Next Generation Triggers for CMS

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For the CMS L1T & HLT teams

NGT BSM Miniworkshop - 04.07 2025
Evolving beyond the Standard Model 30.06-11.07 2025

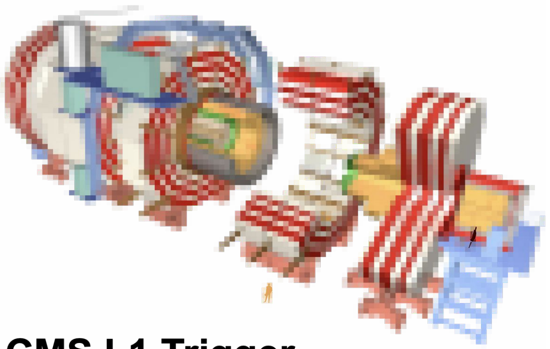
Outline

- **The current CMS Trigger system, the upgraded system (Phase-2) for HL-LHC, and the Next Generation Trigger (NGT) project for HL-LHC**

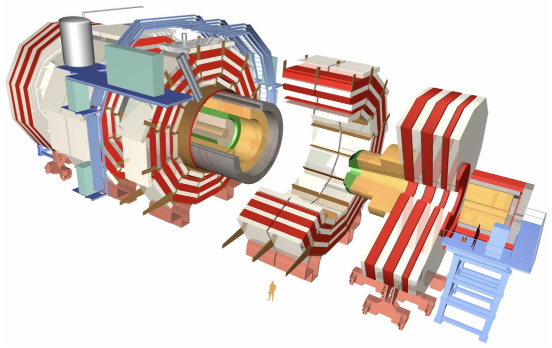
- **Beyond the baseline CMS Physics Program for full hadronic & soft final states, compressed spectra, small coupling and/or heavy mediators**
  - From Run-3 HLT Scouting/Parking strategies to NGT HLT
  - From current L1T acceptance to NGT L1T acceptance

- **New Run-3 triggers for Long-Lived particles (LLP) & new prospects at HL-LHC thanks to upgraded sub-detectors**

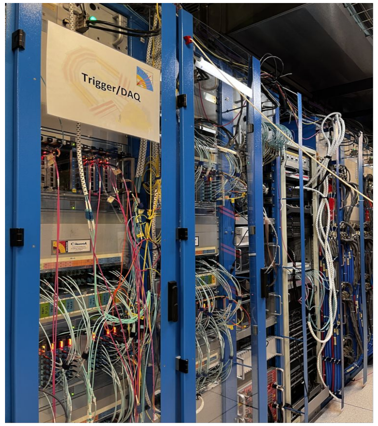
The CMS Trigger System (design)

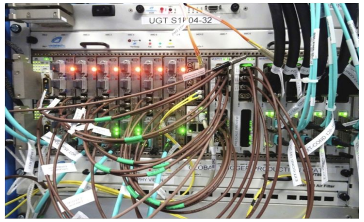


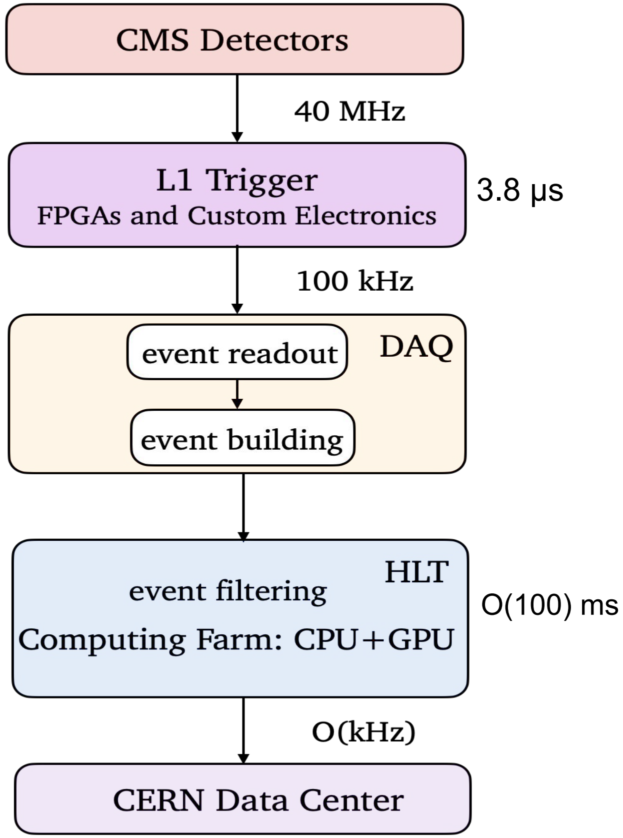
CMS L1 Trigger



CMS High Level Trigger

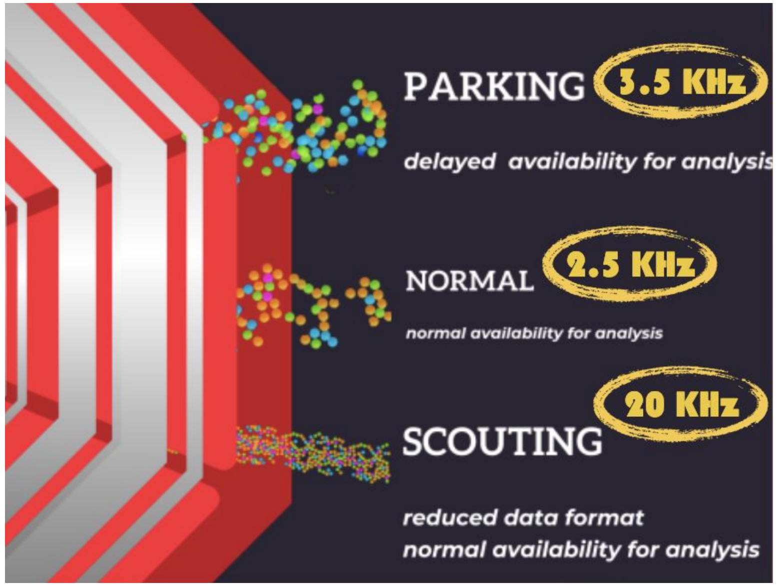




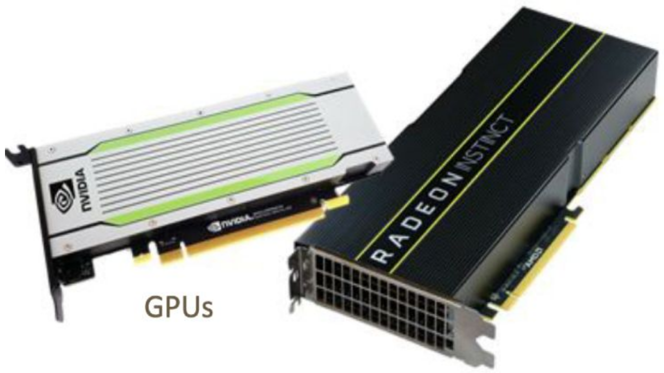


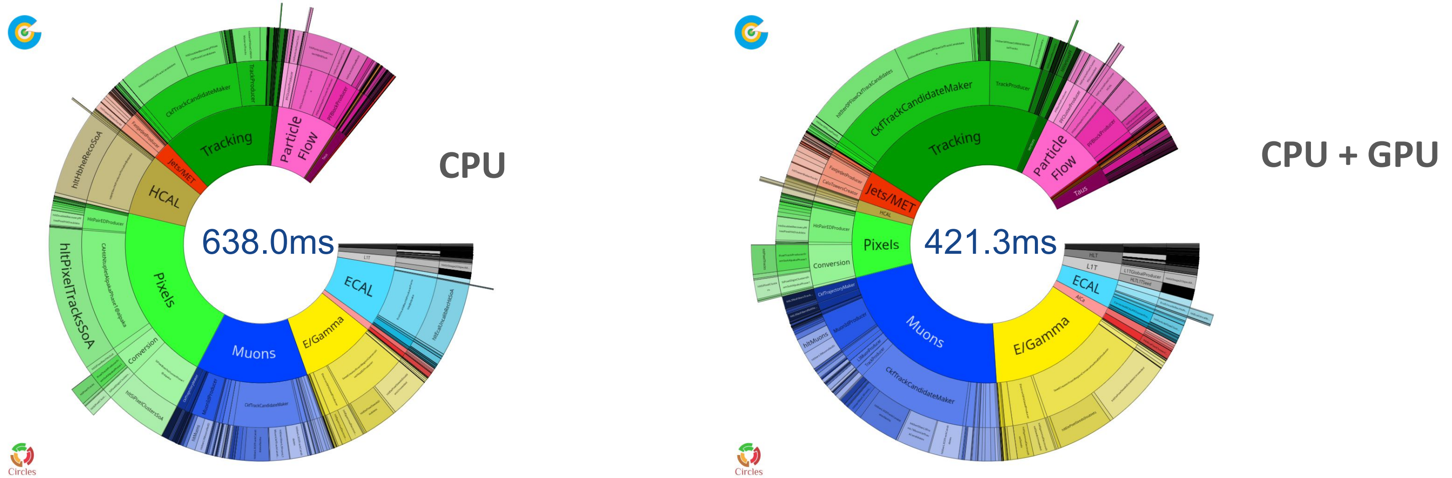
- **Perfect compromise between technological limitations and theory motivating new physics at O(100-1000) GeV scale with ewk-like cross sections**:
    - **99.75%** events rejected at **L1T**, **98%** rejected at **HLT**

The CMS Trigger system (now)



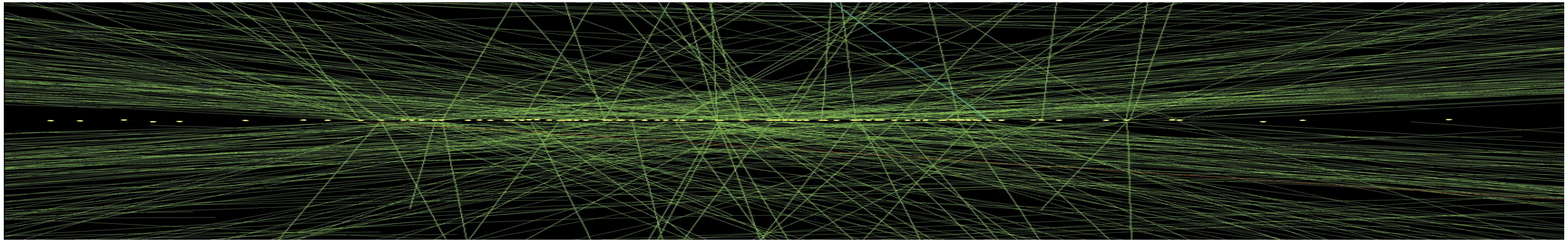
- **After Higgs boson discovery and null results of new physics searches in Run 1 and 2:**
  - Run-3 trigger strategies pushed much further the potentialities of the CMS Data Acquisition system with: **Parking**, **HLT Scouting**
  - Enlarged acceptance for **Low mass resonances (di-μ, di-jets)**, **B-physics, VBF, Long-Lived particles, HH production**
  - Thanks to these new ideas & heterogeneous computing at HLT



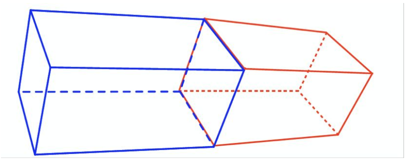


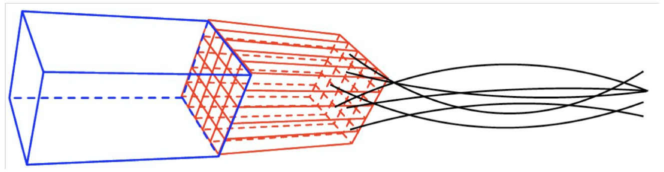
The CMS Trigger system for HL-LHC

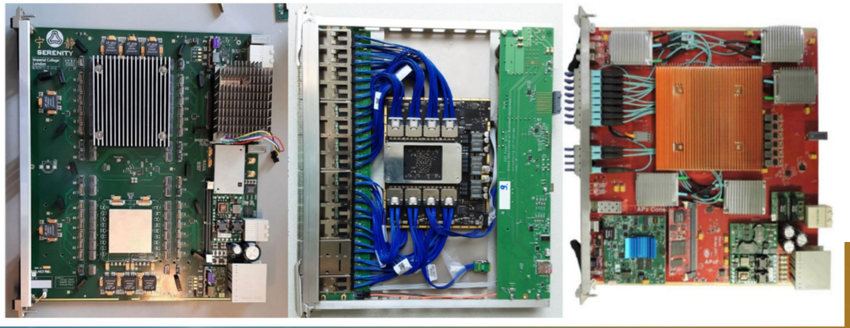
- At HL-LHC, up to 200 pile-up (PU) interactions: **CMS is upgrading the L1T and HLT to enable the same physics program we are doing now (at @60 PU)**



- **New CMS L1T:**
  - input data from 2 Tb/s to 63 Tb/s **(~1/10 of the internet traffic)**: for the first time **tracking at 40MHz** (p_T>2 GeV) & higher granularity from Calo/Muon **(no pixels!)**
  - much **more powerful FPGAs**: 7.5x more resources
  - 12.5μs to take decision, **750 kHz to HLT**

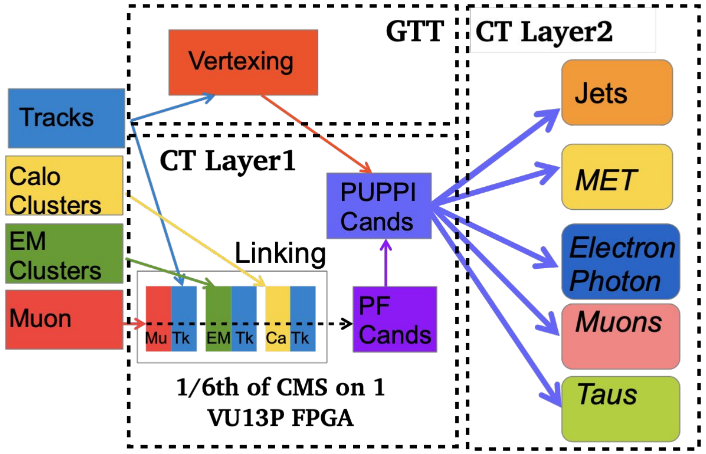


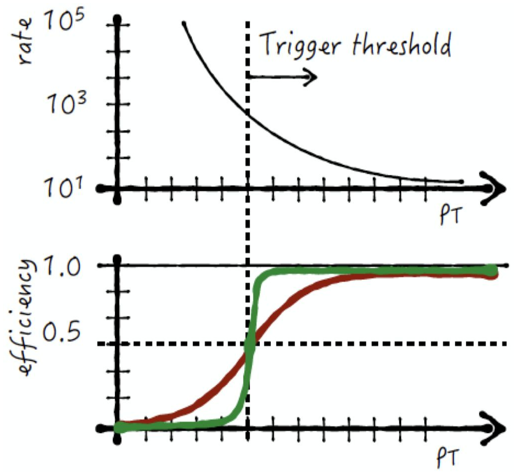




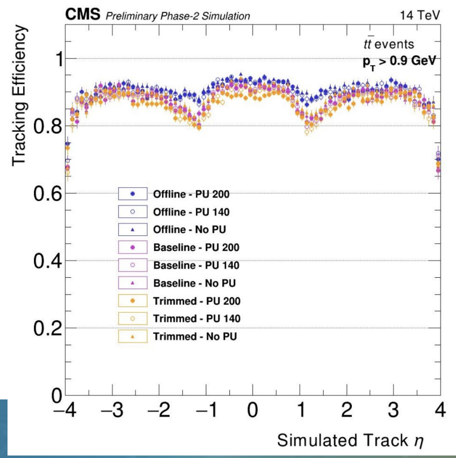
The CMS Trigger system for HL-LHC

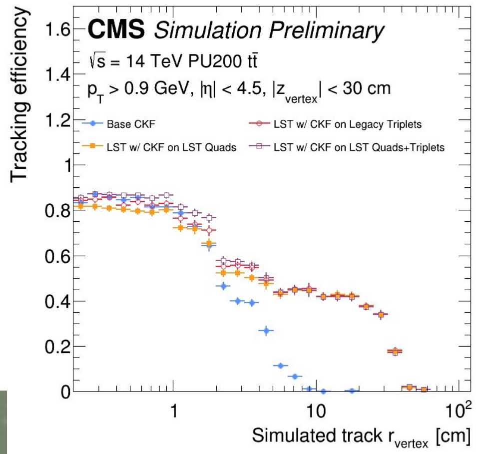
- **At L1T Offline-like algorithms into FPGAs: thanks to higher granularity and powerful hardware**
  - **Track matching:** sharpened μ turn-on, electron identification, γ/e/μ isolation
  - **Particle Flow**: ultimate performance for jets/E^{T}_{miss}/τ_h
  - L1Tracks→vertexing→**PU mitigation (PUPPI)**
  - **FastML: tools to synthesise NN/BDTs into FPGAs**



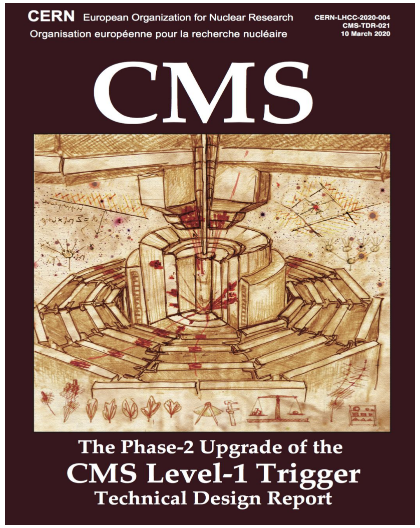


- **At HLT: reduce 750 kHz to O(10)kHz with new algorithms that allow offloading to heterogeneous computing up to 80% and reduce processing time**
  - **TICL (The Iterative CLustering)**: for fast particle flow reconstruction using the High Granularity Calorimeter **(HGCAL)**.
  - **LST** (line-segment-tracking): specifically designed to parallelize the charged hadron pattern recognition on **GPUs**
  - **Trimmed Tracking**
  - …



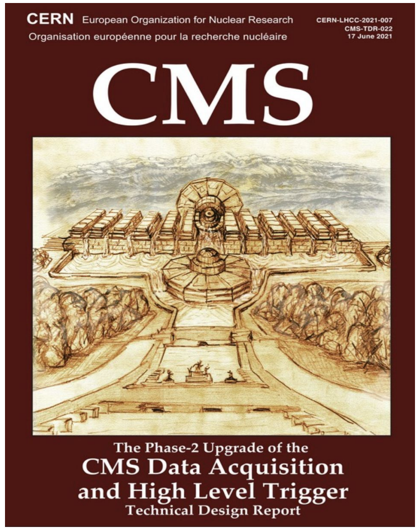


The CMS Trigger system for HL-LHC



[HL-LHC L1 Trigger Technical Design Report (2020)]

[Detector Performance Notes with most recent updates]



[HL-LHC High Level Trigger Technical Design Report (2021)]

[Detector Performance Notes with most recent updates]

Rethinking the HL-LHC CMS Real-Time data processing with NGT

- **But what if New Physics doesn't look as expected, and it's instead buried under the bulk of the background events we are throwing away due to the trigger selections?**

Redesign the data collection and scouting strategy to **reduce the need to reject events in the Level-1 and High-Level triggers** aiming at complementing the current workflows:

At Level-1: develop an advanced Scouting workflow that, profiting from the increased granularity and flexible architecture of the Phase-2 CMS experiment, **can allow to perform trigger-level physics analyses at 40 MHz**

At HLT: replace the trigger filtering task with an event processing task **similar to what happens with offline** events stored on disk.

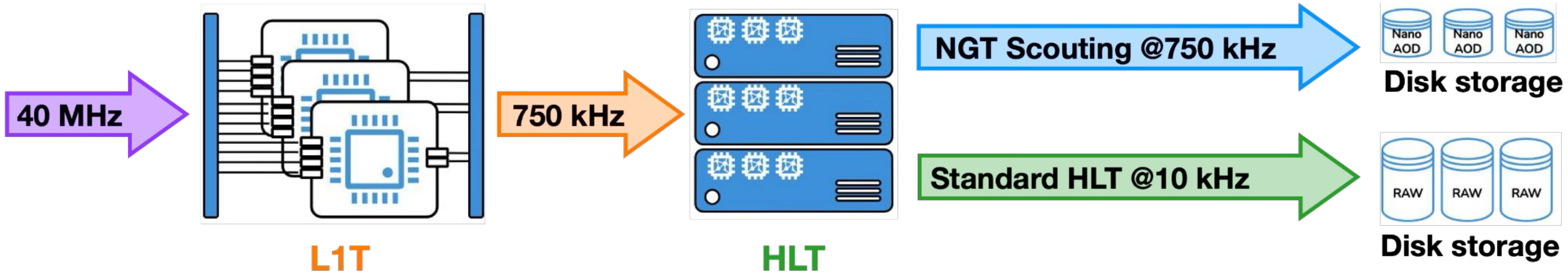
Leverage traditional physics-based algorithms and **advanced AI solutions** to more efficiently select signal processes: **both in hardware and software triggers!**

To extend the CMS discovery and precision measurement reach in those are that were not the original focus: strong interaction & full hadronic final states, compressed spectra, small coupling and/or heavy mediators, LLP

NGT @ HLT

Goal is NGT Scouting:

be able to reconstruct with offline-like quality and save in physics-oriented data-format the full 750 kHz of input data



3.1.1 R^3 faster reconstruction

Improve the physics quality and reconstruction throughput of selected physics objects by leveraging heterogeneous architectures:

- **not only pixel tracks (Patatrack) but also for electrons and photons, taus, jets, MET, and Particle Flow;**

3.1.2 Optimized data structures

Development of data-oriented structures ("Structure of Arrays", SoA) to achieve

- better memory bandwidth and vectorization performance
- provide a seamless interface to AI algorithms

3.2 Towards a distributed architecture

Extend CMSSW to a fully distributed application to achieve more flexibility in the design of the HLT farm:

- independently scale the amount of CPU and GPU processing power;
- support different kind of accelerators, like GPUs and FPGAs.

3.3 Reduction of the RAW data size

RAW data-size: limiting factor in the amount of data that HLT can select for storage and further processing:

- characterize multiple approaches to the **compression of RAW data**
- study trade-offs between compression factor, latency, available hardware, impact on physics results.

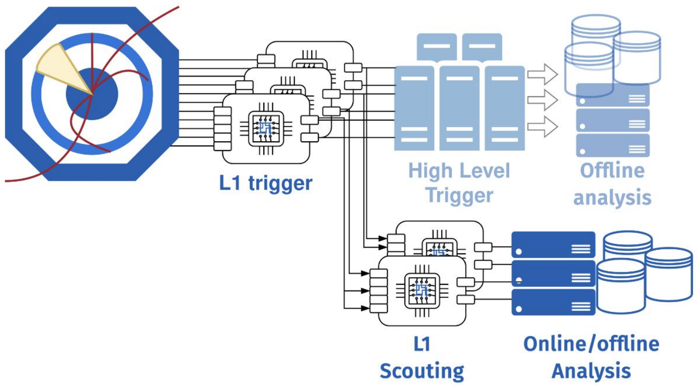
3.4 Optimal Calibrations

Optimise the calibration procedures for the online HLT data-taking, pushing real-time analysis to the same accuracy we do have offline

- run optimized **(fast) online calibrations** and inject them for final HLT reconstruction

NGT @ L1T

3.5 Enhancing the L1T Scouting for HL-LHC

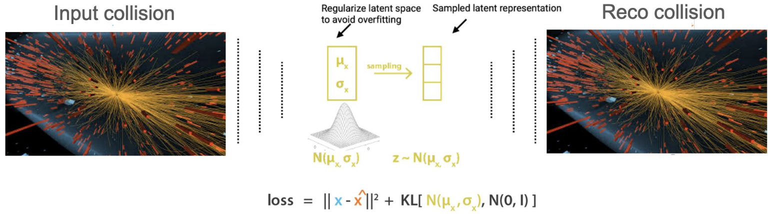


- **Acquire and analyse the L1 Trigger information for all events (at 40 MHz)**
- Look for physics signatures identifiable with **just L1 information** but that would evade the L1T → HLT → Offline chain
- Profit from **high granularity & improved reconstruction at L1T**
- Built a demonstrator of increasing bandwidth and processing power to test **prototype analyses of increasing complexity**

3.6 Practical real-time AI for L1T

- **Advanced Fast-ML algorithms for improving the HL-LHC L1T reconstruction** (increased acceptance for standard triggers, and L1 Scouting)
- **Develop MLOps:** updating & redeploying algorithms for changes in detector conditions, tracking, archiving & retrieving ML models (e.g. for consistent emulation)

3.7 L1T Anomaly Detection

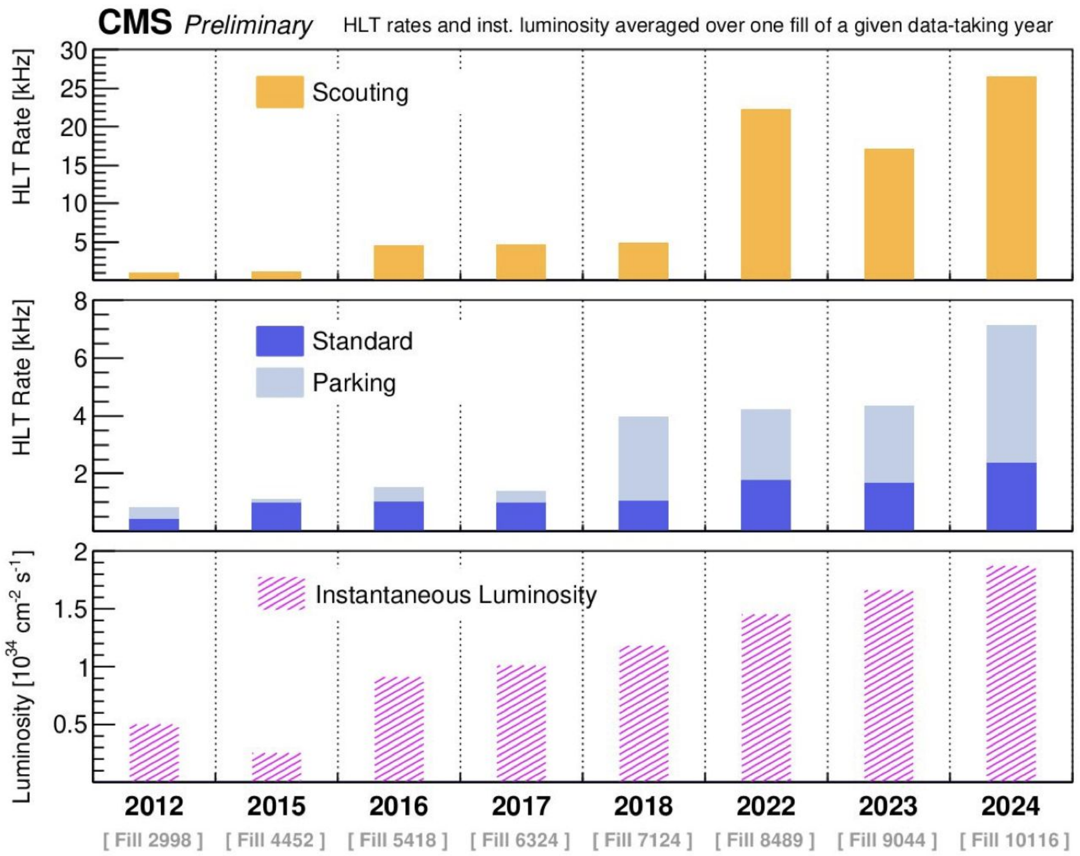


- Push technology to **trigger on "anomalous" events using ML unsupervised models (sub-μs autoencoders)**
- **First model AXOL1TL in data-taking since last year:** learn how to perform physics analysis, MLOps
- **Developing an upgraded model tailored to particle level info of Phase 2 trigger system**

From the new Run-3 HLT opportunities to NGT HLT

HLT Scouting and Parking in LHC Run 3

- **The innovative Scouting & Parking strategies have been deployed since Run 1 into the CMS Data Taking system**
  - **Data Parking: data saved in raw format, full reconstruction eventually postponed at a later time when computing resources are available (Promptly reconstructed since start of Run 3!)**
    - more than doubled the standard HLT rate thanks to parking
  - **Data Scouting: trigger level analysis with real-time processing by the HLT computer farm and minimal object information stored**
    - rate x10 times larger than standard HLT rate
    - ~30% accepted by L1 trigger saved as scouting



[Run 3 CMS Scouting & Parking paper](#)
[2024 DP Note](#)

HLT Scouting and Parking in LHC Run 3

- **Run-3 program much more powerful: new data streams & much lower thresholds**

Data Scouting Streams

- **Dimuon, Jet/H_T , Single μ, Single γ, Double e/γ, Anomaly Detection, ZeroBias**
- **HLT objects that can be used in analysis:**
  - **HLT μ reco with/without vertex constraint** (acceptance up to ~100 cm)
  - **HLT e/γ** (still to develop offline-like ID/pT-regression/scaling for analysis usage)
  - **HLT jets (from PF candidates with PV constraints)**
    - not-yet flavour tagging online, under validation offline: good performance can be achieved
  - **All PF candidates (with PV constraints)**
    - offline τ_h reco on top of PF candidates
- **Main differences wrt offline reco:**
  - **no full tracking/PF from all primary and secondary vertices** (trimmed collection of pixel vertices based on minimal quality requirements: full tracking run only for pixel tracks associated to the reduced set of vertices, ~3), **no MET cleaning** (MET not usable), **no offline-like PU subtraction, no rereco** (for better calibrations)

Data Parking Streams

- **Dimuon, Single μ, VBF, LLP, HH**
- **Objects reco & quality: offline reco**

Run-3 Scouting/Parking thresholds vs standard HLT

- **Run-3 program much more powerful: new data streams & much lower thresholds**
  - most relevant reduction of HLT thresholds achieved throughout Run-3:

Double muon:

L1: two muons with p_T>3 GeV & $|\eta|$<2.0 & ΔR<1.6 (+ many other triggers)

HLT: many triggers targeting specific decay (eg. Jpsi, Y, Onia, …)

Parking: muon p_T> 4, 3 GeV & same vertex & 0.2 < mass($\mu\mu$) < 8.5

Scouting: **no additional filter**

Single Muon:

L1: Muon p_T>22 GeV

HLT: Isolated Muon p_T>24 GeV

HLT: Muon p_T>55 GeV

L1: Muon p_T>11 GeV, barrel only, high purity

Parking: p_T>11 GeV + displacement (B-hadron decays)

Scouting: **no additional filter**

HH:

L1: H_T>280 GeV || H_T>240 GeV & μ > 6 GeV

HLT (old, based on older L1T): 4 jets (70,50,40,35 GeV & $|\eta|$<2.5) & 2-b score (equivalent to two medium b-tags)

Parking: H_T> 250 GeV & 4 jets (p_T>25 GeV & $|\eta|$<2.5) & 2-b score (equivalent to two medium b-tags)

Jets/H_T:

L1: H_T>280 GeV (+ other high p_T single/di-jets)

HLT: HT>1050 GeV

Scouting: **no additional filter**

VBF:

L1: Designed inclusive & exclusive (+ dijet, +MET, + τ , +μ, + e/γ)

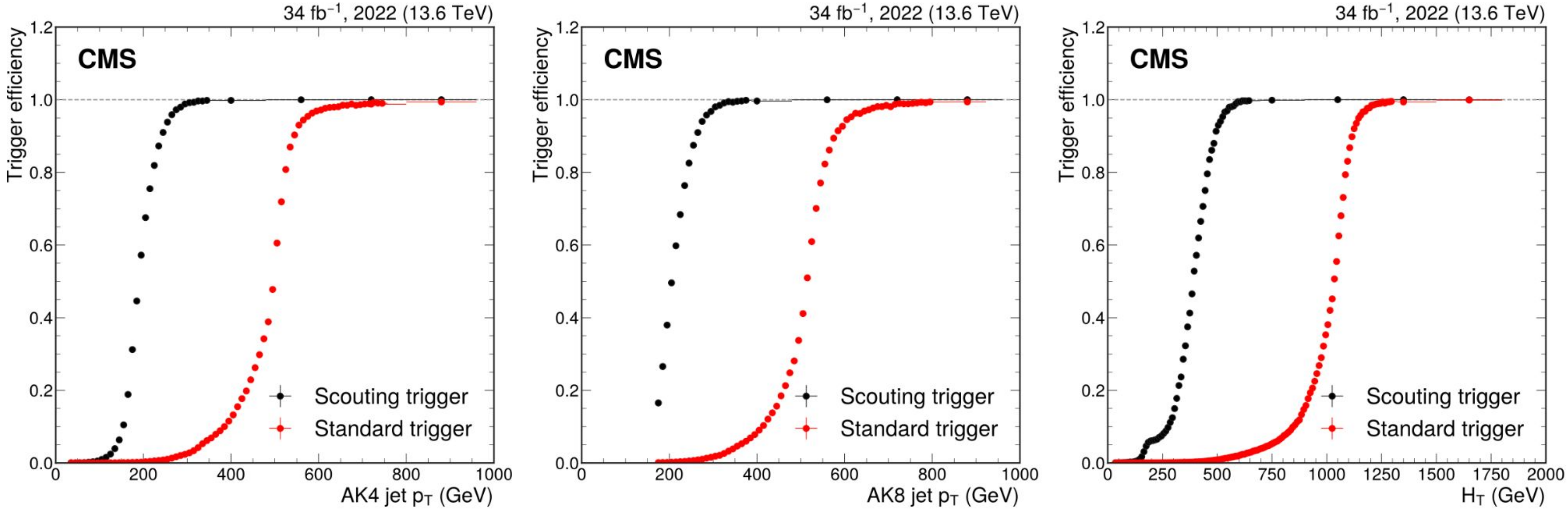
Parking: used to relaxed thresholds on VBFjets+X [more details in slide 23]

[For Anomaly Detection & LLP streams: see dedicated discussion afterwards]

[HT: ∑ jets p_T>30(L1)/25(HLT) GeV]

Run-3 Scouting objects: jets/HT

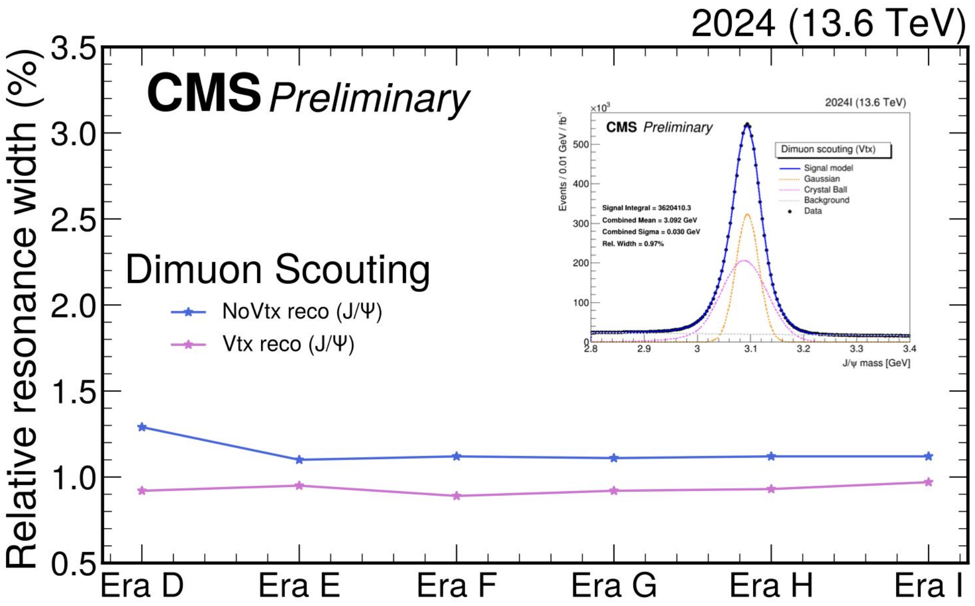
- **Scouting objects performance, as achieved in Run-3:**
  - Good jet scale and resolution with respect to offline reconstruction
    - We can target **boosted topologies** with scouting objects!
  - Each analysis based on (and limited by) $\mathbf{H_T}$ can highly benefit of scouting data

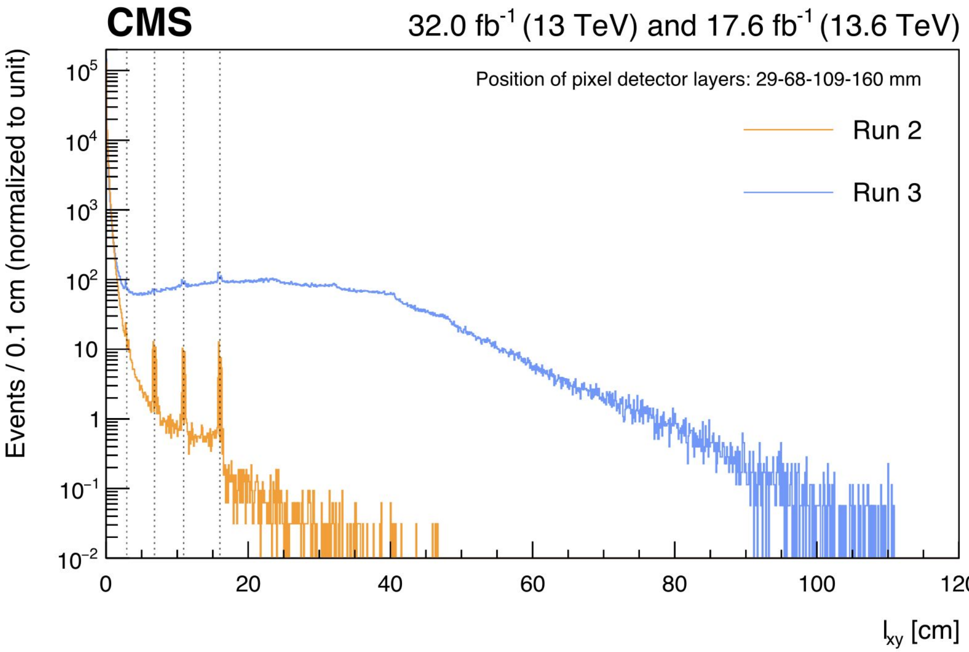


[NOTE: 2022 H_T threshold at L1 was 360 GeV, later 280 GeV]

Run-3 Scouting objects: muons

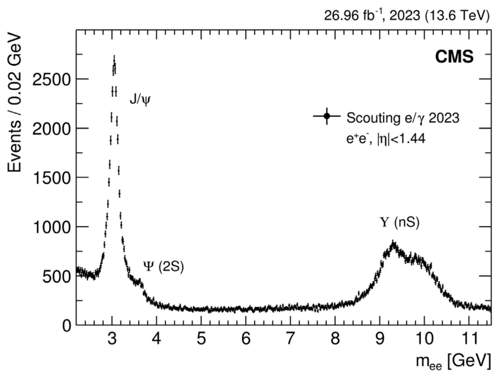
- **Scouting objects performance, as achieved in Run-3:**
  - Dedicated scouting muon reconstruction without any vertex constraint to target very displaced signatures in the full tracking acceptance (up to 100 cm):
    - **Very good resolution on the resonance width**
    - **Good p_T resolution with respect to the offline reconstruction**
  - Vertex-constrained reconstruction is also available → optimal for prompt (low-displacement) searches

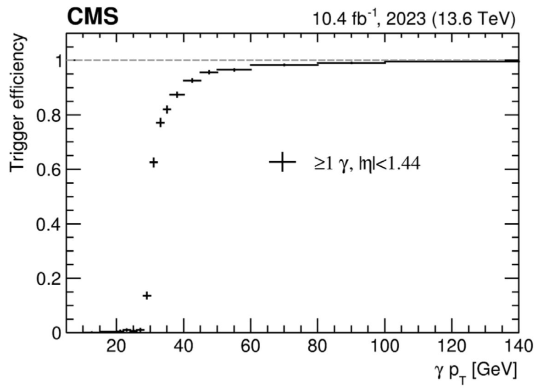


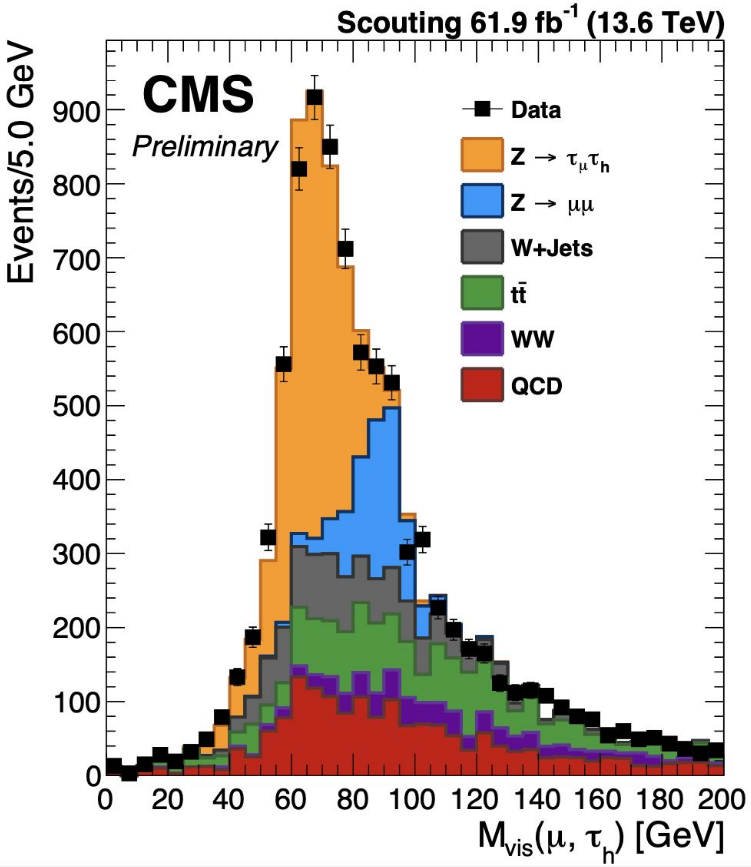


Run-3 Scouting objects: e/gamma and taus

- **Scouting objects performance, as achieved in Run-3:**
  - **Electrons and photons** are available (not yet used, need to derive dedicated ID, scale/smearing, pT regression)



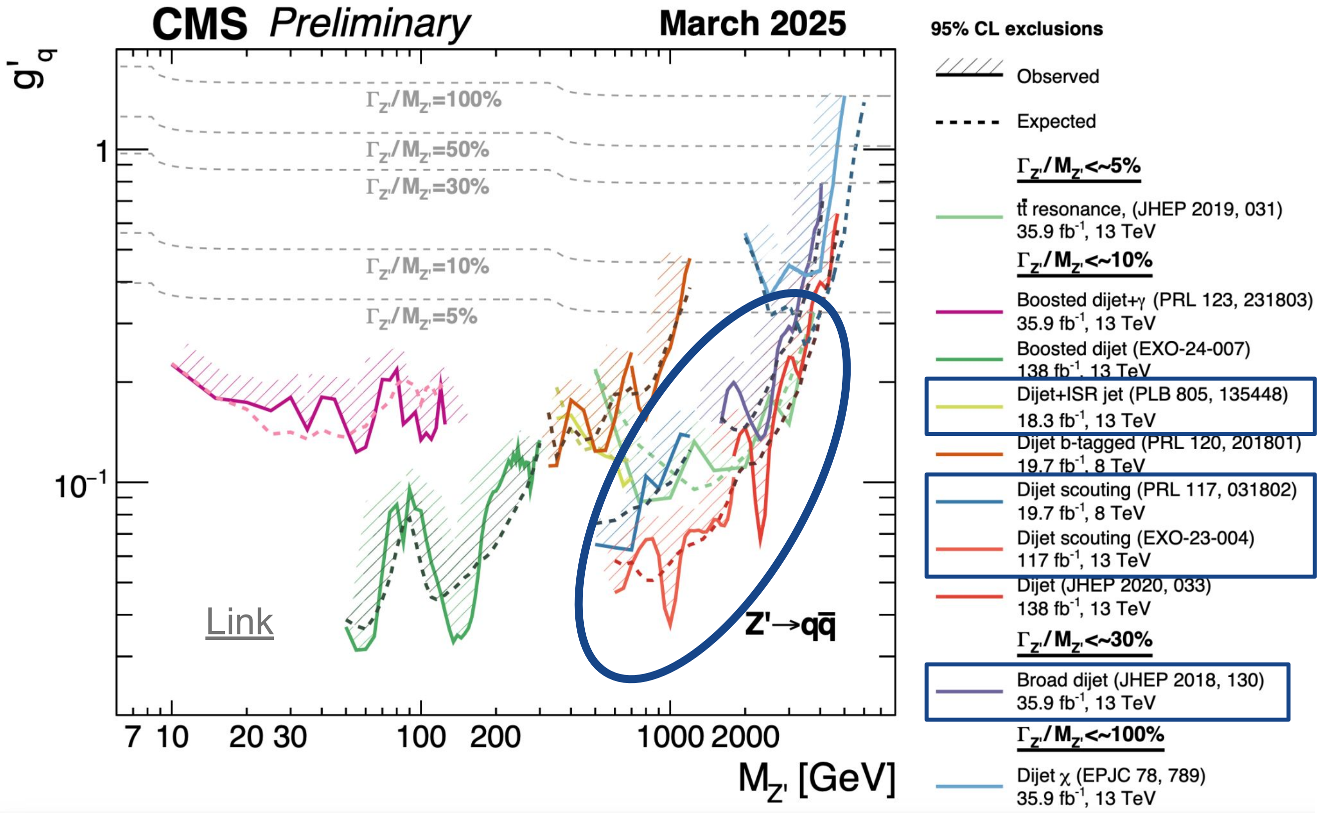




  - **Hadronic taus are reconstructed offline:**
    - Scouting Hadrons Plus Strips (HPS) candidates can be built from scratch using scouting PF candidates. **Dedicated low p_T reconstruction** (CMS-NOTE-2024-006) to improve efficiency at low p_T for both merged and resolved cases.

Jet/H_T stream: di-jets resonances

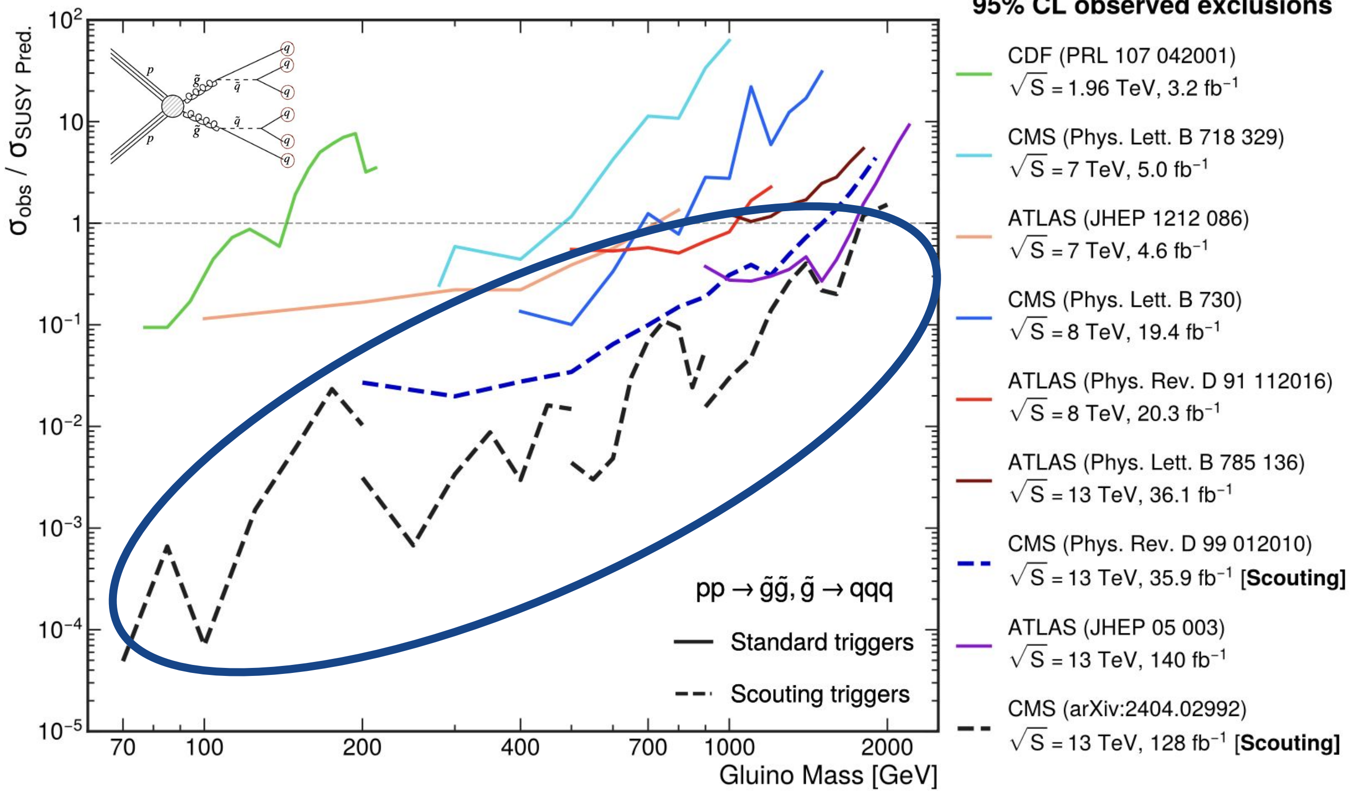
- **The Jet/HT Scouting stream has been used so far for successful searches of resonances in hadronic final states:**
  - Run 3 data not yet analysed, boosted searches not yet performed

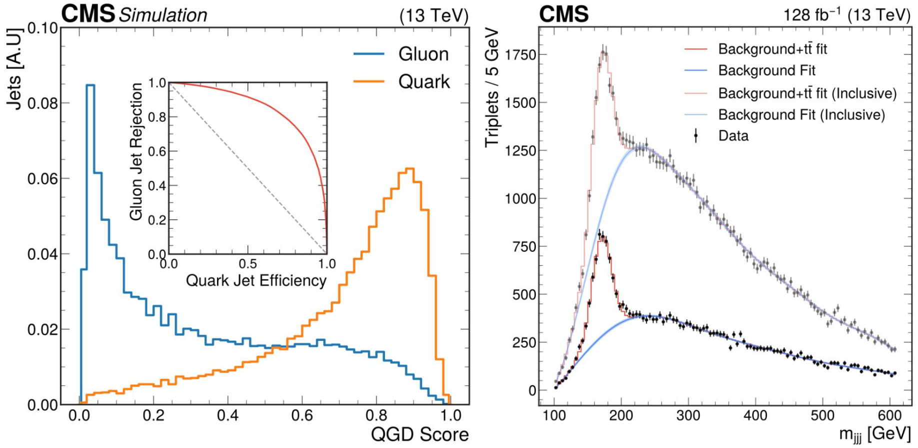


CMS-PAS-EXO-23-004 (superseding
10.1016/j.physletb.2017.02.012,
10.1007/JHEP01(2013)013)
10.1016/j.physletb.2020.135448
10.1007/JHEP08(2018)130
10.1103/PhysRevLett.117.031802

Jet/H_T stream: multi-jet resonances

- **The Jet/HT Scouting stream has been used so far for successful searches of pair-produced multi-jets resonances, both with merged and resolved jets:**
  - results interpreted in RPV SUSY simplified models, Run-3 data not yet analysed



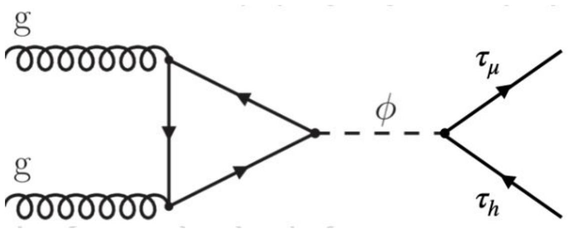


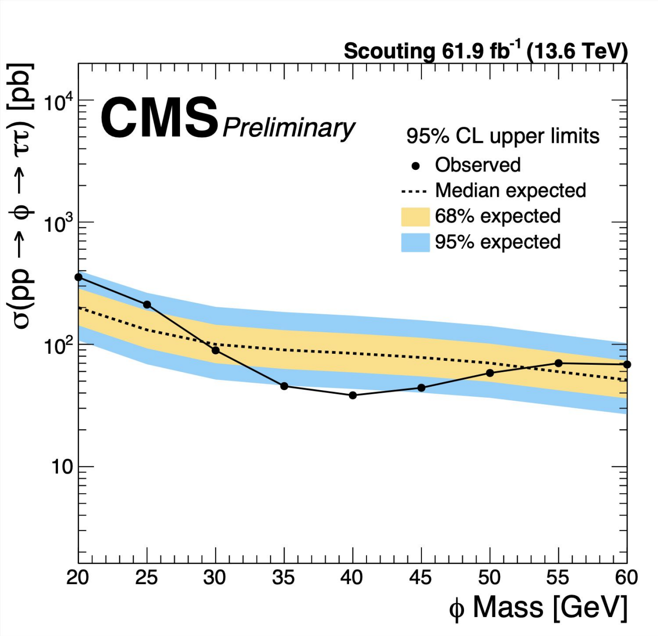
[Run 3 CMS Scouting & Parking paper]

10.1103/PhysRevD.99.012010,
10.1103/PhysRevLett.133.201803

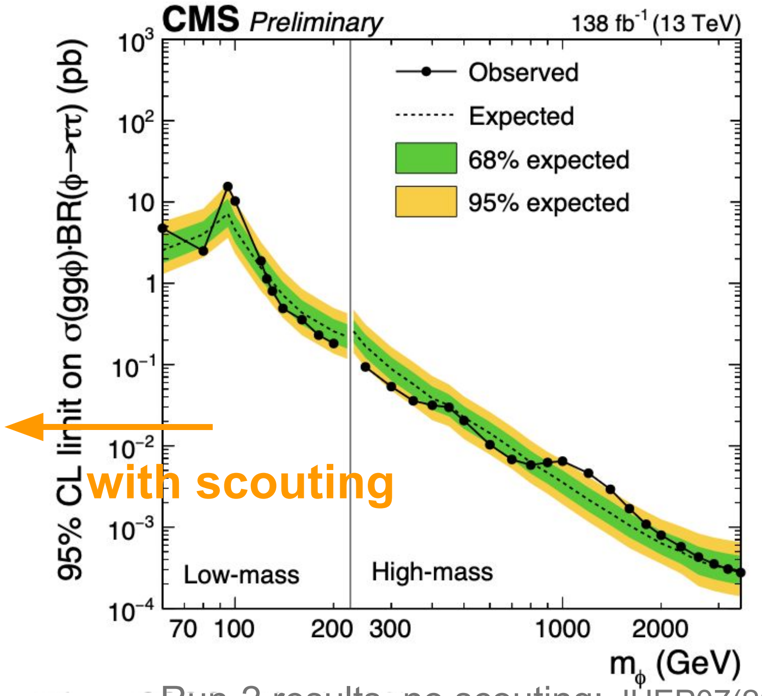
Jet/H$_T$ stream: low mass di-tau resonances

- **The Run-3 Jet/HT Scouting stream has been used for successful searches of low-mass di-τ resonances**
  - Using newly developed τ objects in Scouting (offline) based on PF candidates
  - First exploration of low mass (< 60 GeV) $\Phi \rightarrow \tau\tau$ with $\tau_\mu\tau_h$ final state





Run-3 result, with Scouting
CMS-PAS-EXO-24-012

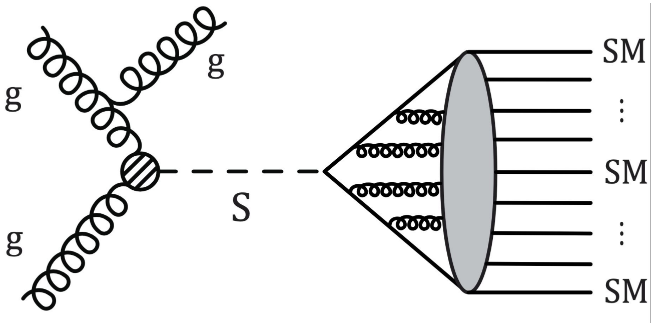


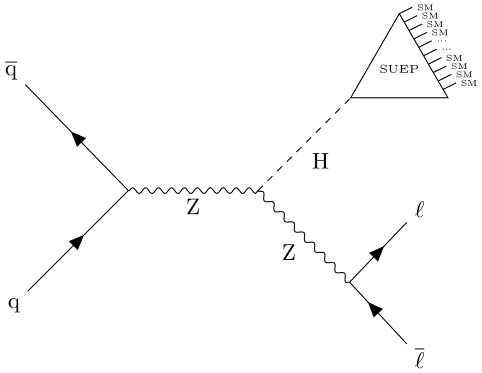
Run-2 results, no scouting: JHEP07(2023)073

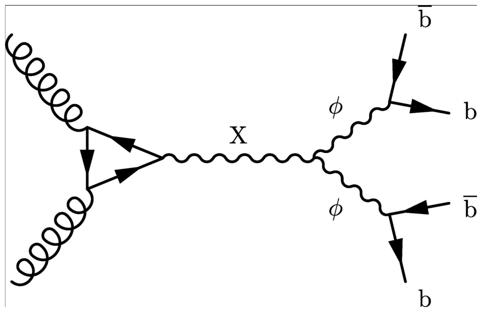
Other ideas for the Jet/H_T stream

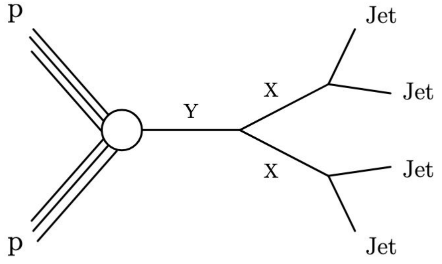
- **Potential for profiting more of low H_T thresholds (H_T > 280 GeV @ L1) and available PF candidates**
  - Search for **Soft Unclustered Energy Patterns (SUEP)** with scouting
    - already searched at CMS with standard data streams
      - **gg-fusion (boosted):** ref: PhysRevLett.133.191902
      - **Z-associated-production:** ref: CMS-EXO-23-003
      - **W-associated-production:** ref: CMS-EXO-24-030
  - X → aa → 4b with scouting (ref: 10.1016/j.physletb.2022.137566)
  - Resolved and merged pairs of di-jets for R-parity-violating (RPV) SUSY models (stops in dijet) (ref: 0.1007/JHEP07(2023)161)

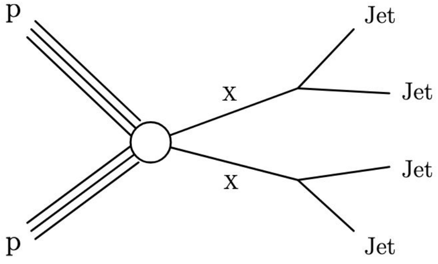
- **Development and optimisation of dedicated jet taggers may open up new possibilities!**







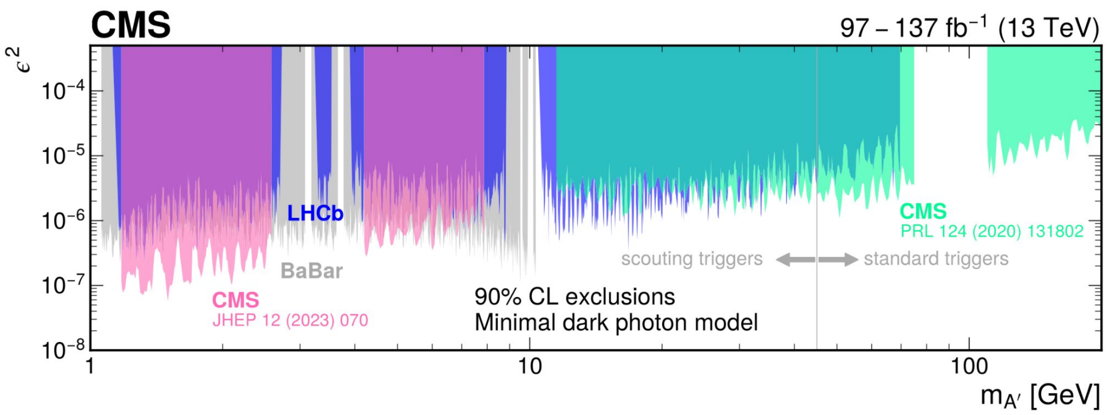




Di-μ stream: low mass resonances

Searches for prompt and displaced production of GeV scale dimuon resonances:

- The very low mass spectrum was studied for the first time with scouting data in Run 2 (for both prompt and displaced production):
  - Now spectrum **below 11 GeV accessible also with parking data in Run 3** (offline resolution available for similar thresholds)

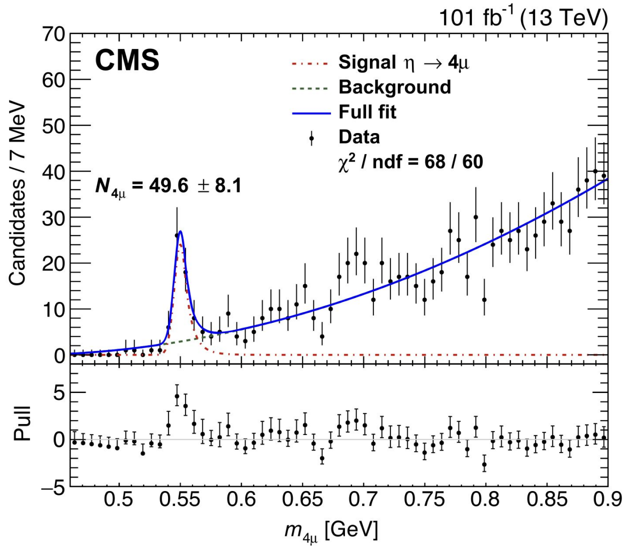


j.physrep.2024.09.013

  - **Searches can be extended down to the eta resonance peak exploiting the new Run 3 parking** dataset w/ inclusive dimuon parking triggers.
  - Scouting still optimal for displaced searches at high displacements!

Measurement of prompt resonance production in muon final states:

- Observation of the muon double Dalitz decay of the η meson (η → 4μ) with Run 2 scouting data



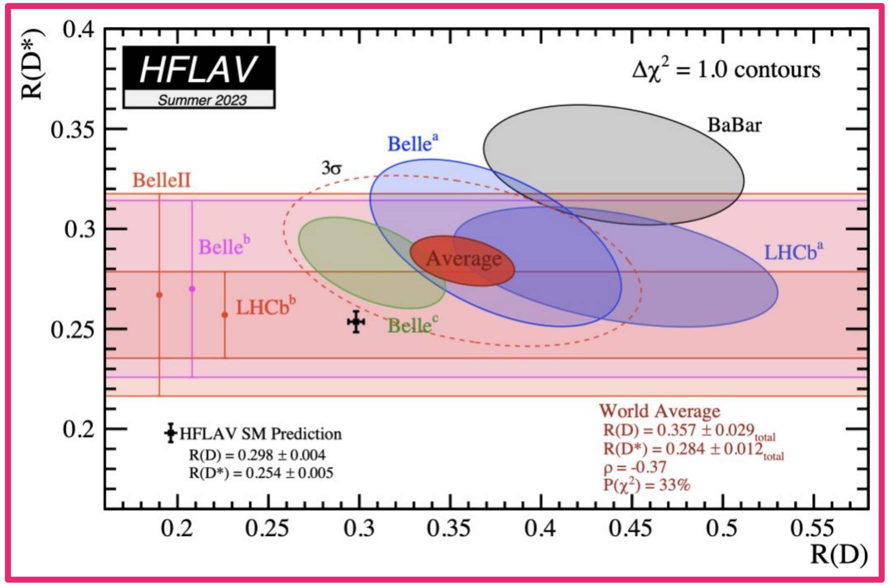
PhysRevLett.131.091903

- Benefit for B-physics measurements (e.g. $B_s \rightarrow \mu\mu$) will come from the rich **Run 3 parking dataset** with improved acceptance for all low p_T μ triggers

Single-μ stream: Expanding B physics with scouting/parking

Since 2018 we are expanding the Heavy Flavour Physics with inclusive single muon triggers:

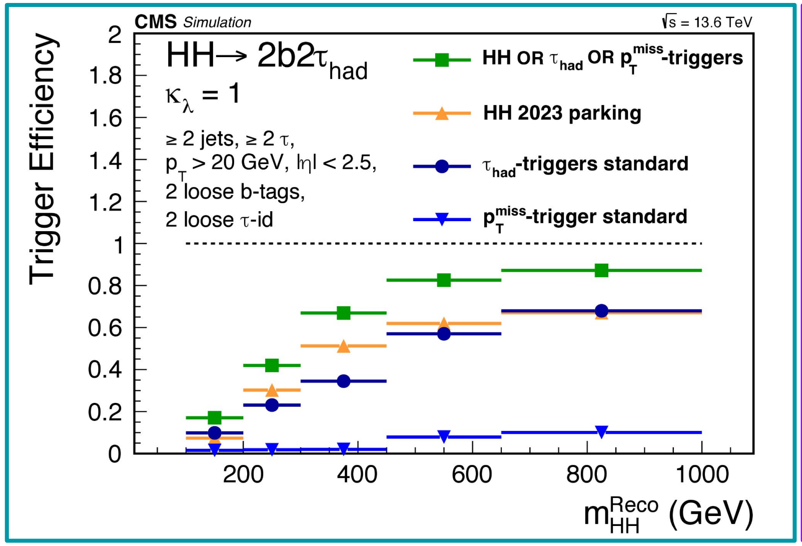
- **2018 B-Parking dataset → two key physics results:**
  - first charm CP violation measurement in $D^0 \to K_s K_s$ decays in CMS (10.1140/epjc/s10052-024-13244-0)
  - a measurement of R_K looking at the process $B^+ \to K^+\mu^+\mu^-$ over $B^+ \to K^+e^+e^-$ (10.1088/1361-6633/ad4e65)
  - a BSM search for long-lived heavy neutral leptons in b hadron decays (10.1007/JHEP06(2024)183)
- **Novelty in 2024: High purity muons at L1 (~10kHz of heavy flavor decays), leading to very high rate at HLT of good physics. Not all of it can be kept at HLT. Complementary strategies to save more data and cover different topologies:**
  - Inclusive displaced muons in parking
  - Non-displaced muons:
    - Scouting for more inclusive signatures
      - Full tracking allows similar performance to offline
      - Major use case: flavor tagging for CP violation. Factor of 5 boost in effective tagging efficiency (compensate for some loss in acceptance)

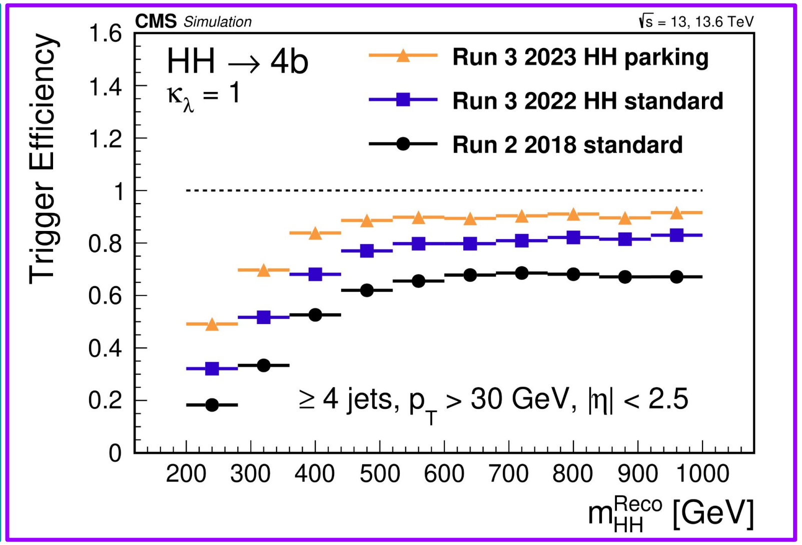


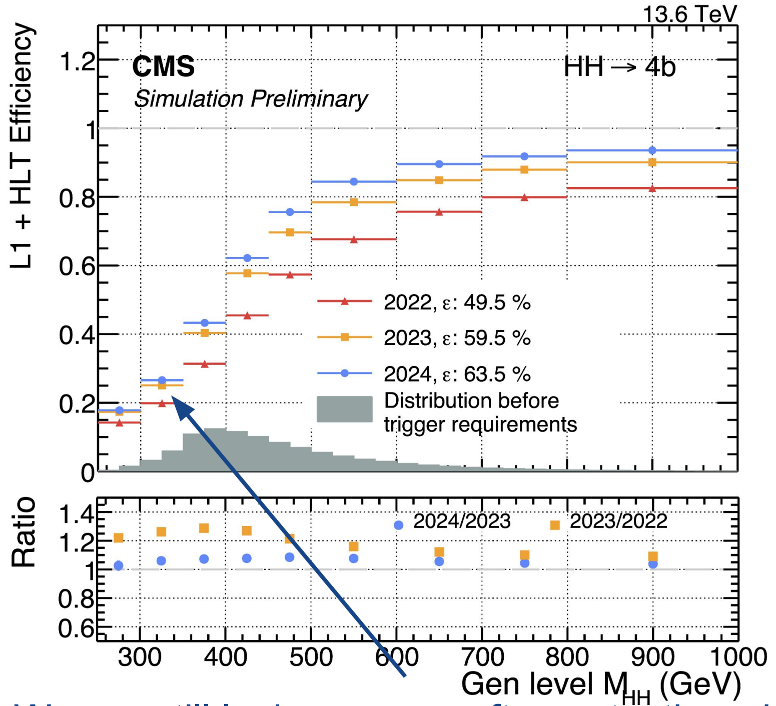
- **Possible interesting topics:** CP violation ($B_s \to \phi\phi$ time-dependent analysis), Exotic and Forbidden decays ($B \to e\mu$, $B \to \Lambda\mu$), Spectroscopy ($B + X$, $B \to D^*\mu\pi\nu$), Lepton flavor universality violation in Charm, Long-lived Heavy Neutral Leptons

HH Parking

- **HH Parking stream allows high-rate paths that expand acceptance for H(bb)H(XX) tagging the H(bb)**
  - +30% in HH → 4b efficiency w.r.t. Run 2
  - Large gain in H($\tau\tau$)H(bb)
  - Dedicated PNet AK4 (AK8) b(bb)-tagging algorithms (CMS-DP-2025-009)







Run 3 CMS Scouting & Parking paper , CMS-DP-2023-050

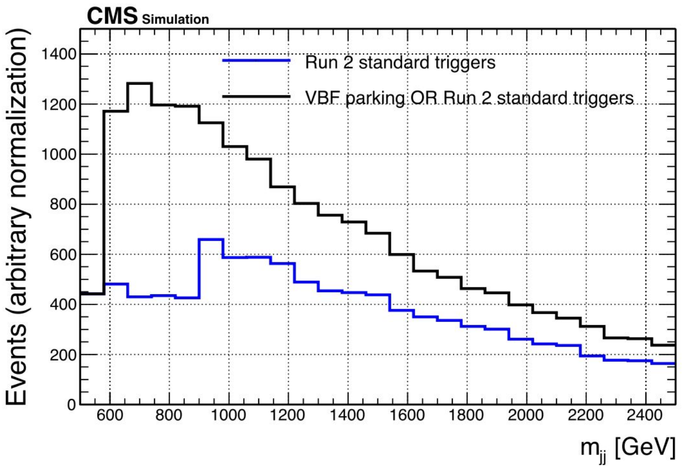
We are still losing many soft events, though

VBF Parking

- **VBF Parking stream allows high-rate path that expand acceptance for VBF+X (trigger or not triggering on X)**
  - Previously: inclusive L1T Seed (jet$_1$ 110 GeV, jet$_2$ 35 GeV, m$_{jj}$ 620 GeV) seeding HLT exclusive paths (+MET, +$\tau\tau$, +μ)
  - **Now (2023-table) a new set of higher-rate inclusive and exclusive paths:**

L1 trigger seed	VBF requirements (p_T^{j1}, p_T^{j2}, m_{jj})	Requirements on additional objects	Rate [kHz]
VBF inclusive	(90, 30, 800)	–	5.0
VBF + 2 central jets	(60, 30, 500)	2 central jets, $p_T^j > 50$ GeV	3.0
VBF + p_T^{miss}	(65, 30, 500)	$p_T^{miss} > 65$ GeV	2.9
VBF + μ	(90, 30, 500)	1 muon, $p_T^{\mu} > 3$ GeV	2.3
VBF + τ_h	(35, 35, 450)	1 isolated τ_h, $p_T^{\tau} > 35$ GeV	3.1
VBF + e/γ	(40, 40, 450)	1 isolated e/γ object, $E_{e/\gamma} > 15$ GeV	1.0

HLT trigger path	VBF requirements(p_T^{j1}, p_T^{j2}, m_{jj}, $\Delta\eta_{jj}$)	Requirements on additional objects	Rate [Hz]
VBF inclusive	(105, 40, 1000, 3.5)	–	800
VBF + 2 central jets	(70, 40, 600, 2.5)	2 central jets, $p_T^j > 60$ GeV	380
VBF + p_T^{miss}	(75, 40, 500, 2.5)	$p_T^{miss} > 85$ GeV	110
VBF + μ	(90, 40, 600, 2.5)	1 muon, $p_T^{\mu} > 3$ GeV	120
VBF + τ_h	(45, 45, 500, 2.5)	1 isolated τ_h, $p_T^{\tau} > 45$ GeV	40
VBF + γ	(45, 45, 500, 2.5)	1 photon, $p_T^{\gamma} > 17$ GeV	100
VBF + e	(45, 45, 500, 2.5)	1 isolated electron, $p_T^{e} > 17$ GeV	2



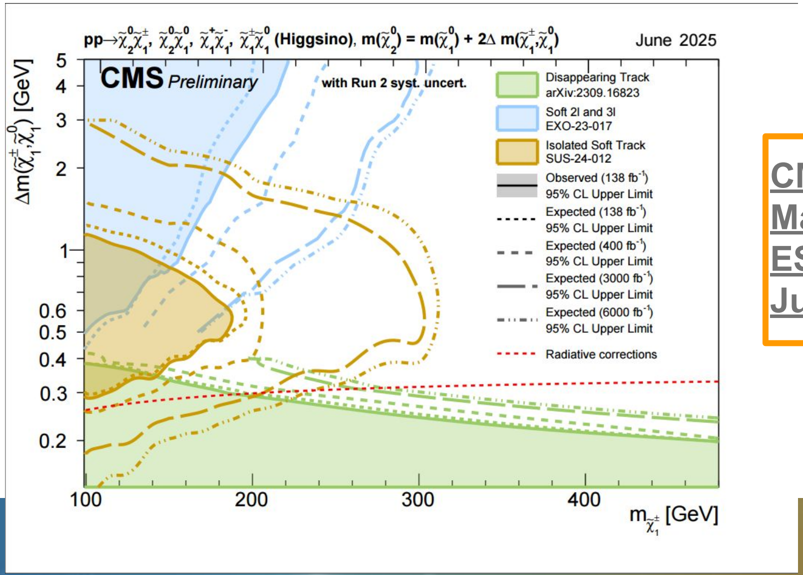
Run 3 CMS Scouting & Parking paper

VBF Parking

- **VBF Parking stream allows high-rate path that expand acceptance for VBF+X (trigger or not triggering on X)**
  - **Expected improvements on signal models:**

Benchmark signal	Standard triggers	Parking triggers	Acceptance gain
VBF $\mathrm{H} \to$ SUEPs	H_{T}	VBF inclusive	+2500%
Fully hadronic VBS	Multijet, H_{T}	VBF + 2 central jets	+30%
VBF $\mathrm{H} \to$ invisible	$p_{\mathrm{T}}^{\mathrm{miss}}$, tight VBF+$p_{\mathrm{T}}^{\mathrm{miss}}$	VBF + $p_{\mathrm{T}}^{\mathrm{miss}}$	+60%
VBF $\mathrm{H} \to \tau\tau(\to \tau_{\mathrm{h}}\tau_{\mathrm{h}})$	Di-τ_{h}, VBF+di-τ_{h}	VBF + τ_{h}	+50%
VBF $\mathrm{H} \to \tau\tau(\to \mu\tau_{\mathrm{h}})$	Single-μ, $\mu + \tau_{\mathrm{h}}$	VBF + μ	+30%
VBF $\mathrm{H} \to \tau\tau(\to \mathrm{e}\tau_{\mathrm{h}})$	Single-e, $\mathrm{e} + \tau_{\mathrm{h}}$	VBF + e	+40%
VBF $\mathrm{H} \to \rho\gamma$	$\gamma + 2$ collimated tracks	VBF + γ	+25%

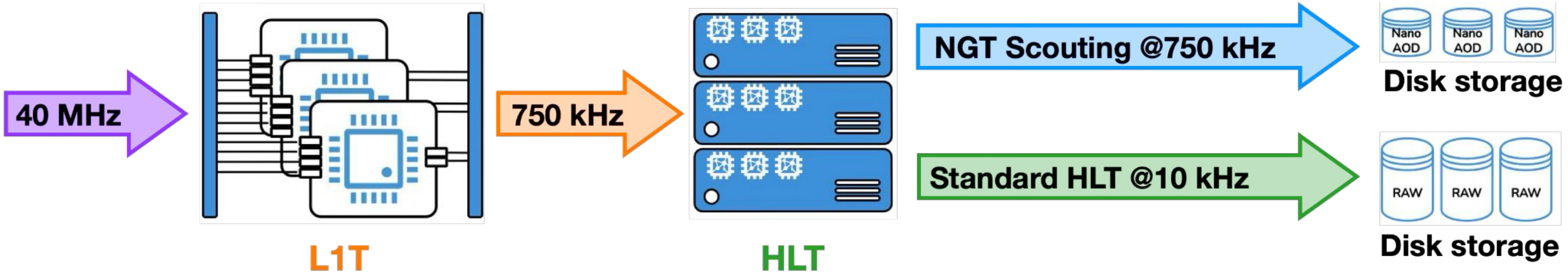
  - **New other ideas:**
    - using VBF production for SUEPS? for X→ ee low mass resonances?
    - triggering on VBF to lower MET thresholds in Compressed Higgsinos searches (or similar)?
      - **searches conducted so far uses only MET/leptons triggers**



CMS EXO Public Material for ESPPU 2025 Just out!

NGT HLT: Scouting all L1T rate at HL-LHC

- **NGT "Scouting" stream up to 750 kHz (100% of the L1T output rate) @ 200 PU with:**
  - logical OR of the L1T seeds in input → **acceptance gain is determined by L1 menu**
    - **the HL-LHC L1T will be smarter:** track-matching (distinguish e vs γ), PFlow, PUPPI, tag pileup jets with PUPPI, hence more pure selection
  - **offline-like quality physics object reconstruction**
    - exploiting offline-like full event reconstruction (including all object with p_T > 0.9 GeV/c, even from the underlying PU=200 interactions)
    - making usage of **real-time calibrations**, profiting of delayed event reconstruction and filtering on buffered input data
  - **storage of lightweight output format** (**NanoAOD**-like - actual content under discussion):
    - include particle kinematics and crude particle-ID (particle flow) of the candidates
    - possibility to re-run at analysis level clustering (e.g. jet reconstruction)
    - (optionally: save additional information for vertex refitting and/or taggers inference)



NGT HLT: Scouting all L1T rate (what to save)

- **The main limitations are the aggregate output event size and the CPU cost of reconstruction**
  - Scouting approach provides higher rate (acceptance) by storing partial event data
  - Might have to opt out from objects too complex to reconstruct (e.g. very displaced particles)

- **Saving full granularity information of tracks and particle flow candidates at 200 PU is not realistically affordable**:
  - Current estimate of ~100 kB/event → ~900 PB/year
    - ~ twice the current CMS projection for the beginning of Run 5
    - Beyond disk / tape budget;
  - Potential selection on the objects (need to understand where):
    - **Must be driven by physics performance estimates**
  - Mixed approaches are also possible:
    - store for part of the “more interesting” events more information to support further analysis-level post-processing;
    - **input from theory community on the interesting phase-space to concentrate upon are welcome!**

Opportunities for HLT Scouting in Phase-2: VBF/HH

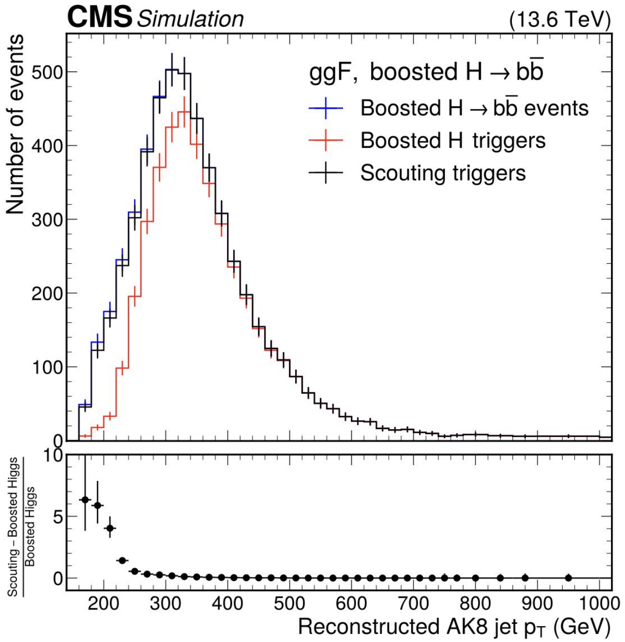
- **With offline-quality HLT reconstruction, we can incorporate most of Run 3 Parking analysis within HLT Scouting and target a removal/further lowering of the thresholds at HLT:**
  - VBF, HH (non)-resonant production (HH→4b, HH→bbττ, …) :
    - Scouting provides huge gain in acceptance for statistically-limited analysis
    - Current Run 3 VBF analysis strategies rely on the parking dataset
      - Either inclusive high-threshold trigger or exclusive seeds
    - Full exploitation of new flavour tagging algos at HLT to reduce QCD background in lower p_T region

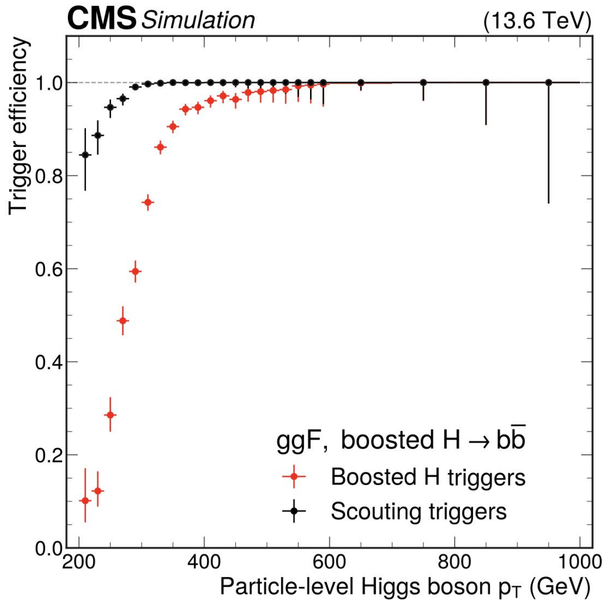
L1 trigger seed	VBF requirements (p_T^{j1}, p_T^{j2}, m_{jj})	Requirements on additional objects
VBF inclusive	(90, 30, 800)	–
VBF + 2 central jets	(60, 30, 500)	2 central jets, $p_T^{j} > 50$ GeV
VBF + p_T^{miss}	(65, 30, 500)	$p_T^{miss} > 65$ GeV
VBF + μ	(90, 30, 500)	1 muon, $p_T^{\mu} > 3$ GeV
VBF + τ_h	(35, 35, 450)	1 isolated τ_h, $p_T^{\tau} > 35$ GeV
VBF + e/γ	(40, 40, 450)	1 isolated e/γ object, $E_{e/\gamma} > 15$ GeV

~~HLT trigger path~~	~~VBF requirements(p_T^{j1}, p_T^{j2}, m_{jj}, $\Delta\eta_{jj}$)~~	~~Requirements on additional objects~~
~~VBF inclusive~~	~~(105, 40, 1000, 3.5)~~	~~–~~
~~VBF + 2 central jets~~	~~(70, 40, 600, 2.5)~~	~~2 central jets, $p_T^{j} > 60$ GeV~~
~~VBF + p_T^{miss}~~	~~(75, 40, 500, 2.5)~~	~~$p_T^{miss} > 85$ GeV~~
~~VBF + μ~~	~~(90, 40, 600, 2.5)~~	~~1 muon, $p_T^{\mu} > 3$ GeV~~
~~VBF + τ_h~~	~~(45, 45, 500, 2.5)~~	~~1 isolated τ_h, $p_T^{\tau} > 45$ GeV~~
~~VBF + γ~~	~~(45, 45, 500, 2.5)~~	~~1 photon, $p_T^{\gamma} > 17$ GeV~~
~~VBF + e~~	~~(45, 45, 500, 2.5)~~	~~1 isolated electron, $p_T^{e} > 17$ GeV~~

Opportunities for HLT Scouting in Phase-2: Higgs

- **With offline-quality HLT reconstruction, we can exploit boosted topologies & lower thresholds**
  - Exploiting scouting jets in boosted topologies is an effective strategy for resonance searches in hadronic final states, like Boosted ggH (H → bb), VH (H → cc), HH:
    - **Traditional triggers not efficient on single large-radius jets**: the usage of Run-3 data scouting has been demonstrated to increase the overall event selection efficiency for boosted H → bb by approximately 20% compared to the standard triggers, in particular at low p_T
    - High potential of scouting has been also demonstrated in boosted VH (H → cc) events, thanks to the **ability to reconstruct AK8 jets and develop dedicated jet tagging techniques for scouting objects**, which can achieve high performance
    - **With NGT-HLT offline-like reconstruction for the whole HL-LHC dataset!**





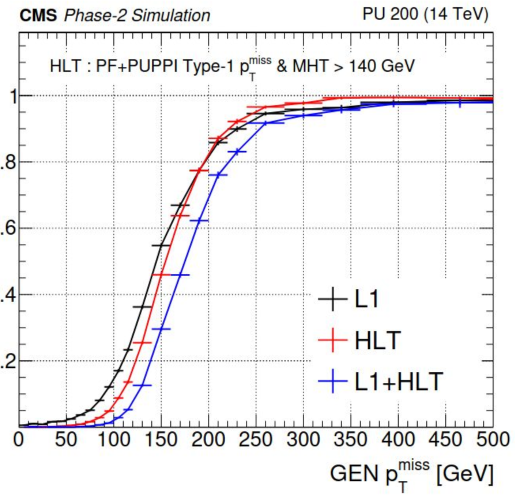
Run 3 CMS Scouting & Parking paper

Opportunities for HLT Scouting in Phase-2: Full L1T Menu

- **Additional acceptance on other signatures will come from scouting all the other L1T seeds and provide offline-like quality on all objects** (not currently possible due to rate and/or computing cost)
  - lower thresholds on MET, τ_h, e/ɣ, and cross lepton/jets/MET triggers

Extract from 2025 L1TMenu

L1 Trigger seeds	Threshold(s) [GeV]	Total Rate <PU>=64 (inst lumi 2.1e34) [kHz]	Additional requirement(s) [GeV]
Single/Double/Triple Electron/photon (EG) seeds			
Single EG	36	17.14	|η|<2.5
Single Iso EG	30	19.51	|η|<2.5
Double EG	15, 11	1.45	|η|<1.2; ΔR<0.6
Double EG	15, 15	3.58	|η|<1.5; Δη<1.5
Double EG	25, 12	8	|η|<2.5
Double LooseIso EG	20, 12	1.17	|η|<1.5
Tau seeds			
SingleTau	120	2.92	|η|<2.1
DoubleTau	70	3.1	|η|<2.1
DoubleIsoTau	34	11.63	|η|<2.1
MET seeds			
MET (including HF)	90	2.87	
Cross lepton-hadronic seeds			
Muon + HT	6, 240	0.82	
Muon + HT	12, 150	1.10	
DoubleMuon + HT	3, 3; 220	0.23	
Muon + Tau	18, 24	2.14	|η|<2.1, |η|<2.1
Muon + Jet + MET	3, 100, 40	1.23	|η|<1.5, |η|<2.5
DoubleMuon + MET+ HT	3, 3; 40; 60	0.46	
DoubleMuon + Jet	0, 0; 90	0.2	muon ΔR<1.6; |η|<2.5 for jet; ΔR with jets<0.8
DoubleEG + HTT	8, 8; 300	1.4	|η|<2.5 for EG
LooseIso EG + IsoTau	22, 26	3.58	|η|<2.1, ΔR>0.3
LooseIso EG + HT	14, 14; 200	4.89	|η|<2.5 for EG
DoubleIsoTau + Jet	34, 26; 55	3.32	|η|<2.1 for taus; overlap removal with jet ΔR<0.5
Cross lepton seeds			
Muon + EG	7, 20	2.67	|η|<2.5 for EG
Muon + EG	20, 10	1.95	|η|<2.5 for EG
Muon + LooseIso EG	7, 20	1.21	|η|<2.5 for EG
Muon + DoubleEG	6; 12, 12	1.11	|η|<2.5 for EG
DoubleMuon + EG	5, 5; 9	1.59	|η|<2.5 for EG
DoubleMuon + DoubleEG	3, 3; 7, 7	0.51	|η|<2.3 for muons, |η|<2.5 for EG Dimuon max mass<14; DiEG max mass<20



Expected Phase-2 L1T+HLT (200PU) from TDRs
- L1T MET threshold 90 GeV
- HLT MET threshold 140 GeV

- Scouting MET
  - MET is known to have tails from **instrumental effects: usually removed by applying specific filters during "offline" analysis**
  - NGT approach can improve the situation profiting from more event-level information

Opportunities for HLT Scouting in Phase-2: offline-quality

- **Additional acceptance on other signatures will come from scouting all the other L1T seeds and provide offline-like quality on all objects** **(not currently possible due to rate and/or computing cost)**
  - **dedicated reconstruction targeting low p_T objects: soft taus, soft b-quarks**
    - as already attempted in Run-3 (**CMS-NOTE-2024-006**), but with better inputs
    - final states need to be selected by L1 H_T- like seeds
  - **with offline-quality on e/ɣ objects allow to use L1T e/ɣ (and others) thresholds**
    - Very low mass **dijet searches with a photon from ISR or FSR** (L1T photon thresholds at 30 GeV)
    - **Monophoton signatures** in a simplified DM model (L1T photon thresholds at 30 GeV, L1T MET at 90 GeV)
      - Genuine signature of single γ and large E_T^{miss}
    - **Increase acceptance for X+γ** (L1T photon thresholds at 30 GeV)
      - H → Meson (ρ/φ) + γ
      - H(ZZ/bb) + γ production with the boosted topology
      - H → Zγ with Z(jj) where both γ and Z are about $M_H/2$
    - **Increase acceptance for X→ee searches** (L1T double e/ɣ at 15,11 GeV)

Other ideas? At HL-LHC new L1T seeds can be designed if they fit the L1T latency/resources/750 kHz of total rate → Feedback is welcome!

From current L1T to the Phase-2 L1T

CERN | NexTGen Next Generation Triggers

Baseline L1T performance at HL-LHC (200PU)

- **Thanks to the upgraded L1T hardware, better inputs, offline-like algorithms & FastML into FPGAs, we have proven that we can sustain - even at 200 PU - the Run-2 L1T Menu [L1T Upgrade Technical Design Report]**
  - Designed a simplified Menu that considers only unprescaled seeds used for physics analysis (70% of total rate), and use Phase-2 L1T objects with same physics thresholds
  - Tested that - with more realistic algorithms wrt TDR (implemented in firmware): **total rate of simplified Menu + 30% additional service seeds → fit nicely in 750 kHz, with some additional space for new ideas**
- **Let's assume that (thanks to continuous improvements in L1T reconstruction) we can sustain all the new seeds/thresholds of Run-3→**
- **What can we do more?**

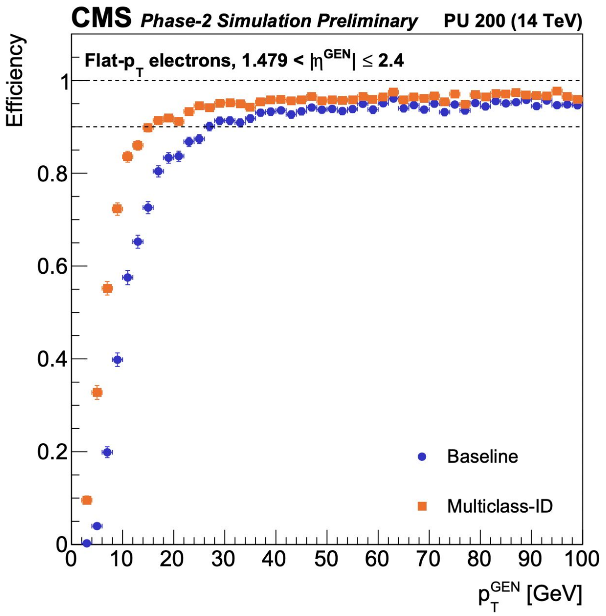
L1 Trigger seeds	Threshold(s) [GeV]	Total Rate <PU>=64 (inst lumi 2.1e34) [kHz]	Additional requirement(s) [GeV]
Single/Double/Triple Muon seeds			
SingleMuon (HighQuality)	11	8.54	Barrel only (BMTF)
SingleMuon	22	9.99	
DoubleMuon	0,0	4.29	$\|\eta\|<1.4$, OS, $\Delta R<1.4$
DoubleMuon	4,4	5.64	$\|\eta\|<2.0$, OS, $\Delta R<1.6$
DoubleMuon	8,8	1.15	
TripleMuon	3,3,3	1.88	
TripleMuon	4,2.5,0	1.1	TripleMu Mass < 12, Total charge = +/- 1
Single/Double/Triple Electron/photon (EG) seeds			
Single EG	36	17.14	$\|\eta\|<2.5$
Single Iso EG	30	19.51	$\|\eta\|<2.5$
Double EG	15, 11	1.45	$\|\eta\|<1.2$; $\Delta R<0.6$
Double EG	15, 15	3.58	$\|\eta\|<1.5$; $\Delta\eta<1.5$
Double EG	25, 12	8	$\|\eta\|<2.5$
Double LooseIso EG	20, 12	1.17	$\|\eta\|<1.5$
Tau seeds			
SingleTau	120	2.92	$\|\eta\|<2.1$
DoubleTau	70	3.1	$\|\eta\|<2.1$
DoubleIsoTau	34	11.63	$\|\eta\|<2.1$
Hadronic seeds (jets, HT)			
SingleJet	180	3.61	
DoubleJet	30	4.55	$\|\eta\|<2.5$; DiJet mass<250; $\Delta\eta<1.5$
DoubleJet	112	2.77	$\|\eta\|<2.3$; $\Delta\eta<1.6$
DoubleJet	150	1.45	$\|\eta\|<2.5$
HT	280	7.14	
MET seeds			
MET (including HF)	90	2.87	
Cross lepton seeds			
Muon + EG	7, 20	2.67	$\|\eta\|<2.5$ for EG
Muon + EG	20, 10	1.95	$\|\eta\|<2.5$ for EG
Muon + LooseIso EG	7, 20	1.21	$\|\eta\|<2.5$ for EG
Muon + DoubleEG	6; 12, 12	1.11	$\|\eta\|<2.5$ for EG
DoubleMuon + EG	5, 5; 9	1.59	$\|\eta\|<2.5$ for EG
DoubleMuon + DoubleEG	3, 3; 7, 7	0.51	$\|\eta\|<2.3$ for muons, $\|\eta\|<2.5$ for EG Dimuon max mass<14; DiEG max mass<20
Cross lepton-hadronic seeds			
Muon + HT	6, 240	0.82	
Muon + HT	12, 150	1.10	
DoubleMuon + HT	3, 3; 220	0.23	
Muon + Tau	18, 24	2.14	$\|\eta\|<2.1$, $\|\eta\|<2.1$
Muon + Jet + MET	3, 100, 40	1.23	$\|\eta\|<1.5$, $\|\eta\|<2.5$
DoubleMuon + MET+ HT	3, 3; 40; 60	0.46	
DoubleMuon + Jet	0, 0; 90	0.2	muon $\Delta R<1.6$; $\|\eta\|<2.5$ for jet; ΔR with jets<0.8
DoubleEG + HTT	8, 8; 300	1.4	$\|\eta\|<2.5$ for EG
LooseIso EG + IsoTau	22, 26	3.58	$\|\eta\|<2.1$, $\Delta R>0.3$
LooseIso EG + HT	14, 14; 200	4.89	$\|\eta\|<2.5$ for EG
Cross hadronic seeds			
DoubleIsoTau + Jet	34, 26; 55	3.32	$\|\eta\|<2.1$ for taus; overlap removal with jet $\Delta R<0.5$
VBF seeds			
DoubleJet	110, 35	2.22	DiJet mass>1000
DoubleJet + IsoTau	45, 45; 45	1.65	$\|\eta\|<2.1$ for tau, DiJet mass>600; Overlap removal in $\Delta R<0.5$
DoubleJet + LooseIso EG	45, 45; 20	0.41	$\|\eta\|<2.1$ for EG, DiJet mass>550; Overlap removal in $\Delta R<0.2$
DoubleJet + Muon	85, 35; 3	1.11	DiJet mass>700
DoubleJet + MET	70, 35; 65	2.13	DiJet mass>600

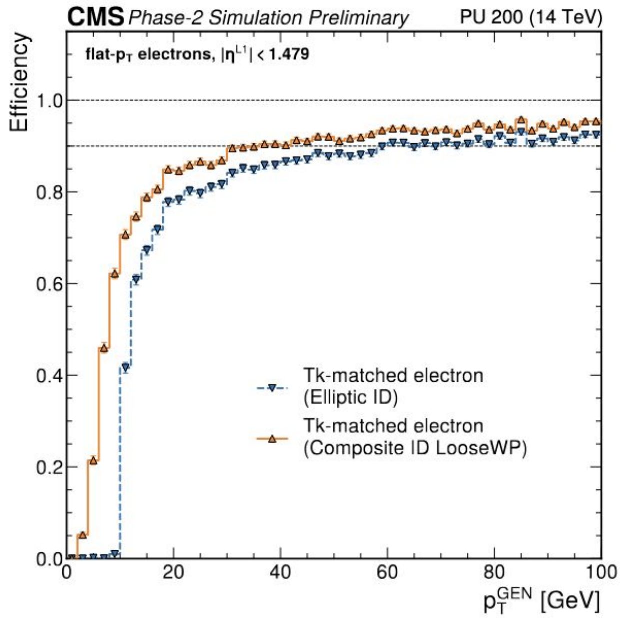
Simplified L1T Menu as in 2025 data-taking
[no LLP seeds, no Anomaly detection (see later)]

Upgraded L1 Trigger & NGT: enlarging acceptance

- **Even at 200PU, the L1 Trigger Menu can provide larger physics acceptance wrt now, thanks to**
  - **Better inputs, Better inputs & larger resources, Better inputs & larger resources & ML@L1**

- **Ex.1: Track matching/ PF&PUPPI combined with NN/BDT to push low transverse momentum reconstruction with better purity than in Run-3 (calo-only) for electrons/taus**
  - can use them in cross(multiple)-object triggers with low thresholds





1. Multiclass BDT ID to identify PU vs pions vs e/ɣ clusters, keeping highest possible efficiency on e/ɣ

2. Loosely match L1 e/ɣ calo-cluster and L1 Tracks are further identify by a BDT that uses in inputs Calo/Tracks features, and whose inference is evaluated in the firmware of the Correlator trigger

3. Track-matching & ID, drastically reduce rate. Composite ID has better turn-on and higher efficiency at the same rate as Elliptic ID.

DP Note

Upgraded L1 Trigger & NGT: enlarging acceptance

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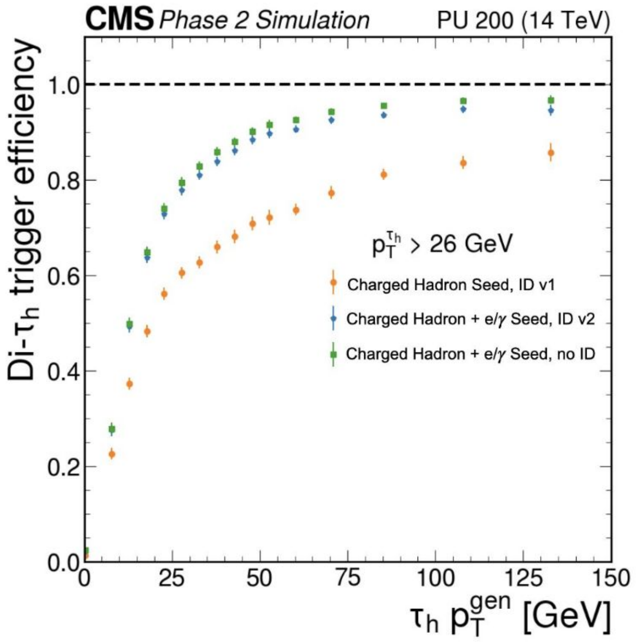
- **Ex.1: Track matching/ PF&PUPPI combined with NN/BDT to push low transverse momentum reconstruction with better purity than in Run-3 (calo-only) for electrons/taus**
  - can use them in cross(multiple)-object triggers



1. From PU-subtracted (PUPPI) PF, find seeding, and feed candidate around seed into NN. Performance tested in VBF H→ττ

2. NN ID cut chose to have sustainable rate at the typical ~30 GeV thresholds of the di-tau trigger (target H→ττ)

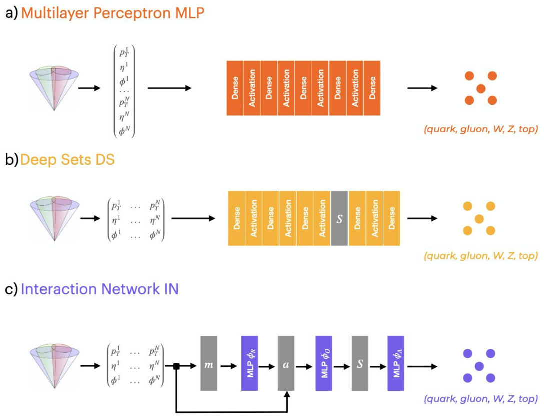
3. rate is reduced wrt Calo-based τ by a factor 10

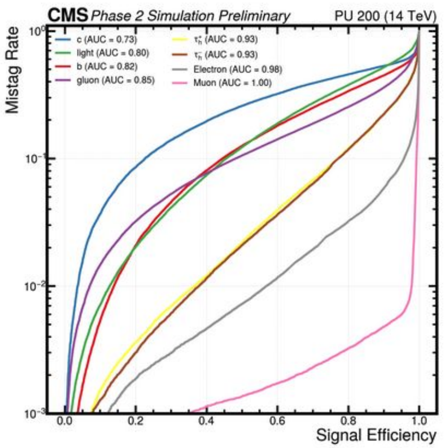
DP Note & TDR

Upgraded L1 Trigger & NGT: enlarging acceptance

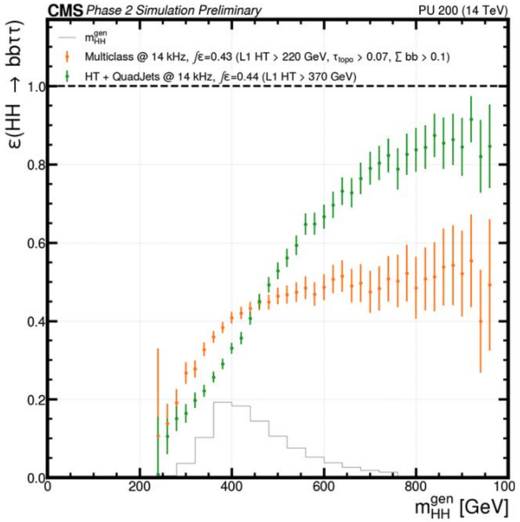
- **Even at 200PU, the L1 Trigger Menu can provide larger physics acceptance wrt now, thanks to**
  - **Better inputs, Better inputs & larger resources, Better inputs & larger resources & ML@L1**

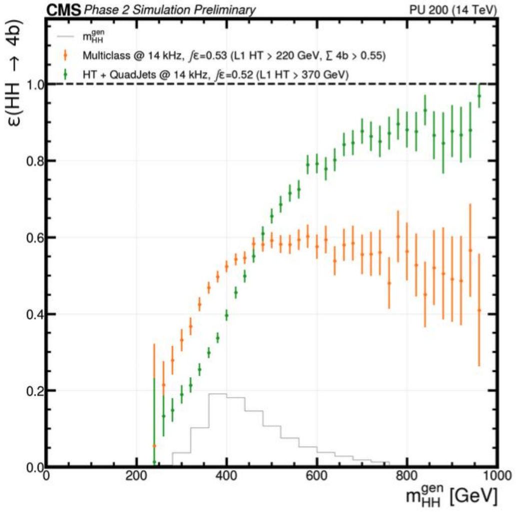
- **Ex.2: Flavour tagging, final states with third generation objects**
  - inspired by offline jet-tagging the new method introduces multiclass tagging of PUPPI-jets trained on a variety of target classes: **b jets, c jets, τ_h (positively charged), τ_h (negatively charged), gluon jets, muon, electron, and light quark (uds) jets**
  - improves acceptance at low H_T for final states with multiple b/τ_h (tested on HH→4b, 2b2τ)





Ultrafast Jet Classification on FPGA at HL-LHC arXiv 2402.01876



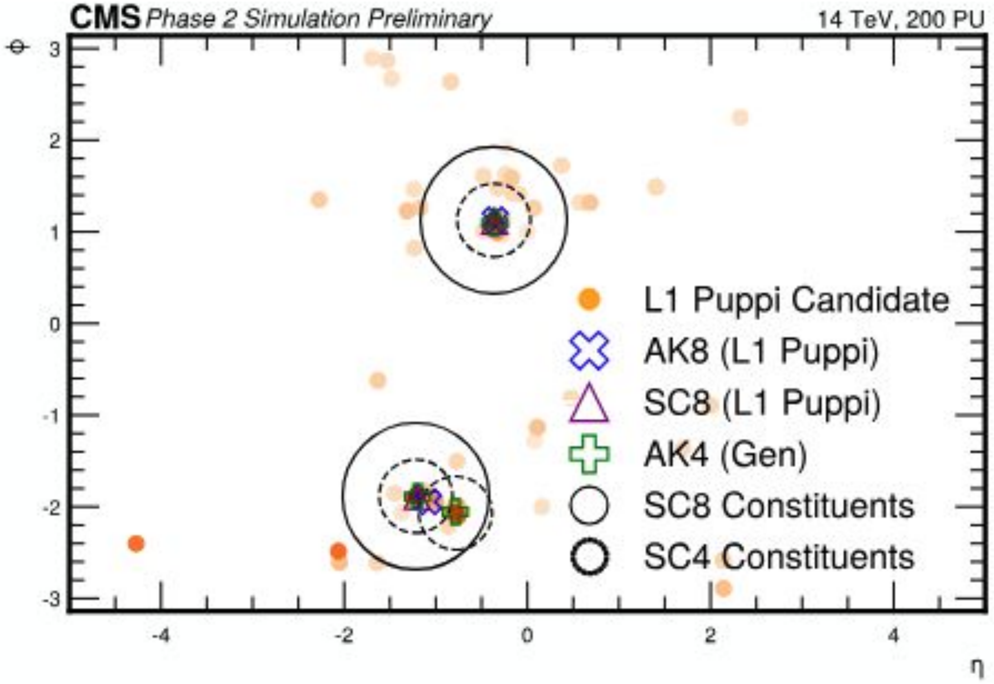


DP Note

Upgraded L1 Trigger & NGT: enlarging acceptance

- **Even at 200PU, the L1 Trigger Menu can provide larger physics acceptance wrt now, thanks to**
  - **Better inputs, Better inputs & larger resources, Better inputs & larger resources & ML@L1**

- **Ex.2: Fat-Jet**
  - with the Seeded Cone jet algorithm, **0.4 and 0.8 radius jets can be both implemented in firmware**
  - can be useful to increase efficiency for boosted H final states (very important for H→cc, HH→4b) and substructure/mass taggers can then be implemented.
    - For p_T > 300 GeV, single Fat-Jet seed more efficient at triggering on H→bb than Double-Jet



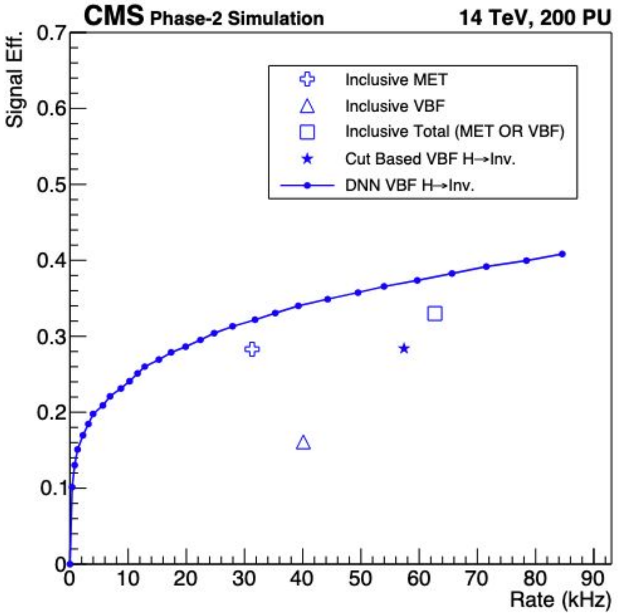
DP Note

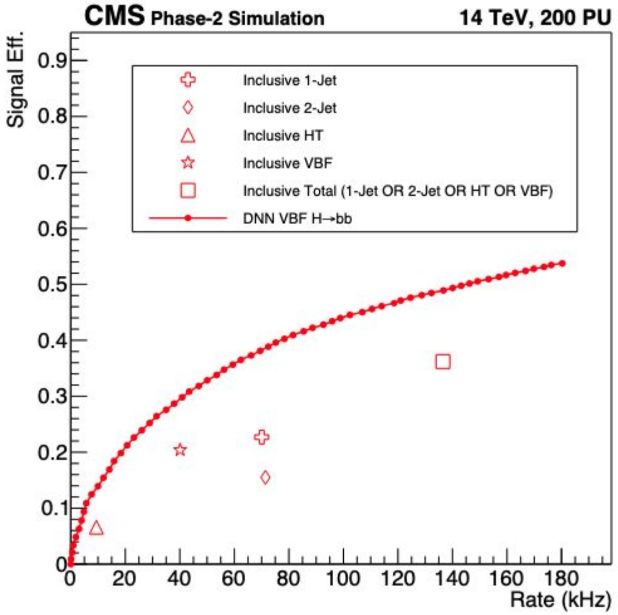
Upgraded L1 Trigger & NGT: enlarging acceptance

- **Even at 200PU, the L1 Trigger Menu can provide larger physics acceptance wrt now, thanks to**
  - **Better inputs, Better inputs & larger resources, Better inputs & larger resources & ML@L1**

- **Ex.2: Topological Triggers with NN**
  - NN can be used on higher level objects (jets, tau, electrons, muons, MET...) or on lower level ones (PUPPI candidates) to **target specific signal topologies**
  - tested on VBF H→inv, VBF H→bb

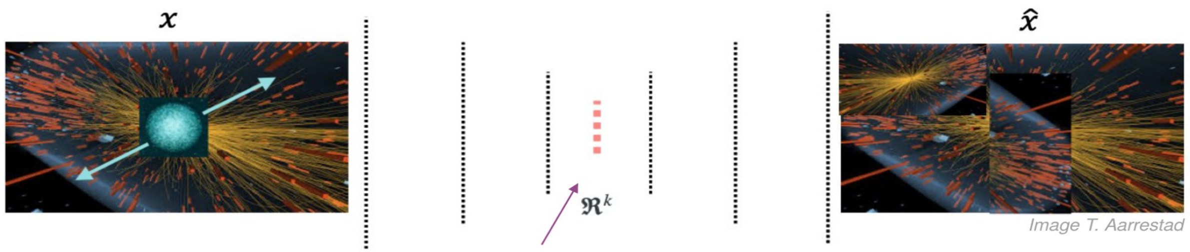
TDR
Performance to be re-evaluated with more realistic(firmware) algoritms





Anomaly Detection with Autoencoders: now

- **Another way:** trigger on "anomalous" events using ML unsupervised models (sub-μs autoencoders!)
  - In Spring 2024 CMS established a **new trigger paradigm with sub-μs autoencoders** for anomaly detection: **AXOL1TL deployed in L1 Global Trigger**
    - 100 fb^{-1} collected by AXOL1TL, L1T rate of ~300Hz-1100 Hz (~5kHz in 2025), passthrough at HLT-Scouting
    - For the moment trained using subset of L1 Global Trigger objects: (pT ,η, ϕ) hardware inputs from MET, 4 e/γ, 4 μ, and 10 jet
    - **Many AXOL1TL events are unique vs existing triggers: unique events fall below existing L1 trigger thresholds, e.g. low-momentum, high-multiplicity final states (many studies on-going)**
  - In 2025 Data Taking a new autoencoder running on **L1 Calorimeter deposits is taking data: CICADA**



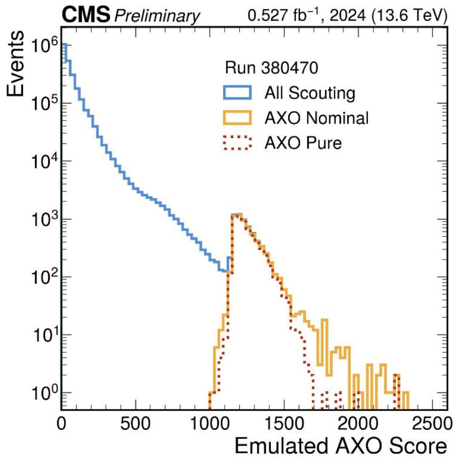
Train on randomly sampled *data*

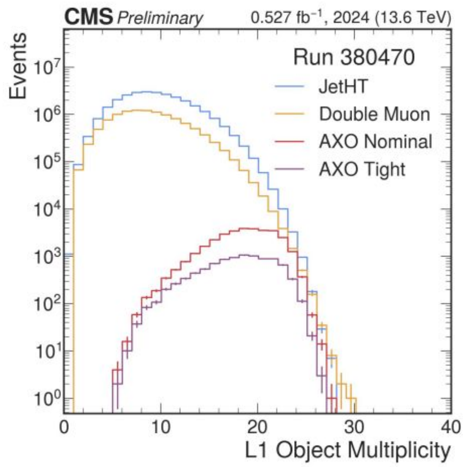
Bottleneck: autoencoder learns to compress high dimensional inputs into low dimensional latent space

Unsupervised learning: $x - \hat{x}$ represents degree of abnormality

Unsupervised Learning: $\text{Loss} = ||x - \hat{x}||^2$

Reconstruction loss

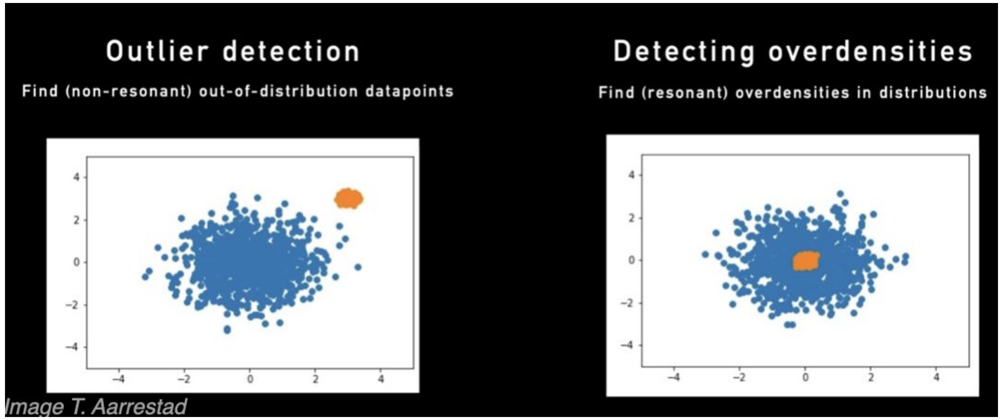




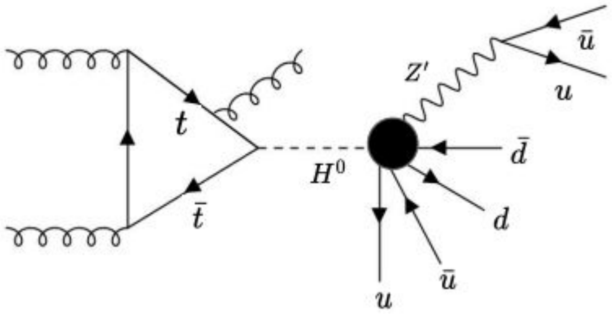
AXOL1TL DP Note (2024)
CICADA DP Note (Test Crate)

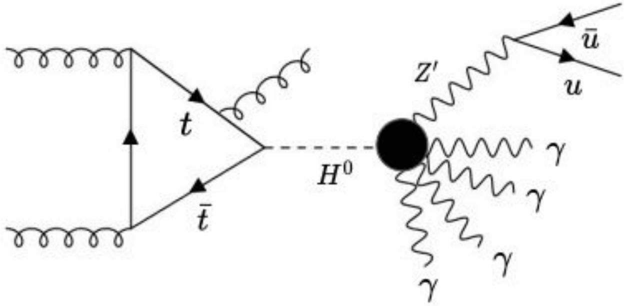
Sensitivity of AD Triggers (?)

- **Assumptions for AD with Autoencoder**
  - Anomalies are **rare** in training set
  - Anomalies are **out-of-distribution**
  - Anomalies are **detectable in input objects**



- **Physics analysis of AXOL1TL data**
  - Analysis with an anomaly detection trigger has never done before, lots of technology to develop. On-going: characterization of trigger performance in 2024 data on SM candles (J/Ψ/Z peak, etc…)
  - **Start simple, bump hunt** in di-object invariant mass spectra with AXOL1TL data as in ATLAS offline search
    - Expect increased acceptance for events with a resonance produced in association with additional objects
    - **Question for theorists:** Examples of well-motivated models for such final states?





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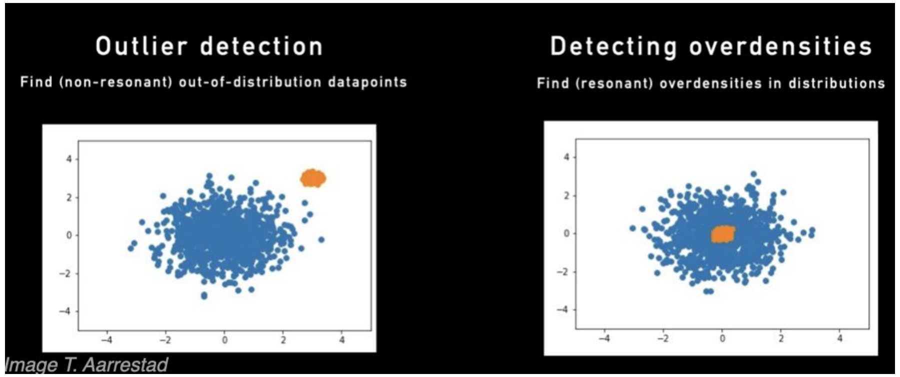
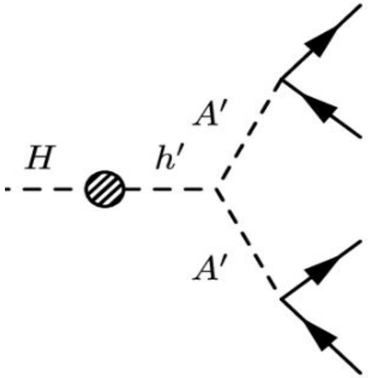
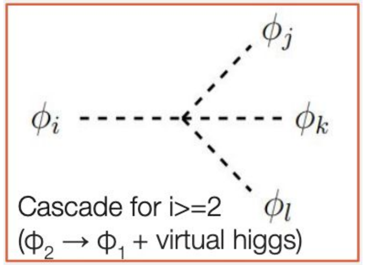
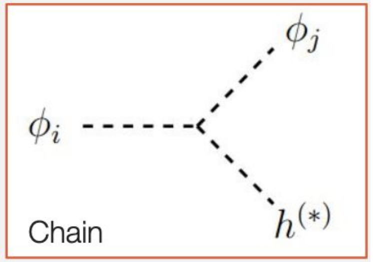
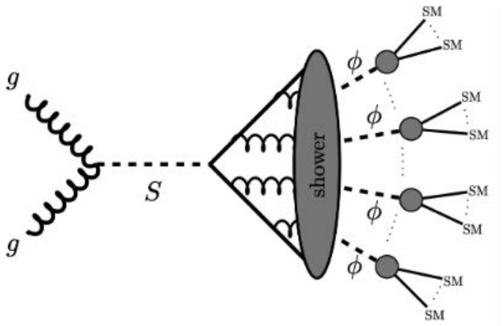


- **Other signatures that could benefit?**
  - Signatures where most events fall below L1 trigger thresholds, being tested:
    - **Soft Jets (e.g. Higgs portal to axion)**
    - **Hidden Valley (e.g. Semi-visible jets, dark photon cascades, SUEPs)**
    - **Multiple Soft Hadronic objects**
      - E.g. arXiv 1902.05535, multiple new states (from 5 to 50) with compressed mass spectra, small couplings
        - with accessible cross section: final states with multiple (O(10)) low pT 5-10 GeV tau, b, c



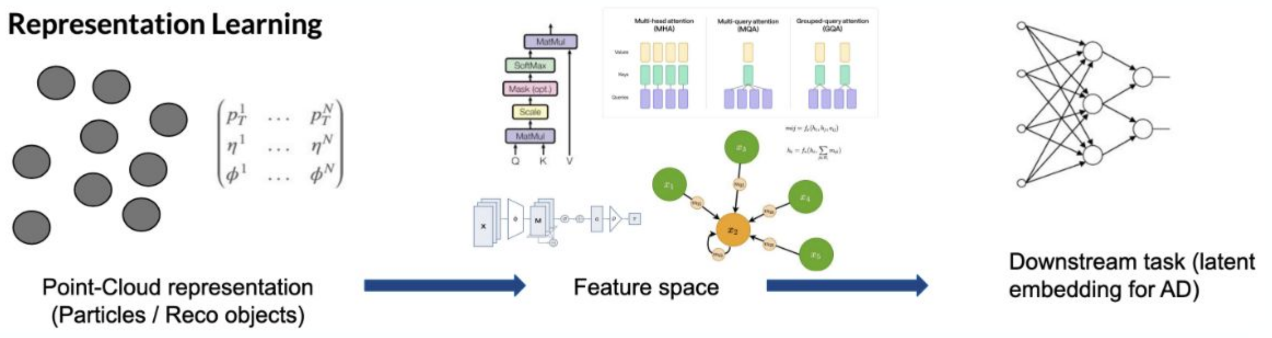


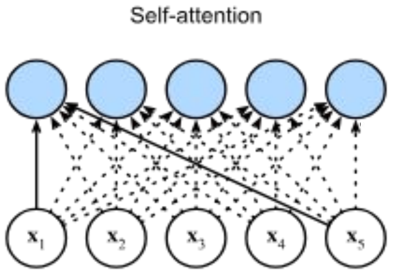


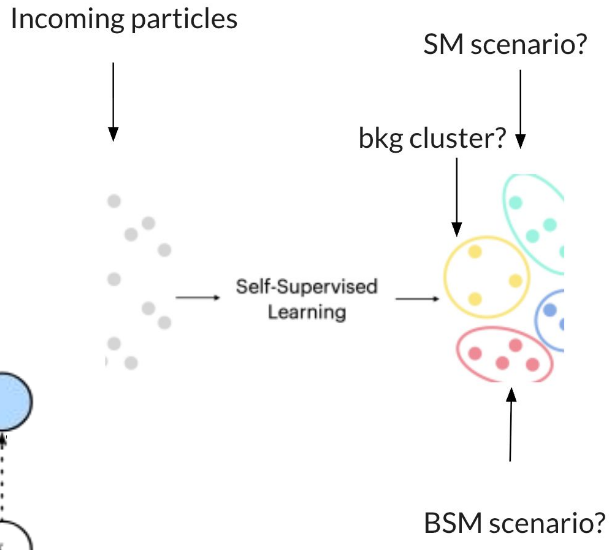


Anomaly Detection at HL-LHC

- **Key step forward: access to particle-level information**
  - design novel point-cloud based AD algo that takes as input all reconstructed PUPPI candidates (building on: Fast Particle-based Anomaly Detection Algorithm with Variational Autoencoder)
  - Possibly useful to capture soft and/or unclustered distributions
- **New generation of models:**
  - Global attention mechanism, fully-connected graphs → build representations from all event constituents (change from local, independent objects)
  - Self-supervised/Representation Learning for unbiased data-driven event grouping, expanding beyond traditional outlier detection
- **We welcome any input/suggestions!**

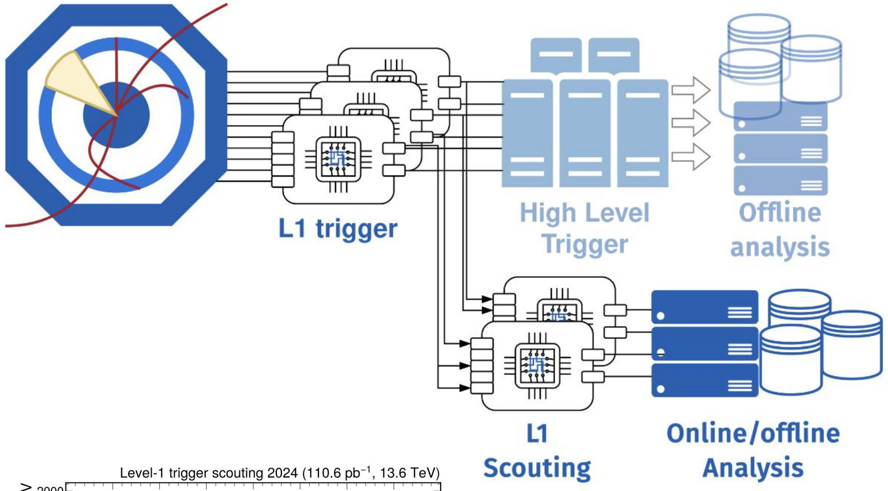


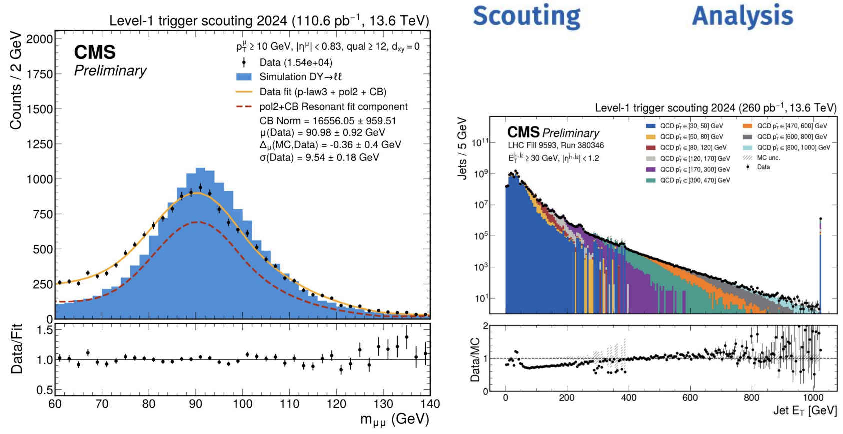




Scouting 40MHz L1T objects

- L1T Data Scouting: **acquire and analyse the L1 Trigger information for all events (at 40 MHz)**
- Look for physics signatures identifiable with **just L1 information** that would evade the L1T → HLT → Offline chain, e.g.:
  - Too large "irreducible" backgrounds, e.g. **narrow resonances of low and unknown mass** (as already done at HLT with di-muon, di-jets)
  - Signal identification requires an algorithm that can't fit the L1 fixed latency and resource budget, e.g. **has too large combinatorics some events, requires a too complex NN, ...**
  - Signal identifications requires time-correlation across several BXs, beyond what is allowed by GT, e.g. **slow or long-lived BSM**
- FPGA-equipped boards that receive L1 data via optical links and transfer it to PCs and the software world via TCP/IP or PCI express
  - **further reconstruction steps/analysis to be run online**, only storing needed info for offline signal extraction
- **at HL-LHC: can profit from much improved L1T object reconstruction quality**
  - **Demonstrated already in 2018 (muons), Run 3 (muons + calo)**

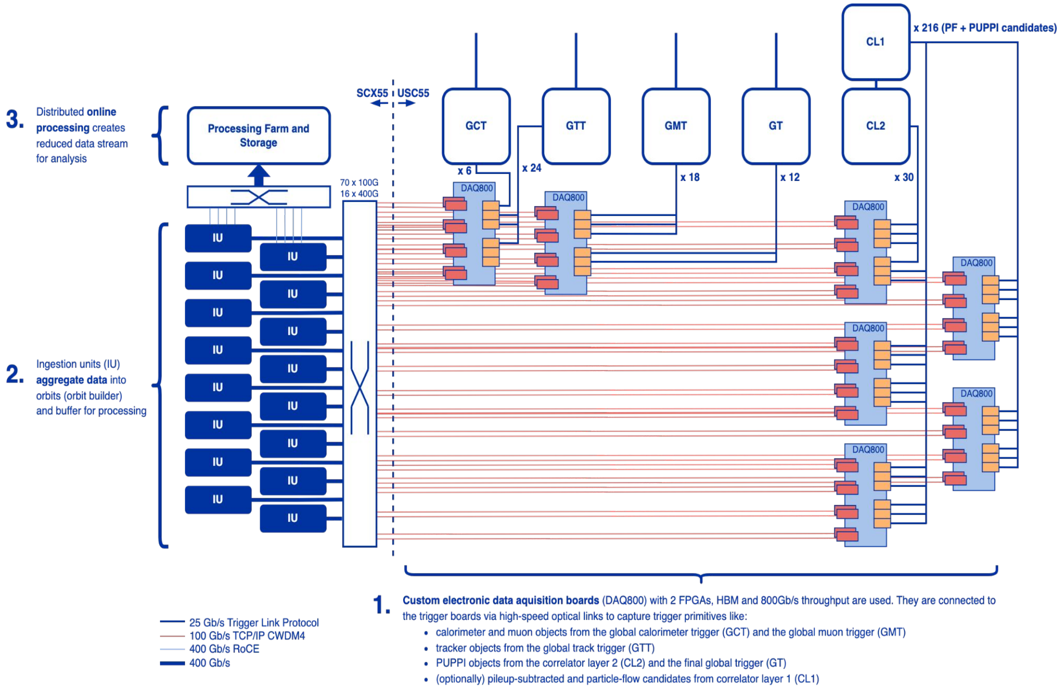




Run-3 Demonstrator: 2024 DP Note on physics objects analysis, Sabrina's poster at ICHEP24, Rocco's talk at TWEPP23, Matteo's talk at CHEP24

Scouting 40MHz L1T objects: NGT goals

- **Thanks to NGT** explore the physics opportunities and technical feasibility using **different L1 inputs with respect to TDR baseline and R&D to investigate different implementations**

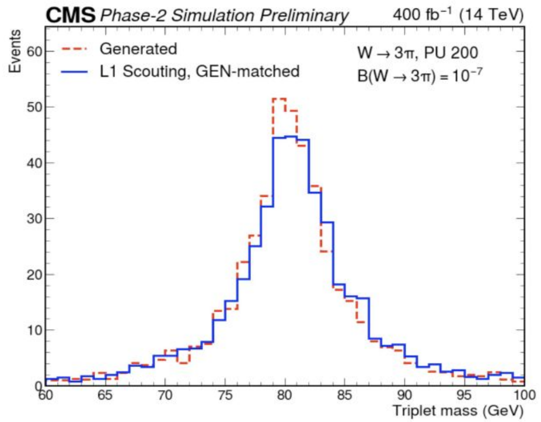


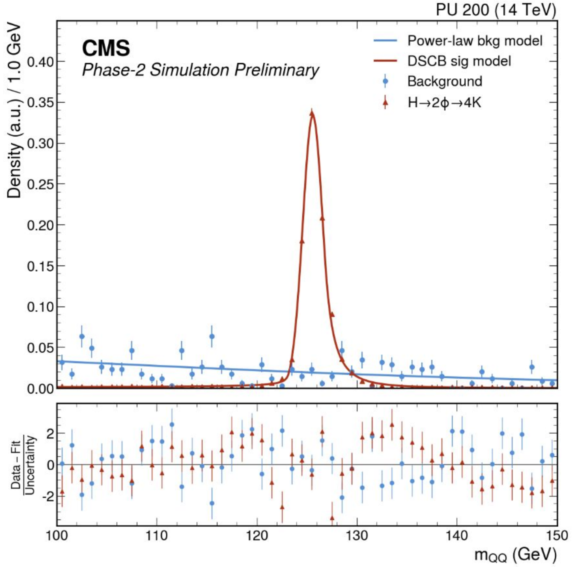
HL-LHC L1T Scouting baseline
Readout of high level objects for the L1T decision: Muons, Electrons, Photons, Jets + PF Subtracted PF (PUPPI candidates)

- How: investigate **different analyses of increasing complexity** in terms of data processing and bandwidth:
  - from dilepton resonances to soft hadronic final states with NN taggers, multi-BX signatures
  - ML algorithms for soft objects (e/ɣ/jet) reconstruction & tagging
- How: incrementally build a **test system of increasing bandwidth & processing power** to run benchmark analyses
  - investigate running algorithms on CPU / GPU / FPGA / AI engines
  - investigate different approaches for data acquisition from DAQ board: protocols (e.g. TCP/IP vs RoCE vs direct fpga-fpga links), networking (400GbE links, NIC vs accelerators cards), workflows
  - prototype a Scouting DAQ board with newer technology (e.g. large Versal devices) to have more links on the same FPGA and more on-board resources

First prototype analyses: exclusive rare decays

- **Developed first set of physics analyses and test the capabilities of 40MHz demonstrator**
  - **Soft final state**, not selected efficiently by the standard L1 Trigger
  - **Small signal yield**, but visible as **narrow peak over smooth background**
  - Combinatorics with many objects may not fit fixed-latency L1
- **Exclusive rare decays of W & H**
  - Started with signatures identifiable with PUPPI candidates and e/γ objects
  - Simple selection on kinematic quantities and isolation reduce drastically the bkg rate by **allowing the selected events to be saved for final analysis**
    - **W → 3π (current BR UL 10^{-6}, SM @ $10^{-8/-12}$)**
      - 5×10^{-7} bgk reduction 5.5% signal selection
    - **W → Ds γ → KKπ γ (current BR UL 10^{-4}, SM @ 10^{-8}), W → π γ (current BR UL 10^{-5}, SM @ $10^{-9/-7}$)**
      - 6×10^{-6} bgk reduction 4% signal selection, 4×10^{-6} bgk reduction 12% signal selection
    - **H →ρρ→ 4π (H→ ϕϕ→ 4K, H→ϕJ/ψ→KKμμ), H→ ργ→ππγ (H→ ϕγ→KKγ, H→J/ψγ→μμγ)**
      - 3 (1, 0.3) $\times10^{-5}$ bkg reduction & 19 (42, 31)% signal selection, 9 (3, 0.1) $\times10^{-6}$ & 28 (44, 34)% signal selection





DP Note

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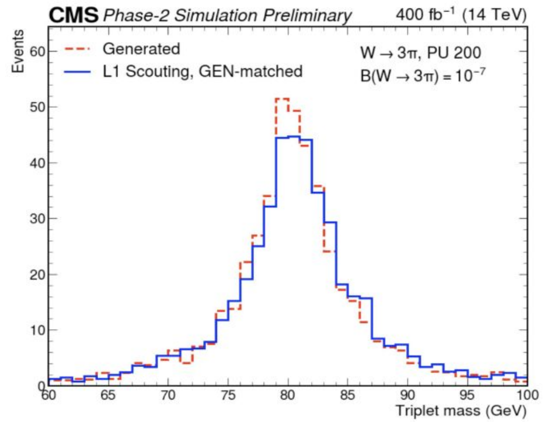
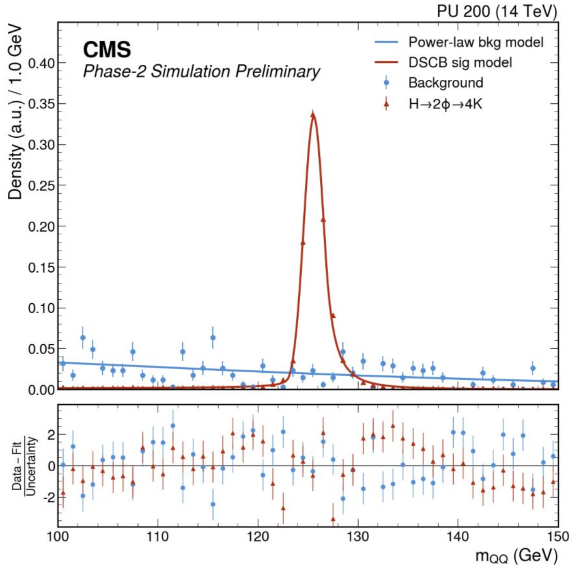
  - Combinatorics with many objects may not fit fixed-latency L1
- **Exclusive rare decays of W & H**
  - **Charged hadrons: quality in the same ballpark as offline**
    - with one notable exception: impact parameter (no pixels!)
  - **Implemented unpacker and 9 analyses into hardware demonstrator**
    - Successfully demonstrated receiving and processing 4 stream of L1 PUPPI and e/γ candidates **(~27MHz),** data rate of **~12 GB/s**
    - On average **~1.3us per BX**
  - **Other signals being studied: $B_s \to \tau\tau \to (3\pi)(3\pi)$, $\tau \to 3\mu$ …**

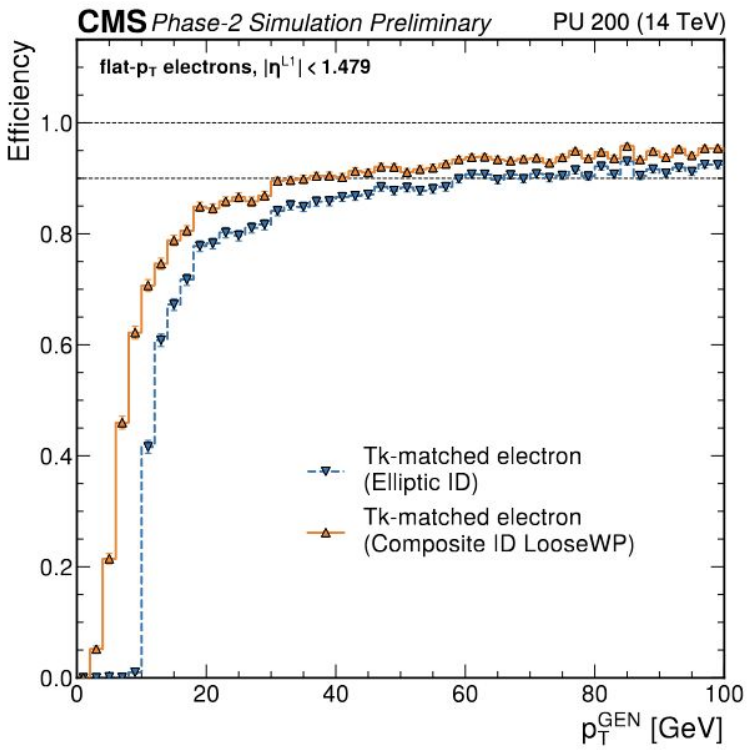




DP Note

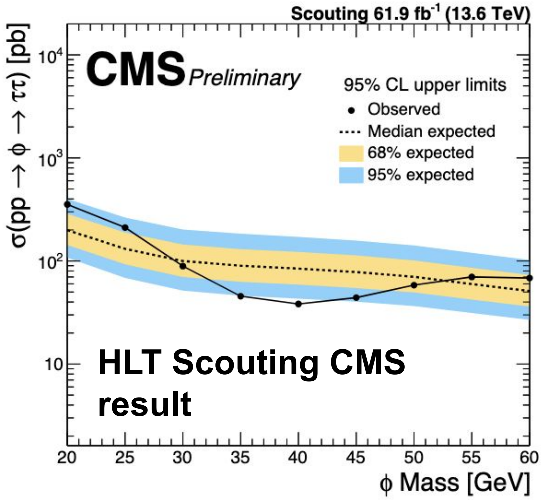
First prototype analyses: low-mass resonances

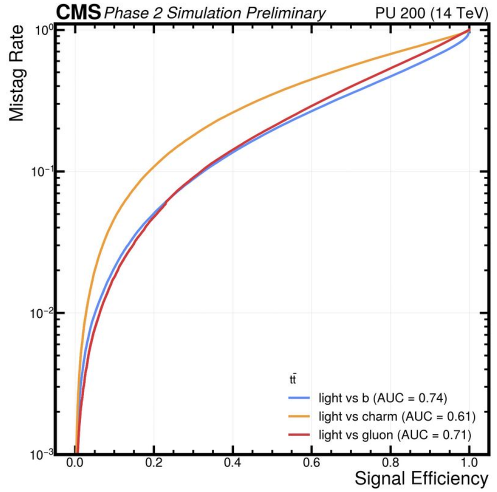
- **Investigating low mass narrow resonances decaying into μμ, ee, ττ, γγ, qq/bb being explored**
  - **Soft final state**, not selected efficiently by the standard L1 Trigger
  - **Small signal yield**, but visible as **narrow peak over smooth background**
  - Too large “irreducible” backgrounds
    - **X→μμ further expand HLT Scouting acceptance (CMS-EXO-21-005, CMS-EXO-19-018)**
      - all L1 tk-matched muons (p_T>2 GeV, η<2.4)
    - **X→ee, γγ further expand HLT Scouting acceptance**
      - all L1 tk-matched electrons, and isolated photons
      - see how far we can push low p_T e/γ reco in the L1 Trigger



First prototype analyses: low-mass resonances

- **Investigating low mass narrow resonances decaying into μμ, ee, ττ, γγ, qq/bb being explored**
  - **Soft final state**, not selected efficiently by the standard L1 Trigger
  - **Small signal yield**, but visible as **narrow peak over smooth background**
  - Too large “irreducible” backgrounds
    - **X→ττ further expand HLT Scouting acceptance (CMS-EXO-24-012)**
      - see how far we can push low p_T τ reco with ML-algo on PF candidates in Scouting, current L1T tau reco NN-based target focusing on high p_T for H → ττ
    - **Investigating di-jets resonances to extend further HLT Scouting reach**
      - any two L1T PUPPI jets (~90% efficient for p_T > 30 GeV in ttbar)
      - exploit L1T PUPPI jets reconstruction quality: flavour tagging, large radius jets
      - can improve further in Scouting with: jet p_T regression (as offline for b-jets), more complex tagging algorithm



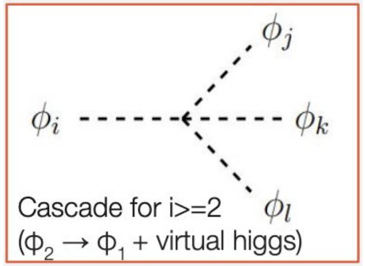


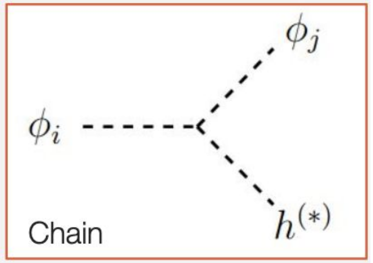
First prototype analyses: hadronic final states

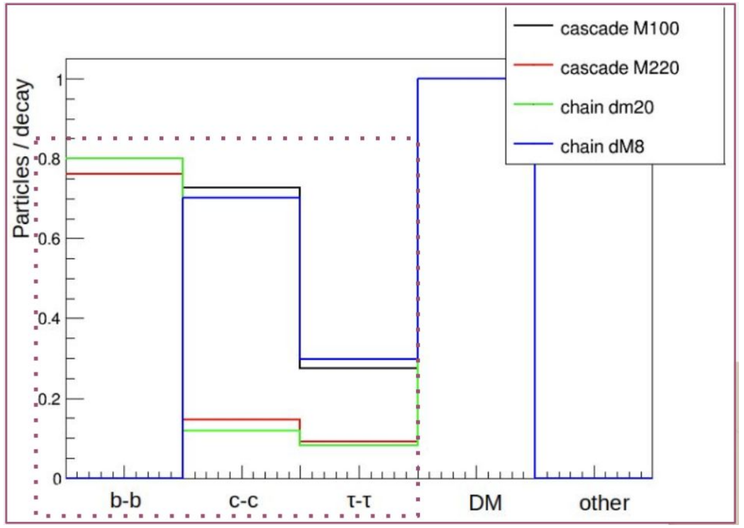
- **Investigating final state with multiple soft hadronic objects**
  - **Soft final state**, not selected efficiently by the standard L1 Trigger
  - **Small signal yield**, but **high multiplicity of soft b/c jets, hadronic taus**
  - Need dedicated soft-objects reco & NN to extract signal

- **Multiple Soft Hadronic objects:**
  - **E.g. arXiv 1902.05535, multiple new states (from 5 to 50) with compressed mass spectra, small couplings**
    - With accessible cross section: final states with multiple (O(10)) low pT 5-10 GeV tau, b, c

- **Could also investigate SUEPs-like signatures with L1 PUPPI**







First prototype analyses: more signatures (?)

- **Slow or long-lived objects: correlate signals across multiple BXs:**
  - Feasibility of multi-BX reco in muon chambers? (needs all segments: rate?)−Dataset of event pairs can be huge^2: analysis feasible computationally?−If scouting data is kept for long time, can be used also together with analysis on triggered events, e.g. to look before/after some OOT signal candidates

- **L1 Data scouting on the whole set of L1 tracks (w/ extended tracking):**
  - Physics case? SUEPs/instantons? need signatures that on average look weaker than PU, otherwise, they'd be captured often enough in the L1 Puppi stream.−One order of magnitude increase in data rate compared to L1 Puppi scouting (average 150-200 tracks/event, 64 → 96 bits), data acquisition still feasible but further processing & storage may become prohibitively expensive?

- **L1 AD on Data Scouting**
  - Same but possibly accessing lower pT, lower level objects (PF candidates? L1 Tracks? High Granularity Calorimeter information?), and multiple BX

- **Inputs from BSM experts very welcome in defining models & benchmarks, and in suggesting more signatures to explore**

New triggers for LLP @L1 & HLT present & future

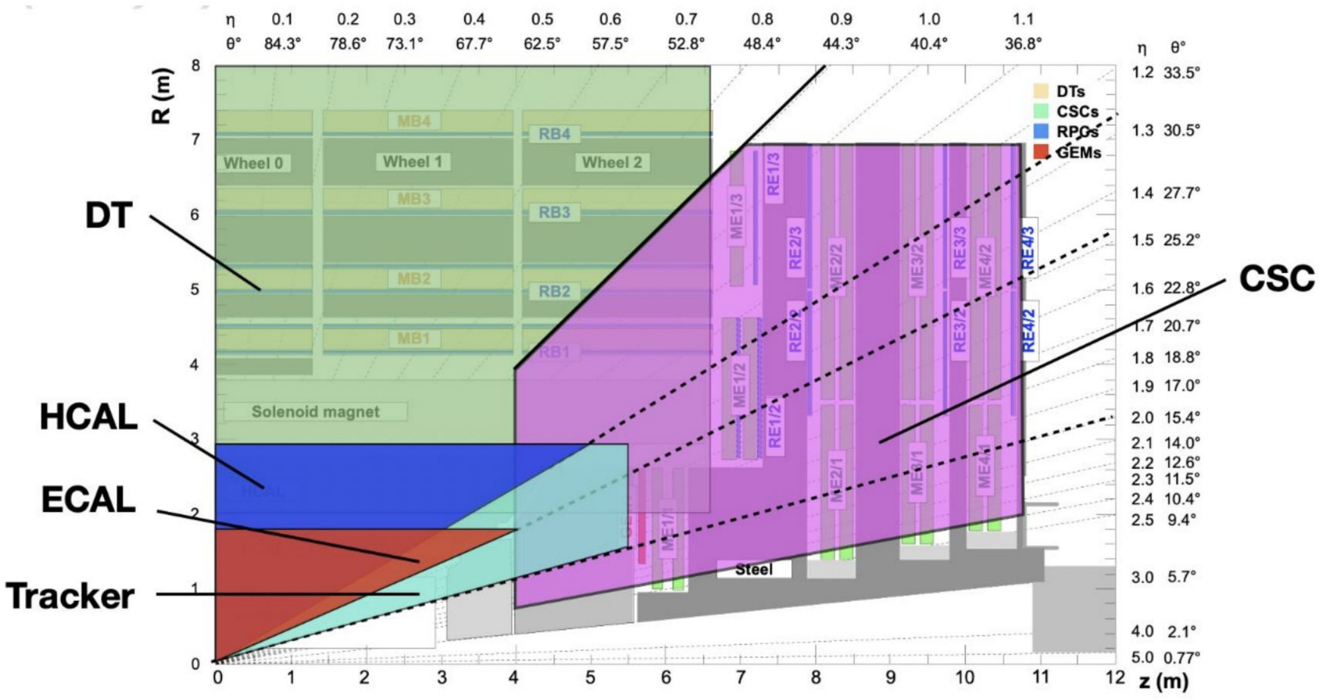
CMS

CERN | NexTGen Next Generation Triggers

New LLP Triggers in Run 3: Track-based

- **As a result of long-standing developments, in Run(2)3 large suit of triggers dedicated to LLPs**
  - **mostly in prompt/parking, only a dedicated displaced muon reconstruction for Di-muon stream in Scouting**

- **Multiple triggers using different detectors to effectively cover a large range of final states and LLP lifetimes**
  - **Track-based: Available at HLT**
  - **Calo-based:**
    - **ECAL timing available at HLT**
    - **Displaced/delayed jets in HCAL available at L1T & HLT**
  - **Muon-based:**
    - **Displaced muon triggers available at L1T & HLT**
    - **Muon detector showers in DTs available at HLT**
    - **Muon detector showers in CSCs available in L1T & HLT**

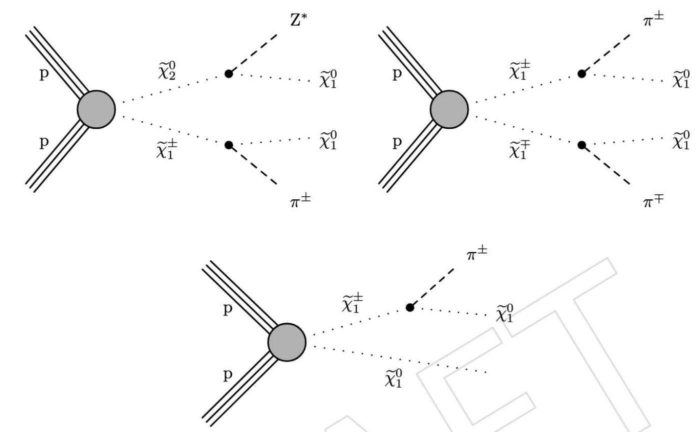


Run-3 LLP Trigger paper coming soon (EPS)

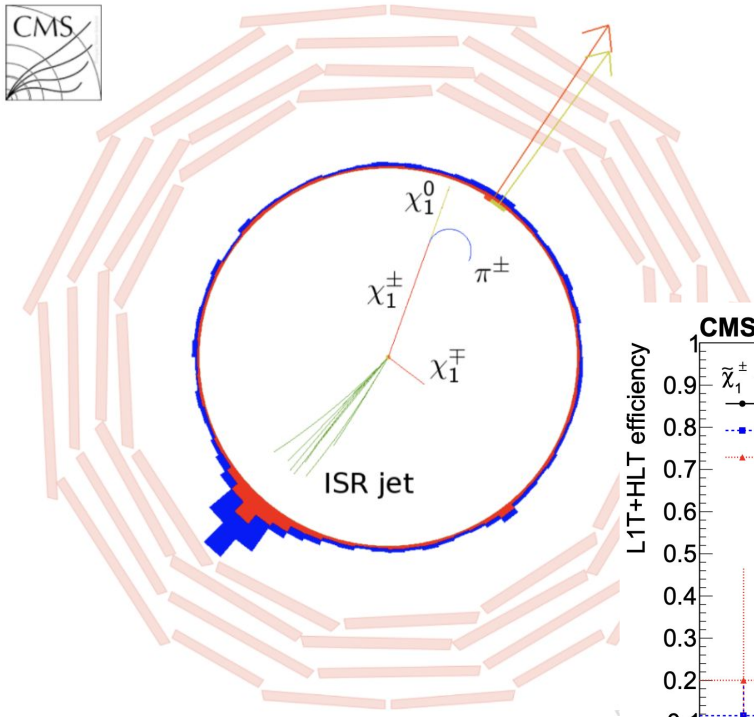
New LLP Triggers in Run 3: Track-based

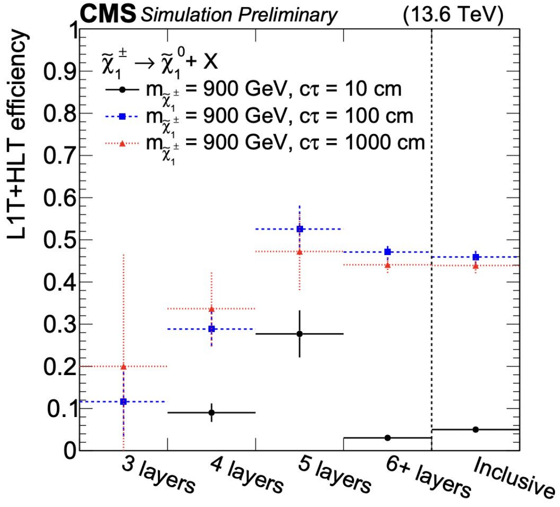
- **As a result of long-standing developments, in Run(2)3 large suit of trigger dedicated to LLP**
  - **mostly in prompt/parking, only a dedicated displaced muon reconstruction for Di-muon stream in Scouting**

Triggered signature	Trigger description
Disappearing track	$p_T^{miss} > 105\,\text{GeV} + \geq 1$ isolated track ($p_T > 50\,\text{GeV}$)
Disp. tau	≥ 2 disp. τ_h ($p_T > 32\,\text{GeV}$, $d_0 > 0.005\,\text{cm}$)† ≥ 1 disp. τ_h ($p_T > 24\,\text{GeV}$) $+ \geq 1\ \mu$ ($p_T > 24\,\text{GeV}$)† ≥ 1 disp. τ_h ($p_T > 34\,\text{GeV}$) $+ \geq 1$ e ($p_T > 34\,\text{GeV}$)†
Disp. jet	≥ 2 jet ($p_T > 40\,\text{GeV}$, inclusive tagging req.) $+ H_T > 430\,\text{GeV}$ ≥ 2 jet ($p_T > 40\,\text{GeV}$, disp. tagging req.) $+ H_T > 240\,\text{GeV} + \geq 1$ L1 μ ($p_T > 6\,\text{GeV}$)



AMSB SUSY model: C1→N1+X, as a function of Δm, chargino can be long-lived and decay after tens of cm.
at L1T: MET
at HLT: Isolated Tracker Track with missing outer layers (lower standard MET HLT thresholds)



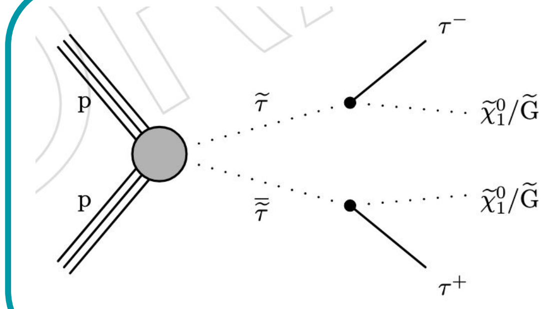


Run-3 LLP Trigger paper coming soon (EPS)

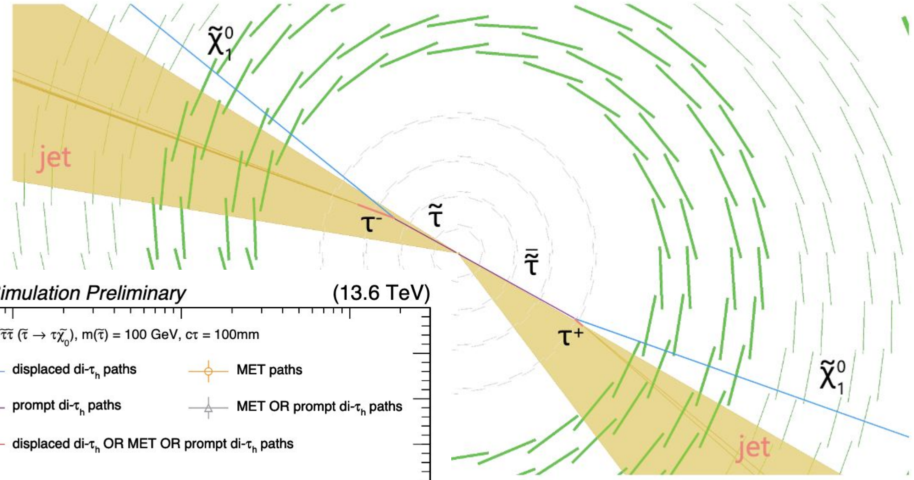
New LLP Triggers in Run 3: Track-based

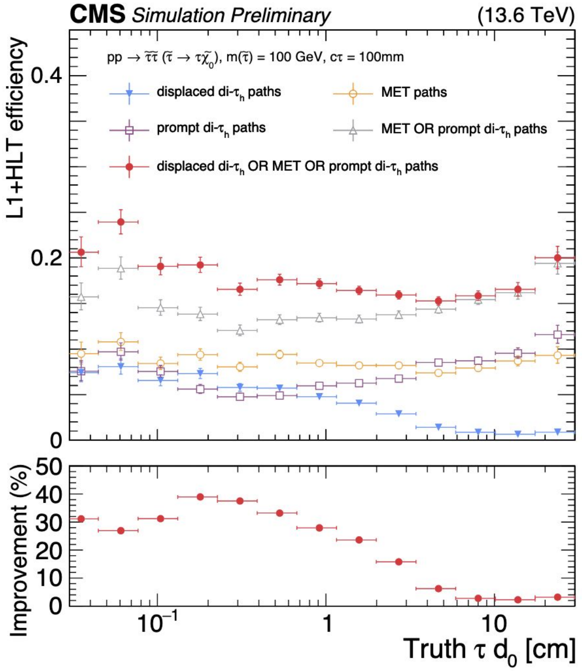
- **As a result of long-standing developments, in Run(2)3 large suit of trigger dedicated to LLP**
  - **mostly in prompt/parking, only a dedicated displaced muon reconstruction for Di-muon stream in Scouting**

Triggered signature	Trigger description
Disappearing track	$p_T^{miss} > 105\,\mathrm{GeV}$ + ≥ 1 isolated track ($p_T > 50\,\mathrm{GeV}$)
Disp. tau	≥ 2 disp. τ_h ($p_T > 32\,\mathrm{GeV}$, $d_0 > 0.005\,\mathrm{cm})^{\dagger}$ ≥ 1 disp. τ_h ($p_T > 24\,\mathrm{GeV}$) + ≥ 1 μ ($p_T > 24\,\mathrm{GeV})^{\dagger}$ ≥ 1 disp. τ_h ($p_T > 34\,\mathrm{GeV}$) + ≥ 1 e ($p_T > 34\,\mathrm{GeV})^{\dagger}$
Disp. jet	≥ 2 jet ($p_T > 40\,\mathrm{GeV}$, inclusive tagging req.) + $H_T > 430\,\mathrm{GeV}$ ≥ 2 jet ($p_T > 40\,\mathrm{GeV}$, disp. tagging req.) + $H_T > 240\,\mathrm{GeV}$ + ≥ 1 L1 μ ($p_T > 6\,\mathrm{GeV}$)



GMSB SUSY model: Direct stau production, stau can be long-lived and decay after tens of cm
at L1T: standard di Calo-Tau
at HLT: pixelless tracking + standard tracking + modified tau reconstruction algorithm





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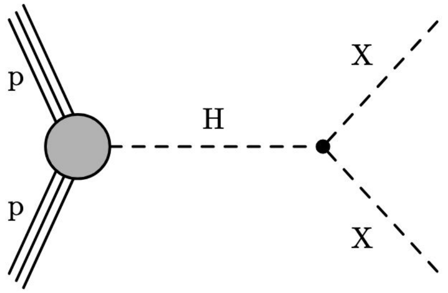
- **As a result of long-standing developments, in Run(2)3 large suit of trigger dedicated to LLP**
  - **mostly in prompt/parking, only a dedicated displaced muon reconstruction for Di-muon stream in Scouting**

Triggered signature	Trigger description
Disappearing track	$p_{\mathrm{T}}^{\mathrm{miss}} > 105\,\mathrm{GeV}$ + $\geq$1 isolated track ($p_{\mathrm{T}} > 50\,\mathrm{GeV}$)
Disp. tau	$\geq$2 disp. τ_{h} ($p_{\mathrm{T}} > 32\,\mathrm{GeV}$, $d_0 > 0.005\,\mathrm{cm}$)† $\geq$1 disp. τ_{h} ($p_{\mathrm{T}} > 24\,\mathrm{GeV}$) + $\geq$1 μ ($p_{\mathrm{T}} > 24\,\mathrm{GeV}$)† $\geq$1 disp. τ_{h} ($p_{\mathrm{T}} > 34\,\mathrm{GeV}$) + $\geq$1 e ($p_{\mathrm{T}} > 34\,\mathrm{GeV}$)†
Disp. jet	$\geq$2 jet ($p_{\mathrm{T}} > 40\,\mathrm{GeV}$, inclusive tagging req.) + $H_{\mathrm{T}} > 430\,\mathrm{GeV}$ $\geq$2 jet ($p_{\mathrm{T}} > 40\,\mathrm{GeV}$, disp. tagging req.) + $H_{\mathrm{T}} > 240\,\mathrm{GeV}$ + $\geq$1 L1 μ ($p_{\mathrm{T}} > 6\,\mathrm{GeV}$)

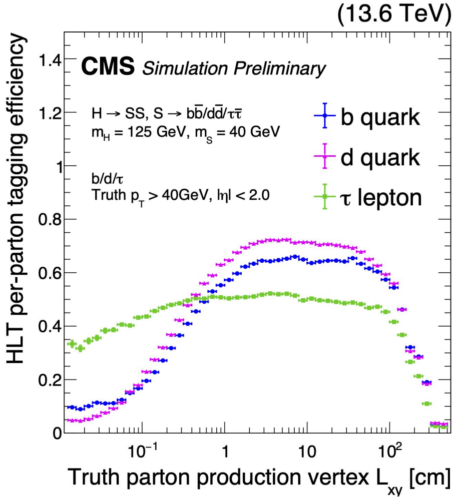


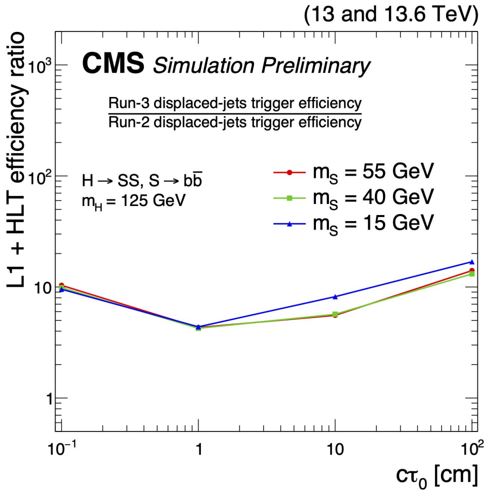
SM Higgs (or heavier) exotic decays. X, general LL (often scalar S, decaying hadronically)

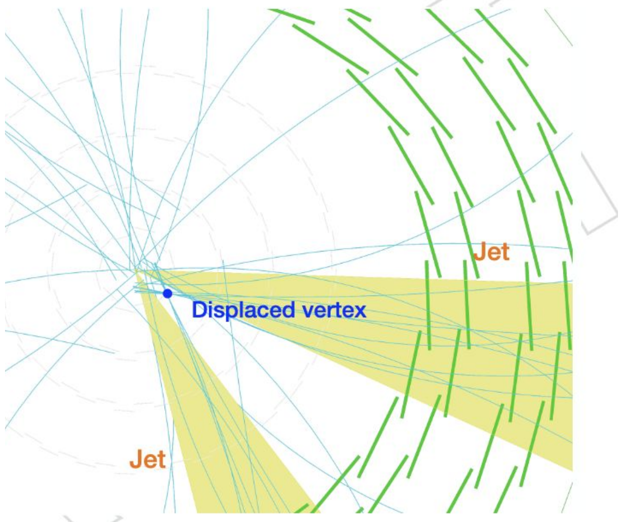
at L1T: standard H_T, or H_T+ µ

at HLT: jets with veto on number of prompt tracks or with displaced tracks

Due to high CPU cost, at HLT displaced tracking iteration is performed only for displaced jets seeds







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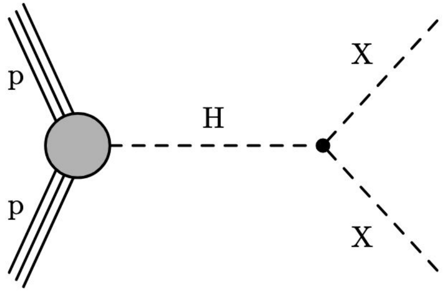
DP Note

New LLP Triggers in Run 3: Calo-based

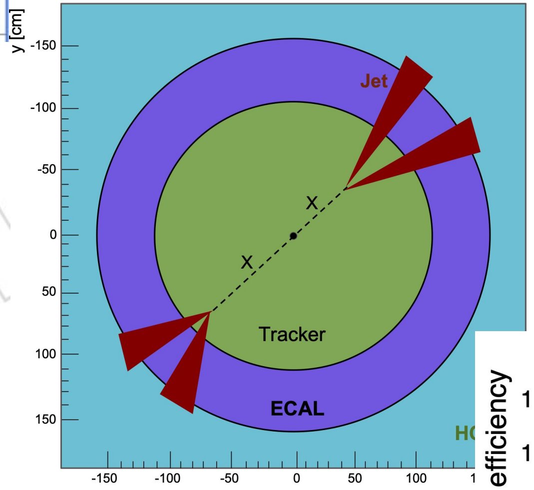
- **As a result of long-standing developments, in Run(2)3 large suit of trigger dedicated to LLP**
  - **mostly in prompt/parking, only a dedicated displaced muon reconstruction for Di-muon stream in Scouting**

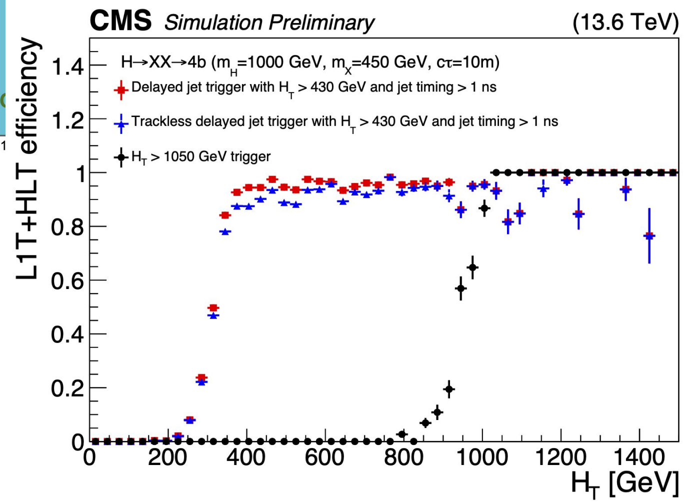
Triggered signature	Trigger description
HCAL-based disp. and delayed jet	$\geq$2 jet ($p_T > 40$ GeV, displ. tagging req.) + $H_T > 170$ GeV† $\geq$2 jet ($p_T > 40$ GeV, inclusive. tagging req.) + $H_T > 200$ GeV† $\geq$1 jet ($p_T > 60$ GeV, neutral hadron energy fraction >0.7) + $H_T > 200$ GeV†
ECAL-based delayed jet	$\geq$1 inclusive and trackless jet†
Delayed diphoton	$\geq$2 ECAL superclusters (time >1 ns)†
Disp. photon + H_T	$\geq$1 γ ($p_T > 60$ GeV) + PF $H_T > 350$ GeV



SM Higgs (or heavier) exotic decays. X is general LLP (often scalar S, decaying hadronically)
at L1T: H_T or di-tau
at HLT: jets with veto on number of prompt tracks or trackless jets with ECAL timing requirements, no H_T

NB: for a displaced vertex in the inner tracker, expected delay in the peak ECAL signature is ~n >> ECAL timing resolution





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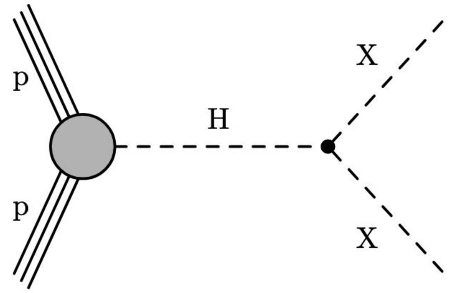
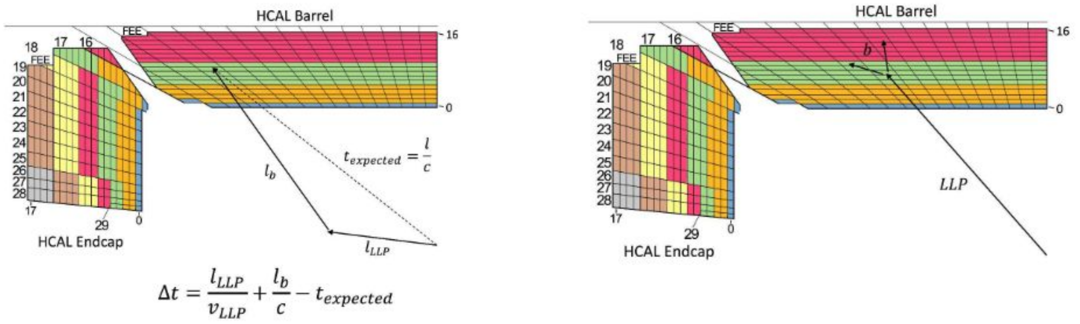
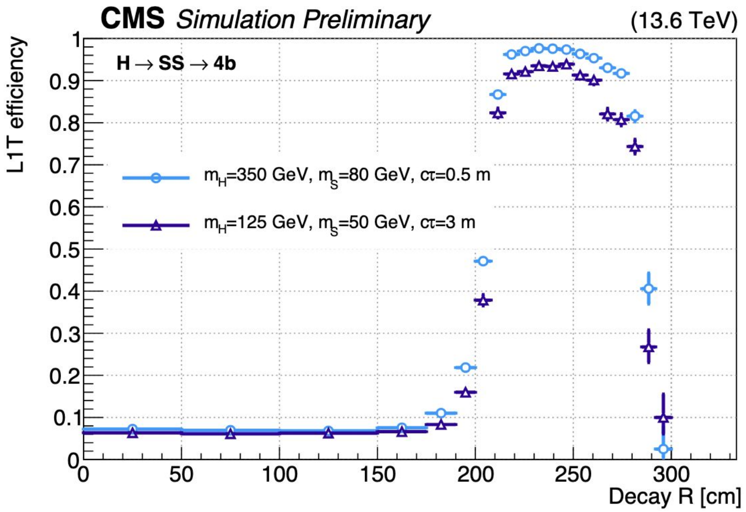


SM Higgs (or heavier) exotic decays. X is general LLP (often scalar S, decaying hadronically)
at L1T: two or more LLP flagged HCAL towers (timing flag or depth flag), no H_T
at HLT: same strategy as before, but lower H_T





Run-3 LLP Trigger paper coming soon (EPS)

L1T DP Note

DP Note

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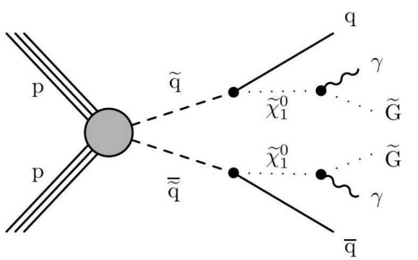
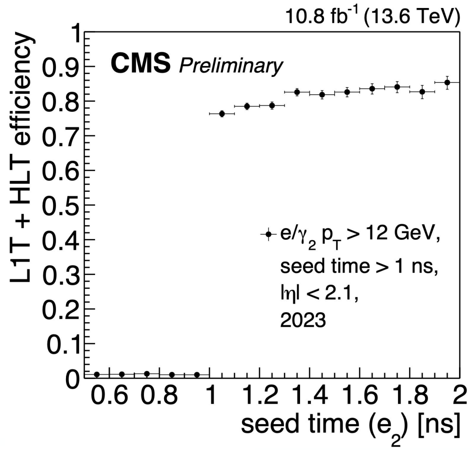
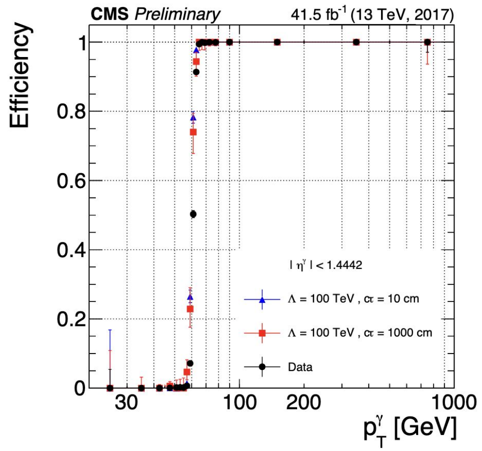


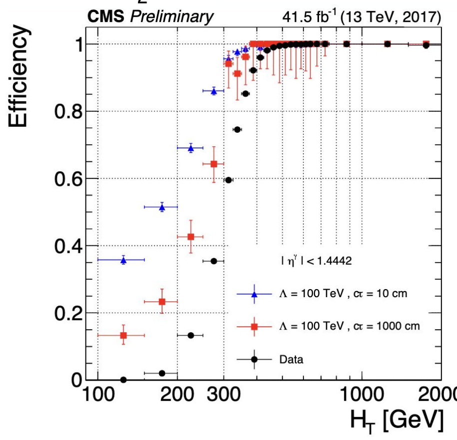
GMSB SUSY model with pair-produced squarks and gluinos that undergo cascade decay: N1 coupling with Gravitino can be weak, N1 can be long-lived, displaced photons

Delayed Diphoton:
at L1T: single/double e/ɣ
at HLT: two ECAL superclusters (e/ɣ) of 22, 12 GeV, and time dealy ECAL crystal > 1ns

Displaced Photon + H_T:
at L1T: single e/ɣ or tau or jet
at HLT: H_T , isolated e/ɣ with dedicated shower shape requirements







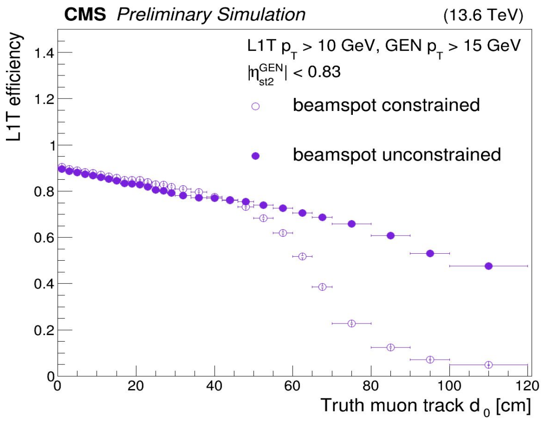
Run-3 LLP Trigger paper coming soon (EPS)

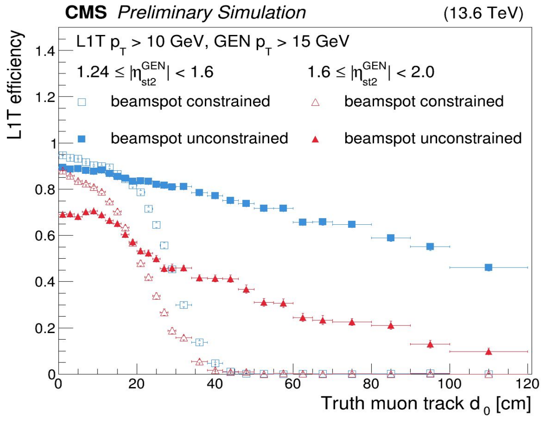
DP Note

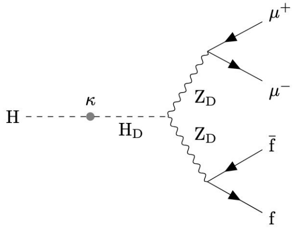
New LLP Triggers in Run 3: Muon-based

- As a result of long-standing developments, in Run(2)3 large suit of trigger dedicated to LLP
  - mostly in prompt/parking, only a dedicated displaced muon reconstruction for Di-muon stream in Scouting

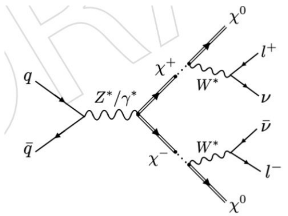
Triggered signature	Trigger description
Disp. single and dimuon	≥ 2 L2 μ ($p_T > 10$ GeV, $d_0 > 1$ cm)† ≥ 2 L3 μ ($p_T > 16, 10$ GeV, $d_0 > 0.01$ cm)† ≥ 2 L2 μ ($p_T > 23$ GeV) ≥ 1 L2 μ ($p_T > 50$ GeV, $d_0 > 1$ cm)† ≥ 1 L3 μ ($p_T > 30$ GeV, $d_0 > 0.01$ cm)†
Double disp. L3 muon	≥ 2 L3 μ ($p_T > 43$ GeV)
Disp. L3 muon+photon	≥ 1 L3 μ ($p_T > 43$ GeV) + γ ($p_T > 43$ GeV) ≥ 1 L3 μ ($p_T > 38$ GeV, $d_0 > 1$ cm) + γ ($p_T > 38$ GeV)
Dimuon scouting	≥ 2 scouting μ ($p_T > 3$ GeV)





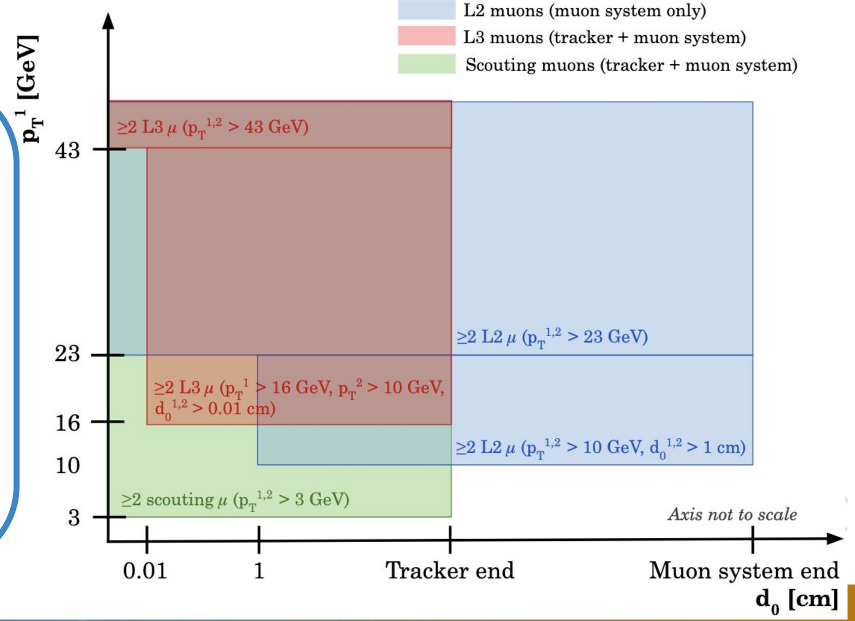


Models with long-lived Dark Photons (Zd), eg HAHM model: pair of displaced muons from same vertex



Dark matter models with compressed dark sector: pair production of long-lived charged states, pair of displaced muons not from same vertex

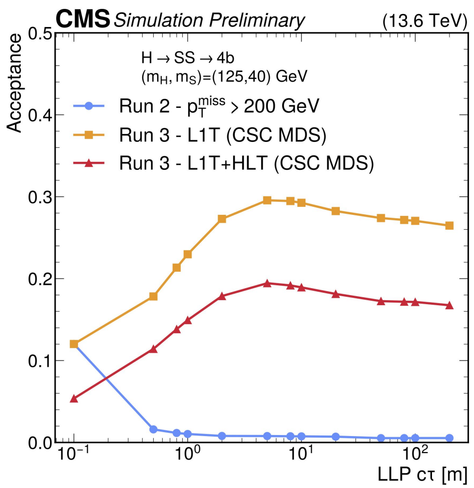
at L1T: new no-beamspot constraint p_T assignment in muon trigger systems
at HLT:
- L2 Muons from muon detectors
- L3 Muons from tracker+muon with no-vtx reco (a different displaced reco is developed for Scouting)

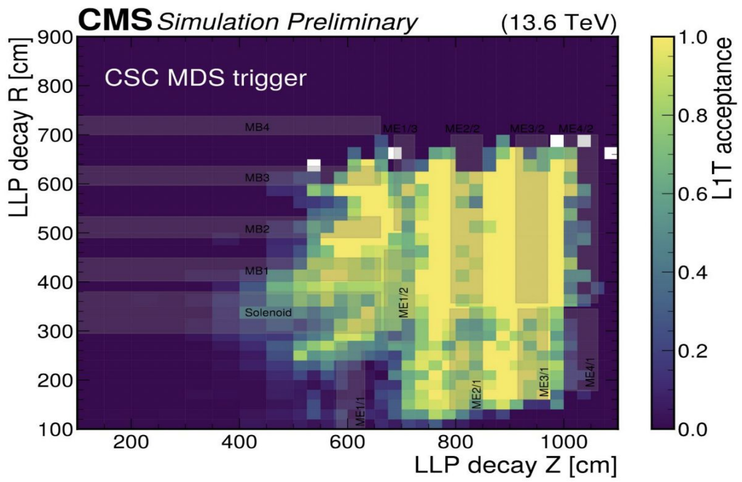


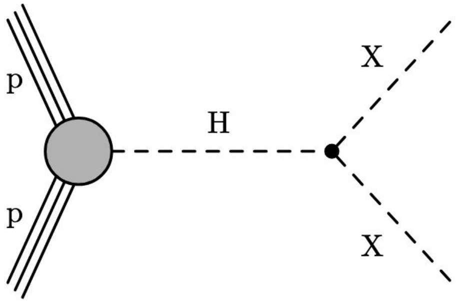
New LLP Triggers in Run 3: Muon-based

- **As a result of long-standing developments, in Run(2)3 large suit of trigger dedicated to LLP**
  - **mostly in prompt/parking, only a dedicated displaced muon reconstruction for Di-muon stream in Scouting**

Triggered signature	Trigger description
MDS in CSCs	$\geq$1 CSC cluster ($\geq$200/500 hits in outer/inner rings)† $\geq$2 CSC clusters ($\geq$75 hits)†
MDS in CSCs + X	$\geq$1 CSC cluster ($\geq$100 hits) + $\geq$1 e ($p_T > 5$ GeV)† $\geq$1 CSC cluster ($\geq$100 hits) + $\geq$1 L3 μ ($p_T > 5$ GeV)† $\geq$1 CSC cluster ($\geq$100 hits) + $\geq$1 τ_h ($p_T > 10$ GeV)† $\geq$1 CSC cluster ($\geq$50 hits) + $\geq$1 γ ($p_T > 20$ GeV)†
MDS in DTs	L1 $p_T^{miss} > 150$ GeV + $\geq$1 DT cluster ($\geq$50 hits)† $\geq$1 L1 CSC cluster + $\geq$1 DT cluster ($\geq$50 hits)†







SM Higgs (or heavier) exotic decays. X is general LLP (often scalar S, decaying hadronically).
if ctau=1m, decays in muon system: **MUON DETECTOR SHOWER**

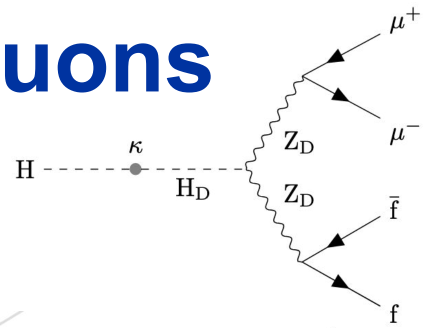
→ High multiplicity of hits in Muon chambers: new Run-3 triggers are based on MDS at L1T & HLT

at L1T: MET trigger
at HLT: >=1 MDS in DT Chambers (barrel)

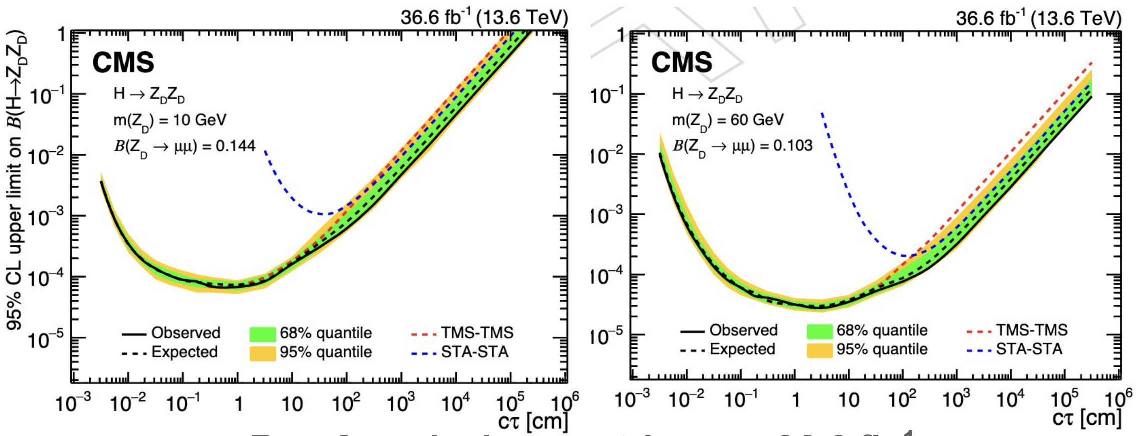
at L1T: >=1 MDS in CSC Chambers (endcap)
at HLT: >=1 MDS in CSC Chambers and additional low p_T objects (or >= 1 MDS in DT (barrel))

DP Note

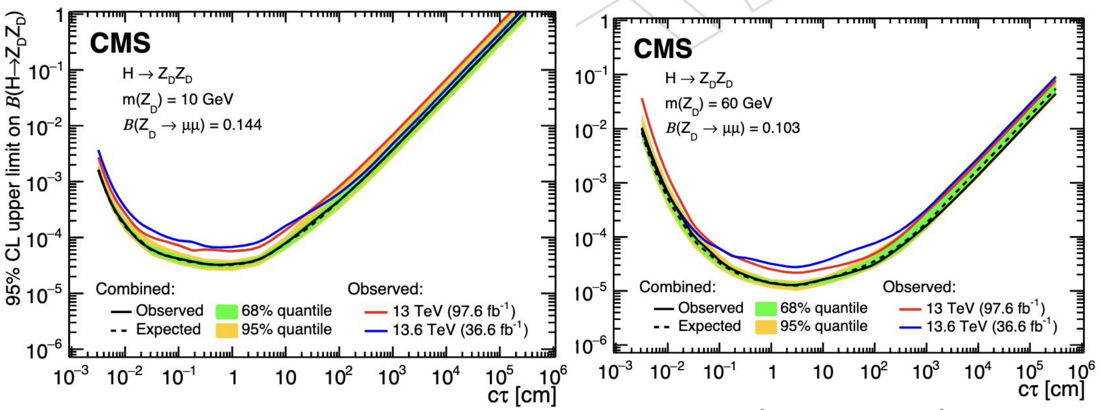
Searches conducted so far: Displaced Di-muons



- **Already published with early Run-3 data (JHEP 05 (2024) 047):**
  - results for HAHM model, **Z_D masses 10-60 GeV**

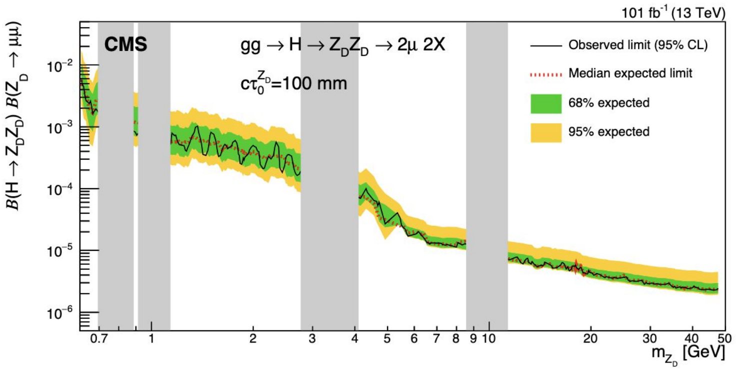


Run-3 analysis, new triggers, 36.6 fb^{-1}

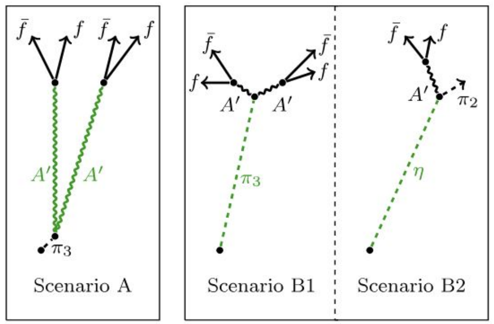


Run-2+Run-3 analysis, 97.6 fb^{-1} + 36.6 fb^{-1}

- **Expected improvements also in low mass search (Z_D<10 GeV) with Run-3 scouting**
  - Target LLP decaying into **μ** pairs with **m_{LLP}> $2m_\mu$ with single or multiple secondary vertices**
  - Target Dark shower models with LL Dark Photons



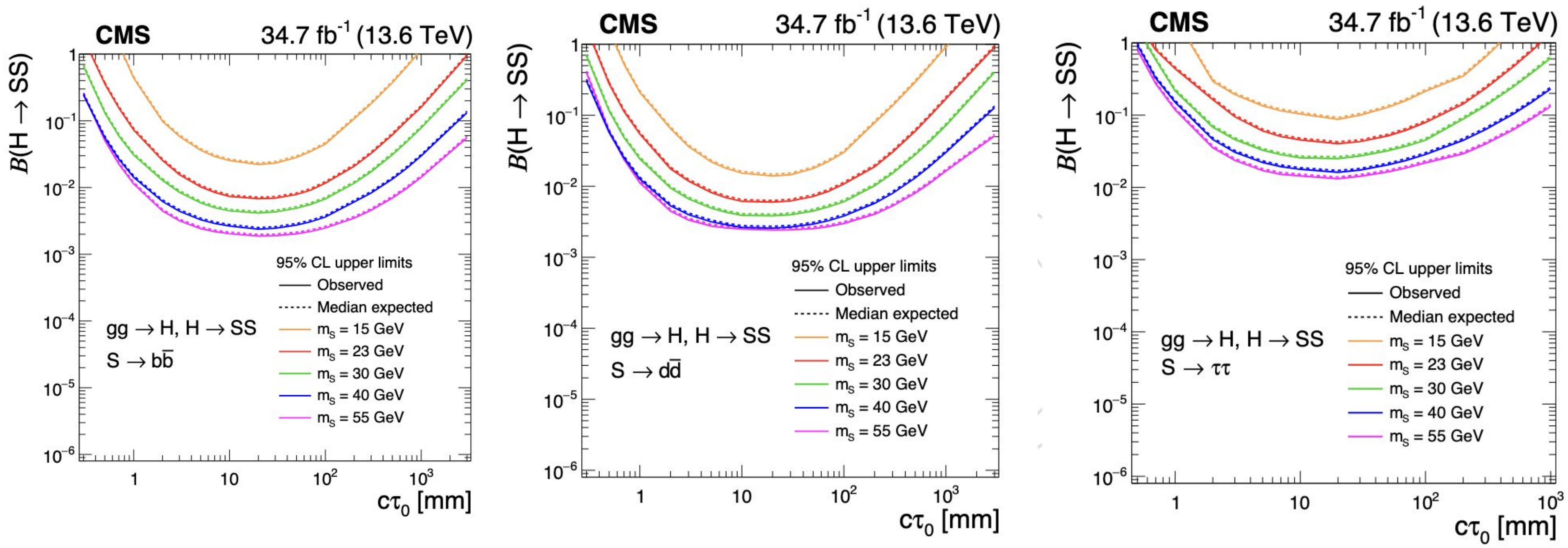
Run-2 analysis (Scouting)



PhysRevD.108.035034
Run-2 analysis (Parking)

Searches conducted so far: Displaced Jets

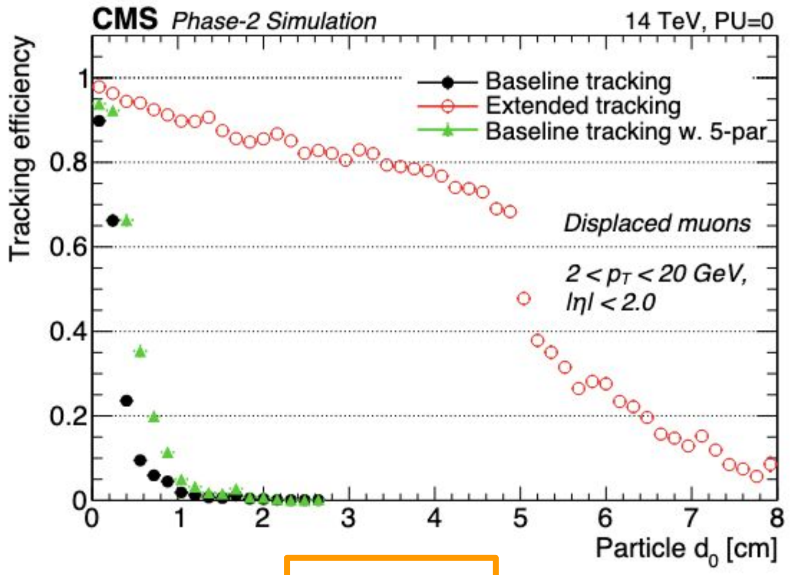
- **Already published with early Run-3 data (Rep. Prog. Phys. 88 (2025) 037801):**
  - using displaced track-based jets seeds, **limits on H→ss→4b, 4τ, 4d much improved wrt Run-2 analyses**



- **Much more data to analysed, many more new triggers to add: stay tuned!**

LLP Triggers for HL-LHC

- **How the acceptance to LLP can improve with HL-LHC Triggers?**
  - **Remember: much more information available in the hardware L1 Trigger**
    - 40 MHz Track Trigger can provide prompt and **displaced (not-baseline) L1 Tracks (p_T>2 GeV)**, ECAL crystal timing information will be also available at L1T, new DTs backend will allow to detect MDS also in barrel
  - **designing LLP seeds already at L1T: allow to reduce p_T/H_T/MET thresholds**



L1T TDR

- **Preliminary developments** (without or partial firmware implementation) **of new L1 algos for LLP:**
  - **Track-based displaced jets, displaced vertices**
  - **Calo-based delayed jets with ECAL timing**
  - **Isolated displaced track?**
  - **MDS in barrel?**
  - **mildly displaced tk-matched muons?**

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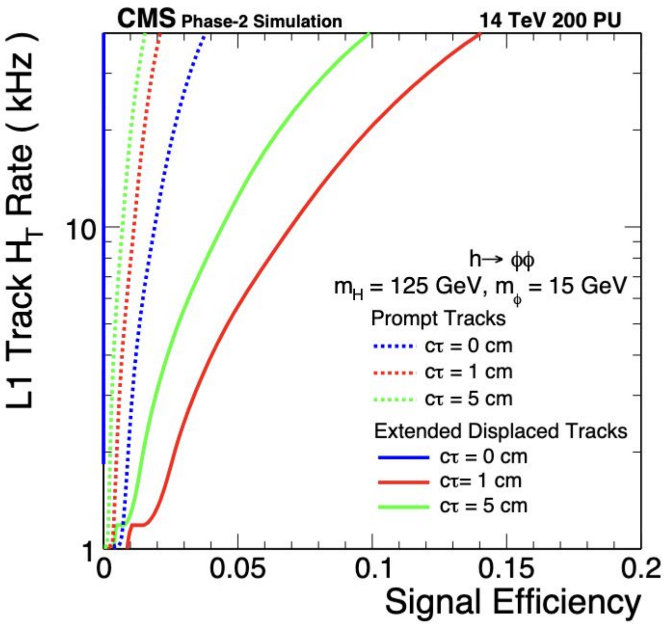
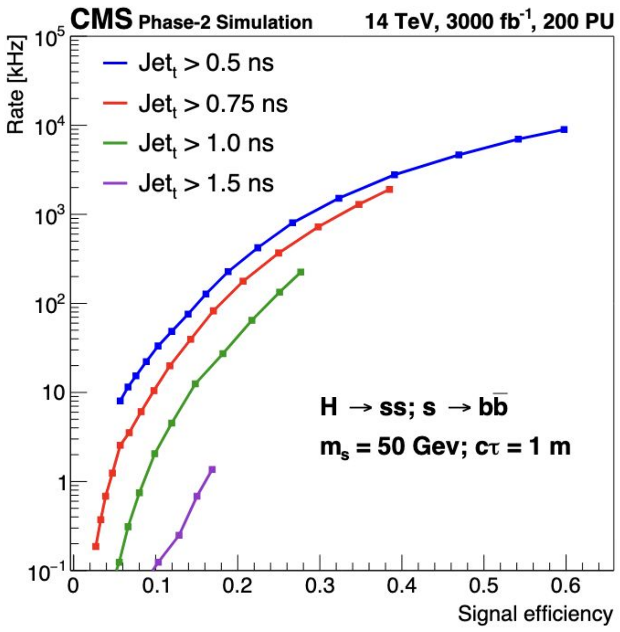
  - **designing LLP seeds already at L1T: allow to reduce p_T/H_T/MET thresholds**

L1T TDR

- **Displaced jets:**
  - Displaced jets can be reconstructed using displaced L1 Tracks (or PUPPI candidates built with displaceds L1 Tracks)
  - Delayed jets can be reconstructed using ECAL crystal timing information in the Calo-Jets





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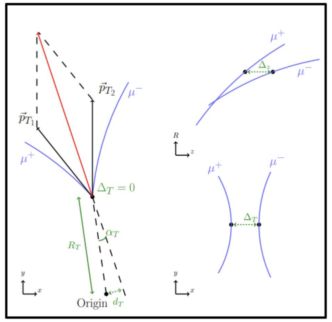
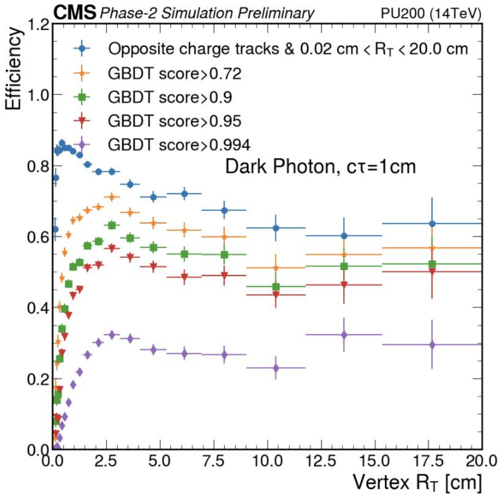
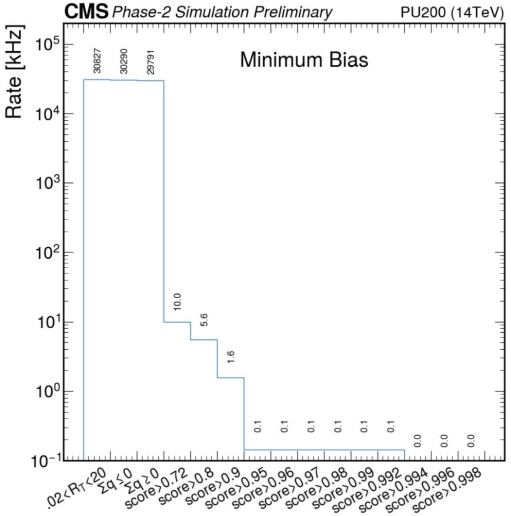
  - **designing LLP seeds already at L1T: allow to reduce p_T/H_T/MET thresholds**

- **Displaced vertices:**
  - Usage of displaced L1 Tracking & ML algorithm (input variables related to L1 Tracks) to identify vertices of LL Dark Photons

DP Note







LLP Triggers for HL-LHC

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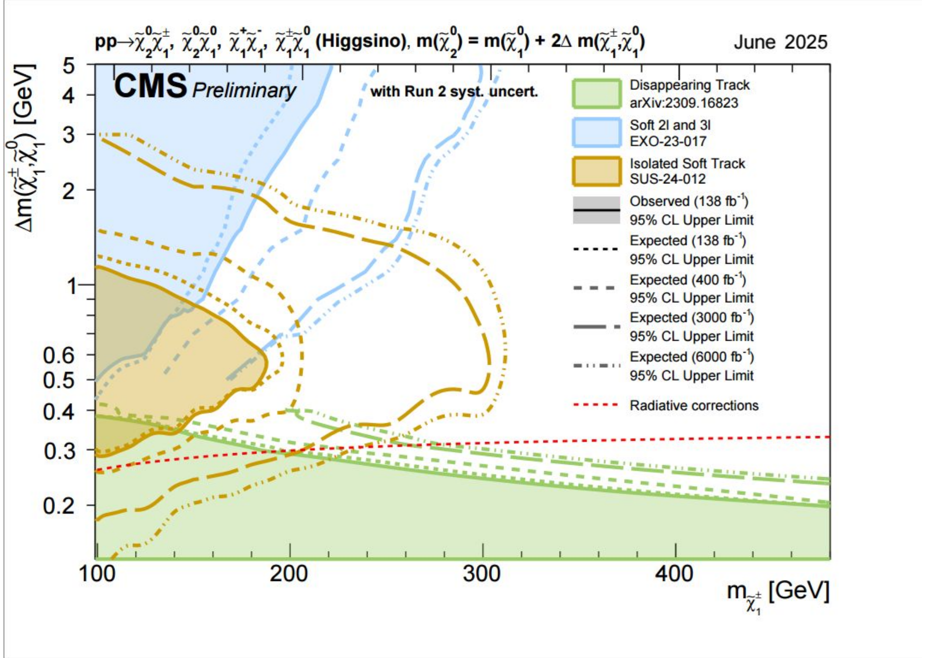
    - 40 MHz Track Trigger can provide prompt and **displaced (not-baseline) L1 Tracks (p_T>2 GeV)**, ECAL crystal timing information will be also available at L1T, new DTs backend will allow to detect MDS also in barrel
  - **designing LLP seeds already at L1T: allow to reduce p_T/H_T/MET thresholds**

- **New ideas are being developed**
  - isolated prompt/displaced L1 Tracks triggers could help to improved compressed Higgsino searches (currently based on MET/leptons triggers)



CMS EXO Public Material for ESPPU 2025 Just out!

Conclusions

- The potentialities of the newly developed CMS trigger strategies for Run-3 as well as the expected additional improvements foreseen at HL-LHC thanks to the upgraded L1T & HLT & and the NGT projects have been presented

- The NGT projects are in R&D phase: there is space for going in different directions
  - it is extremely useful for us to gather interests/suggestions/benchmark models from the theory community

Thank you for your attention

CERN

NexTGen

Next Generation Triggers