CMS L1 Data Scouting for HL-LHC

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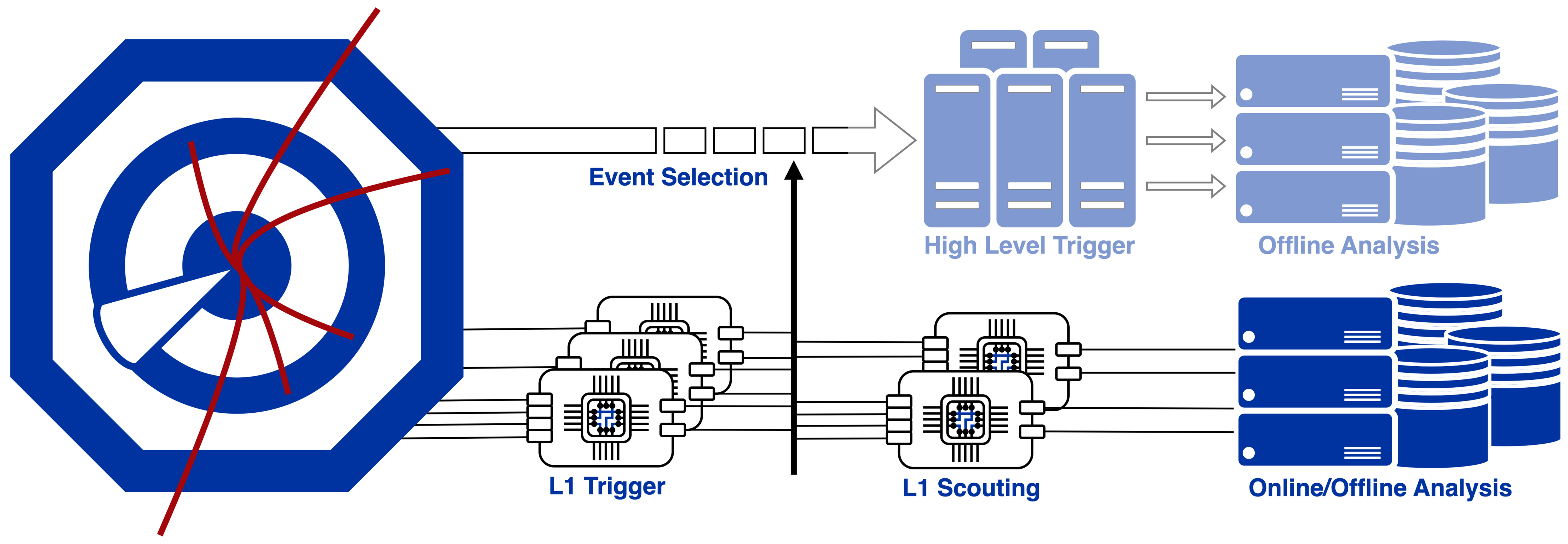
INTRODUCTION TO L1 SCOUTING

Collision events in the CMS experiment at the LHC are first processed by a hardware-based Level-1 Trigger system (L1T) to perform event reconstruction and select the most promising ones for data acquisition (DAQ) and further processing by the High-Level Trigger.
The upcoming high-luminosity run of the LHC (HL-LHC), reaching a peak luminosity of 7.5×10^{34} $cm^{-2}s^{-1}$ and up to 200 pileup interactions per crossing, entails a major upgrade of the CMS detector and the L1 Trigger event reconstruction. This enables the introduction of an alternative Data Scouting approach, where physics analysis is performed on all reconstructed events without a preselection.

The L1 Data Scouting System (L1DS)[1] **collects and analyses trigger objects** produced by the L1 processors at the accelerator bunch-crossing (BX) **rate of 40 MHz**. This enables:

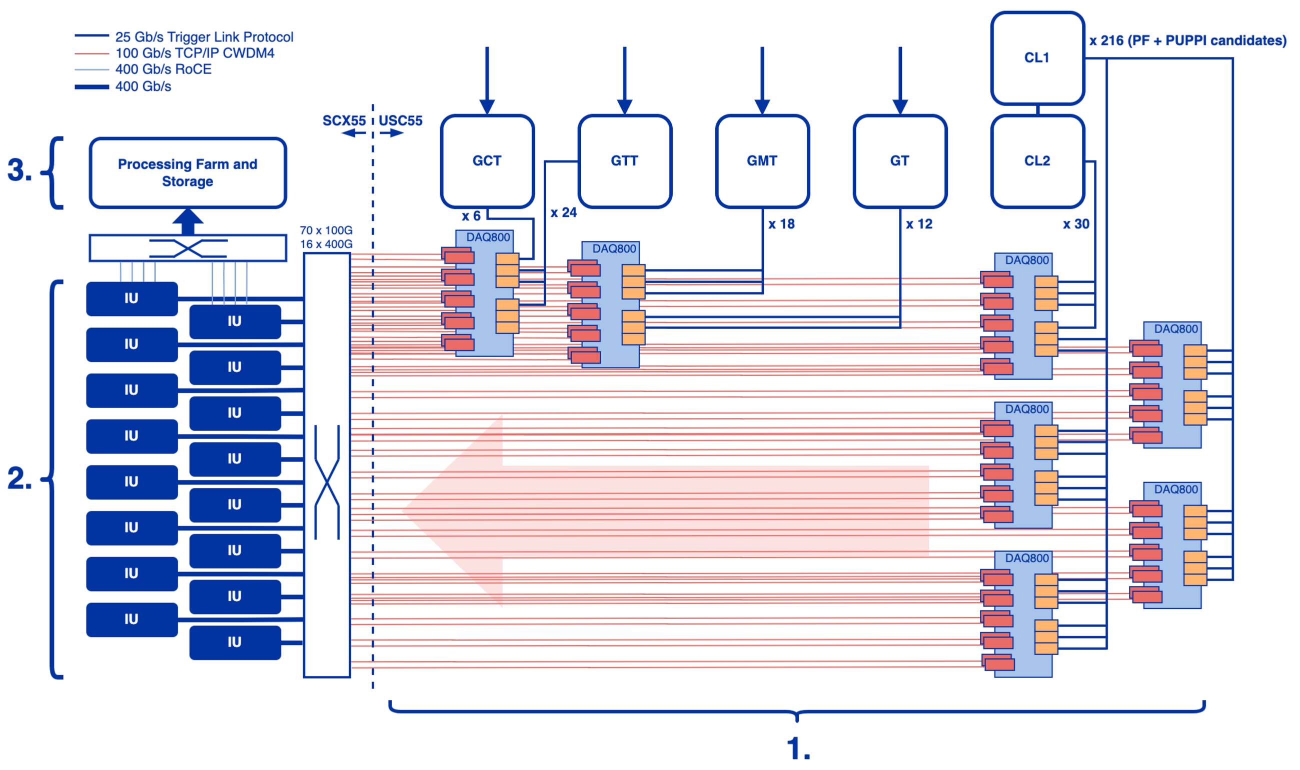
- **full access to physics** otherwise constrained by the L1T latency and max. accept rate dictated by the read-out bandwidth, the offline storage capacity and processing capability
- exploration of additional **exotic signatures**
- studying **correlations over several BXs**



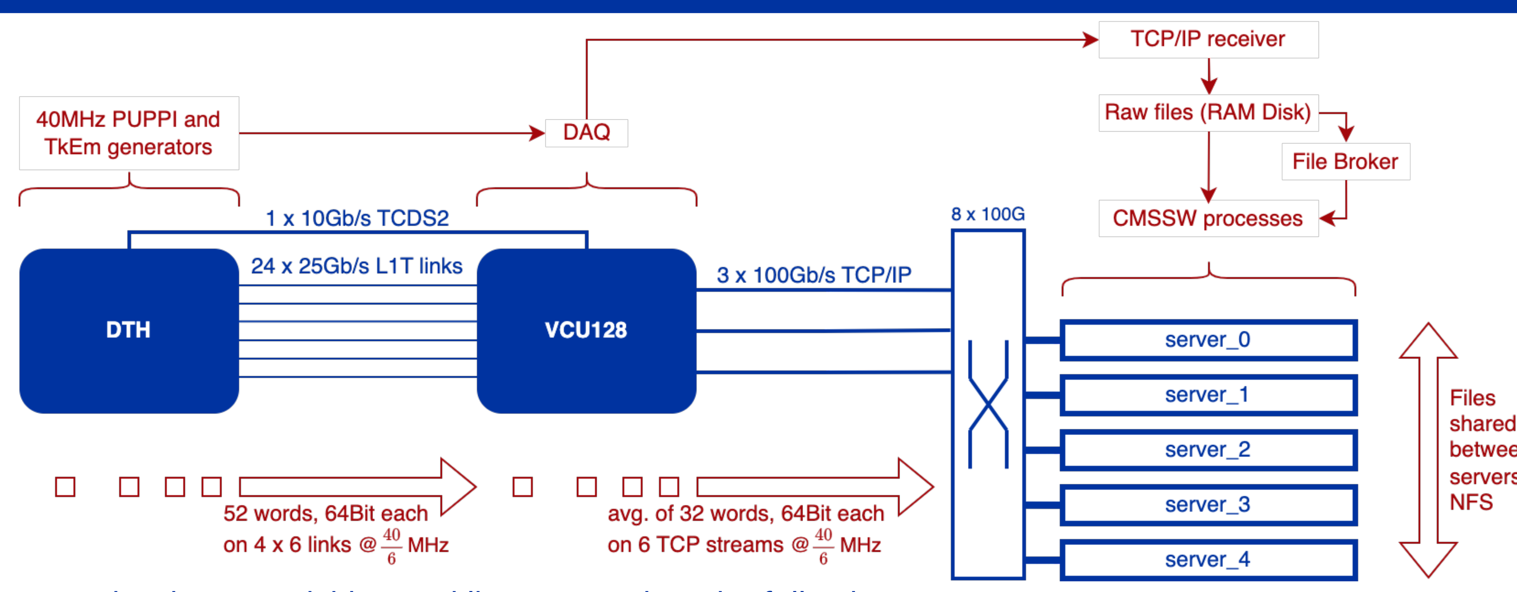
BASELINE ARCHITECTURE

In the baseline architecture of the L1DS system: [2]

1. **Custom electronic data aquisition boards** (DAQ800) with 2 Xilinx VU35P FPGAs, high bandwidth memory (HBM) and 800 Gb/s throughput are connected to the trigger boards via high-speed optical links **to capture trigger primitives** like:
   - calorimeter and muon objects from the global calorimeter trigger (GCT) and the global muon trigger (GMT)
   - tracker objects from the global track trigger (GTT)
   - PUPPI objects from the correlator layer 2 (CL2) and the final global trigger (GT)
   - (optionally) particle-flow (PF) candidates with and without PUPPI pileup subtraction from correlator layer 1 (CL1)
2. Ingestion Units (IUs) **aggregate data** into orbits and buffer for processing
3. Distributed **online processing** and physics analysis creates reduced data stream for permanent storage



DEMONSTRATOR SYSTEM

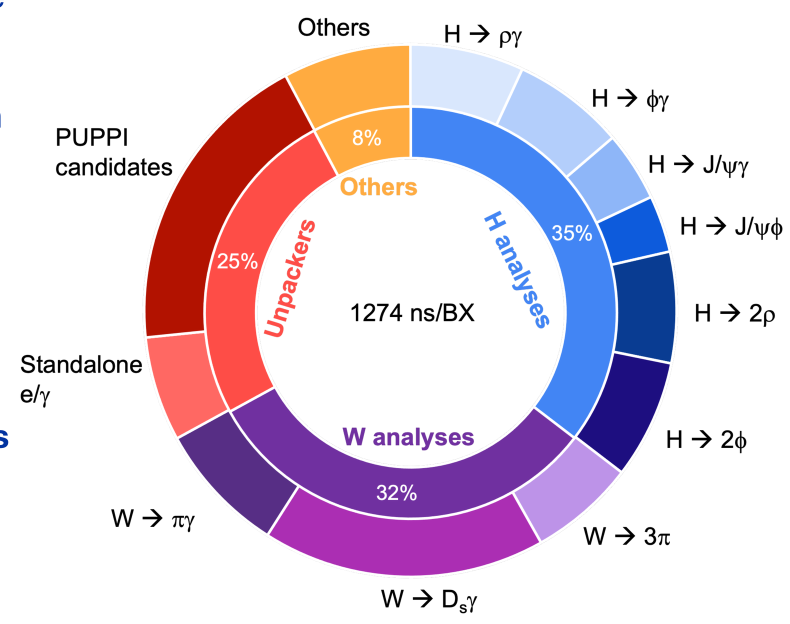


To demonstrate the data acquisition and live processing, the following setup is used:

- A **DTH P1 prototype ATCA board (2x KU15P FPGA)** to generate the TCDS2 clock and synchronisation signal and 6 data streams to simulate L1 PUPPI inputs
- A **Xilinx VCU128 development kit (VU37P FPGA)** as half of a DAQ800 board to demonstrate zero-suppression and transmission via TCP/IP on L1 PUPPI candidates
- A **100 Gb/s network switch** connecting the servers and the VCU128 outputs
- **5 servers** with one AMD EPYC 9654, 768 GB of RAM and 2x100 Gbit/s network card to run several prototype physics analyses in the L1 Scouting online processing framework CMSSW

On this setup, we **successfully demonstrated receiving up to 4 streams of events** (~27 MHz total frequency) of L1 PUPPI candidates and e/γ candidates (~12 GB/s data rate) and processing them with CMSSW **running 9 analyses** for rare W and H boson decays. [3]

Next to this setup, there exists also a demonstrator system that operates with real L1T objects. [4]

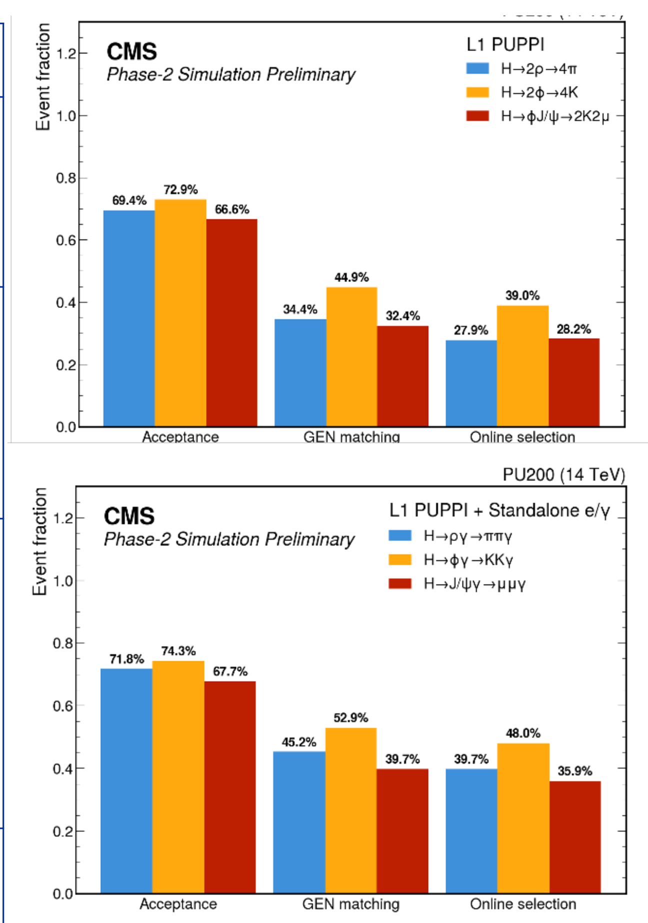


Distribution of the CPU time to run the demonstrator

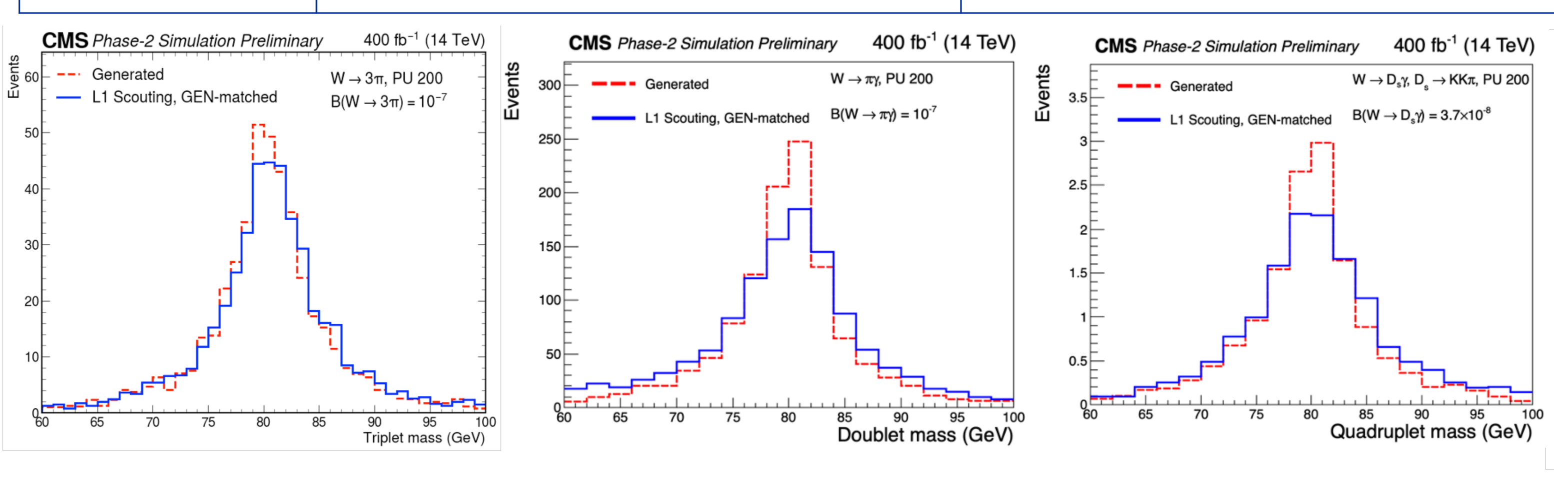
PHYSICS PERFORMANCE

Some of the relevant physics cases were studied using Monte Carlo (MC) data and a detailed simulation of the Phase-2 detector and trigger response. The underlying signals for the physics performance measurements are all simulated at leading order in perturbative QCD using MC event generator PYTHIA 8.212. For the W → 3π and the D_s → KKπ phase space decays are assumed. The background corresponds to a "minbias" sample at pileup 200, generated with PYTHIA 8.212. [3]

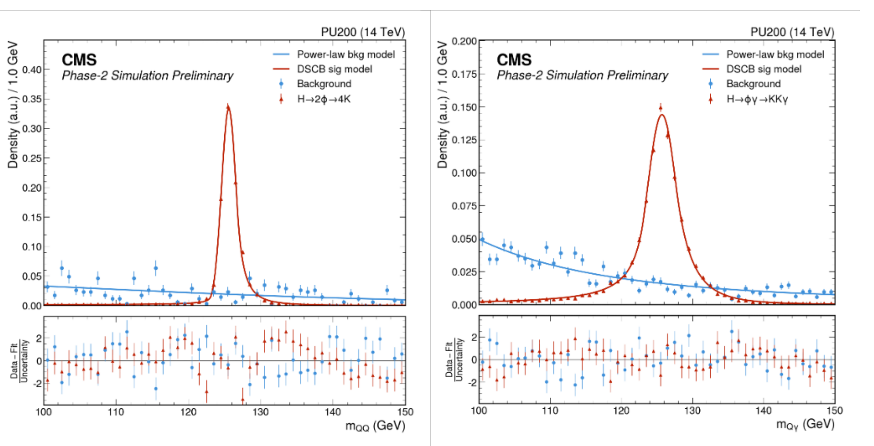
	W → 3π Analysis	**H → QQ and H → Qγ Analysis**	**B_s → ττ → (3π)(3π) Analysis**	**W → πγ and W → D_sγ Analysis**
Branching fraction:	10^{-12} to 10^{-8}, best upper limits at 10^{-6} [5]	10^{-10} to 10^{-4} [6]	7.7×10^{-7} [7]	10^{-9} to 10^{-7}, best upper limits < 1.5×10^{-5} [8] 4×10^{-8}, best upper limits < 6.5×10^{-4} [9]
Reason for not being selected by general-purpose L1T menu:	p_T thresholds for triggers based on hadronically-decaying taus or jets are too high	p_T thresholds on photons that significantly affect the H → Qγ acceptance and does not include algorithms that would select H → QQ events	Soft and collimated taus	p_T thresholds
Signal reconstruction:	Triplets of charged particles from L1 PF and PUPPI pileup-suppression	Quadruplet of charged particles from L1 PF and PUPPI pileup-suppression grouped into 2 highly collimated pairs (H → QQ). Triplet of L1 photon and a pair of close-by charged particles from L1 PF and PUPPI pileup-suppression (H → Qγ).	Through the τ → 3π decay by clustering 6 charged particles from L1 PF and PUPPI pileup-suppression in a cone with size of 0.3 using Density-Based Spatial Clustering of Applications with Noise (DBSCAN)	Doublet of L1 photon and one charged particle from L1 PF and PUPPI pileup-suppression (W → πγ). Through the W → KKπ decay channel by searching for quadruplets of L1 photon and 3 charged particle from L1 PF and PUPPI pileup-suppression (W → D_sγ).
Efficiency (within acceptance):	53 %	40% to 54% (H → QQ) 53% to 65% (H → Qγ)	-	Up to 49% (W → πγ) Up to 26% (W → D_sγ)

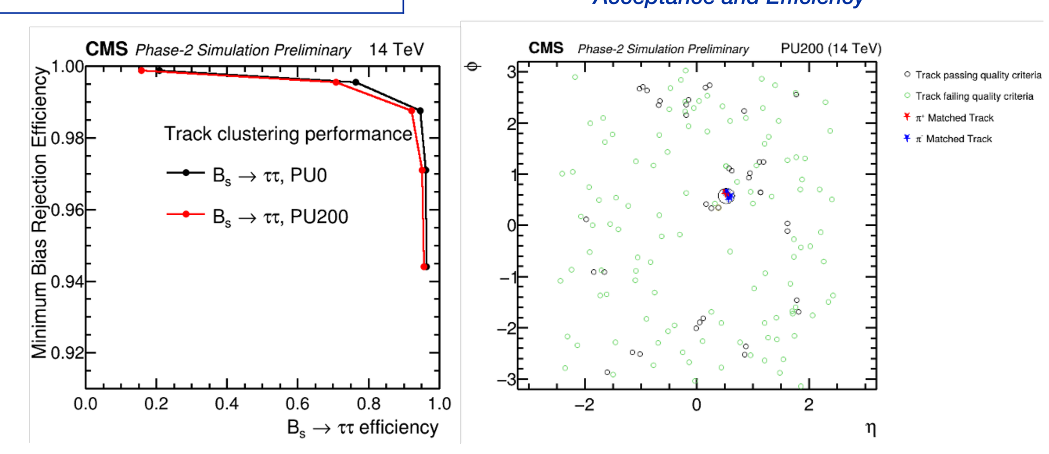


Acceptance and Efficiency



Invariant mass distributions





Signal efficiency and background rejection rate for the track clustering (left) and track-finder track distribution for a single B_s → ττ signal event (right)

References

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[9] LHCb Collaboration, "*Search for the rare decays $W^+ \to D_s^+\gamma$ and $Z \to D^0\gamma$ at LHCb*", Chin. Phys. C 47, 093002 (2023), https://dx.doi.org/10.1088/1674-1137/aceae9

NexTGen
Next Generation Triggers