CMS Calorimeter Trigger for LHC Run II

Dr. Aaron Bundock

Imperial College London

CALOR 2016

17th May 2016

On behalf of the CMS Calorimeter Trigger Project:

R. Aggleton[h], L. Apanasevich[i], M. Baber[c], F. Ball[1], R. Barbieri[e], F. Beaudette[d], J. Berryhill[b], J. Brooke[h], A. Bundock[c], L. Cadamuro[d], I. A. Cali[e], R. Cavanaugh[b,i], M. Cepeda[k], M. Citron[c], S. Dasu[k], L. Dodd[k], T. Durkin[g], A. Elwood[c], R. Forbes[k], C. Fountas[j], T. Gorski[k], M. Guilbaud[f], G. Hall[c], K. Harder[g], S. Harper[g], G. Iles[c], G. M. Innocenti[e], P. Klabbers[k], B. Kreis[b], C. Laner[c], Y.-J. Lee[e], A. Levine[k], W. Li[f], J. Marrouche[a], L. Mastrolorenzo[d], K. Mishra[b], D. Newbold[h], M. Northup[f], I. Ojalvo[k], S. Paramesvaran[h], B. Penning[c], R. Rivera[b], C. Roland[e], T. Romanteau[d], A. Rose[c], T. Ruggles[k], J. B. Sauvan[d], C. Shepherd-Themistocleous[g], D. Smith[h], N. Smith[k], W. Smith[k], T. Strebler[d], A. Svetek[k], A. Tapper[c], A. Thea[g], J. Tikalsky[k], B. Tran[f], L. Uplegger[b], M. Vicente[k], N. Wardle[a], T. Williams[g], B. Wyslouch[e], A. Zabi[d], J. Zhang[i]

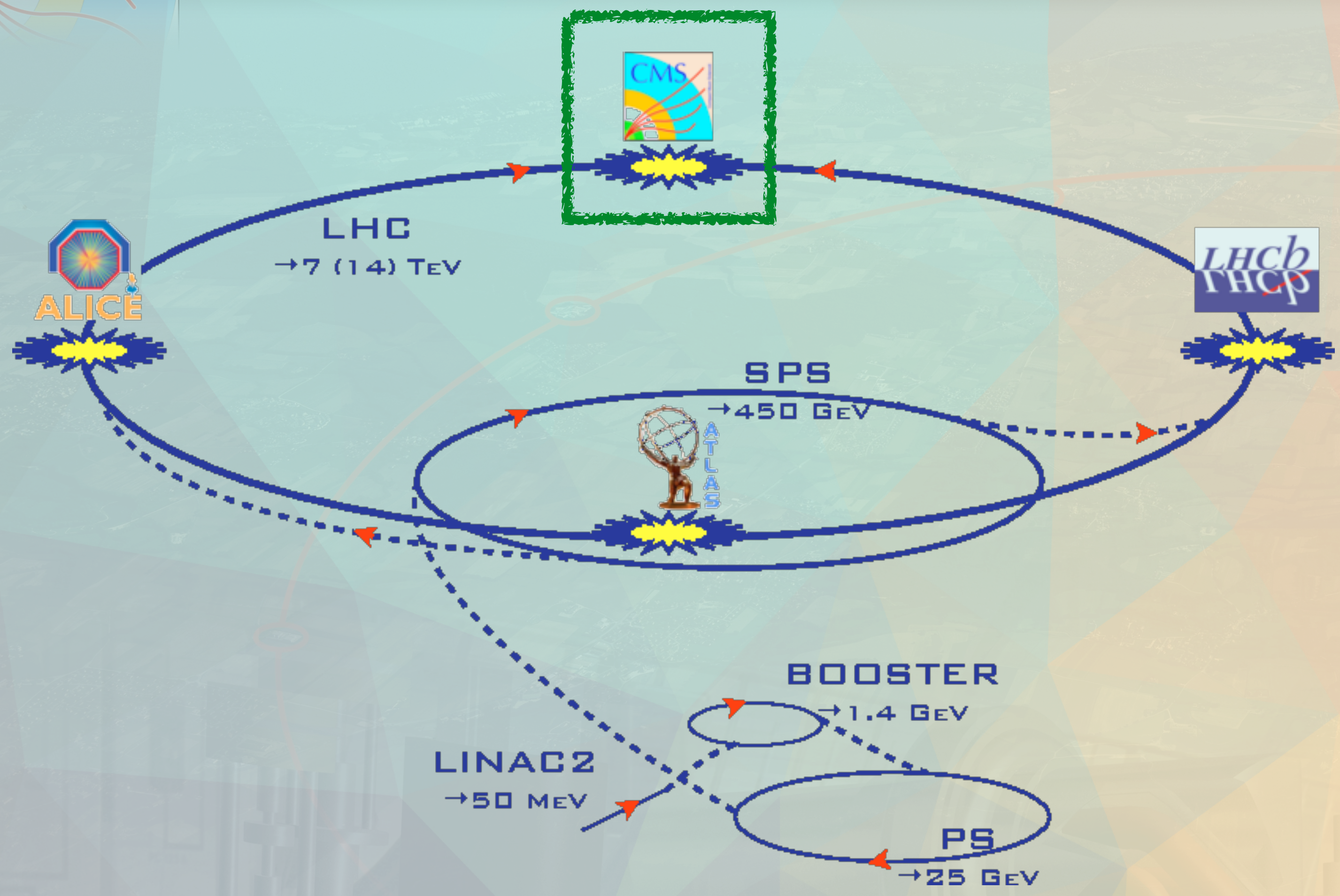
[a] CERN
[b]Fermi National Accelerator Laboratory [c]Imperial College London
[d]Laboratoire Leprince-Ringuet [e]Massachusetts Institute of Technology
[f]Rice University [g]Rutherford Appleton Laboratory [h]University of Bristol [i]University of Illinois at Chicago [j]University of Ioannina [k]University of Wisconsin

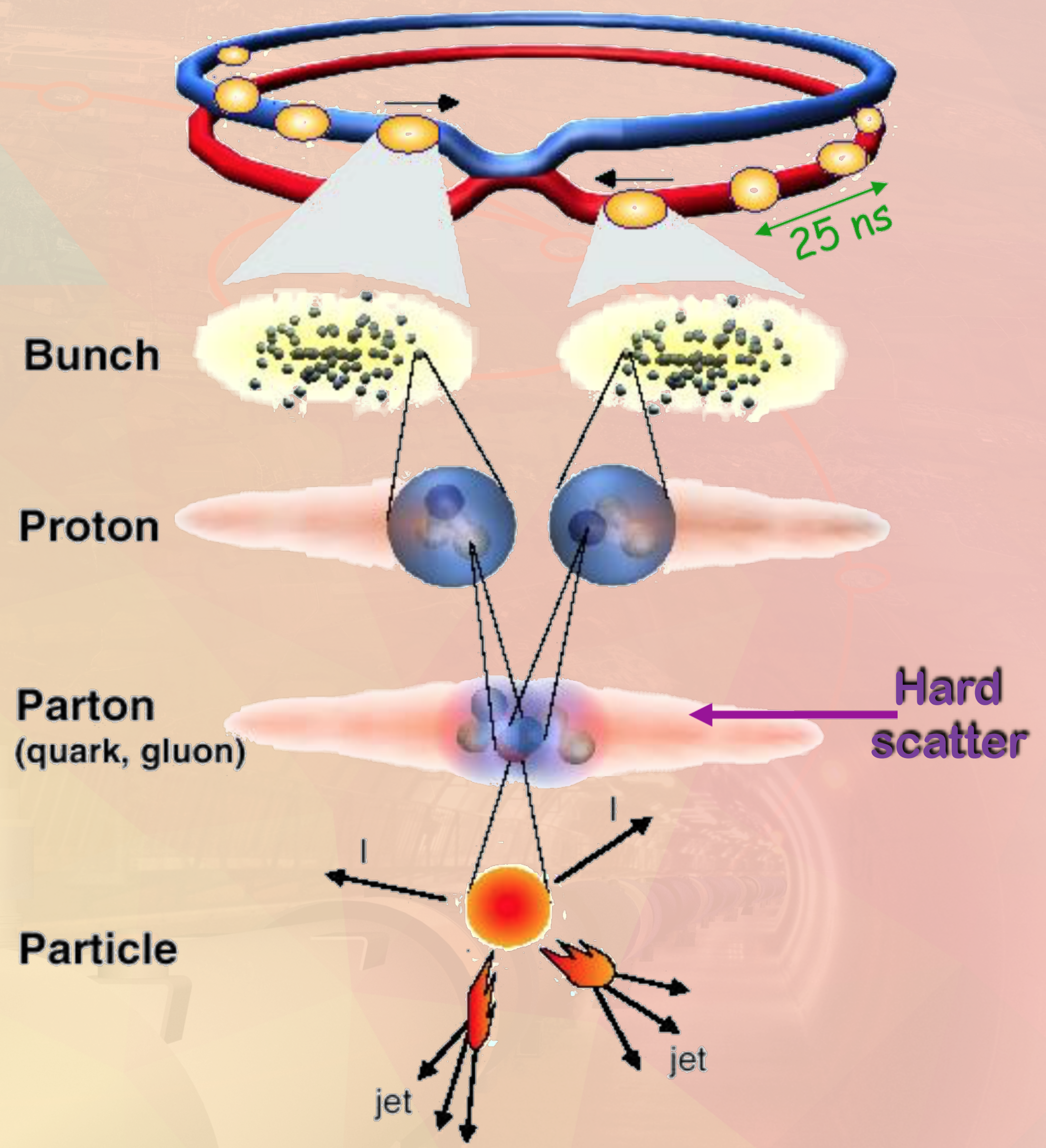
Outline

- Large Hadron Collider and the CMS Detector
- CMS Level 1 Calorimeter Trigger
- Algorithms and Validation
- Calorimeter Trigger Performance
- Summary

- **Large Hadron Collider and the CMS Detector**
- CMS Level 1 Calorimeter Trigger
- Algorithms and Validation
- Calorimeter Trigger Performance
- Summary

Large Hadron Collider



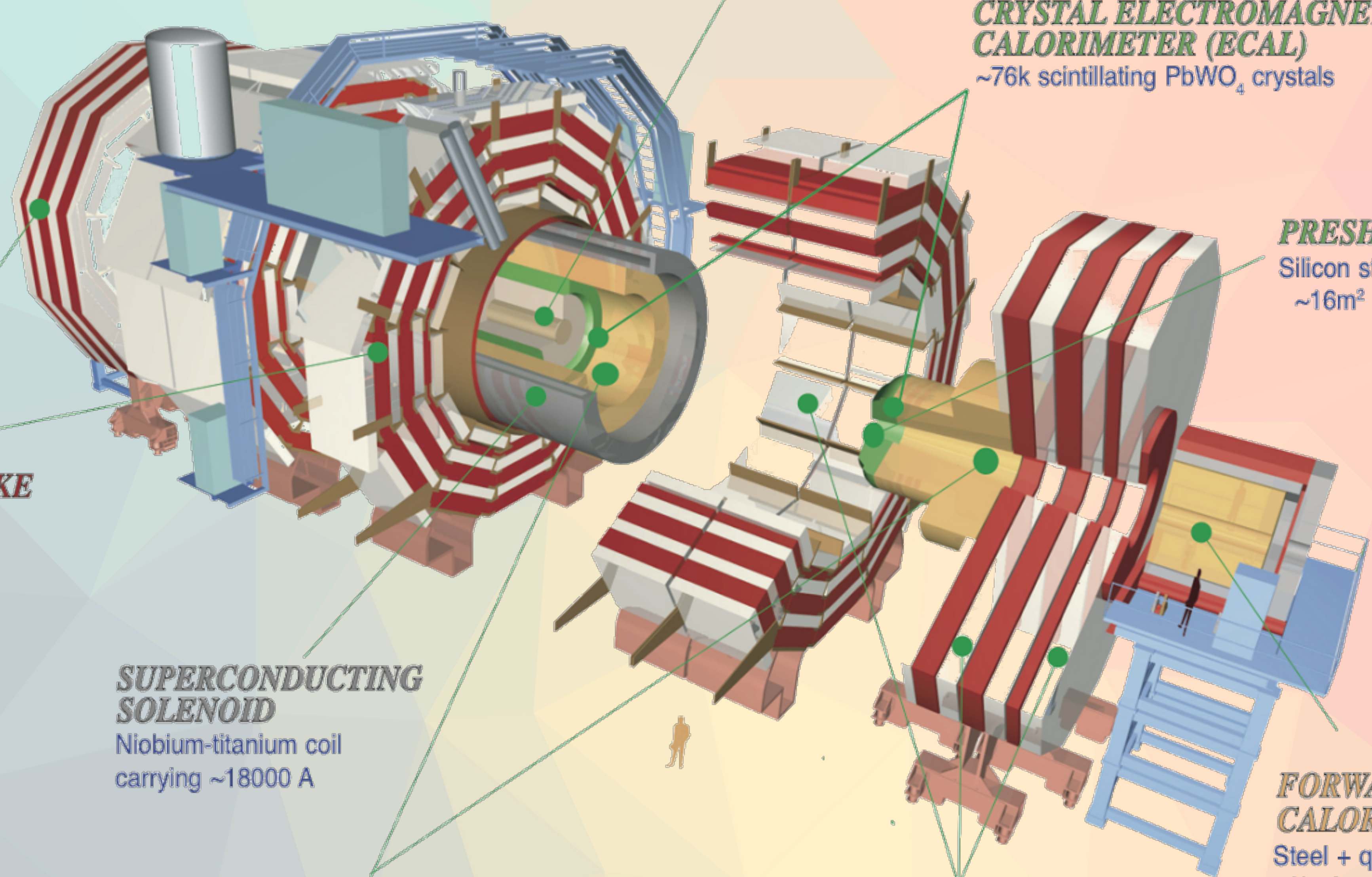


- Proton-proton collider with design centre-of-mass energy of 14 TeV
- 27km ring of superconducting magnets at 8.3 T, cooled to -271 °C
- 8 resonant radio-frequency cavities accelerate each proton beam
- 10^{11} protons/bunch, 25 ns bunch spacing, 2808 bunches/beam
- Designed to produce instantaneous luminosity of 10^{34} cm^{-2} s^{-1}
- All four experiments produce data rate of ~ 700 MB/s when running

- **Built to test Standard Model, perform searches for Higgs (done!), SUSY, dark matter, extra dimensions, and investigate mysteries of gravity and matter antimatter asymmetry**

CMS Detector

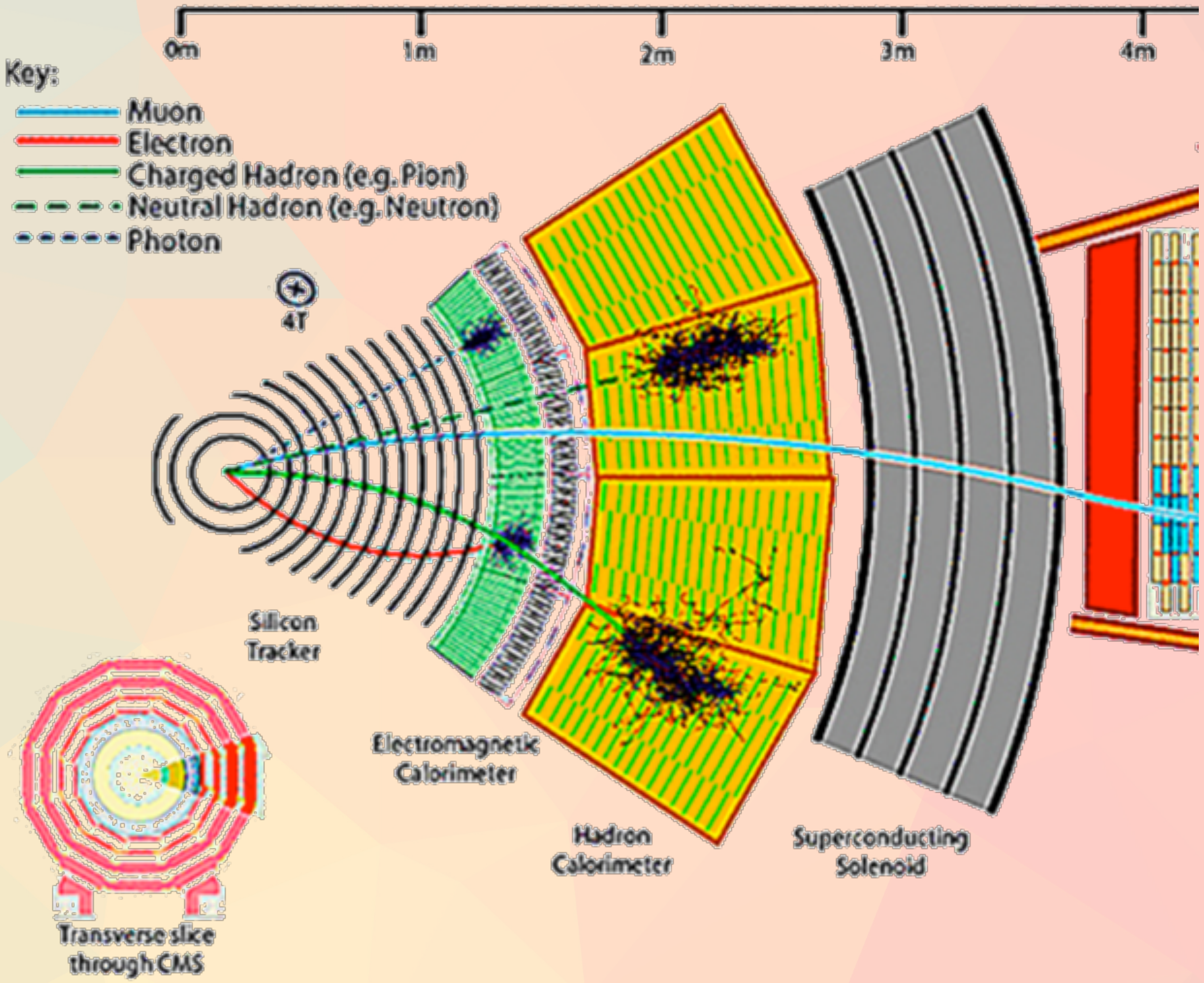
- Pixels
- Tracker
- ECAL
- HCAL
- Solenoid
- Steel Yoke
- Muons



Total weight	**: 14000 tonnes**
Overall diameter	**: 15.0 m**
Overall length	**: 28.7 m**
Magnetic field	**: 3.8 T**

Compact Muon Solenoid Experiment

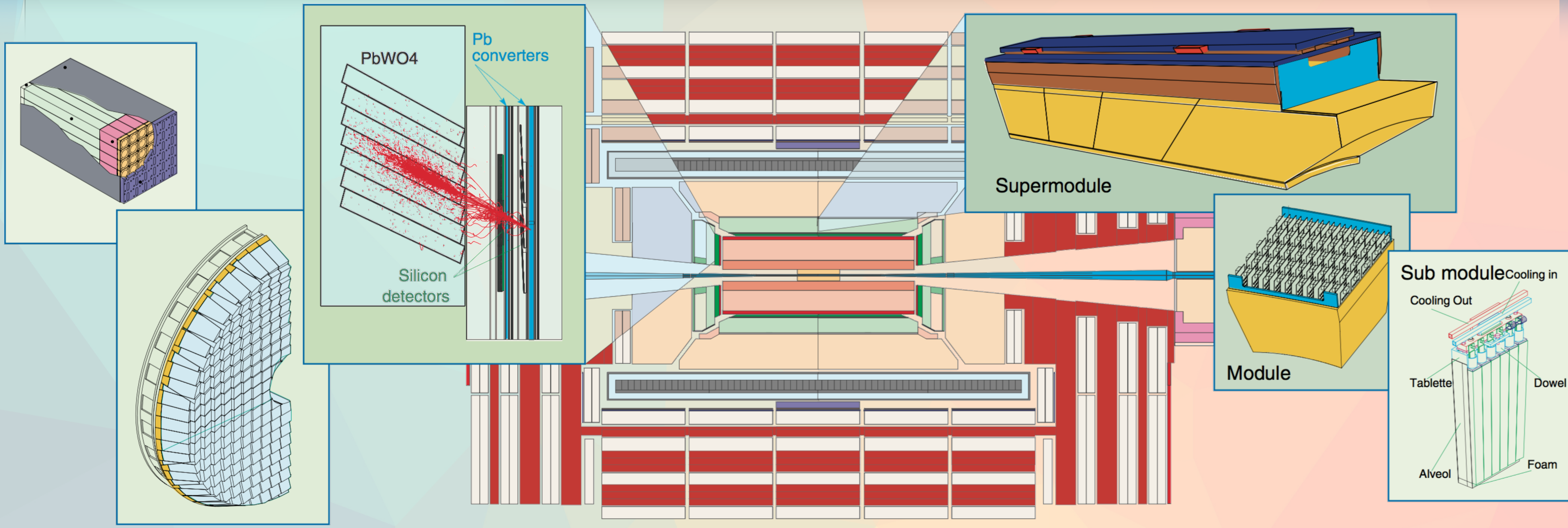
- General purpose detector at the LHC
- Built around huge solenoid magnet
  - cylindrical coil of superconducting cable
  - produces field of 3.8 T
  - field confined by steel yoke
- 14,000 tonnes, built above ground, reassembled underground in 15 sections
- 22m long, 15m diameter
- 3,800 collaborators from 200 institutes



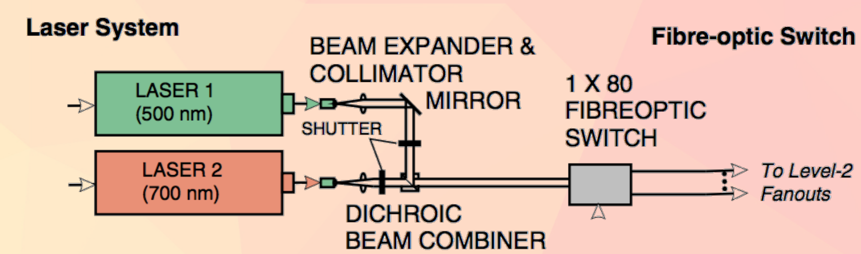
Why do we need a trigger?

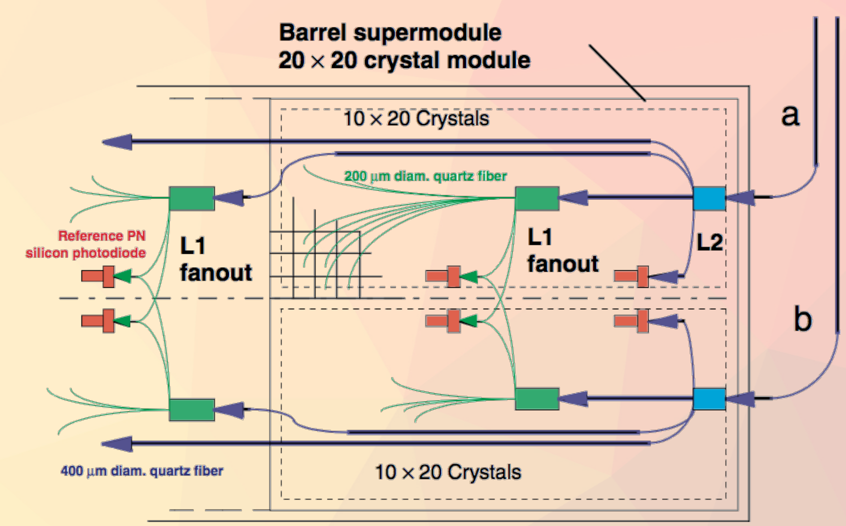
- Too much data (~ 1 PB/s) from detectors to save all events to disk: trigger on interesting events only
- Trigger must very quickly (~ 3 μs) construct physics objects (jet, egamma, tau) from calorimeter data
- Fast hardware triggers built from FPGAs contain complex identification algorithms
- Global trigger contains various 'menus' to provide manageable rate of interesting events to HLT

Electromagnetic Calorimeter

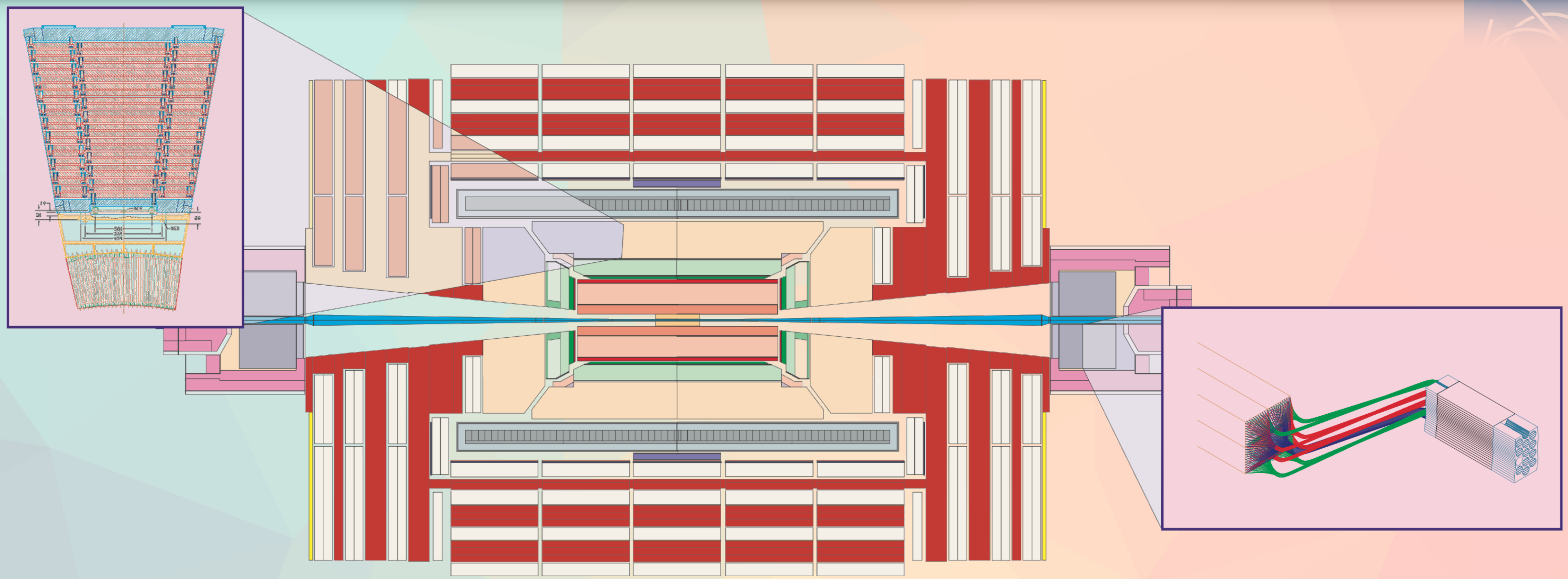


- Scintillating crystal calorimeter: contains almost all energy of electrons and photons
- 80,000 $PbWO_4$ crystals: high density, small Molière radius, short rad length, fast scintillator
- 22mm * 22 mm front face, 23 cm length (= 26 radiation lengths)
- Equipped with avalanche photo-diodes
- Scintillation mechanism and uniformity of light yield unaffected by radiation damage
- Transparency of crystals <u>is</u> affected by radiation through formation of colour centres
  - Injection pulse monitoring system continuously monitors optical transmission



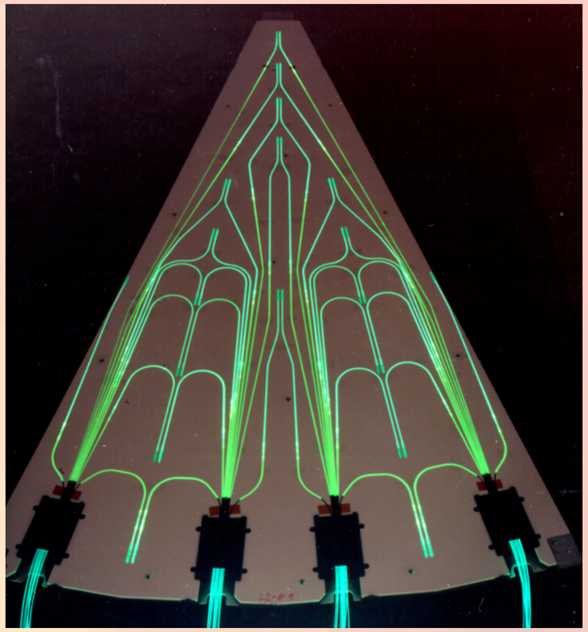


Hadronic Calorimeter



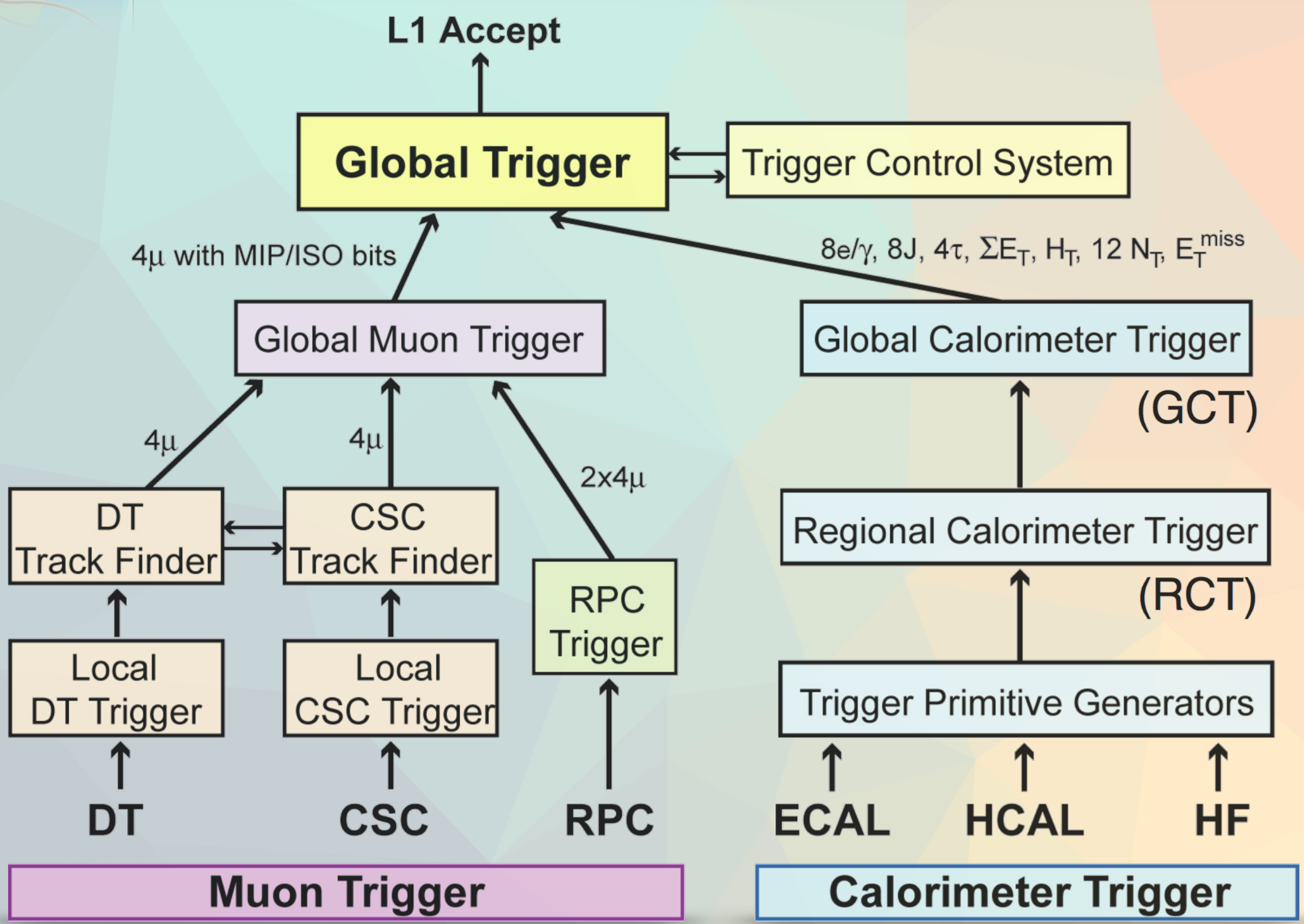
- Barrel and endcap (HBHE): sampling calorimeters built from 50mm thick copper absorber plates interleaved with 4mm thick plastic scintillator tiles
- Blue-violet light emission in tiles absorbed by wave-shifting fibres that fluoresce in green
- HB not deep enough to contain full showers: additional scintillator layers (HOB) outside of solenoid
- Full radiation length of HB + HOB around 11 absorption lengths
- Hermetic coverage to | η | < 5 required for good missing energy resolution

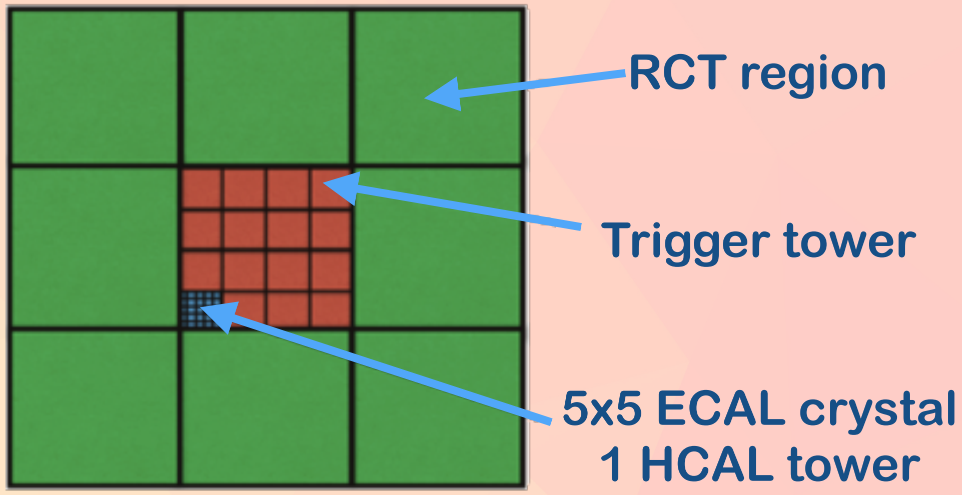
➡ Two forward hadronic calorimeters (HF)
  - Harsh radiation field: built from steel absorbers and quartz scintillator
  - Jet energies measured from Cerenkov light: excellent position resolution



- Large Hadron Collider and the CMS Detector
- **CMS Level 1 Calorimeter Trigger**
- Algorithms and Validation
- Calorimeter Trigger Performance
- Summary

Level 1 Calorimeter Trigger: Legacy





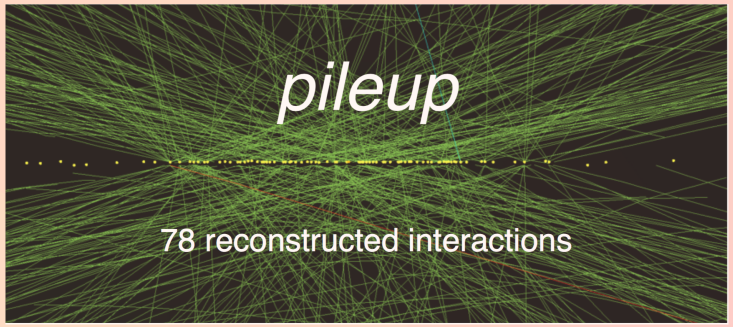
- **Trigger primitives sent from ECAL & HCAL to RCT**
- **EM candidates and regional energies sent to GCT**
- **Each trigger card processes a slice of the calorimeter**
  - ➡ **Data has to be sent between cards to process overlap regions**

L1 Calo Trigger: Upgrade Motivation

Run II:

➡ L1 trigger must support physics program in Run II that allows for TeV scale searches whilst maintaining sensitivity for electroweak scale physics

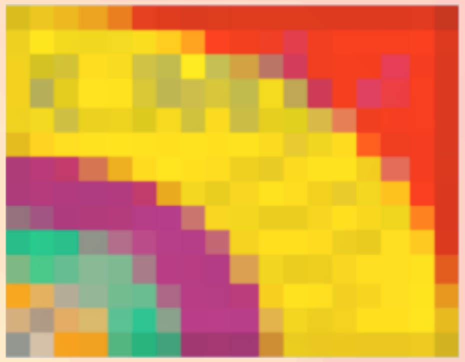
- LHC center-of-mass energy increased to 13 TeV
- Pileup increased from ~20 to ~50 interactions per crossing
- Decreased bunch spacing from 50ns to 25ns
- Instantaneous luminosity tripled to over 2×10^{34} cm^{-2} s^{-1}



➡ Trigger rates in Run II rise by around a factor six for same thresholds applied in 2012 if no improvements to the existing trigger system

→ 2016 Calorimeter trigger upgrade:

- Significantly improved calo resolution available for object ID
- Improved electromagnetic object isolation using calorimeter energy distributions with pile-up subtraction
- Improved jet finding with pile-up subtraction
- Improved hadronic tau identification within a smaller fiducial area
- Improved global trigger menu with more triggers and more sophisticated logical combinations of input objects
- Flexible and scalable to accommodate uncertain physics program (NEW PHYSICS??) and future upgrades to the experiment

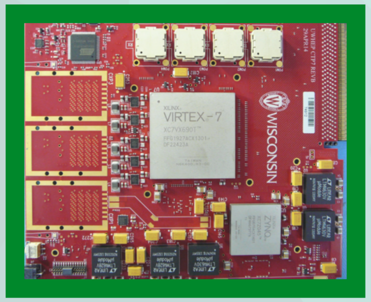


Legacy resolution

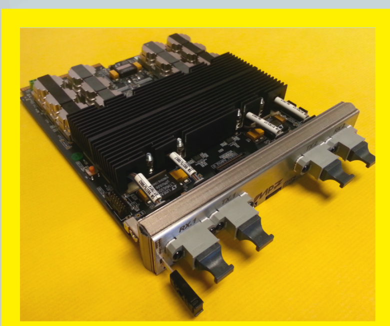
Upgrade resolution

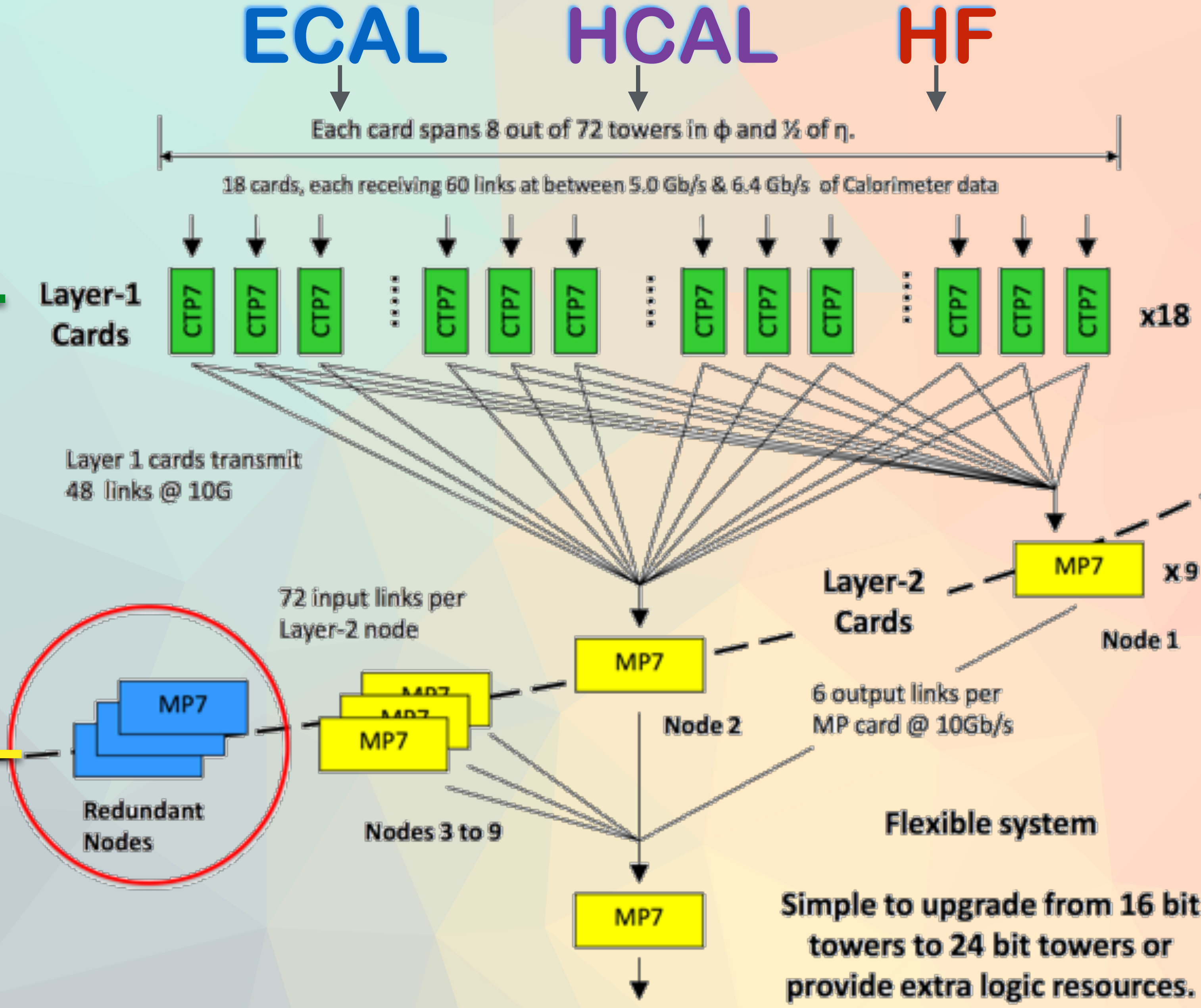
L1 Calorimeter Trigger Upgrade: Overview

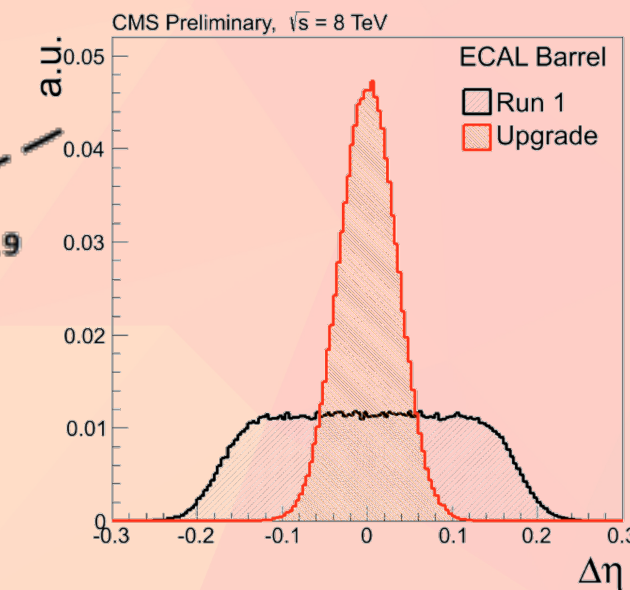
CTP7



MP7







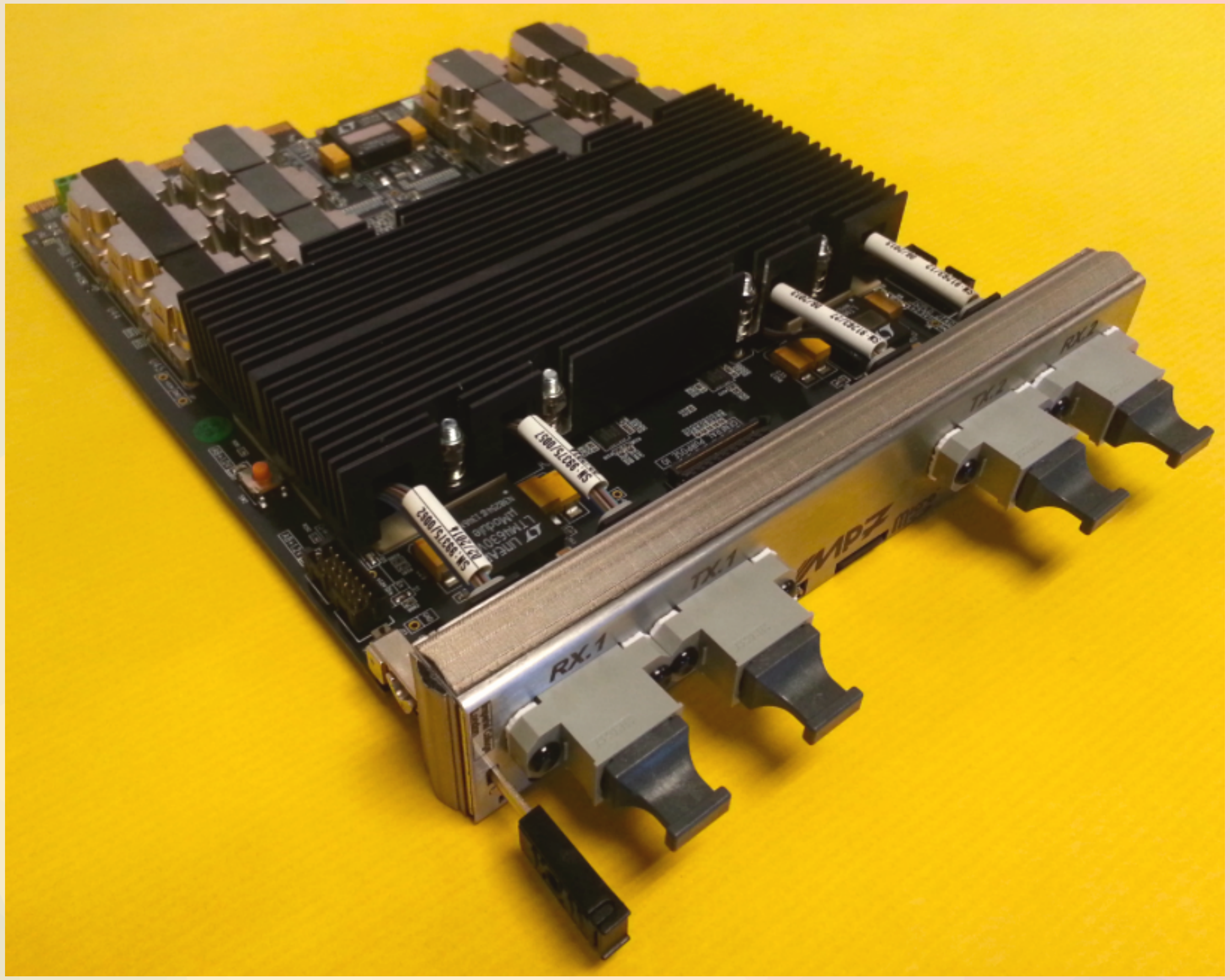
- **In upgraded calorimeter trigger, Layer-1 pre-processors receive trigger primitives**
- **Fan out full detector data for one bunch crossing to one main processor**
- **Time-multiplexed trigger: full detector data from ECAL and HCAL processed in a single MP!**

Master Processor Virtex 7

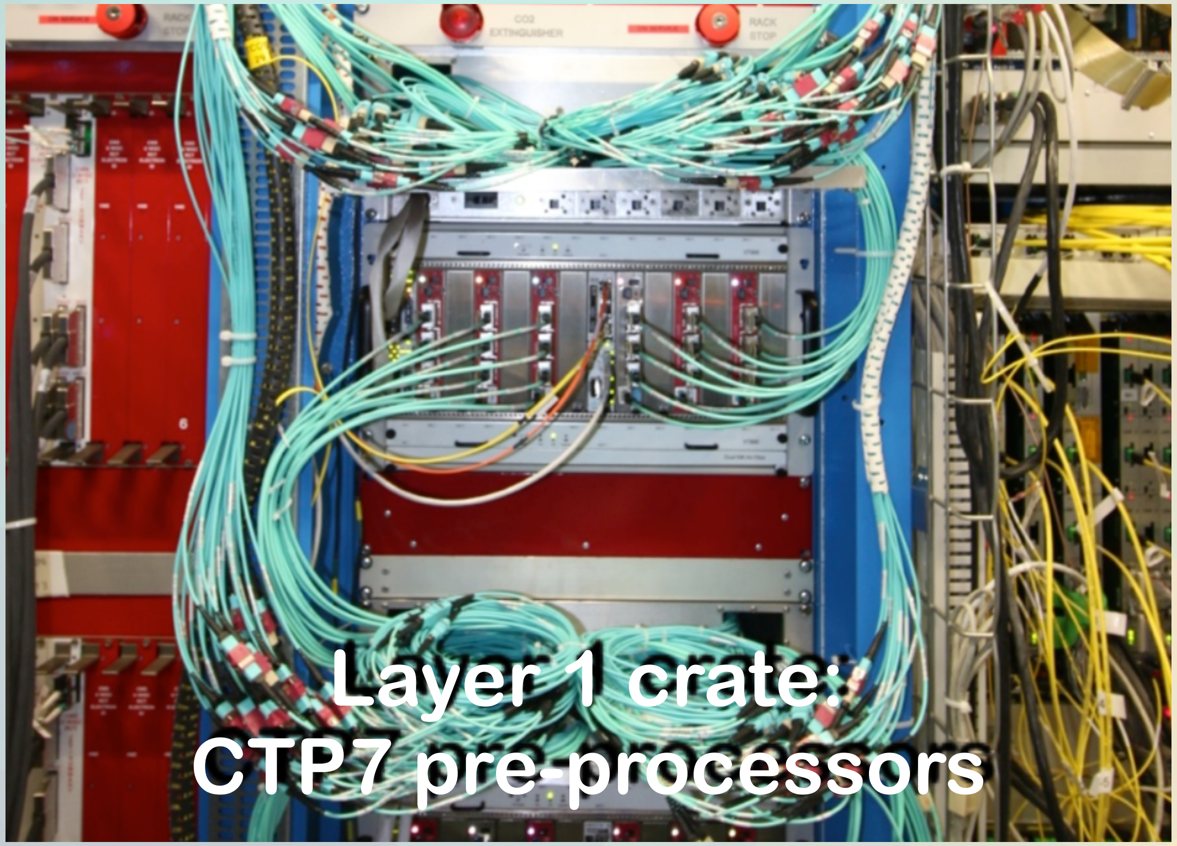
MP7

- Main workhorse for L1 calo trigger upgrade
- Also used in BMTF, uGMT, uGT

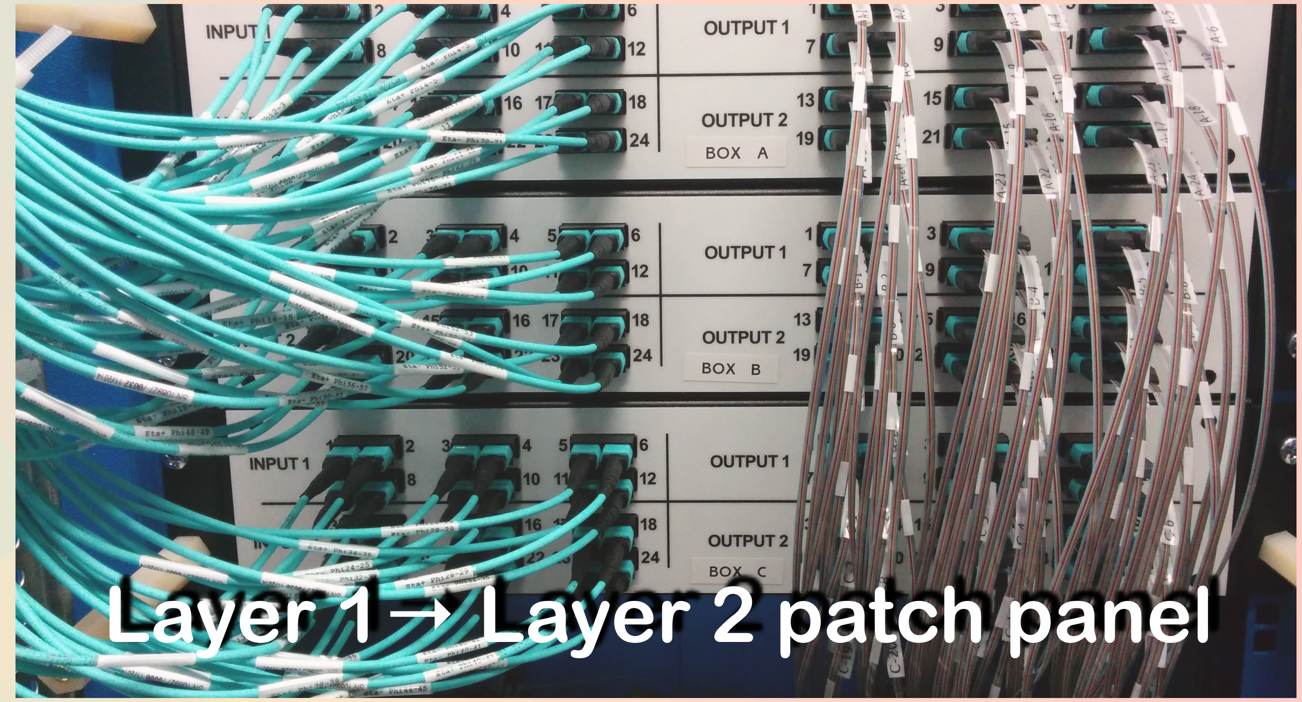
- 1.5 Tb/s signal processor board
- Xilinx XC7VX690T FPGA
- 72 Tx + 72 Rx links @ 10 Gb/s
- Avago MiniPOD embedded optics
- uTCA form factor
- GbE, AMC13/TTC/TTS, PCIe, SAS, SATA, SRIO backplane links
- AVR UC3A3256 microcontroller
- MicroSD for FPGA booting
  - Used as firmware repository



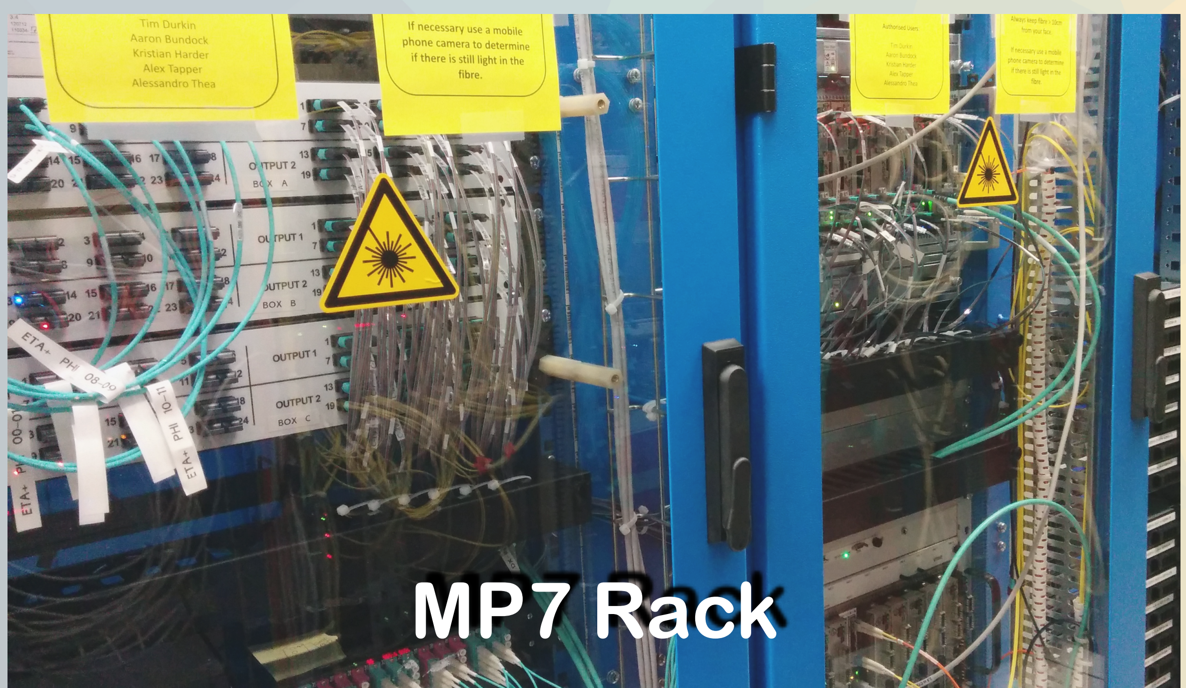
L1 Calorimeter Trigger: Layer 1 & Layer 2



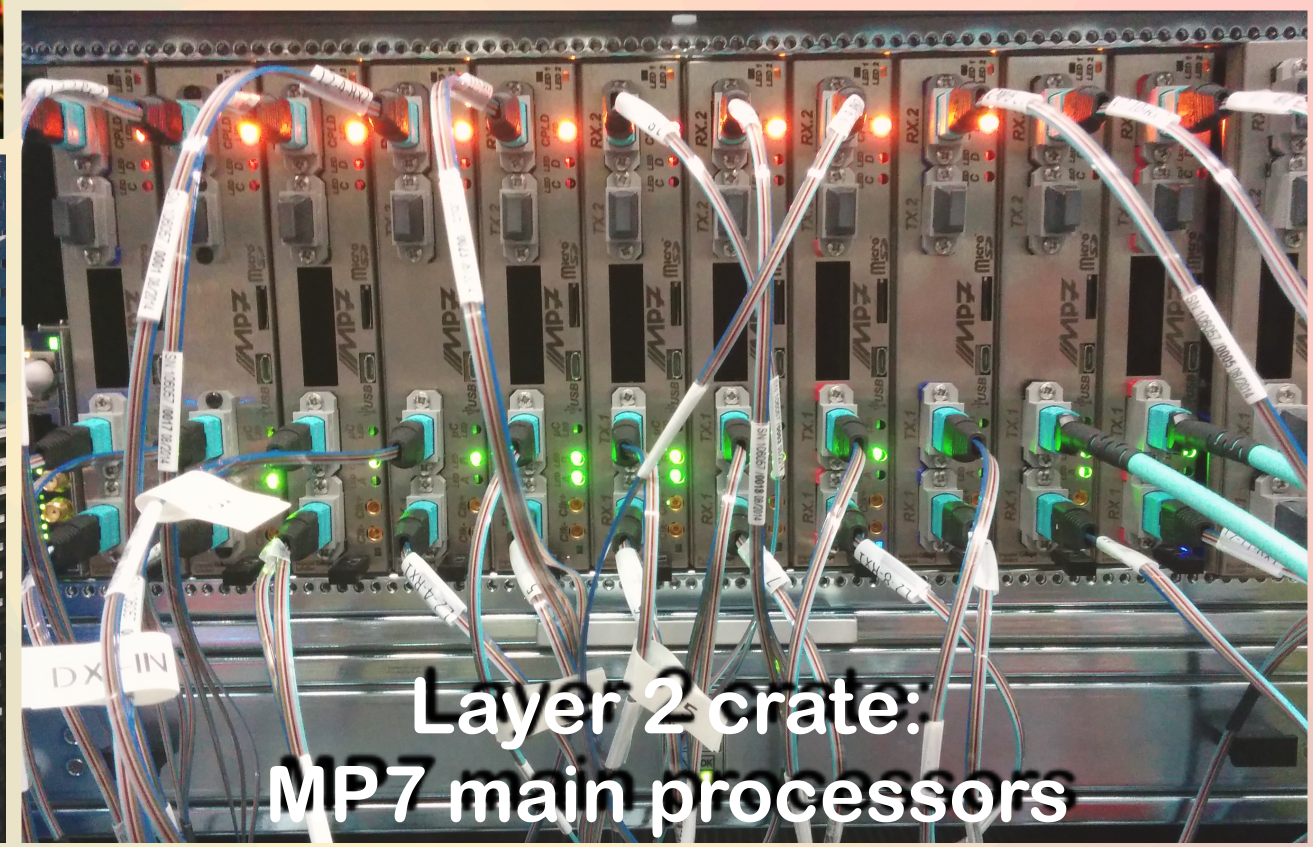
Layer 1 crate:
CTP7 pre-processors



Layer 1→ Layer 2 patch panel



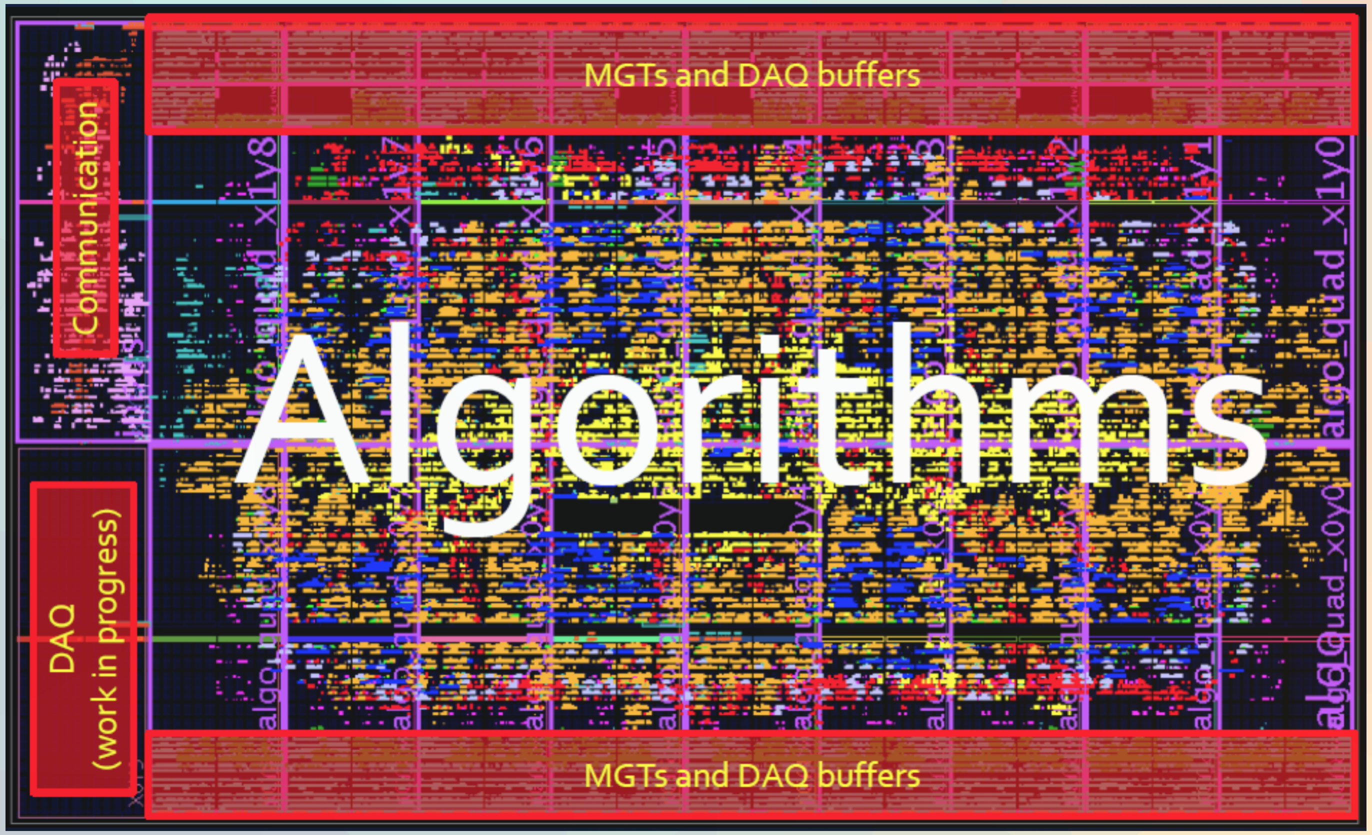
MP7 Rack



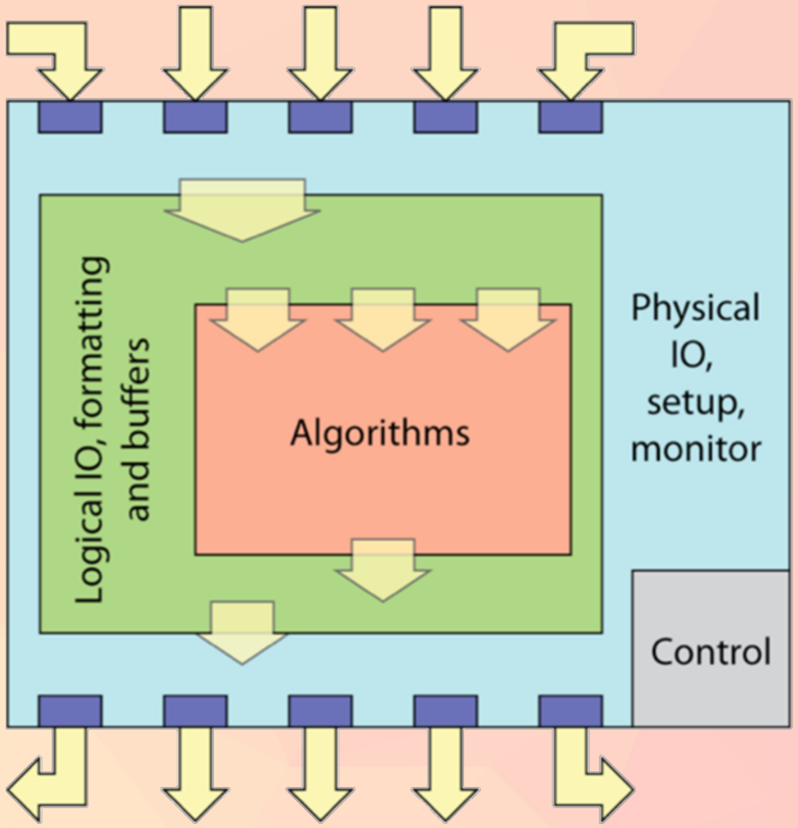
Layer 2 crate:
MP7 main processors

- Large Hadron Collider and the CMS Detector
- CMS Level 1 Calorimeter Trigger
- **Algorithms and Validation**
- Calorimeter Trigger Performance
- Summary

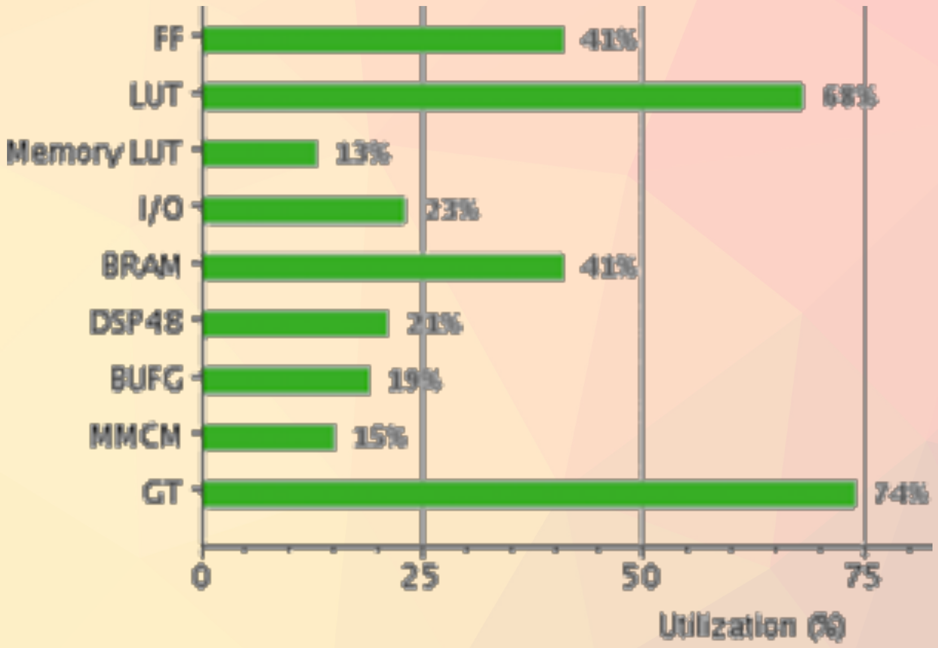
Firmware Architecture



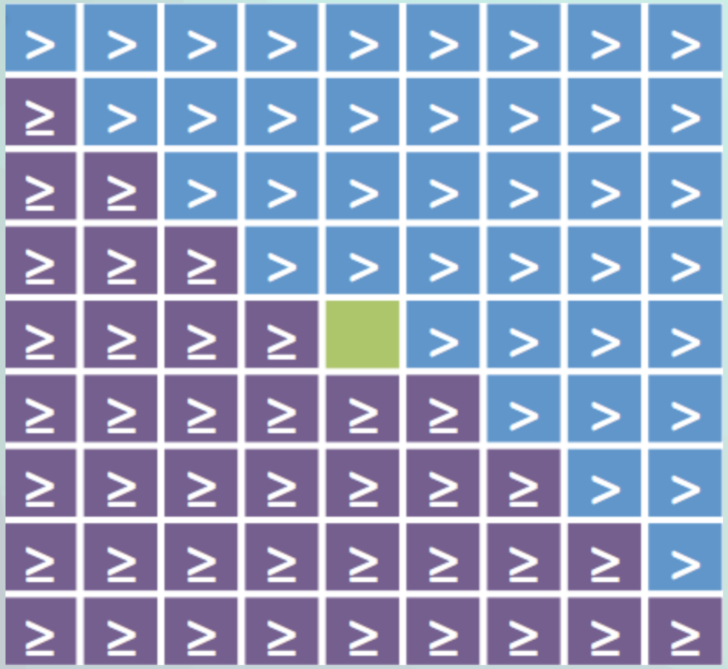
Clusters Towers Jets Sorting



- Modular firmware design
  - ➡ split into algorithm and infrastructure
  - ➡ allows independent development
- High resource usage due to complex algorithms
- A lot of care has to be taken with timing constraints and clock distribution!
- Algorithms clocked at 240 MHz, pipelined in η slices

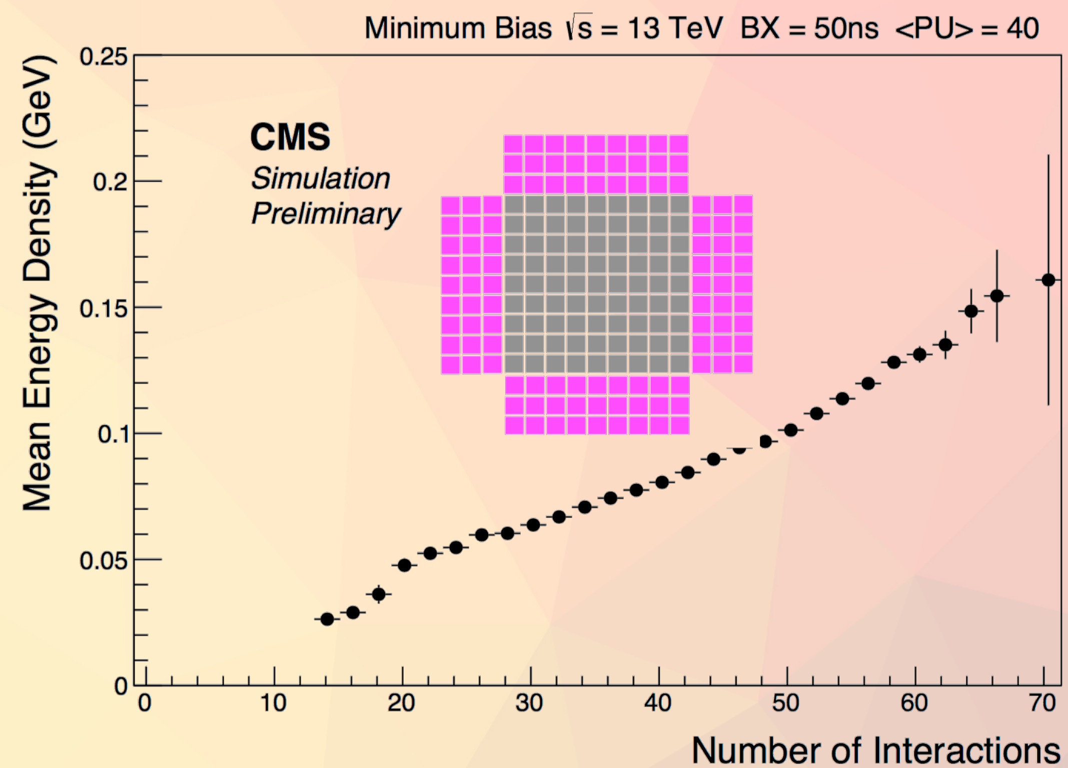


Jet Algorithm



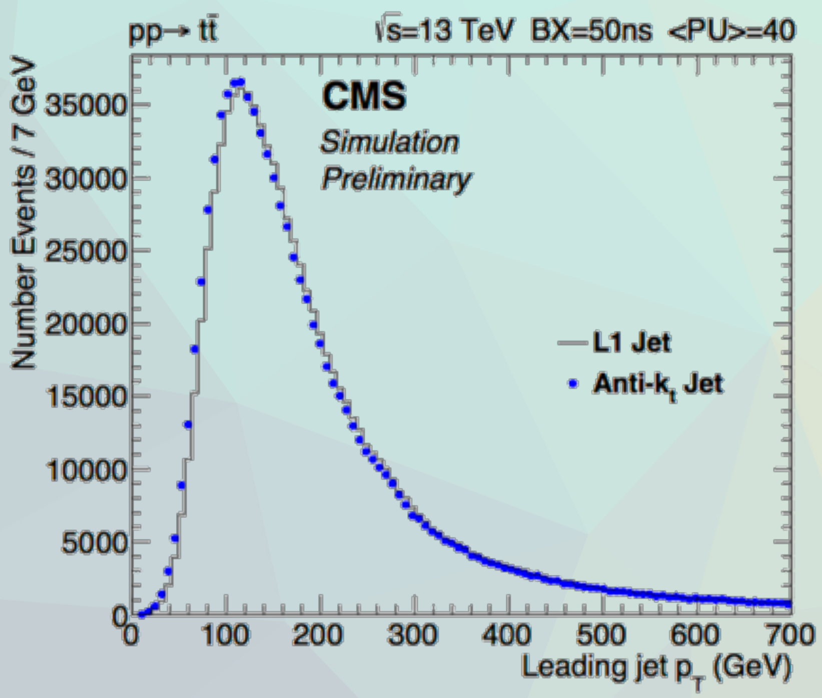
- New trigger architecture provides full trigger tower (TT) resolution
  - improved energy and position resolution
  - flexibility to define different jet sizes
  - multiple pile-up estimation algorithms uawd for pileup subtraction
- 9x9 sliding-window algorithm centred on TT with local max E_T (jet seed)
- Jet E_T = sum of TT E_T in the 9x9 sliding window
- Jet position defined by η,φ position of local maximum (jet seed)
- Inequality mask: avoid self veto & double counting of energy deposits

- ‘Chunky donut’ pileup subtraction applied to jets
  - Total E_T in 3x9 TT rectangle on each side of the jet is determined
  - 3 lowest energy sides used to determine pile-up energy density
  - this value is then scaled to the area of the jet and subtracted from the individual jet E_T
- Testing with minimum-bias MC shows this energy density is a good estimate of pile-up



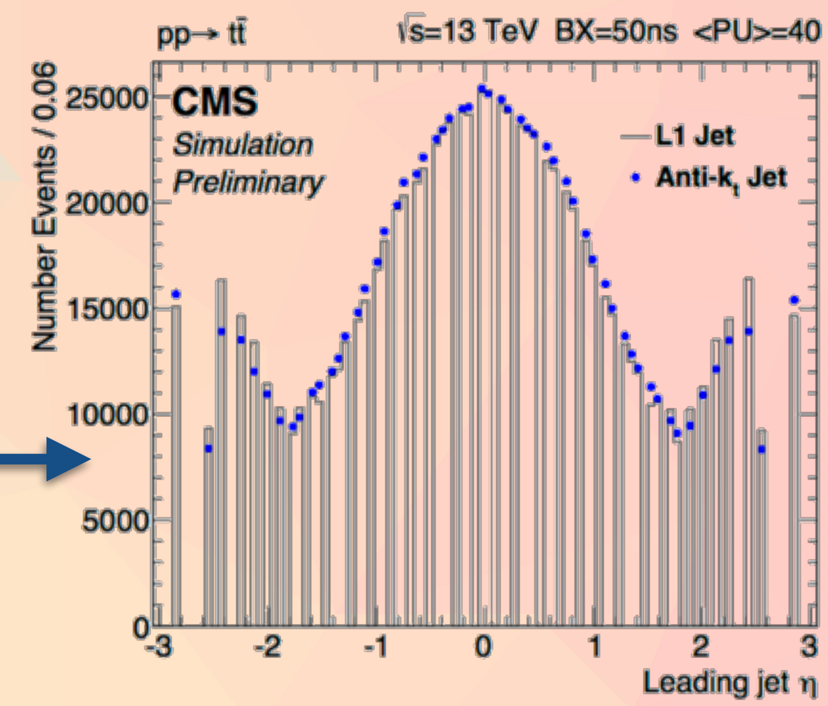
Jet Algorithm Validation

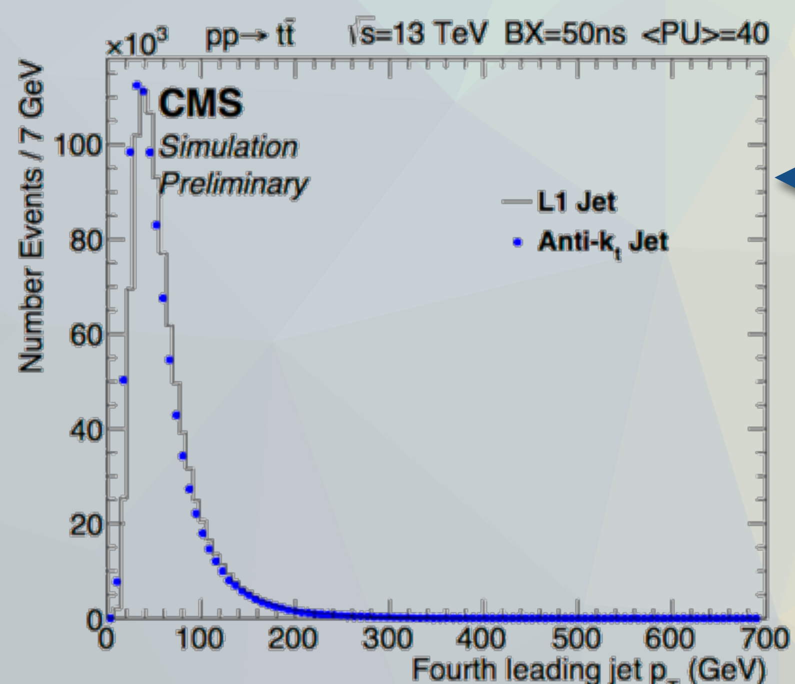
Comparison between jets found by L1 trigger algorithm and jets found by offline Anti-Kt jet finding algorithm in software (with R=0.4) in ttbar MC events



Leading jet E_T

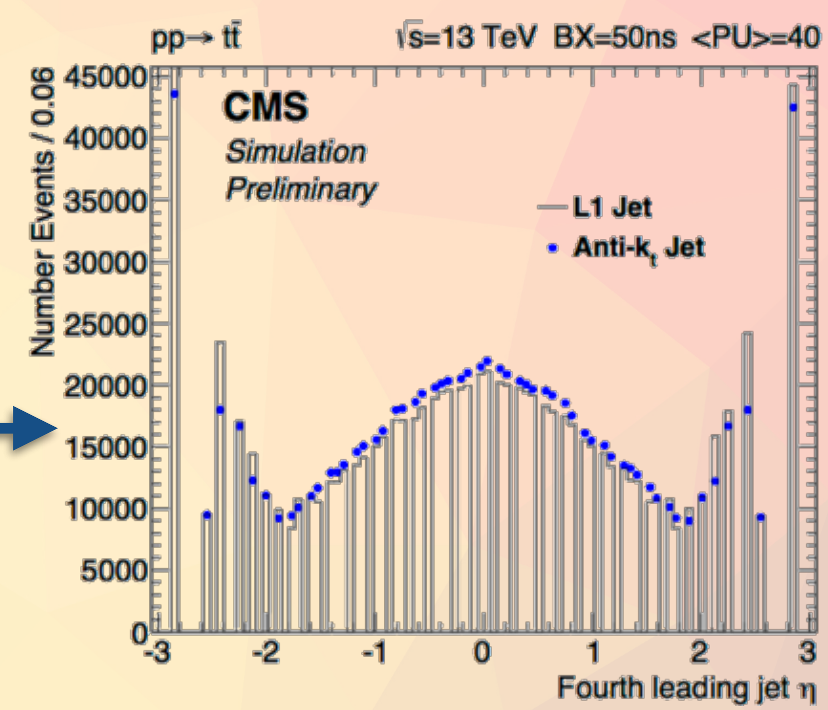
Leading jet η





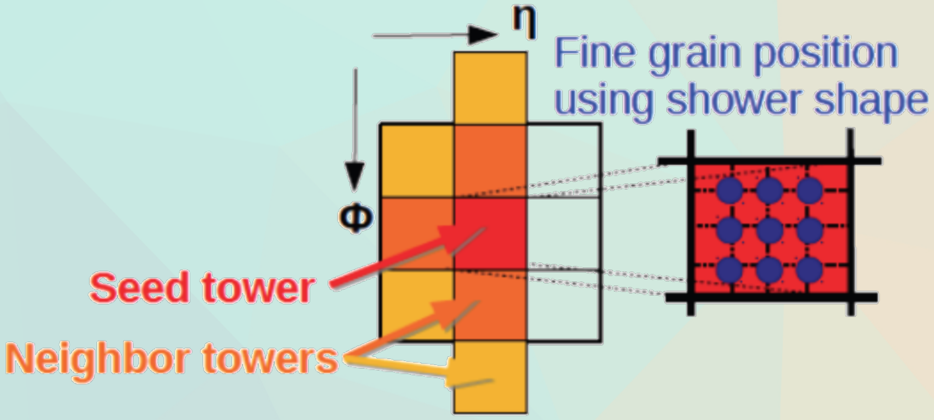
4th leading jet E_T

4th leading jet η



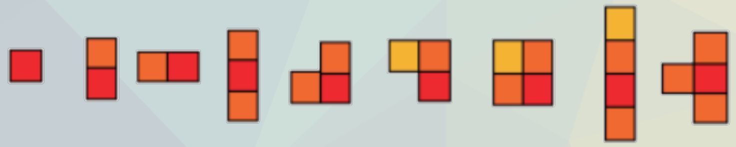
EGamma Algorithm

Dynamic clustering with shape constraints

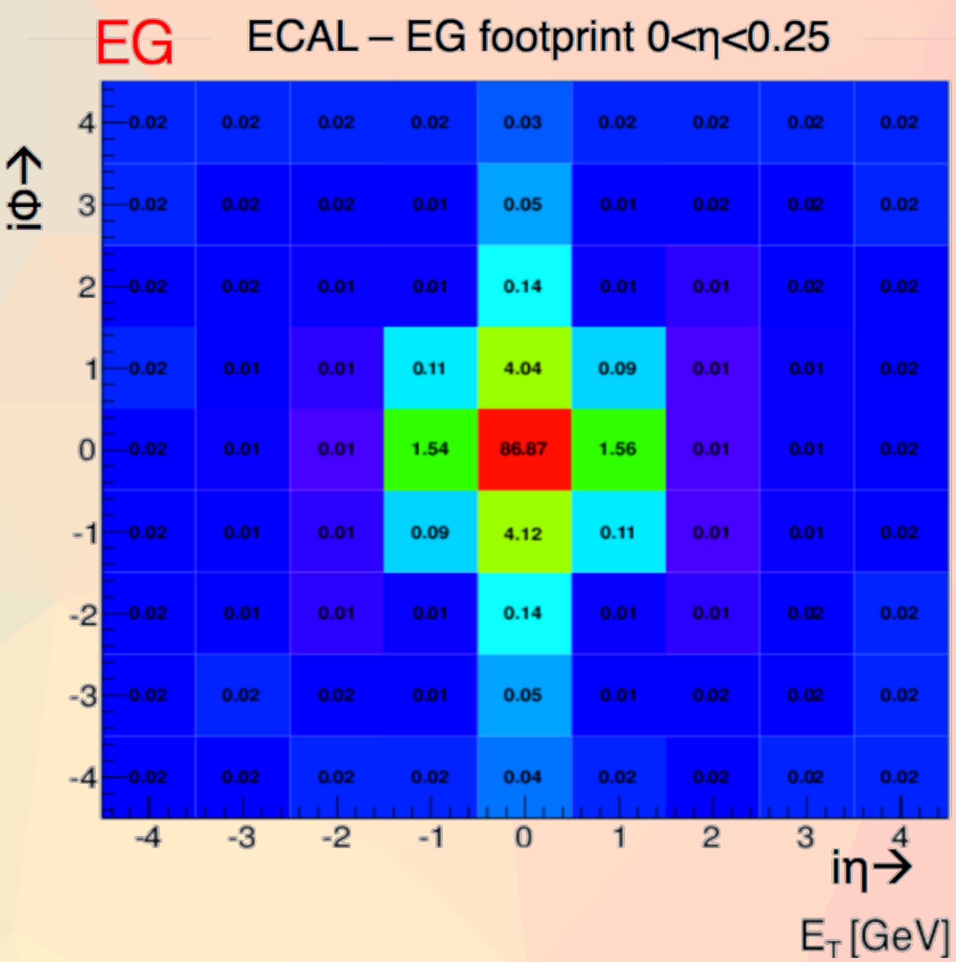


- Better energy containment
  - ↳ Showering electrons, converted photons
- Small impact of pile-up

Examples of cluster shapes

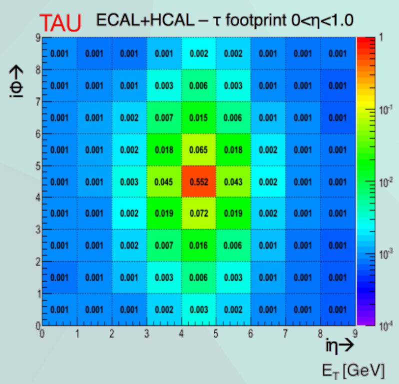


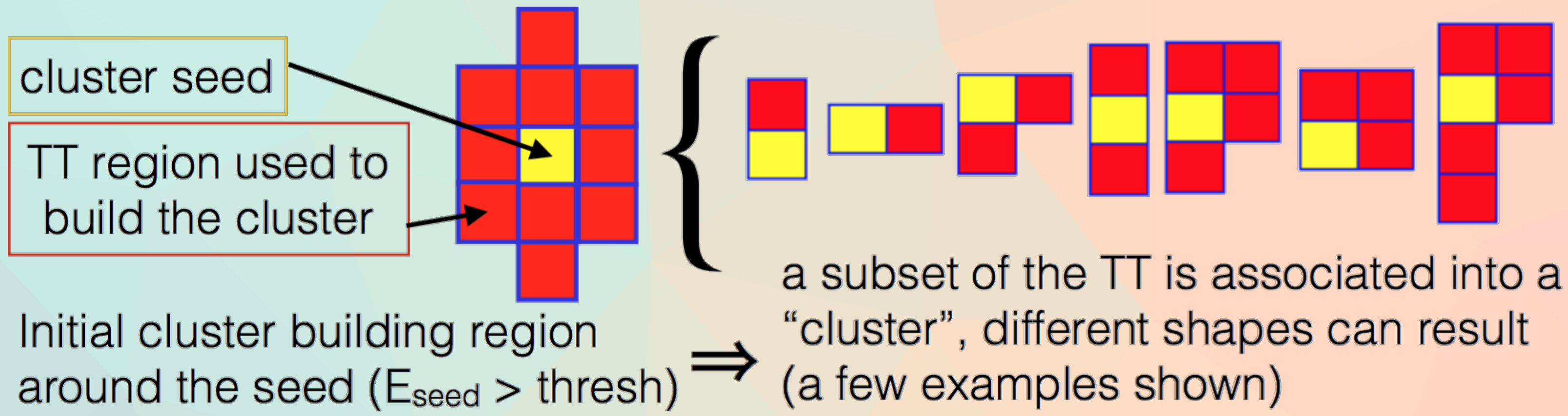
Discriminate e/γ against jets
Veto clusters with specific (jet-like) patterns



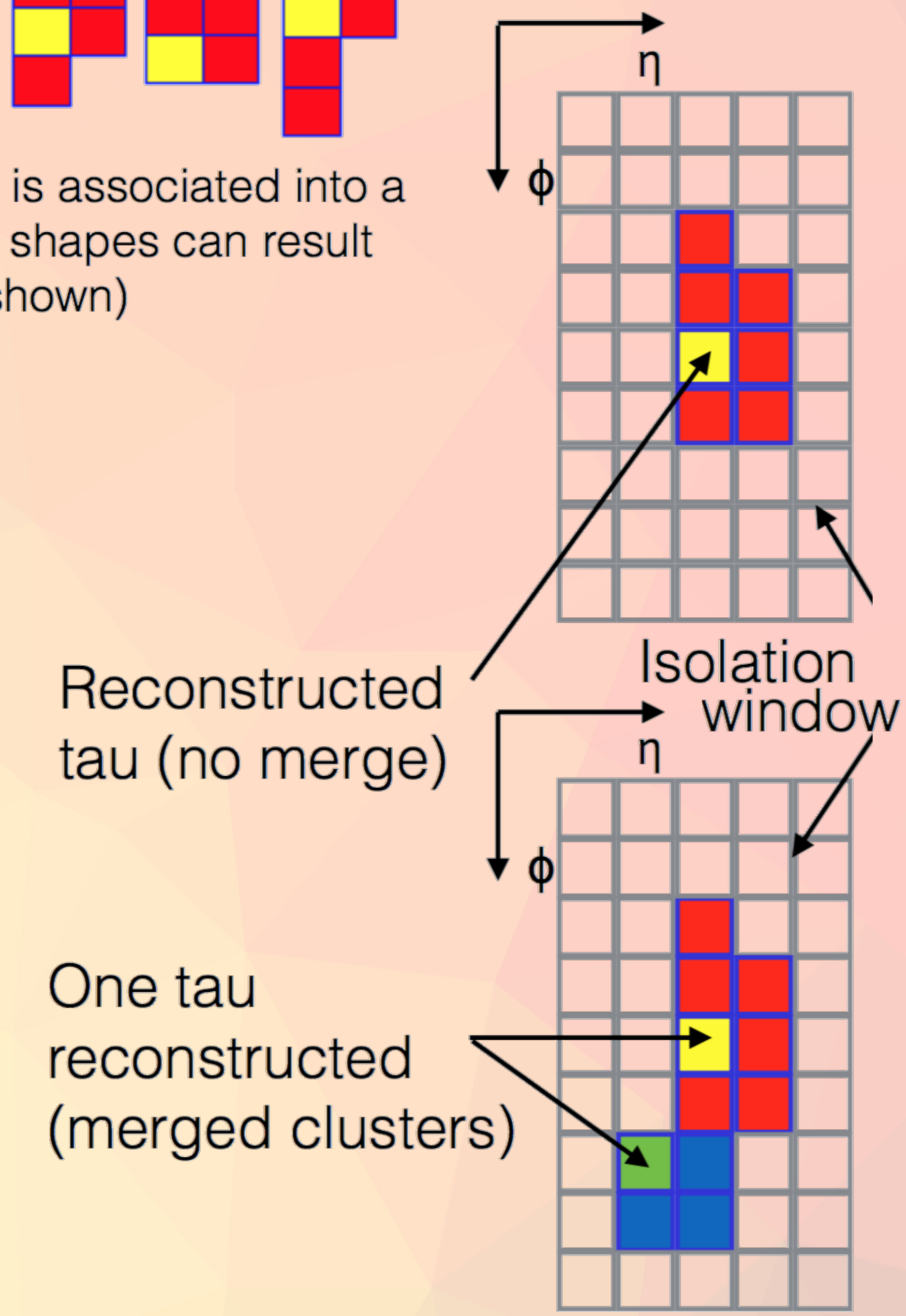
- **Electrons and photons reconstructed in FPGA from clusters of calorimeter towers**
- **Cutting edge FPGA resources allow for advanced clustering techniques with variety of shapes**
- **Electrons and photons also have pileup subtraction for better energy measurements at Level 1**
- **More info on electrons and photons in the CMS Level 1 trigger in talk from T. Strebler later today**

Tau Algorithm

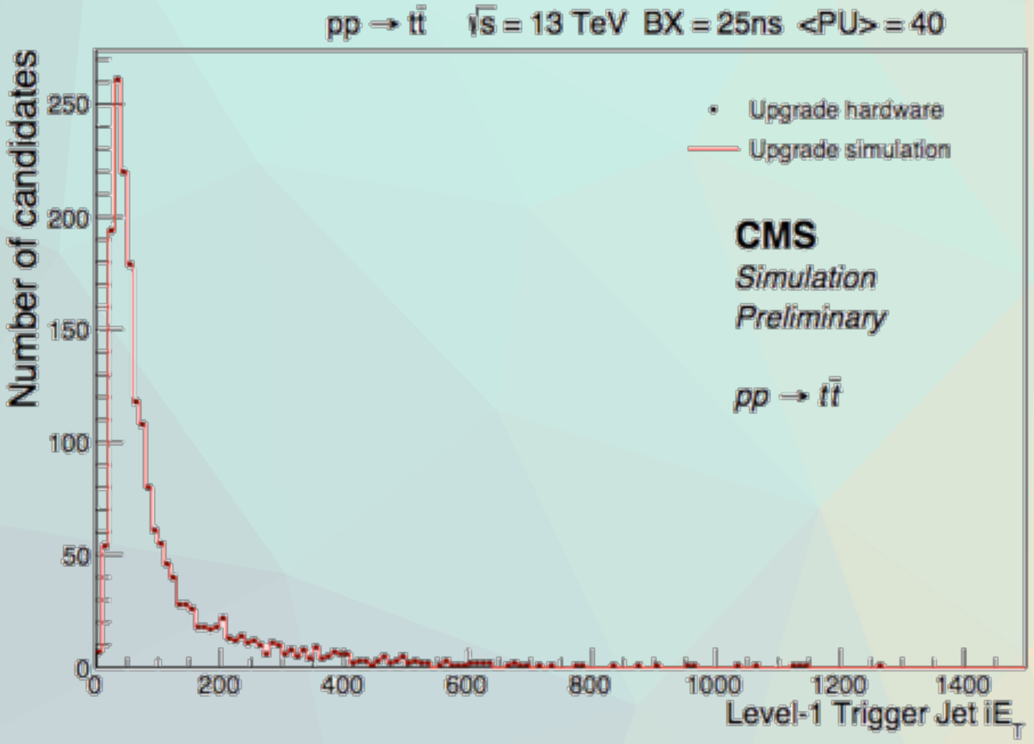


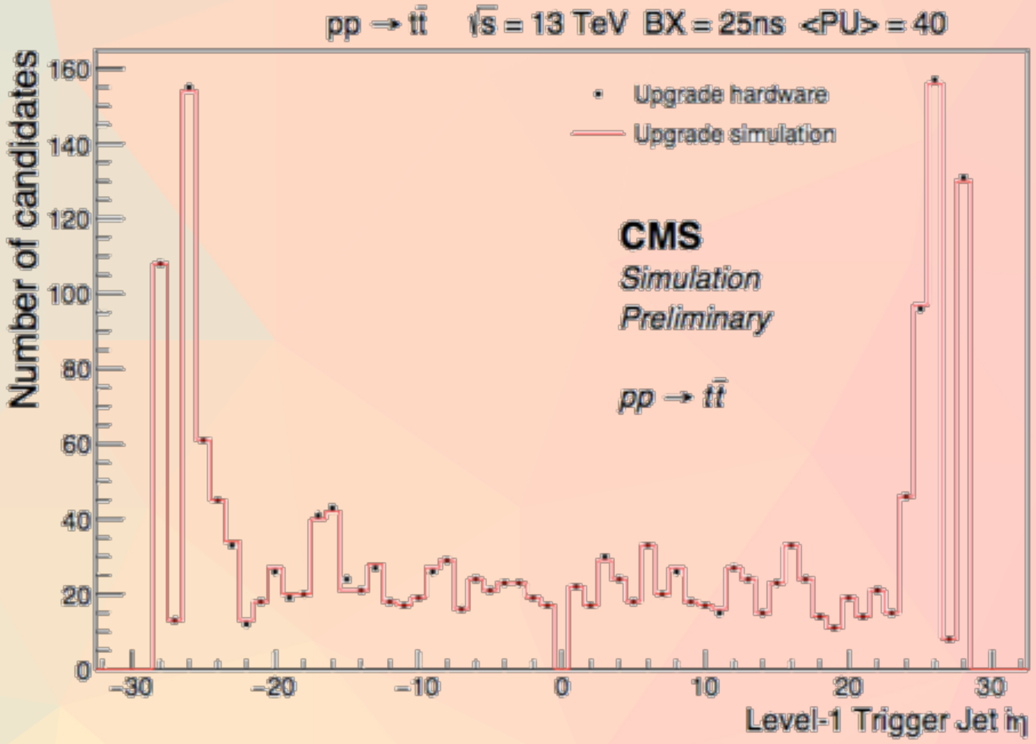


- **Full trigger tower (TT) granularity exploited using dynamic clustering technique**
- **ECAL + HCAL energy used**
- **Two clusters can be merged**
  - **Criteria based on relative neighbour position to better reconstruct multi particles hadronic tau decays**
  - **~85% isolated clusters, ~15% merged clusters**
- **Isolation energy is computed as energy in a 5x9 window around cluster seed, minus L1 τ candidate energy and compared to a threshold**
  - **Threshold depends on PU, η(τ), E_t(τ)**

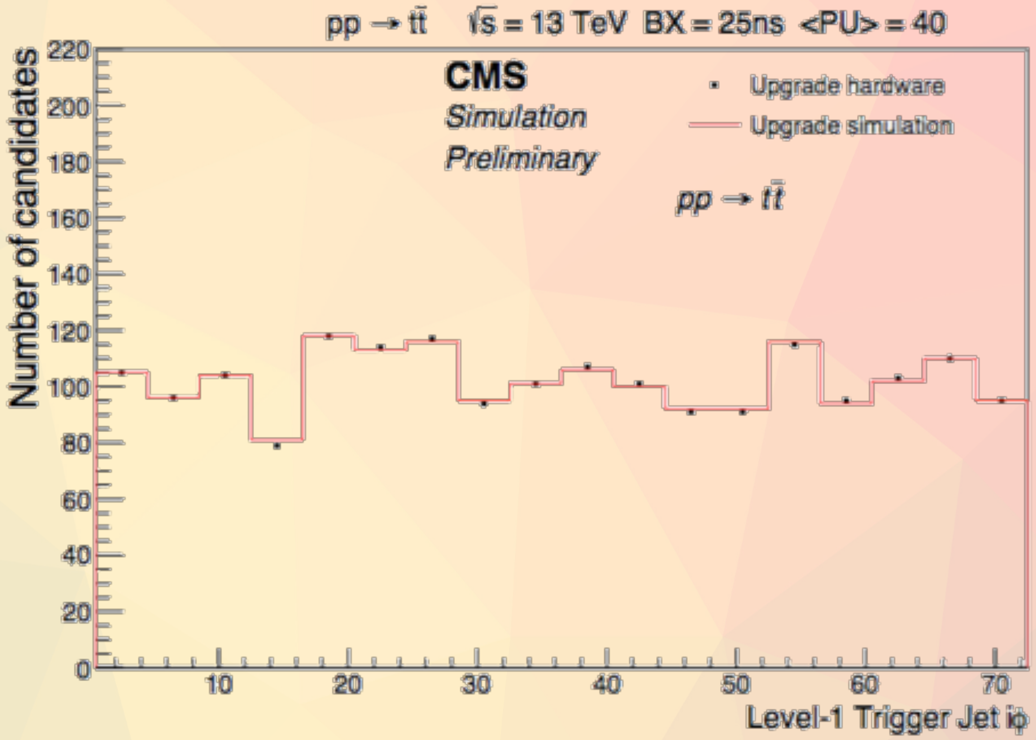


Firmware vs. Emulation: Jets

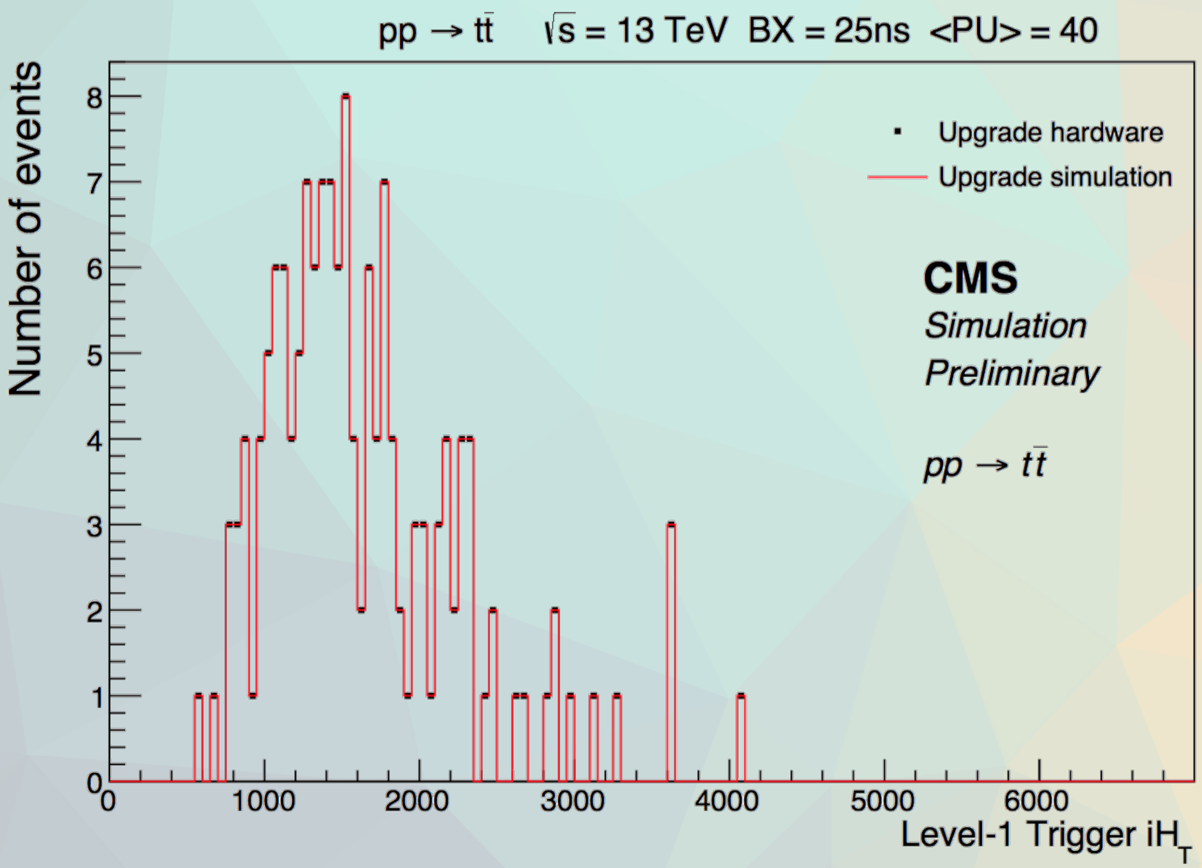


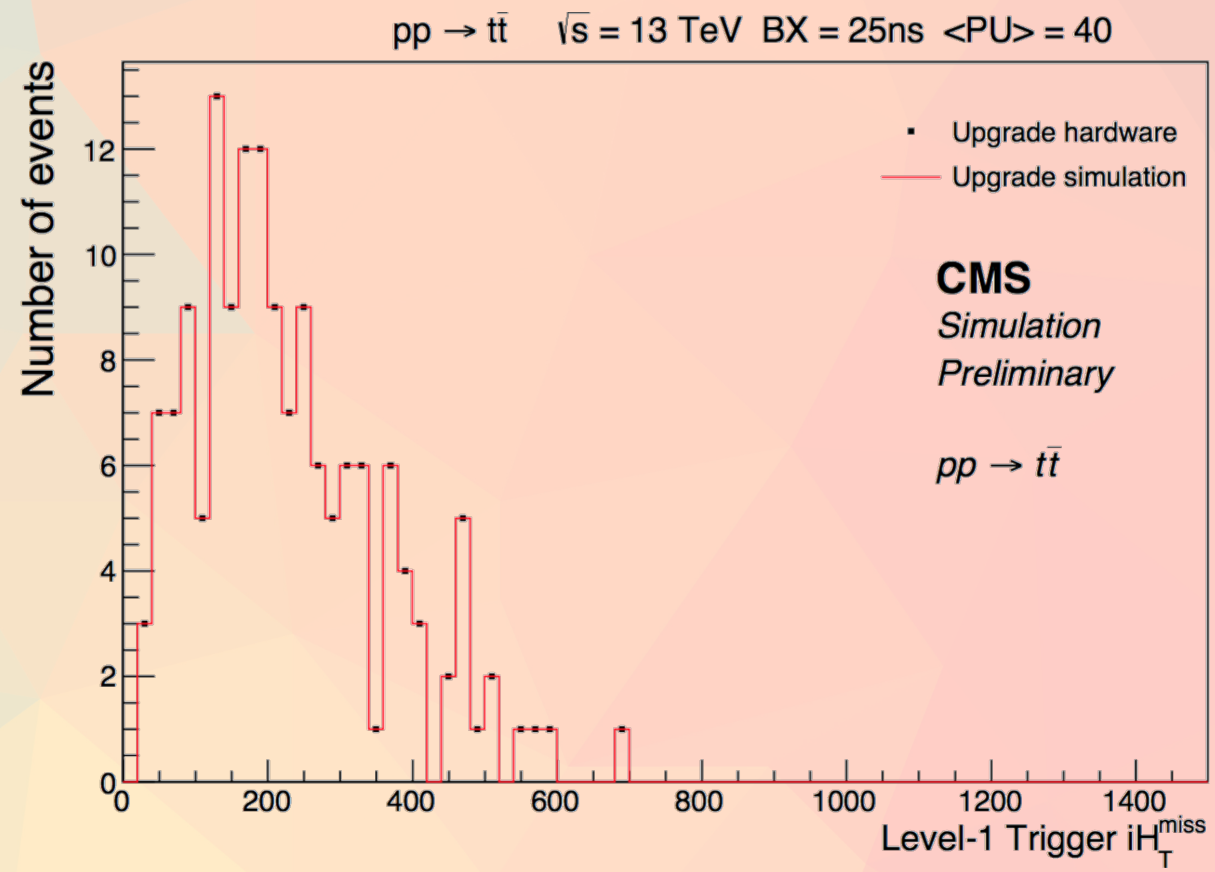


- **Level 1 jet upgraded algorithm firmware output distributions for p_T , η, and φ**
- **Produced by running ttbar MC events through firmware algorithms on MP7**
- **Results are compared to the expected outputs from the simulation**
- **Excellent agreement shows that the algorithms are very well understood**



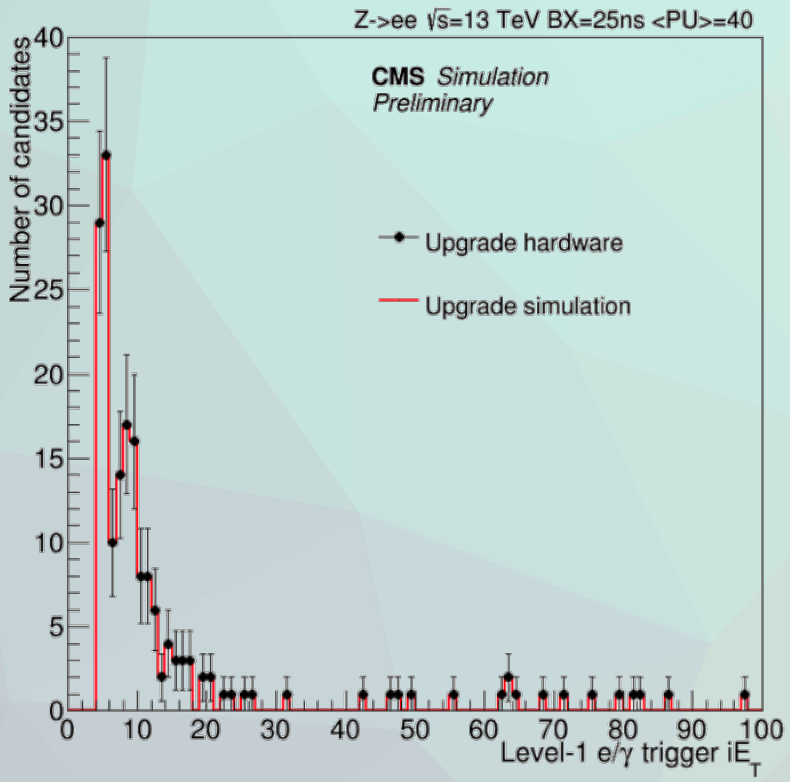
Firmware vs. Emulation: Jet sums

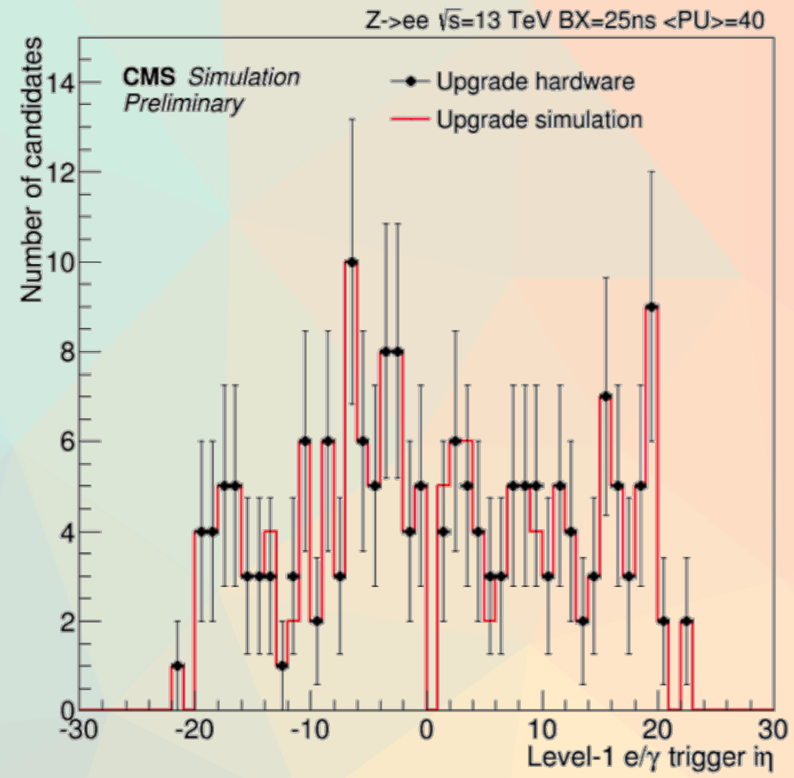


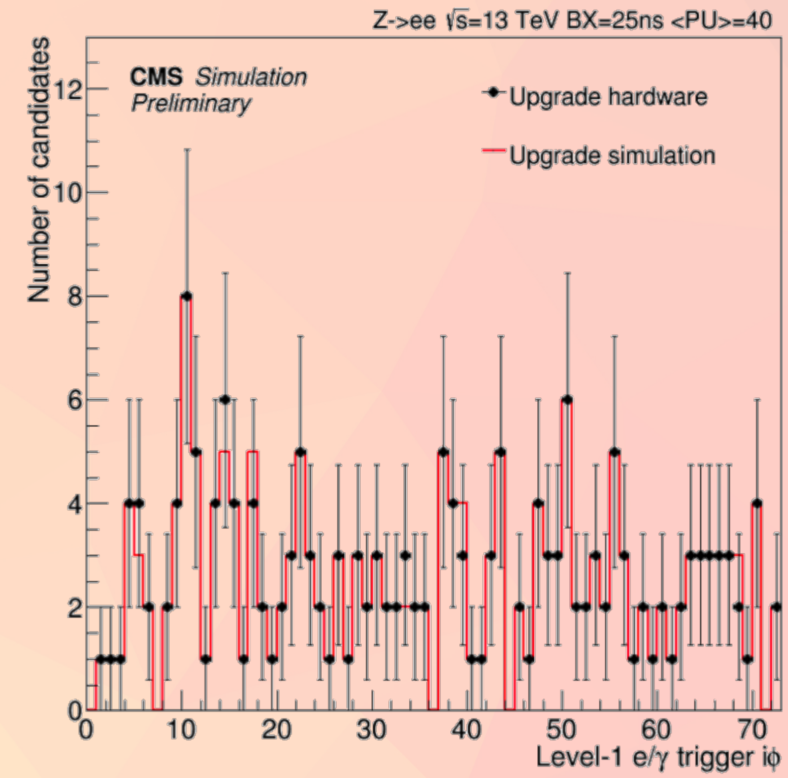


- **Comparison of simulation and hardware results for Level-1 Trigger jet energy sums**
- **Produced by running ttbar MC sample through firmware algorithms on MP7**
- **Distributions show scalar (H_T) and vector (H_T^{miss}) sums of all jets found in hardware units**
- **Excellent agreement observed between hardware and simulation**

Firmware vs. Emulation: EGamma



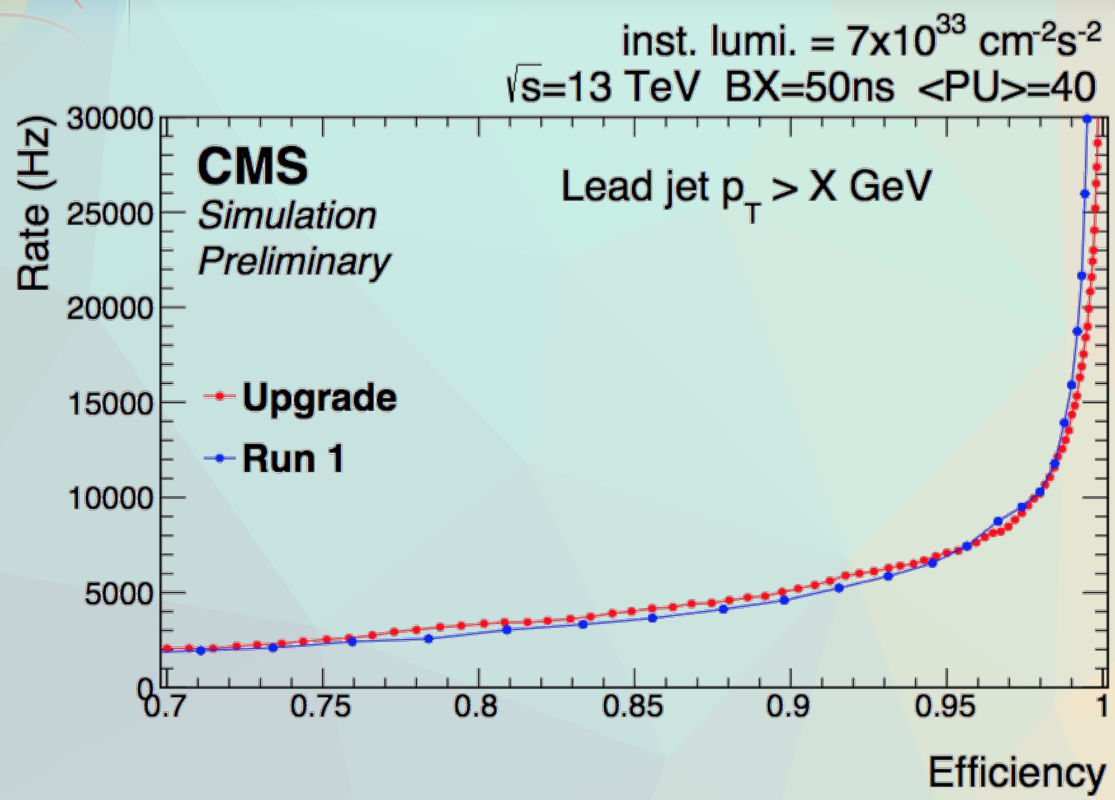


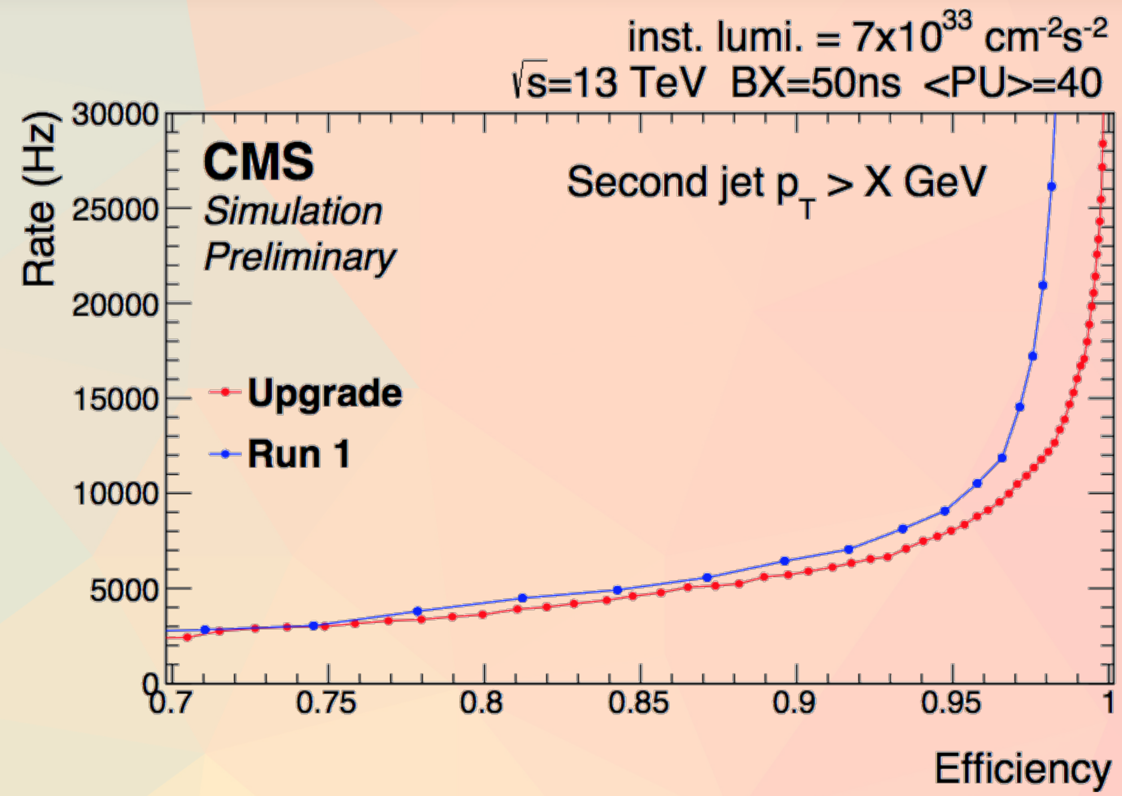


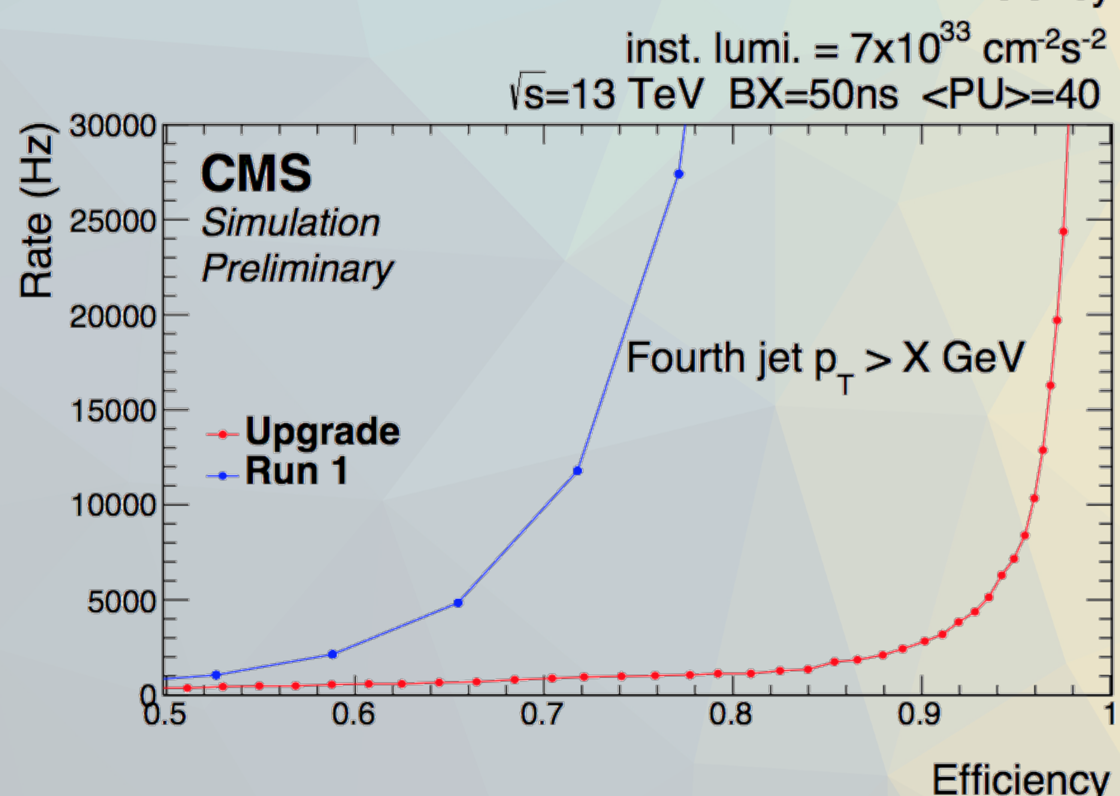
- **Level 1 e/γ upgraded algorithm firmware output distributions for p_T , η, and φ**
- **Produced by running Z→ee MC events through firmware algorithms**
- **Results are compared to the expected outputs from the simulation**
- **Excellent agreement shows that the algorithms are very well understood**

- Large Hadron Collider and the CMS Detector
- CMS Level 1 Calorimeter Trigger
- Algorithms and Validation
- **Calorimeter Trigger Performance**
- Summary

Jet Performance

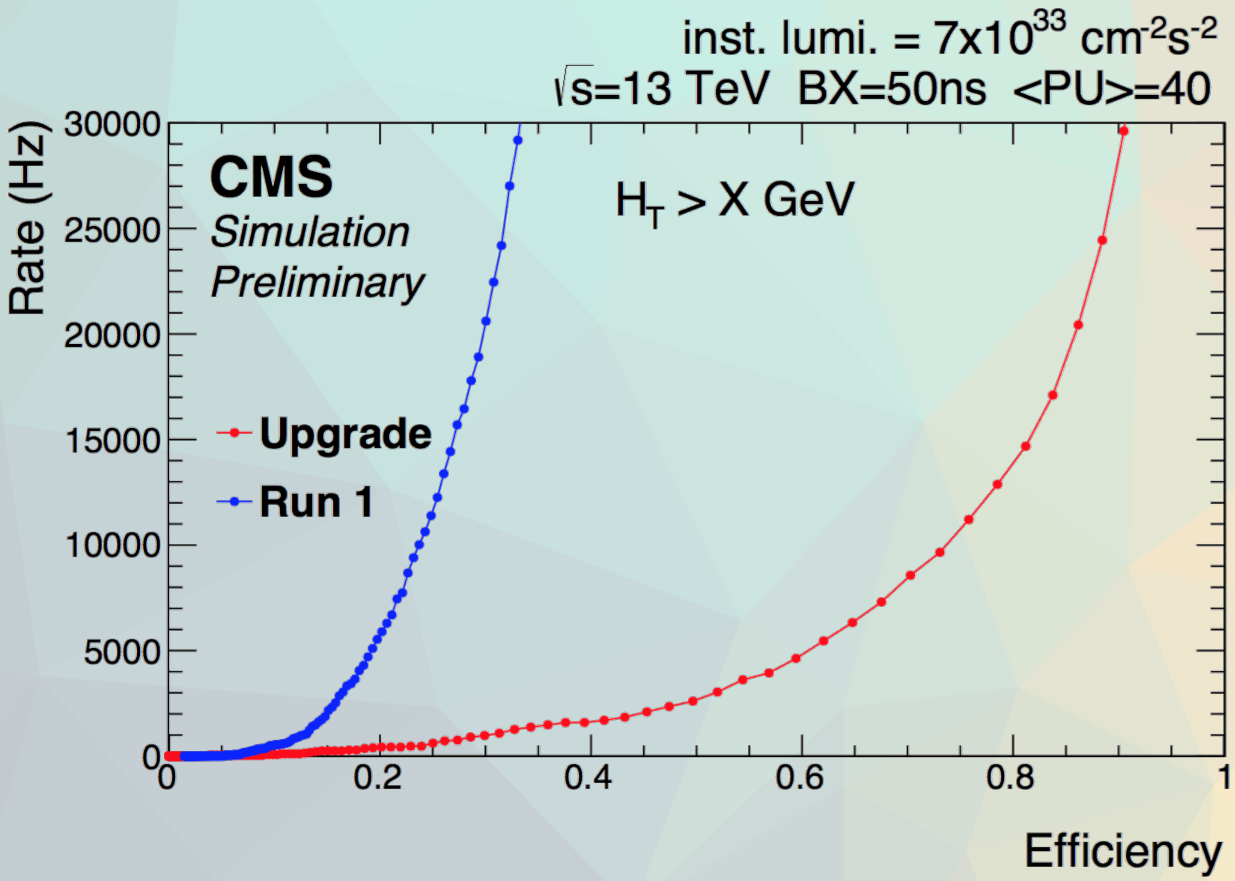


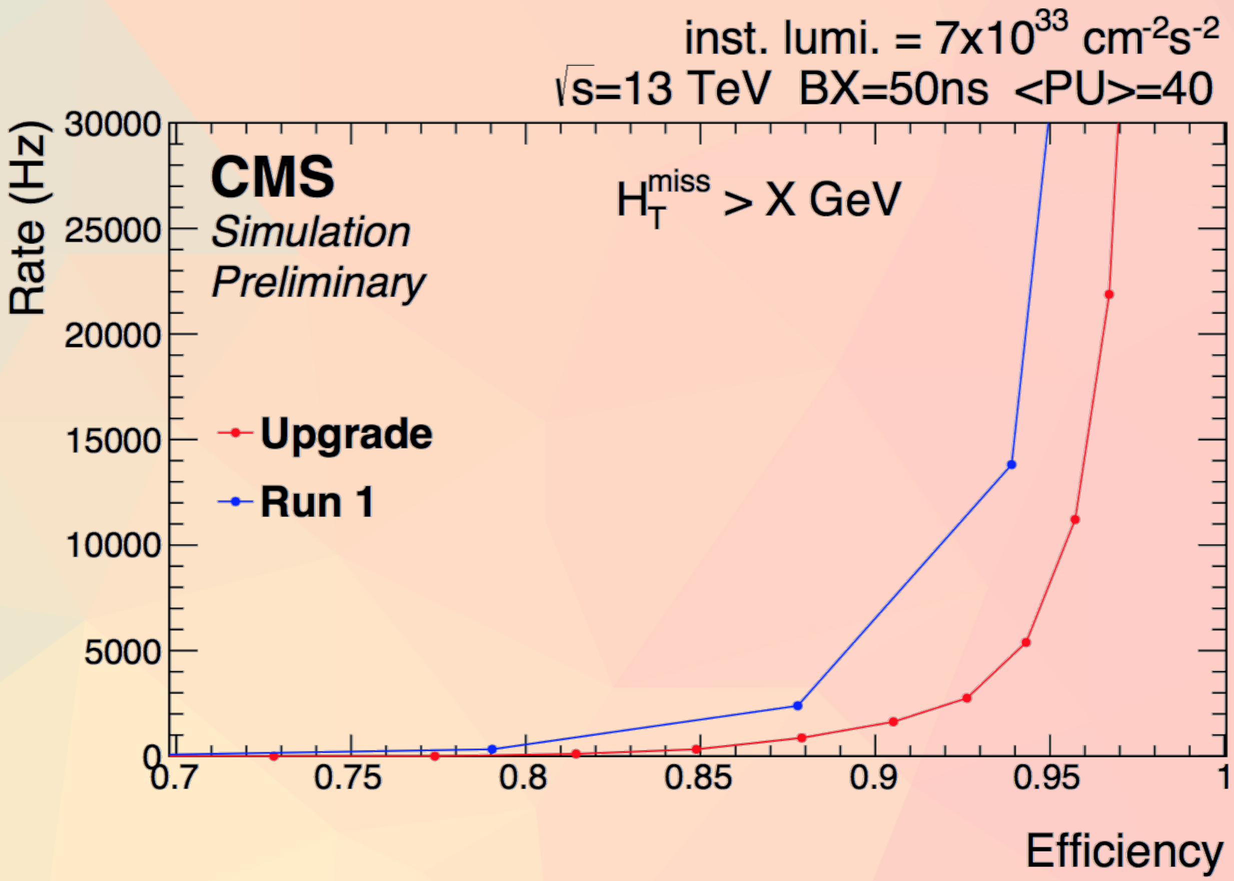




- **Expected performance of Level-1 trigger jet finding benchmarked against legacy trigger performance**
- **Simulated ttbar events used to estimate efficiency**
- **Minimum bias MC was used to estimate rate**
- **Efficiency is computed with respect to events fulfilling corresponding generator-level requirement**
- **Curves made by varying the Level-1 p_T threshold.**
- **Example working points give following rates:**
  - **5kHz Single Jet, p_T > 150 GeV**
  - **5kHz Double Jet, p_T > 110 GeV**
  - **10 kHz quad jet, p_T > 50 GeV**

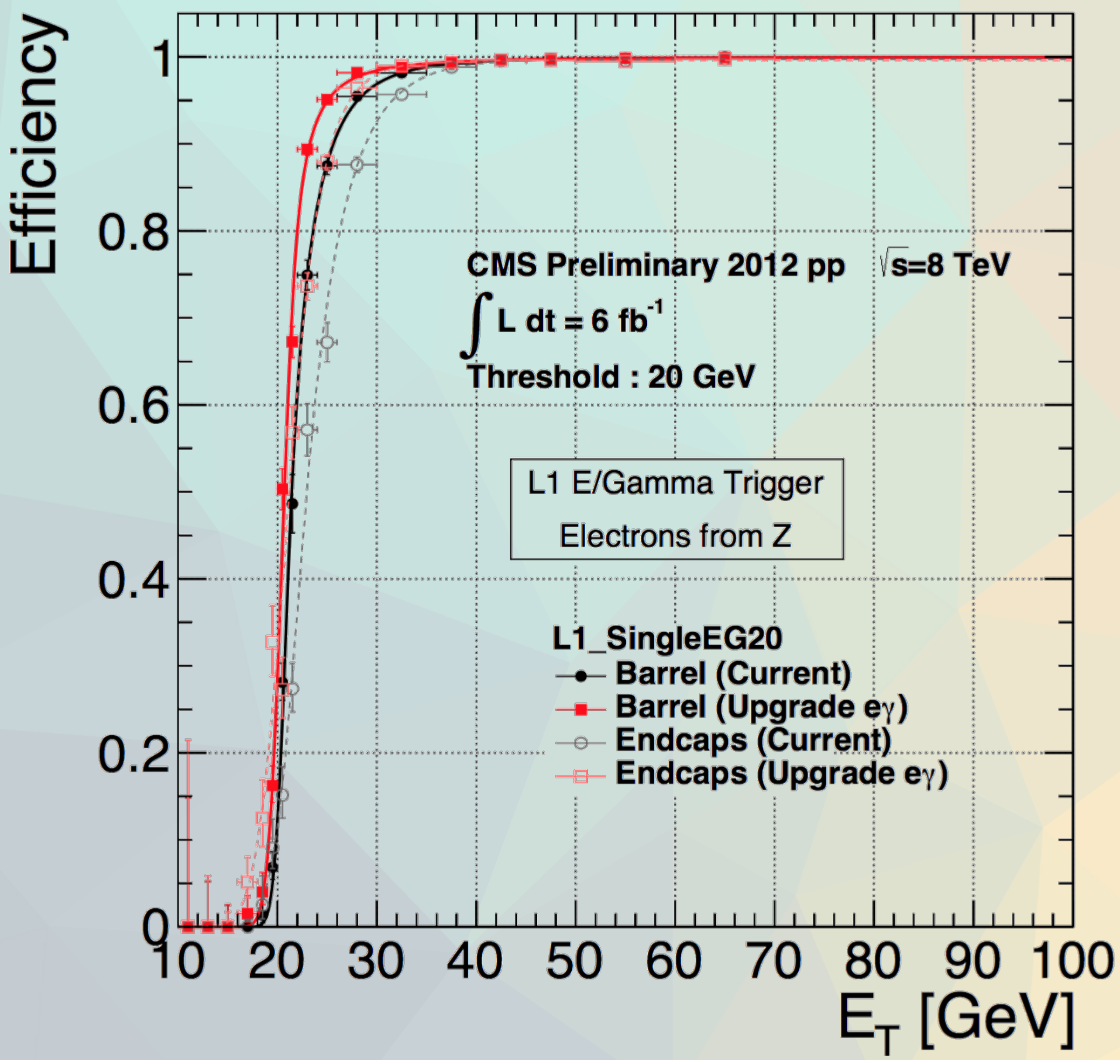
Energy Sums Performance

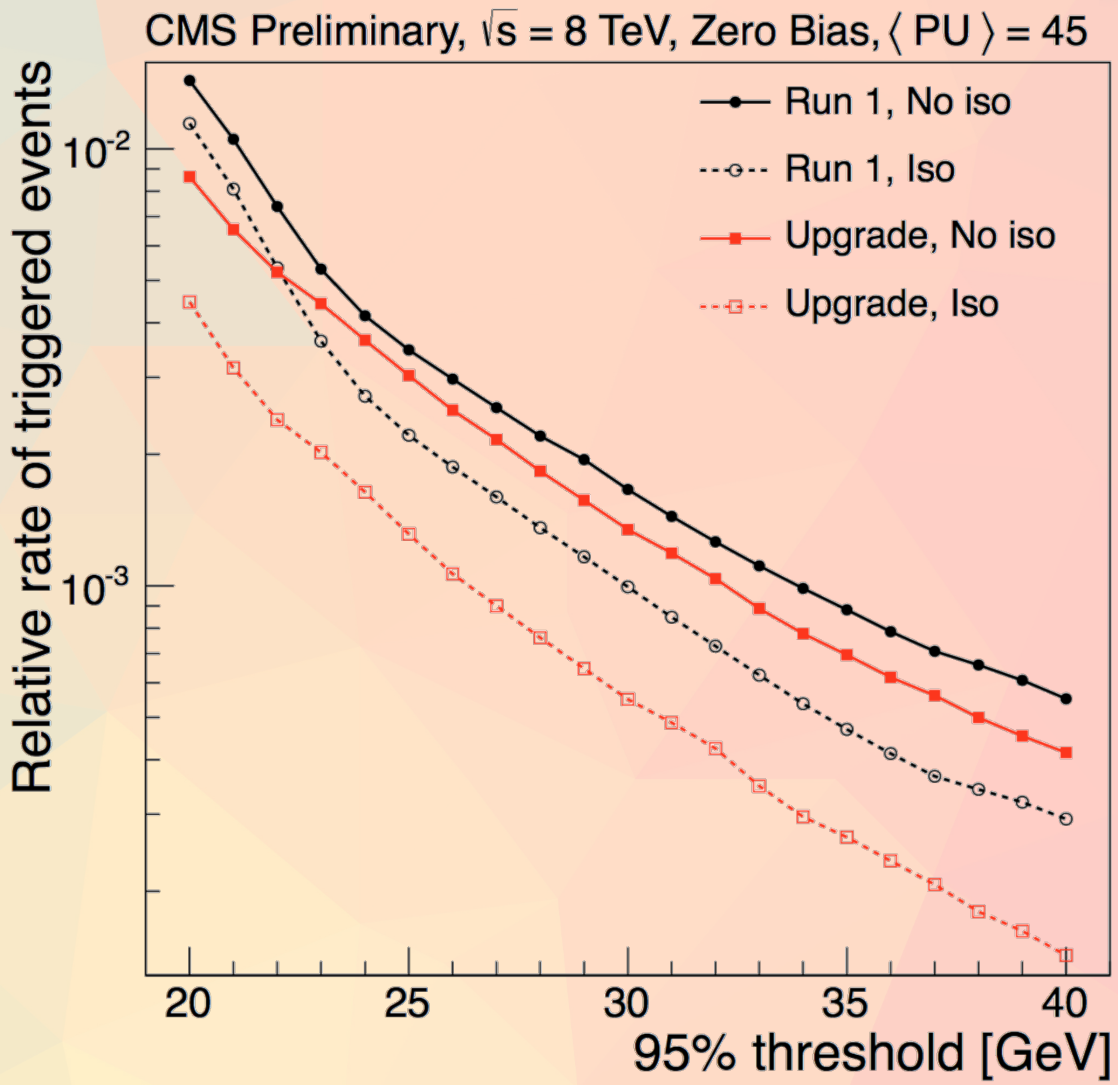




- Level-1 H_T (left) and H_T^{miss} (right) trigger rate vs. efficiency for instantaneous luminosity $7 \times 10^{33} cm^{-2} s^{-1}$
- Demonstrates reduction of H_T rate for large efficiencies with upgrade algorithms
- Provides increase in available trigger bandwidth
  - ➡ More complex algorithms, e.g. multiple object triggers
  - ➡ Crucial in searches for new physics!

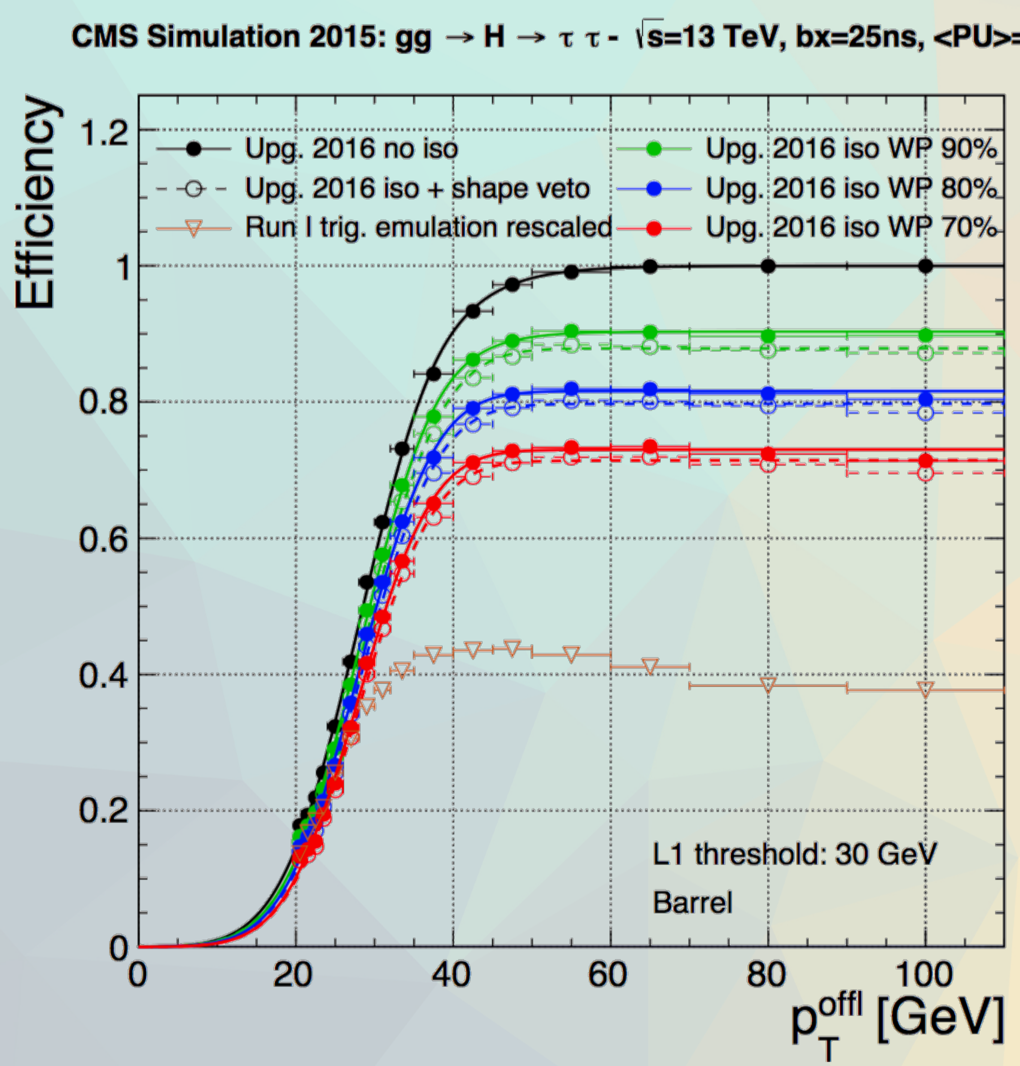
EGamma Performance

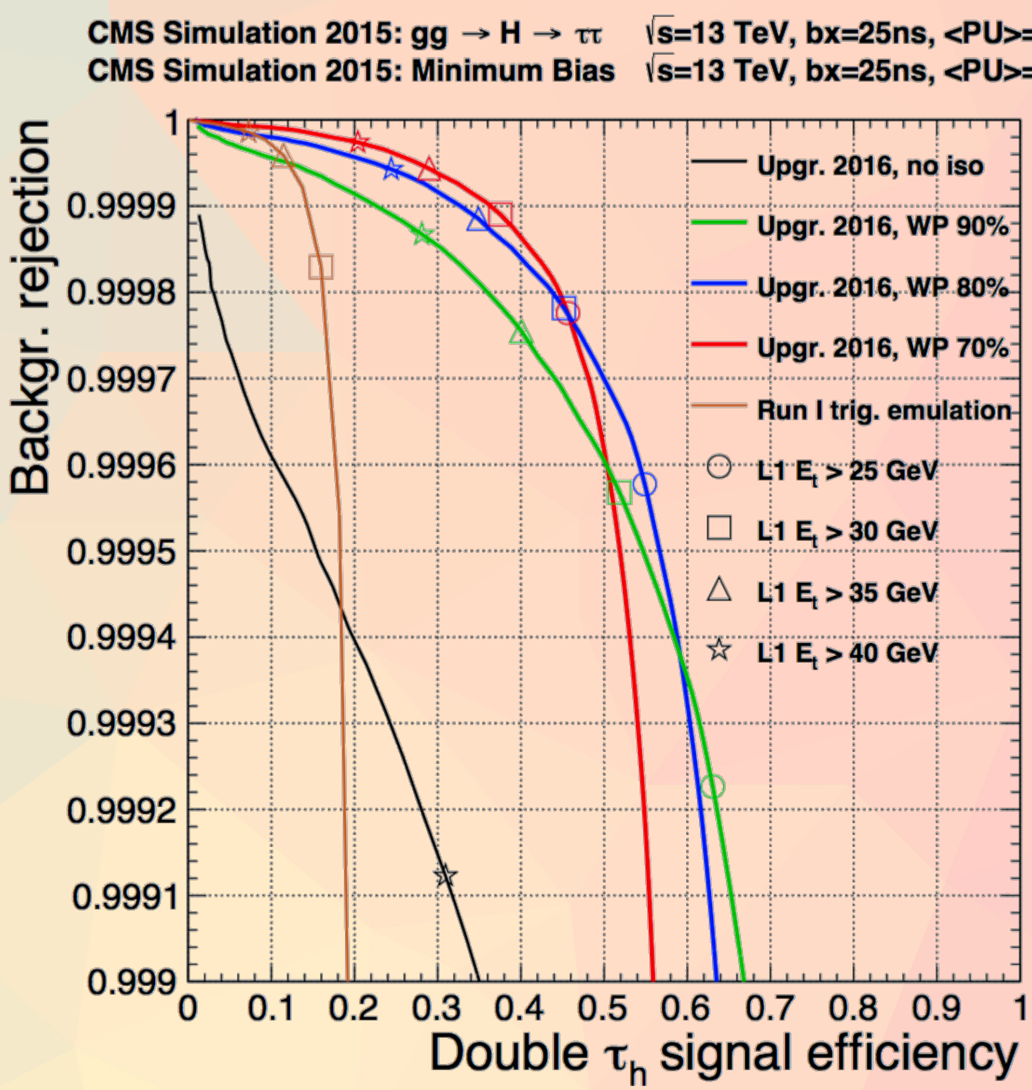




- Electron trigger efficiency for 20 GeV threshold at L1 as function of offline reco E_T in EB and EE (left)
- Relative rate of triggered events from 8 TeV zero bias data obtained from legacy and upgraded algorithms, both with and without isolation requirements
- Efficiencies obtained with current and upgraded algos shown with and without isolation criteria

Tau Performance





- **Level-1 2016 upgraded trigger efficiency (left)**
- **Black line is computed for the upgrade trigger in absence of isolation**
- **Green, blue, red correspond to 90%, 80%, 70% isolation efficiency working points (WP)**
- **Dashed lines correspond to additional requirements on shape veto, orange denotes legacy algorithm**
- **Background rejection for double τ hadronic trigger at Level-1 (right) for various WP and legacy**

- Large Hadron Collider and the CMS Detector
- CMS Level 1 Calorimeter Trigger
- Algorithms and Validation
- Calorimeter Trigger Performance
- **Summary**

Summary and Outlook

- Run II at LHC provides a very challenging environment to search for new physics and measure properties of Higgs Boson
- Increase in instantaneous luminosity (13 TeV collisions, 25 ns bunch spacing, increase in protons per bunch) leads to large increase in pileup
- Requires improved performance online and offline
- Newly installed Level-1 trigger at CMS tackles these challenges head-on
  - State-of-the-art, FPGA based, very high bandwidth processors with complex, programmable algorithms increase efficiencies of identifying physics objects whilst reducing rates to make room for multi-object triggers
- Algorithms very well understood
  - Excellent agreement between firmware and C++ emulation
    - ➡ Will be used online to continuously monitor firmware performance during collision runs
- We shall study the performance of this newly installed trigger and learn from design and commissioning to begin designing Phase II trigger upgrade for High Luminosity LHC - a whole new challenge!