LEVEL-1 TRIGGER AND SCOUTING WITH PHASE-2 UPGRADED CMS DETECTOR FOR HL-LHC

On Behalf of CMS Collaboration

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THE 2025 INTERNATIONAL WORKSHOP ON THE HIGH ENERGY CIRCULAR ELECTRON POSITRON COLLIDER
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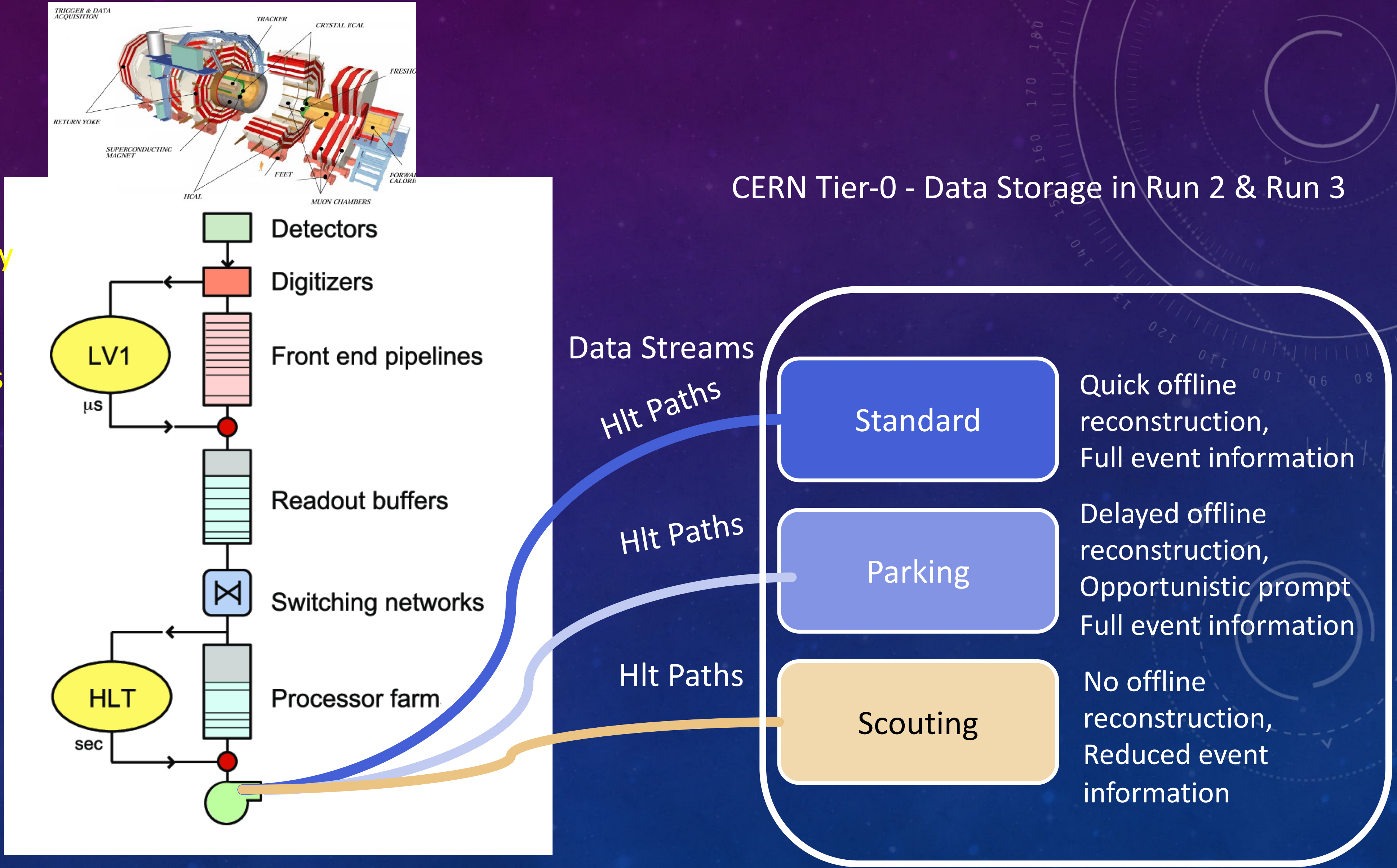
CMS – TWO LEVEL TRIGGERING SYSTEM

Real time event selection

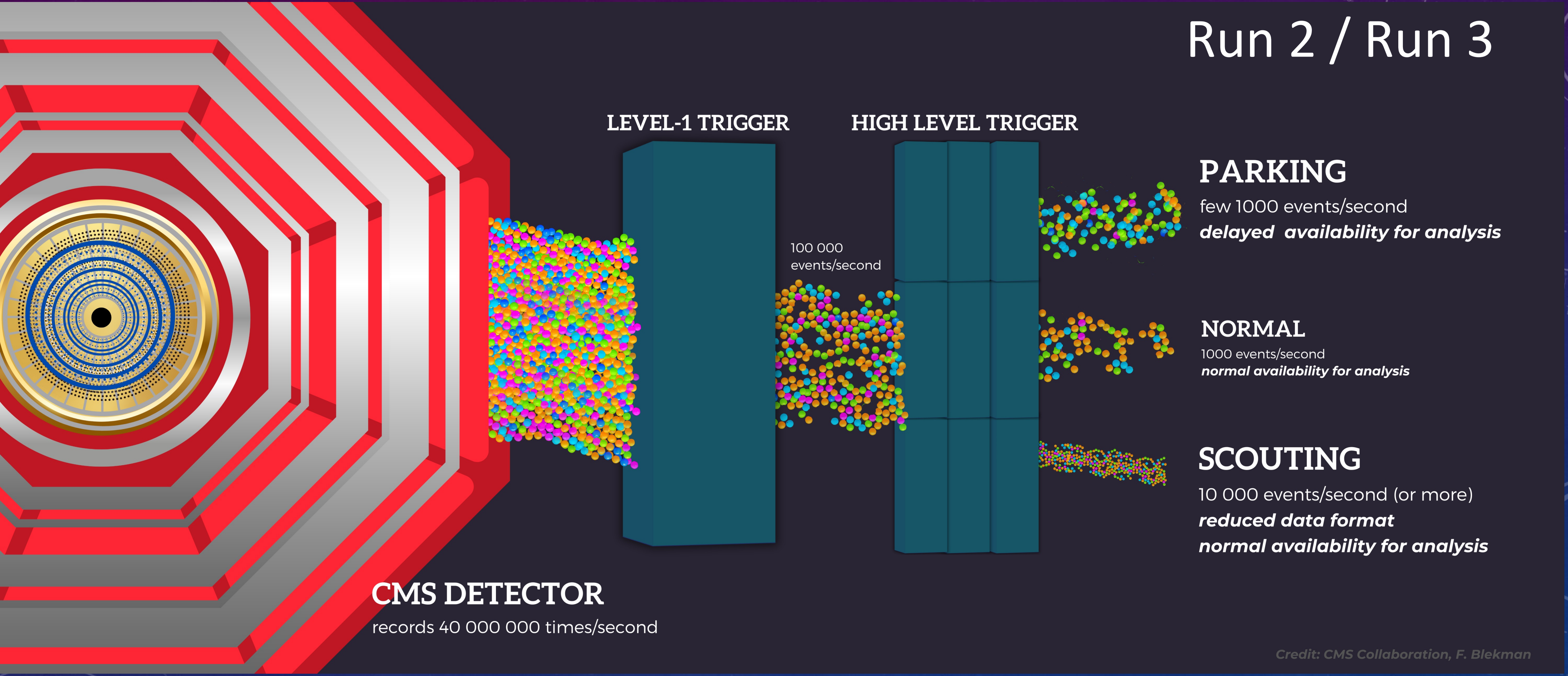
L1Trigger
custom electronics
- only muon and calorimetry
- coarse granularity
- synchronize RO
- initital selection/compress
- Latency 4 µs

High Level Trigger
software-based (CPU/GPU)
- entire detector
- full granularity
- complex reconstruction and selection
- Asyncronous
- Latency 100 ms

CERN Tier-0 - Data Storage in Run 2 & Run 3



CMS TRIGGER STRATEGY – SQUEEZE OUT PHYSICS FROM DETECTOR

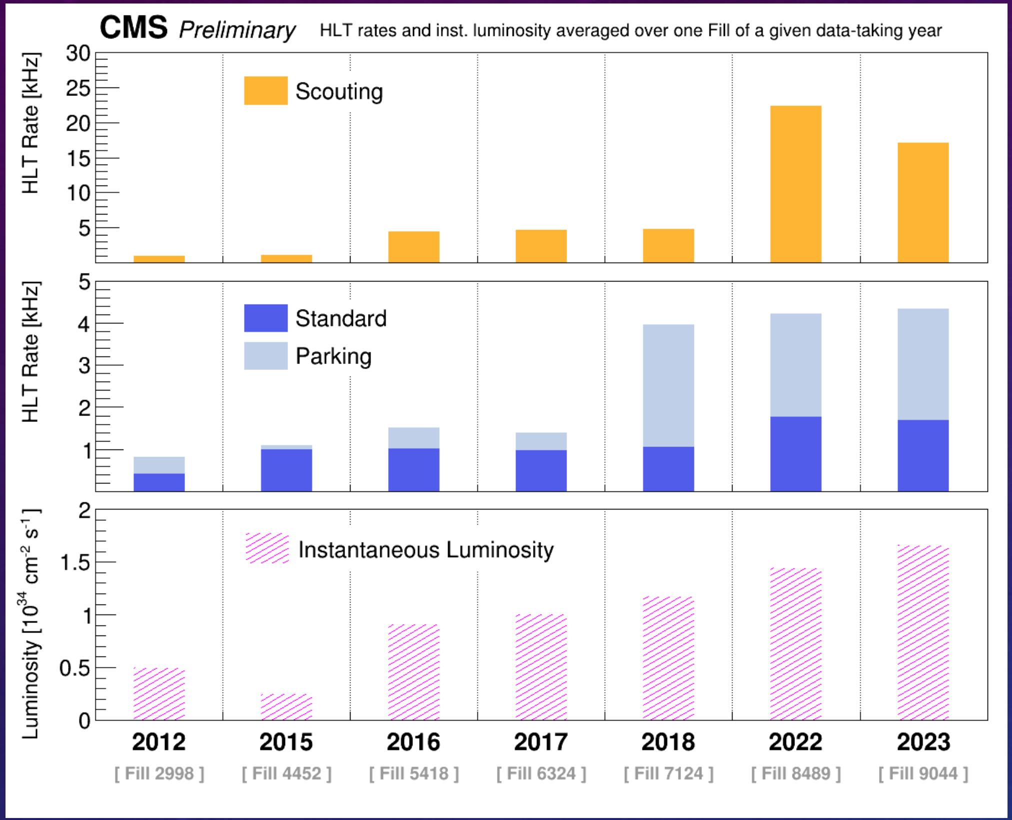


DATA TAKING IN RETROSPECT

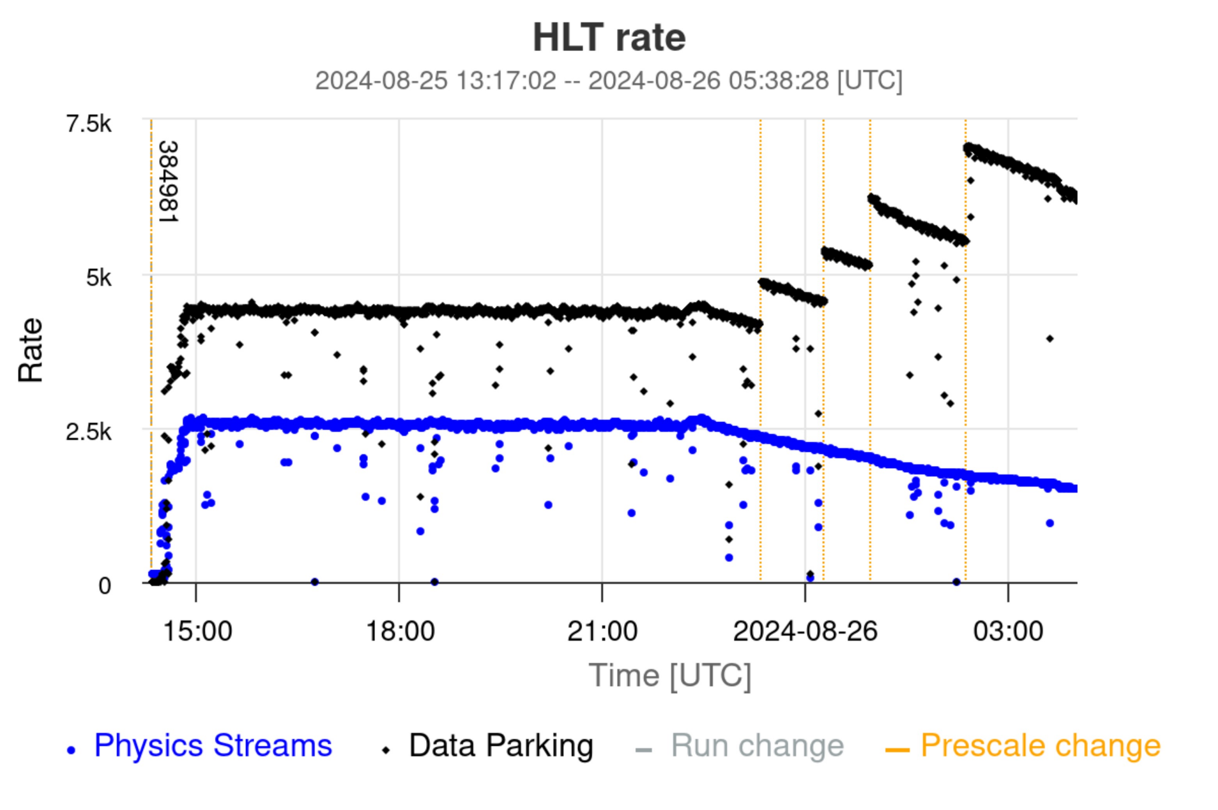
CMS Data STREAM Rates - Historical and Single run example

2012-2023

CMS DP -2024/012



2024



The standard Physics stream follows the luminosity profile, while the Data Parking stream shows the strategy of optimizing the output bandwidth

IMPROVEMENTS IN TECHNOLOGY – NEW PHYSICS OPORTUNITY

HLT Example:

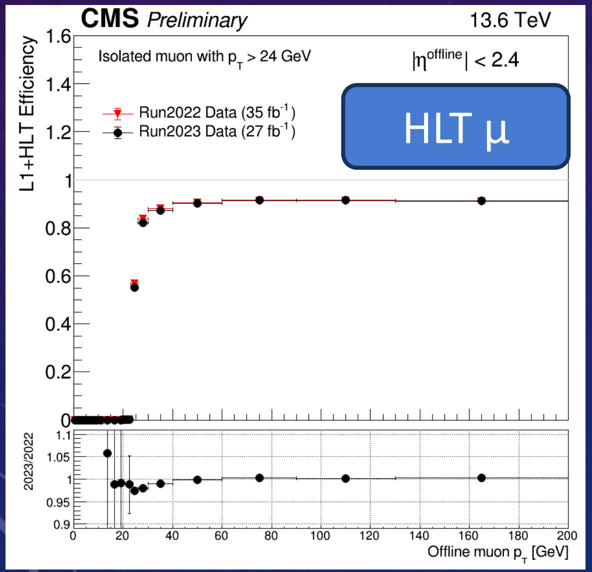
- New technology (heterogeneous resources) CPUs + GPUs increase **compute power** in HLT
  - Comes with a cost: GPUs require re-writing of HLT code and API (Alpaka)
    - Pixel, HCAL ECAL and Particle Flow reconstruction run on GPUs
- More **compute power** allowed CMS to:
  - develop more accurate object reconstruction in HLT
  - improved resolution -> **lower rates** and higher efficiency
- **Lower rates** -> use freed bandwidth to extend the physics program
  - But also frees resources to run **HLT Scouting** paths at much higher rate than Run 2

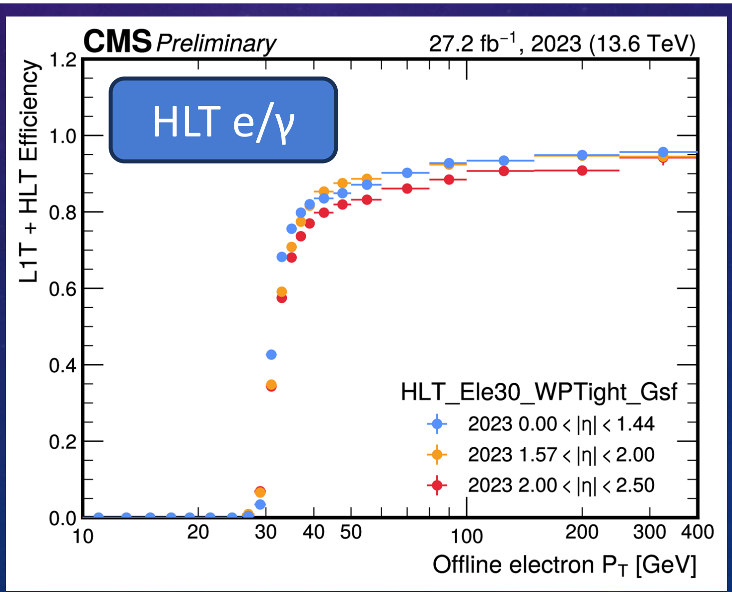
HLT STREAM: Standard

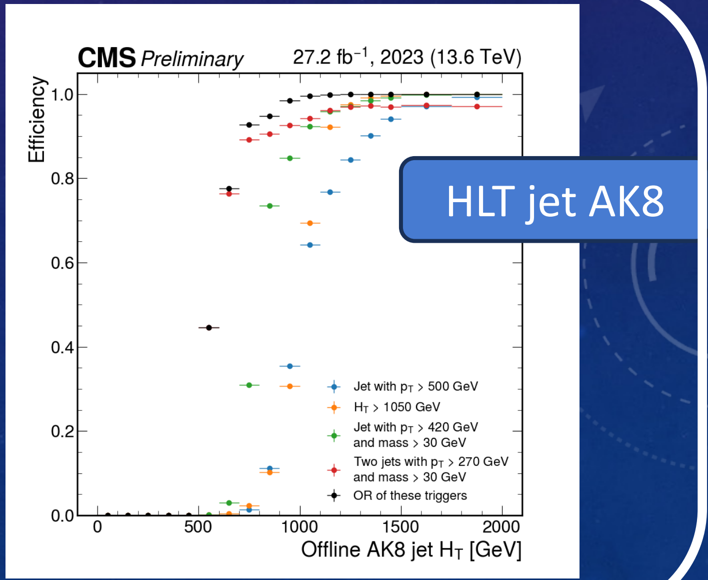
Quick offline reconstruction, full event information

- Most of HLT paths (hundreds)
- Collect data for a wide range of CMS needs (Physics program + Alignment and Calibration)
- Physics program
  - **Generic HLT paths** covering multiple physics analysis needs (broadly used, well studied, high efficiency)
  - Dedicated HLT paths for particular physics analysis that require special requirements for sufficient stats
  - Dedicated HTL paths to catch anomalies to the known physics signatures

Generic Paths





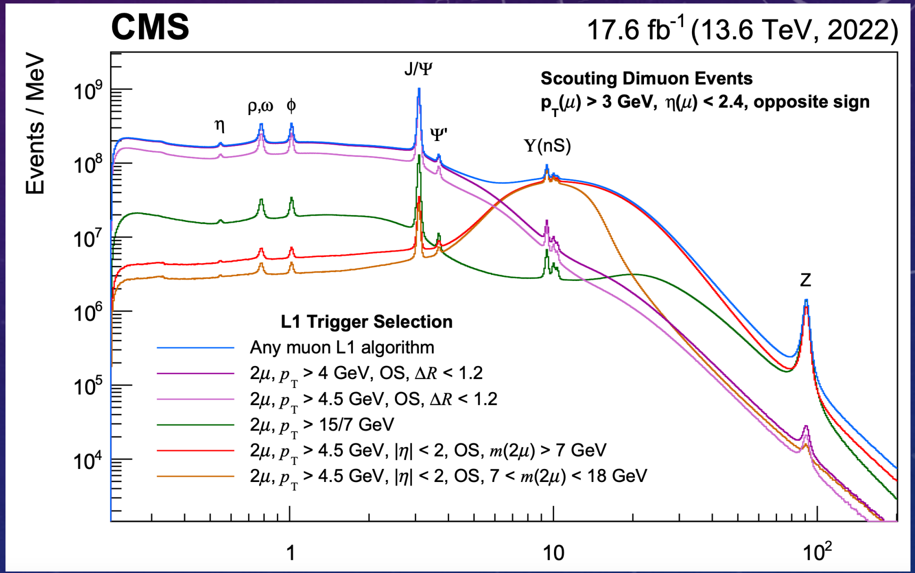


HLT STREAM: Scouting

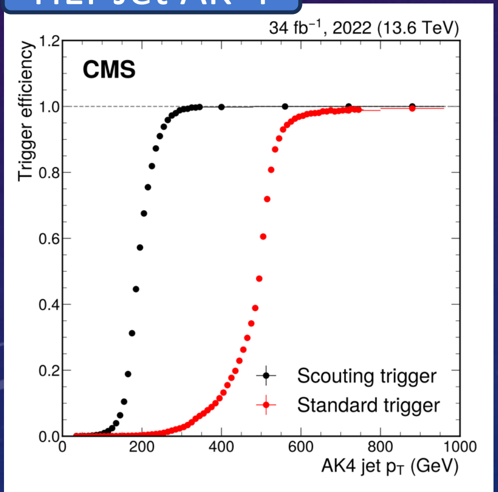
No offline reconstruction, Reduced event information

Scouting path	CPU-only [ms]	CPU+GPU [ms]
1 electron/photon	76.0	49.5
≥2 electrons/photons	9.3	6.8
≥2 muons	69.0	41.6
Jets or MET	83.3	52.1
Full HLT menu	578.4	377.7

- Improvements in HLT reconstruction (use of GPUs) allowed for improved Scouting strategy in Run3
  - PF algorithm w/ tracker tracks built solely with pixel hits
  - offloaded to GPUs only slightly worse resolution for low-pT (Scouting)
  - Run 3 scouting rate > 20 kHz
- Essential in searches for
  - very low-mass resonances
  - Long lived particle s (with LLP decaying to muons, ex. Dark photon).
  - B-physics analyses (first observation of η meson -> 4 μ)



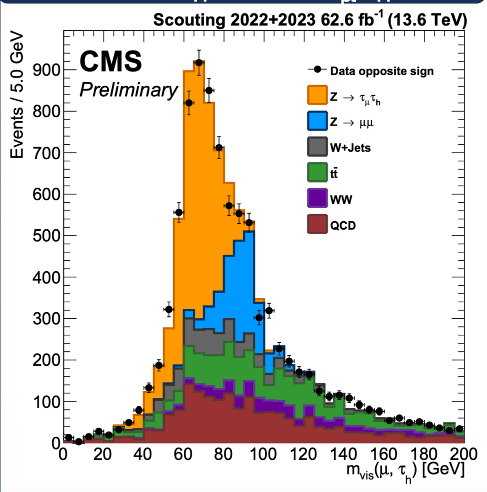
HLT Jet AK-4



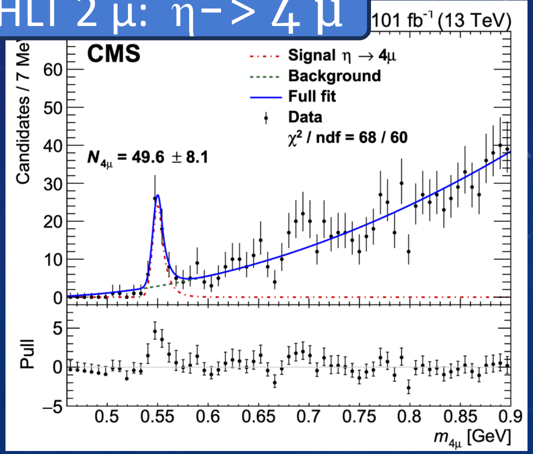
Much lower hadronic trigger thresholds than standard strategy relying on offline reconstructed data

Scouting HLT Jet p_T > **180 GeV**
Main stream HLT Jet p_T > **500 GeV**

HLT τ_h: $Z \rightarrow \tau_\mu \tau_h$



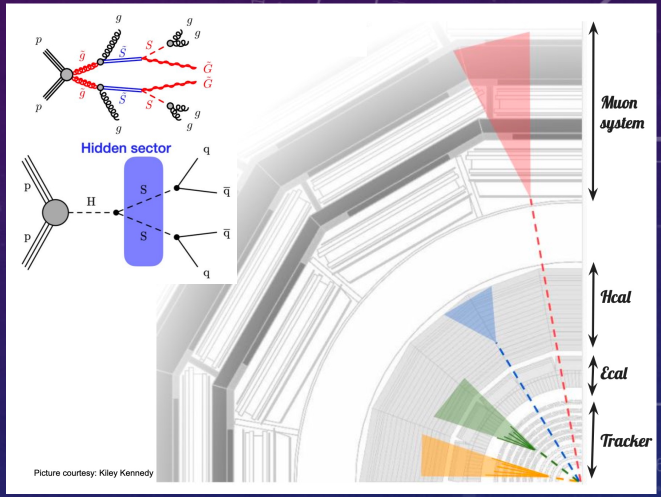
HLT 2 μ: η-> 4 μ



TRIGGERING ON LONG-LIVED-PARTICLES (LLP)

- Run 3 – look for new physics. Eg. LLP.

- Several **displaced-jet HLT triggers** to capture various detector signatures, depending of LLP's lifetime (decay length).

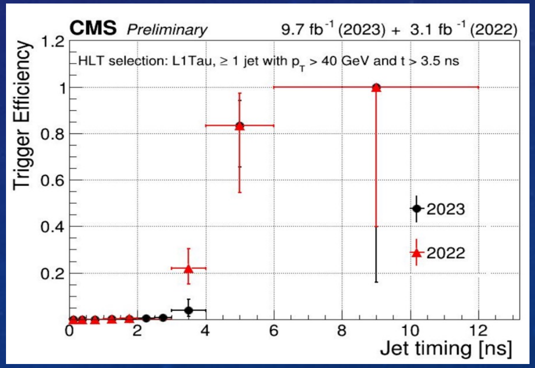


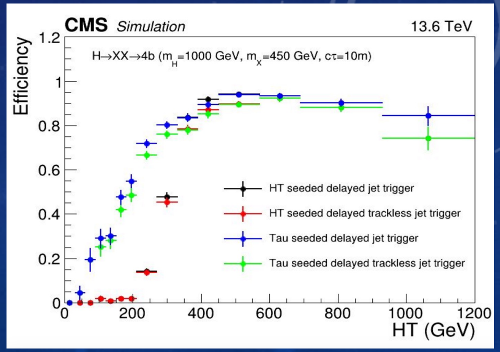
- Tracker-based – Reconstruct objects with **non-prompt tracker-tracks**
  seed L1 H_T > 450 GeV (or Use L1 H_T > 240 GeV + μ)
  HLT jets reconstructed with displaced tracks (prompt veto) Run3 result limits public EXO-23-013

- ECAL-based - Exploit timing of **ECAL that measures arrival within ~200 ps**
  seed L1 HT>430 GeV or (L1 Tau pT>120 GeV and HT>360 GeV)
  HLT jets (nominal track match to ECAL, or ECAL only) w/ timing > 2 ns

- HCAL-based

- Muon system-based



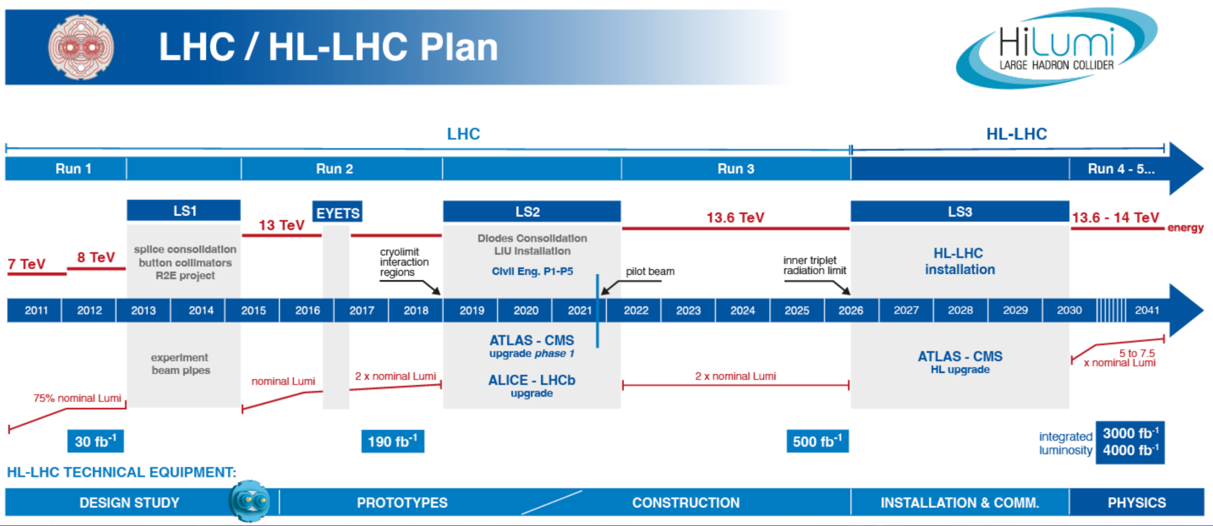


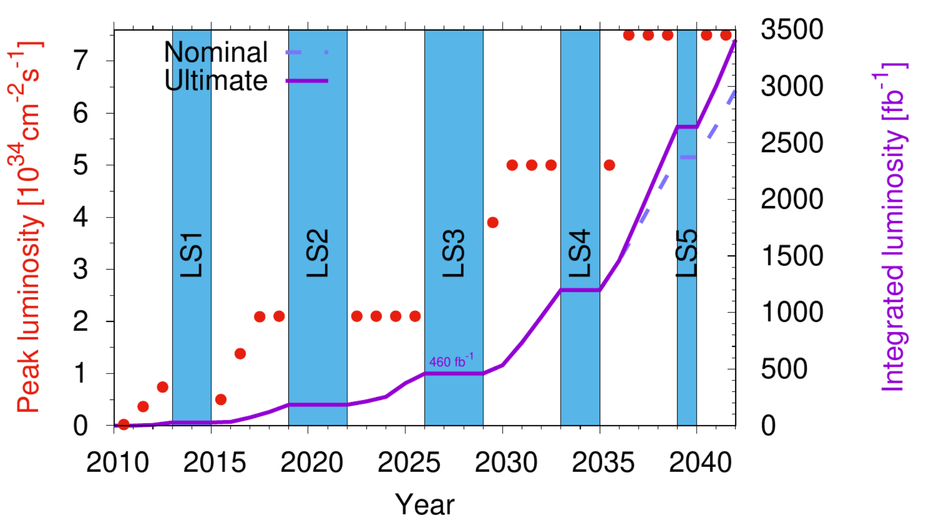
HL-LHC

The Phase II (HL-LHC) project established in 2010

- Inst Luminosity up to 7.5e34 (updated projection for Integrated 4000 fb-1)
- Energy: 14 TeV or more (discussion ongoing on availability of the machine)
- Filling schemes considered: similar to previous experience (8b4e, 48b etc.)

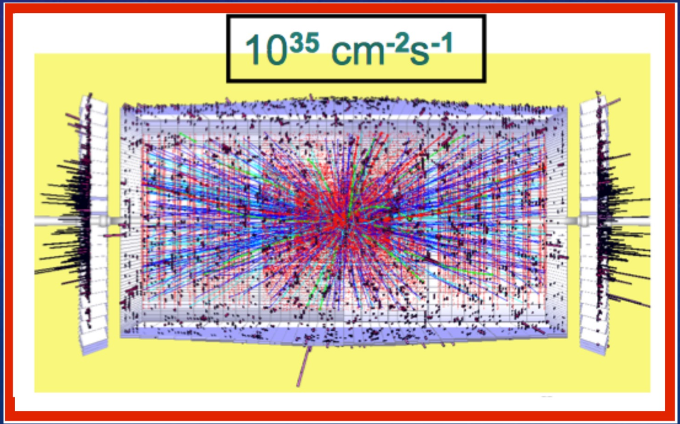
Updated schedule with LS3 starting in June





p-p collisions in HL-LHC

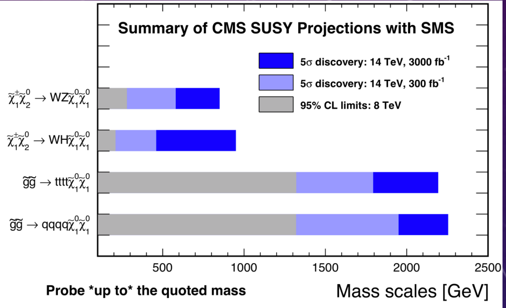
- Interaction region with Gaussian spread 45 mm along beam axis
- Average number of collisions : <μ> 200 (PILEUP)
  - Average interaction density: 1.8 collisions/mm



Major challenge for tracking detectors in ATLAS & CMS

- Efficiently reconstruct charged particles from primary interactions -> up to 0(10k) tracks / bunch crossing
  - Correctly assign them to production vertices

REASONS FOR HL-LHC



Significantly extend the physics program with HL-LHC (10x data of LHC)

- SM Precision measurement: Higgs, PDFs, QCD

- New Physics: DM, SUSY, BSM, extra dim.
- Become more sensitive to BSM signatures
  - Displaced-objects,
    Disappearing tracks,
    Emerging jets, HSCP, …

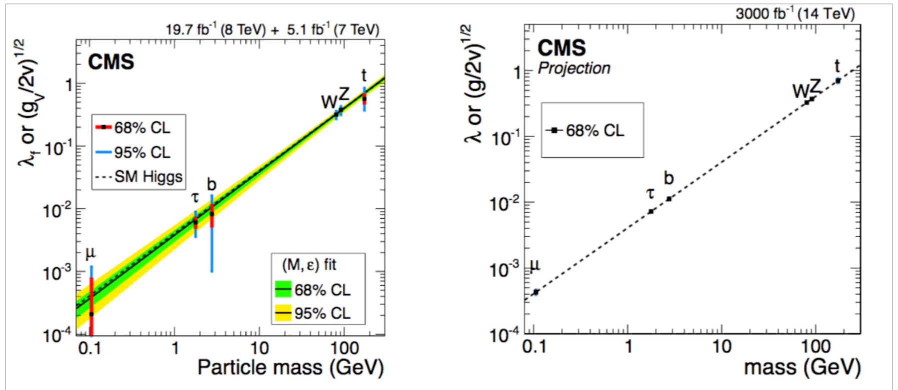
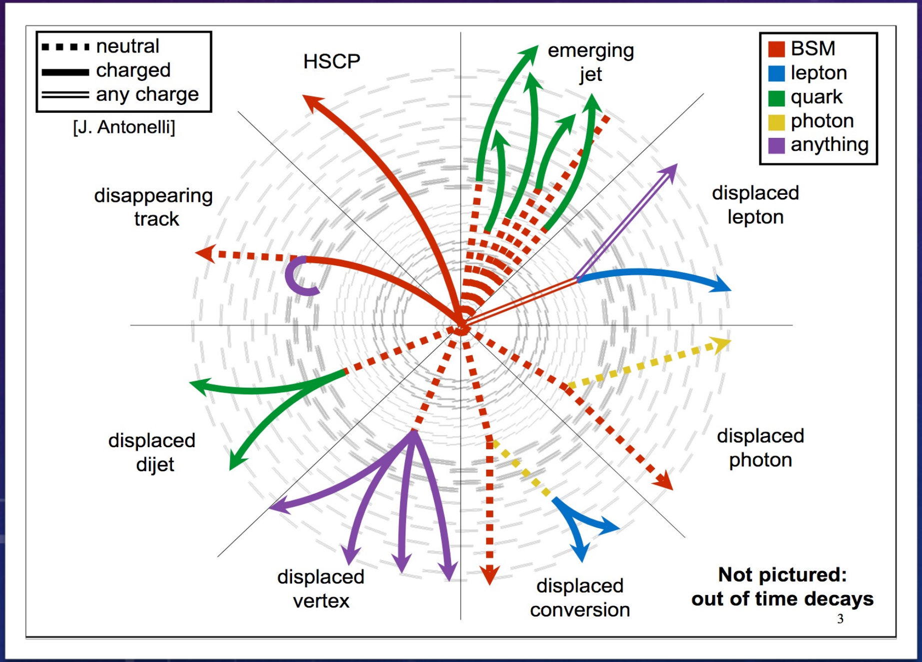


Figure 1.10: Observed and projected precision on Higgs boson couplings as a function of boson or fermion masses.

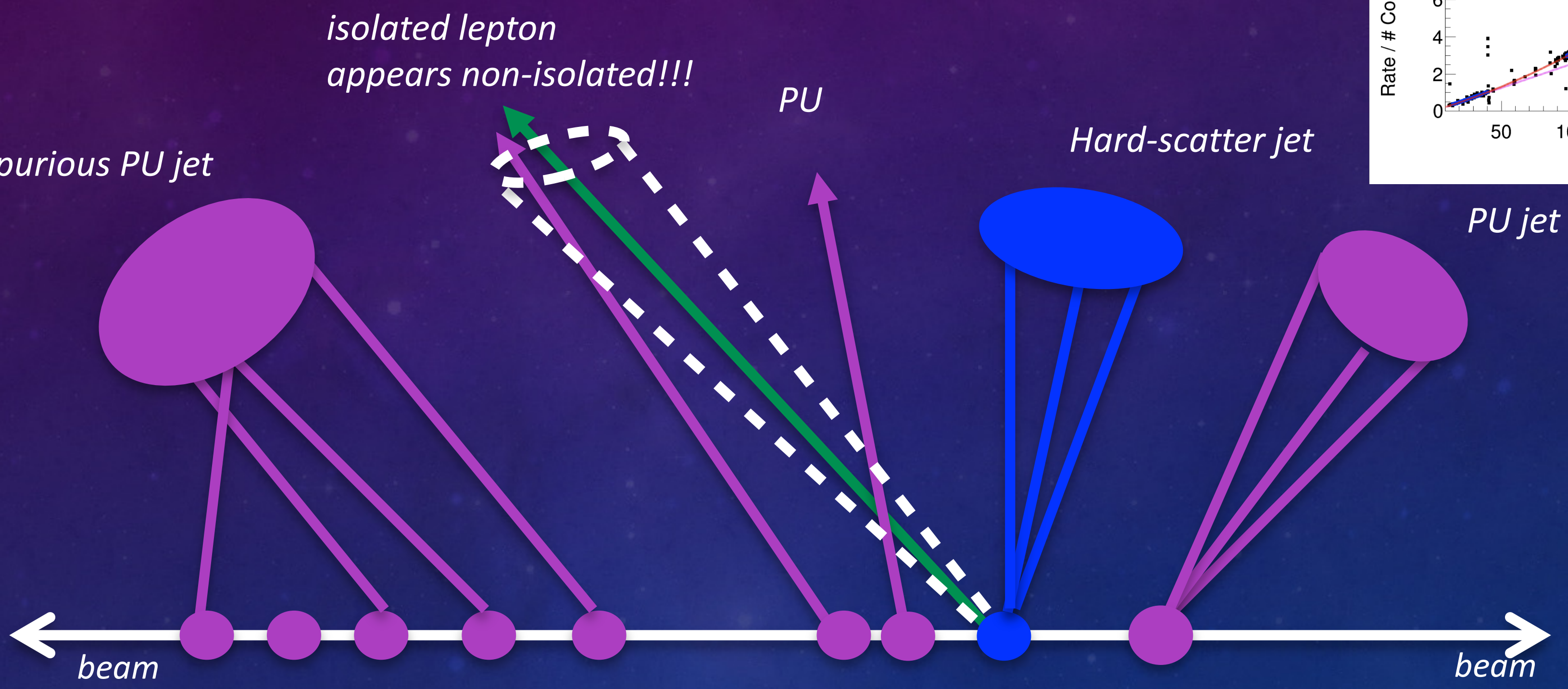


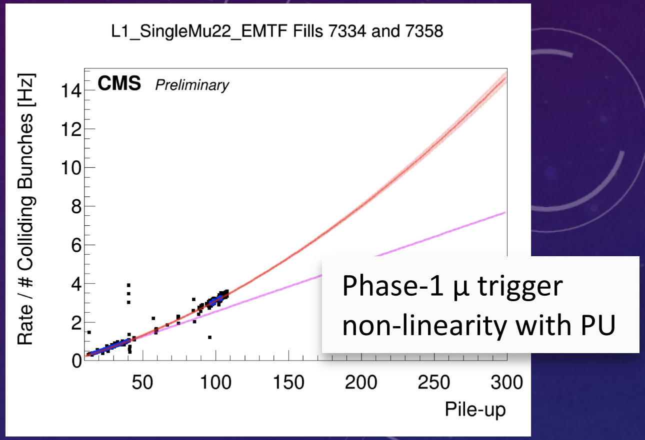
HL-LHC is major challenge for tracking detectors in HL-LHC experiments, CMS

- Efficiently reconstruct charged particles from primary interactions
  - Correctly assign them to production vertices
  - Need upgraded detectors for Phase-2.

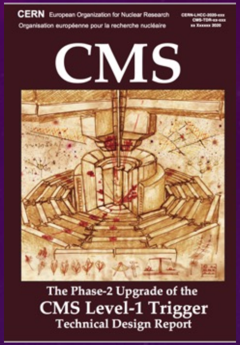
HL-LHC MAIN CHALLENGE - EFFECTS OF PU

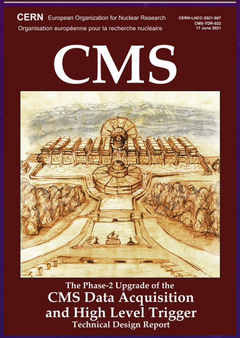
- **Pile-up makes object reconstruction non-trivial**
  - **worsens energy and pt resolution → diverging trigger rates**





THE CMS PHASE 2 UPGRADE





-Trigger , HLT/DAQ CMS-TDR-021 CMS-TDR-022

- Tracks in L1-Trigger at 40 MHz
- PFlow selection 750 kHz L1 output
- HLT output 7.5 kHz
- 40 MHz data scouting

Beam Instr. & Lumi CMS-TDR-023

- Bunch-by-bunch luminosity measure
  1% offline, 2% online

Barrel ECAL CMS-TDR-015

- ECAL crystal granularity readout at 40 MHz
  with precise timing for e/γ at 30 GeV
- ECAL and HCAL new Back-End boards

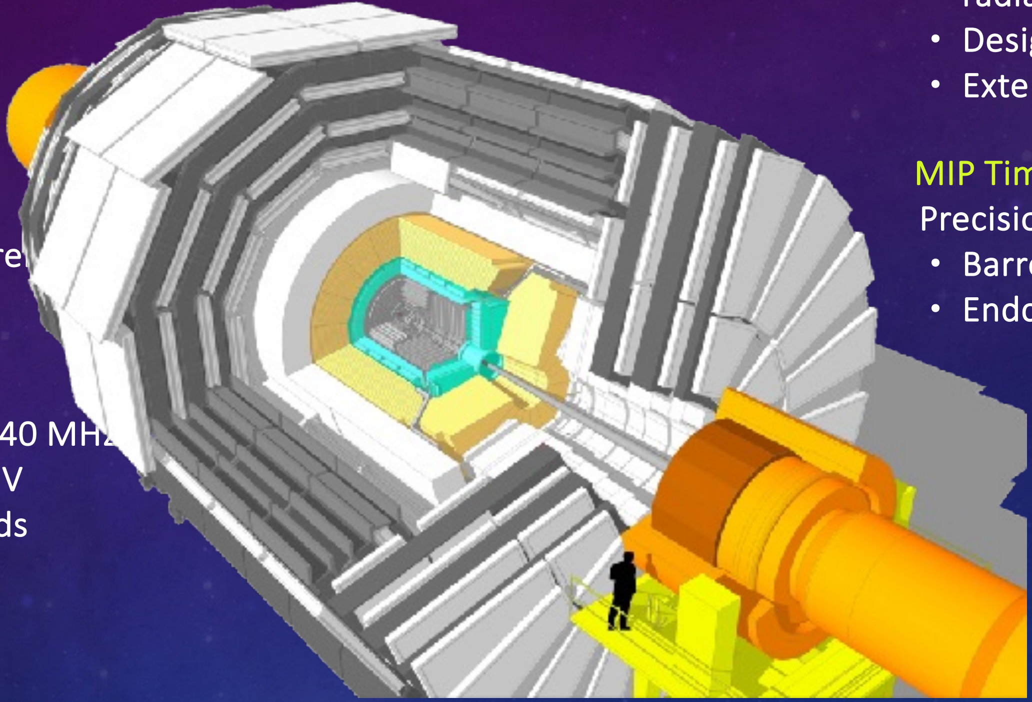
Muon ystems CMS-TDR-016

- DT & CSC new FE/BE readout
- RPC back-end electronics
- New GEM/RPC $1.6 < \eta < 2.4$
- Extended coverage to $\eta \simeq 3$

Ca

EndCap ECAL yste CMS-TDR-019

- 3D showers and precise timing
- Si, Scint+SiPM in Pb/W-SS



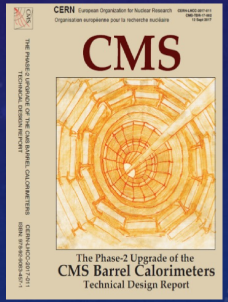
Tracker. CMS-TDR-014

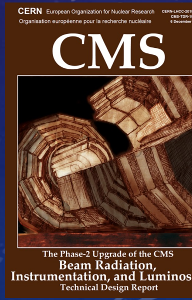
- Si-Strip and Pixels increased granularity
- lightweight carbon-fiber mechanics with two-phase CO cooling
- small pixels (25 × 100 μm2), and fast, radiation-hard ASIC CMOS 65 nm
- Design for tracking in L1-Trigger
- Extended coverage to $\eta \simeq 4.0$

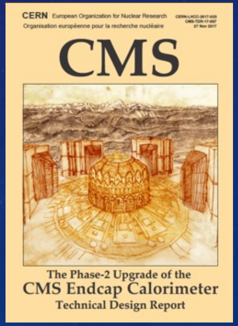
MIP Timing Detector. CMS-TDR-020

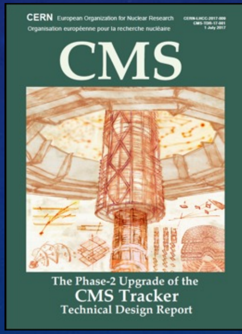
Precision timing with:

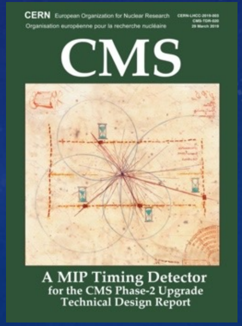
- Barrel layer: Crystals + SiPMs
- Endcap layer: LGADs

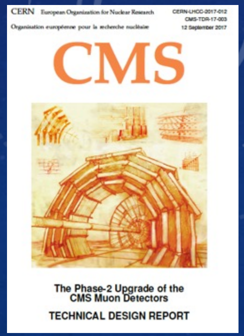












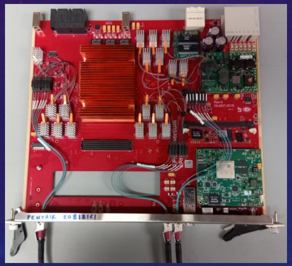
LEVEL-1 TRIGGER PHASE-2 UPGRADE STRATEGY

- Exploit upgraded detector (higher resolution, acceptance, readout, DAQ)
  - high speed optical links between FE and BE
  - allowed increased latency budget 12.5 µs , output bandwidth 750 kHz
- Take advantage of new available technology:
  - high seed optical links (25 Gbps), ATCA w/ Ultrascale FPGAs (VU13P)
- Bring ~ full detector information to custom electronics
  - Exceptions IT, OT for pt<2 GeV (RO limited), MTD
- Move significant part of object reconstruction from HLT upstream to L1T
  - Extensive ML-based algorithms to improve object reconstruction, isolation, identification, selection

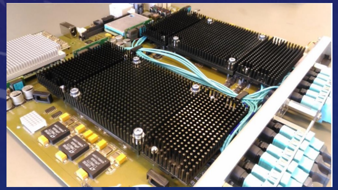
~1200 ATCA BE boards (130 crates) needed to receive FE data from ~50 000 links

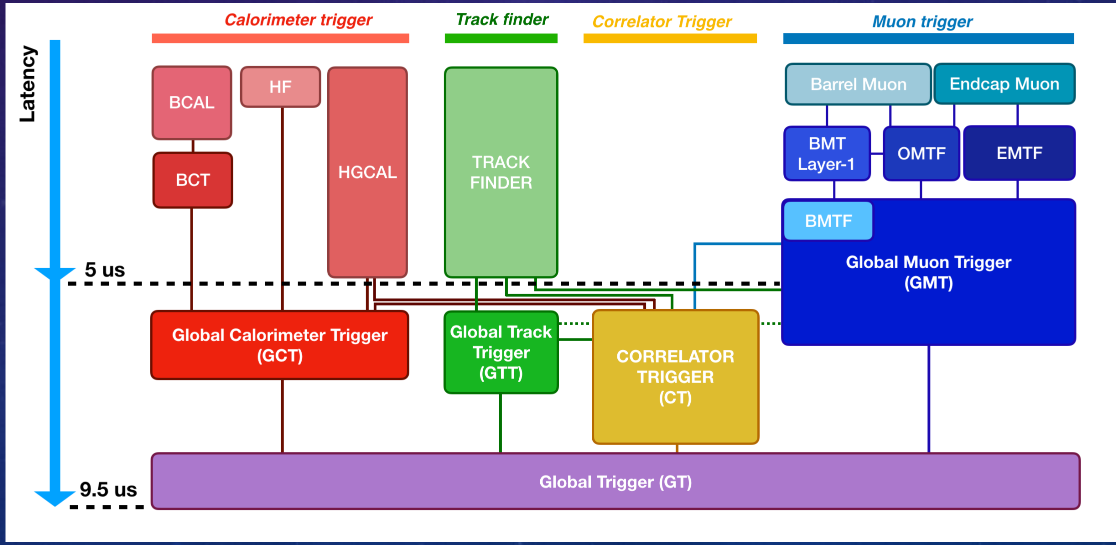
CMS detector	LHC Run-2	HL-LHC Phase-2	
Peak ⟨PU⟩	60	140	200
L1 accept rate (maximum)	100 kHz	500 kHz	750 kHz
Event Size	2.0 MB [a]	5.7 MB [b]	7.4 MB
Event Network throughput	1.6 Tb/s	23 Tb/s	44 Tb/s
Event Network buffer (60 seconds)	12 TB	171 TB	333 TB
HLT accept rate	1 kHz	5 kHz	7.5 kHz
HLT computing power [c]	0.5 MHS06	4.5 MHS06	9.2 MHS06
Storage throughput	2.5 GB/s	31 GB/s	61 GB/s
Storage capacity needed (1 day)	0.2 PB	2.7 PB	5.3 PB

APx

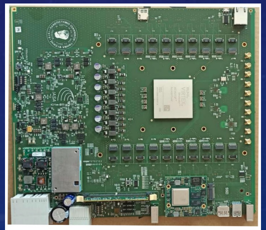


Serenity





BMTL1



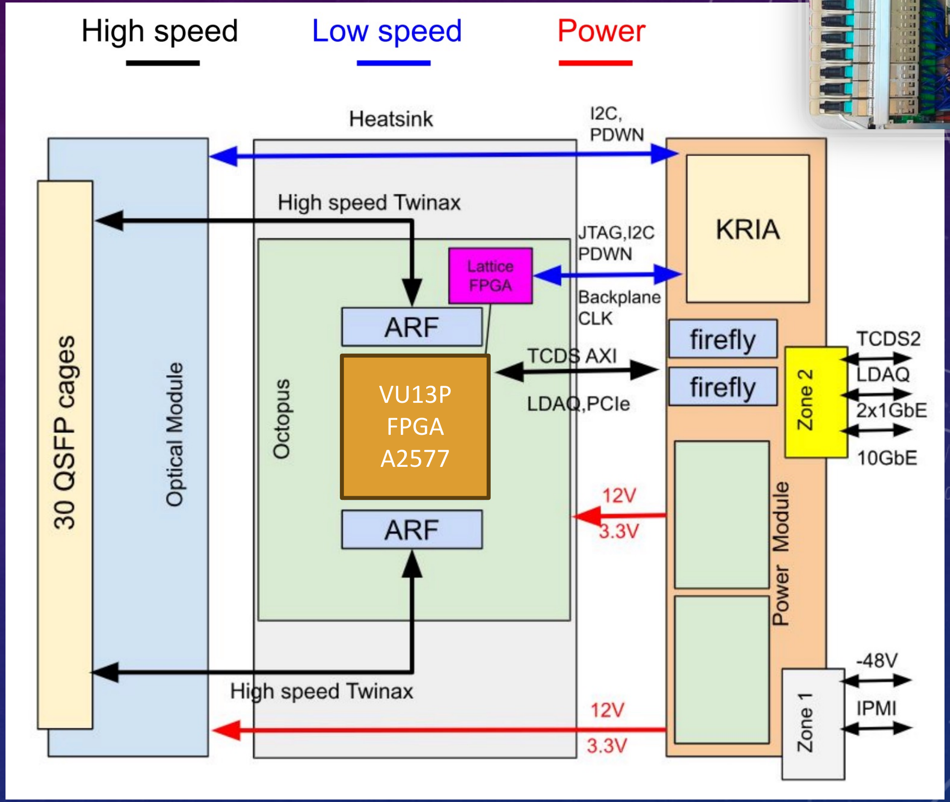
~ 250 ATCA cards in 4 flavours

X20

P2 L1T BOARD EXAMPLE - X2O, MODULAR PCB DESIGN

<u>Power Module</u>

- ATCA power bricks
- Kria control module powered by service power
  - 2x GbE to backplane
  - 1x 10GbE to backplane
  - 2x AXI connections to FPGA
  - 1 PCIe to FPGA
  - Linux filesystem on µSD 3.0 card
  - Integrated IPMC
  - UART
- Two firefly high speed cable connectors
  - TCDS2, 2x AXI, LDAQ , PCIe
- Three low speed connectors
  - JTAG, I2C,3.3V service power, emergency shutdown, backplane clock to FPGA
  - 1x I2C,3.3V service power, emergency shutdown to optical module
- One generic I/O header
  - 8 pins



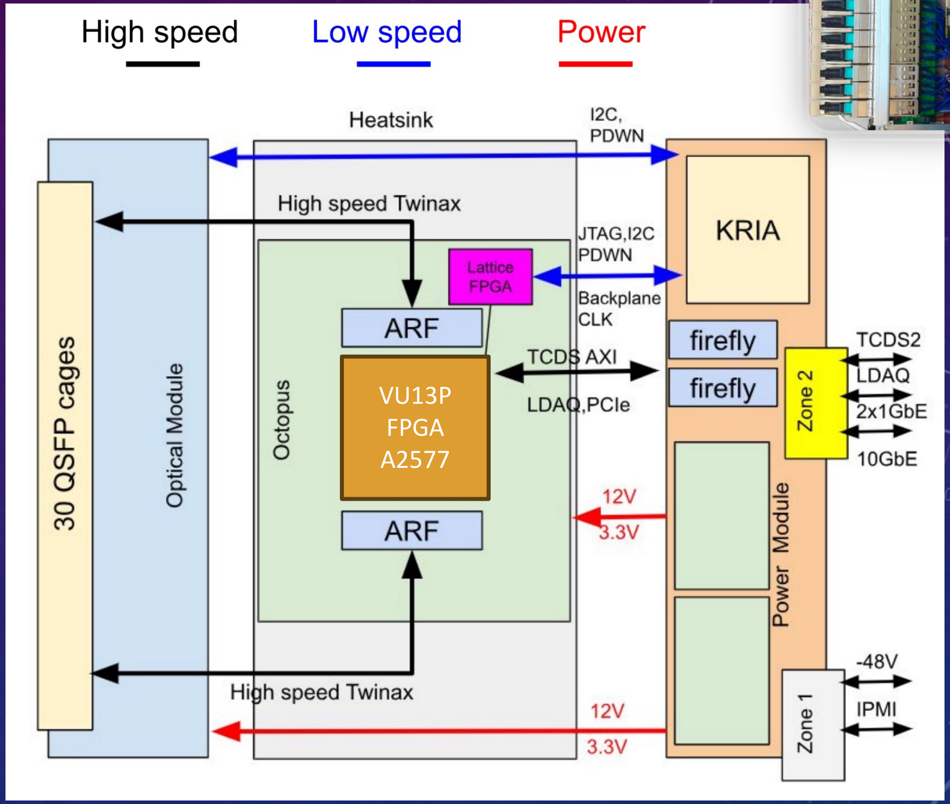
<u>Optical Module</u>

- Power and I2C
- 30 QSFP cages connected to cables with Samtec F-QSFP technology

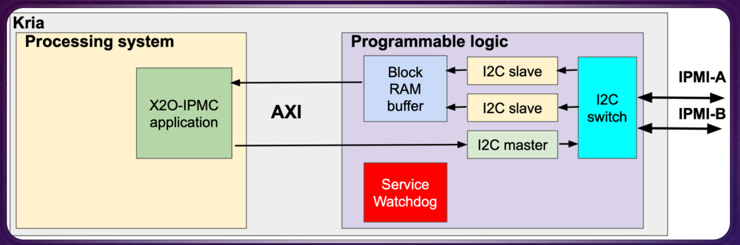
P2 L1T BOARD EXAMPLE - X2O, MODULAR PCB DESIGN

FPGA Module

- 14 layer HDI stackup
- VU13P FPGA-lidless A2577
- 16x Samtec Accelerate connectors to copper cables <56Gb/s
  - Connected to all 128 GTY transceivers
- 300A core power
- Phased GT VCC/VTT power supplies
- 32 fixed asynchronous GT clocks
- 16 output LMK5C33216 jitter cleaner for synchronous clocks
- Lattice MachXO2 service FPGA
  - Level shifter, I2C slave and masters, emergency shutdown system
  - Board seen as an I2C device



X2O: MANAGEMENT CONTROL WITH SOM



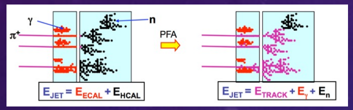
<u>IPMC in Kria SOM</u>

- Integrated solution using both FPGA logic and linux
- Real time signal handling through firmware modules in the FPGA logic
  - I2C slave, masters, arbitration for multi-master systems, glitch filter
  - Operate independently of the SW, no real time SW needed
- Linux application messenger in the processing system
  - Very light (1-3% of CPU)
- Watchdog hard IP checks the state of IPMC application
  - In the case of a crash it shutdowns power and resets the CPU

X2O modules attached to heatsink

L1T PHASE-2 UPGRADE ALGORITHMS AND PERFORMANCE

- Tracker Tracks reconstruced at L1T for pt>2 GeV, up to |η|<2.4
  - Primary Vertex ID of high eff
  - Match to muon tracks and e/γ objects for improved resolution
- Use extended muon coverage and improve muon tracking
- Use higher granularity calorimeter objects
- Particle Flow reconstruction
  - proper ID and separation
  - possible at L1T with tracker and CALO spatial resol.



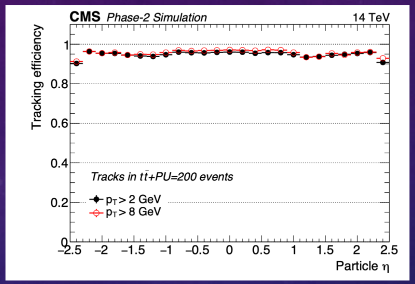
- Pileup subtraction
  - per particle probability of PU-origin
- Reconstruction of prompt and displaced objects
with close-to-offline resolution

⇒ Provides for very high object purity and high signal selection efficien

⇒ Good control of rate (high background rejection efficiency)

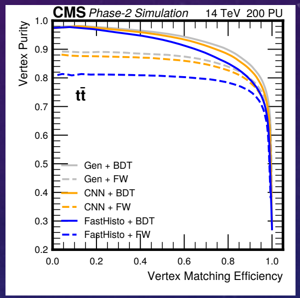
CMS-TDR-014

Track reco eff

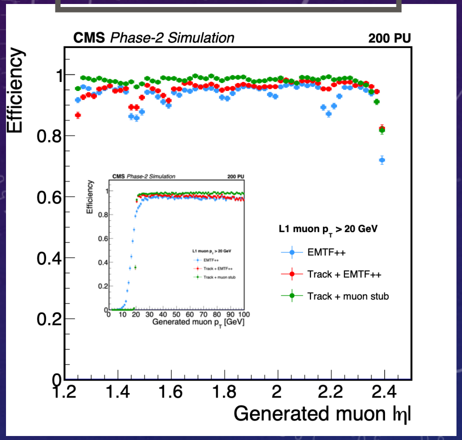


CMS-TDR-021

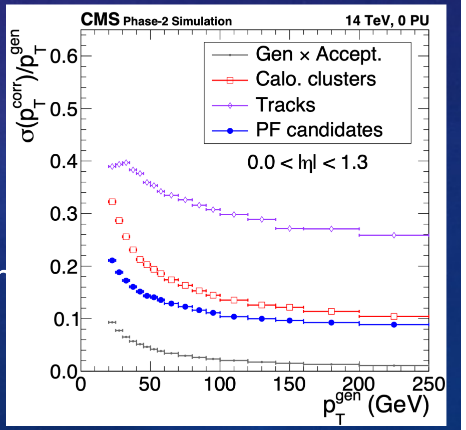
Vtx reco eff



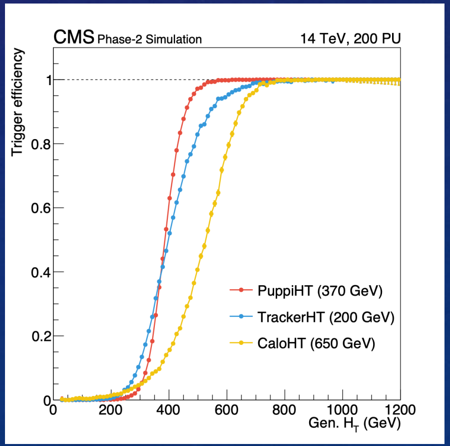
Muon reco eff



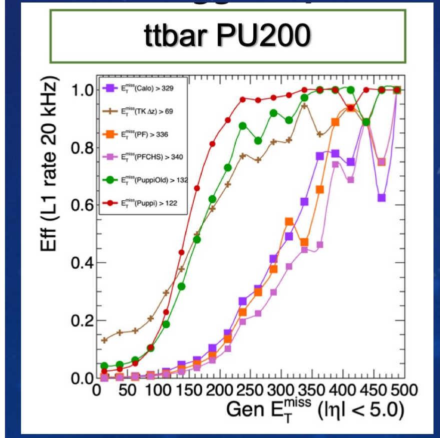
Jet resolution



HT L1T reco eff



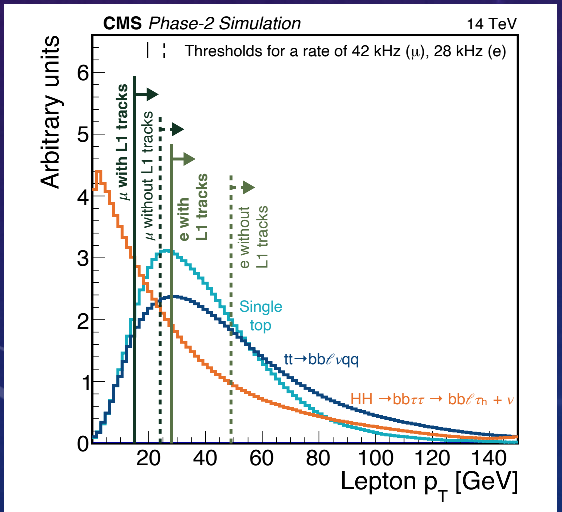
MET L1T reco eff

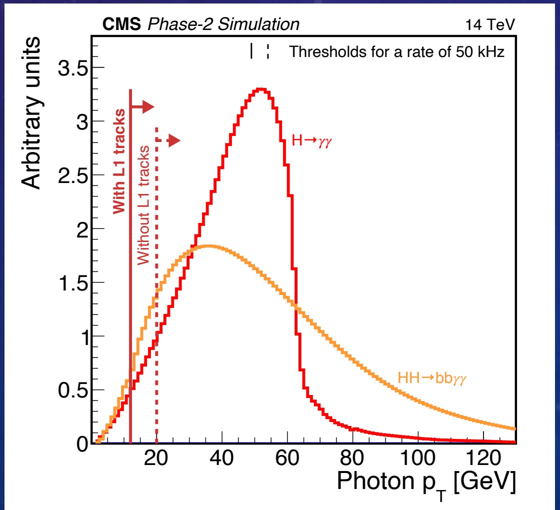


LEVEL-1 TRIGGER PHASE-2 UPGRADE

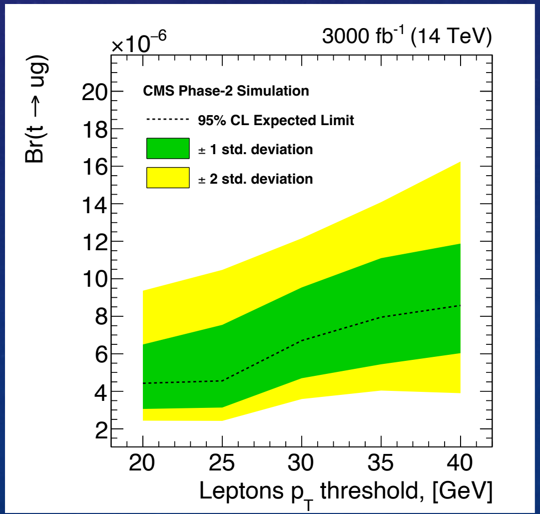
CMS-TDR-021

- Use HL-LHC rate without losing physics acceptance and extend sensitivity
  - All Run3 physics preserved in Run4/5 – no lowering of trigger object threshold
  - Improve capability to efficiently select specific signatures
  - New detectors, new L1T objects –> open new physics search possibilities





Expected exclusion Limit FCNC t → ug



(CMS-TDR-021)

P2 L1T - GLOBAL TRIGGER

Level-1 Trigger physics menu rate

- Table of even selection conditions with objects reconstructed in GMT, CCT, GTT, Correlator
  - Retain object thresholds of Run1/2, with rate below 500 kHz @ PU 200 (with accounting for 30% of uncertainty)

L1 Trigger seeds	Offline Threshold(s) at 90% or 95% (50%) [GeV]	Rate $\langle PU \rangle = 200$ [kHz]	Additional Requirement(s) [cm, GeV]	Objects plateau efficiency [%]
Single/Double/Triple Lepton (electron, muon) seeds				
Single TkMuon	22	12	$\lvert\eta\rvert < 2.4$	95
Double TkMuon	15,7	1	$\lvert\eta\rvert < 2.4, \Delta z < 1$	95
Triple TkMuon	5,3,3	16	$\lvert\eta\rvert < 2.4, \Delta z < 1$	95
Single TkElectron	36	24	$\lvert\eta\rvert < 2.4$	93
Single TkIsoElectron	28	28	$\lvert\eta\rvert < 2.4$	93
TkIsoElectron-StaEG	22, 12	36	$\lvert\eta\rvert < 2.4$	93, 99
Double TkElectron	25, 12	4	$\lvert\eta\rvert < 2.4$	93
Single StaEG	51	25	$\lvert\eta\rvert < 2.4$	99
Double StaEG	37,24	5	$\lvert\eta\rvert < 2.4$	99
Photon seeds				
Single TkIsoPhoton	36	43	$\lvert\eta\rvert < 2.4$	97
Double TkIsoPhoton	22, 12	50	$\lvert\eta\rvert < 2.4$	97
Taus seeds				
Single CaloTau	150(119)	21	$\lvert\eta\rvert < 2.1$	99
Double CaloTau	90,90(69,69)	25	$\lvert\eta\rvert < 2.1, \Delta R > 0.5$	99
Double PuppiTau	52,52(36,36)	7	$\lvert\eta\rvert < 2.1, \Delta R > 0.5$	90
Hadronic seeds (jets,H_T)				
Single PuppiJet	180	70	$\lvert\eta\rvert < 2.4$	100
Double PuppiJet	112,112	71	$\lvert\eta\rvert < 2.4, \Delta\eta < 1.6$	100
PuppiH_T	450(377)	11	jets: $\lvert\eta\rvert < 2.4, p_T > 30$	100
QuadPuppiJets-PuppiH_T	70,55,40,40,400(328)	9	jets: $\lvert\eta\rvert < 2.4, p_T > 30$	100,100
E_T^{miss} seeds				
PuppiE_T^{miss}	200(128)	18		100
Cross Lepton seeds				
TkMuon-TkIsoElectron	7,20	1	$\lvert\eta\rvert < 2.4, \Delta z < 1$	95, 93
TkMuon-TkElectron	7,23	3	$\lvert\eta\rvert < 2.4, \Delta z < 1$	95, 93
TkElectron-TkMuon	10,20	1	$\lvert\eta\rvert < 2.4, \Delta z < 1$	93, 95
TkMuon-DoubleTkElectron	6,17,17	0.1	$\lvert\eta\rvert < 2.4, \Delta z < 1$	95, 93
DoubleTkMuon-TkElectron	5,5,9	4	$\lvert\eta\rvert < 2.4, \Delta z < 1$	95, 93
PuppiTau-TkMuon	36(27),18	2	$\lvert\eta\rvert < 2.1, \Delta z < 1$	90, 95
TkIsoElectron-PuppiTau	22,39(29)	13	$\lvert\eta\rvert < 2.1, \Delta z < 1$ $\Delta R > 0.3$	93, 90

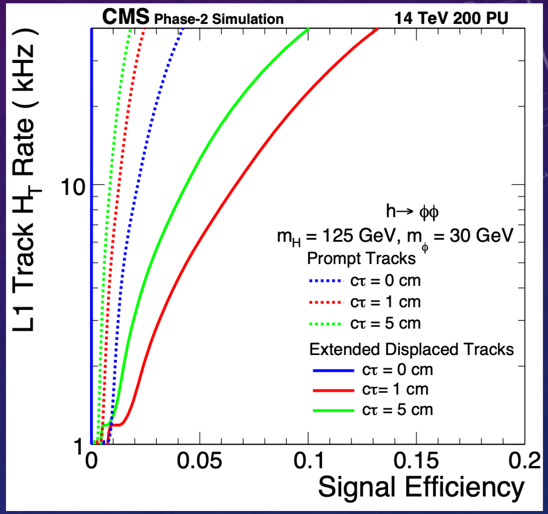
L1 Trigger seeds	Offline Threshold(s) at 90% or 95% (50%) [GeV]	Rate $\langle PU \rangle = 200$ [kHz]	Additional Requirement(s) [cm, GeV]	Objects plateau efficiency [%]
Cross Hadronic-Lepton seeds				
TkMuon-PuppiH_T	6,320(250)	4	$\lvert\eta\rvert < 2.4, \Delta z < 1$	95,100
TkMuon-DoublePuppiJet	12,40,40	10	$\lvert\eta\rvert < 2.4, \Delta R_{j\mu} < 0.4,$ $\Delta\eta_{jj} < 1.6, \Delta z < 1$	95,100
TkMuon-PuppiJet-PuppiE_T^{miss}	3,100,120(55)	14	$\lvert\eta\rvert < 1.5, \lvert\eta\rvert < 2.4,$ $\Delta z < 1$	95,100, 100
DoubleTkMuon-PuppiJet-PuppiE_T^{miss}	3,3,60,130(64)	4	$\lvert\eta\rvert < 2.4, \Delta z < 1$	95,100, 100
DoubleTkMuon-PuppiH_T	3,3,300(231)	2	$\lvert\eta\rvert < 2.4, \Delta z < 1$	95,100
DoubleTkElectron-PuppiH_T	10,10,400(328)	0.9	$\lvert\eta\rvert < 2.4, \Delta z < 1$	93,100
TkIsoElectron-PuppiH_T	26,190(124)	9	$\lvert\eta\rvert < 2.4, \Delta z < 1$	93,100
TkElectron-PuppiJet	28,40	34	$\lvert\eta\rvert < 2.1, \lvert\eta\rvert < 2.4,$ $\Delta R > 0.3, \Delta z < 1$	93,100
PuppiTau-PuppiE_T^{miss}	55(38),190(118)	4	$\lvert\eta\rvert < 2.1$	90,100
VBF seeds				
Double PuppiJets	160,35	40	$\lvert\eta\rvert < 5, m_{jj} > 620$	100
B-physics seeds				
Double TkMuon	2,2	12	$\lvert\eta\rvert < 1.5, \Delta R < 1.4,$ $q1 * q2 < 0, \Delta z < 1$	95
Double TkMuon	4,4	21	$\lvert\eta\rvert < 2.4, \Delta R < 1.2$ $q1 * q2 < 0, \Delta z < 1$	95
Double TkMuon	4.5,4	10	$\lvert\eta\rvert < 2.0, 7 < m_{\mu\mu} < 18,$ $q1 * q2 < 0, \Delta z < 1$	95
Triple TkMuon	5,3,2	7	$0 < m_{\mu5\mu3,q1*q2<0} < 9$ $\lvert\eta\rvert < 2.4, \Delta z < 1$	95
Triple TkMuon	5,3,2.5	6	$5 < m_{\mu5\mu2.5,q1*q2<0} < 17$ $\lvert\eta\rvert < 2.4, \Delta z < 1$	95
Rate for above Trigger seeds				346
Total Level-1 Menu Rate (+30%)				**450**

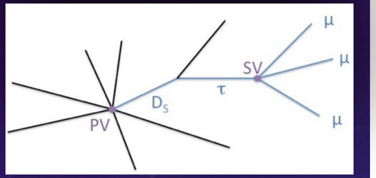
EXTEND PHYSICS - NOVEL TYPES OF TRIGGERS (TOPOLOGICAL)

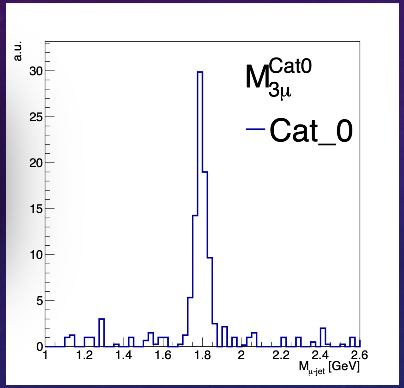
CMS-TDR-021

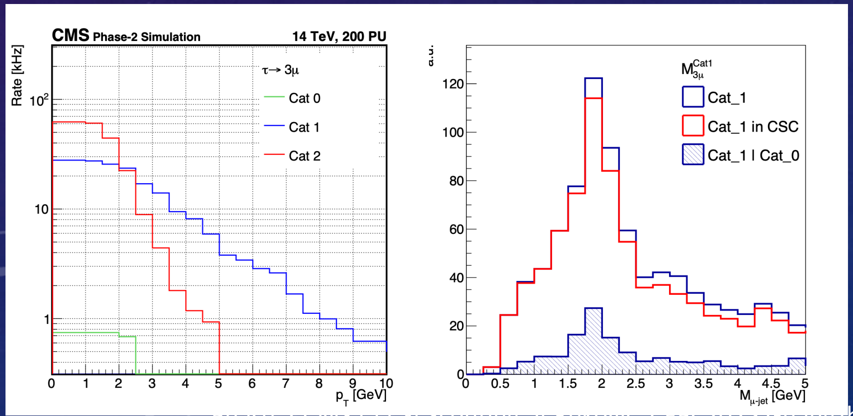
- Presence of Tracker Trigger Tracks allows for a more precise reconstruction and selection of exclusive signatures
- Low mass resonances decaying to charged particles with an acceptable Level-1 trigger rate

H->φφ
L1 tracker jets for displaced signatures



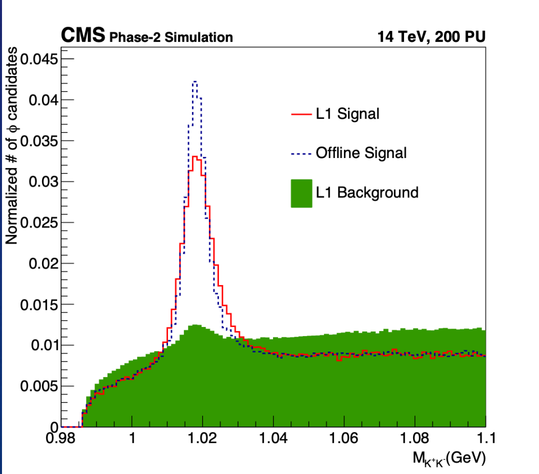






LFV: *Tau-> 3μ*
with low pt L1T global muons and muon hits

Bs->KK->4 L1 tracker tracks



OPORTUNITY TO COMPLEMENT L1T

- **What could Phase-2 L1T miss**?
  - Physics signatures with large backgrounds not fitting in total accept rate
    - dictated by the readout of some detectors and offline storage and processing capacity
  - Signatures whose reconstruction exceed latency constraint or “computing” capacity
    - finite latency limited by length of readout pipelines, complexity limited by finite logic resources available in FPGAs
  - Signature with none or little overlap with “mainstream” physics.

LEVEL-1 TRIGGER PHASE-2 UPGRADE - SCOUTING

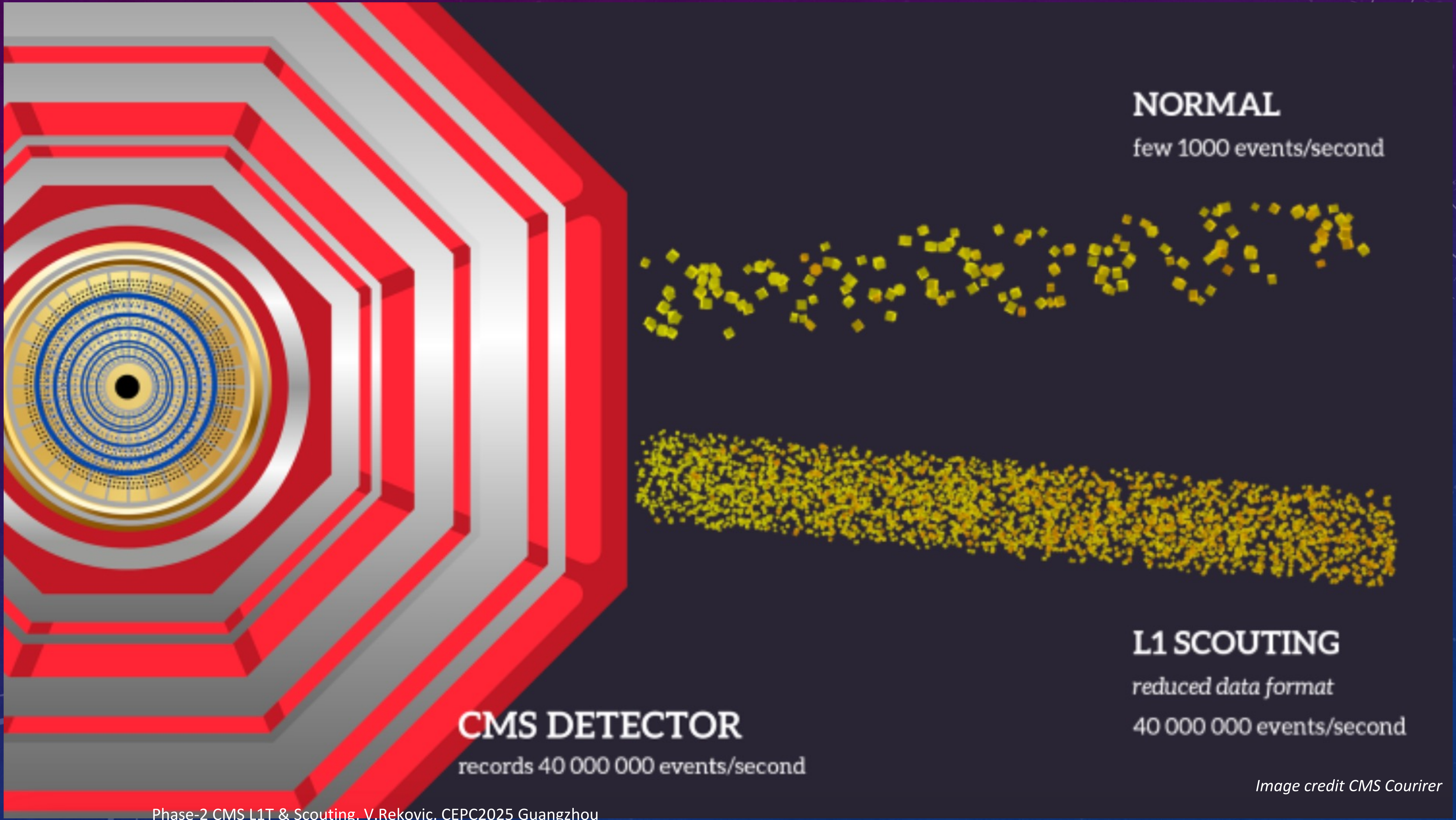


Image credit CMS Courirer

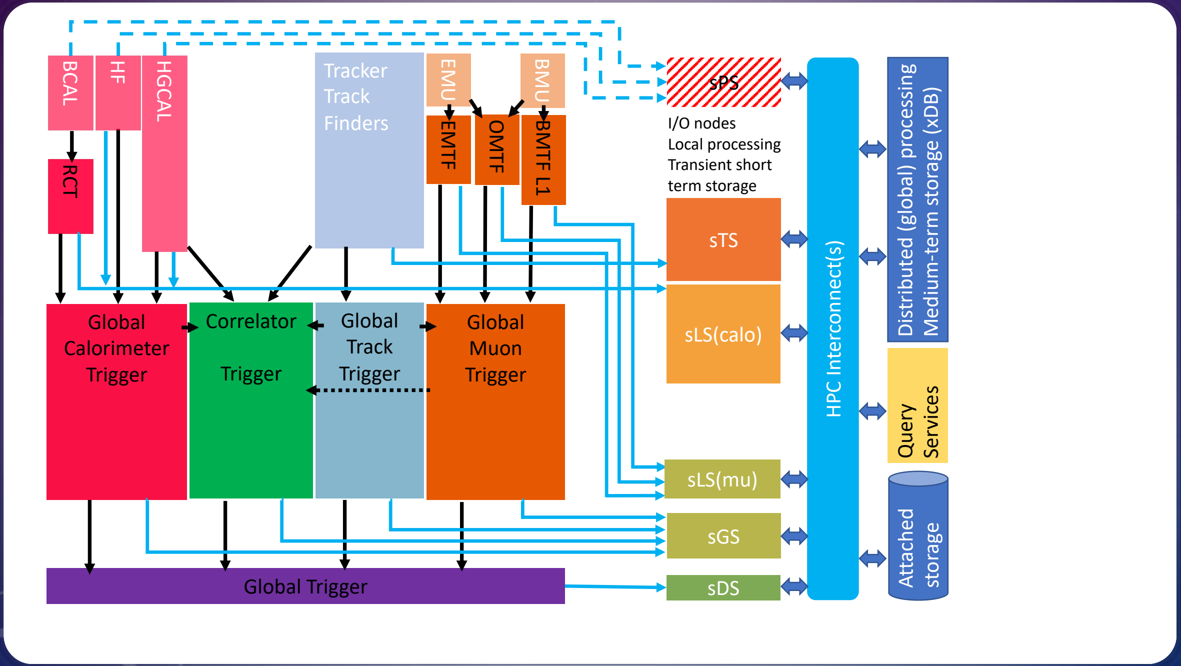
LEVEL-1 TRIGGER PHASE-2 UPGRADE - SCOUTING

CMS-TDR-021

Novel data acquisition and processing system, for collecting and storing the trigger objects reconstructed by the L1T processors at the full LHC collision rate (40 MHz)

P2 L1T

P2 L1T Scouting



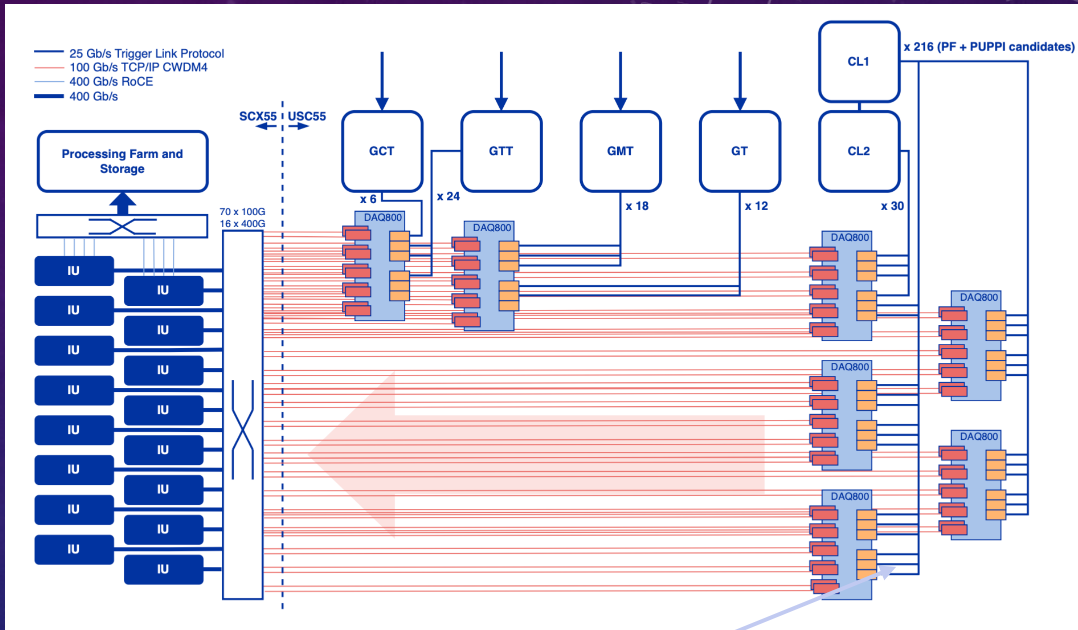
- Has full access to physics rate otherwise constrained by the L1 latency and maximum DAQ accept rate
  - Potentially enables exploration of additional exotic signatures
  - A powerful tool to study correlations over several bunch-crossings, for diagnostics and physics
- Nature of L1T reconstructed data
  - Trigger objects derived from trigger primitives, optimized for maximal and well-understood efficiency of physics object **identification** for sake of online **selection** to control the accept rate
  - Objects of reduced resolution due to limitations of processing power and time
  - Not optimally calibrated
  - Not most optimal for physics….but can be very useful

PHASE-2 L1T SCOUTING – ARCHITECTURE(BASELINE)

CMS-TDR-022

Asynchronous system for data taking of trigger-reconstructed objects

- Use of spare optical outputs of Level-1 trigger boards
- Same 25 Gb/s serial optical links and protocol as L1T
- Capture data by dedicated FPGA boards (DAQ-800)
  - work as interface between the synchronous trigger domain 40 MHz and Scouting data taking
  - perform pre-processing to fit 800 Gbps throughput
    - moderate date reduction zero-suppression, recalibration
  - Buffer data
- Transfer via switched network to Integration units (CPU)



DAQ-800

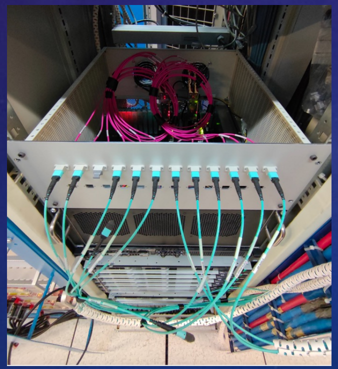
- Designed for CMS Phase-2 central DAQ readout
- Input 48 L1 links via FireFly optical RX (Max 1.2 Tbps)
- Output 1 Tbps via 10 x 100 Gb Ethernet
- Processing two Xilinx Ultrascale+ VU35P FPGAs
  - built-in High-Bandwidth Memory (8 GB)

PHASE-2 L1T SCOUTING – DEMONSTRATOR WITH RUN3

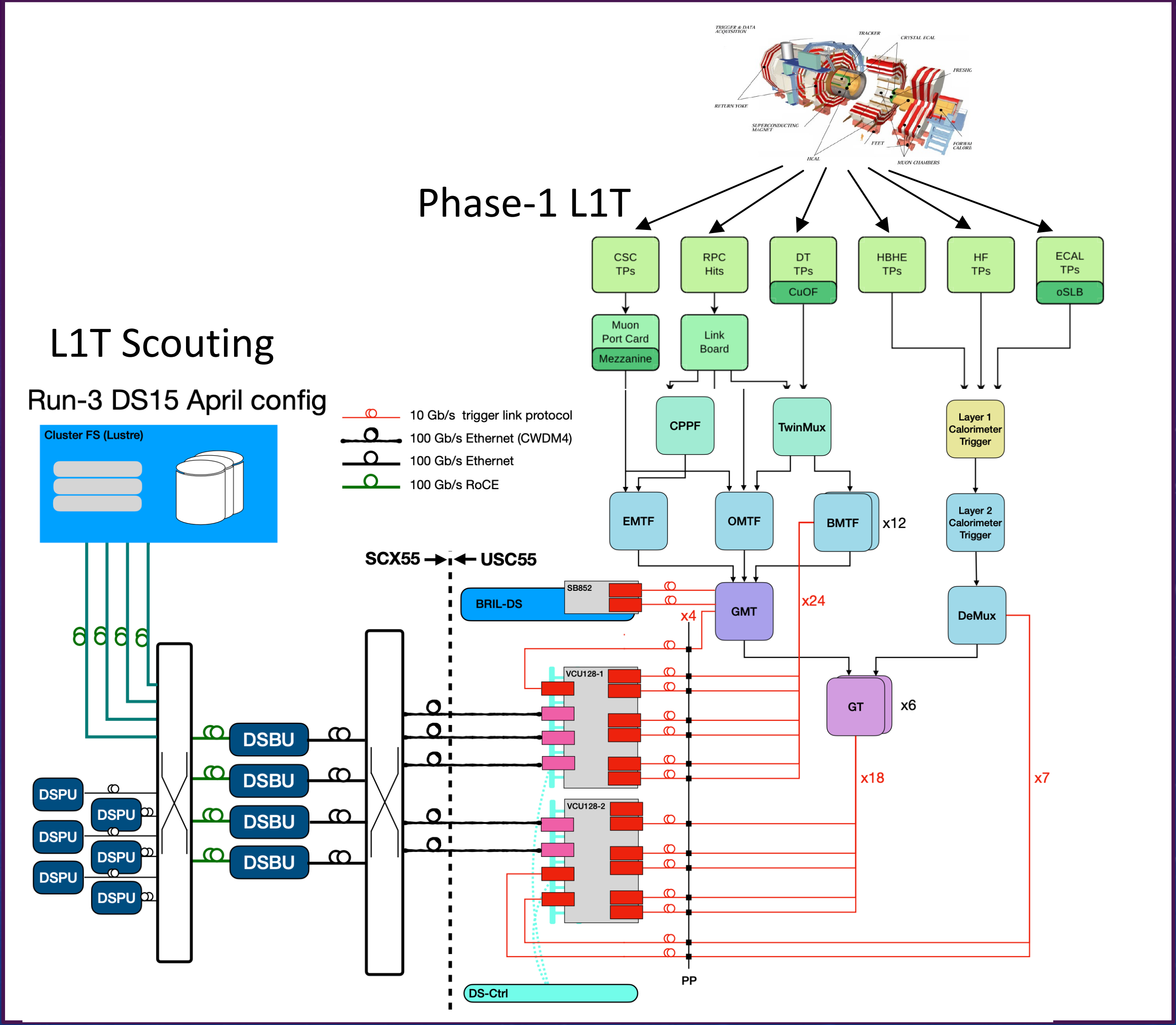
CMS Phase-1 L1T system and Run-3

- Collected P1 L1T data objects
  - ”Global” (muons, e/γ, τ, jets, Esums, GT bits)
  - ”Local ” (only hits in barrel muon detector)
- DAQ board: 2 commercial FPGA boards (Xilinx VCU128 DevKit)
  - In place of ~ 1 DAQ-800
  - concentrate the trigger links, basic pre-processing (0-suppression)

- send data via 100 GbE to compute nodes
  - For buffering (DSBUs) and processing (DSPUs)
- send data to long-term storage



- Successfully demonstrated the full data flow
  - L1T → DAQ → Online processing → Storage

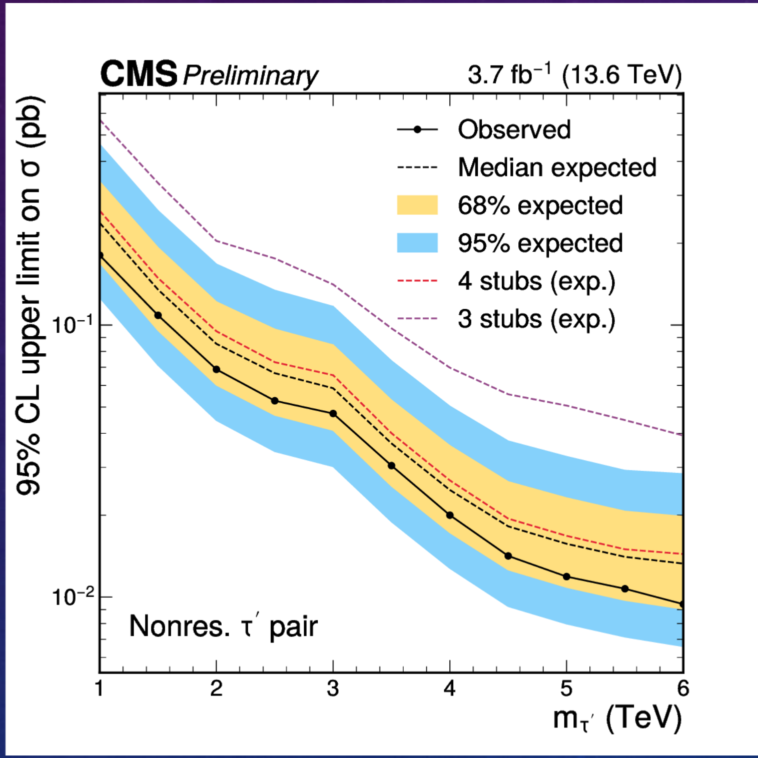


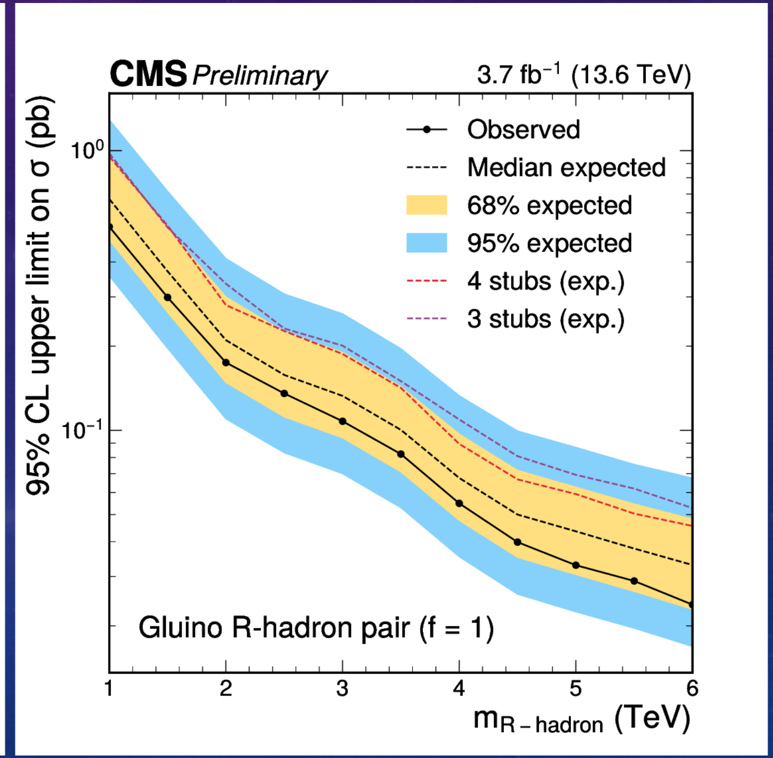
D. S. Rabady et al.A 40 MHz Level-1 trigger scouting system for the CMS Phase-2 upgrade

PHYSICS WITH PHASE-2 L1T SCOUTING DEMONSTRATOR WITH RUN3

CMS-PAS-EXO-25-010

- Recent analysis from Run-3 data collected with L1T Muon Data Scouting
  - Search for Massive Long Lived charged particles with significant lifetime to cross detector in several BXs
    - Looks for correlated signatures in muon chambers between various BXs using only L1T information available
    - Complements existing searches for heavy long-lived charged particles by extending the sensitivity to lower β values

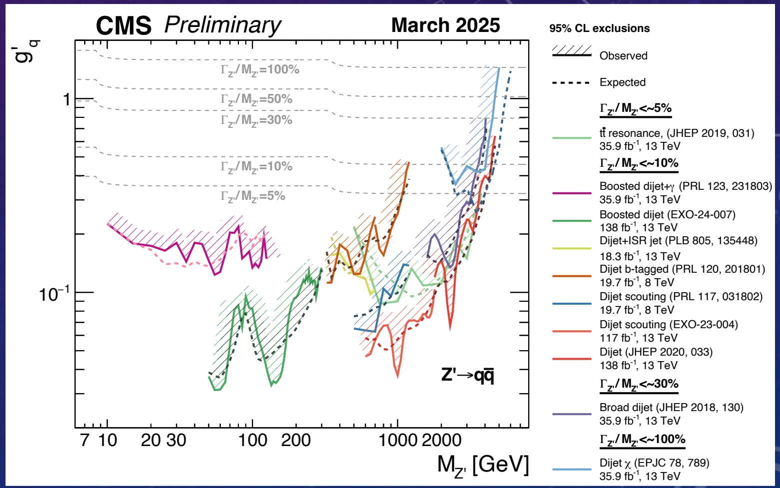




PHYSICS WITH L1T SCOUTING JETS

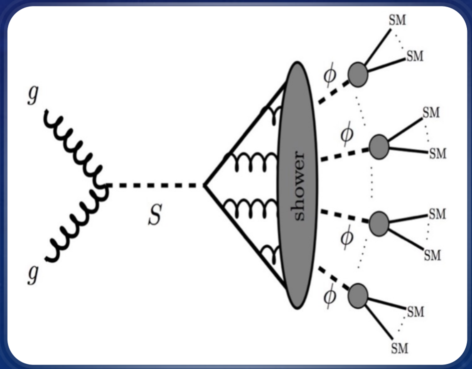
[CMS Exotica Public](#)

Searches for leptophobic Z’ (di-jet channel)



<u>Soft hadronic final states</u>

1. Classic dijet resonance searches in regions of phase-space inaccessible to standard L1 (no rate limitation, PF-jet resolution)
   - Current low-mass searches use boosted jets and jet substructure
2. Multiple jet final states in general, that can benefit from a cut-and-count approach less sensitive to L1 jet features
3. High multiplicity unclustered hadronic final states (from different models, with or w/o ”dark sector”

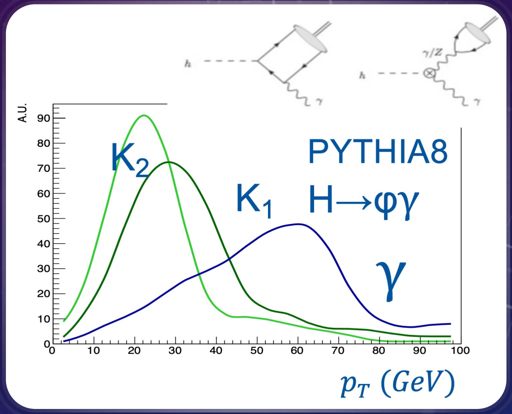


PHYSICS WITH L1T SCOUTING: MORE OPORTUNITY

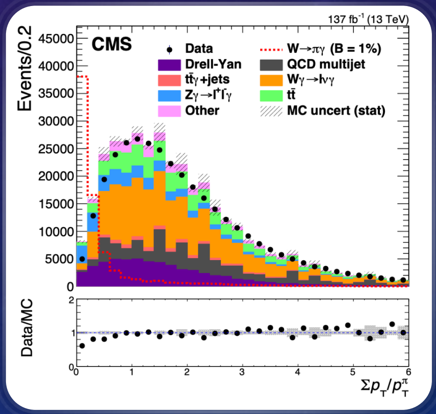
Credit E.Meschi

SM rare decays

1. Exclusive **rare Higgs decay** channels with photons
   - $H \to J/\psi\gamma,\, H \to \phi\gamma,\, H \to \rho\gamma, \ldots$ tiny BRs
   - can all be selected with single photon triggers with low signal efficiency.



2. **Radiative W decays**
   - such as $W \to \pi\gamma, D_s\gamma$
   - currently (Run 3) using W from tt



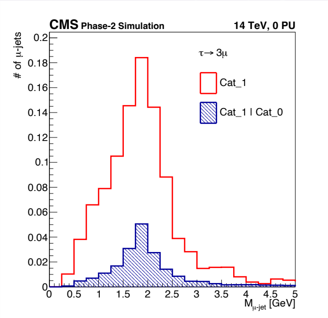
3. **All-hadronic SM boson decays**
   - $H \to \phi\phi,\, W \to \pi\,\pi\,\pi,$
   - In L1T potentially challenging computationally and latency-wise due to large combinatorics

PHYSICS WITH L1T SCOUTING MORE OPORTUNITIES

B physics with τ decays, including anomalies

Single and multiple τ final states can benefit from scouting because of notorious difficulties in controlling trigger rate

1. $\boldsymbol{B_s} \rightarrow \boldsymbol{\tau}\ \boldsymbol{\tau}$ decay (requiring high efficiency τ selection at low-pt) with $\tau \rightarrow 3\pi + X$
2. $\boldsymbol{\tau} \rightarrow \mathbf{3}\ \boldsymbol{\mu}$, low pT muons not necessarily fully reconstructed

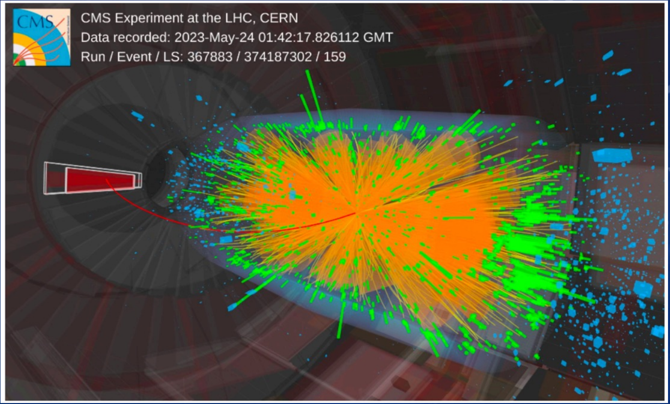


LLP and vLLP, displaced muons and jets

1. small displacement (tracks) and large displacement (standalone objects)

example by **relaxing muon-track matching and looking only at muon tracks**

Anomaly Detection using all available L1 information at the BX rate



Example of CMS event selected by AXOL1TA
not selected by any other CMS trigger

CONCLUSIONS

- CMS physics program of precision measurements and searches for new physcs with LHC will continue and willl expand sensitivity with Phase-2 Upgraded Level-1 trigger with HL-LHC.
    - Successful R&D program of Upgraded Level-1 trigger
    - Hardware with fast optical link and ultrascale FPGAs provide sufficient computing resources
    - Opened opportunities for novel and more complex object reconstruction in hardware, allowing to move physics analyses closer to detector
    - Hardware production on track and preparation for LS3 is advancing

- Scouting in L1T (and HLT) provides important suplement data in searches for new physics, already deployed in Run-3.
    - POC already bearing fruits and new physics analysis emerging from Run-3 integrated demonstrator

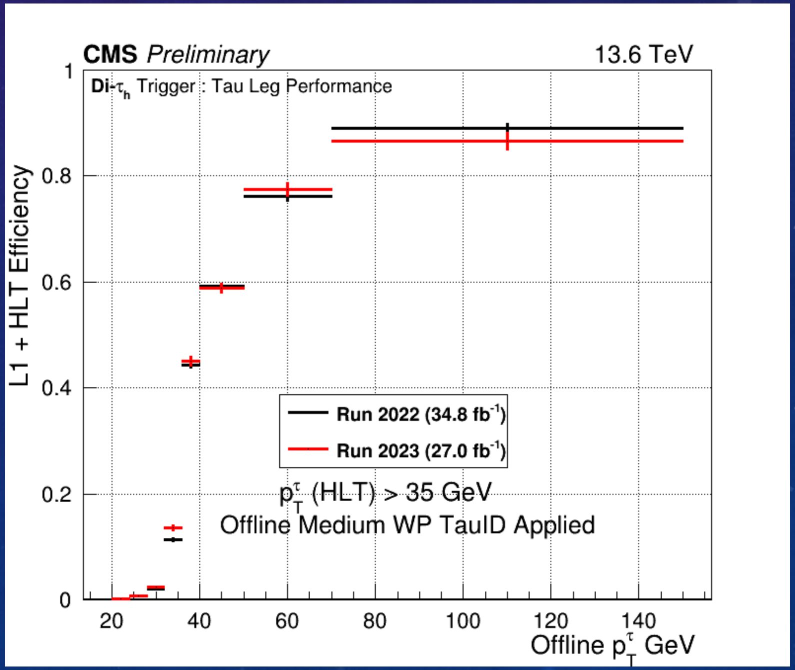
- Potential of CMS L1T Scouting will expand with HL-LHC due to new type of accessebile detector information in the Phase-2 upgraded Level-1 trigger
    - Application to new searches is ongoing in the exciting development of real-time analysis

THANK YOU

BACK-UP

MACHINE LEARNING IN HLT

- Machine Learning is heavily used in CMS HLT object reconstruction and Identification.
- Seed of L1T jet
- HLT Tau:
  - Reconstruction: Hadron plus strip
    - target hadronic decays of taus by aligning calo deposits in strips (from Π^0)
  - Identification with Neural Network :CNN + DNN based tagger



HLT STREAM: Parking

Delayed offline reconstruction (Opportunistically prompt)
Full event information…. no double copy of files

- For physics analysis that need special triggers with rates that don't fit in Standard stream bandwidth
- Stream content is flexible and adjusted to actual physics needs
- Current CMS priorities are signatures of LLP, di-Higgs, and VBF Higgs production, B-Physics
- Novel triggers for Run3 or standard triggers (Run2) but with lower thresholds

- Exceptionally rich B-Physics program with low pT muon and electron triggers
    - Various searches for LFU violation are being considered: measuring R_{D^*} , searching for LFV in tag-side

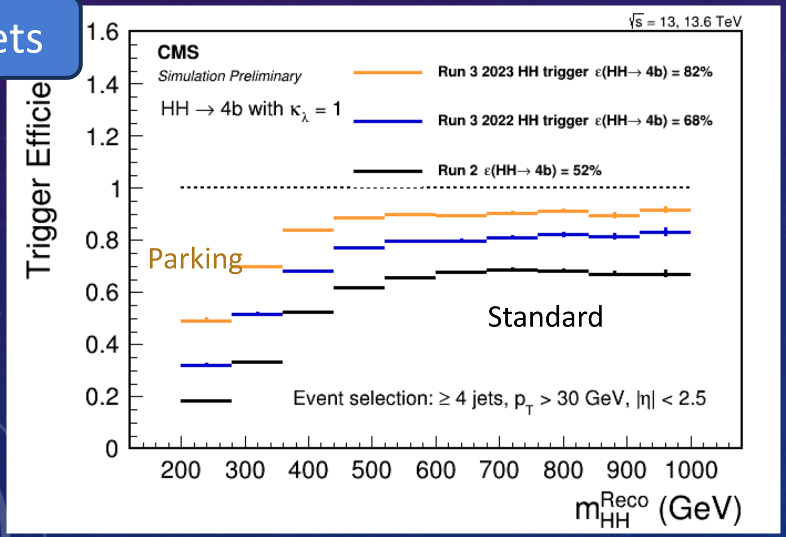
$D^0 \rightarrow \mu^+\mu^-$

$B_s^0 \rightarrow \mu^+\mu^-$

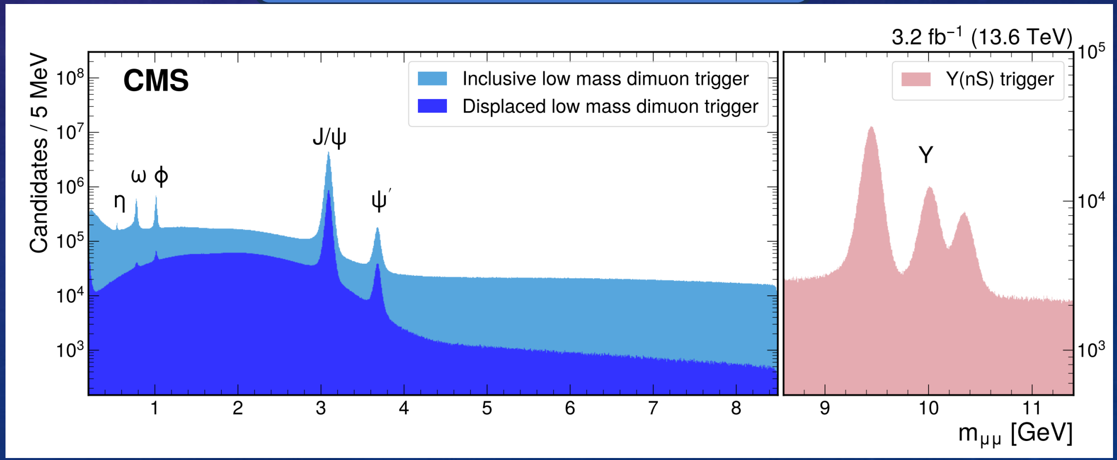
$B^0 \rightarrow J/\psi K_S^0$

$B^+ \rightarrow K^+e^+e^-$

HLT 4-jets



From B parking in 2022



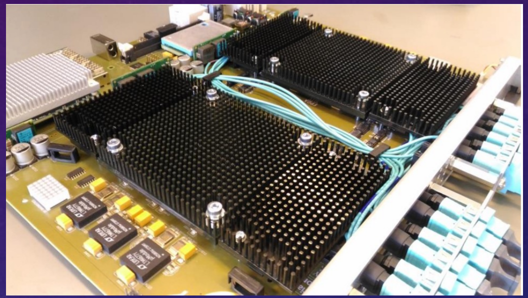
mass distribution for pairs of μ's oppositely charged, originating from a common vertex (inclusive & displaced). Imporoved L1 (Kalman) and HLT (GPUs)

HARDWARE – FPGA BOARDS

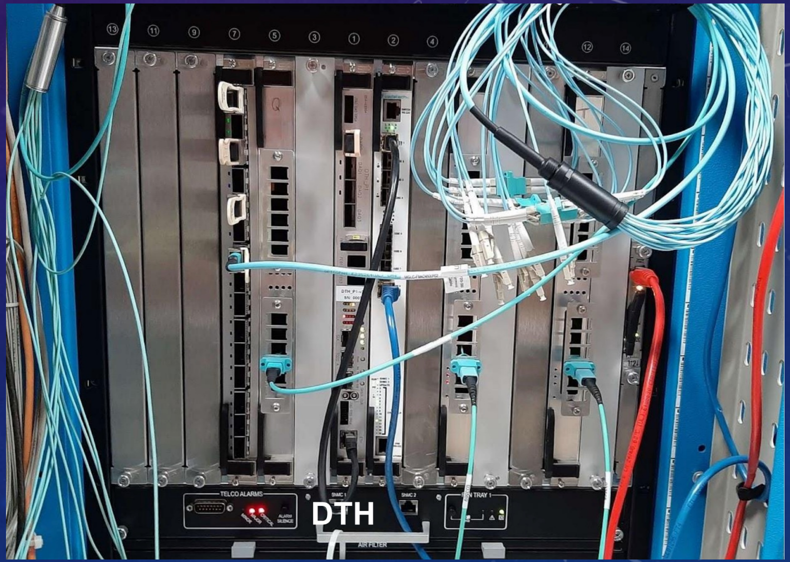
ATCA-technology based boards hosting powerful Xilinx Ultrascale+ FPGAs with high I/O are designed

- 4 different flavors for Phase-2 L1-Trigger (optics Firefly or QSFP)
  - "X2O" for OMTF, EMTF, GMT
  - BMTL1 for Muon Barrel
  - "Serenity" for GCT, Correlator, GT
  - "APx" for GCT

Serenity

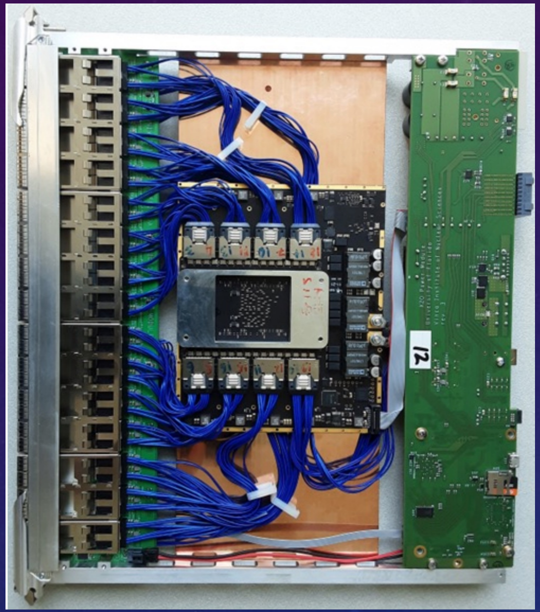


Ongoing Slice Test of FW with hardware connecting multiple boards of different flavors.

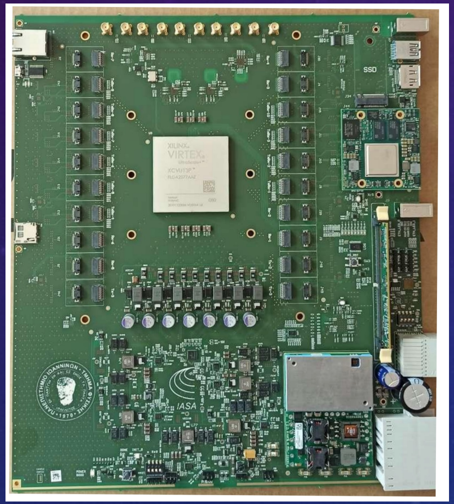


Preparing for Slice Test of the full system .

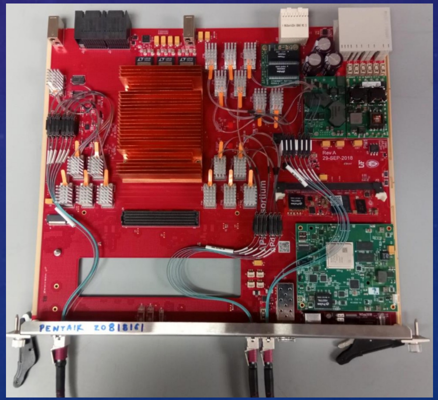
X20



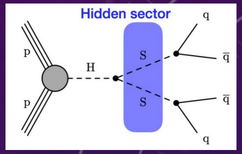
BMTL1



APx

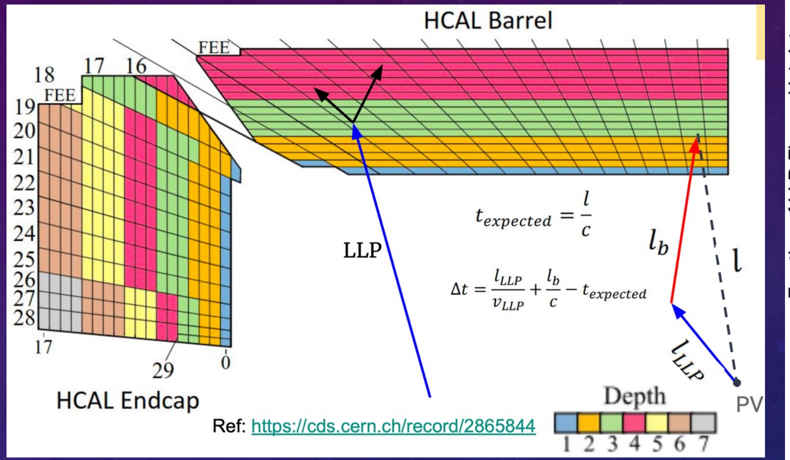


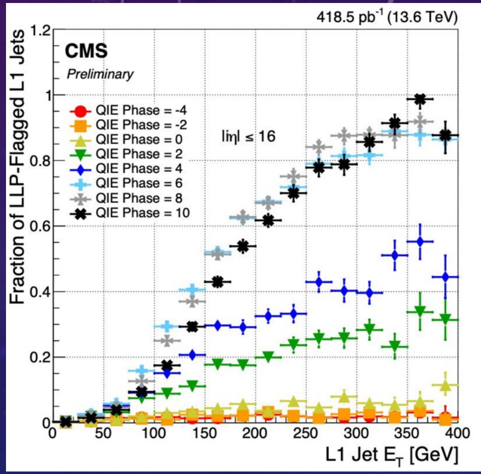
TRIGGERING ON LONG-LIVED-PARTICLES (LLP)



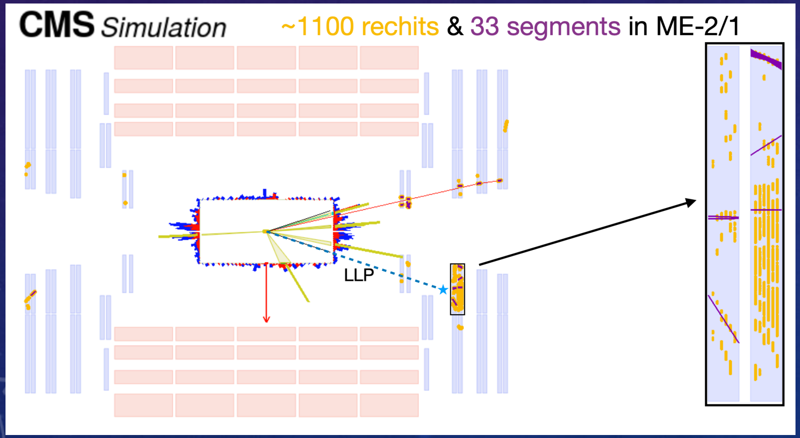
- Several **displaced-jet HLT triggers**

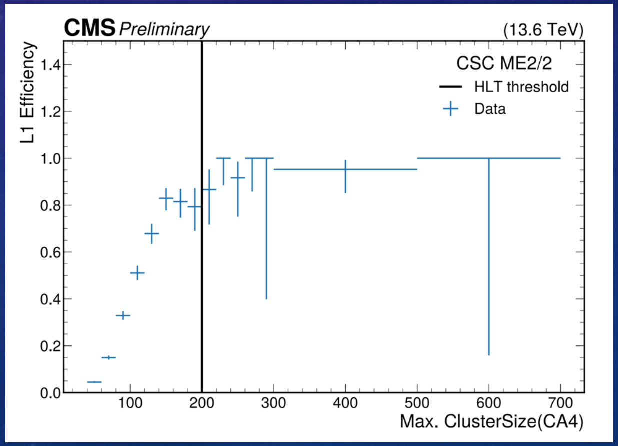
- HCAL-based exploit HCAL depth segmentation + timing
  seed L1 jets with HCAL depth or time – flagged (> 6 ns)
  HLT jets with minimal energy deposit in first 2 layers
  + high energy deposits in later layers





- Muon system-based exploit hit counting capability of muon chambers
  seed L1 a cluster of hits in a given muon chamber. Accept if multiplicity is greater than some threshold.
  CERN-CMS-DP-2022-062





OTHER LLP TRIGGERS

- Displaced Dimuons. EXO-23-014
  - For SUSY particles can have signatures of decays to SM particles at macroscopic distances from the pp IP.
  - Trigger Strategy
    Use L1T and HLT or L1T-P2 reconstruction algorithms for non-prompt muon tracks. Out of Time Objects
- LLP objects could be stopped inside of CMS and decay at some later time.
  - Trigger strategy:
    Look for decay particles in **empty (non colliding) BX**
- Displaced Photons
  - Trigger strategy:
    Use objects with ECAL timing, available in HLT or L1T-P2.