Overview of CMS trigger

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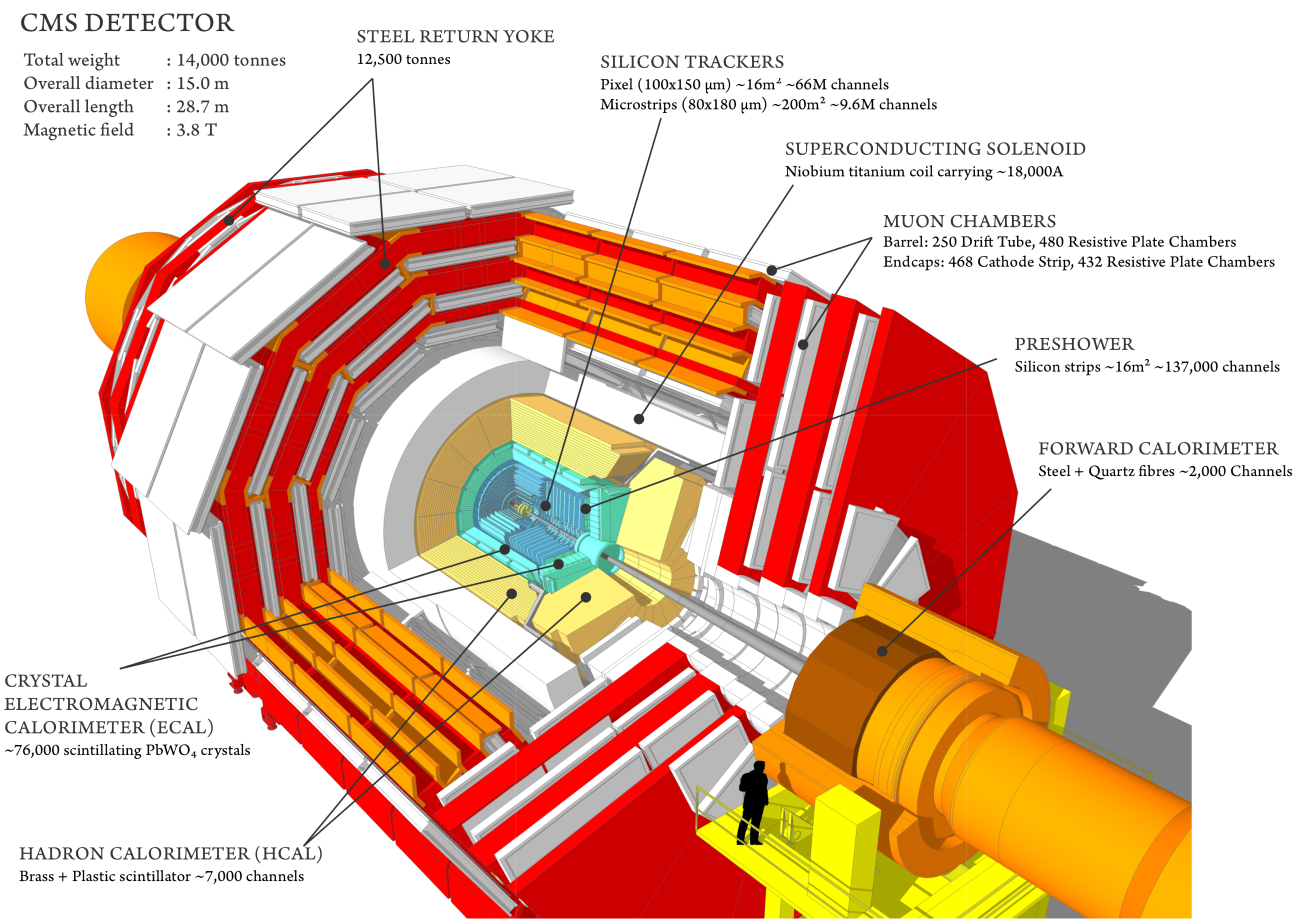
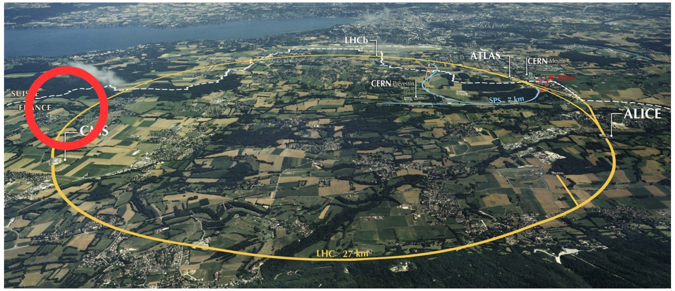
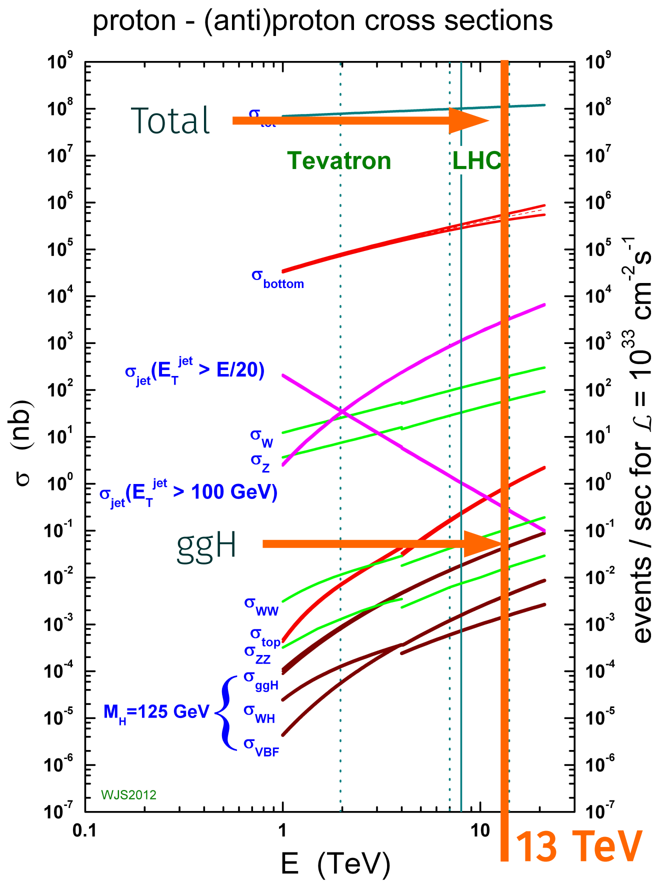
The Compact Muon Solenoid experiment, CMS





- ~ 75M channels total
- 1-2 MB per event
- 40 MHz bunch crossing rate
- O(100 TB/s) raw data



- **Trigger!**
  - Reduces rate while keeping high efficiency to interesting physics
- Two big challenges
  - Handling data rate
  - Selecting physics
- Total pp cross section is ~ 10^8 nb @ 13 TeV
  - Dominated by inelastic QCD scattering
  - Example: Higgs boson production via gluon-fusion is a billion times smaller!
  - Pile-up problem
- CMS physics rate to disk ~ 1 kHz, driven by computing costs

~ 10^5 reduction factor in ~ 1 s

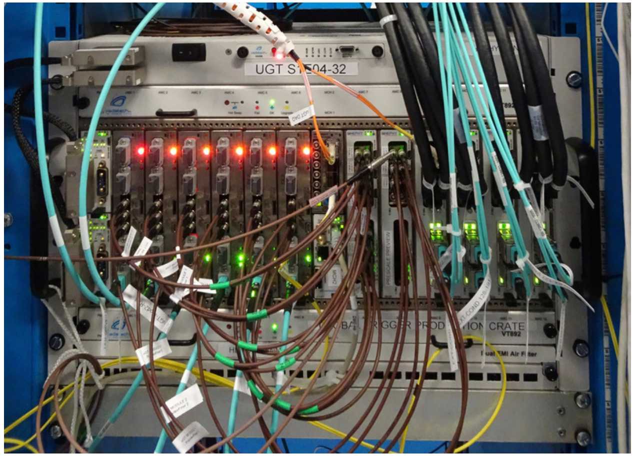
Detector

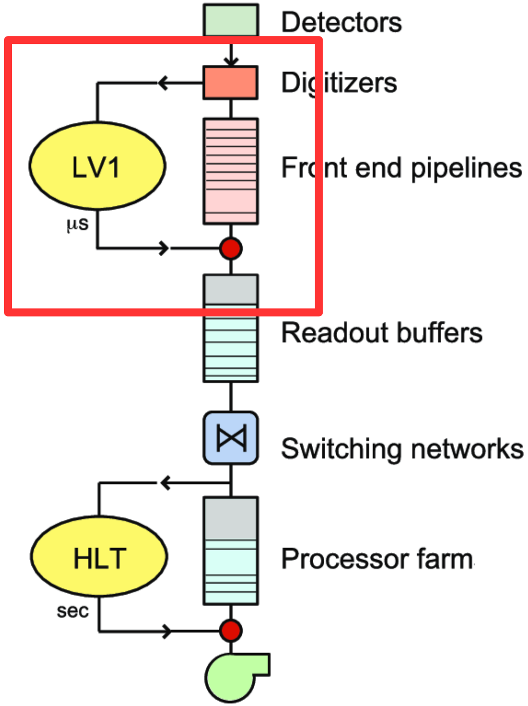
40MHz

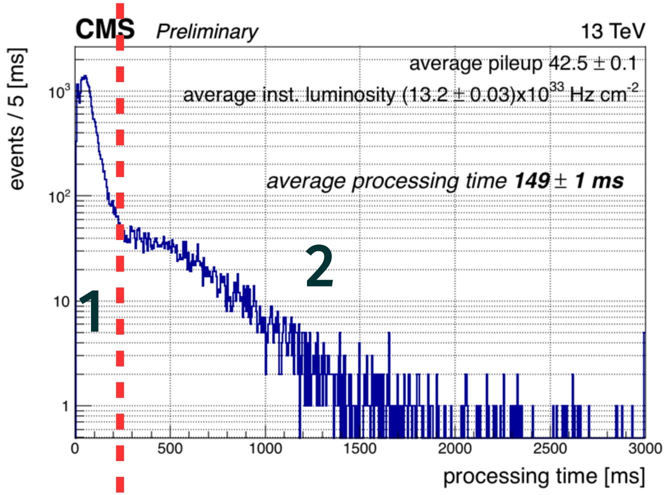
Level-1 Trigger (L1T)

- Hardware-based
- Uses low-res detector information from calorimeter and muon
  - No tracker
- Data stored in on-detector buffers
- 3.8 μs to take a decision
  - Limited by tracker buffer size

100 kHz, ~100 GB/s





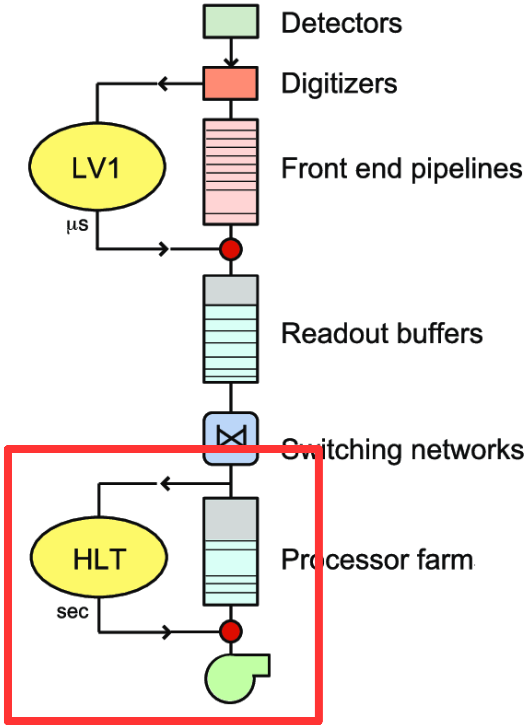


High-Level Trigger (HLT)

- Computer farm with ~ 26000 cores
  - < 300 ms per event
- Uses full-detector information
- Two-stage event selection
  1) Only calorimeter, ~ 50 ms
  2) Full-detector, w/ tracking & PF, ~ 1 s

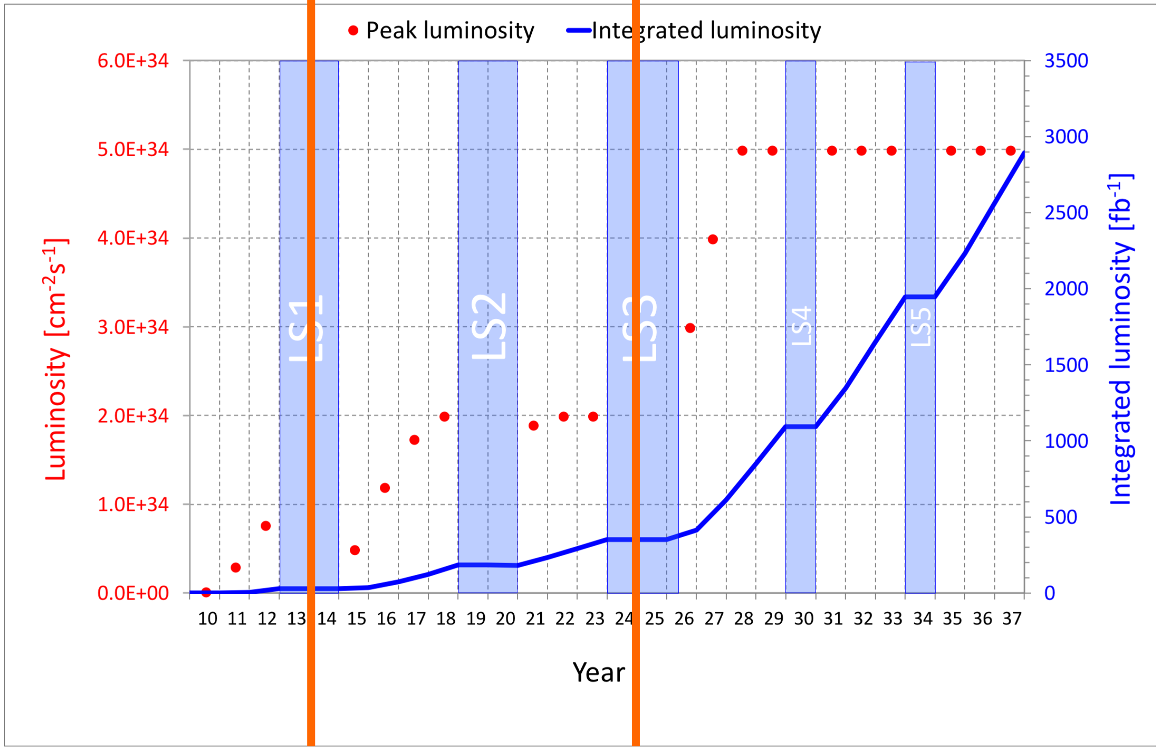
~1 kHz, ~1 GB/s

Disk



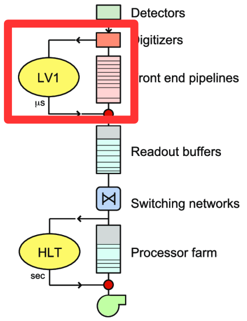
Level-1 Trigger

Run 1 trigger | Run 2/3 trigger | HL-LHC trigger

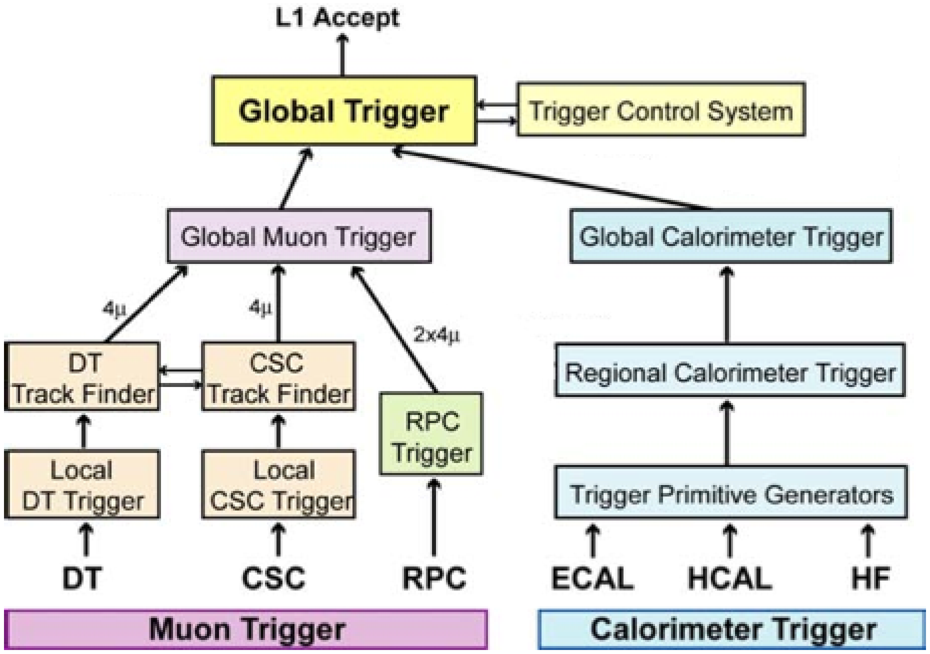


Trigger must be upgraded in order to keep high acceptance to EWK & Higgs physics at higher inst. lumi

Run-1

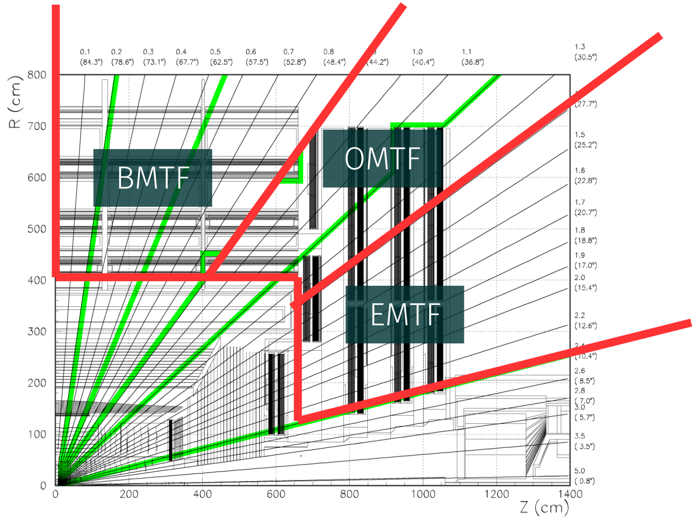


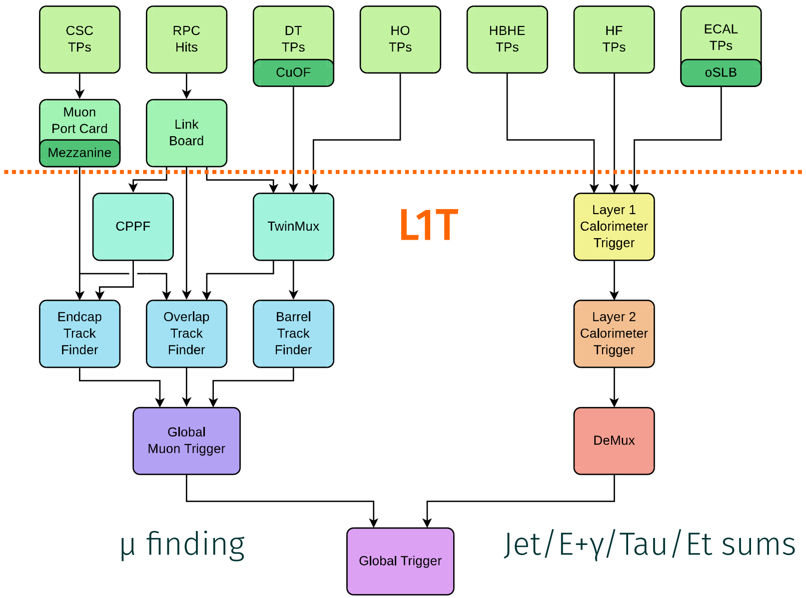
- Hardware technology based on ASICs and copper links
- Heterogeneous system with very diverse boards
  - This made system maintenance and control very hard to perform

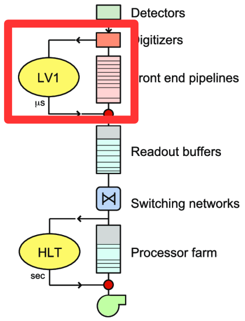


Level-1 Trigger
Run 2/3

- Upgraded L1T deployed in 2015/2016
  - Currently in use
- Muon system has been redesigned to be region-based

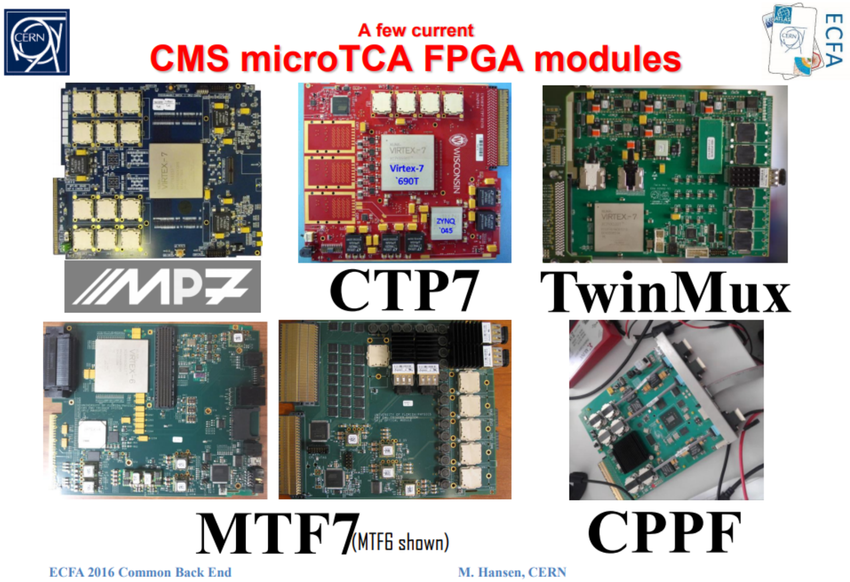






- Two-layer calorimeter trigger
  - Layer-1 packs data and performs calibrations
  - Layer-2 reconstructs calo objects

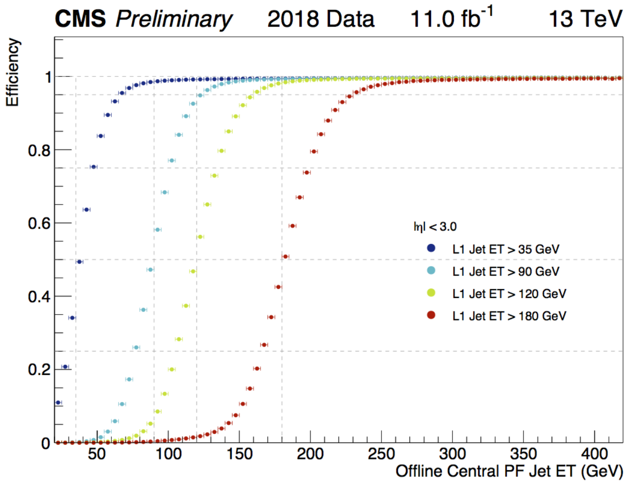
- ASICs → FPGA
- Custom boards → small set of generic boards types
  - MP7, MTF7 for object finding
  - CTP7, TWINMUX, and CPPF for data preprocessing and fan-out
  - AMC13 for clock distribution and event building
  - Firmware shared across L1T subsystems
    - Reduced integration and commissioning time
- Copper links → Optical links
  - Increased bandwidth
    - E.G. this enabled to have an increased granularity in the calorimeter trigger



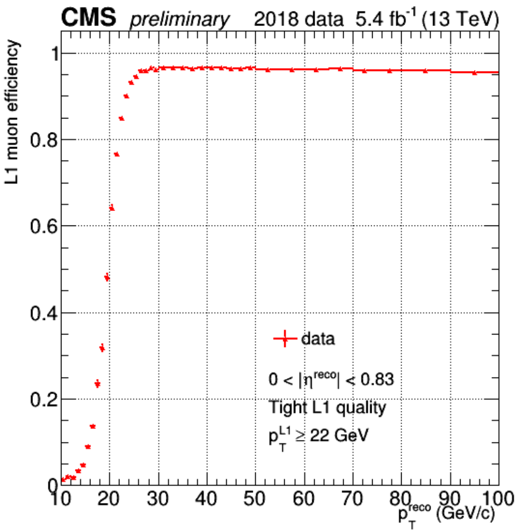
Taken from:
https://indico.cern.ch/event/524795/contributions/2236585/

在 IHEP 制作
Developed by our colleagues in IHEP

- Calorimeter and muon trigger subsystems reconstruct objects
  - μ, EG, tau, jet, sums
- μGT runs up to 512 algorithms in parallel on these objects
  - Able to run complex correlation algorithms, e.g. invariant mass for VBF triggers



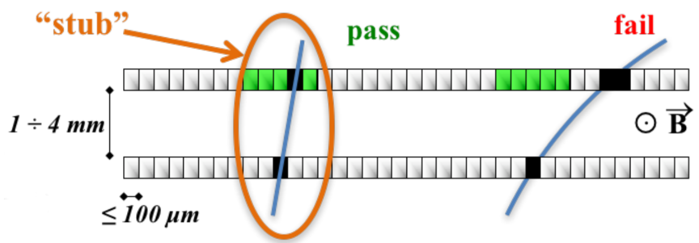
Jet trigger turn-on



Muon trigger turn-on

L1T

- Input from tracker
  - Improved resolution, identification, pile-up rejection, …
- Max rate 100 → 750 kHz
- Latency 3.8 → 12.5 µs



HLT

- Output rate 1 kHz → 7.5 kHz
- ~ 20-time higher computing power
- Heterogeneous computing is being investigated
  - E.G. GPUs for tracking

CMS detector	LHC Run-2	HL-LHC Phase-2	
Peak ⟨PU⟩	60	140	200
L1 accept rate (maximum)	100 kHz	500 kHz	750 kHz
Event Size	2.0 MB [a]	5.7 MB [b]	7.4 MB
Event Network throughput	1.6 Tb/s	23 Tb/s	44 Tb/s
Event Network buffer (60 seconds)	12 TB	171 TB	333 TB
HLT accept rate	1 kHz	5 kHz	7.5 kHz
HLT computing power [c]	0.5 MHS06	4.5 MHS06	9.2 MHS06
Storage throughput	2.5 GB/s	31 GB/s	61 GB/s
Storage capacity needed (1 day)	0.2 PB	2.7 PB	5.3 PB

Summary

- Triggering and data acquisition at hadron colliders is extremely challenging
  - O(100 TB/s) → O(1 GB/s)
  - Interesting events are rare and hidden in many pile-up interactions
- CMS employs a two-level trigger architecture to select physics of interest
  - Level-1 Trigger, hardware-based, uses reduced detector information
  - High-Level Trigger, software-based, uses full-detector data
- Trigger and data acquisition systems are in constant evolution to match the increase in LHC luminosity
- TDAQ technology and techniques developed for LHC will have application in the post-LHC era

Backup

Jet algorithm & performance

Input granularity

Access to higher granularity than previous system (single TT)

Sliding window jet algorithm

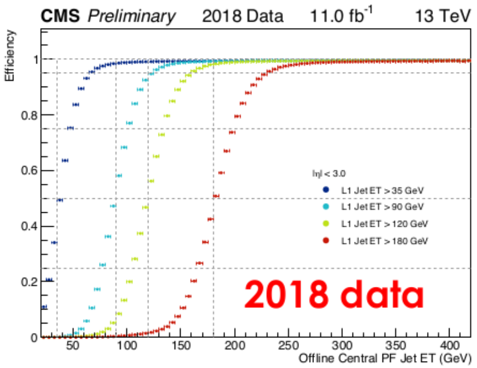
Search for TT above threshold and maximum in 9x9 window (approximately the size of an AK4 offline jet)

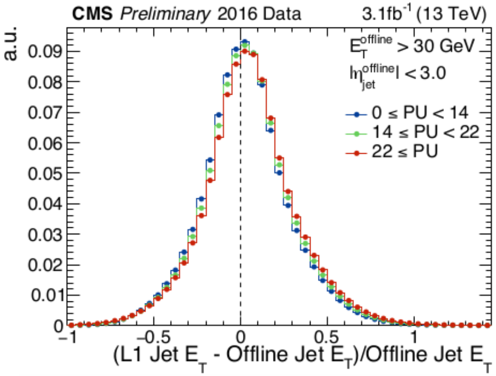
"Chunky donut" pileup subtraction

E_T in 3x9 regions around the jet computed
Energy in 3 lowest E_T regions used to determine PU energy density
Scaled & subtracted to the individual jet E_T

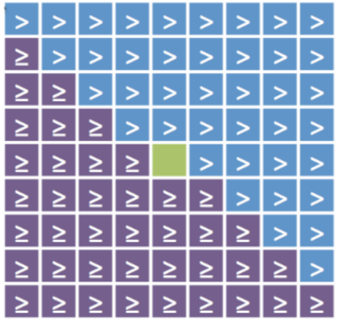
Calibration

Corrected energies as function of η and E_T

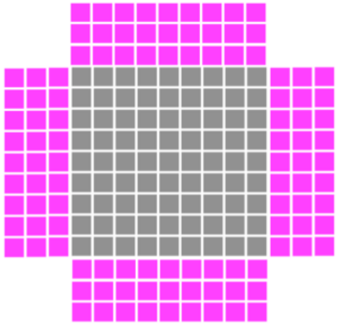




inequality masks avoid self-masking and double counting



chunky donut area



Sums algorithm & performance

Types of algorithms

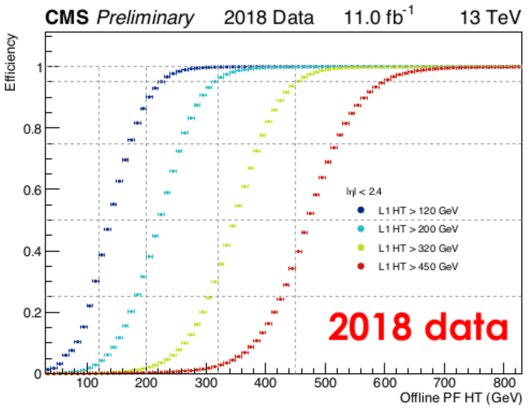
HT: scalar E_T sum of jets with E_T > 30 GeV with $|\eta|<2.4$
Missing transverse energy (MET): norm $|-\Sigma \mathbf{E}_T|$ of trigger towers up to $|\eta|=5$

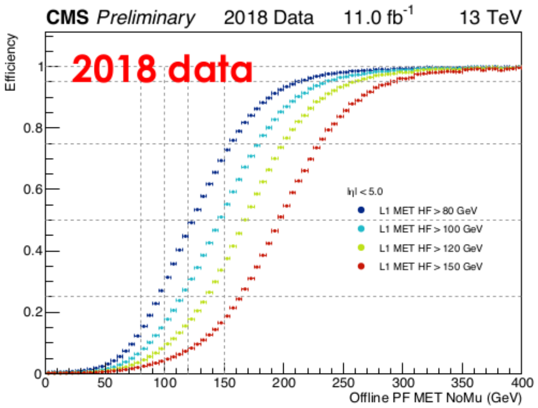
Pileup mitigation

Exclude energy deposits from the MET calculation below a dynamic η-dependent threshold calculated using an estimate of the pileup in the event

Typical thresholds

MET > 130 GeV
HT > 360 GeV





L1 e/γ algorithm & performance

L1 e/γ clustering algorithm

Dynamic clustering around local maximum (seed)

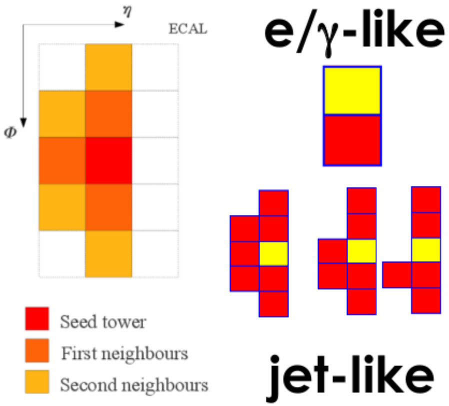
- Recovering the energy loss due to tracker material
- Minimizing effect of pileup contributions
- Improved energy resolution
- Extension of the cluster in ϕ to recover brem

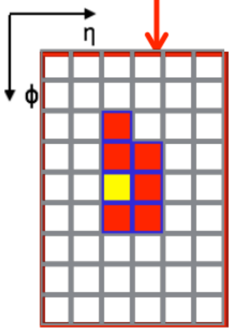
e/γ calibration

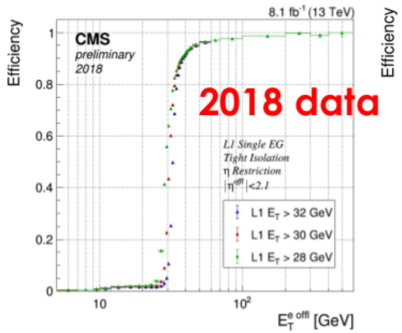
Calibration depending on ET, η and the reconstructed shape

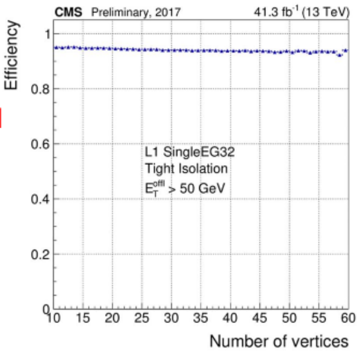
e/γ identification

- Shape veto → e/γ have more compact shapes than jets
- E/H identification → e/γ typically have small hadronic deposits
- Isolation energy (E_T^{6x9}-$E_T^{e/\gamma}$) → larger for jets









Typical thresholds
SingleIsoEG > 30 GeV
DoubleEG > 25,14 GeV
TripleEG > 18,17,8 GeV

- **Excellent performance**
- **Good pileup resilience**
- **Loose/Tight isolation working points adapted to different kinematic regimes**

7

L1 had. τ algorithm & performance

L1 τ clustering algorithm

EG-cluster type as baseline to L1 tau reconstruction
Merging with one neighboring cluster possible → captures multi-prong hadronic tau signatures

τ calibration

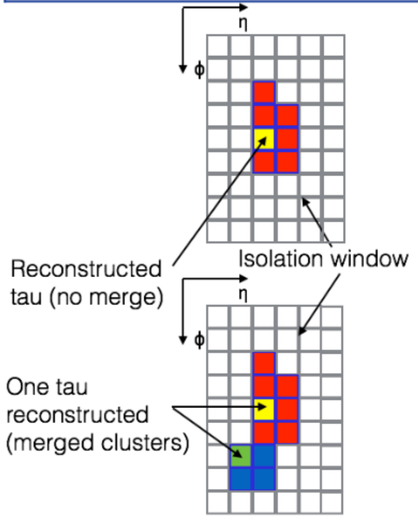
Calibration depending on E_T, η and the E/H fraction

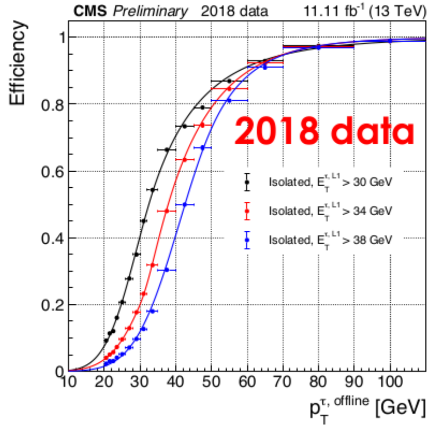
τ identification

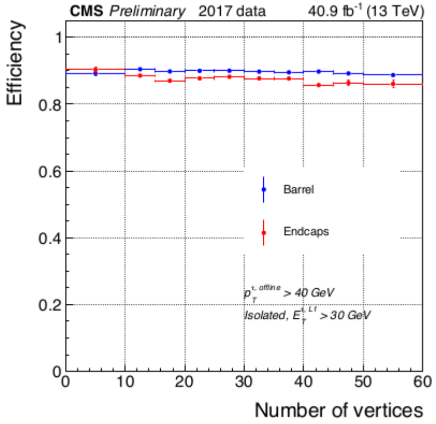
Isolation energy (E_T^{6x9}-$E_T^{e/\gamma}$) → cut depends on n_{TT}, E_T and η

Typical thresholds

DoubleTau > 34, 34 GeV
SingleTau > 120 GeV
EGTau > 22, 26 GeV





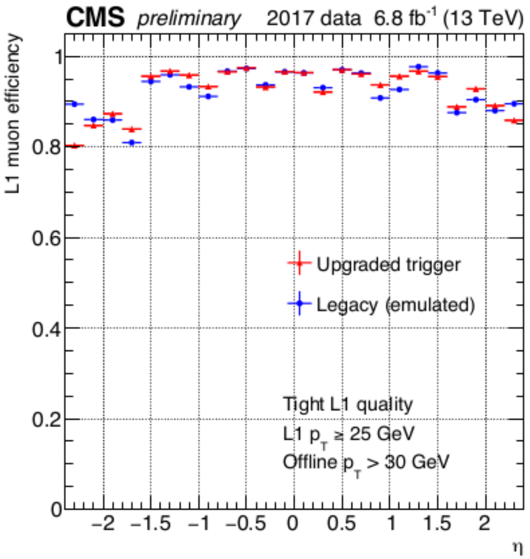


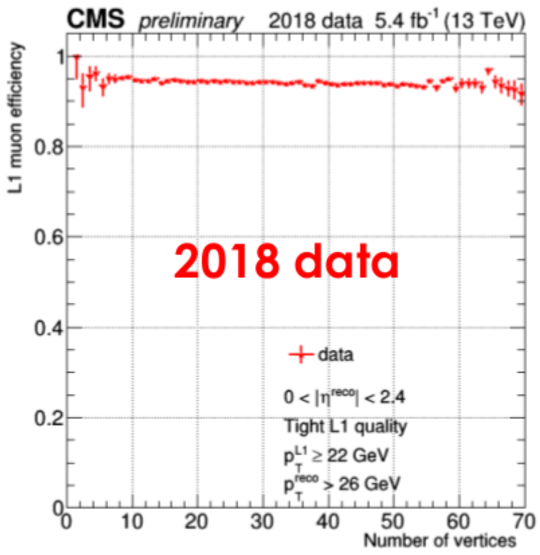
- **Excellent performance**
- **Excellent pileup resilience**
- **Thresholds maintained throughout 2016-2018 thanks to adapted isolation WP**

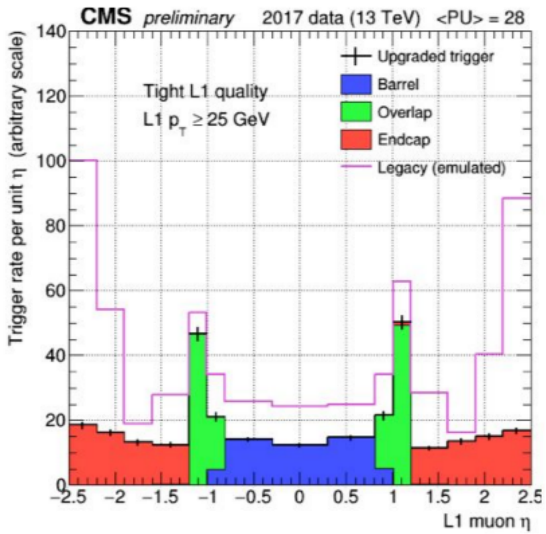
L1T muon trigger performance

Muon thresholds
SingleMu: 22 GeV
DoubleMu: 15 ,7 GeV
TripleMu: 5, 3, 3 GeV

Taken from O. Davignon's talk at ICHEP 2018

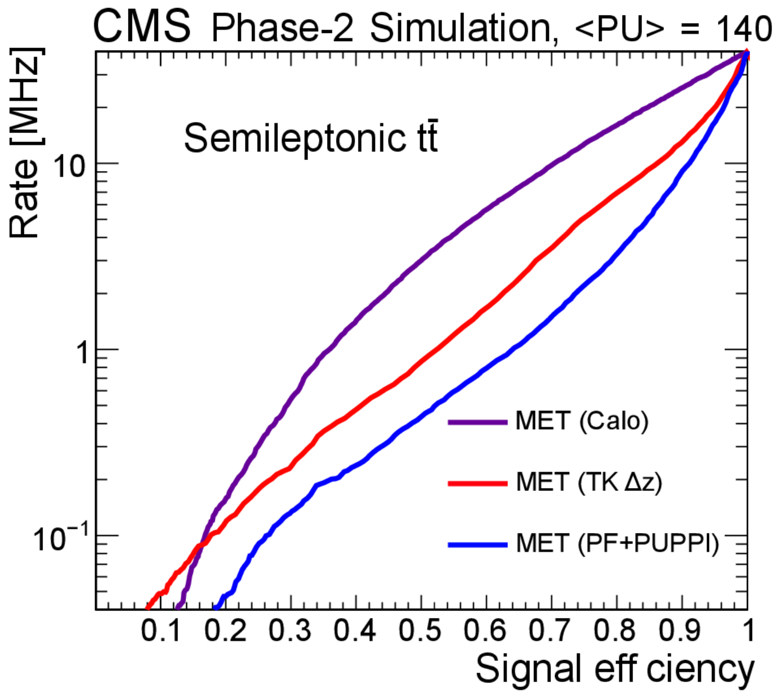


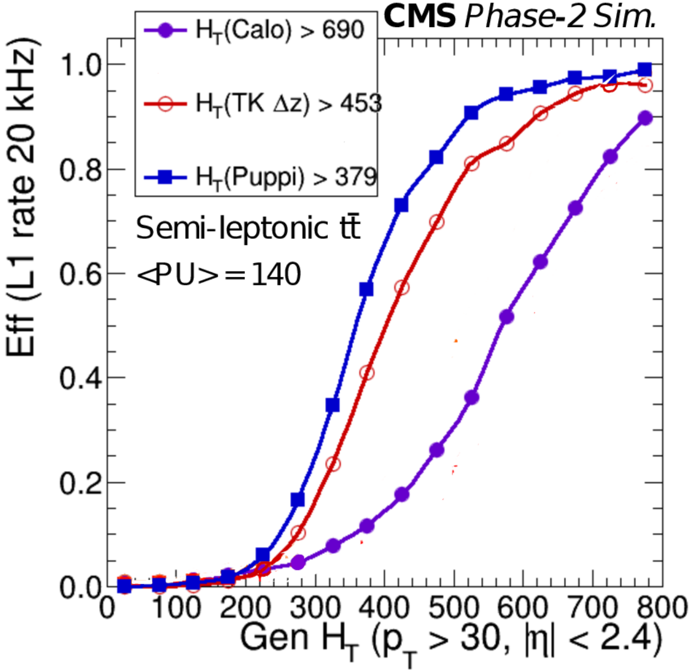




- **Efficiency improved in the overlap region**
- **Excellent pileup resilience**
- **Rate reduced by 20-80% w.r.t. legacy system**

PF @ L1


CMS Phase-2 Simulation, <PU> = 140
Semileptonic tt̄
Rate [MHz]
Signal eff ciency
MET (Calo)
MET (TK Δz)
MET (PF+PUPPI)


CMS Phase-2 Sim.
H_T(Calo) > 690
H_T(TK Δz) > 453
H_T(Puppi) > 379
Semi-leptonic tt̄
<PU>=140
Eff (L1 rate 20 kHz)
Gen H_T (p_T > 30, |η| < 2.4)