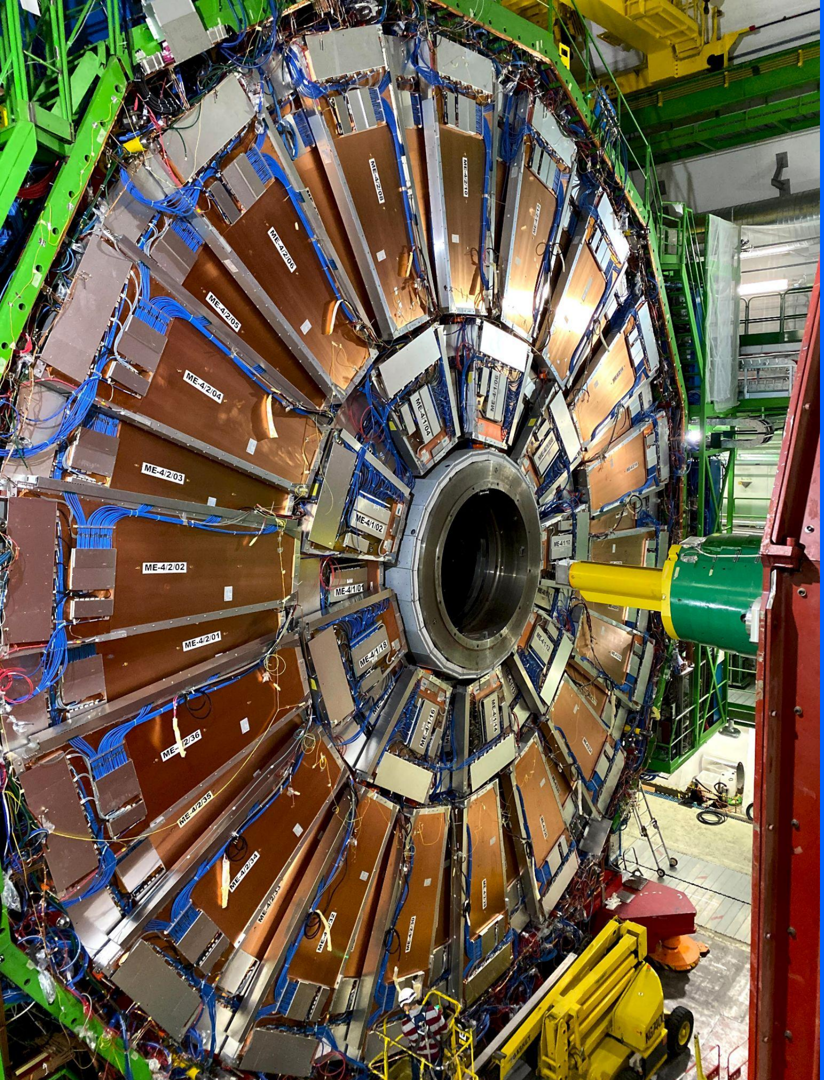


ICHEP 2022 - Bologna

International conference of High Energy Physics

July 9th, 2022

New trigger strategies for CMS during Run 3

ELISA FONTANESI

on behalf of the

CMS Collaboration

CMS

BOSTON UNIVERSITY

Outline

An optimised trigger system for the CMS detector

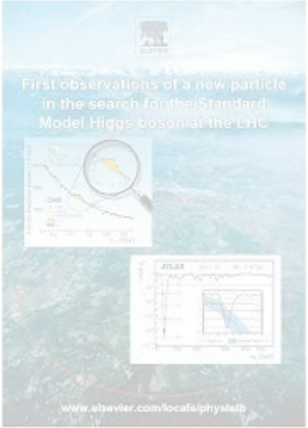
- Introduction to triggering @ CMS
- Level 1 Trigger (L1T) & High Level Trigger (HLT):
    - new features for new trigger strategies @ L1T
    - Run 3 development @ HLT
    - GPU developments

New trigger strategies for the Run 3 physics program

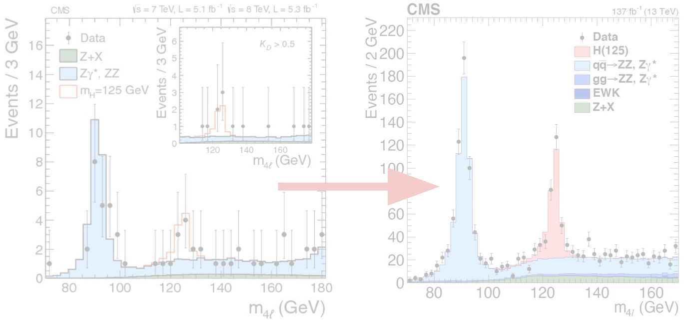
- Overview of new trigger developments:
    - B physics program and B parking strategy
    - Long Lived Particles (LLPs) and new resonances
- A new trigger menu for Run 3

Where are we going now with Run 3 ?

RUN 1			RUN 2				RUN 3	HL-LHC	Post LHC era
2011	2012	2013-2015	2016	2017	2018	2019-2021	2022-2025	…2038	… … …



Higgs boson observation: triumph of the SM



- LHC Run 2 dataset opened the Higgs boson measurements precision era
- New trigger strategies are needed to help the direct and indirect searches for new physics

The investigation of the H sector through precision measurements represents a crucial topic in particle physics!

Direct and indirect searches for new physics in B physics & EXO sectors represent a powerful tool for discoveries

Where are we going now with Run 3 ?

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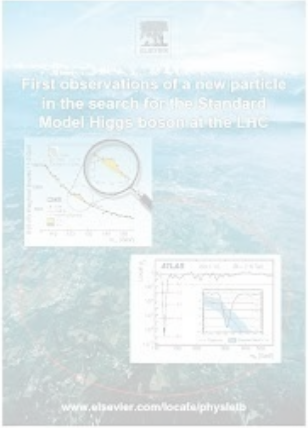


Higgs boson observation: triumph of the SM

Highlights of trigger developments for Run 3

B physics

Large focus on the flavour physics program and B parking strategy

EXO searches

Development of new algorithms and triggers to target LLP signatures at Run 3

Higgs physics

HH non-resonant and resonant searches will be flagship analyses

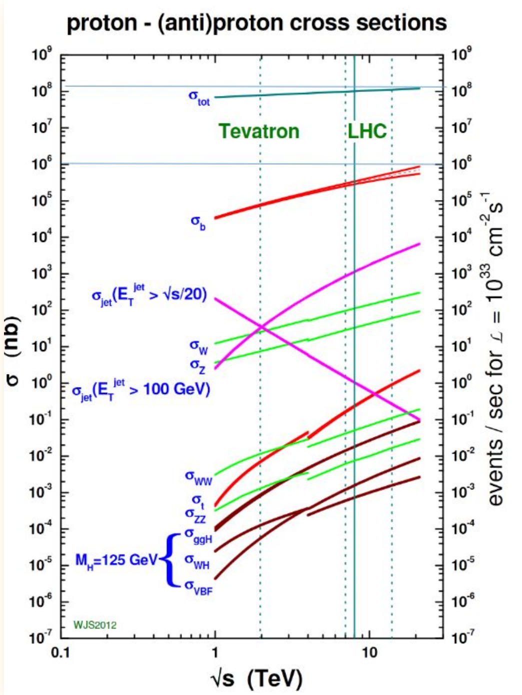
The investigation of the H sector through precision measurements represents a crucial topic in particle physics!

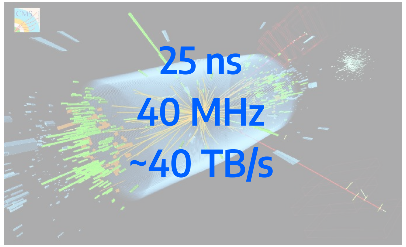
Direct and indirect searches for new physics in B physics & EXO sectors represent a powerful tool for discoveries

An optimized trigger system
for the CMS detector

Introduction to triggering in CMS

CMS was designed as a **general purpose detector able to run at the highest luminosity** at the LHC and it was optimized for the SM H boson search over a mass range from 90 GeV to 1 TeV

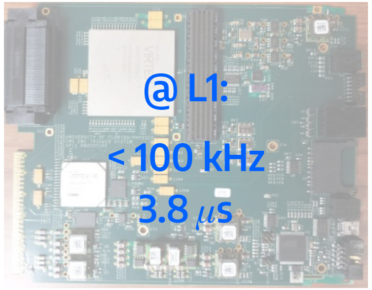




Mostly uninteresting events!

Two level triggering system

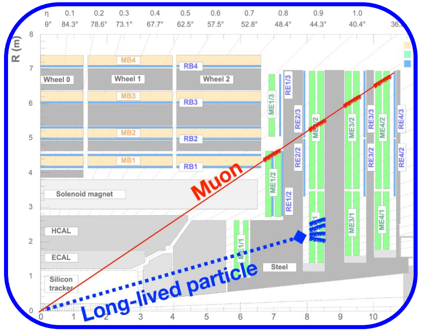
to reduce the rate to a manageable level

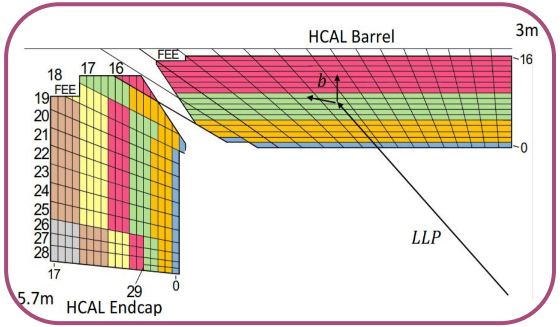


New features for new trigger strategies at L1 (1)

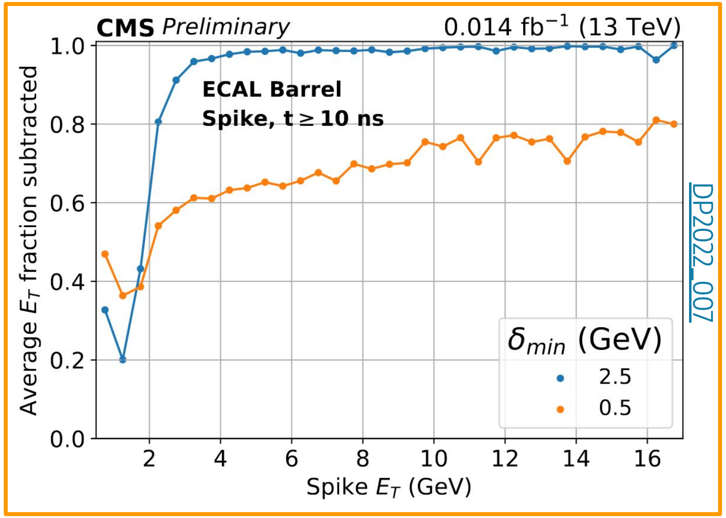
Large effort to develop new seed features, algorithms, and triggers to target LLP signatures and rare signals at Run 3

- Hadronic muon showers for displaced particles
  - The benchmark LLP trigger algorithms rely on counting hits in the Cathode Strip Chambers (CSCs)
- HCAL timing, and HCAL H/E + depth for delayed/displaced jets
  - LLP signature features energy deposited in deep calorimeter layers and delayed time of arrival of hits → HCAL electronics upgraded to read out in 4 depths (barrel) and up to 7 depths (endcap)
  - New timing capabilities for the HCAL detector (0.5 ns resolution)





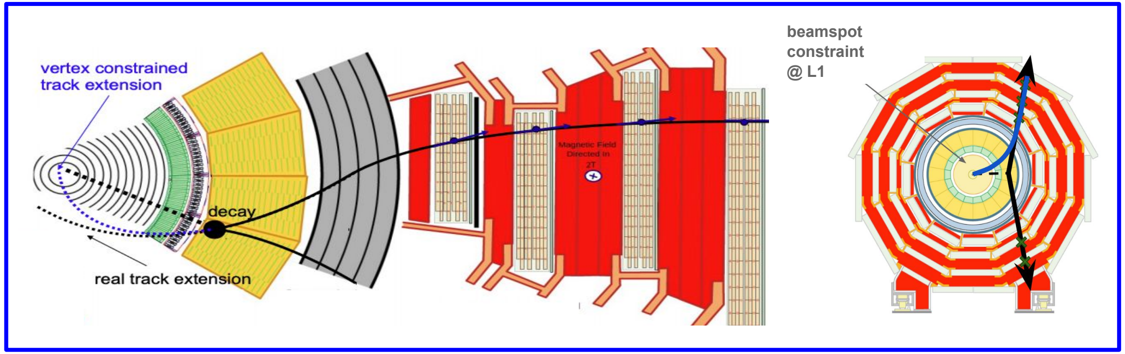
- Two set of ECAL weights to provide:
  - the correct amplitude for in-time signals
  - a larger amplitude to target out-of-time signals (delayed objects)

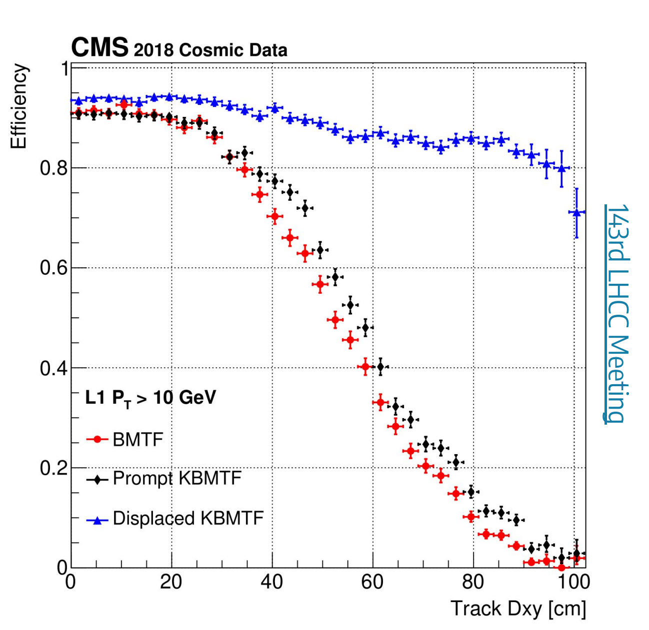


New features for new trigger strategies at L1 (2)

Large effort to develop new seed features, algorithms, and triggers to target LLP signatures and rare signals at Run 3

- Displaced muons in barrel, overlap, and endcap:
  - the Run 2 algorithms provide a measurement of μ coordinates that are beamspot constrained
    - Extrapolation of track parameters back to the primary vertex
      → Misreconstructed p_T for μ from a LLP
    - Muons with large displacements are sometimes not reconstructed at L1
  - unconstrained p_T and/or d_{xy}, and diobject invariant mass





143rd LHCC Meeting

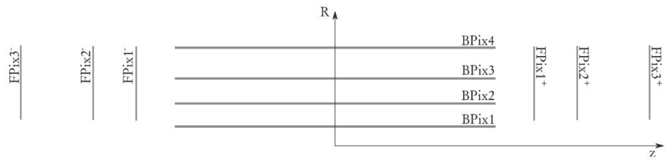
- New kinematic computations in the Global Trigger:
  - Three-body invariant mass for muon final states (e.g. τ → 3μ search)
  - Di-object ratio mass/ΔR (prompt dimuon search for resonances at low masses or B-parking)
  - Check coincidence between objects and overlap removal logic using ΔR for jets + τ triggers

High Level Trigger: Run 3 developments (1)

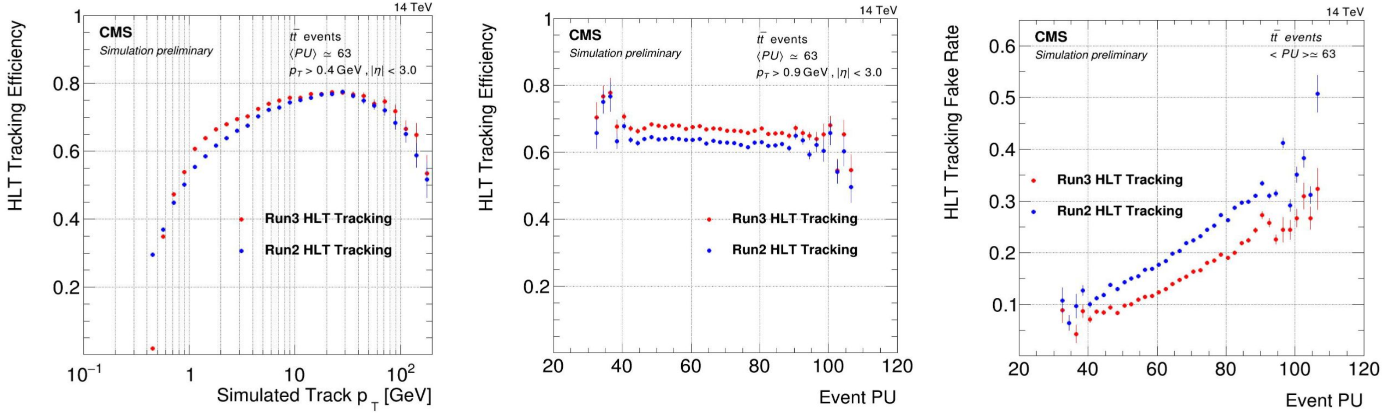
Corresponding updates at the HLT level (reconstruction and trigger paths) will ensure that an interesting physics program can be performed by CMS during Run 3

Recent developments integrated during LS2:

- New tracking based on the optimized pixel track (= Patatrack) reconstruction
  → it allows to reduce the HLT tracking to a **single-iteration approach**
  → pixel tracks can be offloaded to **GPUs**: improvement in reconstruction speed
  - propagated to the muon reco, b-tagging, tau tagging, BPH tracking
  - many new LLP particles paths can profit of it



doi:10.3389/data.2020.601728



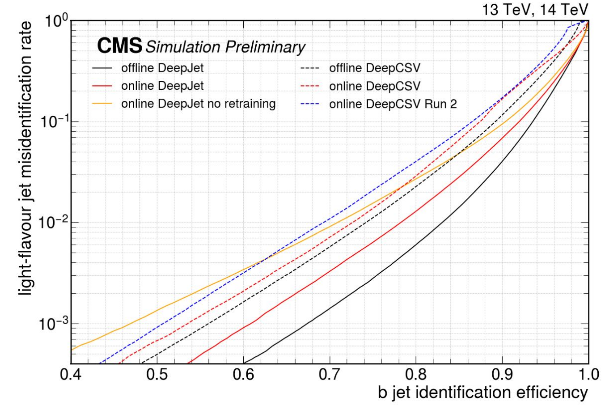
CMS-DP-2022-014

High Level Trigger: Run 3 developments (2)

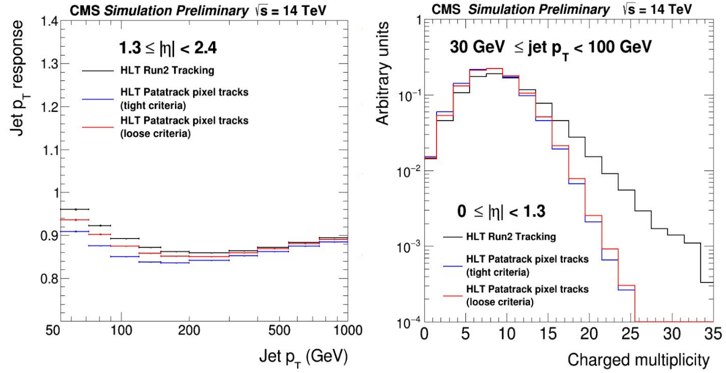
- Improved tagging capabilities of low-level calorimeter objects + new L2 τ reconstruction using pixel tracks
  - **New jet flavour classification techniques**: DeepCSV as default + additional trigger paths using the DeepJet/DeepTau (2020 JINST 15 P12012) and ParticleNet (PhysRevD.101.056019)
  - Model training on **online reconstruction**
  - New τ triggers for H→ττ (boosted) and H→bb (boosted and resolved) and for VBF+ττ, ττ+jet, HH->bbττ
  - New paths for MSSM Hbb

- New muon reconstruction and ML-based inside-out and outside-in seeding

- Improved performance of PF jets reconstructed with Patatrack pixel tracks as inputs to the Particle Flow (PF) algorithm
  - The **better quality of pixel tracks** allows them to be used as input to PF algorithm at **higher rates**, extending the reach of physics analysis to lower energies and weaker couplings



DP2022



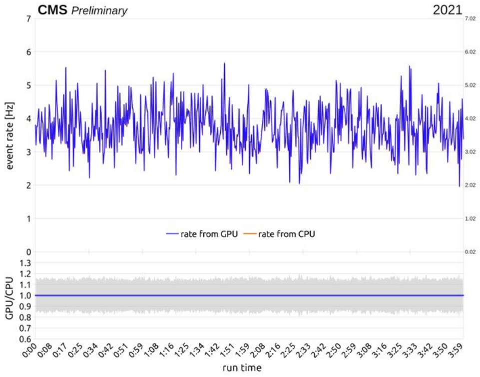
CMS-DP-2021-005

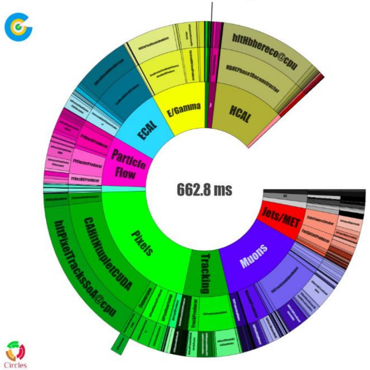
High Level Trigger: a new CPU + GPU farm

Software based trigger with full event information available will be running on CPU + GPU based farm

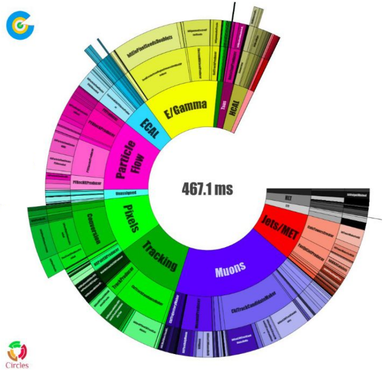
- Run 3 HLT farm composed of **200 nodes (25600 CPU cores and 400 GPUs in total!)**
  - Each node equipped with two AMD Milan 64-core CPUs and two NVIDIA Tesla T4 GPUs (**~20% more powerful** than the previous Intel Xeon "Cascade Lake" Silver 4216)
- Increasing usage of GPUs at Run 3, very powerful in parallel computing
  - We are currently offloading **30% of the HLT reconstruction to GPU**
- GPU reconstruction implemented and fully commissioned (both offline, running with GPUs on 30M events collected during the October pilot beam, and online, adding GPUs to P5 machines)
  - calorimeter and pixel local reconstruction + pixel tracking
  - **Full HLT menu with GPU enabled successfully run this Thursday!**

gpus-cms



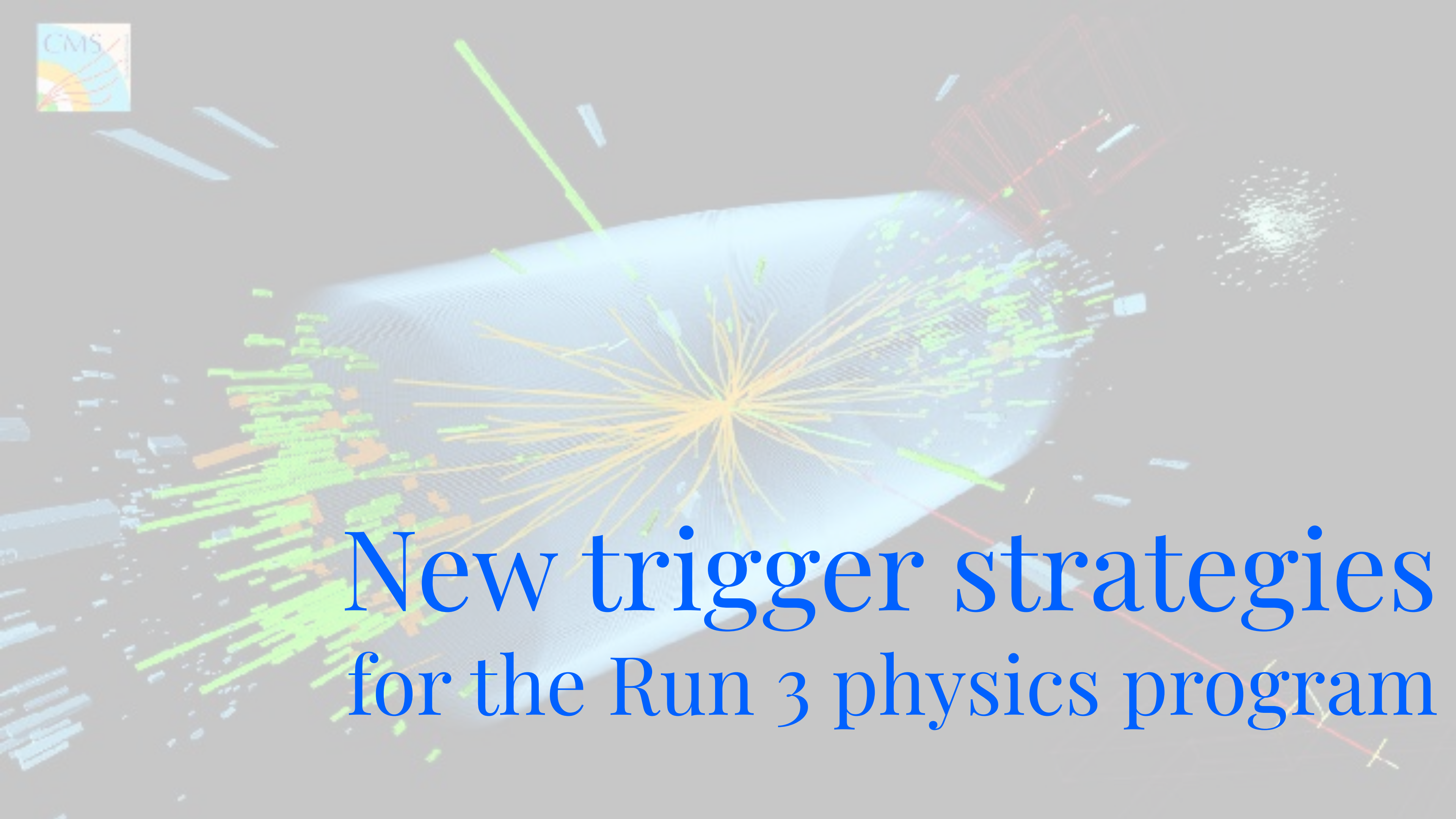


CPU only: 662.8 ms



CPU + GPU 467.1 ms

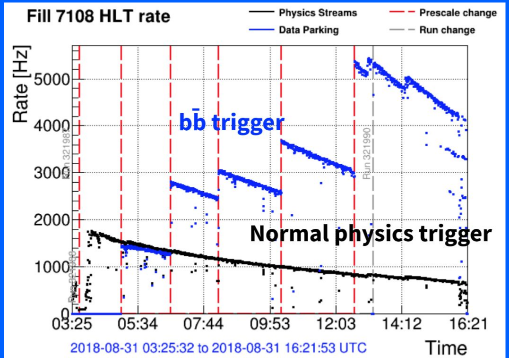
Preliminary study on 2018 data



New trigger strategies for the Run 3 physics program

B physics & parking data

Latest LHCb studies has strengthened the significance of the flavour anomalies



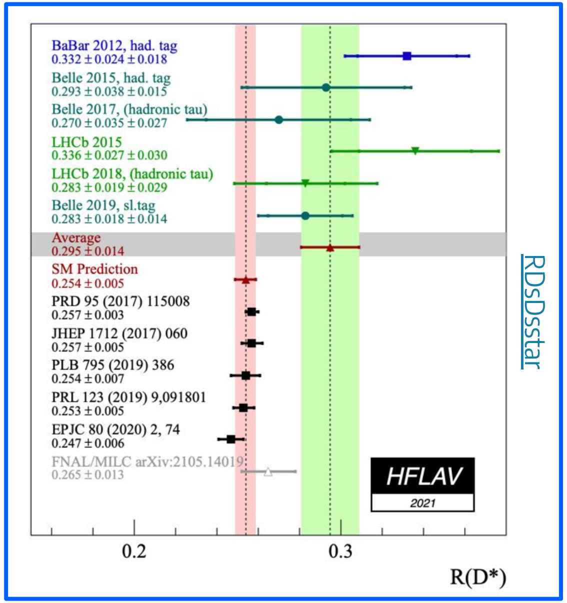
- R(D*) and R(K)/R(K*) measurement with Parking Data
- $B_s \rightarrow \mu\mu$ analysis
- $\tau \rightarrow 3\mu$ search

Tests of lepton flavour universality in charged-current B decays offer an excellent opportunity to test the SM

Hints of new physics in the measurement of the flavor ratios R(D*):

$$\mathcal{R}(D^*) \equiv \frac{\mathcal{B}(B \to D^* \tau \nu)}{\mathcal{B}(B \to D^* \mu \nu)}$$

→ the average values of these measurements differ from their respective SM predictions by 3.9σ

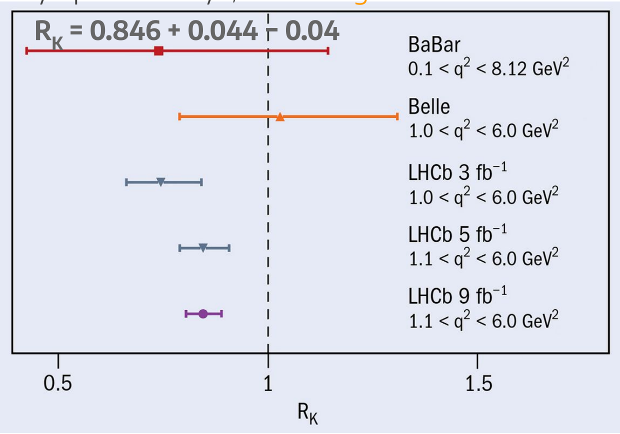


RDsDsstar

LFU: R(K) and R(K*) measurement with Parking Data

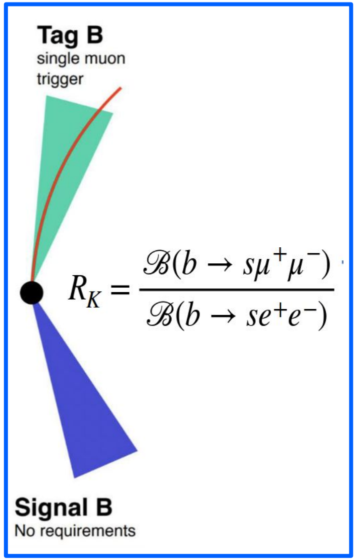
Lepton Flavour Universality tests targeting flavor-changing neutral currents (FCNC)

- Previous LHCb measurements of R_K and R_{K^*} probing $B^0 \to K^*\ell\ell$ decays provided hints of deviations from unity
- Latest R_K analysis (full Run 1 + Run 2 dataset) → evidence for the breaking of lepton universality in beauty-quark decays, with a significance of 3.1σ



arXiv:2103.11769v1

CMS goal: study of FCNC processes using **Parking data** (= high rate trigger without prompt reconstruction due to CPU limitations) → 2018 parking strategy collected 10 billions $b\bar{b}$ events in order to address "R(K)" anomaly



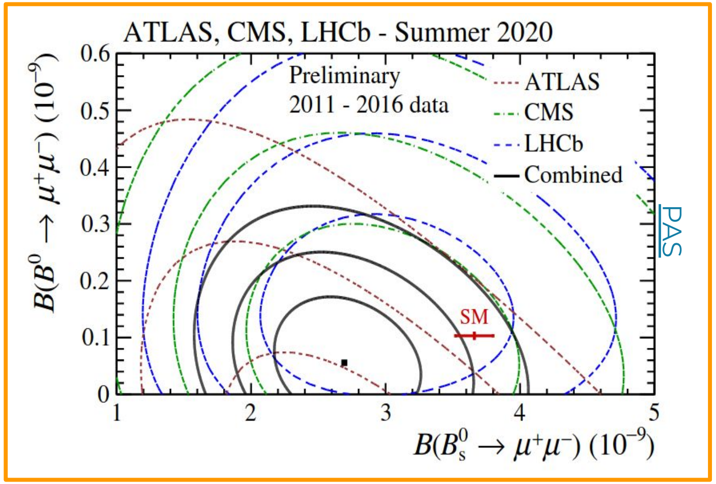
Extra effort invested to address B physics anomalies since 2018

↓

Revised **parking strategy** to target specific B physics topics based on double muon, double electron, single muon triggers

New B physics triggers: Bs → μμ analysis and τ → 3μ search

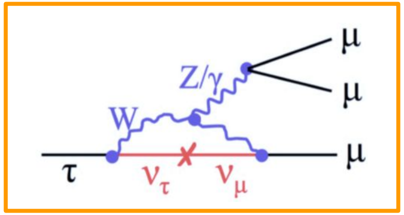
Leptonic B meson decays offer excellent opportunities to perform **precision tests of the SM**: hints of new physics in b → sℓℓ processes!



- Run 1 and Run 2 → CMS and LHCb have comparable sensitivity
- Run 3 → LHCb will have peak lumi 5 times higher: LHCb and CMS datasets increased by a factor of 3 and 2, respectively
  → **Dedicated trigger strategy needed to stay competitive**

Study of **flavor violation with charged leptons** is possible through neutrino oscillation

- In SM with neutrino oscillations: $\mathcal{B}(\tau \to 3\mu) \sim 10^{-54}$ but in BSM theories: $\mathcal{B}(\tau \to 3\mu) \sim 10^{-8} - 10^{-9}$
- The τ → 3μ decay has never been observed so far
  - Best experimental upper limit set by Belle (L = 782 fb^{-1}): $\mathcal{B}(\tau \to 3\mu) < 2.1 \times 10^{-8}$ @ 90%CL [j.physletb.2010.03.037]
  - CMS limit with 2016 data at LHC (L = 33 fb^{-1}): $\mathcal{B}(\tau \to 3\mu) < 8.0 \times 10^{-8}$ @ 90%CL [JHEP01(2021)163]



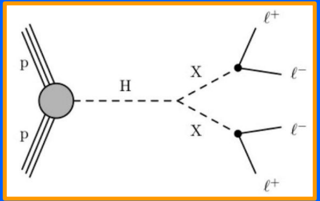
- New **double- and triple-muon** events lowering p_T thresholds to recover events in the endcaps + three-muon invariant mass cut to reduce rates

Exotic searches

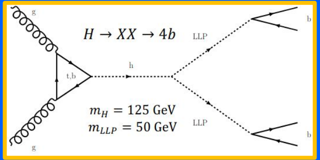
LLPs are predicted by many extensions of the SM
in particular by various supersymmetric scenarios
and “hidden sector” models

Search for such particles target decays to SM particles at macroscopic distances from the p-p interaction point

- **Displaced muons searches**



- **Displaced jets searches**



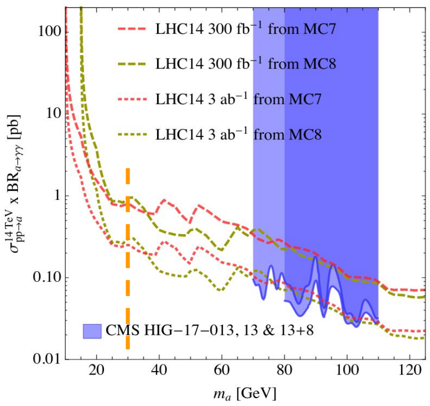
- **Low mass diphoton search**

- **Displaced muons searches** were limited by the trigger efficiency at high displacement in Run 2 due to the imposed beamspot constraint at L1 → thanks to the new available features, L1 efficiency at high displacement is highly recovered (**larger than 80%**)

- **Displaced jets searches** will profit of the HCAL timing information; new hadronic showers triggers show an efficiency on non-prompt signatures from **~35% to ~65%**

- **Low mass diphoton searches** are sensitive to different BSM scenarios at the LHC: [High-Quality QCD Axions]() that can solve the strong CP problem live in region can be uniquely probed at the LHC → focus on ALPs in diphoton

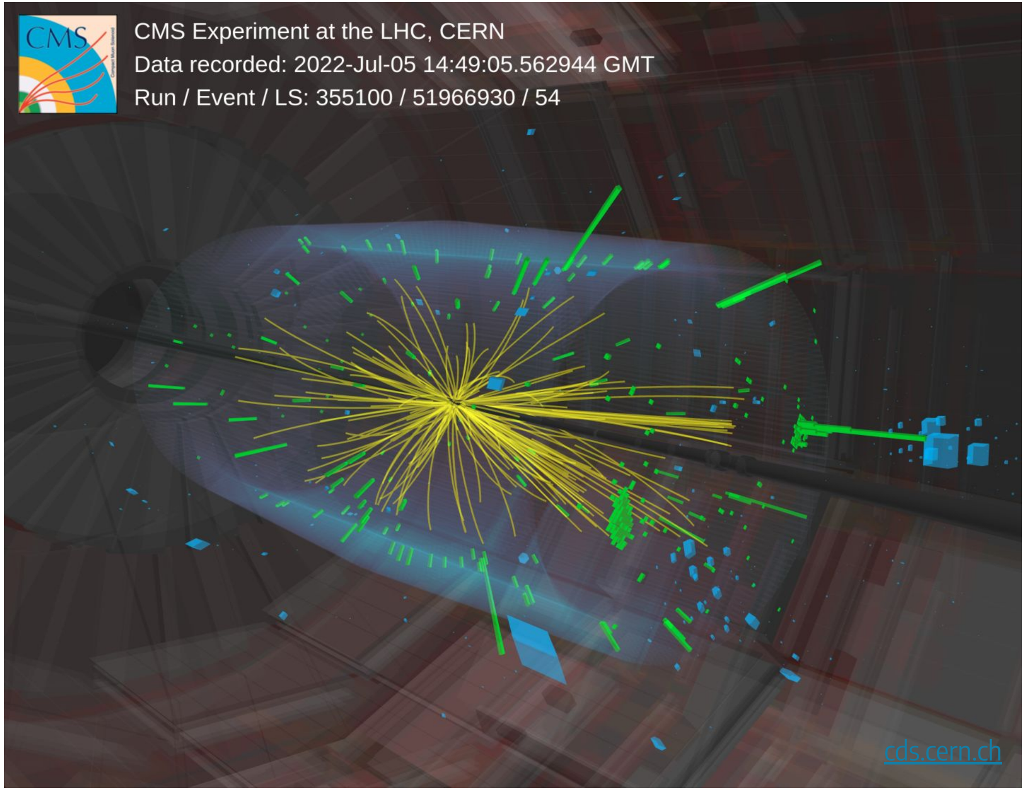
[arXiv:1710.01743v3]()



The goal is to lower the thresholds for both γ, restrict |η|, and add loose isolation cuts

Conclusions

Outlook



LHC Run 3 has started now!

- New trigger strategies have been investigated in CMS both on the L1 and HLT sides
- An optimized L1T & HLT menu has been prepared including new algorithms to target a **specific physics program**:
  - Additional rate from new L1 seeds around **19 kHz @ 2E34**
  - Total HLT rate @ 2E34 around **2 kHz**

We are looking forward to check the first Run 3 collisions at 13.6 TeV to measure the performances on new data!!

CMS aims to take fully part in the investigation of the hottest topics currently spotlighted!


Thank you!

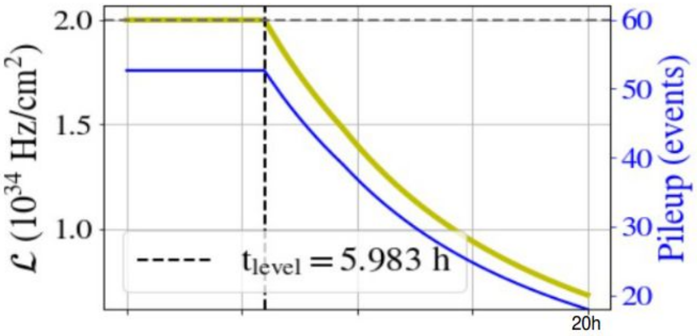
Additional slides

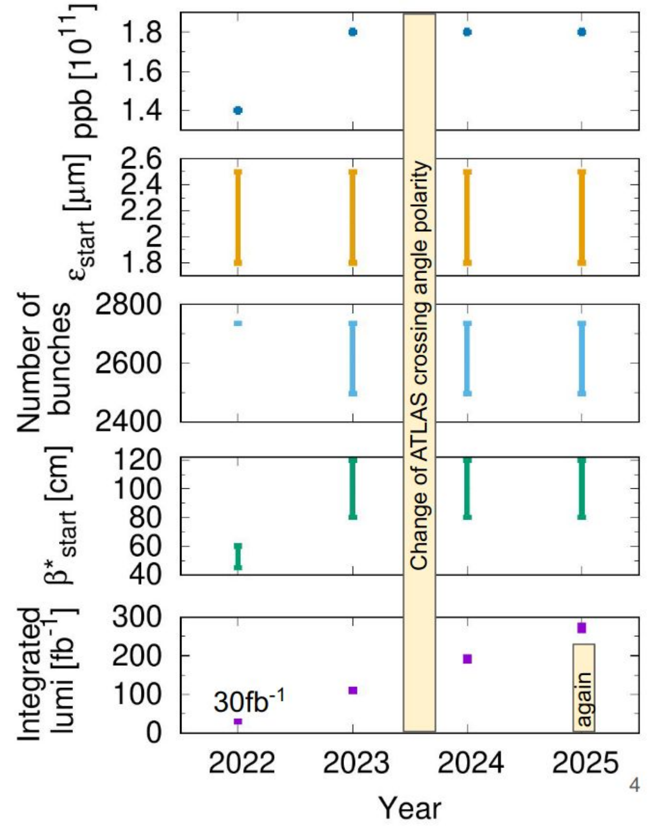
Questions? Comments?

Run 3 at a glance

Changes by the LHC for Run 3:

- Center-of-mass energy → 13.6 TeV
  - Different pileup profile from Run 2
- Increased bunch to bunch variations in pileup per crossing as the fill progresses lumi leveling at 2x10[34] → PU ~ 53

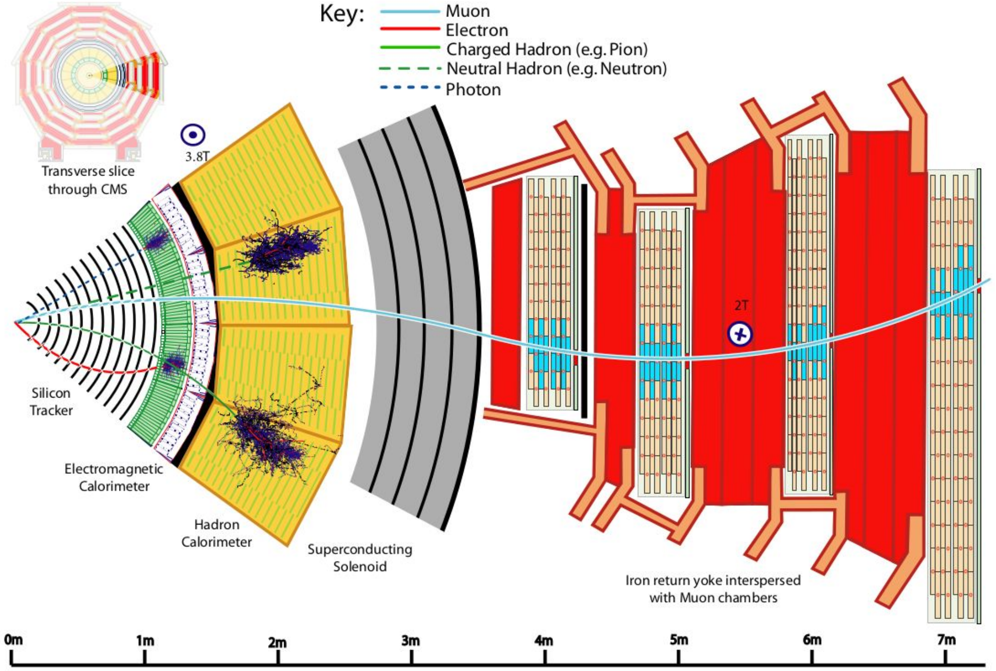




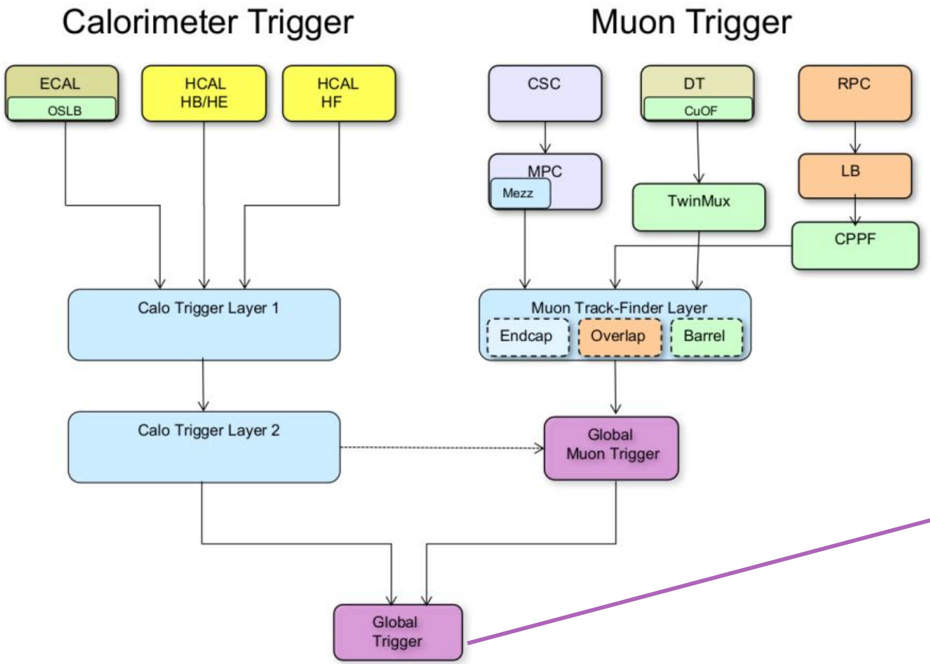
CMS detector

CMS was designed as a general purpose detector able to run at the highest luminosity at the LHC and it was optimized for the SM H boson search over a mass range from 90 GeV to 1 TeV

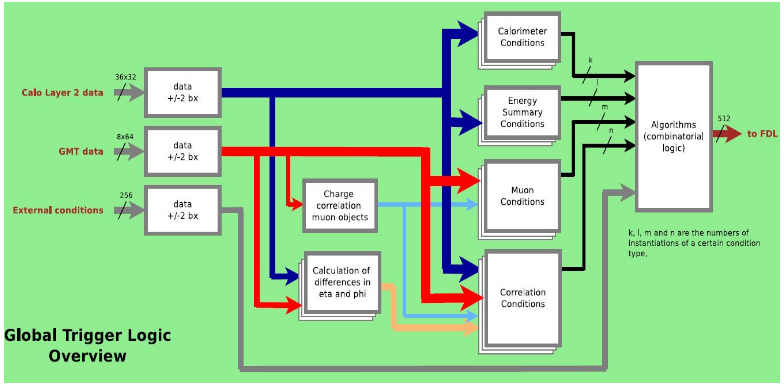
- 3.8T superconducting solenoidal magnet with 6m diameter
- Tracker System: silicon strip+pixel system which reconstructs the trajectories of charged particles
- Electromagnetic calorimeter (ECAL): scintillator made from lead tungstate crystals sensitive to energy deposits from electrons and photons
- Hadronic calorimeter (HCAL): brass scintillator sensitive to energy deposits from hadrons, mainly pions and kaons
- Gas ionization chambers for muon detection



Level 1 Trigger of the CMS detector



The Global Trigger Logic (μGTL)
firmware runs on a FPGA and
contains conditions and algorithms for trigger decision



Level 1 trigger emulator

Emulation of Muon Track Finders (TF), and TwinMux

- ★ input: DT and CSC Trigger Primitives (TPs) + RPC Hits
- ★ output: collection of simulated Muon Tracks

Emulation of Global Muon Trigger (uGMT)

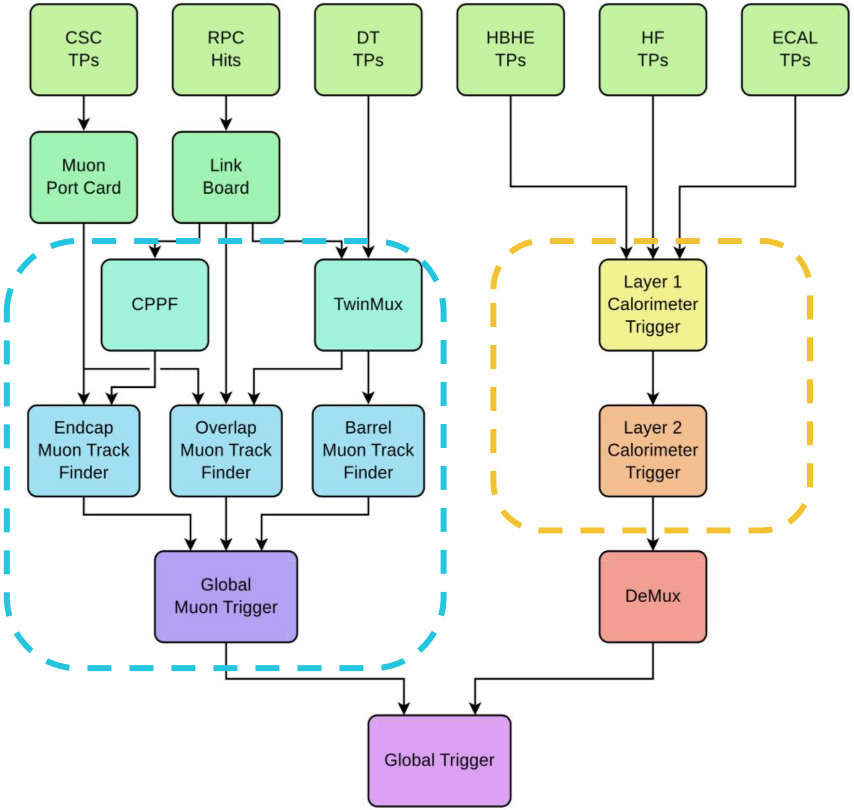
- ★ input: info from Muon TF info (simulated or unpacked)
- ★ output: list of simulated L1T muon objects

Emulation of Calorimeter Towers (CaloLayer1)

- ★ input: ECal and HCal TPs
- ★ output: collection of calibrated calo towers

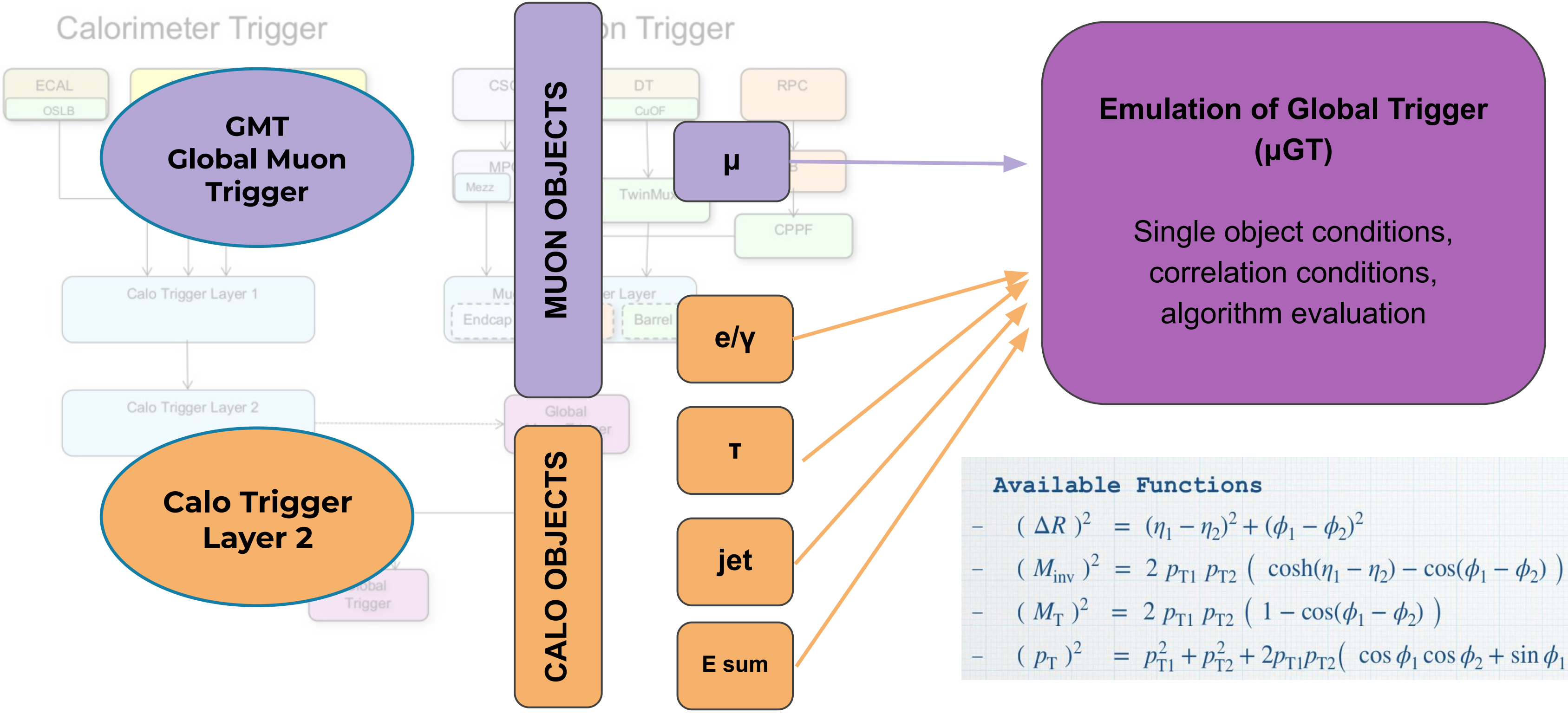
Emulation of CaloLayer2

- ★ input: info from CaloLayer1
- ★ output: list of simulated L1T calorimeter objects (τ, jets, egamma, energy sums)



Level 1 trigger emulator

At the software level, there is a L1T emulator able to reproduce each step of the GT decision in the hardware



Available Functions

- $(\Delta R)^2 = (\eta_1 - \eta_2)^2 + (\phi_1 - \phi_2)^2$
- $(M_{\mathrm{inv}})^2 = 2\, p_{\mathrm{T}1}\, p_{\mathrm{T}2} \left(\cosh(\eta_1 - \eta_2) - \cos(\phi_1 - \phi_2) \right)$
- $(M_{\mathrm{T}})^2 = 2\, p_{\mathrm{T}1}\, p_{\mathrm{T}2} \left(1 - \cos(\phi_1 - \phi_2) \right)$
- $(p_{\mathrm{T}})^2 = p_{\mathrm{T}1}^2 + p_{\mathrm{T}2}^2 + 2 p_{\mathrm{T}1} p_{\mathrm{T}2} \left(\cos\phi_1 \cos\phi_2 + \sin\phi_1 \sin\phi_2 \right)$

Level 1 trigger emulator

FIRMWARE

SOFTWARE

★ Online

- HLT **-** Every event runs the GT emulation before proceeding with HLT filtering/object reconstruction
- DQM **-** checking data/emulator agreement at every step of emulation

★ Offline

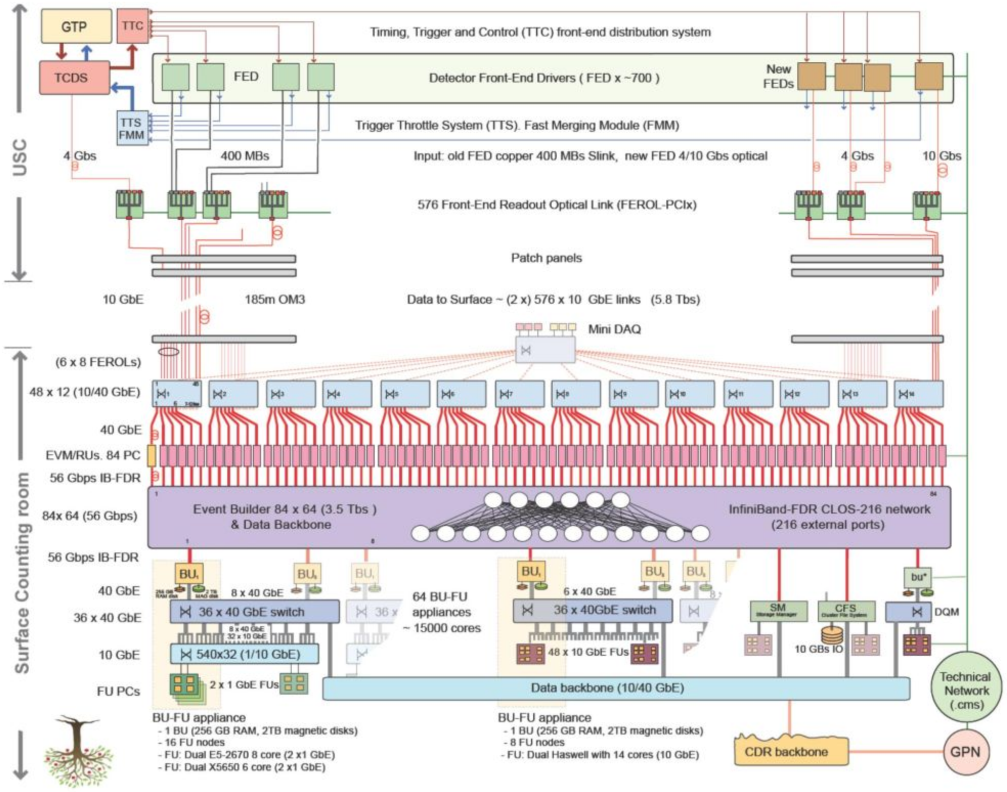
- New L1T features or algorithms developments
- Updates to L1T objects - e.g. object type or calibration constants
- New input conditions into L1T - e.g. new detector calibrations

DAQ system

40MHz

100kHz

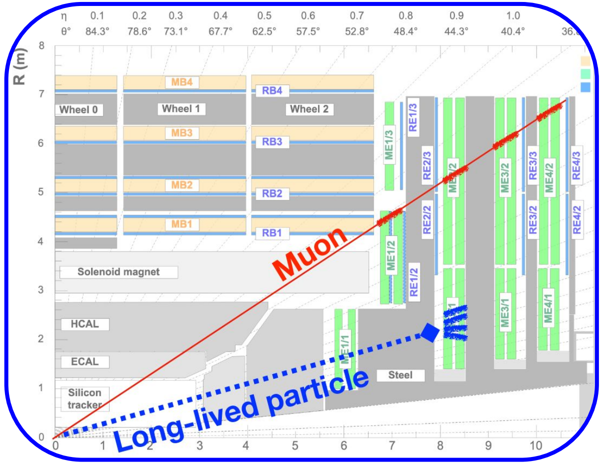
1.3kHz

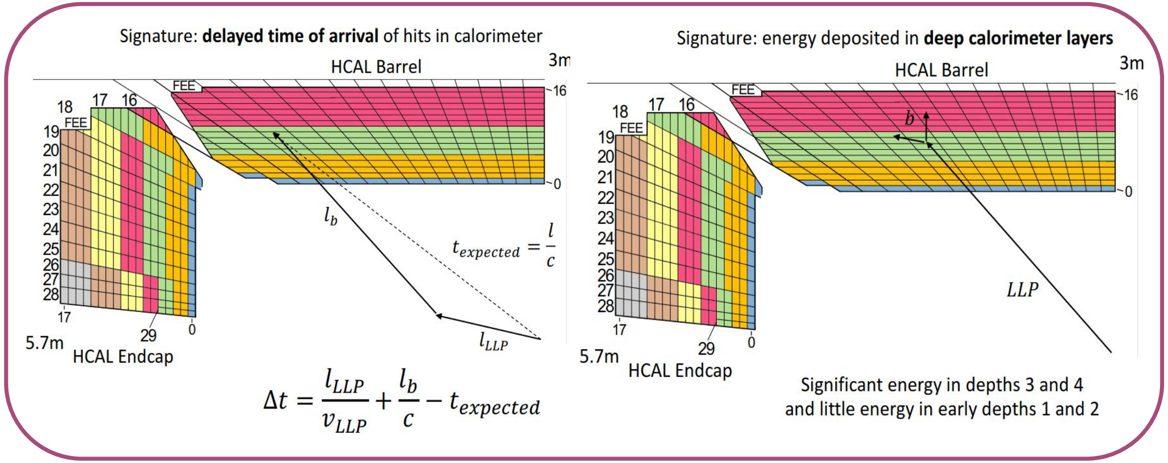


Delayed and displaced jets

Large effort to develop new seed features, algorithms, and triggers to target LLP signatures and rare signals at Run 3

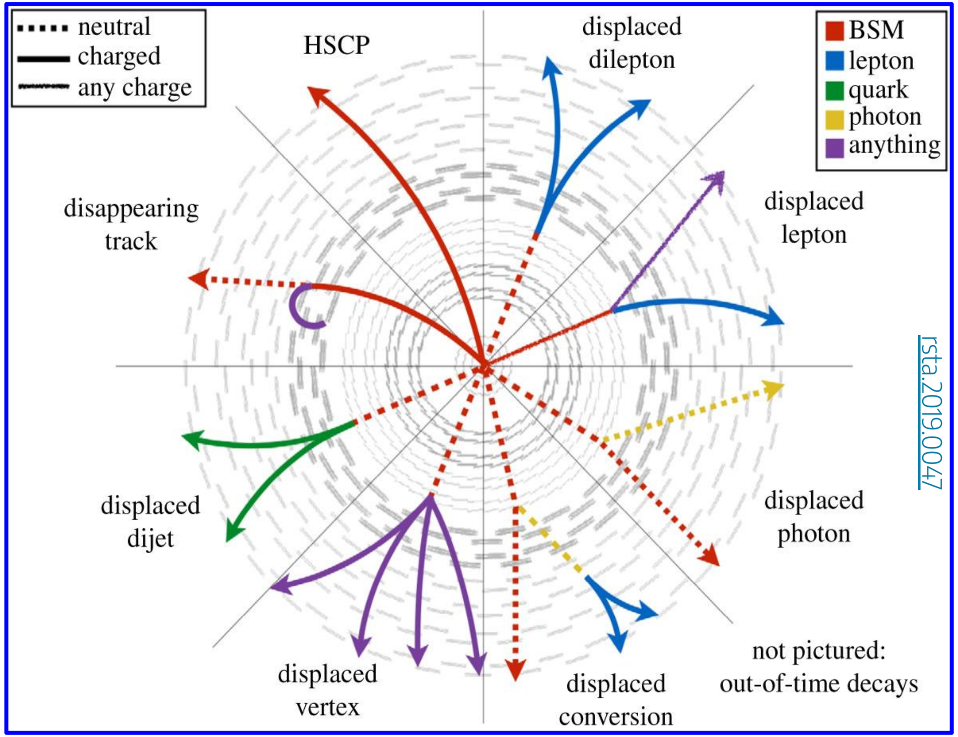
- Hadronic muon showers for displaced particles (e.g. LLP decaying to jets)
- HCAL timing, and HCAL H/E + depth for delayed/displaced jets





New features for new trigger strategies at L1 (2)

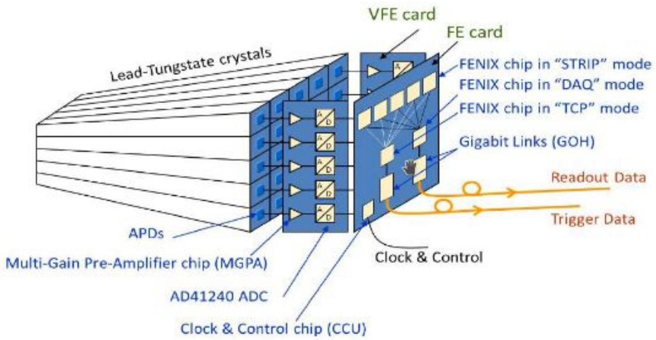
Large effort to develop new seed features, algorithms, and triggers to target LLP signatures and rare signals at Run 3

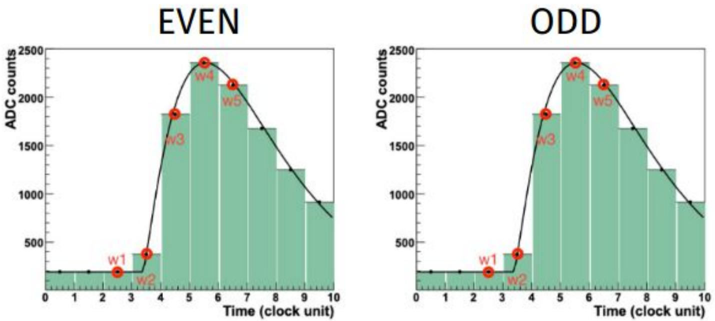


rsta.2019.0047

Displaced muons in barrel, overlap, and endcap:
→ unconstrained p_T and/or d_{xy}, and diobject invariant mass

ECAL double weights (1)





Completely unused feature of ECAL Frontend

- Two parallel set of weights available in the Strip FENIX chip → configurable behaviour by setup registers
  - The chip performing tower sum in EB (TCP Fenix) has definite behaviours based on flags from the strip FENIX
  - Investigated the double weights mechanism from firmware code and confirmed by hardware tests in 904 and P5

- Useful feature for different scenarios:
  - improve spike killing,
  - tagging out of time signals

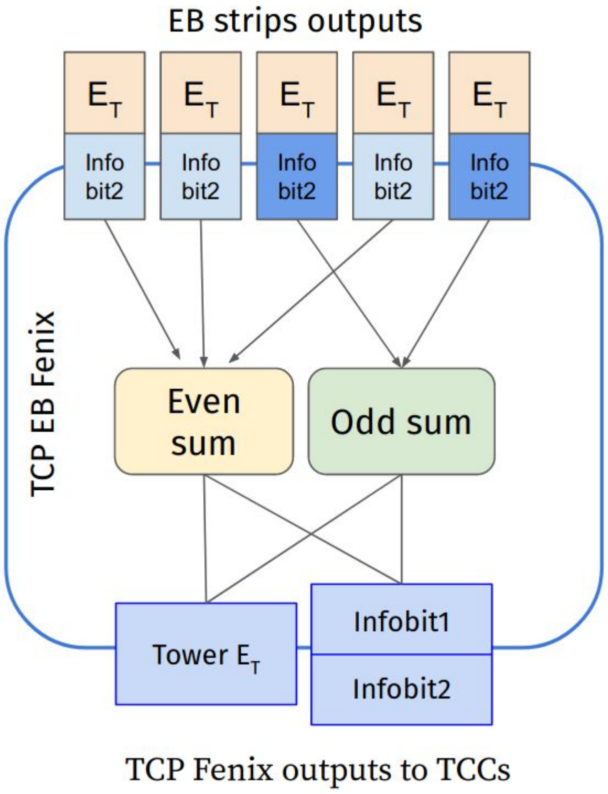
TPG Emulator changes and new DB conditions needed to use the feature in Run 3

ECAL double weights (2)

Enough flexibility for different scenarios

- Spike killer: odd filter can be used to identify out-of-time signals. An odd strip amplitude larger than even one can flag the strip, that is then zeroed out by the TCP Fenix. In this way a timing cut is applied directly on-detector.

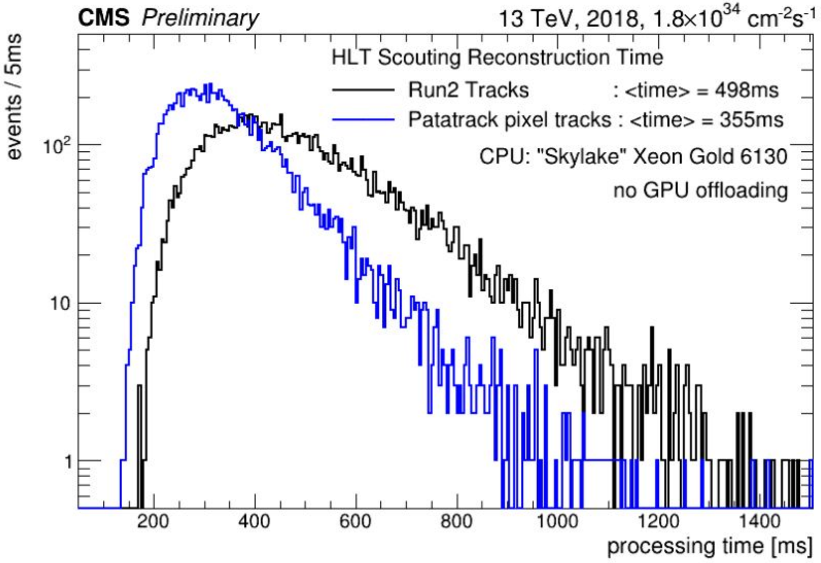
- Out-of-time signals flagging: odd filter can be used to identify out-of-time signals, but this information is not used to zero the strip. Instead the normal even amplitude is output from the TCP along with an info bit to signal that there is some out-of-time energy in the tower



High Level Trigger: Run 3 developments

PF scouting reconstruction time:

a comparison of the time it takes to reconstruct scouting objects for different track reconstruction algorithms used by the PF algorithm at the HLT



Overview of the trigger developments for Run 3

B physics

- Double-EG seeds for **B parking analyses** like **R(K) and R(K*)**
- New Double-muon seeds for **$B_s \to \mu\mu$**
- Triple-muon seeds for the **$\tau \to 3\mu$** search

EXO searches

- Double-EG seeds for **low mass diphoton search**
- ISR-originated MET + jet L1 seeds for **disappearing tracks**
- *MET + lepton cross triggers*

Long-lived particles

- **Displaced muons** triggers
- Hadronic shower triggers for **displaced jets**
- HCAL depth & timing triggers for **displaced jets**
- *Displaced $\tau_h\tau_h$ and displaced soft leptons*
- *Delayed jets (ECAL timing at HLT)*

Higgs physics

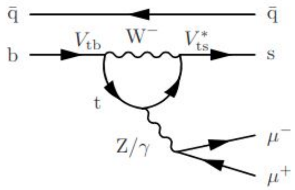
- Double τ + 1 jet for **$H \to \tau\tau$ and $HH \to bb\tau\tau$**
- VBF + τ triggers for **$H \to \tau\tau$**
- *Multijet + btag triggers for **resolved & boosted HH → 4b***

Low threshold Single Tau
Monitoring Path

New physics opportunities with Parking data

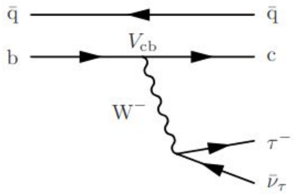
LFU tests

FCNC $R = \dfrac{\mathscr{B}(b \to s\mu^+\mu^-)}{\mathscr{B}(b \to se^+e^-)}$



- R(K)
- R(K*)
- R(ϕ)
- R(Λ_b)

FCCC $R = \dfrac{\mathscr{B}(b \to c\tau\nu_\tau)}{\mathscr{B}(b \to c\mu\nu_\mu)}$



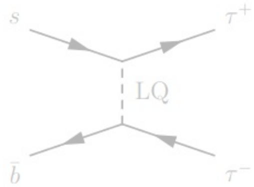
- R(D*)
- R(D)

Direct LFV tests

- B → μτ, μe;
- B → ϕτμ
- B → Kτμ
- Using charm decays
- …

Br measurements

- Bs → ττ
- Bs → ϕττ
- Bs → Kττ
- …



Other topics

- Fragmentation function ratio measurements (fs/fu, fs/fd, fd/fu)
- CPV measurement using D-mesons
- Exotic searches (e.g. QCD inflatons, Heavy neutrino searches using Ds mesons)
- τ → ϕK
- LLP searches

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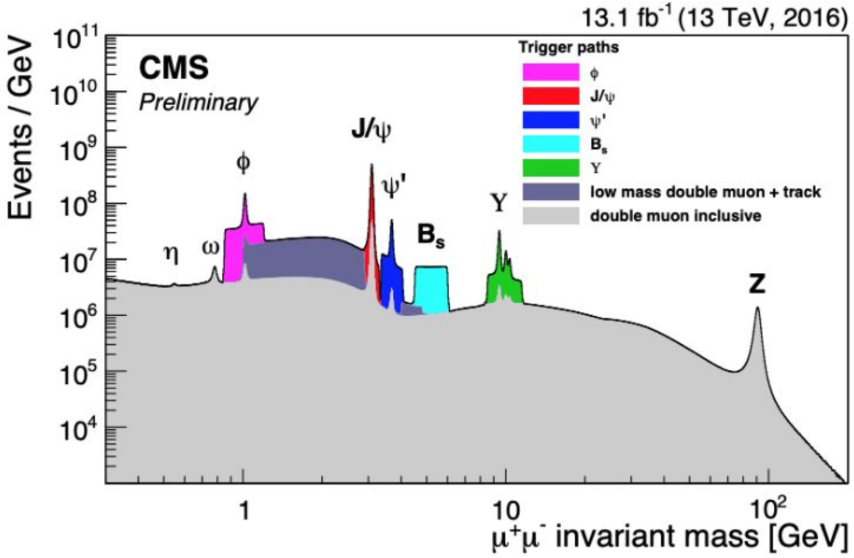
B physics program in CMS

- Key point: Unlike LHCb, we operate our detector at **high instantaneous luminosity** and a lot of trigger bandwidths have been allocated to high-p_T physics programs (e.g. Higgs, BSM searches)
- We need to do B-physics measurements with the final state that is easy to trigger (i.e. low rate) enough to fit the overall trigger budget → final states including μμ (~10Hz out of total 1kHz trigger budget



2018 rates

* [Run 321283 in OMS, LS48-52 (2e34)]

The baseline Run 3 menu is a ~perfect* copy of the latest 2018 menu

Goal for Run 3:

increase the trigger efficiency for some specific physics cases without increasing the total rate notably (< 100 kHz!) AND keep the thresholds of the most utilised (by PAGs) L1 seeds unchanged

L1 algo	Indicative rate at 2e34 (WBM) [Hz]
L1_SingleMu22	8405
L1_SingleMuOpen_er1p1_NotBptxOR_3BX	86
L1_DoubleMu0er1p5_SQ_OS_dR_Max1p4	3701
L1_DoubleMu4_SQ_OS_dR_Max1p2	3686
L1_DoubleMu4p5er2p0_SQ_OS_Mass7to18	1954
L1_DoubleMu9_SQ	654
L1_DoubleMu_15_5_SQ	1004
L1_DoubleMu_15_7	619
L1_TripleMu3_SQ	1614
L1_TripleMu_5SQ_3SQ_0OQ_DoubleMu_5_3_SQ_OS_Mass_Max9	1155
L1_TripleMu_5_3_3	1734
L1_TripleMu_5_3p5_2p5_DoubleMu_5_2p5_OS_Mass_5to17	997
L1_SingleEG36er2p5	15822
L1_SingleIsoEG28er2p5	22732
L1_IsoEG32er2p5_Mt40	15256
L1_DoubleEG_25_12_er2p5	5496
L1_DoubleEG_LooseIso22_12_er2p5	5668
L1_TripleEG_18_17_8_er2p5	939
L1_SingleTau120er2p1	2789
L1_DoubleIsoTau32er2p1	16078
L1_DoubleTau70er2p1	2499
L1_SingleJet180	3313
L1_SingleJet43er2p5_NotBptxOR_3BX	754
L1_DoubleJet112er2p3_dEta_Max1p6	2793

L1_DoubleJet_110_35_DoubleJet35_Mass_Min620	4203
L1_TripleJet_95_75_65_DoubleJet_75_65_er2p5	3277
L1_ETMHF100	4032
L1_ETMHF100_HTT60er	3695
L1_HTT360er	4303
L1_DoubleMu3_OS_DoubleEG7p5Upsilon	366
L1_DoubleMu3_SQ_ETMHF50_Jet60er2p5	578
L1_DoubleMu3_SQ_ETMHF50_Jet60er2p5_OR_DoubleJet40er2p5	801
L1_DoubleMu3_SQ_HTT220er	385
L1_DoubleMu5Upsilon_OS_DoubleEG3	533
L1_DoubleMu5_SQ_EG9er2p5	1388
L1_Mu12er2p3_Jet40er2p3_dR_Max0p4_DoubleJet40er2p3_dEta_Max1p6	1351
L1_Mu18er2p1_Tau24er2p1	4008
L1_Mu20_EG10er2p5	1589
L1_Mu3er1p5_Jet100er2p5_ETMHF40	1601
L1_Mu6_DoubleEG17er2p5	122
L1_Mu6_HTT240er	1351
L1_Mu7_EG23er2p5	1233
L1_Mu7_LooseIsoEG20er2p5	1237
L1_DoubleEG8er2p5_HTT300er	1668
L1_LooseIsoEG22er2p1_IsoTau26er2p1_dR_Min0p3	6189
L1_LooseIsoEG26er2p1_HTT100er	14689
L1_LooseIsoEG28er2p1_Jet34er2p5_dR_Min0p3	12775
L1_IsoTau40er2p1_ETMHF90	4068
L1_HTT320er_QuadJet_70_55_40_40_er2p4	2623