MAKING DISCOVERIES WITH THE TRIGGER

HIGGS BIRTHDAY 2022, 9TH SEPT 2022

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OUTLINE

- Concept of triggering @ collider experiments: why are trigger systems needed ? The conceptual design of trigger systems in intense hadronic environment (focusing on CMS here).

- Our contributions: How did we take part to this adventure, operating such a complex trigger system. Our involvement from internship students to PhD students, engineers, and postdocs.

- Impact of the trigger performance on physics: What was the role of the trigger in discovering the Higgs boson.

- Perspectives for the future: Even greater challenges ! How triggers are shaping the future of analyses with gigantic datasets.

TRIGGER CONCEPTS
PRINCIPLES AND CHALLENGES @ LHC

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)

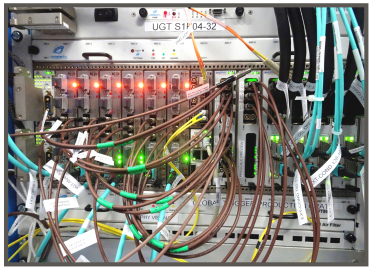
- Selecting efficiently signal $\sigma << 10^{12}\ \sigma_{pp}$
- Huge input volume > Tb/s
- Short amount of time < 3.8 us (latency)

→ *CMS implemented a 2-level Trigger system*

Focus here

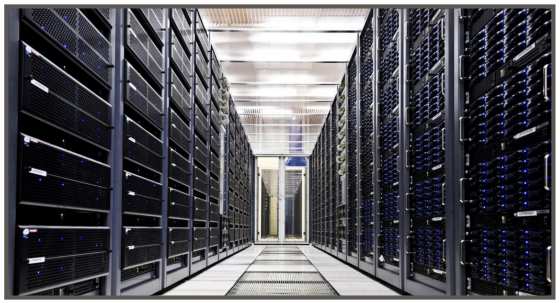
CMS Level-1 Trigger Hardware system

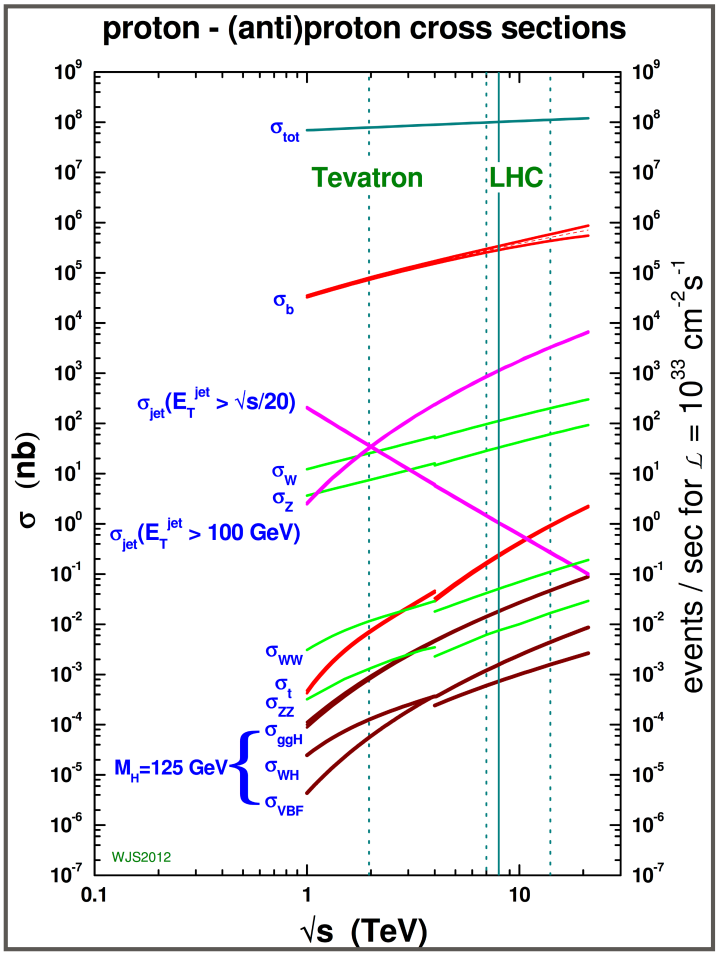
100 kHz



High Level Trigger Software farm

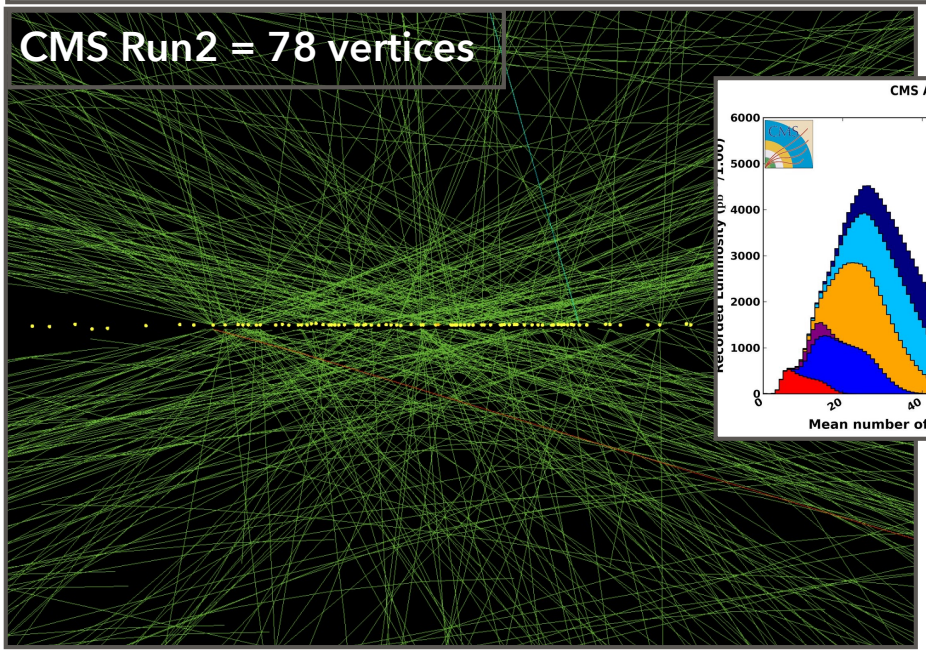
1.5 kHz

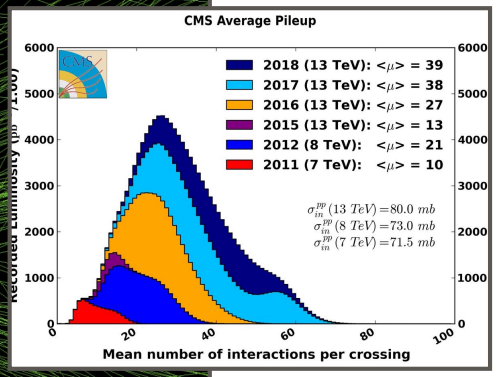


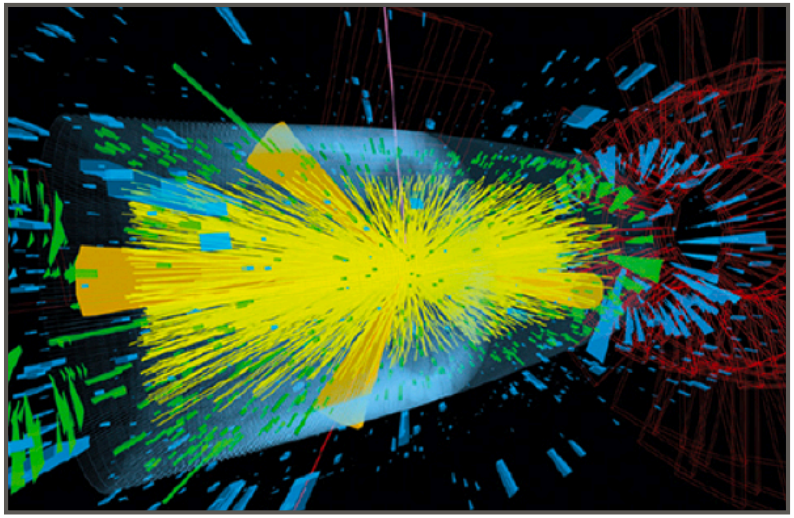


CHALLENGE OF TRIGGERING @ LHC

- LHC: Large Hardon Collider. Run 2 parameters:
  - Luminosity = 2.0×10^{34} cm^{-2} s^{-1}
  - E_{com} = 13 TeV (6.5 TeV / beam)
  - Collision rate 40 MHz
  - 10^{13} protons / bunch, <pileup> ~ 35

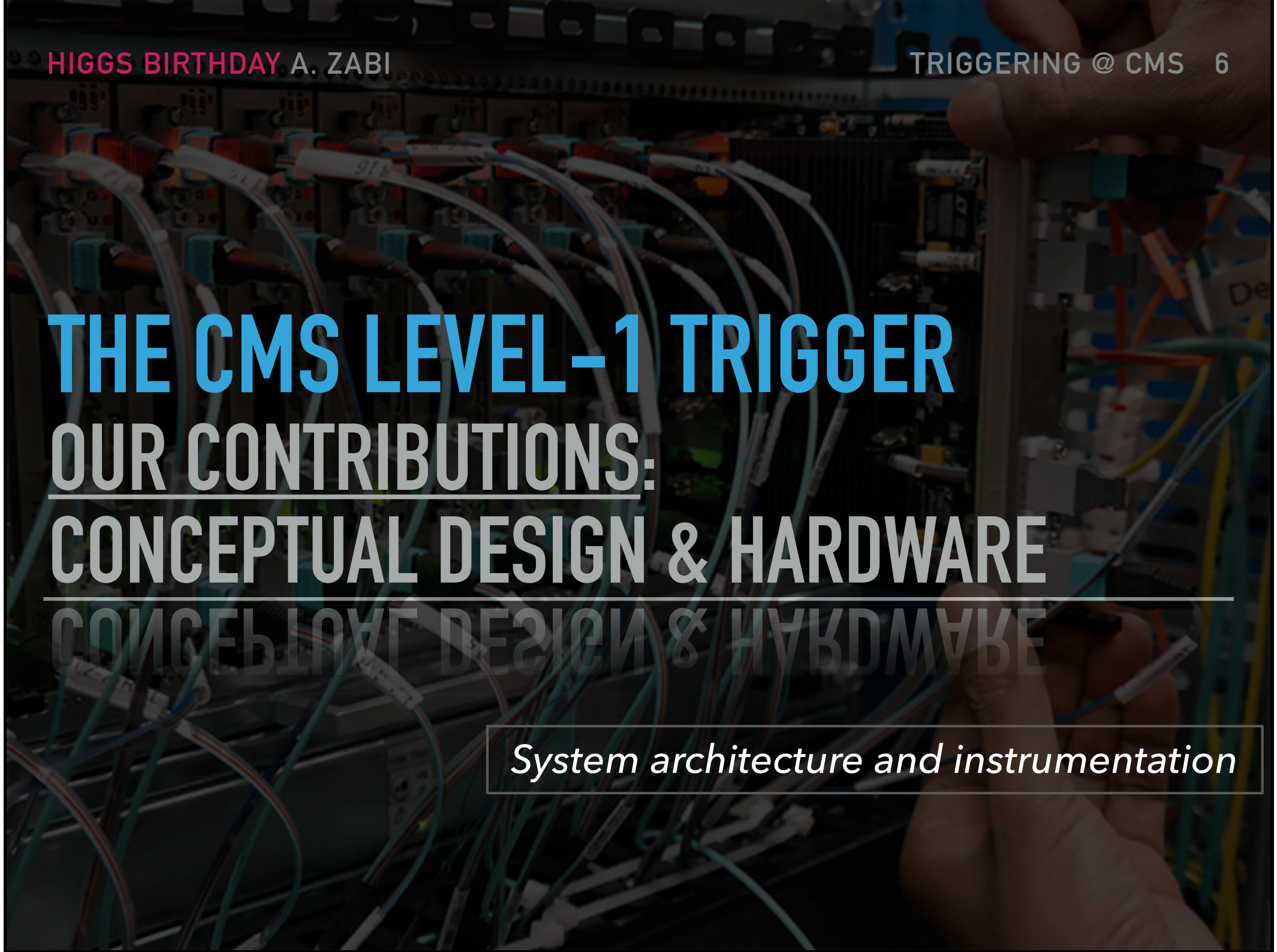






Pile-UP: low pT particles coming from additional interaction vertices (varying every bunch crossing)
Average energy density fluctuations that degrading severely the particle energy measurement.

- HL-LHC: High Luminosity LHC.
  - Luminosity = 7.5×10^{34} cm^{-2} s^{-1}
  - E_{com} = 14 TeV (7 TeV / beam)
  - <pileup> ~ 200



THE CMS LEVEL-1 TRIGGER

OUR CONTRIBUTIONS:

CONCEPTUAL DESIGN & HARDWARE

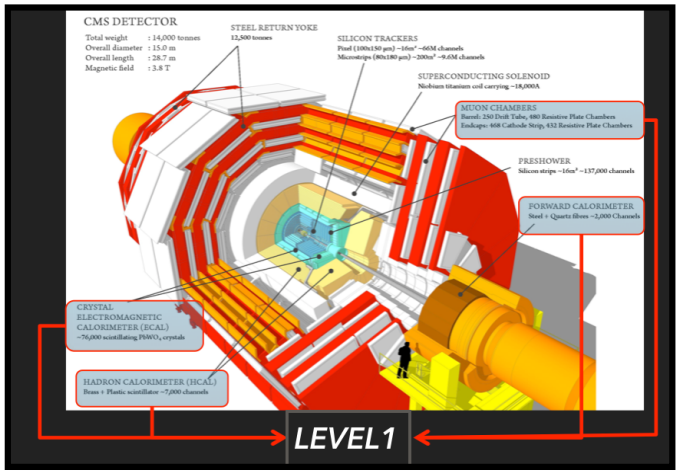
System architecture and instrumentation

PRINCIPLE OF TRIGGERING ON INTERESTING EVENTS

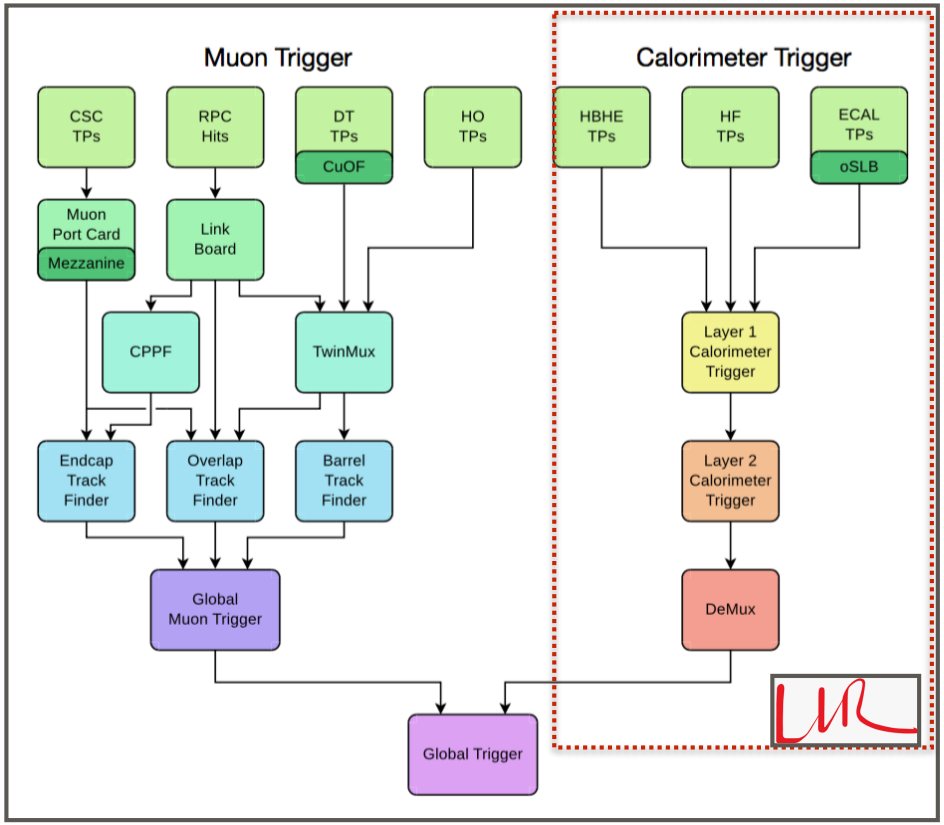
CMS Level-1 Trigger system: Today !

Harvesting data from calorimeters and muon spectrometers. With > 2 Tb/s input = Electronics

Note: tracker data cannot be readout @ 40 MHz



The CMS Level-1 Trigger System



INPUT DATA

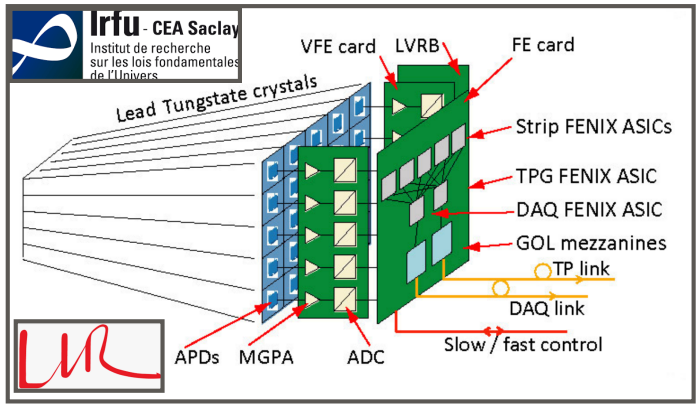
PHYSICS OBJECTS reconstruction

FINAL DECISION

PRINCIPLE OF TRIGGERING ON INTERESTING EVENTS

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

DAQ sent upon L1A

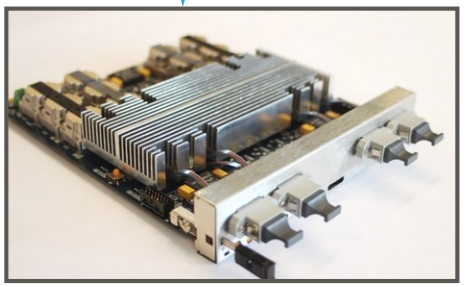
Trigger Towers/xtal → HLT

Trigger Towers

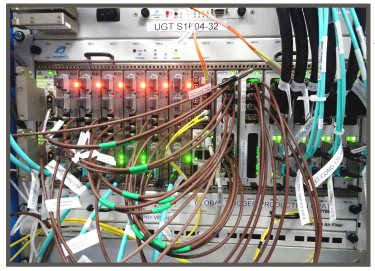
high-speed optical serial links

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

L1-Accept (L1A)

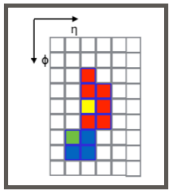


e/g, jets, taus..



high-speed optical serial links

Calorimeter Trigger
Reconstruct e/tau/jets



Combining TPs into objects

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

HOW TO MAKE THIS COME TRUE!

the trigger team

OUR CONTRIBUTION: TRIGGER CONCENTRATOR CARD (TCC)

LLR has designed, installed and operated 108 TCC boards

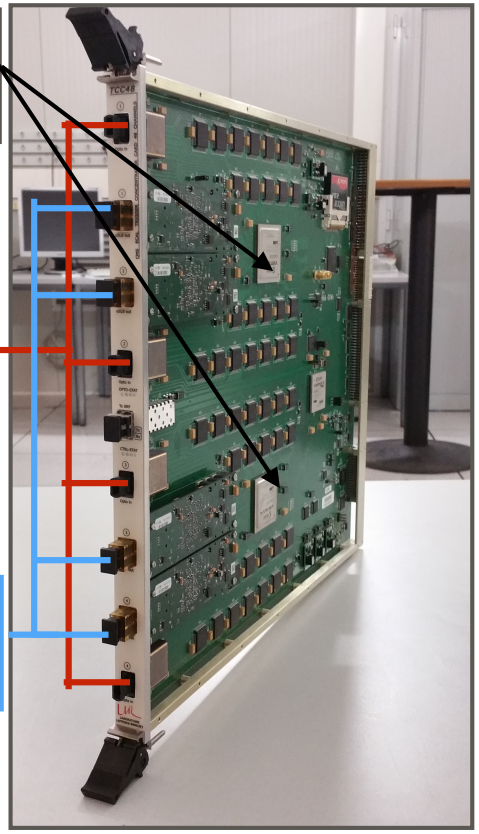
Complex electronics design (14 layers PCB), Dense FPGA (BGA), High-Speed serial optical links (http://cds.cern.ch/record/593916). Fully configurable board to adapt to ECAL geometry (projective towers).

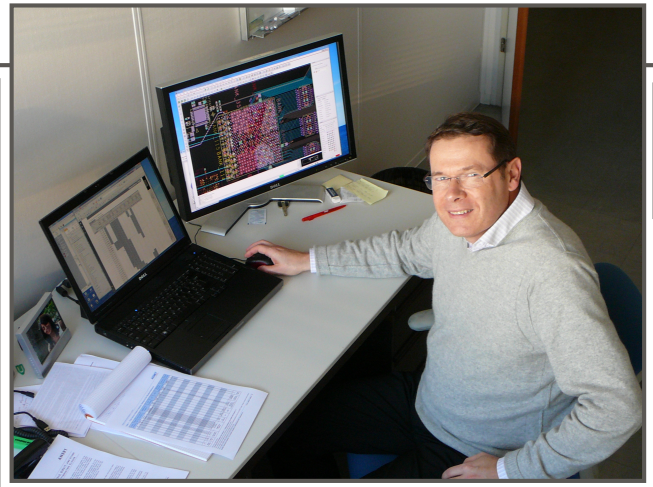
→ You need talented electronics engineers! (… and trying to make sense of physics requests…)

FPGA Algorithms

INPUTS ECAL

OUTPUTS L1T

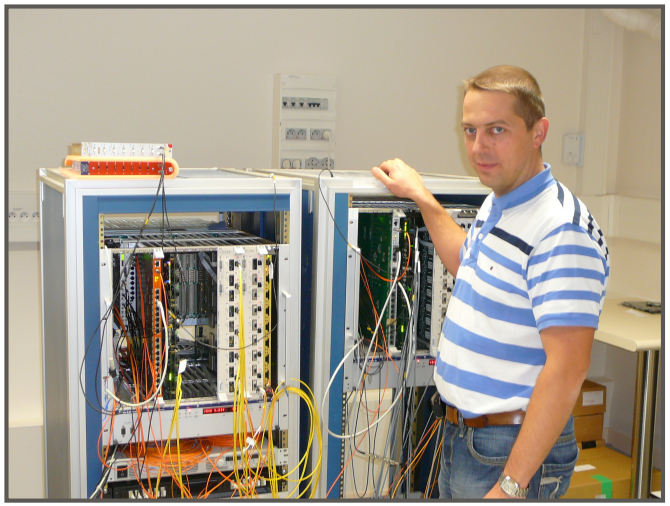




T. Romanteau (LLR):
Endcap TCC Designer

I. Mandjavidze (CEA):
Endcap TCC

Y. Geerebaert (LLR):
Barrel TCC Designer



OUR CONTRIBUTION: MORE THAN THE BOARDS

- Trigger Primitive Algorithm: Trigger primitive generation algorithm
- Online & Offline Software: Config/Control/Emulator/Monitoring
- Mechanics: Front Panels & Board Services

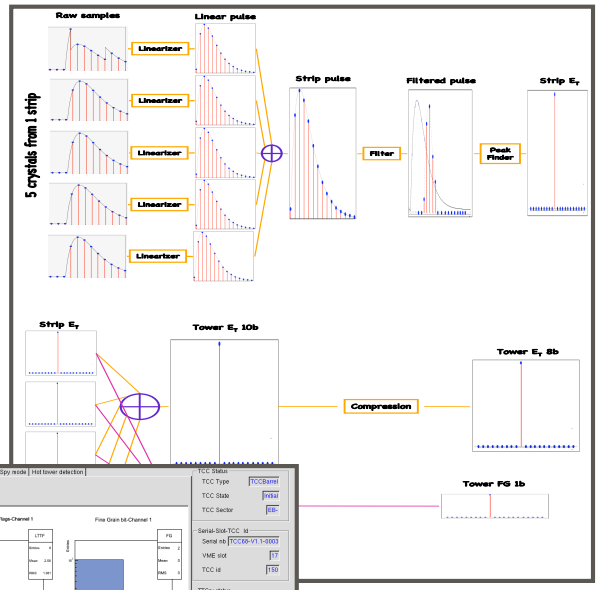
Along with the boards you need to rely on many lab services

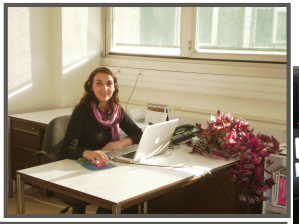
P. Busson

P. Paganini

S. Baffioni

F. Beaudette



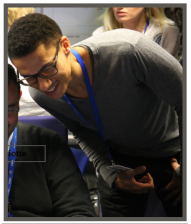


E. Becheva

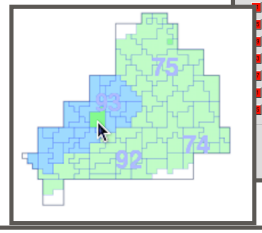
F. Magniette

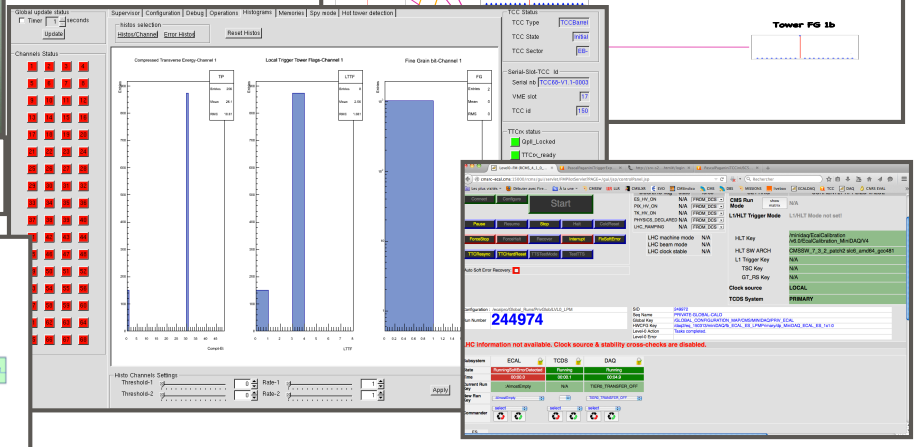
Y. Sirois

C. Charlot



F. Thiant

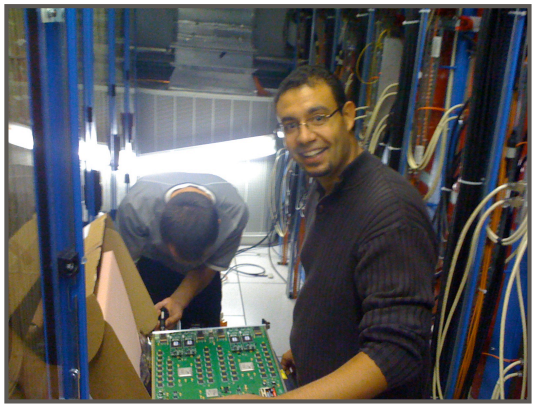


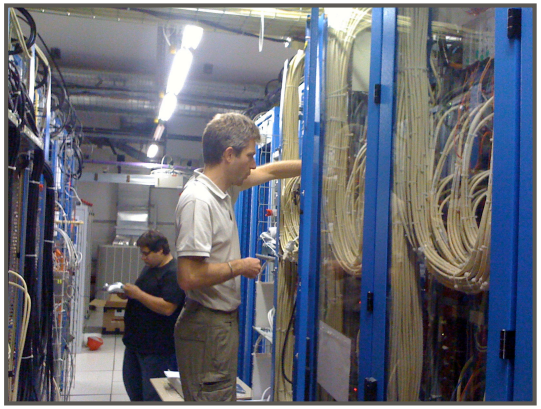


L. Dobrzynski, M. Bercher, D. Lecouturier, U. Berthon, C. Collard…

OUR CONTRIBUTION: MORE THAN THE BOARDS

And willing physicists to look after the system, install, commission, operate, maintain, take shifts in the control room etc.





TCC Installation (September 2009)

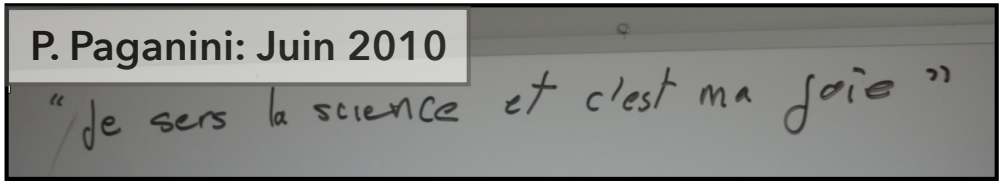
Start of Run-3

A. Zghiche, responsible for the ECAL TPG system today

Start of Run-2

Start of Run-1

P. Paganini: Juin 2010



OUR CONTRIBUTION: MORE THAN THE BOARDS

And even more willing young physicists ! (internship students also!)

Life around the trigger: nice place to start working in HEP (bridge between physics and detector work), **original and personal contributions** ensuring visibility in large collab (often rewarded!).

N. Daci
CMS Award 2012

L. Mastrolorenzo
Polytechnique
Award 2016

C. Amendola
CMS Award 2022

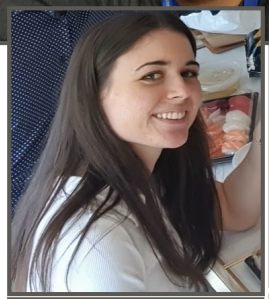
T. Strebler
CMS Award 2016
CNRS 2018

L. Cadamuro
CMS Thesis Award
2017, CNRS 2021

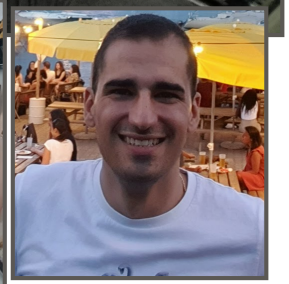
O. Davignon
CMS Award 2018
CNRS 2019

C. Martin-Perez
CMS Thesis
Award 2020

J. B Sauvan
CNRS 2016



E. Vernazza

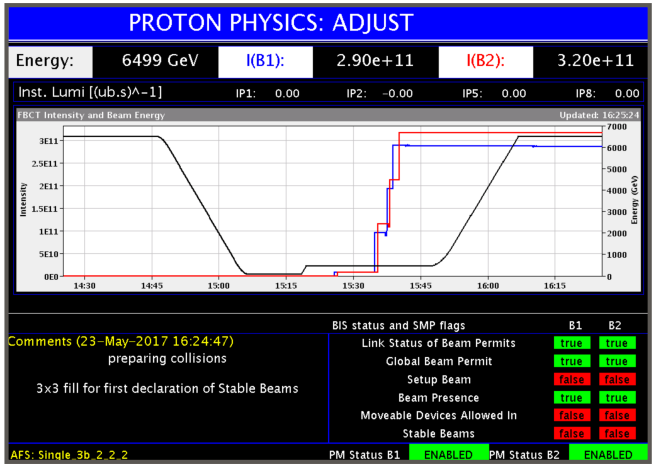


J. Motta

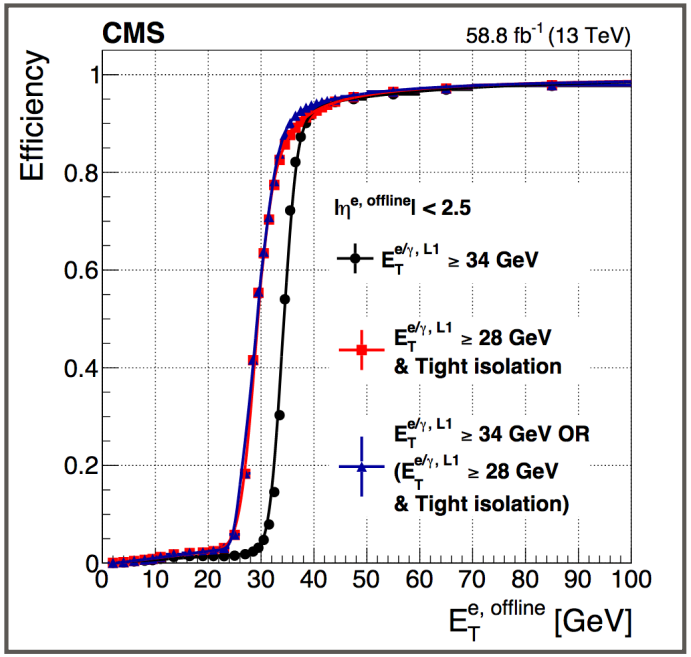
OUR CONTRIBUTION: MORE THAN THE BOARDS

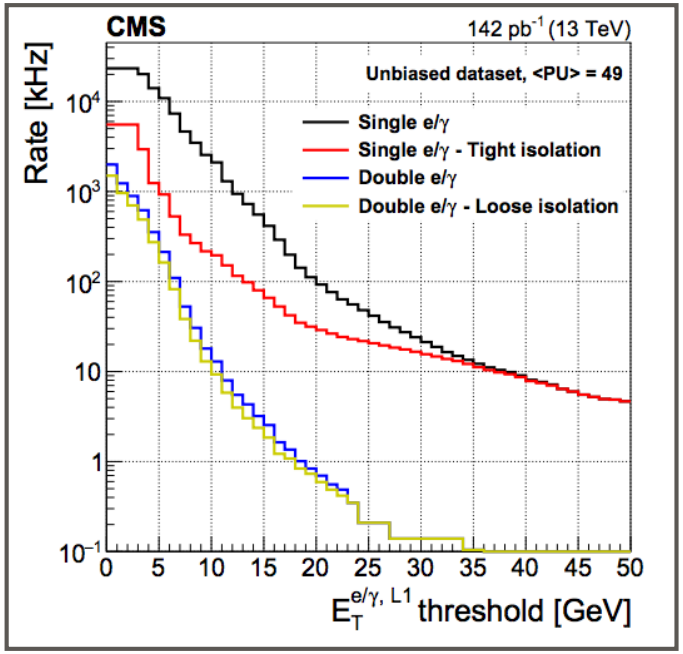
Every day operations:

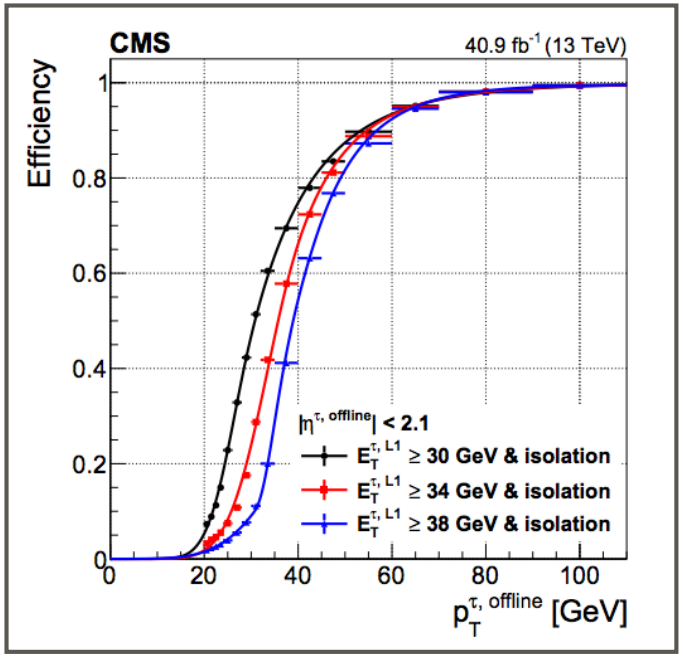
- Monitoring of data quality: timing alignement, trigger rate, occupancy (potential hot tower masking)
- Trigger Performance: checking performances (rates resolution and efficiency) on data. Optimisation of working points etc.



https://arxiv.org/pdf/2006.10165.pdf







TRIGGERING THE HIGGS DISCOVERY

TRIGGER ALGORITHMS

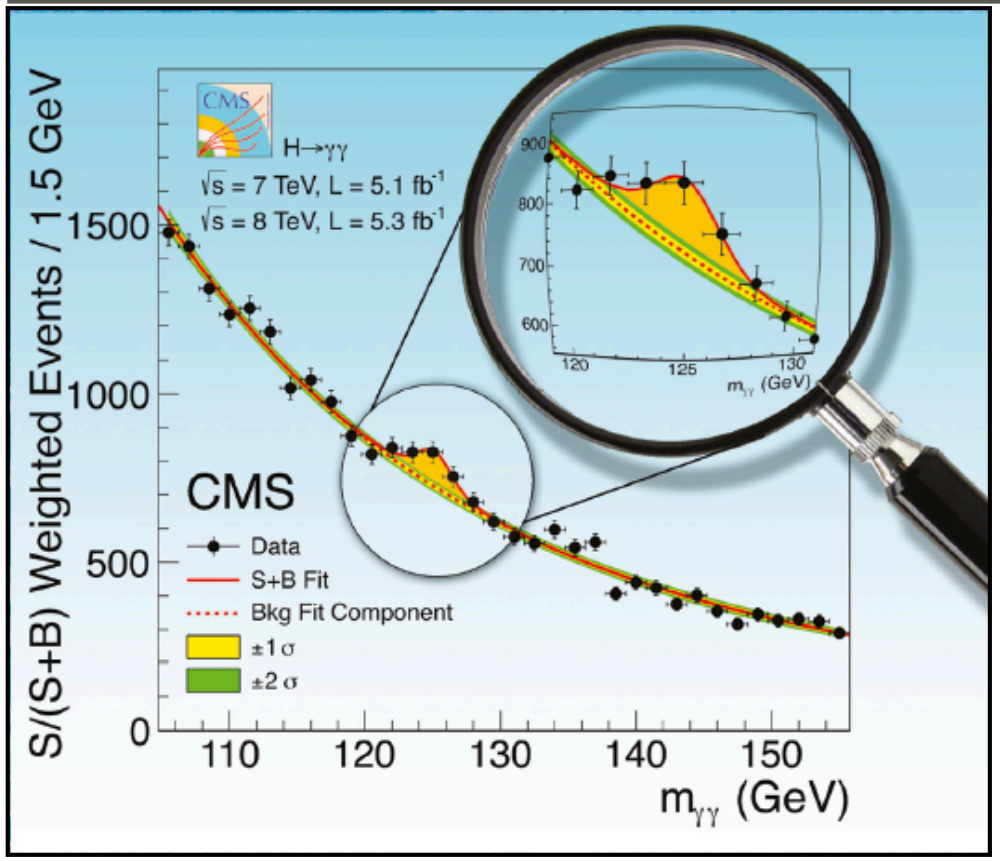
Higgs hunting

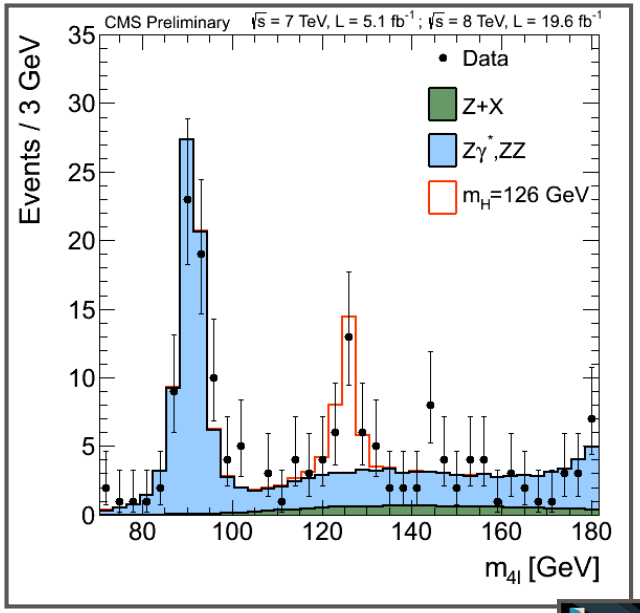
IMPACT OF THE TRIGGER ON PHYSICS

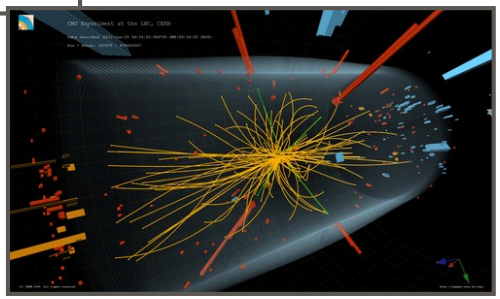
Could we have found the Higgs without an adapted trigger system?

The answer is quite simple = NO!

But why Alex? The Higgs discovery channels: H →γγ (clean signal), H →ZZ→4l (not many SM backgrounds). Well this is not only about efficiency but purity (high bkg rate → high thresholds → lower signal acceptance)







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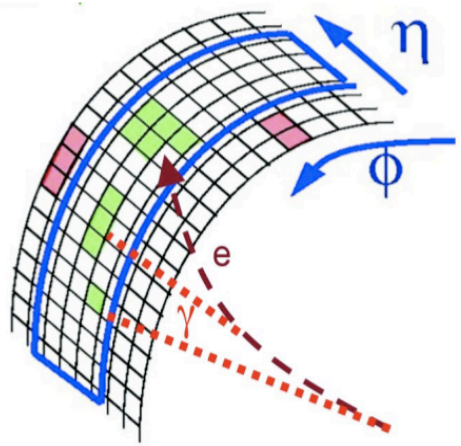
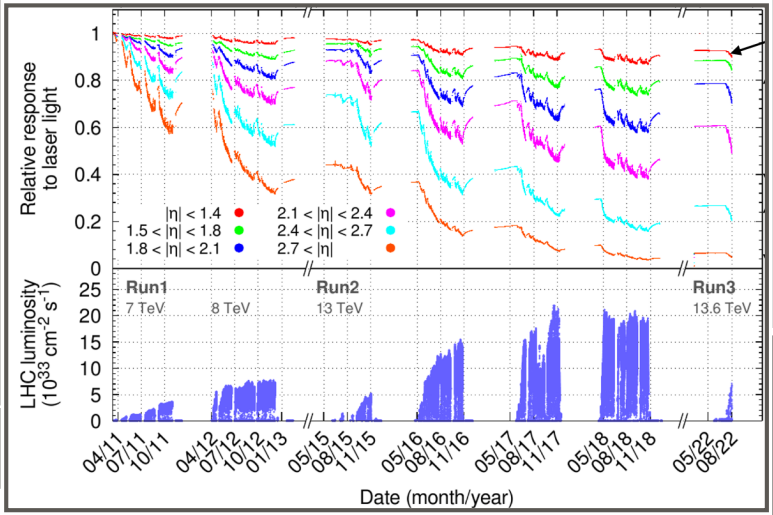
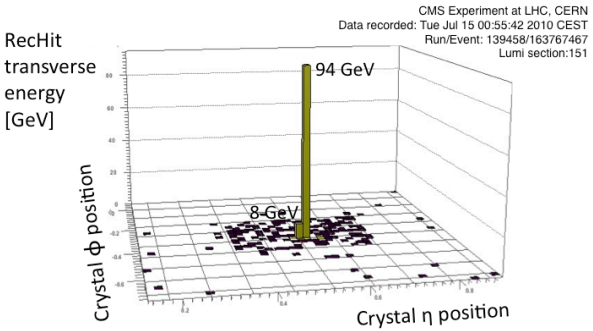


An E/Gamma is not a square!

ECAL response not constant with time ! due to radiation damage





ECAL Spikes from direct ionisation of APD = saturation of L1 bandwidth

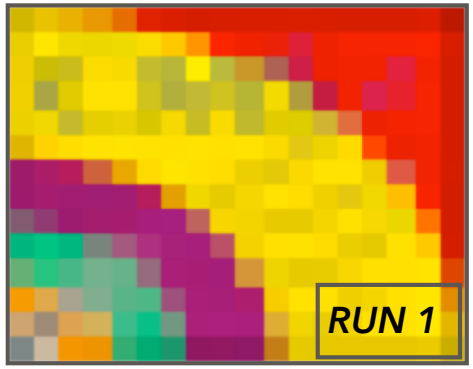
and more… pile-up, electronics issues (hot towers), out-of-time PU, pre-firing, etc.

Technically challenging but trigger thresholds low enough for the discovery!

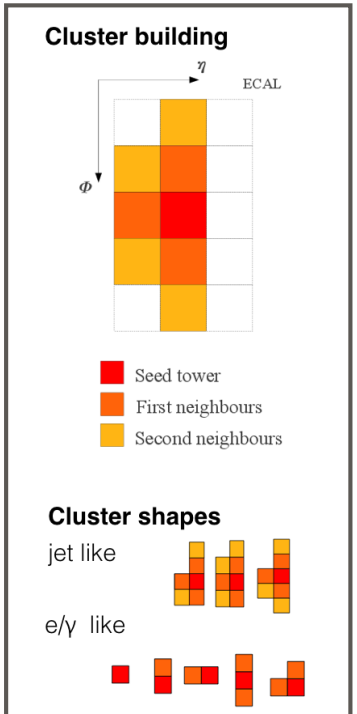
IMPACT OF THE TRIGGER ON PHYSICS

Could the trigger do more ? YES ! Phase-1 upgrade revolution

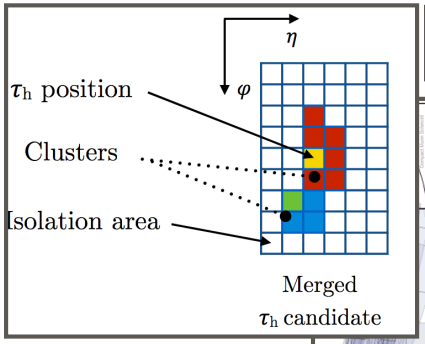
- Bigger FPGA & faster optical links: more sophisticated algorithms using higher granularity = enhanced bkg rejection, complete detector view = event global reconstruction (MET, PU, VBF)
- Flexible and modular architecture: Generic processing engines (hot swappable), reconfigured to adapt to running conditions and physics needs.



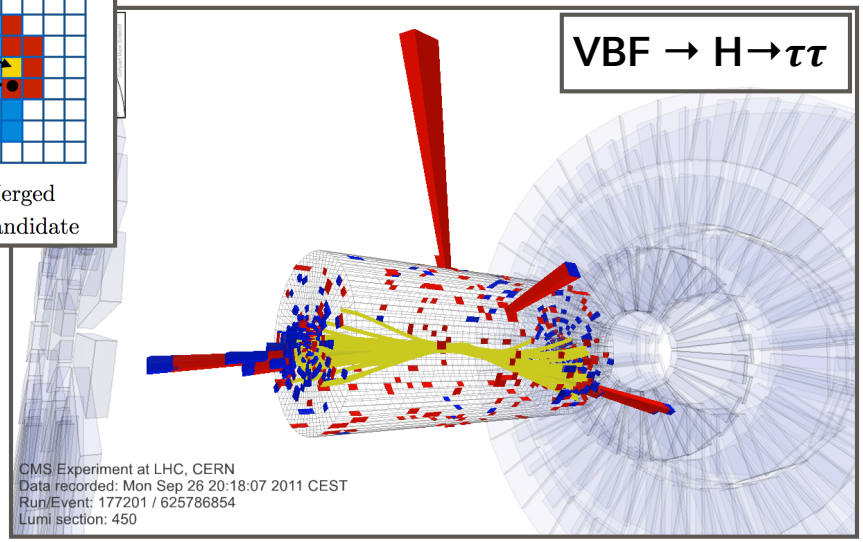
calorimeter granularity

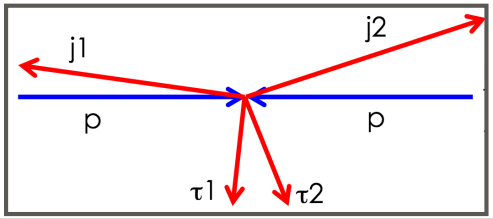


EG algo first dynamic clustering



Tau Trigger algorithm and isolation





L1_DoubleJet_110_35_DoubleJet35_Mass_Min620

Using jet invariant mass computation at the L1 Global Trigger

Trigger algorithms developed by LLR's talented postdoc and students. Technological choices that redefined trigger designs in HEP (Run-2 observations: ttH, H→bb, H→ττ)

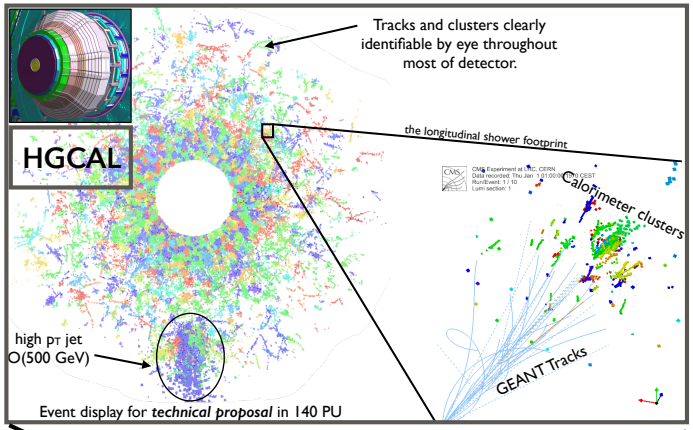
THE FUTURE OF TRIGGERING
DEALING WITH INSANE DATA VOLUME

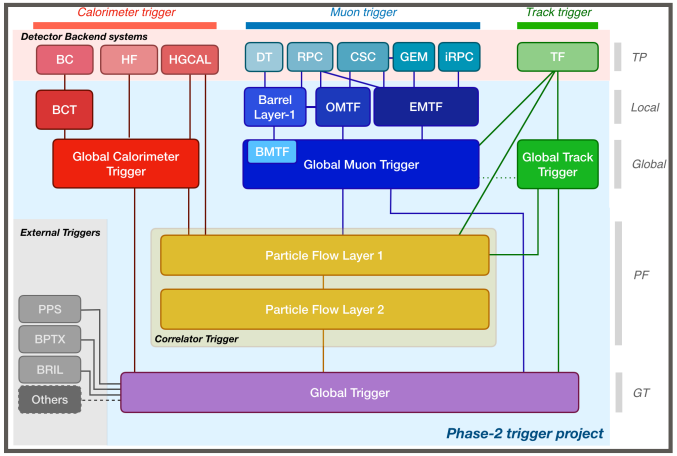
towards real-time analysis with the trigger

EXPECTING THE UNKNOWN

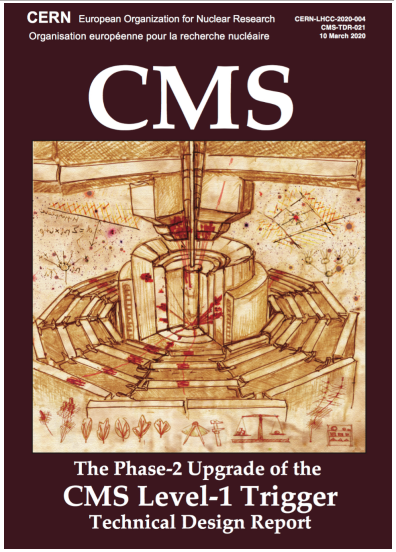
Maintaining thresholds low enough is NOT the motivation for upgrading the L1 trigger. HL-LHC research program opens a door to the unknown → The Trigger system is our scout !

The goal is to extend the physics reach by increasing the available phase space through global event reconstruction based on enhanced granularity & tracking already at hardware level (particle-flow!).

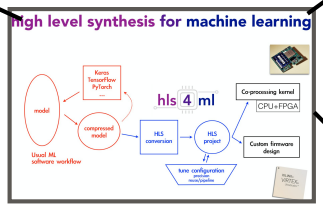


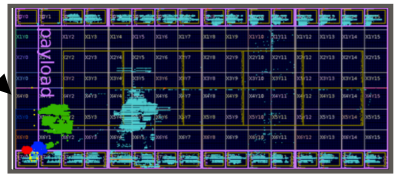


L1 Trigger for HL-LHC



L1T TDR





First implementation of a CNN-based tau trigger using HGCAL data in an FPGA. J. Motta (PhD)

- Physics Objects: reconstructed with particle flow, displaced objects,
- Cutting-edge hardware: FPGA VU9Px 8 resources of Virtex 7 (Phase-1), 28 Gb/s links
- High-Level-Synthesis: much faster turn-around, novel techniques based on machine learning
- *Scouting System @ 40 MHz: scrutinise further the data (aid the trigger), low mass resonances*

WORD OF THE END

OUTLOOK TO MORE DATA PROCESSING

exploring high energy frontiers

WORD OF THE END

- There is a lot more than just an electronics system: triggers are essential to making discoveries, modern technologies allows us to do more and more. Today triggers are leading us towards real-time analysis with electronics systems powered by machine learning.

- Trigger and people: we had the chance to participate to the great adventure of the Higgs boson discovery, literally on the front seat :) All this was possible thanks to the support of our team leaders and of course CNRS / IN2P3, CEA Irfu. Today french institutes have important responsibilities in the trigger world !

- More challenge ahead: FCC detectors will produce 1-2 PB/s of trigger data ! *Design of these systems represent unprecedented opportunities to push the technologies for the benefit of fundamental science.*