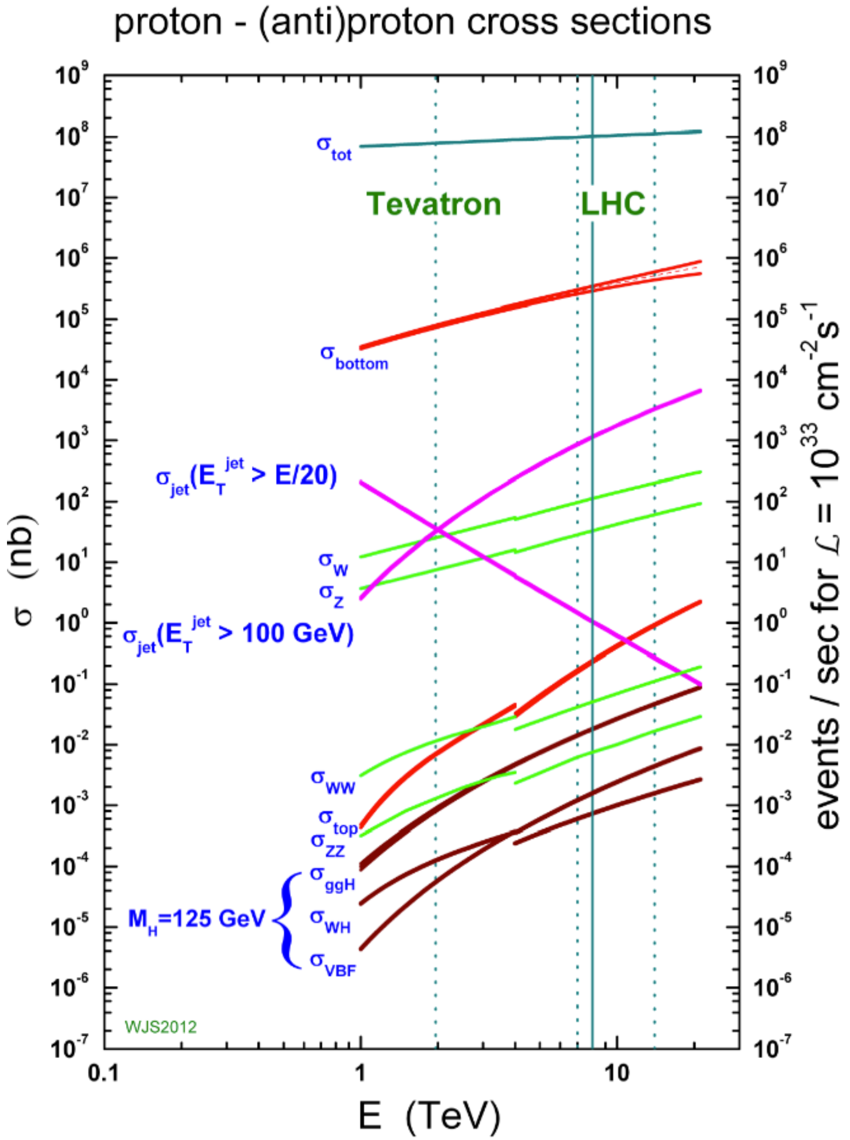
Trigger systems of the LHC experiments

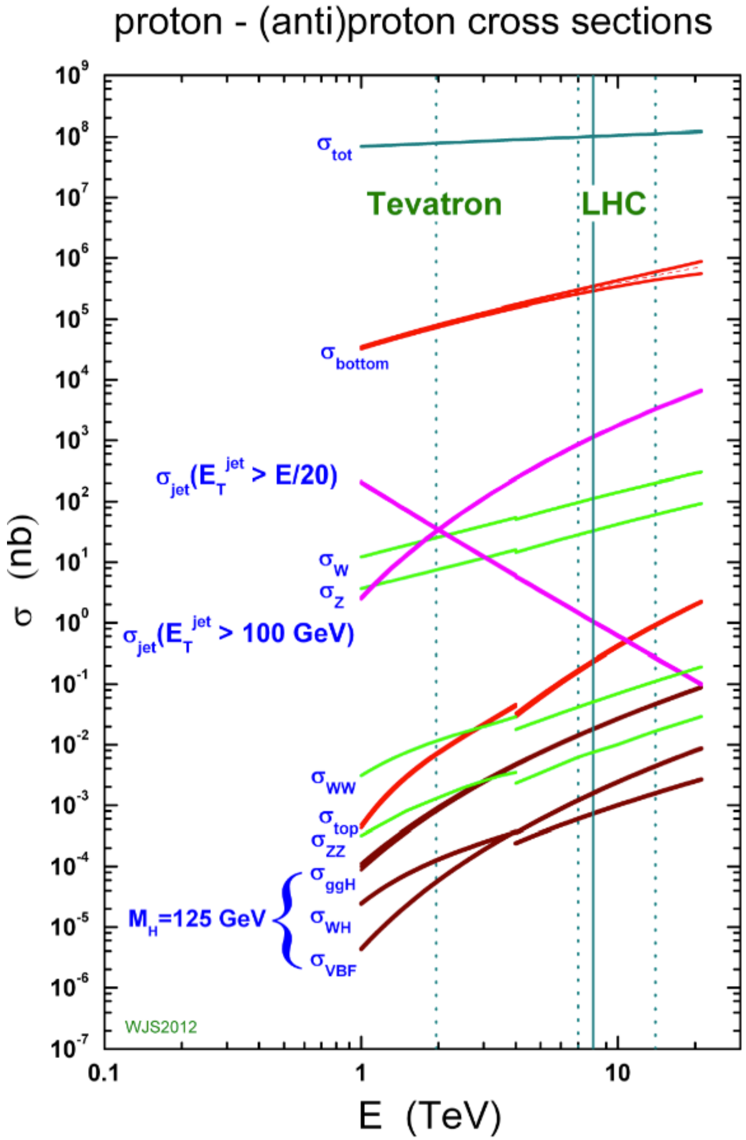
Present systems and upgrade plans

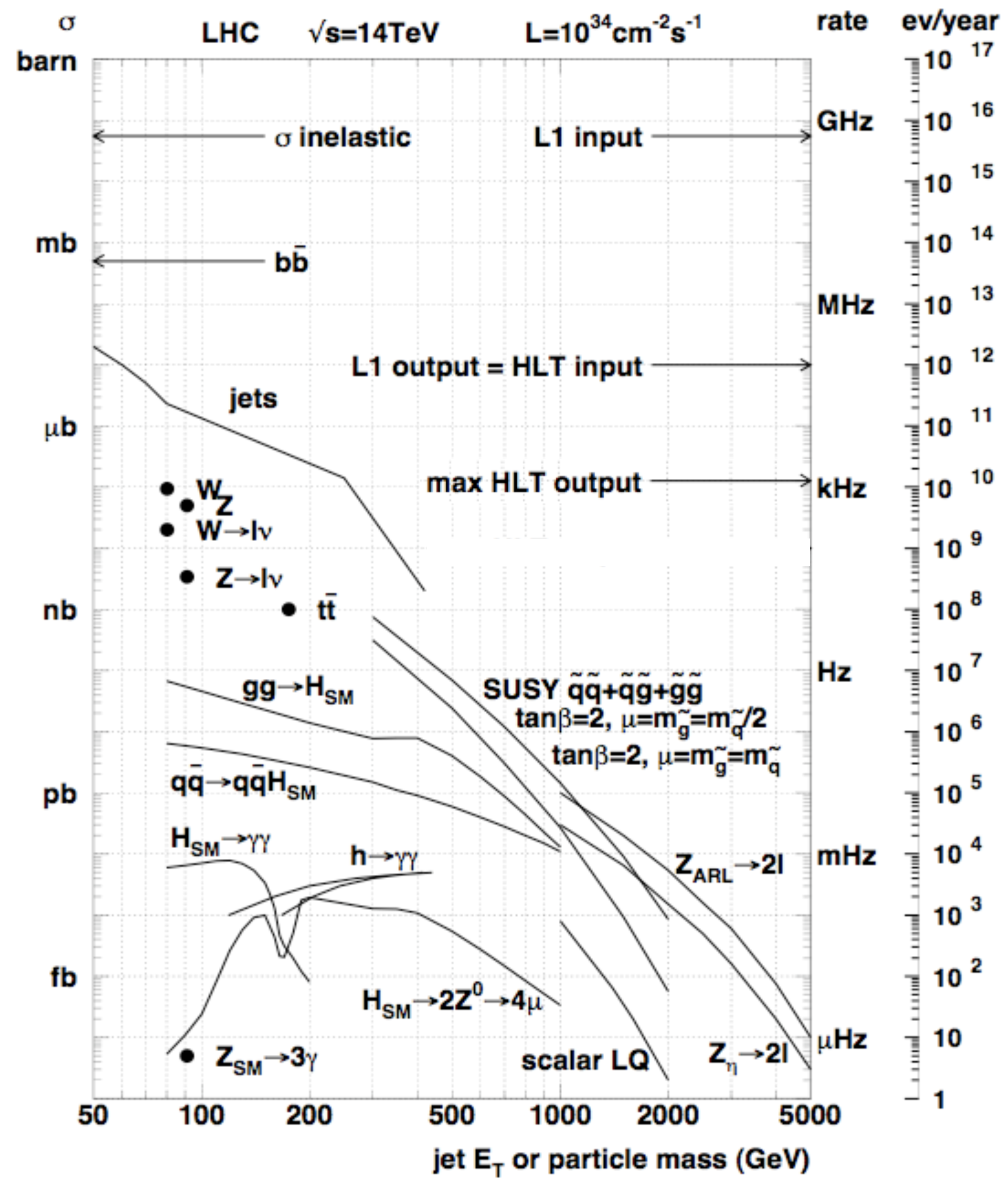
Manfred Jeitler
Institute of High Energy Physics of the
Austrian Academy of Sciences

rates of processes at LHC



rates of processes at LHC





data selection challenges at hadron colliders

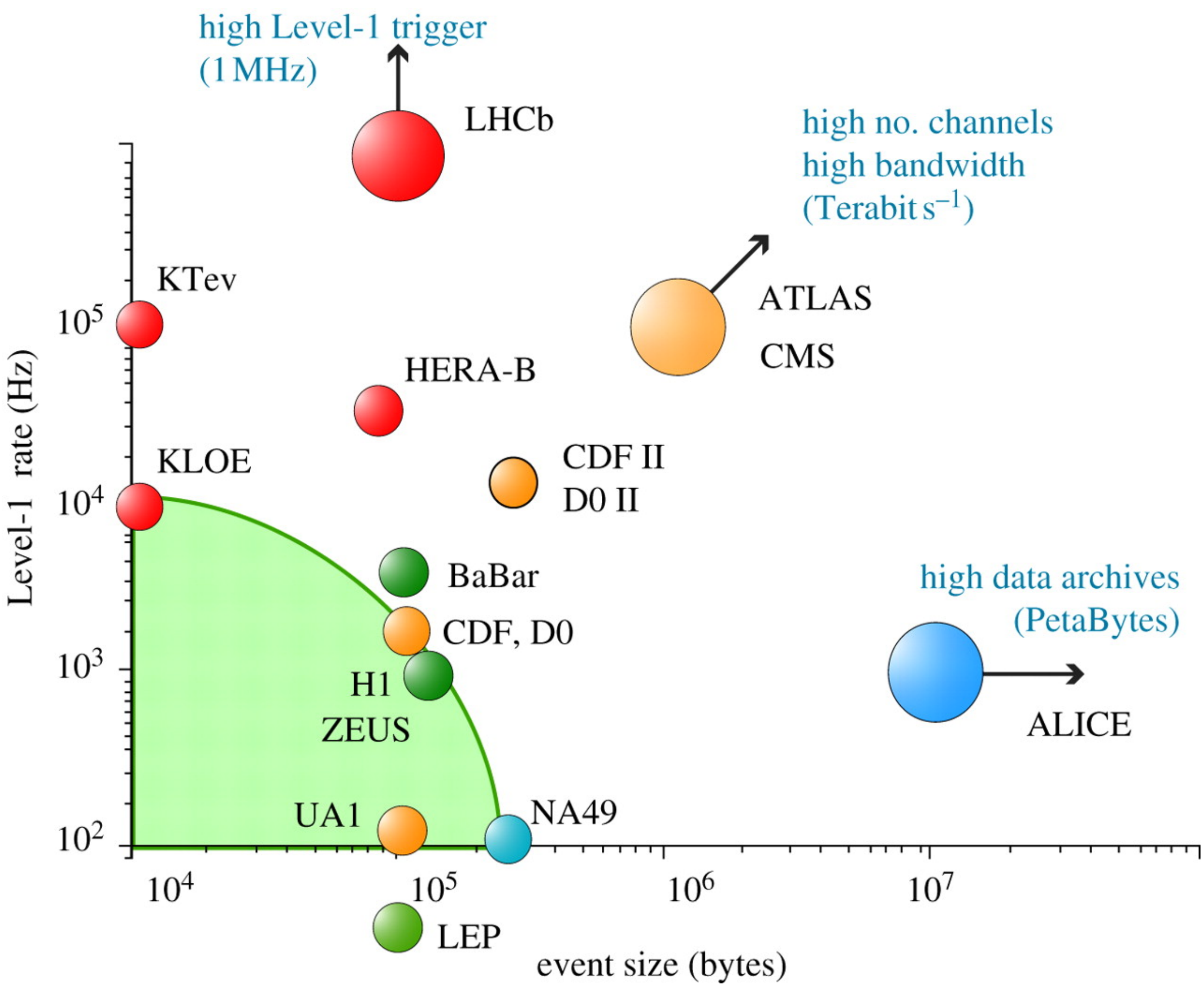
- high background rates
  - intrinsic problem of hadron colliders

- interesting events make up tiny fraction

- cutting hard on transverse momentum → signal loss

- sophisticated rate reduction methods needed

Trigger rates and data sizes



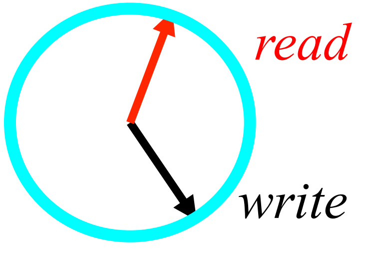
Differences between LHC experiments

- 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 → 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" → 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") → "latency"



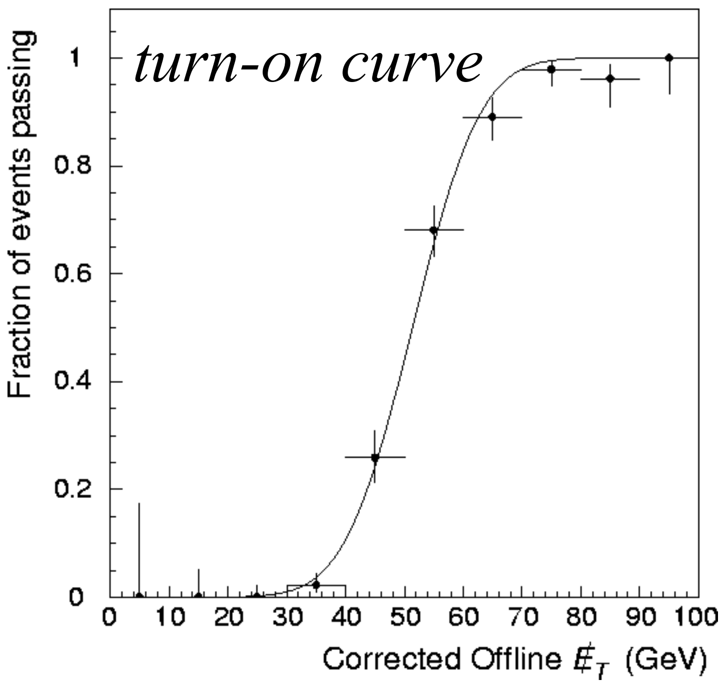
HEPHY Institute of High Energy Physics

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
  - 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



hardware trigger based on reduced information has

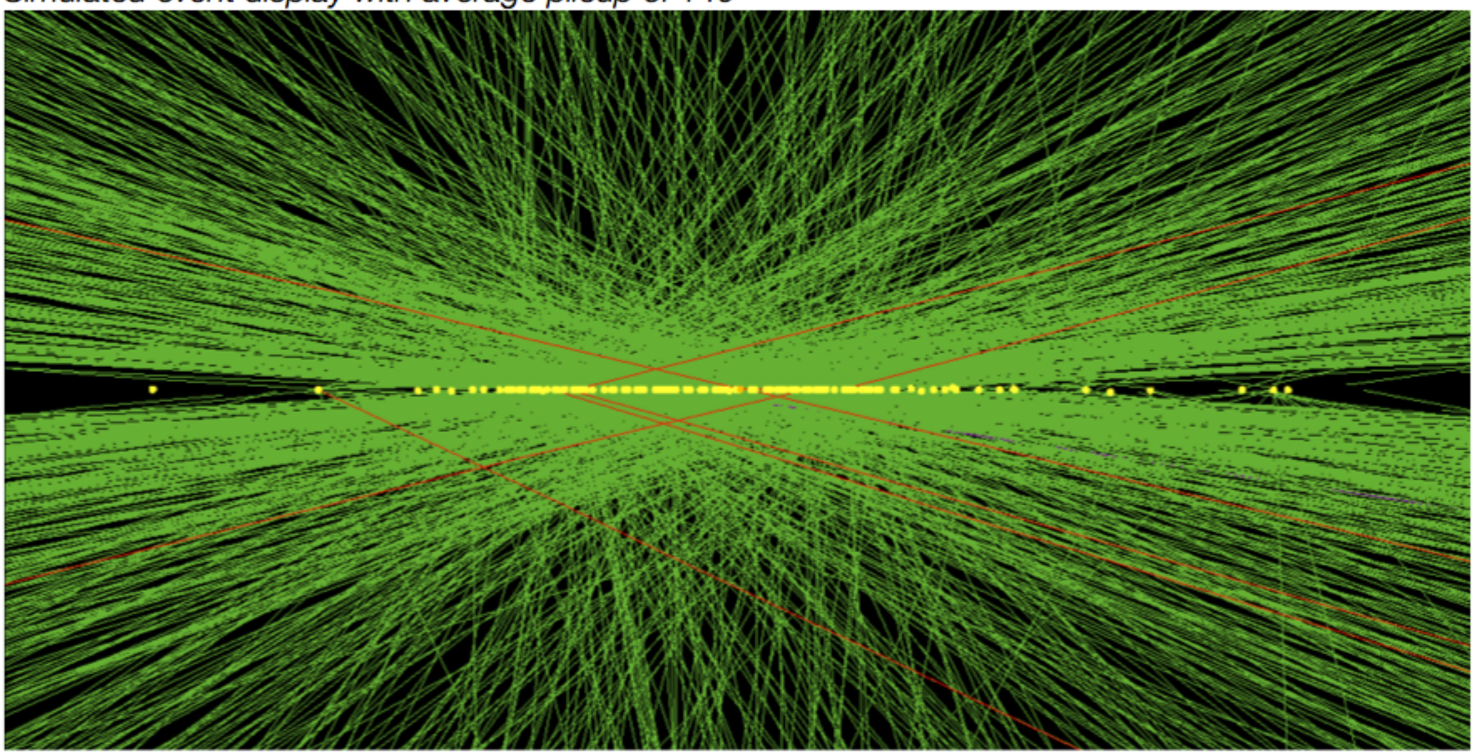
- *worse momentum resolution*
- *worse particle identification*
  - *electrons / photons*
  - *electrons / jets*

HEPHY
Institute of High Energy Physics

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

Simulated event display with average pileup of 140



pileup

about 50 - 60 in 2017

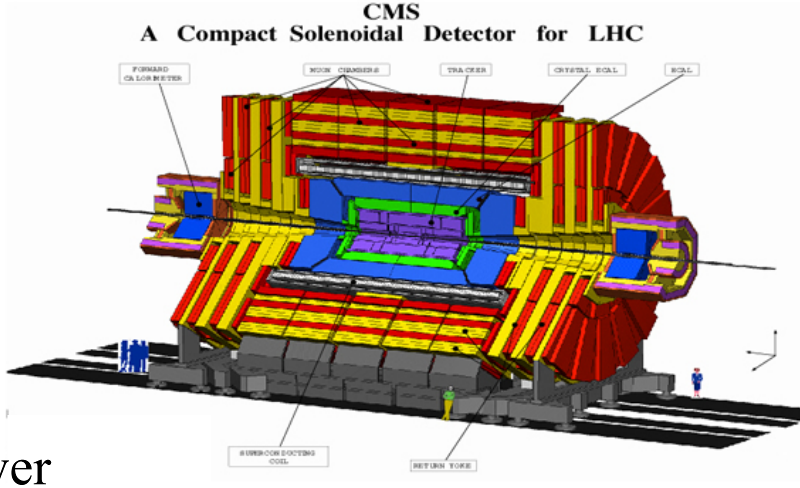
140 – 200 at High-Lumi LHC

need full resolution to resolve vertices!

HEPHY
Institute of High Energy Physics

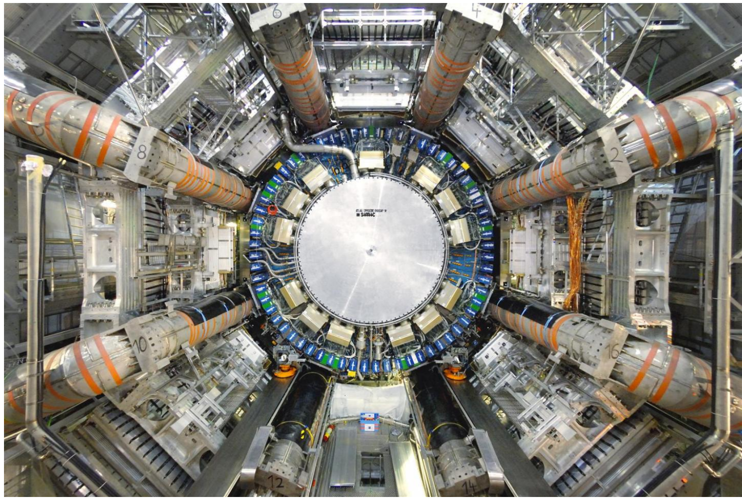
Why a hardware trigger?

- 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 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

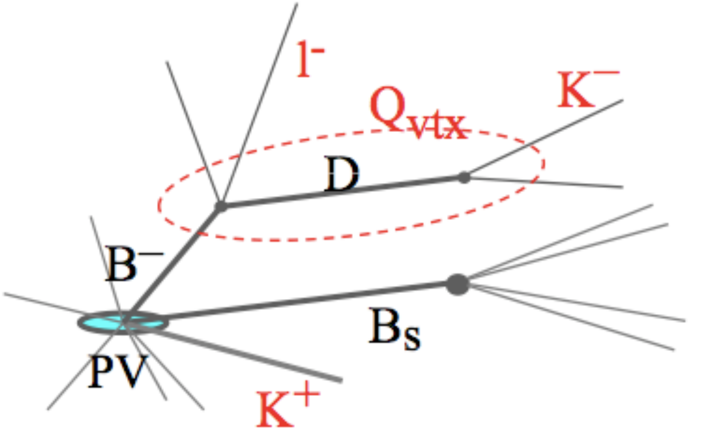
- *similar approach in both experiments:*
- both use data from muon systems and calorimeters
  - in reduced resolution
- both read out tracker only in case of "Level-1 Accept"
- similar latency (2.5 - 4 µs)



- *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

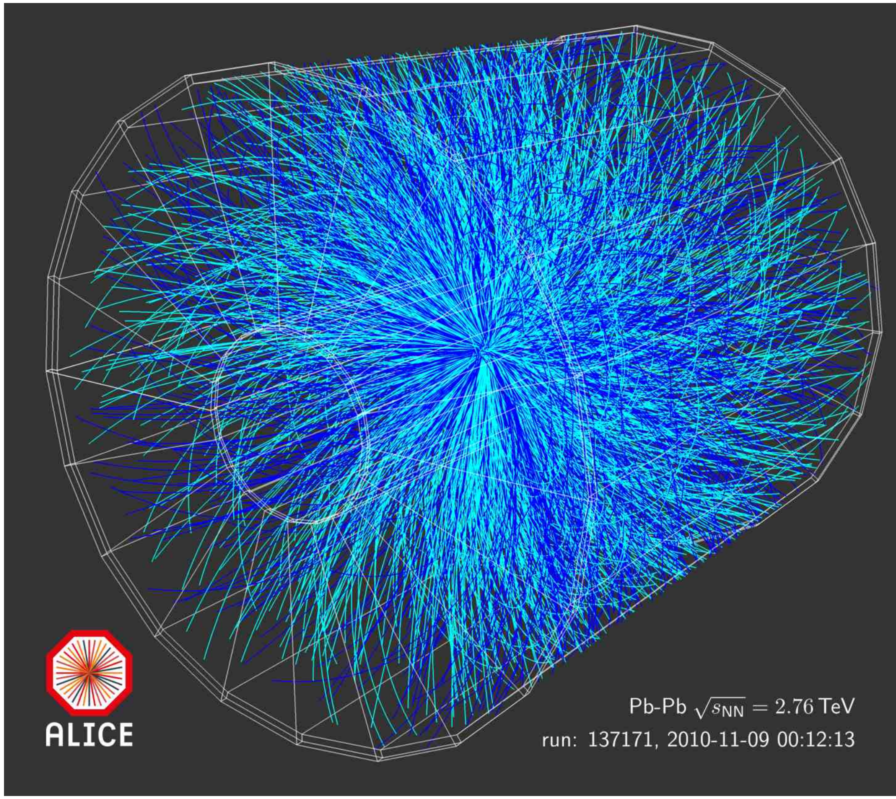
LHCb

- 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

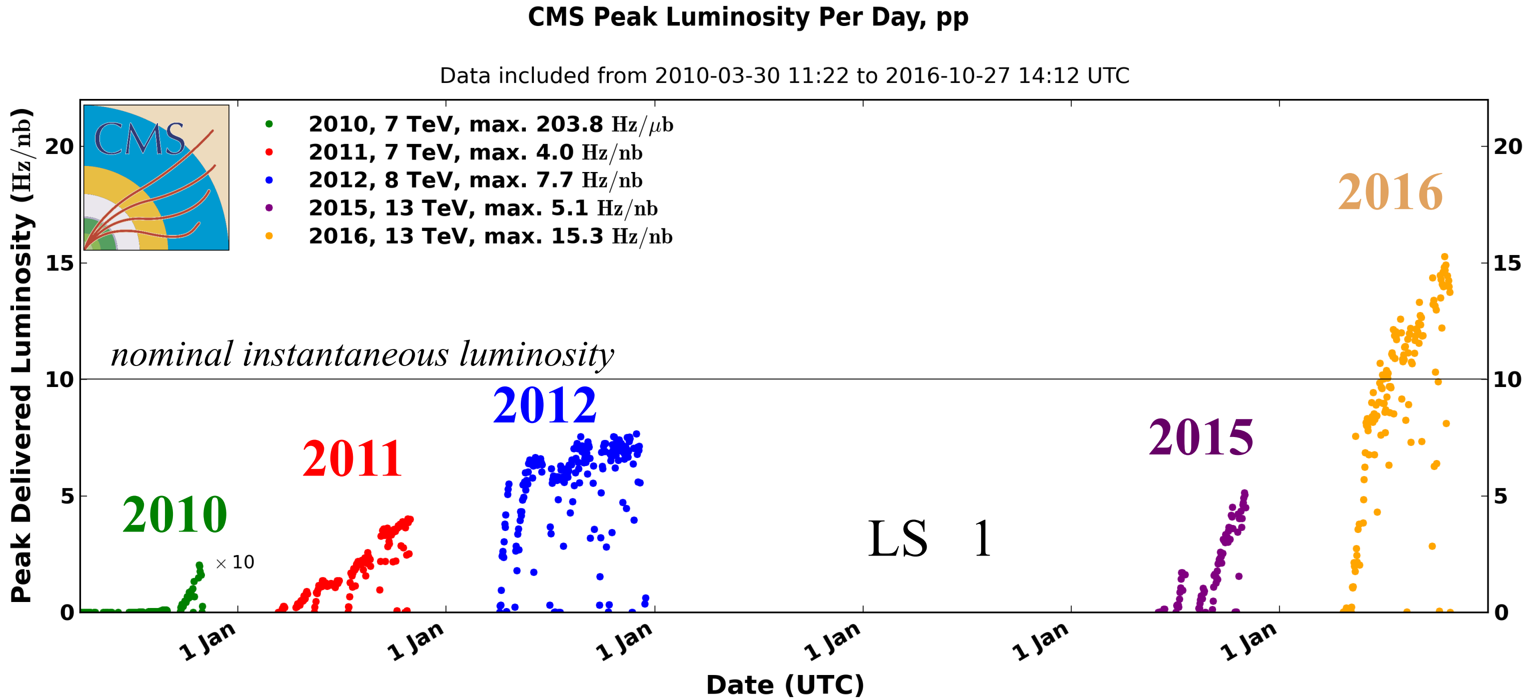


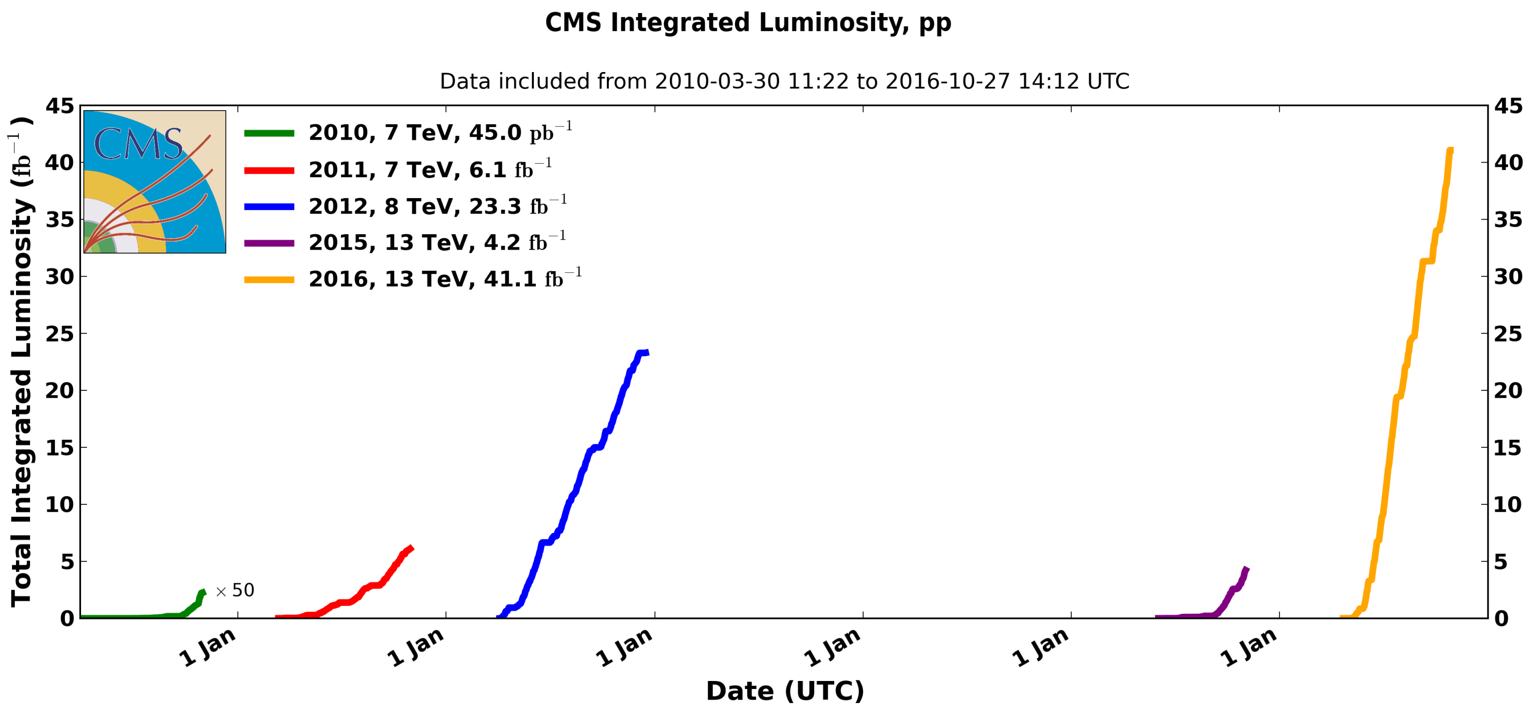
ALICE

- 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} cm^{-2} s^{-1} rather than 10^{34} cm^{-2} s^{-1}
- enormous complexity of events
  - tens of thousands of tracks per event
- core detector: TPC
  - Time Projection Chamber
  - slow readout → events overlapping in time hard to analyze
  - → "past-future protection"
- multi-layer trigger
  - hardware Level-0, Level-1, Level-2
  - High-Level Trigger computer farm



LHC luminosity build-up





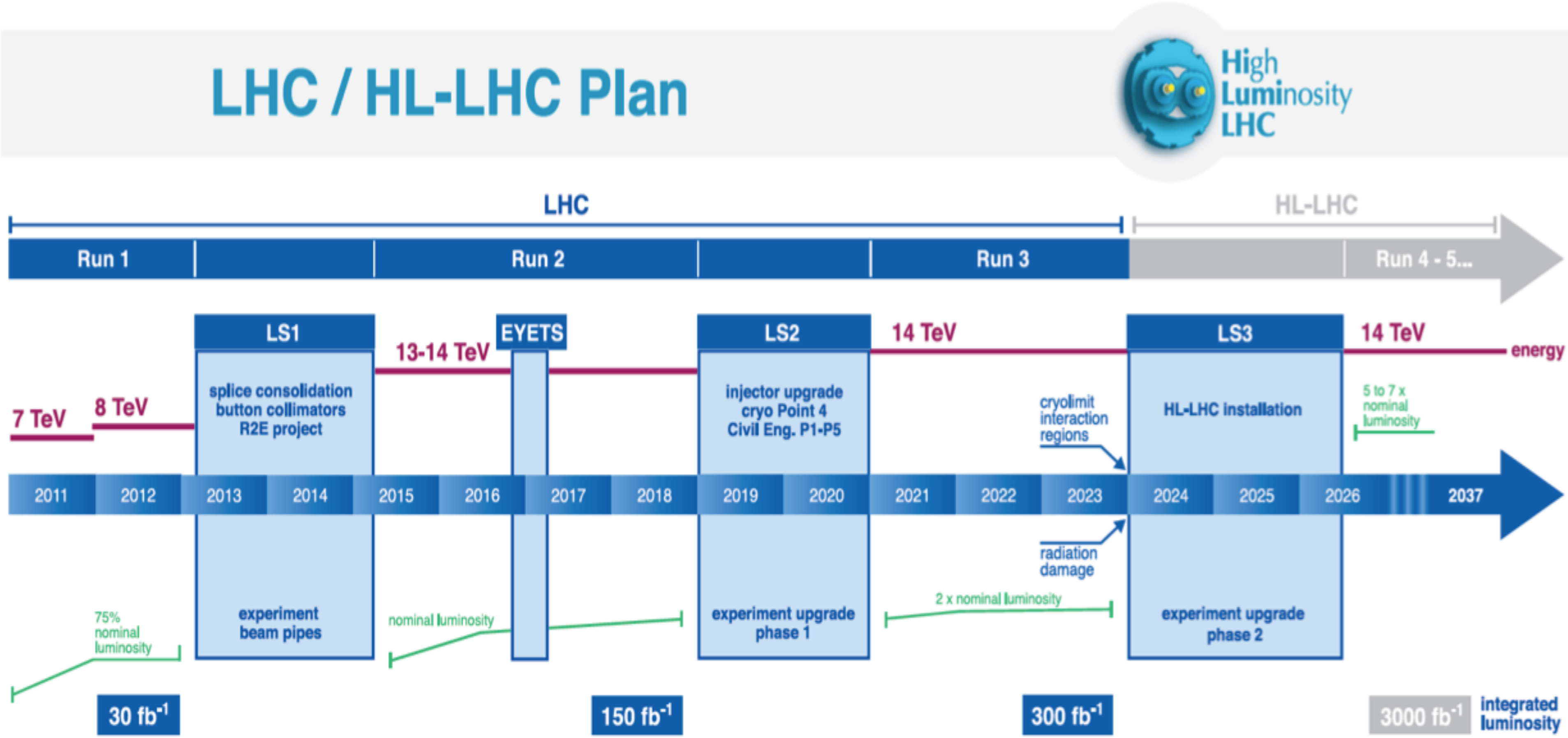
HEPHY Institute of High Energy Physics

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} cm^{-2} s^{-1}
- design goal for High-Luminosity LHC:
  - luminosity: 5 to 7.5 10^{34} cm^{-2} 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!

HEPHY Institute of High Energy Physics

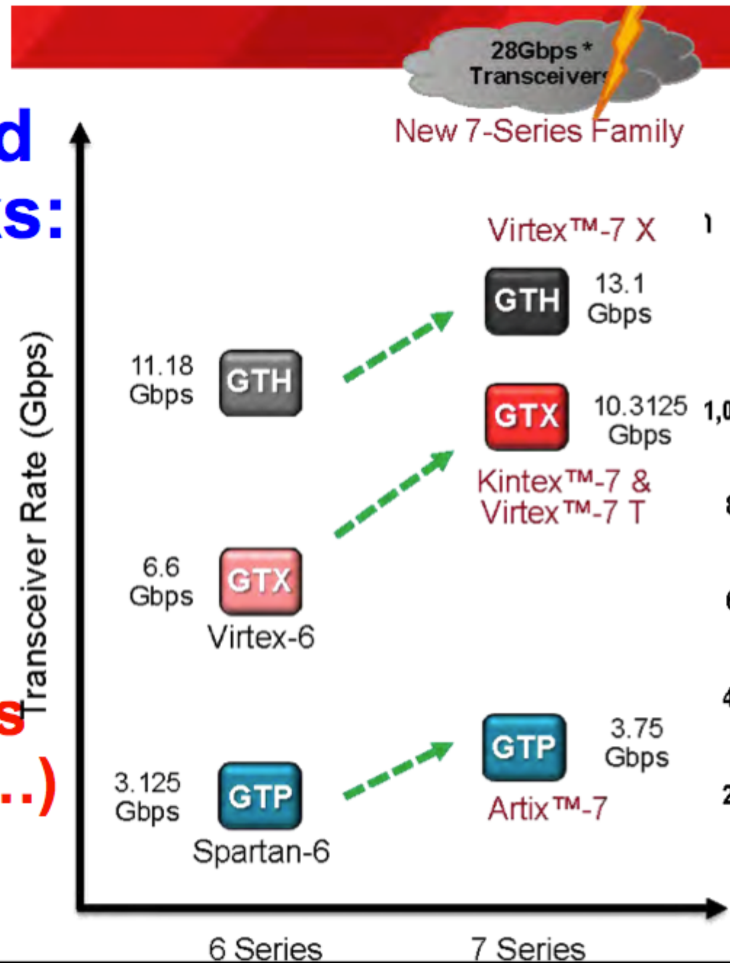
Progress in FPGAs

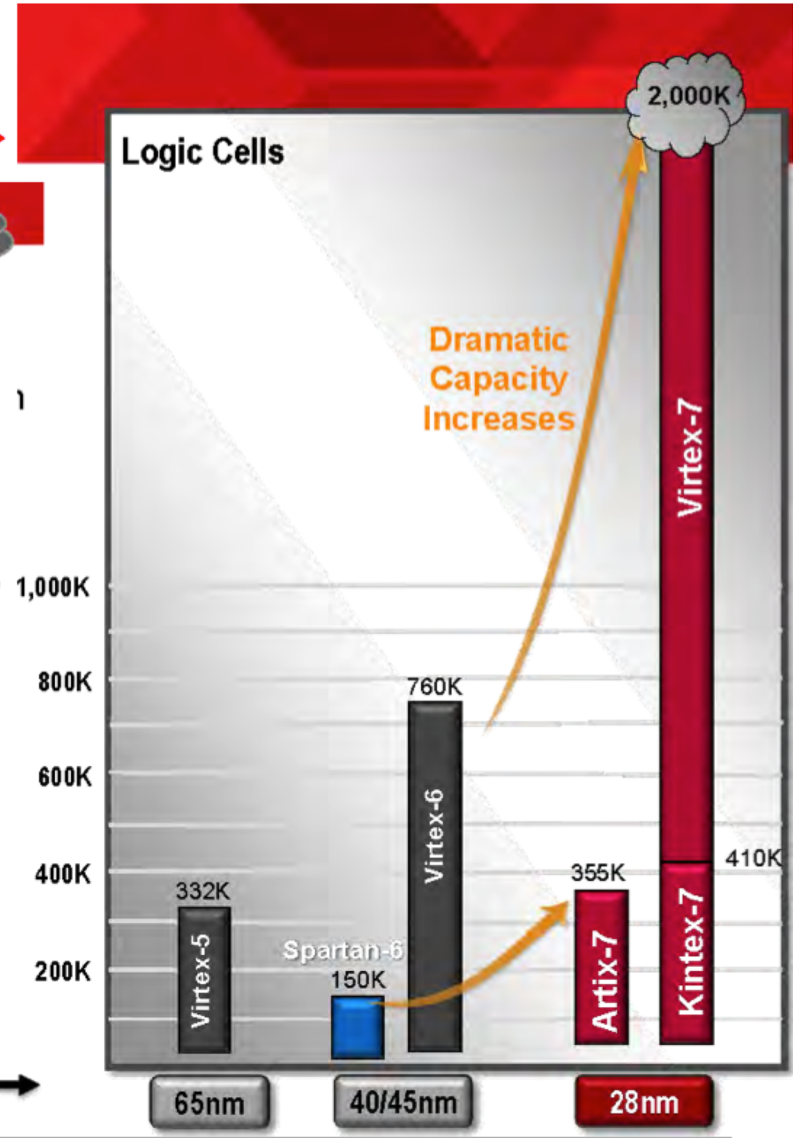
Logic Cells

- 28 nm: > 2X gains over 40 nm→

On-Chip High Speed Serial Links:

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





HEPHY Institute of High Energy Physics

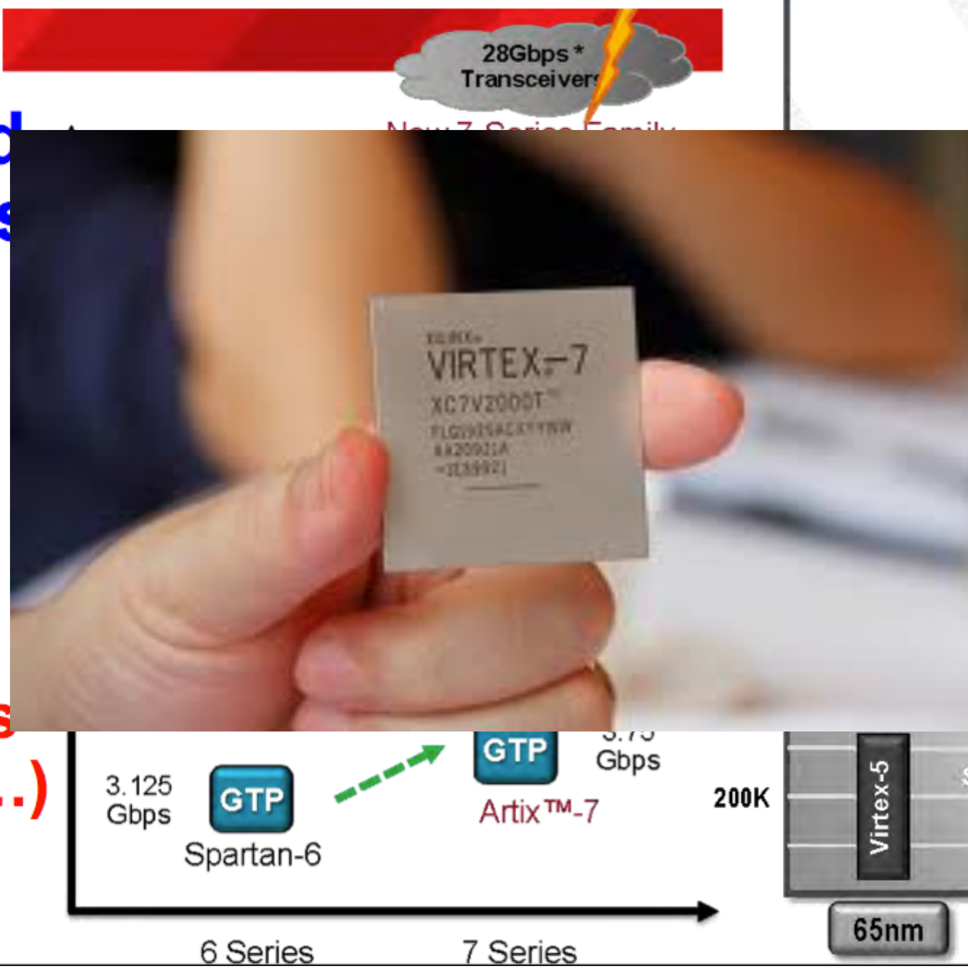
Progress in FPGAs

Logic Cells

- 28 nm: > 2X gains over 40 nm→

On-Chip High Speed Serial Links

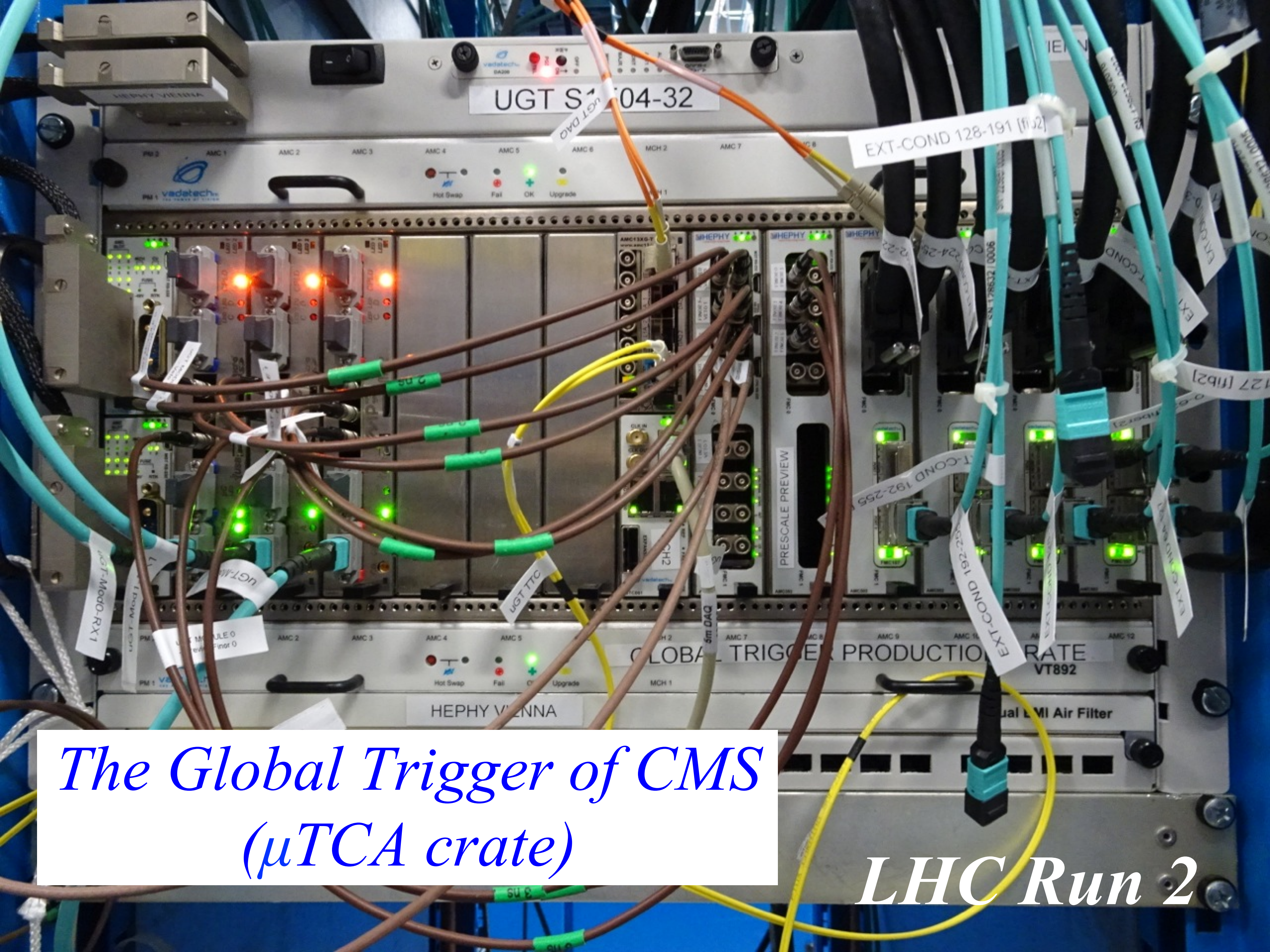
- Connect to new compact high density optical connectors (SNAP-12…)



FPGA trigger code example

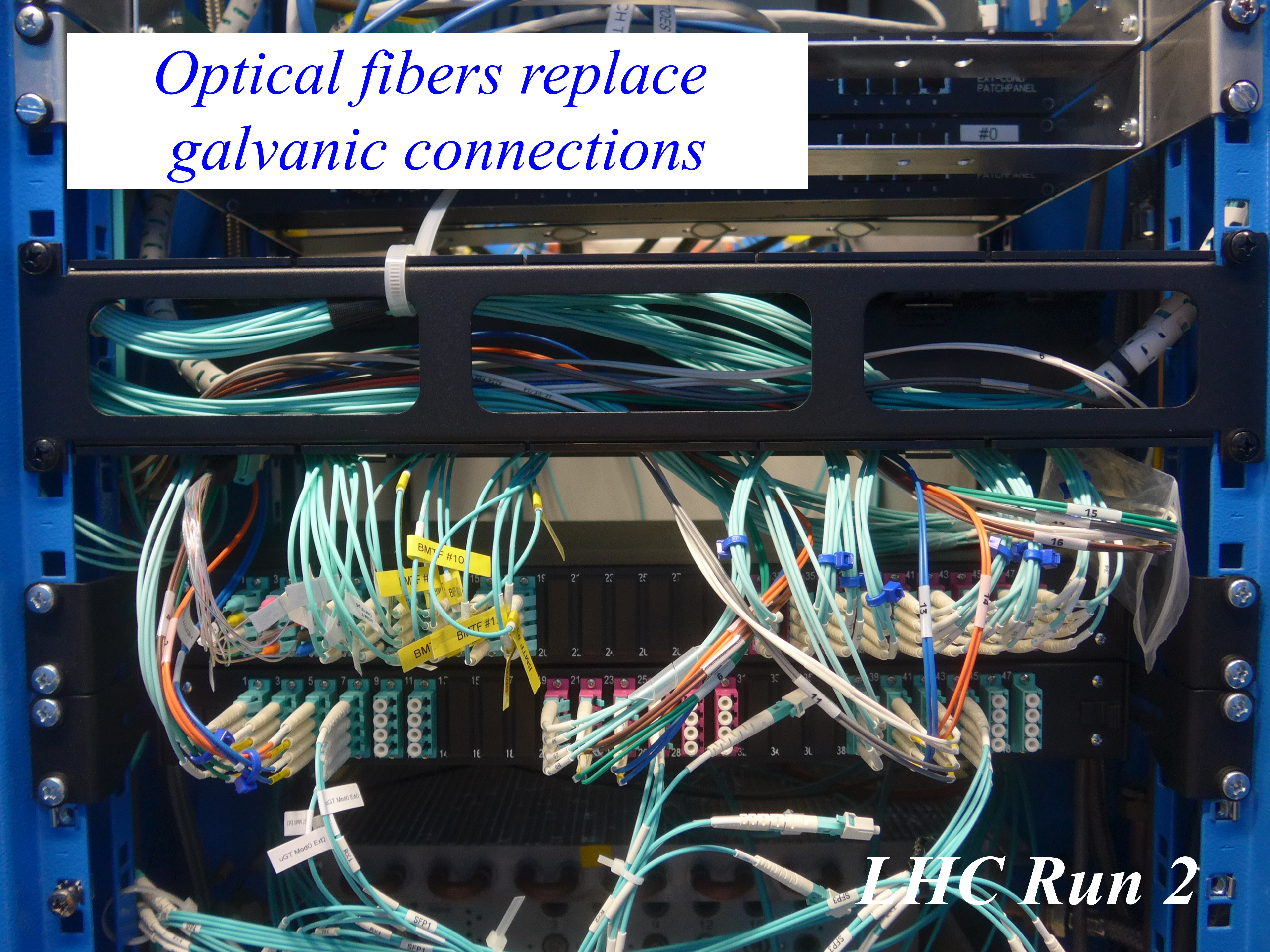
example: calculation of invariant mass of two objects

```
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;
        cosh_cos_width: positive := 28;
        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);
        cosh_deta : in std_logic_vector(cosh_cos_width-1 downto 0);  -- cosh of eta1 - eta2
        cos_dphi : in std_logic_vector(cosh_cos_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+cosh_cos_width-1 downto 0)
    );
end invariant_mass;

architecture rtl of invariant_mass is

  constant INV_MASS_VECTOR_WIDTH : positive := pt1_width+pt2_width+cosh_cos_width;
  constant INV_MASS_PRECISION_FACTOR : real := real(10**INV_MASS_PRECISION);.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_MAS

  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

    -- Converting the boundary value for the comparison
    upper_limit_vector <= conv_std_logic_vector((integer(upper_limit*INV_MASS_PRECISION_FACTOR)),INV_MASS_VECTOR_WIDTH-FACTOR_4_VECTOR'length)*FACTOR_4_VECTOR;
    lower_limit_vector <= conv_std_logic_vector((integer(lower_limit*INV_MASS_PRECISION_FACTOR)),INV_MASS_VECTOR_WIDTH-FACTOR_4_VECTOR'length)*FACTOR_4_VECTOR;

    -- Calculation of invariant mass with the formula: M**2/2 = pt1*pt2 * (cosh(eta1 - eta2) - cos(phi1 - phi2))
    inv_mass_sq_div2 <= pt1 * pt2 * (cosh_deta - cos_dphi);
    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)

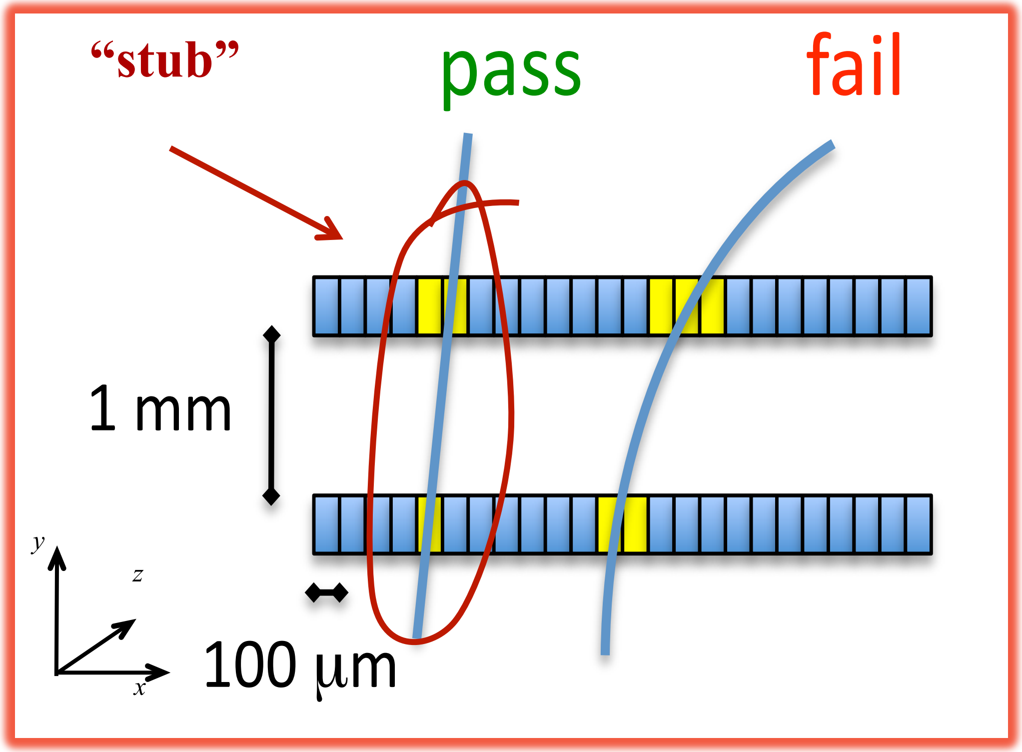
LHC Run 2


Optical fibers replace galvanic connections
LHC Run 2
#0
BMTF #10
15
16
13
14
uGT Mod0 Ext2
SFP1

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, μ, τ)
- 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 4π 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

CMS Experiment at the LHC, CERN
Data recorded: 2016-Sep-08 08:30:28.497920 GMT
Run / Event / LS: 280327 / 55711771 / 67

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

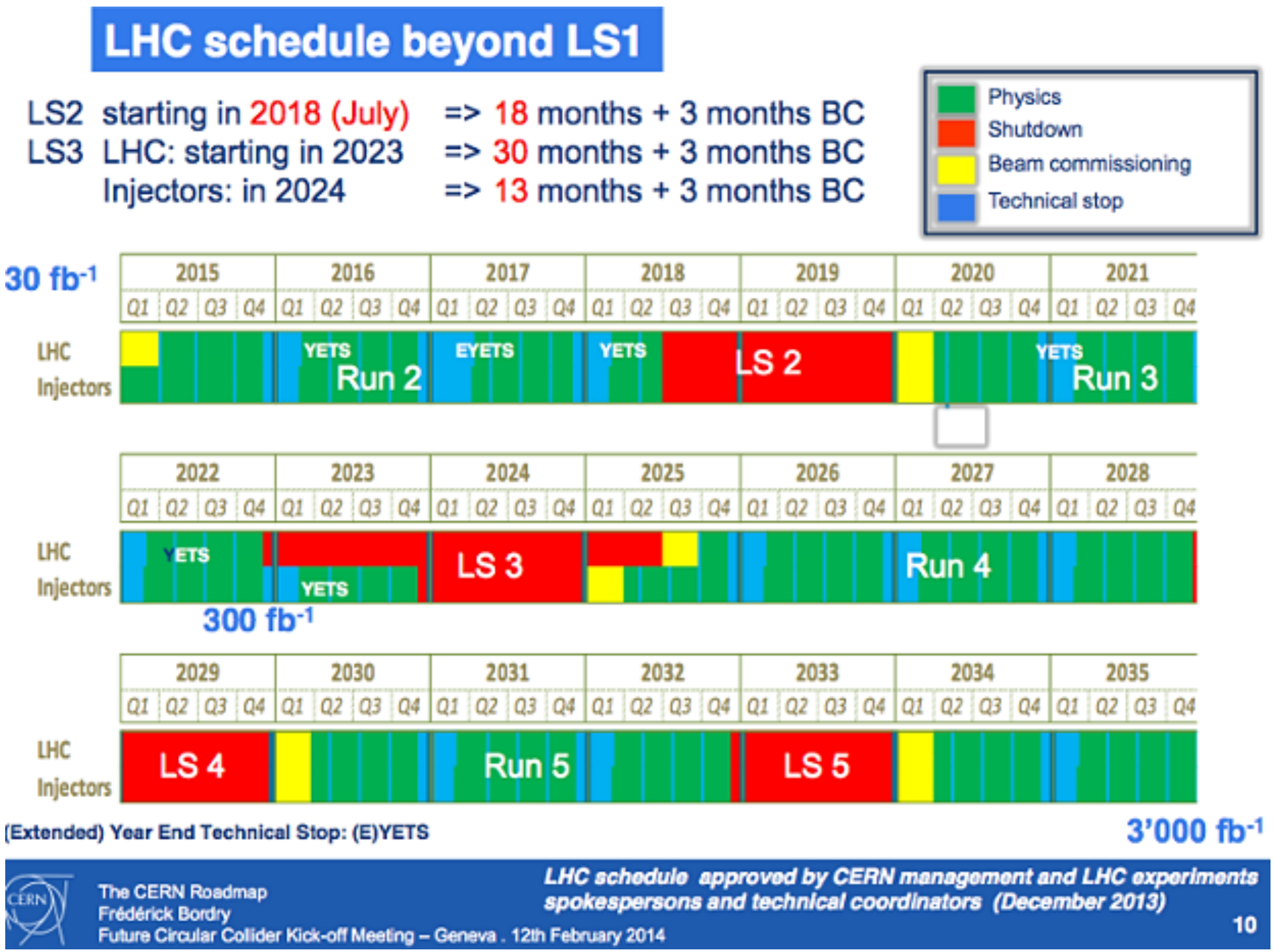
References

- Letter of Intent for the Phase-II Upgrade of the ATLAS Experiment
  - https://cds.cern.ch/record/1502664
- ATLAS Phase-II Upgrade Scoping Document
  - https://cds.cern.ch/record/2055248/files/LHCC-G-166.pdf
- 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
  - https://cds.cern.ch/record/1701361/files/LHCB-TDR-016.pdf
- ALICE Upgrade of the Readout & Trigger System TDR
  - https://cds.cern.ch/record/1603472/files/ALICE-TDR-015.pdf

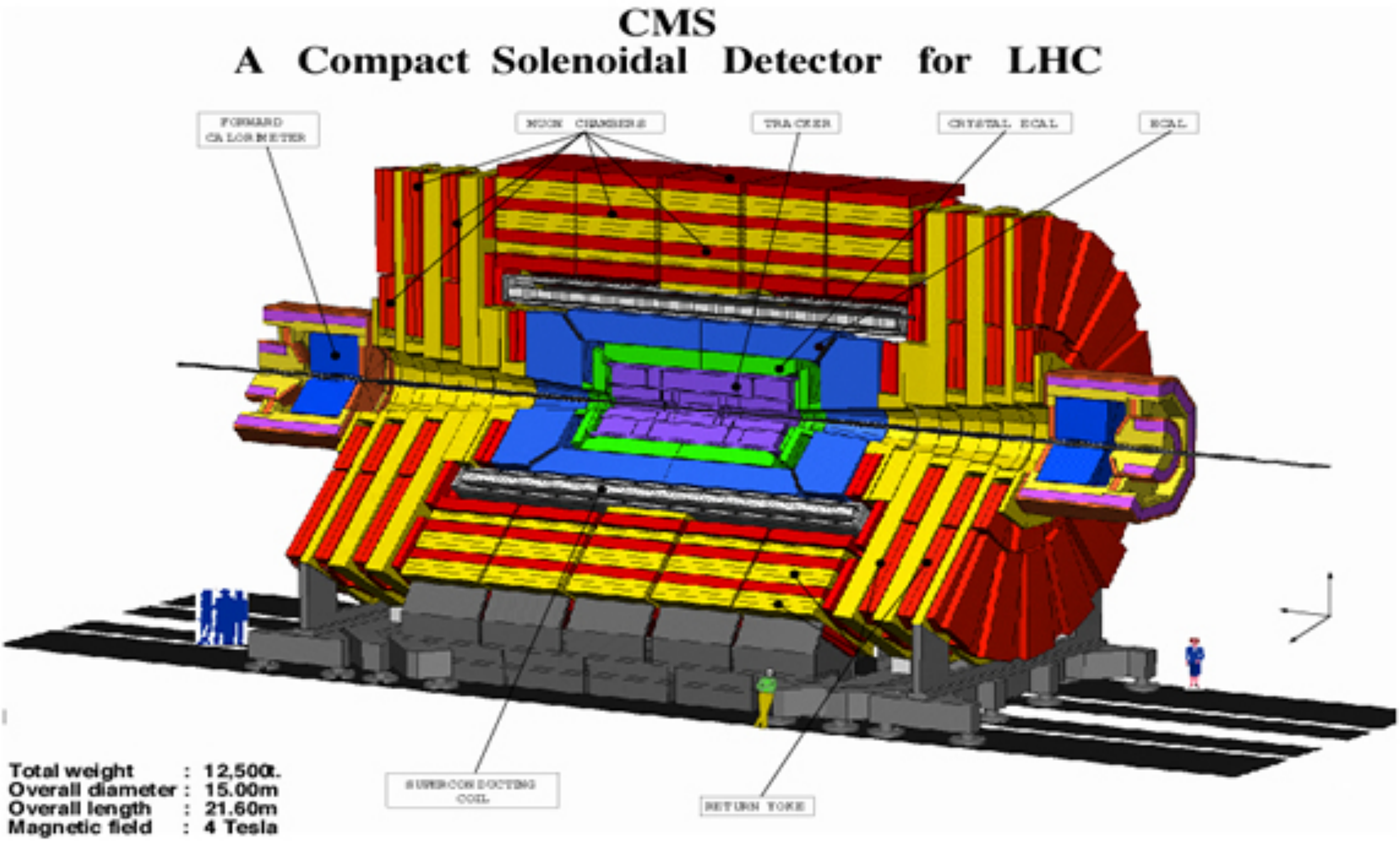
BACKUP

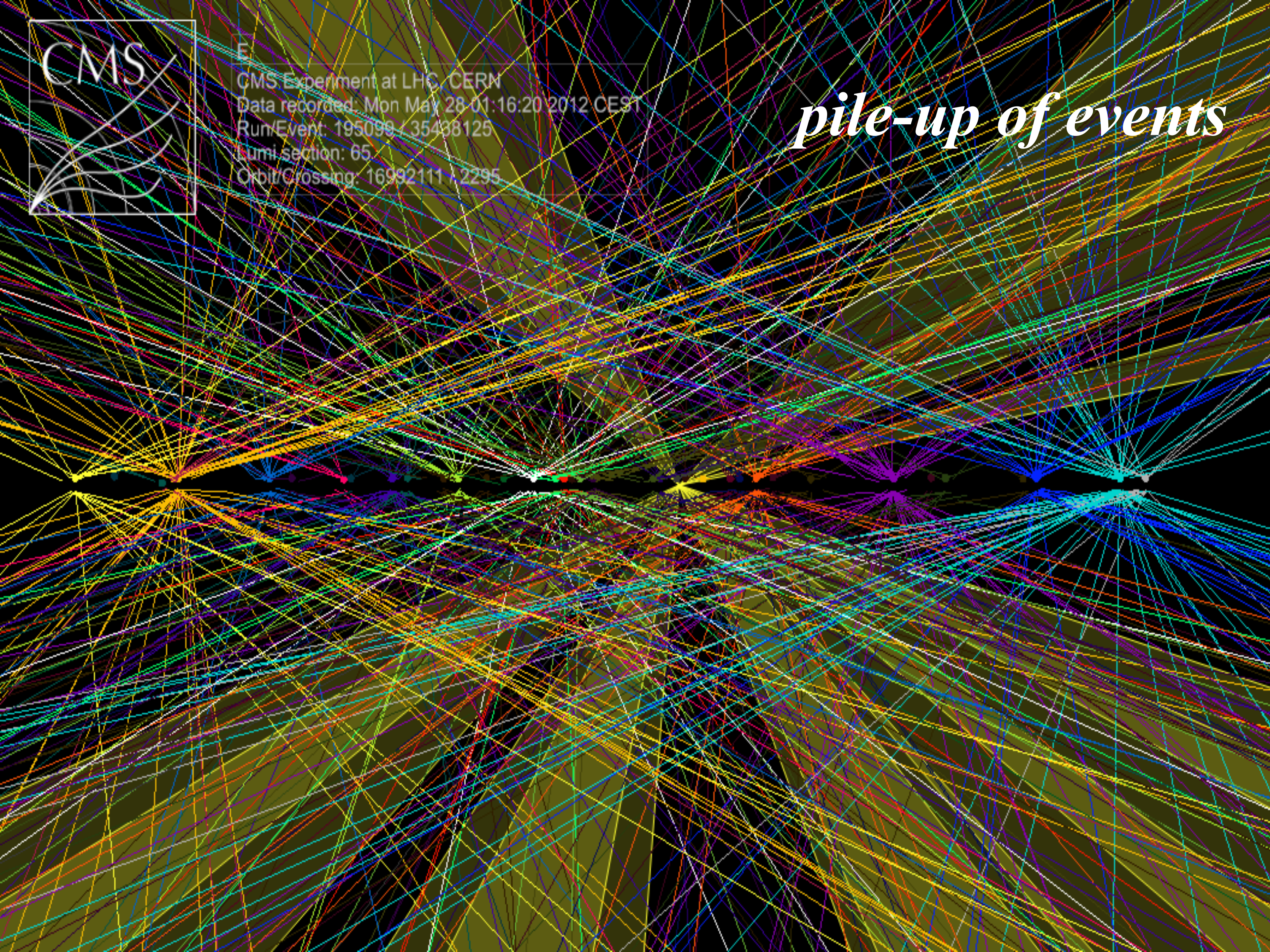
HEPHY
Institute of High Energy Physics

LHC upgrade schedule

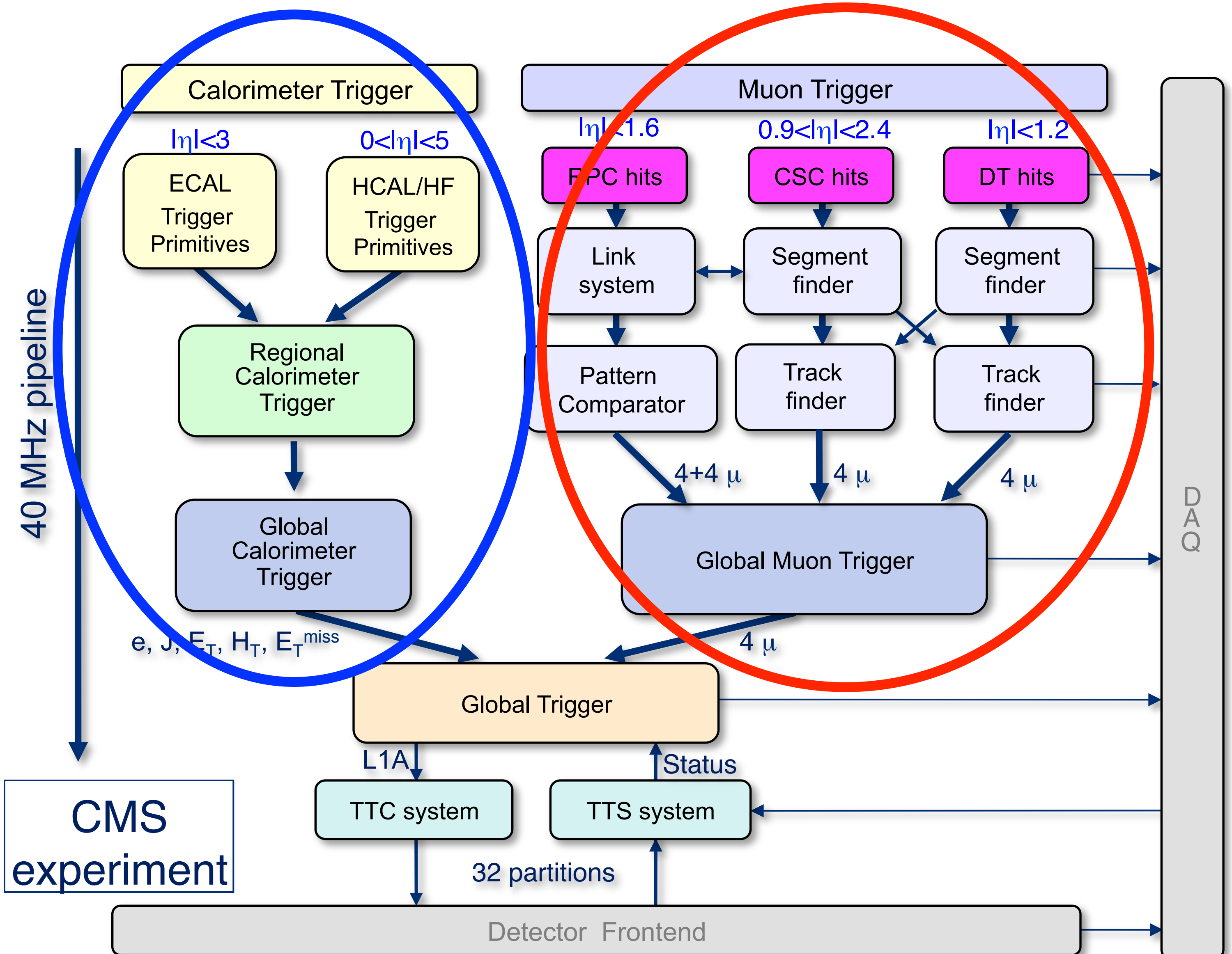


*The Compact **MUON** Solenoid*

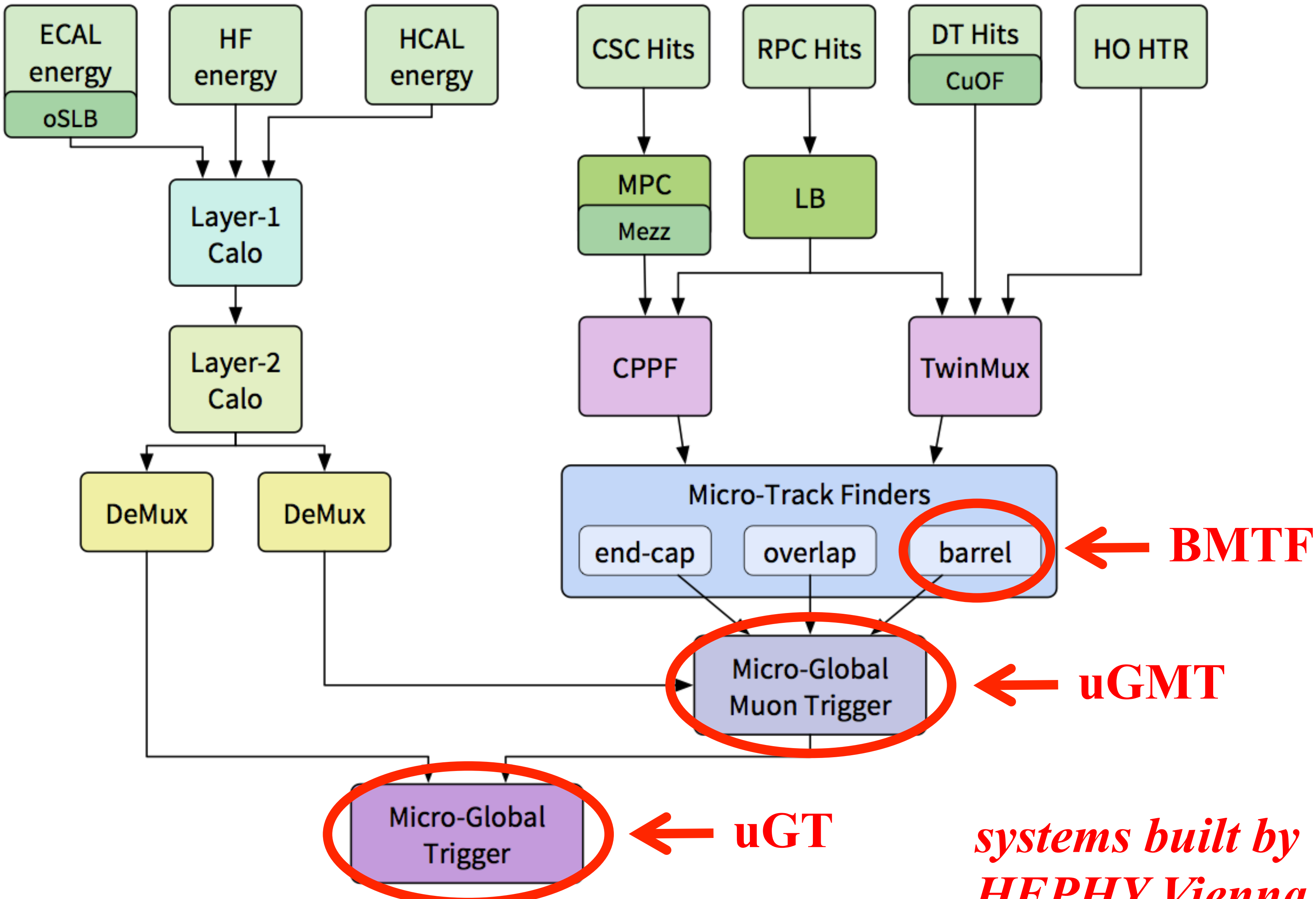



CMS
CMS Experiment at LHC, CERN
Data recorded: Mon May 28 01:16:20 2012 CEST
Run/Event: 195099 / 35438125
Lumi section: 65
Orbit/Crossing: 16992111 / 2295
pile-up of events

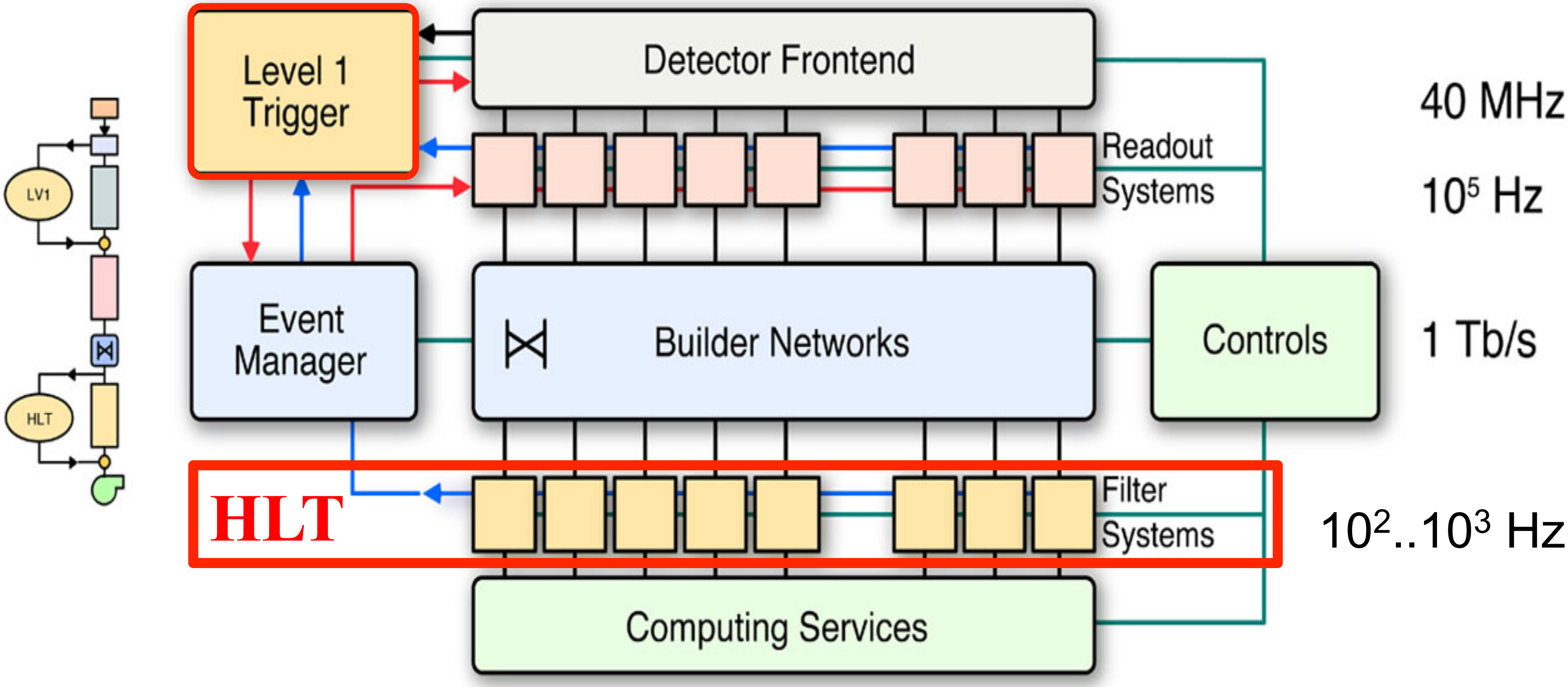
L1 Trigger Layout in LHC Run 1



L1 Trigger Layout in LHC Run 2

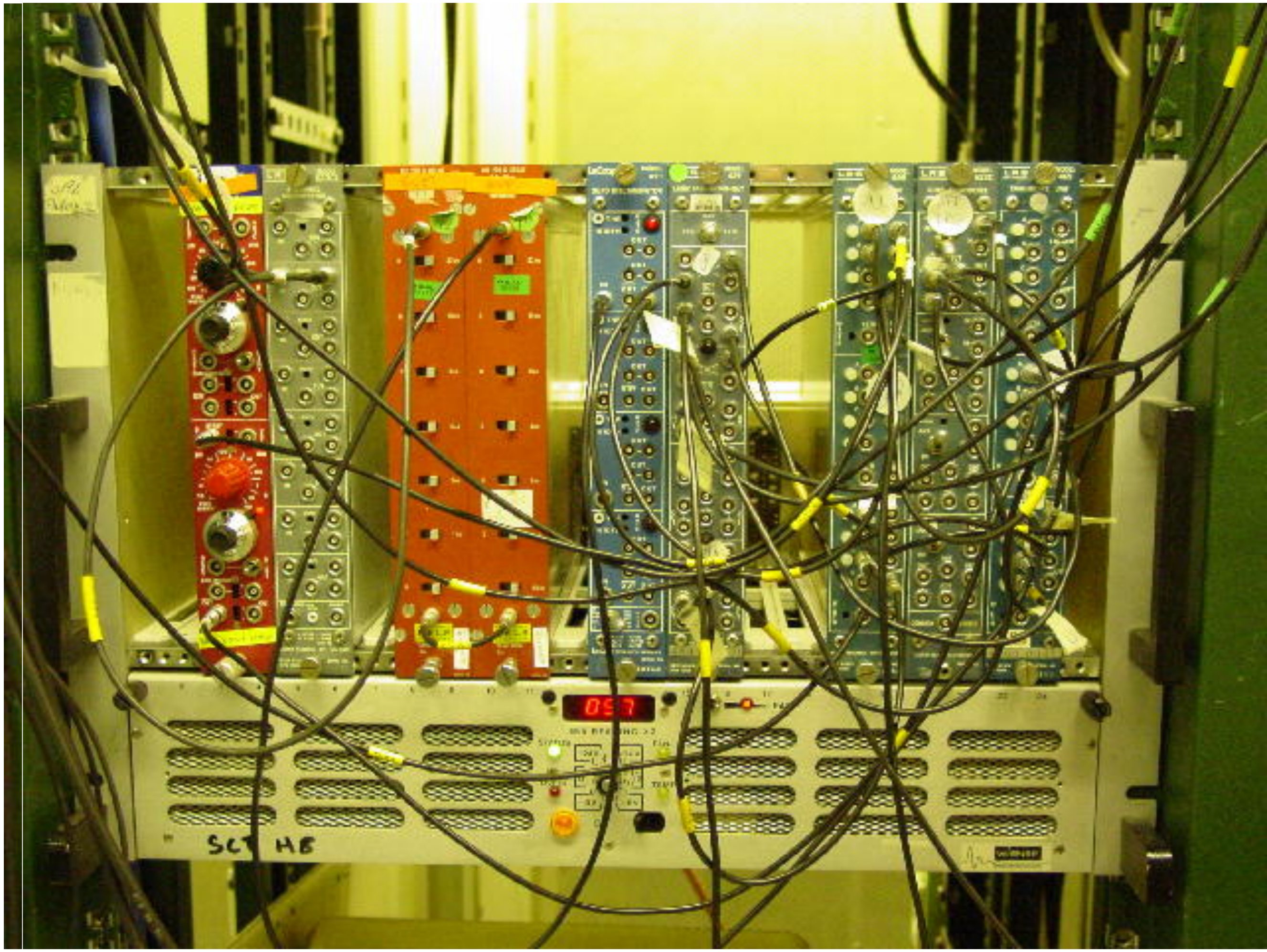


CMS Trigger & DAQ Systems



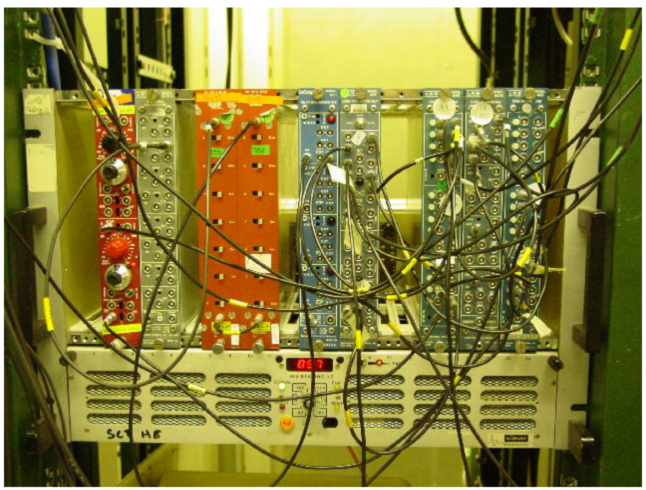
detectors yielding electrical output signals allow to select events to be recorded by electronic devices

- 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  ⇒ 1x 

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

LHC Run 1

LHC Run 1 (<=2012): many parallel galvanic connections

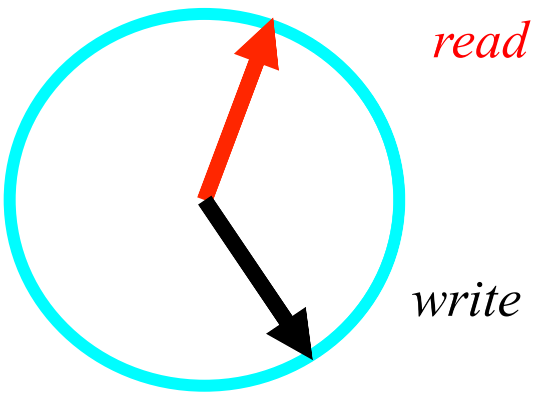
Example:

Drift Tube Track Finder (part of muon trigger)

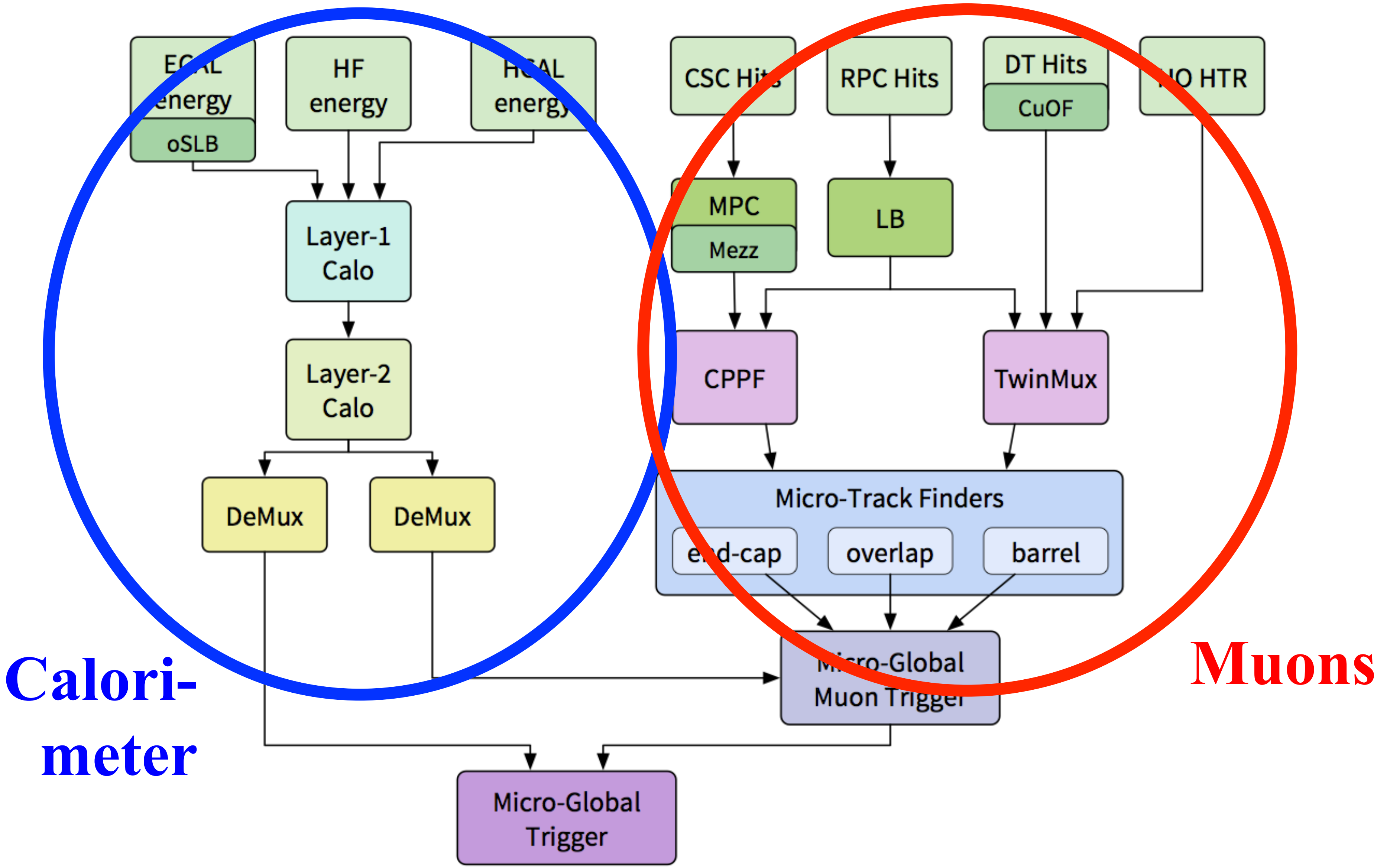
LHC Run 1

How do we trigger ?

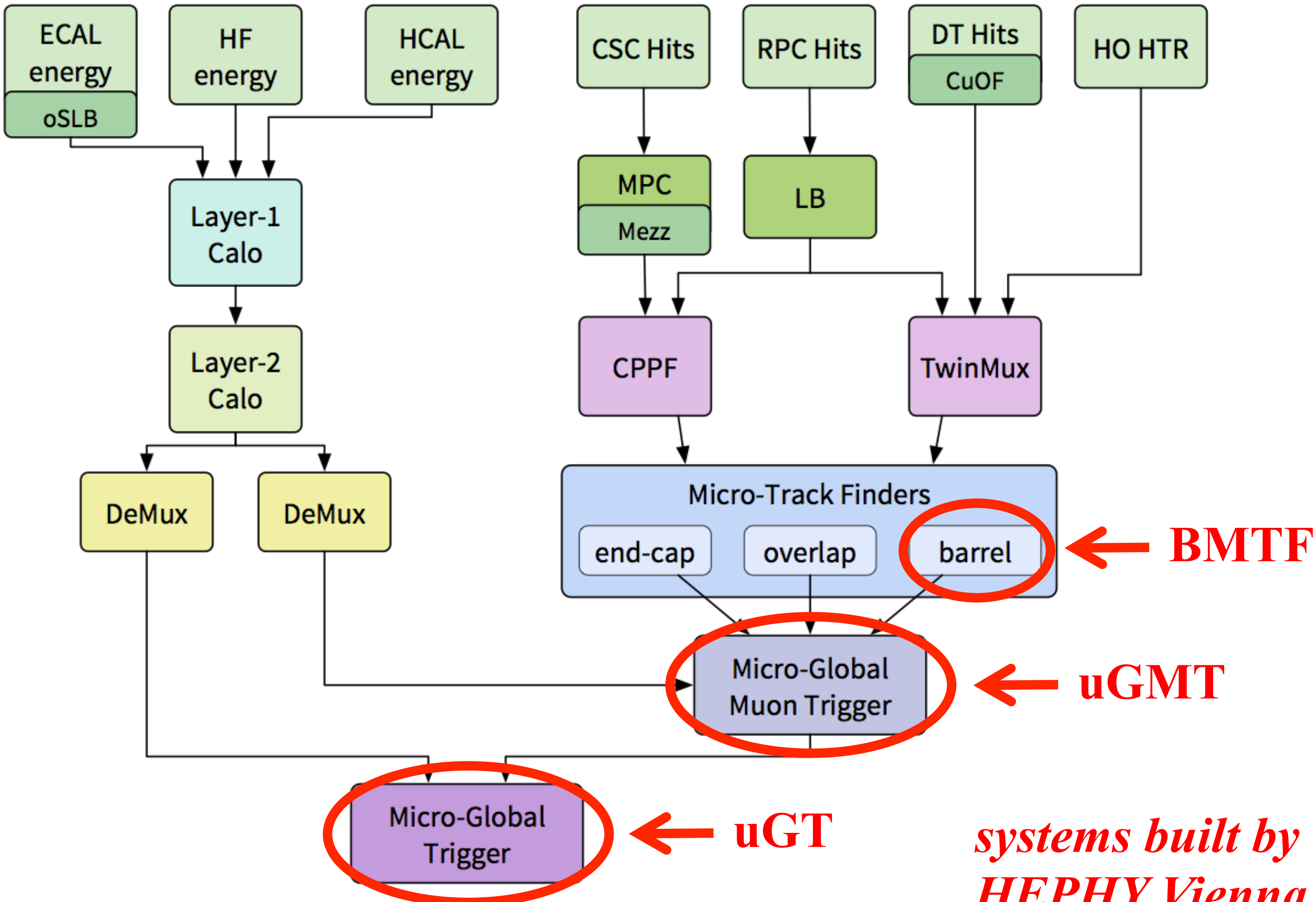
- at a rate of 40 MHz impossible to read out all detector data
- preliminary decision based on part of the event data only
- be quick!
  - in case of positive trigger decision all detector data must still be available
  - data are stored temporarily in a "pipeline" in the detector electronics
    - "short 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

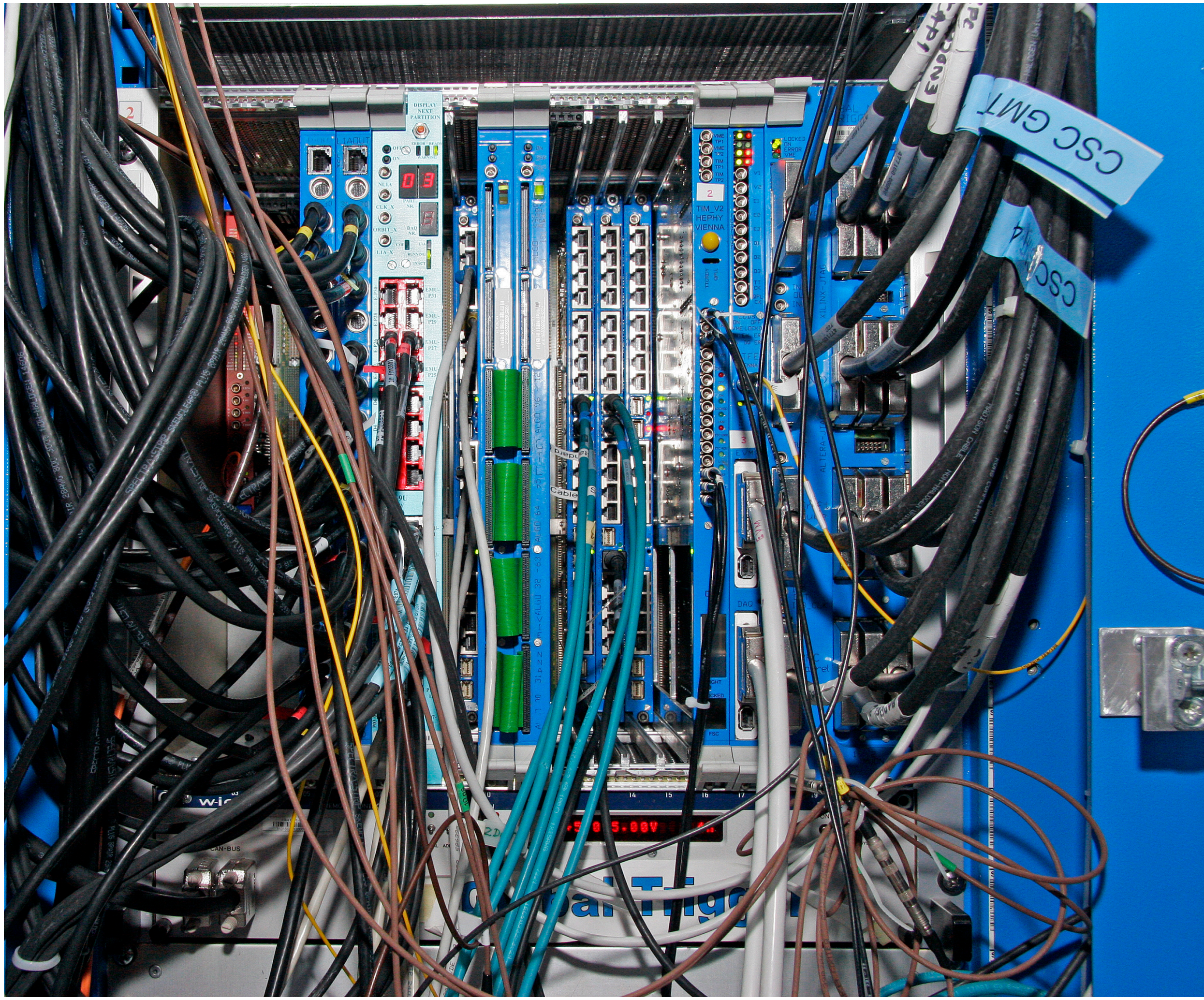


L1 Trigger Layout in LHC Run 2



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)

LHC Run 1

Commercial µTCA module
MCH (MicroTCA Carrier Hub)

When do we trigger ?

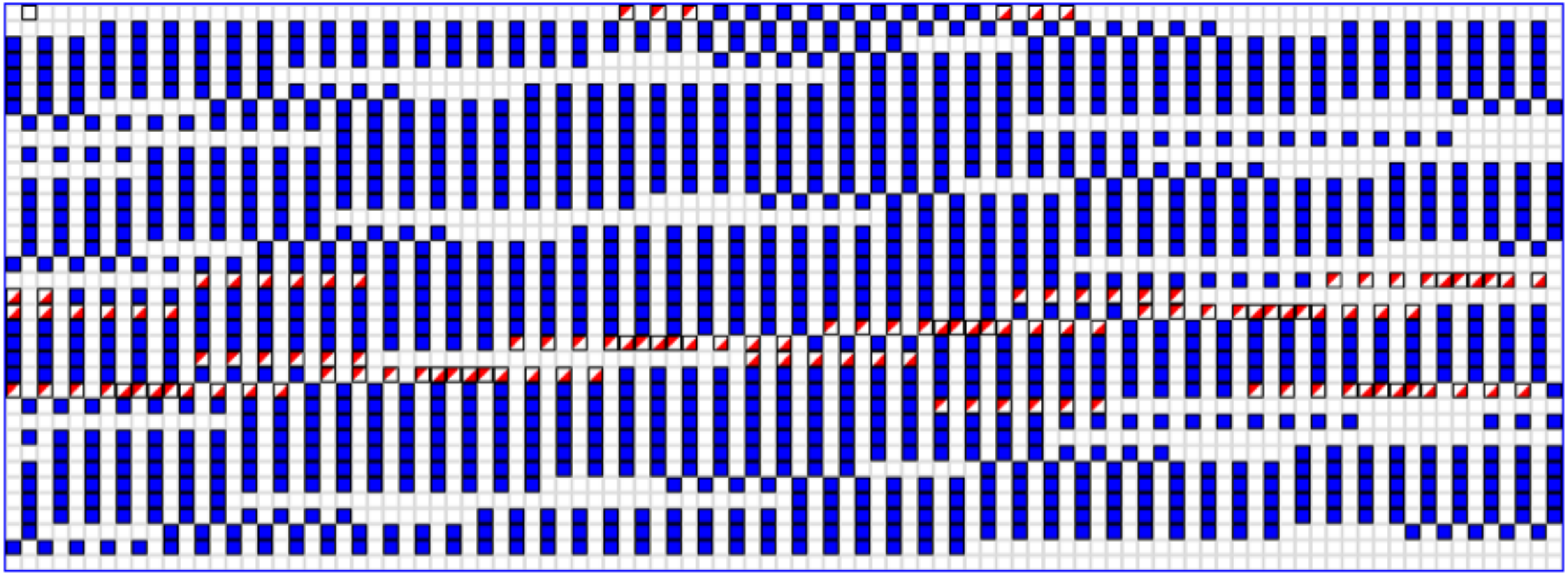
- „bunch" structure of the LHC collider
  - „bunches" of particles
  - 40 MHz
    - a bunch arrives every 25 ns
    - bunches are spaced at 7.5 meters from each other
    - bunch spacing of 125 ns for heavy-ion operation
- at present luminosity of the LHC collider (>10^{34} cm^{-2} s^{-1}) we have about 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):

Fill 2129 Bunch Pattern at CMS *1317 luminosity bunch pairs – $\times 10^{27} cm^{-2} sec^{-1}$*

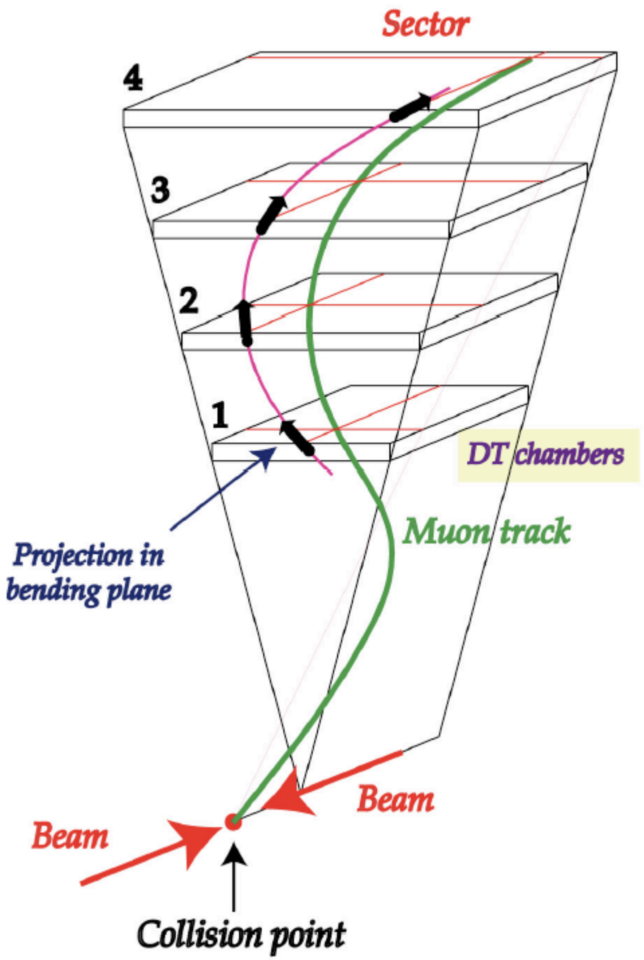
BX 0 → 98

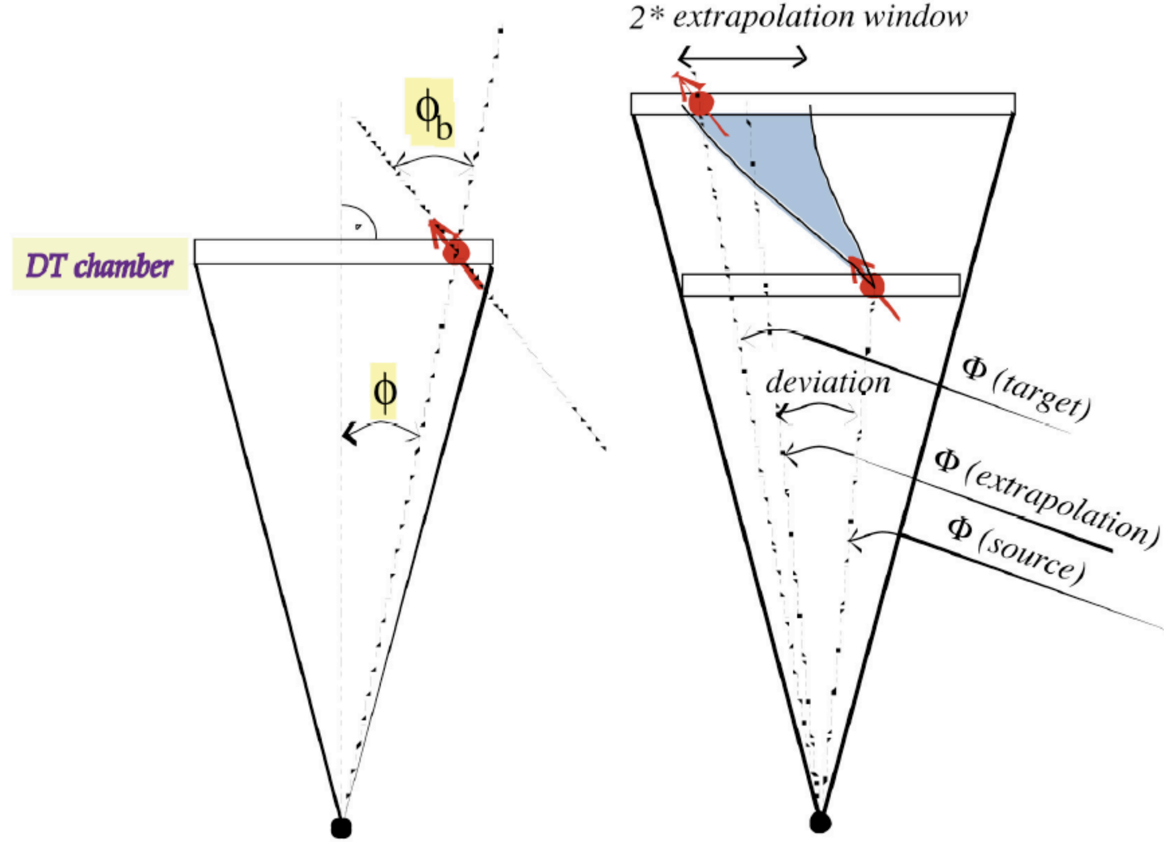


⇒ *multi-level trigger*

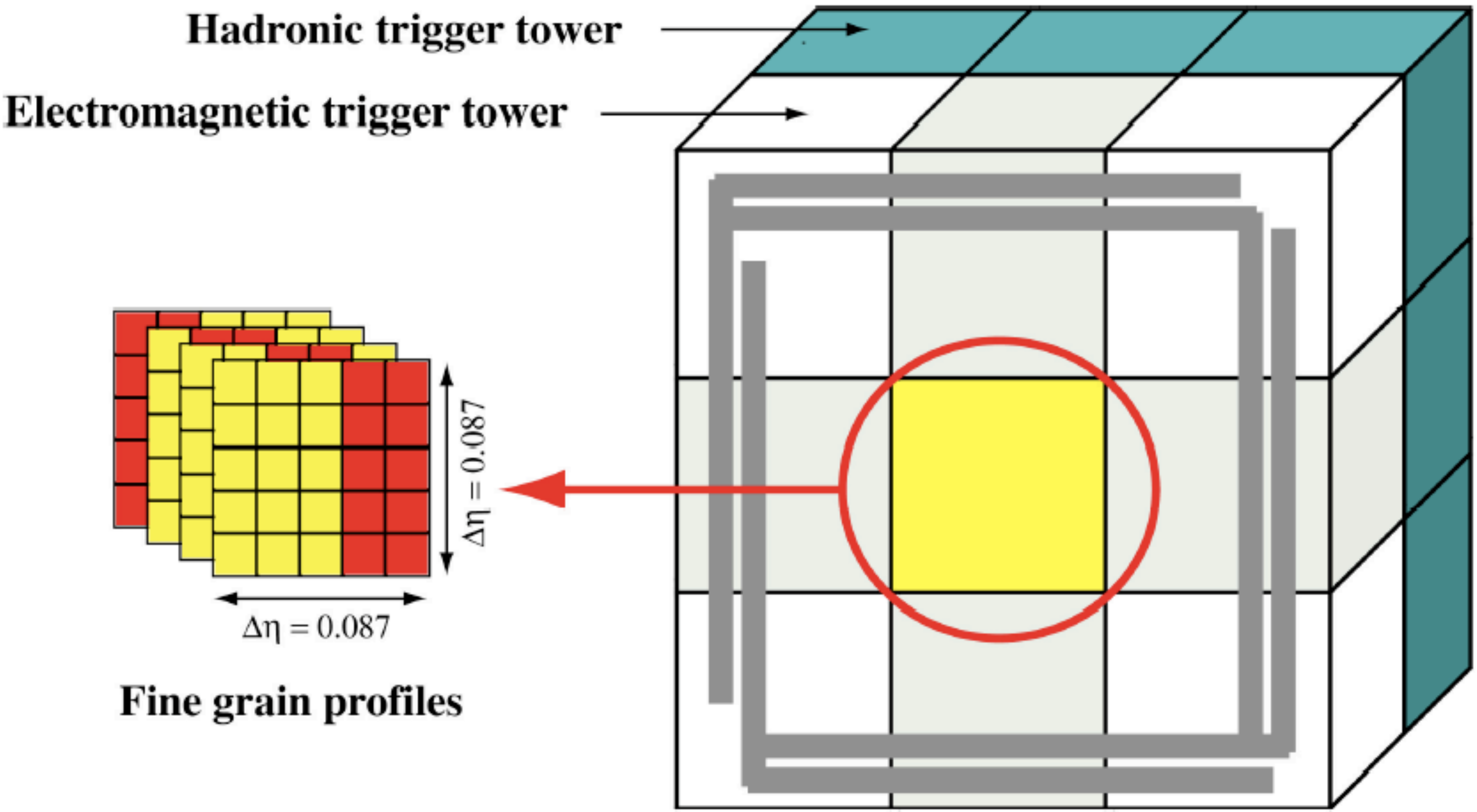
- first stage takes preliminary decision based on part of the data
  - rate is already strongly reduced at this stage
  - ~1 GHz of events (= 40 MHz bunch crossings) → ~100 kHz
  - only for these bunch crossings are all the detector data read out of the pipelines
  - still it would not be possible (with 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: ~100 kHz → ~ 1 kHz
  - only the events thus selected (twice filtered) are permanently recorded

how to find muon tracks ? (CMS: solenoidal field)

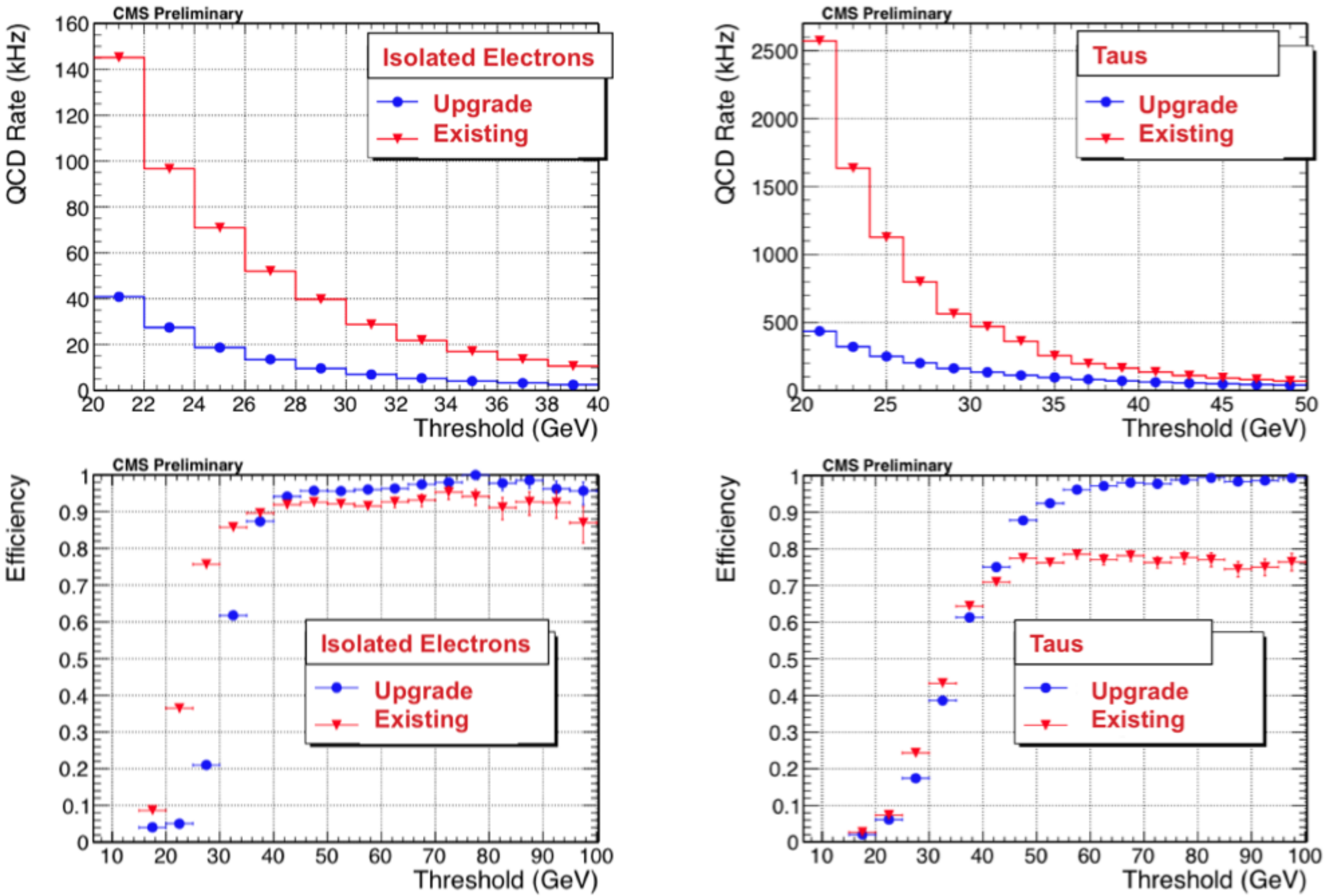




calorimeter trigger



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

```
pre_algo_a(54) <= tau_2_s(2);
pre_algo_a(55) <= tau_2_s(1);
pre_algo_a(56) <= muon_1_s(10) 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(20) 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);
```

ex

ved)

HEPHY Institute of High Energy Physics

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 ~ 4 μs
  - ~ 160 clock cycles
  - limited by tracker pipeline length
- will be increased only during tracker upgrade
  - Long Shutdown 3: phase-2 upgrade
  - ~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} $cm^{-2}s^{-1}$ in 2012
    - → > 10^{34} $cm^{-2}s^{-1}$ now
    - → > 5 x 10^{34} $cm^{-2}s^{-1}$ 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 (η, φ) 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 (η, φ) 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

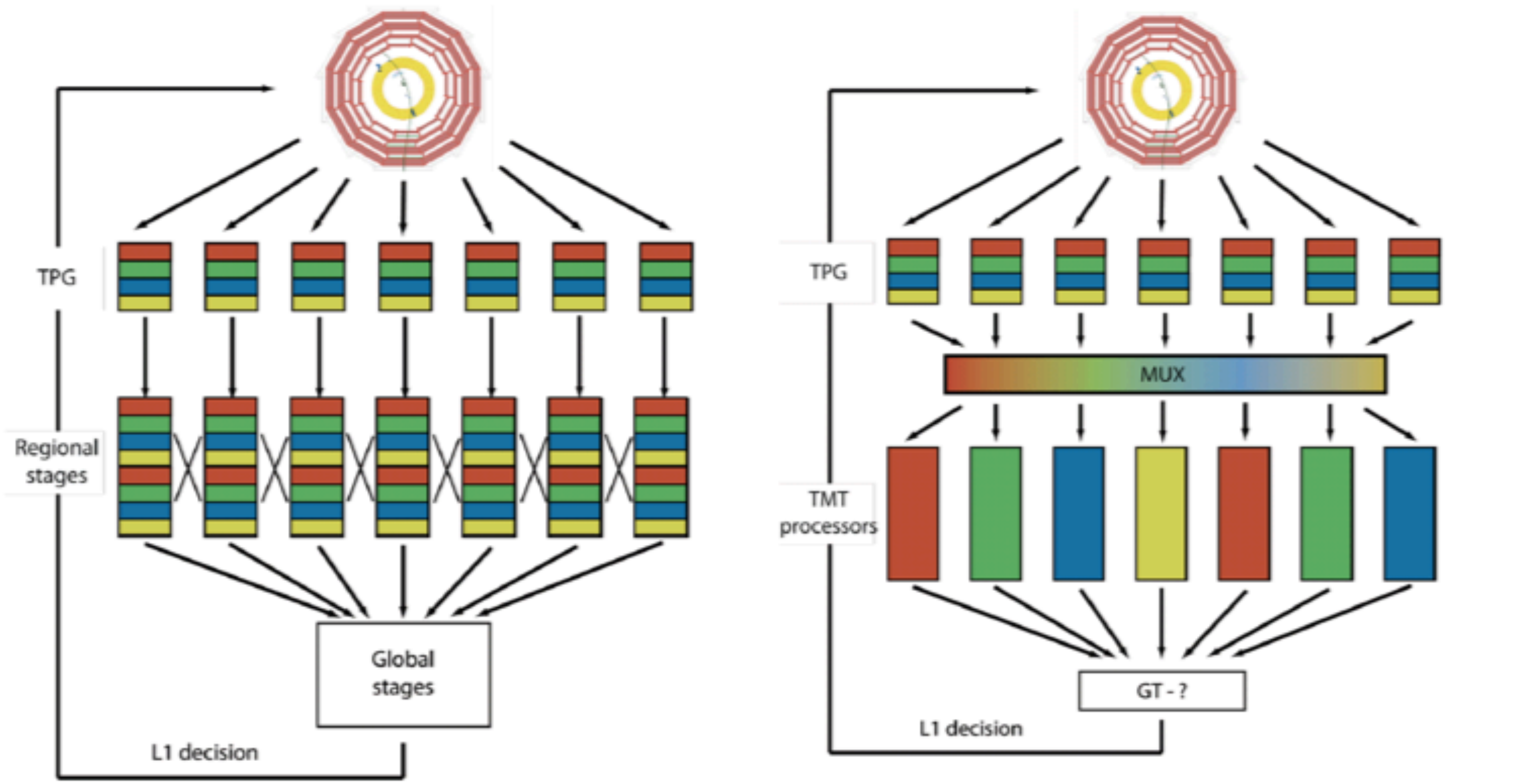
Level-1 Trigger phase-1 upgrade technology

- 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: μTCA (Micro Telecommunications Computing Architecture)
- use optical links
  - higher data rates (higher precision, more trigger objects)
  - less space for connectors (μTCA 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 ($\Delta\varphi$ comparisons) does not scale well
  - → 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

Calorimeter trigger



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: ~ 13 000 CPU cores
- more and faster computers will allow for more calculation time
  - more complex algorithms
  - ~ 100 → ~ 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 @ ($\sqrt{s}$ = 13 TeV)
  - LHC may exceed design luminosity (10^{34} $cm^{-2}s^{-1}$) 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**"

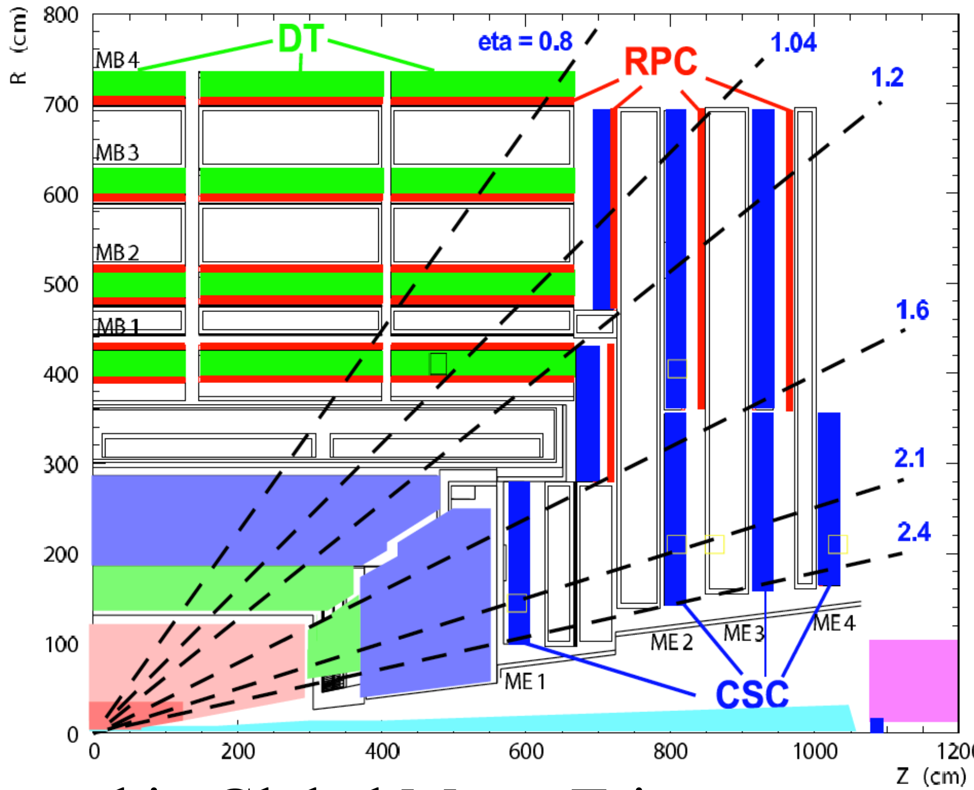
- *schedule may change over time*

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



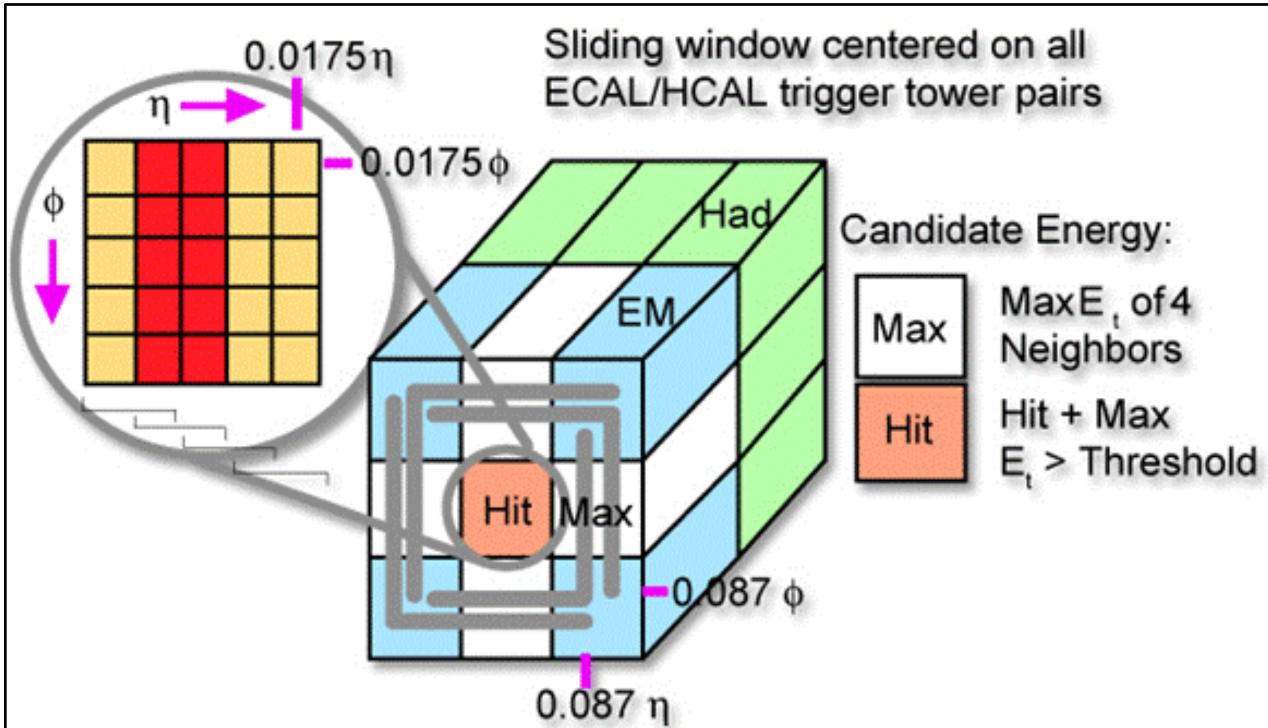
- muons from all 3 systems processed in Global Muon Trigger

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

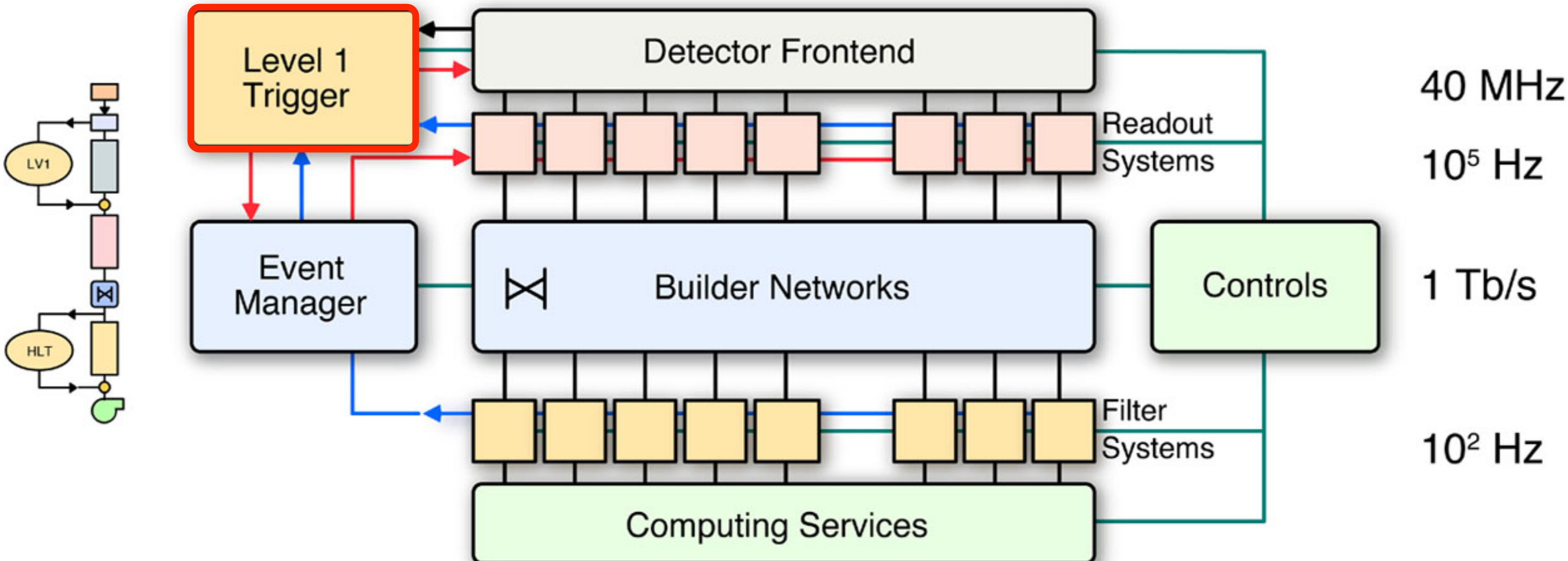
1 MHz (Triggered):

- **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(PU)x1.5(energy)x200kHS6 (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(PU)x1.5(energy)x200kHS6 (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 …**

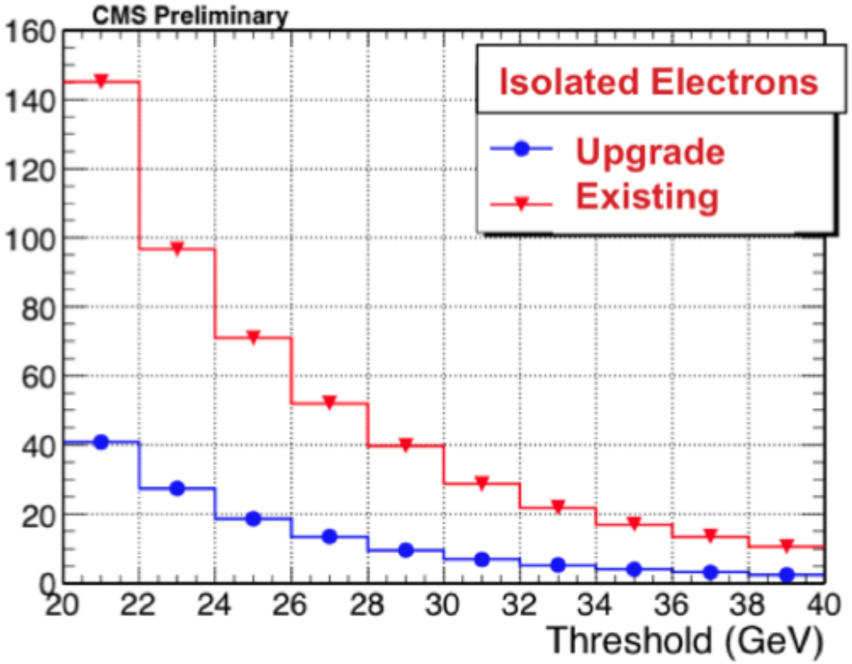
CMS Trigger & DAQ Systems

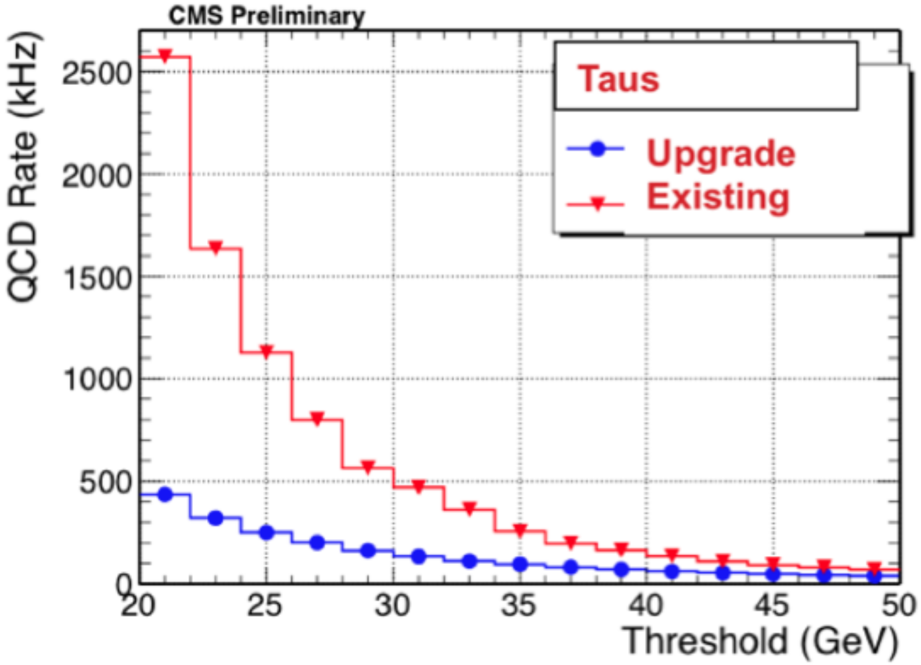


- LHC beam crossing rate is 40 MHz & at full Luminosity of 10^{34} $cm^{-2}s^{-1}$ yields 10^9 collisions/s
- Reduce to 100 kHz output to High Level Trigger and keep high-P_T physics
- Pipelined at 40 MHz for dead time free operation
- Latency of only 4 μsec for collection, decision, propagation

Calorimeter trigger upgrade

- improve resolution in coordinates
  - azimuth φ and pseudorapidity η
- improve identification of tau jets
  - better isolation criteria
- further improve e/gamma isolation determination



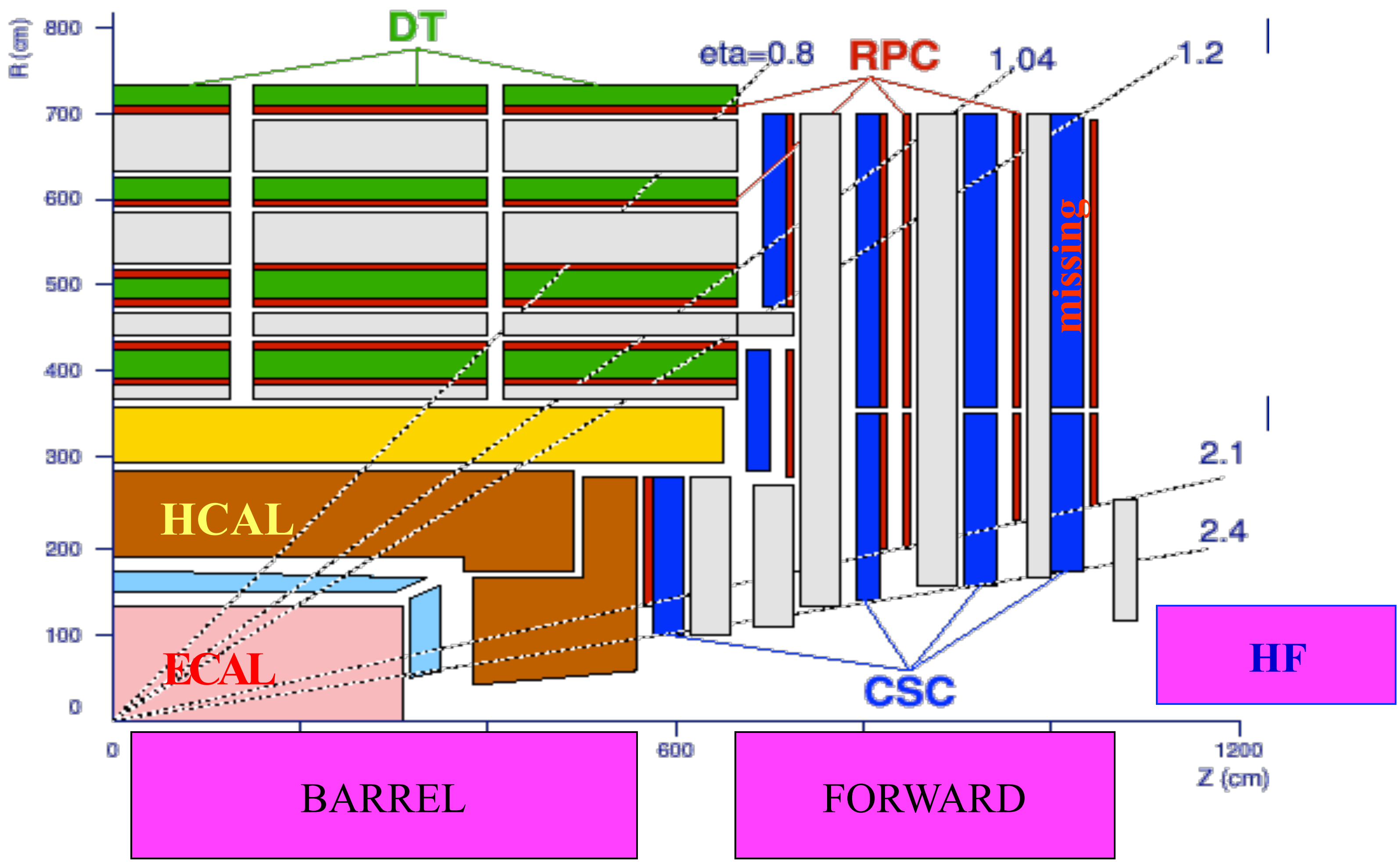


signals used by the first-level trigger

- 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

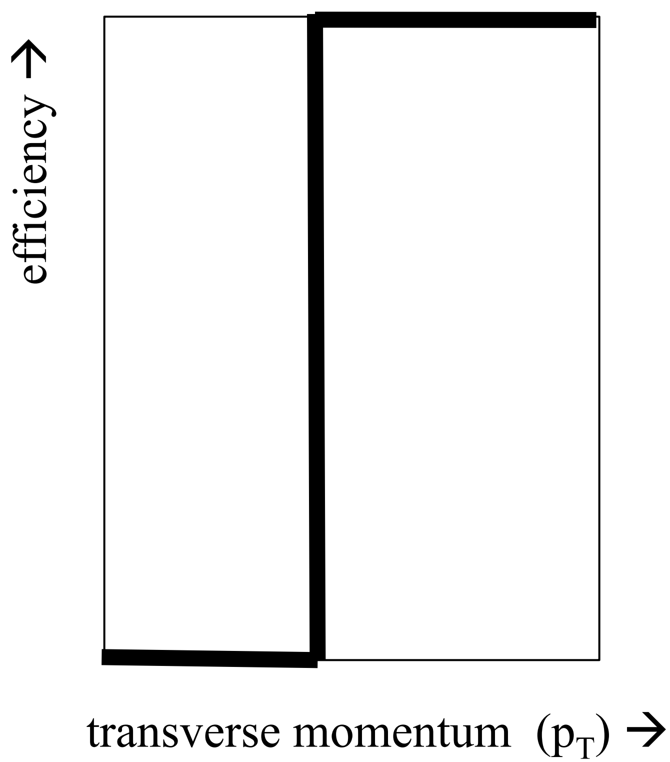
HEPHY
Institute of High Energy Physics

TRIGGER COMPONENTS

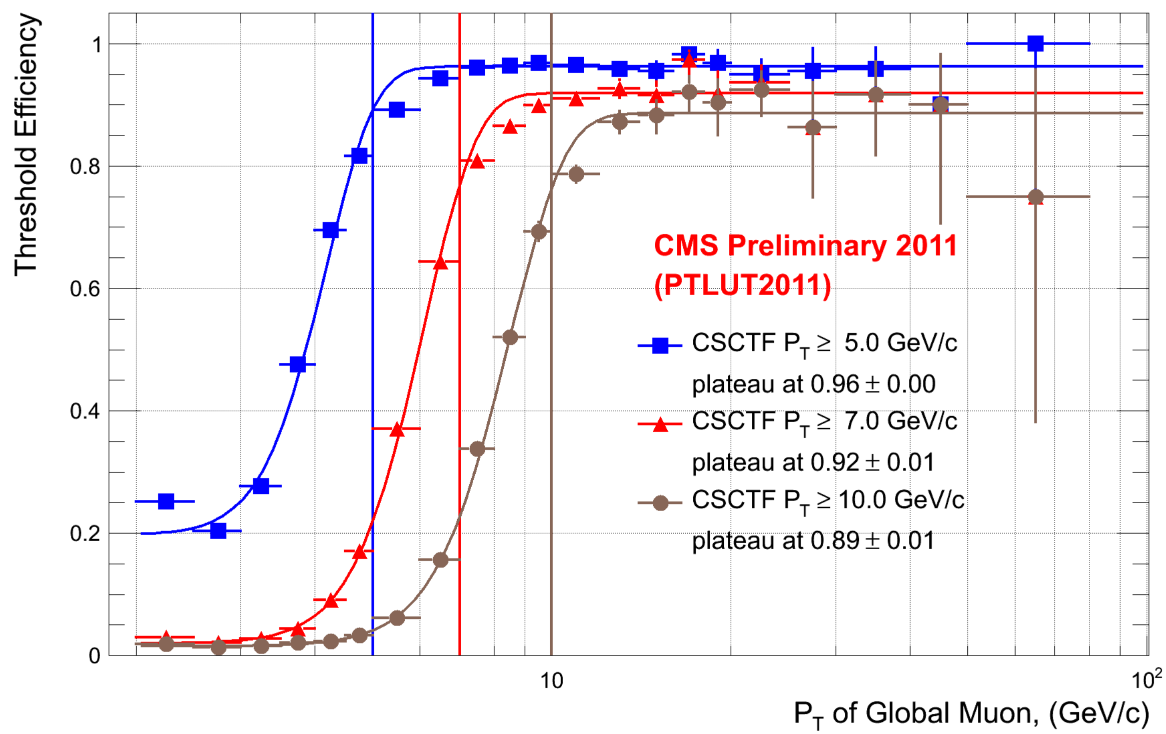


turn-on curves

ideal:

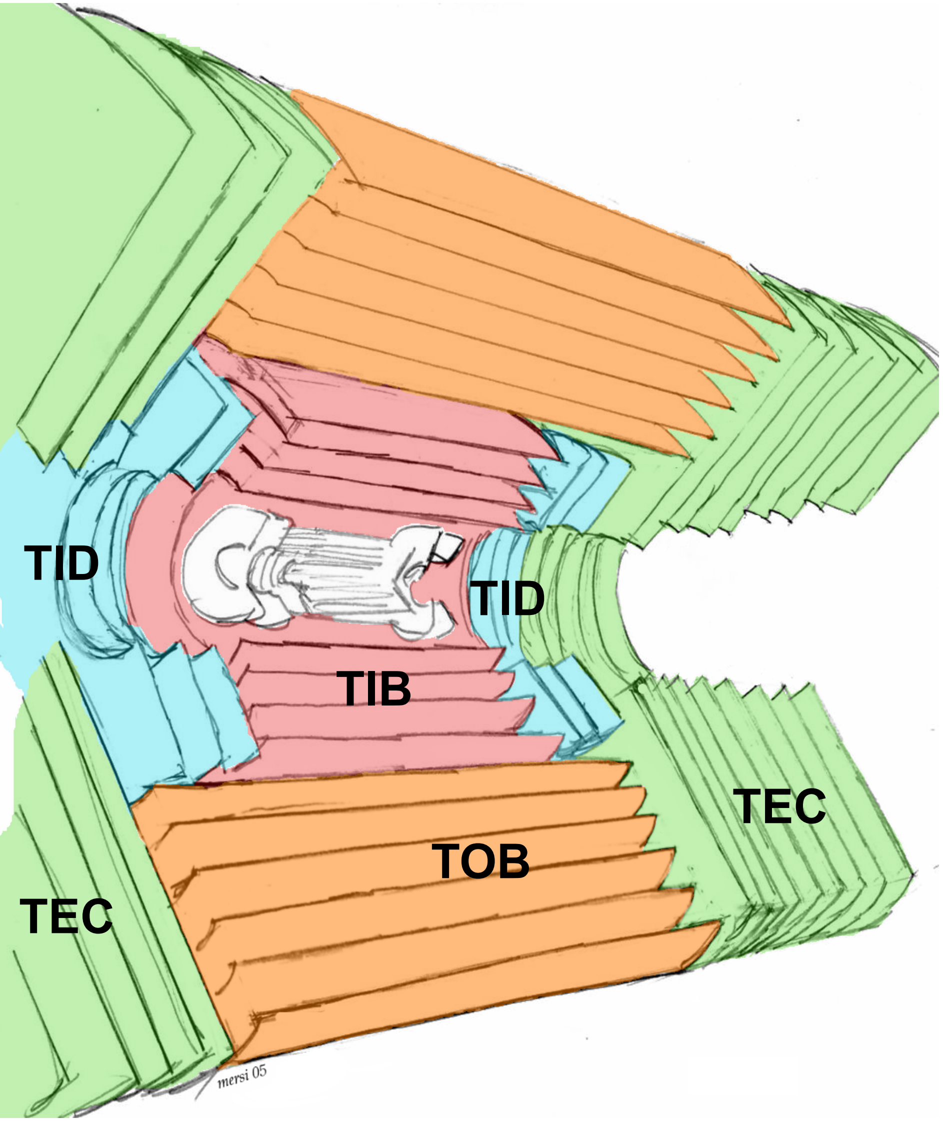


reality:

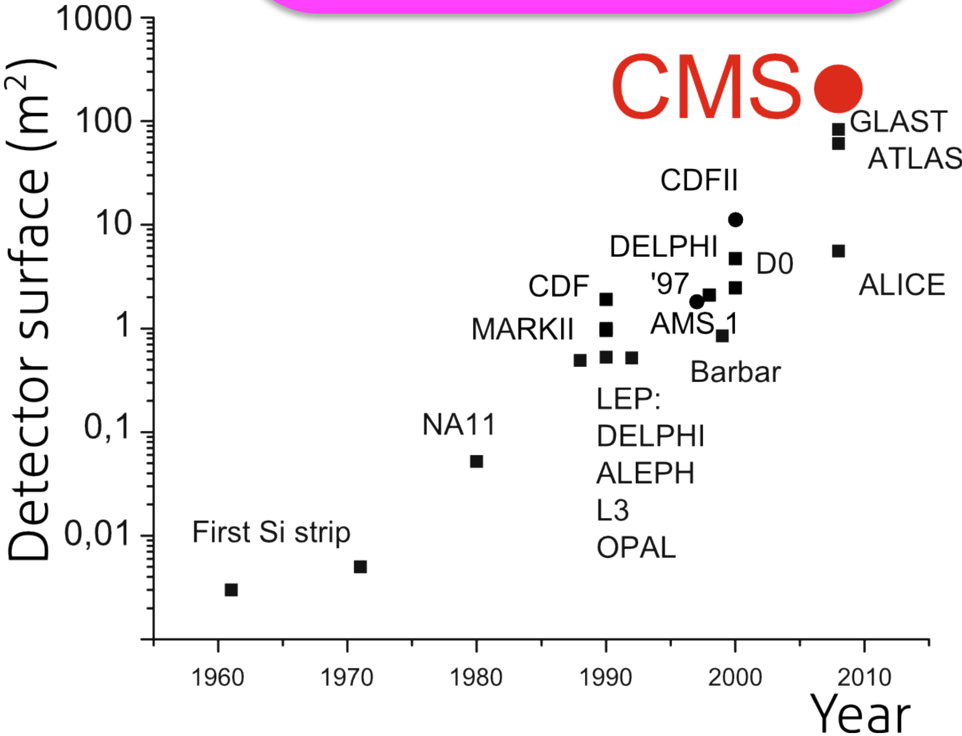


BACKUP Track Trigger

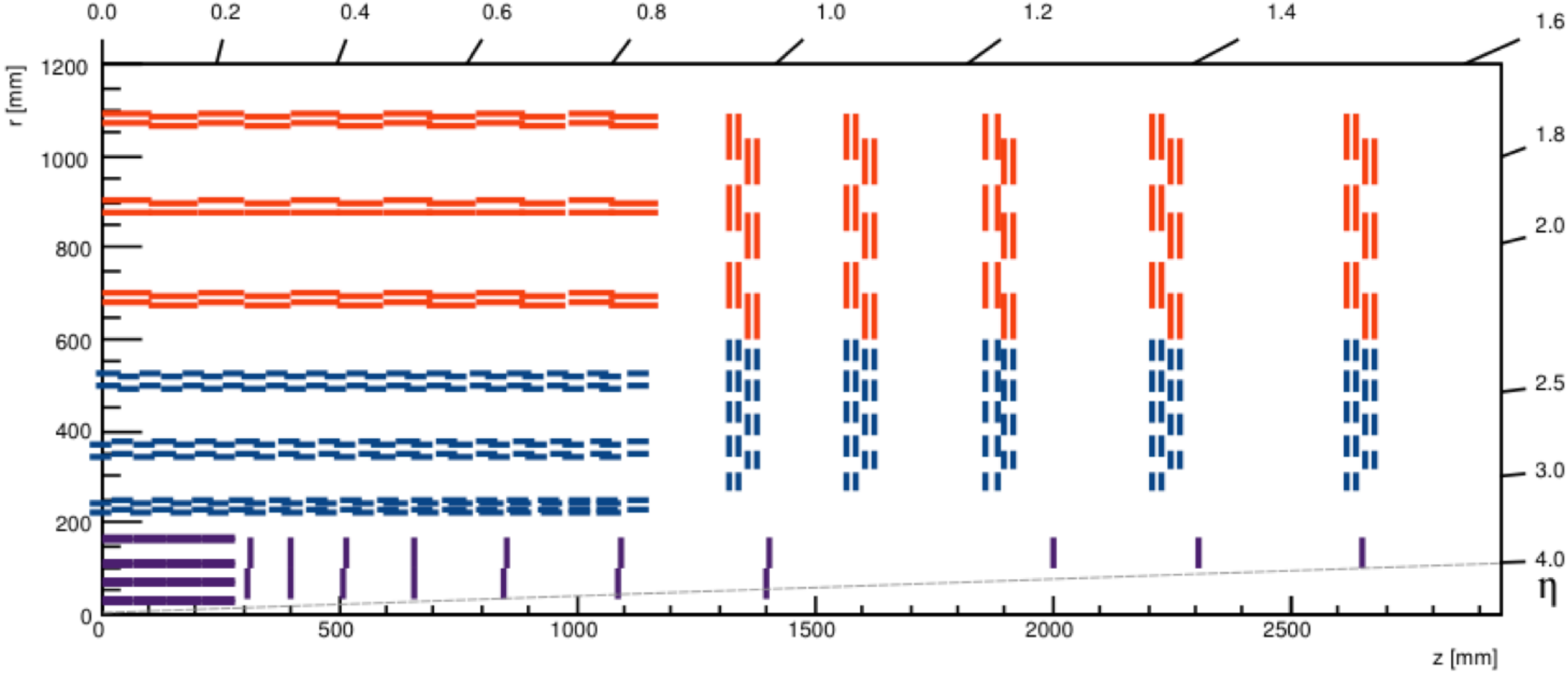
Level-1 Tracker (original detector)



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°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

HEPHY Institute of High Energy Physics

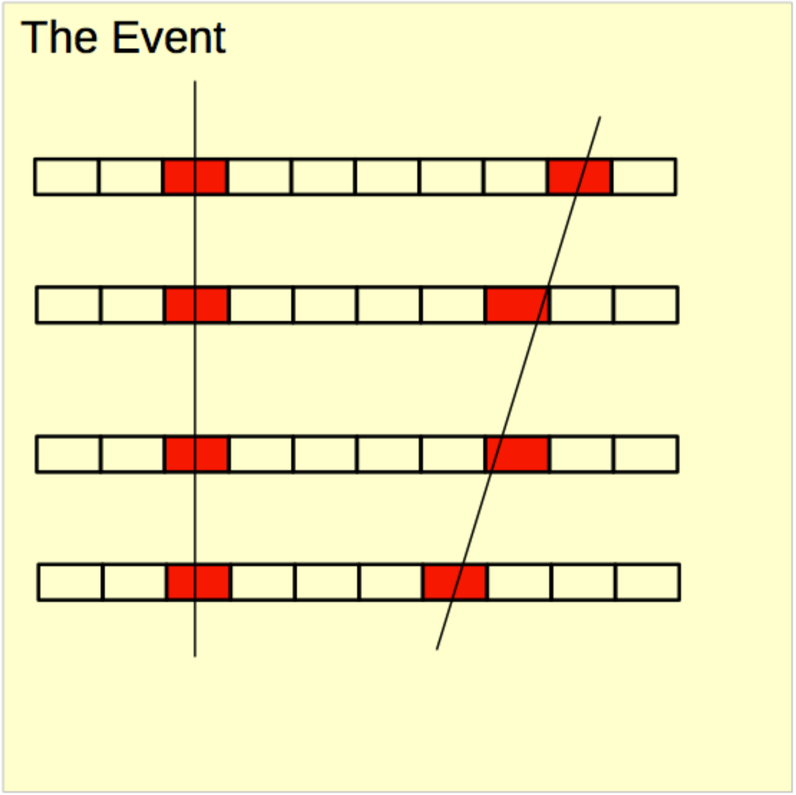
Tracker trigger concept

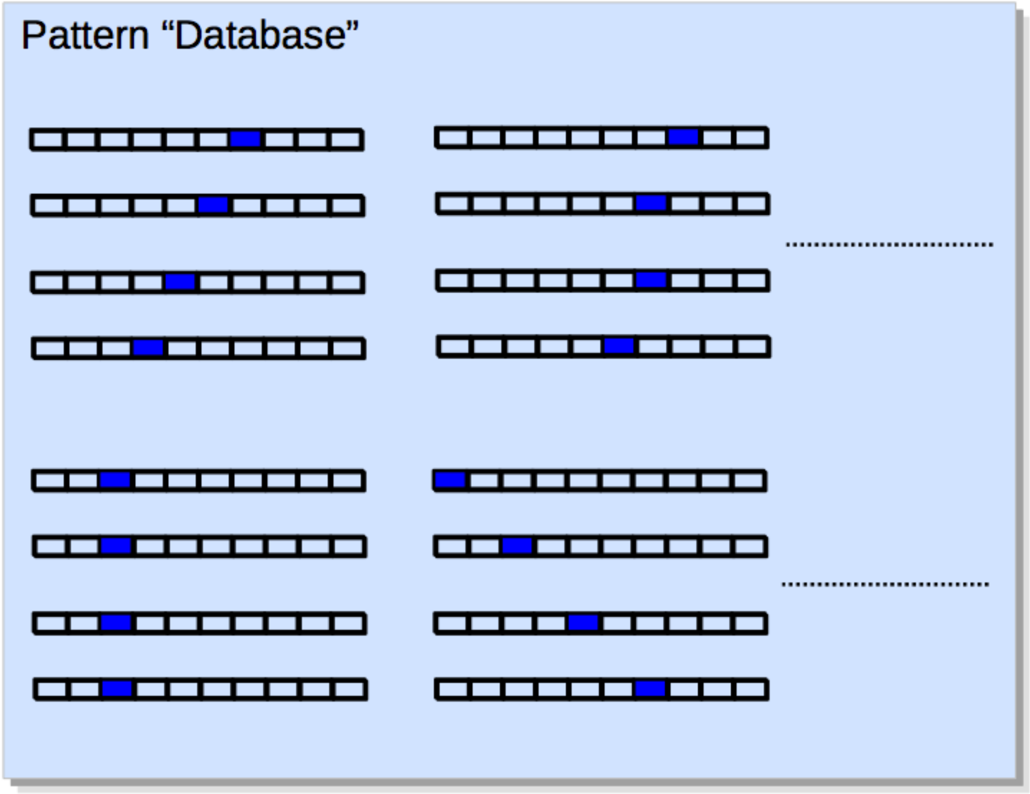
- Silicon modules provide at the same time "Level-1 data" (@ 40 MHZ), and "readout data" (upon Level-1 trigger)
  - whole tracker sends out data at each bunch crossing: "push path"
- Level-1 data require local rejection of low-p_T tracks
  - reduce data volume and simplify track finding @ Level-1
  - Threshold of ~ 2 GeV ⇒ 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 ~2 GeV
- Pixel option
  - possibly also use Pixel detector in "pull" architecture
  - longer latency needed (20 μs)

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, γ, μ or τ)
- 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

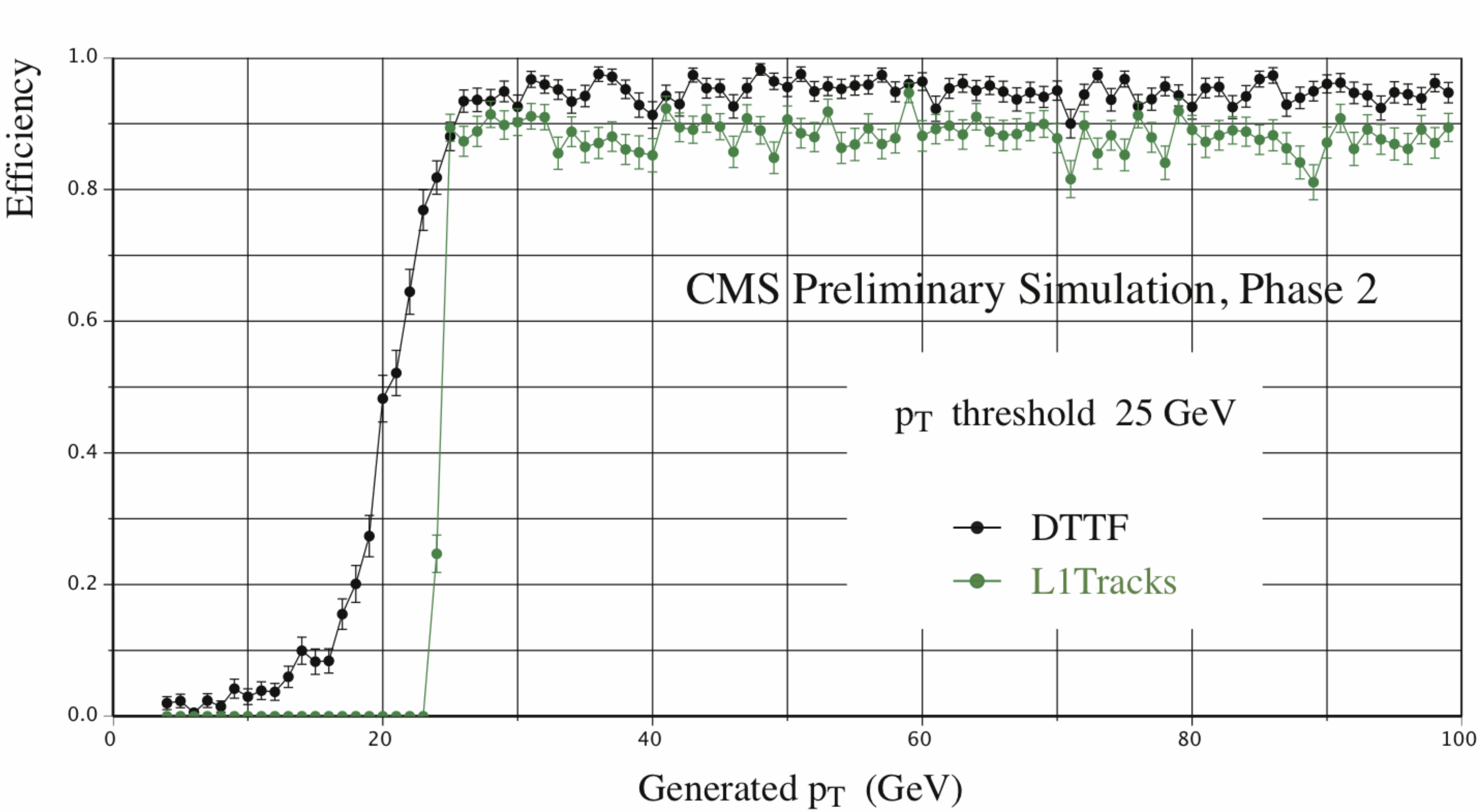




- pattern recognition using "associative memory"
  - CAM = "content addressable memory"
- by comparing with patterns find candidates ("roads")

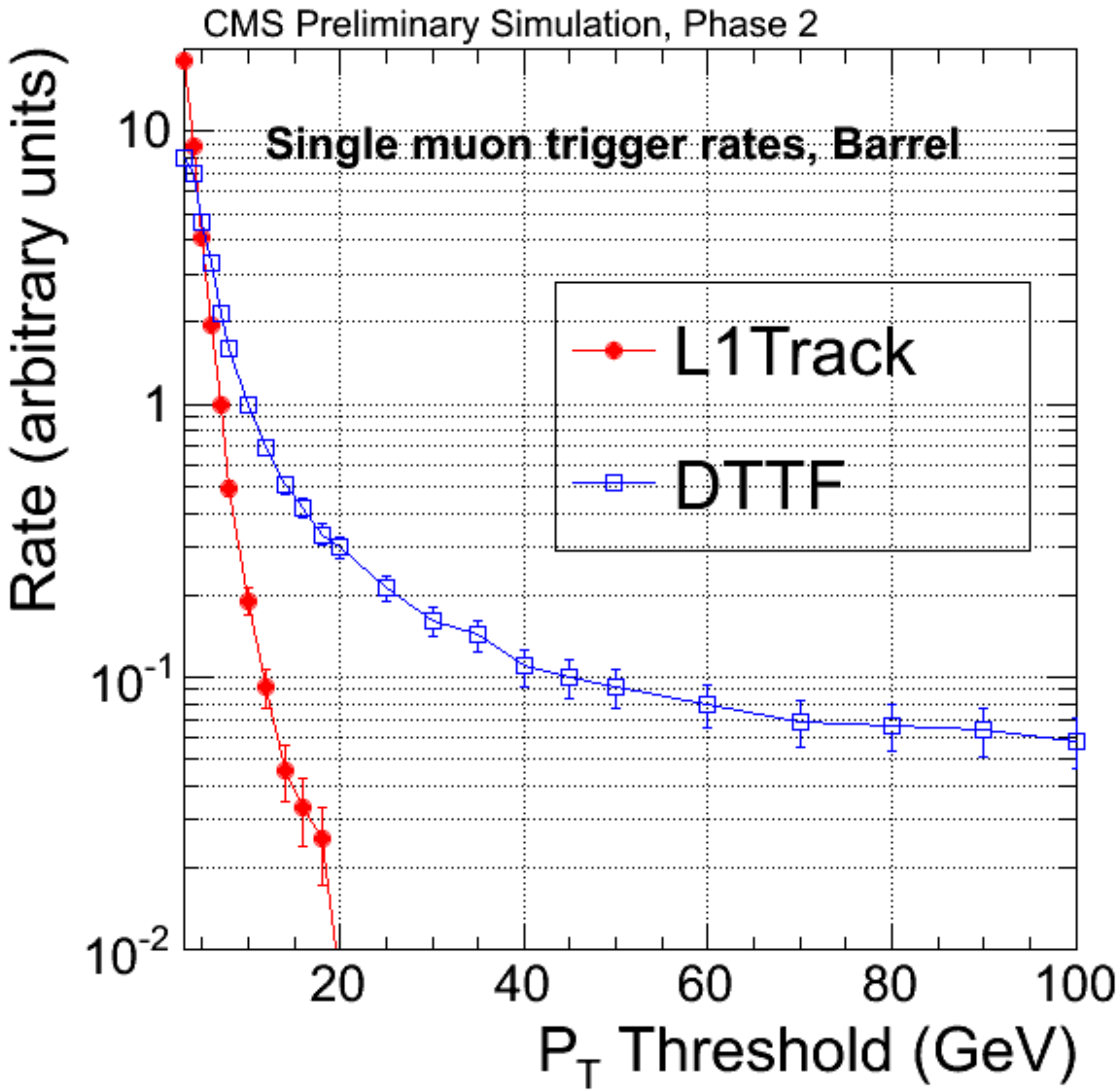
Trigger, Threshold	Algorithm	Rate reduction	Full eff. at the plateau	Comments
Single Muon, 20 GeV	Improved Pt, via track matching	~ 13 (| η | < 1)	~ 90 %	Tracker isolation may help further.
Single Electron, 20 GeV	Match with cluster	> 6 (current granularity) >10 (crystal granularity) (| η | < 1)	90 %	Tracker isolation can bring an additional factor of up to 2.
Single Tau, 40 GeV	CaloTau – track matching + tracker isolation	O(5)	O(50 %) (for 3-prong decays)	
Single Photon, 20 GeV	Tracker isolation	40 %	90 %	Probably hard to do much better.
Multi-jets, HT	Require that jets come from the same vertex			Performances depend a lot on the trigger & threshold.

Muons : turn-on curves



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.

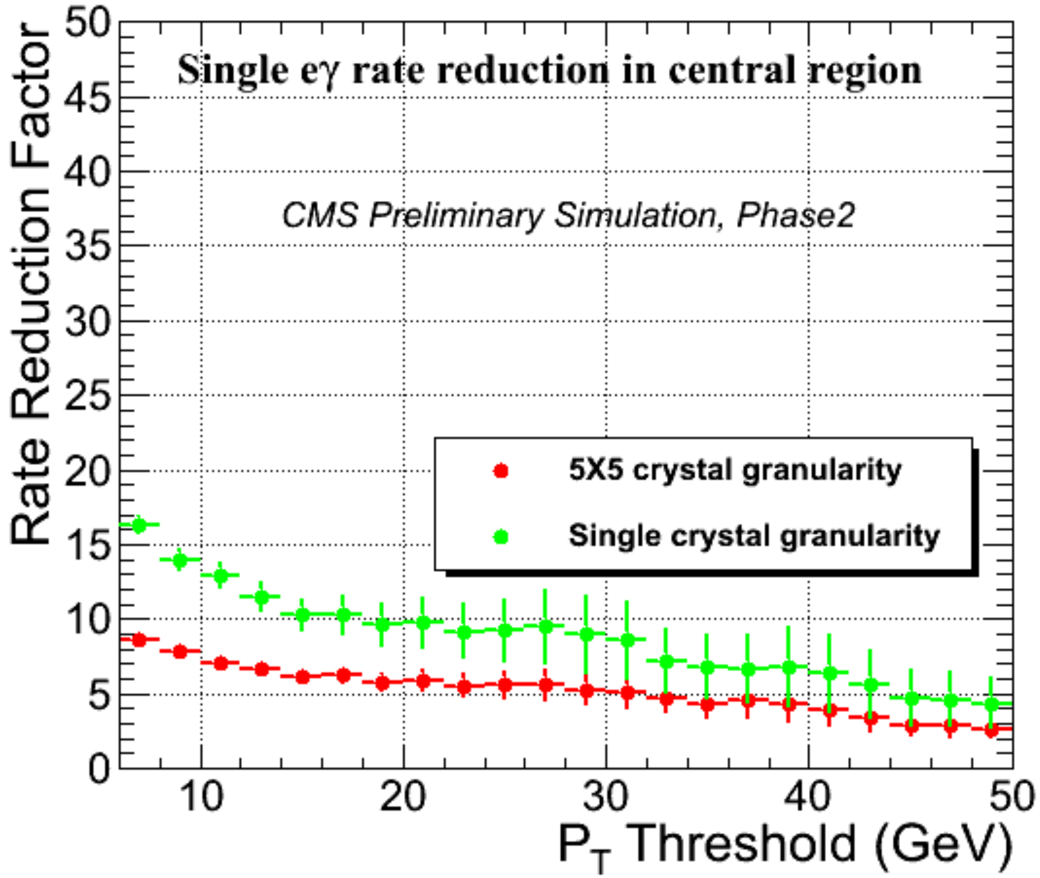
Muons : rates



- DTTF : Flattening of the rates at high threshold

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

Electrons



Rate reduction brought by matching L1EG to L1Tkstubs in the central region (| eta | < 1)

Red : with the current L1Cal granularity.

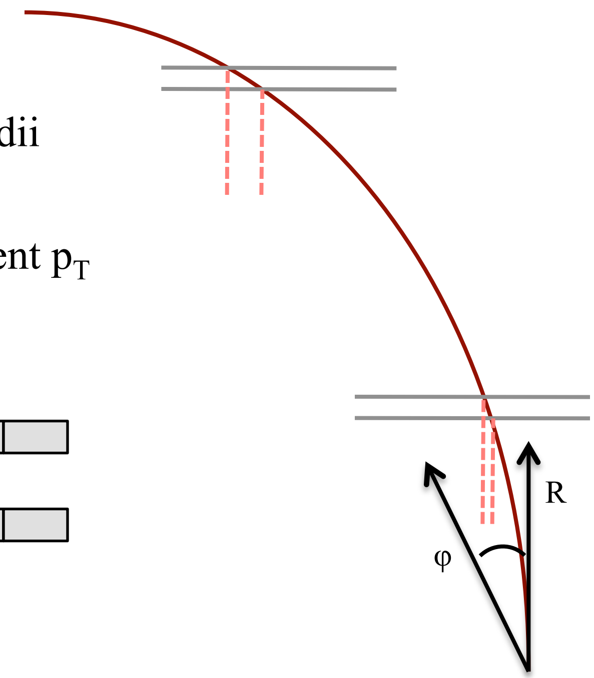
Green : if crystal-level information is available for L1EG. The better position resolution for the L1EG object improves the performance of the matching to the tracker.

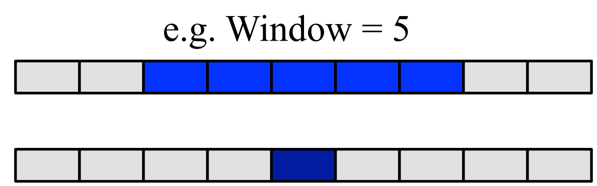
(NB : the pure calorimetric L1EG rates could also be reduced with the finer granularity. Not taken into account here.)

HEPHY Institute of High Energy Physics

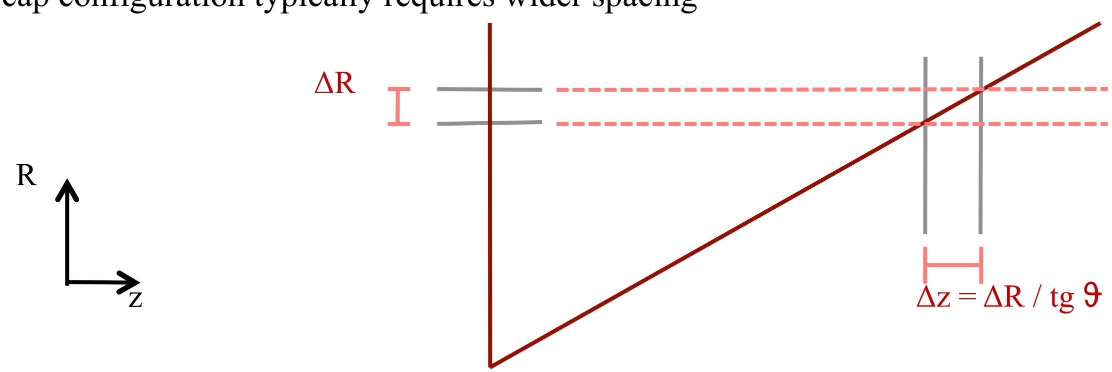
p_T modules: working principle

- measure p_T via $\Delta(R\varphi)$ over a given ΔR
- for a given p_T, $\Delta(R\varphi)$ 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



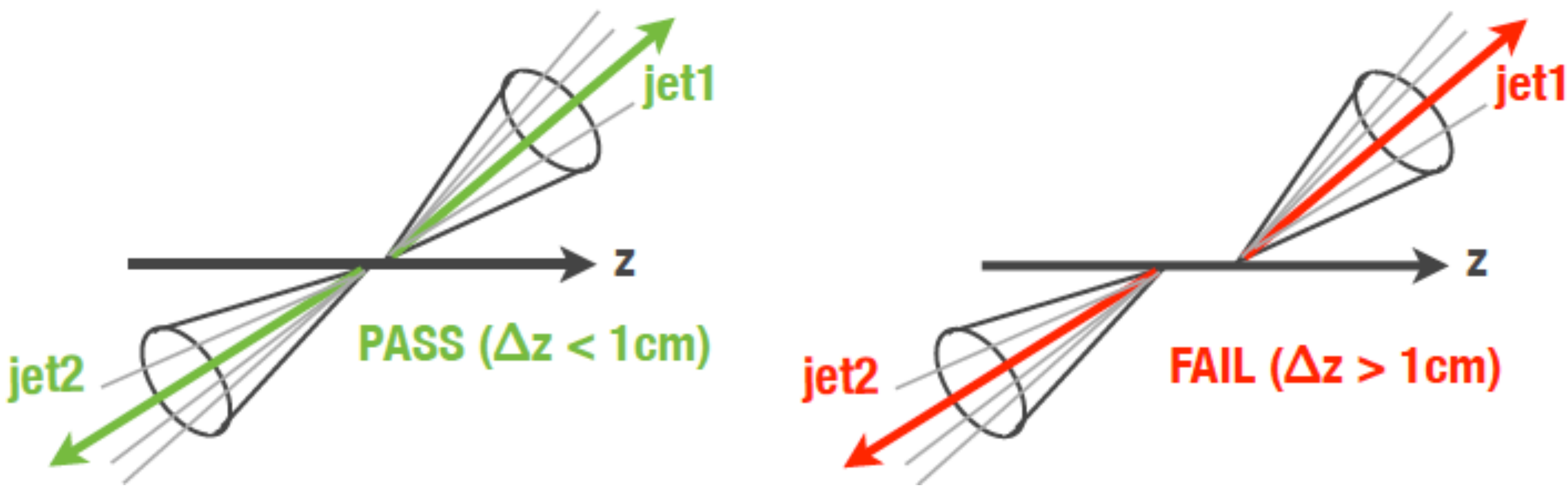


- barrel: ΔR is given directly by the sensors spacing
- end-cap: dependence on detector location
  - End-cap configuration typically requires wider spacing

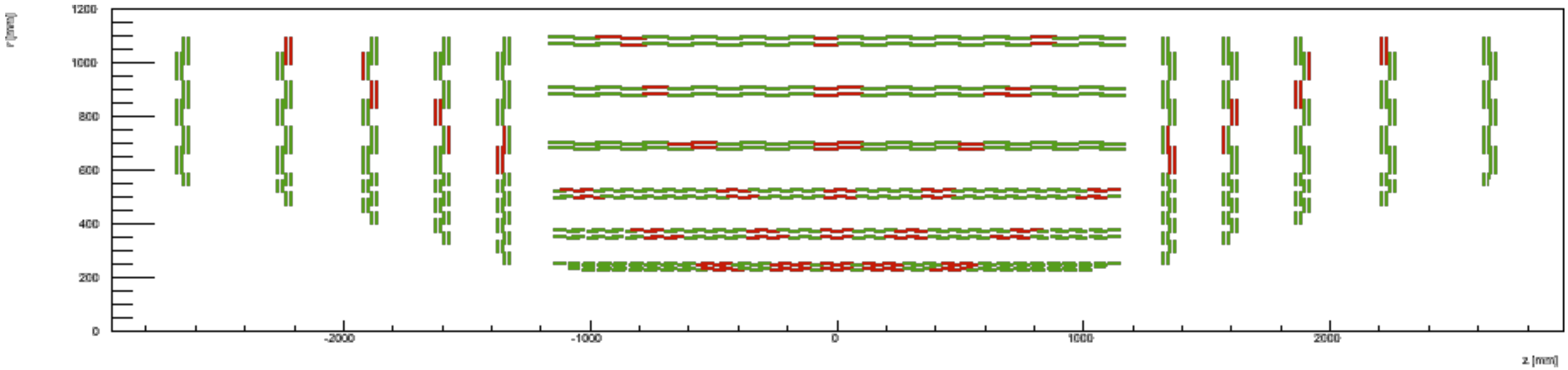


Jets

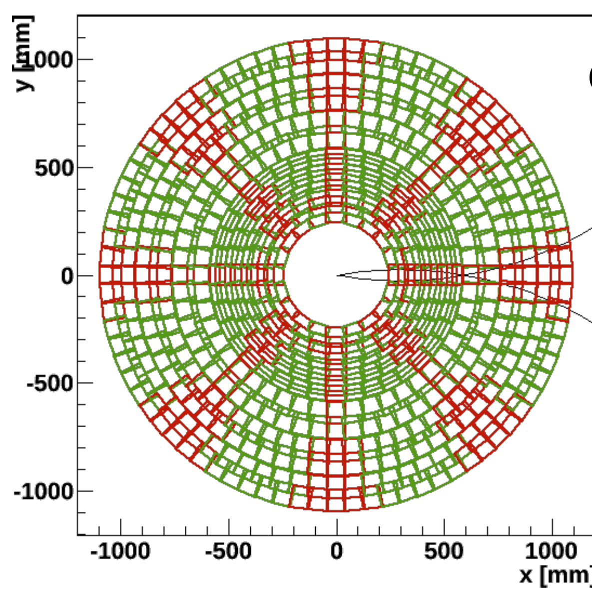
- Associate jets to nearby L1 tracks to determine z position
  - **(1)** Select tracks with dR(track, jet) < 0.40
    - $|z_{track}| < 25$ cm
    - $chi2_{track} < 100$
  - **(2)** p_T averaged z position of selected tracks ⟶ *initial jet z position "z_1(jet)"*
  - **(3)** Remove outliers in two steps & recalculate z position
    - *First outlier step:* $|z_{track} - z_1(jet)| <$ **5cm** ⟶ *updated z position "z_2(jet)"*
    - *Second outlier step:* $|z_{track} - z_2(jet)| <$ **1cm** ⟶ *final z position "z_{final}(jet)"*



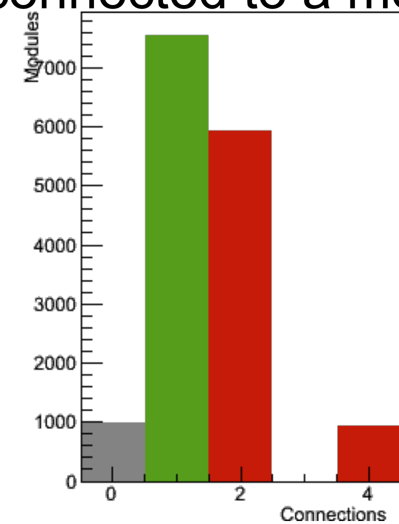
Track finding @ Level-1



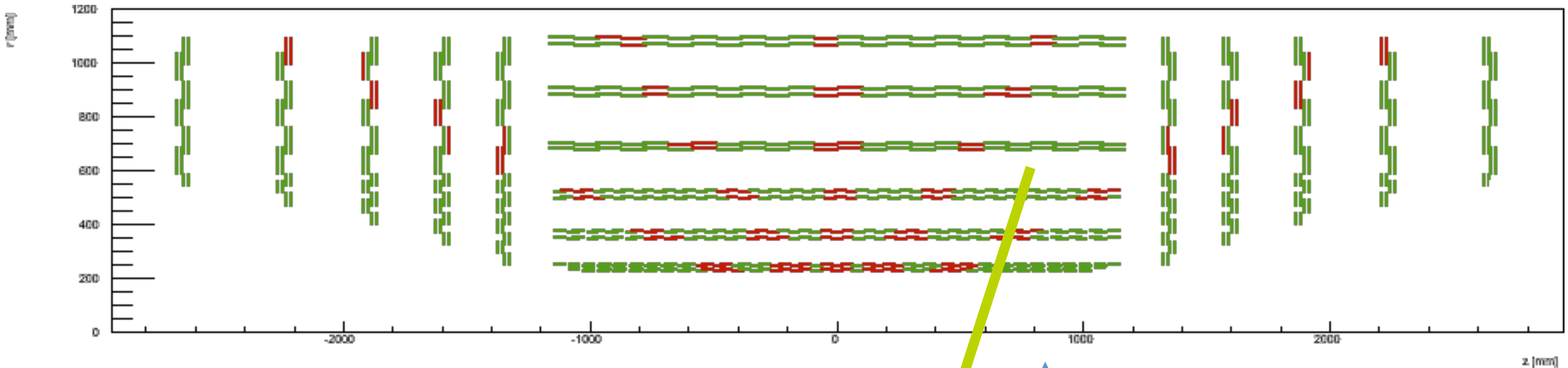
- Each sector independent
- Overlap regions depend on
  - Luminous region Δz
  - Minimum p_T cut



Number of sectors connected to a module

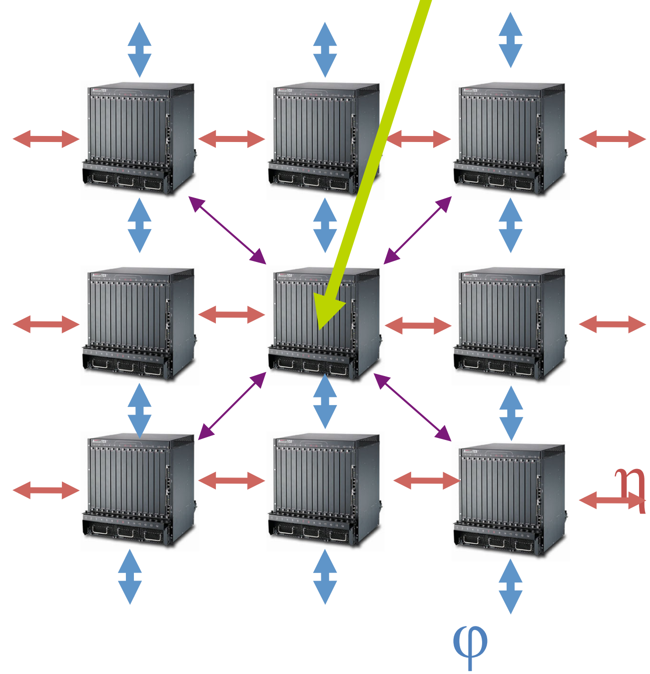


Track finding @ Level-1



Simple
Trigger Tower
Interconnections

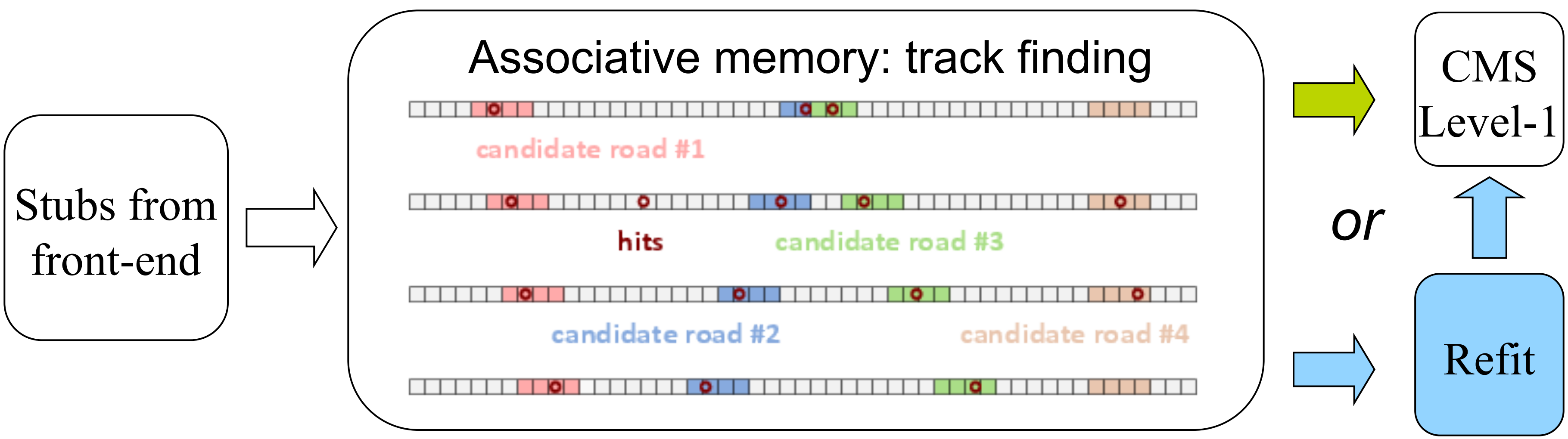
Each box represents
a trigger tower



HEPHY Institute of High Energy Physics

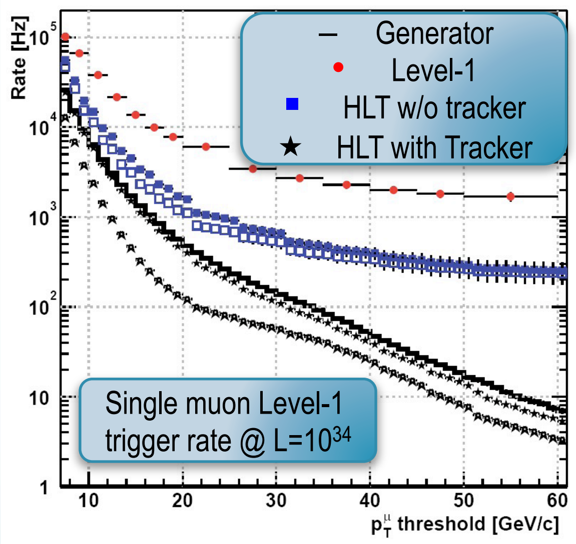
Track finding at Level-1

- Within a latency of O(μs): 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 **F**ast**T**rac**K**er boards (started)
    - » Develop dedicated AM chips and boards



Basic requirements and guidelines – II

- Tracker input to Level-1 trigger
  - μ, 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 ~ 1 mm precision