Design and performance of the upgrade of the CMS L1 trigger

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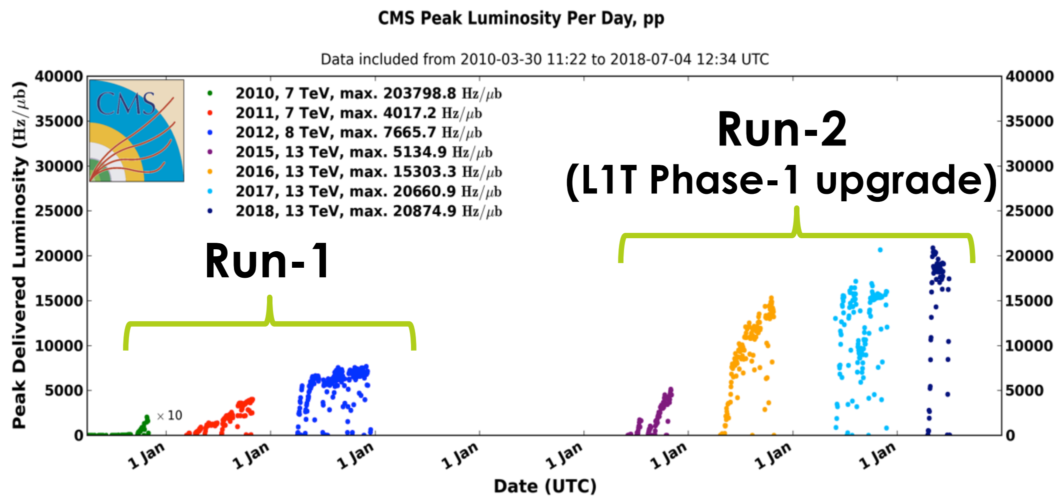
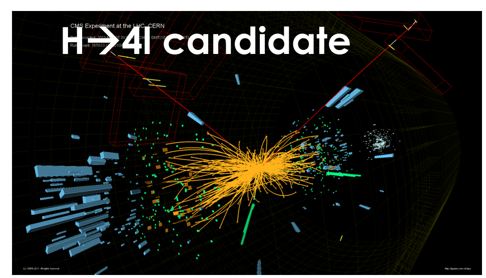
The trigger challenge at LHC/CMS

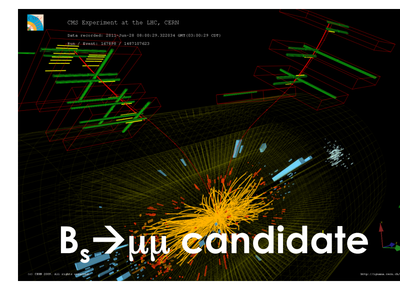
- **Run-2 LHC**
  - **$L_{inst} > 2 \times 10^{34}$ cm^{-2}.s^{-1}**
  - **<PU> ~ 60**
  - **Rate ~ 40 MHz**
  - → **Huge raw bandwidth**
  - → **Necessity to reduce rate by factor ~40,000**

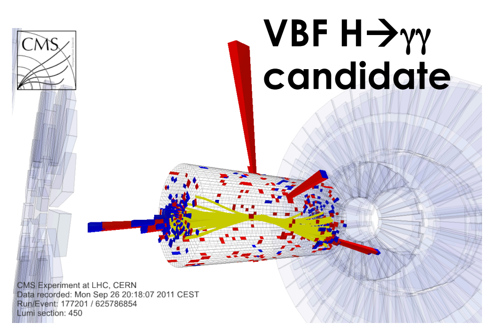


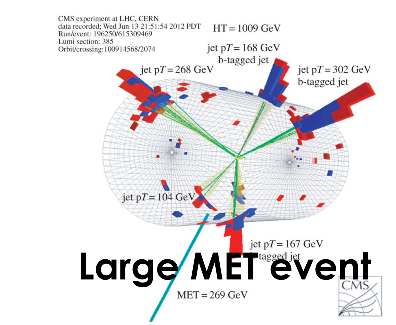
- **CMS is looking for rare processes**

- **Trigger: reject most of the uninteresting events while keeping as much of our signals as possible**
  - **Efficiency: rely on signal's distinctive features: presence of high p_T objects, topology, etc.**
  - **Resilience: as independent to LHC conditions as possible, in particular pileup**
  - **Stability: large availability and easy monitoring / maintenance**



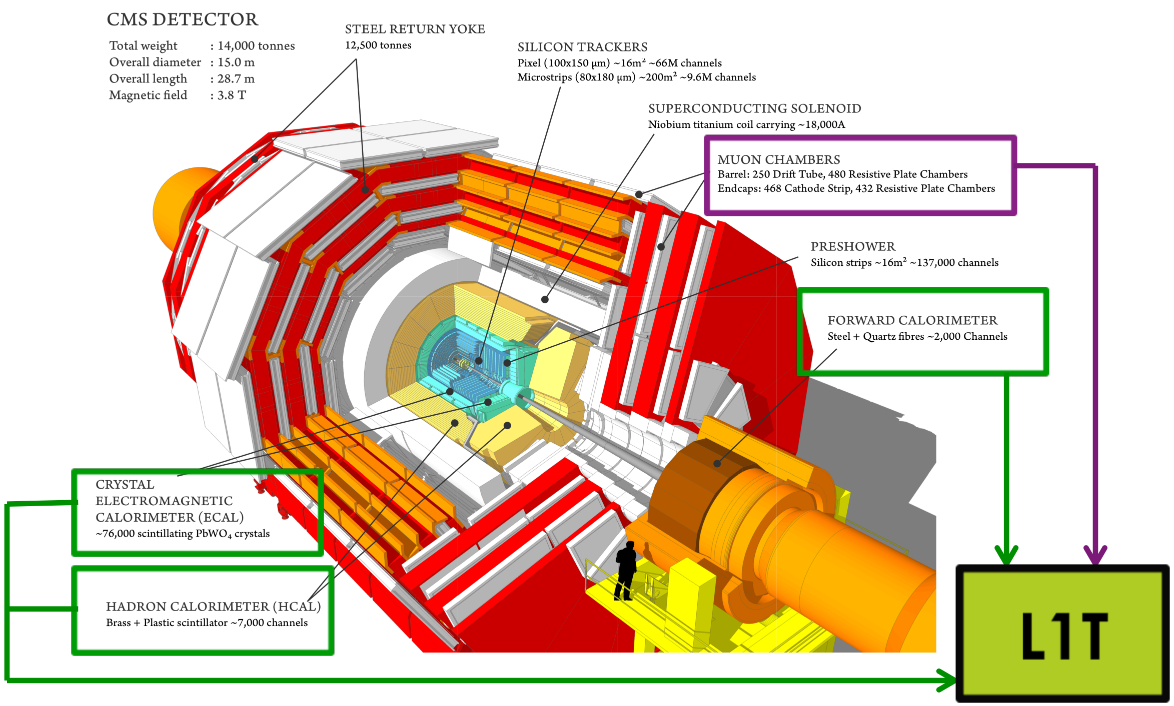


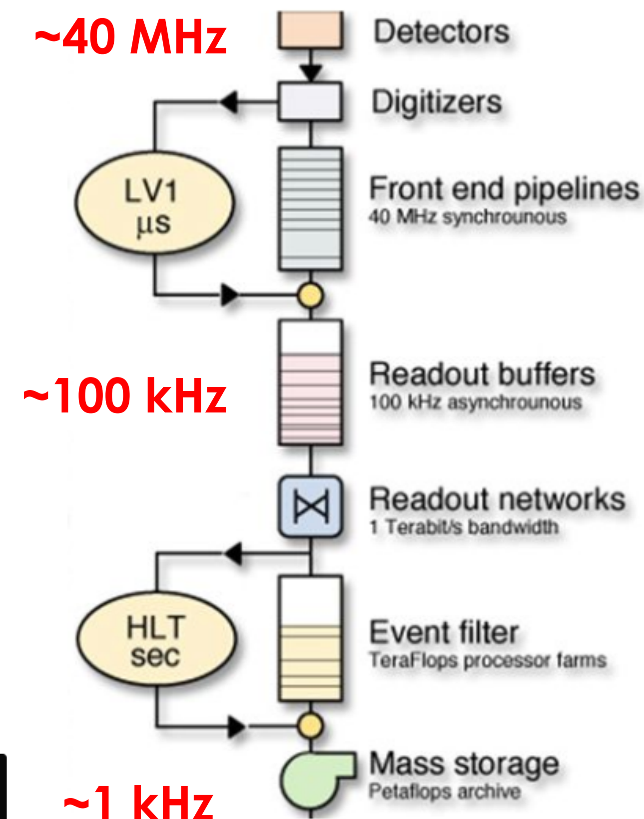




The CMS trigger system

- CMS implements a sophisticated trigger system in two levels: Level-1 Trigger (L1T, this talk) and High-Level Trigger (HLT, see Laurent Thomas' talk)
  - $>10^5$ rate reduction!



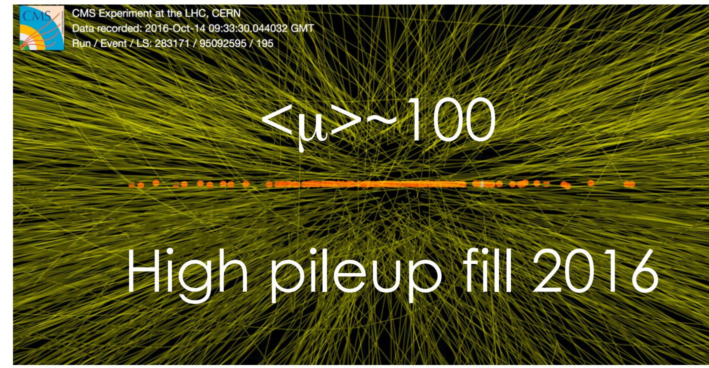


- Level-1 is implementing generic-designed electronics boards to process the data from the Calorimeters (ECAL+HCAL) and the Muon systems
- Total latency: 3.8 μs

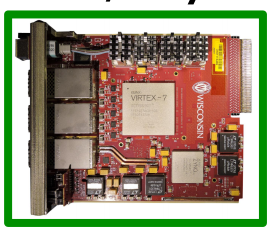
Calorimeter trigger upgrade

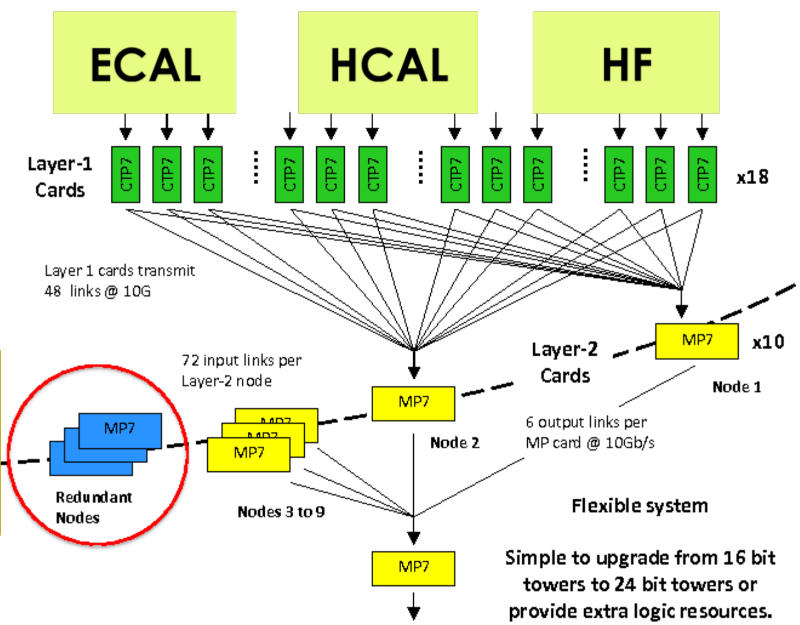
Upgraded calorimetric trigger: Reconstruction of L1 e/γ, tau, jets and sums (MET, HT)

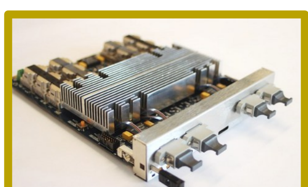
- Improved calorimetric resolution → better E_T assignement
- Improved e/γ and tau isolation → better object ID
- Implementation of L1 PU estimator and subtraction → better resilience to LHC conditions for all objects
- Enhanced capabilities at Global Trigger → many more/more sophisticated algorithms
- See also poster by Sandeep Bhowmik



CTP7 / Layer-1







MP7 / Layer-2

New architecture & new hardware (since 2016)

- Layer-1 receives Trigger Primitives from the subdetectors & performs calibrations
- Time-multiplexing: full-detector data from a single bunch-crossing sent to a single card in Layer-2: L1-calo objects built and sent to μGT
- Objects combined into algorithms by μGT, final decision taken

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

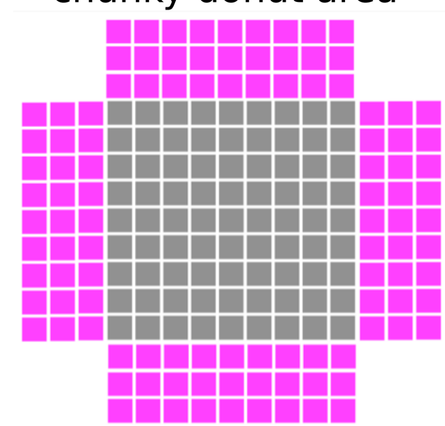
E_T in 3x9 regions around the jet computed
Energy in 3 lowest E_T regions used to determine PU energy density
Scaled & subtracted to the individual jet E_T

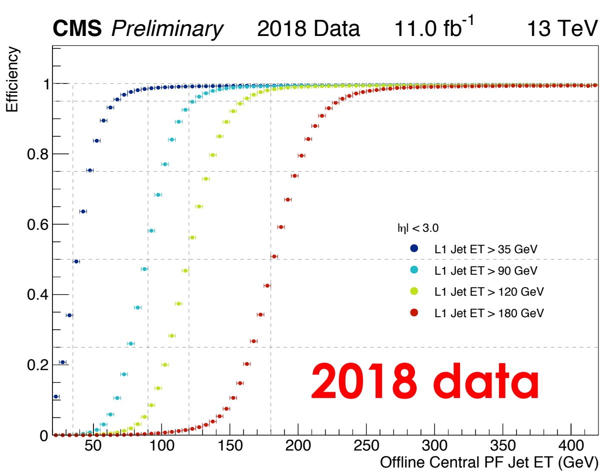
Calibration

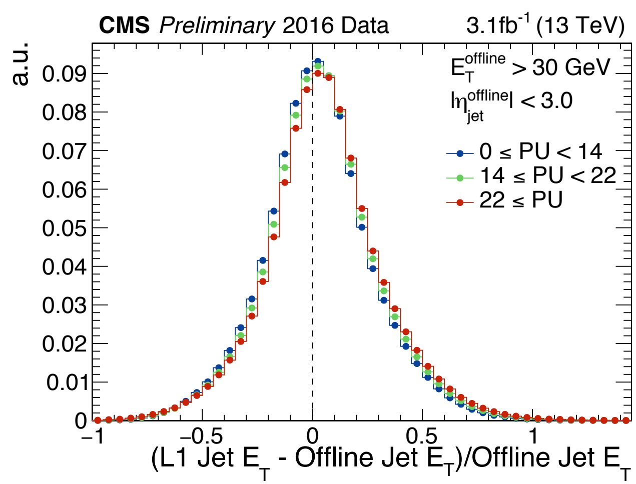
Corrected energies as function of η and E_T

inequality masks avoid self-masking and double counting

chunky donut area







Sums algorithm & performance

Types of algorithms

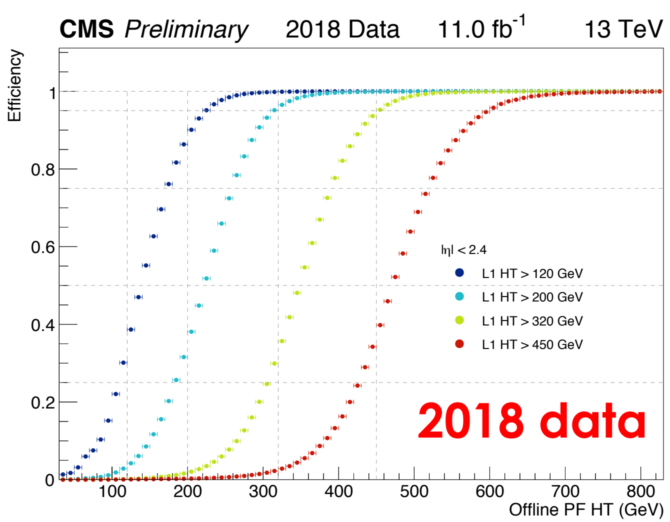
HT: scalar E_T sum of jets with E_T > 30 GeV with $|\eta|<2.4$
Missing transverse energy (MET): norm $|-\Sigma \mathbf{E}_T|$ of trigger towers up to $|\eta|=5$

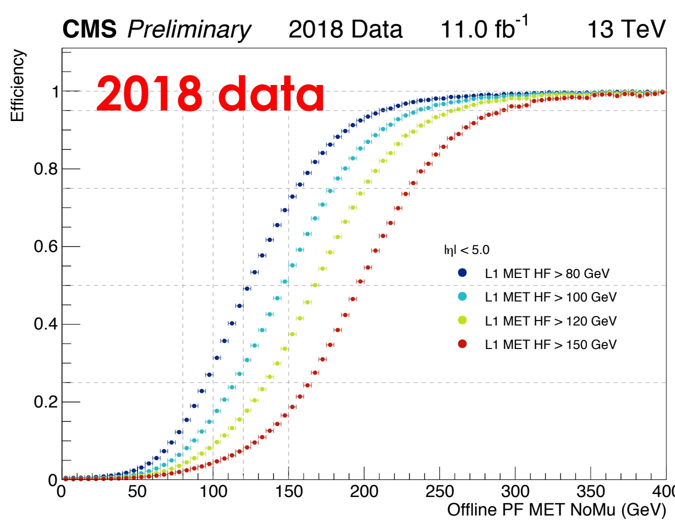
Pileup mitigation

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 @ 2E34

MET > 130 GeV
HT > 360 GeV





L1 e/γ algorithm & performance

L1 e/γ clustering algorithm

Dynamic clustering around local maximum (seed)

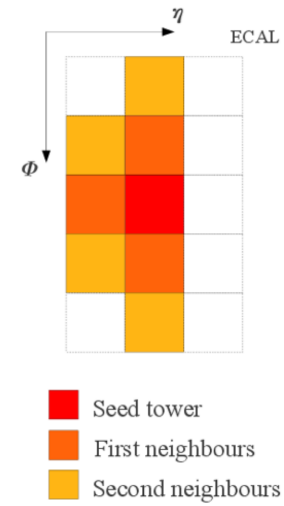
- Recovering the energy loss due to tracker material
- Extension of the cluster in ϕ to recover brem
- Minimizing effect of pileup contributions
- Improved energy resolution

e/γ calibration

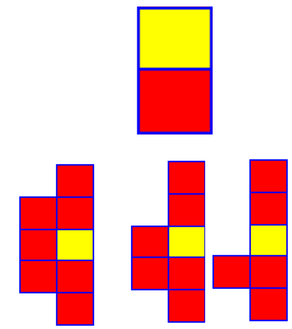
Calibration depending on ET, η and the reconstructed shape

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

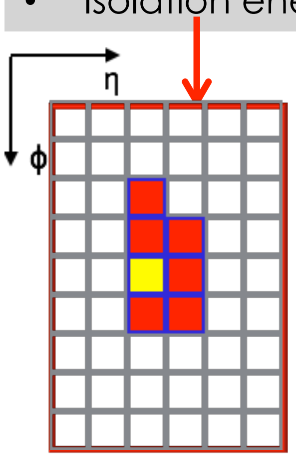


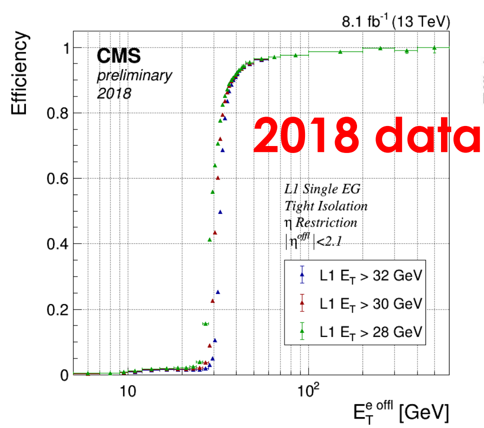
e/γ-like

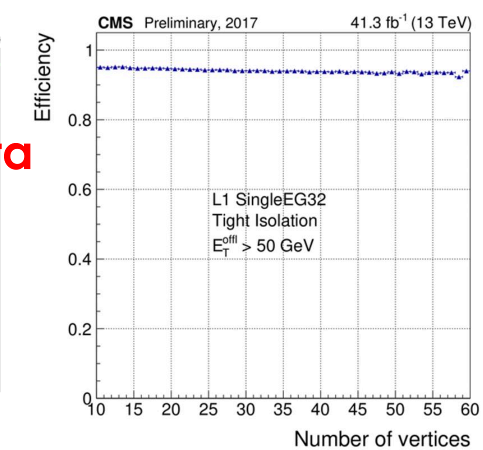


jet-like

Typical thresholds @ 2E34
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**

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

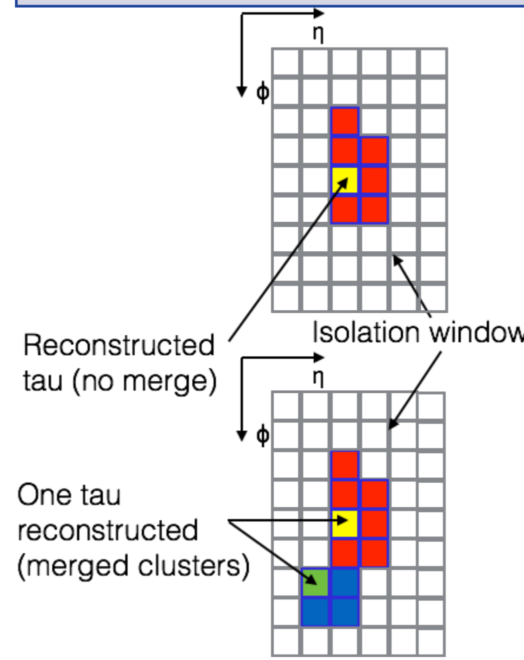
Calibration depending on E_T, η and the E/H fraction

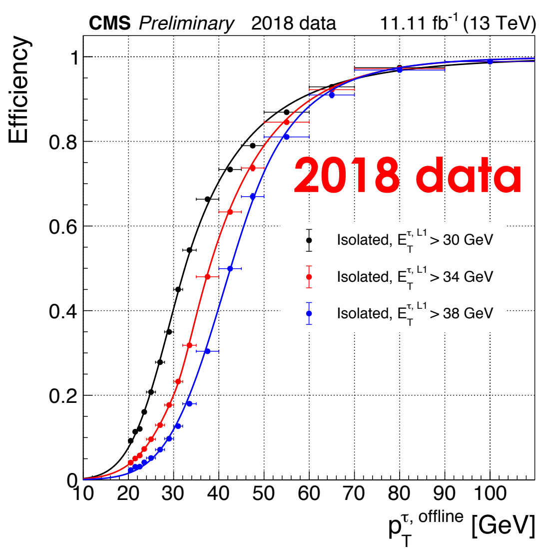
τ identification

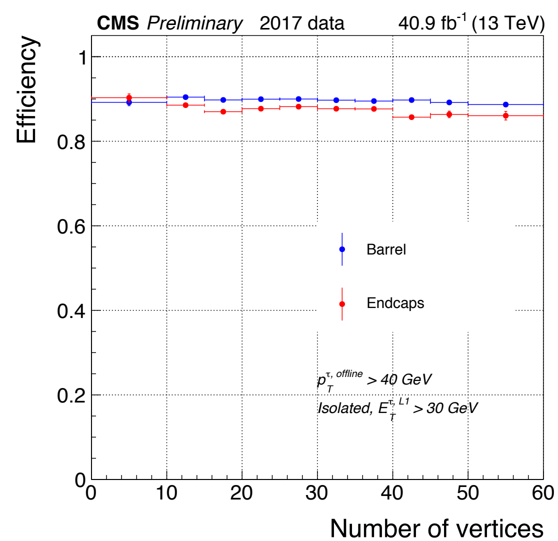
Isolation energy (E_T^{6x9}-$E_T^{e/\gamma}$) → cut depends on n_{TT}, E_T and η

Typical thresholds @ 2E34

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

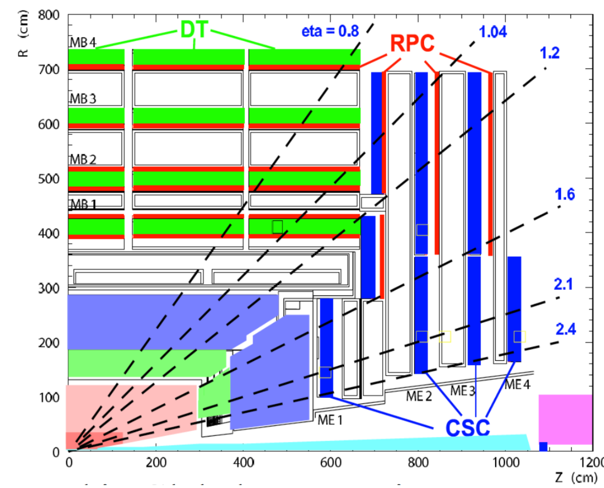






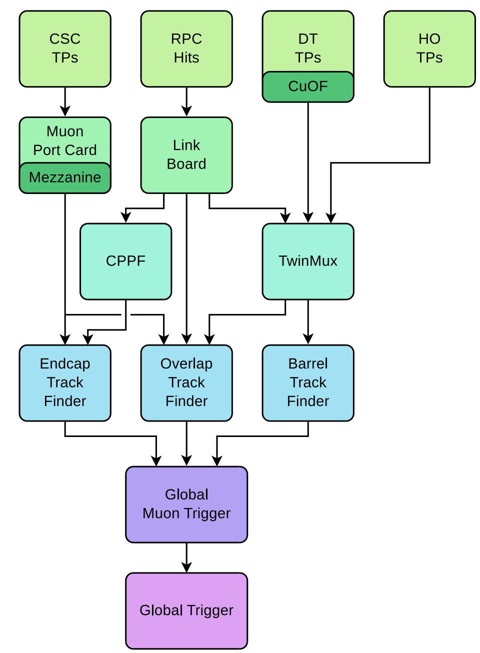
- **Excellent performance**
- **Excellent pileup resilience**
- **Thresholds maintained throughout 2016-2018 thanks to adapted isolation WP**

Muon trigger upgrade



Upgraded muon triggers (2016)

- ❖ Moved from a muon detector-based scheme (DT, RPC, and CSC) to a geometry-based system
- → Muon track finders: **BMTF, OMTF and EMTF**
- ❖ Bring in together data from the three complementary detector technologies early in the track finding procedure to improve resolution & redundancy
- → higher efficiency and better rate reduction
- ❖ See also poster by Marcin Konecki



Muons from all 3 systems processed in Global Muon Trigger, which provides

- ❖ Transverse momentum
- ❖ Quality (e.g. number of hits)
- ❖ Correlation between systems (RPC+DT, RPC+CSC)

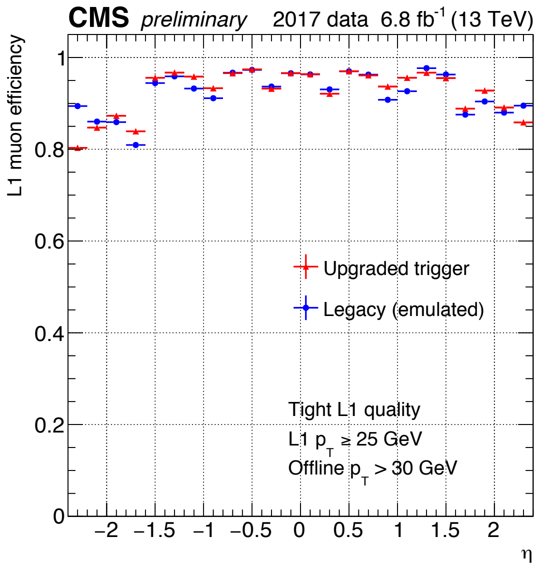
Muon trigger algos & performance

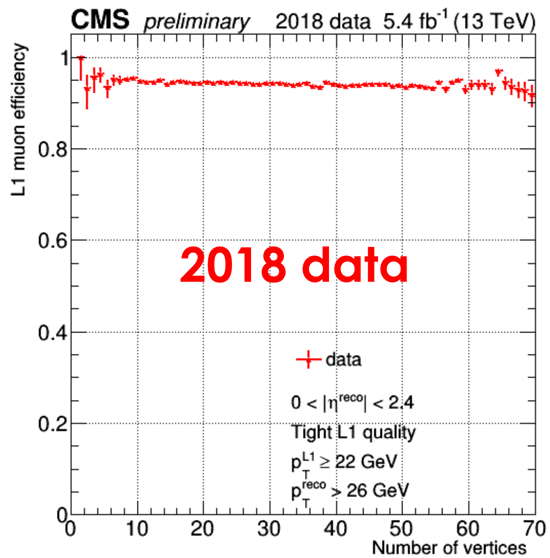
Algorithms

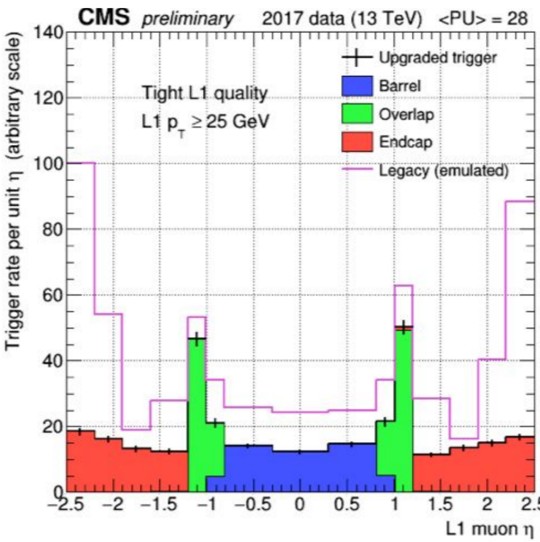
OMTF & EMTF: pattern-based track finding and p_T assignment w/ look-up-table based on an MVA for p_T assignment in EMTF
BMTF: road search extrapolation track finder is used

Typical thresholds @ 2E34

SingleMu > 22 GeV
DoubleMu > 15, 7 GeV
TripleMu > 5, 3, 3 GeV







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

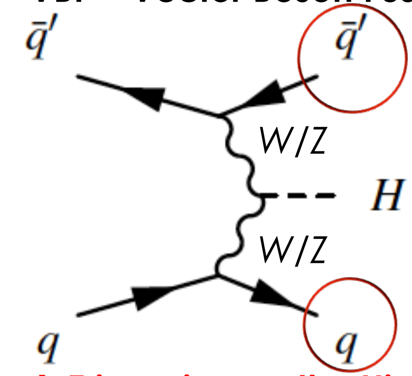
L1 Global Trigger & advanced algos

μGT: receives all objects from calorimeter trigger (jets, sums, e/γ, τ) and muons (from μGMT)

- Combination of objects: algorithms tailored for physics
- Implements multiple processing boards to accommodate ~512 algorithms (486 in 2017)
- Processing power enables complex correlation algorithms (including invariant mass computation)
- Evolution of the trigger menu with luminosity and pile-up conditions

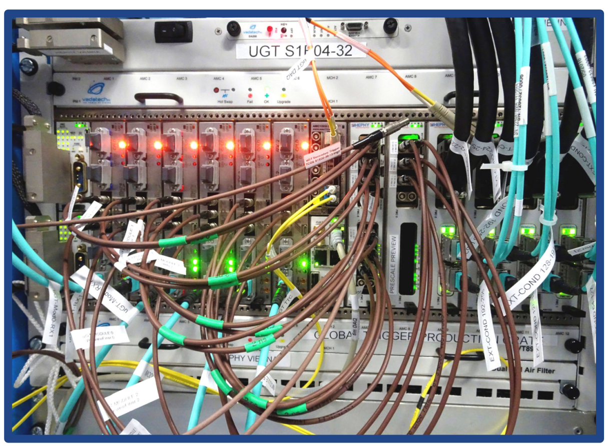
→ Implementing twice as much cross-triggers in 2017 w.r.t. 2016 to provide efficient triggering w/ low thresholds

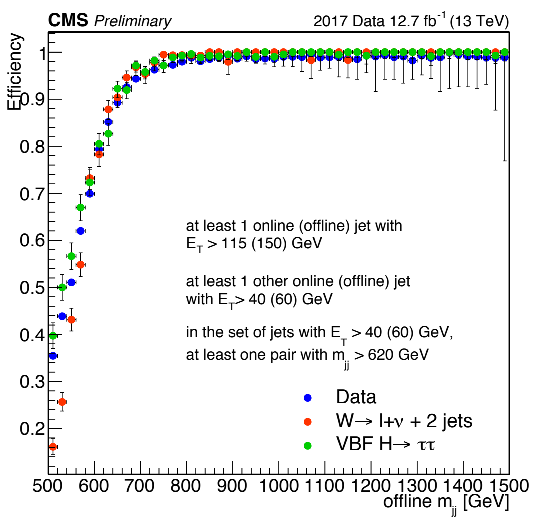
VBF = Vector Boson Fusion



→ Triggering on the Higgs production mode

μGT crate with 6 MP7 boards





Advanced algorithm for VBF

→ First dedicated VBF trigger implemented in the core of the level-1 decision: significant gain in acceptance for a large panel of physics analyses

Summary

CMS fully upgraded its L1 Trigger hardware & strategy in 2015-16

- **Excellent performance: thresholds maintained in spite of LHC exceeding all expectations in terms of instantaneous luminosity and pileup**

- **System features advanced technical solutions (high-speed links, large FPGA, μTCA platforms, time-multiplexing, central control systems) that enable flexibility of algorithms, scalability and easy maintenance**

- **Development of increasingly sophisticated and targeted algorithms to increase acceptance to specific signals**
  - **Algorithms progressively getting closer to what is done at higher levels**

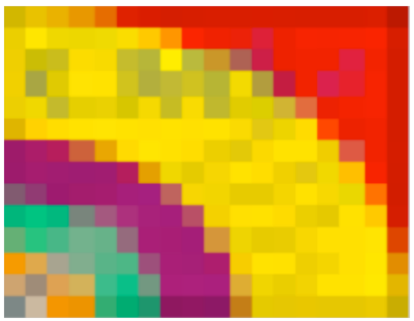
- **System is a working baseline for the Phase-2 CMS L1T upgrade: experience in the Phase-1 upgrade extremely valuable**
  - **Flexibility and standardization of processor boards to insure high selectivity**
  - **See following talk by Silvio Donato**

BACKUP

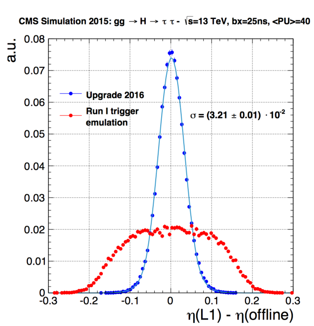
Calo trigger: algorithms & firmware

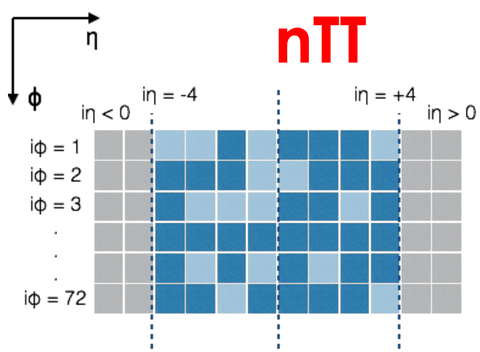
Key algorithmic features

- full calorimeter tower granularity @ 720 Gb/s (72 x 82 TT)



- Dynamic clustering
- Full event view: event-by-event pileup estimation for (e/γ, τ & MET)





Firmware design

- Split into algo. and infrastructure
- Resource usage due to complex algorithms
- Algorithms clocked @ 240 MHz
- Pipelined in η slices
- → Easily scalable