The CMS Trigger System

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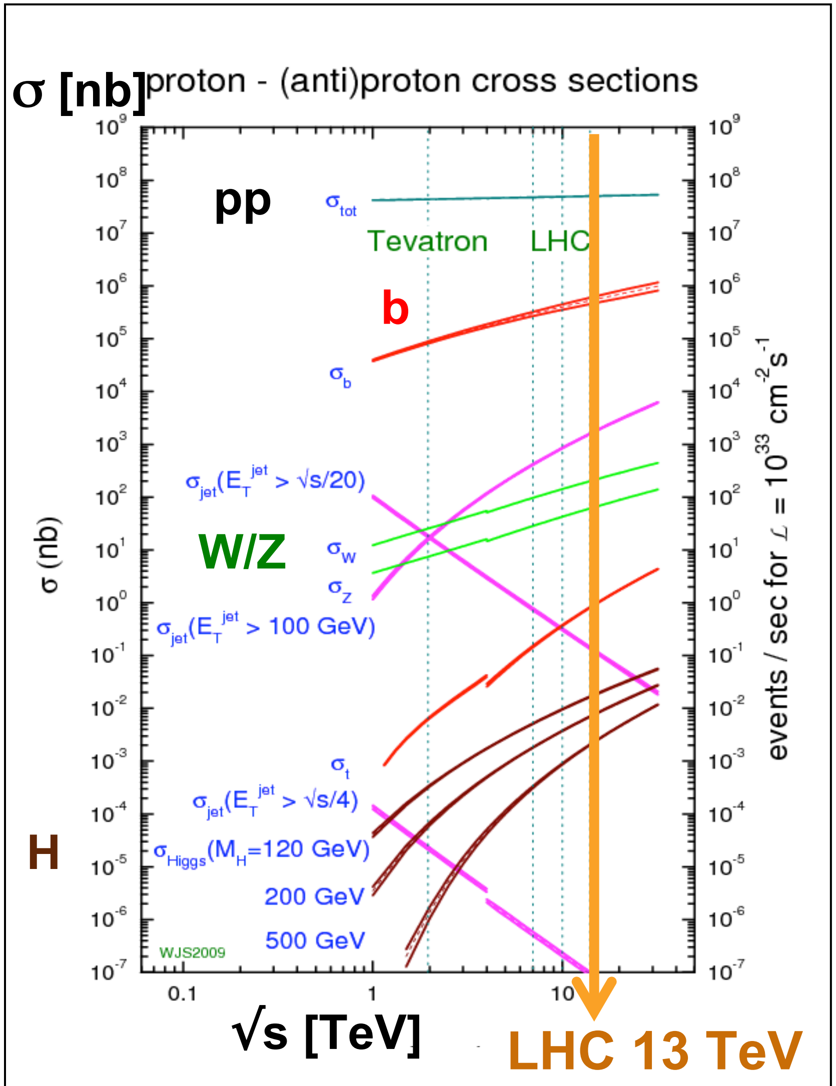
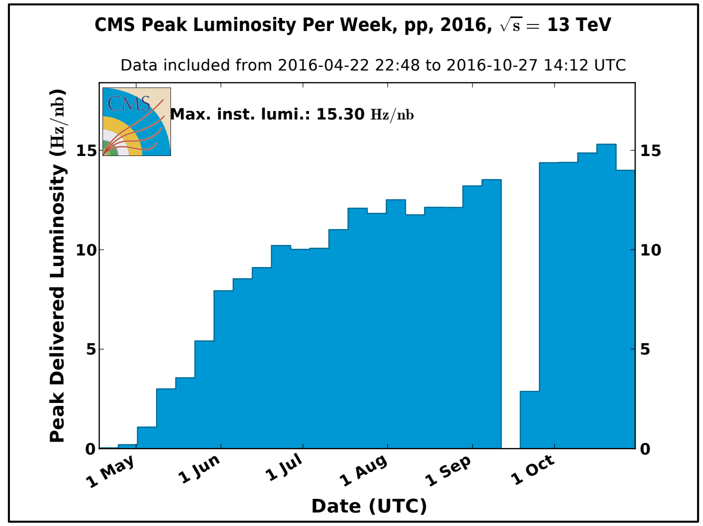
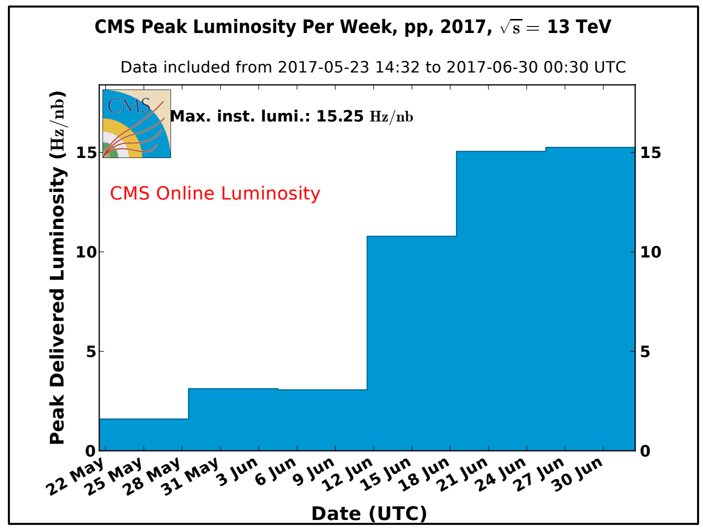
On behalf of the CMS Collaboration

Triggering at the LHC





2016 Peak
15.30 Hz/nb
@ PU ~ 49

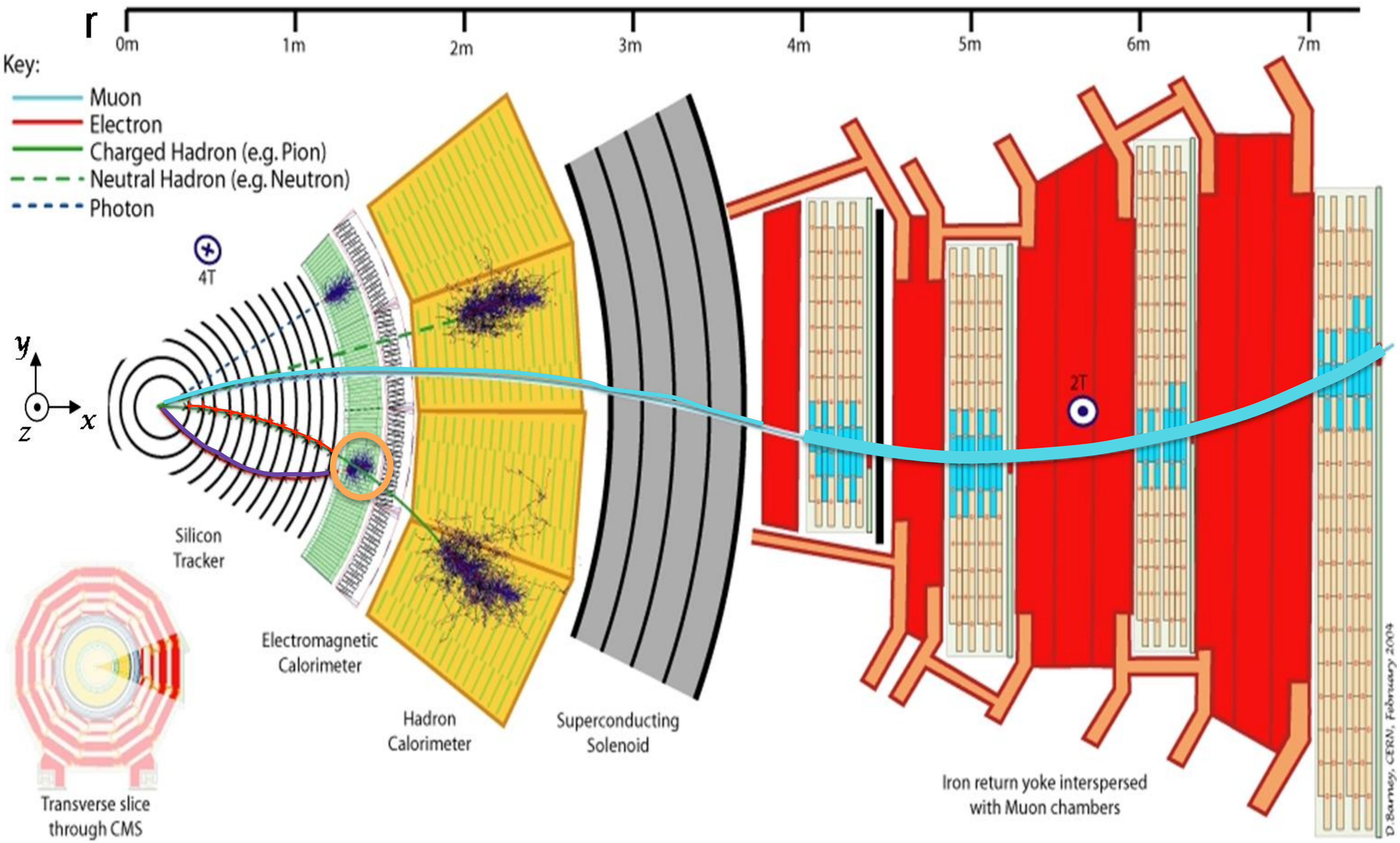


2017 Peak
15.25 Hz/nb
@ PU ~ 43

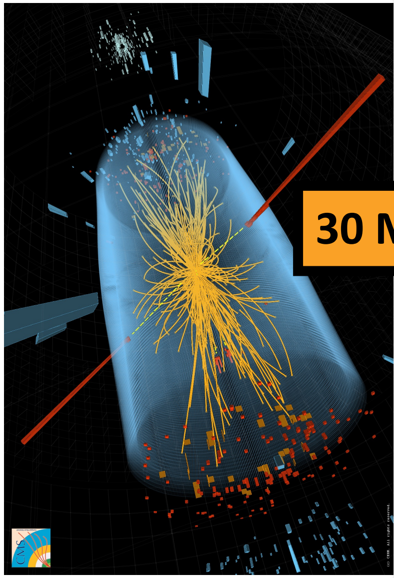
In 2017, LHC reached 2016 record within a month

- ✧ **LHC** provided a luminosity up to **15 Hz/nb** in order to reach rare physics events (*Higgs: 0.3 Hz*)
- ➢ **Trigger systems:** designed to sort out the small fraction (*~1/28000*) of events useful for physics

Particle identification in CMS

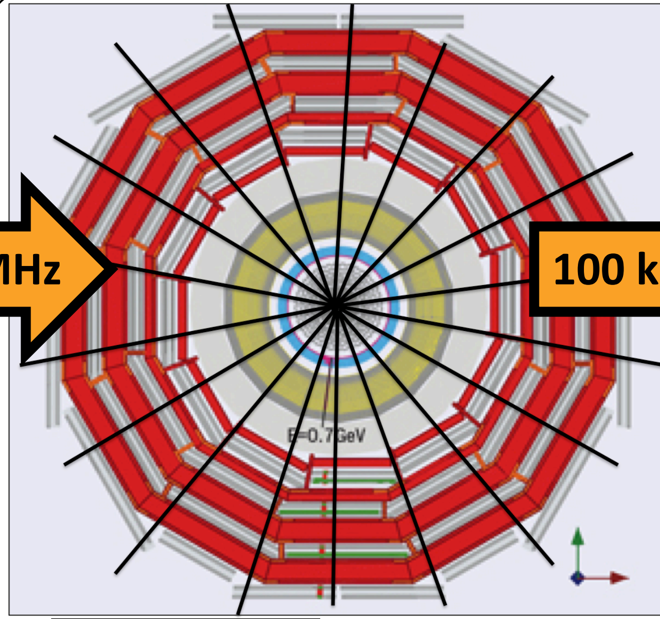


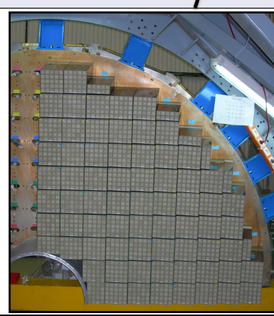
A tale of two levels



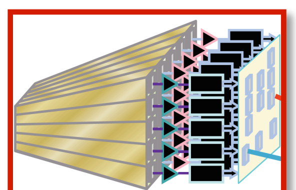
LHC pp

30 MHz



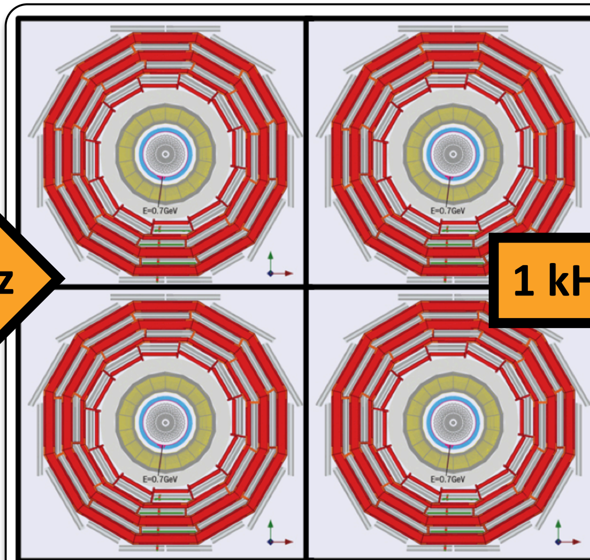


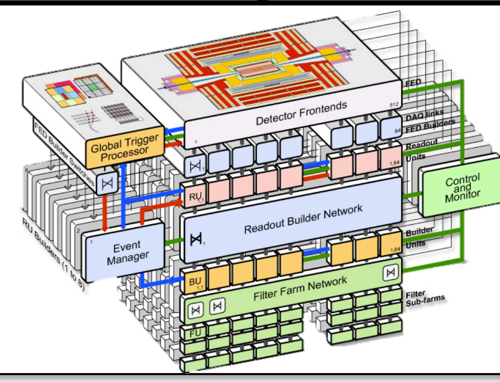
← ¼ ECAL Endcap



ECAL trigger tower

100 kHz





1 kHz

Tier-0 Offline Reco ~48h

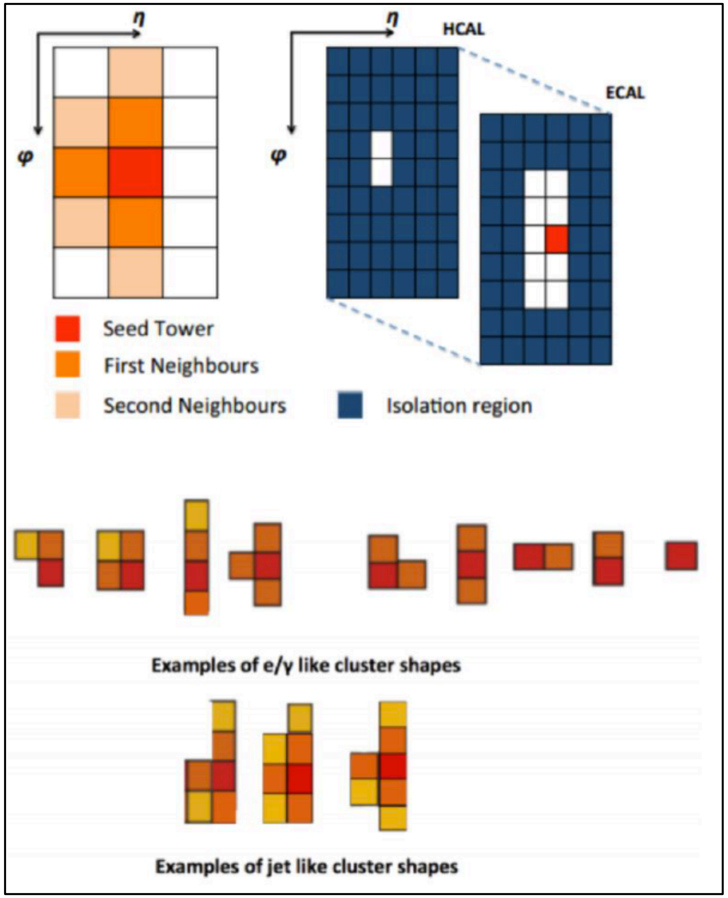
Level-1: fixed latency of 4 μs

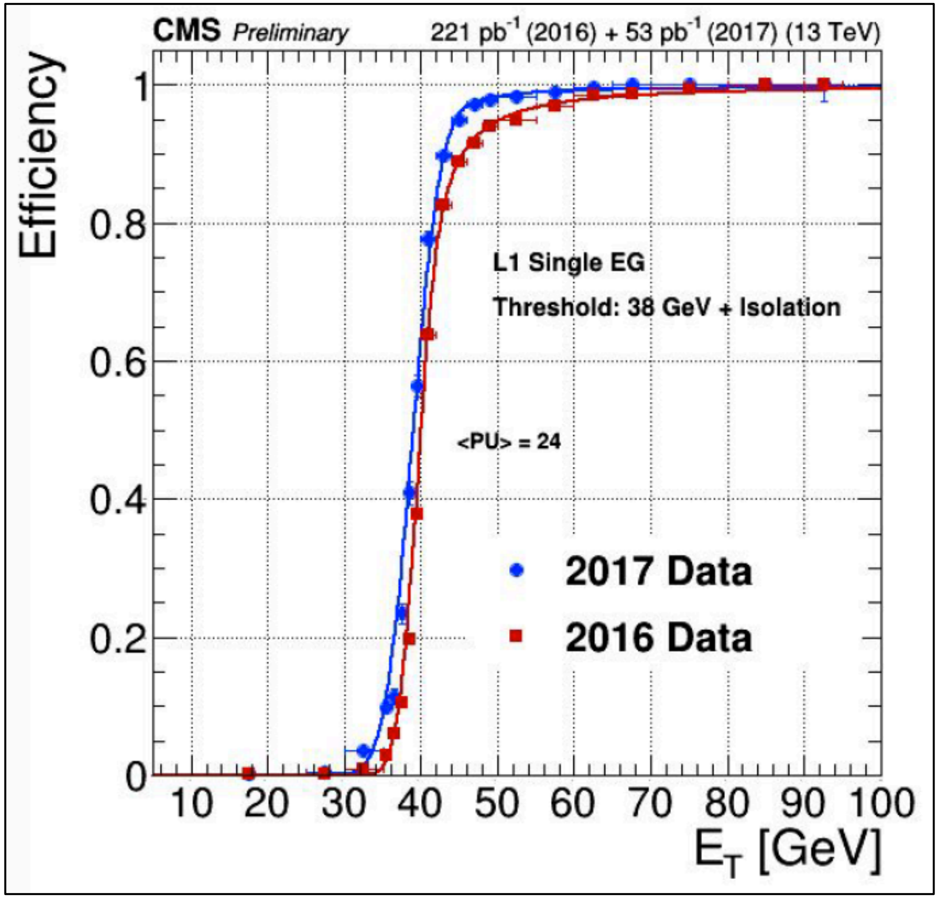
- **Process basic inputs** (calo trigger towers, muon hits)
- Local **matching** (ECAL+HCAL towers, CSC/DT/RPC hits)
- **Build** trigger **objects** in **regions** and send the **hardest** ones
- **Global Trigger** gathers **hardest** objects from **regions** to make **decisions** based on L1 trigger algorithms

High-Level: CPU farm

- Full event readout (with Zero-Suppression)
- Sequential reconstruction similar to offline
- Process events in parallel using **13k CPU cores**
- Average CPU timing per event: **200 ms**
- Average output rate: **1 kHz**

Level-1 electron/photon





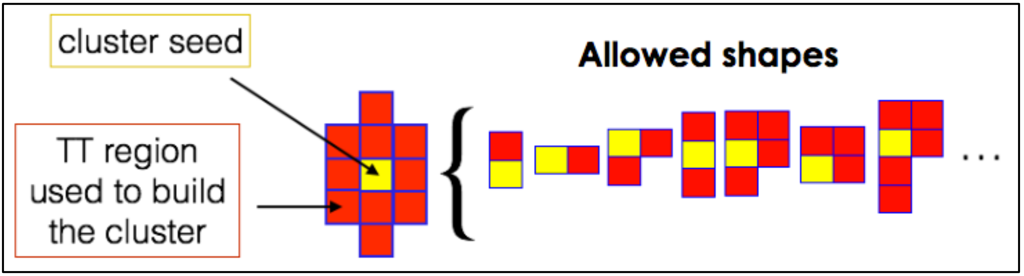
- ✧ **L1 electron/photon** reconstruction: cluster ECAL and HCAL "trigger towers"
  - ➢ **Rejecting** jets using HCAL vs ECAL energy (**H/E**) and **cluster shape** veto
- ✧ **L1 electron/photon** strategy: **OR** (**3 algos**: non-isolated, isolated, isolated + eta-restricted)
  - ➢ Using tighter identification but looser transverse energy (E_T) cuts: {**X** ; X-**2** ; X-**4**}
  - ➢ 2017 Improvements: reoptimization of the isolation relaxation (high E_T) and the H/E cut

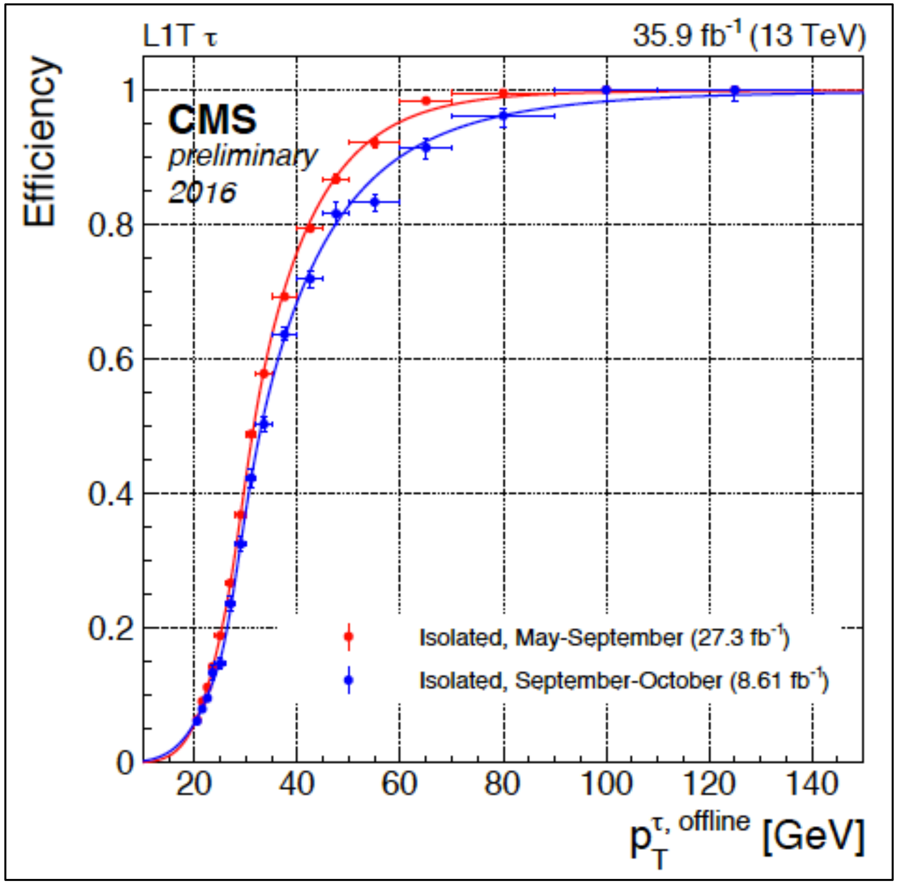
Thresholds used at record lumi (15.3 Hz/nb)

- ➢ 2016: X = 40 GeV
- ➢ 2017: X = 36 GeV
- ➢ 20 Hz/nb: X = 40 GeV ?

Level-1 Taus

- ✧ **Cluster** ECAL/HCAL towers
- ➢ Define a **region** of **10 towers** around "seed"
- ➢ Define a **list** of allowed cluster **shapes** to identify energy **deposits** from hadronic tau decays



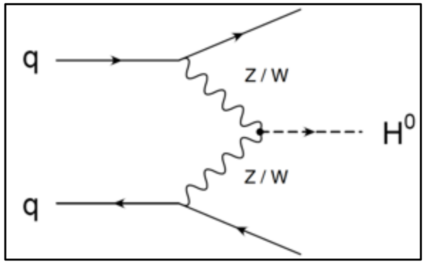


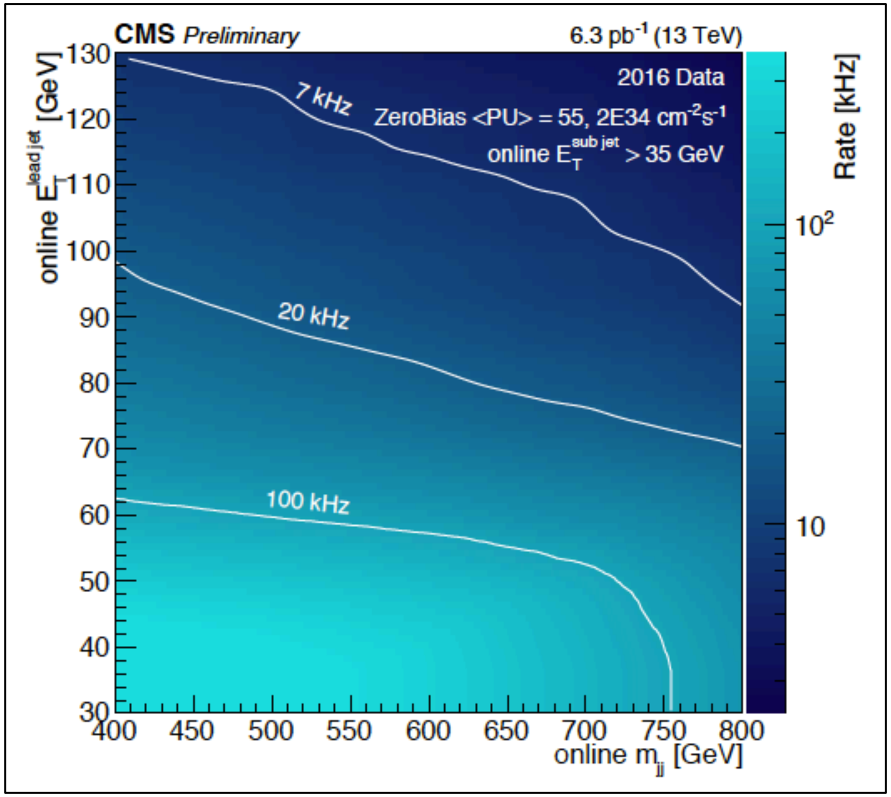
- ✧ **Hadronically-decaying taus** used in particular in tau final states (Higgs, Z', W'…)
- ➢ **Efficiency** in two periods: May-Sep (peak 13.4 Hz/nb) and Sep-Oct (peak 15.3 Hz/nb)
- ➢ **Strategy** to cope with higher luminosity in 2016: tighten **isolation** criterion.
- ➢ **High p_T taus** are covered by Single Tau algorithms **without isolation**.

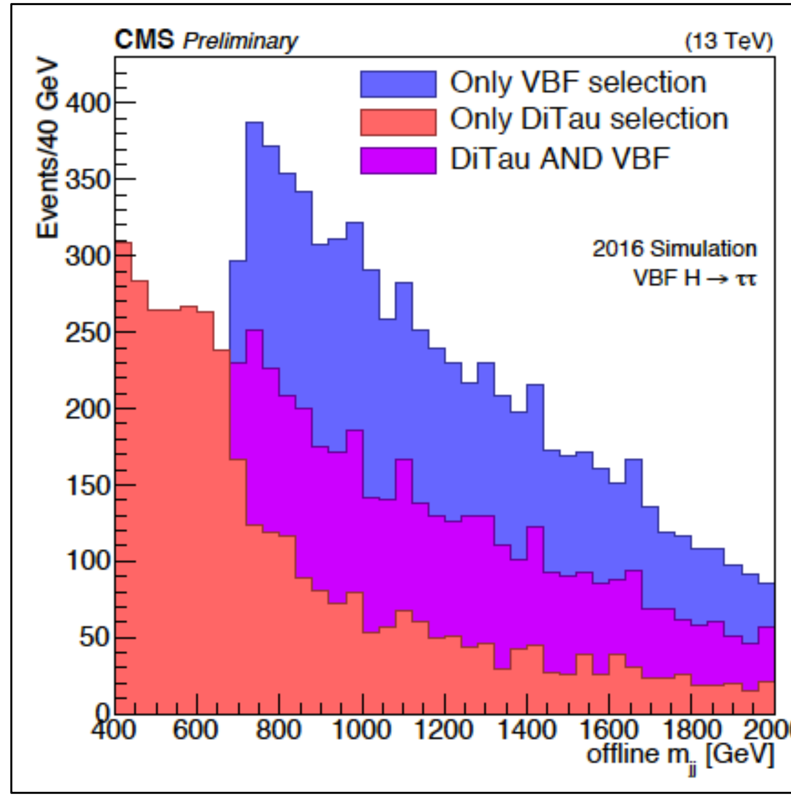
Thresholds used at record lumi (15.3 Hz/nb) on L1 isolated ditau

- ➢ 2016: X = 30 GeV
- ➢ 2017: X = 32 GeV
- ➢ 20 Hz/nb: X = 34 GeV ?

Level-1 VBF

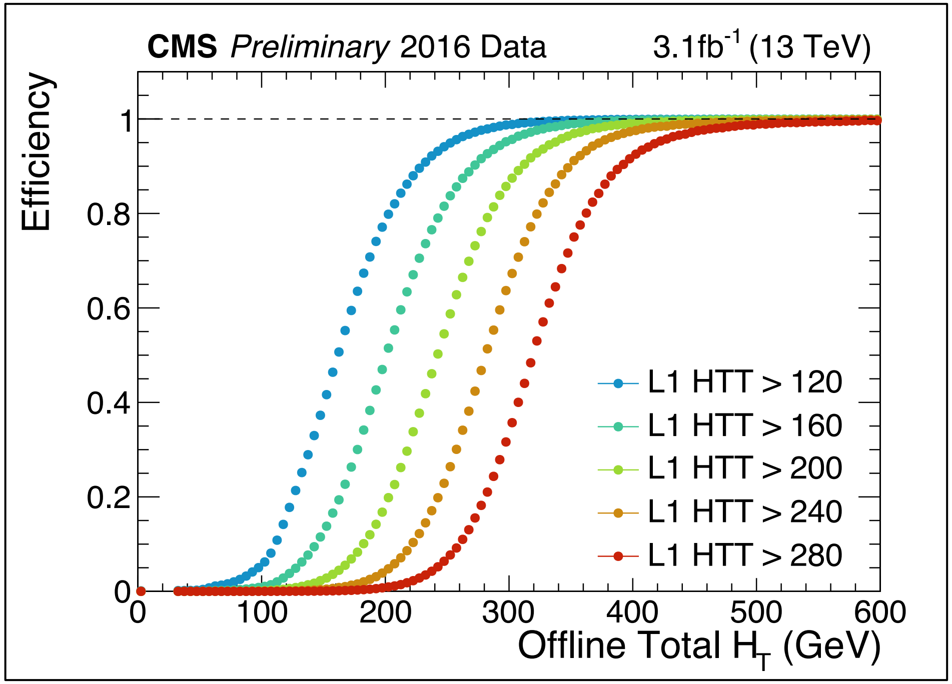


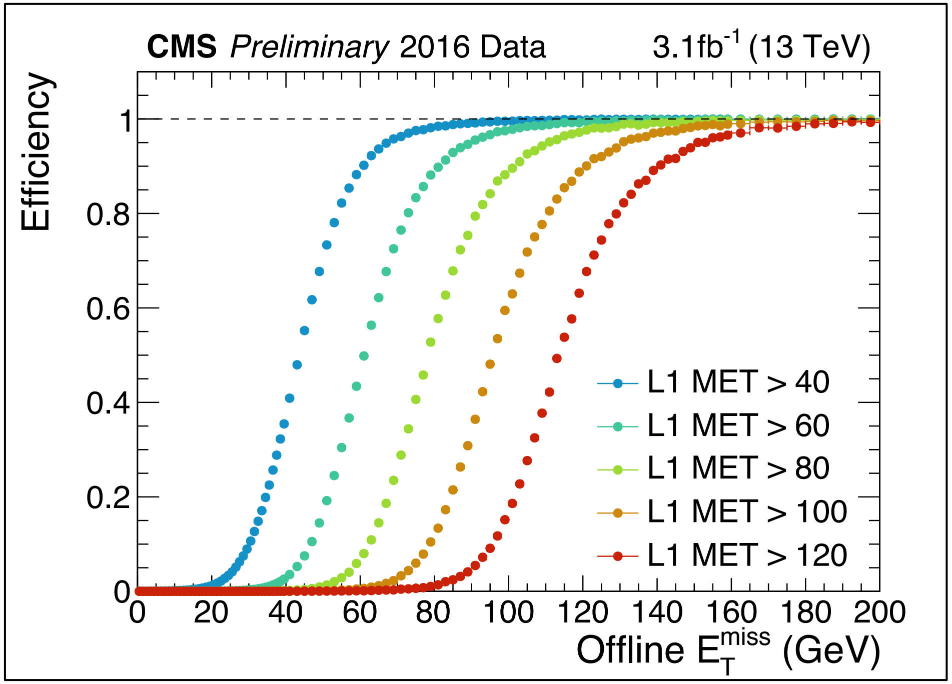




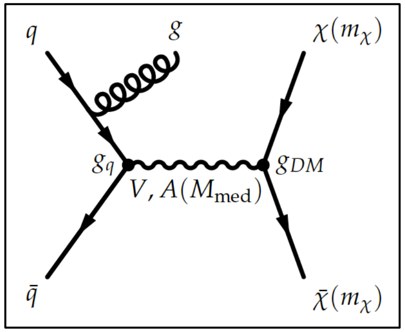
- ✧ **VBF** production mode very **sensitive** for searches such as **Higgs ditau** and **invisible** final states
- ➢ **Level-1** trigger allows the calculation of complex variables such as **invariant mass** since 2017
- ➢ **Rate** scan in the online **{m_{JJ} ; leading jet E_T}** 2D plane performed in special 2016 high PU data
- ➢ **Thresholds** considered at 2e34: **m_{JJ} > 620** GeV & leading jet **E_T > 110** GeV → **7.3 kHz**
- ➢ **Gain** in signal acceptance for VBF H→ditau events wrt L1 ditau trigger: **58%**

Level-1 Energy sums





- ✧ **Energy sum triggers** widely used in analyses based on **hadronic** final states
  - ⟹ dijet resonances, dark matter in final states with MET (+jets, +lepton, +photon…) etc
- ➢ **Challenge**: mitigate the MET rates due to pile-up and detector noise
- ➢ For **2017**: **HTT** restricted to **tracker acceptance** + **MET** cross-triggers with **Jets** or **HT**



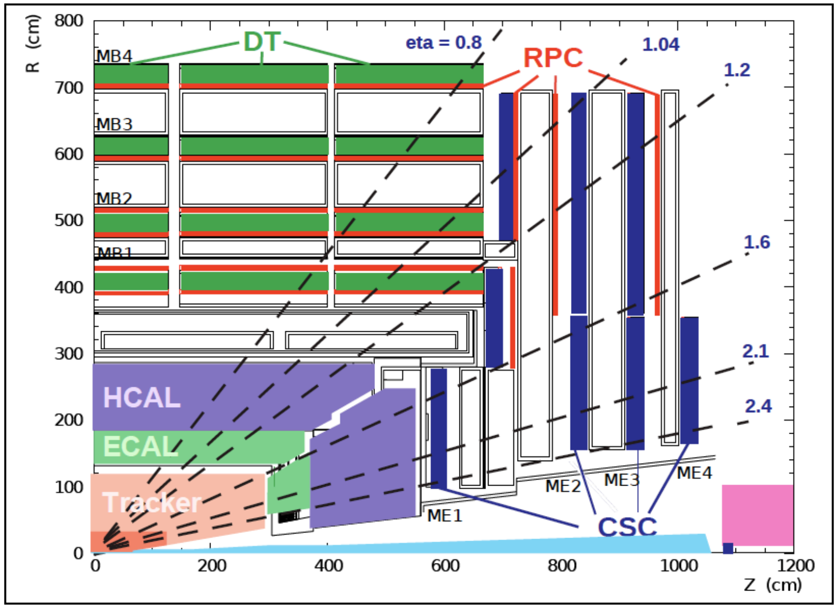
✧ **Thresholds**

- ➢ 2016 peak lumi: HTT > 300 GeV MET > 100 GeV
- ➢ 2017 same lumi: HTT > 380 GeV MET > 120 GeV
- ➢ 2017 20 Hz/nb : HTT > 450 GeV MET > 150 GeV

Level-1 Muons

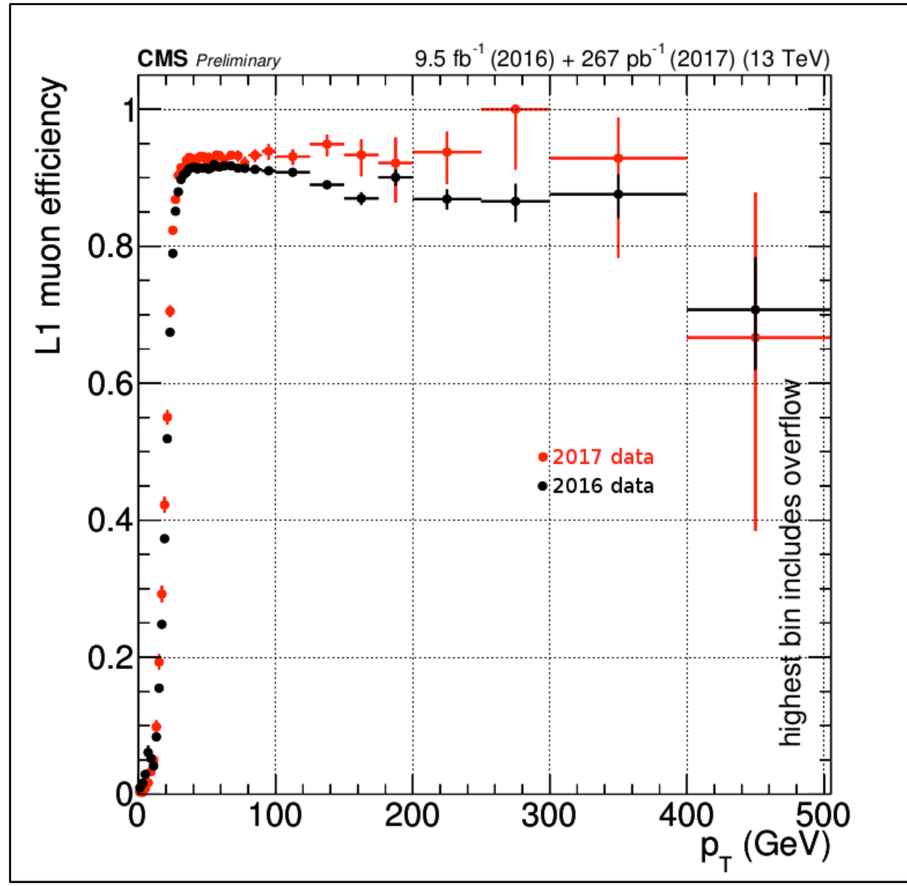
Muon Track Finders (MTF)

BMTF: Barrel (DT+RPC) **OMTF: Overlap (DT+RPC+CSC)**



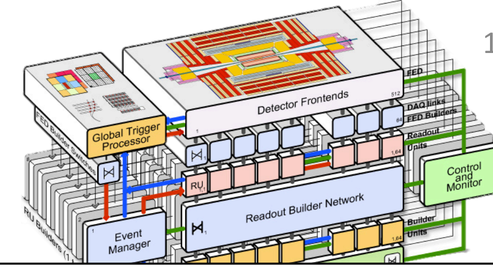
EMTF: Endcap (RPC+CSC)

Redundancy in muon detectors used to find tracks in each eta region

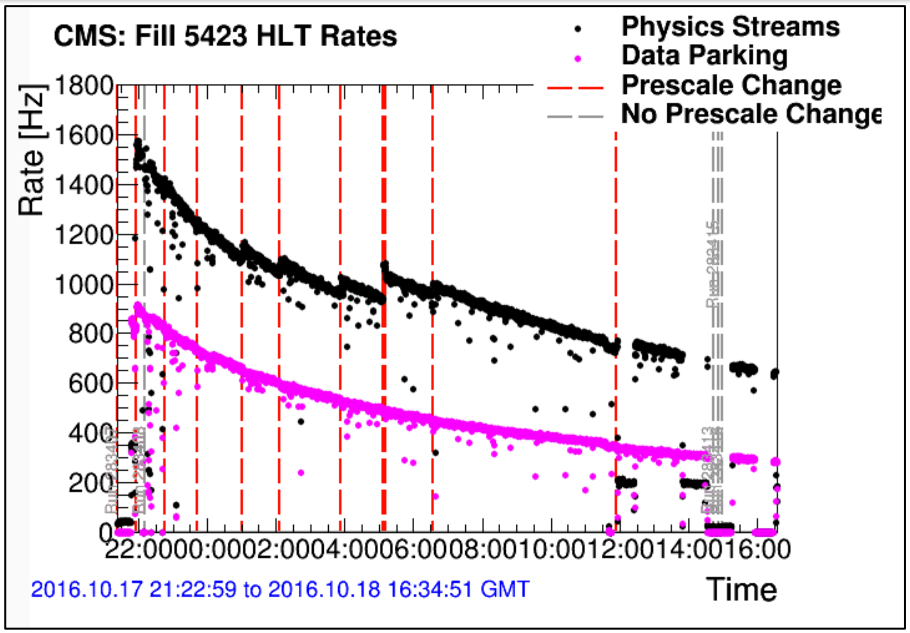


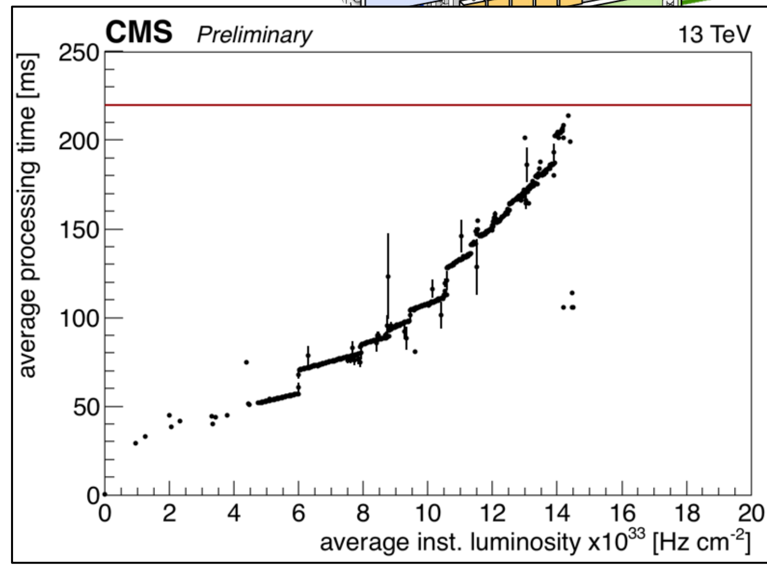
- ✧ **Level-1 muon** efficiency turn-on vs offline muon pT
- ➢ **L1 threshold** up to the max lumi expected in 2017
- ➢ 20 Hz/nb: 25 GeV + 22 GeV (|eta| < 2.1)

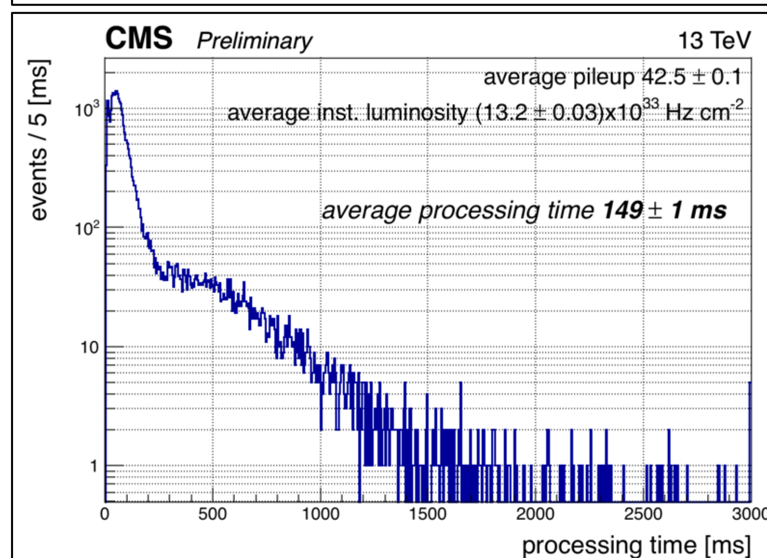
High-Level Trigger



- HLT algorithm = sequence of object **producers** and **filters**
- **Reject events asap** by running fast producers first
- Example (electron): L1 electron → ECAL cluster → tracking
- **Focus** on few vertices, perform regional reconstruction, etc





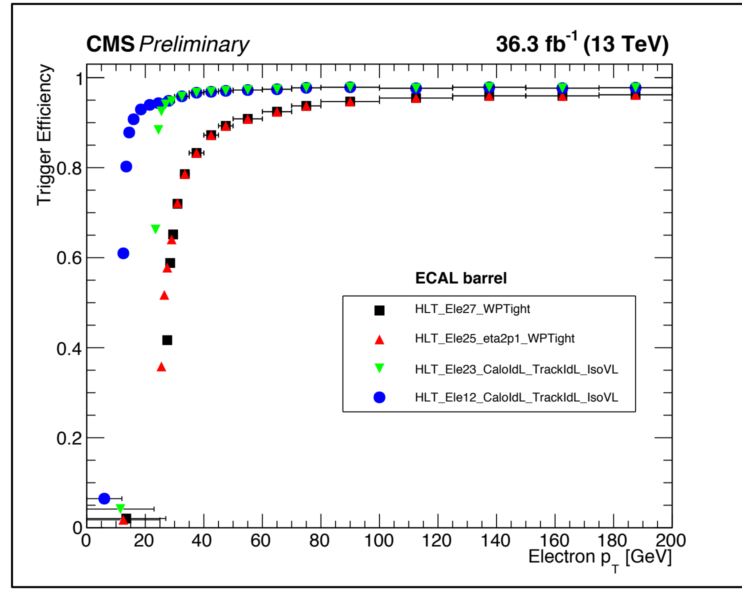


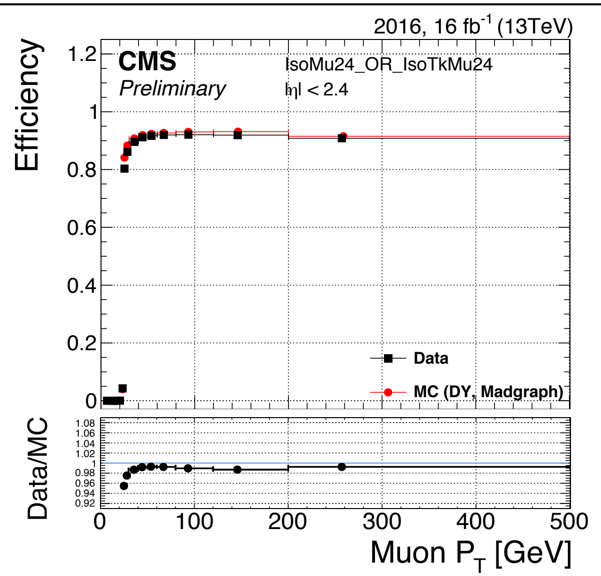
- **Timing:** process 100 kHz (L1) with 20k processes ⟹ 200 ms/ event
- **Output rate**: storage + offline reco ⟹ **avg 1 kHz (3 GB/s)**
- Additional strategies to afford larger rates
- Scouting: saving only trigger objects
- Parking: record extra data, perform reco later

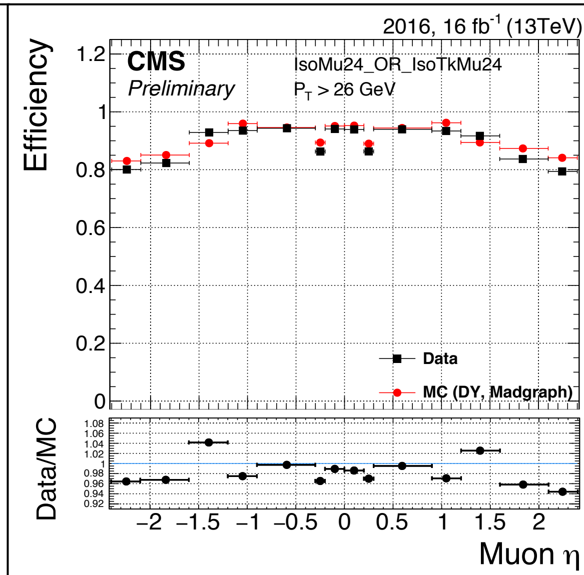
High-Level Trigger: Leptons

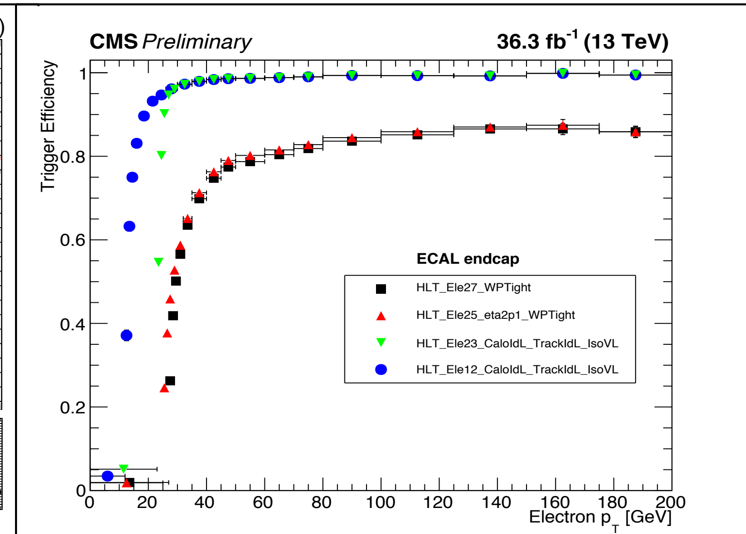
- ✧ **Muons** 2016 thresholds: L1=22 (20) GeV (eta<2.1); HLT=24 GeV)
- ➢ Plateau >90% around 30 GeV, dominated by isolation and L1 eff
- ➢ Efficiency for muons (pT>26 GeV) above 80% in endcaps

- ✧ **Electrons** 2016 thresholds at large luminosity
- ➢ HLT: Single Ele **27** (**25** |eta|<2.1) and Double Ele **23**-**12**
- ➢ L1 : Single Ele 40 (Iso : 34) and Double Ele 24-17
- ➢ L1 thresholds became larger than HLT ones at large luminosity, causing a loss of efficiency as seen on the plots

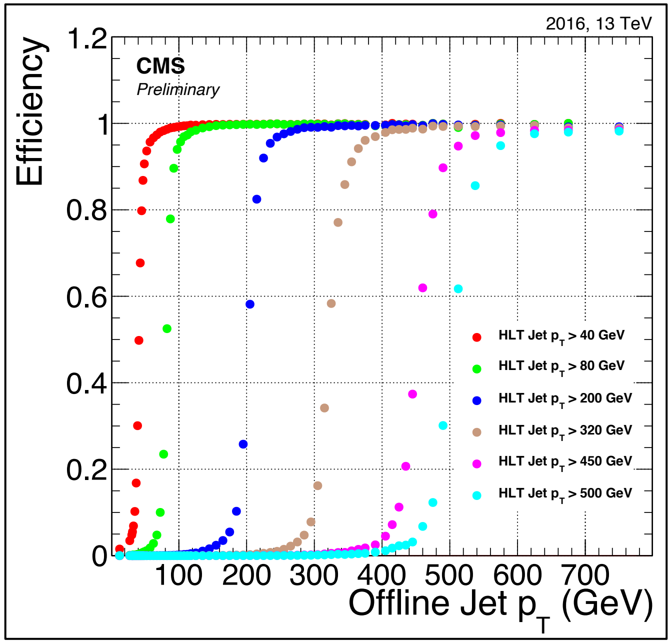




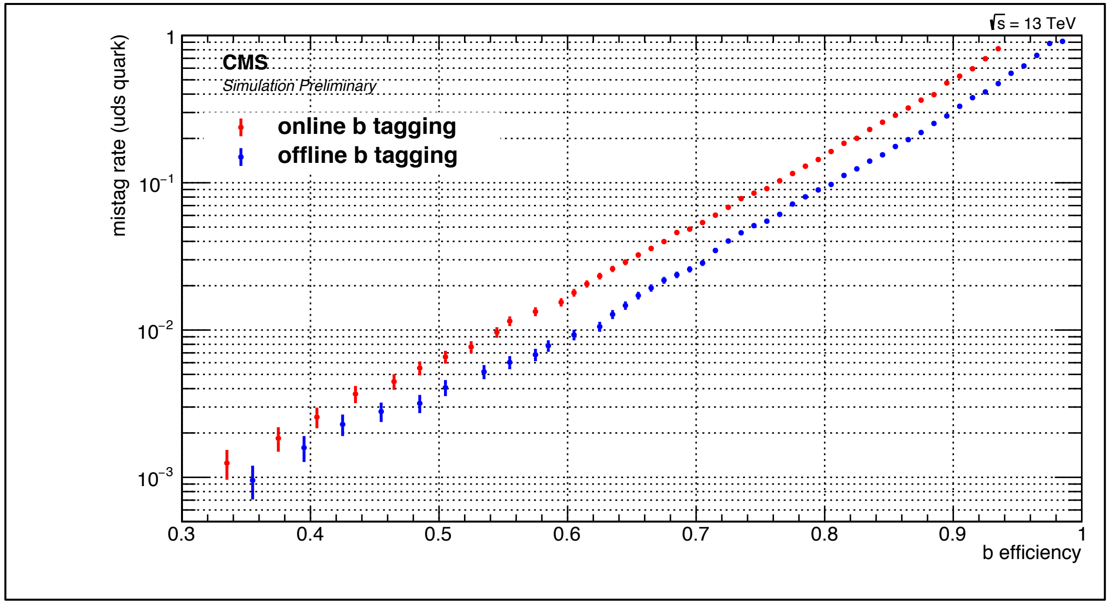


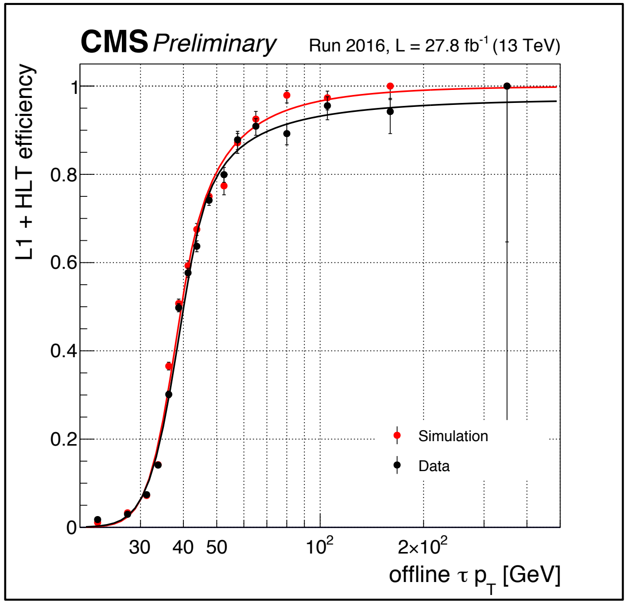


High-Level Trigger: Jets

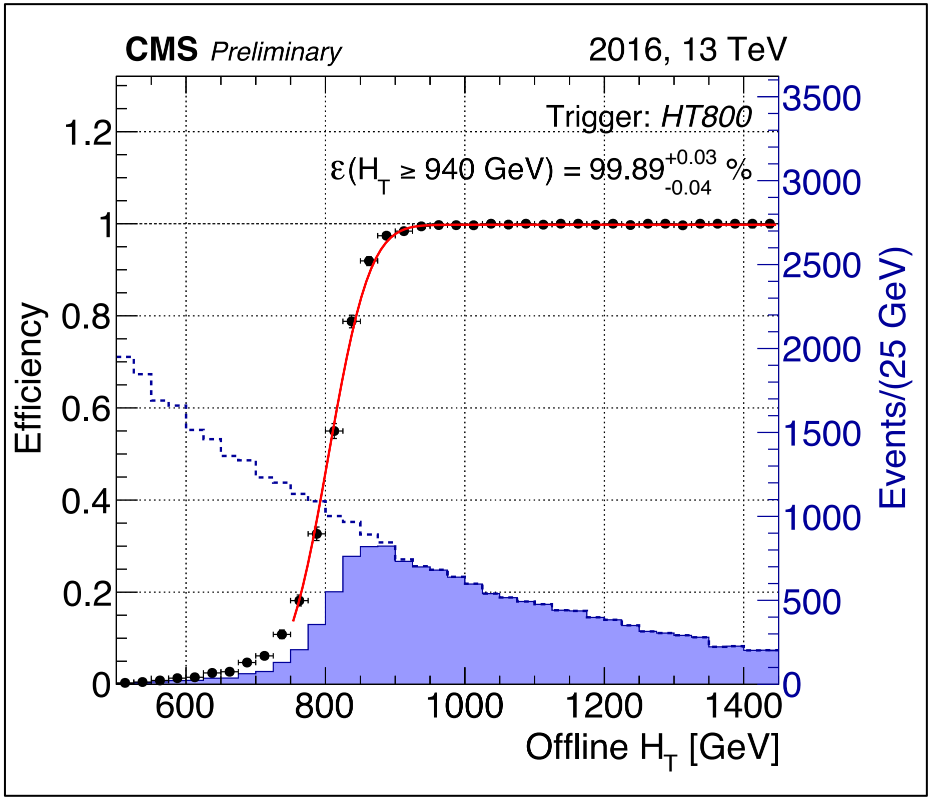


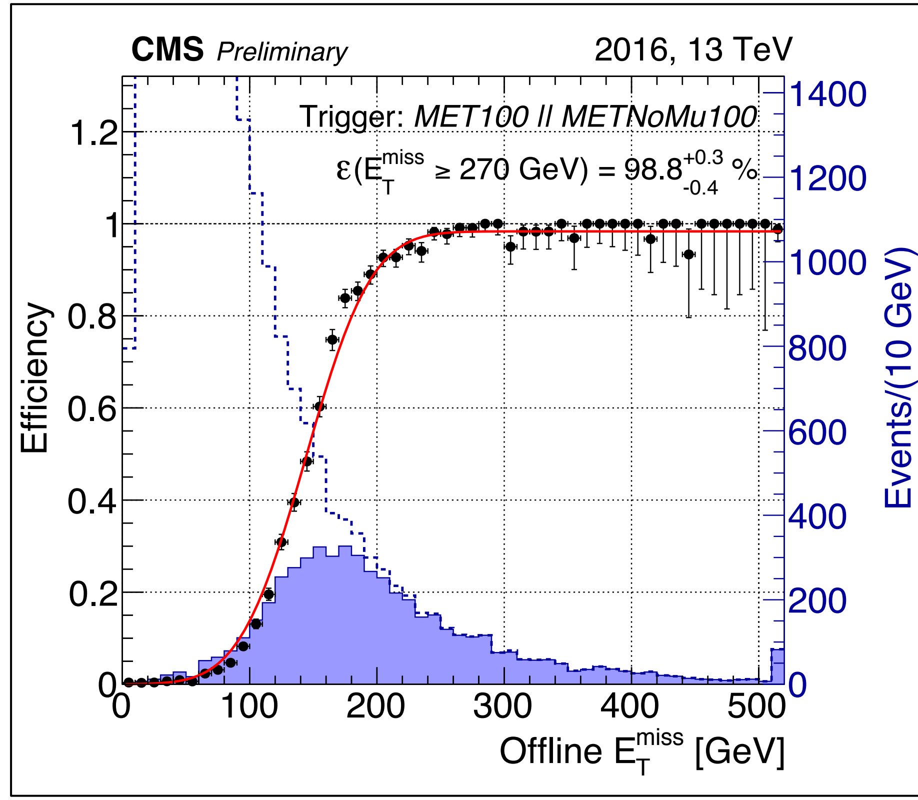
- ✧ **Jet thresholds** in 2016: Single Jet **450** GeV ⟹ **95%** eff @ **520** GeV
- ✧ **Hadronic Ditau** threshold: 35 GeV ⟹ >80% efficient @ pT>50
- ✧ **B-tagging**: fake rate (uds) vs efficiency (b) for online and offline
  - ➢ Online b-tagging provids a 70% efficiency for a 5% fake rate
  - ➢ Once events are triggered, there is room for improvement @ offline level





High-Level Trigger: Energy Sums



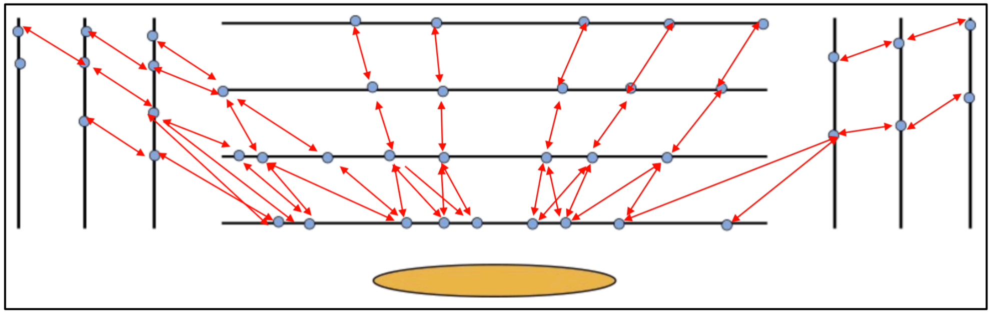


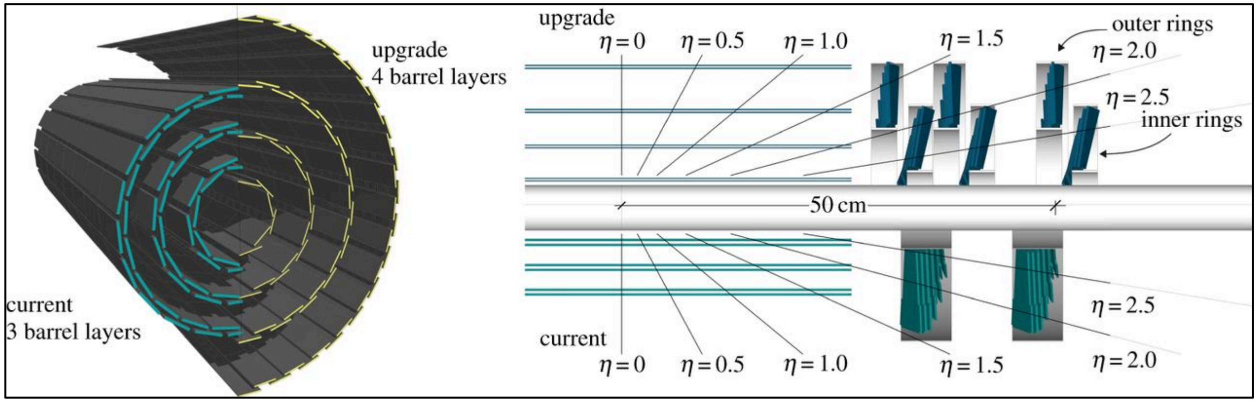
✧ **Efficiency of the pure HT trigger**
- ➢ Definition: scalar sum of jet pT>30 GeV
- ➢ Main threshold in 2016 at medium lumi: 800 GeV
- ➢ Efficiency at HT > 940 GeV ⟹ 99.9 %
- ➢ Generic trigger for analyses of hadronic final states

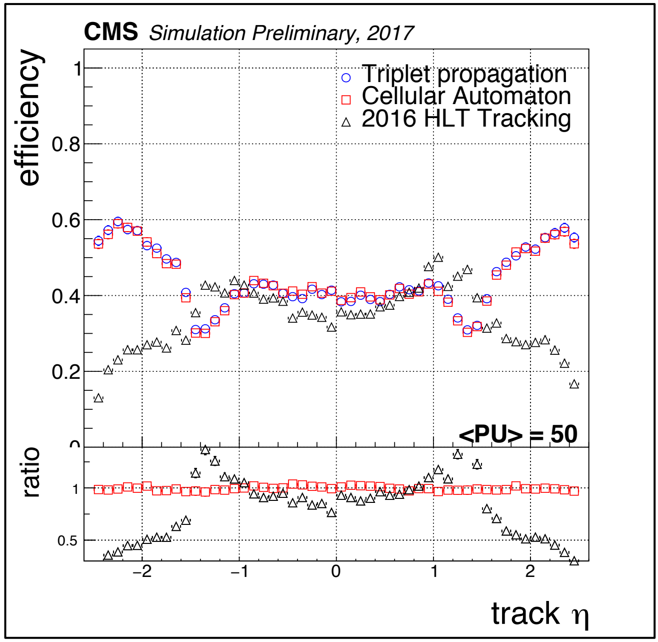
✧ **Efficiency of MET+MHT cross trigger**
- ➢ MET: vector sum of individual “ParticleFlow” candidates pT
- ➢ MHT: vector sum of jet pT>30 GeV
- ➢ Cross-trigger to maintain reasonable rates & low thresholds
- ➢ Efficiency(threshold 100 GeV) = 98.8% @ MET > 270 GeV

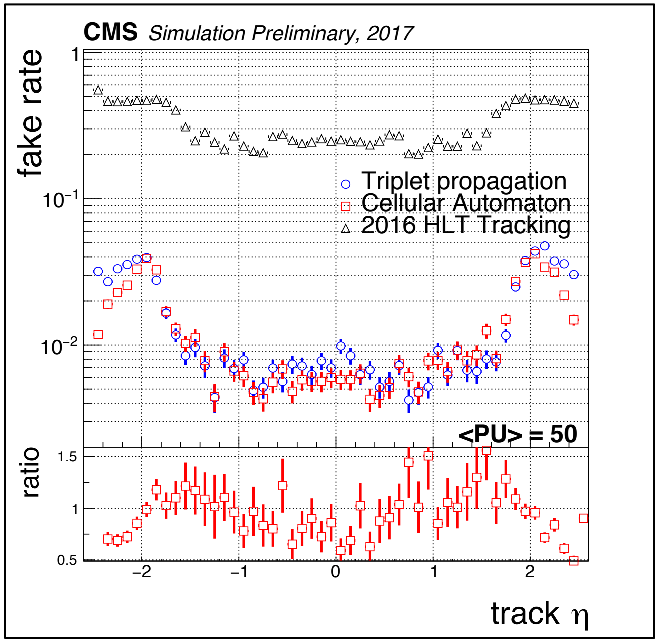
High-Level Trigger: Pixel upgrade

- ✧ **CMS Phase-1 Pixel Upgrade**: added 1 extra layer (3+1=4)
- ➢ Cellular Automaton: track seeding algorithm
- ➢ Creates hit doublets in adjacent layers
- ➢ Joins compatible doublets to form triplets then quadruplets
- ➢ **5 times faster** than old algo (triplet propagation)
- ➢ **Efficiency**: similar in barrel, **50% gain** in endcap
- ➢ **Fake rate**: divided by **4**









Conclusion

- ✧ **Upgraded Level-1** trigger system commissionned in **2016**
- ➢ Demonstrated **excellent performances** during the 2016 data taking
- ➢ Some **improvements** deployed **from 2016 to 2017**: E/gamma isolation and H/E cuts; Tau ET-dependent shape identification; HTT eta restriction on input jets; Muons using RPC in endcap and better eta/phi correlations (project coordinates to vertex)
- ➢ In **2017**, CMS exploits further the features of the upgraded system: **invariant mass**, more evolved **correlations**, **VBF** dijet algorithm.

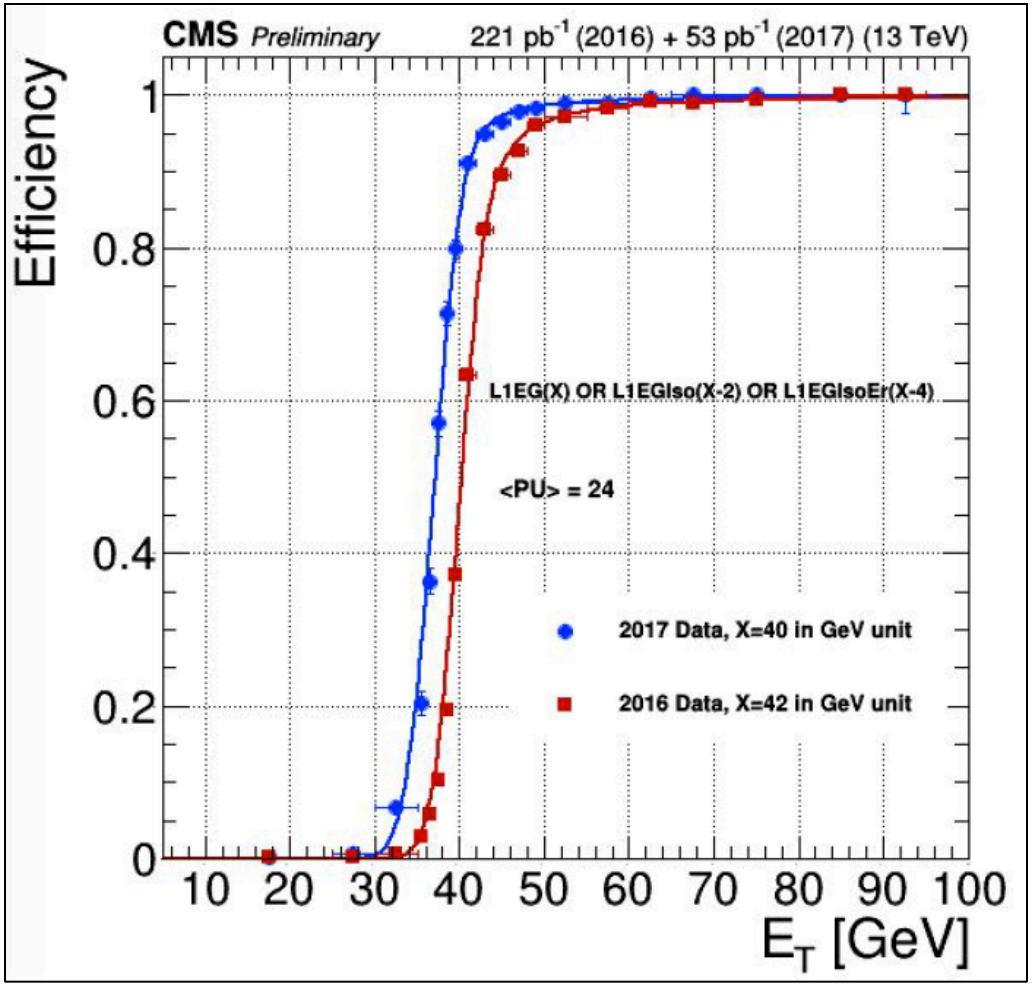
- ✧ **Upgraded detectors** being exploited at **High-Level** Trigger:
- ➢ HCAL endcap upgrade prototype being commissioned; HCAL forward upgraded readout
- ➢ Phase-1 **pixel** upgrade $\Longrightarrow$ commissioning progressing
- ➢ Reconstruction algorithms at HLT were adapted accordingly: tracking, muon reconstruction, electron pixel matching

$\Longrightarrow$ reduce CPU **timing** at high **pile-up** while improving **efficiencies** and reducing **fake** rates

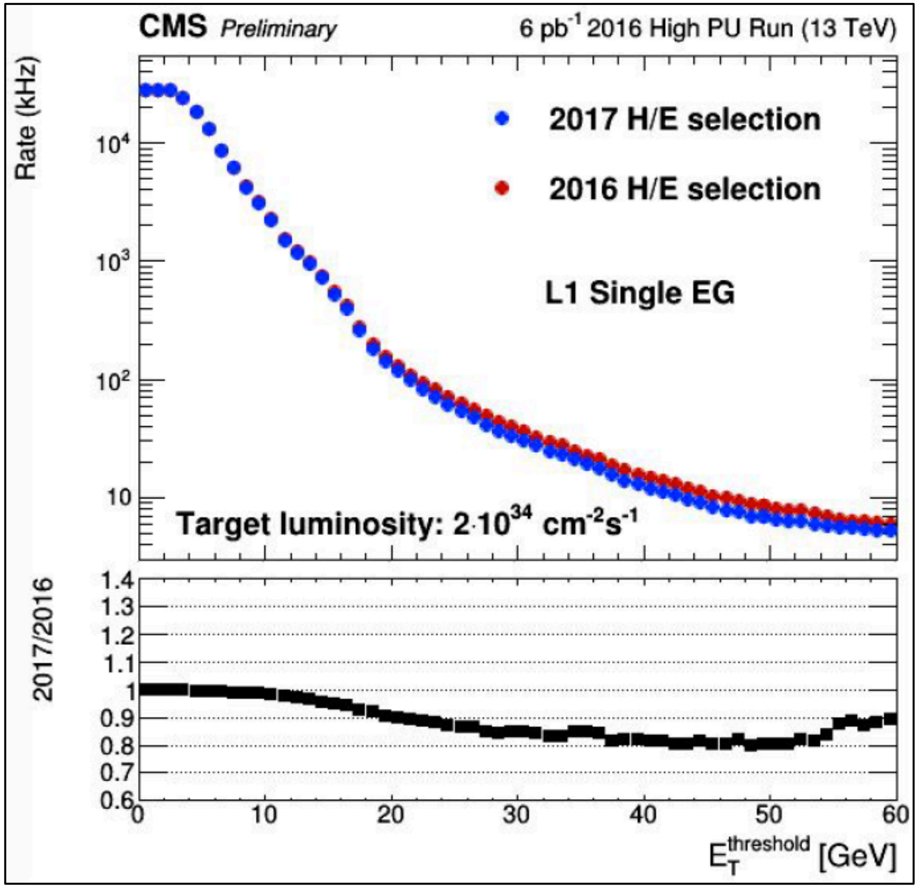
BACKUP

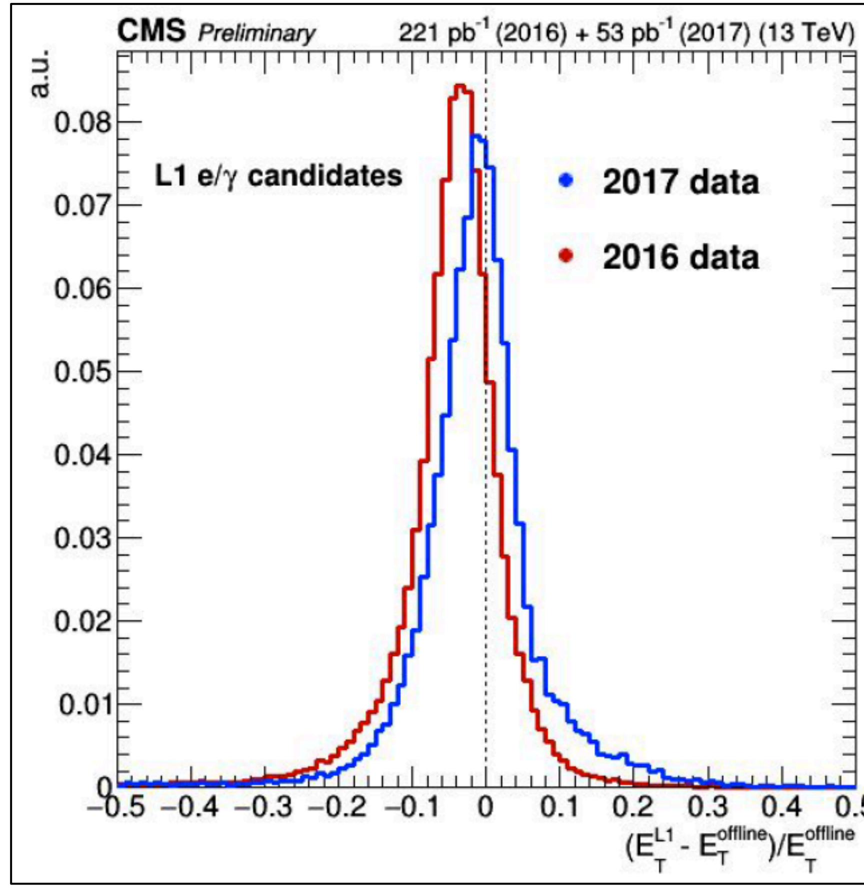
Level-1 electron/photon

- ✧ **L1 electron/photon** strategy: **OR** (**3 algos**: non-isolated, isolated, isolated + eta-restricted)
- ➢ Using tighter identification but looser transverse energy (E_T) cuts: {**X** ; X**-2** ; X**-4**}
- ➢ 2017 Improvements: reoptimization of the isolation relaxation (high E_T)
- ➢ Right plot: efficiency of the OR of the three algorithms
- ➢ Comparing thresholds giving the same rate (at PU=24) using 2016 and 2017 configurations

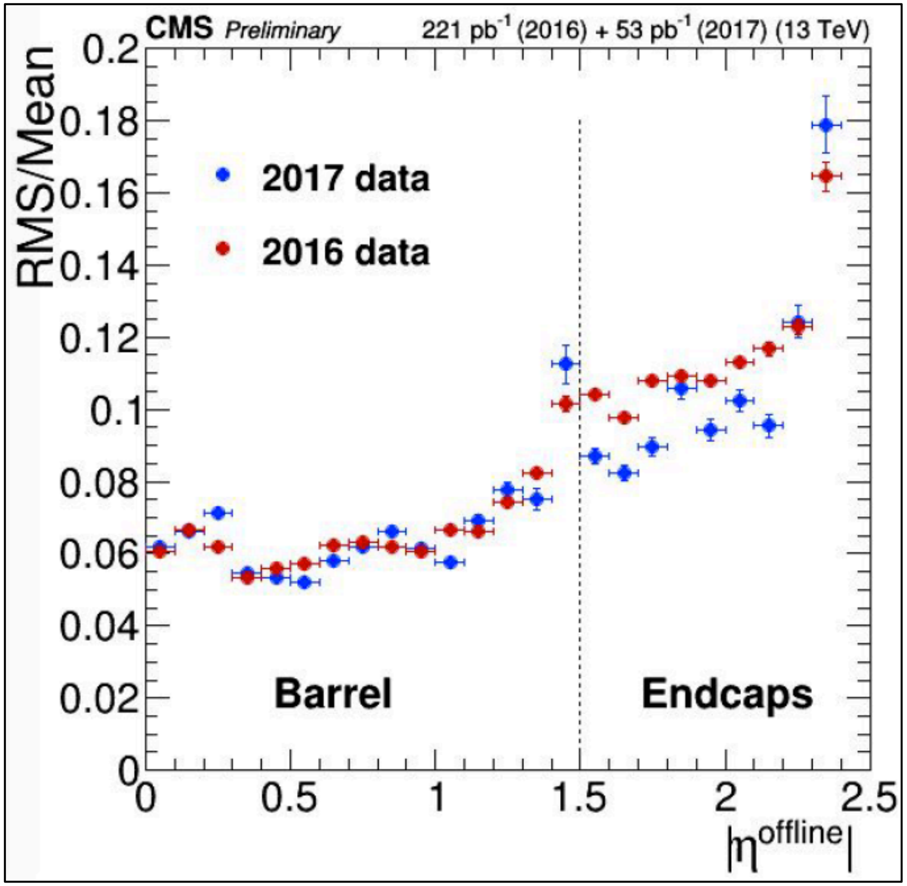


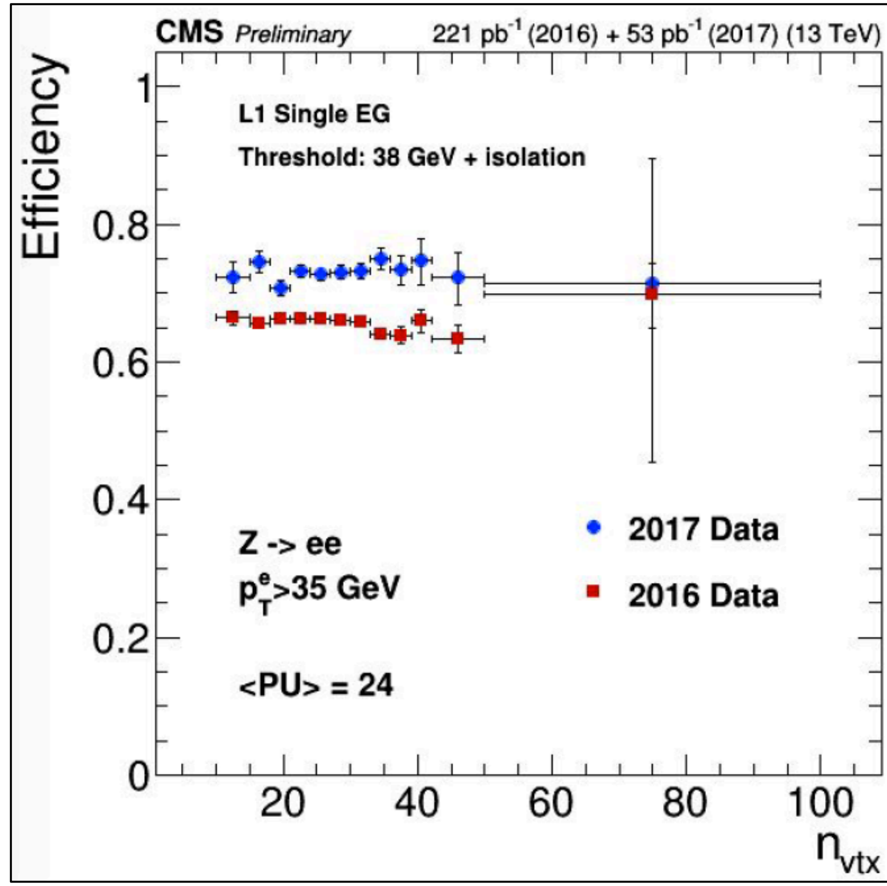
Level-1 electron/photon



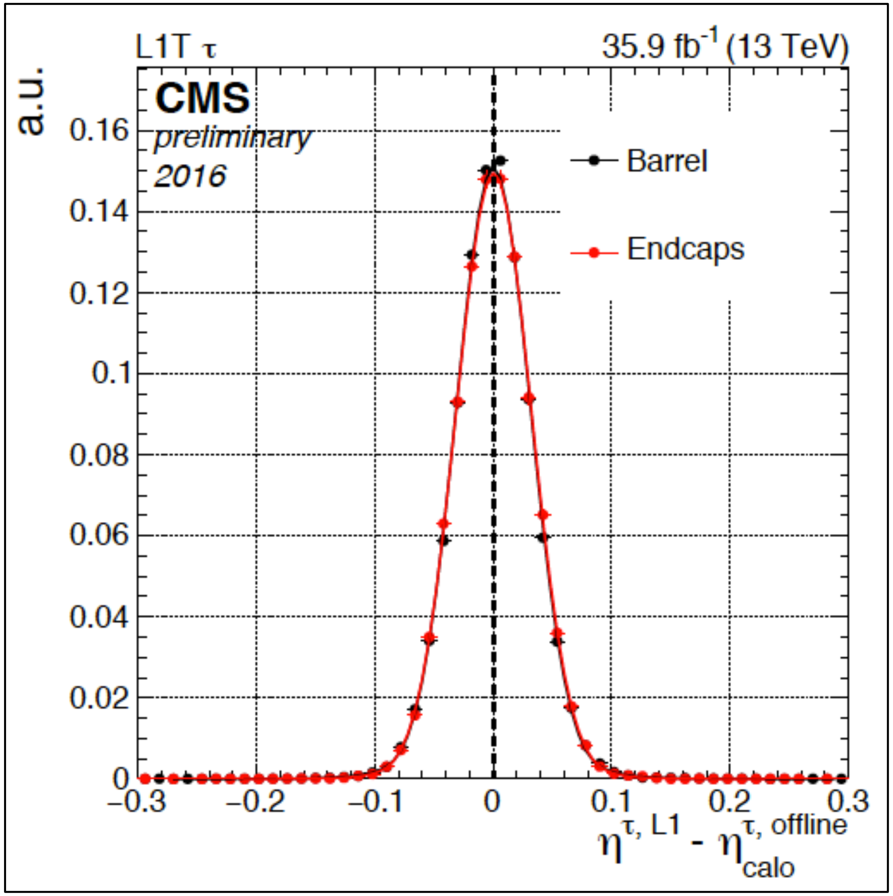


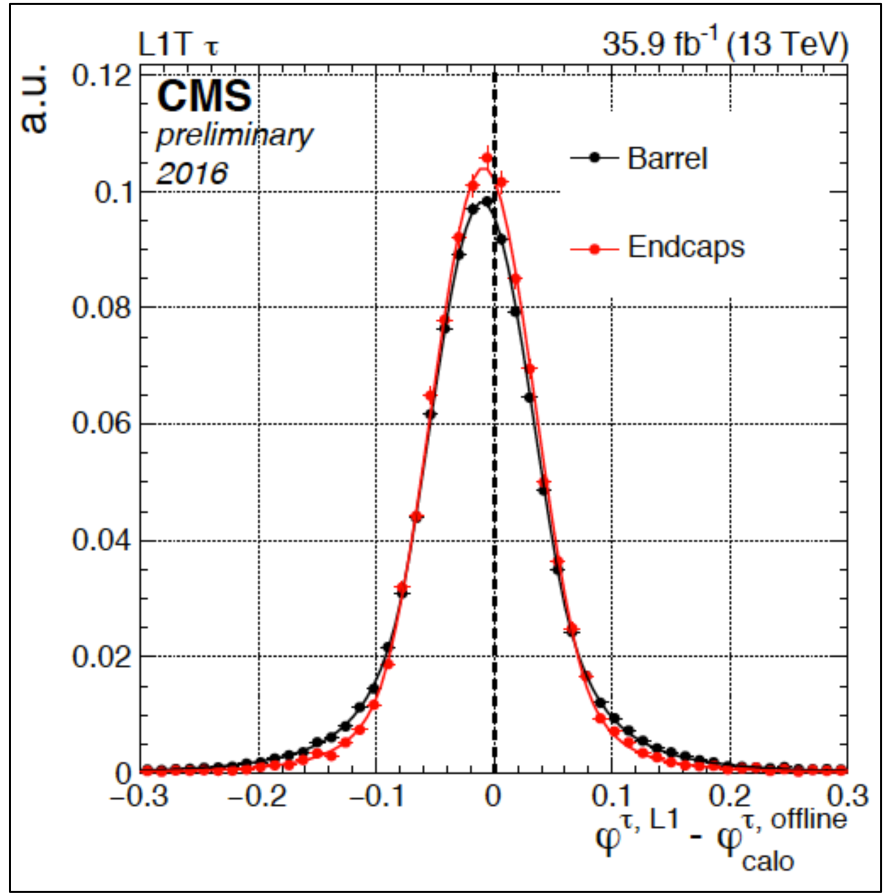
Level-1 electron/photon





Level-1 taus


L1T τ
35.9 fb-1 (13 TeV)
CMS
preliminary
2016
Barrel
Endcaps
a.u.
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
−0.3
−0.2
−0.1
0
0.1
0.2
0.3
η τ, L1 - η τ, offline calo


L1T τ
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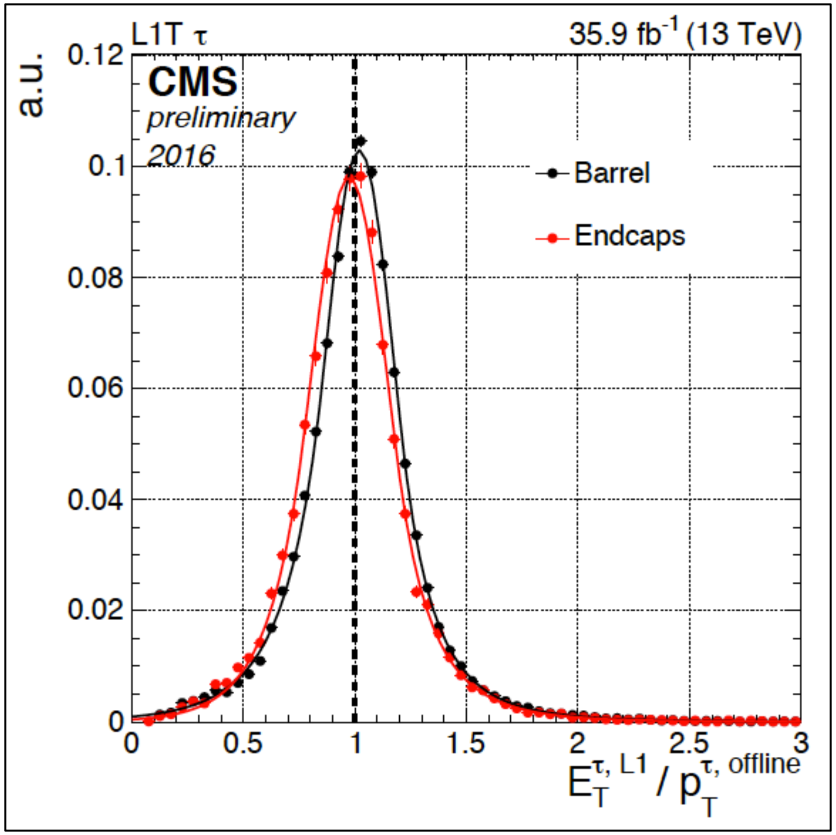
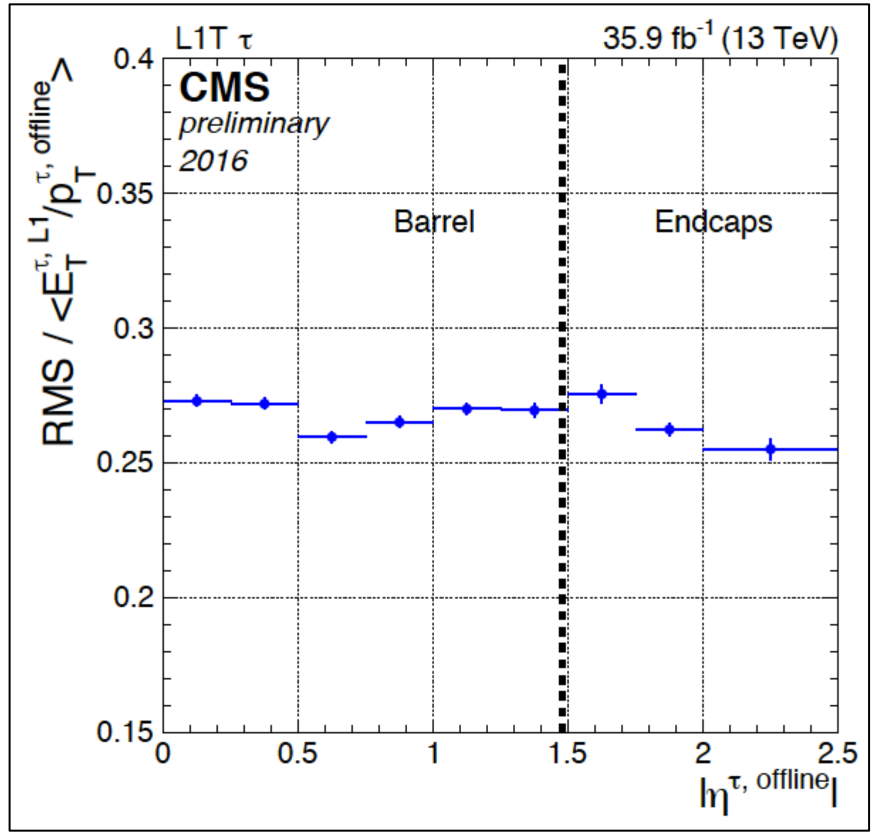
0
0.1
0.2
0.3
φ τ, L1 - φ τ, offline calo

Level-1 taus

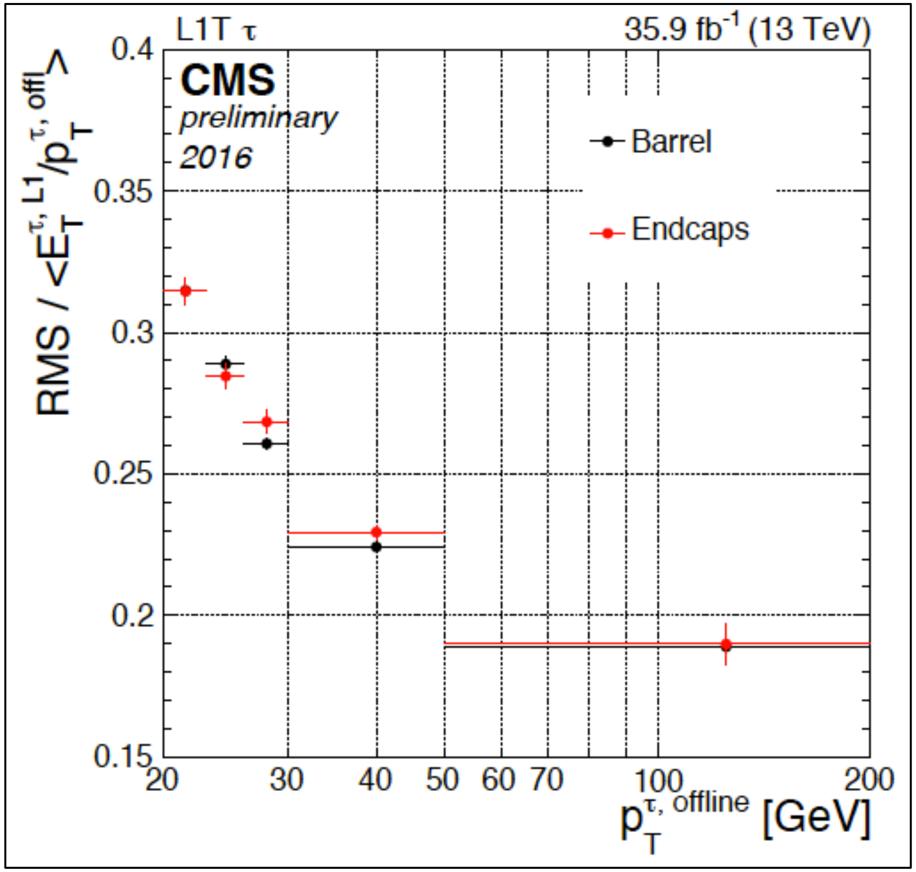


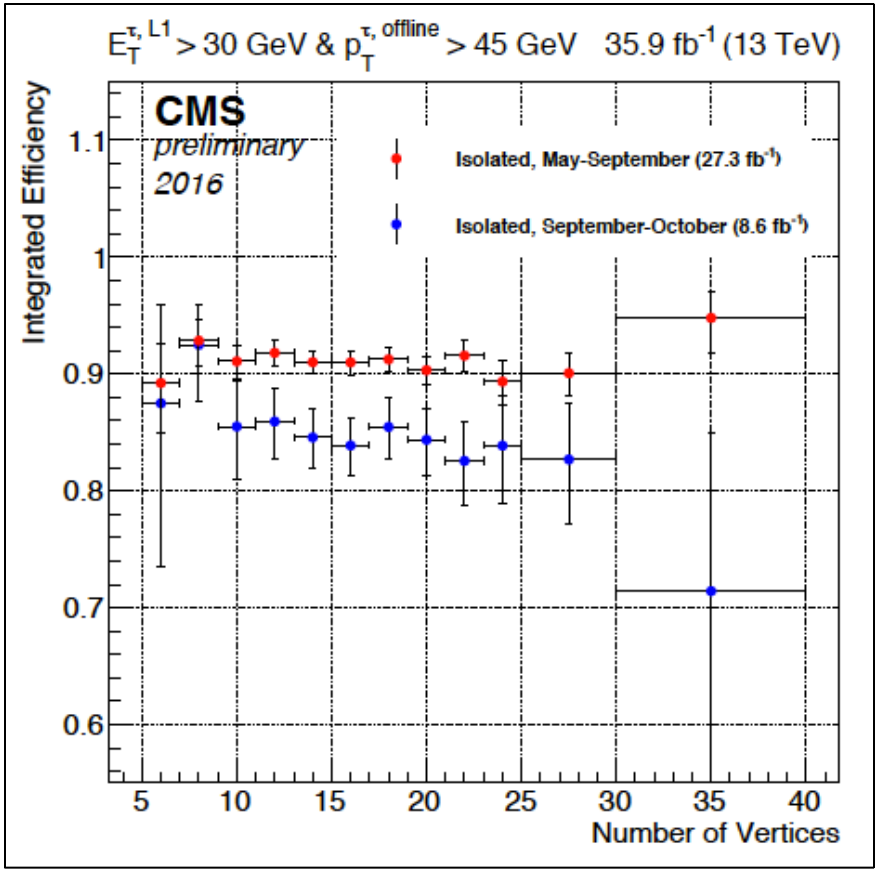
L1T τ
35.9 fb-1 (13 TeV)
CMS
preliminary
2016
a.u.
Barrel
Endcaps
0.12
0.1
0.08
0.06
0.04
0.02
0
0
0.5
1
1.5
2
2.5
3
$E_T^{\tau, L1} / p_T^{\tau, offline}$



L1T τ
35.9 fb-1 (13 TeV)
CMS
preliminary
2016
$RMS / \langle E_T^{\tau, L1}/p_T^{\tau, offline} \rangle$
Barrel
Endcaps
0.4
0.35
0.3
0.25
0.2
0.15
0
0.5
1
1.5
2
2.5
$|\eta^{\tau, offline}|$

Level-1 taus


L1T τ
35.9 fb-1 (13 TeV)
CMS
preliminary
2016
Barrel
Endcaps
RMS / <E_T^{τ, L1}/p_T^{τ, offl}>
p_T^{τ, offline} [GeV]
0.15
0.2
0.25
0.3
0.35
0.4
20
30
40
50
60
70
100
200


E_T^{τ, L1} > 30 GeV & p_T^{τ, offline} > 45 GeV
35.9 fb-1 (13 TeV)
CMS
preliminary
2016
Isolated, May-September (27.3 fb-1)
Isolated, September-October (8.6 fb-1)
Integrated Efficiency
Number of Vertices
0.6
0.7
0.8
0.9
1
1.1
5
10
15
20
25
30
35
40

Level-1 Jets

- **Cluster** ECAL/HCAL towers in a 9*9 matrix around a seed tower (local maximum, tunable threshold)