Trigger systems of the LHC experiments

Present systems and upgrade plans

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rates of processes at LHC

proton - (anti)proton cross sections

\[
\begin{align*}
\sigma_{\text{tot}} & \quad \text{Tevatron} \\
\sigma_{\text{bottom}} & \quad \text{LHC} \\
\sigma_{\text{jet}}(E_T^{\text{jet}} > E/20) & \\
\sigma_{\text{jet}}(E_T^{\text{jet}} > 100 \text{ GeV}) & \\
M_H = 125 \text{ GeV} & \\
\end{align*}
\]

events/sec for \( \mathcal{L} = 10^{33} \text{ cm}^2\text{s}^{-1} \)
rates of processes at LHC

proton - (anti)proton cross sections

\[ \sigma_{\text{jet}}(E_T^{\text{jet}} > E/20) \]

\[ \sigma_{\text{jet}}(E_T^{\text{jet}} > 100 \text{ GeV}) \]

\[ M_h = 125 \text{ GeV} \]

LHC \[ \sqrt{s} = 14 \text{ TeV} \]

L = \[ 10^{34} \text{ cm}^{-2} \text{s}^{-1} \]

rate \[ \text{ev/year} \]

GHz \[ 10^9 \]

MHz \[ 10^6 \]

kHz \[ 10^3 \]

Hz \[ 10^2 \]

mHz \[ 10^1 \]

Hz \[ 10^0 \]

fb \[ 10^{-2} \]

pb \[ 10^{-3} \]

\( \sigma_{\text{inveslastic}} \)

L1 input

L1 output = HLT input

max HLT output

SUSY \( \tilde{q}+\tilde{q}+\tilde{g}+\tilde{g} \)

\( \tan\beta = 2, \mu = m_g = m_q/2 \)

\( \tan\beta = 2, \mu = m_g = m_q \)

SUSY \( \tilde{q}+\tilde{q}+\tilde{H}_\text{SM} \)

Higgs \( H_{\text{SM}} \rightarrow H^{\pm} \rightarrow 4\mu \)

Z_{\text{ARL}} \rightarrow 2l \]

Z_{\text{SM}} \rightarrow 3\gamma \)

scalar LQ

Z_{\text{SM}} \rightarrow 2l \]

10^3

10^4

10^5

10^6

10^7

10^8

10^9

10^10

10^11

10^12

10^13

10^14

10^15

10^16

10^17

0.1

1

10

E (TeV)

10^0

10^1

10^2

10^3

10^4

10^5

10^6

10^7

10^8

10^9

10^10

10^11

10^12

10^13

10^14

10^15

10^16

10^17

0.1

1

10

100

200

500

1000

2000

5000

jet E_T or particle mass (GeV)
data selection challenges at hadron colliders

- high background rates
  - intrinsic problem of hadron colliders

- interesting events make up tiny fraction

- cutting hard on transverse momentum → signal loss

- sophisticated rate reduction methods needed
Trigger rates and data sizes

- ATLAS, CMS: high no. channels, high bandwidth (Terabit s⁻¹)
- LHCb: high Level-1 trigger (1 MHz)
- ALICE: high data archives (PetaBytes)

Graph showing Level-1 rates vs. event size (bytes) for various experiments:
- KTeV
- KLOE
- HERA-B
- CDF II, D0 II
- BaBar
- CDF, D0
- H1, ZEUS
- UA1, NA49
- LEP
- LEP
Differences between LHC experiments

- **ATLAS and CMS**: investigate particles at energy frontier
  - high data rates and large event sizes

- **LHCb**: precision studies of b-physics processes
  - very high statistics needed
  - moderate event size

- **ALICE**: heavy-ion collisions and studies of quark-gluon plasma
  - collision rate much lower than for proton-proton collisions
  - very high multiplicities \(\rightarrow\) very big event sizes
Hardware trigger: the idea

- read out some parts of detector at full bunch-crossing rate
  - possibly at reduced granularity
- these data allow a first guess if event is interesting
- if yes: “Level-1 Accept” $\rightarrow$ read out everything and take a closer look
  - in “High-Level Trigger” computer farm

- constraint: data must still be available in on-detector memory (“pipeline”) $\rightarrow$ “latency”
Why a hardware trigger?

- Ideal: read out everything
  - read out detector data for every “bunch crossing”: every 25 ns, so read out at 40 MHz
  - reconstruct events using all detector data in computers
  - discard data without interest before writing to tape
Why a hardware trigger?

- Ideal: read out everything
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**turn-on curve**

- hardware trigger based on reduced information has
  - worse momentum resolution
  - worse particle identification
    - electrons / photons
    - electrons / jets
Why a hardware trigger?

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  - read out detector data for every “bunch crossing”: every 25 ns, so read out at 40 MHz
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pileup

- about 50 - 60 in 2017
- 140 – 200 at High-Lumi LHC

need full resolution to resolve vertices!
Why a hardware trigger?

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  - read out detector data for every “bunch crossing”: every 25 ns, so read out at 40 MHz
  - reconstruct events using all detector data in computers
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- Why not work without hardware trigger?
  - need very big computer farms (money problem)
  - but also:
  - have to get all data out from detector
  - have to supply detector with much power
  - not only money problem but resolution degradation due to amount of material in detector (“copper tracker”)
**ATLAS and CMS**

- **similar approach in both experiments:**
  - both use data from muon systems and calorimeters
    - in reduced resolution
  - both read out tracker only in case of “Level-1 Accept”
  - similar latency (2.5 - 4 µs)

- **minor differences:**
  - ATLAS uses different muon detectors for trigger (RPCs and TGCs) and precision data (Monitored Drift Tubes and CSCs)
    - Resistive Plate Chambers, Thin Gap Chambers, Cathode Strip Chambers
  - CMS uses same muon detectors for both trigger and data
  - at “Level-1 Accept”, ATLAS reads out “Regions of Interest” while CMS reads out full detector
specialized for studying b-physics

forward detector only
- differently from the “4 π” geometry of ATLAS, CMS and ALICE
- ⇒ smaller detector and smaller data volume

needs very good vertex resolution for resolving b-decays

events with pileup hard to disentangle ⇒ luminosity and pileup reduced by LHC
- by defocussing beams

since LHC startup: hardware trigger rate 1 MHz
ALICE

- specialized to observe heavy-ion collisions
  - take proton-proton data also for reference

- luminosity in heavy-ion collisions much lower than for protons
  - $10^{27} \text{ cm}^{-2} \text{ s}^{-1}$ rather than $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$

- enormous complexity of events
  - tens of thousands of tracks per event

- core detector: TPC
  - Time Projection Chamber
  - slow readout $\Rightarrow$ events overlapping in time hard to analyze
  - $\Rightarrow$ “past-future protection”

- multi-layer trigger
  - hardware Level-0, Level-1, Level-2
  - High-Level Trigger computer farm
CMS Peak Luminosity Per Day, pp

Data included from 2010-03-30 11:22 to 2016-10-27 14:12 UTC

- 2010, 7 TeV, max. 203.8 Hz/μb
- 2011, 7 TeV, max. 4.0 Hz/μb
- 2012, 8 TeV, max. 7.7 Hz/μb
- 2015, 13 TeV, max. 5.1 Hz/μb
- 2016, 13 TeV, max. 15.3 Hz/μb

nominal instantaneous luminosity

Peak Delivered Luminosity (Hz/μb)

Date (UTC)

CMS Integrated Luminosity, pp

Data included from 2010-03-30 11:22 to 2016-10-27 14:12 UTC

- 2010, 7 TeV, 45.0 pb⁻¹
- 2011, 7 TeV, 6.1 fb⁻¹
- 2012, 8 TeV, 23.3 fb⁻¹
- 2015, 13 TeV, 4.2 fb⁻¹
- 2016, 13 TeV, 41.1 fb⁻¹

Total Integrated Luminosity (fb⁻¹)

Date (UTC)
LHC is evolving

- “Run 1” at lower than design energy
  - 8 TeV instead of 14 TeV collision energy
- now almost at design energy
  - 13 TeV collision energy
- luminosity has been steadily going up
  - now exceeding design goal of $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$

- design goal for High-Luminosity LHC:
  - luminosity: 5 to 7.5 $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$
  - pileup: 140 to 200

- to make use of improved accelerator performance, detectors also have to evolve
LHC upgrade schedule

“Runs” interrupted by “Long Shutdowns” (“LS”)
**ATLAS and CMS current upgrades**

- electronics gets quickly obsolescent
  - hard to maintain, difficult to purchase old components for repairs
- getting more functionality into bigger chips allows to increase performance, reduce size and improve reliability
  - fewer points of failure
- during LS1, ATLAS and CMS started switching from VME-based to TCA-based electronics
  - ATCA for ATLAS, μTCA for CMS
- replacing galvanic connections by optical fibers → higher data rates, better reliability, smaller form factors
  - but does not come for free: (de)serialization needs extra latency!
  - so far, have to fit into 2.5 - 4 μs latency budget!
Progress in FPGAs

Logic Cells

- 28 nm: > 2X gains over 40 nm

On-Chip High Speed Serial Links:

- Connect to new compact high density optical connectors (SNAP-12...)

Manfred Jeitler, HEPHY Vienna

Trigger systems of the LHC experiments

INSTR17 Novosibirsk
Progress in FPGAs

Logic Cells

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Trigger systems of the LHC experiments
FPGA trigger code example

example: calculation of invariant mass of two objects

```vhdl
library ieee;
use ieee.std_logic_1164.all;
use ieee.std_logic_unsigned.all;
use ieee.std_logic_arith.all;
use work.gtl.pkg.all;

entity invariant_mass is
  generic (upper_limit : real := 15.0;
            lower_limit : real := 10.0;
            pt1_width : positive := 12;
            pt2_width : positive := 12;
            cossq : positive := 20;
            INV_MASS_PRECISION : positive := 1;
            INV_MASS_COSH_COS_PRECISION : positive := 3
  );
  port(
    pt1 : in std_logic_vector(pt1_width-1 downto 0);
    pt2 : in std_logic_vector(pt2_width-1 downto 0);
    cos cos : in std_logic_vector(cossq_width-1 downto 0);
    -- cos of eta1 - eta2
    cos phi : in std_logic_vector(cossq_width-1 downto 0);
    -- cos of phi1 - phi2
    inv_mass_comp : out std_logic;
    sim_inv_mass_sq_div2 : out std_logic_vector(pt1_width+pt2_width+cossq_width-1 downto 0)
  );
end invariant_mass;

architecture rtl of invariant_mass is

constant INV_MASS_VECTOR_WIDTH : positive := pt1_width+pt2_width+cossq_width;
constant INV_MASS_PRECISION_FACTOR : real := real(10**(INV_MASS_COSH_COS_PRECISION+1)).pkg.

constant FACTOR_4_VECTOR : std_logic_vector((INV_MASS_COSH_COS_PRECISION+1)*4-1 downto 0) := conv_std_logic_vector(10**(INV_MASS_COSH_COS_PRECISION+1),(INV_MASS_VECTOR_WIDTH+2));

signal inv_mass_sq_div2 : std_logic_vector(INV_MASS_VECTOR_WIDTH+1 downto 0);
signal upper_limit_vector : std_logic_vector(INV_MASS_VECTOR_WIDTH+1 downto 0);
signal lower_limit_vector : std_logic_vector(INV_MASS_VECTOR_WIDTH+1 downto 0);

begin
  -- Calculating the invariant mass with the formula: M^2/2 = pt1*pt2 * (cosh(eta1 - eta2) - cos(phi1 - phi2))
  inv_mass_sq_div2 <= pt1 * pt2 * (cos cos - cos phi);
  sim_inv_mass_sq_div2 <= inv_mass_sq_div2;
  -- Comparison with boundary values
  inv_mass_comp <= '1' when (inv_mass_sq_div2 > lower_limit_vector) and (inv_mass_sq_div2 <= upper_limit_vector) else '0';
end architecture rtl;
```
The Global Trigger of CMS (µTCA crate)
Optical fibers replace galvanic connections
ATLAS and CMS future upgrades (LS3)

- very important step will be inclusion of silicon trackers into Level-1 trigger during “Long Shutdown 3”

- will select tracks with transverse momentum above a few GeV at local level
  - look for low bending (close azimuth in adjacent strip modules)
Why will ATLAS and CMS need a tracker trigger?

- better identify charged leptons ($e, \mu, \tau$)
- improve the $p_T$ determination of muon candidates
  - $p_T$ threshold of a few GeV
- determine the isolation of leptons and photons with respect to the neighboring tracks
- determine the “vertex” of charged leptons and jet objects
  - position resolution along beam of about 1 mm
- determine an event primary vertex and the transverse missing energy carried by Level-1 Tracks that come from this vertex
**ATLAS and CMS future upgrades (LS3)**

- latency will increase from 2.5-4 µs to 10-30 µs
  - required by including tracker into hardware trigger
  - ATLAS: 30  CMS: 12.5
- hardware trigger rate will be about 1 MHz
  - ten times higher than present
  - ATLAS: above 1 MHz ("Level-0") and possibly "Level-1" stage with output of 400 kHz
  - CMS: 750 kHz
- also: use full calorimeter granularity in hardware trigger
- ATLAS will also significantly improve its muon trigger
  - "Monitored Drift Tubes" (MDT, precision muon chambers) will be included in trigger
  - for CMS, all muon detectors have been in trigger since LHC startup
LHCB upgrade

- **High-Level Trigger upgrade during LS1**
  - Level-1 data can be stored for up to one week
  - final calibration accessible for High-Level trigger
  - no reprocessing needed
  - make optimum use of LHC inter-fill periods

- **Hardware trigger to be removed during LS2**
  - send full data rate at almost 40 MHz to computer farm buffer
  - store until final calibration available and High-Level Trigger analysis can be run
  - only then discard events without interest

- **why is this possible for LHCB and not for ATLAS and CMS?**
  - smaller detector and smaller event size
  - no compact $4\pi$ geometry, easier access from side
ALICE upgrade

- Heavy-Ion collision rates will increase
- need large amount of proton-proton data

- adapt various subdetectors for higher rates
- main detector (Time Projection Chamber) gets new readout (GEMs instead of MWPCs)
  - continuous readout of Pb-Pb collision data at 50 kHz
  - based on minimum-bias trigger (provided by Fast Interaction Trigger detector (FIT))

- introduce readout buffers for many subdetectors
Summary

- Trigger systems are vital ingredients to make use of the enormous data rates at modern hadron colliders
- Upgrades of hardware, firmware and software continue over the lifetime of each experiment
- In most cases, hardware event selection will still be needed for some time to come
References

- Letter of Intent for the Phase-II Upgrade of the ATLAS Experiment
  - https://cds.cern.ch/record/1502664

- ATLAS Phase-II Upgrade Scoping Document

- Technical Proposal for the Phase-II Upgrade of the CMS Detector
  - https://cds.cern.ch/record/2020886/files/LHCC-P-008

- CMS Phase II Upgrade Scope Document
  - https://cds.cern.ch/record/2055167

- LHCb Trigger and Online Upgrade Technical Design Report

- ALICE Upgrade of the Readout & Trigger System TDR
BACKUP
LHC upgrade schedule

LHC schedule beyond LS1

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LHC:
- Run 2

LS 2: starting in 2018 (July) => 18 months + 3 months BC

LHC: starting in 2023 => 30 months + 3 months BC

Injectors: in 2024 => 13 months + 3 months BC

LHC schedule approved by CERN management and LHC experiments spokespersons and technical coordinators (December 2013)
The Compact **MUON** Solenoid
pile-up of events
L1 Trigger Layout in LHC Run 1

Calorimeter Trigger
- $|\eta|<3$
- $0<|\eta|<5$
- ECAL Trigger Primitives
- HCAL/HF Trigger Primitives
- Regional Calorimeter Trigger
  - Global Calorimeter Trigger

Muon Trigger
- $|\eta|<1.6$
- FPC hits
- Link system
- Pattern Comparator
- Segment finder
- Track finder
- Segment finder

Global Muon Trigger
- 4+4 $\mu$
- $4 \mu$
- $4 \mu$
- 4 $\mu$

Global Trigger
- L1A
- Status
- TTC system
- TTS system
- 32 partitions

CMS experiment

Detector Frontend

40 MHz pipeline

CMS experiment
L1 Trigger Layout in LHC Run 2

- ECAL energy
- HF energy
- HCAL energy
- Layer-1 Calo
- Layer-2 Calo
- DeMux

- CSC Hits
- RPC Hits
- DT Hits CuOF
- HO HTR
- MPC Mezz
- LB
- CPPF
- TwinMux

- Micro-Track Finders
  - end-cap
  - overlap
  - barrel

- Micro-Global Muon Trigger

- Micro-Global Trigger

- BMTF
- uGMT
- uGT

systems built by HEPHY Vienna
CMS Trigger & DAQ Systems

Level 1 Trigger -> Detector Frontend

Event Manager -> Builder Networks

Controls

Computing Services

Filter Systems

40 MHz

10^5 Hz

1 Tbps

10^2 .. 10^3 Hz

HLT
detectors yielding electrical output signals allow to select events to be recorded by electronic devices

- thresholds (discriminators)
- logical combinations (AND, OR, NOT)
- delays
- available in commercial “modules”
- connections by cables (“LEMO” cables)

pre-LHC
because of the enormous amounts of data at major modern experiments electronic processing by such individual modules is impractical
  – too big
  – too expensive
  – too error-prone
  – too long signal propagation times

⇒ use custom-made highly integrated electronic components ("chips")

⇒ stay flexible by using Field-Programmable Gate Arrays (FPGAs)

400 x 10 logical operations / module  ⇒  ~ 40000 logical operations in one chip

LHC Run 1
LHC Run 1 ($\leq$2012):
many parallel galvanic connections

Example:

Drift Tube
Track Finder
(part of
muon trigger)
How do we trigger?

- at a rate of 40 MHz impossible to read out all detector data
- preliminary decision based on part of the event data only
- be quick!
  - in case of positive trigger decision all detector data must still be available
  - data are stored temporarily in a “pipeline” in the detector electronics
    » “short term memory” of the detector
    » “ring buffer”
  - in hardware, can only afford a few µs (presently, 4 µs)
L1 Trigger Layout in LHC Run 2

Calorimeter

Muons
L1 Trigger Layout in LHC Run 2

systems built by HEPHY Vienna
LHC Run 1 (<=2012):
many different custom-built electronics modules (VME)

Example:

Global Trigger (left) and Global Muon Trigger (right)
Commercial μTCA module
MCH (MicroTCA Carrier Hub)
When do we trigger?

- **„bunch” structure of the LHC collider**
  - „bunches” of particles
  - 40 MHz
    - a bunch arrives every 25 ns
    - bunches are spaced at 7.5 meters from each other
    - bunch spacing of 125 ns for heavy-ion operation

- **at present luminosity of the LHC collider (>10^{34} \text{ cm}^{-2} \text{ s}^{-1})** we have about 30 proton-proton interactions for each collision of two bunches
  - only a small fraction of these “bunch crossings” contains at least one collision event which is potentially interesting for searching for “new physics”
  - in this case all information for this bunch crossing is recorded for subsequent data analysis and background suppression
  - luminosity quoted for ATLAS and CMS
    - reduced luminosity for LHCb (b-physics experiment)
    - heavy-ion luminosity much smaller
LHC bunch-filling scheme

LHC orbit with 3564 “bunch crossings”
(colliding bunches in CMS: blue; single bunches in CMS: red/white):
⇒ *multi-level trigger*

- **first stage takes preliminary decision** based on part of the data
  - rate is already strongly reduced at this stage
  - $\sim 1$ GHz of events ($= 40$ MHz bunch crossings) $\rightarrow \sim 100$ kHz
  - only for these bunch crossings are all the detector data read out of the pipelines
  - still it would not be possible (with reasonable effort and cost) to write all these data to tape for subsequent analysis and permanent storage

- **the second stage can use all detector data** and perform a “complete analysis” of events
  - further reduction of rate: $\sim 100$ kHz $\rightarrow \sim 1$ kHz
  - only the events thus selected (twice filtered) are permanently recorded
how to find muon tracks? (CMS: solenoidal field)
calorimeter trigger

Hadronic trigger tower

Electromagnetic trigger tower

Fine grain profiles

$\Delta \eta = 0.087$
Rates and efficiencies of current and upgraded calorimeter trigger
How does the trigger actually select events?

- the first trigger stage has to process a limited amount of data within a very short time
  - relatively simple algorithms
  - special electronic components
    » ASICs (Application Specific Integrated Circuits)
    » FPGAs (Field Programmable Gate Arrays)
  - something in between “hardware” and “software”: “firmware”
    » written in programming language (“VHDL”) and compiled
    » fast (uses always same number of clock cycles)
    » can be modified at any time when using FPGAs

```plaintext
pre_algo_a(54) = tau_2_s(2);
pre_algo_a(55) = tau_2_s(1);
pre_algo_a(56) = muon_1_s(18) AND ieg_1_s(2);
pre_algo_a(57) = muon_1_s(6) AND ieg_1_s(28);
pre_algo_a(58) = muon_1_s(8) AND (ieg_1_s(25) OR eg_1_s(7));
pre_algo_a(59) = muon_1_s(9) AND (jet_1_s(9) OR fwdjet_1_s(5) OR tau_1_s(26));
pre_algo_a(60) = muon_1_s(4) AND (jet_1_s(8) OR fwdjet_1_s(4) OR tau_1_s(25));
pre_algo_a(61) = muon_1_s(7) AND (jet_1_s(4) OR fwdjet_1_s(20) OR tau_1_s(16));
pre_algo_a(62) = muon_1_s(3) AND (jet_1_s(28) OR fwdjet_1_s(15) OR tau_1_s(10));
pre_algo_a(63) = muon_1_s(2) AND tau_1_s(9);  
pre_algo_a(64) = muon_1_s(1) AND tau_1_s(20);
pre_algo_a(65) = ieg_1_s(26) AND (jet_1_s(7) OR fwdjet_1_s(3) OR tau_1_s(24));
pre_algo_a(66) = ieg_1_s(24) AND (jet_1_s(19) OR fwdjet_1_s(14) OR tau_1_s(8));
pre_algo_a(67) = ieg_1_s(10) AND (jet_1_s(5) OR fwdjet_1_s(1) OR tau_1_s(19));
pre_algo_a(68) = ieg_1_s(9) AND (jet_1_s(3) OR fwdjet_1_s(19) OR tau_1_s(15));
pre_algo_a(69) = ieg_1_s(8) AND tau_1_s(7);
```
How does the trigger actually select events?

- The first trigger stage has to process a limited amount of data within a very short time
  - relatively simple algorithms
  - special electronic components
    » ASICs (Application Specific Integrated Circuits)
    » FPGAs (Field Programmable Gate Arrays)
  - something in between “hardware” and “software”: “firmware”
    » written in programming language (“VHDL”) and compiled
    » fast (uses always same number of clock cycles)
    » can be modified at any time when using FPGAs

- The second stage (“High-Level Trigger”) has to use complex algorithms
  - not time-critical any more (all detector data have already been retrieved)
  - uses a “computer farm” (large number of PCs)
  - programmed in high-level language (C++)
Level-1 Trigger latency

- presently \( \sim 4 \, \mu s \)
  - \( \sim 160 \) clock cycles
  - limited by tracker pipeline length

- will be increased only during tracker upgrade
  - Long Shutdown 3: phase-2 upgrade
  - \( \sim 2023 \)

- phase-1 trigger upgrade will have to fit into same latency budget
  - challenge because of optical links
    » parallel-serial conversion (SerDes) needs time
  - we have some reserve
CMS trigger upgrade

- upgrade of LHC
  - higher energy: 8 → 13 TeV collision energy in 2015
    » higher cross-sections → higher rates
  - higher luminosity:
    » 0.7 x 10^{34} \text{ cm}^{-2}\text{s}^{-1} in 2012
    »  → > 10^{34} \text{ cm}^{-2}\text{s}^{-1} now
    »  → > 5 x 10^{34} \text{ cm}^{-2}\text{s}^{-1} at High-Luminosity LHC (HL-LHC)
  - higher pile-up (from 30 in 2013 to 140 at HL-LHC)
  - narrower bunch spacing (50 ns → 25 ns)

- Higgs precision measurements

- search for new physics

→ upgrade CMS trigger
  - to keep physics potential
  - else: would have to raise thresholds more and more
Level-1 Trigger phase-1 upgrade strategy

- task: reduce rates and occupancy while keeping efficiency

- calorimeter trigger
  - higher precision in coordinates ($\eta$, $\phi$) and transverse energy ($E_T$)
  - flexibility for improved and more complex algorithms (pile-up subtraction, tau-jets etc.)
  - more candidate objects

- muon trigger
  - higher precision in coordinates ($\eta$, $\phi$) and transverse momentum ($p_T$)
  - more candidate objects
  - combine candidates from different detectors at track-finder level
  - profit from additional chambers in endcaps (YE04 and RE04)

- global trigger
  - more algorithms (current limit: 128)
  - more sophisticated algorithms:
    - Run 1: multiple objects, simple angular correlations
    - Run 2: invariant mass, transverse mass, complex correlations
**Level-1 Trigger phase-1 upgrade technology**

- current system consists of many different custom-built electronics modules
  - VME based
  - digital electronics implemented in FPGAs and ASICs
  - maintenance and spare-module management problematic

- in future aim for **higher integration**
  - use larger FPGAs
  - build system in more compact way (fewer boards)

- use **standardized electronics where possible**
  - custom built but same for many systems
  - partly also COTS (Commercial off-the-shelf) components
  - new form factor: $\mu$TCA (Micro Telecommunications Computing Architecture)

- use **optical links**
  - higher data rates (higher precision, more trigger objects)
  - less space for connectors ($\mu$TCA instead of 9U-VME)
Muon trigger upgrade

- make use of redundant systems already at track-finder level
  - so far candidates from CSC/RPC and DT/RPC combined only after track finding, in Global Muon Trigger

- 3 regional systems: Barrel Track Finder (DT+RPC), Endcap Track Finder (CSC+RPC), Overlap Track Finder (DT+CSC+RPC)

- high rate particularly problematic in end caps
  - Cathode Strip Chambers (CSC) and Resistive-Plate Chambers (RPC)
  - outermost chambers being added now
  - improve $p_T$ resolution and thus reduce rate
  - current design ($\Delta\phi$ comparisons) does not scale well
  - $\rightarrow$ switch to pattern matching system to accommodate higher occupancy

- Drift Tube trigger relocation
  - moved front-end electronics ("sector collectors") from experimental cavern to electronics cavern
  - all trigger electronics close to Global Trigger, always accessible in radiation-safe area
transition from parallel triggering systems to *time-multiplexed trigger*

- processors take turns
- each processor gets all the data for a given bunch crossing
- same hardware with different connections could run parallel triggering system
Level-1 Global Trigger upgrade

- again centralizing all final decision taking in one crate

- Global Trigger Logic in one μTCA module
  - if needed, several modules can run in parallel for more trigger algorithms

- use of big FPGA (Xilinx Virtex-7) allows much more complex logic
  - large number of high-speed IO links and logic cells
  - big lookup tables, floating-point operations in DSPs

- Trigger Control System has moved to different crate
  - combined with trigger distribution system (TTC) into “TCDS” (Trigger Control and Distribution System)
High Level Trigger (HLT)

- now: $\sim 13\,000$ CPU cores
- more and faster computers will allow for more calculation time
  - more complex algorithms
  - $\sim 100 \rightarrow \sim 1000$ ms per event
- improving the object reconstruction and physics selection to bring it closer to the offline version

- phase 2: higher pileup and input rate
- use L1 Track trigger info at very first stage of HLT processing
  - reduce HLT processing time (unpacking)
Scenario for phase-2 upgrade

Tracker replacement allows for

- Track Trigger
- increased latency (10-20 µs)
  - replace ECAL electronics, for 20 µs also endcap muon (CSC) electronics

- finer granularity
  - use single-crystal granularity in ECAL instead of “trigger towers”

- L1 trigger rate 0.5 – 1 MHz
  - up from 100 kHz
  - replace muon Drift Tube electronics
  - needed for hadronic triggers (do not benefit so much from Track Trigger)
  - HLT should cope with this (estimate 50x increase; Moore’s law)

- HLT output rate of 10 kHz
Summary on upgrades

- LHC development makes trigger upgrade mandatory
  - else we lose much of the data

- Phase 1 upgrade has been successful
  - commissioning in 2015
  - full deployment in 2016

- Phase 2 upgrade > 2022
  - Track Trigger
  - increase latency to 10 or 20 µs
  - L1 rate ~ 0.5-1 MHz
  - HLT rate ~ 10 kHz
LHC / CMS schedule

- **2013-2014** first “long shutdown” (“LS 1”)  
  - part of trigger electronics being upgraded: “phase-1 upgrade”

- **2015-2017** data taking @ (√s = 13 TeV)  
  - LHC may exceed design luminosity (10^{34} \text{ cm}^{-2}\text{s}^{-1}) and run at higher than design pile-up!  
    - original design: ~20 interactions per bunch crossing  
  - during this period evolve to improved system  
  - Pixel detector replacement at end of 2016

- **2018-2019** second “long shutdown” (“LS 2”)  

- **2023-2025** third “long shutdown” (“LS 3”)  
  - silicon strip tracker upgrade  
  - plans to use tracker in Level-1 Trigger: “phase-2 upgrade”

- **schedule may change over time**
Why upgrade the CMS trigger?

- **radiation damage** to inner detectors (Pixels, Silicon Strips) and on-detector electronics
  - replacement planned from the beginning
  - put as many systems as possible out of radiation area (move to “electronics cavern”)

- **obsolescence**
  - long preparation times for big experiments
  - newer electronics will improve reliability and performance

- **higher performance**
  - higher LHC luminosity and pileup
  - need better detector resolution and more sophisticated triggering algorithms

- *must not jeopardize performance of detector during data taking!*
Level-1 Muon trigger

- three technologies
  - Drift Tubes (DT, in barrel)
  - Cathode Strip Chambers (CSC, in endcaps)
  - Resistive Plate Chambers (RPC, everywhere)
- redundant
- complementary technologies
- geometrical overlap

- muons from all 3 systems processed in Global Muon Trigger
  - final muon candidates determined by
    - quality (e.g. number of hits)
    - correlation between systems (RPC+DT, RPC+CSC)
    - transverse momentum
**Level-1 Calorimeter trigger**

- **Electromagnetic Calorimeter (ECAL)**
  - block of 5x5 lead-tungstate crystals forms a “trigger tower”
- **Hadronic Calorimeter (HCAL)**
- combination of signals from both calorimeters allows to determine candidates for
  - e/gamma (discriminated only at High-Level Trigger)
  - jets (“central” and “forward”)
  - tau jets
- as well as
  - total and missing energy
  - total and missing hadronic energy
ATLAS & CMS Triggered vs. Triggerless Architectures

1 MHz (Triggered):
- **Network:**
  - 1 MHz with ~5 MB: aggregate ~40 Tbps
  - Links: Event Builder-cDAQ: ~500 links of 100 Gbps
  - Switch: almost possible today, for 2022 no problem
- **HLT computing:**
  - General purpose computing: 10(rate)x3(Primary)x1.5(energy)x200kHzS6 (CMS)
    - Factor ~50 wrt today maybe for ~same costs
  - Specialized computing (GPU or else): Possible

40 MHz (Triggerless):
- **Network:**
  - 40 MHz with ~5 MB: aggregate ~2000 Tbps
  - Event Builder Links: ~2,500 links of 400 Gbps
  - Switch: has to grow by factor ~25 in 10 years, difficult
- **Front End Electronics**
  - Readout Cables: Copper Tracker! – Show Stopper
- **HLT computing:**
  - General purpose computing: 400(rate) x3(Primary)x1.5(energy)x200kHzS6 (CMS)
    - Factor ~2000 wrt today, but too pessimistic since events easier to reject w/o L1
    - This factor looks impossible with realistic budget
  - Specialized computing (GPU or ...)
    - Could possibly provide this ...
- LHC beam crossing rate is 40 MHz & at full Luminosity of $10^{34}$ cm$^{-2}$s$^{-1}$ yields $10^9$ collisions/s
- Reduce to 100 kHz output to High Level Trigger and keep high-$P_T$ physics
- Pipelined at 40 MHz for dead time free operation
- Latency of only 4 µsec for collection, decision, propagation
Calorimeter trigger upgrade

- improve resolution in coordinates
  - azimuth $\phi$ and pseudorapidity $\eta$
- improve identification of tau jets
  - better isolation criteria
- further improve e/gamma isolation determination
signals used by the first-level trigger

- **muons**
  - tracks
  - several types of detectors (different requirements for barrel and endcaps):
    - in ATLAS:
      - RPC (Resistive Plate Chambers): barrel
      - TGC (“Thin Gap Chambers”): endcaps
      - not in trigger: MDT (“Monitored Drift Tubes”)
    - in CMS:
      - DT (Drift Tubes): barrel
      - CSC (Cathode Strip Chambers): endcaps
      - RPC (Resistive Plate Chambers): barrel + endcaps

- **calorimeters**
  - clusters
  - electrons, jets, transverse energy, missing transverse energy
  - electromagnetic calorimeter
  - hadron calorimeter

- **only in high-level trigger: tracker detectors**
  - silicon strip and pixel detectors, in ATLAS also straw tubes
  - cannot be read out quickly enough
TRIGGER COMPONENTS
turn-on curves

ideal:

transverse momentum \( (p_T) \) →

reality:

\[
\begin{align*}
\text{Threshold Efficiency} & \\
0 & \quad 0.2 \\
0.2 & \quad 0.4 \\
0.4 & \quad 0.6 \\
0.6 & \quad 0.8 \\
0.8 & \quad 1 \\
\end{align*}
\]

\( P_T \text{ of Global Muon, (GeV/c)} \)

CMS Preliminary 2011 (PTLUT2011)

- CSCTF \( P_T \geq 5.0 \text{ GeV/c} \) plateau at 0.96 ± 0.00
- CSCTF \( P_T \geq 7.0 \text{ GeV/c} \) plateau at 0.92 ± 0.01
- CSCTF \( P_T \geq 10.0 \text{ GeV/c} \) plateau at 0.89 ± 0.01
BACKUP

Track Trigger
Level-1 Tracker  
(original detector)

- Volume: 23 m$^3$
- Active area: 210 m$^2$
- Modules: 15,148
- Front-end chips: 72,784
- Read-out channels: 9,316,352
- Bonds: 24,000,000
- Optical channels: 36,392
- Raw data rate: 1 Tbyte/s
- Power dissipation: 30 kW
- Operating T: $-10^\circ$C
Level-1 Tracker trigger: new tracker layout

- roughly same total sensor area and number of sensors
- number of readout channels up by almost one order of magnitude
Tracker trigger concept

- Silicon modules provide at the same time “Level-1 data” (@ 40 MHZ), and “readout data” (upon Level-1 trigger)
  - whole tracker sends out data at each bunch crossing: “push path”
- Level-1 data require local rejection of low-$p_T$ tracks
  - reduce data volume and simplify track finding @ Level-1
  - Threshold of $\sim 2$ GeV $\Rightarrow$ data reduction of one order of magnitude or more
- tracker modules with $p_T$ discrimination (“$p_T$ modules”)
  - correlate signals in two closely-spaced sensors
  - exploit the strong magnetic field of CMS
- Level-1 “stubs” are processed in the back-end
  - form Level-1 tracks with $p_T$ above $\sim 2$ GeV
- Pixel option
  - possibly also use Pixel detector in “pull” architecture
  - longer latency needed (20 $\mu$s)
Track trigger: goals

- presence of track match validates a calorimeter or muon trigger object,
  - e.g. discriminating electrons from hadronic ($\pi^0 \rightarrow \gamma \gamma$) backgrounds in jets
- link precise tracker system tracks to muon system tracks
  - improve precision on the $p_T$ measurement
  - sharpen thresholds in muon trigger
- check isolation of candidate (e, $\gamma$, $\mu$ or $\tau$)
- primary z-vertex location within 30-cm “luminous region”
  - from projecting tracks found in trigger layers
  - discrimination against pile-up events in multi-object triggers
    (e.g. lepton-plus-jet triggers)
Track Trigger: pattern recognition

- pattern recognition using “associative memory”
  - CAM = “content addressable memory”
- by comparing with patterns find candidates (“roads”)
<table>
<thead>
<tr>
<th>Trigger, Threshold</th>
<th>Algorithm</th>
<th>Rate reduction</th>
<th>Full eff. at the plateau</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single Muon, 20 GeV</td>
<td>Improved Pt, via track matching</td>
<td>~ 13 (</td>
<td>( \eta )</td>
<td>&lt; 1 )</td>
</tr>
<tr>
<td>Single Electron, 20 GeV</td>
<td>Match with cluster</td>
<td>&gt; 6 (current granularity) &gt;10 (crystal granularity) (</td>
<td>( \eta )</td>
<td>&lt; 1 )</td>
</tr>
<tr>
<td>Single Tau, 40 GeV</td>
<td>CaloTau – track matching + tracker isolation</td>
<td>O(5)</td>
<td>O(50 %)</td>
<td>(for 3-prong decays)</td>
</tr>
<tr>
<td>Single Photon, 20 GeV</td>
<td>Tracker isolation</td>
<td>40 %</td>
<td>90 %</td>
<td>Probably hard to do much better.</td>
</tr>
<tr>
<td>Multi-jets, HT</td>
<td>Require that jets come from the same vertex</td>
<td></td>
<td></td>
<td>Performances depend a lot on the trigger &amp; threshold.</td>
</tr>
</tbody>
</table>
Much sharper turn-on curves w.r.t. DTTF, as expected from the much better PT resolution. Hence the contribution from mis-measured low PT muons (which makes most of the DTTF rate) is dramatically reduced.
**Muons : rates**

- DTTF : Flattening of the rates at high threshold
- Matching the DT primitives with L1Tracks : large rate reduction, > 10 at threshold > ~ 14 GeV.

![Graph showing single muon trigger rates, Barrel with L1Track and DTTF lines.](image-url)
Electrons

Rate reduction brought by matching L1EG to L1Tkstubs in the central region ($|\text{eta}| < 1$)

Red: with the current L1Cal granularity.

Green: if crystal-level information is available for L1EG. The better position resolution for the L1EG object improves the performance of the matching to the tracker.

( NB: the pure calorimetric L1EG rates could also be reduced with the finer granularity. Not taken into account here. )
$p_T$ modules: working principle

- measure $p_T$ via $\Delta(R\phi)$ over a given $\Delta R$
- for a given $p_T$, $\Delta(R\phi)$ increases with $R$
  - same geometrical cut corresponds to harder $p_T$ cuts at large radii
  - at low radii, rejection power limited by pitch
  - optimize selection window and/or sensors spacing for consistent $p_T$ selection through the tracking volume

  e.g. Window = 5

  \[
  \Delta R \approx \Delta z = \Delta R / \tan \theta
  \]

- barrel: $\Delta R$ is given directly by the sensors spacing
- end-cap: dependence on detector location
  - End-cap configuration typically requires wider spacing
Jets

- Associate jets to nearby L1 tracks to determine z position
  - **(1)** Select tracks with $dR(\text{track}, \text{jet}) < 0.40$
    - $|z_{\text{track}}| < 25 \text{ cm}$
    - $\chi^2_{\text{track}} < 100$
  - **(2)** $p_T$ averaged z position of selected tracks $\rightarrow$ initial jet z position “$z_1(\text{jet})$”
  - **(3)** Remove outliers in two steps & recalculate z position
    - First outlier step: $|z_{\text{track}} - z_1(\text{jet})| < 5\text{cm}$ $\rightarrow$ updated z position “$z_2(\text{jet})$”
    - Second outlier step: $|z_{\text{track}} - z_2(\text{jet})| < 1\text{cm}$ $\rightarrow$ final z position “$z_{\text{final}}(\text{jet})$”

Diagrams showing the association of tracks to jets and the criteria for pass and fail in terms of $\Delta z$.
Track finding @ Level-1

- Each sector independent
- Overlap regions depend on
  - Luminous region $\Delta z$
  - Minimum $p_T$ cut

Number of sectors connected to a module
Track finding @ Level-1

Simple Trigger Tower Interconnections

Each box represents a trigger tower
Track finding at Level-1

- Within a latency of $O(\mu s)$: Associative Memories
  - Pattern matching using AM technologies dates back to CDF SVT to enhance collection of events with long-lived hadrons
  - HL-LHC: much higher occupancy, higher event rates, higher granularity
  - Plan of development
    - Software emulation (ongoing)
    - Build a demonstrator system using ATLAS FastTracKer boards (started)
    - Develop dedicated AM chips and boards

![Diagram](image)
Tracker input to Level-1 trigger

- $\mu$, e and jet rates would substantially increase at high luminosity
  - Even considering “phase-1” trigger upgrades
- Increasing thresholds would affect physics performance
  - Performance of algorithms degrades with increasing pile-up
    - Muons: increased background rates from accidental coincidences
    - Electrons/photons: reduced QCD rejection at fixed efficiency from isolation
- Even HLT without tracking seems marginal
- Add tracking information at Level-1
  - Move part of HLT reconstruction into Level-1!

Goal for “track trigger”:

- Reconstruct tracks above 2 GeV
- Identify the origin along the beam axis with $\sim 1$ mm precision