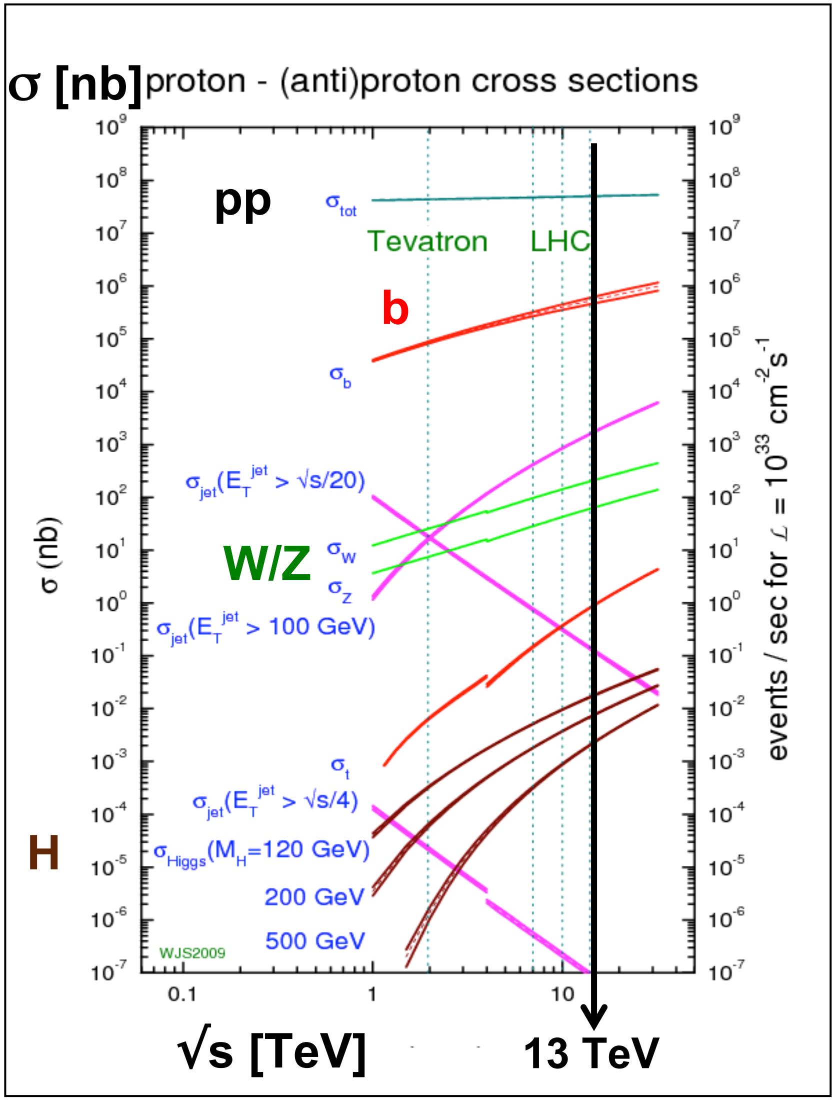
The CMS Trigger Performances during LHC Run 2

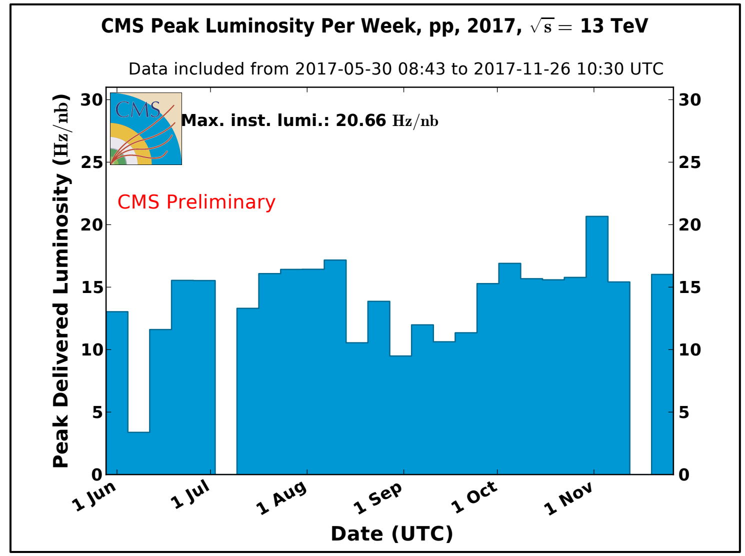
Nadir Daci
CERN

On behalf of the CMS Collaboration

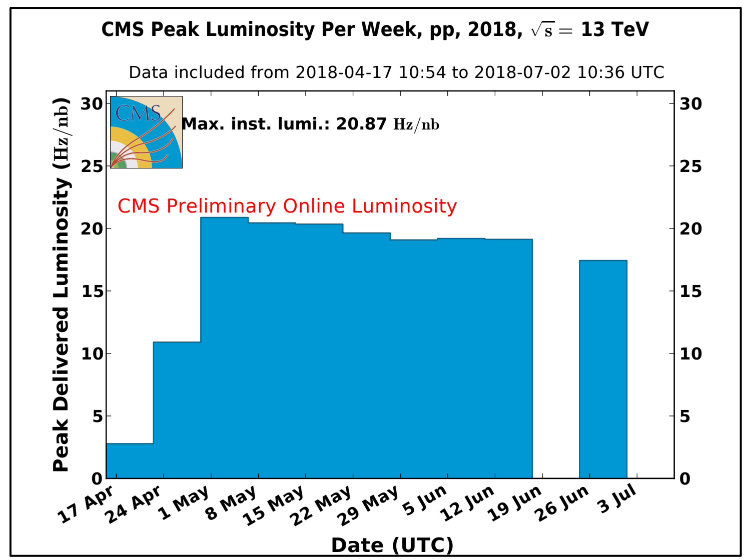
Introduction

Triggering at the LHC





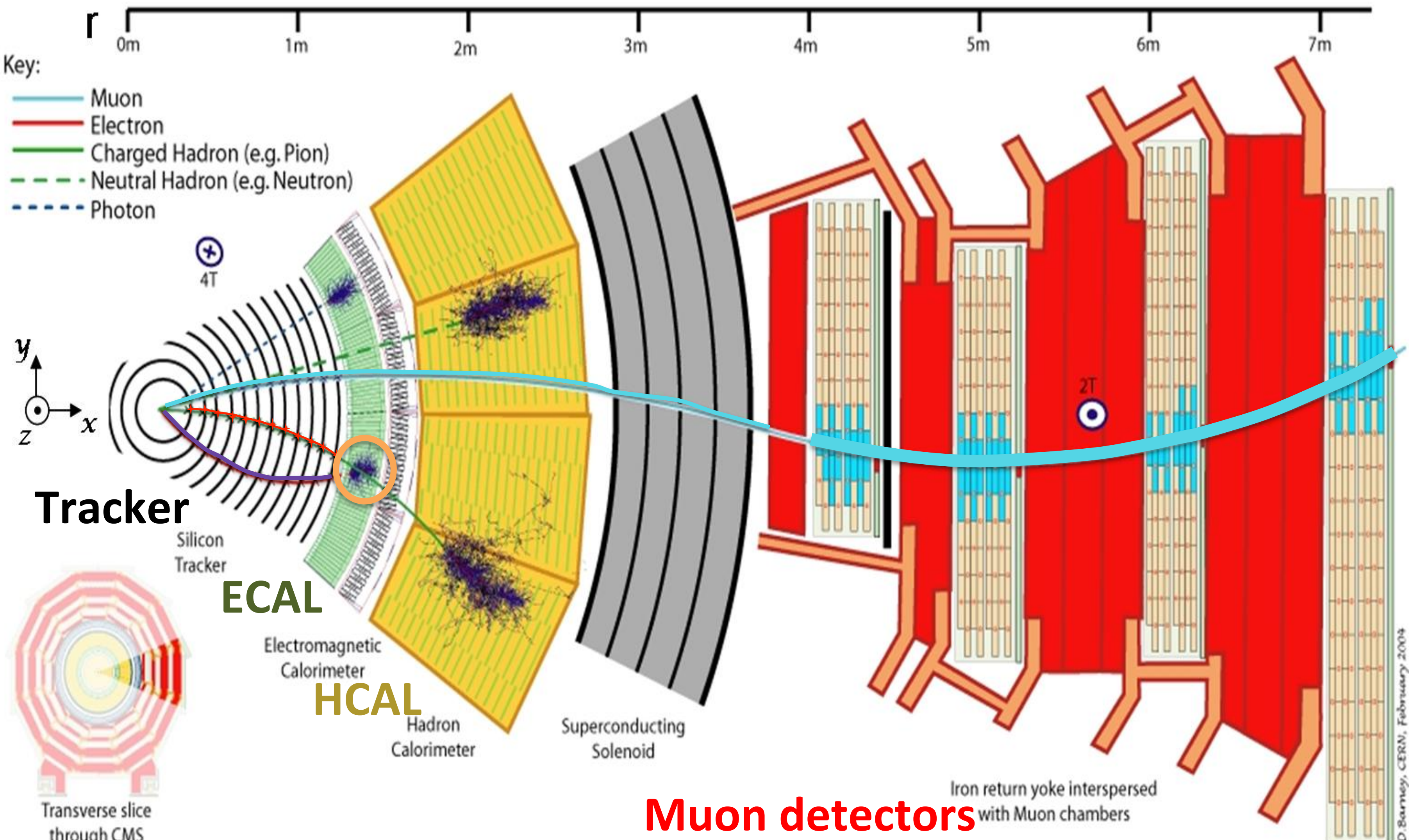
2017 Peak
$2.07e34\ cm^{-2}s^{-1}$
@ PU 78



2018 Peak
$2.09e34\ cm^{-2}s^{-1}$
@ PU 58

- ✧ **LHC** provided a luminosity up to **$2.0e34\ cm^{-2}s^{-1}$** which allows to study **rare physics** events (*Higgs production: 0.4 Hz*).
- ➢ **Trigger systems:** designed to **sort out** a tiny fraction (*< 0.02 %*) of events with **interesting physical contents.**

Particle identification in CMS



Muon detectors

- Drift Tubes (**DT**) in the central region
- Cathode Strip Chambers (**CSC**) in the forward region
- Resistive Plate Chambers (**RPC**) overlapping with both

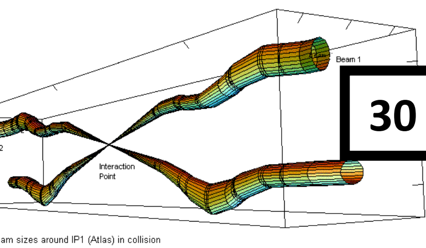
A two-level trigger system

Level-1: custom on/off-detector electronics, fixed latency of 4 μs

- **Process basic inputs** (calo trigger towers, muon hits).
- Reduces the event rate by a factor 300.

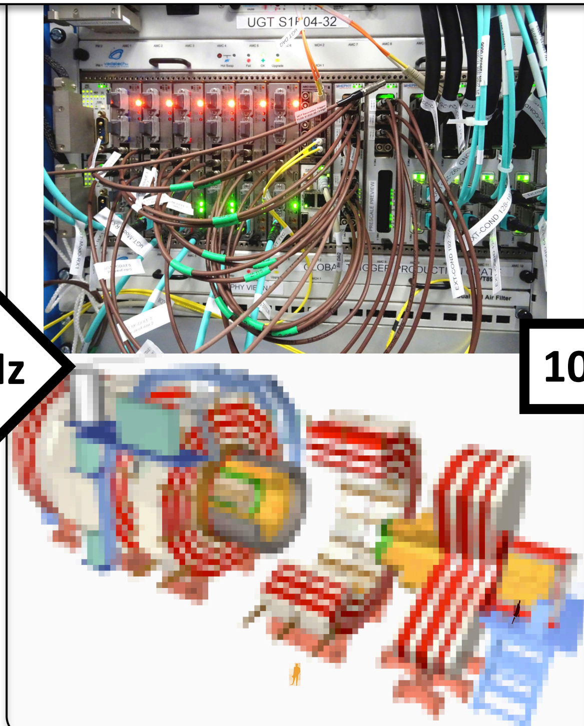
High-Level: CPU farm

- **Full event** readout (with zero suppression).
- Reduces the event rate by a factor 100.

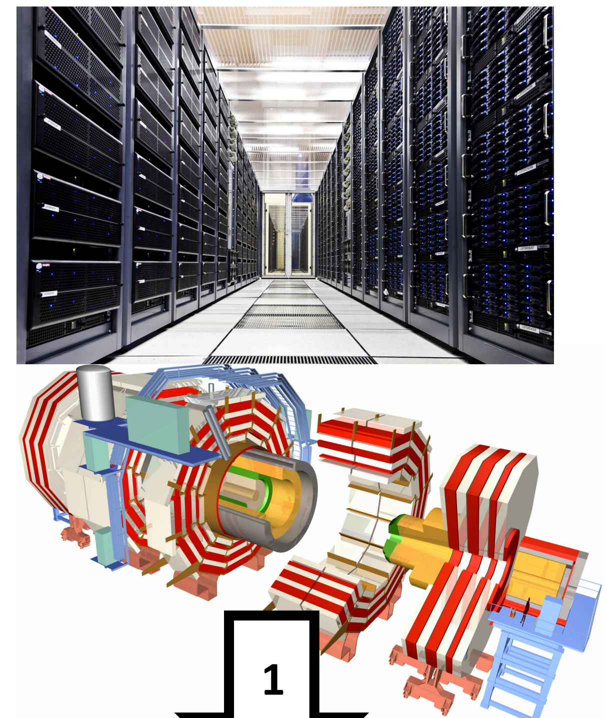


LHC pp bunch crossing

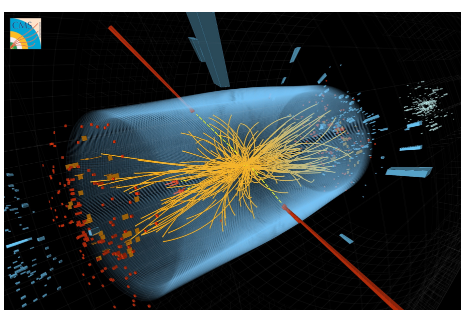
30 MHz



100 kHz



1 kHz

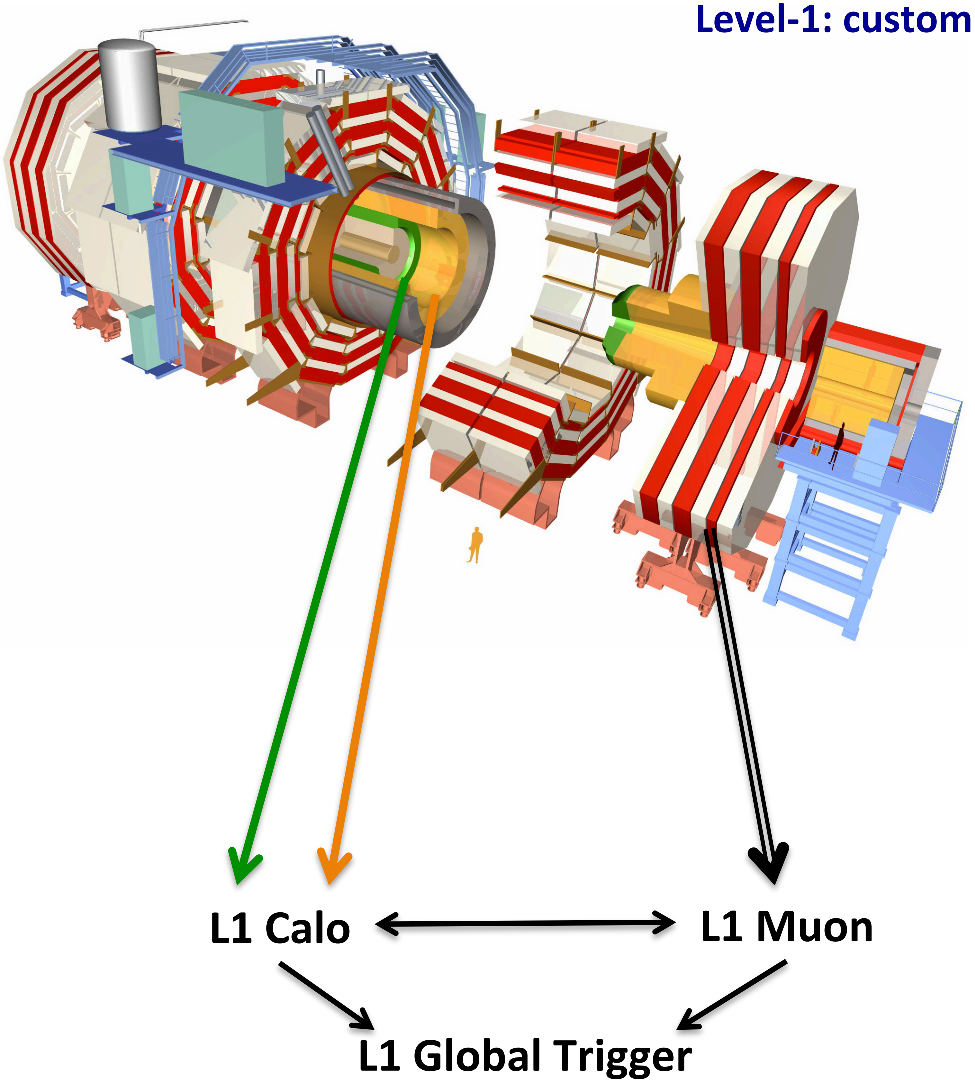


CERN Data Centre
Long-term storage (TAPE)
Transfer to LHC Grid
Offline reconstruction

Level-1 Trigger

Level-1 architecture

Level-1: custom on/off-detector **electronics**



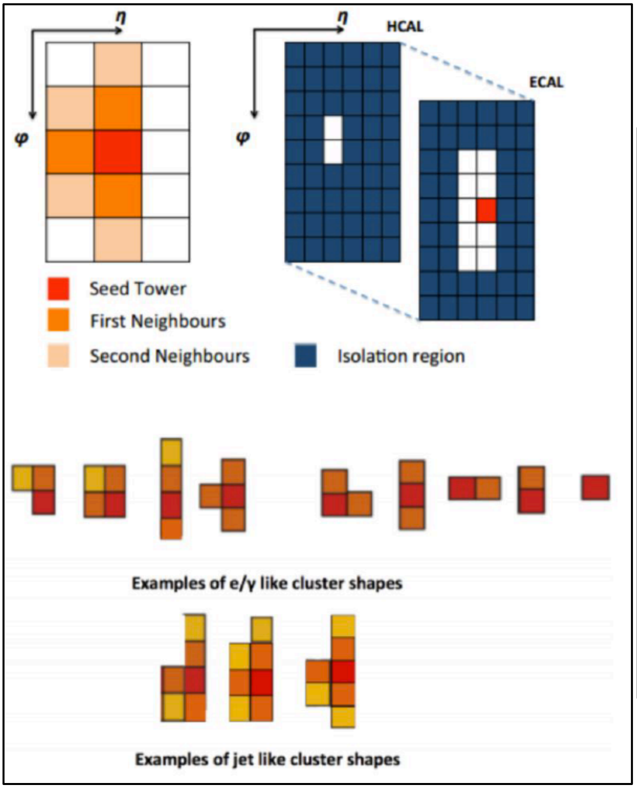
- **Process basic inputs** (calo trigger towers, muon hits)
- Local **matching** (ECAL+HCAL towers, CSC/DT/RPC hits)

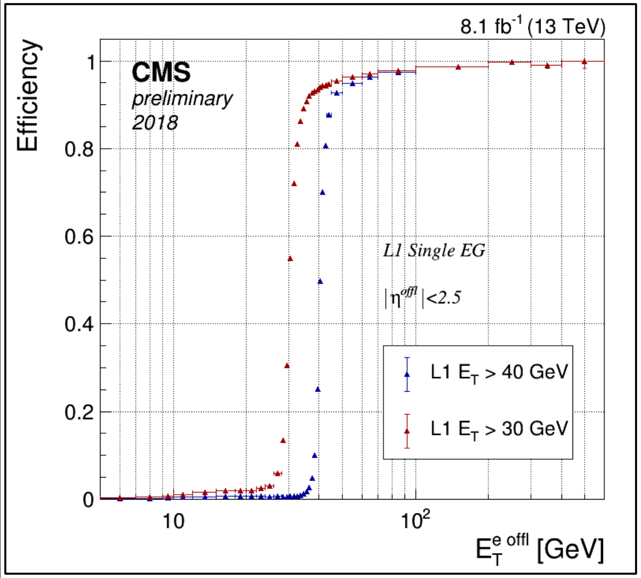
- **Build** coarse trigger **objects** (e/γ, jets, μ, energy sums)
- **Global Trigger** gathers objects to make **decisions** based on L1 algorithms
- Kinematic selections, cross-triggers, geometric correlations, invariant mass…

Level-1 electrons & photons

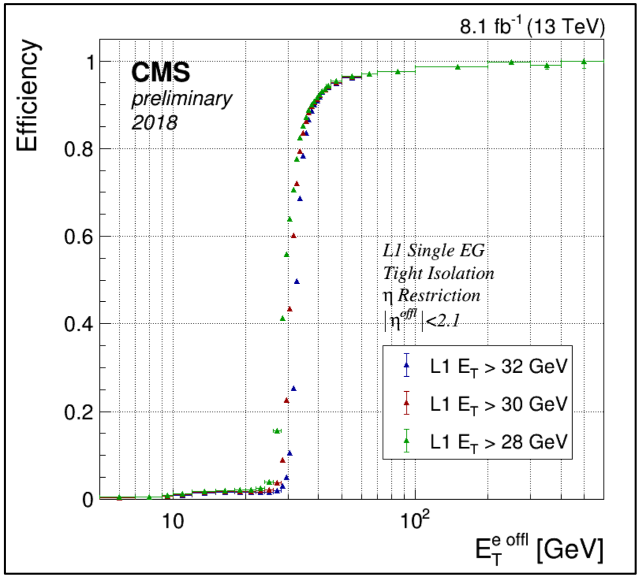
✧ **L1 electron/photon** reconstruction: cluster ECAL and HCAL trigger towers.

➢ **Reject** jets using HCAL vs ECAL energy (**H/E**) and **cluster shape** veto.





No isolation, thresholds: 30, 40 GeV



Tight isolation, thresholds: 28, 30, 32 GeV

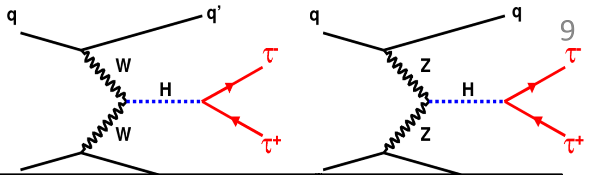
✧ **L1 electron/photon** in **2018**

➢ The **isolation** variable is a function of the candidate's $\mathbf{E_T}$, η, and a **pile-up** estimator.

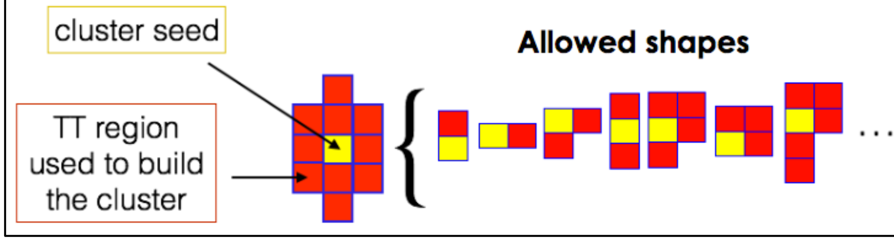
➢ **3 levels** of isolation are available: none, loose, tight.

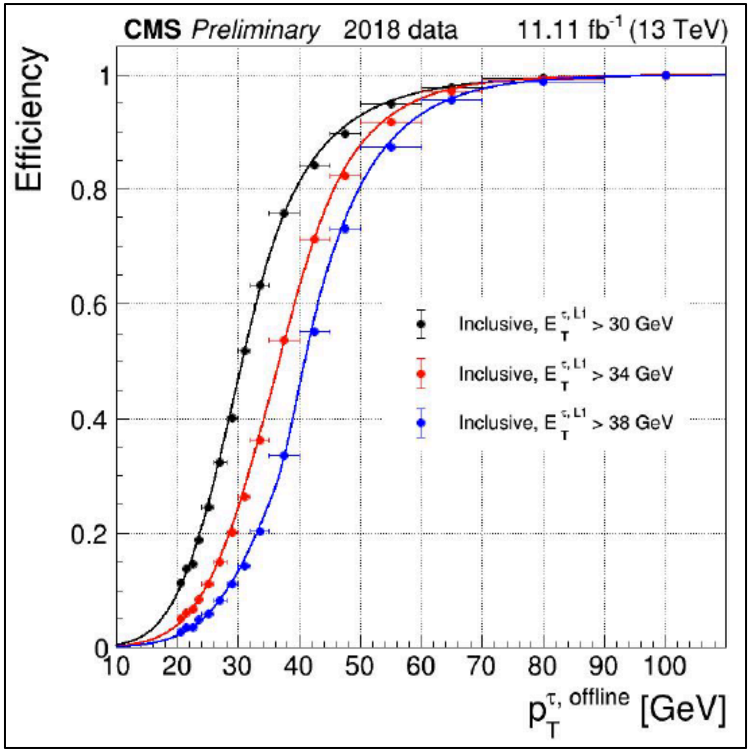
➢ Most **EG** algorithms are restricted in |η| to remain within the tracker coverage (offline & HLT reco).

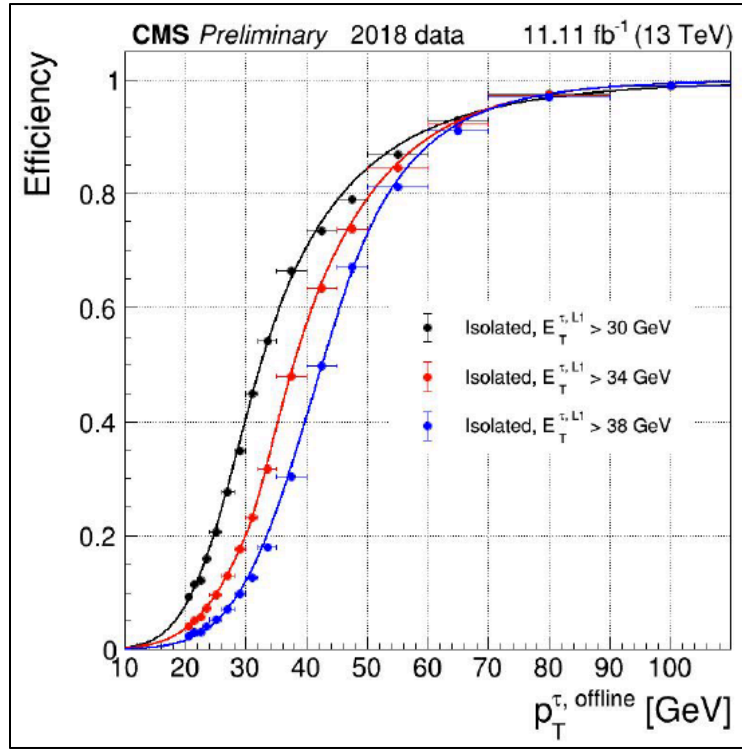
Level-1 taus



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



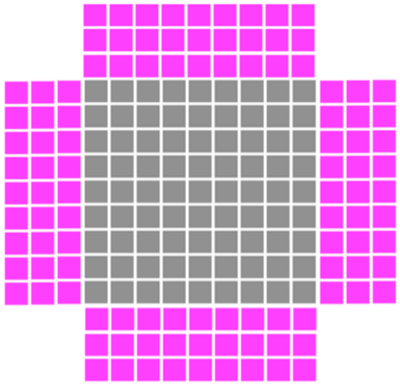




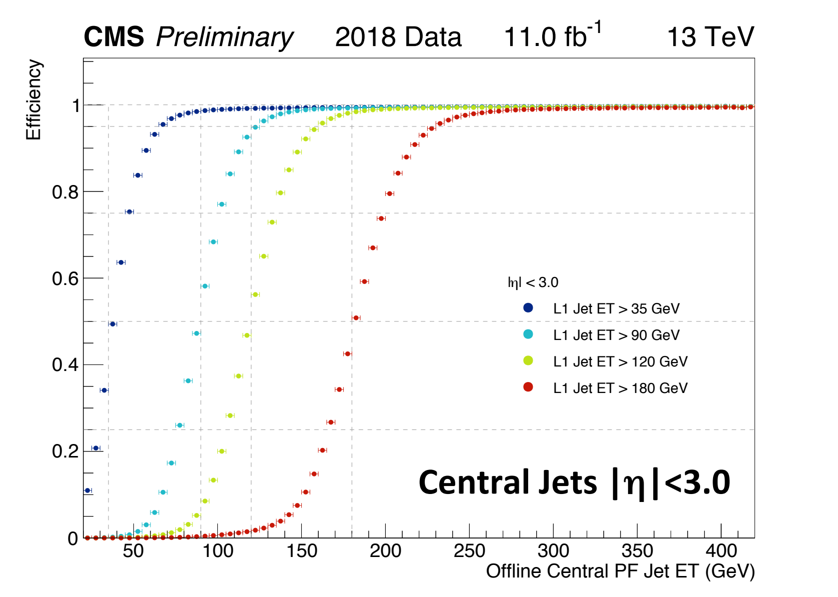
- **Hadronically-decaying taus** used in tau final states: **Higgs, Z', W'…**
- **High p_T taus** are covered by Ditau and SingleTau algos **without isolation**.

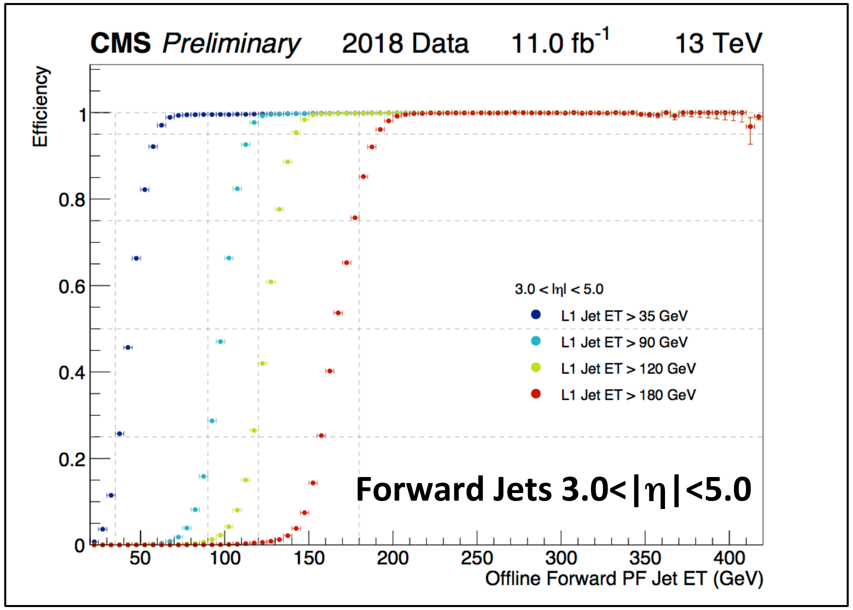
Level-1 jets

chunky donut area



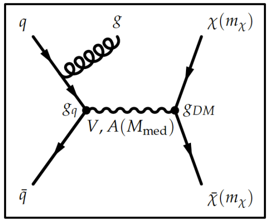
- **L1 Jets reconstruction**: sliding window (9x9 towers, $\Delta\eta \times \Delta\phi = 0.78 \times 0.78$)
- **Pile-up energy density** estimator: energy in 3 lowest-E_T surrounding **3x9** regions.
- This **density** is then **scaled** to the L1 Jet **area** and **subtracted** to its E_T.
- Jet energy **corrections** are applied in bins of η and E_T.





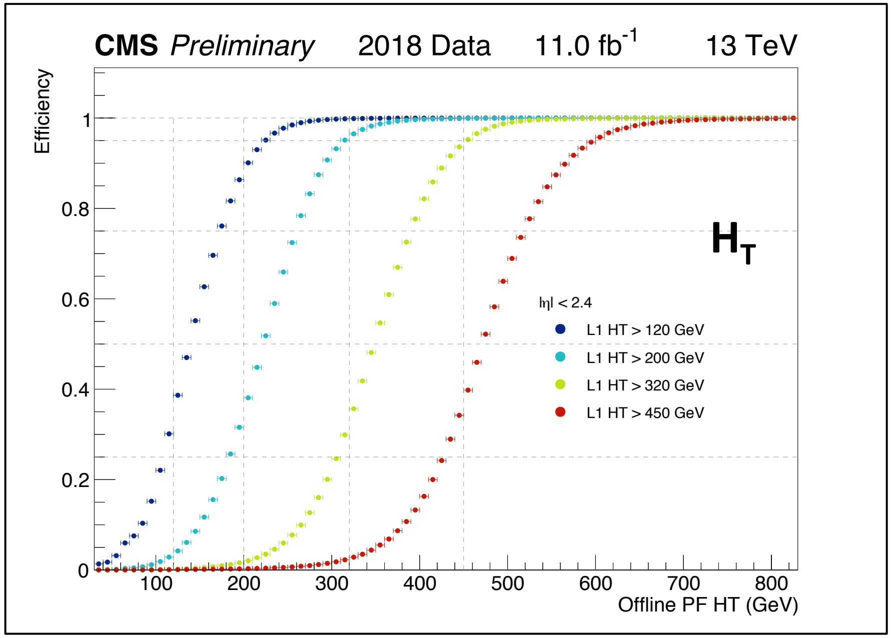
- The 120 (180) thresholds are **90%** efficient at:
  $\Longrightarrow$ offline central jet p_T > 150 (215) GeV

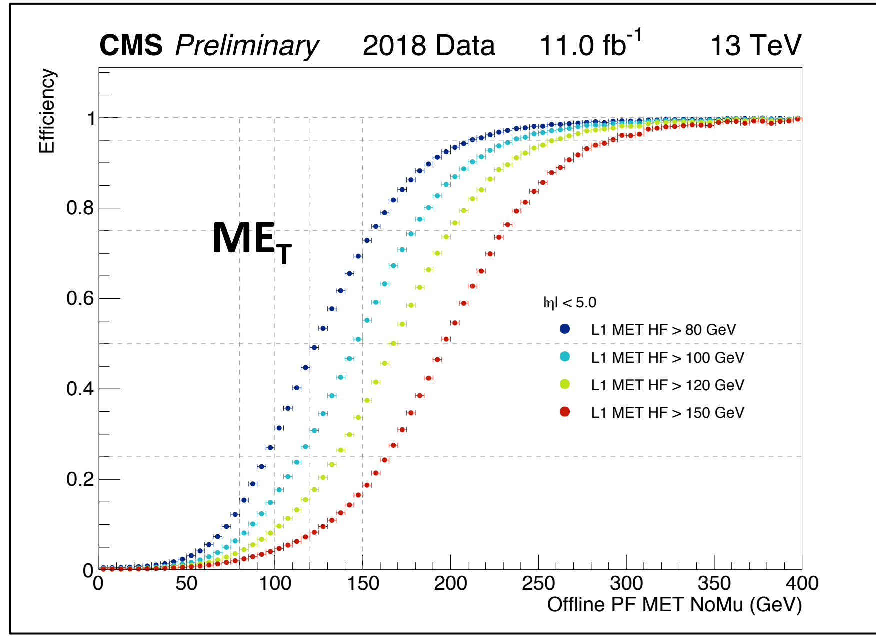
- The 120 (180) thresholds are **90%** efficient at:
  $\Longrightarrow$ offline forward jet p_T > 140 (190) GeV



Level-1 energy sums

- ✧ **Energy sum triggers** widely used in analyses based on **hadronic** final states
  - ⟹ e.g. dijet resonances, dark matter in X+MET final states, etc.
- ➢ **Challenge**: mitigate the effects from **pile-up** and **instrumental noise**.

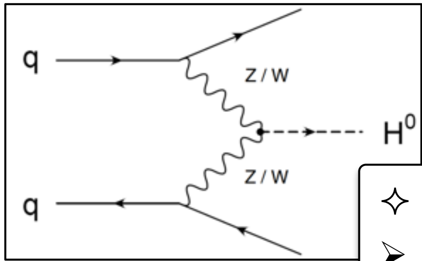




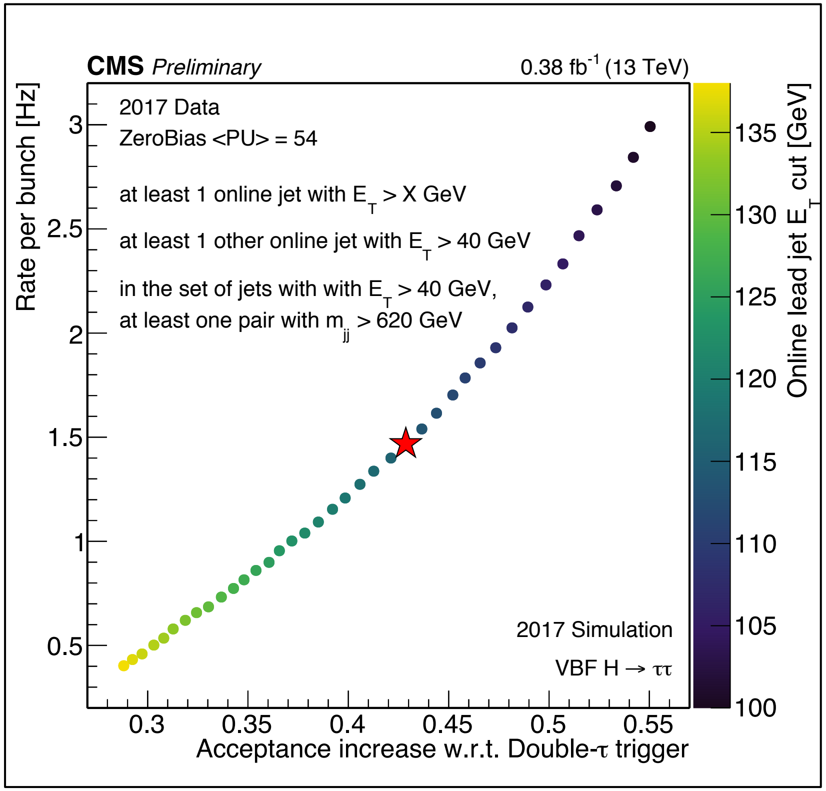
- ➢ **H_T :** scalar E_T sum of L1 jets (E_T > 30 GeV, |η|<2.4).
- ➢ The **320** (**450**) thresholds are **90%** efficient at:
  - ⟹ offline HT > **420** (**550**) GeV

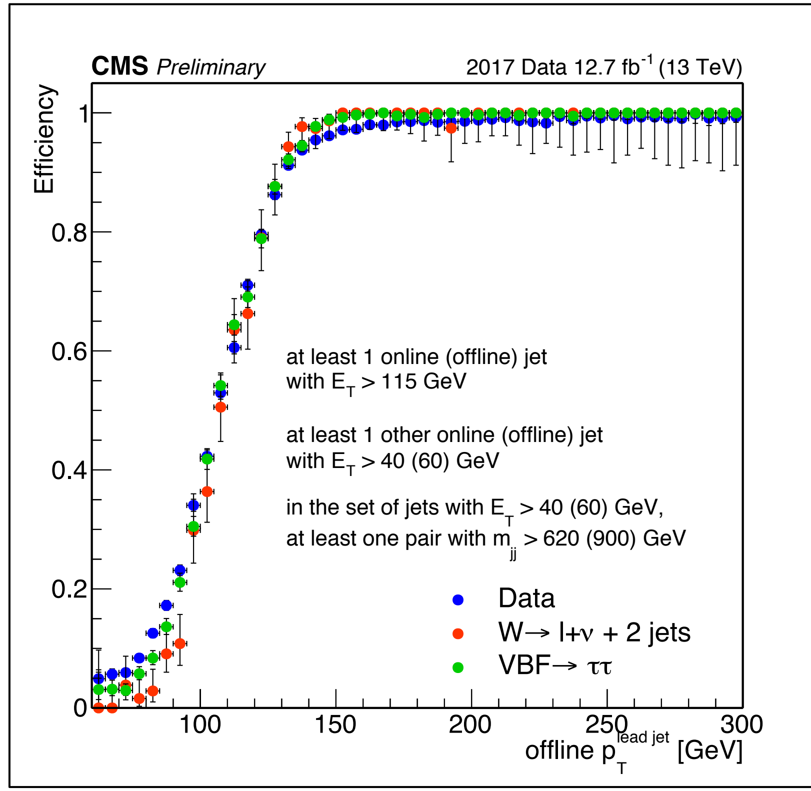
- ➢ **ME_T:** vector E_T sum of calorimeter trigger towers (|η| < 5)
- ➢ *L1 object suffering the most from lack of tracker info.*
- ➢ **Pile-up mitigation**: dynamic η-dependent **E_T threshold** calculated using an estimation of the event **pile-up**.
- ➢ The **100 GeV** threshold is **90%** efficient at:
  - ⟹ offline PF ME_T > **210** GeV *(excluding muons)*

Level-1 VBF



- ✧ **VBF** production mode very **sensitive** for searches such as **Higgs ditau** and **invisible** final states.
- ➢ **Level-1** implements the calculation of **invariant mass** since **2017**.
- ➢ **VBF** trigger strategy: target VBF-induced jets rather than Higgs bosons decay products.





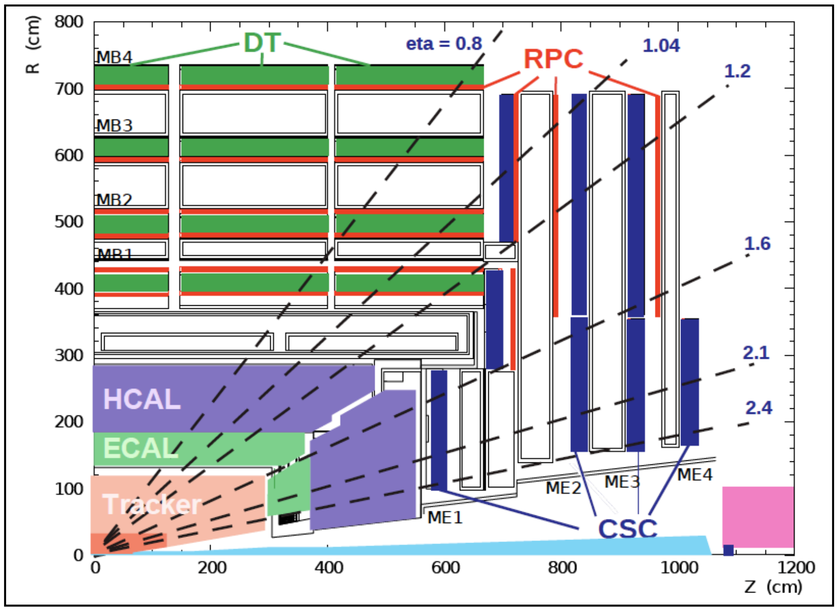
- ➢ **Efficiency** evaluated in the **VBF H(ττ)** topology in a data sample recorded by a **single muon** trigger algorithm.
- ➢ The **addition** of the **VBF** algorithms increased the **acceptance** on the VBF H(ττ) signal by more than **40%**.

Level-1 muons

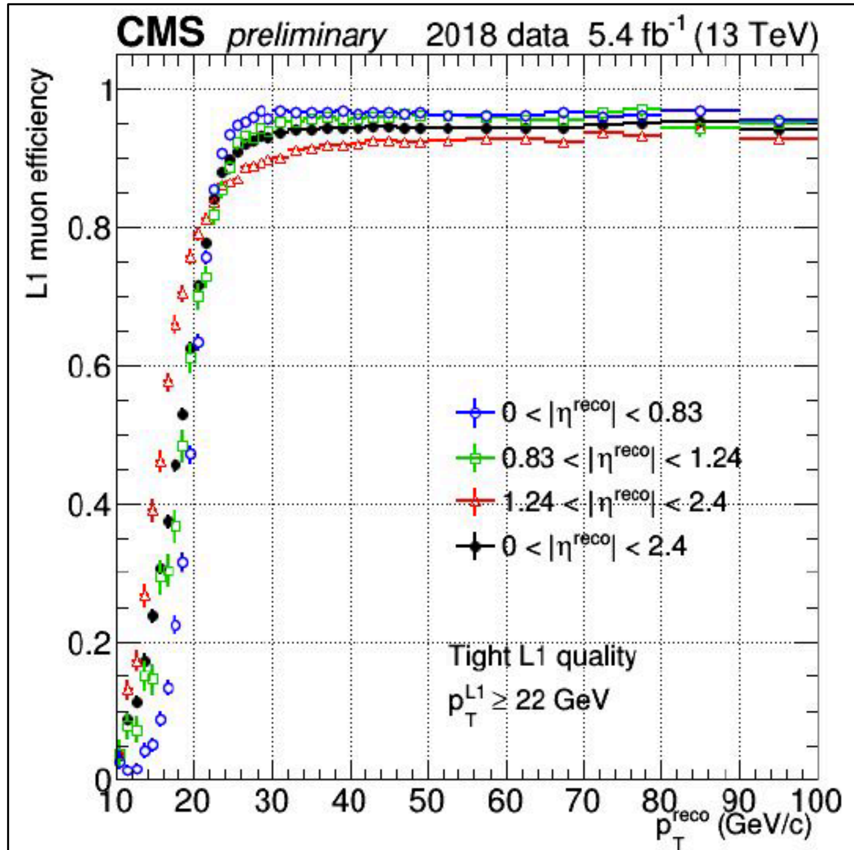
- ✧ **2016** upgrade: move from a **detector**-oriented to a **coordinate**-based architecture.
- ➢ **L1 muons** are reconstructed separately in **3 eta regions**, thus exploiting the **redundancy** created by muon detector **overlaps**. The L1 Global Muon System subsequently **sorts** candidates in **pT** and **quality**, and suppresses **duplicates**.

Muon Track Finders (MTF)

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



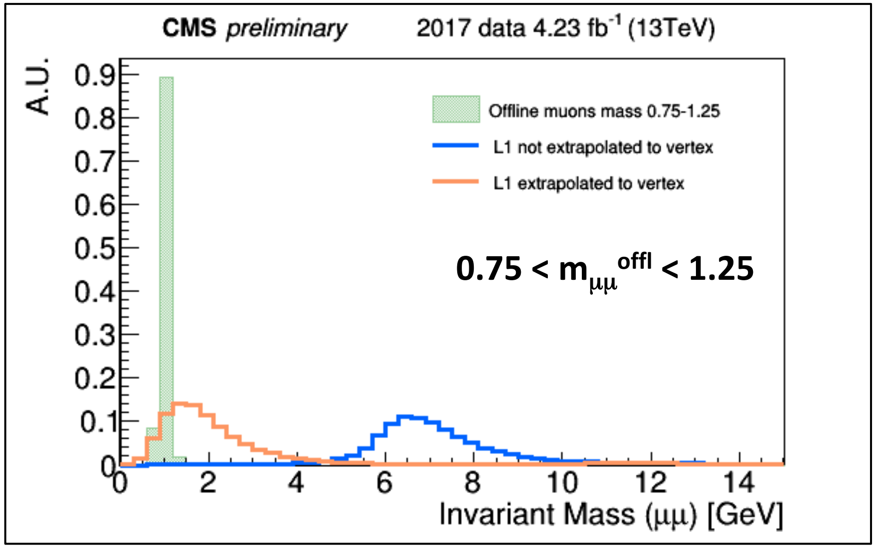
EMTF: Endcap (RPC+CSC)

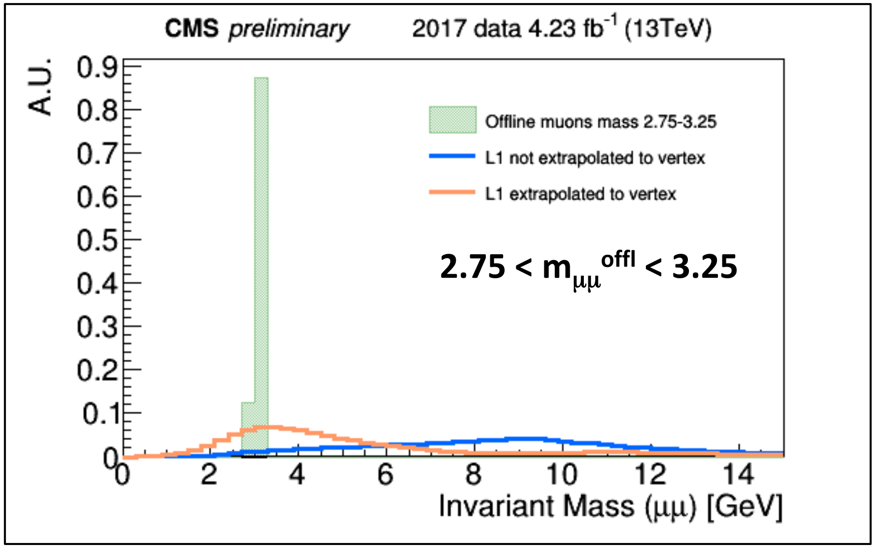


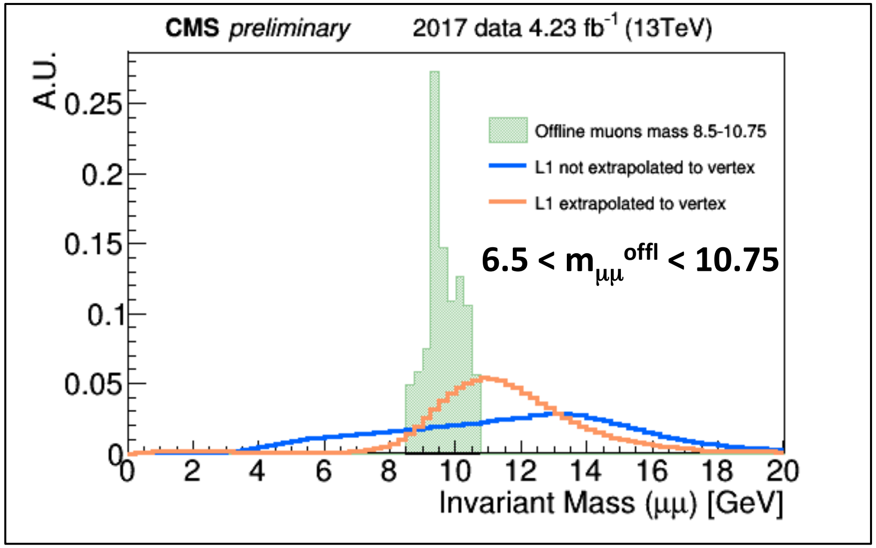
- ✧ **2017** improvements: add **RPC** segments in **BMTF** & **EMTF**; project **coordinates** to the collision **vertex.**
- ✧ The upgrade **reduced** the **rates** by a factor **two** at constant efficiency.

Level-1 dimuon resonances

- The **L1** system allows to target specific **dimuon resonances**.
- This has been made possible by introducing the muon **track extrapolation** to the collision **vertex** in 2017.





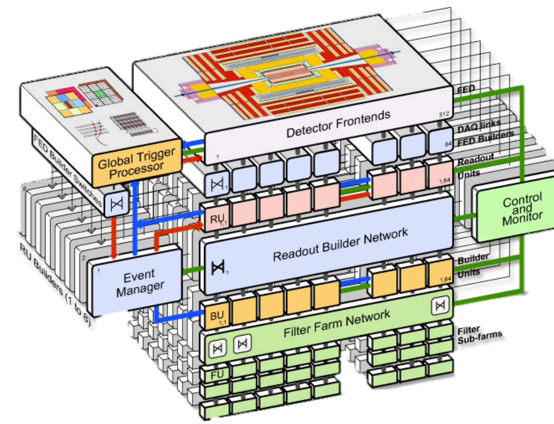


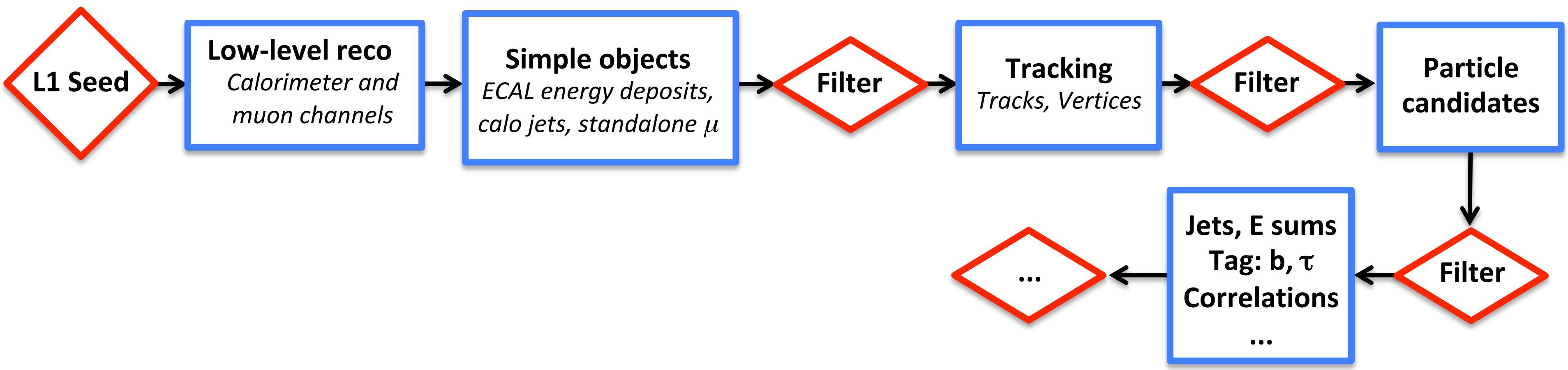
- These plots display the **L1 mass** distribution in 3 offline mass ranges, **with** and **without** extrapolation.
- The extrapolation **improves significantly** the **L1** dimuon invariant **mass** response and resolution.

High-Level Trigger

HLT reconstruction

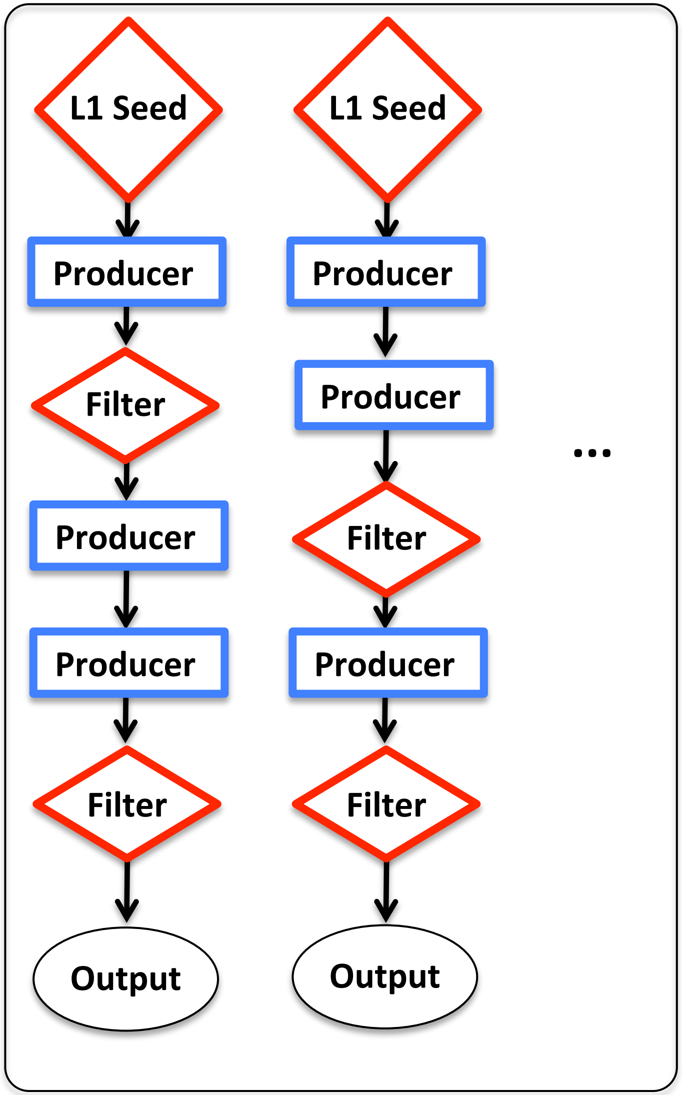
- ✧ **HLT** algorithm = sequence of object **producers** and **filters**
- ➢ **Seeded** by a **Level-1 requirement** (single L1 algo / OR of several L1 algos).
- ➢ **Low-level** reconstruction: calorimeter channels, hits in muon chambers.
- ➢ **Start filtering events as soon as possible** using **basic objects**





- ➢ Match **pixels** in successive layers to produce "**seeds**" for tracking algorithms.
- ➢ Match **tracks** to **energy** deposits, perform global **tracking fits** for **muons**.
- ➢ Run the **Particle Flow** (PF) algorithm and produce **particle candidates**.
- ➢ Reconstruct more advanced **observables** and **topologies** from the individual particles.

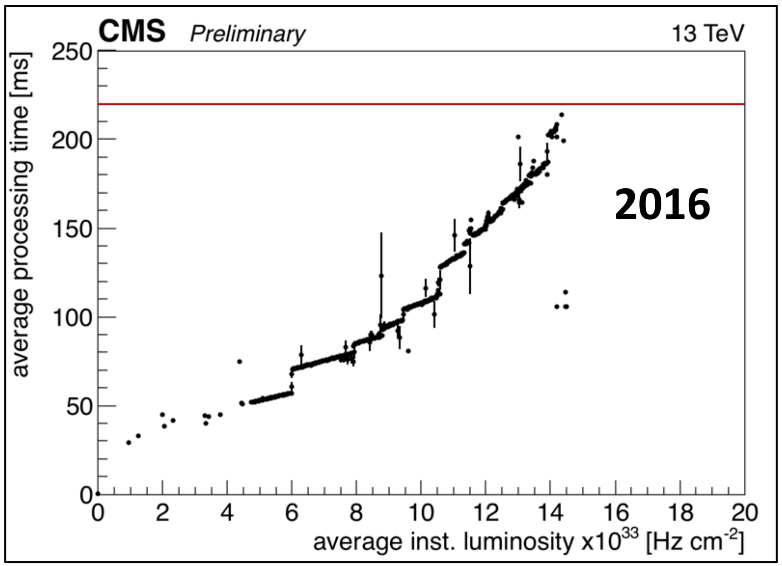
HLT reconstruction

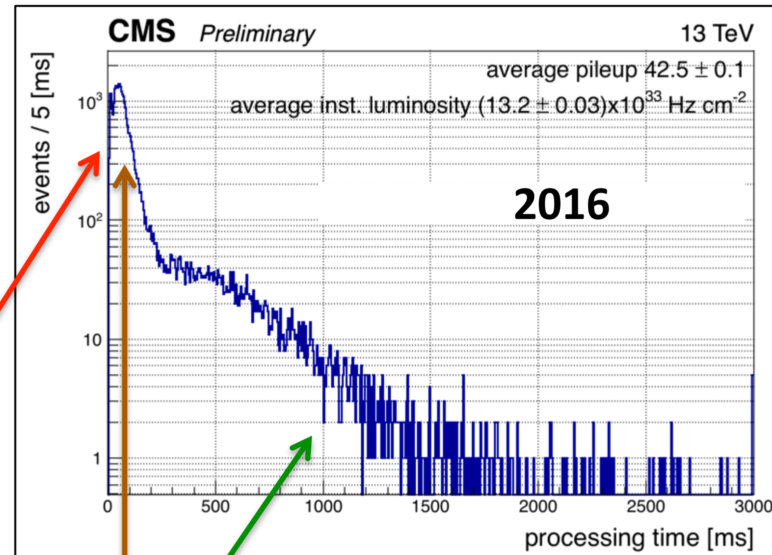


- **HLT Menu**
- O(**600**) independent algorithms are run in parallel for each event.
- Common **producers** are **shared** by several paths, in order to **optimize** the event processing **time**.
- The **selected** events are written out in various **data streams**, with various event **contents**.

HLT timing

- ✧ Main constraint **intrisic** to the **HLT CPU farm: timing**
- ➢ Process **100 kHz** (L1) with **32k** cores (since 2018) ⟹ Naive timing budget: **320 ms/event**
- ➢ Extra CPU features such as **Hyperthreading** ⟹ Actual budget is larger (by at least **10%**)
- ➢ The HLT menu currently used online complies with these constraints.





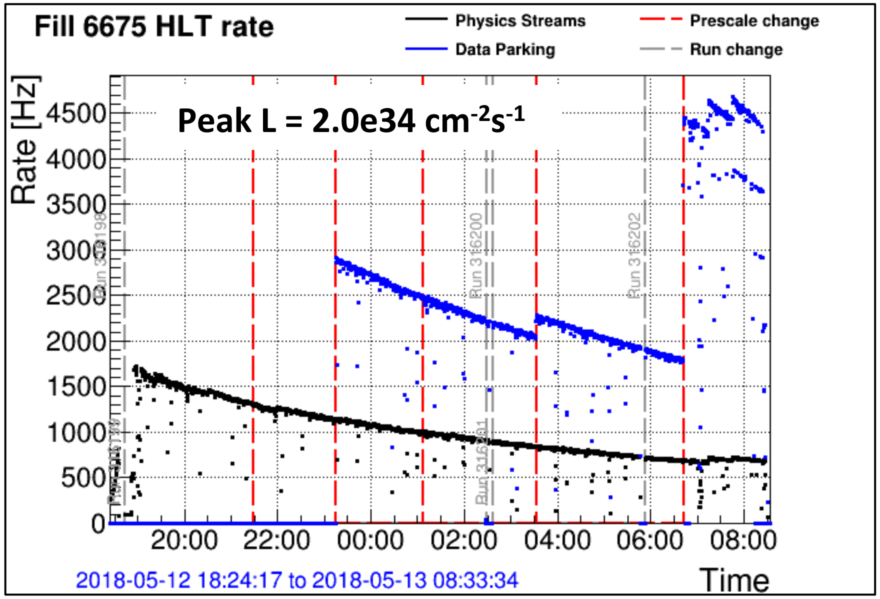
Peak at 0 ms: events rejected by the **L1** requirement

Peak around **50 ms**: events accepted/rejected based on **simple objects** ie **calorimeter** energy deposits / jets / missing energy, and **standalone muons**.

Tail: events accepted/rejected based on **particle candidates** & **advanced requirements**: kinematics, topology, tau or b identification...

Bandwidth constraints

- ✧ **Bandwidth** constraints ⟹ **average** output **rate** of **1 kHz** (main physics data streams)
- ➢ **Transfer** from LHC Point 5 to CERN Tier-0 Computing Centre: **max 5 GB/s**.
- ➢ **Storage** space on Tapes and Disks.
- ➢ **Offline reconstruction**: the main physics data streams are **promptly reconstructed**, ie as soon as the data is stored on **disks** on the LHC computing grid.

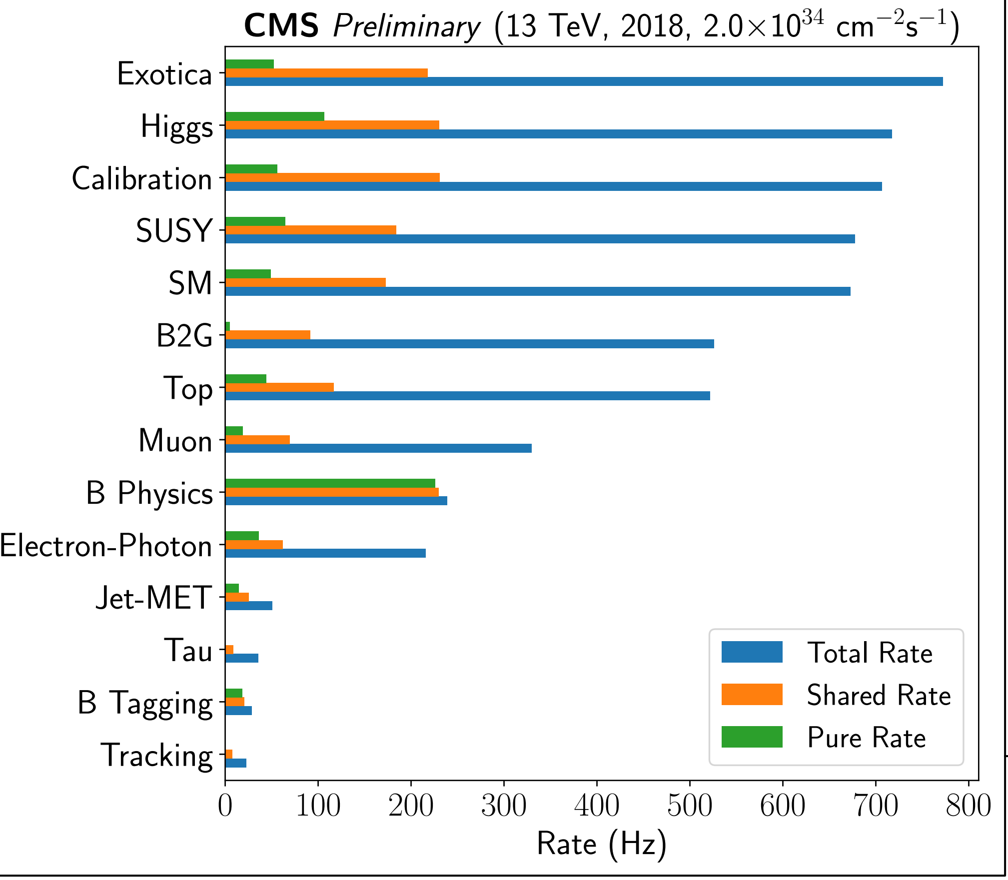


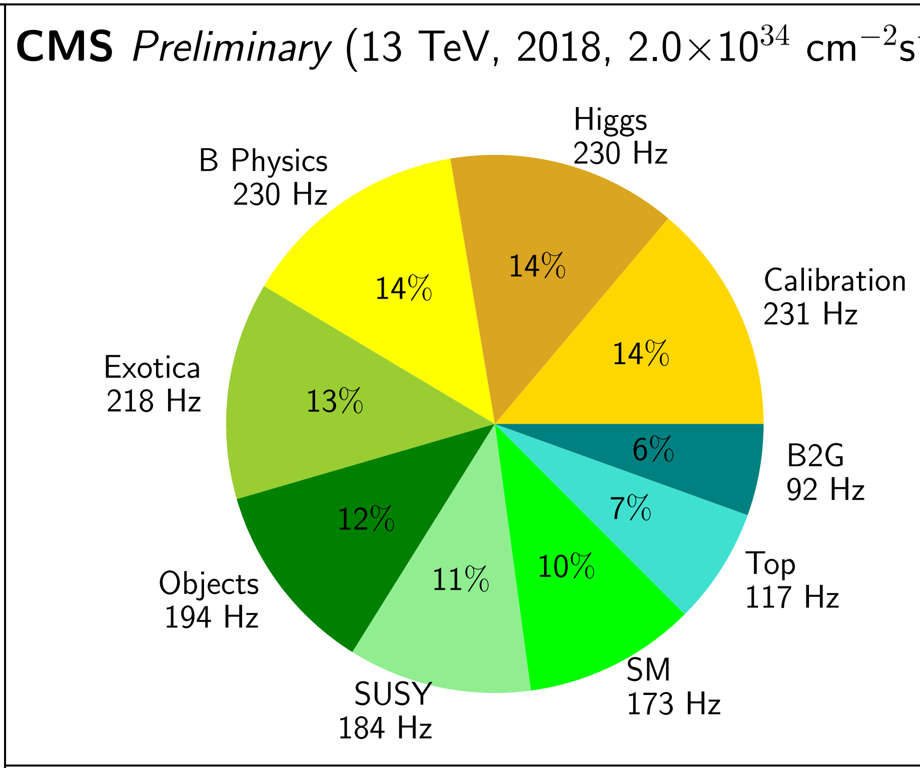
- ✧ Extra **strategies** to **enlarge** the recorded **phase space**:

- ✧ **Scouting**
- ➢ **Save only** trigger particle candidates + event observables.
- ➢ Allows **looser HLT thresholds:** pure HT, dimuon algorithms.
- ➢ **Peak bandwidth** (2.0e34 $cm^{-2}s^{-1}$): **13 kHz** for **100 MB/s**.
- ➢ *Average bandwidth approx. 20% lower*

- ✧ **Parking**: record **extra data** on **tape**, reconstruct it later (LS2)
- ➢ Allows looser HLT algorithms, esp. for B Physics in 2018.

Physics bandwidth sharing





Shared rate

For each group, three types of rate are studied:

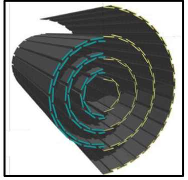
- **Total**: rate of the **OR** of **all** HLT algorithms from the group.
- **Shared**: rate **equally shared** among groups that trigger the same event.
- **Pure**: rate from events triggered **only** by the group.

- The **shared** rate indicates the **bandwidth allocation** to each physics group.
- **Major analysis group** consumers: **Higgs**, **B Physics**.
- The **B Physics** group has the **purest** rate due to its very particular **phase space**.

2018 HLT Menu

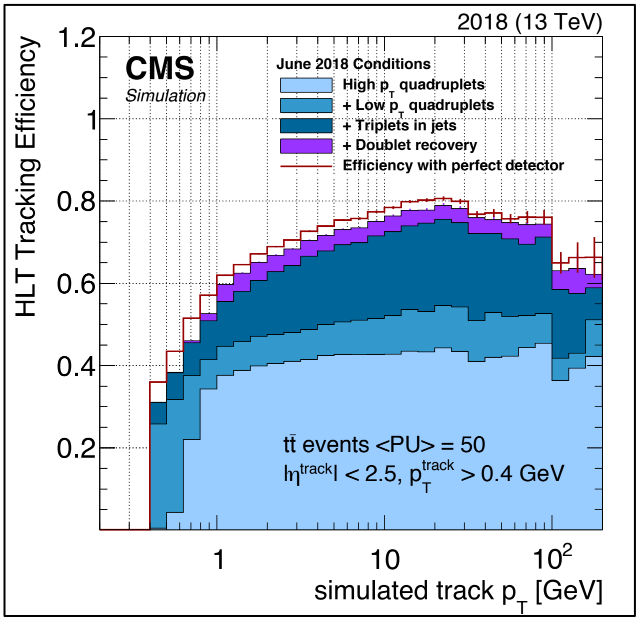
- **HLT menu** for **pp** collisions: **O(600)** algorithms, including **O(350)** dedicated to **physics analyses**.
- Non-exhaustive extract here: **leptons** (multileptons, J/Psi), **photons** (H(γγ)), and **hadrons** (H(ττ), VBF H(inv)).

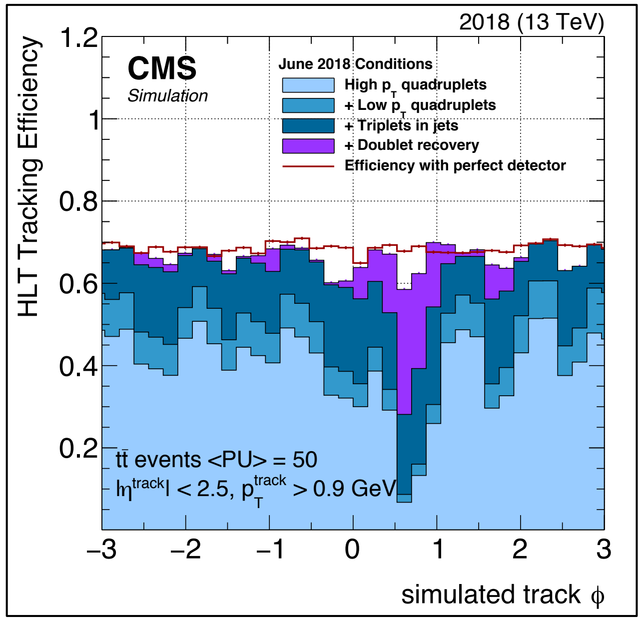
	Signature	HLT kinematic thresholds			Rates (2.0e34)
					indicative values
Leptons	**Single muon** (isolated)	p_T > **24** GeV			**306 Hz**
	Single electron (isolated)	p_T > **32** GeV			**186 Hz**
	Double muon (isolated)	p_T > **17**, **8** GeV	**Mμμ > 3.8** GeV		42 Hz
	Double electron (isolated)	p_T> **23**, **12** GeV			27 Hz
	Muon + electron (isolated)	p_T (**e**) > **23** GeV	pT(**μ**) > **8** GeV		14 Hz
		p_T (**e**) > **12** GeV	pT(**μ**) > **23** GeV		7 Hz
	Triple muon	p_T > **5**, **3**, **3** GeV	**M**μμ > **3.8** GeV		11 Hz
	Double muon + electron (isolated)	p_T (**μ**) > **4** GeV	pT(**e**) >**9** GeV		4 Hz
	Displaced J/Psi(μμ)	p_T> **4** GeV	**2.9** < **M**μμ < **3.3**		34 Hz
Photons	Single photon (isolated)	p_T > **110** GeV	|η| < 1.479 (barrel)		13 Hz
	Single photon (non-isolated)	p_T > **200** GeV			14 Hz
	Double photon (isolated)	p_T > **30, 22** GeV	**M**γγ > 90 GeV		50 Hz
Hadrons	Double tau (isolated)	p_T > **35** GeV	|η| < 2.1		46 Hz
	Missing transverse energy	MET > **120** GeV	MHT > **120** GeV		23 Hz
	Hadronic transverse energy	HT > **1050** GeV			12 Hz
	VBF + Missing energy	p_T (jet 1, 2) > **110, 35**	**M**jj > **650**	**MET** > **110**	31 Hz
	Boosted jet (anti-kT 0.8)	p_T > **400**	**M**j> **30**		31 Hz
	Boosted jet (anti-kT 0.8, double b)	p_T > **330**	**M**j> **30**		58 Hz

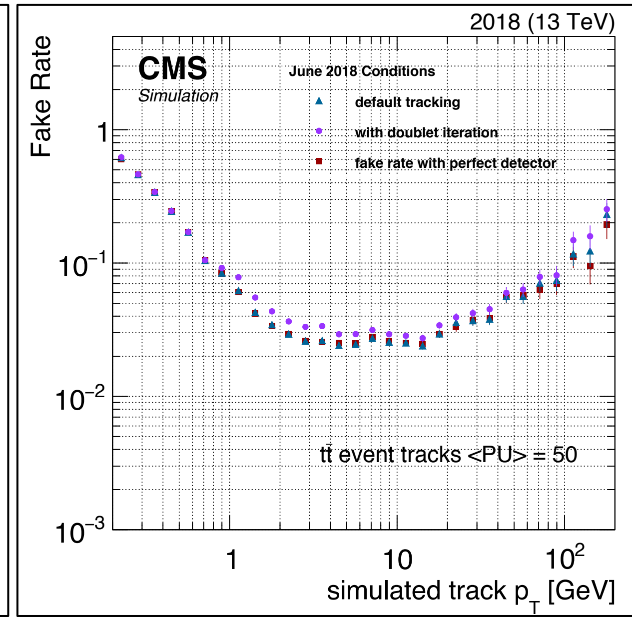


HLT tracking: pixel upgrade

- ✧ **Successive iterations** target progressively **looser** tracks. Hits used in a track are removed for the next iteration.
- ✧ HLT tracking in **2017 → 3 iterations** targeting:
- ➢ High-pT tracks with 4 hits, low-pT tracks with 4 hits, tracks with 3 hits around calorimeter jets or other tracks.



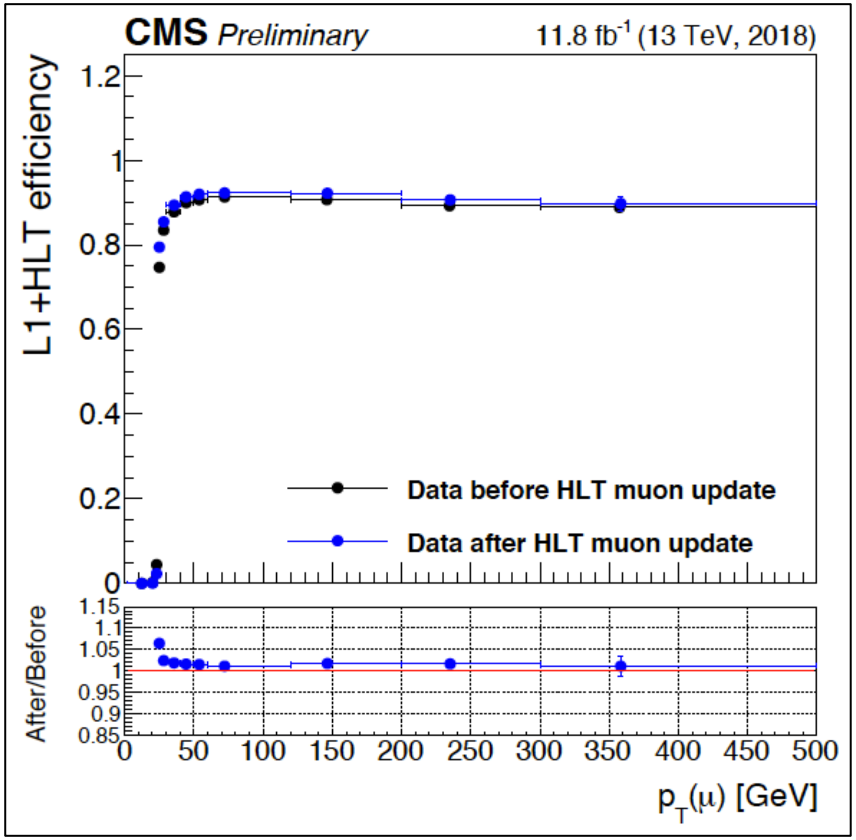


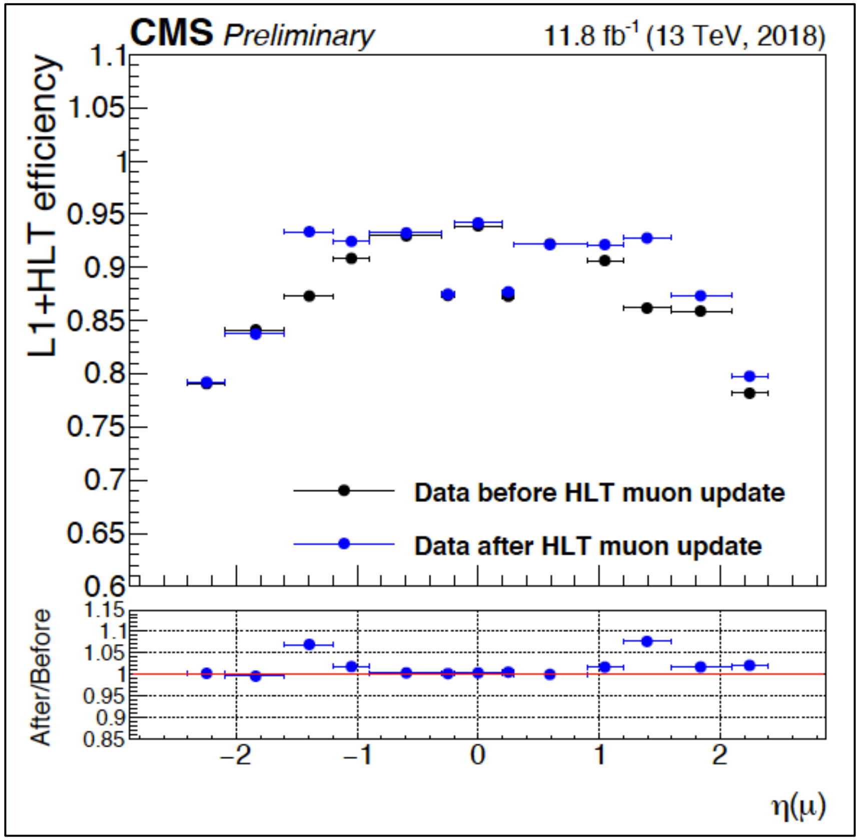


- ➢ **2017 operation**: several issues caused a non-negligible fraction of non-active pixel modules.
- ➢ 2017-**2018** technical stop: **new DCDC converters** were installed and the initial performance was restored.
- ➢ To safeguard against possible detector failures, an **additional recovery iteration** was added.
- ➢ Track **seeds** consisting of just **two pixel hits** are created in **regions** of the detector where **two inactive modules** overlap (iteration restricted to tracks with pT > 1.2 GeV).

HLT muons

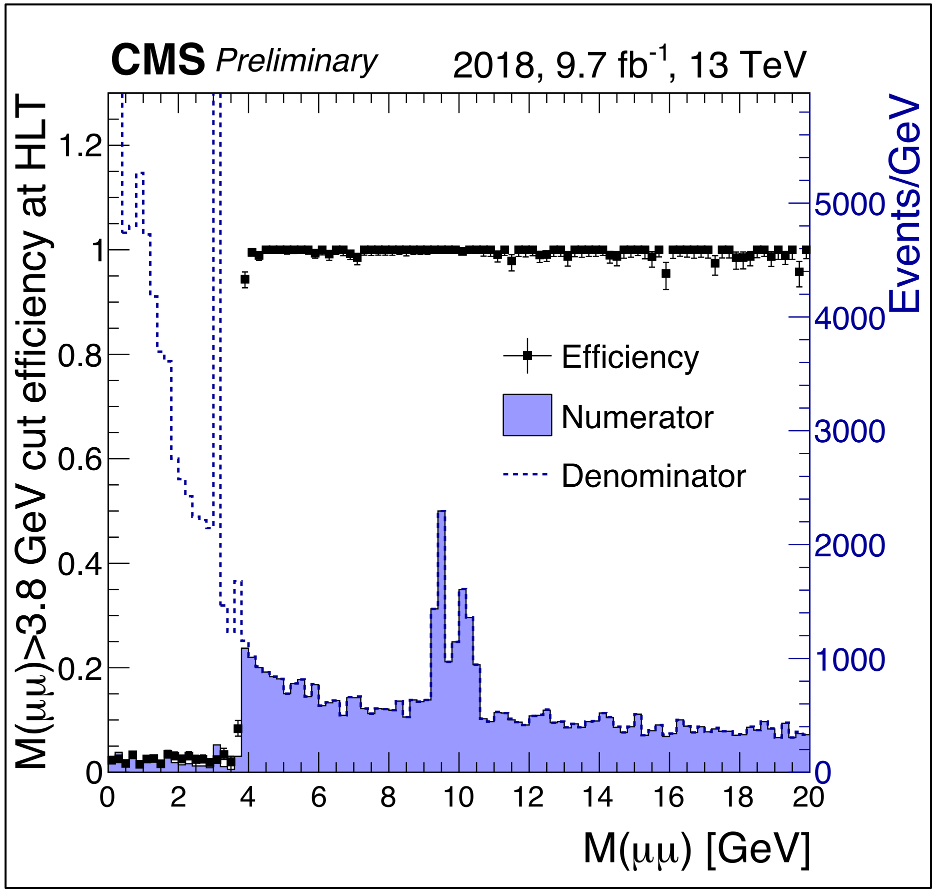
- ✧ **Main isolated single muon** thresholds in 2018: **L1**=22 GeV **HLT**=24 GeV
- ➢ **Plateau > 90%** around 30 GeV, dominated by **isolation** and **L1** efficiency.
- ➢ **Efficiency** for muons (pT>26 GeV) above **80%** in **endcaps.**





- ➢ Muon update in **2018**: more pixel seeds + extra tracking iteration + ID.
- ➢ Allowed to **maintain efficiency/purity** while **decreasing** the HLT **rate**.

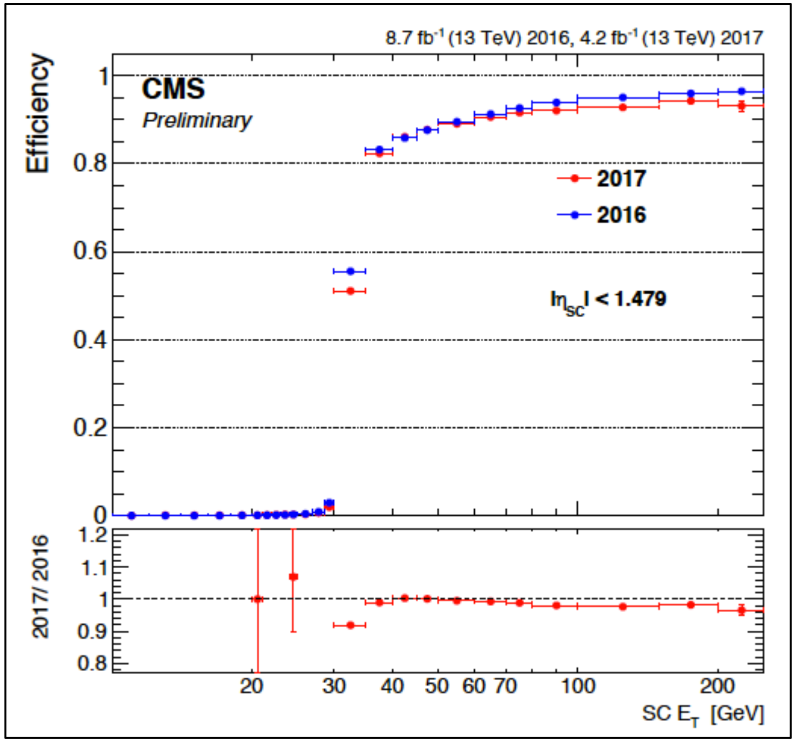
HLT dimuons

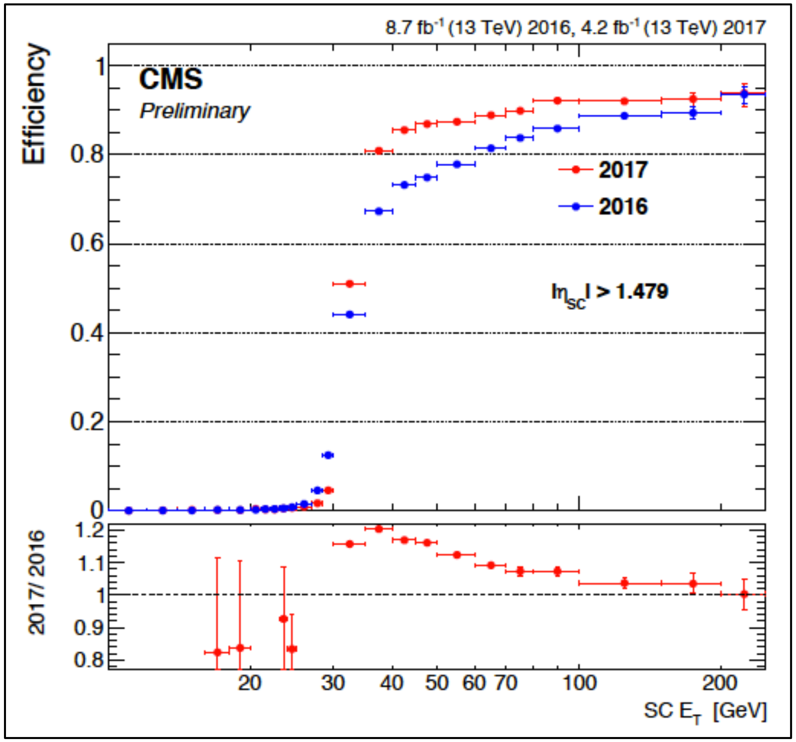


- ✧ HLT algorithm selecting **dimuons** with **p_T** > **17**, **8** GeV and invariant **mass** > **3.8** GeV.
- ✧ The **excellent** invariant mass resolution allows to **reject** efficiently **J/Psi** background events.
- ➢ The invariant mass threshold **reduces** the **rate** by **30%**.
- ➢ **Leading muon p_T** threshold is **7 GeV lower** than the lowest-pT **single muon** algorithm.

HLT electrons

- **Single electron** (pT > 32 GeV) efficiency for barrel (|η| < 1.48) and endcap (|η| > 1.48) electrons.
- In 2017, the **single electron identification** criteria were **retuned**, thus leading to a **significant efficiency recovery** in the **endcaps** (at constant rate).



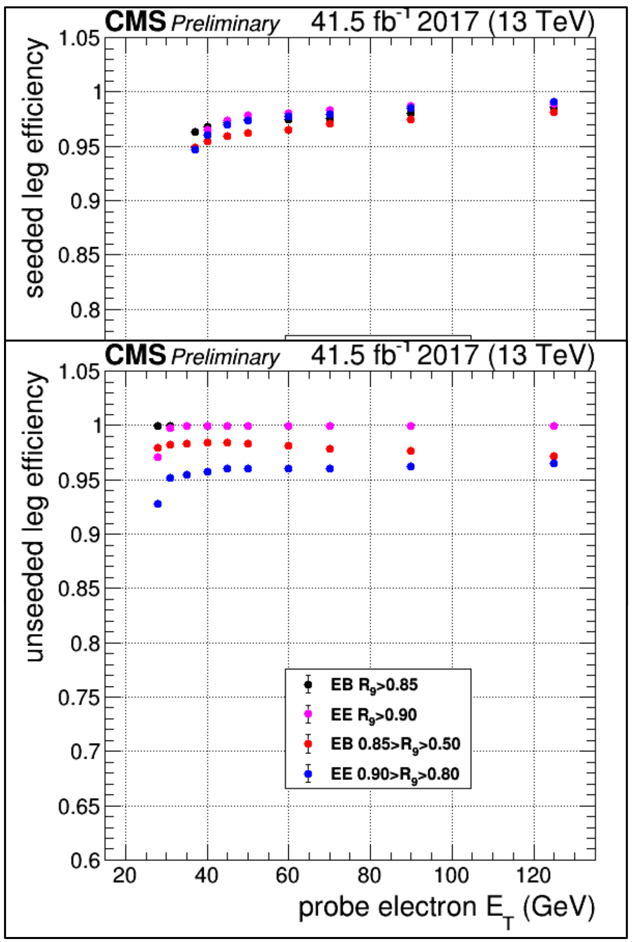


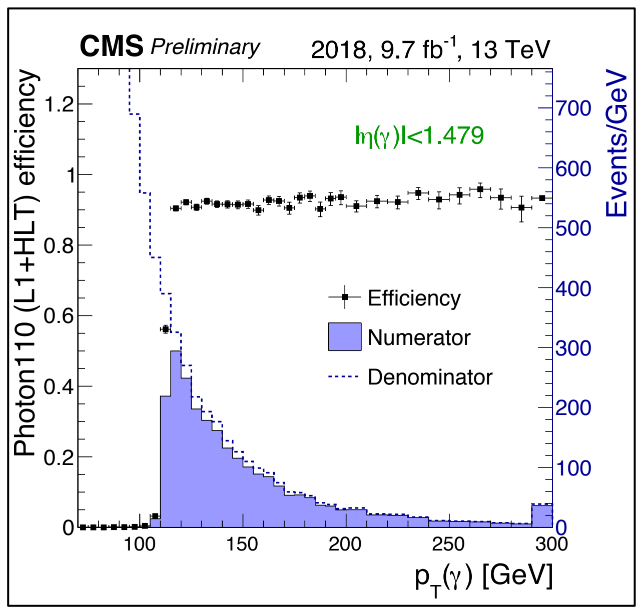
- The **new** 4-layer **pixel** detector helped **reducing** the **rate** of the **dielectron** algorithm (pT > 23, 12 + isolation) by **70%** at a **small efficiency cost** (1-2 %).
- The **impact** of the **2017 pixel** operation **issues** on electron-photon trigger efficiencies was estimated to be in the **1-2 %** range.

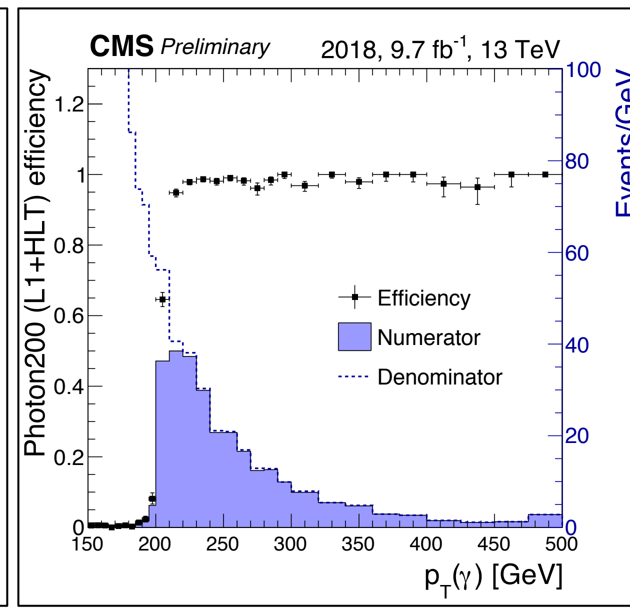
HLT photons

- ✧ **HLT Higgs diphoton algorithm:** two photons with ET > 30 and 22 GeV, mass threshold at 90 GeV
- ➢ Efficiency displayed in **categories** of eta (ECAL barrel/endcap) and R9 (photon identification variable).

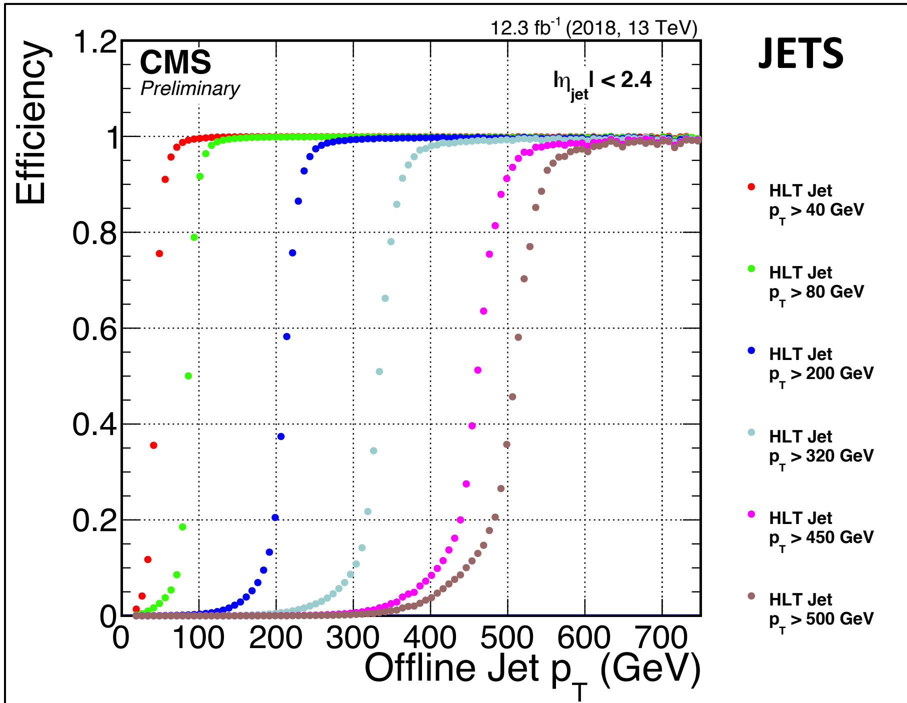
- ✧ HLT **single photon** algorithm: **isolated** barrel photon (E_T>**110** GeV) and **non-isolated** (E_T>**200** GeV).
- ✧ The former reaches a plateau efficiency of **90%** at **120** GeV, while the latter is above **95%** at **220** GeV.



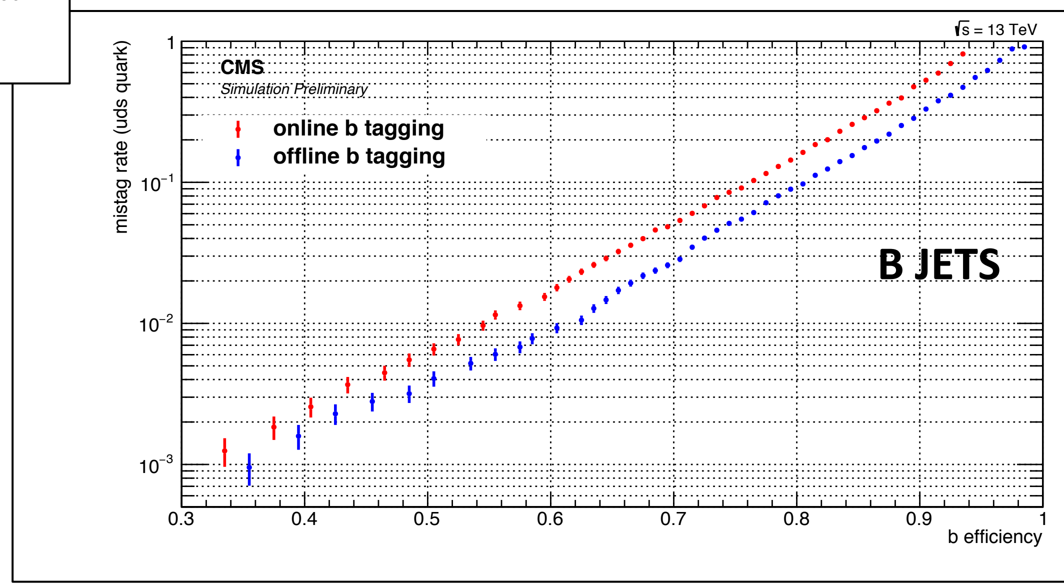




HLT jets



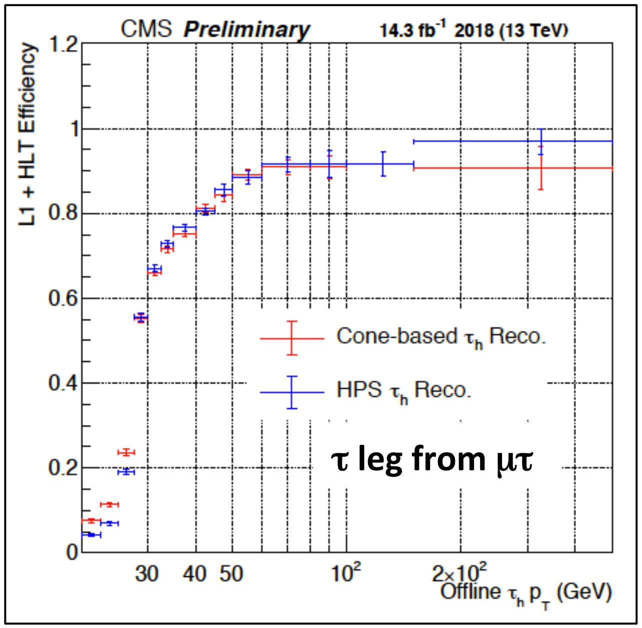
- ✧ The efficiency of a **single jet** threshold of **500 GeV** is above **90%** at offline jet **pT > 550 GeV**.

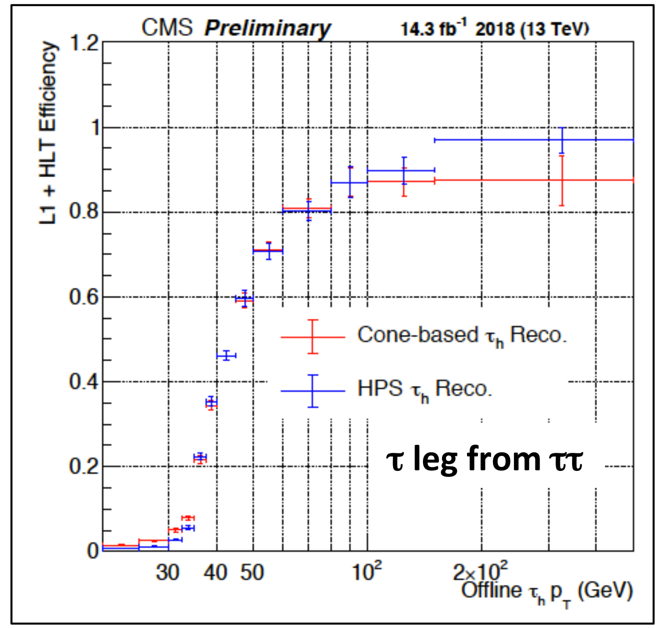


- ✧ **B-tagging**: fake rate (uds) vs efficiency (b) for online and offline
- ➢ Online b-tagging provides a **70% efficiency** for a **5%** **fake** rate
- ➢ **CPU timing** reduced by using regional tracking (tracking only around leading jets).
- ➢ **2018**: replaced **CSV** with **DeepCSV** (DNN).

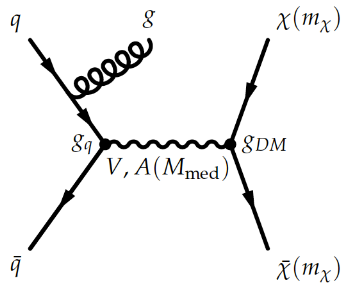
HLT hadronic taus

- ✧ **HLT hadronic tau** reconstruction **before 2018**: **cone**-based algorithm
- ➢ **Signal cone** (ΔR from 0.08 to 0.12) that contains the tau decay products: **hadrons** and **photons** w/in the cone are included in the reconstructed tau candidate.
- ➢ Two **HLT algorithms** are studied here: **$\mu\tau$** (pT(μ)>20, pT(τ)>27, isolation) and **$\tau\tau$** (pT>35 + isolation)

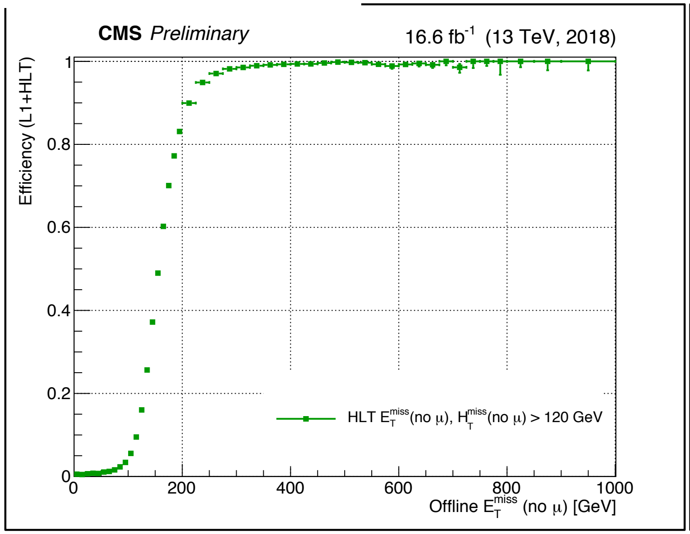


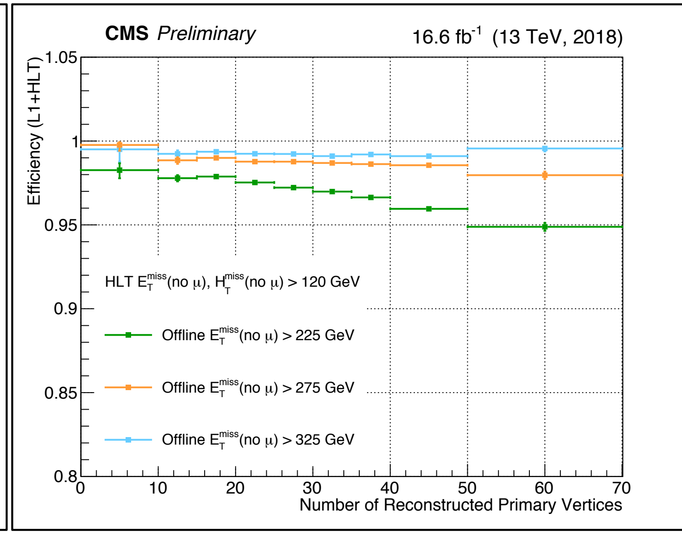


- ✧ **2018** update: introduction of the **Hadron Plus Strips** (HPS) algorithm that is used in **offline reconstruction**.
- ➢ **HPS**: reconstructs **decay modes**; **charged hadrons** and **photons** w/in the signal cone are **combined** in **multiple ways** and **ranked** based on their consistency with a genuine tau decay.
- ➢ **HPS** is able to maintain a **consistently looser isolation** accross the full tau **pT spectrum** wrt cone-based.
- ➢ **HPS**: **similar rate** for the **$\mu\tau$** HLT algorithm and **20% lower rate** for the **$\tau\tau$** HLT algorithm.

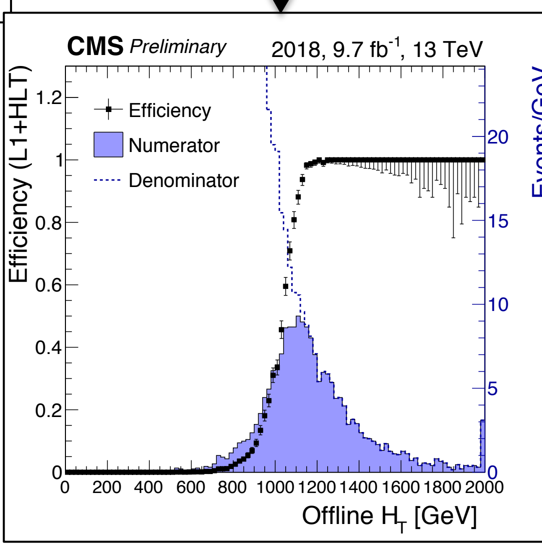


HLT energy sums





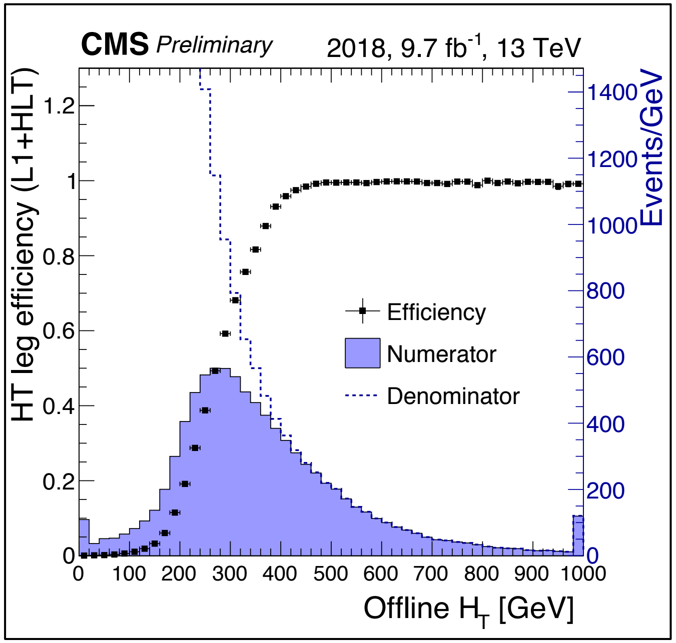
- ✧ **Pure HLT H_T** algorithm.
- ➢ Threshold: **1050 GeV**.
- ➢ **90% efficient** at **1100 GeV**.
- ➢ **2017**: update **online** jet **eta** and $\mathbf{p_T}$ threshold to widely used offline thresholds.



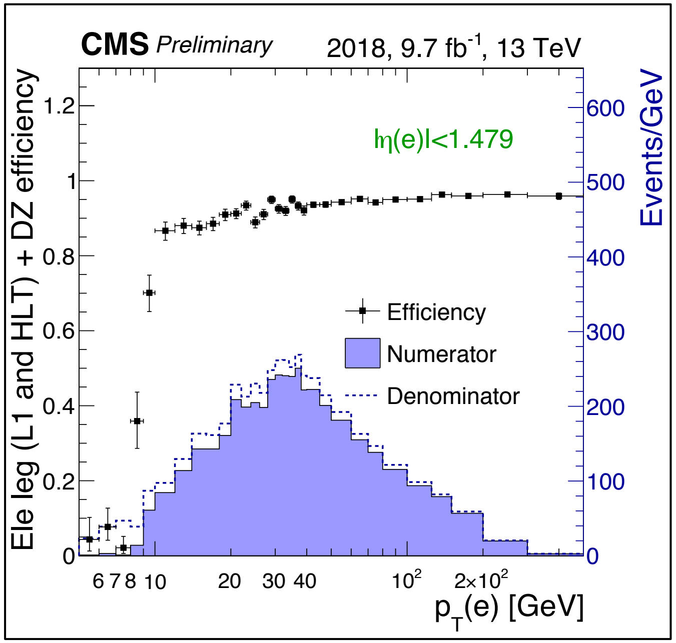
- ✧ **Main HLT MET** algorithm: thresholds on **MET**(NoMu) and **MHT**(NoMu) at **120** GeV.
- ➢ **Efficiency** turn-on significantly influenced by the **L1** efficiency (threshold **110** GeV).
- ➢ **2018 improvement**: update **ECAL zero-suppression** thresholds to suppress the **noise** in the high-eta region of the ECAL.
- ➢ Efficiency **reasonably flat vs PU** when selecting events with offline **MET > 275** GeV.

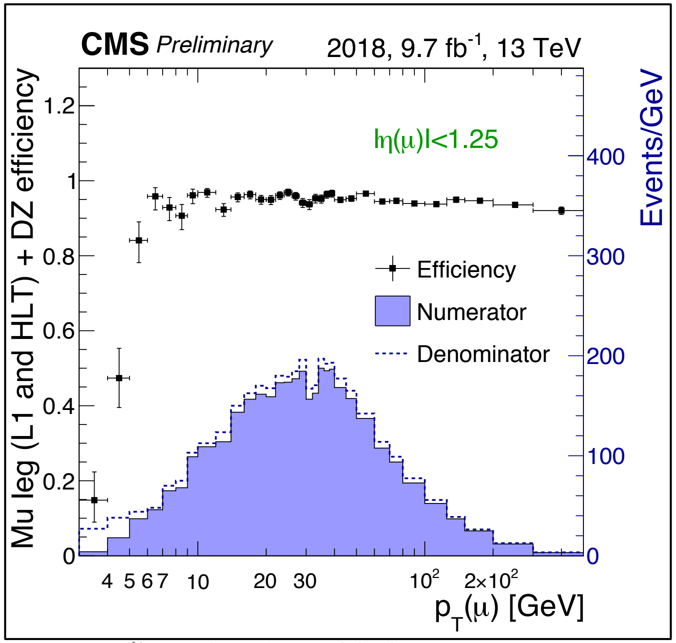
- ✧ Note: there are also a number of **cross triggers** MET+MHT+**X** (X = Jet, HT, b-tagged jet...) that allow for **lower** MET/MHT **thresholds** (e.g. **110** instead of **120** GeV)

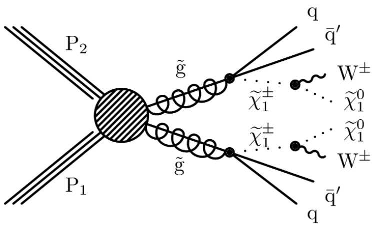
HLT leptons + HT



- ✧ **Cross-triggers** combining leptons and HT allow to reach significantly lower lepton pT thresholds
- ➢ **Dilepton + HT**: HT > 350 GeV pT(m) > 4 GeV pT(e) > 8 GeV
- ➢ No isolation criteria are applied

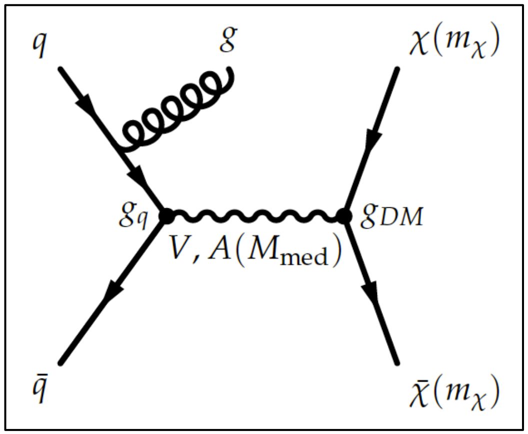


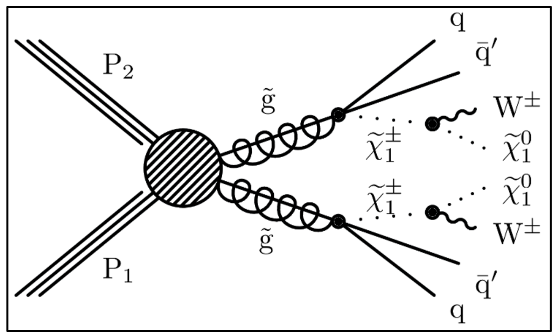


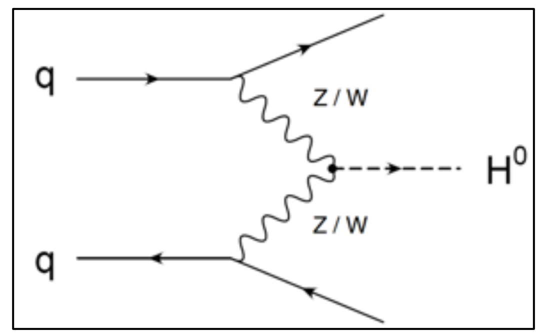


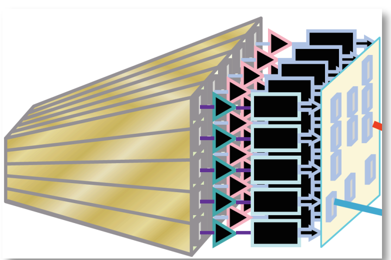
Conclusion (I)

- ✧ **The upgraded L1** system has been **successfully** commissionned in **2016**.
- ➢ In **2017** and **2018**, CMS has been **exploiting further** the features of the upgraded system
- ➢ **Invariant mass**, more evolved **correlations**, **VBF** dijet algorithm...





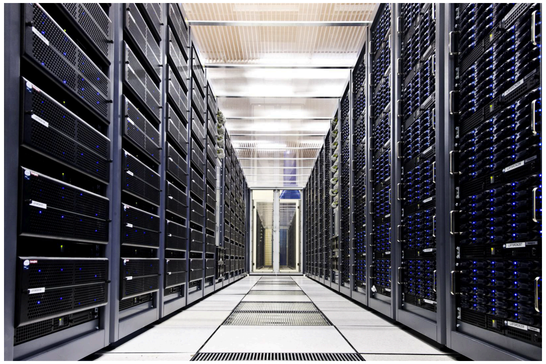


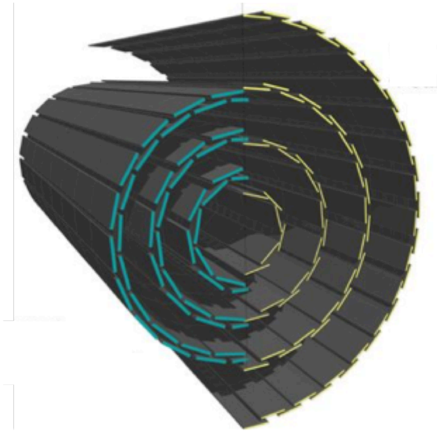


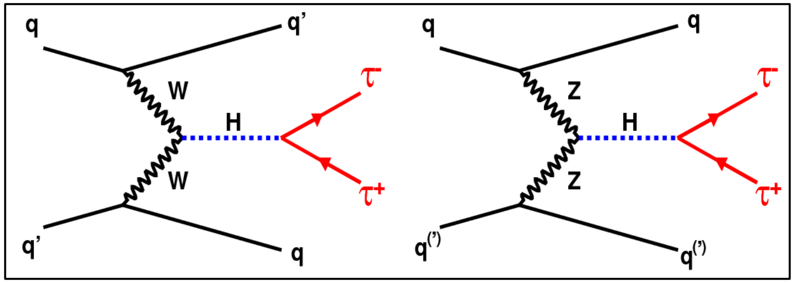
The Level-1 system is able to **cope** with an instantaneous **luminosity twice larger** than the **original** LHC **design** value, while **preserving** the **CMS physics** programme.

Conclusion (II)

- The **HLT** has been **regularly updated** in order to cope with **varying LHC** and **detector** operation conditions.
- Phase-1 **pixel** upgrade **fully exploited** at **HLT**, including dynamic **mitigation** strategies for **problematic** modules.
- **Reconstruction** algorithms at **HLT** were **adapted** accordingly: **tracking**, **muons**, **electrons...**







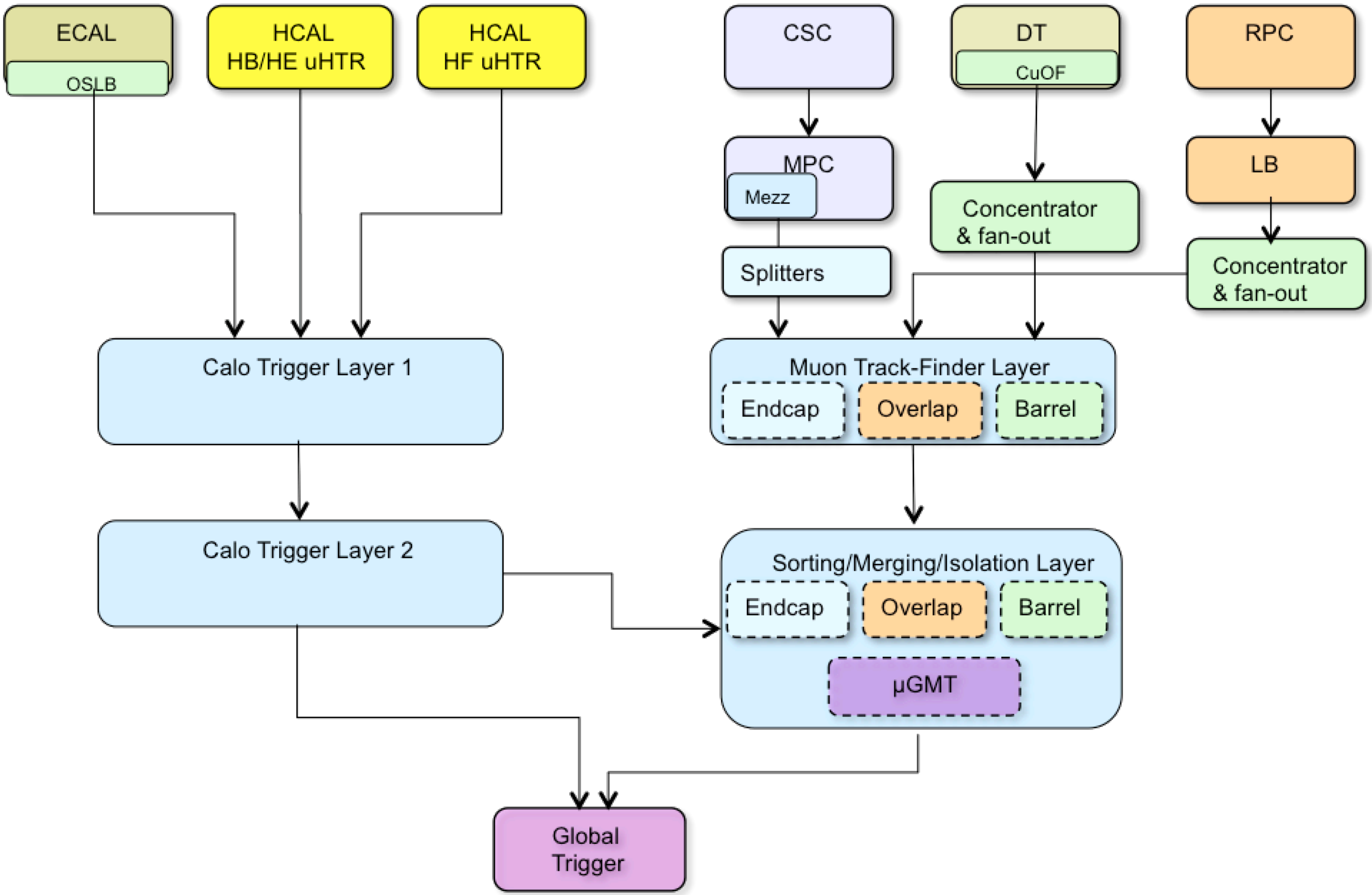
- **2018 updates**: **muon** reconstruction, **MET noise** mitigation, switch to **HPS taus**.
- **Extra data taking strategies** are in place to fully exploit the **Run 2 physics potential**: **parking** and **scouting**.
- So far the **2018 trigger performances** are **satisfying**, thus making the 2018 data taking campaign **promising**.

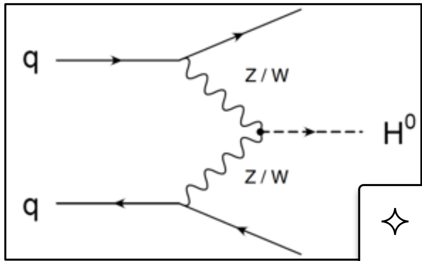
Thanks for your attention

BACKUP

Calorimeter Trigger

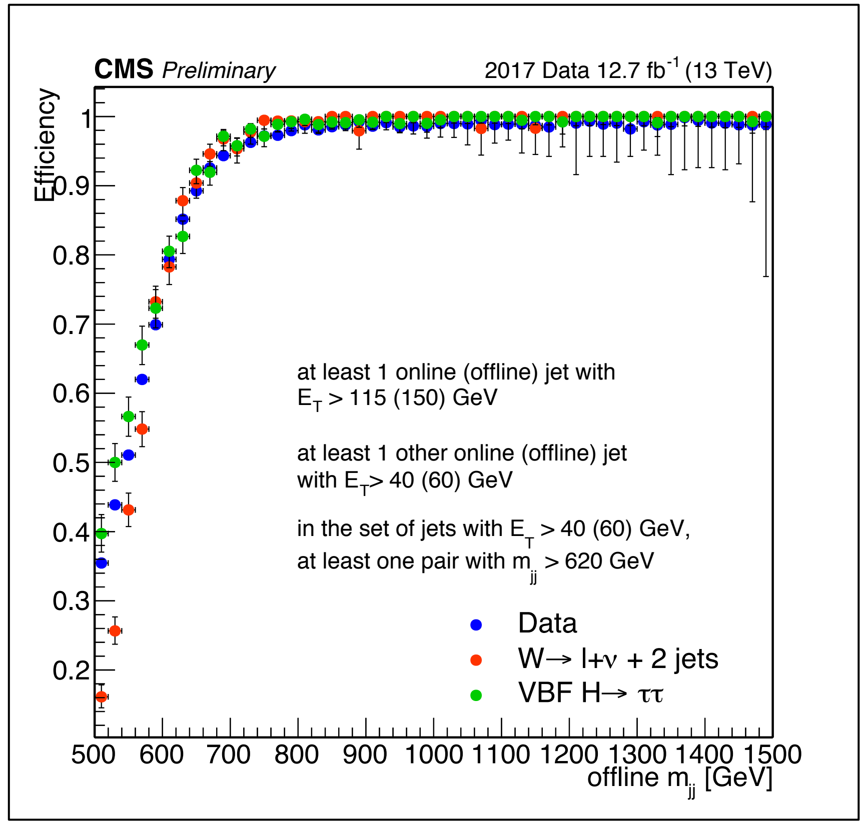
Muon Trigger



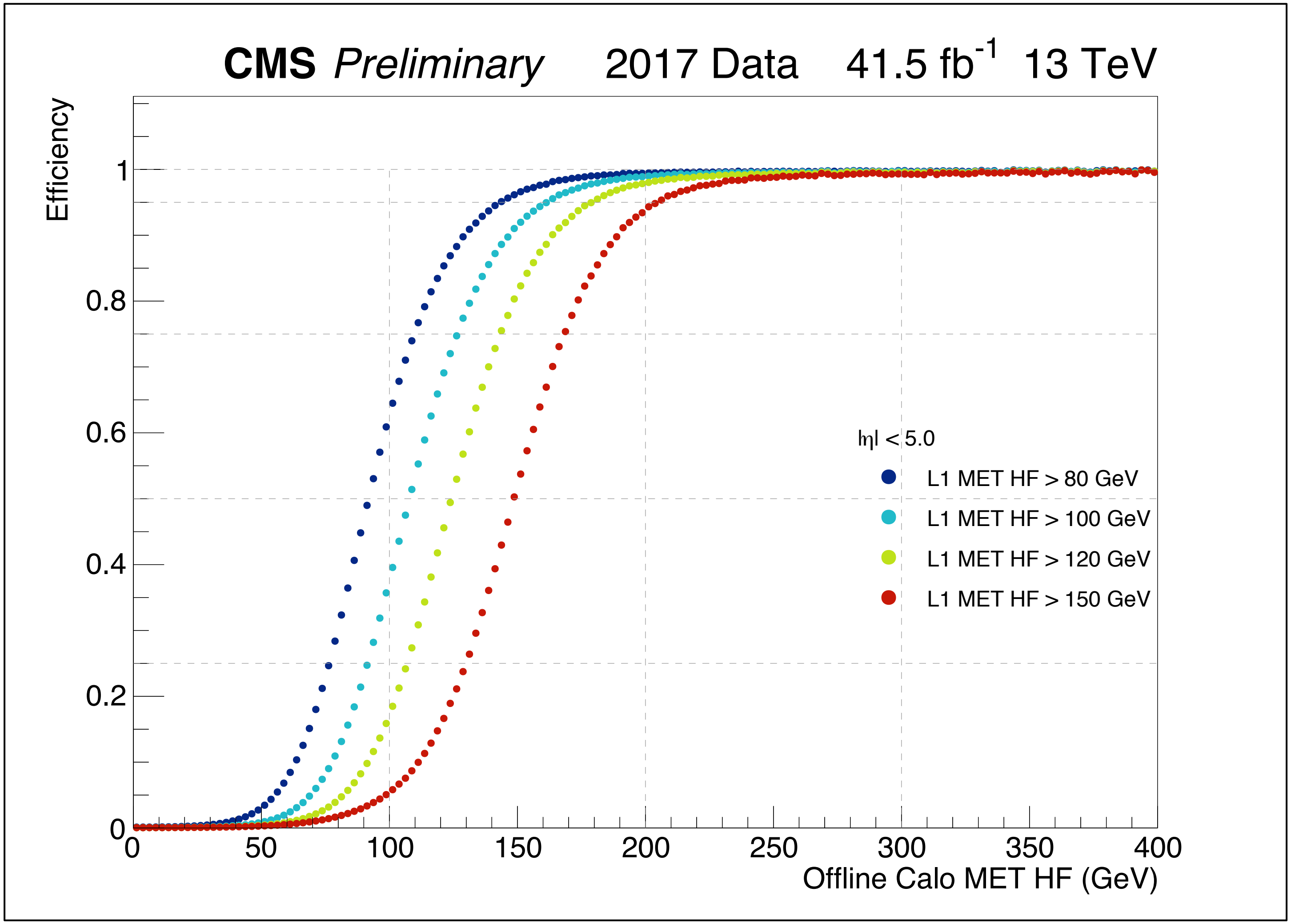


Level-1 VBF

- ✧ **VBF** production mode very **sensitive** for searches such as **Higgs ditau** and **invisible** final states.
- ➢ **Level-1** allows the calculation of advanced observables such as **invariant mass** since 2017.



Level-1 MET

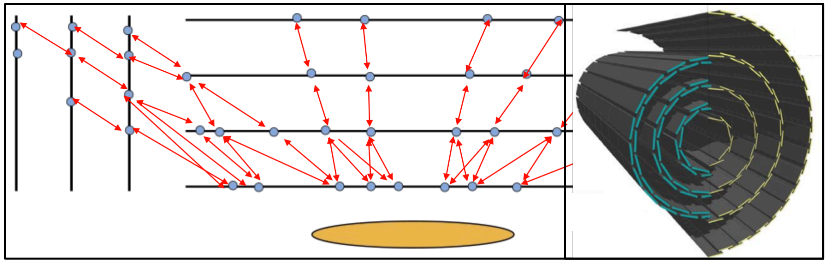


- The **100 GeV** threshold is **> 90%** efficient at:

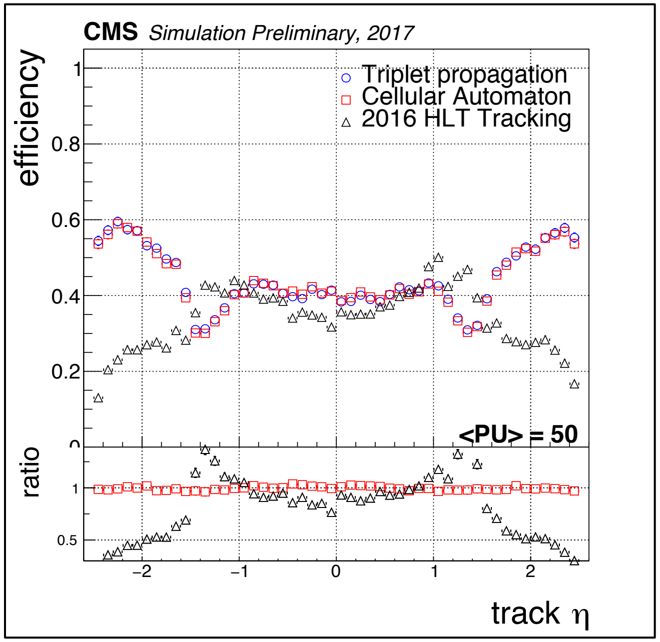
  ⟹ offline Calo ME_T > **150** GeV *(including forward calo)*

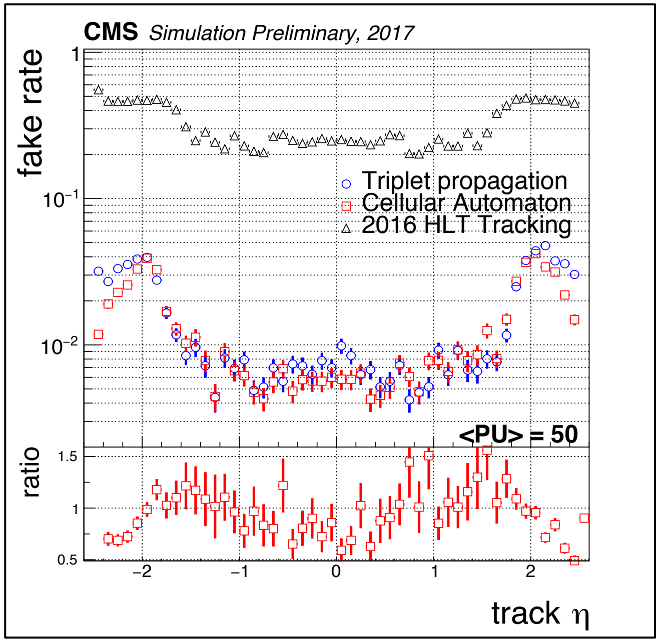
HLT tracking: pixel upgrade

- ✧ **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**



- ✧ **Successive iterations** target progressively **looser** tracks. Hits used in a track are removed for the next iteration.
- ✧ HLT tracking in **2017 → 3 iterations** targeting:
  - ➢ High-pT tracks with 4 hits, low-pT tracks with 4 hits, tracks with 3 hits around calorimeter jets or other tracks.





Cellular automaton:

- ➢ **5 times faster** than old algo (triplet propagation)
- ➢ **Efficiency**: similar in barrel, **50% gain** in endcap
- ➢ **Fake** rate: divided by **4**