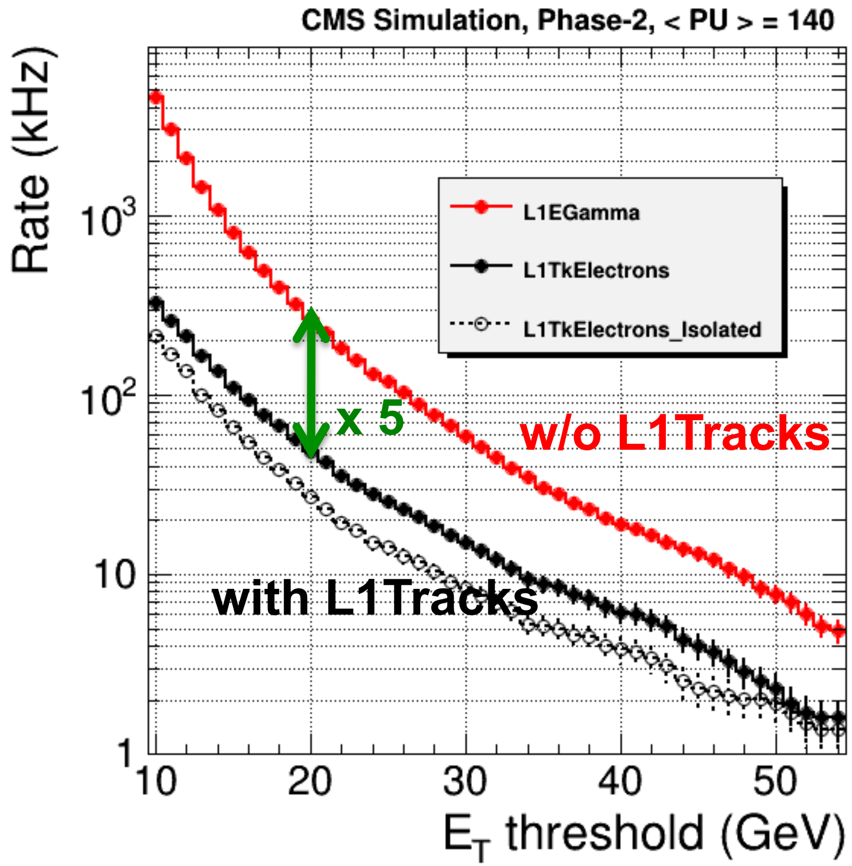
Electron trigger

Challenge : retain a high track-match efficiency

- lower track ε for electrons due to brems



Algorithm uses tracks with looser criteria (esp. dedicated extrapolation windows, in the "tracklet" approach)



For an efficiency of > 90% in the central region: track-matching reduces the rate of a single-electron trigger by O(5) at 20 GeV

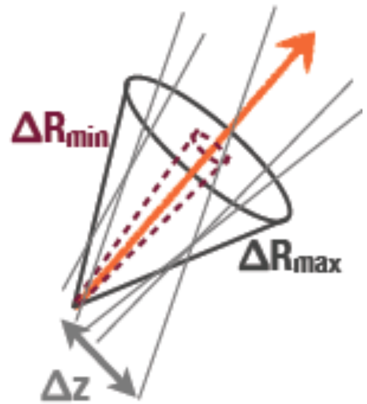
With L1e/γ objects made from full granularity: same rate reduction observed so far (can't cut tighter on Δφ despite the better gran, because brems → tails in Δφ. Can be improved)

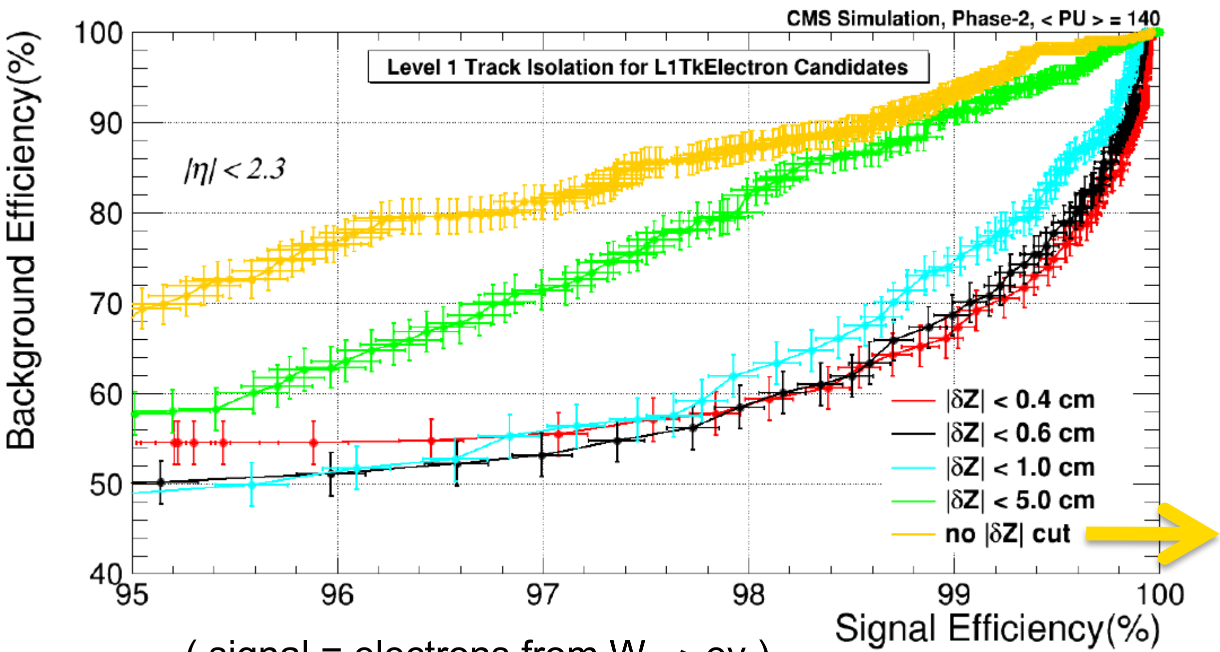
Track-based isolation for leptons

Tracker-based isolation much more powerful at high PU than calorimeter-based isolation.

Isolation variable = ΣpT of tracks :
- within ΔR < cut around the lepton track
- and with z0 consistent with the z0 of the lepton track
  e.g. | Δz | < 0.5 cm

Best = relative isolation : divide by pT (lepton)





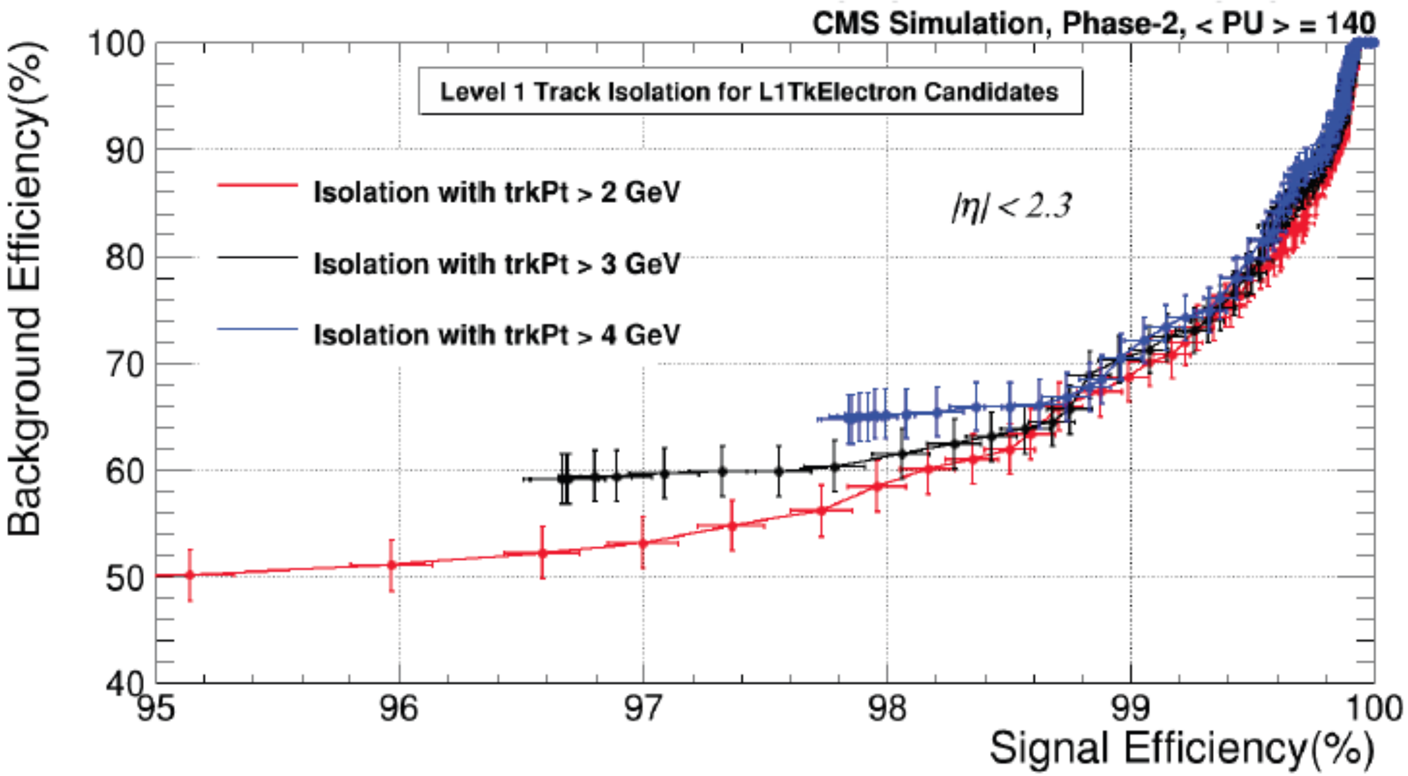
(signal = electrons from W → ev)

Rate reduction by O(2) for an efficiency of 95% over isolated leptons.

Discrimination also without any cut on Δz i.e. can be used for isolated photons as well.

Isolation and low PT tracks

The plots shown earlier assume that all tracks down to PT > 2 GeV are available to the system.
What happens if lowest PT stubs are not transferred to the BE ?

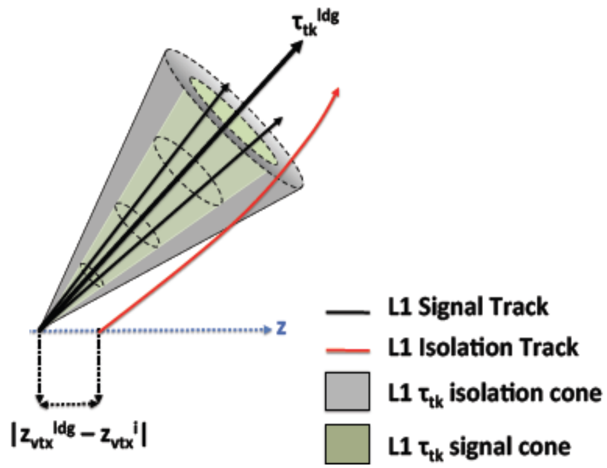


No big degradation when going to PTmin = 3 GeV.

Tau leptons at L1

Two approaches have been studied :

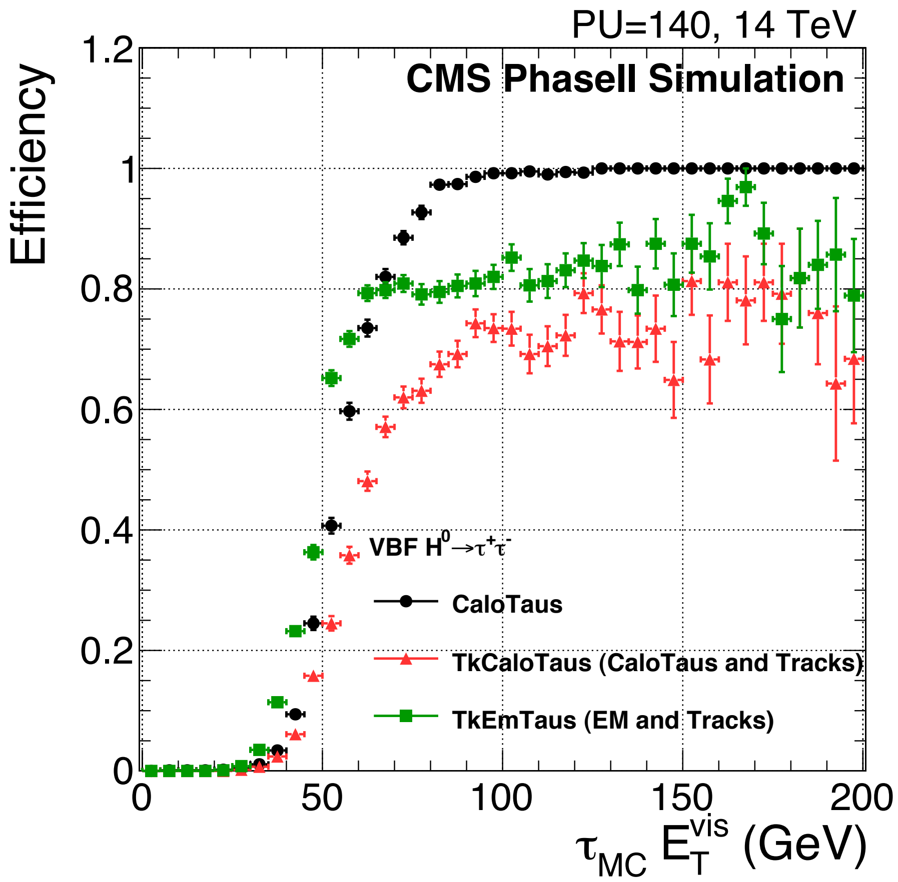
- Match L1Tracks with calo-L1Tau candidate
  - Good quality track pT > 15 GeV around the calo-Tau
  - no other track in an isolation cone

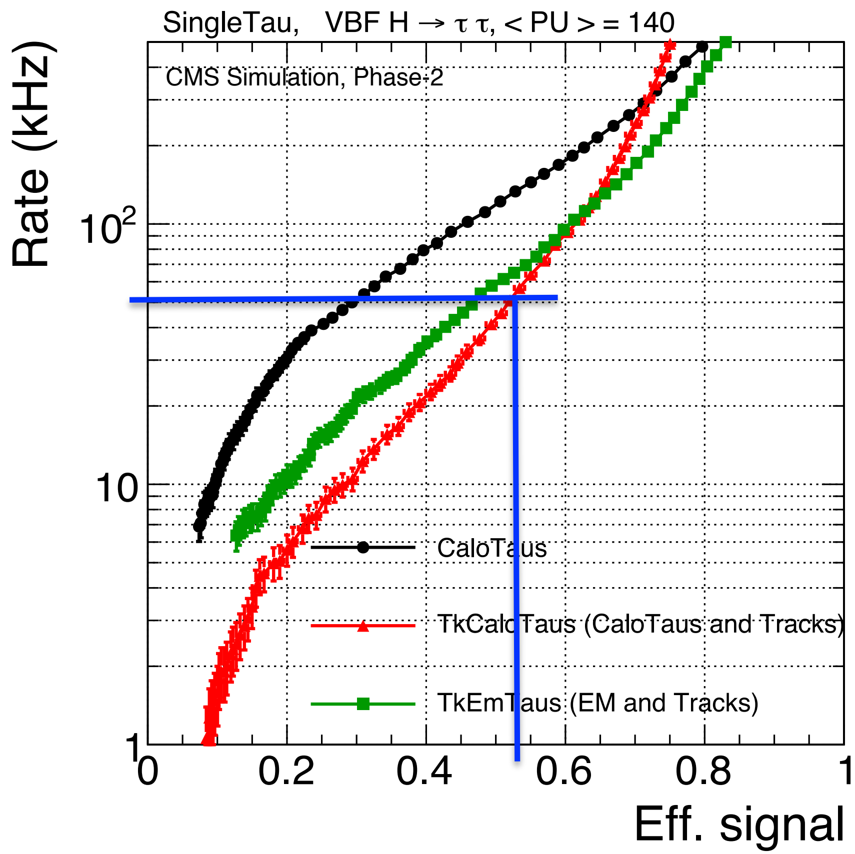


- Match L1Tracks with L1 e/γ objects (crystal granularity)
  - Start with L1Track pT > 5 GeV, “local maximum”
  - aggregate neighboring tracks coming from the same vertex
  - aggregate neighboring L1 e/γ objects of ET > 5 GeV
  - isolation condition

} as long as mass < m(τ)

Tau leptons at L1



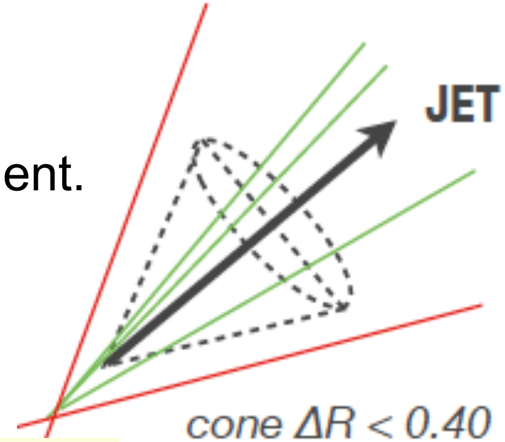


- SingleTau trigger for H → ττ (VBF) : rate reduction by O(2) w.r.t. L1Calo-Taus
- Efficiency of 50% on VBF H → ττ for a rate of 50 kHz
- DoubleTau trigger also considered

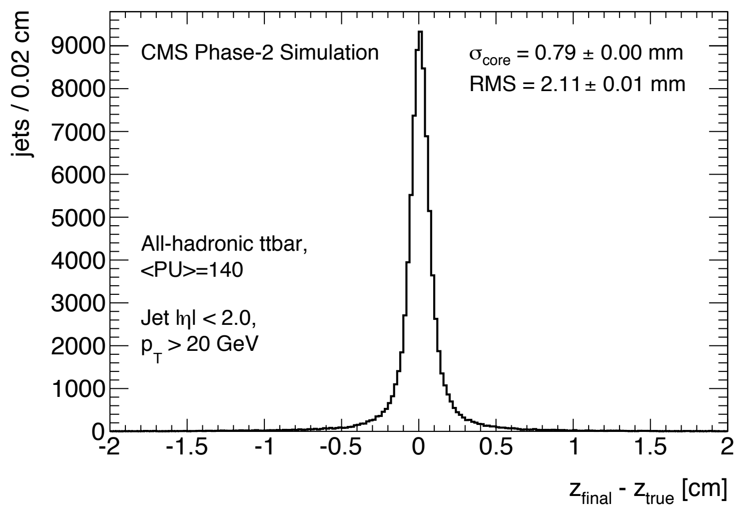
L1Tracks for jets : jet vertex

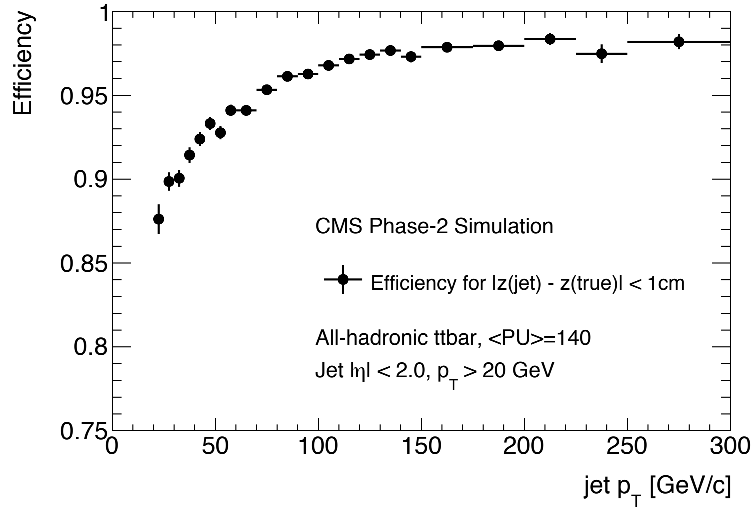
L1Tracks not used yet to improve jet ID or jet energy measurement.
But used to reconstruct the jet vertex :

- use tracks around the jet
- pT-weighted average of the track z0 + outlier removal

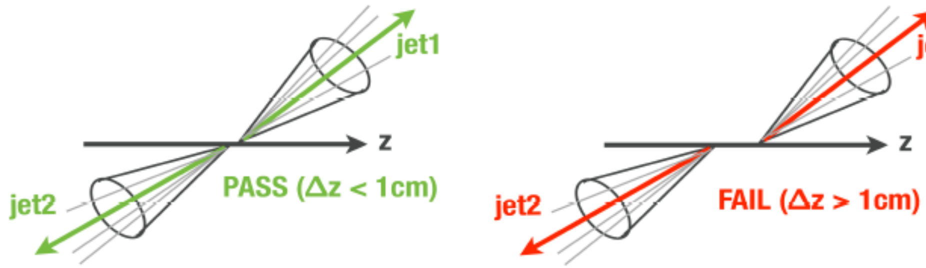


- Resolution is O (1 mm) in ttbar events
- Efficiency to find the right vertex (< 1 cm) is 95% for PT > 70 GeV





Triggers based on multijets, HT, Missing-HT : very sensitive to PU.
Requiring that all jets involved come from the same vtx: more robust w.r.t PU (example later).



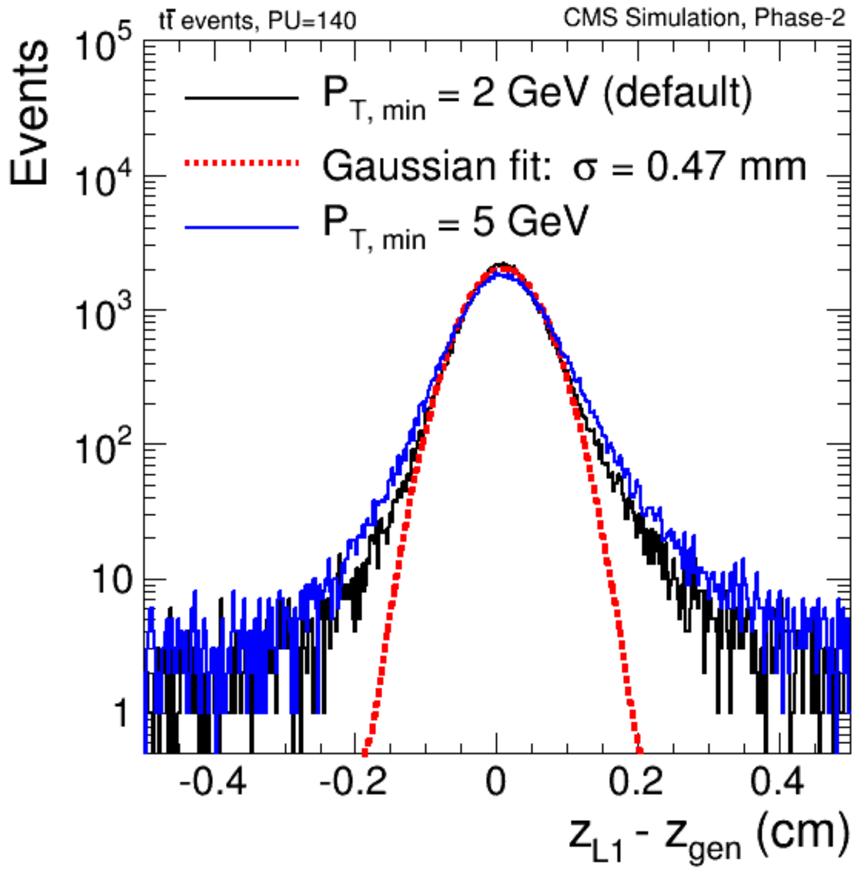
Reconstruction of the event primary vertex

Pre-requisite for determining a Track-based, inclusive missing transverse energy.

- Histogram the z0 of all L1Tracks that fulfill minimal quality requirements
- and do a simple peak finding

Resolution of < 1 mm can be obtained in events with large track multiplicity.

Need L1Tracks from the whole event but OK with only those with e.g. PT > 5 GeV

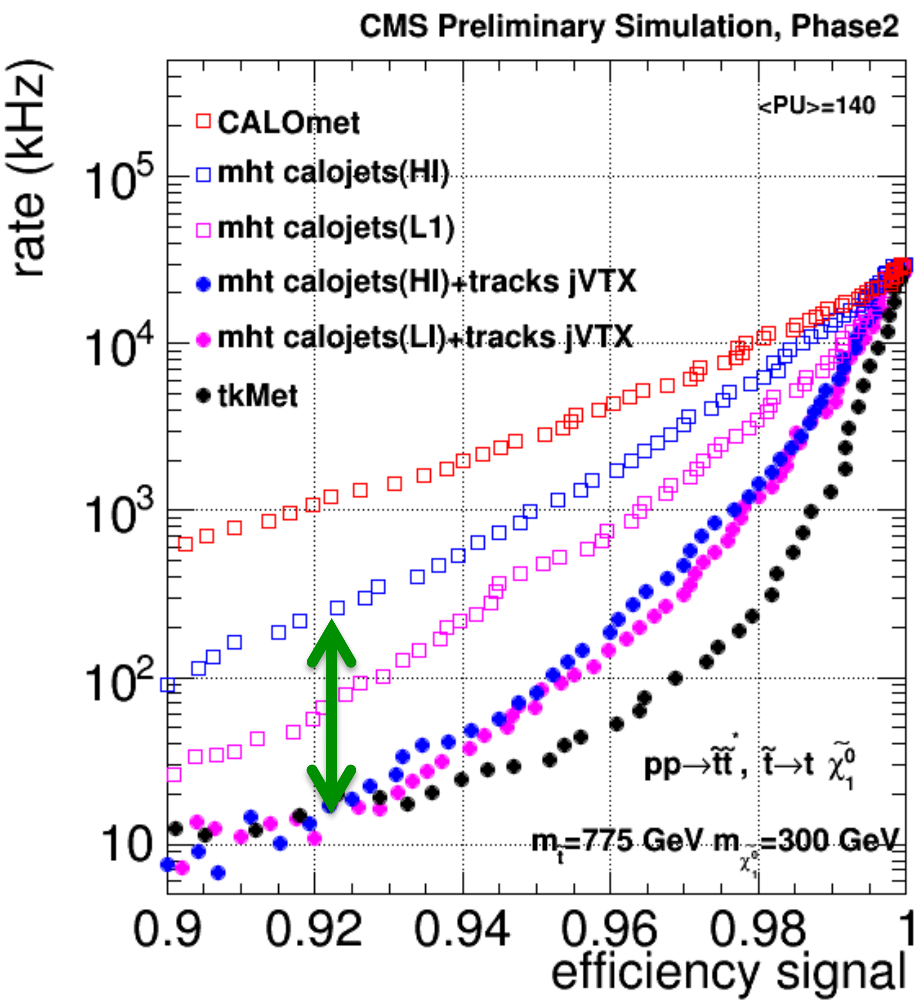


In events with a low track multiplicity, L1PV does not work so well. E.g. probability that zvtx(L1) is within 5 mm of zvtx(true) :

- 97% in ttbar events
- 70% in ZH, Z → νν and H → bb
- 35% in H → γγ events

Energy sum triggers : HT, MHT, Missing ET

- Reconstruct HT and MHT from jets that come from the same vertex (e.g. leading jet)



Example: MHT trigger on SUSY events (stop pair production, hadronic top decays)
< gen MET > ~ 300 GeV

Blue and magenta : MHT triggers without (open) or with (closed) vtx constraint.
blue vs magenta = two different calo L1Jet algorithms, different PU subtraction.

MHT rate reduced by up to O(5 - 10) with vertex constraint.

- Reconstruct Tk-MET from L1Tracks that come from the primary vertex within 1 cm
  - quality cuts important to limit tails
  - intrinsically robust w.r.t. PU

Very good performance of TkMET trigger

Simplified L1 trigger menu

Simplified menu with basic single / double object triggers :

- with thresholds = O (phase 1)
- known to account for O(70%) of the total L1 rate

rate of total menu would be 260 kHz at PU = 140

At PU = 200: increases to 500 kHz.

Adding a safety factor of 1.5 leads to the design for 750 kHz

$L = 5.6 \times 10^{34}$ cm^{-2}s^{-1} $\langle PU \rangle = 140$	Level-1 Trigger with L1 Tracks	
Trigger Algorithm	Rate [kHz]	Offline Threshold(s) [GeV]
Single Mu (tk)	14	18
Double Mu (tk)	1.1	14 10
ele (iso tk) + Mu (tk)	0.7	19 10.5
Single Ele (tk)	16	31
Single iso Ele (tk)	13	27
Single γ (tk isol)	31	31
ele (iso tk) + e/γ	11	22 16
Double γ (tk isol)	17	22 16
Single Tau (tk)	13	88
Tau (tk) + Tau	32	56 56
ele (iso tk) + Tau	7.4	19 50
Tau (tk) + Mu (tk)	5.4	45 14
Single Jet	42	173
Double Jet (tk)	26	2@136
Quad Jet (tk)	12	4@72
Single ele (tk) + Jet (tk)	15	23 66
Single Mu (tk) + Jet (tk)	8.8	16 66
Single ele (tk) + H_T^{miss} (tk)	10	23 95
Single Mu (tk) + H_T^{miss} (tk)	2.7	16 95
H_T (tk)	13	350
Rate for above Triggers	180	
Est. Total Level-1 Menu Rate	**260**	

Summary

- Big improvements from bringing the tracker in the trigger
  - For all objects / triggers

- Goal of maintaining the current thresholds at HL-LHC in order to maintain sensitivity to EW scale physics looks within reach
  - performances could be improved w.r.t. what was shown here
    - e.g. more sophisticated algorithms
    - also planned improvements of L1Calo and L1Muon, not used here

- Mostly studied so far: correlate L1Tracks with “objects” (ele, mu, etc) identified by the L1Calo or L1Muon system
  - instead of correlating tracks with calo / muon Trigger Primitives (a la particle-flow)
    - consequences for architecture; feasibility, expected gain ?

- Phase-2 L1 anyway not a straightforward extension of phase-1…
  - L1Tracking
  - several L1 systems with 25 - 50 Tbps of input

Backup

Upgraded Tracker

- Baseline geometry for upgraded tracker -- barrel & endcaps with 5 disks
- Two types of p_T modules
  - **2S modules** (strip-strip sensors)
  - **PS modules** (pixel-strip sensors)