EXPLORING THE HIGH ENERGY FRONTIER WITH THE CMS LEVEL-1 TRIGGER AT THE HL-LHC

ICTEA2024, OVIEDO, SPAIN, 6TH MAY 2024

A. ZABI, ON BEHALF OF THE CMS COLLABORATION

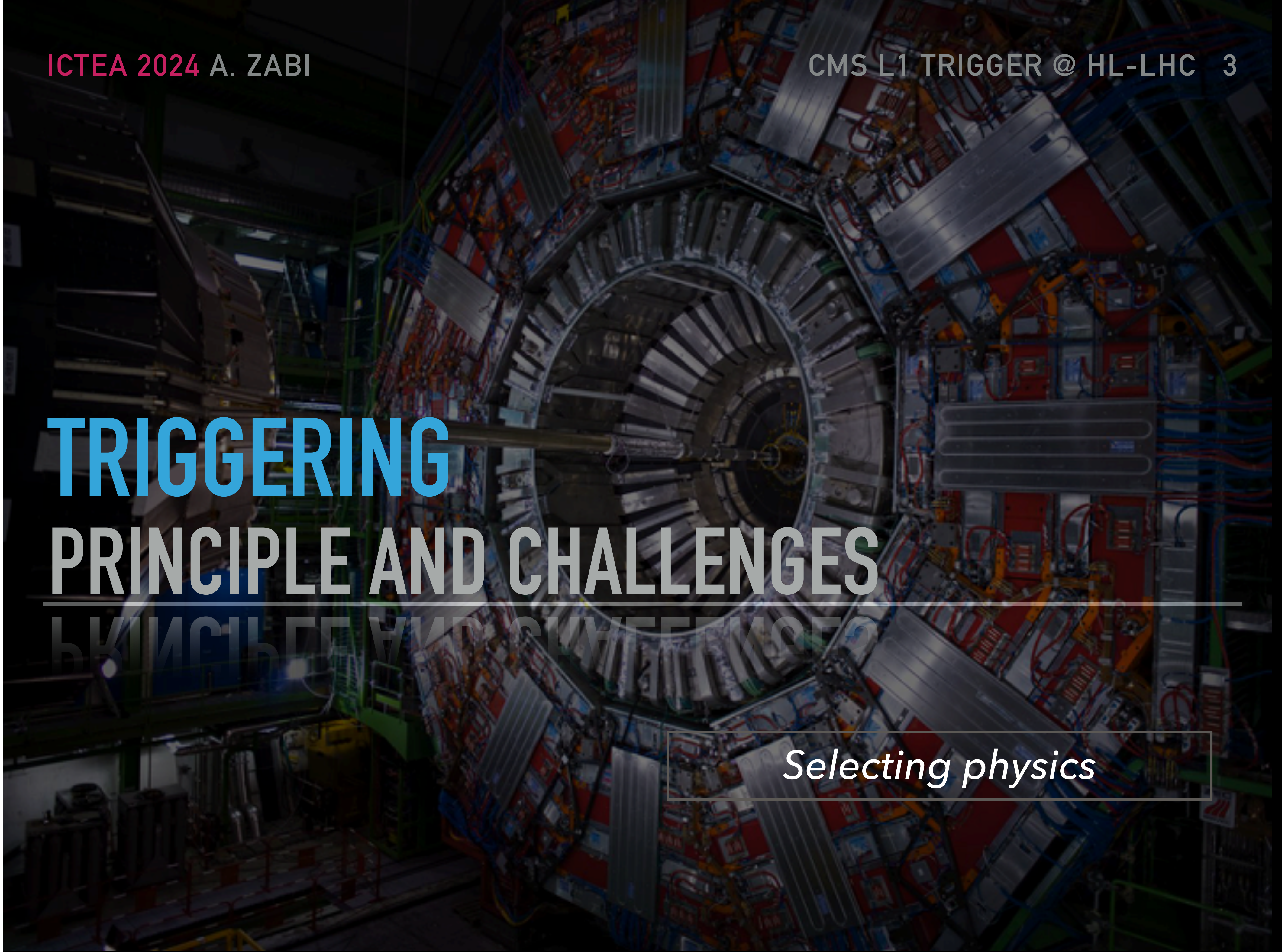
OUTLINE

- Principle and challenges of triggering, choosing interesting physics events. What are the working principles ?

- Context of triggering @ HL-LHC: scientific case and system requirements (technological choices)

- L1 trigger upgrade conceptual design and instrumentation: System interfaces & Architecture. Key features and hardware prototyping.

- Level-1 trigger upgrade algorithm design, firmware developments & testing: selecting physics with sophisticated firmware algorithms. System demonstration.
- Beyond HL-LHC. The future of triggering.



TRIGGERING

PRINCIPLE AND CHALLENGES

Selecting physics

PRINCIPLE OF TRIGGERING ON INTERESTING EVENTS

Find a needle ~~in hay stack~~ in tonnes of hay !

The Trigger System is used to quickly select the potentially interesting collision events among the millions produced per second

Essential component: defines acceptance for physics and potential discoveries

The challenge @ LHC (40 MHz collision rate)

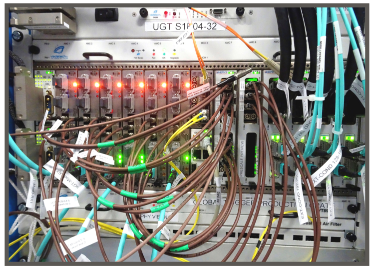
- Selecting efficiently signal $\sigma << 10^{12}\ \sigma_{pp}$
- Huge input volume > Tb/s
- Short amount of time < 3.8 us (latency)

→ *CMS implemented a 2-level Trigger system*

Focus here

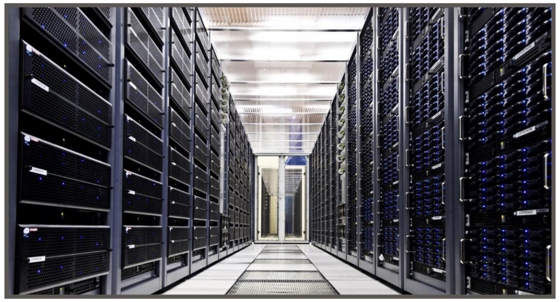
CMS Level-1 Trigger
Hardware system

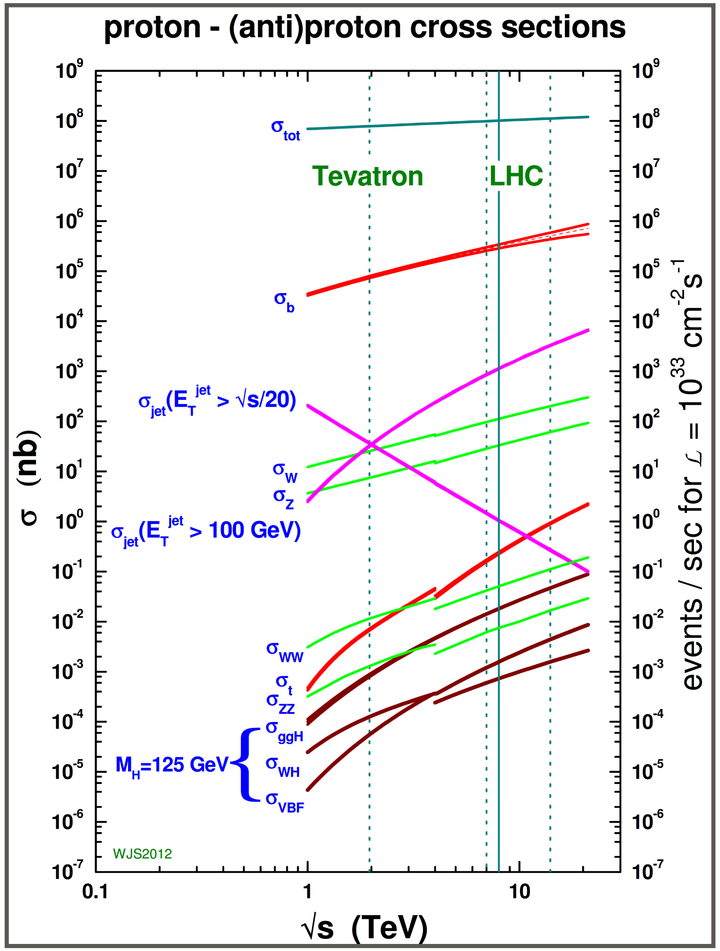
100 kHz



High Level Trigger
Software farm

1.5 kHz

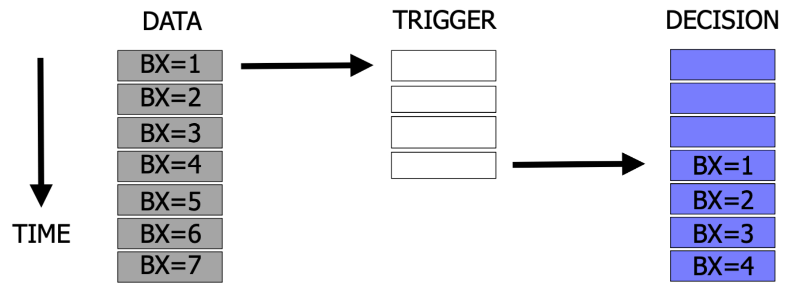




CHALLENGES OF SELECTING INTERESTING PHYSICS

Selecting interesting collision events can be a challenging and constraining task at hadron colliders:

- What can you write on tape?: Huge rate, multiple interactions, etc.
- Physics selection based on what criteria?: your knowledge particle physics, but can you trigger on what you are not expecting ?
- Triggering is an online process: you can't go back !
- Short decision time, large data volume: rely on hardware → simplified algorithms, more difficult to modify, tied to detector geometry, fixed latency (no iterative algorithms), etc.



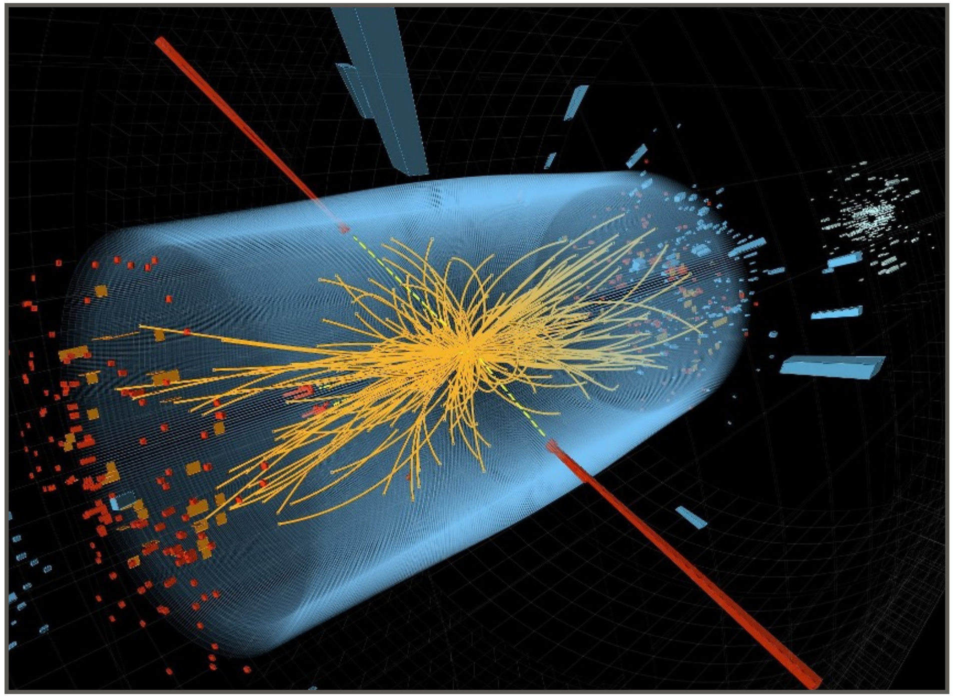
Good trigger will capture it's design physics and anything unexpected and reject common processes

CHALLENGES OF SELECTING INTERESTING PHYSICS

Early in the game: selecting physics with simple criteria implementable in hardware

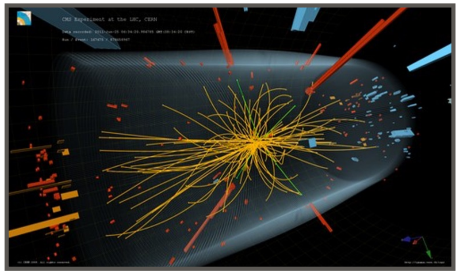
- Local energy deposits in calorimeters
- Identifying muon tracks with rough segments into the spectrometers
- Simple correlations or physics observable (energy > threshold)

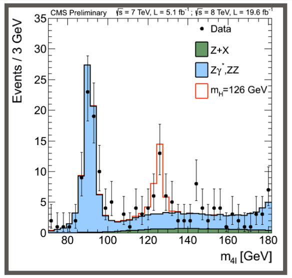
Collider environment and luminosity (measures the collision rate) have made this work increasingly complicated.



H → 2 photons @ CMS/LHC
- Looking for 2 high energetic deposits into the calorimeters @ Level-1 Trigger (Double_EG)

H → ZZ → *4 leptons* @ CMS/LHC
- Combinations of 2, 3 high energetic deposits into the calorimeters @ Level-1 Trigger (Double_EG or Triple_EG)

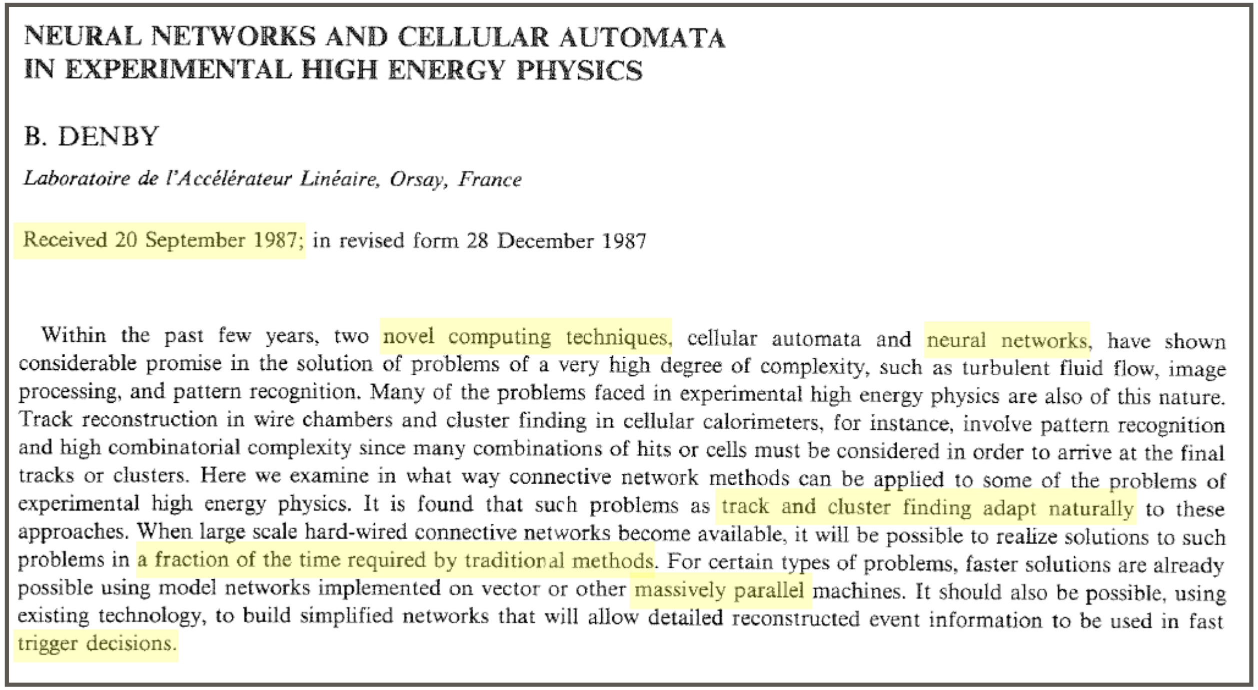




MODERNISING TRIGGER SYSTEMS

Introduction of the FPGA revolutionised trigger systems

- Have been around for a while since 1985 (Altera/Xilinx)
- The logic (algorithm) does not need to be fixed when the board is produced
- Trigger Algorithms can be changed in light of better detector understanding and physics discoveries
- Much more can be done with triggers: sophisticated algorithms, iterative algorithms, neural network inference (B. Denby 1987 CPP 49 (1988) 429-448)
- Requires low-level languages (VHDL), can be difficult to program..


NEURAL NETWORKS AND CELLULAR AUTOMATA
IN EXPERIMENTAL HIGH ENERGY PHYSICS

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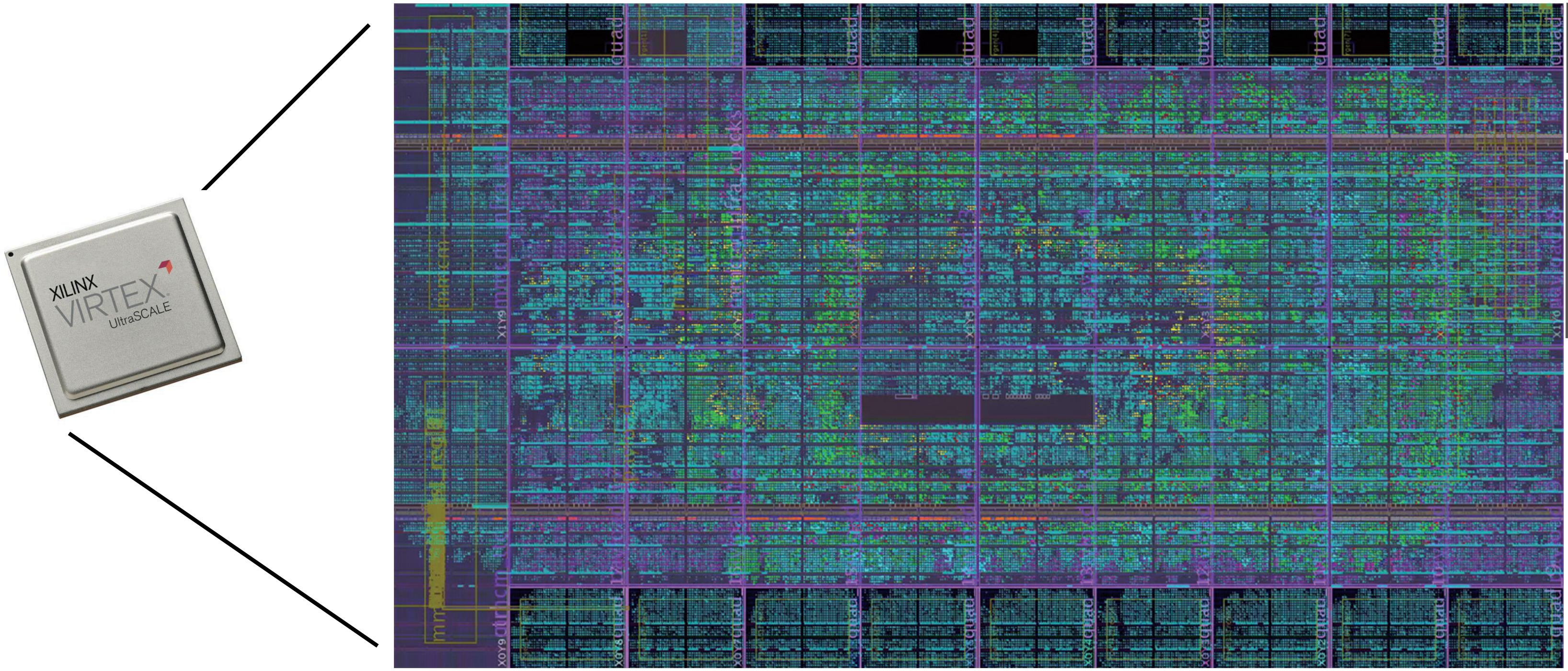
Received 20 September 1987; in revised form 28 December 1987

Within the past few years, two novel computing techniques, cellular automata and neural networks, have shown considerable promise in the solution of problems of a very high degree of complexity, such as turbulent fluid flow, image processing, and pattern recognition. Many of the problems faced in experimental high energy physics are also of this nature. Track reconstruction in wire chambers and cluster finding in cellular calorimeters, for instance, involve pattern recognition and high combinatorial complexity since many combinations of hits or cells must be considered in order to arrive at the final tracks or clusters. Here we examine in what way connective network methods can be applied to some of the problems of experimental high energy physics. It is found that such problems as track and cluster finding adapt naturally to these approaches. When large scale hard-wired connective networks become available, it will be possible to realize solutions to such problems in a fraction of the time required by traditional methods. For certain types of problems, faster solutions are already possible using model networks implemented on vector or other massively parallel machines. It should also be possible, using existing technology, to build simplified networks that will allow detailed reconstructed event information to be used in fast trigger decisions.

MODERNISING TRIGGER SYSTEMS

Recent developments around FPGA programming and low latency algorithms have expanded the trigger capabilities

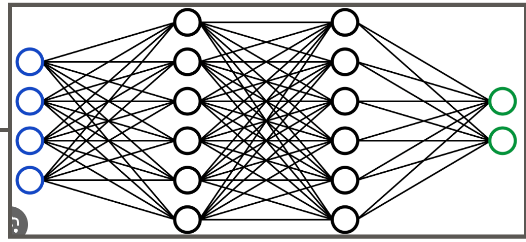
- Recent **huge progress** with high-level language translation
- **New tools** have been designed within various collaborative frameworks, including major contributions from CMS L1T team (HLS4ML, CONIFER) to help with neural network inference.
- ***Moving towards real time analysis with hardware systems.***



Conifer

hls4ml

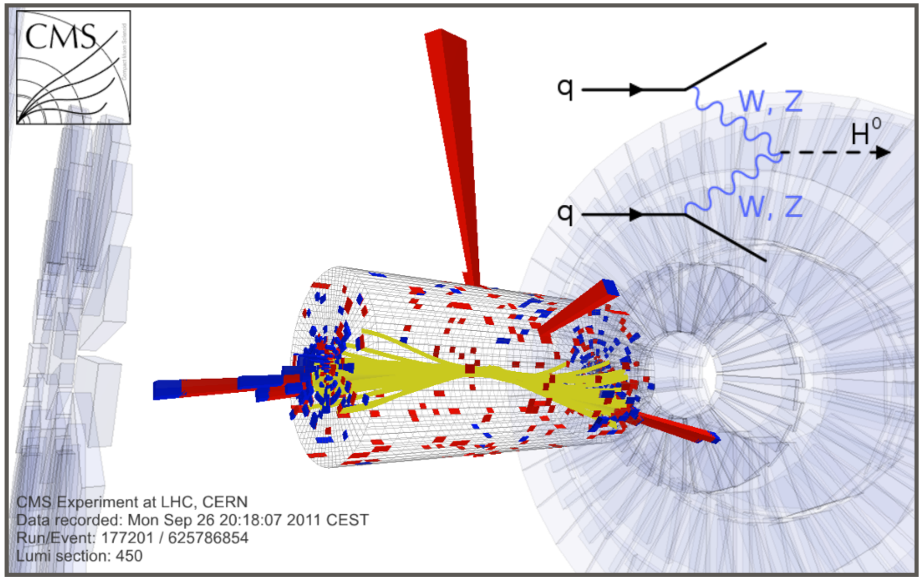
MODERNISING TRIGGER SYSTEMS

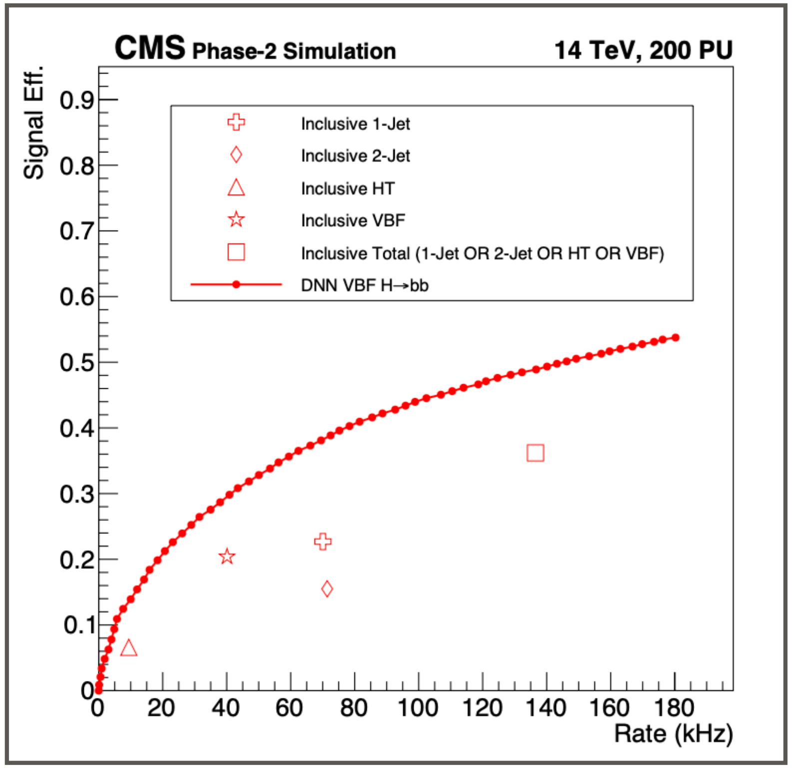


Why investing into neural networks (NN)?

- Neural networks allows you to build a powerful multivariate discriminator
- Used now in all modern data analyses, instead of simple 1D cuts on object variables and correlations. NN Training techniques are well established.
- **NN are truly adapted to hardware triggers**. Software tools can synthesise such algorithms into FPGA firmware. **A trigger is technically a binary classifier !**

Example here with VBF Higgs signal
Traditionally selected with these variables:
pT, η, M(jj), Δη(jj), etc.

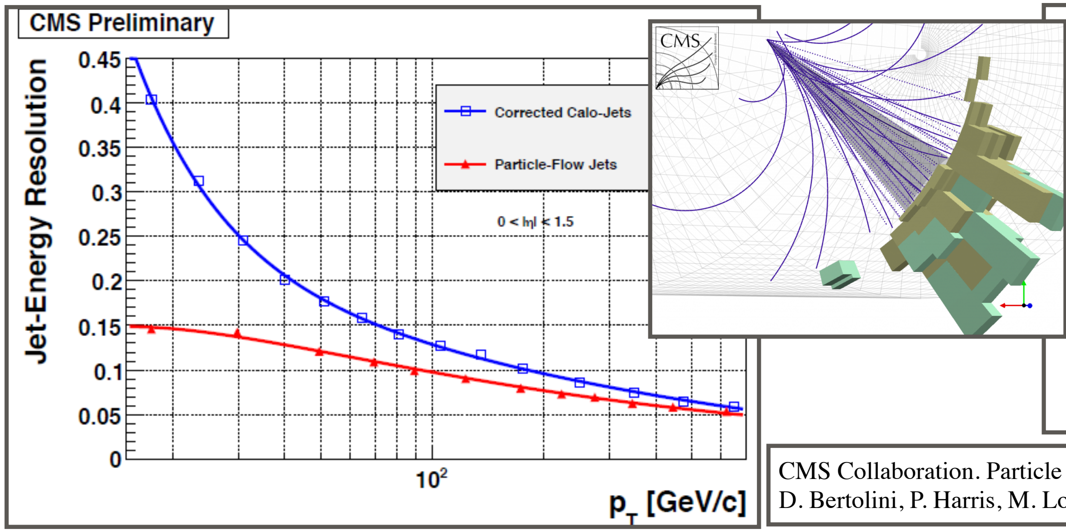


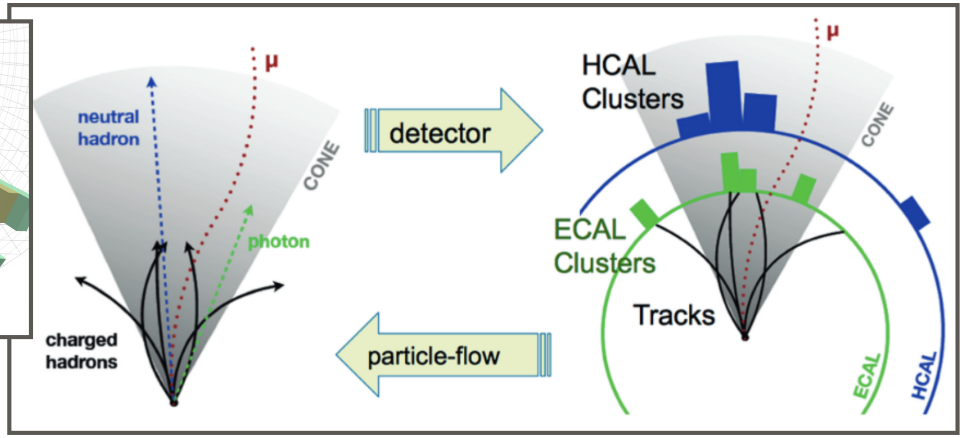


MODERNISING TRIGGER SYSTEMS

Investing into modern data analyses techniques

- Today, many CMS data analyses rely on global event reconstruction algorithms, such as **particle flow**.
- *The particle flow reconstruction algorithm aims at reconstructing and identifying all particles in an even using all subdetector information*
- Complemented with **pile-up per particle identification** (associating a weight to each particle to discriminate pileup from signal) using the vertex information.
- ***Established as powerful tools to extract major physics results.***





CMS Collaboration. Particle Flow CMS *JINST* **12** (2017) P10003, arXiv:1706.04965.
D. Bertolini, P. Harris, M. Low, and N. Tran, PUPPI, *JHEP* **10** (2014) 059, arXiv:1407.6013.

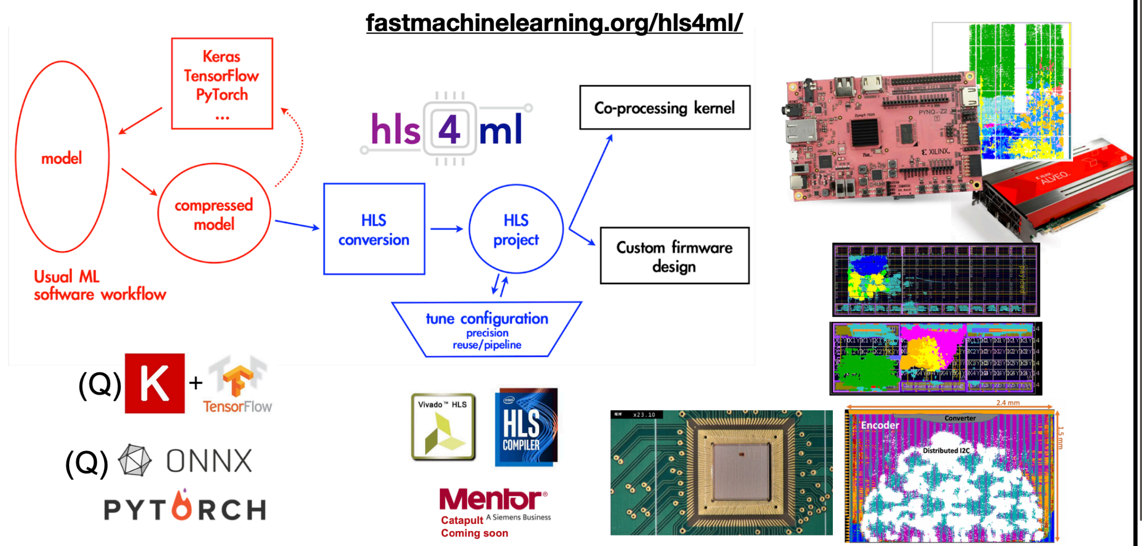
Can such sophisticated algorithm (w/ complex combinatorics, can computing intensive) be implemented into hardware ?

MODERNISING TRIGGER SYSTEMS

The upcoming of machine learning into the trigger world

- **Machine learning (ML) techniques** are now used in large range of applications, including physics data analysis @LHC. Reconstruction programs, particles identifications are now relying on ML approaches.
- ***What does it take to introduce ML into hardware systems and can it be turned into a decisive tool to achieve discoveries ?***

high level synthesis for machine learning



The dataflow architecture

- Independent compute unit with tunable quantization
- Target FPGA resources & latency
- Quantization Aware Training, Pruning, Knowledge Distillation

Physicists involved in their design!

Applications already underway:

- Autonomous vehicles: Developed new image-streaming CNN implementations for **hls4m**
- using **hls4ml** to monitor plastics pollution in the ocean onboard Earth Observation satellites

WHAT TO TAKE FROM THIS ?

- **TRIGGER SYSTEMS and potential evolutions:**
  - ✔ **First selection layers are hardware trigger systems (not much choice w/ > Tb/s input data).**
    - ✔ **Fully synchronised system**
    - ✔ **Fixed latency**
  - ✔ **Increased performance: modern technologies (FPGAs)**
  - ✔ **Increased physics selectivity using modern data analysis tools: NN, global event reconstruction (particle-flow), machine learning techniques**

Let's go now over its working principles and how it can evolves into a more sophisticated real time analsysis system

TRIGGERING @ LHC

WORKING PRINCIPLES AND EVOLUTION

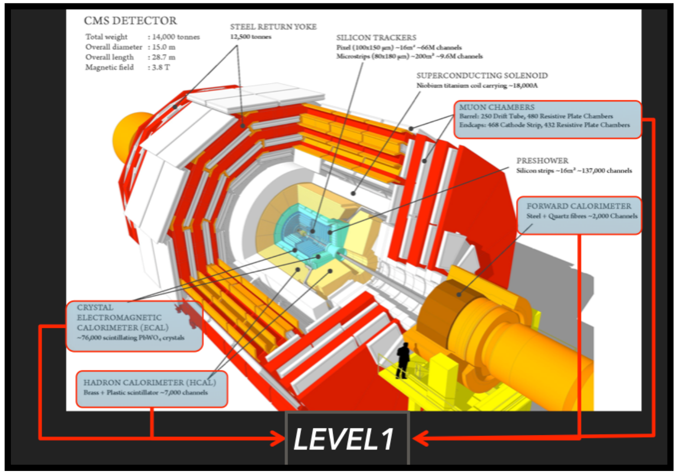
Discovering the Higgs Boson, and more

PRINCIPLE OF TRIGGERING ON INTERESTING EVENTS

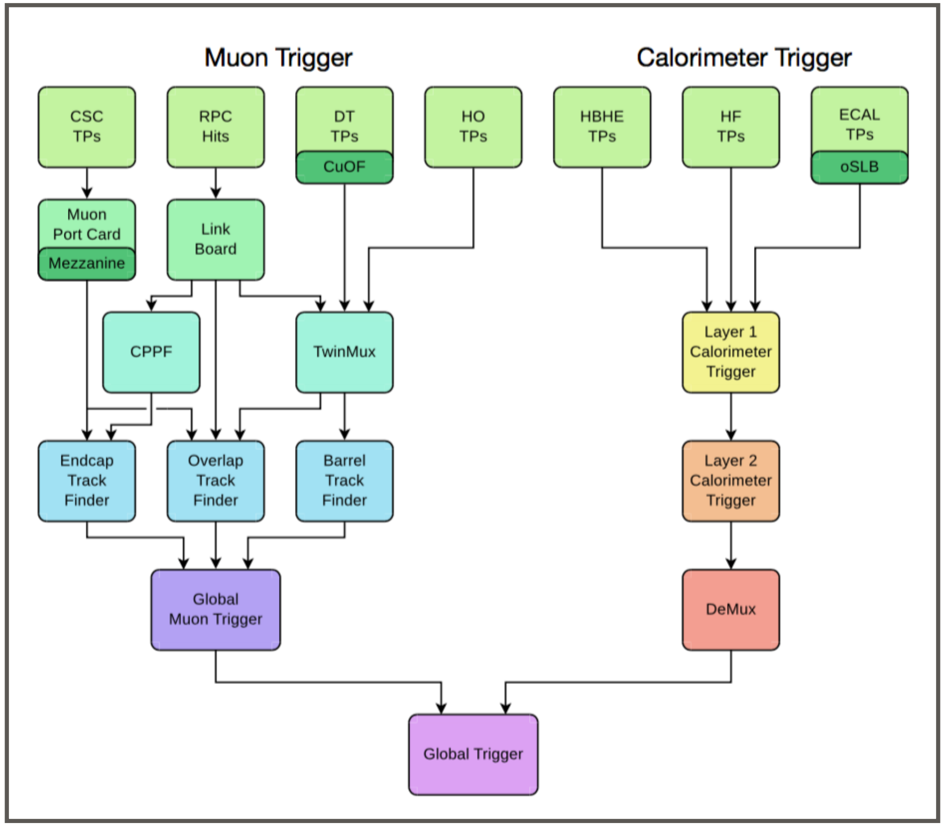
CMS Level-1 Trigger system: Today !

Harvesting data from calorimeters and muon spectrometers

Note: tracker data cannot be readout @ 40 MHz



The CMS Level-1 Trigger System



INPUT DATA

PHYSICS OBJECTS reconstruction

FINAL DECISION

PRINCIPLE OF TRIGGERING ON INTERESTING EVENTS

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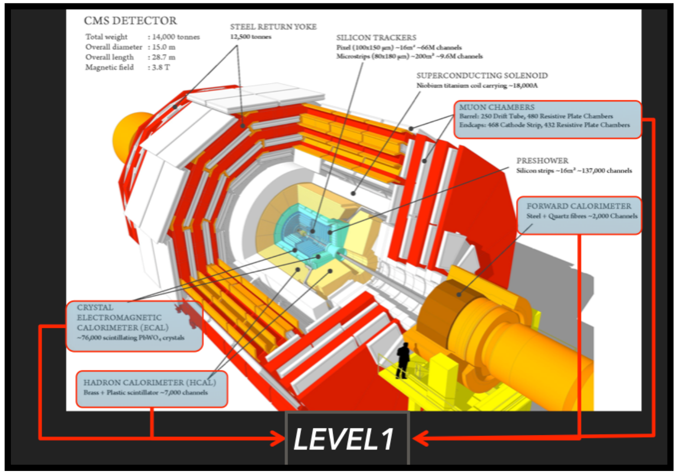
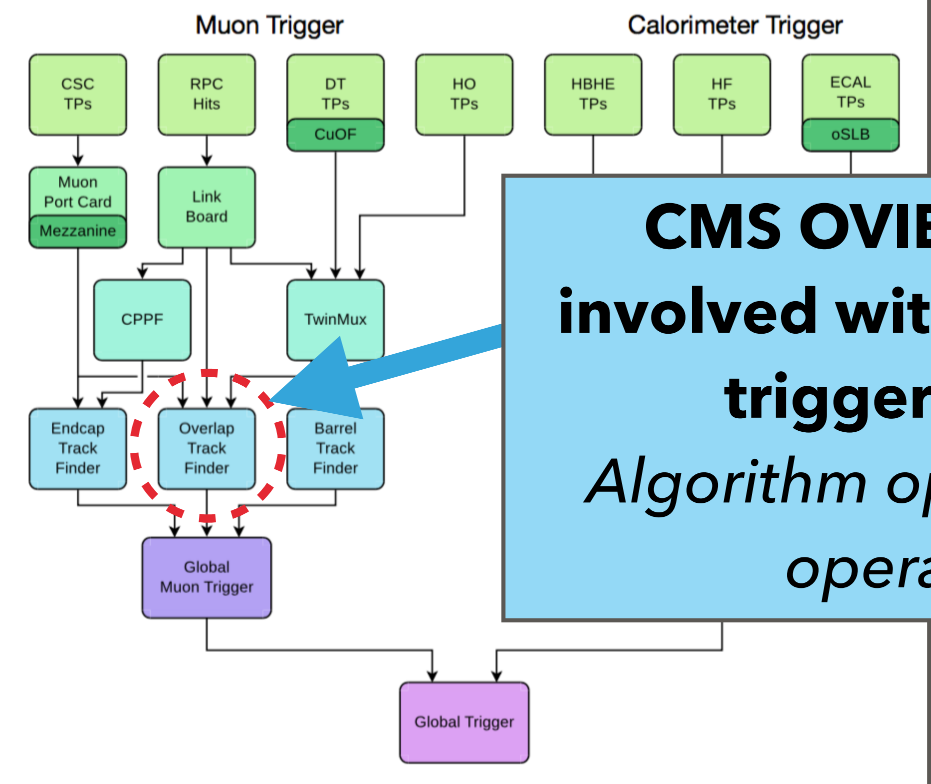


The CMS Level-1 Trigger System



INPUT DATA

CMS OVIEDO TEAM involved within the Muon trigger project

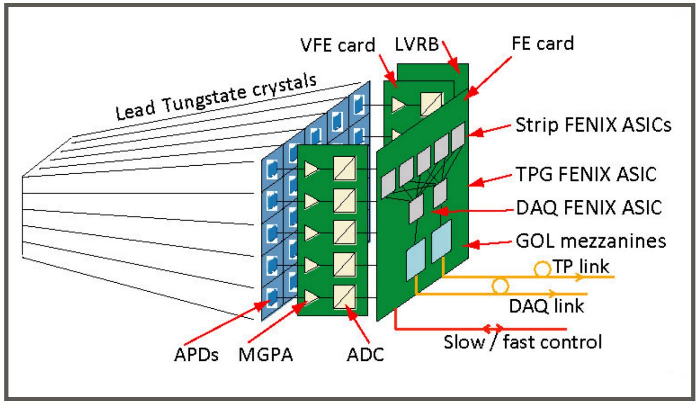
Algorithm optimisation & operations.

FINAL DECISION

PRINCIPLE OF TRIGGERING ON INTERESTING EVENTS

Working principle of the Phase-1 Level-1 Trigger system

Example: Calorimeter Trigger system (current system in operation)



Front-End (on-detector) Trigger Primitive (TPG) = ∑ 5 xtal E_T
Typically coarse information, computed quickly

DAQ

TPG

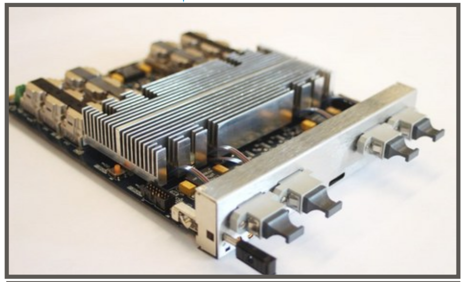
high-speed optical serial links

Back-End (off-detector)
Filter/Synch/Buffer

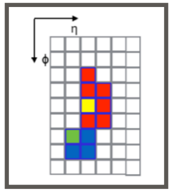
DAQ sent upon L1A

HLT

high-speed optical serial links



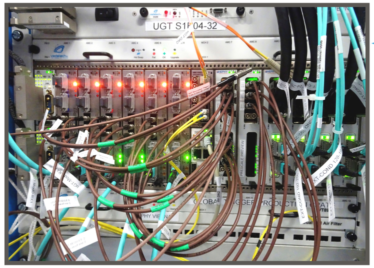
Calorimeter Trigger
Reconstruct e/tau/jets



Combining TPs into objects

high-speed optical serial links

L1A



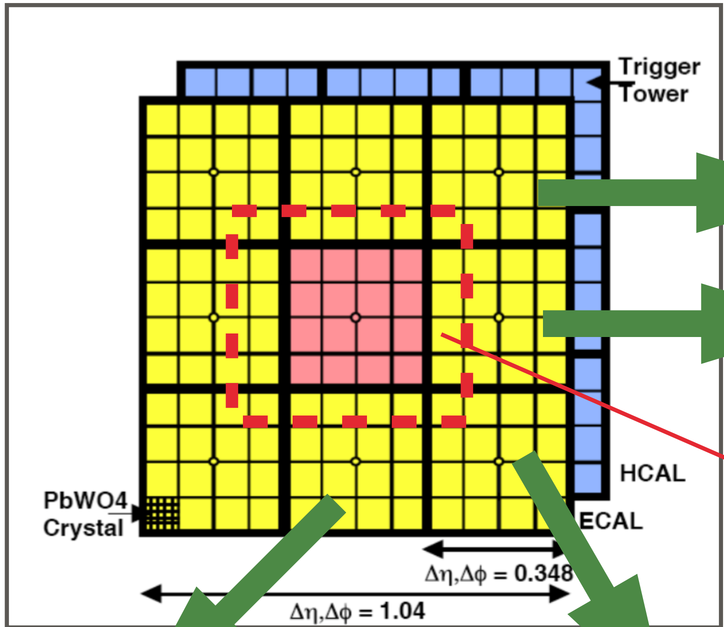
Global Trigger (final decision)
L1-Accept (L1A).

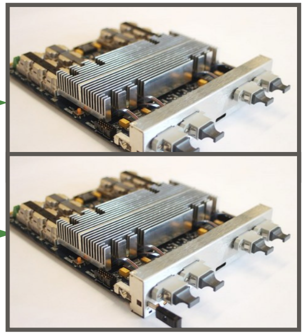
NOTE:
- fully synchronised system w/ fixed latency (3.8 us)
- Lots of resources & time used in serialise / de-serialise the data

APPROACHES TO DATA PROCESSING

Various data processing subdivision: region, task, timing

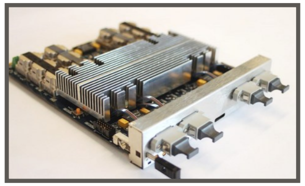
Example: Phase-1 upgrade Calorimeter Trigger system (in operation)



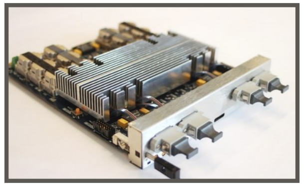


Regionalise detector: Separate hardware processes data from different region.

→ Duplication of data across regions



Electron/ Photon processor



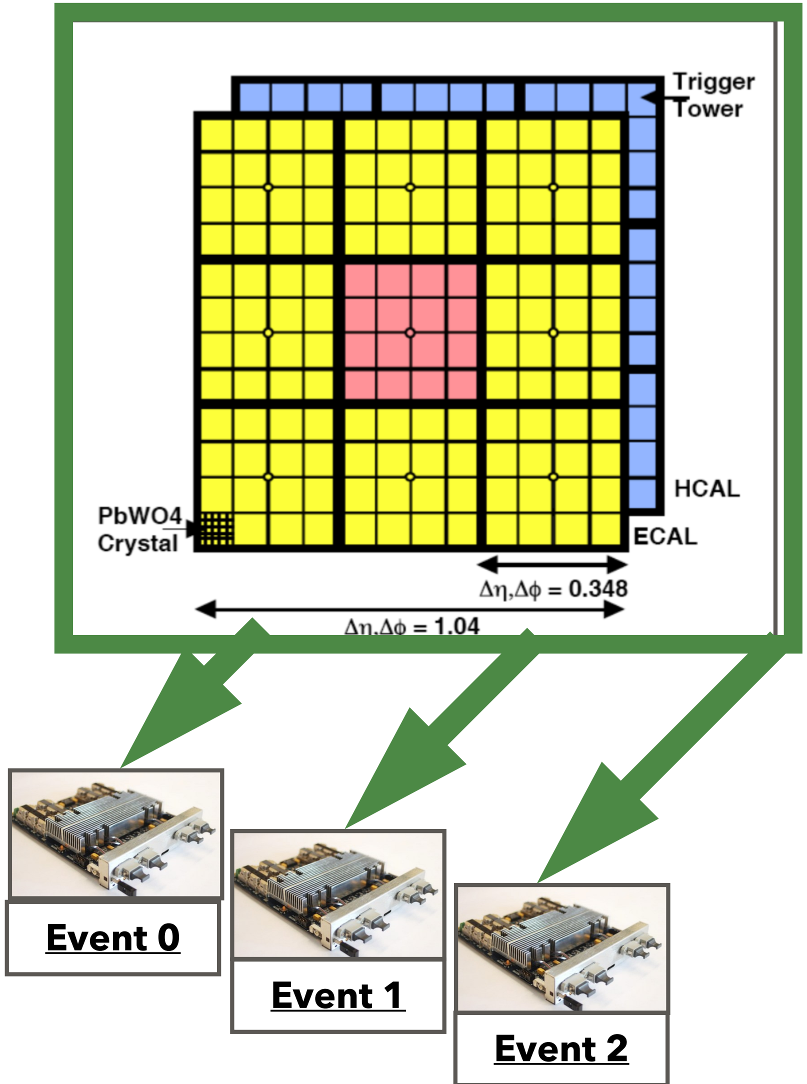
Jet/MET processor

Task subdivision: calorimeter data are set to different hardware to reconstruct different physics objects

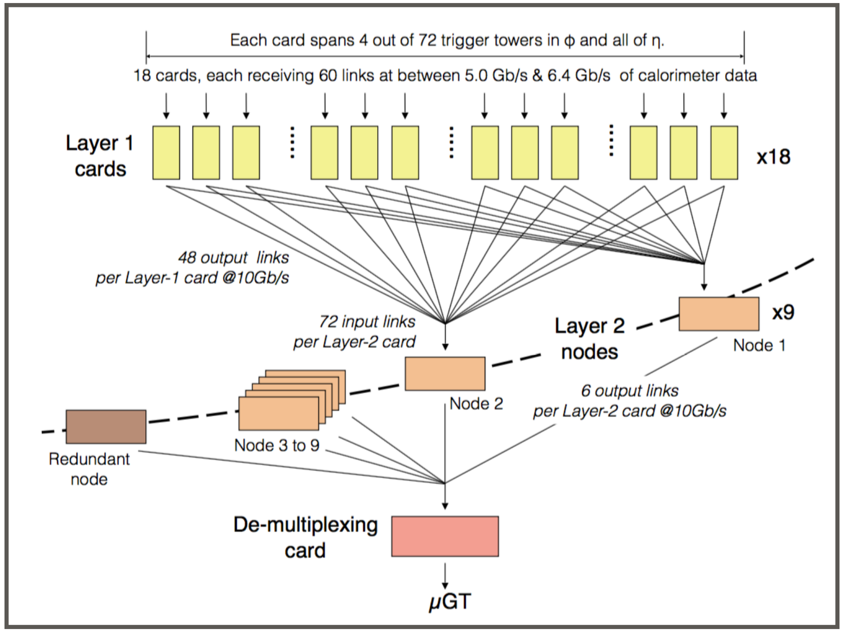
APPROACHES TO DATA PROCESSING: INNOVATION

CMS Innovative approach: Time-Multiplexing Trigger (TMT)

Example: Phase-1 upgrade Calorimeter Trigger system (in operation)



Phase-1 upgrade of the Calorimeter Trigger



Calorimeter inputs

Layer-1: calibration TPs & organisation in TMT

Layer-2: reconstruct trigger objects. Algo fully pipelined

De-Multiplexer: send data to GT

Time-Multiplexing Trigger: All calorimeter data for a given event sent to one processor, TMT depth = N. Processor

- ***No region boundaries = No duplication of data***
- ***Global detector view : global quantities MET, PU mitigation..***

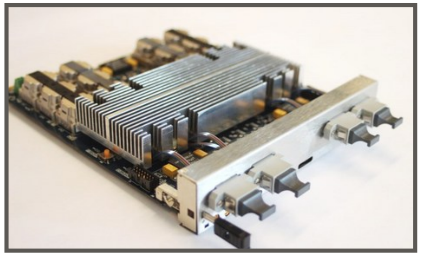
→ADAPTED TO LARGE DATA VOLUME PROCESSING

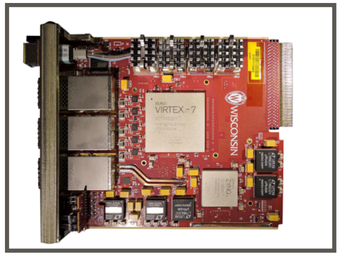
SYSTEM DESIGN: TECHNOLOGICAL CHOICES

Phase-1 Upgrade technological choices inspired future of triggering

- **FPGA:** The extensive use of state-of-the-art FPGAs → optimised reconstruction, identification, isolation and energy calibration of trigger objects using high-granularity detector information.
- **High-speed optical links:** facilitate the aggregation of data from across the entire detector → A complete view of the detector (evaluation of global quantities MET, pileup, specific VBF)
- **Flexible and modular architecture:** Reconfigured to adapt to HL-LHC running conditions and physics needs. Extra resources → Compute sophisticated quantities → richer menu and increased selectivity

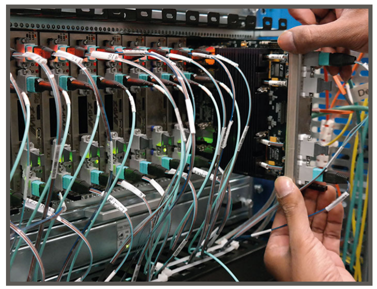
Phase-1 Upgrade: increased calorimeter granularity
LHC Run-1 2009 - 2012
LHC Run-2 2015 - 2018





Generic processing engines: MP7/CTP7

>1000 optical links

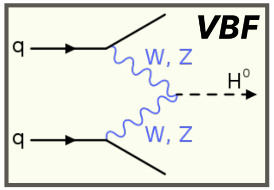


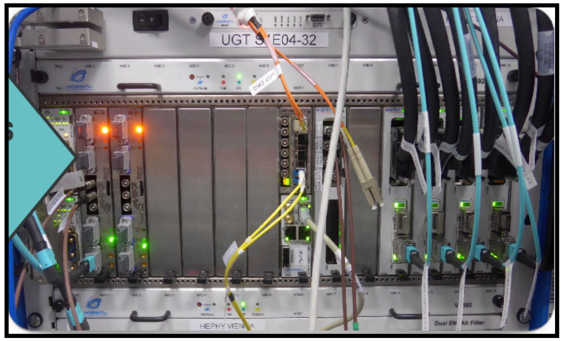
Calorimeter Trigger

SYSTEM DESIGN: TECHNOLOGICAL CHOICES

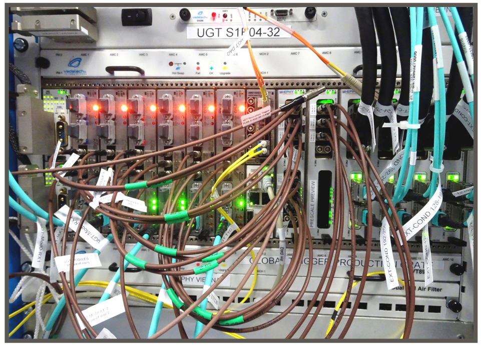
Phase-1 Upgrade technological choices inspired future of triggering

- **Flexibility of the design:** **increased global trigger capacity from 1 (2015), to 3 (2016) to 6 (2017) global trigger boards, increasing the total number of available trigger algorithms >500. in 2022, a extra crate was introduced to test new trigger algorithms, etc.**
- **Extended physics menu:**
  - 3-muon invariant mass (tau → 3mu)
  - Vector Boson Fusion (VBF). Most sensitive channel
  - Scouting/Bphysics Parking schemes

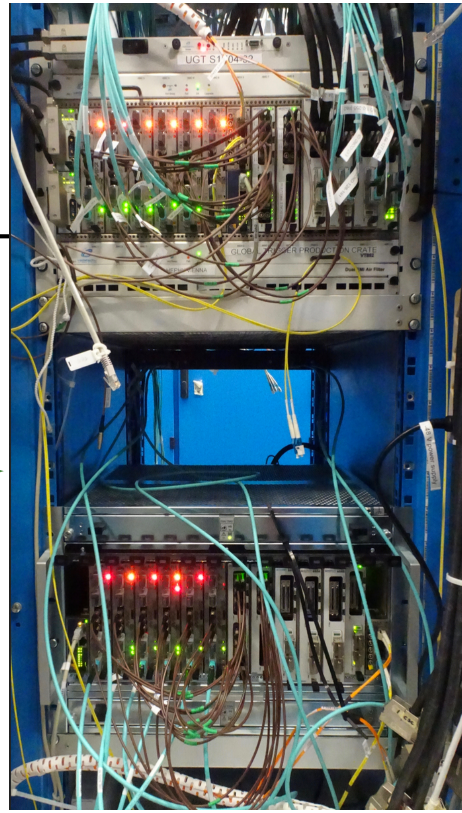




CMS L1 Global Trigger in 2015 1 MP7 board



CMS L1 Global Trigger in 2017: 6 MP7 Boards



CMS L1 Global Trigger in 2022: 12 MP7 Boards

→ Defined a new standard in modern HEP trigger system design

SYSTEM DESIGN: TRIGGER ALGORITHMS

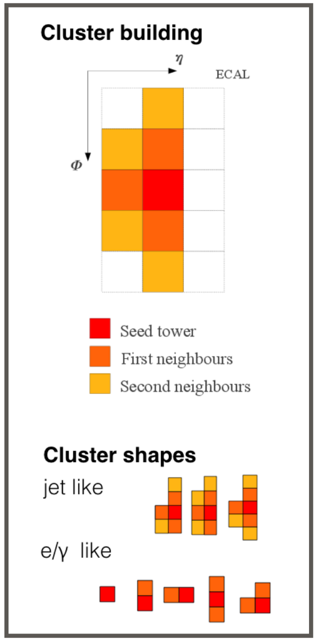
Reconstructing and identifying physics objects @ L1: Today !

Example: Calorimeter Trigger system (current system in operation)

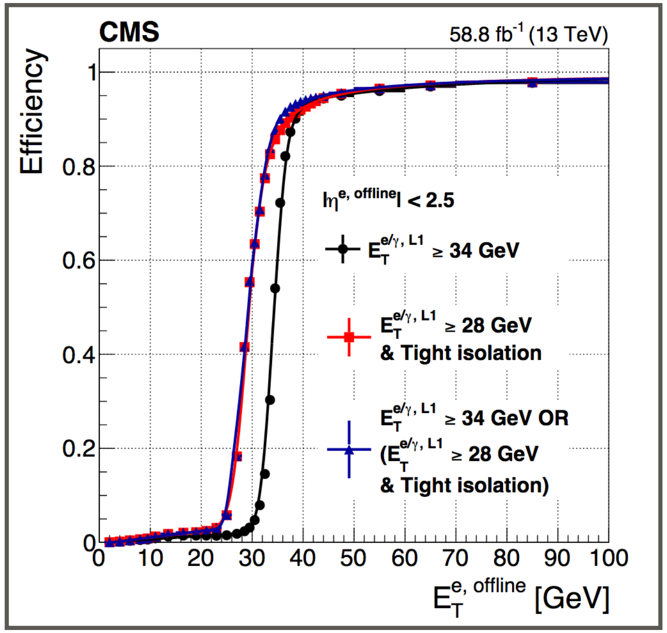
Reconstructing Electron/Photon: L1 EG

- *Traditionally using fixed window 3x3 Algorithm*
- *Introducing first dynamic clustering in FPGA*

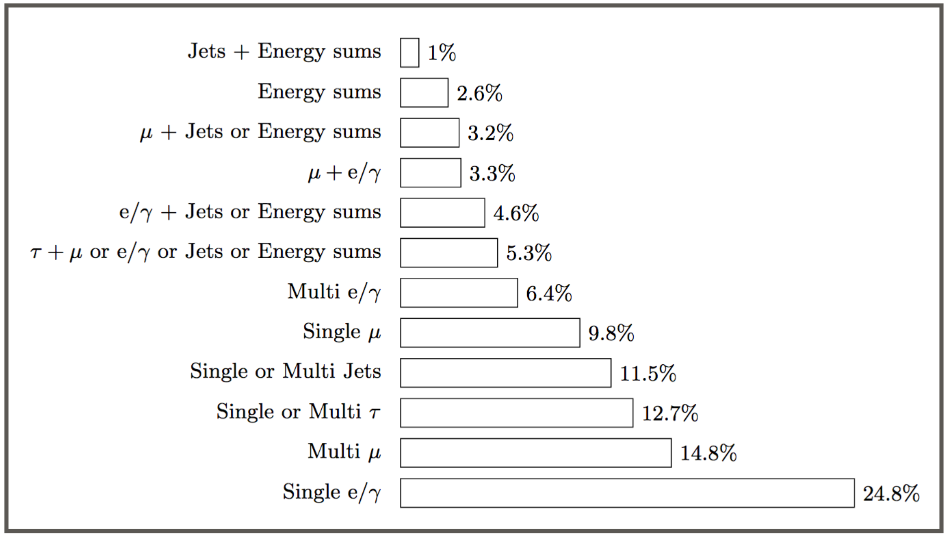
Algorithm name	Description
L1_SingleLooseIsoEG28er2p5	Single loosely isolated e/γ with $E_T > 28$ GeV and $\lvert\eta\rvert < 2.5$
L1_DoubleIsoTau32er2p1	Double isolated τ with $E_T > 32$ GeV and $\lvert\eta\rvert < 2.1$
L1_SingleMu22	Single muon with $p_T > 22$ GeV
L1_DoubleEG_25_12_er2p5	Double e/γ with $E_T > 25$ GeV, 12 GeV and $\lvert\eta\rvert < 2.5$
L1_DoubleMu_15_7	Double muon with $p_T > 15$ GeV, 7 GeV
L1_ETMHF100	$E_T^{miss} > 100$ GeV
L1_SingleJet180	Single jet with $E_T > 180$ GeV
L1_DoubleJet150er2p5	Double jet with $E_T > 150$ GeV and $\lvert\eta\rvert < 2.5$



Phase-1 EG algo



Phase-1 EG algo



Level-1 Physics Menu for Run 2

Triggers that permitted a large range of observations in the Higgs sector during Run-2:

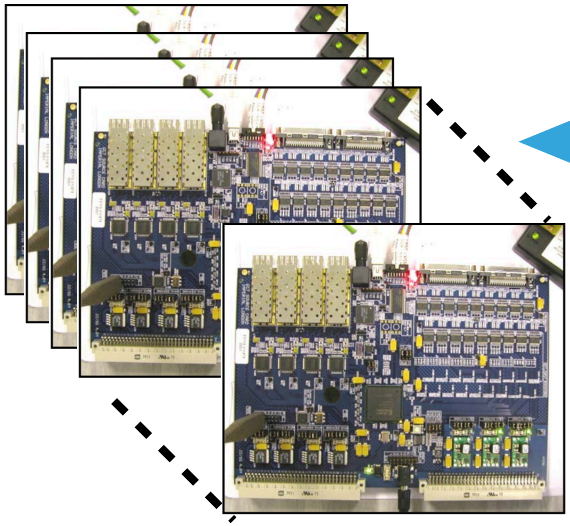
- *Observation of ttH, H → bb, H→ ττ.*

EVOLUTION OF TRIGGER SYSTEMS

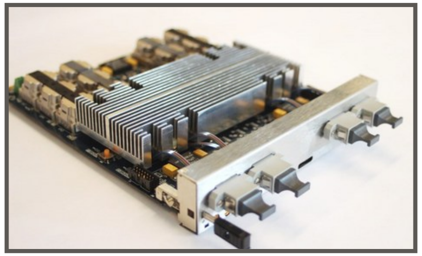
Aiming towards a hardware trigger system capable to select physics in real time with modern data analyses techniques

- What do bigger FPGAs and higher speed optical links do for you? Can you achieve better selectivity and trigger on unconventional physics signatures ?
- Can you perform all this in a harsher environment? Very intense running conditions expected after the upgrade of the LHC (HL-LHC)

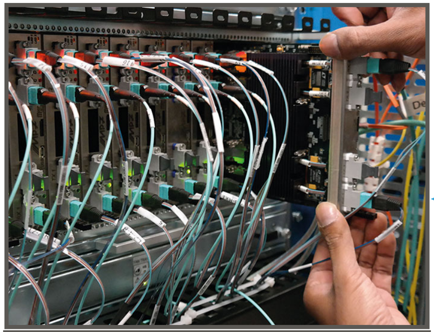
→ ***Motivation for the upgrade of trigger system***



Global Calorimeter Trigger in Run-1 (2009-2012)
~64 electronic boards



1 MP7 board !



Calorimeter Trigger in Run-2/3 ~ ***7 MP7***

1 Serenity board!
ATCA board for the CMS upgrade

TRIGGERING @ HL-LHC

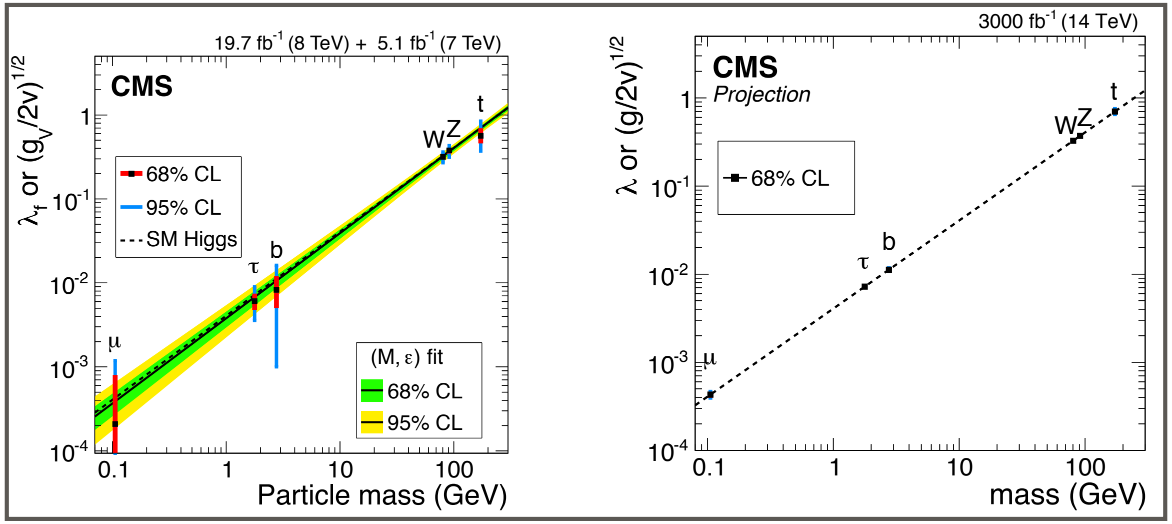
INTRODUCTION & DESIGN REQUIREMENTS

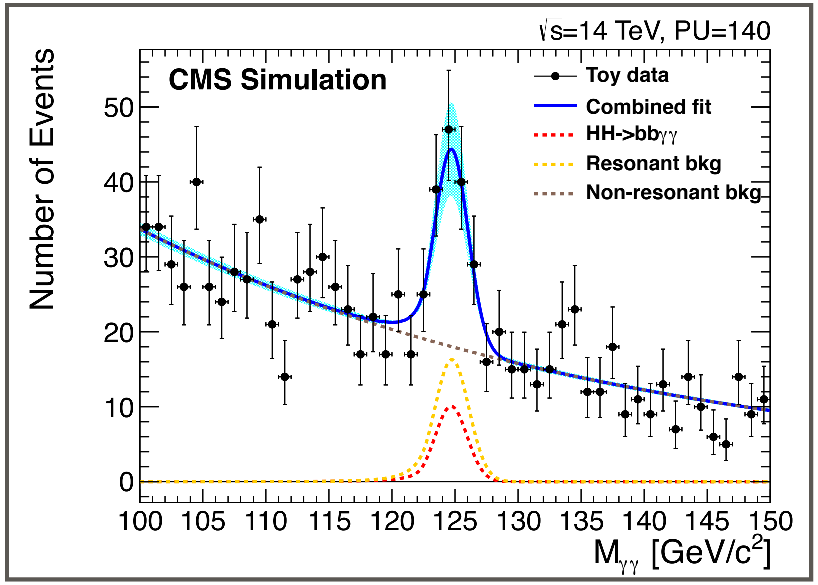
The scout of the HL-LHC

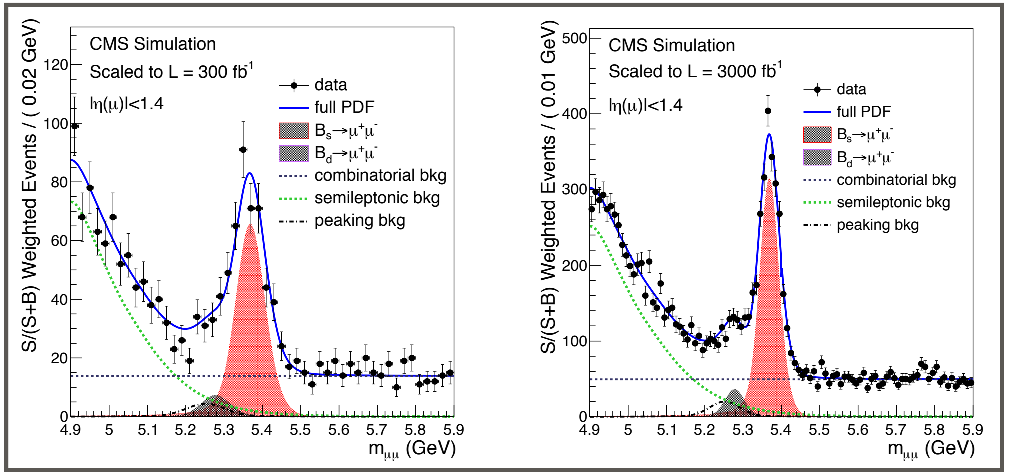
PHYSICS @ HL-LHC

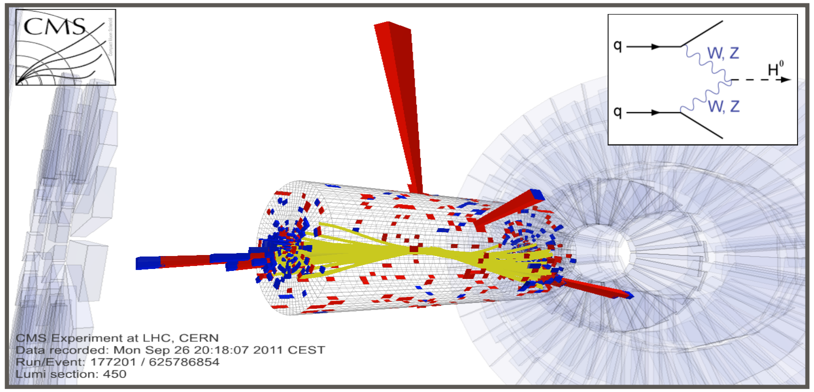
CMS Phase-2 physics drivers

- **Exploring the unknown** : Searches for new physics beyond the Standard Model (SM) DM, LLP,etc.
- **Standard Model as tool for discovery** : Precise knowledge of SM processes, probe anomalous couplings, 4 tops, VBS, VBF, etc. Higgs Sector: couplings (Hcc, Hμμ), differential xc, self-coupling HH
- **Understanding the Standard Model**: parton shower, underlying event, differential measurements







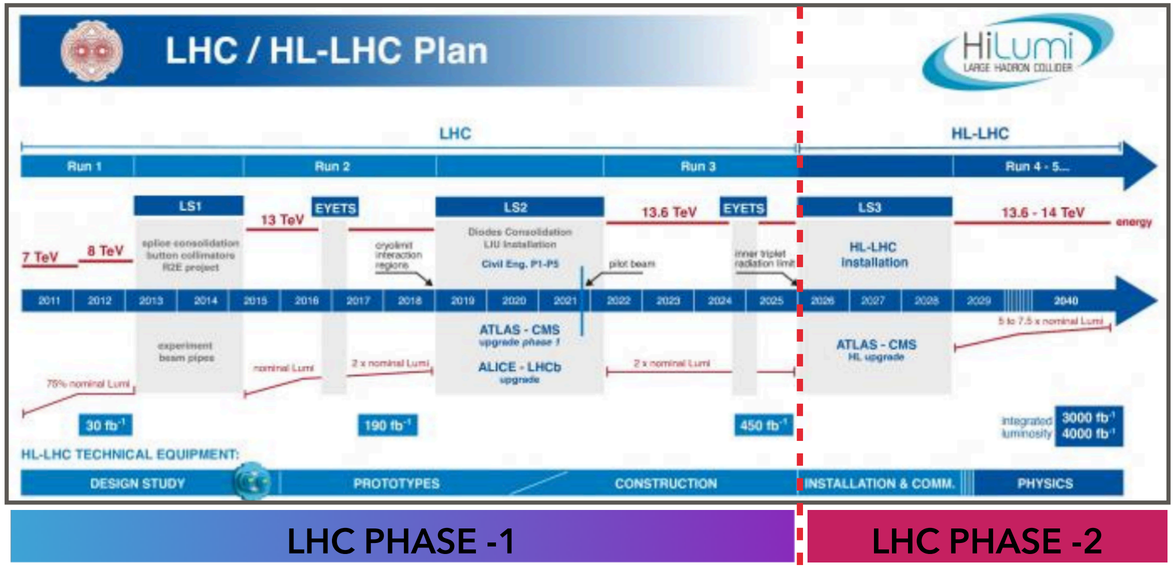


INTRODUCTION: CONTEXT OF TRIGGERING

- **HL-LHC Upgrade Project: offers an unprecedented opportunity to explore uncharted lands and achieve scientific progress.**
- **A new LHC machine and a new CMS Detector:**

The HL-LHC and the CMS Phase-2 detector

→ ***Set the context of triggering & define system requirements***

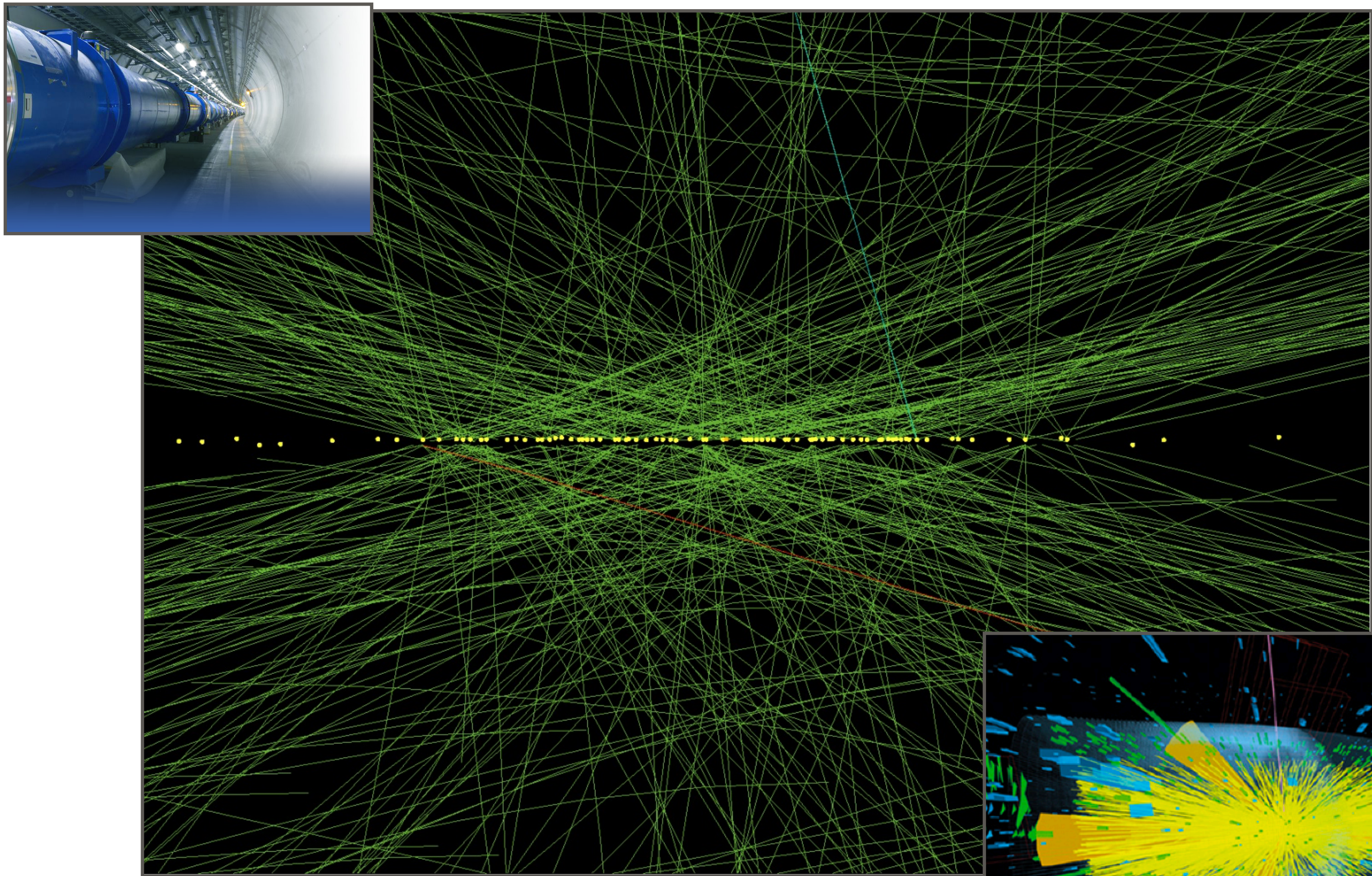


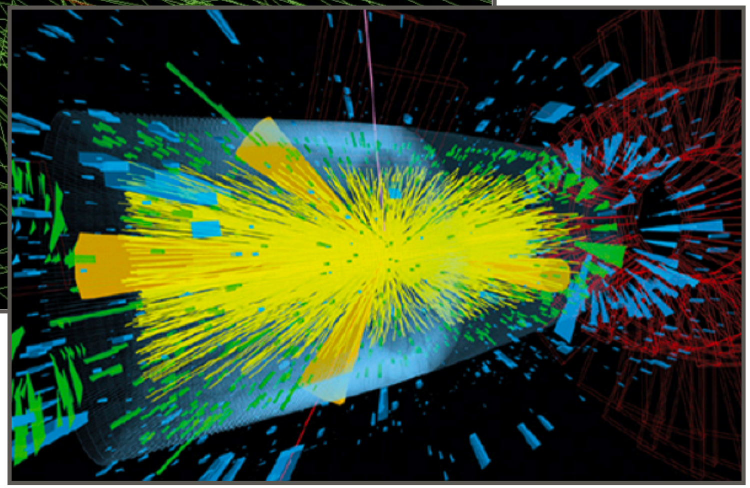
High-Luminosity-LHC: 13 TeV (Nominal : $5x10^{34}$ & 140 PU, Int Lumi = 3000 fb^{-1})

- **Ultimate: $7.5x10^{34}$ & 200 PU, Int Lumi = 4000 fb^{-1} (baseline for all TDR studies)**

→ ***unprecedented running conditions, exceeding machine design values 7 fold.***

ENVIRONMENT @ HL-LHC: THE NAME OF THE GAME





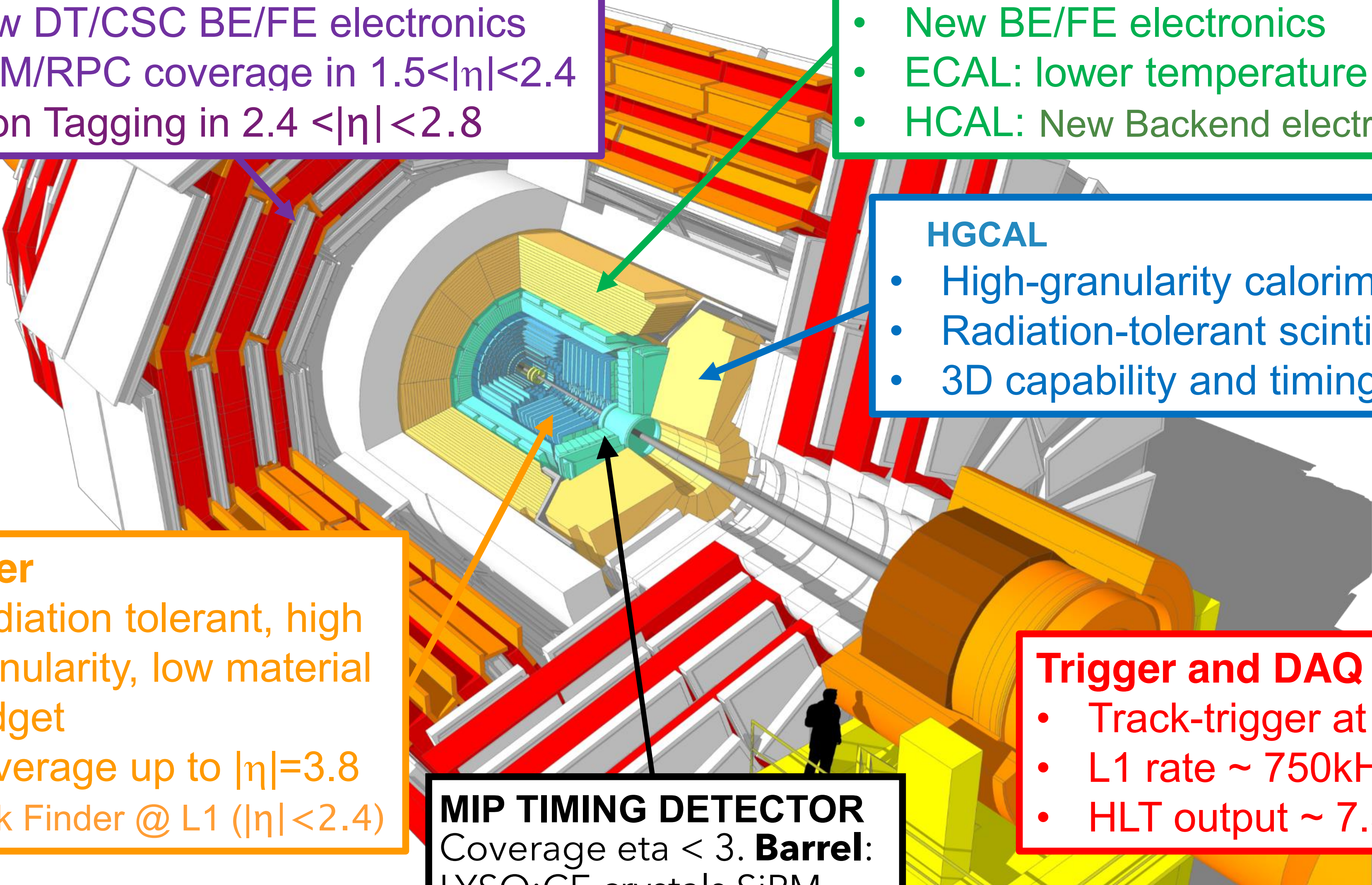
Expecting huge particle multiplicity !

AN UPGRADED CMS DETECTOR

Muon System
- New DT/CSC BE/FE electronics
- GEM/RPC coverage in $1.5<|\eta|<2.4$
- Muon Tagging in $2.4 <|\eta|<2.8$

Barrel Calorimeter
- New BE/FE electronics
- ECAL: lower temperature
- HCAL: New Backend electronics

HGCAL
- High-granularity calorimeter
- Radiation-tolerant scintillator
- 3D capability and timing



Tracker
- Radiation tolerant, high granularity, low material budget
- Coverage up to $|\eta|=3.8$
- Track Finder @ L1 ($|\eta|<2.4$)

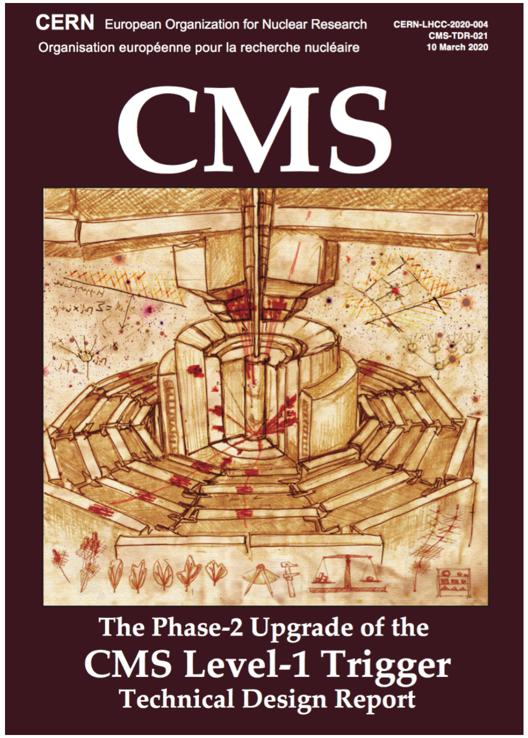
MIP TIMING DETECTOR
Coverage eta < 3. **Barrel**: LYSO:CE crystals SiPM. **EndCap**: Silicon Sensors (LGAP). **Timing ~**

Trigger and DAQ
- Track-trigger at L1
- L1 rate ~ 750kHz
- HLT output ~ 7.5kHz

PHASE-2 TRIGGER UPGRADE: KEY PARAMETERS & STRATEGY

- **CMS Phase-2 Trigger:**
  - CMS keeps a 2-level triggering approach: **L1 & HLT**
  - **Level-1 (hardware) system**
    - Increase bandwidth 100 kHz → 750 kHz
    - Increase latency 3.8 us → 12.5 us
- **Benefiting from upgrade of the CMS detector:**
  - Include high-granularity information (calo&μ)
  - Include tracking information (first time!)

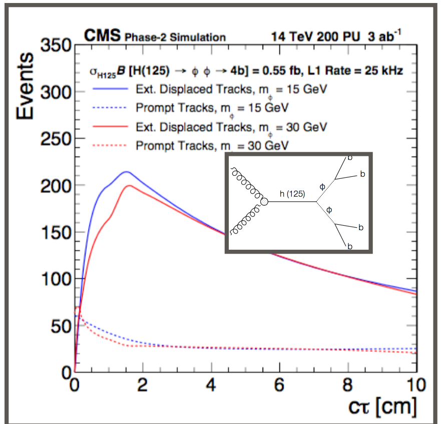
  → Manageable object rate (L1 Physics Menu)
- **Strategy:**
  - Exploit sub-detector back-end electronics
  - Sophisticated reconstructed objects and correlations → Enhanced physics selectivity
  - Expand reach with Scouting System

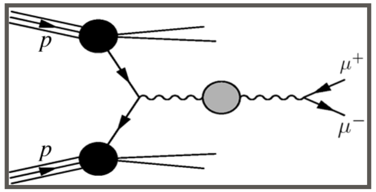


TDR approved in 2020

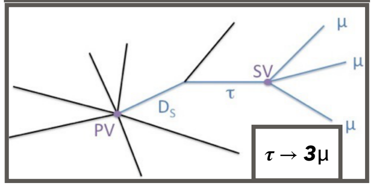
L1 PHASE II TRIGGER UPGRADE: SCIENTIFIC CASE

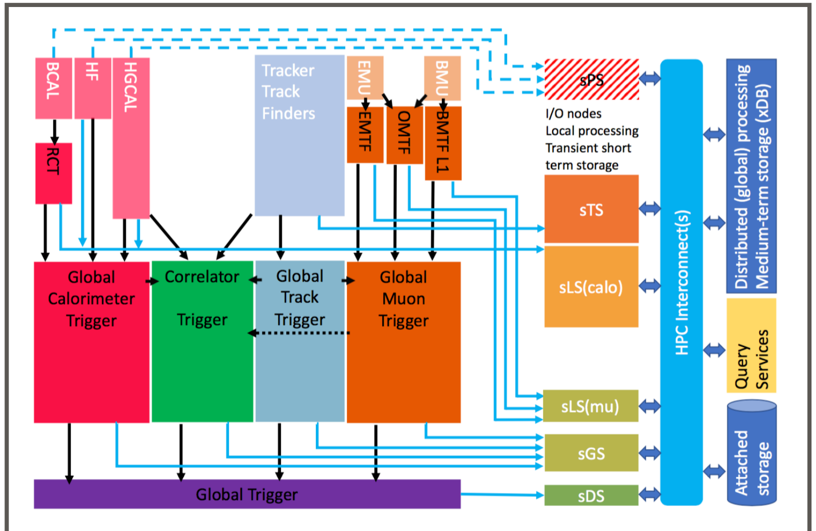
Maintaining thresholds is <u>NOT</u> the only motivation for upgrading the L1 trigger. HL-LHC research program opens a door to the unknown → **<u>the Phase-2 Level-1 Trigger system is our scout !</u>**
The goal is to extend the physics reach by increasing the available phase space





DarkPhoton(displaced mu)





<u>L1 Trigger algorithm requirements</u>:

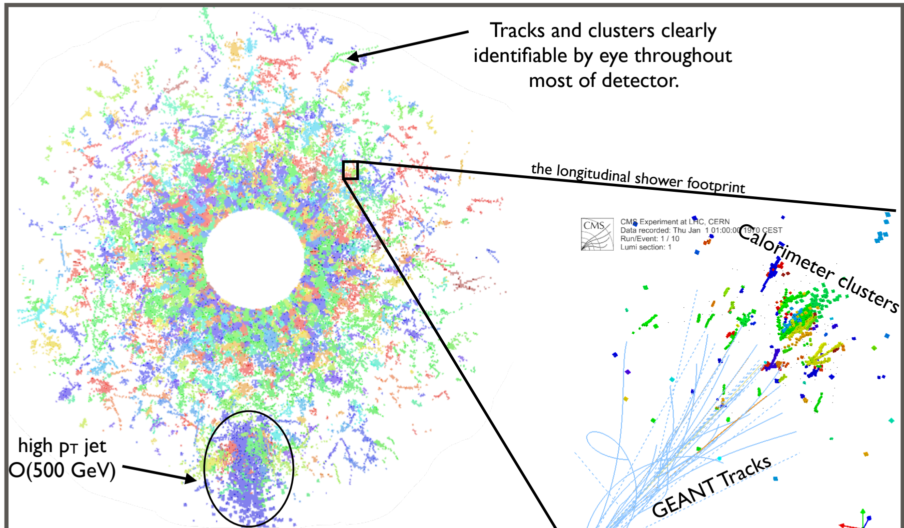
- Object reconstruction closer to offline performance: higher-level trigger objects **(particle-flow)** w/ optimised response and resilient to pileup (up to 200)
- Sophisticated triggers to select specific topologies: VBF production, rare B-meson decays **(tracking@L1),** forward muon trigger for τ → μμμ **(muon extended coverage)**, dedicated algos for displaced jets and muons, etc.
- Expand reach: Low mass resonances

<u>Scouting into HL-LHC data @ 40 MHz</u>:

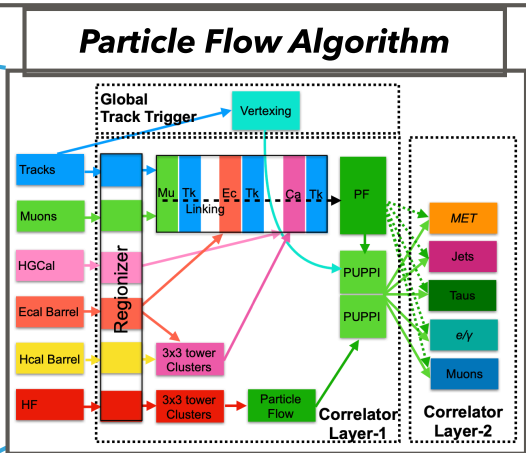
- Physics objects: reconstructed from L1 objects
- Storage: Only high-level information (selected events)
- Specific features: analyse multiple contiguous BX, identify signatures unreachable through standard trigger techniques

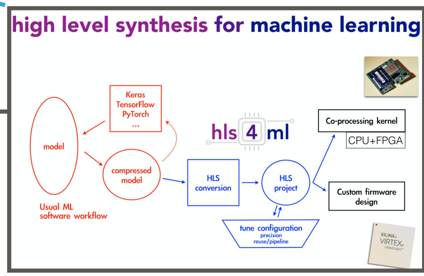
L1 PHASE II TRIGGER UPGRADE: TECHNOLOGICAL CASE

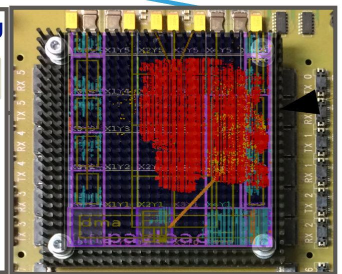
The Phase-2 Level-1 Trigger system performs precise physics selection using a global event reconstruction based on enhanced granularity already at hardware level.
Considering: Inputs > **70 Tb/s** (vs 2 Tb/s during LHC Phase-1), operate: 7.5e34 along w/ 200 PU events



Event display for *technical proposal* in 140 PU



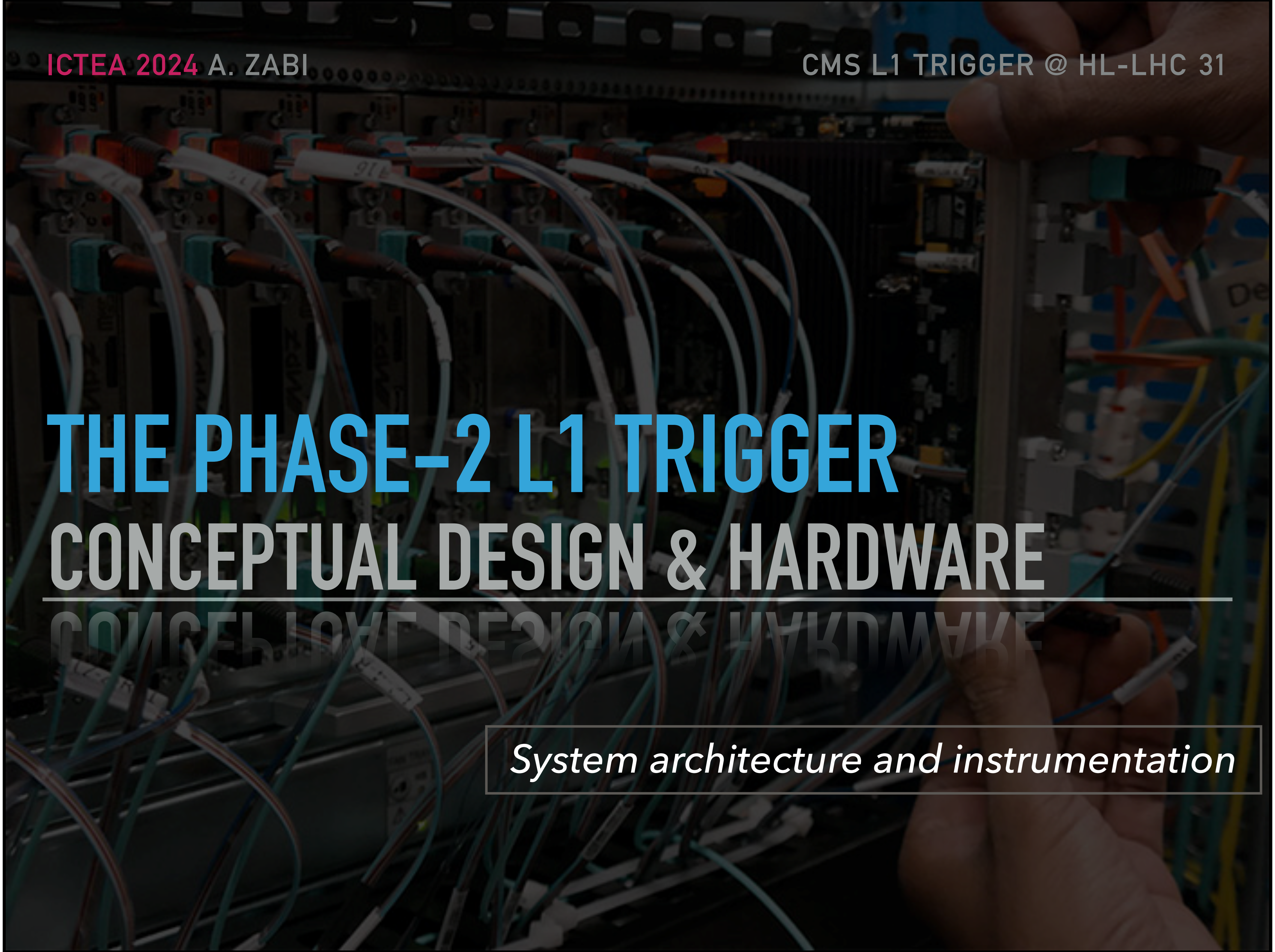




L1 Trigger requirements:

- Cutting-edge hardware: modern technology
  → FPGA VU9P x 8 resources of Virtex 7 (Phase-1), 28 Gb/s links
- High-Level-Synthesis: used successfully, much faster turn-around, novel techniques based on machine learning → *The Phase-2 L1 Trigger can do much more!*
- Advanced Architecture: platform and interconnections (ATCA) → robust, flexible & modular design
- Handling all technical issues: integration, commissioning, etc.

Conceptual design of the upgrade trigger inspired by the current system's technological choices !

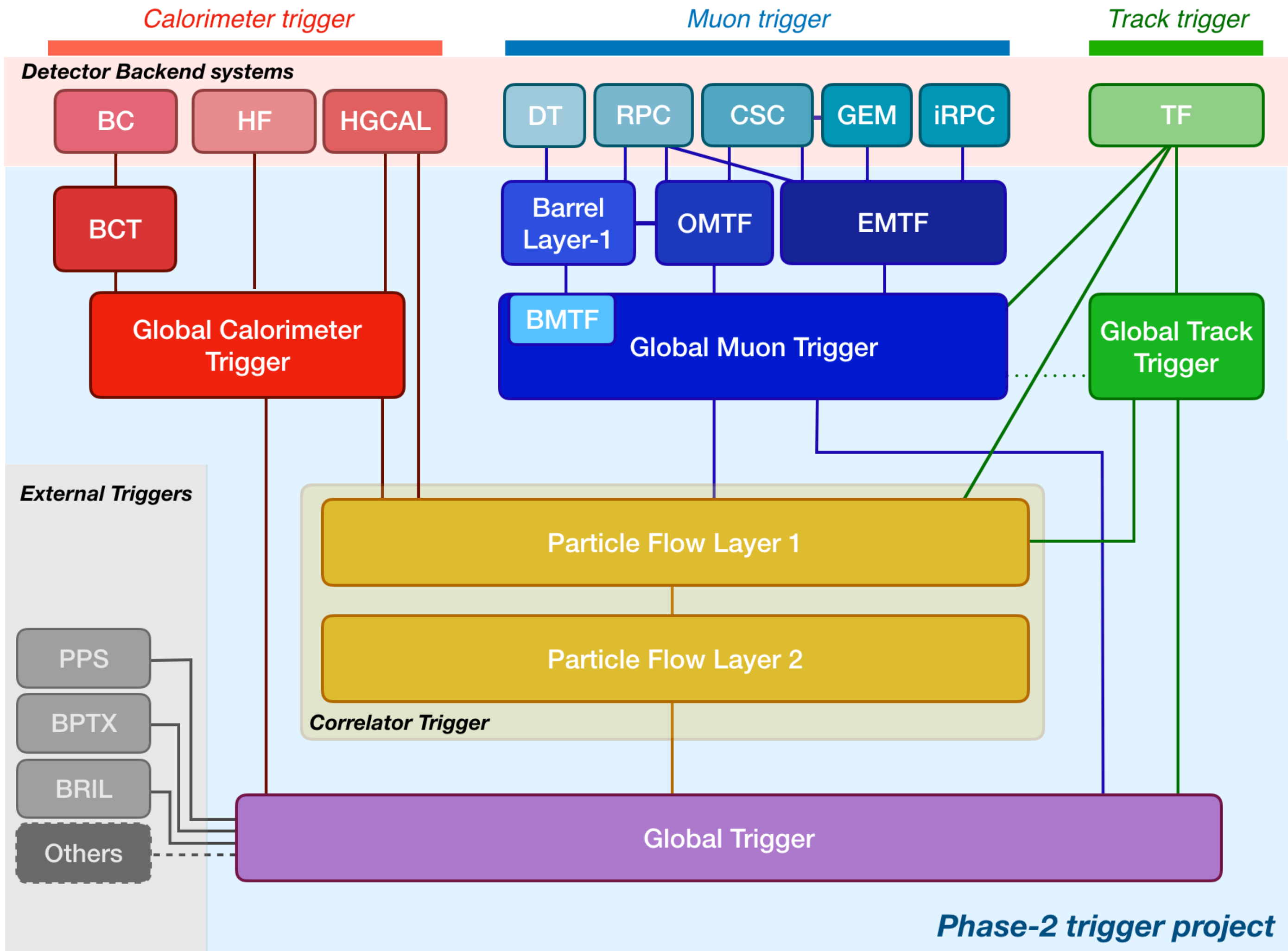


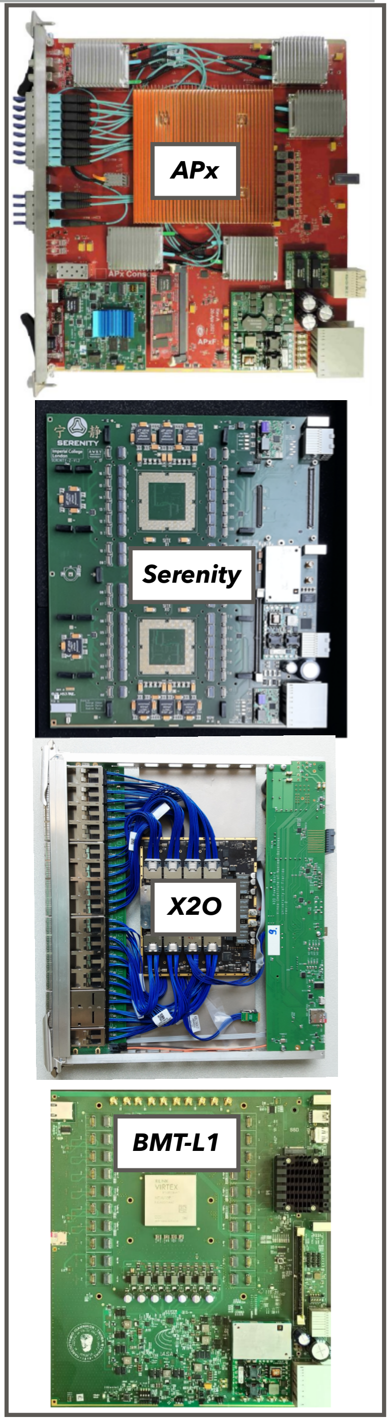
THE PHASE-2 L1 TRIGGER

CONCEPTUAL DESIGN & HARDWARE

System architecture and instrumentation

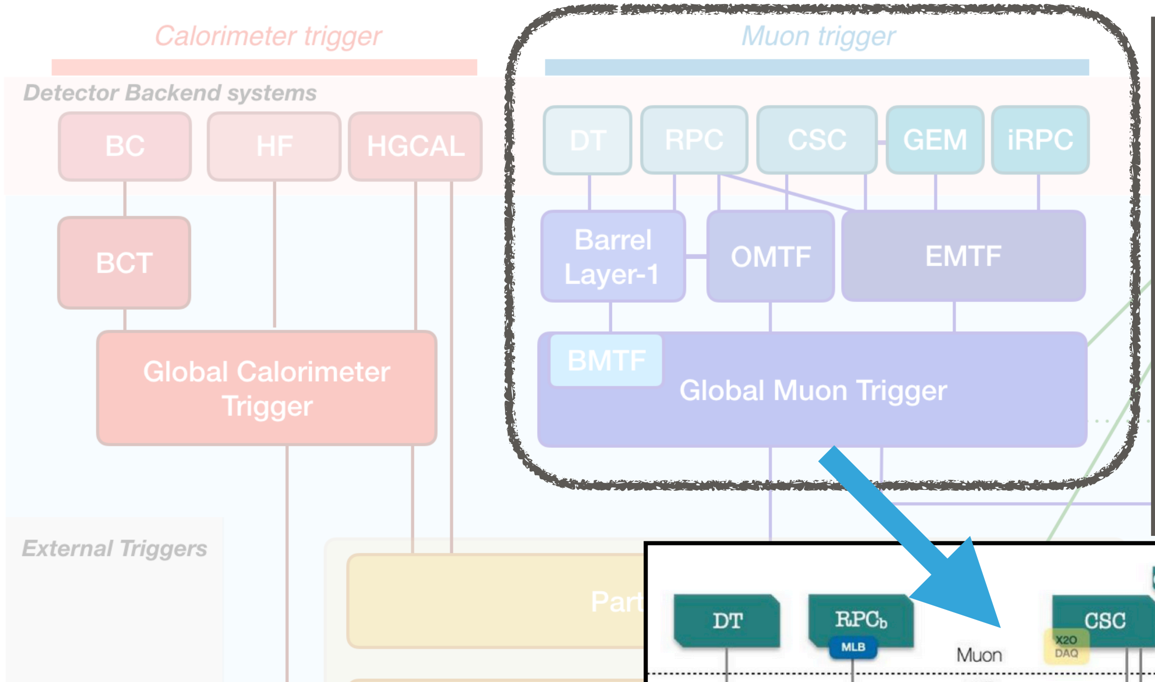
LEVEL-1 PHASE II TRIGGER UPGRADE SYSTEM





- **Level-1 Architecture:** **Efficient distribution and processing of trigger primitives, provision appropriate resources and interconnections, retain enough headroom future flexibility & Robustness**
- **Level-1 technological choices**: **generic processing engines (inspired from Phase-1 upgrade)**
- **Key design feature:** **Correlator Trigger. Collects all inputs and feed sophisticated algorithms**
- **Design Constraints :** **HW processors > 100 links , FPGA resources < 50 %, Latency (< 9.5 us (keep 20%) while HGCAL/TF~5us)**

LEVEL-1 PHASE II TRIGGER UPGRADE SYSTEM

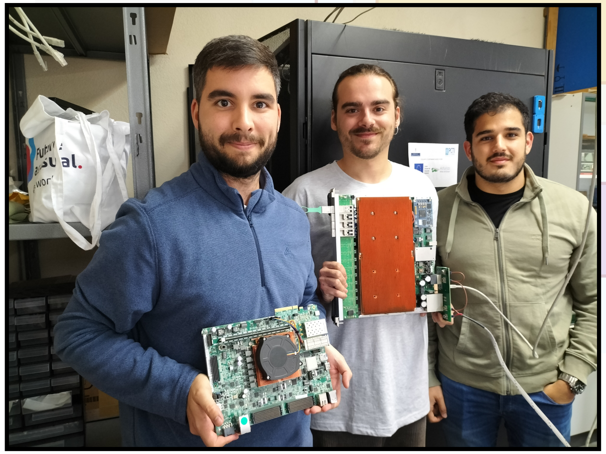


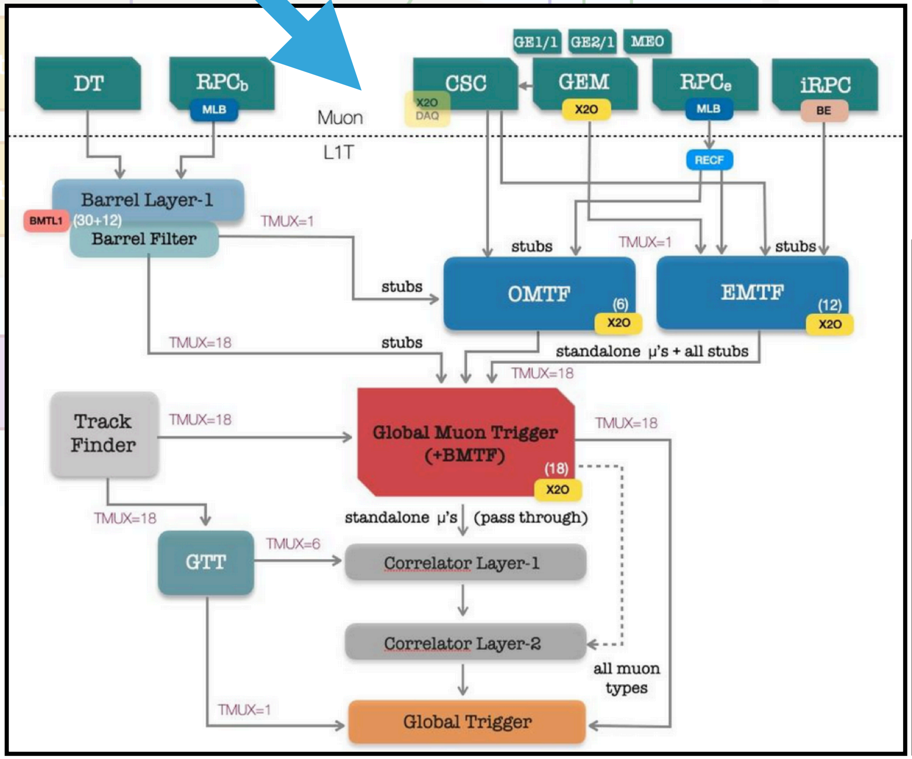
CMS OVIEDO TEAM involved within the Phase-2 Muon trigger project

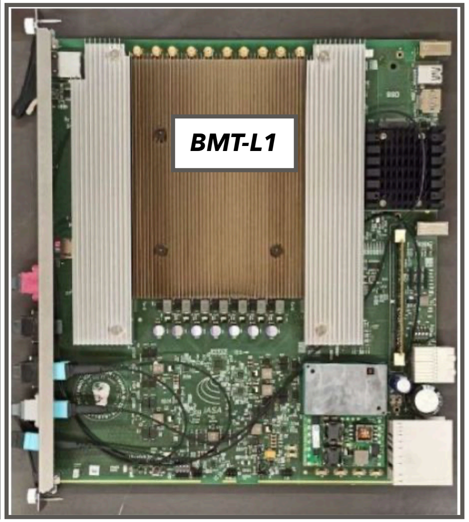
OMTF, BMTF, GMT

Hardware & Algo & firmware

in collaboration w/ CIEMAT



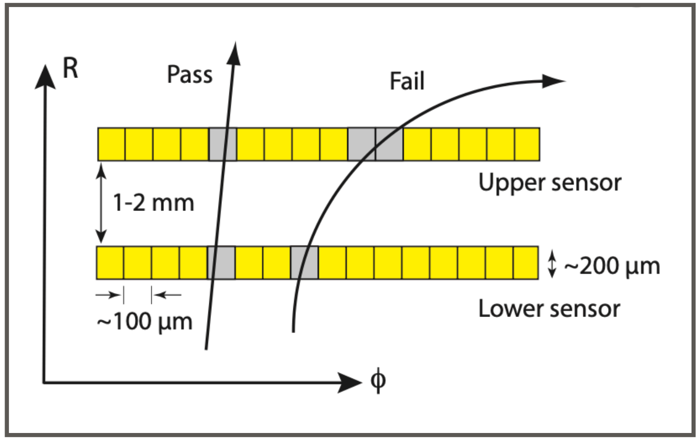


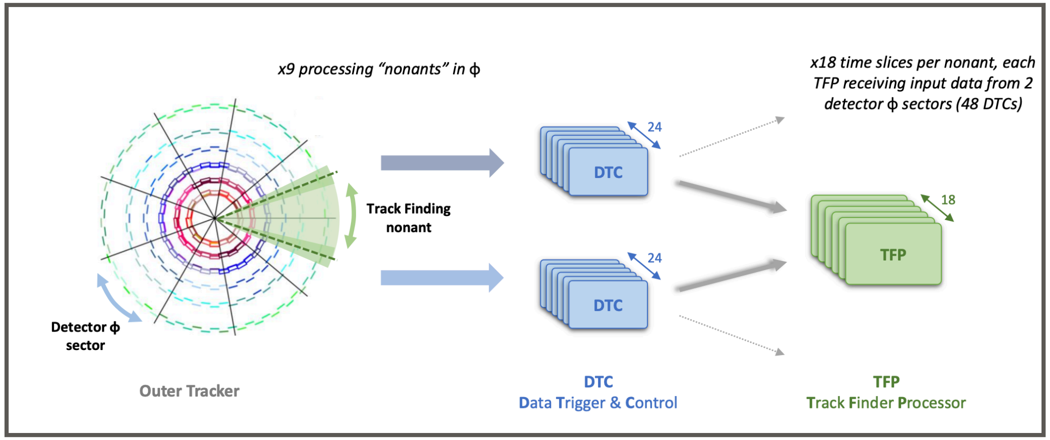


INPUTS TO THE TRIGGER SYSTEM: TRACKING

<u>Tracks</u>: fully reconstructed tracks are available at the Level-1 Trigger for the first time.

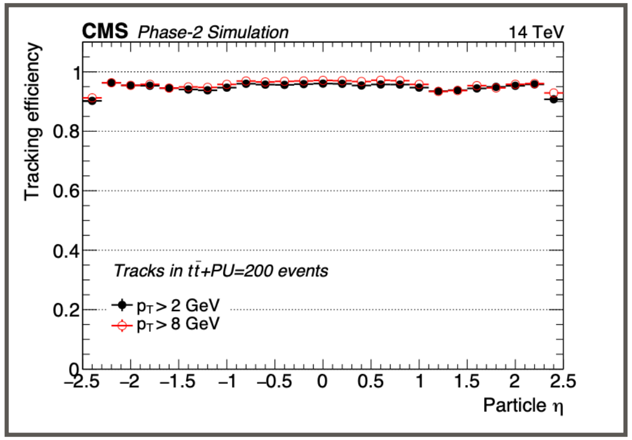
- Used to reconstruct the event's primary vertex
- Matching tracks to calorimeter clusters, muon stubs, etc.
- Calculating track-based quantities including isolation.





<u>L1 Track finder</u>: doublet sensors w/ common electronics to correlate hits and form stubs for trigger

- Efficiently remove tracks from PU
- Control trigger rate
- Extended tracking for displaced tracks

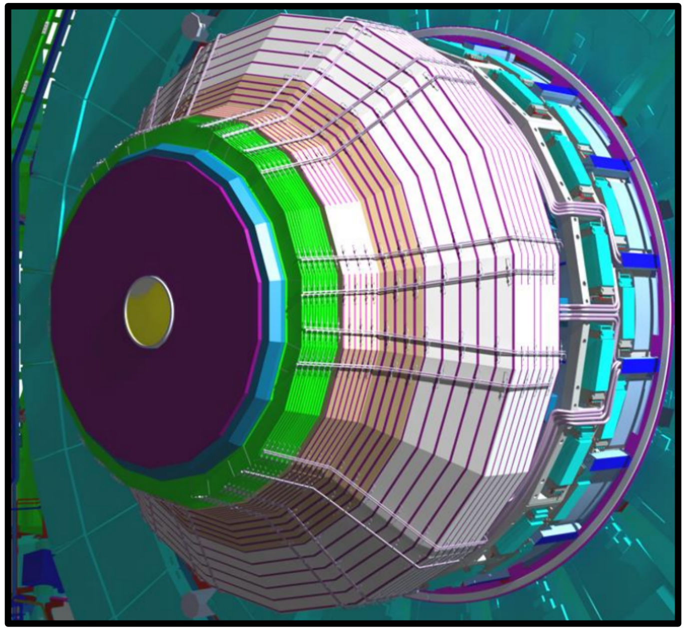


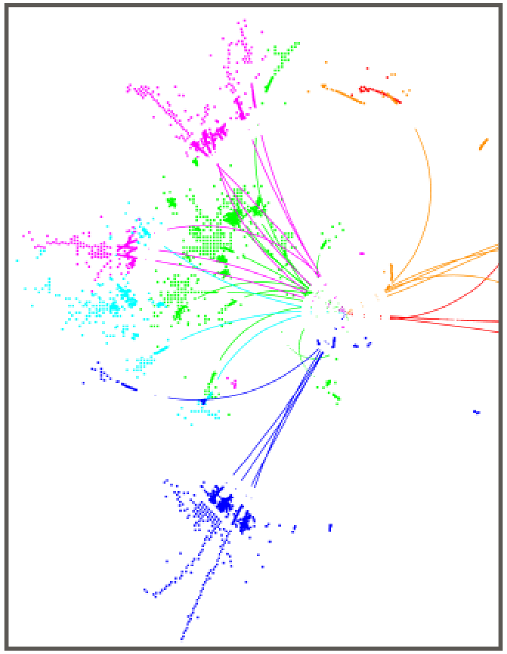
INPUTS TO THE TRIGGER SYSTEM: CALORIMETRY

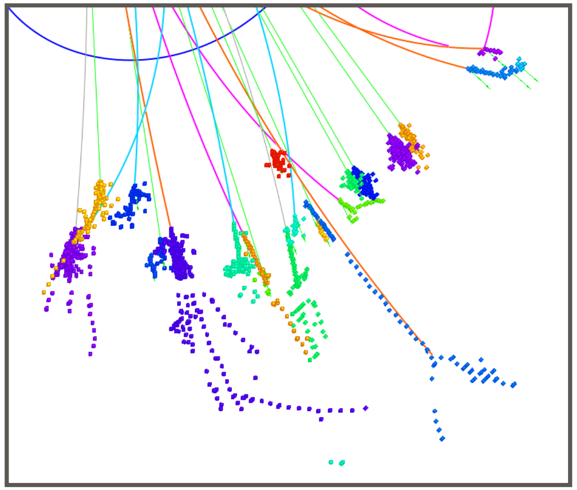
Calorimeter: expecting higher calorimeter granularity

- 25x in the ECAL Barrel, depth in the HCAL Barrel
- 6M channels in the endcap with the High-Granularity Calorimeter (HGCAL). First imaging calorimeter with 5D capabilities (position, energy, timing)

Physics potential: improve on jet resolution (energy & position) to exploit fully hadronic modes, VBF topologies, hadronic tau reconstruction etc.
Adapted to particle-flow approach





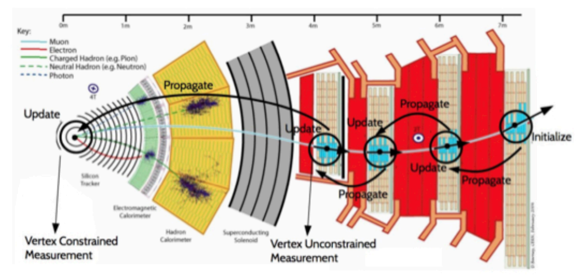


HGCAL = 47 layers,
Si-area = 3 x CMS tracker !!
Forward region 1.5< eta < 3

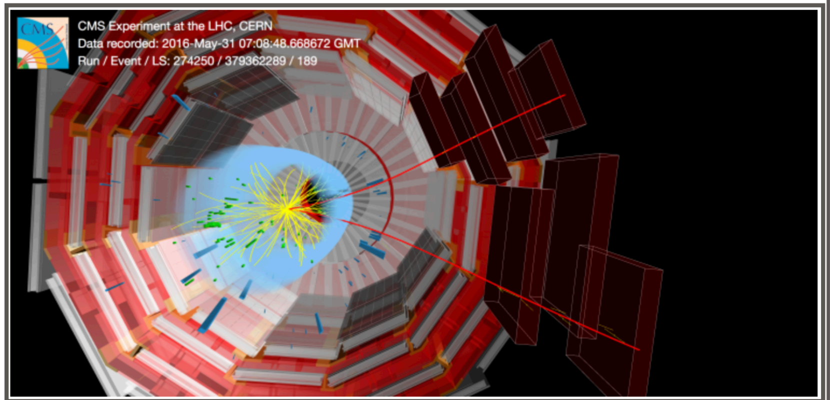
INPUTS TO THE TRIGGER SYSTEM: MUONS

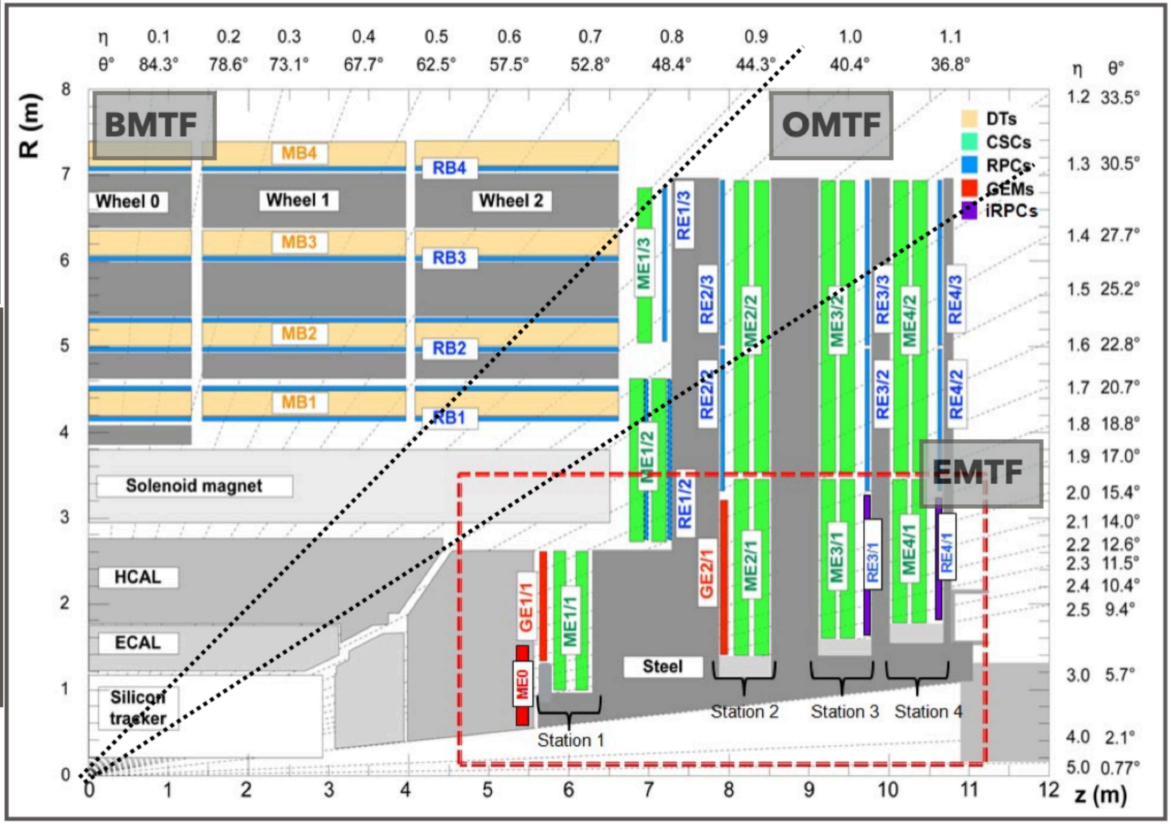
Muons: Muon Spectrometer with full redundancy

- Divided into 3 regions Barrel, Overlap and Endcap.
- Pattern based track finding in endcap and overlap
- Kalman filter in the barrel



New algorithms capable of reconstructing displaced muons with trajectories not pointing to primary vertex.





TRIGGER ARCHITECTURE: PARTICLE FLOW INTO HARDWARE

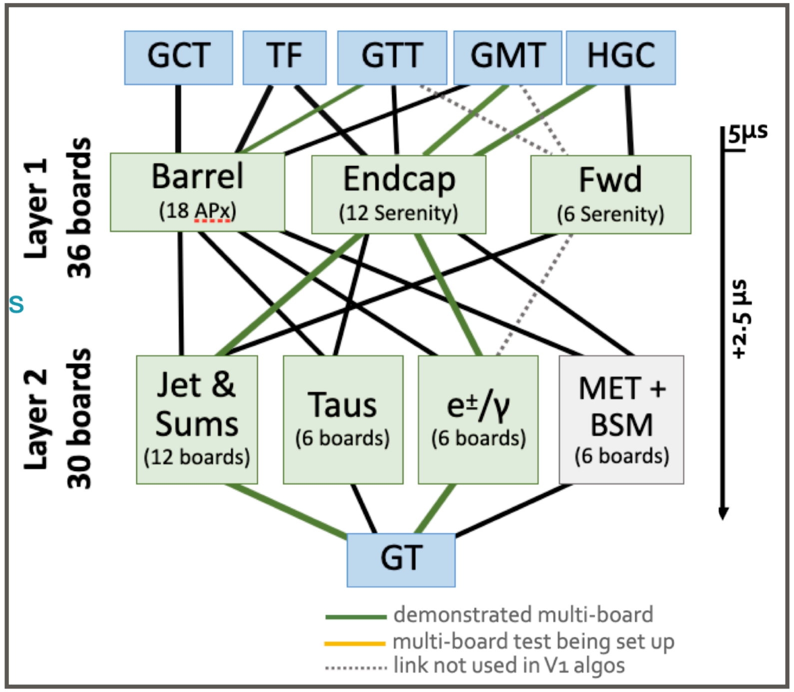
Key feature of the design: the Correlator Trigger system is hosting the particule flow and puppi algorithms

- All input information from tracker, calorimeters and muons are collected
- **Layer-1**: used to correlate and combine information into particle flow/puppi candidates.
- **Layer-2**: reconstruct physics objects (electrons, jets, taus and sums) from the layer-1 candidates

Correlator Trigger architecture uses complementary data processing approaches:

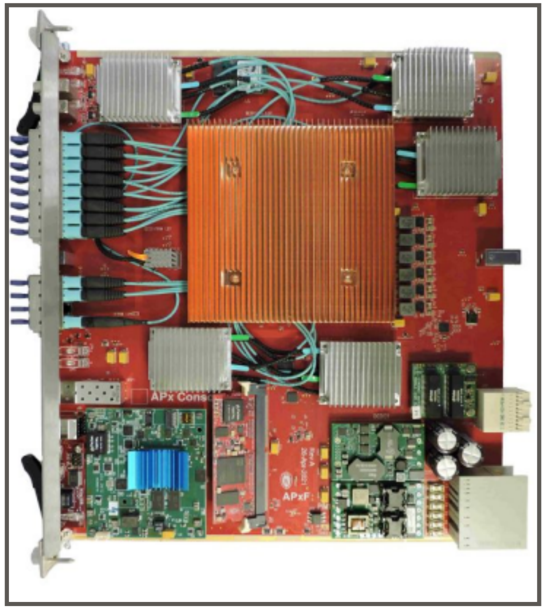
- Regional segmentation and timing (TMT6)
- Functional separation and timing (TMT6)

Architecture chosen to optimise processing while keeping FPGA resources acceptable and functional flexibility (adding algo boards)

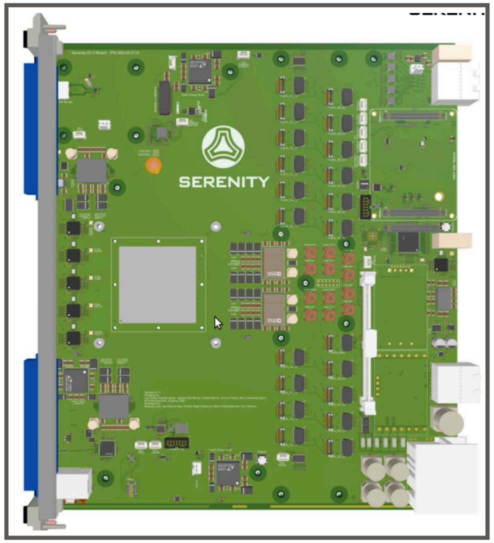


INSTRUMENTATION: HARDWARE PROTOTYPES

Design philosophy: Generic Processing Engines → I/O, FPGA → sophisticated algo, arch flexibility
Design evolution (since TDR): increased I/O and computing power
- FPGA : larger A2577 pin package, Xilinx Virtex Ultrascale VU13P
- Optics : New denser version of on-board flyover Samtec Firefly & QSFP
- Processors on board running commercial linux for flexible configuration and monitoring

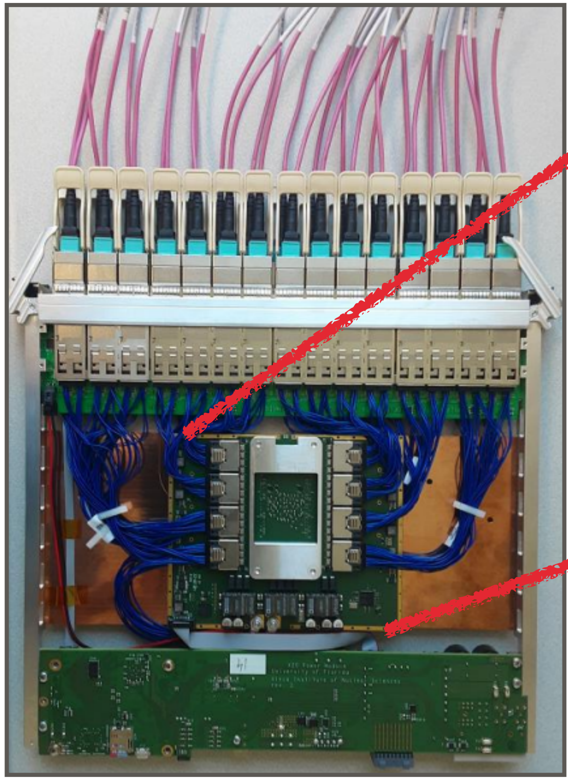


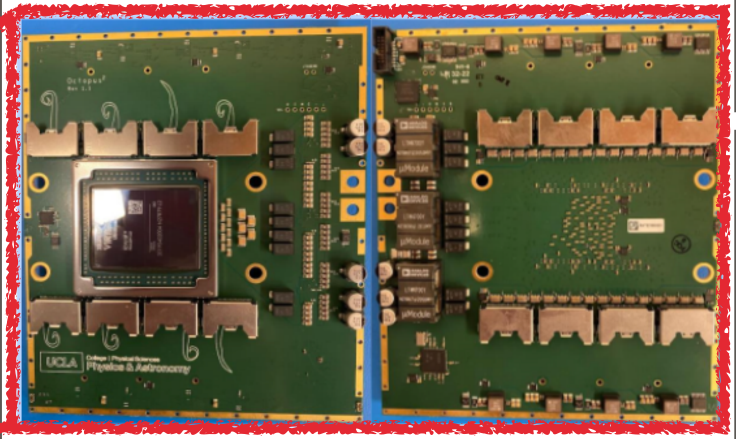
Serenity:
- New halogen free design.
- 120 links with FireFly12
- Up to 144 bidirectional links (extendable to 192)
- Control & Monitoring: COM express (x86 processor)
- IPMI management through CERN IPMC



APx-F:
- Powered by a VU13P FPGA
- 120 bidirectional links (FireFly x12) up to 25 Gb/s
- Control, management, and monitoring by an embedded linux mezzanine (ELM) (ZYNQ SoC)
- Shelf management via custom IPMI mezzanine (OS)

HARDWARE CAN DO MORE: EVOLUTION

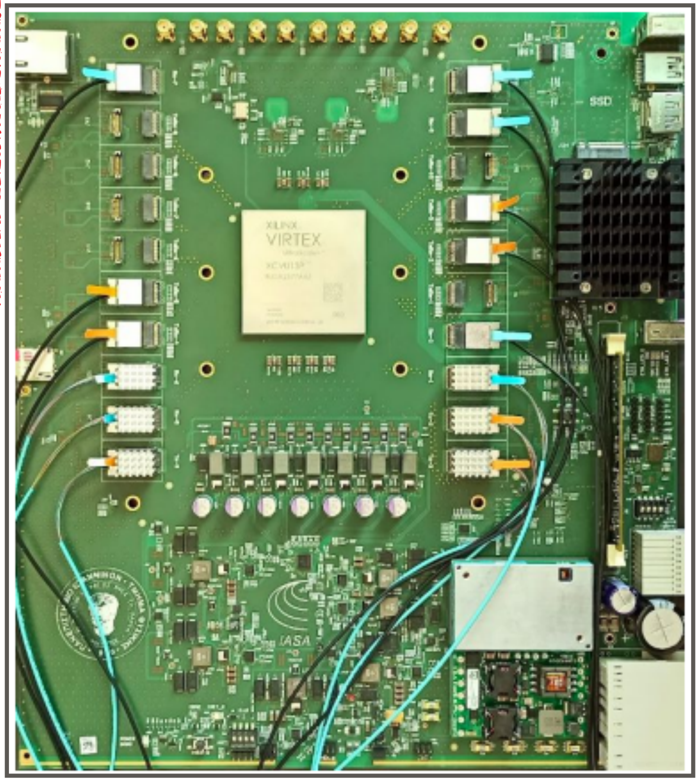




Variant: Intensive processing in muon trigger. Octopus Mezzanine (A2577-VU13P)

BMT-L1: Barrel Muon Trigger

- Interface with FrontEnd lpGBT
- Optics: FireFly x4 25 Gb/s
- IPMC



X2O: Evolution from OCEAN Prototype (TDR)

Board redesigned with

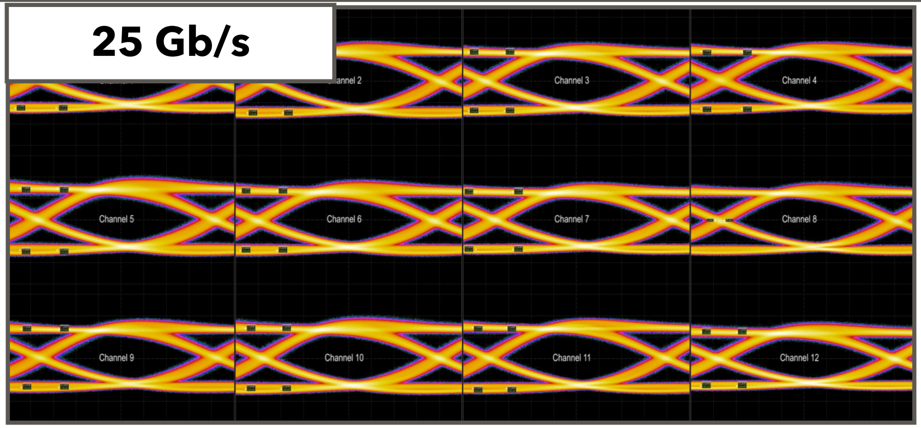
- Improved safety and interlock system with a lattice small FPGA
- New Optical Module
  - Up to 30 QSFP cages (120 links)
  - Compatible with 25G and 10G transceivers
- Power Module: Off-the-shelf Xilinx Kria, IPMC on ZYNQ
- Inter-module connections with cables

HARDWARE CAN DO MORE: OPTICS & THERMAL TESTS

Optics requirements:

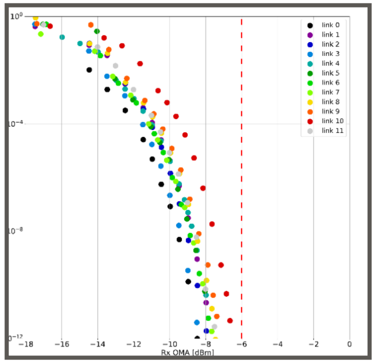
- Support sufficient signal integrity in both the electrical and optical domains by demonstrating a bit error rate (BER) much better better that 10^{-12}
- Optics should provide sufficient optical margin with a receiver sensitivity better than -6 dBm to ensure operability at end of life (as laser degrades)

25 Gb/s



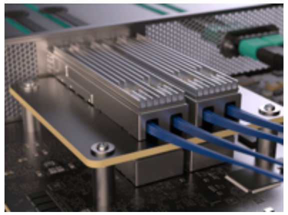
Samtec Firefly x12

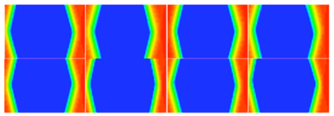
- One module: x12 RX or x12 TX
- Note Module in beta-stage
- Observing an RX sensitivity in OMA better than -6 dBm



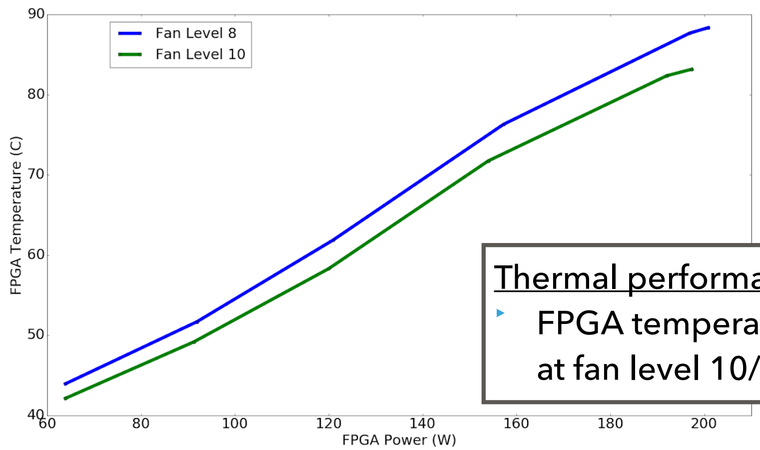
Alternatives: QSFP

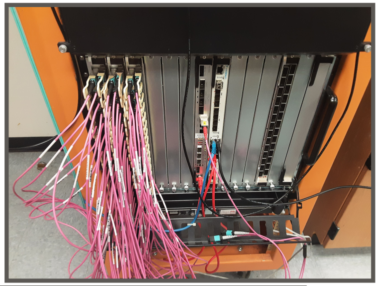
- widely used in industry
- x4 TX / x4 RX (x8 TX / x8 RX QSFP DD)
- Under qualification (BER etc)





QSFP on X2O



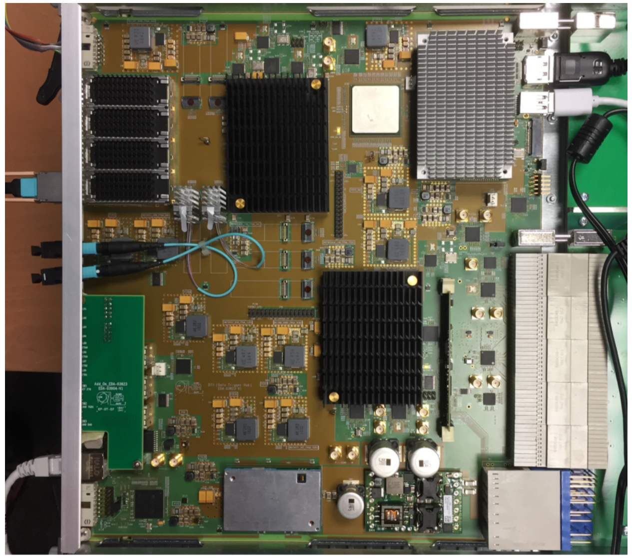


Thermal performance:

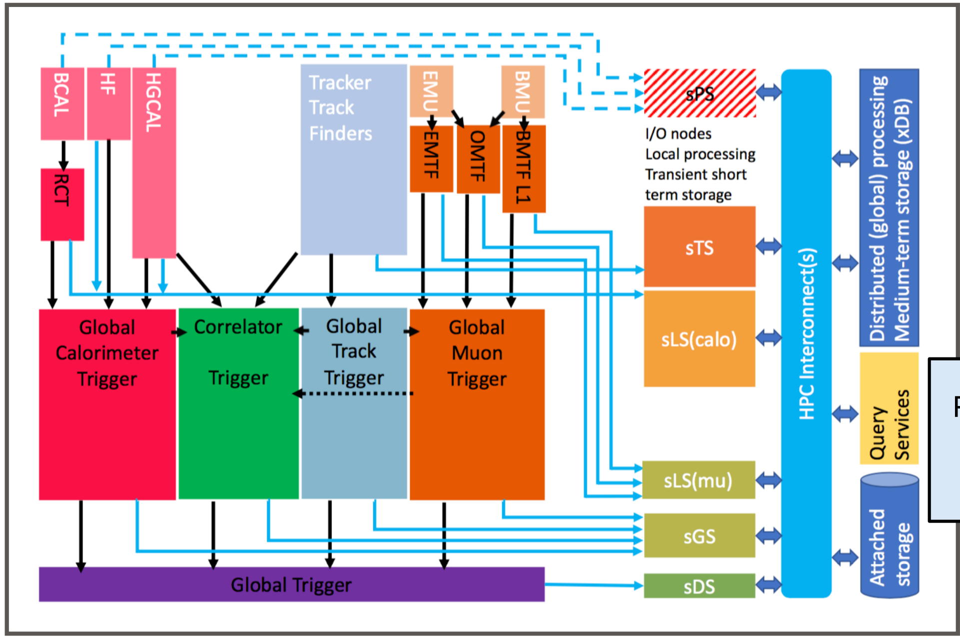
- FPGA temperature of 85C with 200W at fan level 10/15

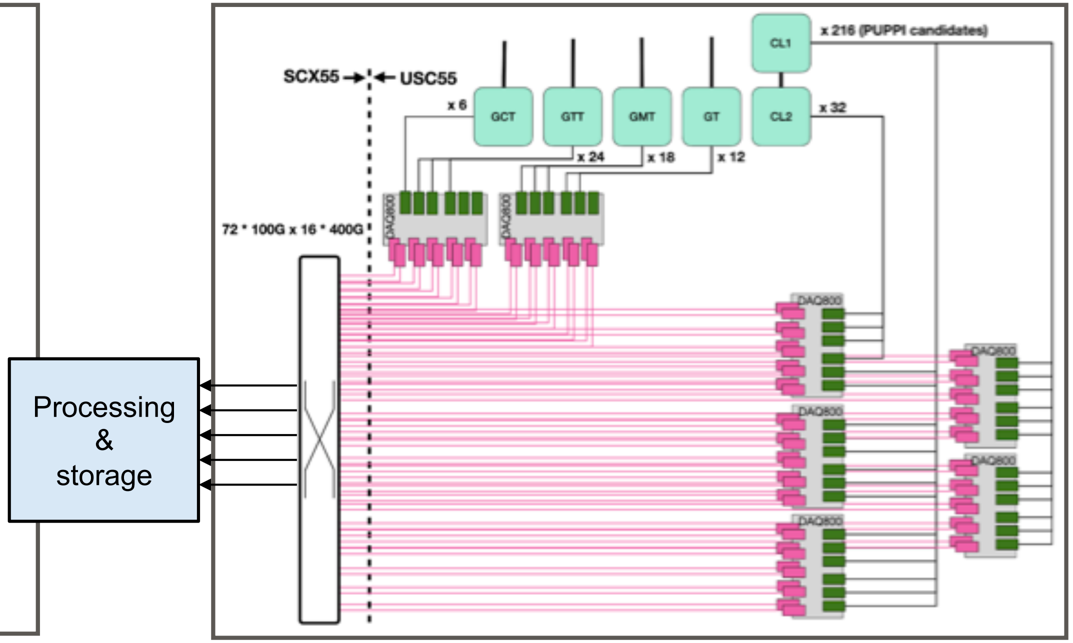
SCOUTING @ 40MHZ: SCRUTINISING THE DATA

- Enables many features: real-time diagnostics (even at lower level systems), monitoring, testing new algorithms and developing menus, selecting an reconstructing physics objects w/o rate limitation.
- Analyses conducted trough queries (from storage)
- Demonstrated during LHC Run-2 with Level-1 Phase-1 muon output, now being prepared for Run-3 data taking
- Uses DTH board (DAQ800) designed for large readout detectors



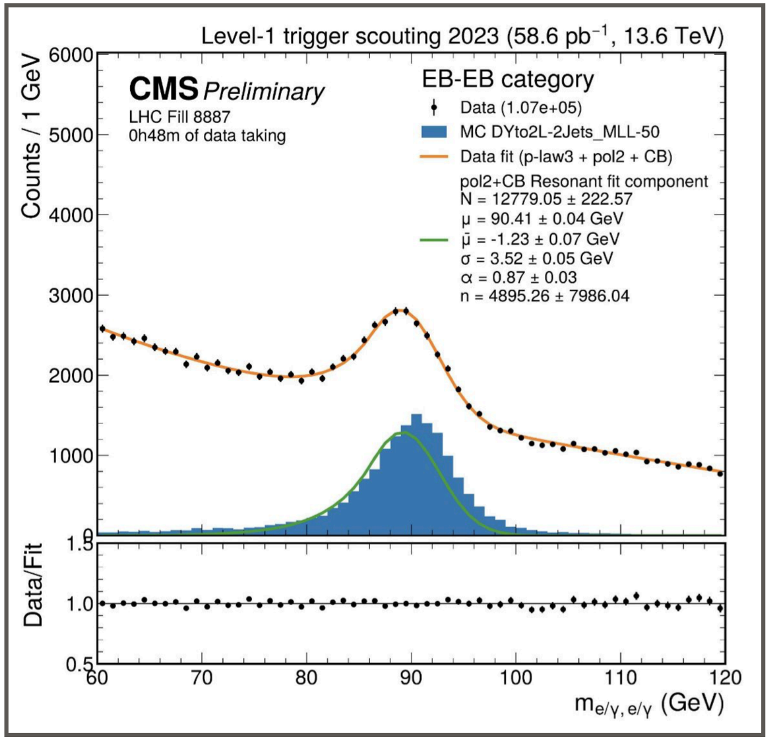
DTH

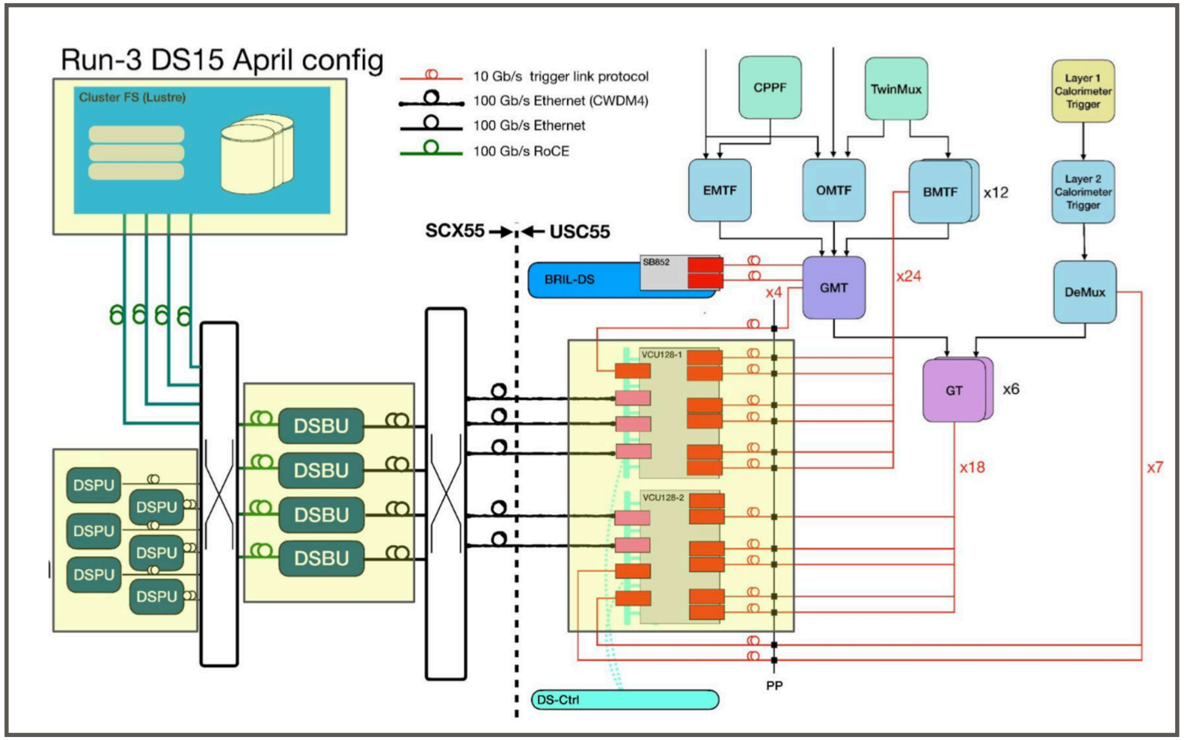




SCOUTING @ 40MHZ: DEMONSTRATION IN RUN-3

- Scouting system demonstration during Run-3: The system started to be installed in Run-2, w/ connection to the muon systems. Including calorimeter data since start of Run-3 (2022)
- Hardware emulation of the DTH boards (VCU128 boards Xilinx XCVU37P)
- ***Targeting potential physics cases already now.***





THE PHASE-2 L1 TRIGGER

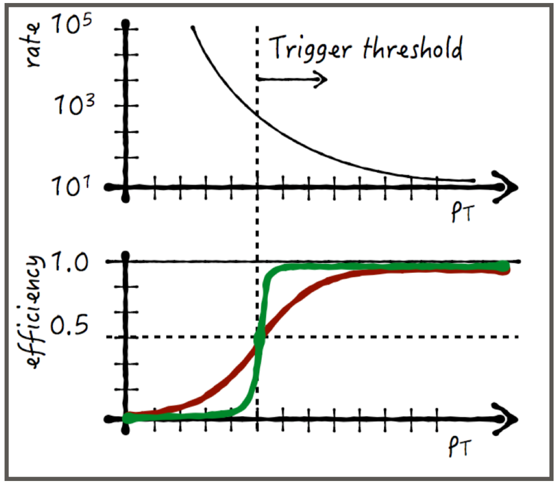
ALGORITHMS, FIRMWARE & TESTING

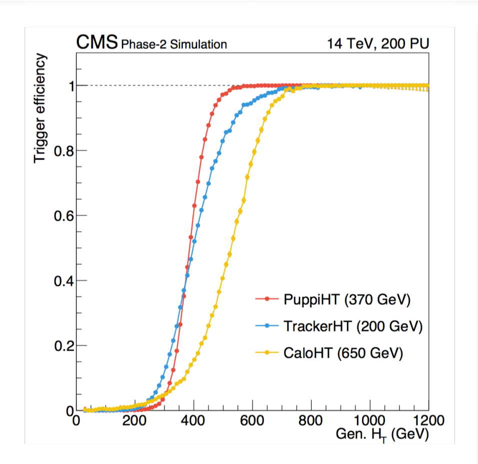
selecting physics

PHASE II LEVEL-1 TRIGGER: ALGORITHMS & MENU

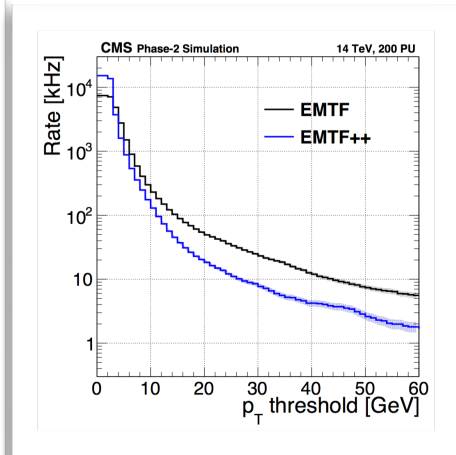
Algorithms for the Level-1 trigger:

- Extensive use of tracking to reach near offline performance (sharper efficiency turn-on curves) + reconstruction of **Primary Vertex.**
- Exploit complementarity of different object flavour:
  - **Standalone objects:** robust triggers based on independent sub-detectors
  - **Track-matched objects:** tracking used to confirm standalone Muon and Calo objects, significant improvement with simple design
  - **Particle-flow objects**: ultimate performance improvement, combine all information to match offline algorithms, require most processing time and resources for calculation

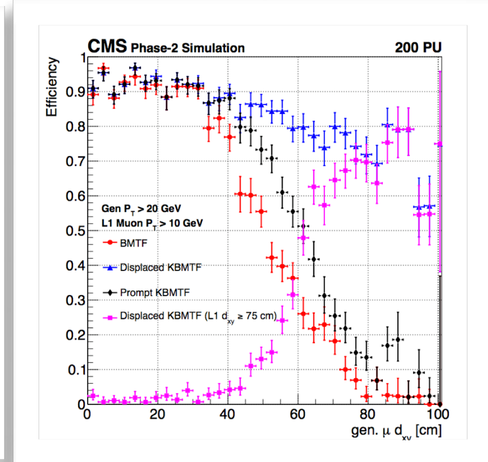




Particle-flow/puppiHT



Standalone forward Muon reconstruction Endcap



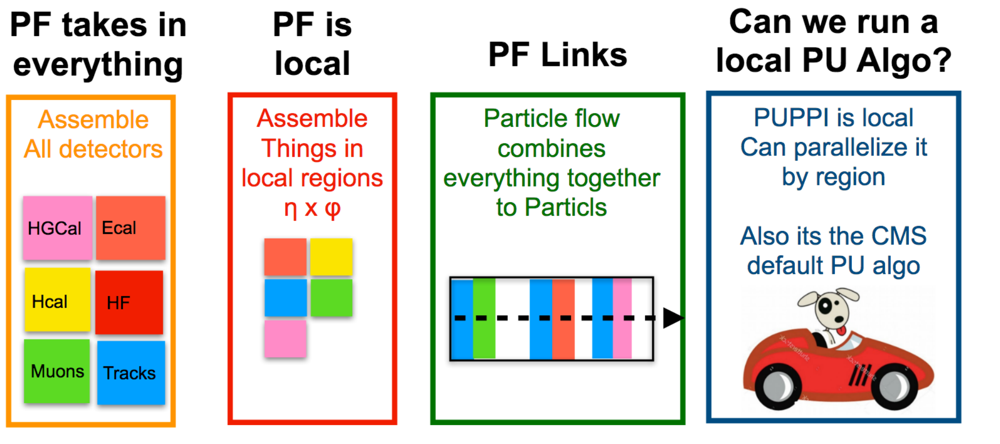
Displaced Muon trigger Barrel (Kalman Filter) → *Run-3*

Level-1 Menu:

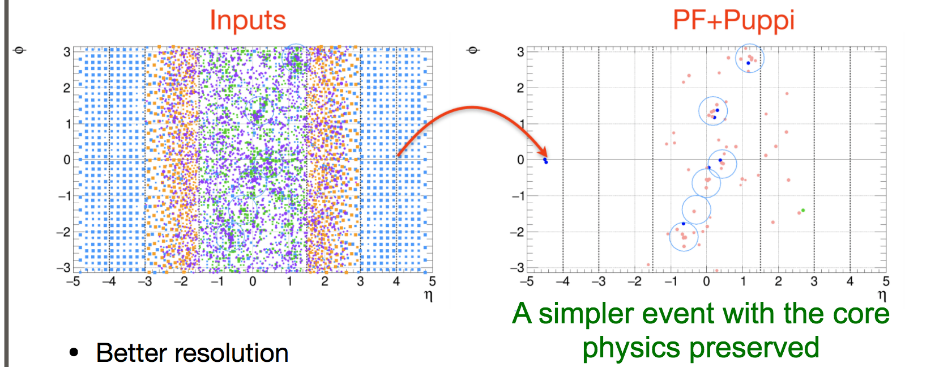
- Simplified: Phase-1 physics built from Run-2 L1 Menu (346 kHz)
- Extended: new triggering strategy to expand physics reach (+110 kHz)

GLOBAL EVENT RECONSTRUCTION @ LEVEL-1

- Availability of tracks & high-granularity calos
- Implement global event reco @ L1 (like PF)
- Additionally it makes sense to mitigate pileup
- *Challenge : can we run full PF+PUPPI within the hardware of the L1 trigger?*



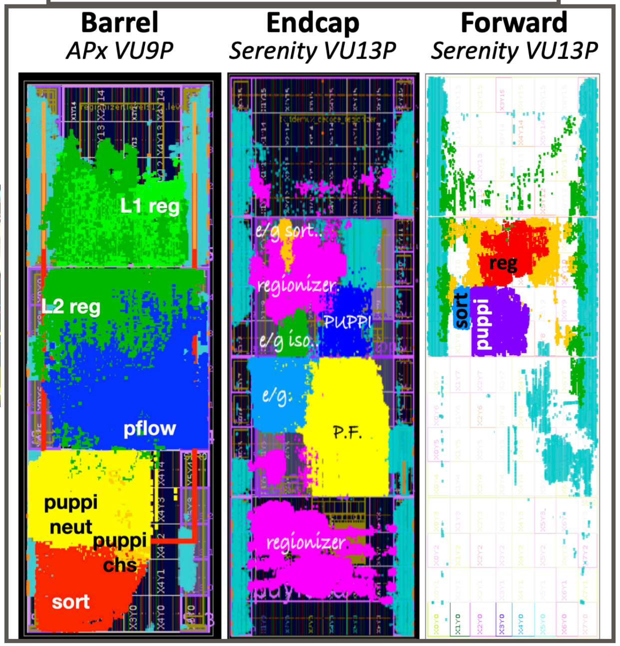
- What are the advantages of particle flow?



- Better resolution
- Ease of use → build particle level algorithms
- Reduction in bandwidth and reduction of resources

- **Demonstrated a working PF+PUPPI algorithm**
- PF+PUPPI hugely reduces the event complexity
- Allows for a lot of flexibility in downstream design
- L1 Algorithms looks like offline reconstruction
- PF+PUPPI developed with Vivado HLS (a lot of written by physicists along with engineers)

Hardware demonstrator

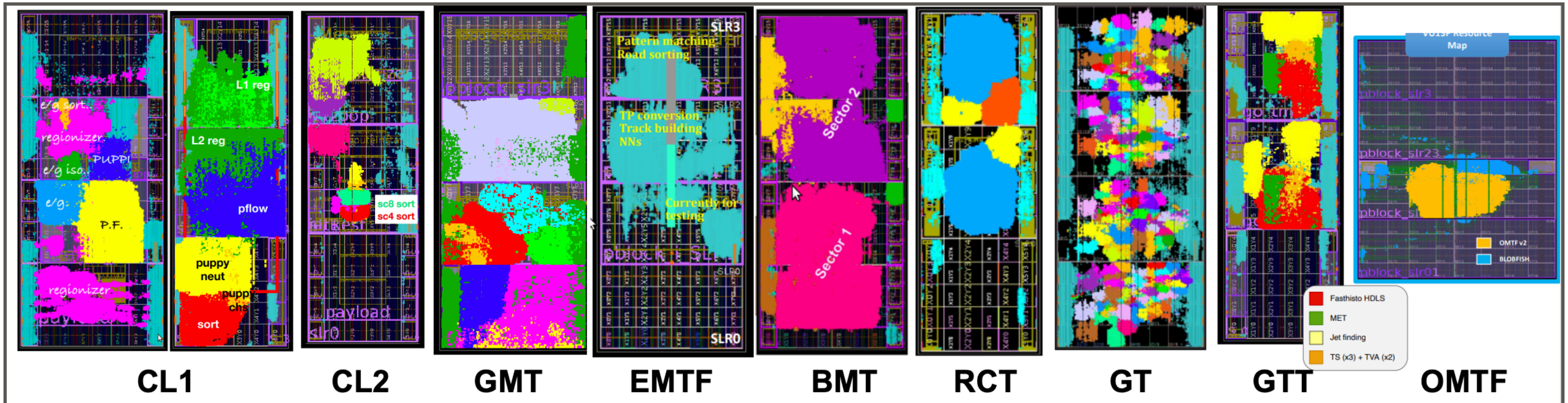


CMS Collaboration. Particle Flow CMS *JINST* **12** (2017) P10003, arXiv:1706.04965.
D. Bertolini, P. Harris, M. Low, and N. Tran, PUPPI, *JHEP* **10** (2014) 059, arXiv:1407.6013.

ALGORITHM INTO FIRMWARE

Firmware design:

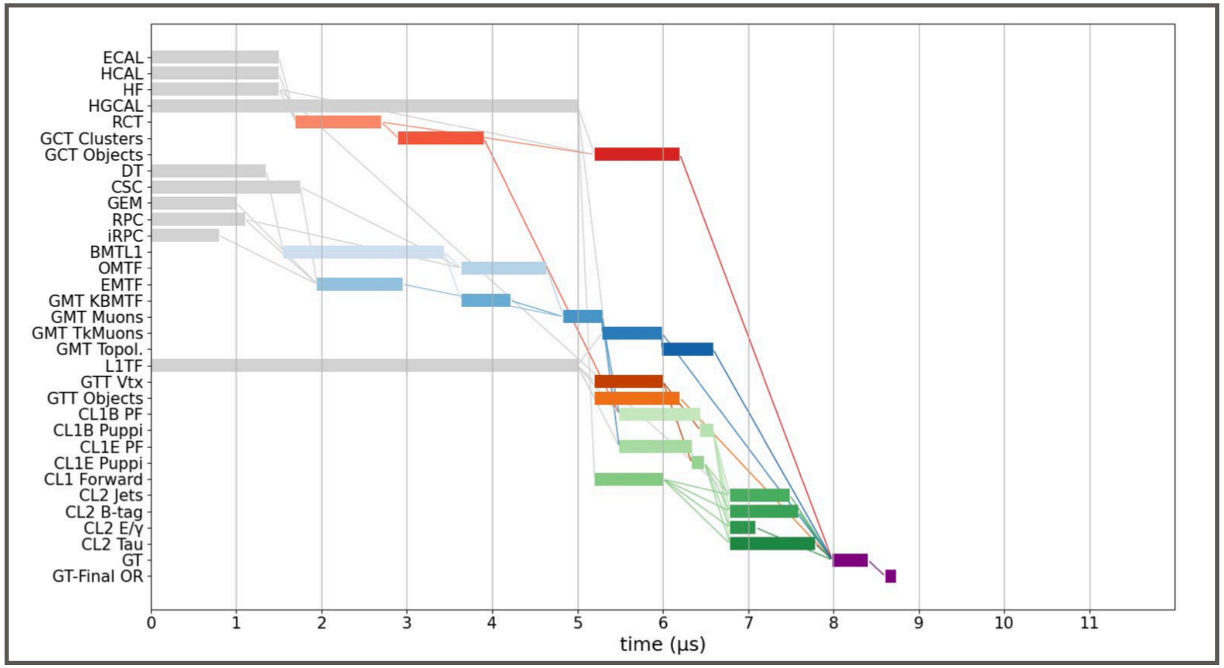
- Algorithm developed mostly in C → High Level Synthesis (HLS). Using Vivado HLS, Vitis HLS
- Many tools available for Machine Learning inference: hls4ml, Conifer for BDT evaluation
- New fixed point arithmetic in C++ [taken from Xilinx libraries] → emulator firmware
- Continuous integration of the firmware in repository



Firmware integration:

- All algo & manage I/O
- Verify timing, resources utilisation & latency: all using less than 50% resources, whole system evaluated to 8.73us (well within 9.5us)
- 100% correspondance emulator - firmware
- **Common framework wrapper** → firmware implementation board agonistic

LATENCY USAGE/RESOURCES

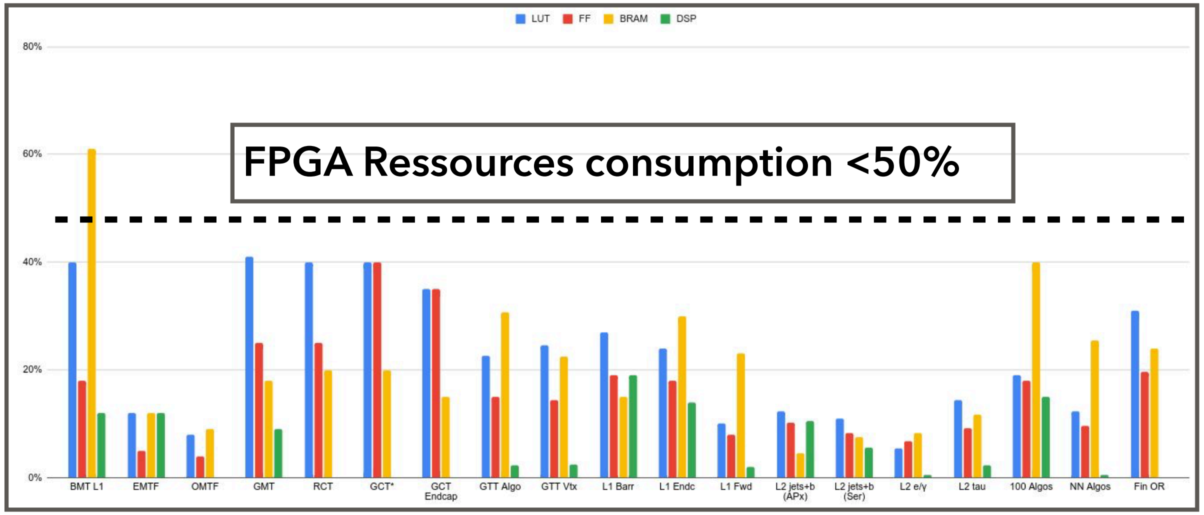


Breakdown of the latency consumption from each subsystems.

Well bellow limit of 12.5 us (enough contingency planned)

Breakdown of the FPGA from each subsystems.

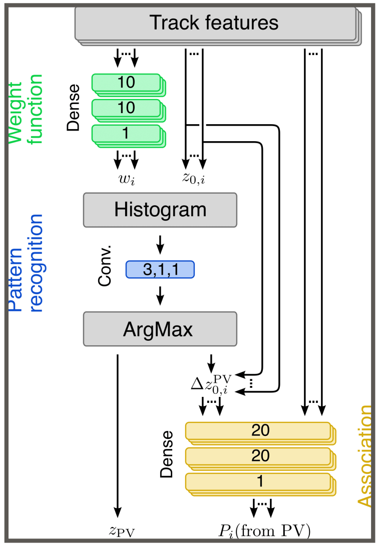
All < 50%, well on target !

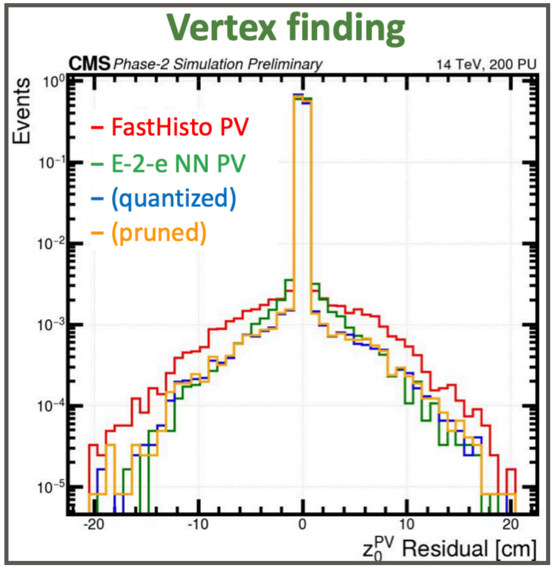


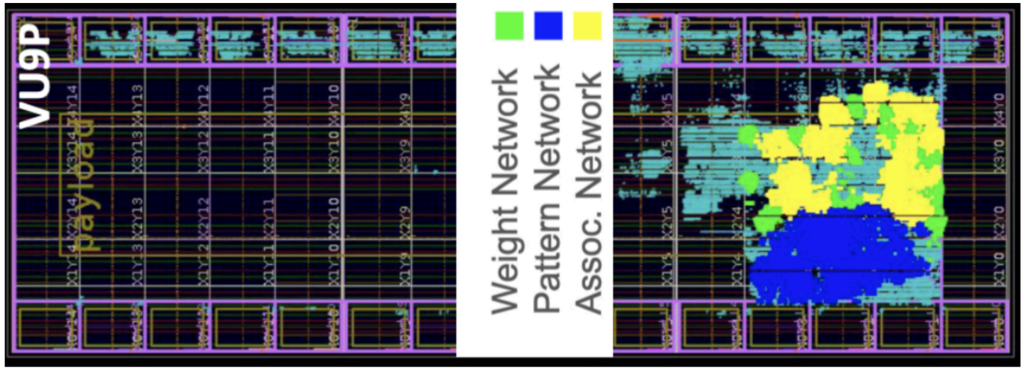
RECENT DEVELOPMENTS HIGHLIGHTS

NN Vertex Finding: publication

- Combinaison of dense BDTs and CNN to perform Vertex Finding and Track-to-Vertex association
- Firmware quantised and pruned to fit within FPGA
- ***Improved performance wrt to baseline (reduction in the tails of the residual by 50%***



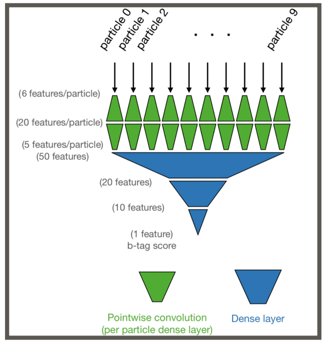


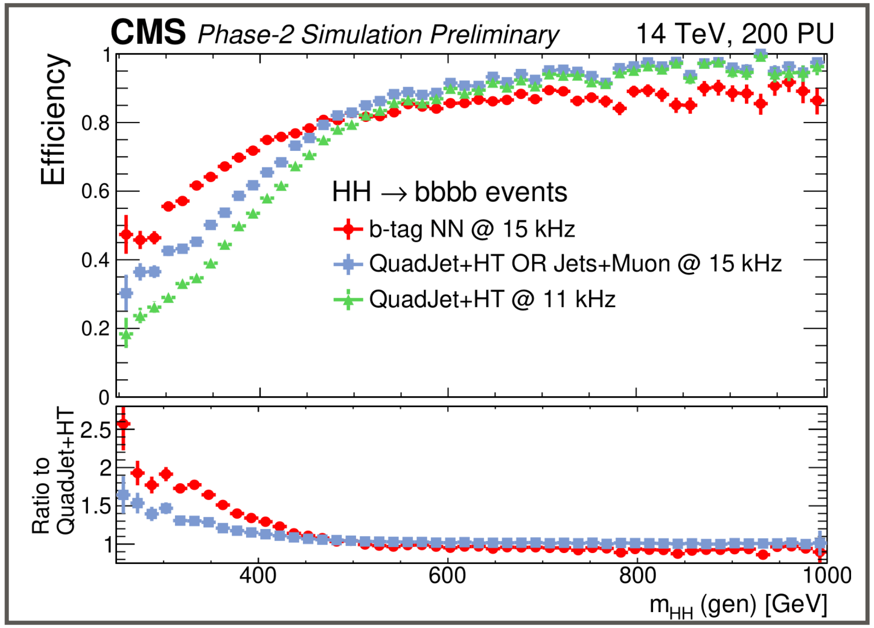


b-tagging:

- Training NN to ID jets from b-quarks
- Runs on PUPPI particles within each jet and discriminate between b-quark jets and those from light quarks and gluons

- ***Better performance compared to QuadJet+HT for M(HH) < 500 GeV (or Jets+Muon triggers)***

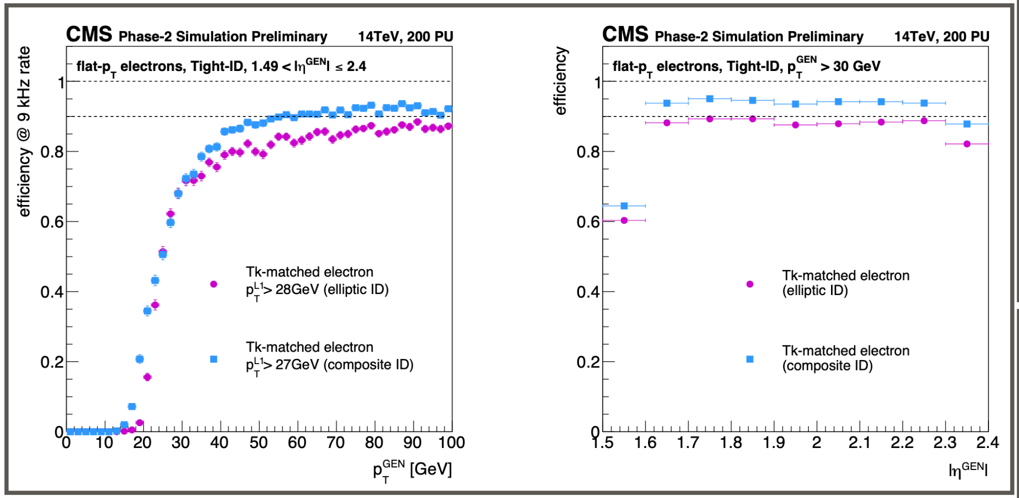


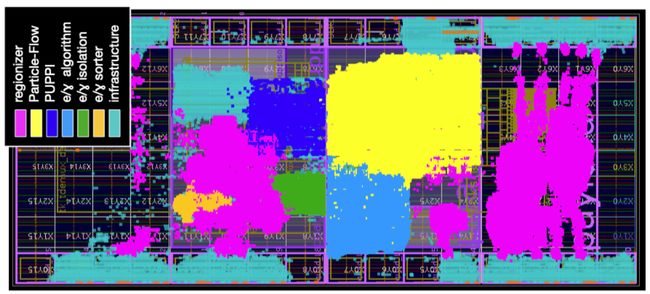


RECENT DEVELOPMENTS HIGHLIGHTS

Electron-ID:

- New Composite-ID, combines information about tracks and clusters in the HGCAL into a single model for matching and identification
- A single BDT model: controlling the identification of track and calorimeter deposit and the tightness of the matching.
- 10% more efficiency for the same rate

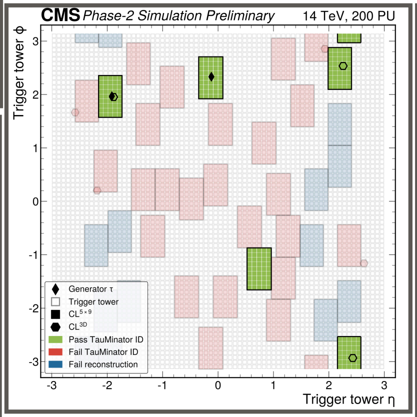


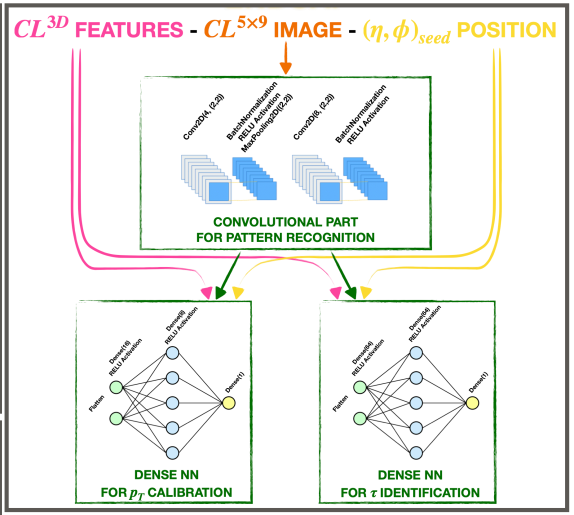


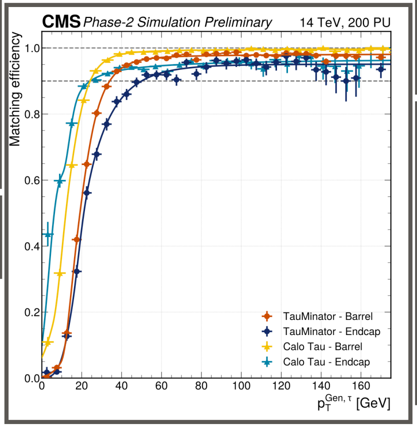
	LUT	FF	BRAM	DSP
e/γ IP	3.1%	0.4%	0.0%	1.6%
Total	24.4%	17.6%	29.5%	14.3%

Tau reconstruction: Tauminator

- Training dedicated CNN to reconstruct and identify Tau-induced signal in calorimeters (5x9)
- Elegant way to deal with different geometries in Barrel (Crystals) and EndCap (HGCAL 3D clusters).





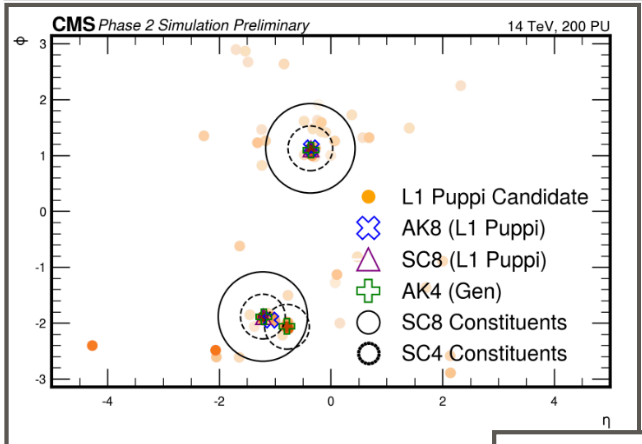


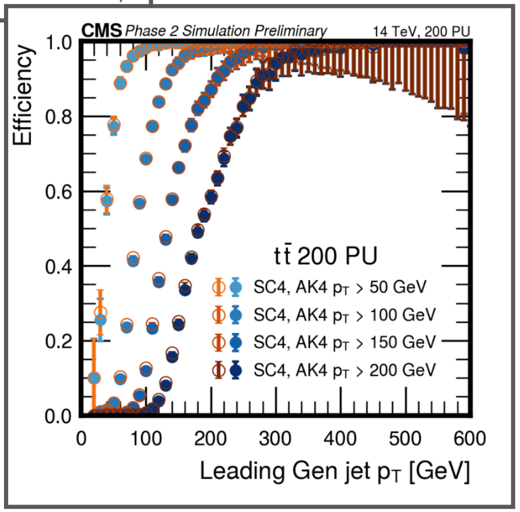
- Much improved efficiency with respect to CaloTaus
- 21% rate reduction on DoubleTau with 90GeV threshold

RECENT DEVELOPMENTS HIGHLIGHTS

SeededConeJets:

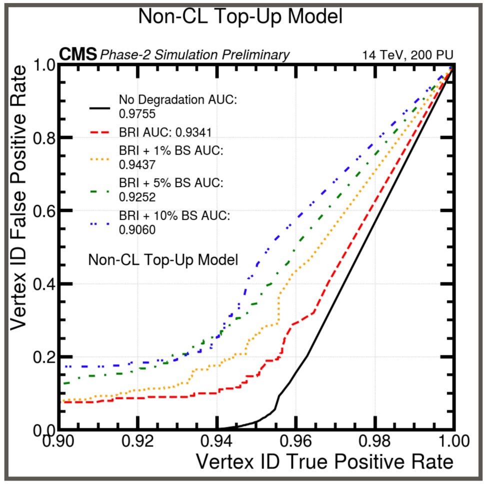
- Jet finding based on PF candidates
- Iterative approach computing distance between each particle and jet radius (SC4 or 8), compute jet axis and energy.
- Jet matching anti-kt jets

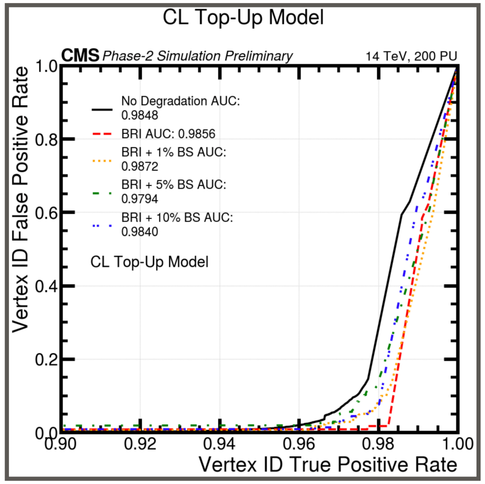




Continual learning:

- Elegant way to deal with changing detector conditions (ageing, noise, LHC interfill, etc.)
- Train a model with a continuous stream of data. Learns from a sequence of partial experiences rather than all the data at once.
- Update model to changing conditions without large MC production.
- Method tested on Vtx reconstruction



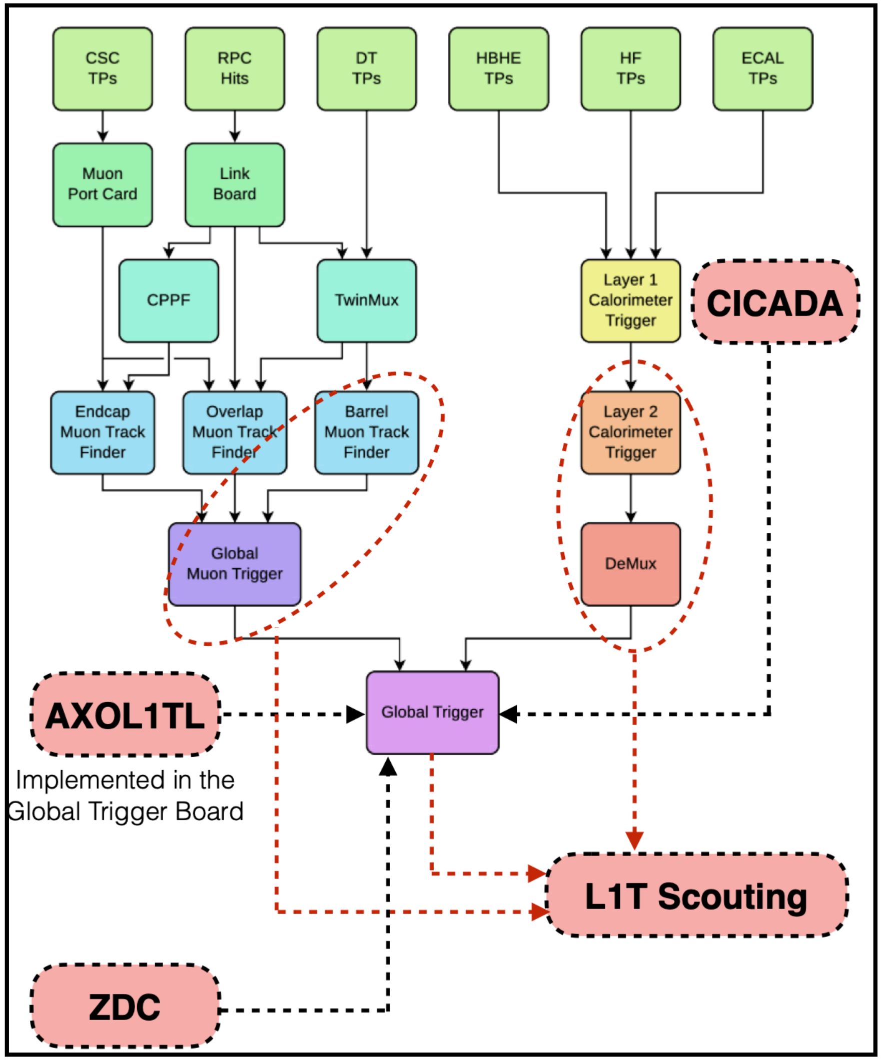


BRING PHASE-2 IDEAS INTO PHASE-1

<u>Successful feedback loop into the current system</u>: the Run-3 system now features new algorithms, optimisation techniques, hardware, inspired from the phase-2 upgrade project !

- Displaced muon algorithm in the barrel
- New algorithms for LLP, delayed jets, muon showers
- Zero Degree Calorimeter for Heavy Ion
- 40MHz scouting (real time data analysis)
- New calibration techniques based on Machine Learning methods
- Inclusion of the first Anomaly detection trigger on live data (non-supervised ML), w/ AXOL1TL1 and CICADA project (CNN into extra hardware).
- System running now at 120 kHz for 65 PU while originally designed for 100 kHz.

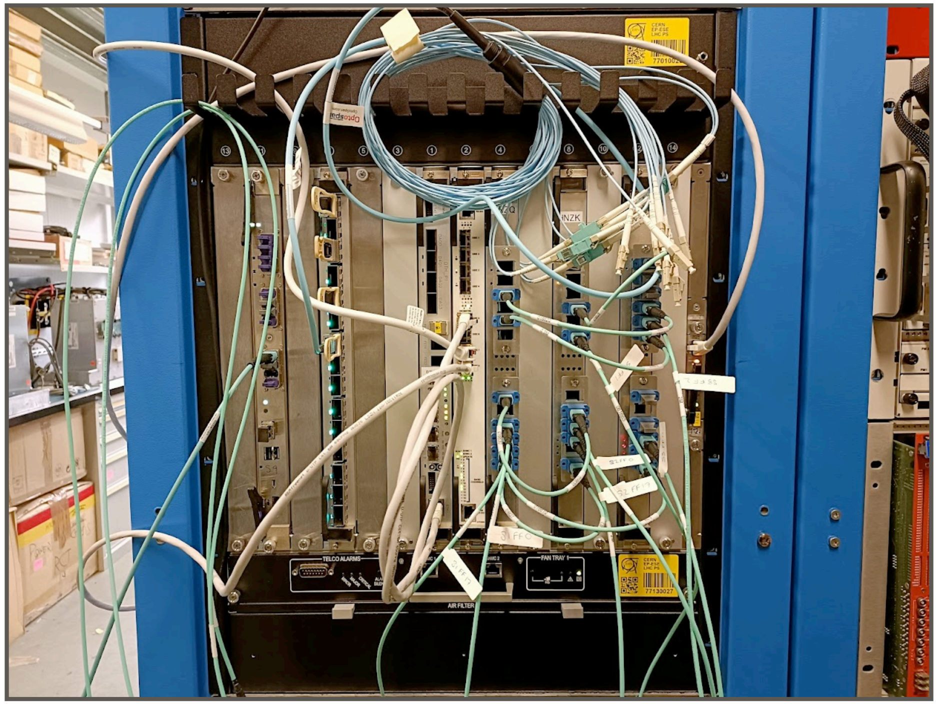
→ ***Clear advantage of a flexible design!***



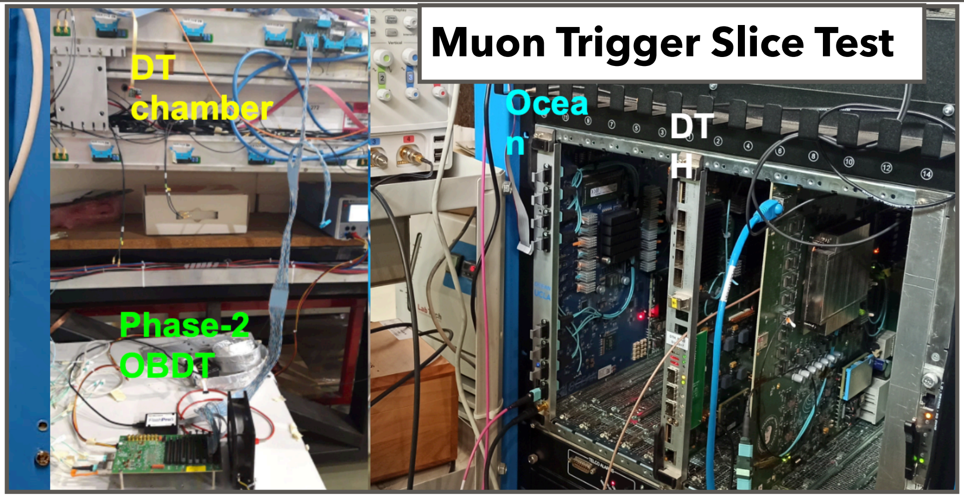
TESTING AND SYSTEM DEMONSTRATION

Phase-2 Level-1 Trigger system demonstration

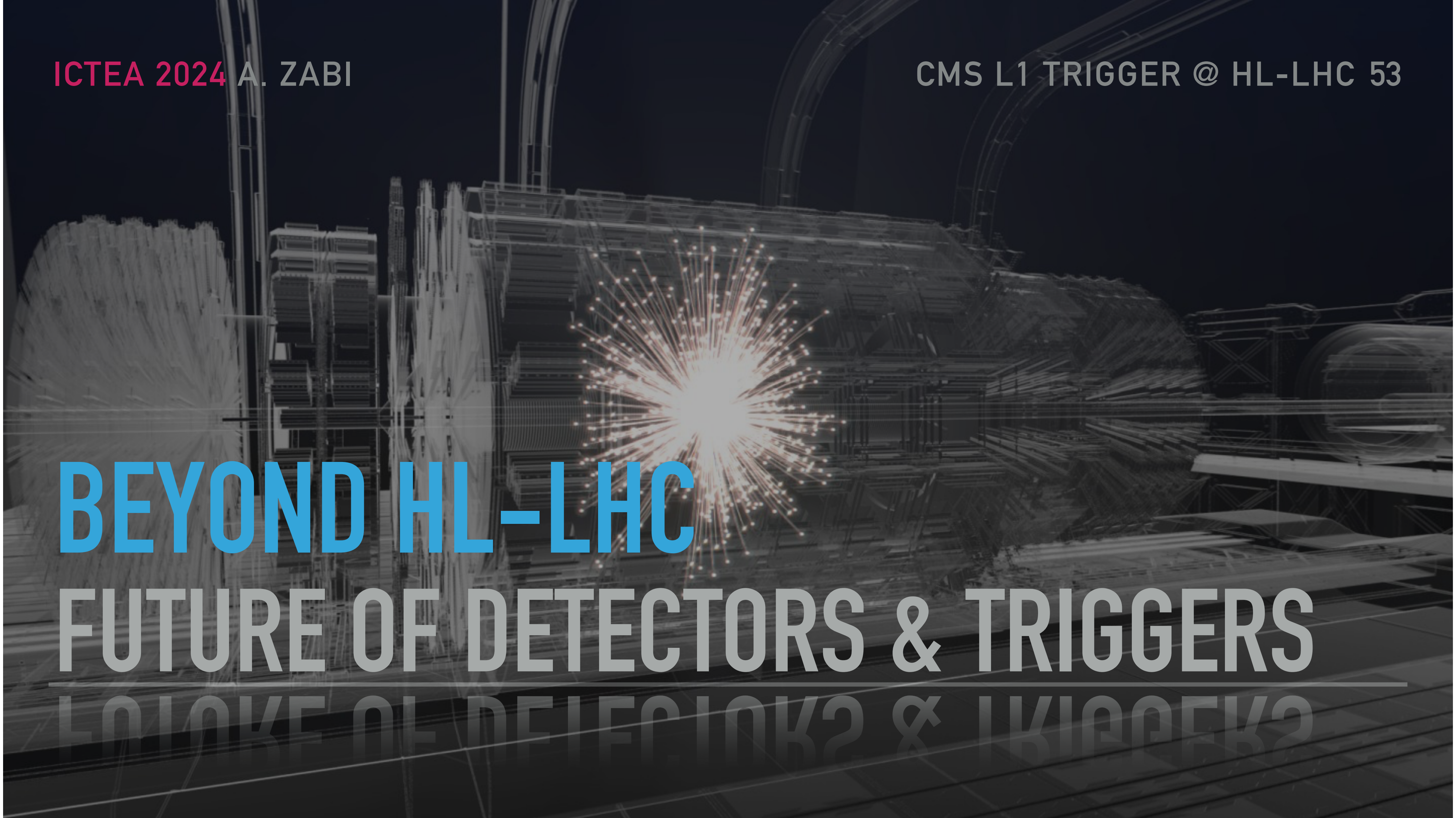
- Single-board and multiple board tests performed
- Integration centers across the globe: larger scale integration @ CERN (904). Multiple flavour board tests.
- Slice test in Muon Barrel Trigger during Run-3. Installation @P5: DT–>BMT–>GMT–>GT
- **Board interconnection: protocol**
  - Links (asynchronous) operation @ 25.78 Gb/s
  - L1 Trigger boards sending packets only once (no retransmission) ➞ error proof
  - Protocols (64/66b or 64/67b) encoding achieved low error rate, validated recovery mechanism etc.



Building 904 @ CERN



Muon Trigger Slice Test

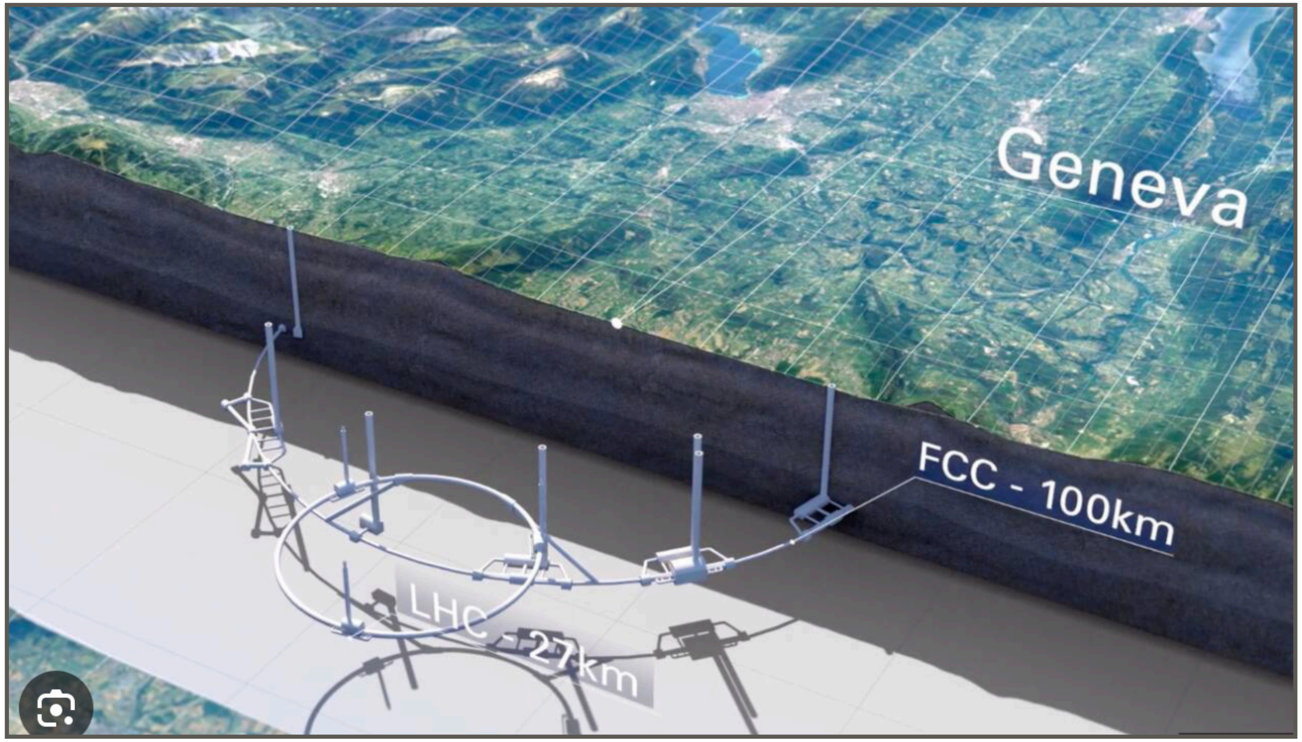


BEYOND HL-LHC

FUTURE OF DETECTORS & TRIGGERS

ACCELERATING PARTICLES: THE FUTURE FCC

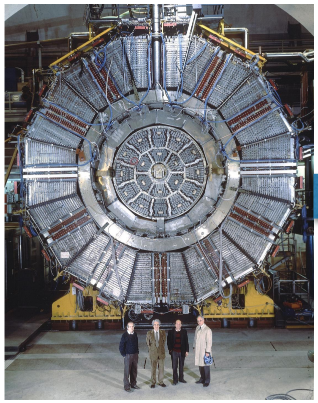
CERN preparing the future: 100 km collider called the Futur Circular collider targeting an expanded physics program.



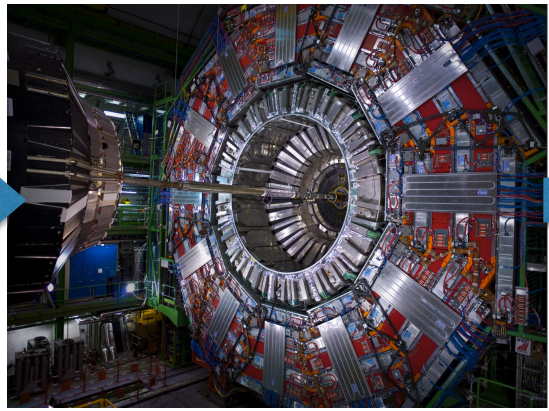
FUTURE OF PARTICLE DETECTION

- **What physics are we after ?*** ***"Higgs is really new physics, put it under a microscope and study it to death !"*** *N. Arkani-Hamed, Higgs boson's anniversary 4th July 2022*. The Higgs boson is a portal → **Higgs boson factories** → unprecedented precision measurements → detectors uncertainties brought to statistical levels! & knowledge of beam energy $O(10^{-6})$, luminosity $O(10^{-4})$, detector acceptance $O(10^{-5})$, B-field to $O(10^{-6})$.
- **Detector requirements:** Incredible precision on all detector components

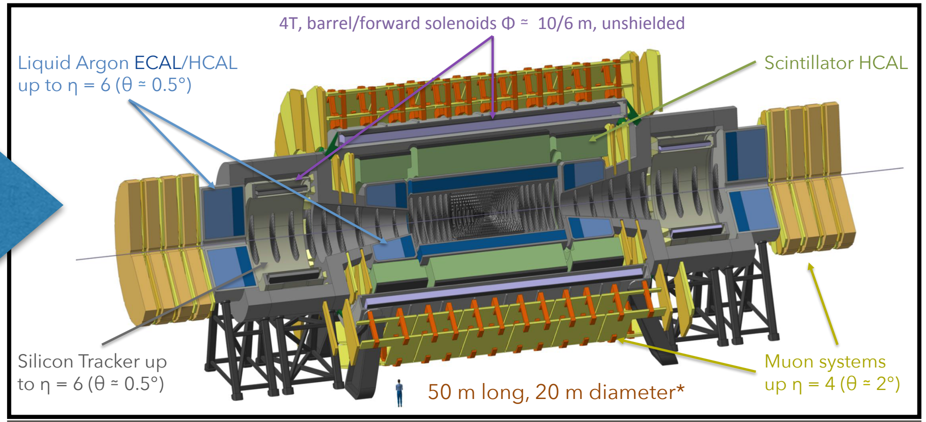
The "Particle Flow" paradigm emerging as baseline for future detector design: high-granularity & timing information.



ALEPH 12x16m



CMS 15m x 28m 14kT



FCC-hh Detector 20m x 50m

Challenge of precision on a massive scale!

FUTURE OF PARTICLE DETECTION

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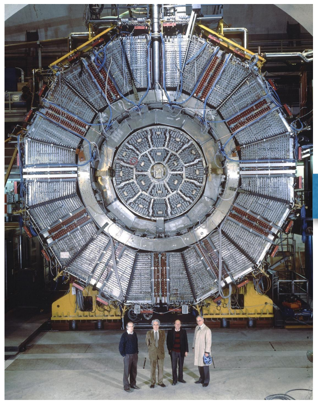
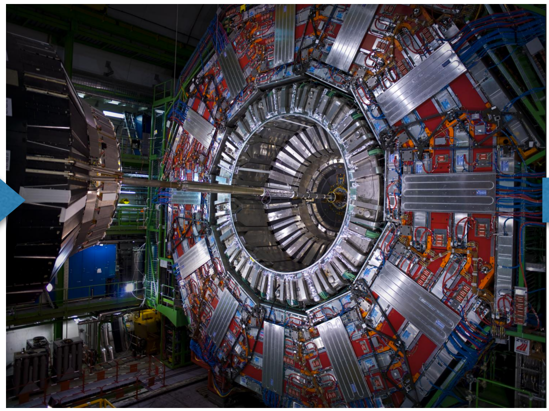
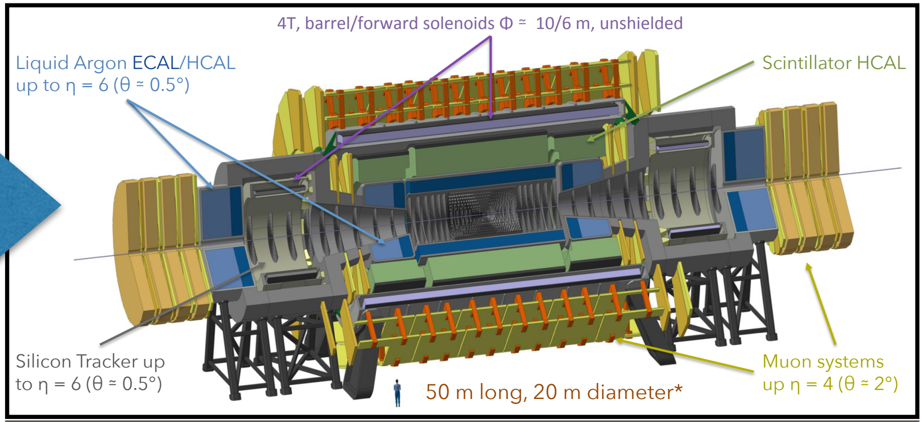


ALEPH 12x16m



CMS 15m x 28m 14kT

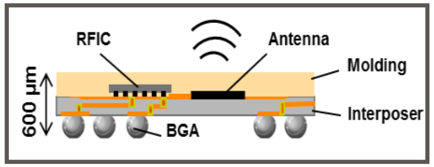


FCC-hh Detector 20m x 50m

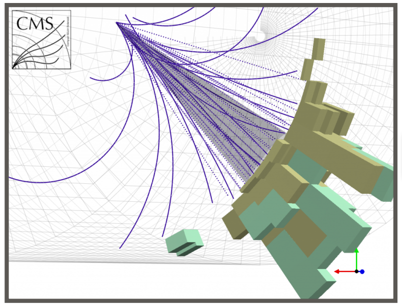
Challenge of precision on a massive scale!

DATA ACQUISITION & TRIGGER

- **Readout challenge @ every level (FCC-hh ~ O(3)PB/s)**
- **Front-End ASICS (25nm nodes, data reduction)**

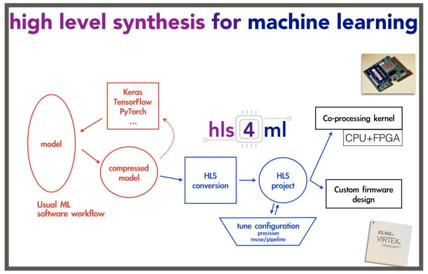


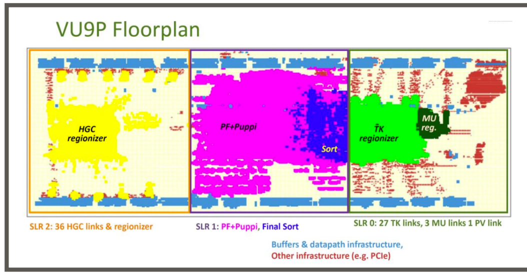
- **Back-End (off-detector electronics)**
  - Data transfert high-speed optical links & commercial network
  - Trigger with generic processing engine (**porting AI engines into FPGA**, progress at LHC & for HL-LHC) 10µs latency @L1 & 100ms @ HLT w/ 500kHz output
- **Event building & data selection:** custom FPGA boards, GPU & CPU. HCb demonstrated GPUs data selection at 5TB/s, ALICE performs full reconstruction on-line with GPUs, CMS achieved 25% off-loaded of selection to GPUs



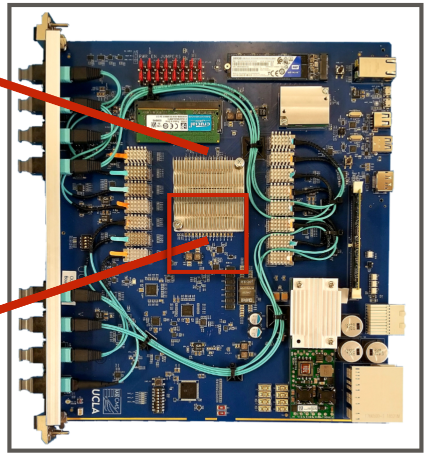
Particle Flow reconstruction
Pile-Up Per Particle Identification

Implementation of the algorithm in VHDL





Implementation of the algorithm in firmware and placement in hardware



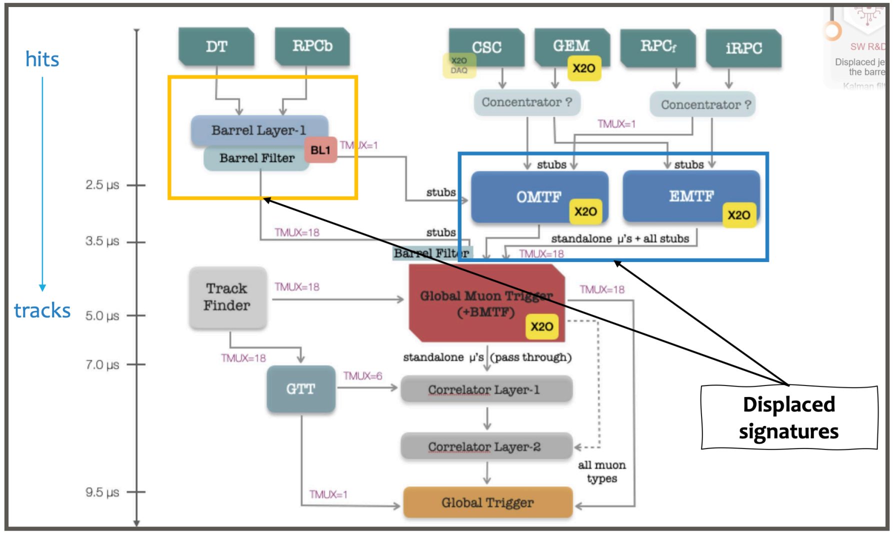
Triggering on the unknown with advanced machine learning techniques (including anomaly detection) Introducing Trigger-Less approaches, etc.

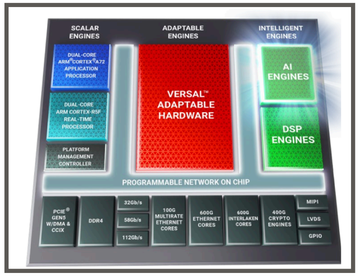
DATA ACQUISITION & TRIGGER: THE INTREPID PROJECT

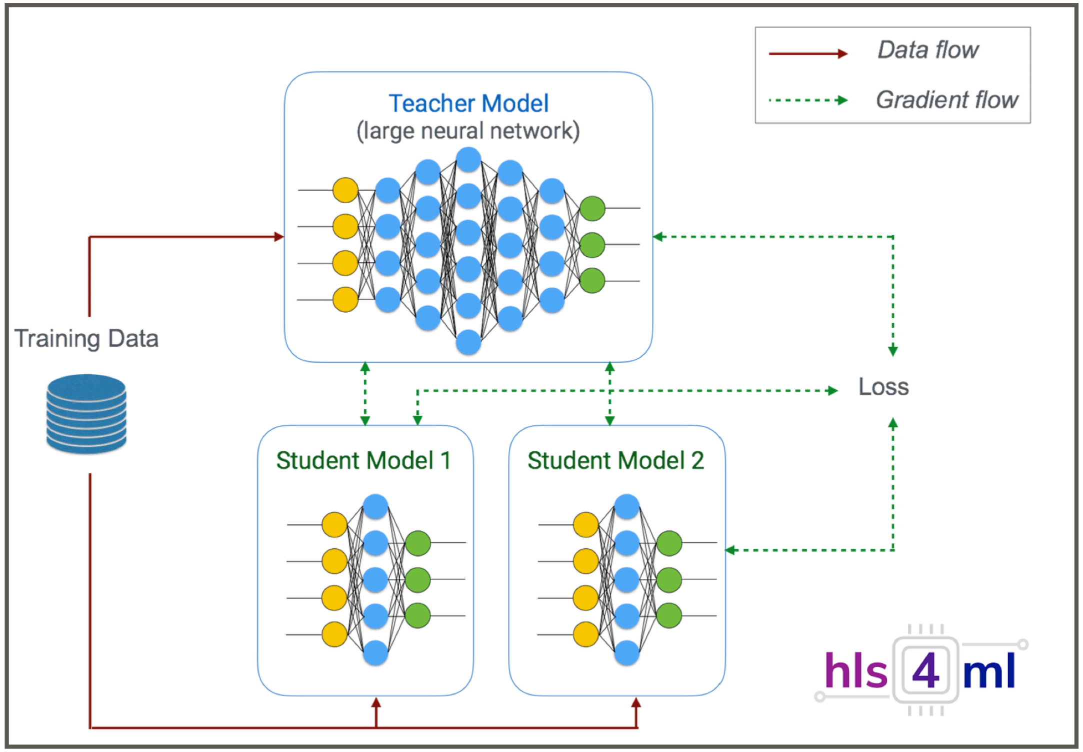
INnovativeTRiggEr techniques for beyond the standard model PhysIcs Discovery at the LHC. Santiago Folgueras

Will be presented to you in details later this week.

- Improve muon trigger reconstruction with advance techniques based on machine learning: Graph Neural Network.
- Considering AI accelerators (AI Xilinx Versal Chip)







IMPACT OF TRIGGER DESIGNS BEYOND HEP

- **Societal impact:** We are fast approaching a data epoch when our lives are going to be heavily influenced, and to some extent determined, by data and its interpretation by Artifical Intelligence (AI) algorithms. Total data production is increasing at an exponential rate – more than doubling every two years. The ability to handle, process and draw conclusions from this vast amount of information will create an ever-increasing challenge. ***HEP experiments represent the perfect test bed for advanced AI algorithm developments.***
- **Much interest in these projects**
  - **Much support seen from national agencies and beyond (ERC)**
  - **Cross disciplinary projects encouraged**
  - **Industrials interested in partnership. L1T CMS working with Amazon, google, Micron, etc. Science Foundations, etc.**

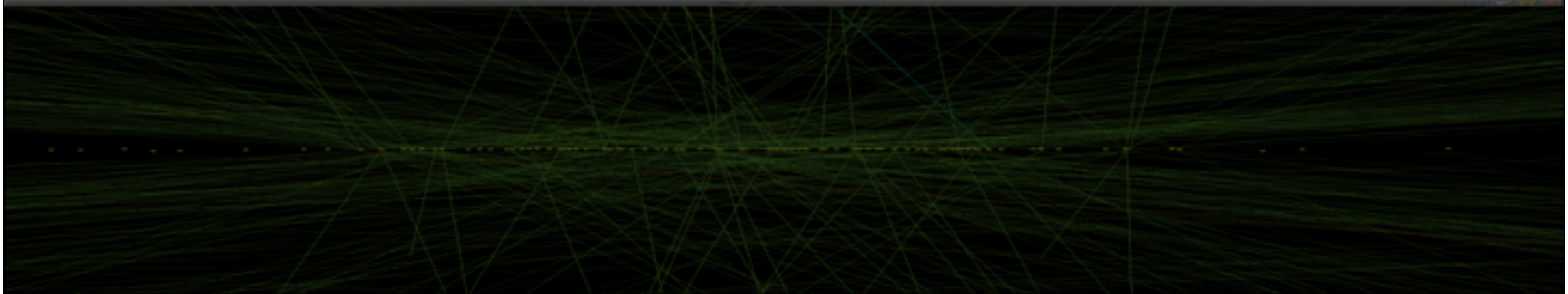
SUMMARY

CMS PHASE II L1 TRIGGER UPGRADE

- CMS proposing solid solutions to triggering and data acquisition challenge @ HL-LHC
- Phase-2 Level-1 Trigger Upgrade project: project approved in 2020 (https://cds.cern.ch/record/2714892?ln=en), steady progress with construction
- Level-1 Hardware trigger with enhanced capabilities complying with physics requirements. Sophisticated algorithms (particle-flow) are prototyped in FPGAs and exploit target hardware (VU13P/25Gb/s links)
- Modular and flexible architecture
- Hardware development lines pursuing 4 flavours of ATCA boards meeting the requirements of the project.
- Hardware demonstration ongoing and planned for testing with live data during LHC Run-3

Future designs are showing exciting prospects, even beyond HEP

BACK UP



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  - https://cds.cern.ch/record/2814727?ln=en
- **B-Tagging**
  - https://cds.cern.ch/record/2814728?ln=en
- **Continual Learning**
  - https://cds.cern.ch/record/2859651?ln=en
- **Seeded Cone Jet**
  - https://cds.cern.ch/record/2859652?ln=en
- **TauMinator**
  - https://cds.cern.ch/record/2868783?ln=en

LEVEL-1 PHASE II TRIGGER UPGRADE SYSTEM

Phase-2 L1 trigger: latency

Latency budget = 9.5 us (20% margin to get to 12.5 us)