THE CMS LEVEL-1 TRIGGER DATA SCOUTING FOR LHC RUN 3 AND THE CMS PHASE-2 UPGRADE

05.03.2024 - YSF LA THUILE 2024
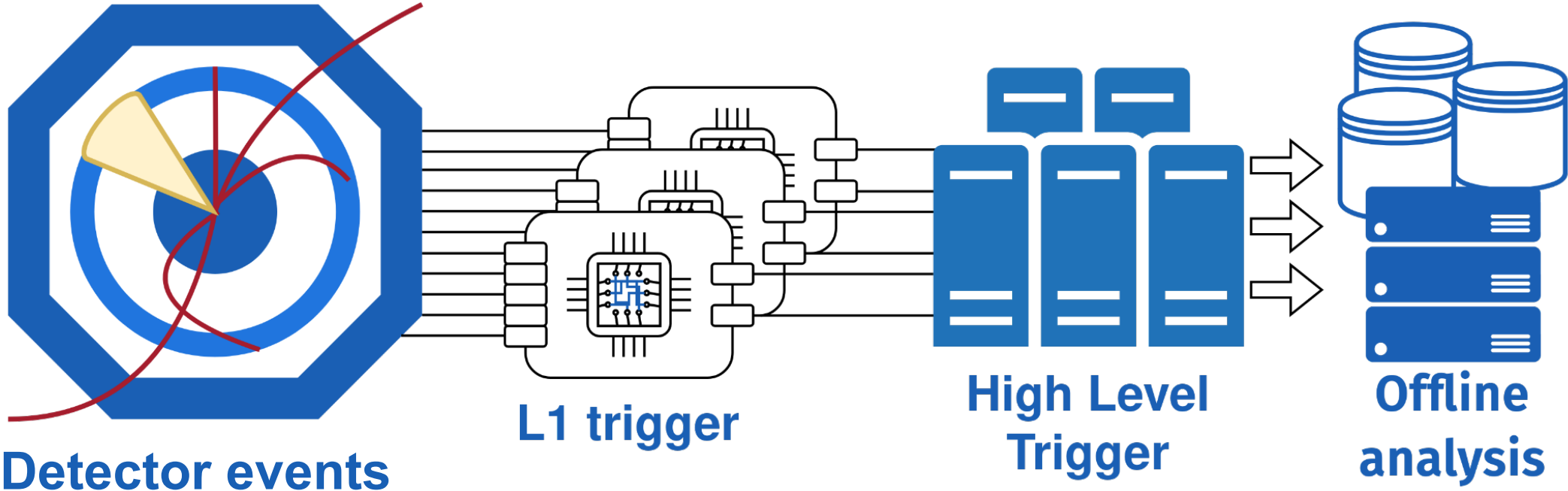## LES RENCONTRES DE PHYSIQUE DE LA VALLÉE D'AOSTE

Sabrina Giorgetti[1,2,*] on behalf of the CMS Collaboration
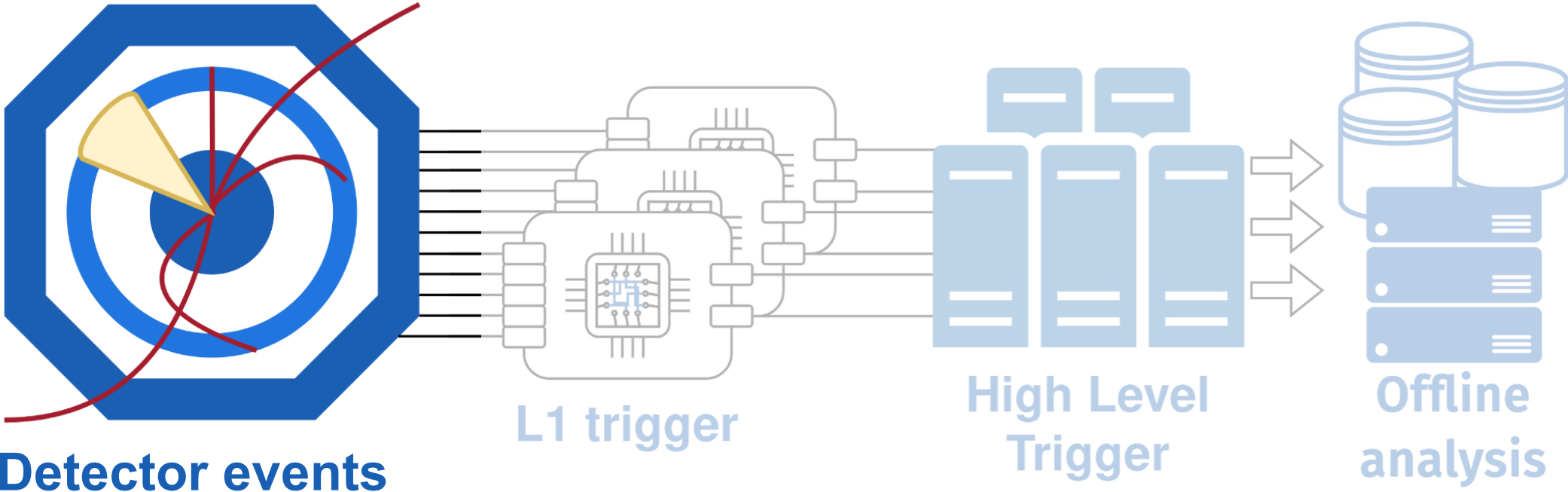
[1] Università Degli Studi di Padova
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CMS DATA FLOW

Detector events — **L1 trigger** — **High Level Trigger** — **Offline analysis**

CMS DATA FLOW

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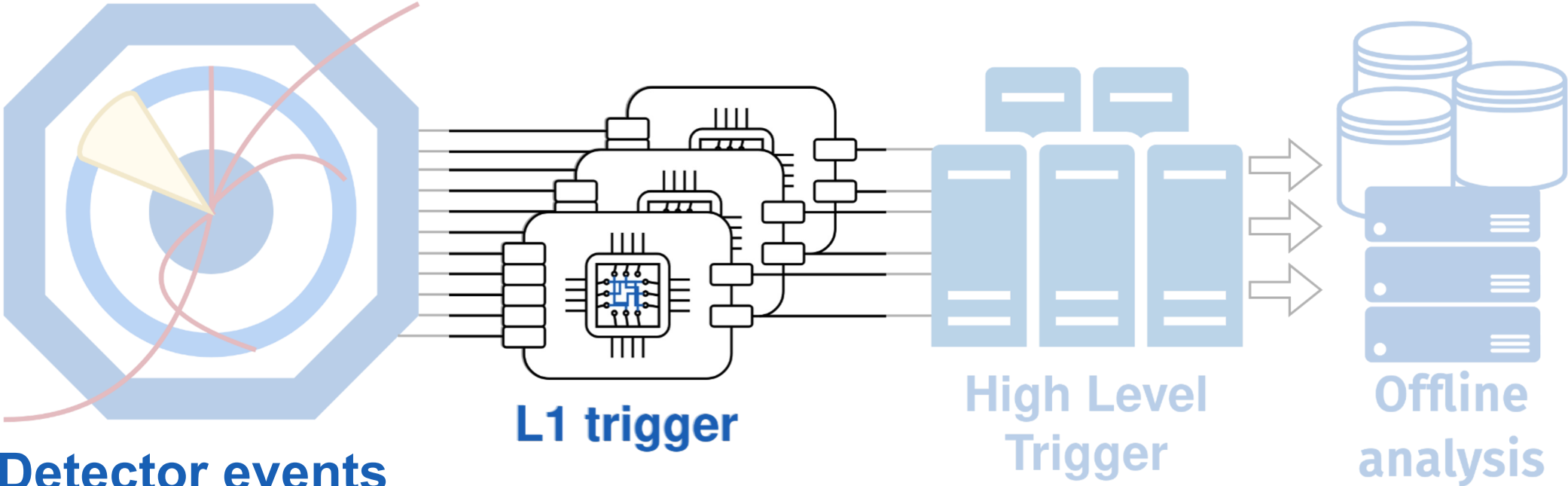
The CMS detector records a 40MHz event rate originating from pp collisions at the LHC.

2MB of data per collision : CMS deploys a two-level trigger system to reduce the data volume.

CMS DATA FLOW

Detector events

L1 trigger

High Level Trigger

Offline analysis

Reduces the rate from 40MHz to 100kHz.

Hardware trigger with a latency of less than 4 μs.

Coarser data from calorimeters and muons subsystems.

CMS DATA FLOW

Detector events

L1 trigger

High Level Trigger
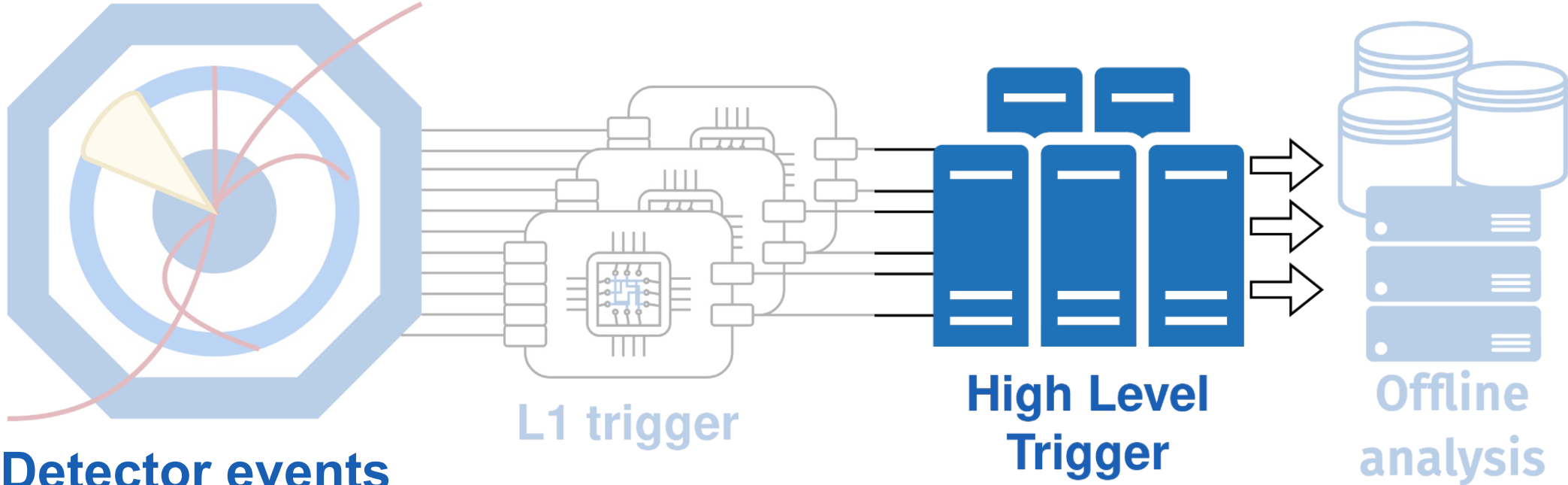
Offline analysis
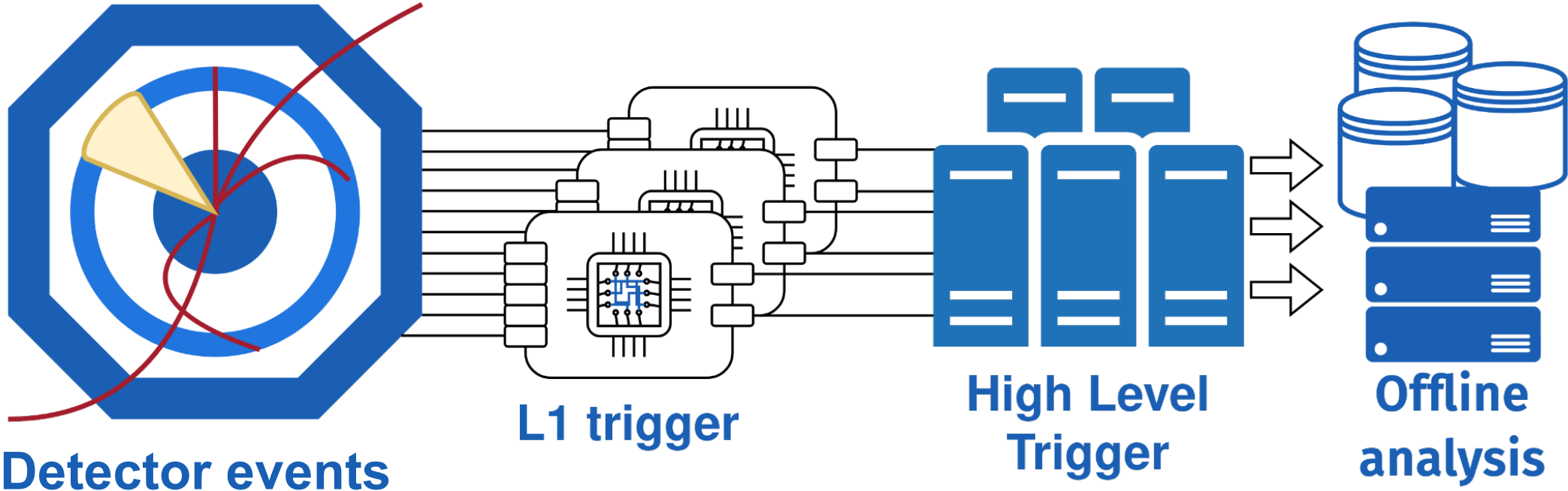
Software trigger that further reduces the rate down to 1kHz.

Readout of the full detector and reconstruction of the entire event.

CMS DATA FLOW

Detector events

L1 trigger

High Level Trigger

Offline analysis

Data selected by trigger criteria are stored for offline analysis.

CMS DATA FLOW

Detector events

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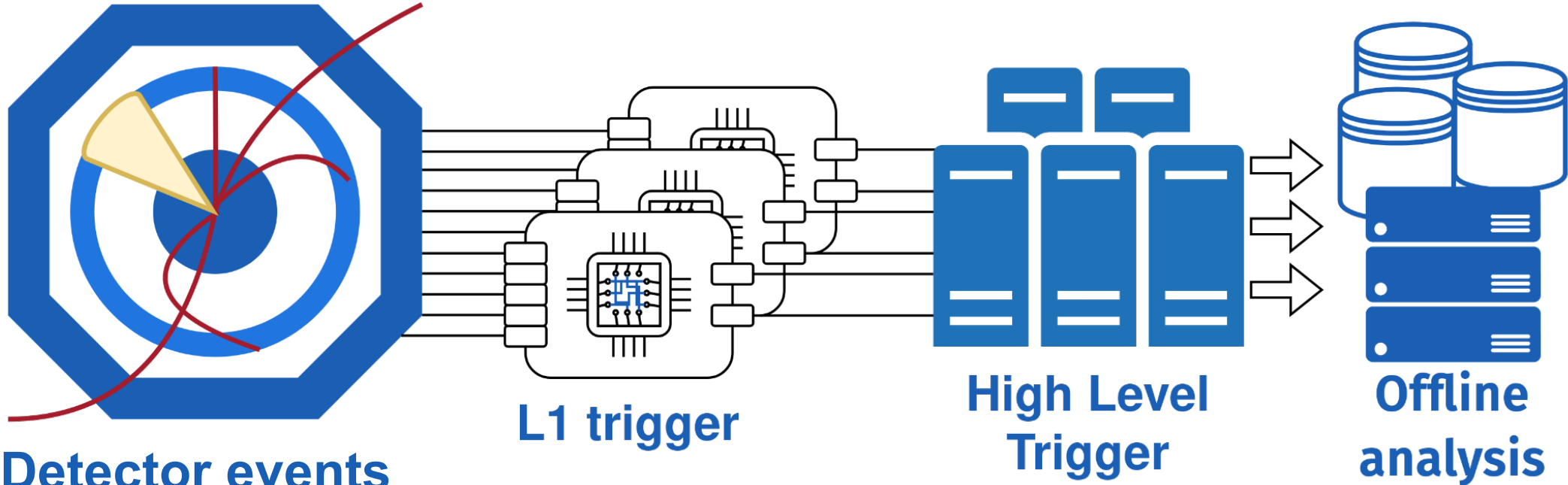
Offline analysis

99.75% events rejected

99% events rejected

Data selected by trigger criteria are stored for offline analysis.

Events rejected by triggers are lost!

LEVEL-1 SCOUTING

ARE WE OVERLOOKING THESE LOST EVENTS?
COULD NEW PHYSICS BE THERE?
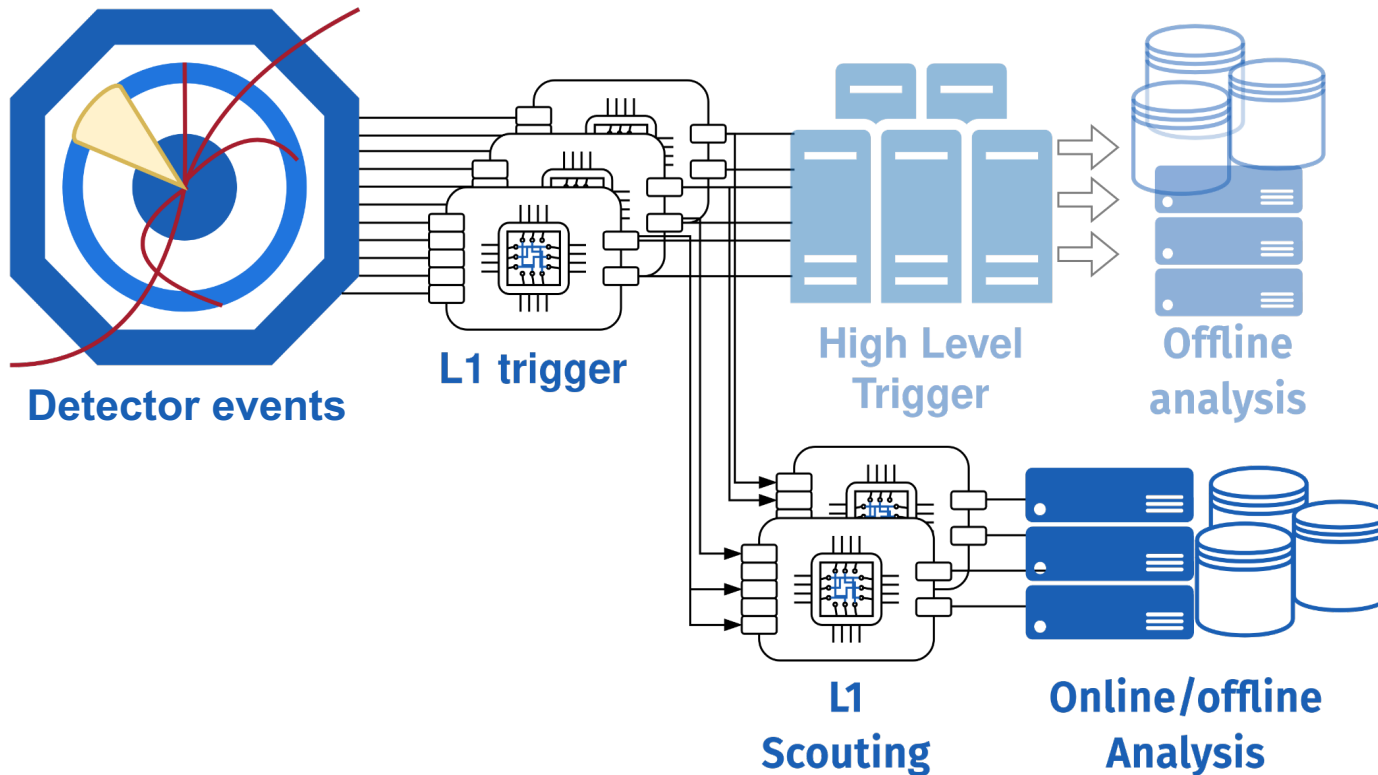
SCOUTING

- Collection of reduced-event-content data at considerably higher rates than the standard accept rate.

- Reduce the trigger bias enhancing new physics searches and exploring novel phase space.

- First introduced in CMS at the High Level Trigger (HLT) in 2011 [PhysRevLett.117.031802].

Detector events   **L1 trigger**   **High Level Trigger**   **Offline analysis**   **L1 Scouting**   **Online/offline Analysis**

LEVEL-1 SCOUTING

- Acquisition and quasi-online processing of the Level-1 Trigger (L1T) primitives at the full bunch-crossing (BX) rate.

- Process and store trigger-less data with limited resolution before the L1T selection (L1 Accept).

- A Level-1 Trigger Data Scouting (L1DS) system is being develop for the CMS Phase-2 Upgrade at the High-Luminosity-LHC (HL-LHC).

CMS PHASE-2 UPGRADE FOR HL-LHC

- At HL-LHC the instantaneous luminosity will reach up to $7.5 \cdot 10^{34}$ cm^{-2}s^{-1} increasing the average number of proton-proton collisions per bunch crossing (pileup) to around 200.
- The CMS detector will be significantly upgraded for Phase-2 to run in these challenging conditions.

Level-1 trigger
- Tracks in L1 trigger at 40MHz
- Particle Flow selection
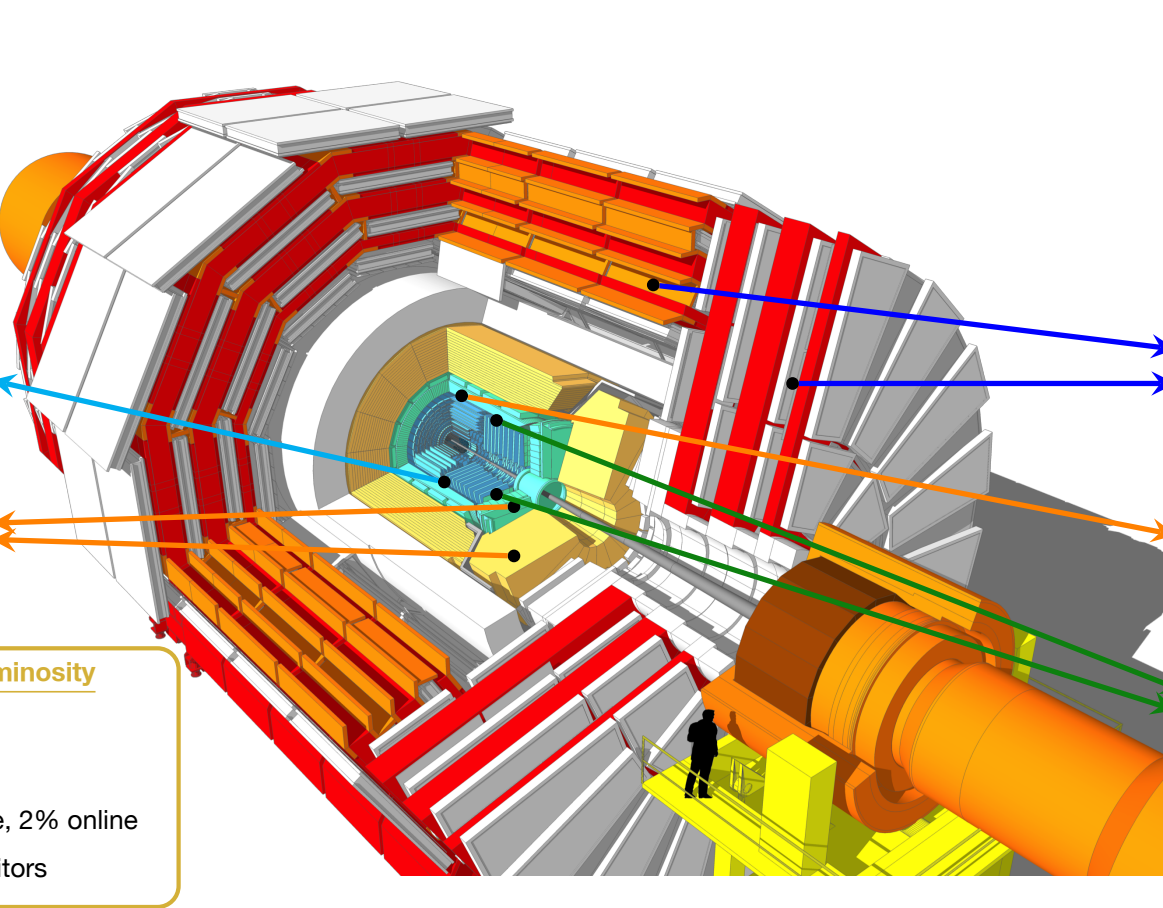- 750 kHz L1 output

Tracker
- Increased granularity
- Track-trigger at 40 MHz
- Extended coverage to $|\eta| \lesssim 3.8$

High-Granularity Calorimeter Endcap
- 3D showers and precise timing
- Si, Scint+SiPM in Pb/Cu-W/SS
- 30 ps TOF resolution

Beam Radiation Instrumentation and Luminosity
- Beam abort and timing
- Beam-induced background
- Bunch-by-bunch luminosity: 1% offline, 2% online
- Neutron and mixed-field radiation monitors

DAQ and High-Level Trigger
- Full optical readout
- Heterogenous architecture
- 60 TB/s event network
- 7.5 kHz HLT output

Muon system
- DT and CSC FE/BE new read-out
- New GEM/RPC $1.6 < |\eta| < 2.4$
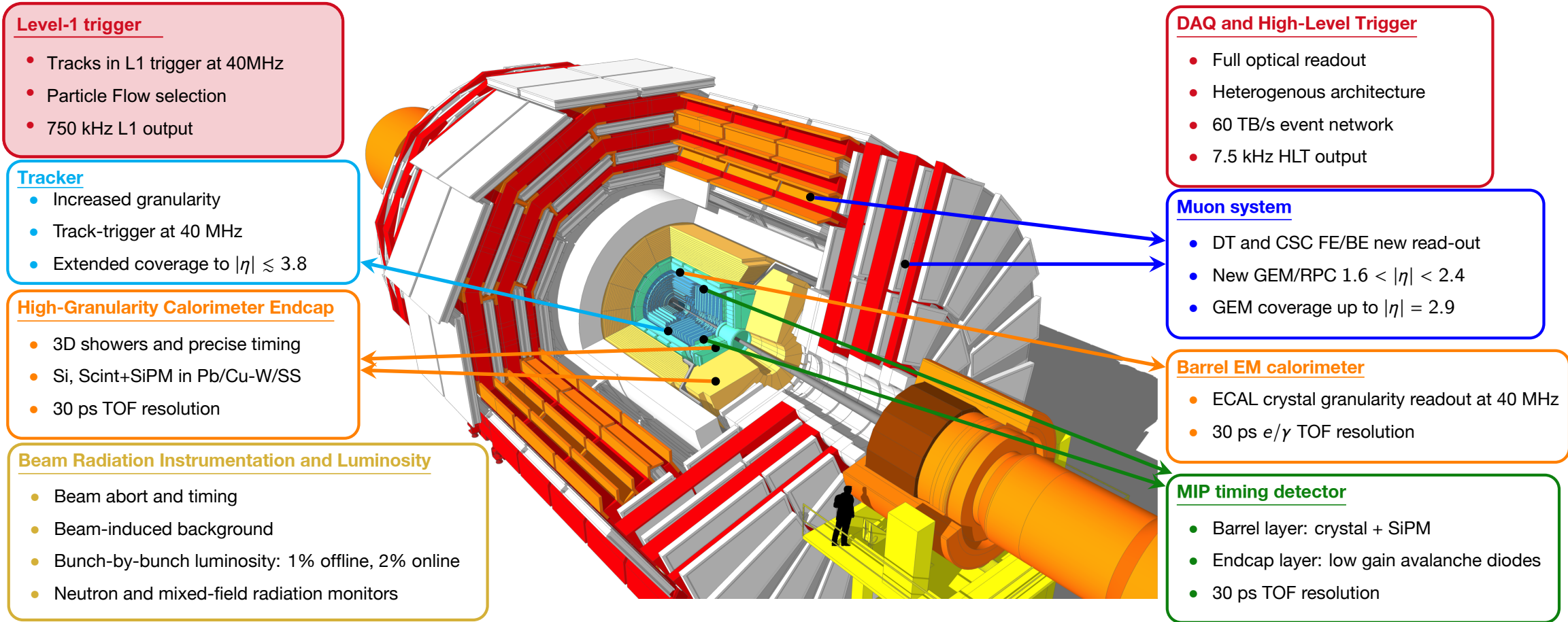- GEM coverage up to $|\eta| = 2.9$

Barrel EM calorimeter
- ECAL crystal granularity readout at 40 MHz
- 30 ps e/γ TOF resolution

MIP timing detector
- Barrel layer: crystal + SiPM
- Endcap layer: low gain avalanche diodes
- 30 ps TOF resolution
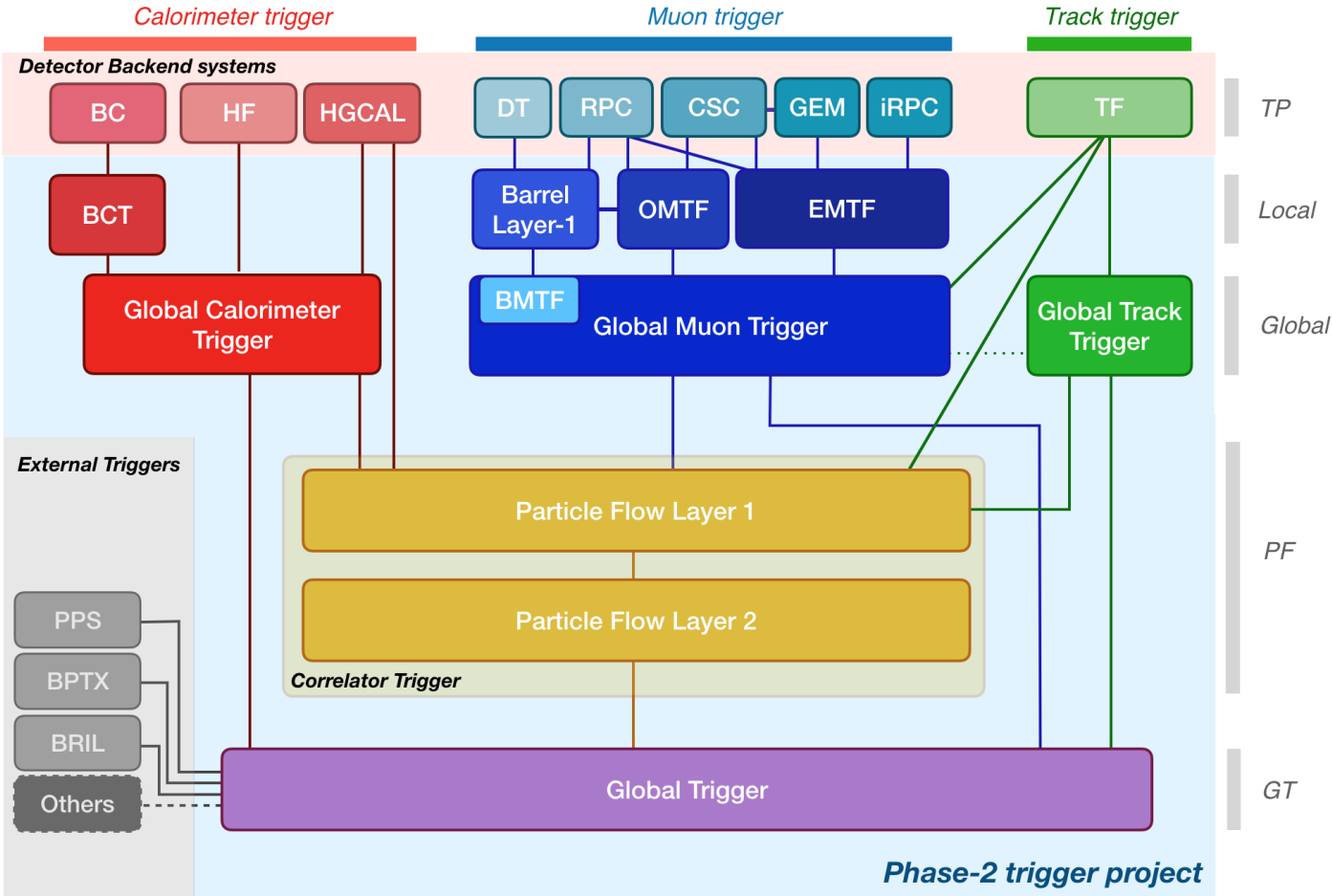
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CMS PHASE-2 LEVEL-1 TRIGGER

CMS PHASE-2 L1T

- The CMS Phase-2 L1T will have an increased latency of 12.5 μs and a rate of 750kHz.

- The increased latency allows for the inclusion of high-granularity data and tracker information for the first time.

- Key introduction of the Correlator Layer:
  - Development of state-of-the-art techniques for reconstruction and object analysis.
  - Improved object resolution, closer to offline.
  - Data path for tracking, calorimetry, muon systems.

- The CMS Phase-2 L1T will fully integrate the L1DS which will harvest the trigger objects produced at various levels.

Functional diagram of the CMS L1 Phase-2 upgraded trigger design [CMS-TDR-021].

CMS PHASE-2 LEVEL-1 TRIGGER DATA SCOUTING

CMS-TDR-021

CMS PHASE-2 L1DS

- The CMS Phase-2 L1DS architecture can scale and stage effectively, with each data source being acquired independently.
- Stage1: *scouting Global System* (sGS) and *scouting Decision System* (sDS).
- Stage2: *scouting Local System* (sLS) which can be added in later phases to further expand the system.
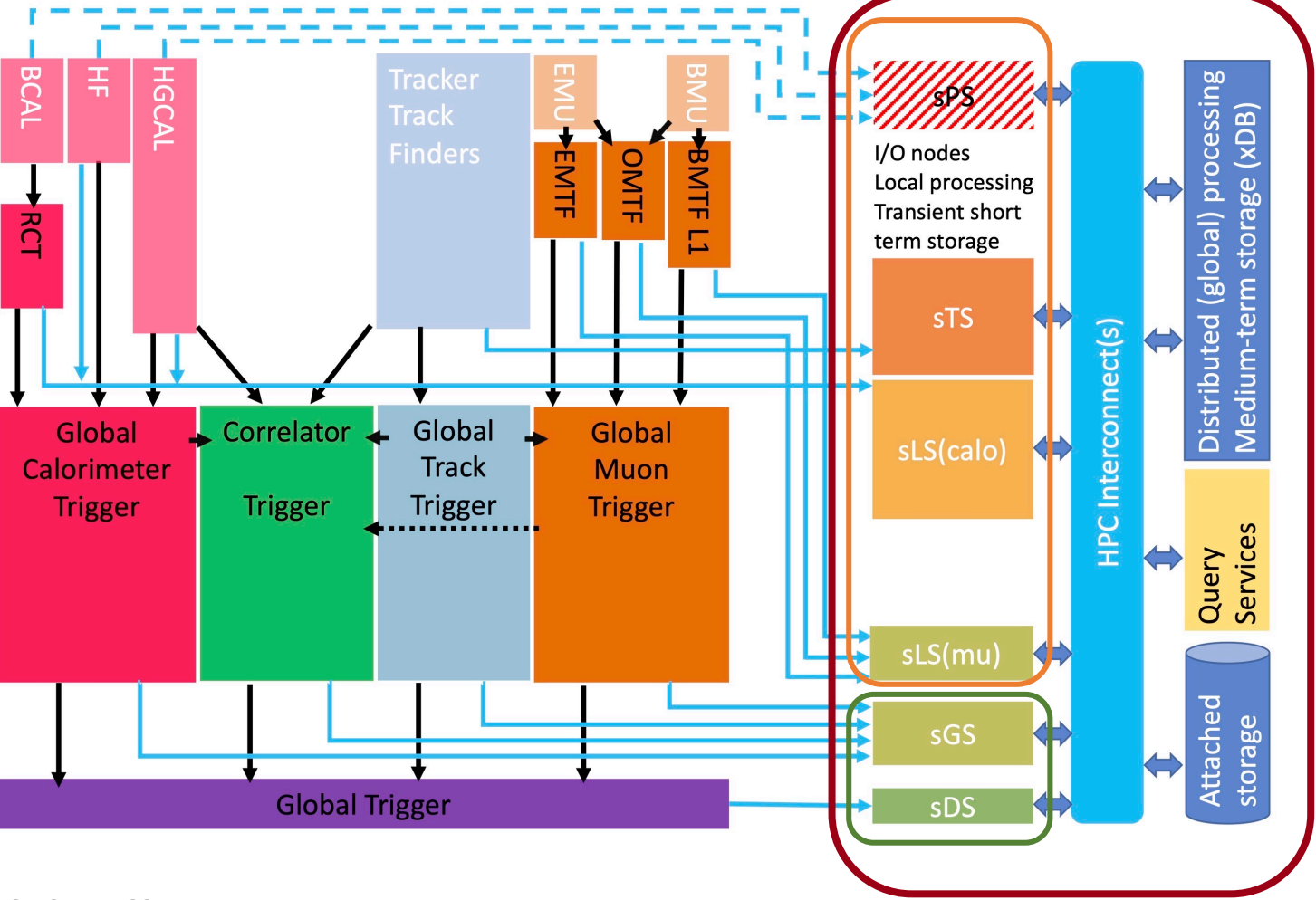
Scouting system	Source	Objects	Possible extensions
sDS	GT	Final decision word	
sGS	GTT	Vertices, track combinations with thresholds	Zero-suppressed list of input tracks
	GCT	Standalone calorimeter objects	
	GMT	Standalone muon objects	
	CL2	Correlator objects (jets, electrons, etc.)	Zero-suppressed PUPPI candidates
sLS	CL1	PUPPI candidates	Zero-suppressed PF candidates |η|≤3 instead

L1T objects collected by the CMS Phase-2 L1DS baseline system.

LEVEL-1 TRIGGER DATA SCOUTING FOR LHC RUN 3
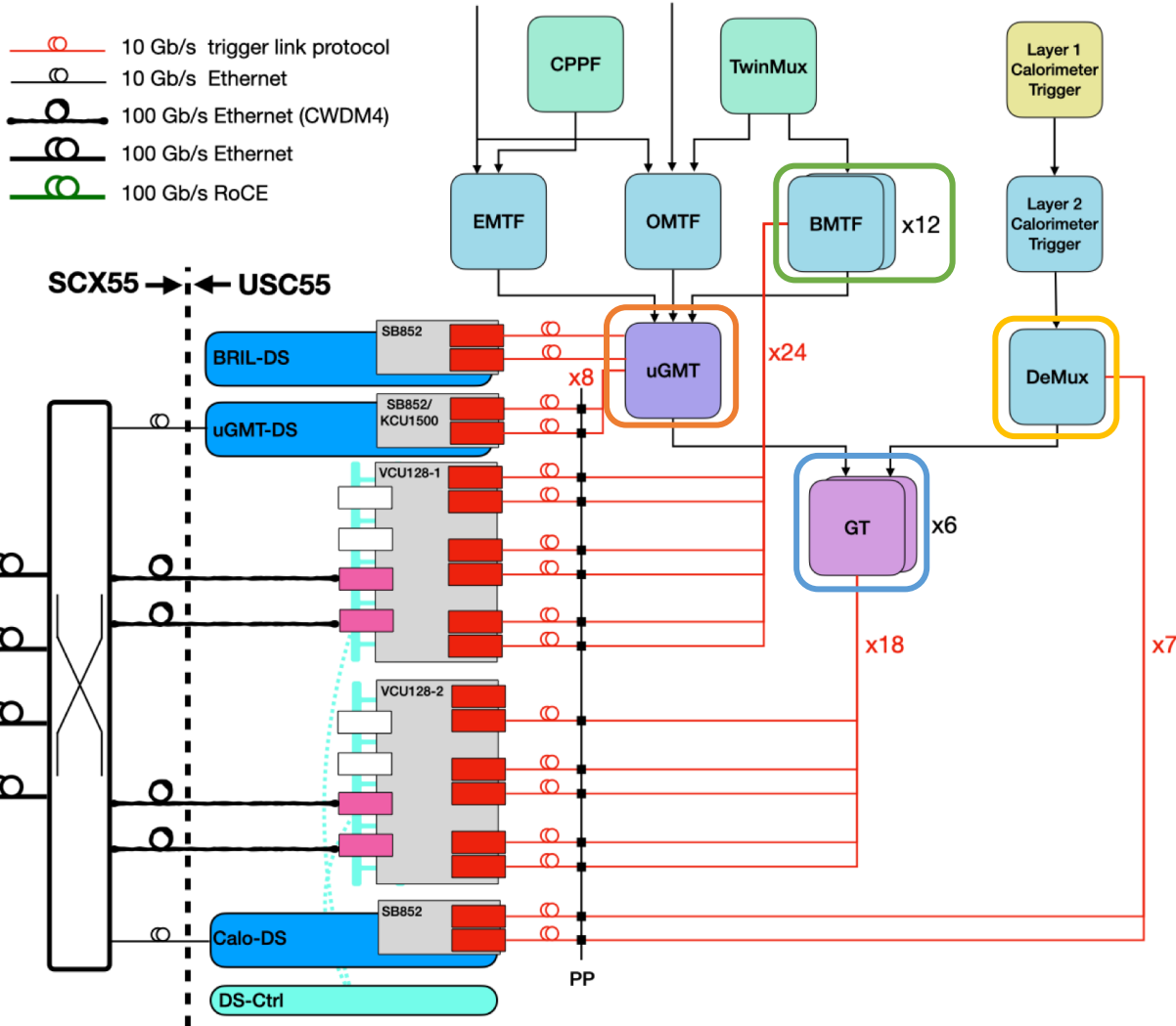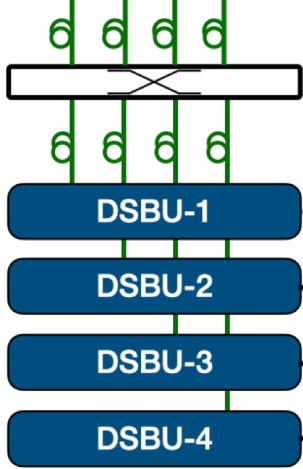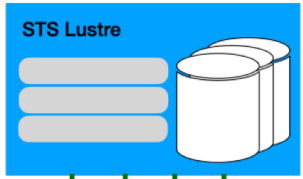
L1DS DEMONSTRATOR

- A L1DS demonstrator has been operational since the start of Run 3.
- It collects for every BX the L1T objects from four different sources.
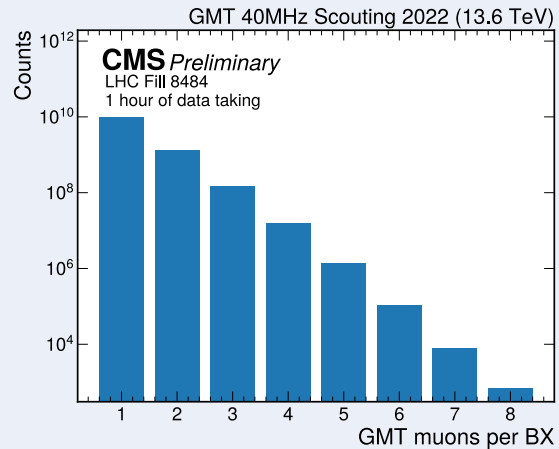
Global Muon Trigger (GMT)
Up to 8 muons

Layer-2 Calorimeter Trigger
Up to 12 jets, e/γ, τ, missing transverse energy, energy sums

Barrel Muon Track Finder (BMTF)
Stub primitives
[production planned for 2024]

Global Trigger (GT)
GT algorithm decision bits
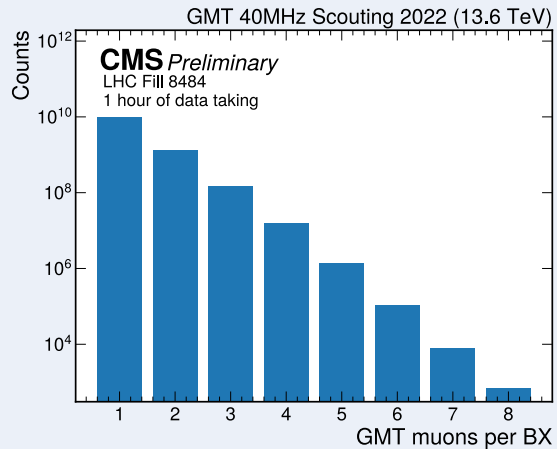[production planned for 2024]

PHYSICS AT 40MHz

Global Muon Trigger (GMT) muons multiplicity in the same bunch crossing (BX). The system captures up to 8 muons per BX from the GMT; the zero suppression removes the empty bunch crossings (bunch crossings with no muons recorded) [CMS-DP-2023-025].

L1DS POTENTIAL

L1DS collects L1 objects as reconstructed by the L1T at the collision rate performing on-the-fly analysis.

- Virtually unlimited statistics for trigger and detector diagnostics.
- Enables studies of otherwise inaccessible region of signals.
- Allows for systematic search of correlations among multiple contiguous bunch crossing:
  - Per-bunch luminosity studies
  - L1T pre/post-firing estimation

PHYSICS AT 40MHz

GMT 40MHz Scouting 2022 (13.6 TeV)

CMS *Preliminary*
LHC Fill 8484
1 hour of data taking

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PHYSICS CASES

Identify potential signatures unreachable through standard trigger selection processes.

- Rare decays: $W \rightarrow \pi\pi\pi$, $H \rightarrow \phi\gamma$ or $H \rightarrow \rho\gamma$.
- Multiple soft jets and displaced soft leptons.
- Heavy Stable Charged Particles (HSCPs) covering multiple BXs.
- Long-Lived Particles (LLP): e.g. displaced muons signatures.
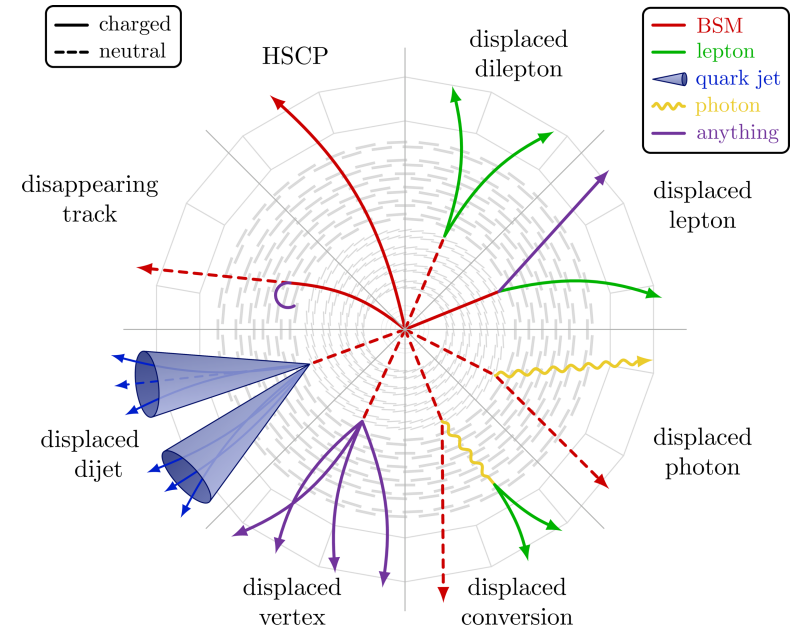
Signatures of long-lived particles in the CMS detector.

LEVEL-1 TRIGGER DATA SCOUTING FOR LHC RUN 3
RESULTS
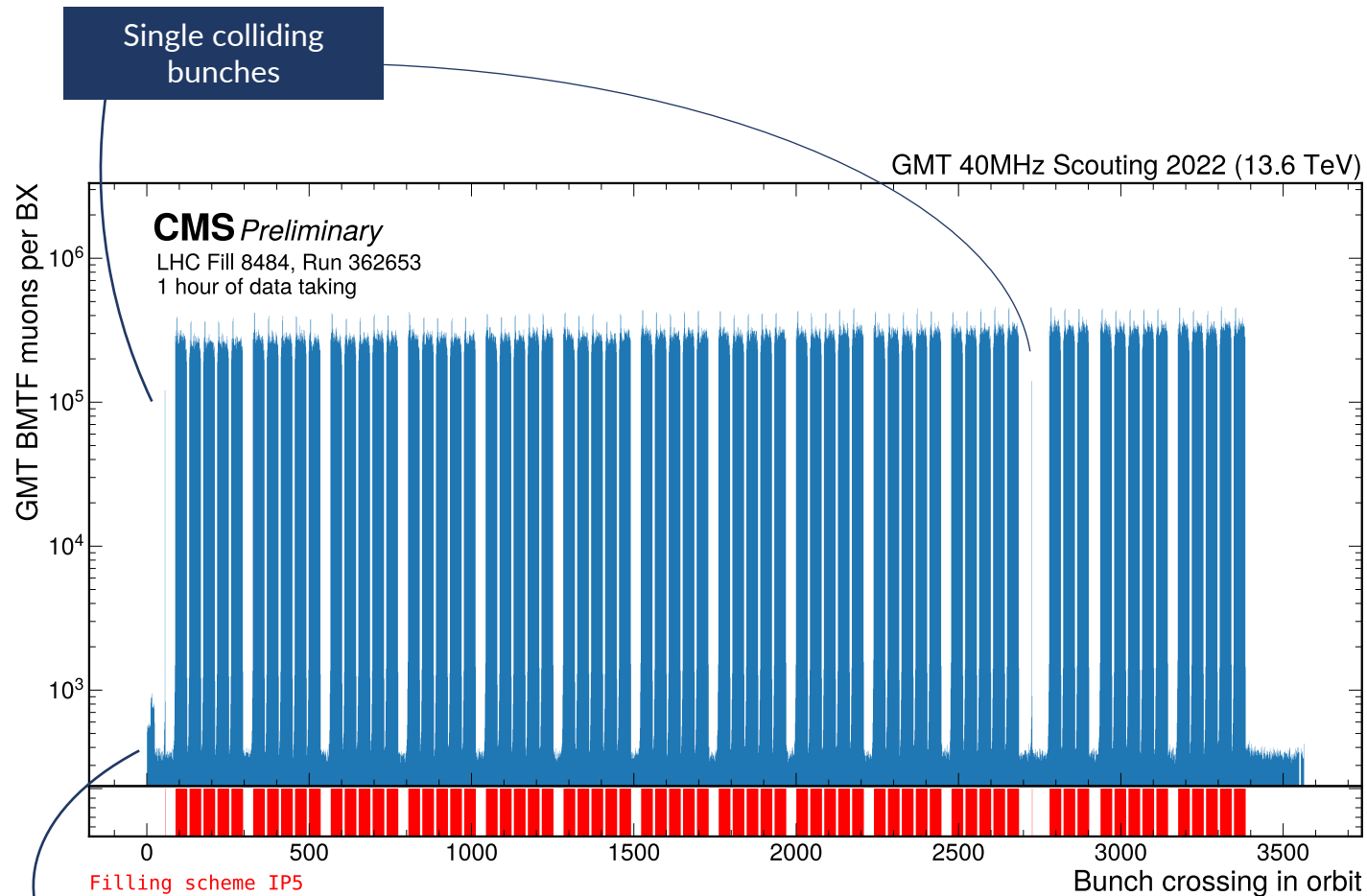
Global Muon Trigger (GMT) muons occupancy per bunch crossing (BX) within an LHC orbit for muons recorded by the 40MHz Scouting system in 2022 [CMS-DP-2023-025].

L1DS DATA

- The primary objective was to validate L1DS data.
- Ongoing characterization of the data collected during Run 3.
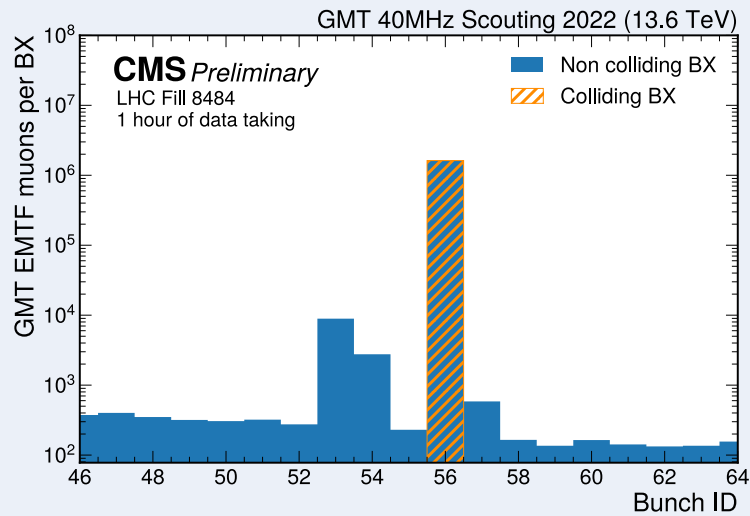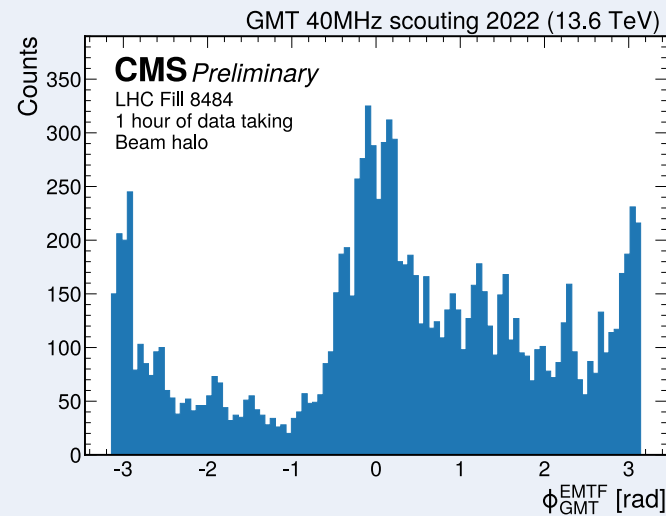
GMT MUONS

- Perform a study of the GMT muons across multiple bunch crossings.
- GMT muons occupancy per BX highlights the LHC filling scheme structure.
- An LHC orbit contains 3564 bunch crossings spaced at 25 ns.
- For LHC Fill 8484 we have 2450 colliding bunches in CMS.
- High rate: colliding bunches.
- Low rate: other contributions e.g. cosmic muons or beam halo.

RESULTS

Global Muon Trigger (GMT) muons occupancy per bunch crossing (BX) within an LHC orbit for muons reconstructed by the Endcap Muon Track Finder (EMTF) in the BX range [46,64]. The single isolated colliding bunch (BX 56) is highlighted by the orange transversal lines [CMS-DP-2023-025].
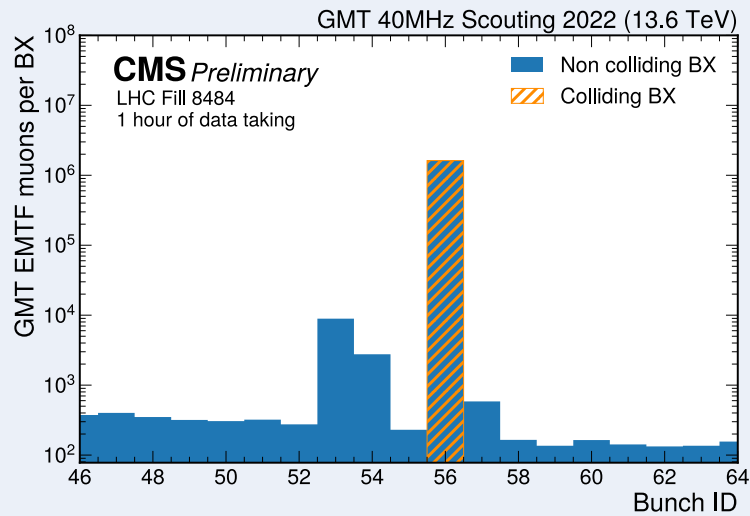
The distribution of the azimuthal angle ϕ for the GMT muons reconstructed by the Endcap Muon Track Finder (EMTF) for -3 and -2 bunch crossings (BXs 53, 54) before a single isolated colliding bunch (BX 56) [CMS-DP-2023-025].
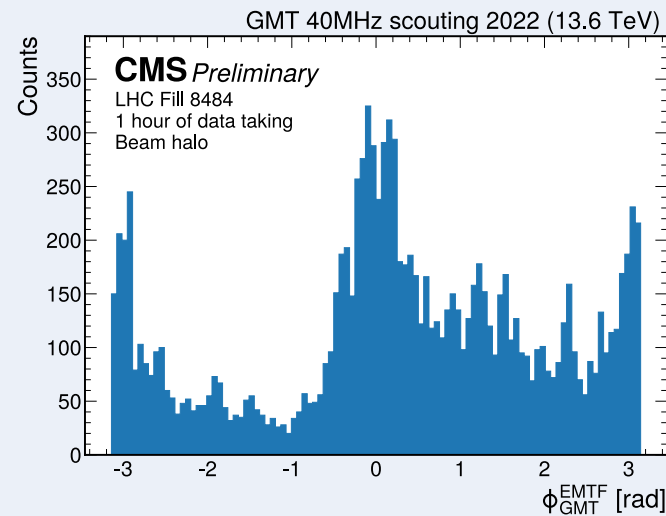
BEAM HALO EFFECT

- The beam halo is caused by the interaction of the beam with accelerator material and its flux is parallel to the beam line.
- The effect of the beam halo is particularly evident for an isolated colliding bunch for muons reconstructed by the EMTF: observe a "satellite peak" -2 and -3 BXs before the colliding bunch.
- In the "satellite peak", the muon ϕ distributions shows indeed a higher occupancy in a detector region corresponding to the accelerator plane ($\phi \sim 0$ and $|\phi| \sim \pi$).
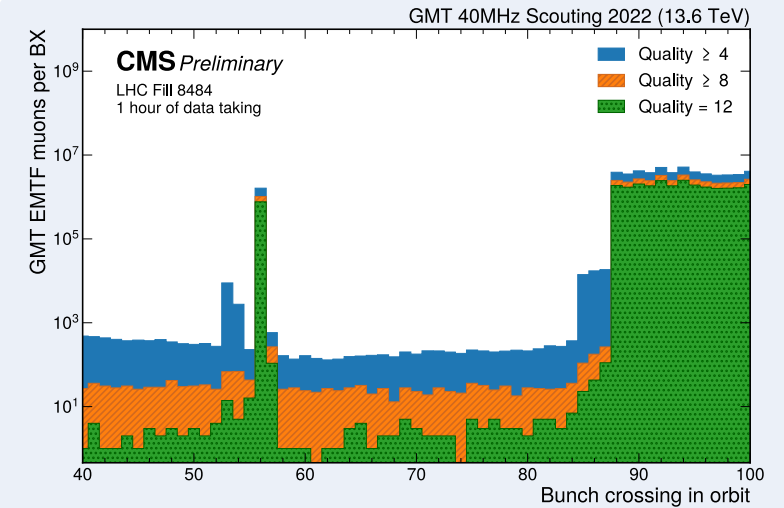
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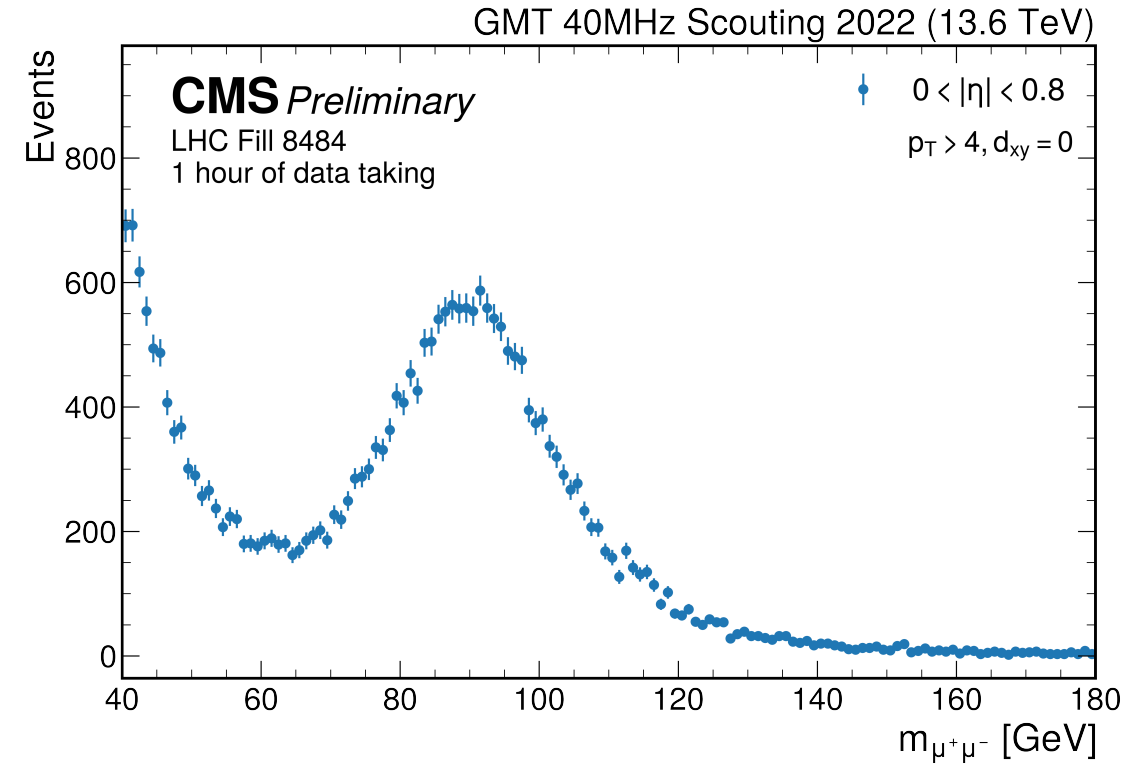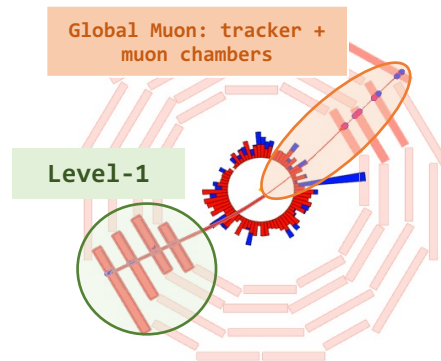
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- In the "satellite peak", the muon ϕ distributions shows indeed a higher occupancy in a detector region corresponding to the accelerator plane ($\phi \sim 0$ and $|\phi| \sim \pi$).

- The same effect of beam halo can be seen before a train of colliding bunches. Moreover, the beam halo becomes less noticeable as the muon quality Q improves (greater Q denotes a muon of higher quality).

DI-MUON EVENTS

- Study SM candles like the $Z \to \mu\mu$ as a means of validation.

- Select di-muons events and reconstruct the invariant mass spectra in the Z boson mass region.

- Events with only two muons per BX with $p_T > 4$ GeV and impact parameter $d_{xy}^{L1} = 0$ (≤ 40 cm).

- The limited resolution of L1T muons leads to a broader peak in the distribution:

  o L1T primitives lack tracker information.
  o Muon's momentum is calibrated to ensure trigger efficiency.

- Currently, there is ongoing work on developing machine learning algorithms on FPGA for muon recalibration [CMS-DP-2022-066].

GMT 40MHz Scouting 2022 (13.6 TeV)

CMS *Preliminary*
LHC Fill 8484
1 hour of data taking

$0 < |\eta| < 0.8$
$p_T > 4$, $d_{xy} = 0$

The invariant mass distribution produced from opposite sign pairs of GMT muons reconstructed by the Barrel Muon Track Finder (BMTF) as recorded by the 40MHz Scouting in 2022.

CONCLUSIONS

CMS LEVEL-1 TRIGGER DATA SCOUTING

- Presented the L1DS project and system architecture for the CMS Phase-2 Upgrade at HL-LHC.

- The potential of L1DS ranges across various domains, from trigger diagnostics to enhancing physics searches.

- Firmware and system development are already underway within the Run 3 demonstrator.

- Future work includes R&D on novel ideas for acquisition boards and processing units.

CMS LEVEL-1 TRIGGER DATA SCOUTING DEMONSTRATOR

- Serves as a proof-of-concept of scouting within the L1T.

- Preliminary results are providing insights on the Run 3 L1 objects, and they validate the L1DS as a significant tool.

- L1DS data are now centrally accessible within the CMS analysis framework.
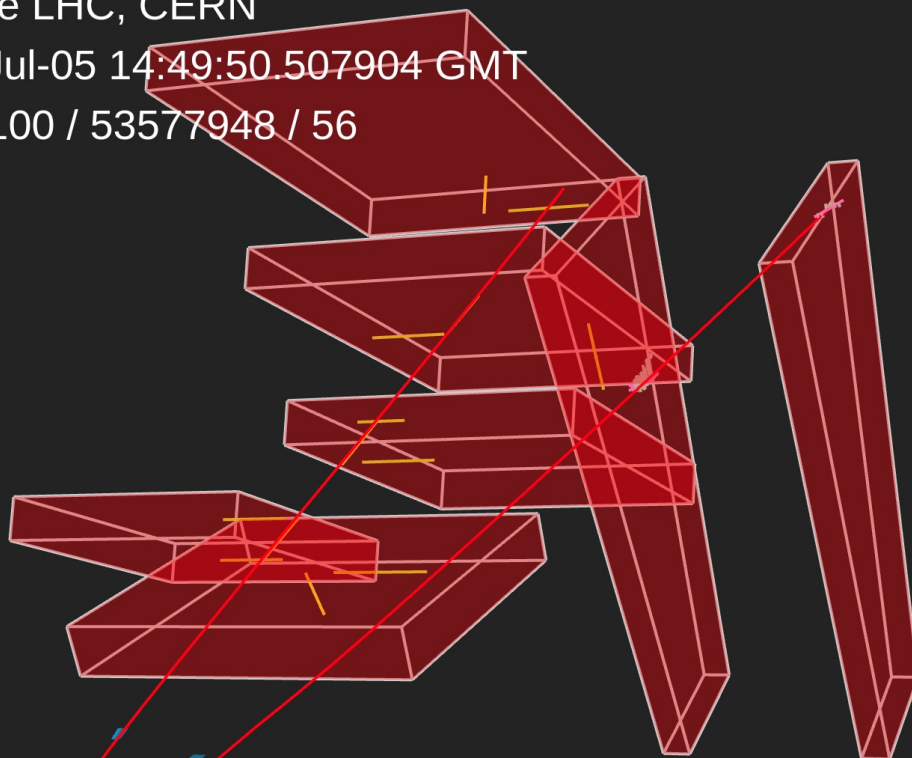
  ⇒ **Further studies and more results are on their way!**

Level-1 Data Scouting rack

THANK YOU!