Tracking, particle flow and muon performance at CMS and ATLAS

Marco Vanadia, on behalf of the ATLAS and CMS collaborations
LHCP 2024 June 7th 2024, Boston (USA)
ATLAS and CMS detectors: tracks & muons

- **Silicon + gas tracker in 2T solenoid**
- **Muon Spectrometer in toroid**

- **Silicon tracker in 4T solenoid**
- **Muon spectrometer in return yoke of solenoid**
**ATLAS** in Run-3: upgrade of endcap muon spectrometer (among other things)

**CMS** in Run-3: upgrade of Pixel tracker (among other things)
For HL-LHC we need **better performance** and resilience vs **pileup** and **aging**
- New trackers, **full Si**, up to $|\eta| \sim 4$
- **New chambers** in muon spectrometers
- New detectors with **high granularity/better timing** resolutions $\rightarrow$ **particle flow**
- Electronics, calorimeters, trigger…

See the dedicated plenary session!
O(10^3) charged particles per event: high efficiency, purity and track parameters resolution without using too much CPU!

Figures by M. Musih

Different strategies run in parallel

Comput Softw Big Sci 8, 9 (2024)
Excellent performances

Measurements of HLT tracking performance for CMS shows good efficiency (~80% for $p_T > 1$ GeV) vs offline with low fake rate (~15%)!

→ see also S. Donato’s talk
Improving software performance

**ATLAS**
ID Track and Vertex Reconstruction
**Legacy Reconstruction**
- Run 2 (LHC fill 6291)
**Updated Reconstruction**
- Run 2 (LHC fill 6291)
- Run 2 without LRT
- Run 3 (LHC fill 8112)

**Results on NVIDIA A30 GPU**

**ATLAS**

**CMS Simulation Preliminary**
muon-gun w/ 5 cm cube prod. origin
\(p_T > 0.9\) GeV, \(|\eta| < 2.4, |z_{\text{vertex}}| < 30\) cm
- pre-DNN
- DNN

**CMS:**
significant improvements for HL-LHC with ML-approach without affecting throughput

**Improvement in reconstruction software → more space for physics**
ATLAS added displaced ID and muon tracks to **standard data flow** in Run-3

**Comput Softw Big Sci 8, 9 (2024)**
Displaced tracks reconstruction

ATLAS Large Radius Track (LRT) Run-3 vs Run-2:
● 10 times less CPU
● 50 times smaller event size
● Now included in standard data processing

New results from CMS calibration on Run-2 data on $K_s$ show good agreement with simulation for displaced track reconstruction


CMS-DP-2024-010
Tracking @ HL-LHC: software and algorithms

- New trackers designed for high PU @ HL-LHC
- Both new detector design and improvements in the software to profit from that ensure linear behaviour vs pileup

- Tracking for trigger @ HLT demanding due to combinatorics
- Requires improved algorithms + parallel computing
Tracking with Machine Learning

GNN-based pattern recognition with ITK
- New result with improved algorithms and updated detector simulation
- Performance close to standard algorithms
- Work ongoing to evaluate computing performance

CNN-based tracking within high-$p_T$ jets (Run-3 detector)
- Challenging due to cluster merging & combinatorics
- Updated CNN algo analyses pixel maps
- Standard vs ML-based algorithms performance differ in phase space regions
  - combining both has best performance
Muons reconstructed separately in Tracker (ID)/Spectrometer (MS)

In most cases a combined track (CB) is then produced
  - different strategies of reconstruction and single-detector or partial trk to recover acceptance

Different Working Points for different use cases

Isolation criteria for muons from prompt resonances

Different momentum measurement strategies available:
  - ID+MS or CB for ATLAS
  - Tune-P algorithm for CMS picks best measure
New Small Wheels 
performance in ATLAS

Efficiencies on a 2024 run

Resolution per layer in 2024

NSW commissioned in 2022 and now fully included in data taking

MDET-2024-02
Muon performance ATLAS

**Significant $\varepsilon$ improvement in 2023 after commissioning of NSW**

**Important to correct for detector effects for precision measurements**

Alignment in Run-3

**MDET-2024-03**

<table>
<thead>
<tr>
<th>[(\mu^+)]</th>
<th>$\sigma_{\text{all}}(\mu_0)$</th>
<th>$\sigma_{\text{all}}(\mu_0)$</th>
<th>$\sigma_{\text{all}}(\mu_0)$</th>
<th>$\sigma_{\text{all}}(\text{total})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>BA large</td>
<td>25 ± 2</td>
<td>9 ± 1</td>
<td>10 ± 1</td>
<td>29 ± 2</td>
</tr>
<tr>
<td>BA small</td>
<td>25 ± 4</td>
<td>19 ± 3</td>
<td>21 ± 4</td>
<td>38 ± 4</td>
</tr>
<tr>
<td>EC large</td>
<td>69 ± 3</td>
<td>20 ± 1</td>
<td>28 ± 2</td>
<td>77 ± 2</td>
</tr>
<tr>
<td>EC small</td>
<td>95 ± 4</td>
<td>28 ± 2</td>
<td>26 ± 2</td>
<td>103 ± 3</td>
</tr>
<tr>
<td>EE large</td>
<td>106 ± 10</td>
<td>22 ± 3</td>
<td>52 ± 6</td>
<td>121 ± 9</td>
</tr>
<tr>
<td>EE small</td>
<td>66 ± 9</td>
<td>36 ± 9</td>
<td>58 ± 8</td>
<td>94 ± 9</td>
</tr>
<tr>
<td>BEE</td>
<td>59 ± 8</td>
<td>50 ± 7</td>
<td>33 ± 6</td>
<td>84 ± 7</td>
</tr>
</tbody>
</table>

**ATLAS Preliminary**

$\sqrt{s} = 13.6$ TeV, 28 fb$^{-1}$

**Combined Tracks**

1.57 $< \phi < 1.77$

Before $\delta_{\phi}$ correction

After $\delta_{\phi}$ correction
Muon performance CMS

- Recently published results on muon online & offline performance
- Detailed studies using $Z \rightarrow \mu\mu$ events show high performance and good data/MC agreement
- High-$p_T$ results based on Drell-Yan data

CMS-DP-2024-005
CMS-DP-2024-019
CMS-DP-2024-023
Muon developments

Machine Learning offers great potential for improving muon performance

New isolation based on a transformer neural network from ATLAS

CMS published new results for muon identification with MVA techniques:

- Major improvement in signal eff vs bkg rejection
- Performance calibrated in data, using also non-prompt muons enriched selections
Particle Flow

- Particle Flow algorithms currently used in ATLAS mostly for jet reconstruction
  - Pflow isolation used for leptons *EPJC 81 (2021) 578*
  - Ongoing effort towards a ML-based PFlow implementation
    *ATL-PHYS-PUB-2022-040*

- Particle Flow algorithms used by CMS for global event reconstruction
  *JINST 12 (2017) P10003*

- Studies for ML-based Pflow
  *J. Phys.: Conf. Ser. 2438 012100* with heterogeneous architectures
  - Based on a scalable GNN model
PFlow news from CMS

- New result on **hadronic PFlow clusters** reconstruction @ HLT using the Alpaka library show significant improvement when CPUs → GPUs

- PFlow will go through a **major overhaul for HL-LHC** to profit from new detectors (HGCAL and MTD above all) providing info with **high granularity** and great **timing resolution**

- New reconstruction framework (TICL) for HGCAL being developed *J. Phys.: Conf. Ser. 2438 012096*

Clustering step removing noise around back-to-back muon tracks
Conclusion

- Presented most recent results for tracking, muon and PFlow performance from ATLAS and CMS
  - Performance measurements are challenging analyses with demanding precision requirements
  - They provide crucial inputs for physics measurements and searches
- Soft collisions makes life hard; more and more challenging conditions must be addressed with:
  - Better detectors → Phase-1 upgrades in, Phase-2 upgrades on their way
  - Better algorithms → optimised usage of resources can significantly impact physics output
  - Better tools → Machine Learning techniques, parallel computing...
- Run-3: high performance in demanding conditions
- HL-LHC is not so far now, crucial work ongoing for that
ATLAS detector
CMS detector

CMS DETECTOR
- Total weight: 14,000 tonnes
- Overall diameter: 15.0 m
- Overall length: 28.7 m
- Magnetic field: 3.8 T

STEEL RETURN YOKE
12,500 tonnes

SILICON TRACKERS
- Pixel (100x150 μm²) ~1.9 m⁻² ~124M channels
- Microstrips (80–180 μm) ~200 m⁻² ~9.6M channels

SUPERCONDUCTING SOLENOID
- Niborium tinicosium coil carrying ~18,000 A

MUON CHAMBERS
- Barrel: 250 Drift Tubes, 480 Resistive Plate Chambers
- Endcaps: 140 Carbon Fibre Strip, 576 Resistive Plate Chambers

PRESHOWER
- Silicon strips ~16 m⁻³ ~137,000 channels

FORWARD CALORIMETER
- Steel + Quartz fibres ~2,000 channels

CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)
- ~70,000 scintillating PbWO₄ crystals

HADRON CALORIMETER (HCal)
- Brass + Plastic scintillator ~7,000 channels

Phase-1 upgrade

BPIX
- η = 0.5
- η = 1.0
- D1
- D2
- D3

FPix
- η = 2.0
- η = 2.5
CMS Tracking

- Seeding from pixels/strips
- Pattern recognition from outward KF + inward search for additional hits
- Fit: outward KF followed by a smoother filter, weighted average, iteration to remove outliers
- Track selection DNN-based
- Online tracking:
  - Streamlined version of offline
  - HLT ported to GPUs, heterogenous CUDA-based architecture → CKF algo seeded by Patatrace pixel tracks
  - Improved fake rejection and IP reso wrt Run-2
- Offline tracking:
  - Improved parallelized and vectorized algorithm (mkfit)
  - Similar perf to Run-2 CKF, significant speed-up
ATLAS Tracking

- Primary tracking Inside → Out
  - Seeding from Si Hits
  - CKF to extend up to all SCTs
  - Track ambiguity solver based on track quality + NN
  - Global fitting + extension to TRT with refit
- Back-tracking Outside → In
  - Used e.g. for photon conversion
  - Seeding from TRTs
  - Then add hits/segments not included by primary tracking
- LRT tracking
- Improvements for Run-3
  - Tighter selections to reduce combinatorics
  - New PV algorithm: Adaptive multi-vertex fitter (AMVF): better efficiency and lower fake rate
CMS Muon Reconstruction

- Standalone reconstruction: uses Kalman filter
- If MS compatible with ID track → global muon
- ID track + MS segment(s) → tracker muon
- Then muons fed to PFlow algorithm
- Loose muons (i.e. global or tracker) are passed to MVA
  - Prompt-muon MVA: used for isolated prompt muons
  - Muon MVA ID: used for generic muon id vs hadrons, developed in the paper for more general usage
  - Work focus on $p_T > 10$ GeV, for soft muons there is a different Soft Muon MVA algorithm developed in Run 2

General muon MVA:
Random forest using $p_T$, eta, number of this, chi-squares etc...

Prompt muon MVA:
BDT using kinematics, isolation, closest jet information, impact parameter
ATLAS Muon Reconstruction

- Hough transform to build segments in MS
- Segments combined in preliminary track, then a 3D candidate is formed combining both views, then a global chi2 fit is performed
- Now outliers are removed and missing hits on the trajectory are added and a refit performed
- Ambiguities are resolved, and a final refit is performed with loose IP constraint and calo information
- Muons can be globally reconstructed as:
  - CB: ID+MS (including SiF in fwd region)
  - IO: ID track + MS hits combined
  - MS only
  - Segment tagged: ID track tagged by MS segment
  - CaloTagged: ID track tagged by calorimeter deposit
Tune-P algorithm selects best measurements among:

- Inner Track fit: ID only, best at low $p_T$
- Tracker-Plus-First-Muon-Station fit: ID + first MS station
- Pick fit: for muons with showering in one chamber, selects MS hits compatible with extrapolated track
- Dynamic-Truncation fit: treats cases with high energy loss by iteratively adding stations to track

The PF algorithm finally refines measurement from Tune-P

Momentum calibration:

- from $Z\rightarrow\mu\mu$ using $<1/p_T^\mu>$
- from $J/\Psi$ and $\Upsilon$ using a Kalman filter technique
- from cosmic rays
- from Drell-Yan events using $q/p_T$
ATLAS Muon Momentum measurement

- Data correction: sagitta bias correction using $Z$
  - from variance of $M_{\mu\mu}$
  - from local effects on $\langle M_{\mu\mu} \rangle$
- MC calibration from iterative procedure to determine calib constants using
  - $Z$ events
  - $J/\Psi$ events
  - $\Upsilon$ events for validation
• Individual particles produce several PF elements in various subdetectors
• Reconstructions via a link algorithm connecting the different contributions
• Particles reconstructed by standard reconstruction algorithms are selected in sequence and connected appropriately
• A postprocessing cleans up and further corrects difficult cases
Pflow algorithm diagram for overlap removal between tracker and cluster

PFlow ATLAS

In 2023 the proton-proton physics data taking at 13.6 TeV was from May 6th to July 16th. An extended LHC downtime from June 13th to July 1st splits the data taking in two periods. In the second period readout problems were observed in the layer 3 and 4 of the barrel pixel tracker both in the same sector in $\phi$ on the negative half along beamline, with track coverage within $-1.5 < \eta < -0.2$ and $-1.1 < \phi < -0.9$. Dedicated MC samples are used for the two periods.
In Run 3, track reconstruction at the CMS High-Level Trigger (HLT) is based on a single iteration of the Combinational Kalman Filter (CKF), using hits recorded by both the pixel and strip detectors. The track reconstruction needs an initial estimate of the track parameters, i.e. a trajectory seed. The single iteration is seeded by pixel tracks reconstructed by the Patatrack algorithm, which can be offloaded to GPUs [1,2].

Heterogeneous architecture based on CUDA platform exploiting GPUs for parallel computing *Front. Big Data* 3 (2020), 601728

Performance of Track Reconstruction at the CMS High-Level Trigger in 2023

**CMS-DP-2024-013**
Performance of Track Reconstruction at the CMS High-Level Trigger in 2023

CMS-DP-2024-013
ATLAS Muon & Tracking software

ATLAS Primary Tracking
- Space Point & Drift Circle Formation
- Pixel & Strip Seed Finding
- Track Finding
- Ambiguity Resolution
- TRT Extended Track Refit

ATLAS Back-Tracking
- TRT Segment Finding in Calorimeter Regions of Interest
- Track Finding
- Ambiguity Resolution
- Track Fit

ATLAS Muon Outside-In
- Clustering & Segment Formation
- Track Finding
- Ambiguity Resolution
- Extrapolation to IP & Selection of ID tracks
- Combine & Refit

ATLAS Muon Inside-Out
- ID Candidate Selection
- Extrapolation through MS
- MS Segment or Calo Tag Identification
- ID Combined Reconstruction
- Track Refit
ATLAS Muon & Tracking software
Improved Performance of Line Segment Tracking Using Machine Learning @ HL LHC

- Hits from outer tracker combined using local information
  - Parallelized on GPUs
- Objects with more and more hits are subsequently built and finally combined with inner tracker
The LST algorithm creates the following objects in OT through linking of objects [1]:
- MiniDoublet (MD): linked pair of hits in individual $p_T$ modules
- Line Segments (LS): linked pair of MDs in neighboring layers
- Triplet (T3): linked pair of LSs with a common MD
- Quintuplet (T5): linked pair of T3s with a common MD

Using a subset of inner tracker (IT) pixel seed iterations, (i.e. initial iteration seed, and highPtTriplet iteration seed [3, 4]), LST algorithm creates following objects through linking of OT objects with IT seeds:
- pixel + Quintuplet ($pT5$): linked pair of a pixel seed and a T5
- pixel + Triplet ($pT3$): linked pair of a pixel seed and a T3 (both not in a pT5)

**T5 DNN input features**

<table>
<thead>
<tr>
<th>Object</th>
<th>Feature</th>
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</thead>
<tbody>
<tr>
<td>$p_T$</td>
<td>Inner anchor hit $r$, $z$, $\phi$, $\eta$, layer</td>
</tr>
<tr>
<td>T3 (x2)</td>
<td>Middle anchor hit $r$, $z$, $\phi$, $\eta$, layer</td>
</tr>
<tr>
<td></td>
<td>Outer anchor hit $r$, $z$, $\phi$, $\eta$, layer</td>
</tr>
<tr>
<td>T5 candidate</td>
<td>Radius of circle fit</td>
</tr>
<tr>
<td></td>
<td>$p_T$, $\eta$, $\phi$</td>
</tr>
<tr>
<td></td>
<td>Radius of circle fit for “Bridge T3”</td>
</tr>
</tbody>
</table>
Improved Performance of Line Segment Tracking Using Machine Learning @ HL LHC

<table>
<thead>
<tr>
<th></th>
<th>T5</th>
<th>1/Throughput</th>
<th>N streams</th>
</tr>
</thead>
<tbody>
<tr>
<td>pre-DNN</td>
<td>$3.37 \pm 0.13$</td>
<td>$28.4 \pm 1.5$</td>
<td>1</td>
</tr>
<tr>
<td>DNN</td>
<td>$3.39 \pm 0.07$</td>
<td>$28.7 \pm 1.1$</td>
<td>1</td>
</tr>
</tbody>
</table>
Table 2: Most important selection criteria that differ between the primary tracking (inside-out sequence only) and LRT setups. Common selection criteria that were changed from the legacy implementation are also shown.

<table>
<thead>
<tr>
<th>Selection criteria</th>
<th>Primary (inside-out)</th>
<th>LRT</th>
</tr>
</thead>
<tbody>
<tr>
<td>max. $</td>
<td>d_{0}</td>
<td>$ [mm]</td>
</tr>
<tr>
<td>max. $</td>
<td>z_{0}</td>
<td>$ [mm]</td>
</tr>
<tr>
<td>min. $p_{T}$ [GeV]</td>
<td>0.5</td>
<td>1</td>
</tr>
<tr>
<td>max. $</td>
<td>\eta</td>
<td>$</td>
</tr>
<tr>
<td>max. silicon holes</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>max. double holes</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>max. holes gap</td>
<td>2</td>
<td>1</td>
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<tr>
<td>road width [mm]</td>
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<td>5</td>
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<tr>
<td>seeding</td>
<td>Pixels and SCT</td>
<td>SCT only</td>
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<tr>
<td>max. seeds per middle Pixel SP</td>
<td>1</td>
<td>–</td>
</tr>
<tr>
<td>max. seeds per middle SCT SP</td>
<td>5</td>
<td>1</td>
</tr>
</tbody>
</table>

Common selection criteria

|                                | 8        |
|                                | 6        |
|                                | 9        |
| keep all confirmed seeds       | true     |
ATLAS LRTs

CMS displaced tracking calibration

CMS Preliminary

$0.00 < \Delta R_{\mu} \, (\text{cm}) < 0.50$

$0.50 < \Delta R_{\mu} \, (\text{cm}) < 1.00$

$19.50 < \Delta R_{\mu} \, (\text{cm}) < 20.00$

138 fb$^{-1}$ (13 TeV) Legacy
CMS displaced tracking calibration
Expected tracking performance of the ATLAS Inner Tracker Upgrade for Phase-II

**ATLAS Simulation Preliminary**
HL-LHC, ITk Layout: 03-00-00
Single Particle, $p_T = 10$ GeV

**ATLAS Simulation Preliminary**
HL-LHC, ITk Layout: 03-00-00
Run 3, $|\eta| < 2.4$
- Single $\mu$, $p_T = 10$ GeV
- ITk

**ATLAS Simulation Preliminary**
HL-LHC, ITk Layout: 03-00-00
- $f$, HS, $\sqrt{s} = 14$ TeV
- ITk, $\langle \mu \rangle = 200$

**ATLAS Simulation Preliminary**
HL-LHC, ITk Layout: 03-00-00
Run 3, $\langle \mu \rangle = [0, 80]$

**ATLAS Simulation Preliminary**
HL-LHC, ITk Layout: 03-00-00
- ITk
- Local PU density [Vertices/mm]
Performance of the Line Segment Tracking Algorithm in the CMS Phase-2 High Level Trigger Tracking

Detector modules in OT consist of two closely spaced silicon sensors per layer. This configuration provides a handle for hits in adjacent sensors to be correlated and allows for an estimation of the local transverse momentum ($p_T$) of the track. The resulting local hit pairs, called MiniDoublets (MDs), provide an opportunity to reduce occupancy of the detector. MDs with $p_T$ more than 0.8 GeV are considered in the following implementation of LST. Below, a qualitative representation of the expected Phase-2 CMS tracker geometry [2] is given:
Performance of the Line Segment Tracking Algorithm in the CMS Phase-2 High Level Trigger Tracking
Track finding performance plots for a Graph Neural Network pipeline on ATLAS ITk simulated data
DeepCore2.0: Target and Prediction

- Target and prediction format: three $30 \times 30$ Track Crossing Point (TCP) maps and three $30 \times 30$ Track Parameters (TP) maps.

- TCP maps:
  - Target TCP map: every BPIX2 pixel is assigned a value of 1 if a particle crossed a pixel and 0 otherwise.
  - Prediction TCP map: every BPIX2 pixel is assigned a score between 0 and 1 reflecting the likelihood of a track crossing point being within the boundaries of that pixel.

- TP maps:
  - Track Parameters are $\Delta x$ and $\Delta y$ between the center of a pixel and a TCP, relative azimuthal angle ($\Delta \phi$) and relative pseudorapidity ($\Delta \eta$) between the center of a pixel and the merged-cluster axis, and $p_T$ of the reconstructed track associated to the TCP. The TCP charge is positive by default and adjusted as needed when testing candidate tracks.
  - Target TP maps: track parameters of TCP pixels and pixels within 2-pixel radius.
  - Prediction TP maps: predicted track parameters for every TCP pixel.

- If 2 particles cross the same pixel, the second set of Target TCP/TP maps (Overlap maps 2) is filled with the second TCP information. Similarly, Overlap maps 3 are used if 3 particles cross the same pixel. Prediction TCP/TP Overlap maps 2 and 3 are always filled.
DeepCore 2.0: Convolutional Neural Network for Tracking in Jets with High Transverse Momentum

An example of the pixel maps used as input for DeepCore2.0 is shown above. For each BPIX layer, the normalized ADC count per pixel is shown as a function of the pixel position within the 30×30 window. The BPIX2 pixel map also shows multiple target TCPs (red) and the TCPs predicted by DeepCore (black) for a calo-jet with $p_T^{\text{jet}} = 1786$ GeV and $\eta^{\text{jet}} = -0.08$. DeepCore predicts the same number of TCPs as the number of target TCPs (7), including 6 TCPs (2 – 7) in the same cluster and 2 TCPs (4 and 5) in the same pixel (x = 2, y = −2). The position of the predicted TCPs is relatively close to the position of target TCPs, which shows that DeepCore2.0 makes good predictions.
DeepCore 2.0: Convolutional Neural Network for Tracking in Jets with High Transverse Momentum
CMS MVA muon identification

JINST 19 P02031 (2024)
Comparison of 3 point deep DL algo:
- Deep Sets
- GNN
- Transformers

With image-based CNN and DNN.
Tested options with and without tracking.
Identification and energy response are evaluated.
Machine Learning for Particle Flow Reconstruction at CMS

J. Phys.: Conf. Ser. 2438 012100

- heterogeneous architectures based on a scalable GNN model
- Task is to identify $y_k$ particles, described as $(ID, p_T, \eta, \phi, E, q)$, from $x_i$ detector signals
- Performance mostly in line with standard PF
- Computing scales linearly vs multiplicity, comparison with standard PF not trivial
Heterogeneous Reconstruction of Hadronic Particle Flow Clusters with Alpaka Portability Library

CMS-DP-2024-026

Data converted to format optimized for GPUs

The Alpaka-based implementation was included in HTL menu at beginning of 2024

PF cluster energy validation

- We port steps producing hadronic barrel and endcap (HBHE) PF clusters to GPU as a first step of PF reconstruction acceleration.
  - GPU porting is done with the Alpaka portability library, allowing future hardware flexibility [2]
  - This PF clustering step is relatively slow on CPU (a few % of timing of recent Run-3 CMS High Level Trigger (HLT) menus).
The Iterative Clustering framework for the CMS HGCAL Reconstruction

J. Phys.: Conf. Ser. 2438 012096

TICL: modular software framework for HGCAL reconstruction, with configurable:
- Seeding region production and layer-cluster selection
- Pattern recognition
- Linking

Integrated in CMS software and suited for integration with ML techniques

Comparison of Tracksters produced during pattern recognition with different algorithms