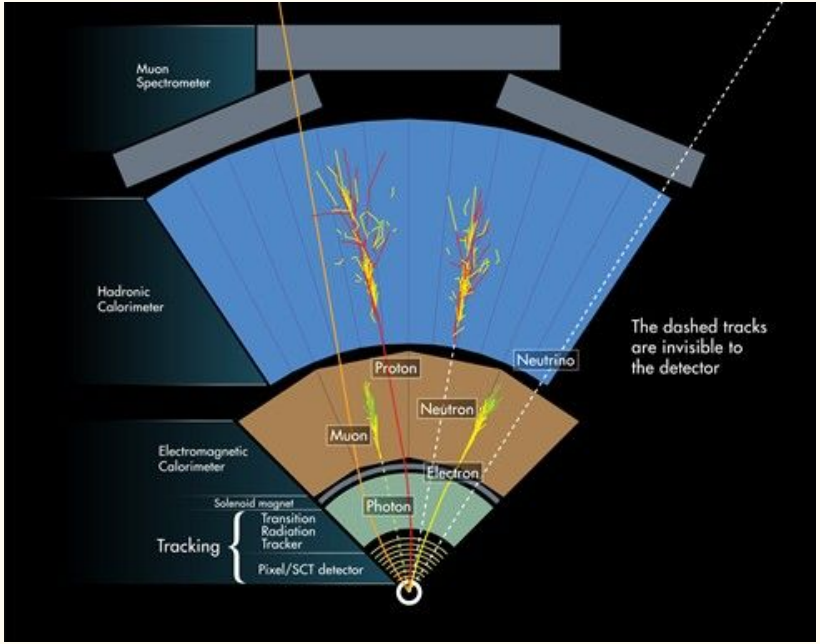
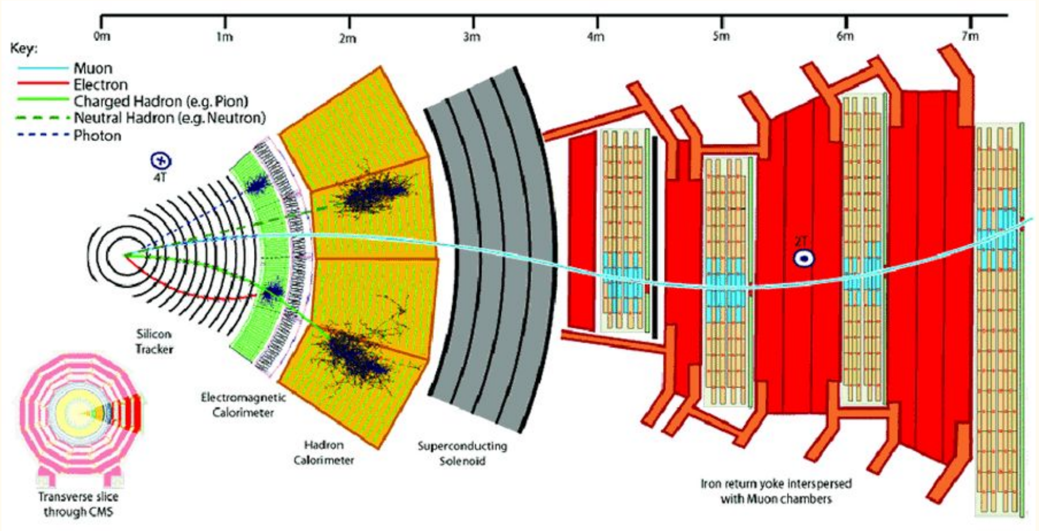
Tracking, particle flow and muon performance at CMS and ATLAS

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

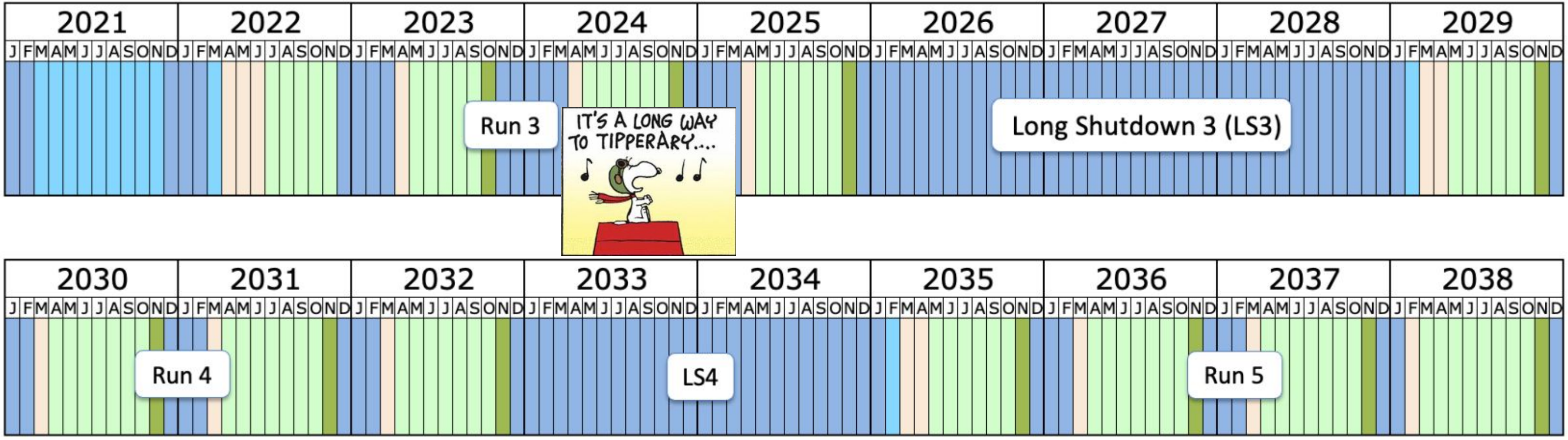
ATLAS and CMS detectors: tracks & muons



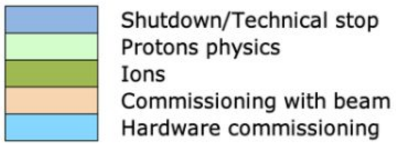


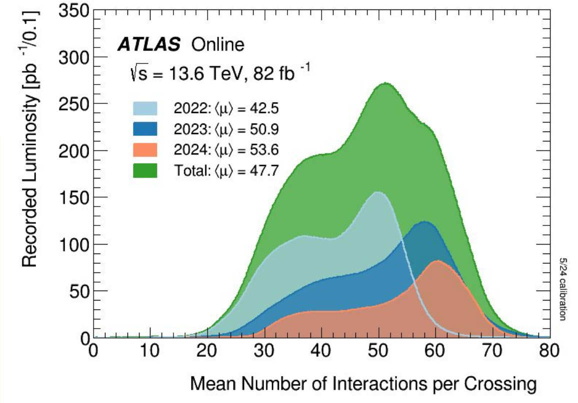
- **Silicon + gas** tracker in **2T solenoid**
- Muon Spectrometer in **toroid**

- **Silicon** tracker in **4T solenoid**
- Muon spectrometer in **return yoke** of solenoid



13.6 TeV pp collisions with <μ>~50-60

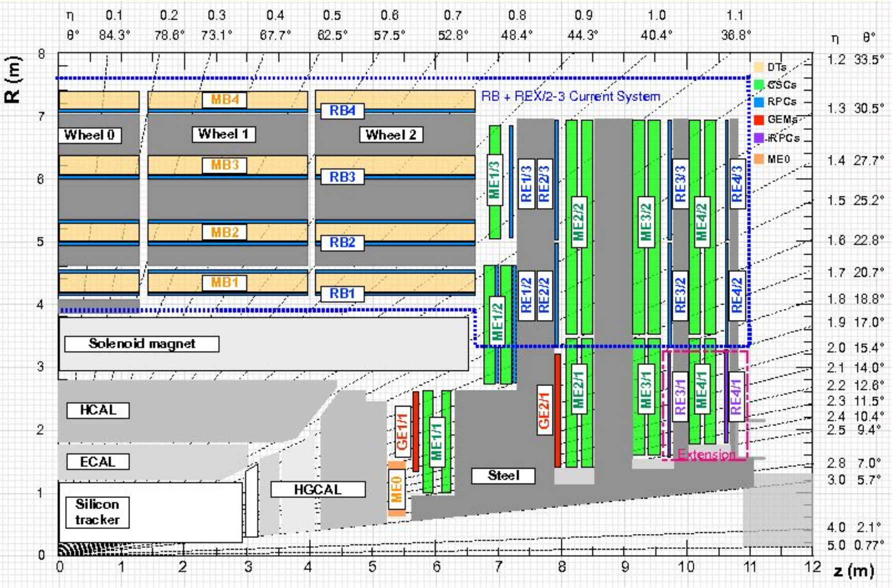


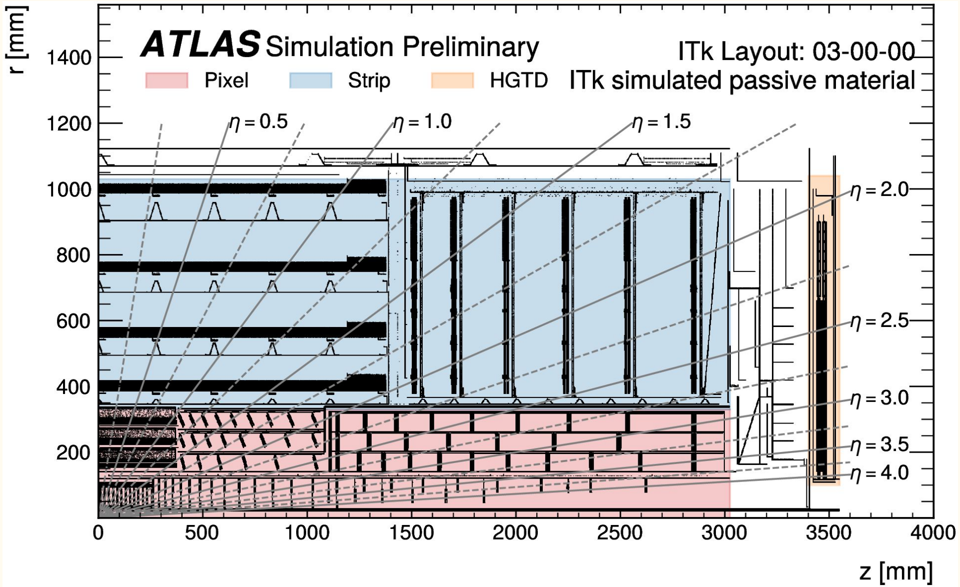


ATLAS in Run-3 :
upgrade of endcap muon spectrometer (among other things)

CMS in Run-3:
upgrade of Pixel tracker (among other things)

Coming soon...





For HL-LHC we need **better performance** and resilience vs **pileup** and **aging**

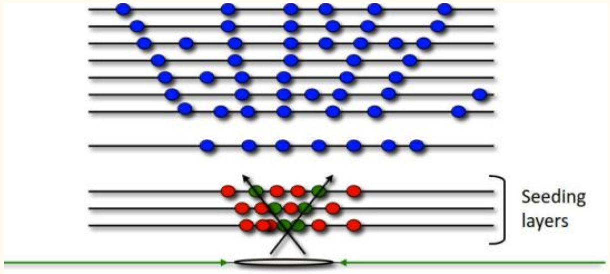
- New trackers, **full Si**, up to **|η|~4**
- **New chambers** in muon spectrometers
- New detectors with **high granularity/better timing** resolutions → **particle flow**
- Electronics, claorimeters, trigger...

See the dedicated plenary session!

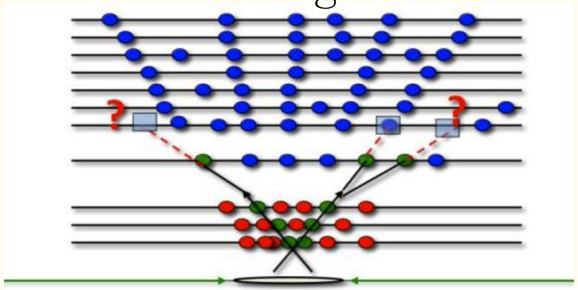
Tracking @ LHC

Figures by M. Musich

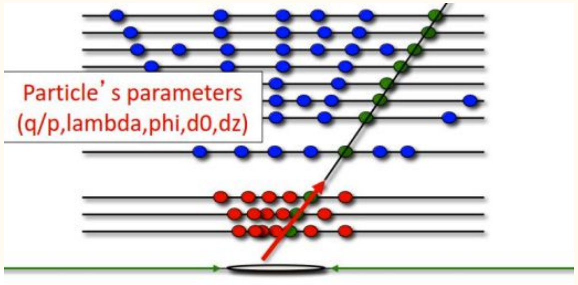
Seeding



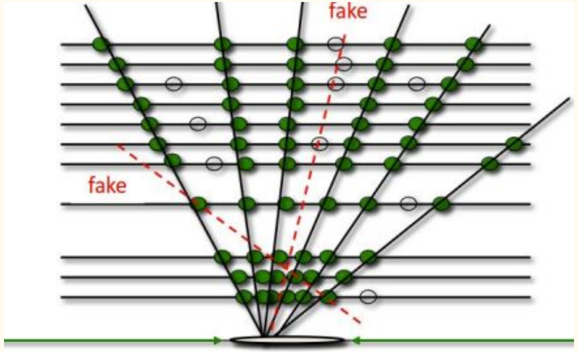
Pattern recognition

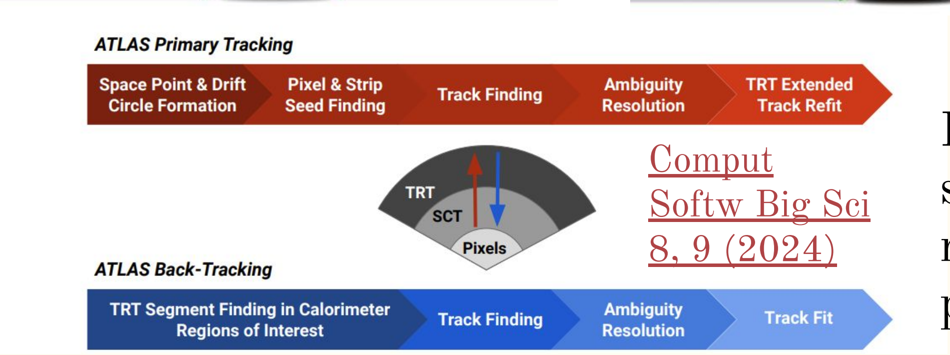


Fitting



Selection

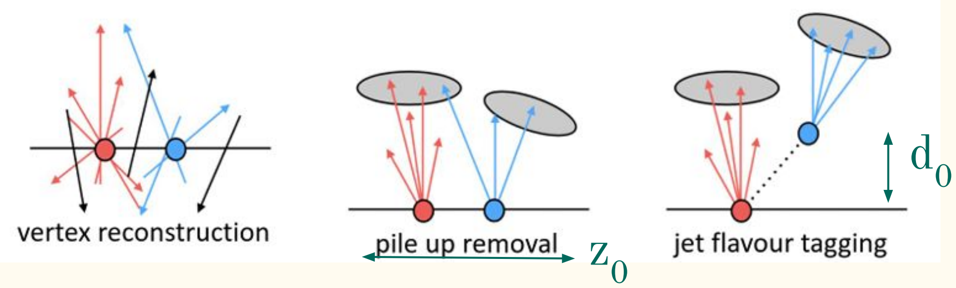




Comput Softw Big Sci 8, 9 (2024)

Different strategies run in parallel

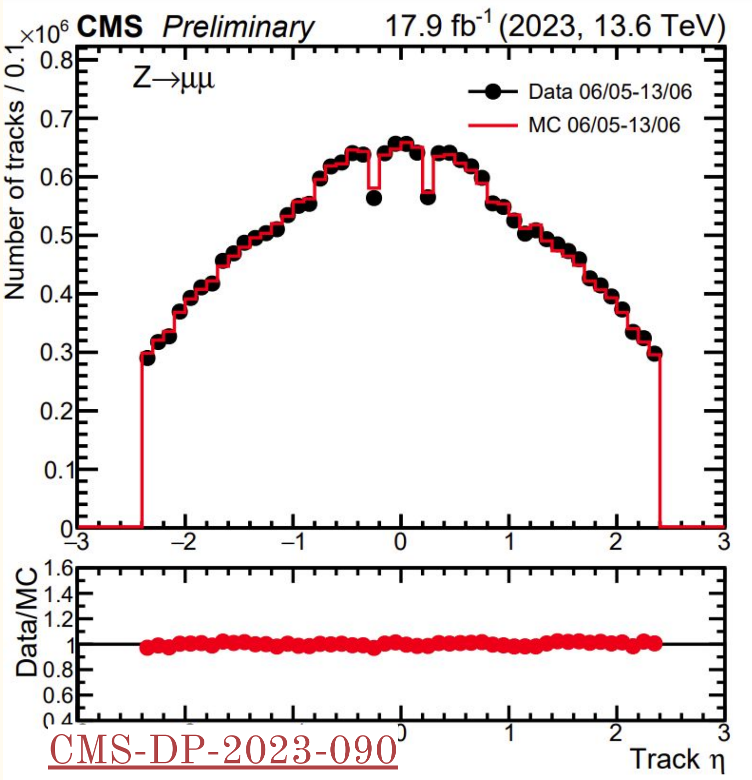
$O(10^3)$ charged particles per event: high efficiency, purity and track parameters resolution without using too much CPU!



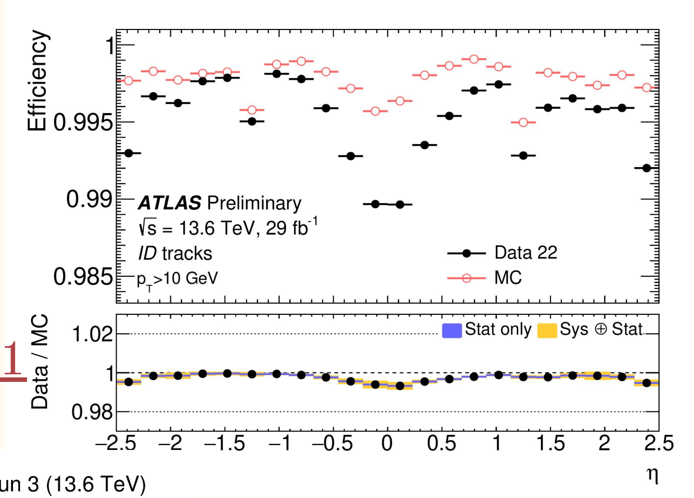
Tracking in Run-3

Excellent performances

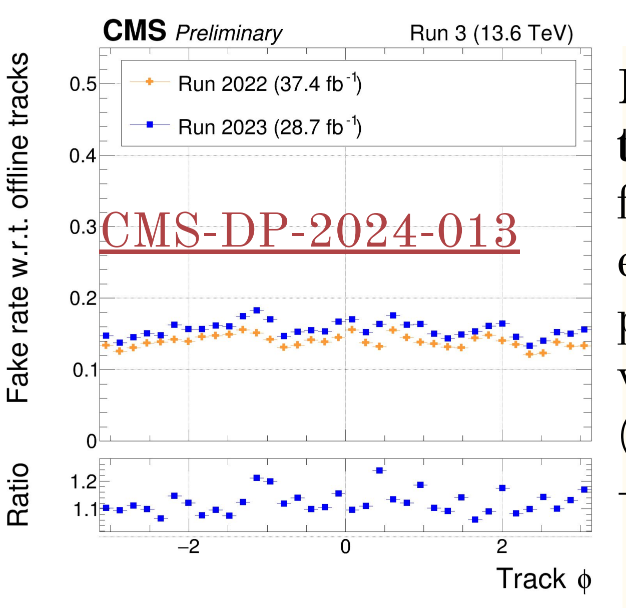
data/MC agreements typically at **sub-percent** level!



CMS-DP-2023-090



MUON-2023-01



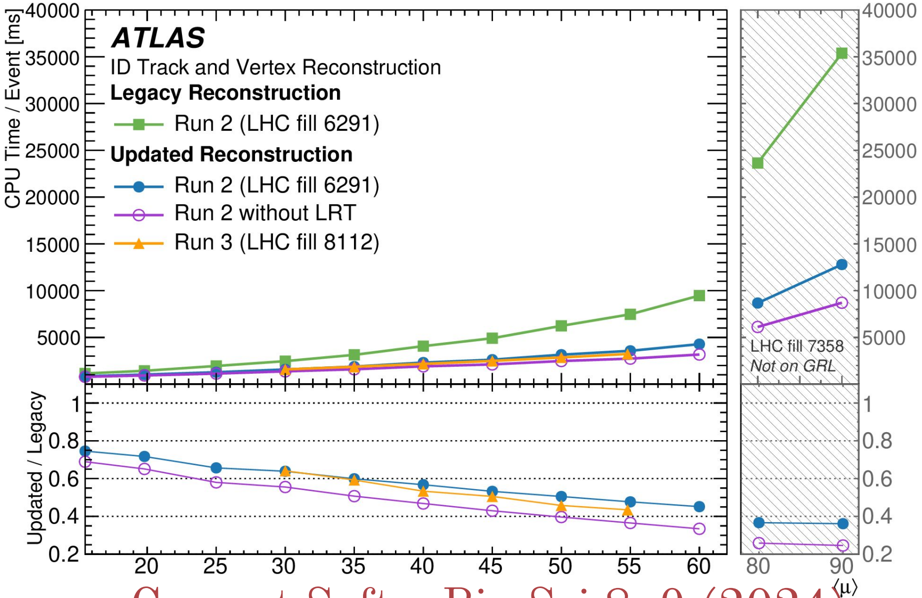
CMS-DP-2024-013

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

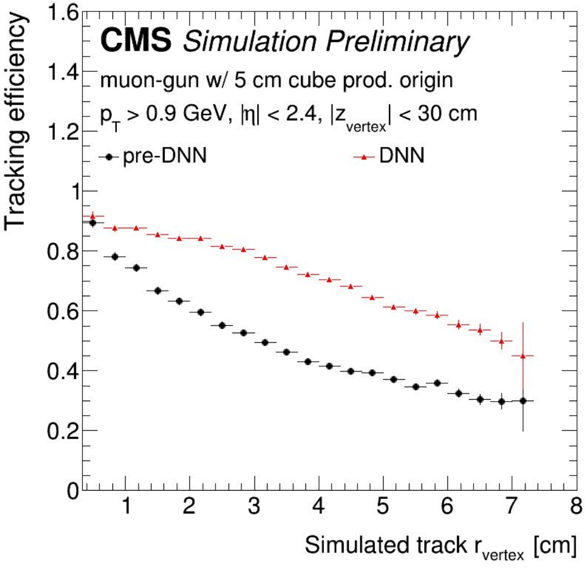
→ see also S. Donato's talk

Improving software performance

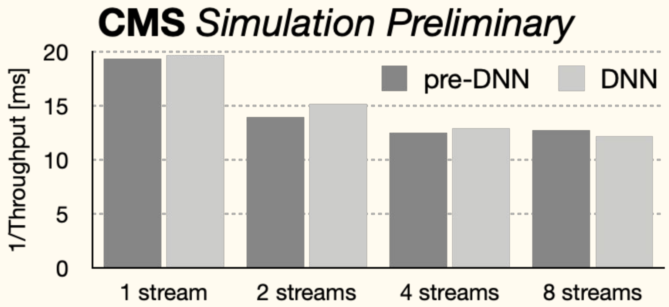
CMS-DP-2023-075



Comput Softw Big Sci 8, 9 (2024)



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

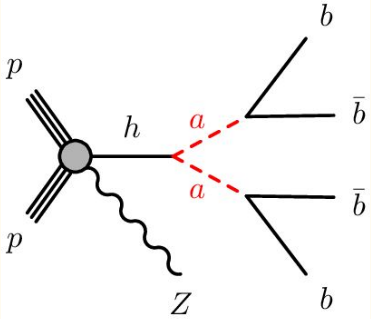


Results on NVIDIA A30 GPU

Improvement in reconstruction software → more space for physics

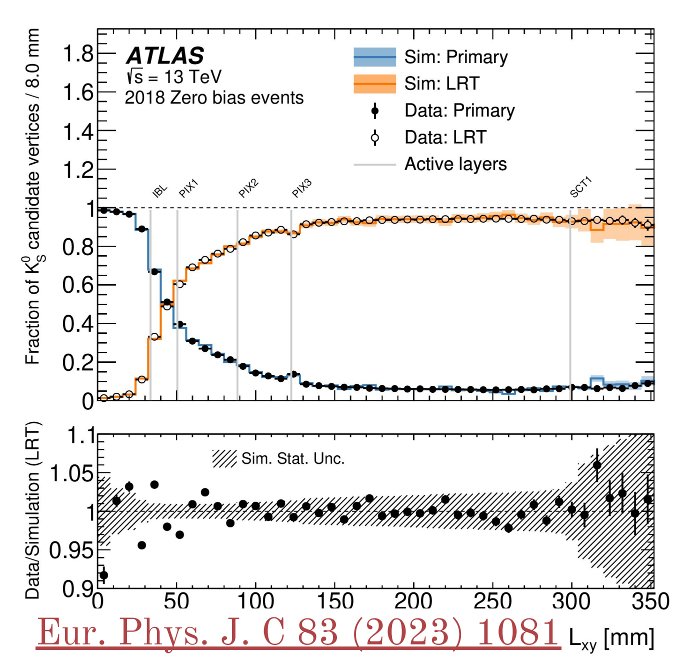
ATLAS added displaced ID and muon tracks to **standard data flow** in Run-3

Displaced tracks reconstruction

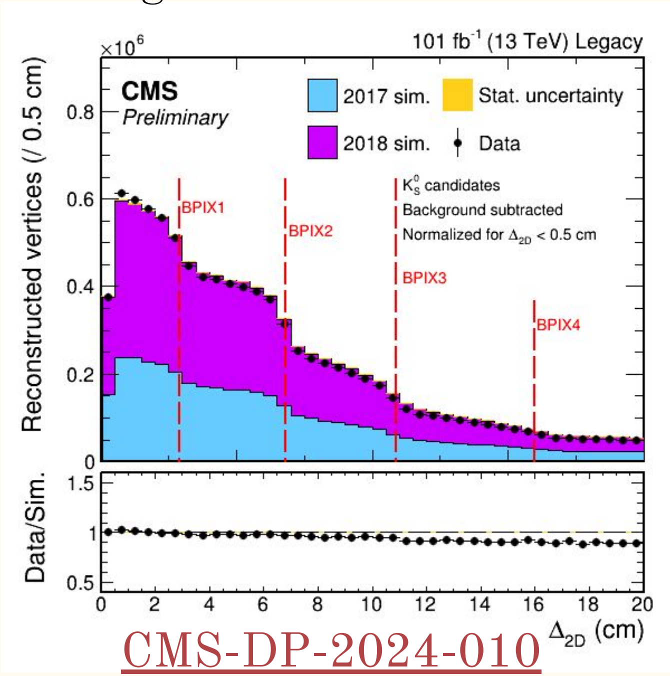


ATLAS Large Radius Track (LRT) Run-3 vs Run-2:

- 10 times less CPU
- 50 times smaller event size
- Now included in standard data processing



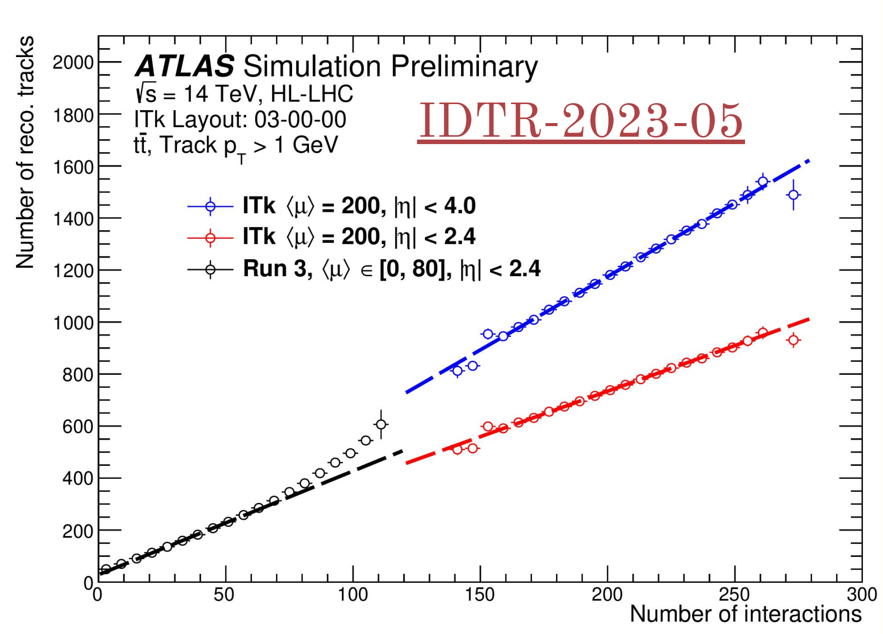
[Eur. Phys. J. C 83 (2023) 1081]

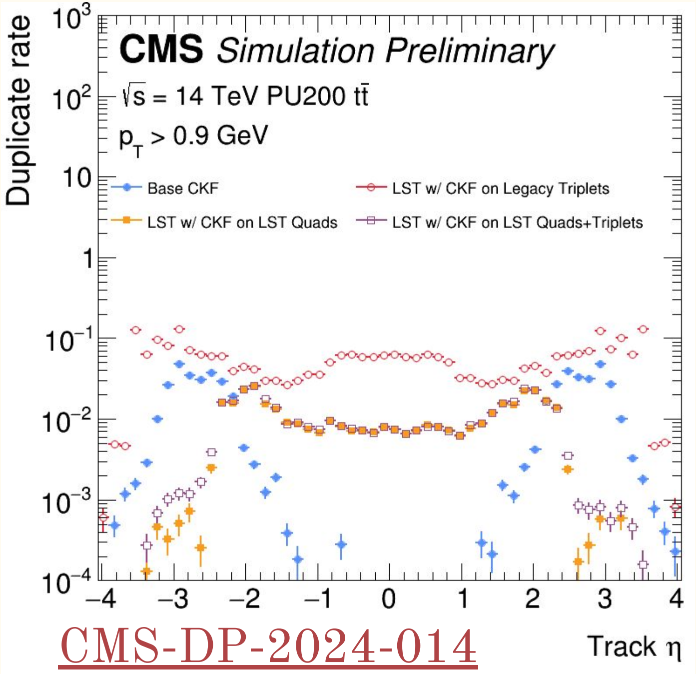


[CMS-DP-2024-010]

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

Tracking @ HL-LHC: software and algorithms



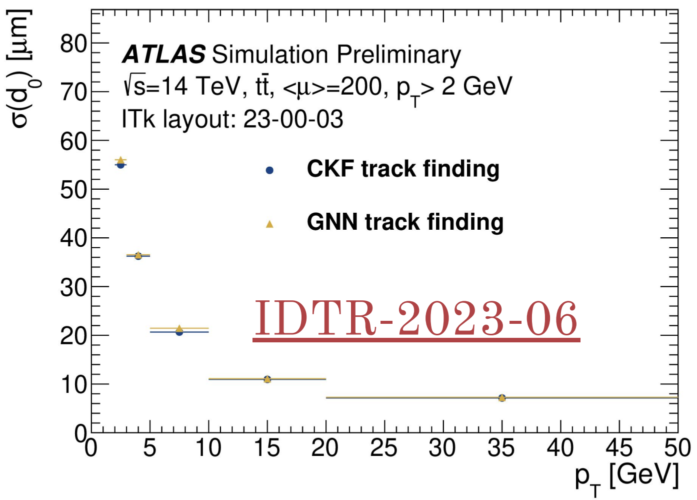


- New trackers designed for **high PU** @ HL-LHC
- Both new detector design and improvements in the software to profit from that ensure **linear behaviour** vs pileup

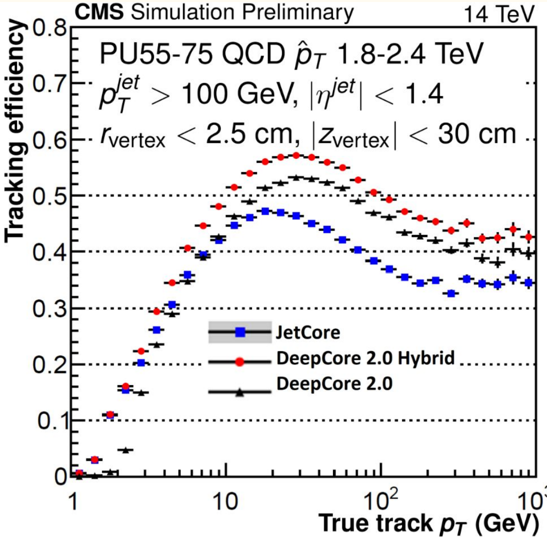
- Tracking for trigger @ HLT demanding due to **combinatorics**
- Requires **improved algorithms** + **parallel computing**

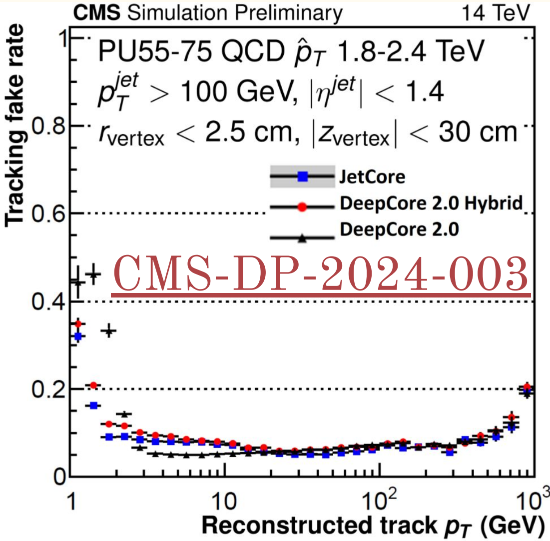
Tracking with Machine Learing

Machine Learning R&D ongoing



IDTR-2023-06





CMS-DP-2024-003

GNN-based pattern recognition with ITK

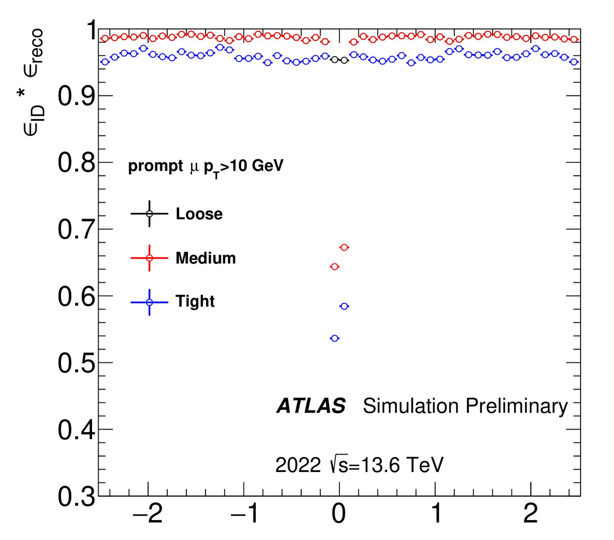
- New result with improved algorithms and updated detector simulation
- Performance close to standard algorithms
- Work ongoing to evaluate computing performance

CNN-based tracking within **high-p_T jets** (Run-3 detector)

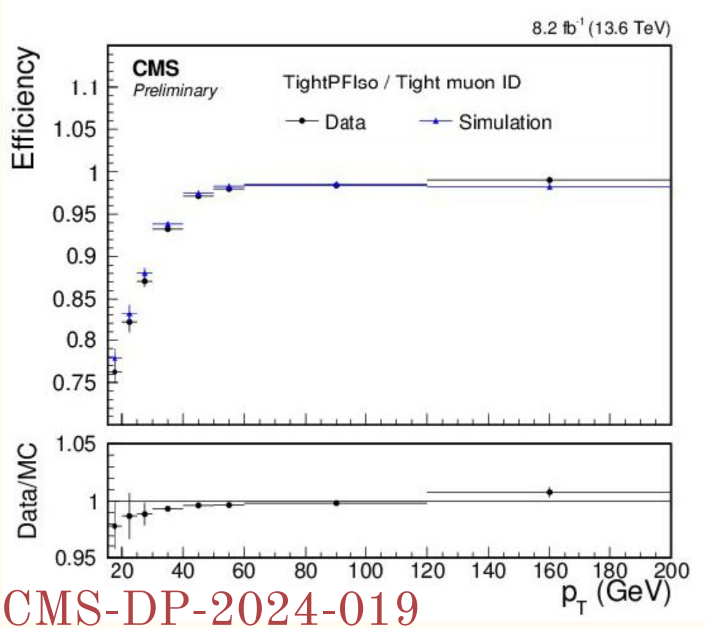
- Challenging due to cluster merging & combinatorics
- Updated CNN algo analyses pixel maps
- Standard vs ML-based algorithms performance differ in phase space regions
  - **combining** both has best performance

Muon reco, identification & isolation

- 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



MUON-2023-02

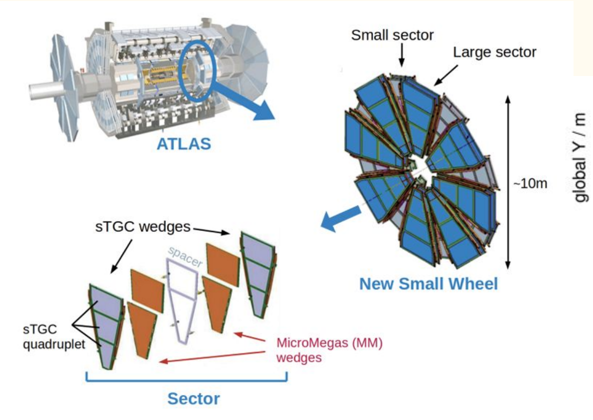


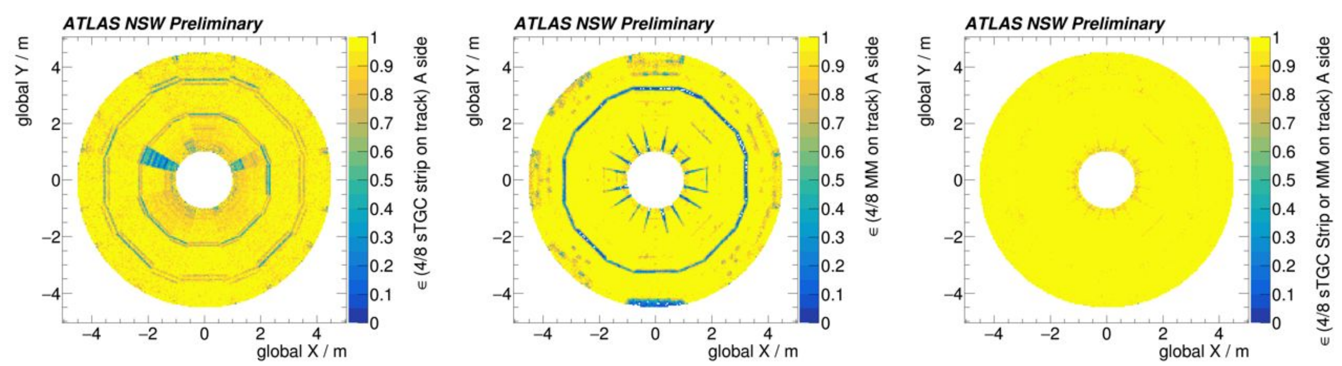
CMS-DP-2024-019

- 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

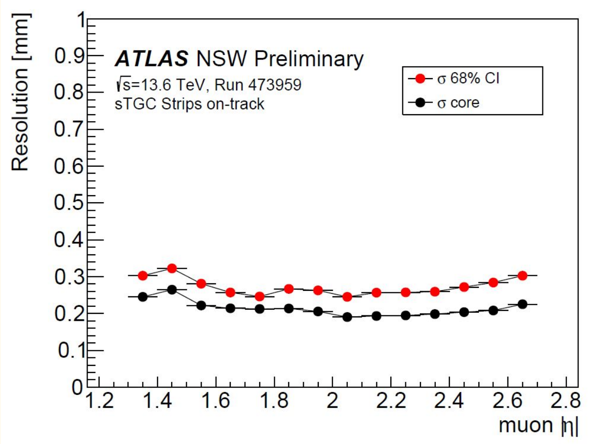
MDET-2024-02

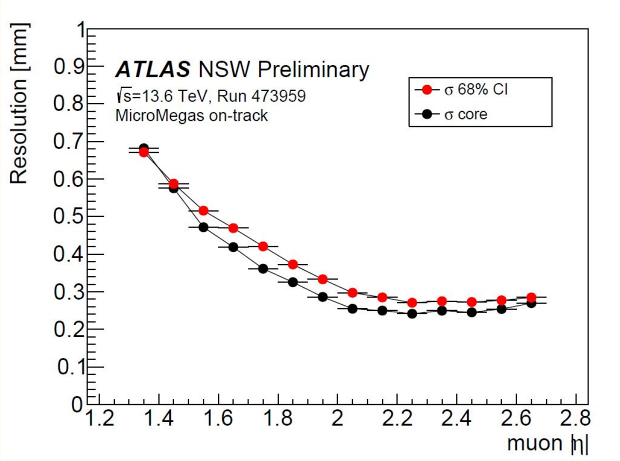




Efficiencies on a 2024 run

Resolution per layer in 2024

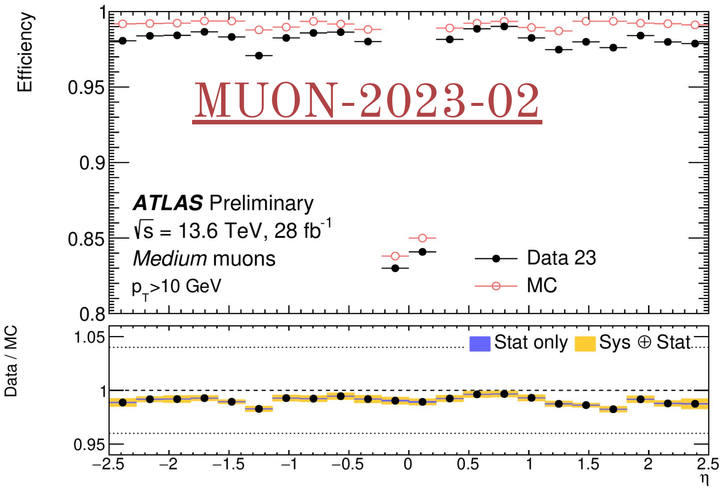


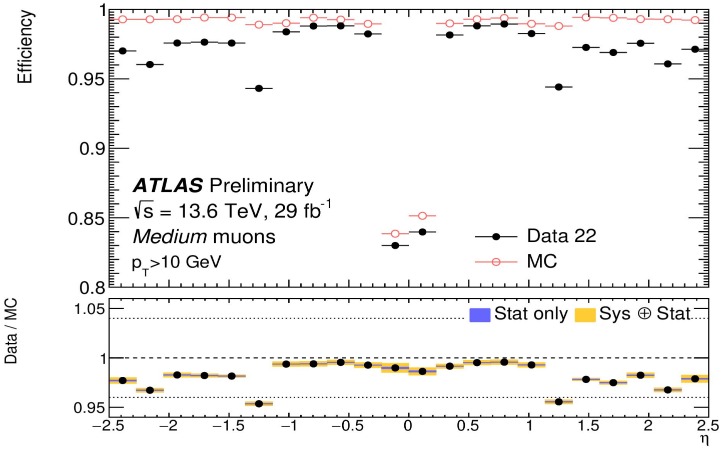


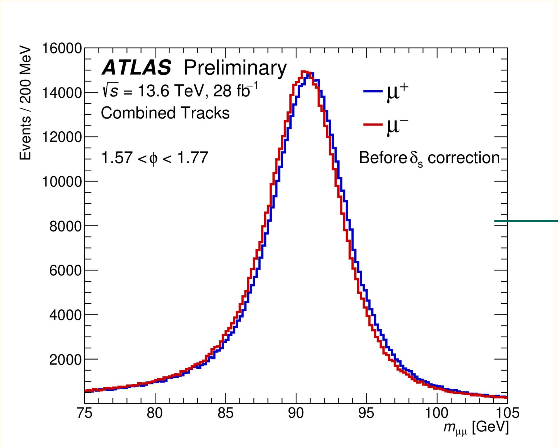
NSW commissioned in 2022 and now fully included in data taking

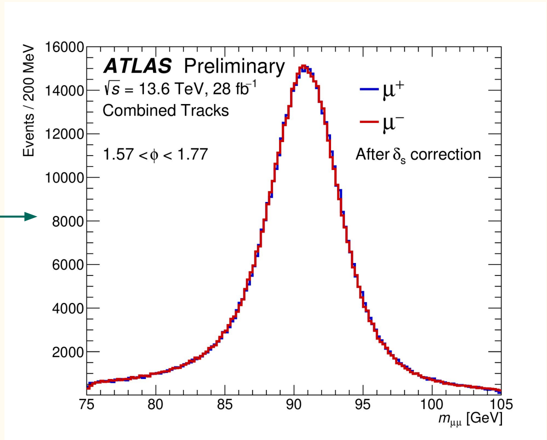
Muon performance ATLAS

MUON-2023-02









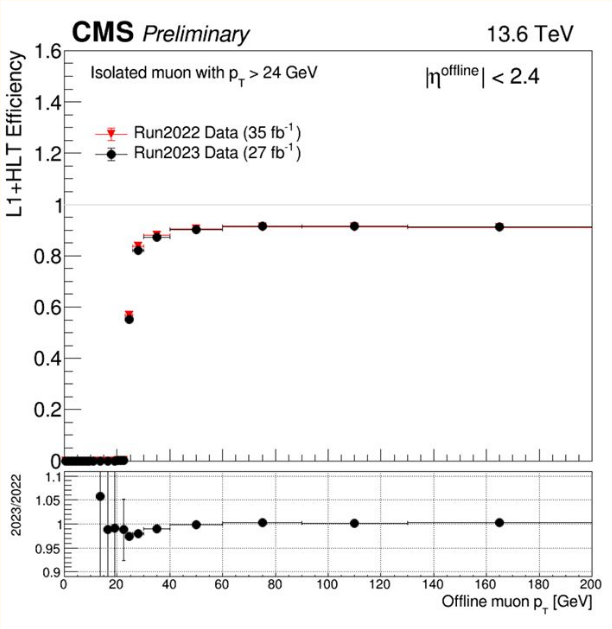
[μm]	$\sigma_{\text{ali}}(\mu_0)$	$\sigma_{\text{ali}}(\mu_\theta)$	$\sigma_{\text{ali}}(\mu_\phi)$	$\sigma_{\text{ali}}(\text{total})$
BA large	25 ± 2	9 ± 1	10 ± 1	29 ± 2
BA small	25 ± 4	19 ± 3	21 ± 4	38 ± 4
EC large	69 ± 3	20 ± 1	28 ± 2	77 ± 2
EC small	95 ± 4	28 ± 2	26 ± 2	103 ± 3
EE large	106 ± 10	22 ± 3	52 ± 6	121 ± 9
EE small	66 ± 9	36 ± 9	58 ± 8	94 ± 9
BEE	59 ± 8	50 ± 7	33 ± 6	84 ± 7

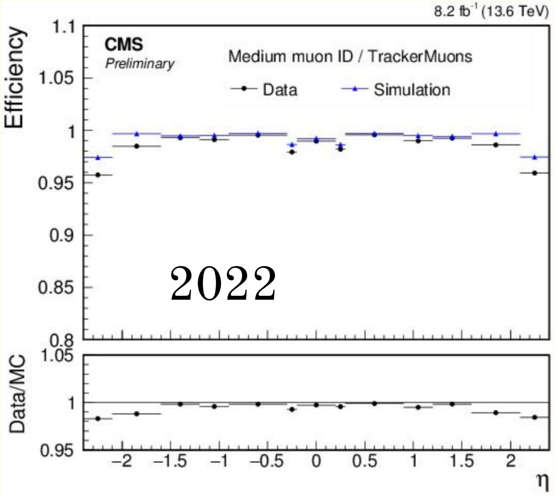
Alignement in Run-3
MDET-2024-03

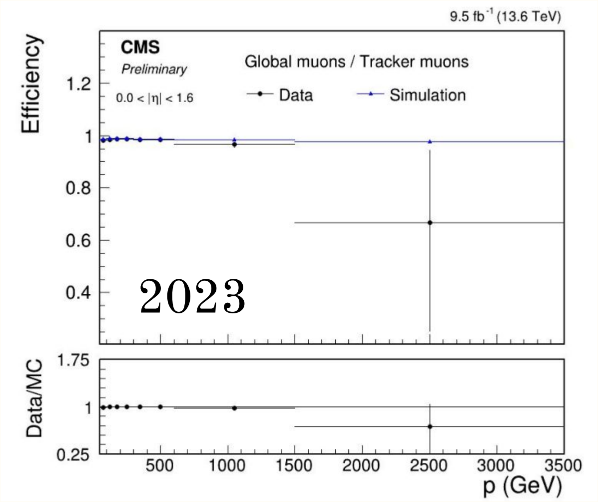
- **Significant ε improvement** in 2023 after commissioning of NSW
- Important to correct for **detector effects** for precision measurements

Muon performance CMS

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







[CMS-DP-2024-005](#)

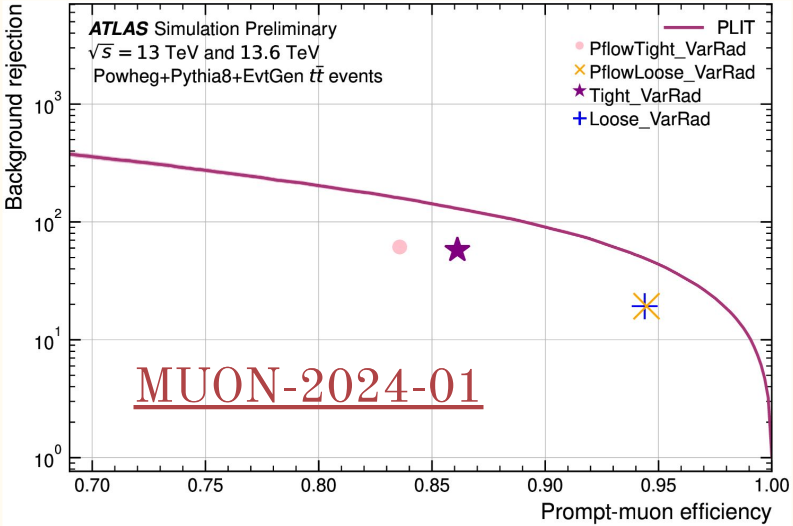
[CMS-DP-2024-019](#)

[CMS-DP-2024-023](#)

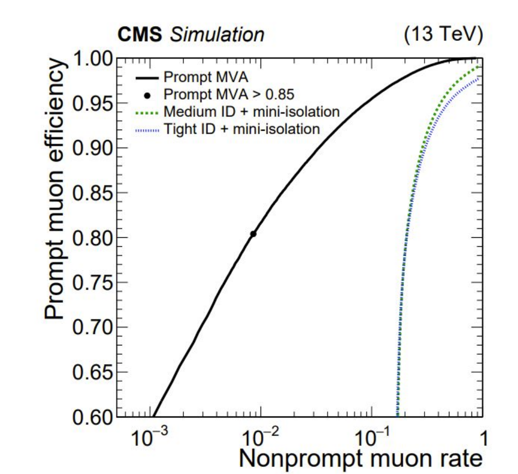
Muon developments

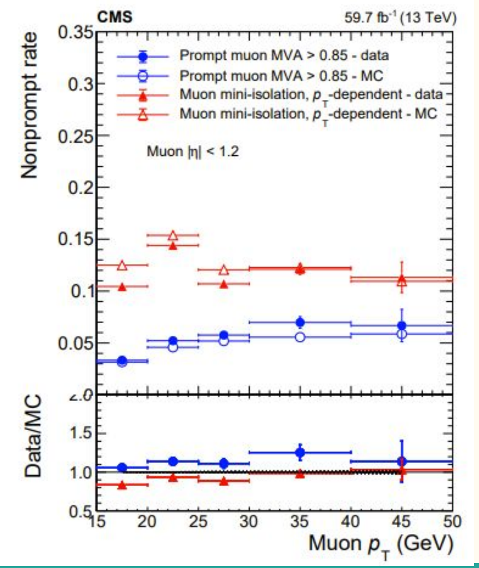
Machine Learning offers great potential for improving muon performance

New isolation based on a **transformer neural network** from ATLAS



MUON-2024-01





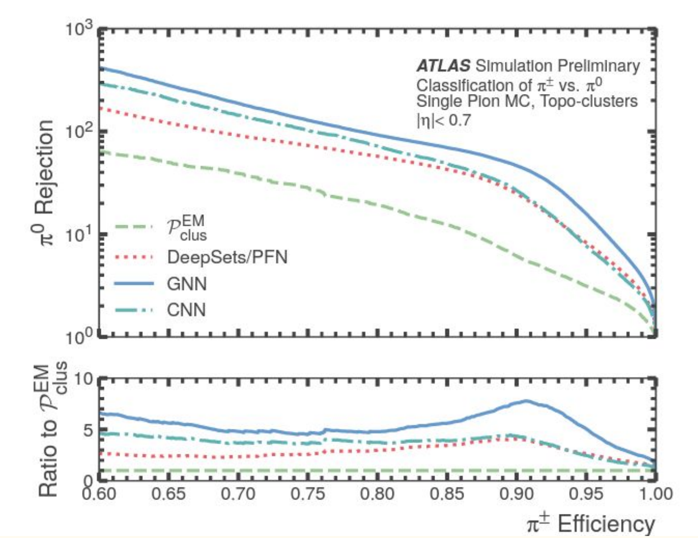
JINST 19 P02031 (2024)

CMS published new results for **muon identification** with **MVA** techniques:

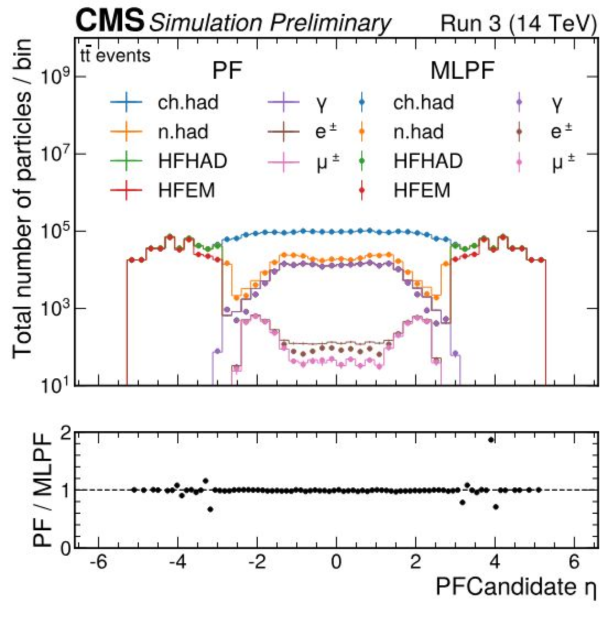
- Major improvement in signal eff vs bkg rejection
- Performance **calibrated in data**, using also non-prompt muons enriched selections

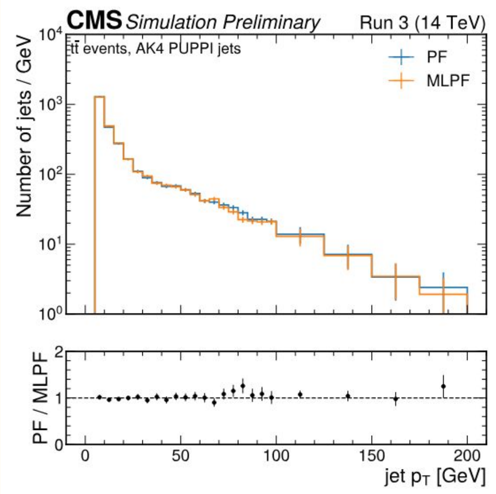
Particle Flow

- 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



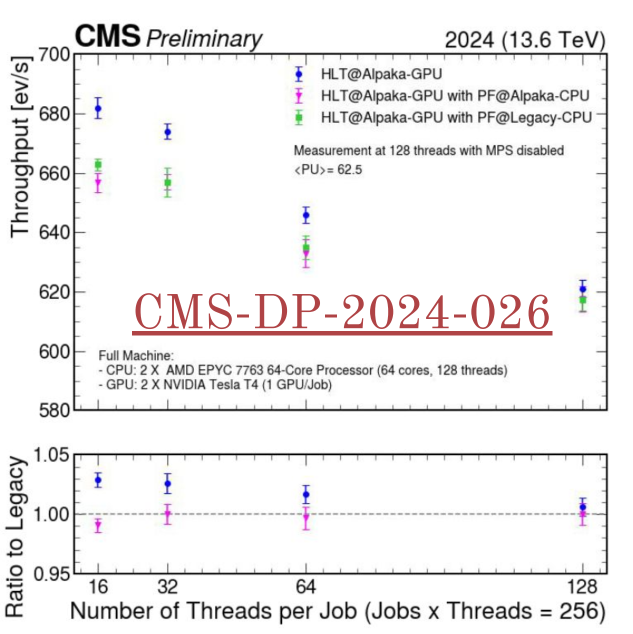
- Particle Flow algorithms used by CMS for **global event reconstruction** JINST 12 (2017) P10003
- Studies for **ML-based Pflow** J. Phys.: Conf. Ser. 2438 012100 with heterogeneous architectures
  - Based on a **scalable GNN model**



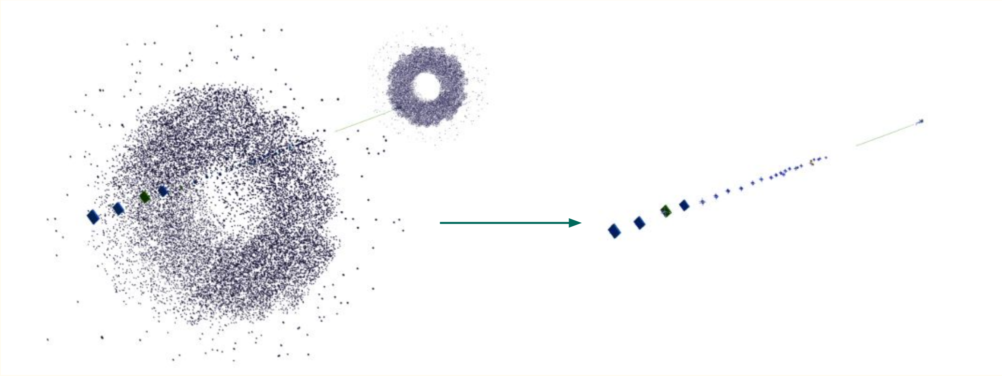


PFlow news from CMS

- 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



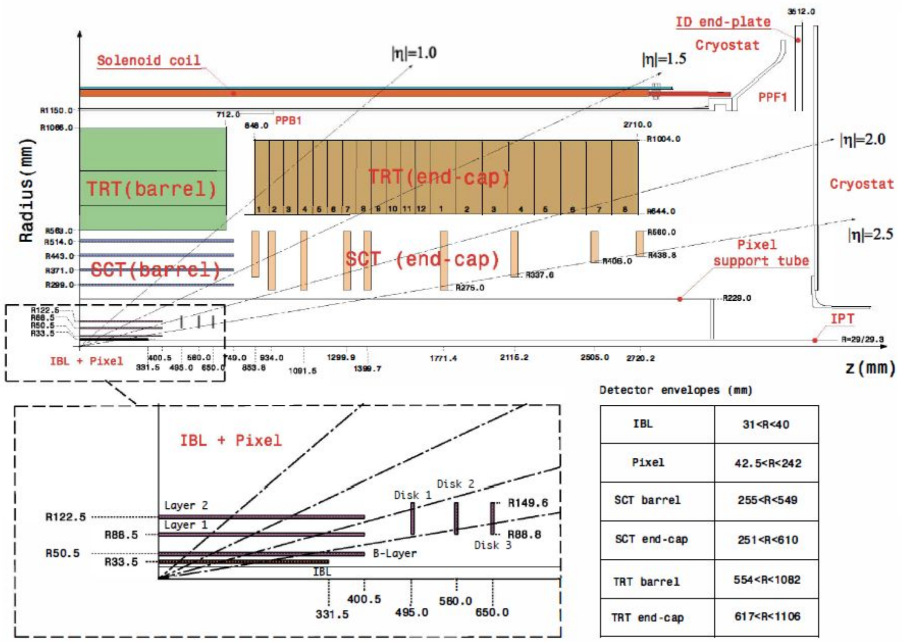
Clustering step removing noise around back-to-back muon tracks

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

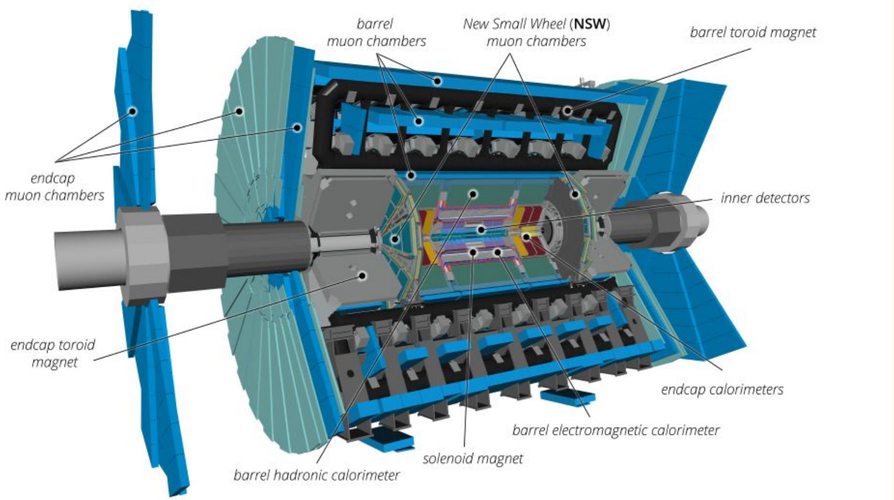
BACKUP

ATLAS detector

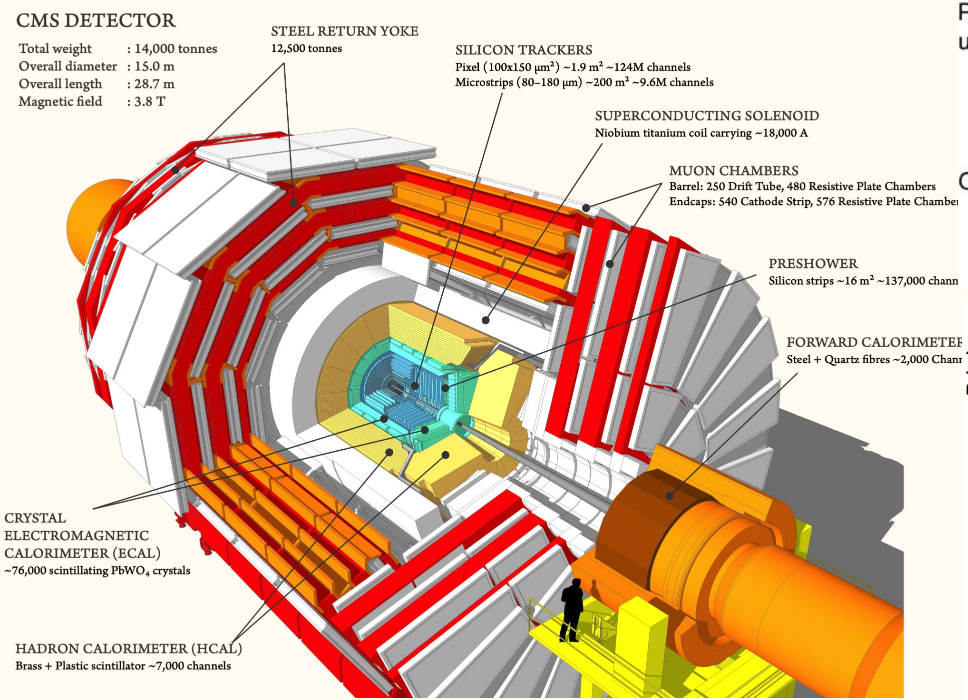


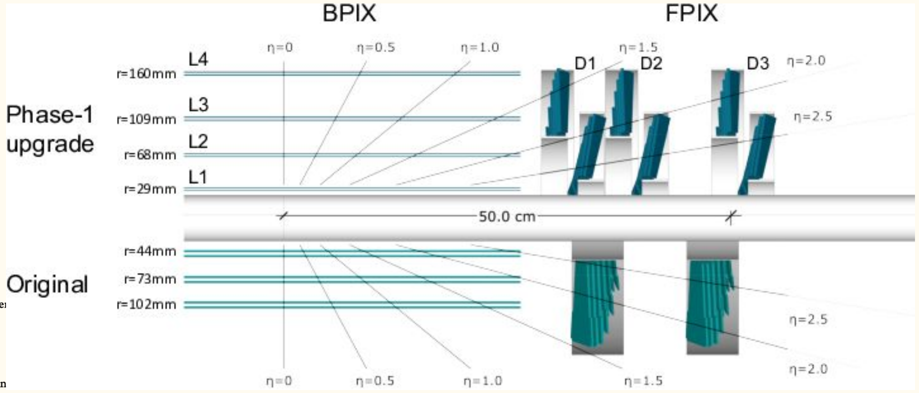
Detector envelopes (mm)

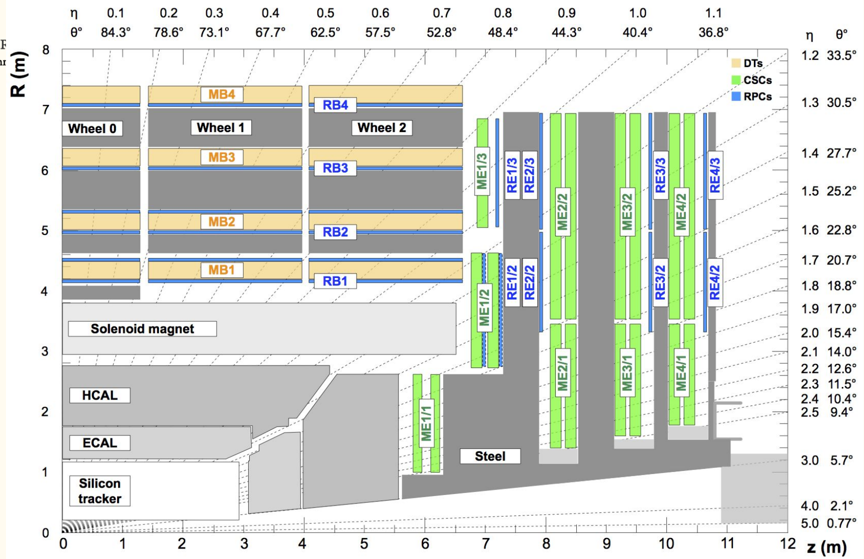
IBL	31<R<40
Pixel	42.5<R<242
SCT barrel	255<R<549
SCT end-cap	251<R<610
TRT barrel	554<R<1082
TRT end-cap	617<R<1106



CMS detector



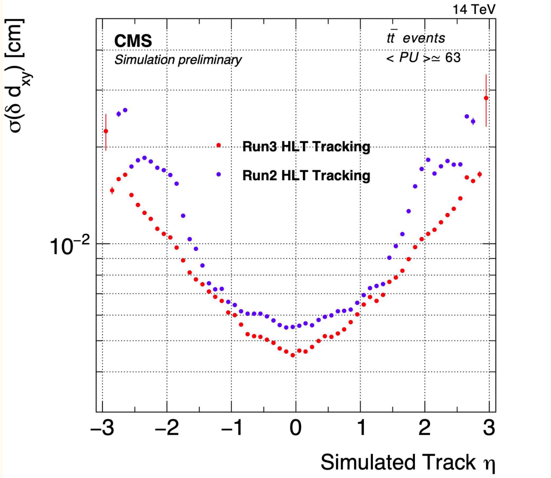


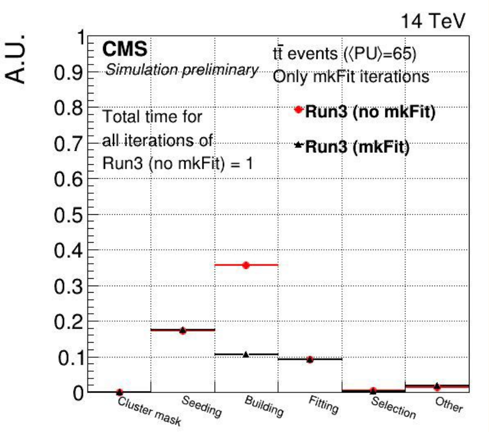


CMS Tracking

- 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 Patatrack pixel tracks
  - Improved fake rejection and IP reso wrt Run-2
- Offline tracking:
  - Iproved parallelized and vectorized algorithm (mkfit)
  - Similar perf to Run-2 CKF, significant speed-up

CERN-CMS-DP-2022-014

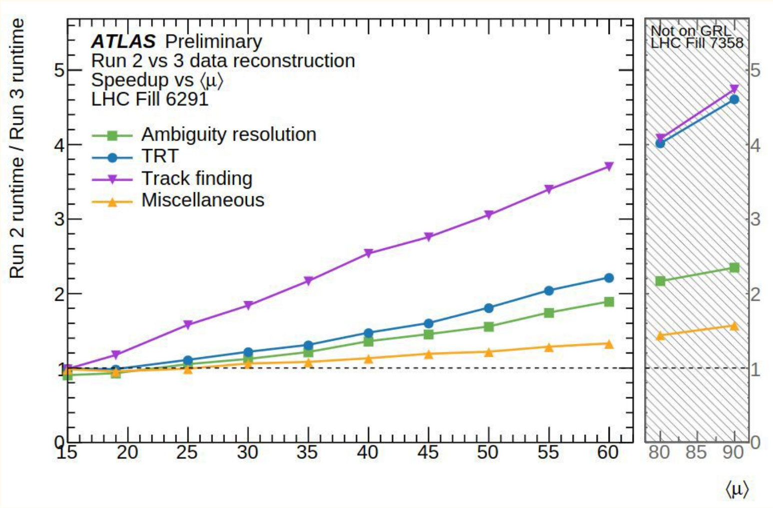




CERN-CMS-DP-2022-018

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 reuce combinatorics
  - New PV algorithm: Adaptive multi-vertex fitter (AMVF): better efficiency and lower fake rate



CMS Muon Reconstruction

JINST 19 P02031 (2024)

- Standalone reconstruction: uses Kalman filter
- If MS compaitble 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

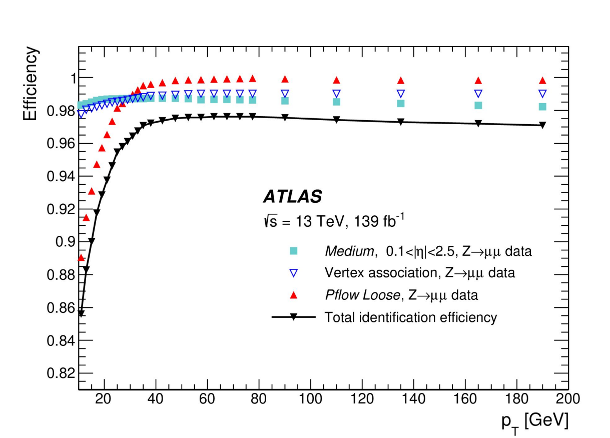
General muon MVA:
Random forest using pt, eta, number of this, chi-squares etc...

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

ATLAS Muon Reconstruction

Eur. Phys. J. C 81, 578 (2021)

- 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 (ncluding 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



CMS Muon Momentum measurement

2018 JINST 13 P06015

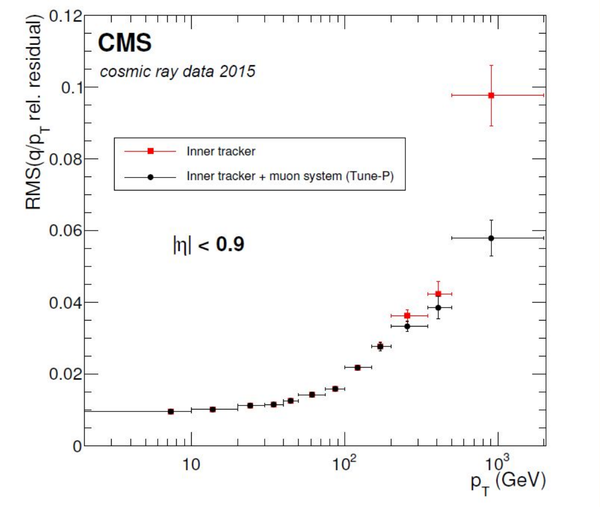
Tune-P algorithm selects best measurements among:

- 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:

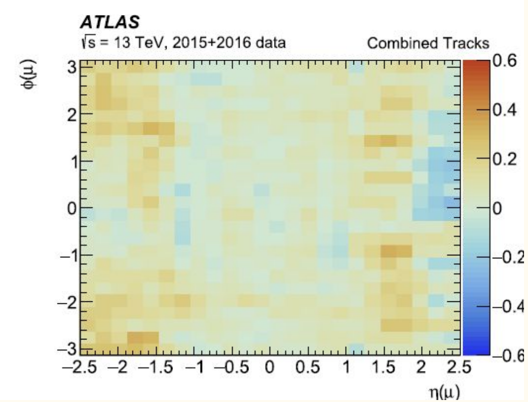
- from $Z \to \mu\mu$ using $\langle 1/p_T^{\mu} \rangle$
- from J/Ψ and Υ using a Kalman filter technique
- from cosmic rays
- from Drell-Yan events using q/p_T

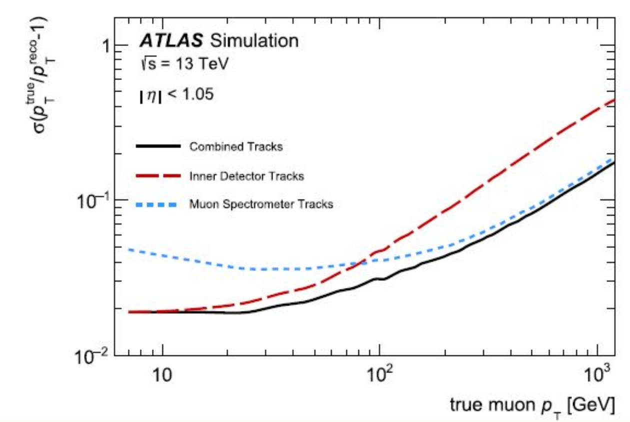


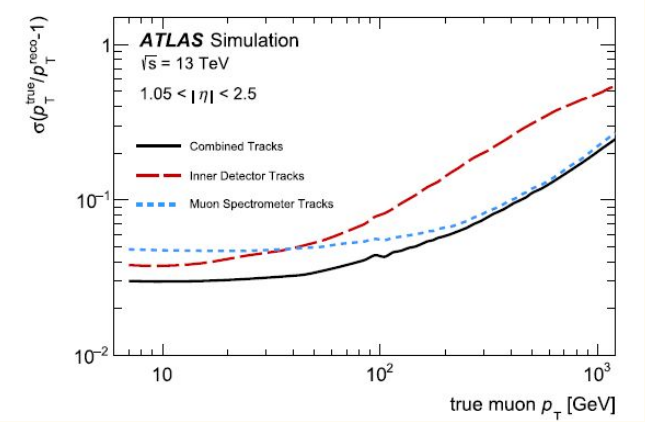
ATLAS Muon Momentum measurement

Eur. Phys. J. C 83 (2023) 686

- Data correction: sagitta bias correction using Z
  - from variance of $M_{\mu\mu}$
  - from local effects on $<M_{\mu\mu}>$
- MC calibration from iterative procedure to determine calib constants using
  - Z events
  - J/Ψ events
  - ϒ events for validation



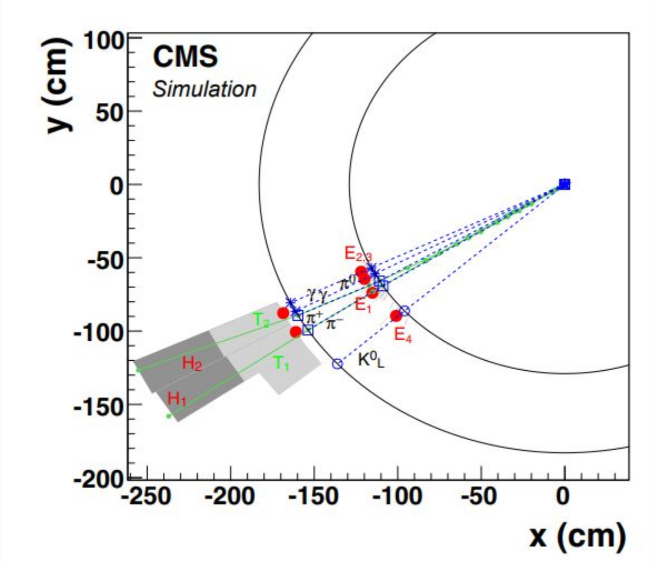


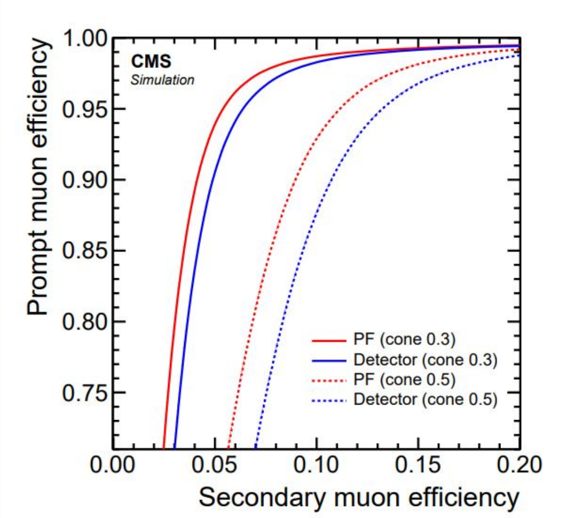


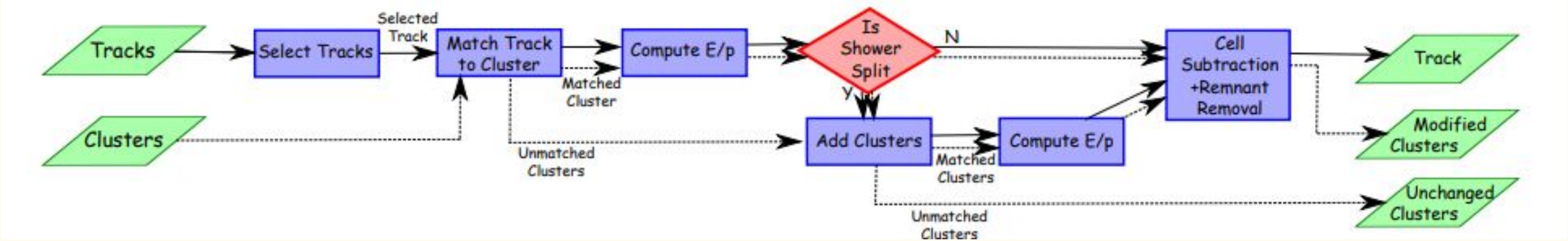
PFlow CMS

[JINST 12 (2017) P10003]

- 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



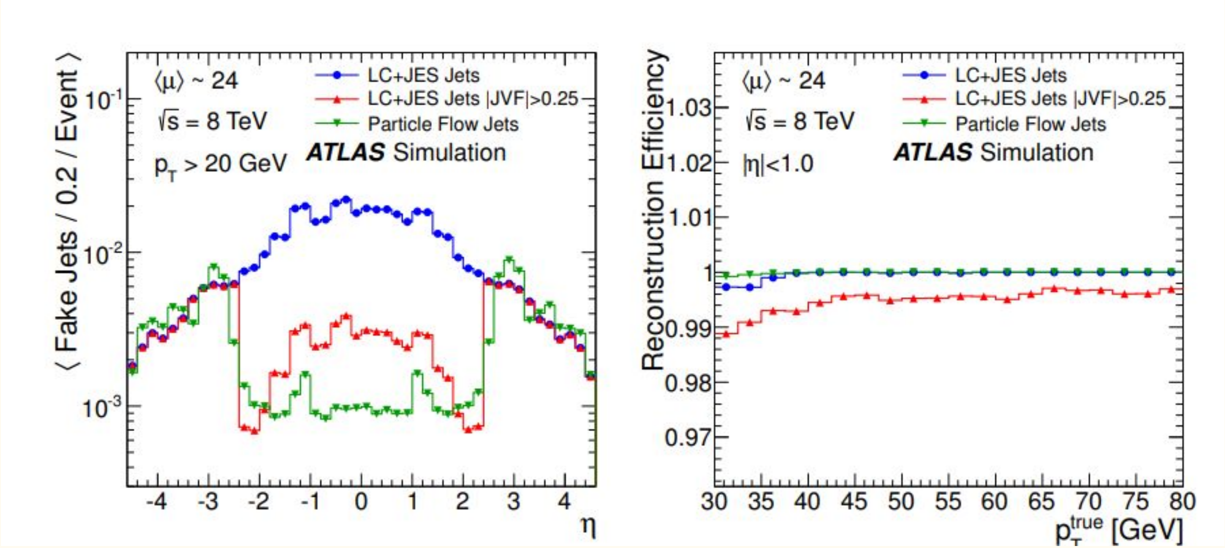




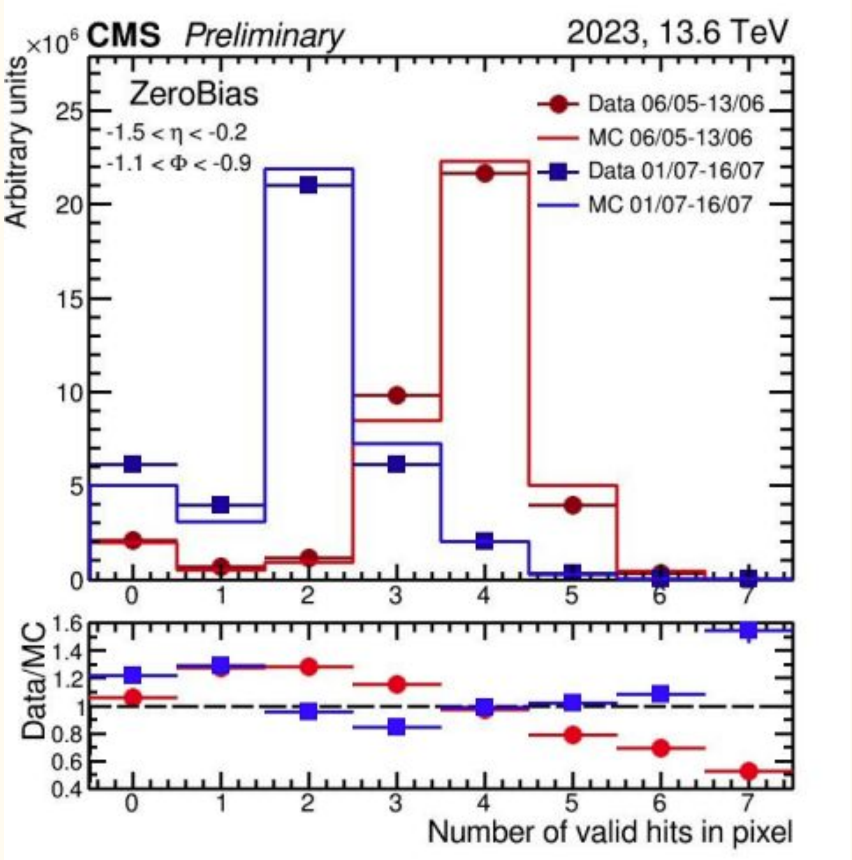
Pflow algorithm diagram for overlap removal between tracker and cluster

PFlow ATLAS

[Eur. Phys. J. C 77 (2017) 466]

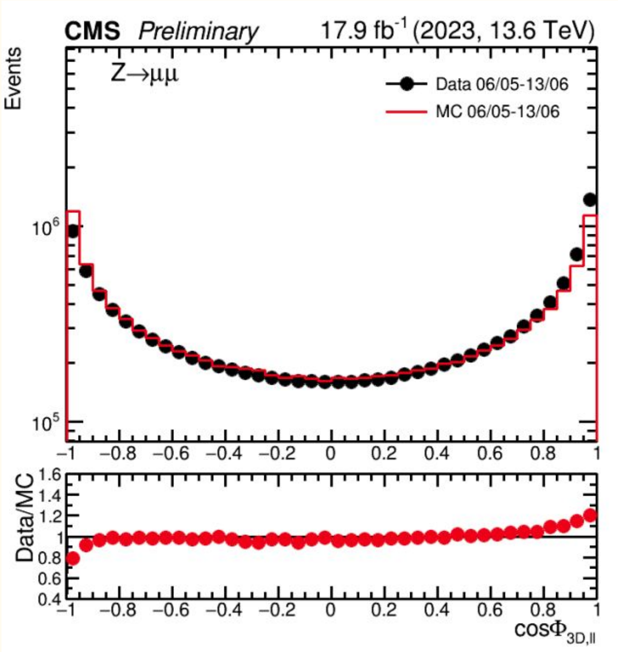


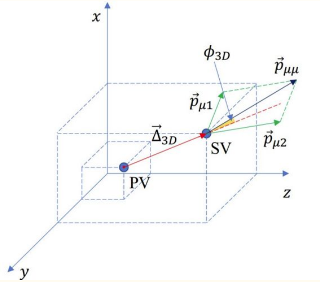
CMS Tracking performance in 2023: localised issue

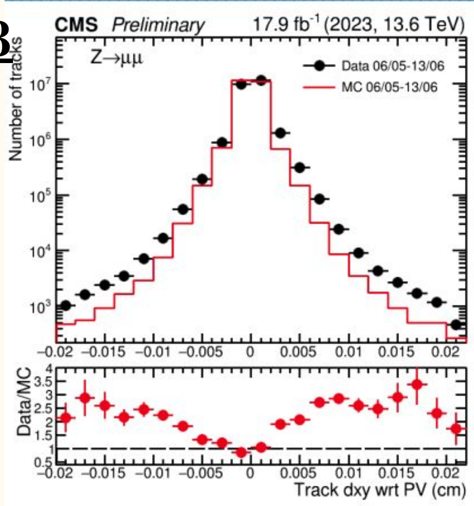


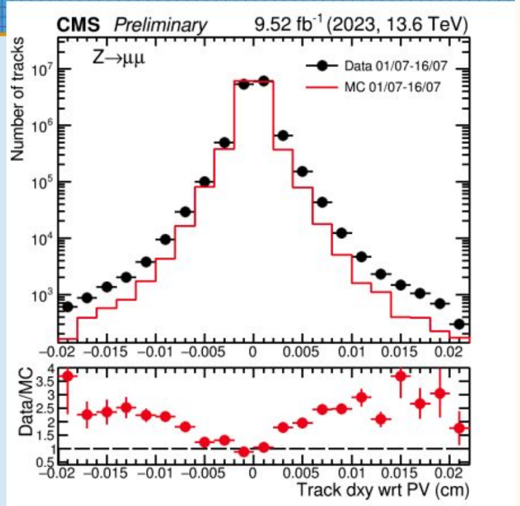
In 2023 the proton-proton physics data taking at 13.6 TeV was from May 6th to July 16th. An extended LHC downtime from June 13th to July 1st splits the data taking in two periods. In the second period readout problems were observed in the layer 3 and 4 of the barrel pixel tracker both in the same sector in φ on the negative half along beamline, with track coverage within $-1.5 < \eta < -0.2$ and $-1.1 < \varphi < -0.9$. Dedicated MC samples are used for the two periods.

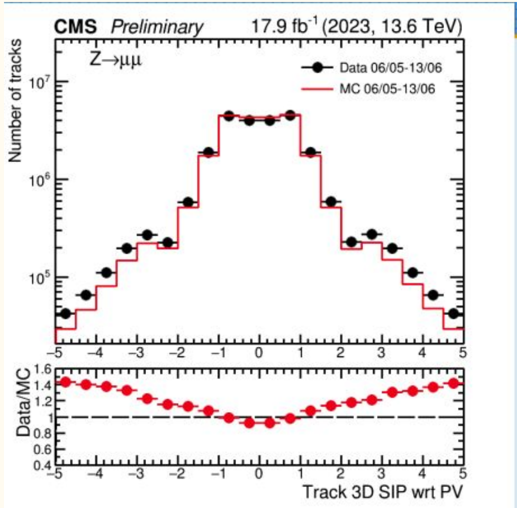
CMS-DP-2023-090 **IP performance 2023**

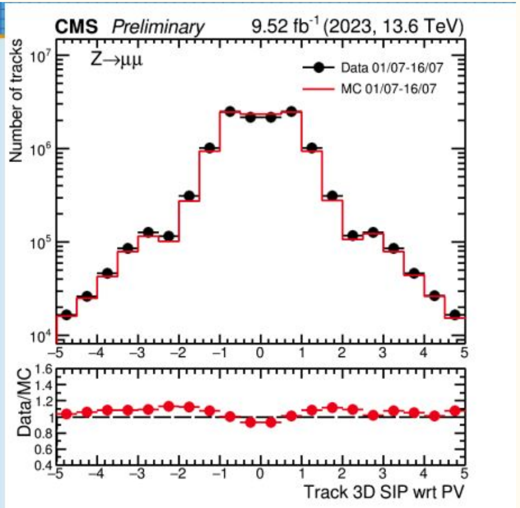






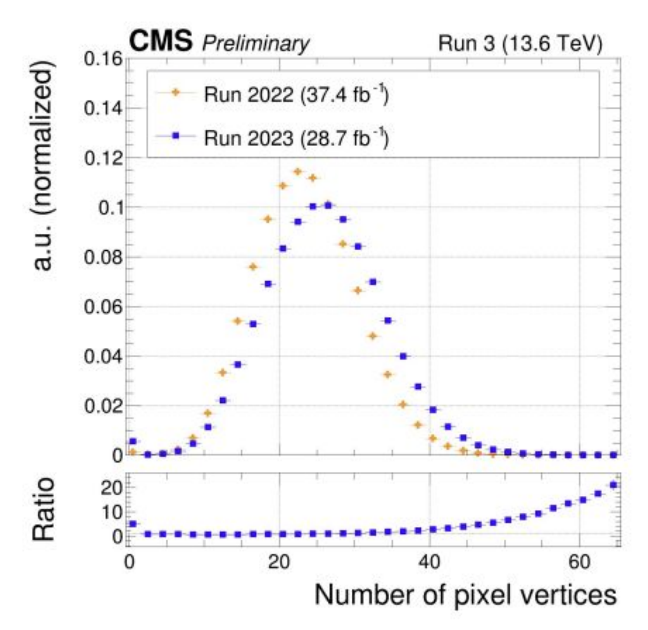


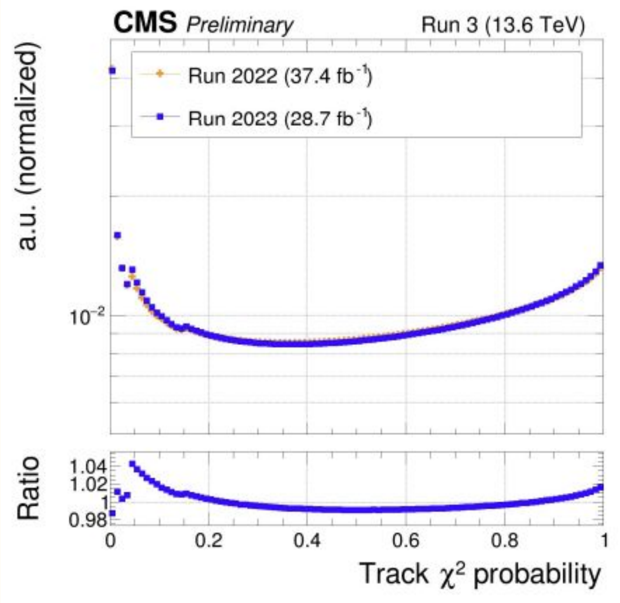




In Run 3, track reconstruction at the CMS High-Level Trigger (HLT) is based on a single iteration of the Combinational Kalman Filter (CKF), using hits recorded by both the pixel and strip detectors. The track reconstruction needs an initial estimate of the track parameters, i.e. a trajectory seed. The 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

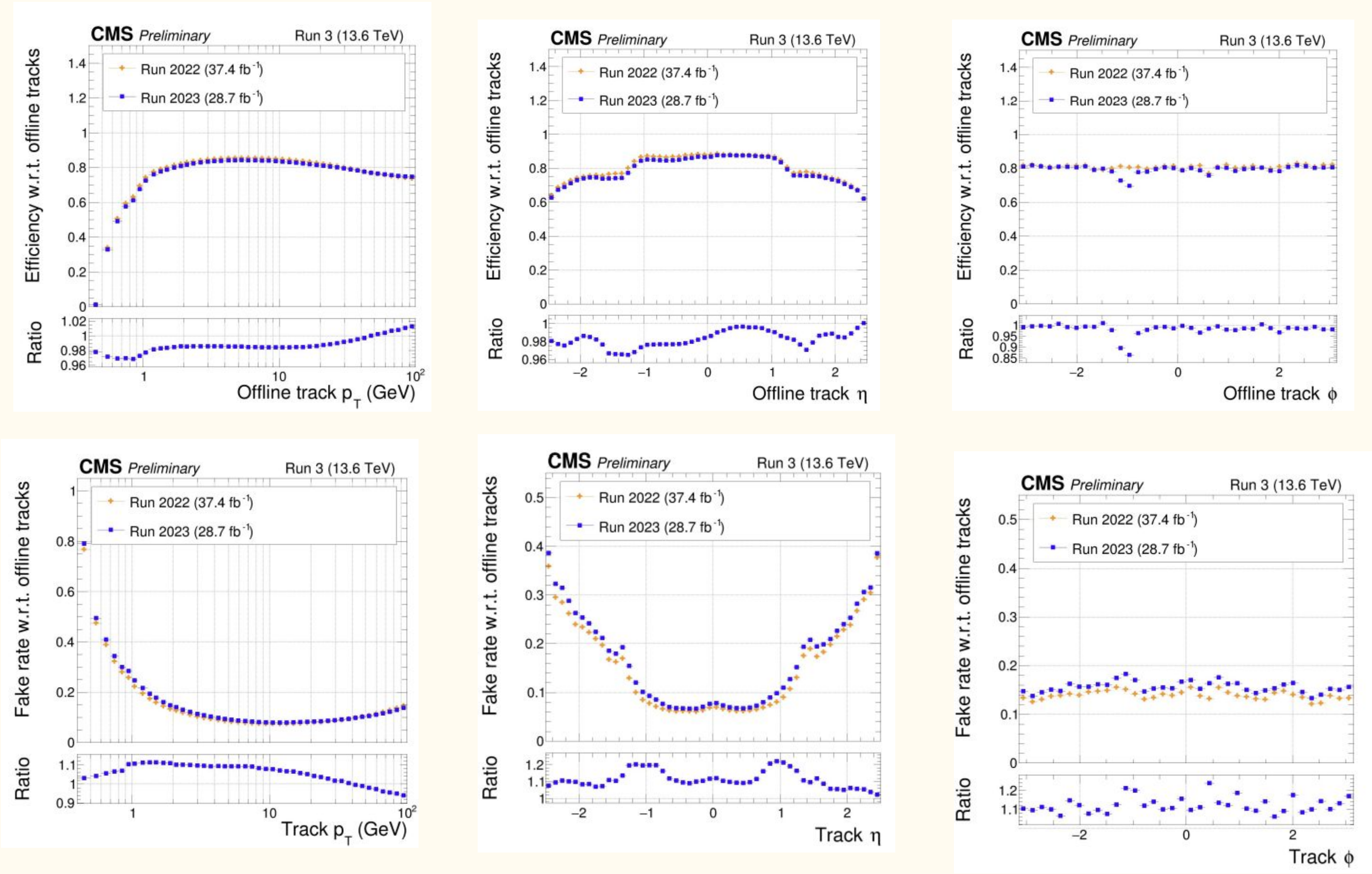




Performance of Track Reconstruction at the CMS High-Level Trigger in 2023

CMS-DP-2024-013

CMS-DP-2024-013

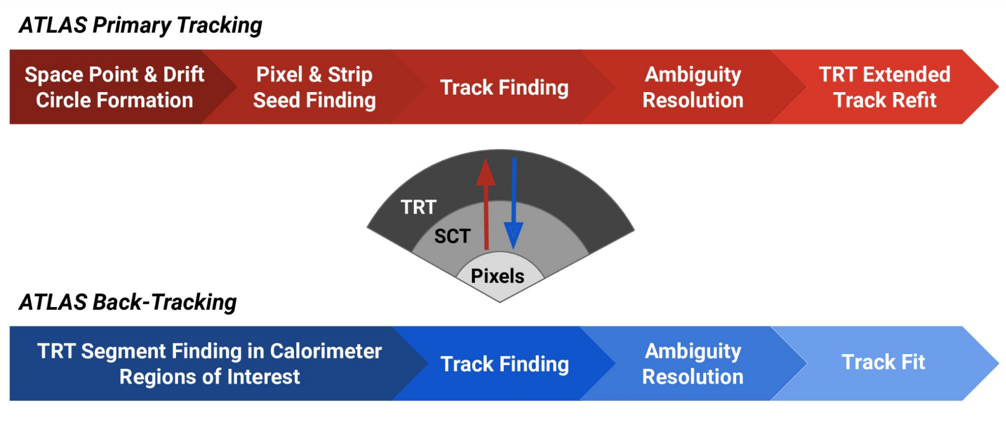


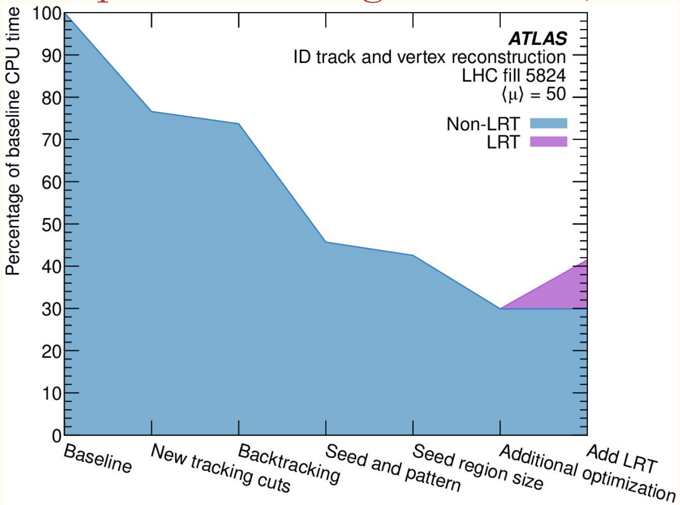
Performance of Track Reconstruction at the CMS High-Level Trigger in 2023

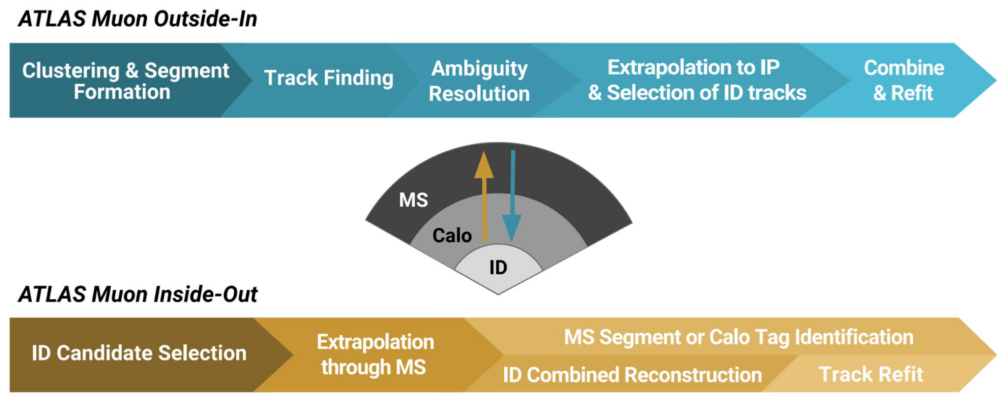
CMS-DP-2024-013

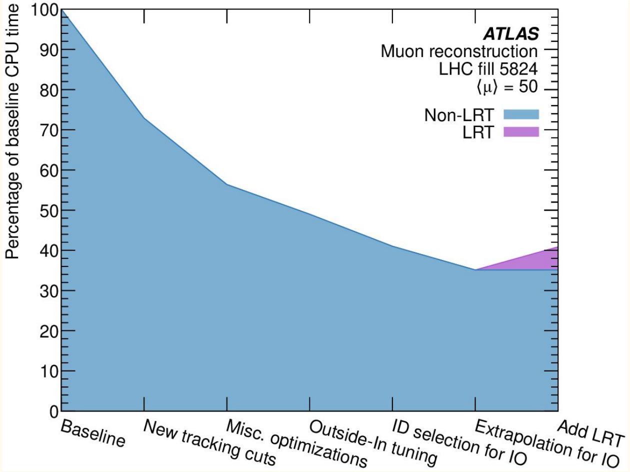
ATLAS Muon & Tracking software

Comput Softw Big Sci 8, 9 (2024)



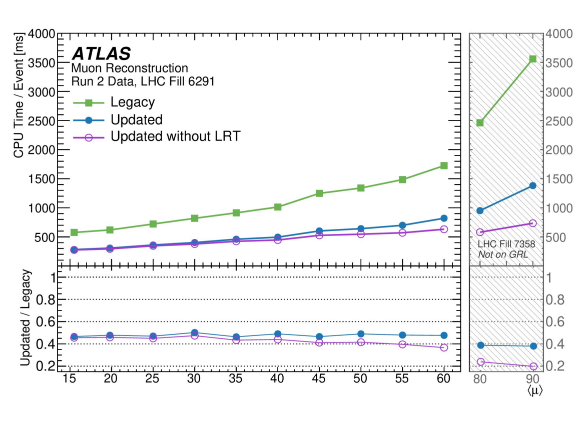


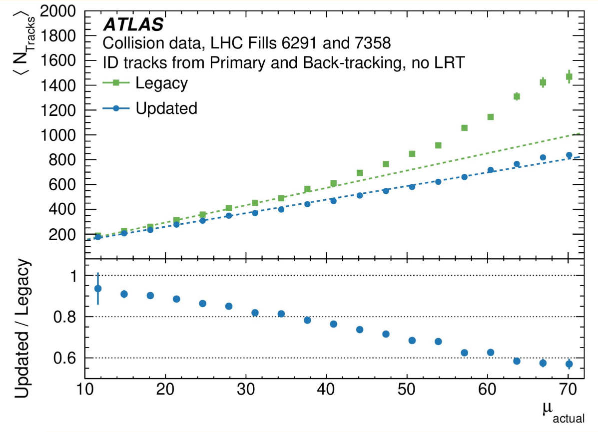


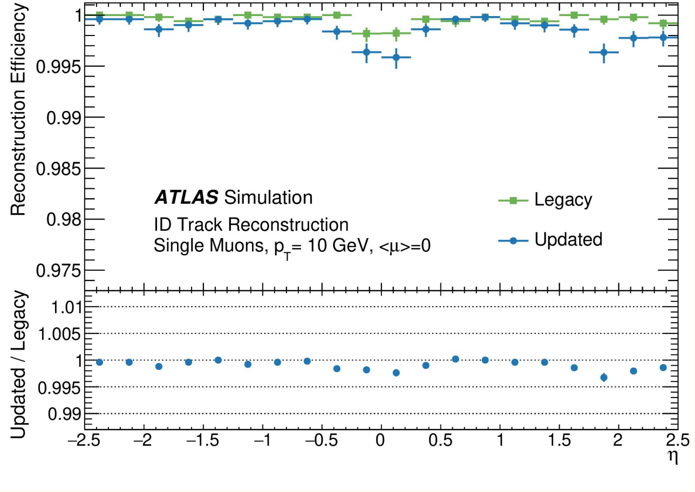


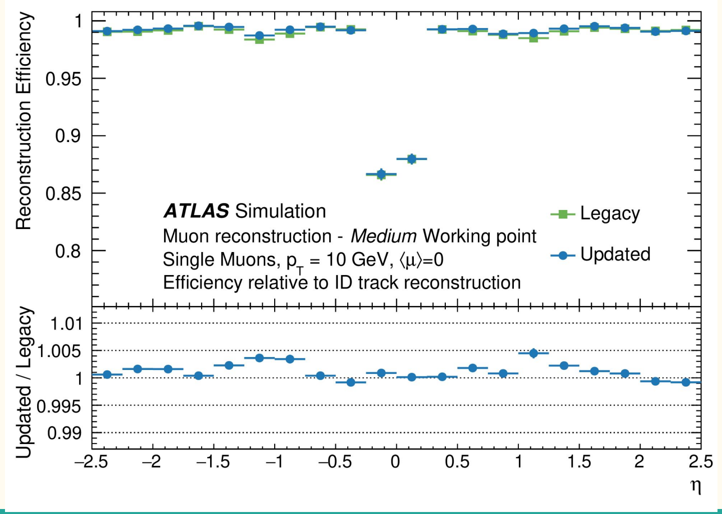
ATLAS Muon & Tracking software

Comput Softw Big Sci 8, 9 (2024)



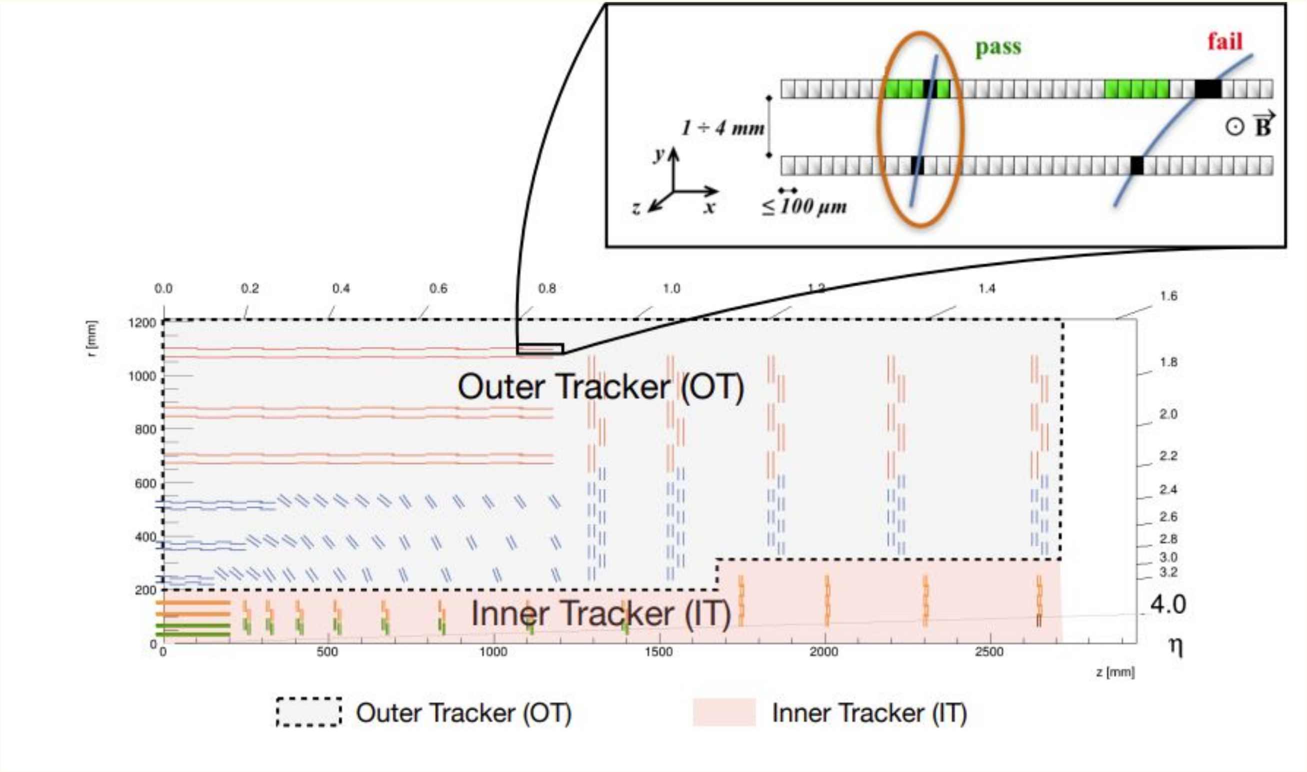






Improved Performance of Line Segment Tracking Using Machine Learning @ HL_LHC

CMS-DP-2023-075



- 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]:

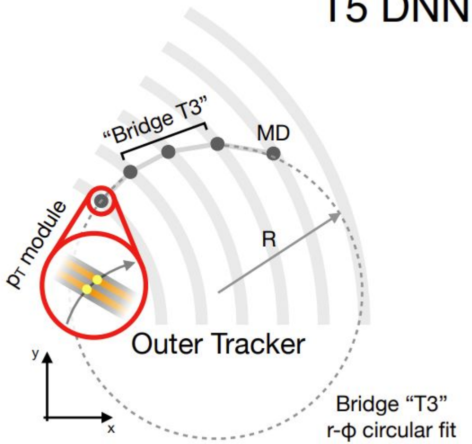
- MiniDoublet (**MD**): linked pair of hits in individual p_T modules
- Line Segments (**LS**): linked pair of MDs in neighboring layers
- Triplet (**T3**): linked pair of LSs with a common MD
- Quintuplet (**T5**): linked pair of T3s with a common MD

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)

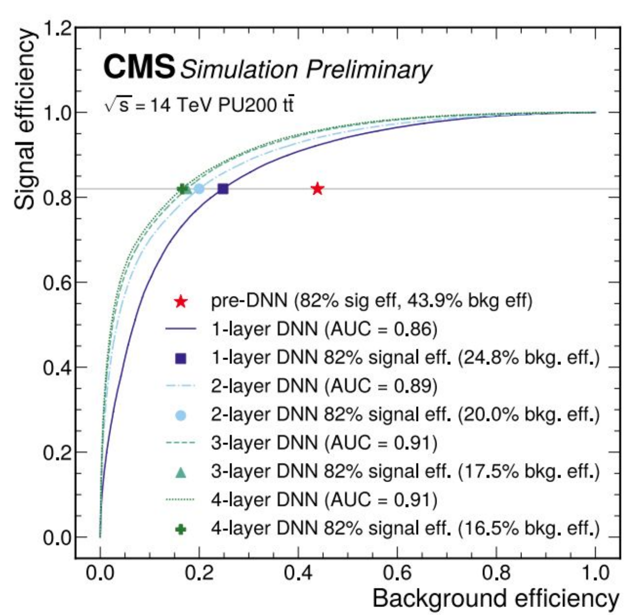
Improved Performance of Line Segment Tracking Using Machine Learning @ HL_LHC

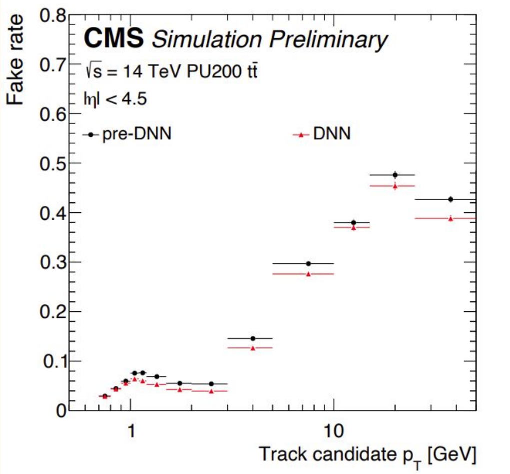
T5 DNN input features

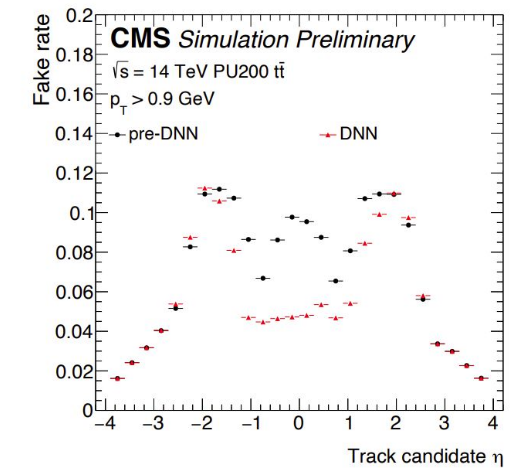


Object	Feature
T3 (x2)	p_T
	Inner anchor hit r, z, ϕ, η, layer
	Middle anchor hit r, z, ϕ, η, layer
	Outer anchor hit r, z, ϕ, η, layer
	Radius of circle fit
T5 candidate	p_T, η, ϕ
	Radius of circle fit for "Bridge T3"

Both T5-level and T3-level features are provided to the DNN as input.

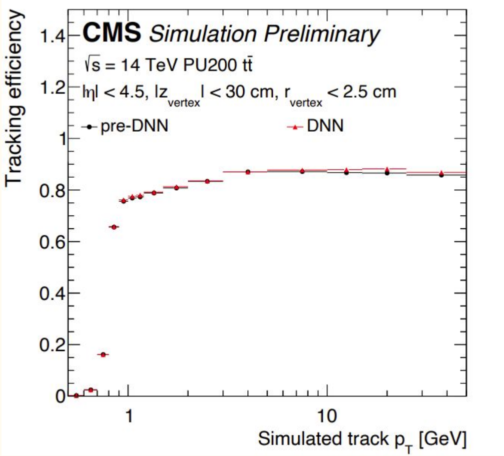


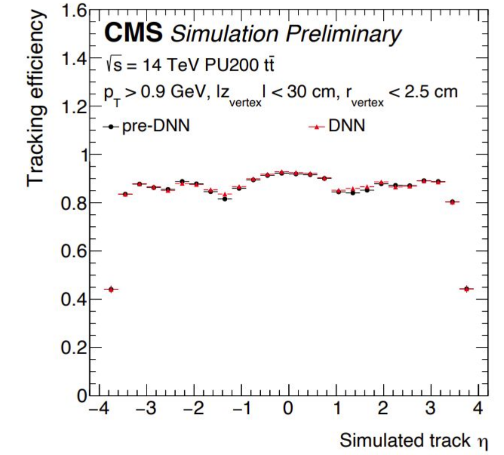




Improved Performance of Line Segment Tracking Using Machine Learning @ HL_LHC

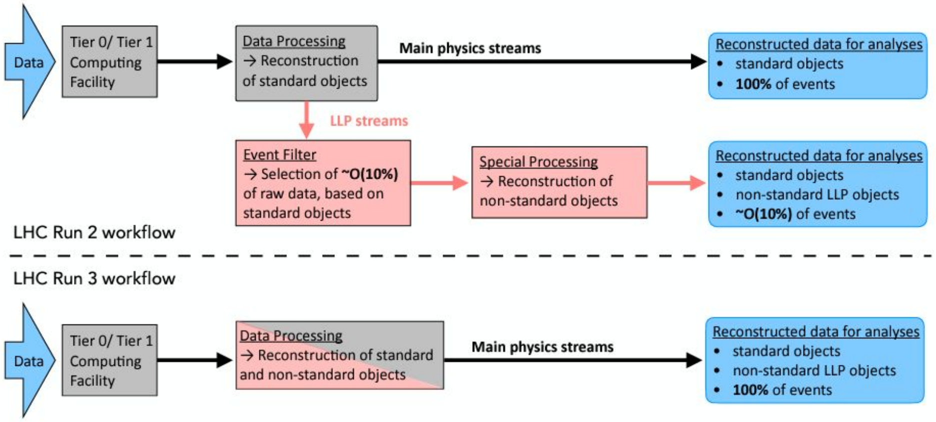
	T5	1/Throughput	N streams
pre-DNN	3.37 ± 0.13	28.4 ± 1.5	1
DNN	3.39 ± 0.07	28.7 ± 1.1	1





ATLAS LRTs

Eur. Phys. J. C 83 (2023) 1081



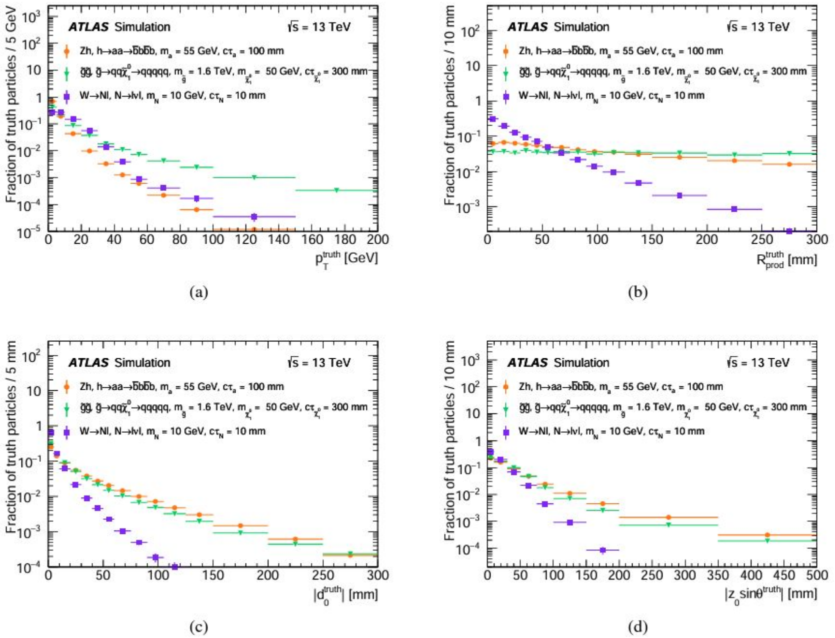
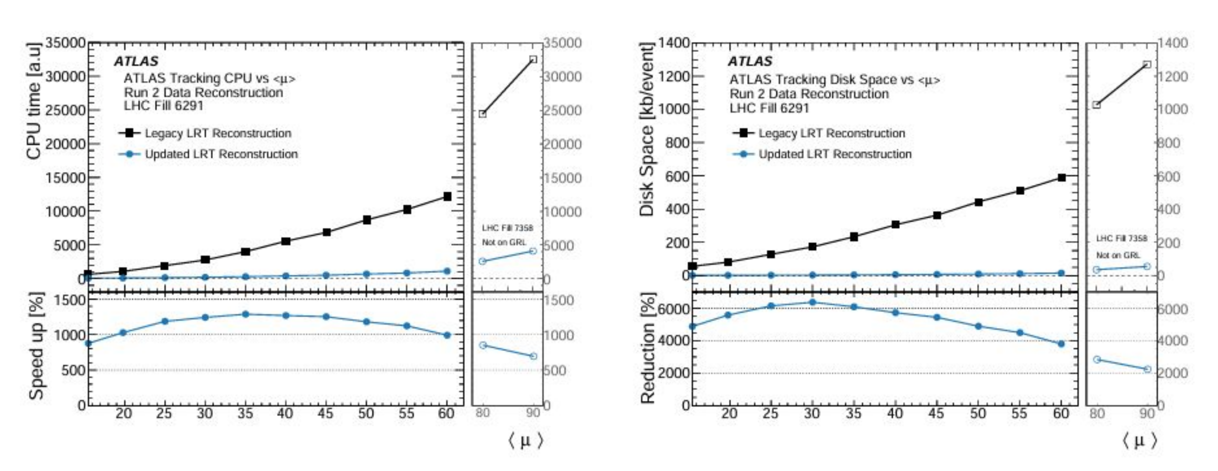


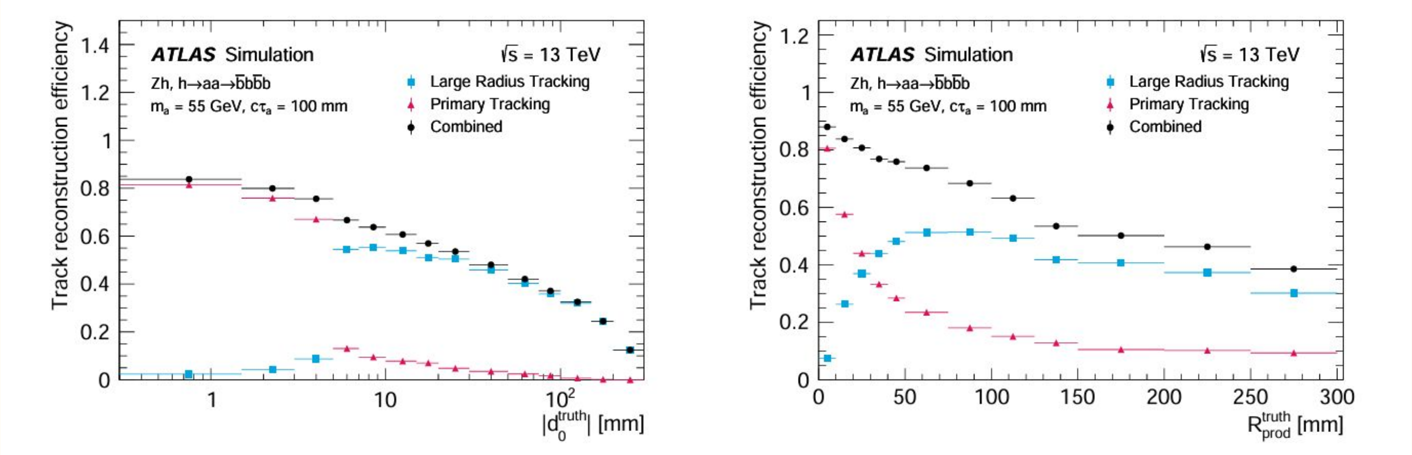
Table 2: Most important selection criteria that differ between the primary tracking (*inside-out* sequence only) and LRT setups. Common selection criteria that were changed from the legacy implementation are also shown.

Selection criteria	Primary (*inside-out*)	LRT
max. $\|d_0\|$ [mm]	5	300
max. $\|z_0\|$ [mm]	200	500
min. p_T [GeV]	0.5	1
max. $\|\eta\|$	2.7	3.0
max. silicon holes	2	1
max. double holes	1	0
max. holes gap	2	1
road width [mm]	12	5
seeding	Pixels and SCT	SCT only
max. seeds per middle Pixel SP	1	–
max. seeds per middle SCT SP	5	1
Common selection criteria		
min. silicon hits	8	
min. unshared silicon hits	6	
max. track χ^2/n_{DoF}	9	
keep all confirmed seeds	true	

ATLAS LRTs

[Eur. Phys. J. C 83 (2023) 1081]

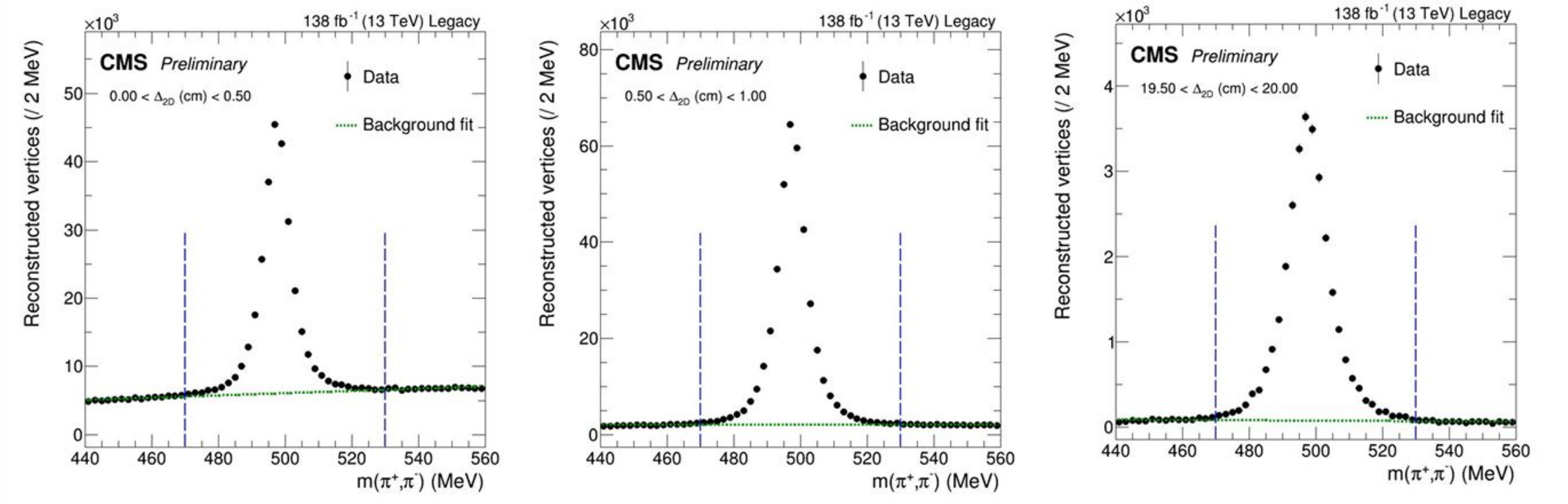




(a) (b)

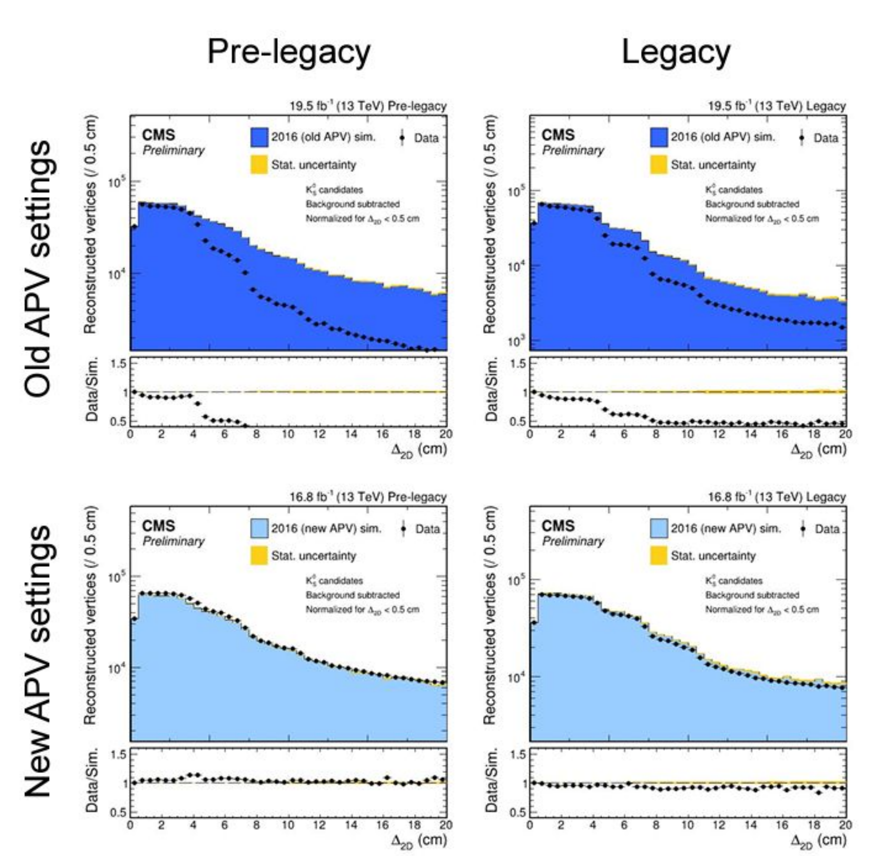
CMS displaced tracking calibration

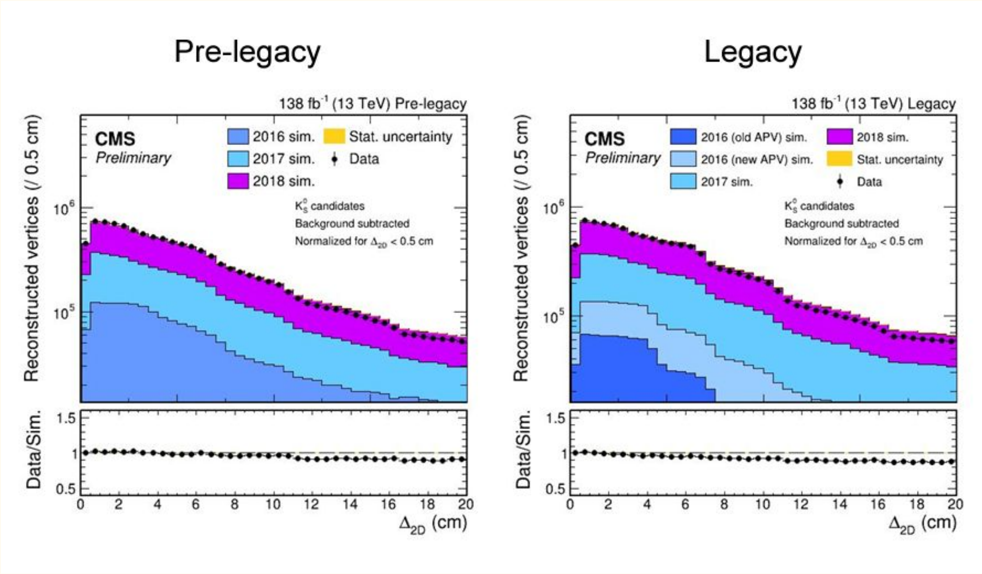
CMS-DP-2024-010



CMS displaced tracking calibration

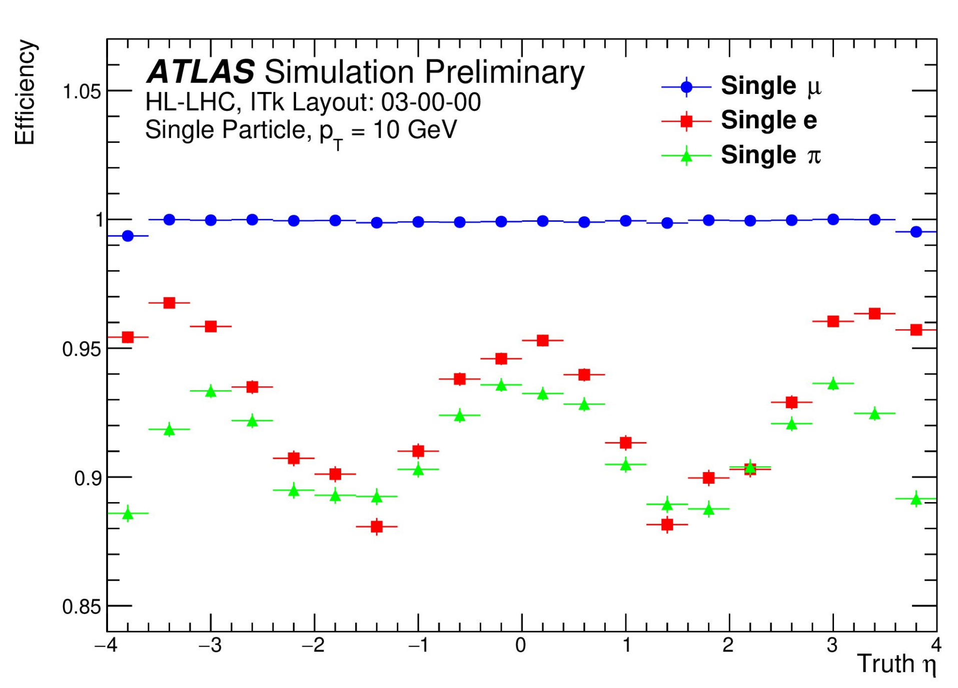
CMS-DP-2024-010

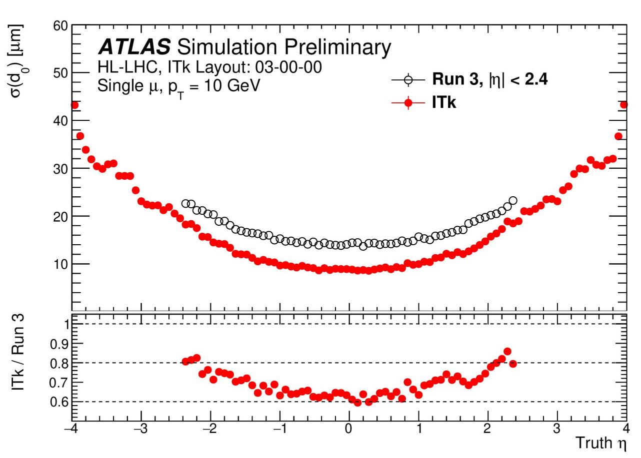


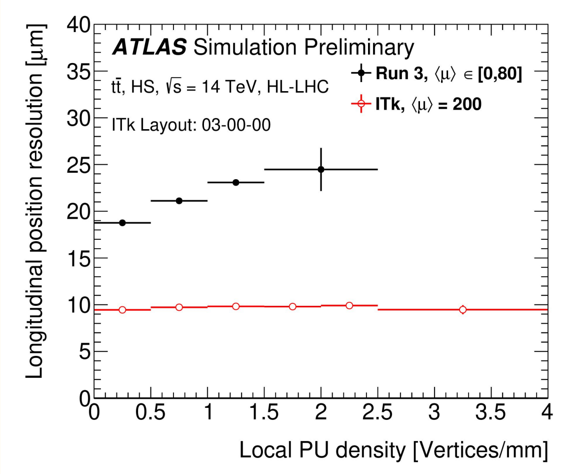


Expected tracking performance of the ATLAS Inner Tracker Upgrade for Phase-II

IDTR-2023-05



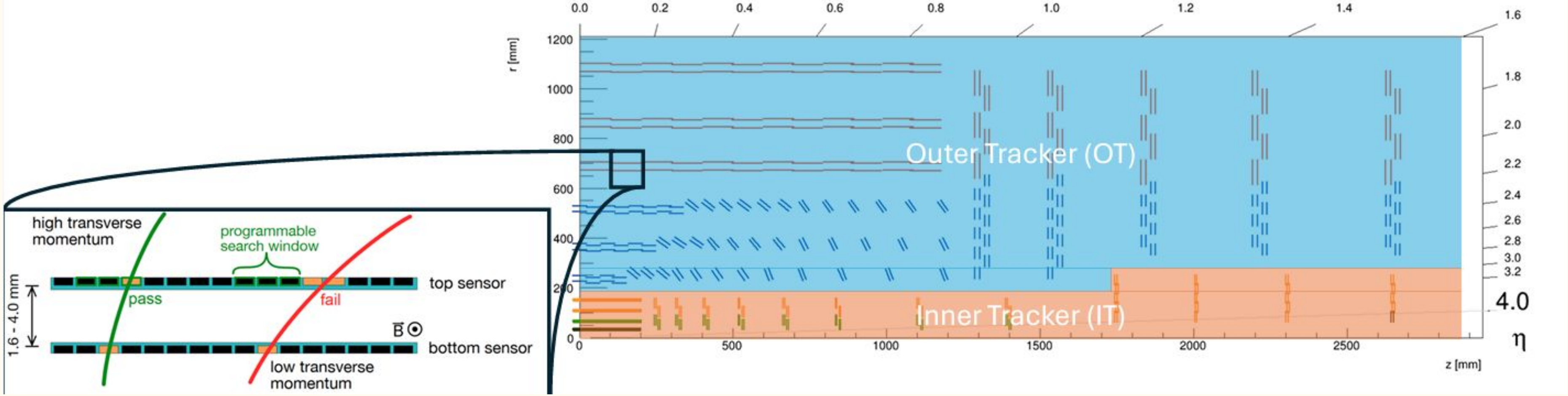


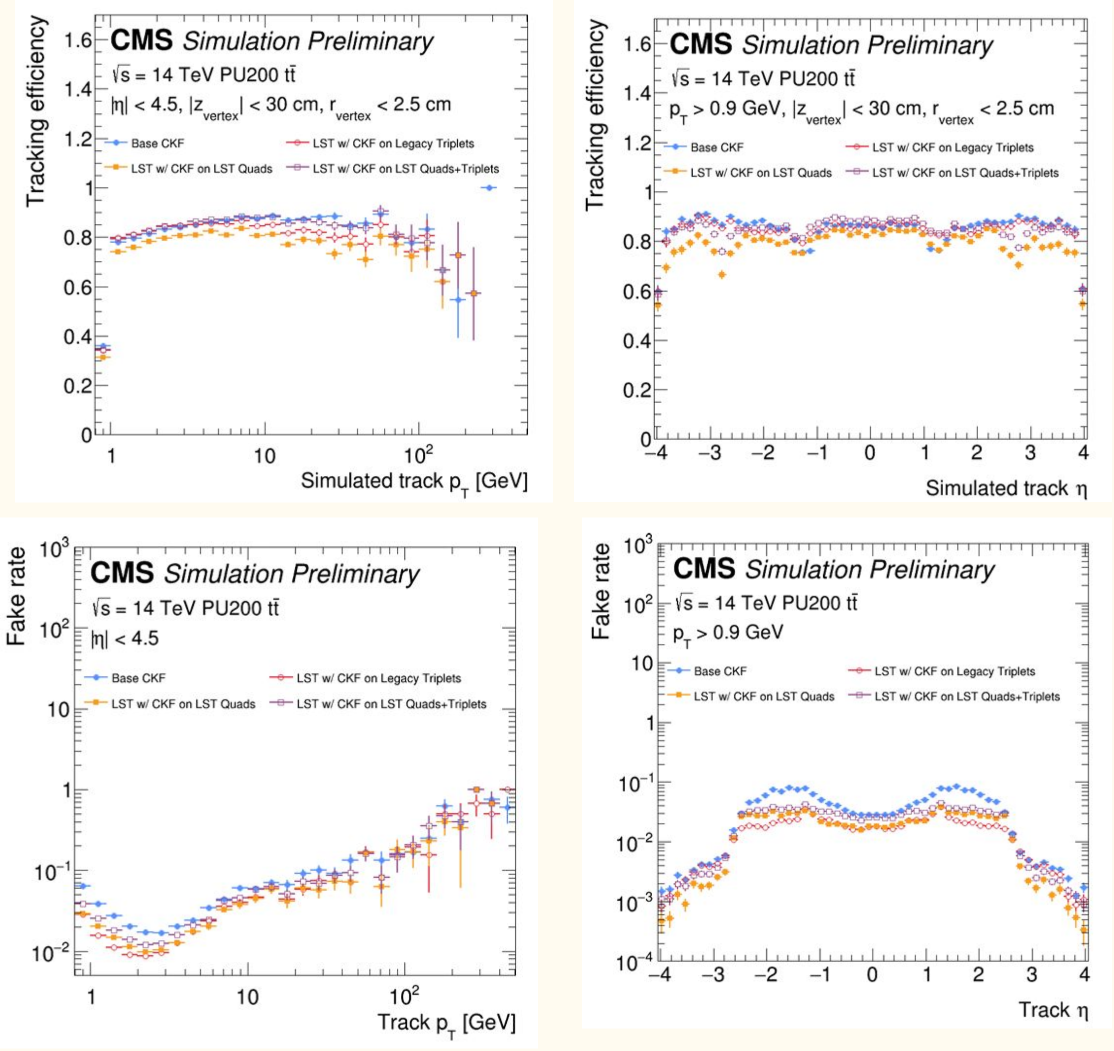


Performance of the Line Segment Tracking Algorithm in the CMS Phase-2 High Level Trigger Tracking

CMS-DP-2024-014

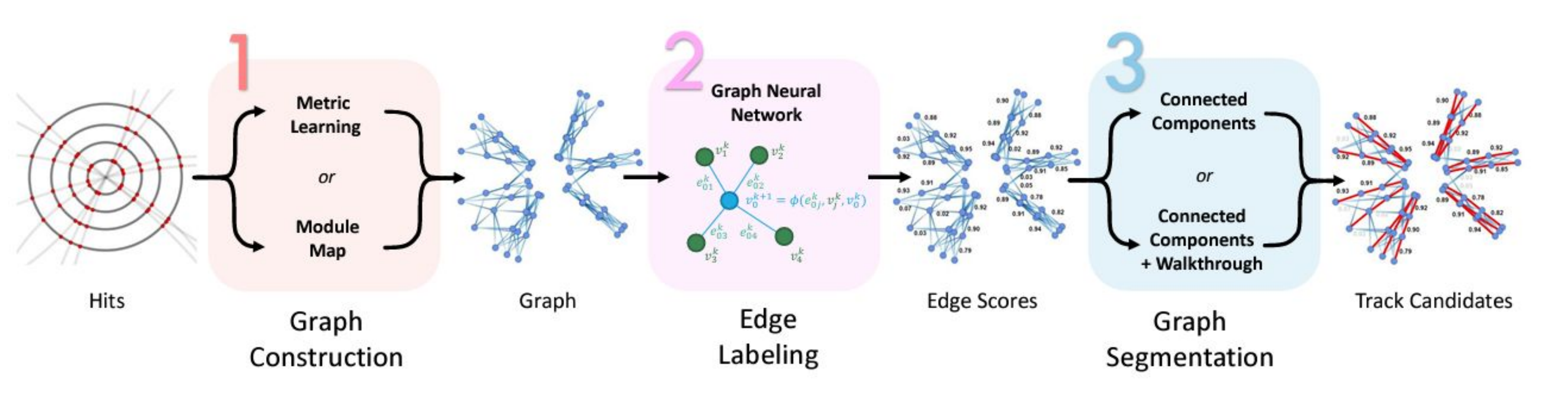
Detector modules in OT consist of two closely spaced silicon sensors per layer. This configuration provides a handle for hits in adjacent sensors to be correlated and allows for an estimation of the local transverse momentum (p_T) of the track. The resulting local hit pairs, called MiniDoublets (MDs), 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:

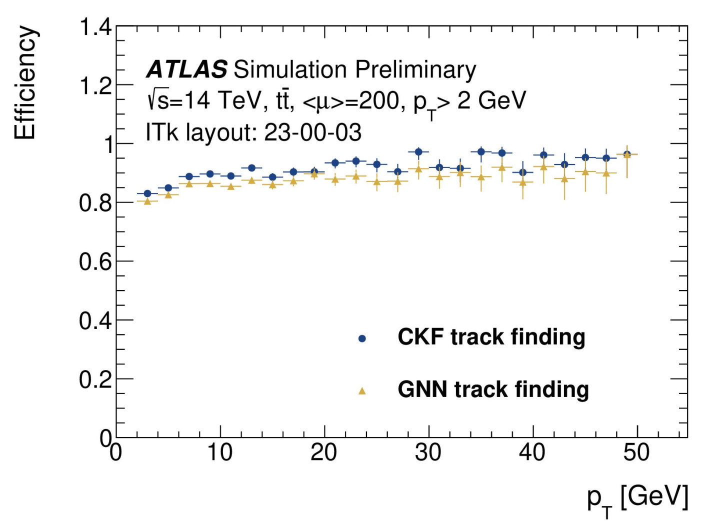


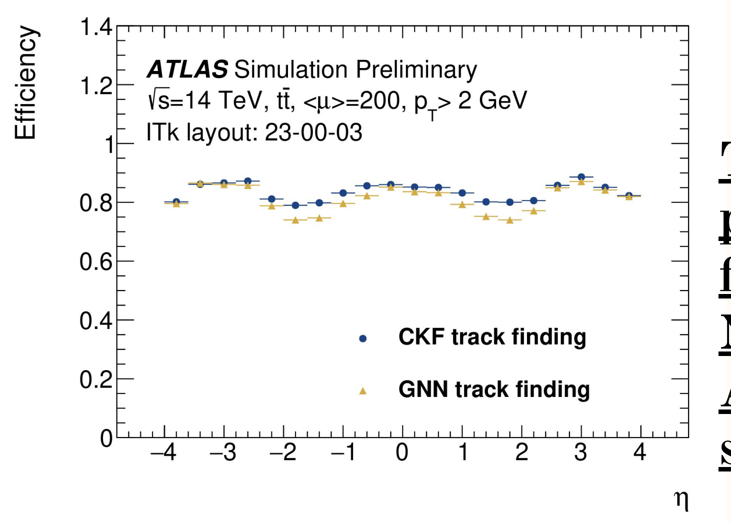


[CMS-DP-2024-014](CMS-DP-2024-014)

Performance of the Line Segment Tracking Algorithm in the CMS Phase-2 High Level Trigger Tracking







IDTR-2023-06

Track finding performance plots for a Graph Neural Network pipeline on ATLAS ITk simulated data

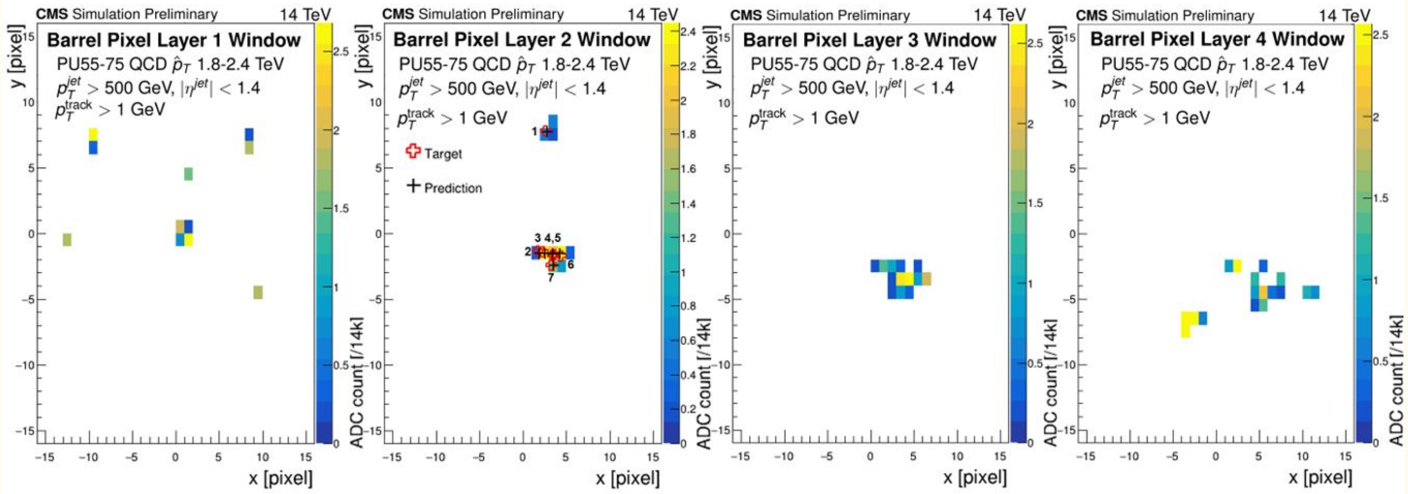
[CMS-DP-2024-003]

DeepCore 2.0: Convolutional Neural Network for Tracking in Jets with High Transverse Momentum

DeepCore2.0: Target and Prediction

- Target and prediction format: three 30 × 30 Track Crossing Point (TCP) maps and three 30 × 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 Δx and Δy 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.

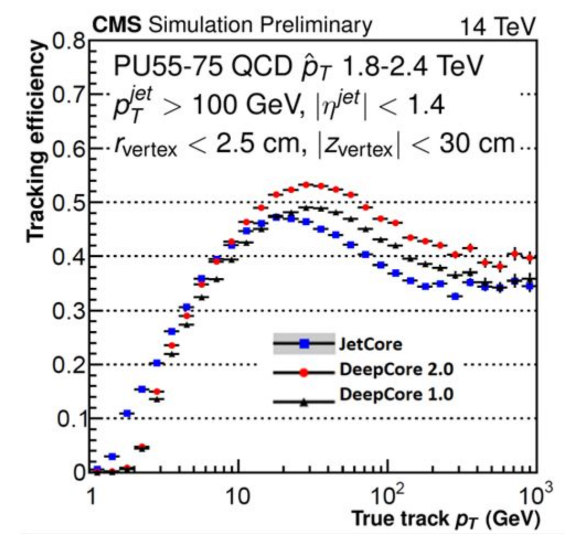
DeepCore 2.0: Convolutional Neural Network for Tracking in Jets with High Transverse Momentum

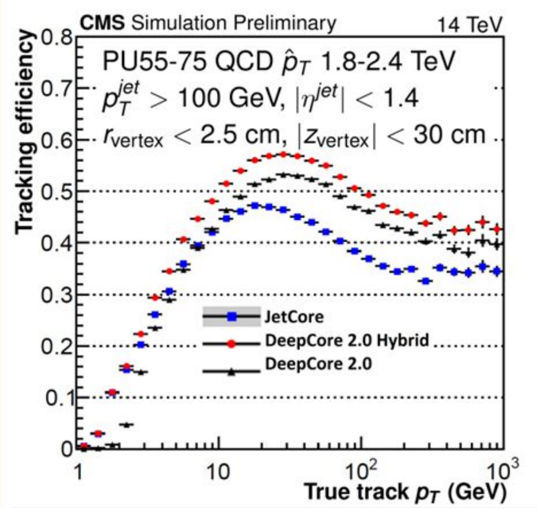


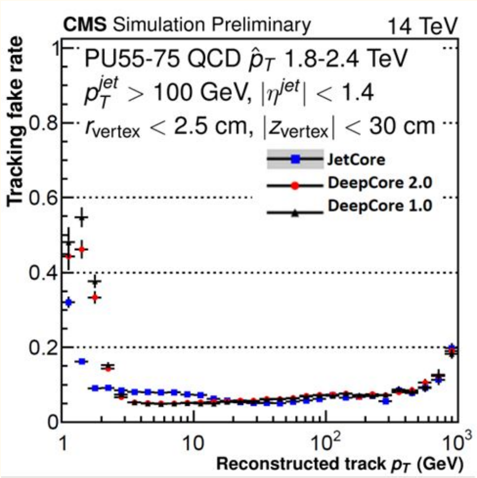
An example of the pixel maps used as input for DeepCore2.0 is shown above. For each BPIX layer, the normalized ADC count per pixel is shown as a function of the pixel position within the 30×30 window. The BPIX2 pixel map also shows multiple target TCPs (red) and the TCPs predicted by DeepCore (black) for a calo-jet with $p_T^{jet} = 1786$ GeV and $\eta^{jet} = -0.08$. 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. 10

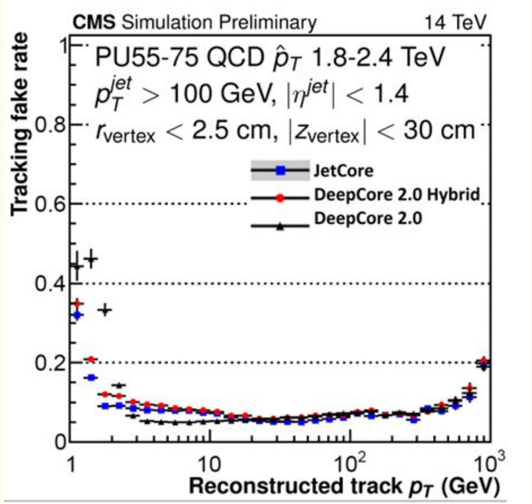
CMS-DP-2024-003

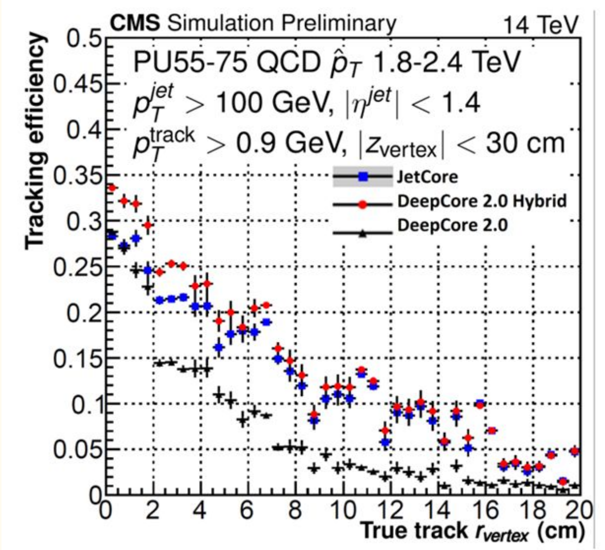
DeepCore 2.0: Convolutional Neural Network for Tracking in Jets with High Transverse Momentum





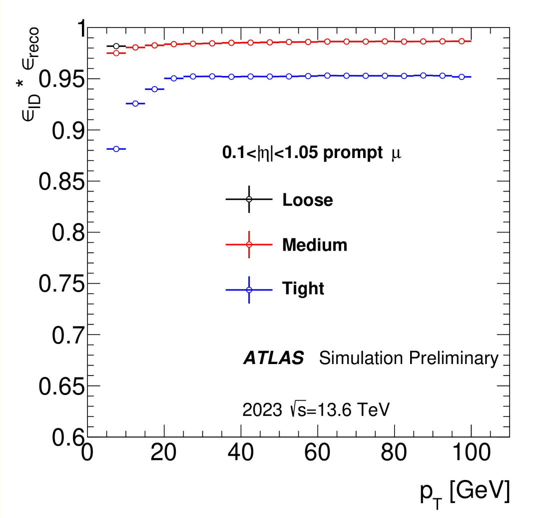


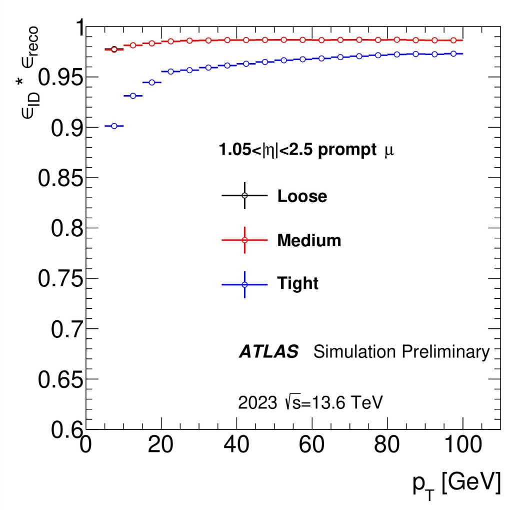


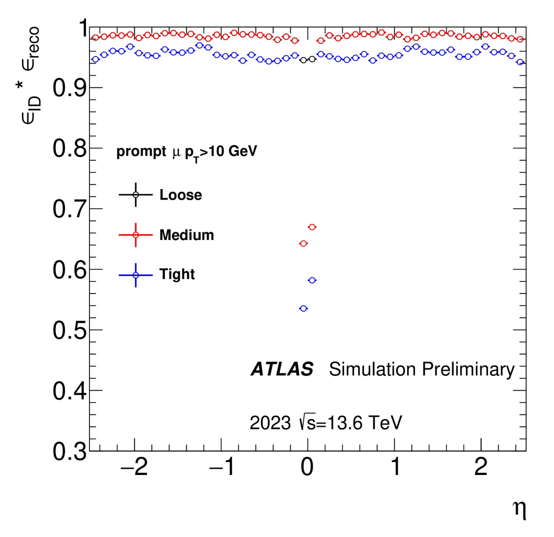


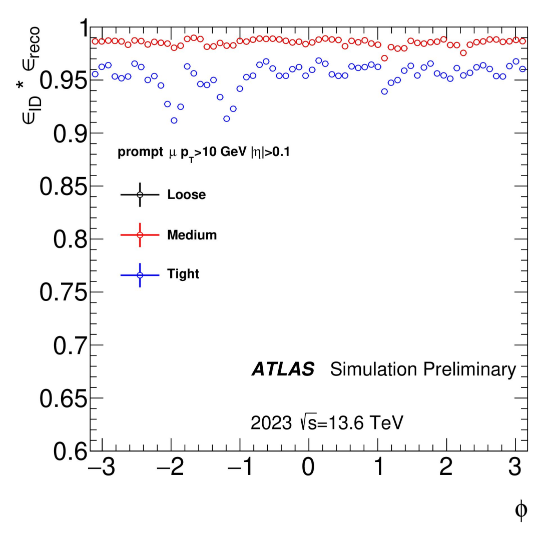
ATLAS Muon Performance 2023

MUON-2023-02









ATLAS Muon Performance 2023

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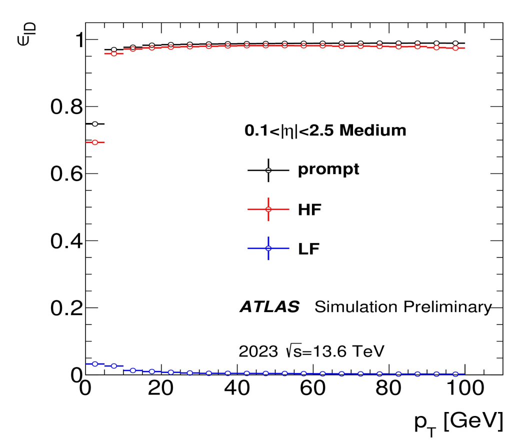

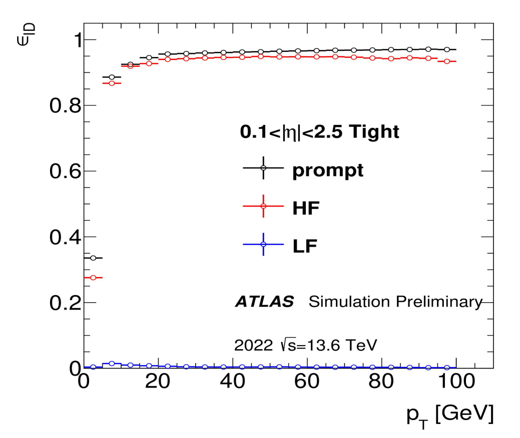

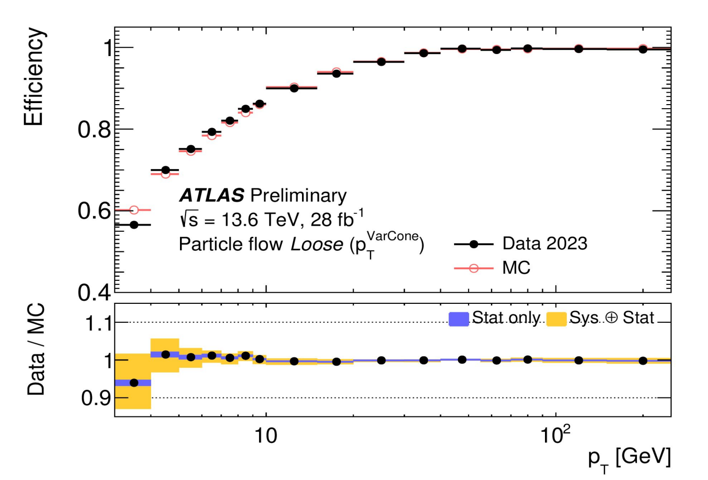

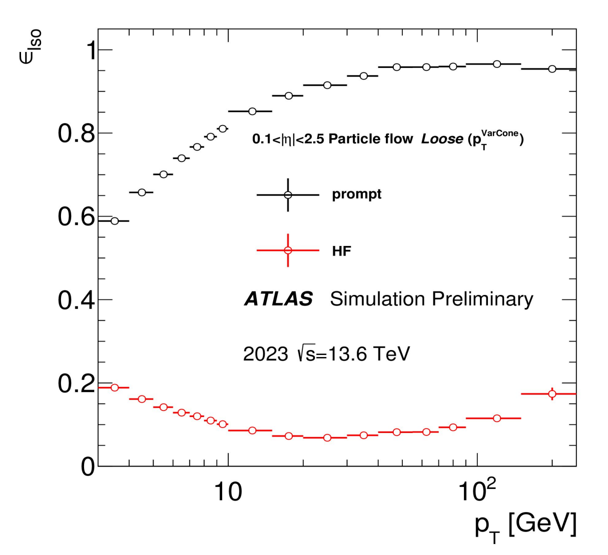

ATLAS Muon Performance 2023

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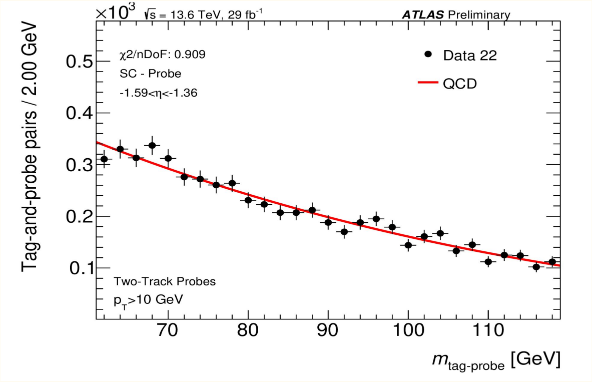
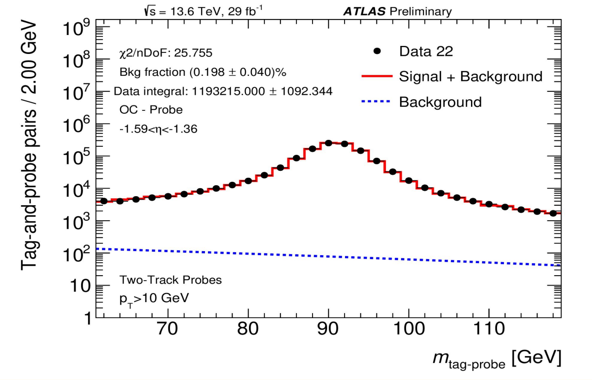
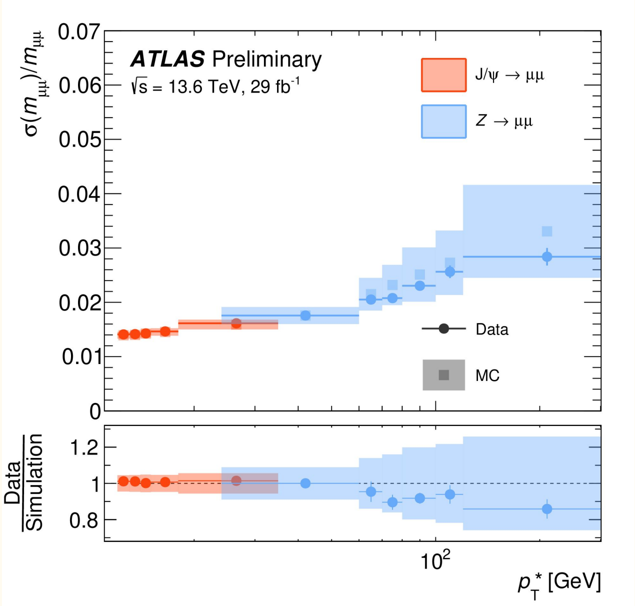
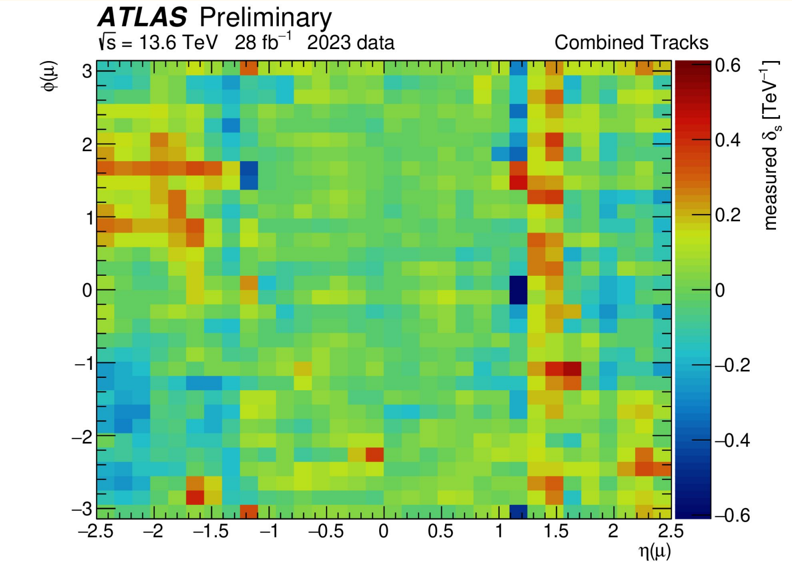


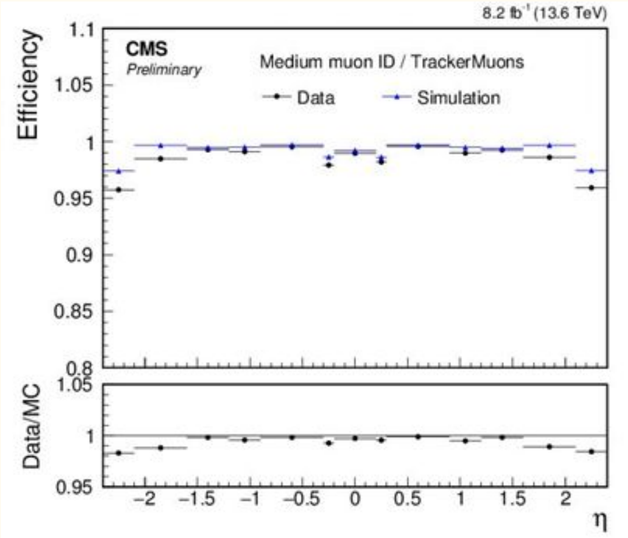


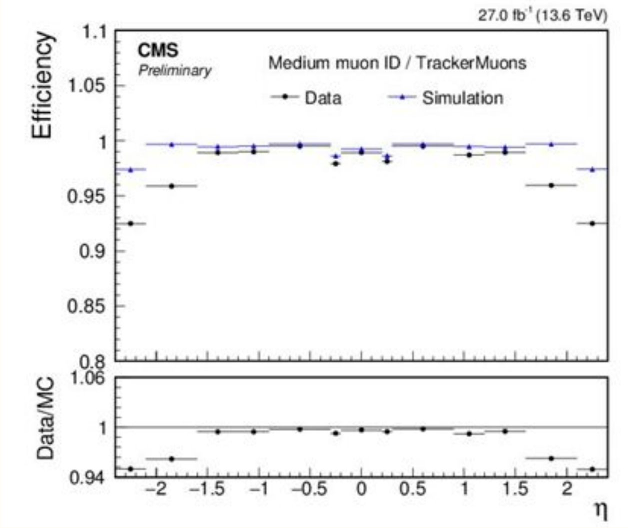


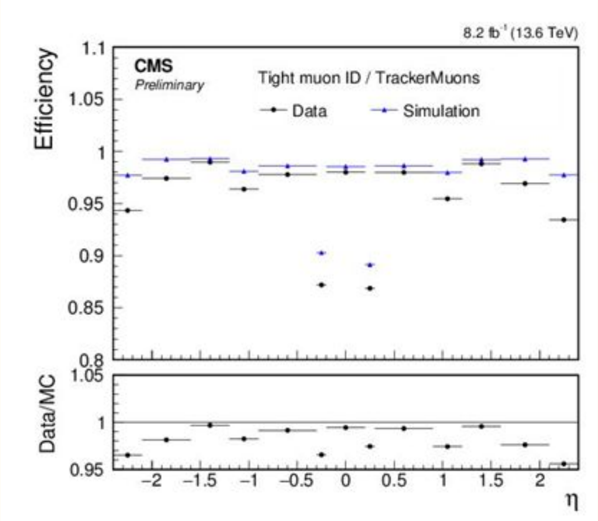


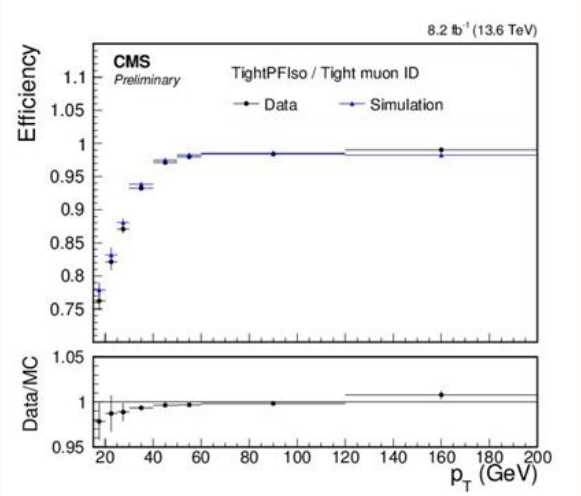
CMS Muon Performance 2022

CMS-DP-2024-019



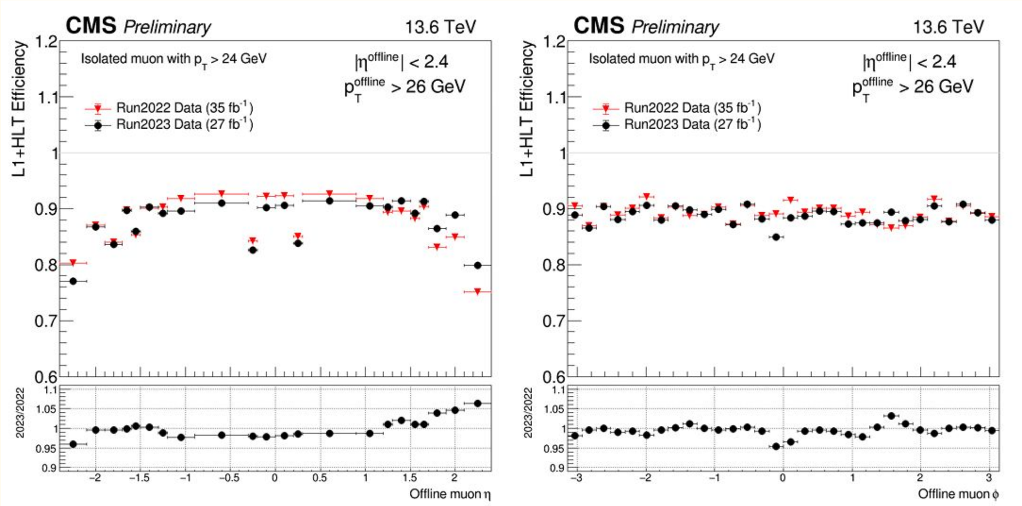


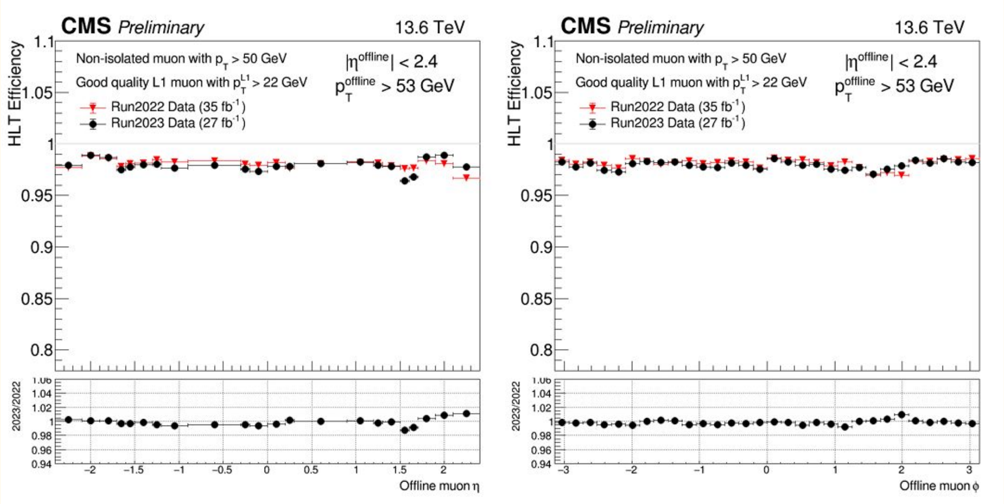


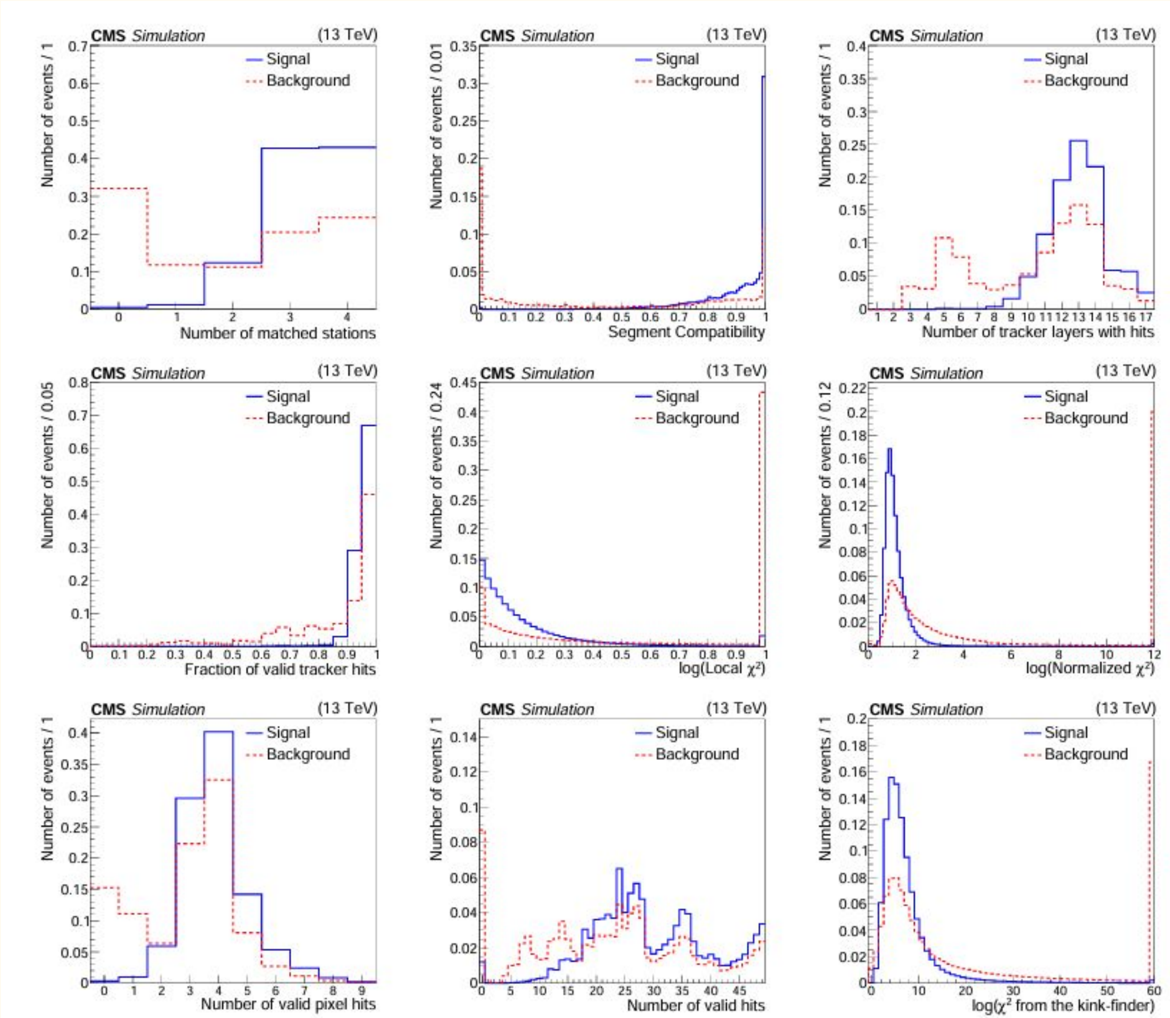


CMS Muon Online Performance 2022

CMS-DP-2024-005





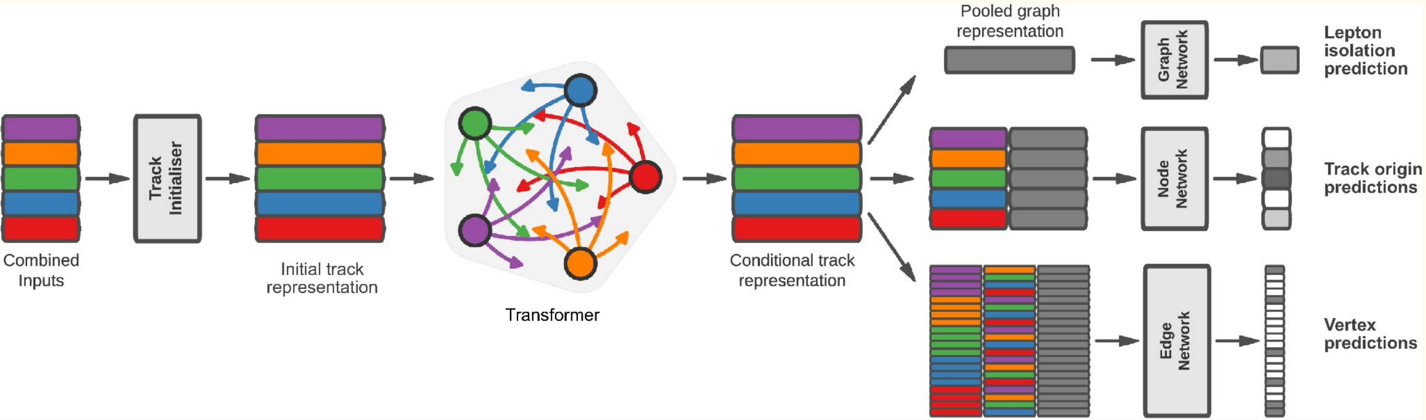


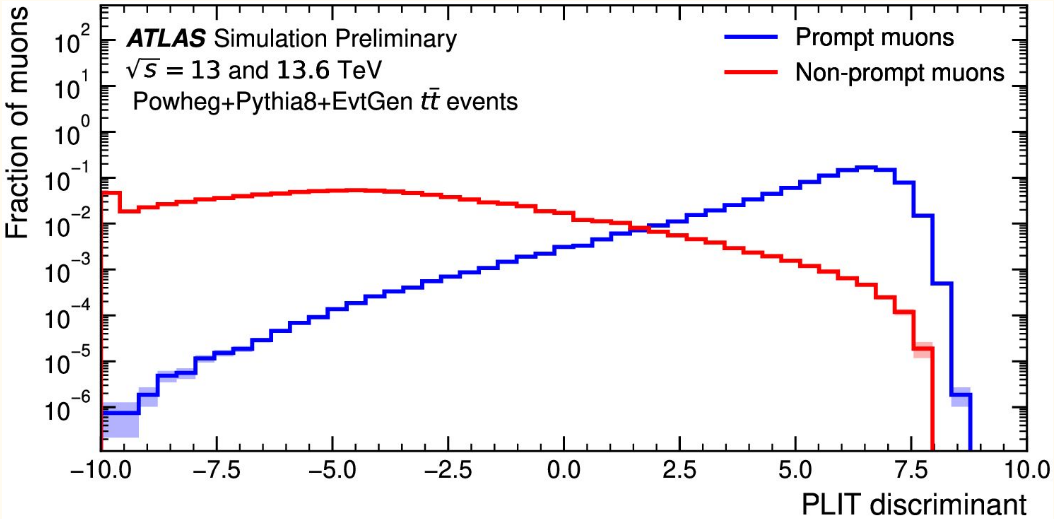
CMS MVA muon identification

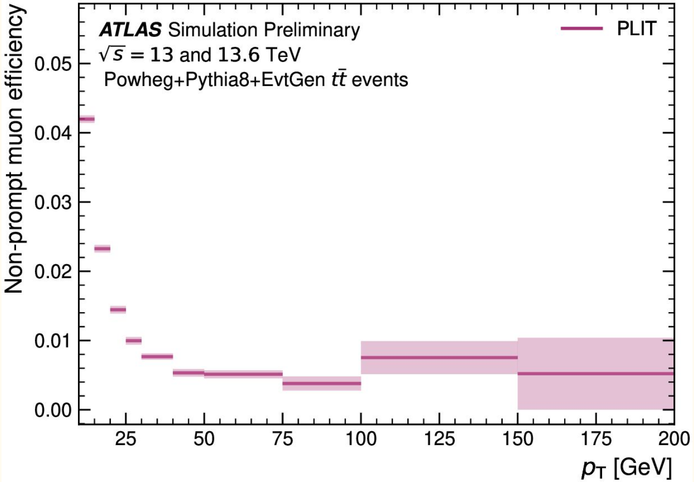
JINST 19 P02031 (2024)

ATLAS PLIT

MUON-2024-01





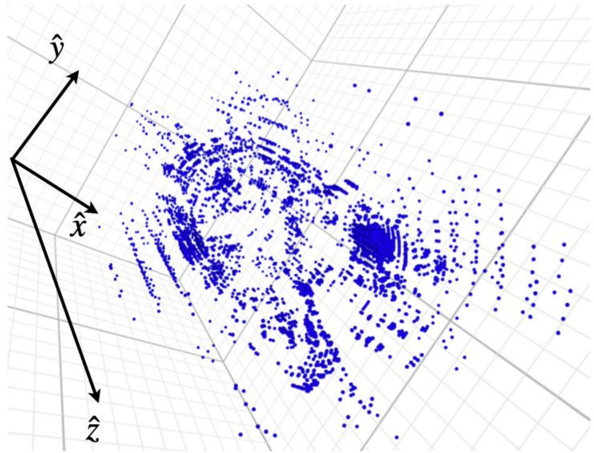


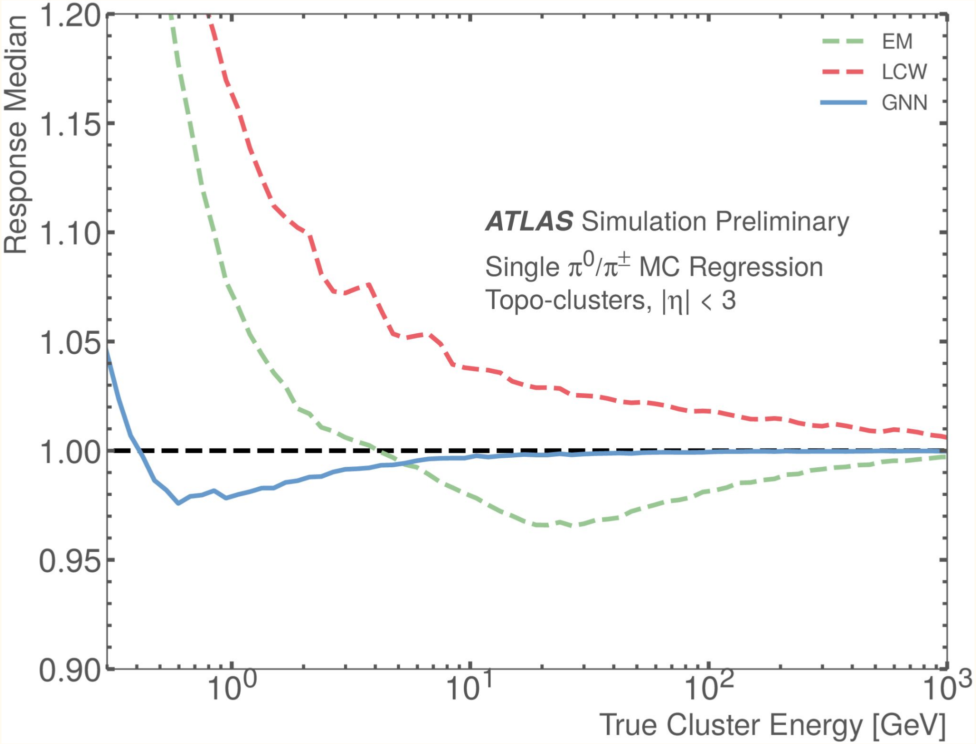
Point Cloud Deep Learning Methods for Pion Reconstruction in the ATLAS Experiment

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.

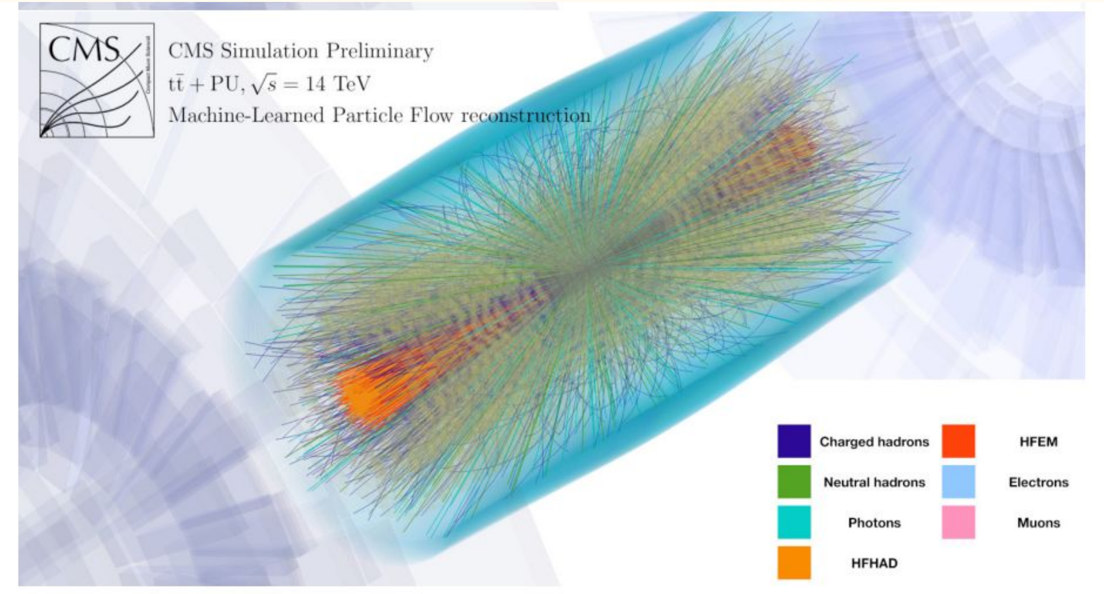


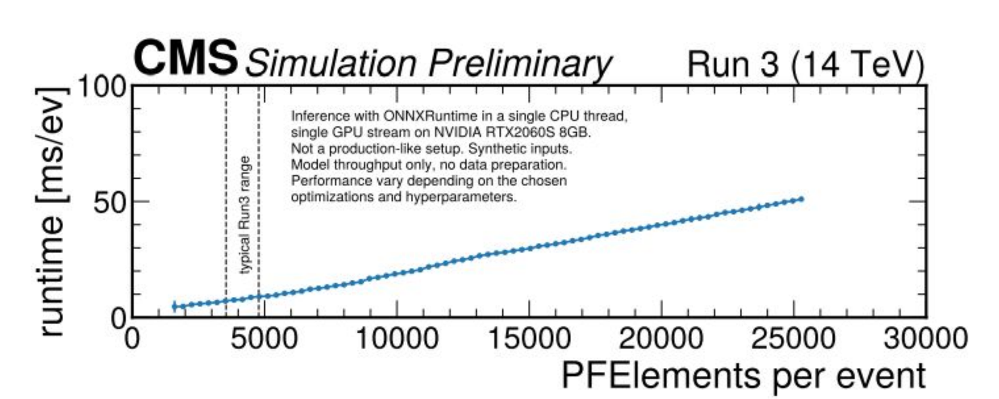


ATL-PHYS-PUB-2022-040

Machine Learning for Particle Flow Reconstruction at CMS

J. Phys.: Conf. Ser. 2438 012100



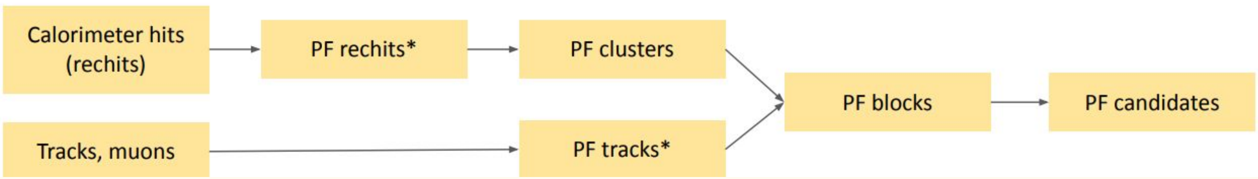


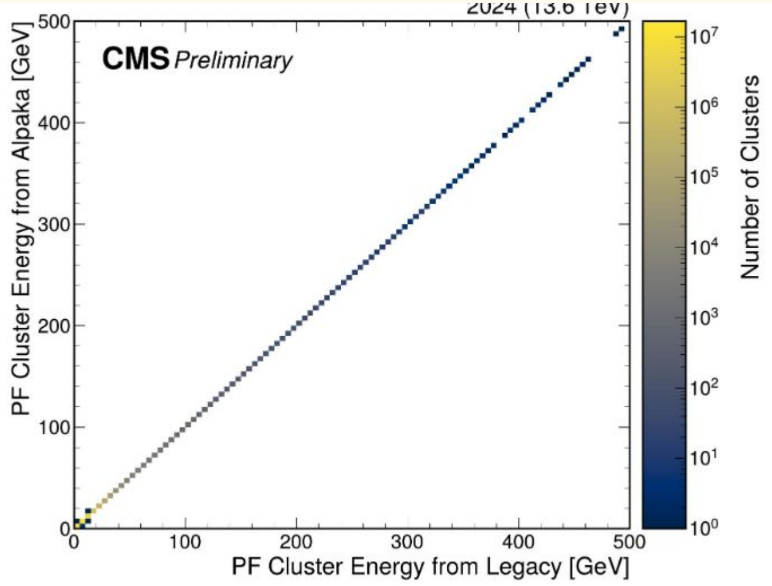
- heterogeneous architectures based on a scalable GNN model
- Task is to identify y_k particles, described as (ID,p_T,η,ϕ,E,q), from x_i detector signals
- Performance mostly in line with standard PF
- Computing scales linearly vs multiplicity, comparison with standard PF not trivial

Heterogeneous Reconstruction of Hadronic Particle Flow Clusters with Alpaka Portability Library

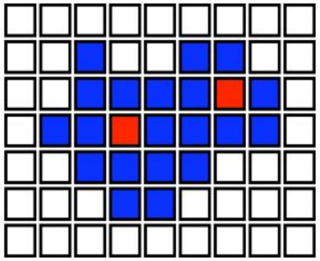
CMS-DP-2024-026

- 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).





PF cluster energy validation



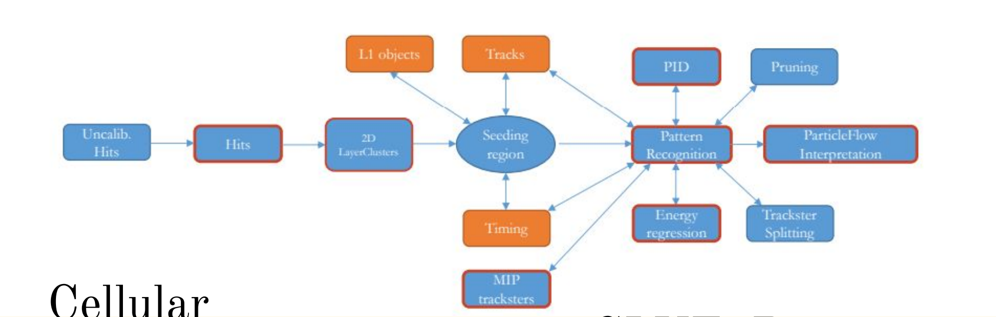
Topologically-connected calorimeter hits are associated into a single topological cluster. Seeds for PF clusters are shown in **red** and associated rechits in **blue**. Seeds are defined based on the local energy maxima of neighboring calorimeter hits. Each seed will become a PF cluster [1].

Data converted to format optimized for GPUs

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

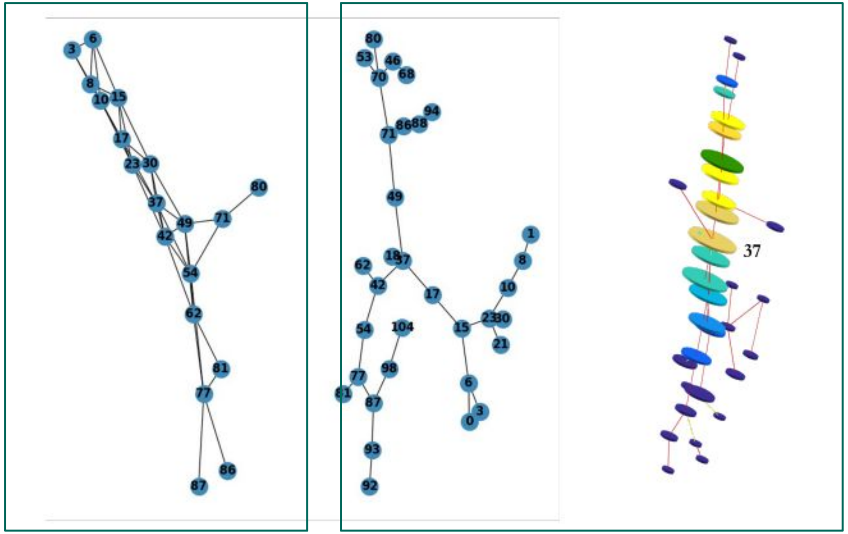
The Iterative Clustering framework for the CMS HGCAL Reconstruction

J. Phys.: Conf. Ser. 2438 012096



Cellular Automaton

CLUE3D



Comparison of Trcksters produced during pattern recognition with different algorithms

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