Tracking in Dense Environments

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On Behalf of the Tracking POG

CMS Week Plenary
February 7, 2024

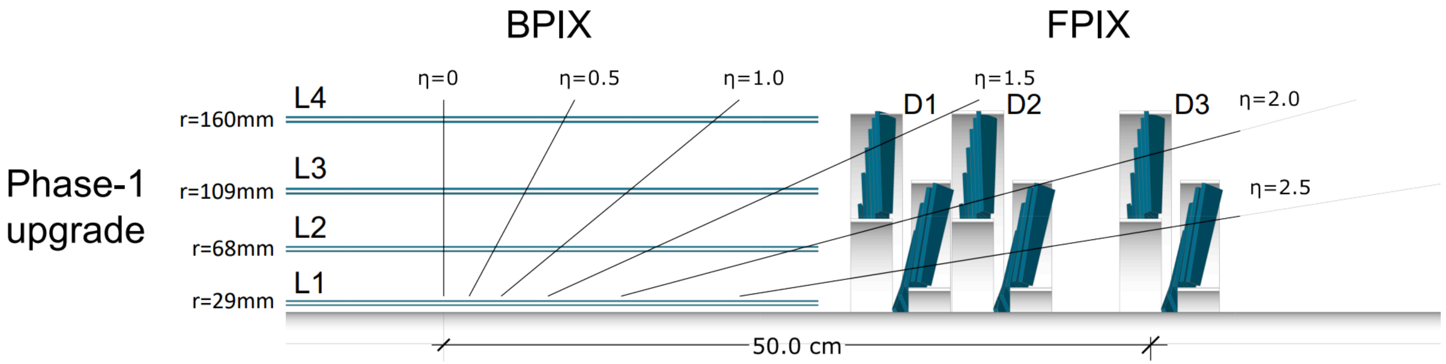
The CMS Tracker and Tracking Algorithm

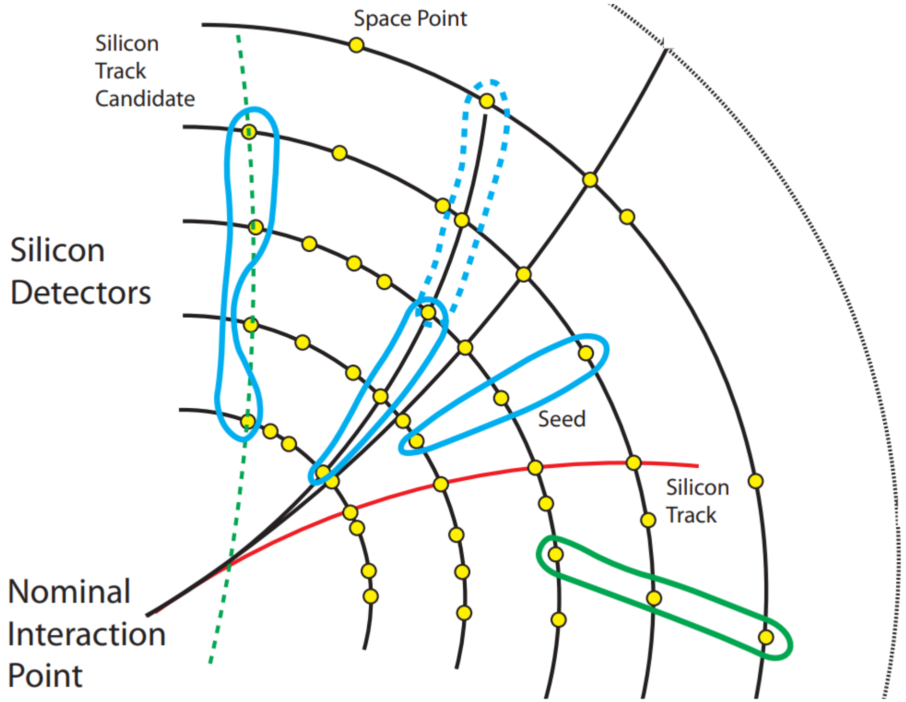
M. Musich, S. Krutelyov's talk at Tracking Days

- The CMS Tracker has coverage up to $|\eta|$ = 3 and 4 layers in the barrel of the pixel detector after the Phase-1 upgrade [*JINST* 16 (2021) P02027].
- CMS Tracking algo: Combinatorial Track Finder (CTF) → **Iterative.**

Four steps in each iteration:

1. **Seed generations**: initial track candidate using up to 4 hits.
2. **Track finding** based on Kalman filter (pattern recognition), sped up in Run3 with mkFit [CMS-DP-2022-018].
3. **Track fitting**: best estimate of track parameters.
4. **Track selection**: track quality requirements (χ^2 and missing hits).



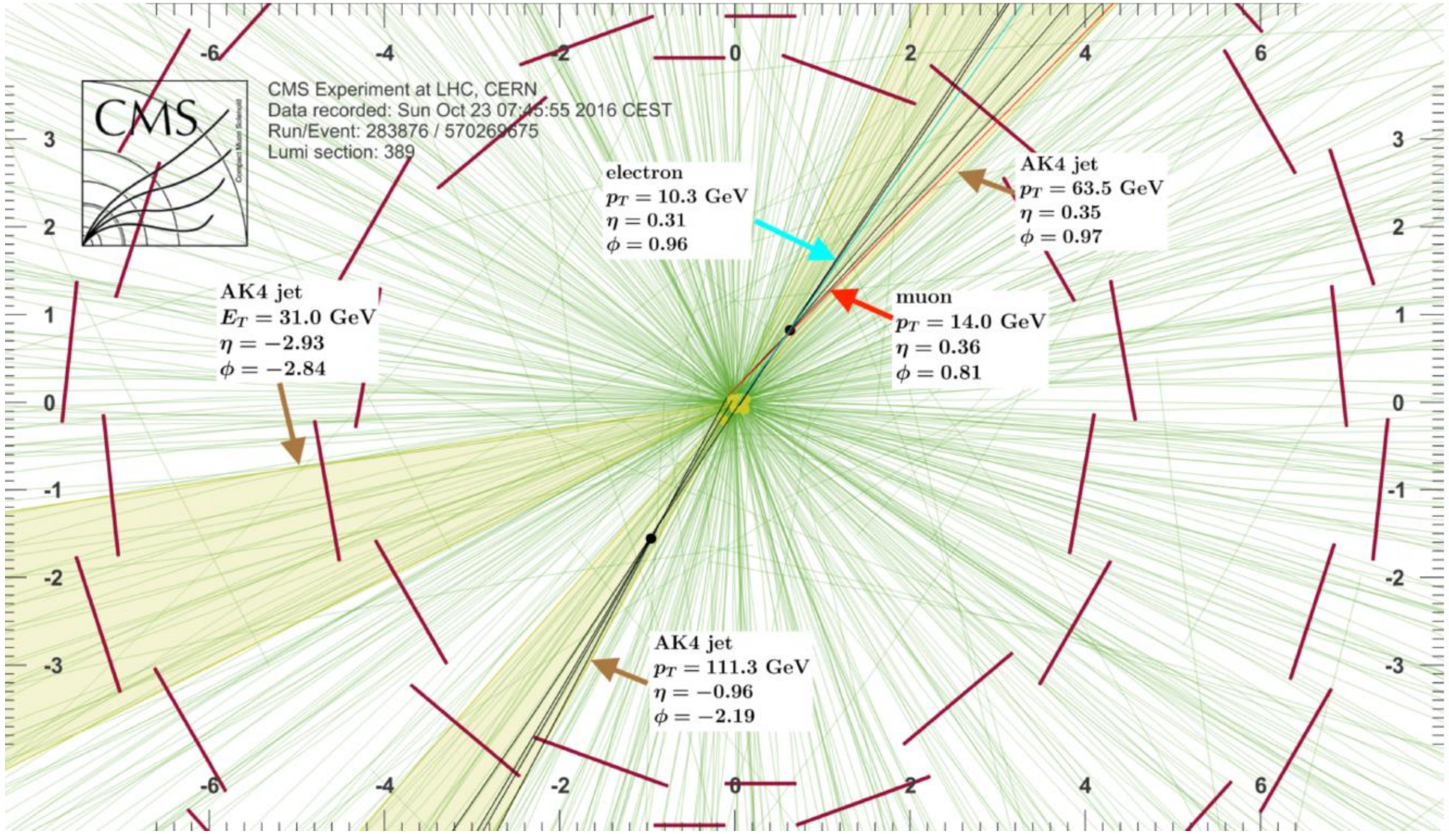


Pierfrancesco Butti's talk at LHCP

Challenges of Tracking in High p_T Jets

Isolated high momentum primary tracks are easy to reconstruct and CPU efficient (PV constraint, small search window..), however **as p_T^{jet} increases**:

- Increasing **density of hits and occupancy** of merged clusters → increased **combinatorics**.
- More **candidate tracks** → increased **CPU time**.



Dedicated tracking iteration in core of high p_T jets: **JetCore**.

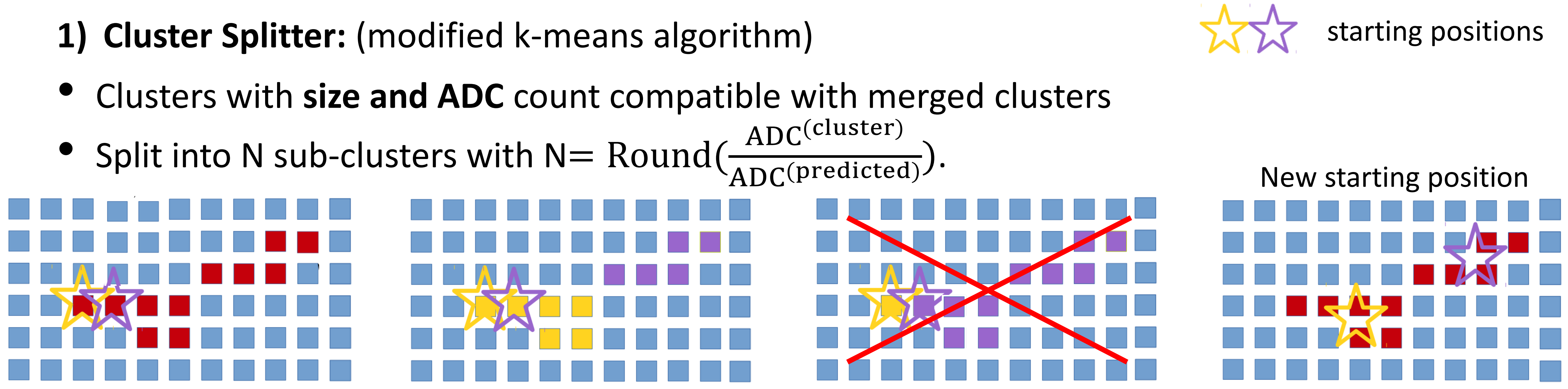
JetCore Algorithm

Andrea Rizzi, Silvio Donato

Cluster splitting and track iteration in the core of high p_T jets:

1) Cluster Splitter: (modified k-means algorithm)

- Clusters with **size and ADC** count compatible with merged clusters
- Split into N sub-clusters with N= $\mathrm{Round}(\frac{\mathrm{ADC}^{(\mathrm{cluster})}}{\mathrm{ADC}^{(\mathrm{predicted})}})$.



1. Initial random position
2. Sub-cluster assignment
3. Low probability pair
4. Repeat until convergence

2) Tracking iteration (one of the last):

- Execute on clusters within $d\phi, d\eta < 0.2$ of calo-jet axis for jets with $p_\mathrm{T}^{\mathrm{jet}} > 100$ GeV
- Use CKF Trajectory Builder testing a max of **50 track candidates**
  - **CPU intensive** relative to standard tracking (5 candidates).

CMS DP-2014/032

JetCore Performance

Andrea Rizzi, Silvio Donato

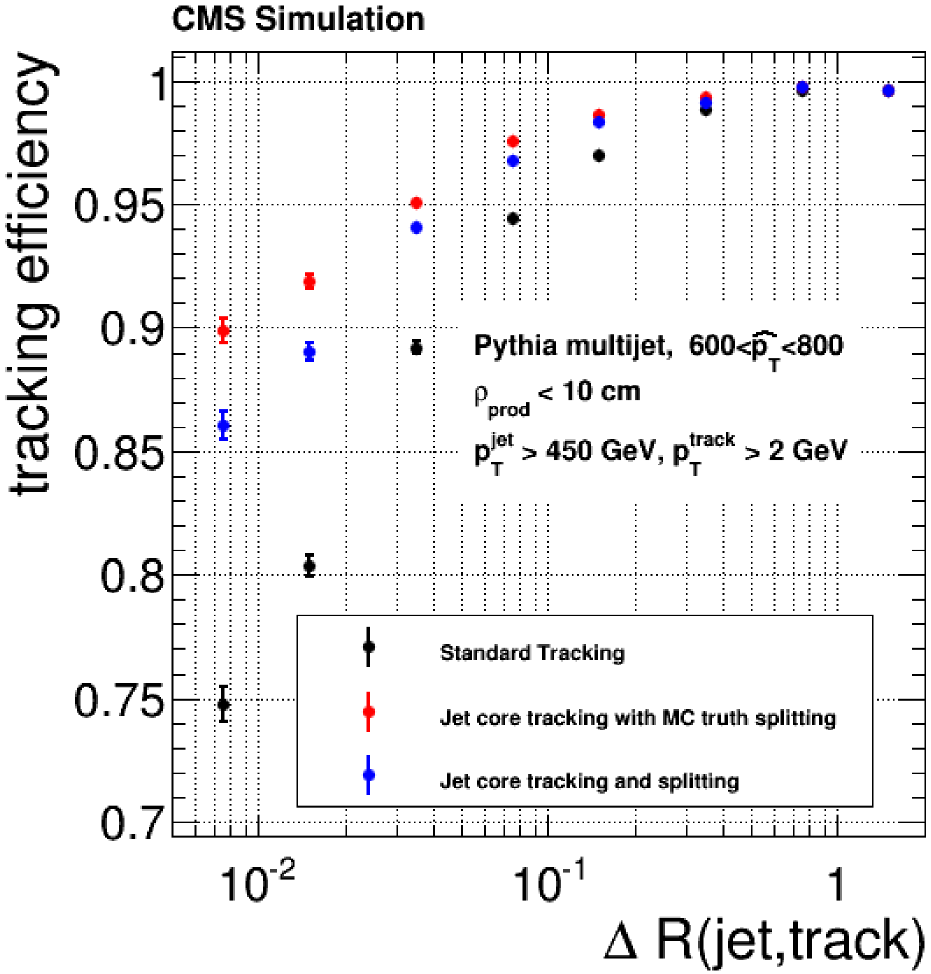
Significant improvement in tracking efficiency, especially for ΔR(jet, track) < 0.1.

CMS DP-2014/032

Challenges:

- Near the **limit** set by MC truth cluster splitting.
- Uses **loose (50%) hit matching**, using standard tighter (75%) matching leads to significant decrease in efficiency.
- Increased max candidate limit requires **increased CPU time** relative to standard tracking.

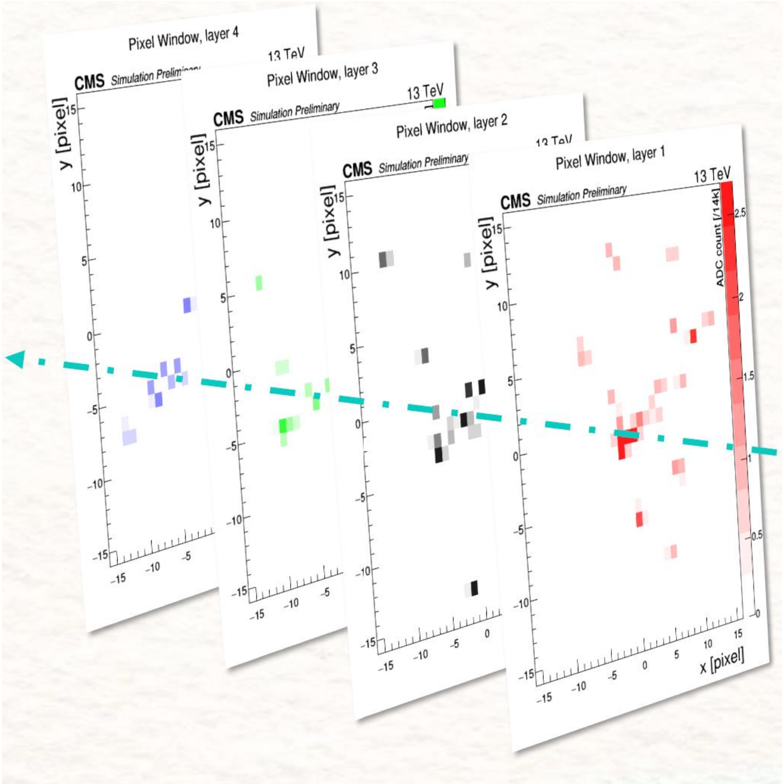
→ **Solution:** **direct seed creation** using a Convolutional Neural Network (CNN).

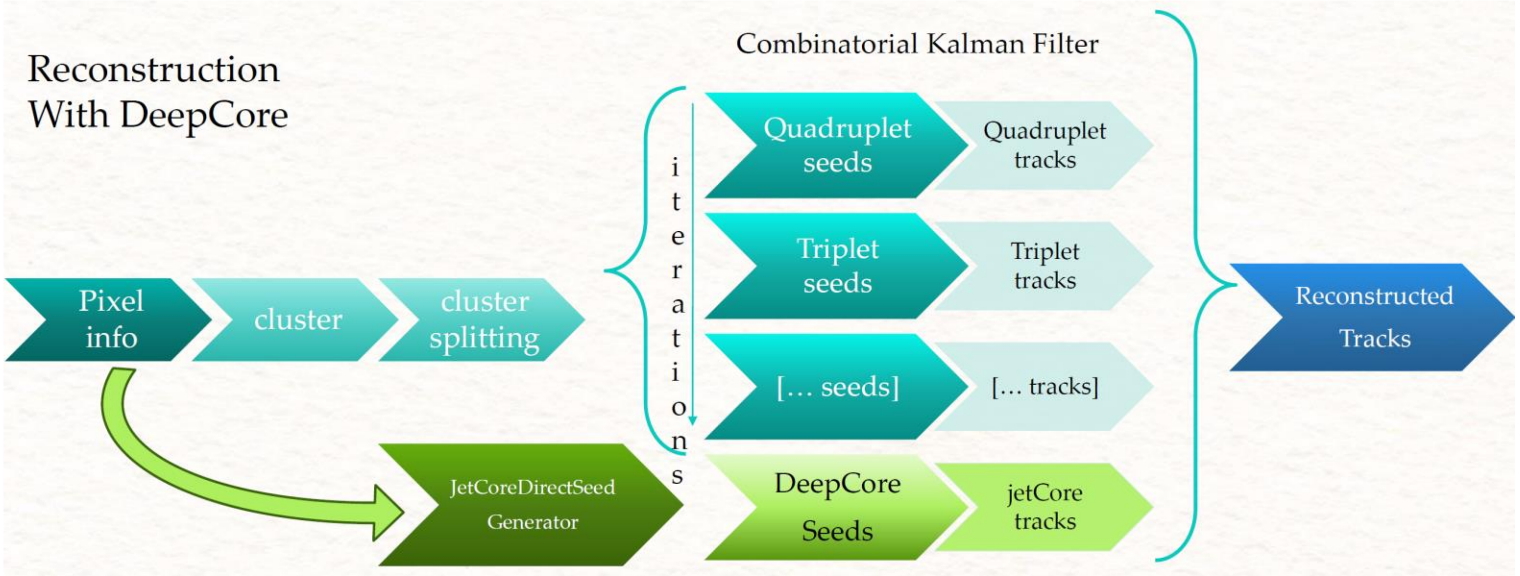


DeepCore: CNN for Tracking in the Core of High p_T Jets

Valerio Bertacchi, Mia Tosi

- CNN recognizes **charge deposition patterns** in BPIX for single vs. multiple particles.
- DeepCore **predicts BPIX2** Track Crossing Points (TCP) used for seeding.
- Trained with Run2 MC in the **barrel region** ($|\eta^{\text{jet}}| < 1.4$).



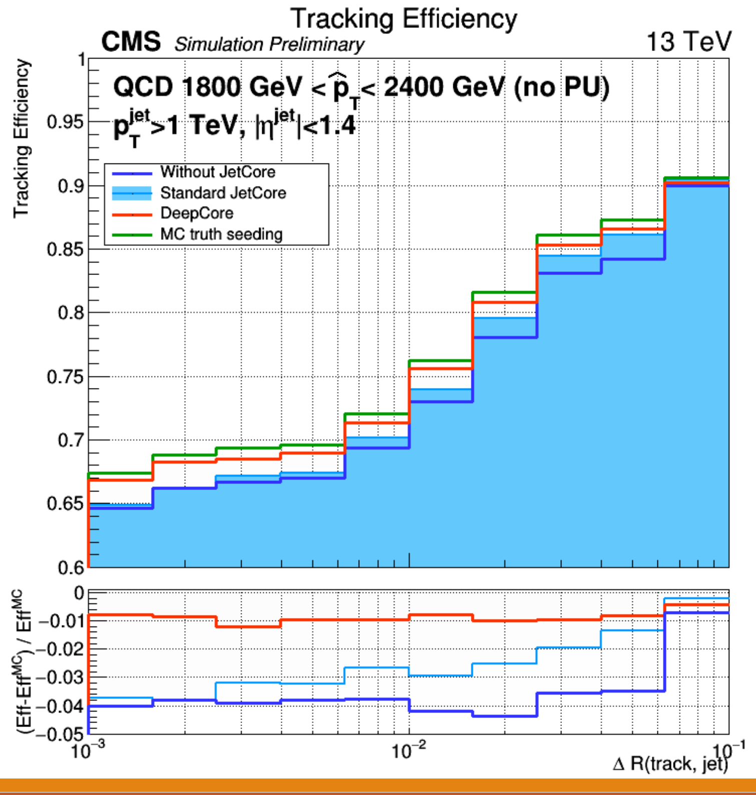


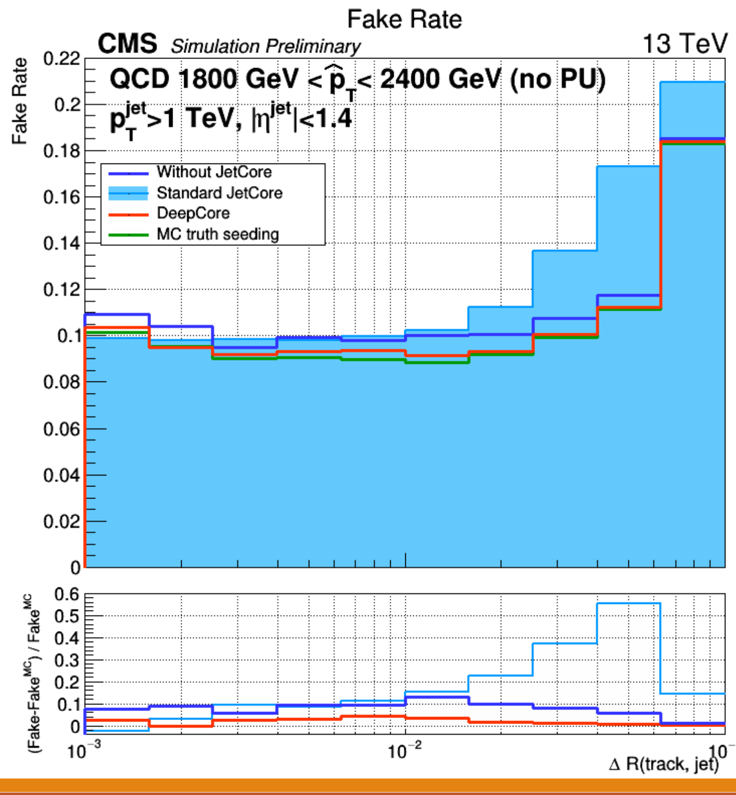
CMS DP-2019/007

DeepCore Performance

Valerio Bertacchi, Mia Tosi

- Improved **timing** performance, tracking **efficiency and fake rate** in the tracking iteration in the core of high p_T jets .
- DeepCore **not deployed in Run3** due to degraded performance for non-prompt tracks.





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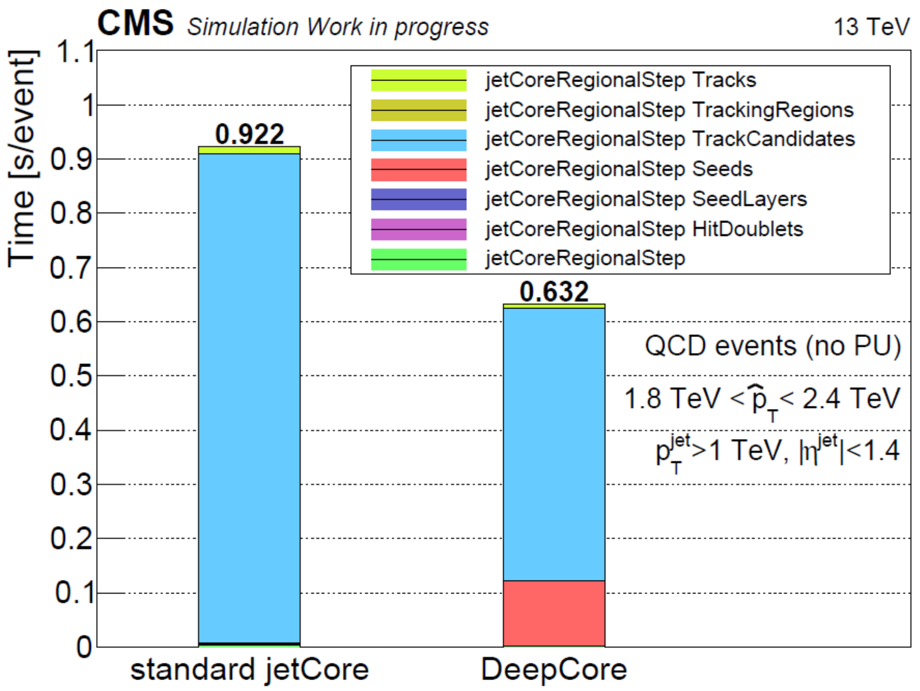
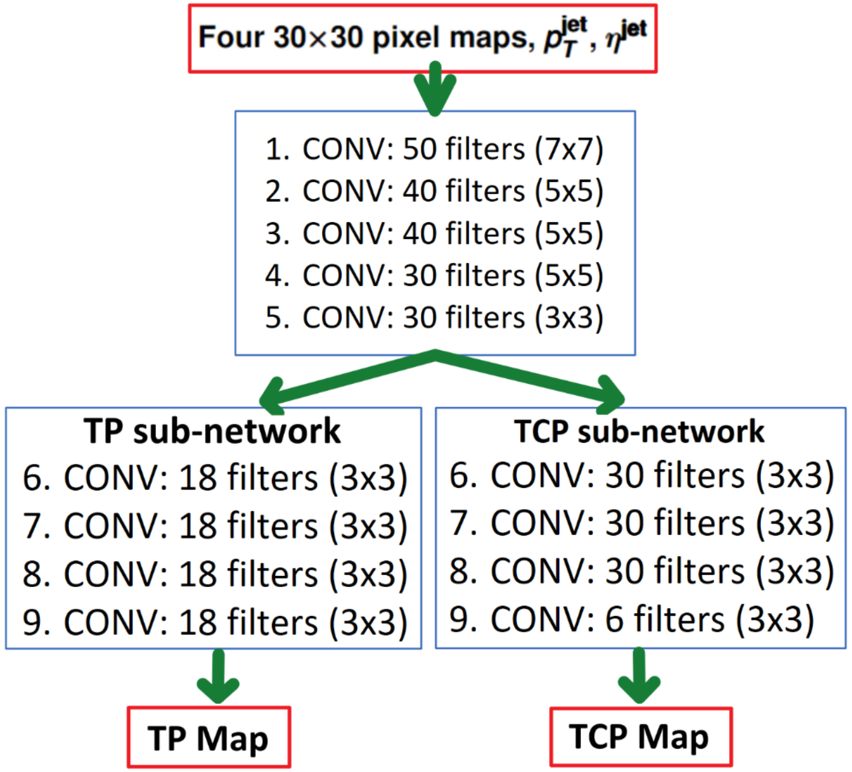


DeepCore 2.0 Overview

Hichem Bouchamaoui, Nick Haubrich, Soohyun Yoon, Jim Olsen

CMS DP-2024/003

- **Updated version of DeepCore** (bug fixes, tuned hyperparameters, Run3 configuration).
- **Cluster selection**: calo-jets with $p_T^{jet} > 100$ GeV and $dR(\text{cluster, jet}) < 0.25$.
- **Cluster inputs**: p_T^{jet} , η^{jet} and 30x30 pixel maps (x, y, normalized ADC) for all 4 BPIX layers.
- **Prediction:** position and p_T of TCPs for BPIX2 pixel (30x30).
  - DeepCore2.0 can predict **up to 3 TCP per pixel**, similar to DeepCore.



Example Output

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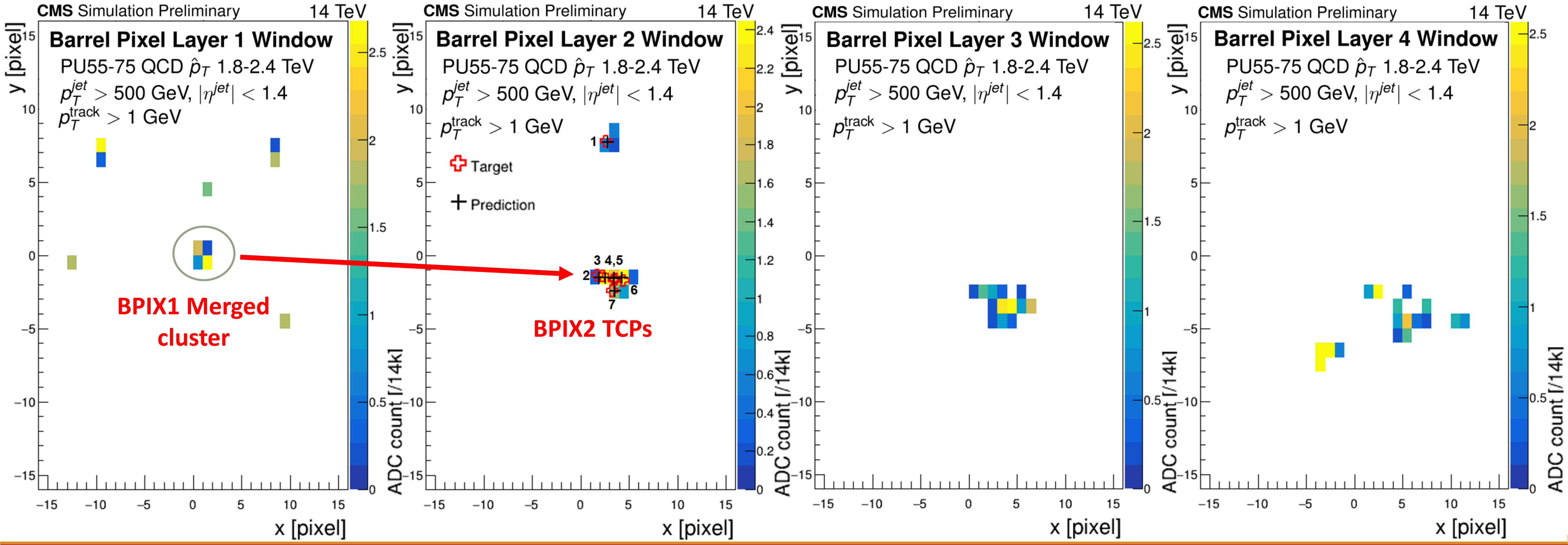
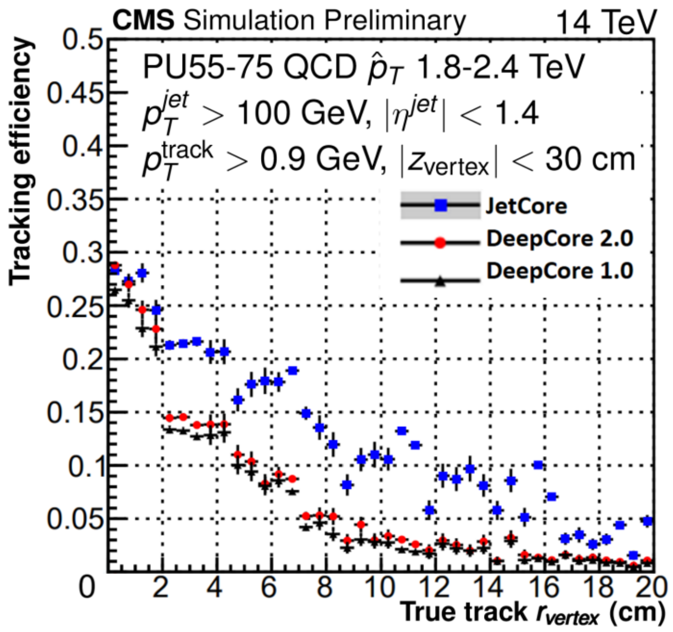
For a calo-jet with $p_{\mathrm{T}}^{\mathrm{jet}}$ = 1786 GeV and η^{jet} = −0.08, DeepCore2.0 predicts:

- The **same number** of TCPs as the number of target TCPs (7).
- TCP **positions relatively close** to target TCPs.



DeepCore 2.0 Performance

[CMS DP-2024/003]



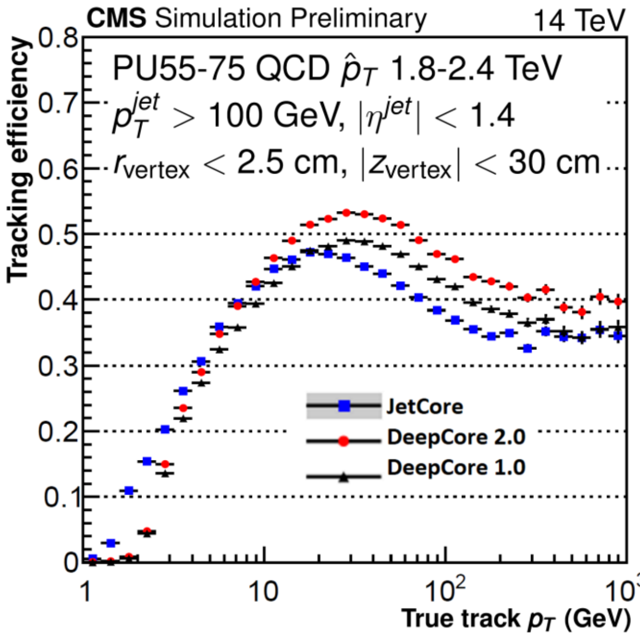
- ➢ DeepCore2.0's CPU time **~35% of JetCore**.

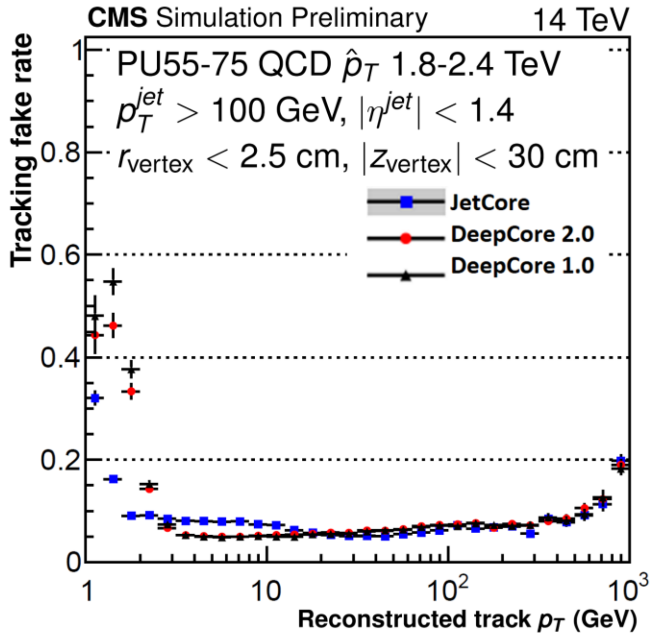
Evaluated on 10k high p_T QCD MC events using Run 3 conditions:

- **10-15% higher** efficiency relative to DeepCore.
- **20% higher** efficiency relative to JetCore for tracks with $p_T^{\text{track}} > 100$ GeV.
  - No increase in fake rate.

Challenge: significantly lower efficiency for displaced tracks (similar to DeepCore).

→ **Solution:** Run a hybrid combination of DeepCore2.0 and JetCore.





Tracking efficiency and fake rate for tracking iteration replacing JetCore

Hybrid Tracking: JetCore + DeepCore2.0

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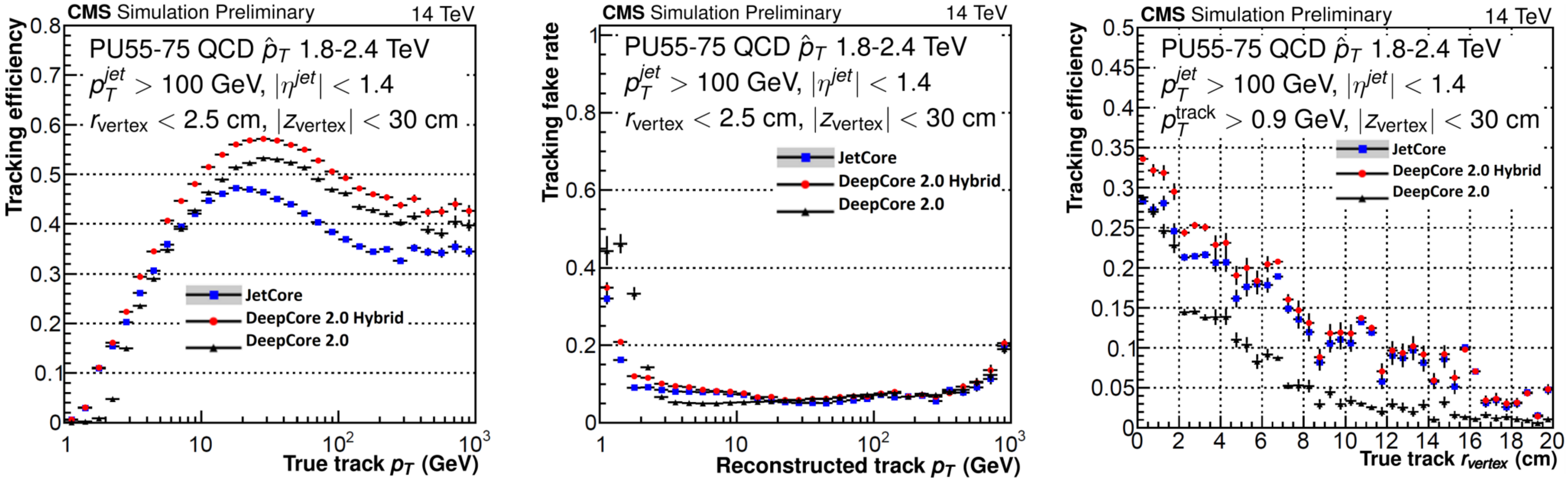
Run both algorithms together using 30 max candidates (instead of 50):

- Overall track reconstruction **CPU time reduced by 1%.**
- Higher efficiency than either algorithm separately (**up to 35% improvement**).
  - No significant increase in fake rate.
- **Improved efficiency for displaced tracks**.



Tracking efficiency and fake rate for tracking iteration replacing JetCore

Effect on Total Tracking Efficiency

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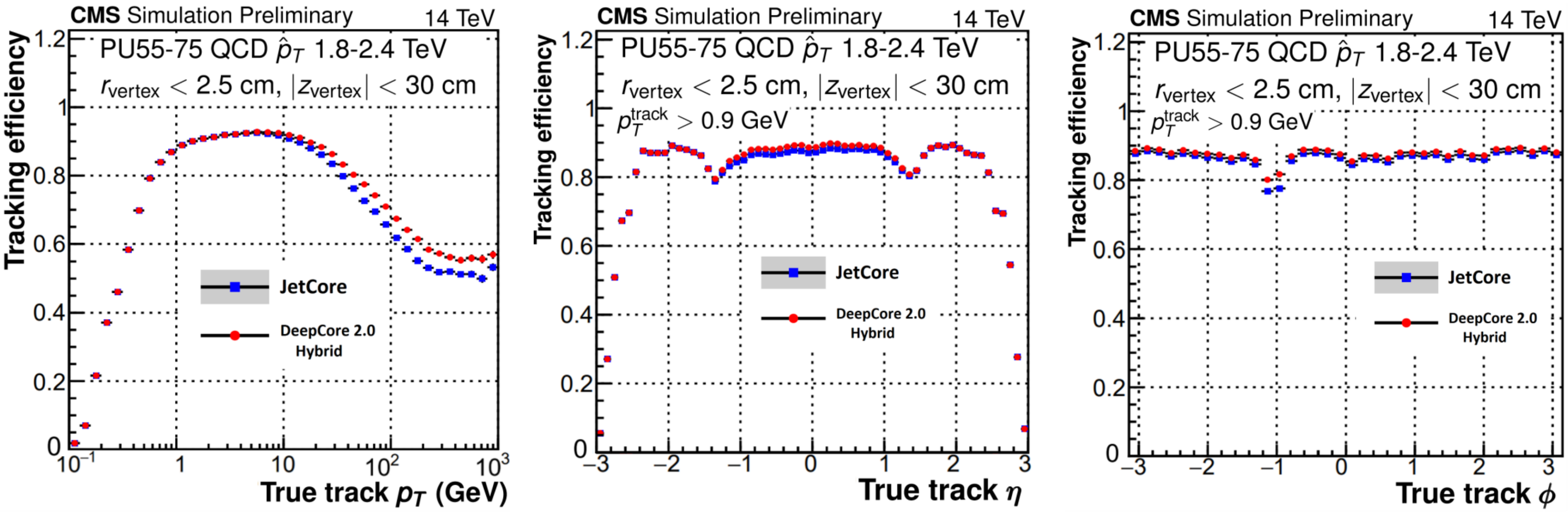
- Overall tracking efficiency increases by **10% relative to JetCore** for $p_\mathrm{T}^\mathrm{track} > 100$ GeV.
- Slight improvement in efficiency vs. η^track and ϕ^track.
  - **5% higher in the BPIX3/4 inefficiency** region [CMS-DP-23/090].
- DeepCore2.0-Hybrid is now enabled since CMSSW_14_0_0_pre2 release for **2024 data taking/MC** and future **(re)processing**, with **validation ongoing.**
- **Further improvements:** timing optimization, 40x40 window size, and BPIX3 predictions.



Tracking efficiency and fake rate for **all tracking iterations**

Merged Clusters in Dense Jet Cores in the Phase-2 Inner Tracker

Phase-2 upgrade [CMS-CR-2022-162]: the upgraded pixel modules will improve the pixel detector granularity

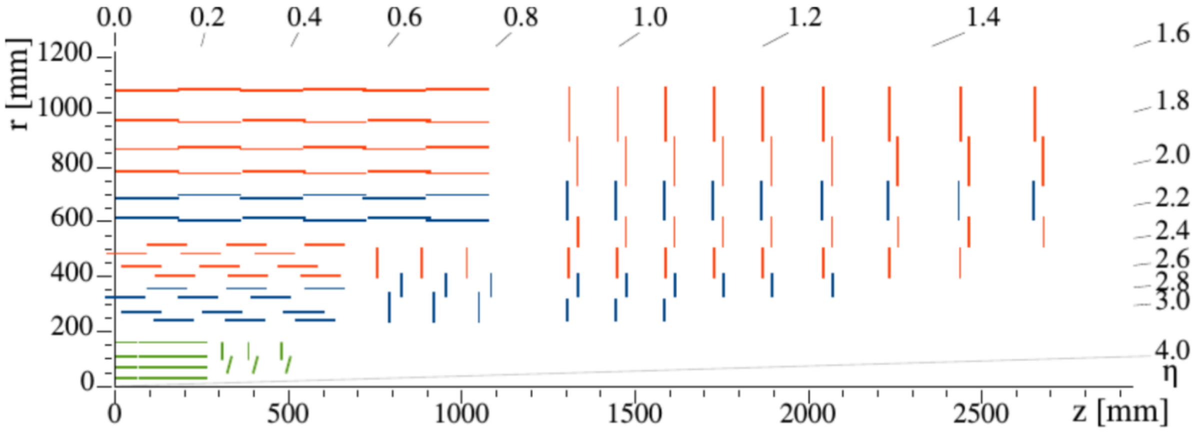
Phase-1 BPIX		Phase-2 TBPX		
$100\ \mu m$ (azimuthal) x $150\ \mu m$ (beam)	→	$25\ \mu m$ x $100\ \mu m$	→	Area reduction by a **factor of 6**

- **Improved granularity** expected to mitigate merged clusters → **Are JetCore/DeepCore2.0 still needed?**

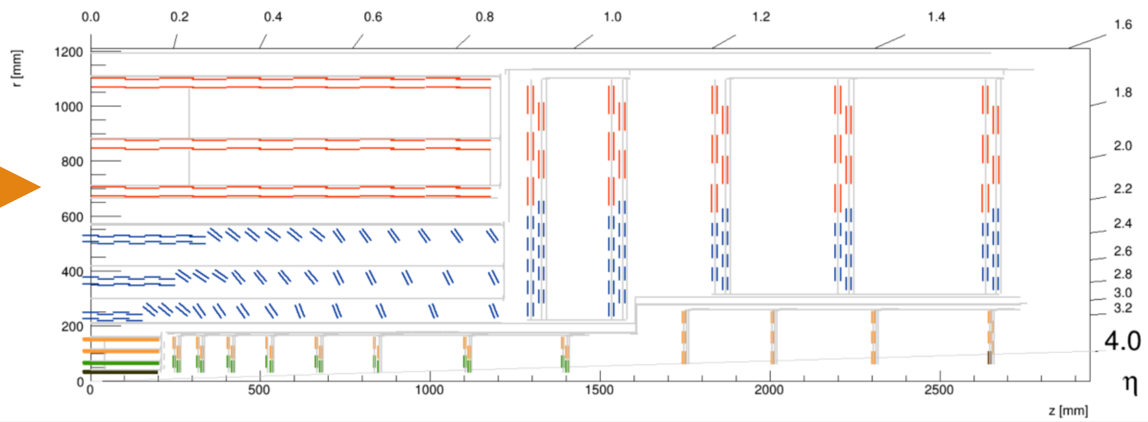
Method: **count SimTracks** in RecHit cluster (Phase-1 vs Phase-2) via PixelDigi and perform **jet-RecHit association** by maximizing collinearity (for simplicity: no PU + consider SimTracks from main PV).

Fabio Luongo, Ernesto Migliore

Phase-1 Tracker



Phase-2 Tracker



Merged clusters in dense jet cores in the Phase-2 Inner Tracker

- **Significantly less clusters** associated with more than 1 SimTrack on Layer 1 with $\mathrm{d} < 0.1$ cm

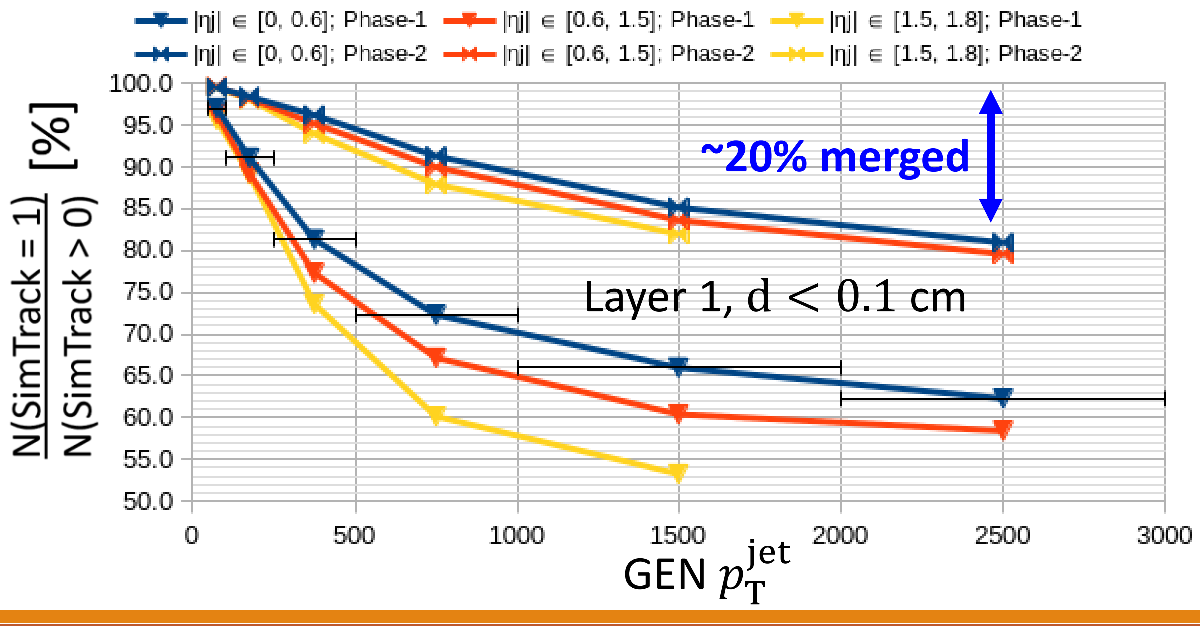
→ Less dense environment means fewer merged clusters expected.

- However still **~20% clusters** with 2+ SimTracks for $p_{\mathrm{T}}^{\mathrm{jet}} > 2$ TeV → cluster splitting is still needed.

Future plans:

- Run **JetCore cluster splitter with Phase-2** configuration and repeat this study.
- Evaluate the impact of **DeepCore2.0 with Phase-2** configuration vs Phase-1 configuration.

$$\mathrm{d} = |x_{\mathrm{jet}} - x_{\mathrm{hit}}|$$



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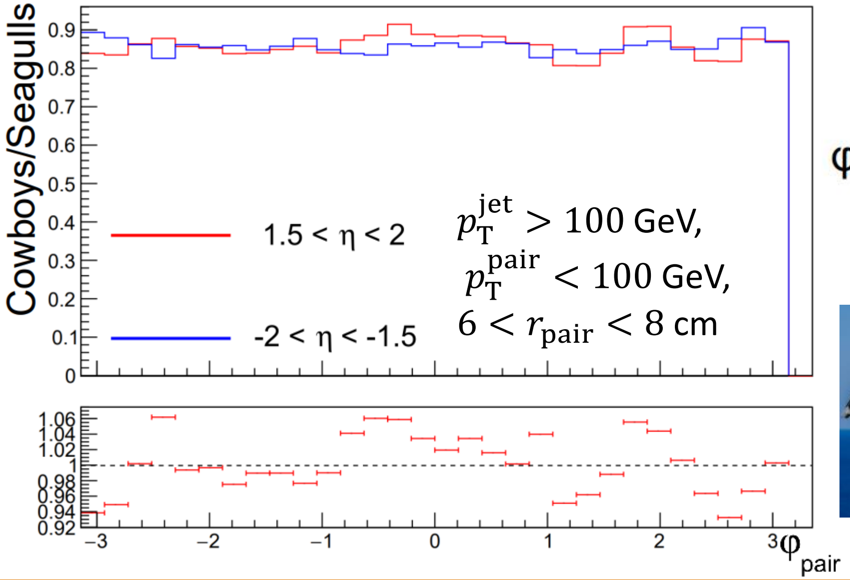
Note that Phase-2 samples do not include radiation damage

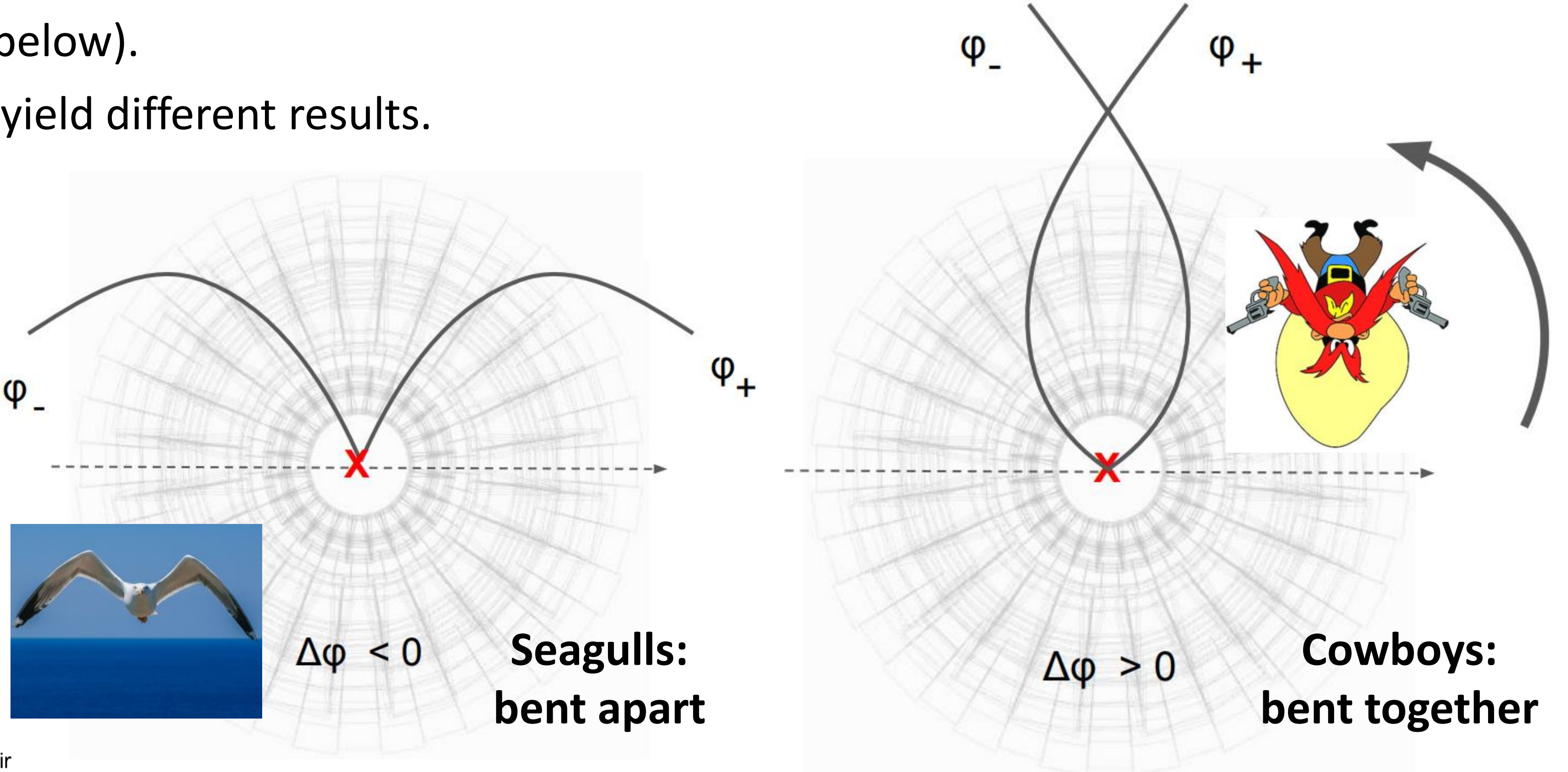
Seagulls & Cowboys (S&C) in Dense Environments

[Cristina Giordano, Robert Schoefbeck]

- Run2-based performance study of **track pairs in high p_T jets** using DY events.
- S&C production is expected to be symmetric → **an asymmetry** can indicate the tracking inefficiencies in dense environment (overlapping tracks).
- Preliminary results show **similar efficiencies** between S&C in most regions except the mid-rapidity region (plot below).
  - **Improved selection** may yield different results.

Profile plot

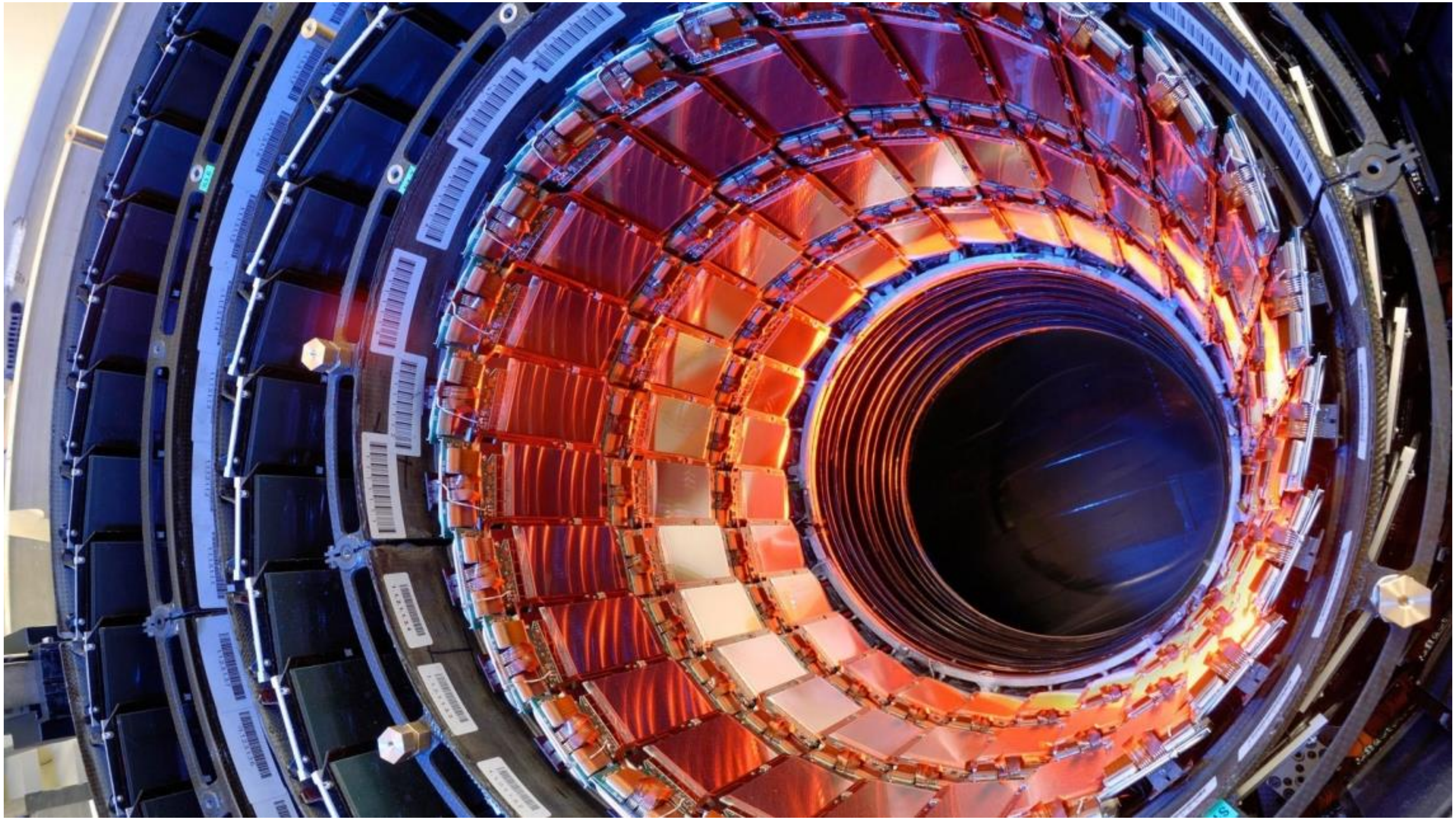




Summary

- Tracking in the core of high p_T jets is challenging due to the increasing **occupancy and combinatorics**.
- CMS currently mitigates these challenges with JetCore and enabling DeepCore2.0-Hybrid can further **improve tracking** in dense environments and **free up CPU resources** for other iterations.
- Despite the **significant improvement in granularity** provided by the Phase-2 pixel detector, preliminary studies show that cluster splitting is still needed.
  - However, more testing is required to **evaluate the need of JetCore** and the impact of **DeepCore2.0 on Phase-2** tracking performance.
- The study of **seagull/cowboy pairs** may offer ways to improve **the tracking efficiency in dense environments**.

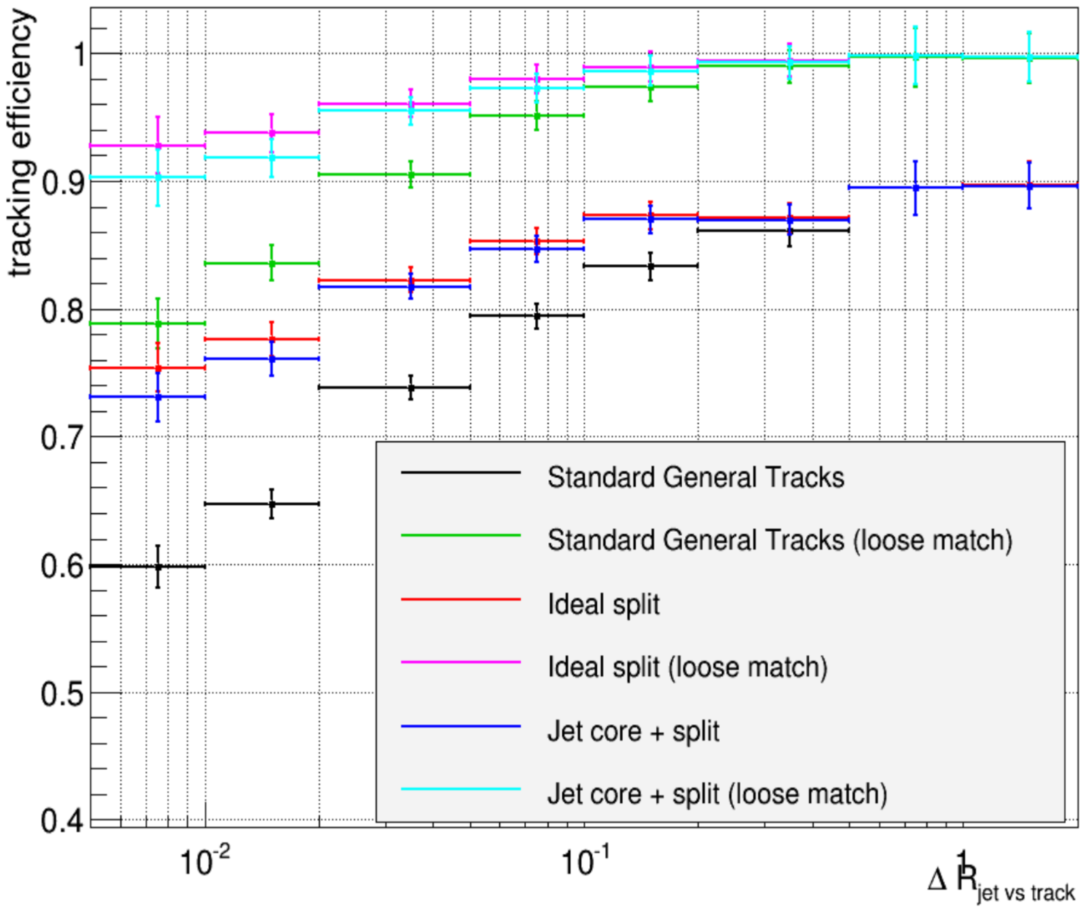
BACKUP

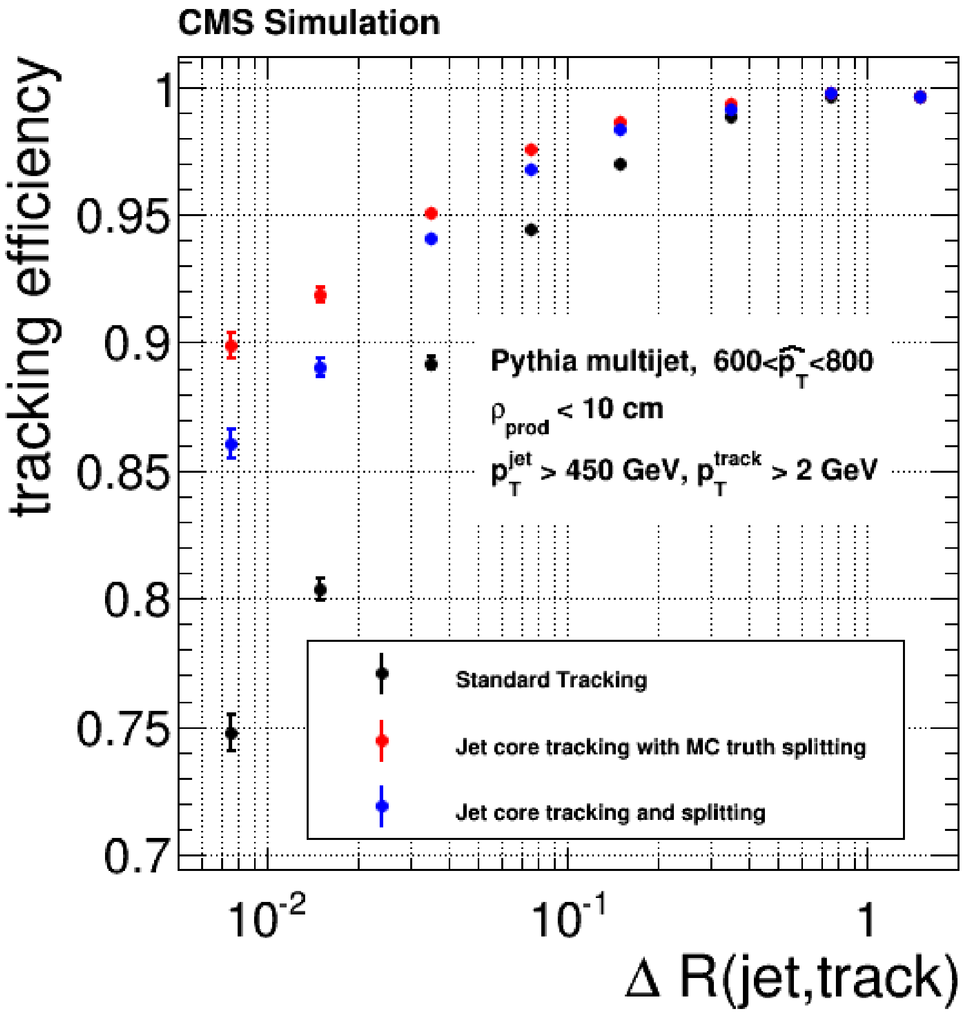


JetCore Hit-Match

CMS DP-2014/032

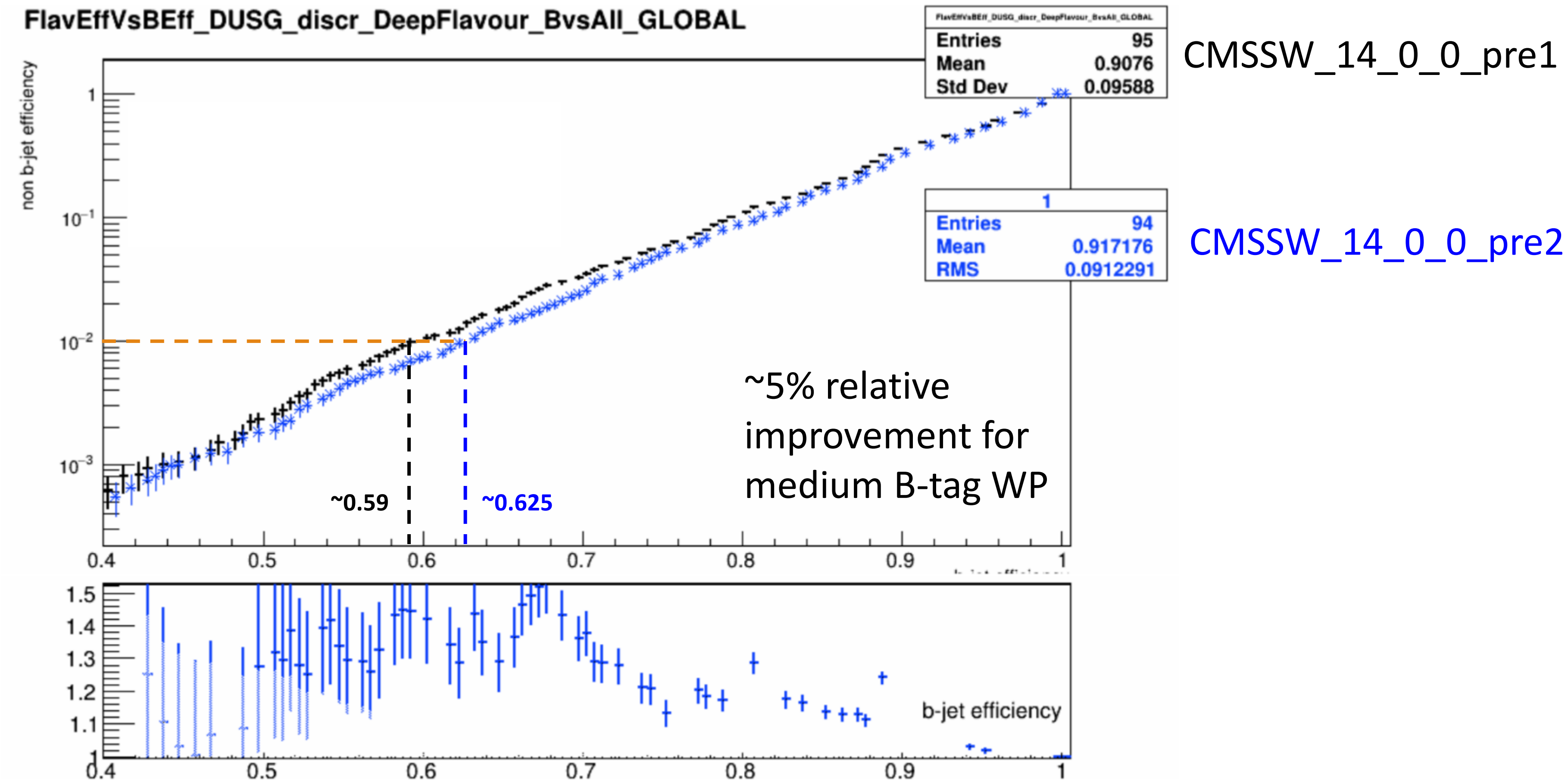
Andrea Rizzi, Silvio Donato





Impact of DeepCore2.0-Hybrid on B-tagging Efficiency

- From recent Relval of CMSSW_14_0_0_pre2 (after enabling DeepCore2.0-Hybrid)
  - e.g. deepFlavor in RelValQCD_Pt_1800_2400_14.



DeepCore2.0: Inputs

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- **Merged cluster selection**:
  - Clusters that have charge and shape consistent with the expected charge and shape of a merged cluster are selected.
  - Selected merged clusters on BPIX1 must satisfy the following criteria:
    - Associated with AK4 calo-jets with $p_T^{jet} > 500$ GeV.
    - Within a cone of $\Delta R(\text{jet, cluster}) = \sqrt{\Delta\eta^2(\text{jet, cluster}) + \Delta\phi^2(\text{jet, cluster})} \leq 0.1$ of the intersection of BPIX1 and the calo-jet jet axis, where η is the pseudorapidity and ϕ is the azimuthal angle.
  - If there are no merged clusters on BPIX1, then merged clusters on BPIX2 satisfying the above criteria are selected.
- **Merged cluster information**:
  - p_T^{jet} and η^{jet}.
  - 30×30 pixel maps in x (azimuthal direction) and y (beam direction) with normalized analog-to-digital converter (ADC) counts for each pixel.
    - The ADC count is normalized to the mean value of the charge deposition in a pixel (14k) since the CNN yields better results with input values of order 1.
    - The pixel maps are centered on the axis connecting the merged cluster with the primary vertex (PV) for all 4 BPIX layers (merged-cluster axis).

DeepCore2.0: Target and Prediction

CMS DP-2024/003

- 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.

DeepCore2.0: Training Details

CMS DP-2024/003

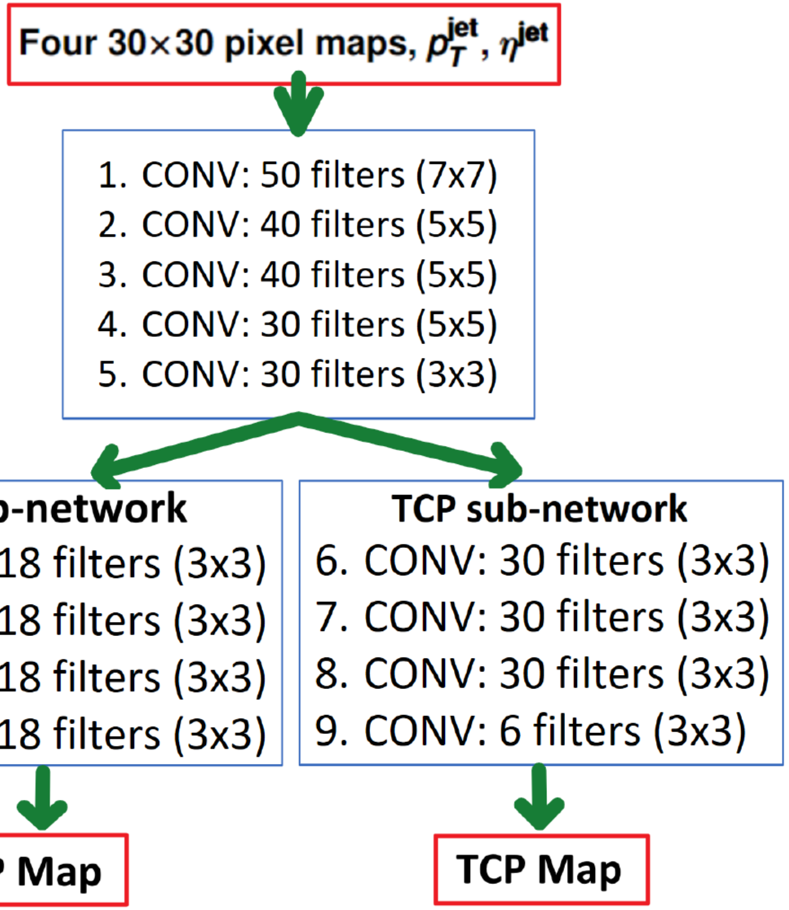
- Dataset: 2M QCD multijet simulated events generated with Pythia 8 [7], with:
  - Proton-proton center of mass energy $\sqrt{s} = 14$ TeV.
  - Transverse momentum of hard-scatter sub-process ($\hat{p}_T$) between 1.8 TeV and 2.4 TeV.
  - Flat pileup (PU) of 55-75 in the Run 3 configuration of the CMS detector.
- Jet selection: $p_T^{\text{jet}} > 500$ GeV, $|\eta^{jet}| < 1.4$.
- Cluster selection: clusters with charge and shape similar to the minimum expected charge and shape of a merged cluster and ΔR(jet, cluster) ≤ 0.1.
- Simulated track selection: $p_T^{\text{track}} > 1$ GeV.
- Training sample: 10.5M clusters with validation subset of 20%.
  - This subset of the training sample is used to monitor and mitigate over-training, which occurs when a CNN "learns" features specific to the samples it was trained on and do not apply to other samples.
- Testing sample: 150k clusters.

DeepCore2.0: Training Details

CMS DP-2024/003

- Activation Function: all ReLu [8] except Sigmoid on the last TCP CONV layer.
- Loss function: a weighted Binary Cross Entropy [9] for TCP maps and a clipped Mean Square Error for TP maps.
- Optimizer: Adam [10]
- batch size: 64.
- Total Parameters: 192,769.
- Training steps and architecture:

Epochs	Learning Rate (LR)	TCP Loss Function
1-15	10^{-4}	Weighted Binary Cross Entropy
16-20	10^{-5}	Weighted Binary Cross Entropy
21-25	10^{-5}	Weighted Binary Cross Entropy (including far pixels)
26-30	10^{-6}	Weighted Binary Cross Entropy (including far pixels)



DeepCore2.0: Prediction Threshold

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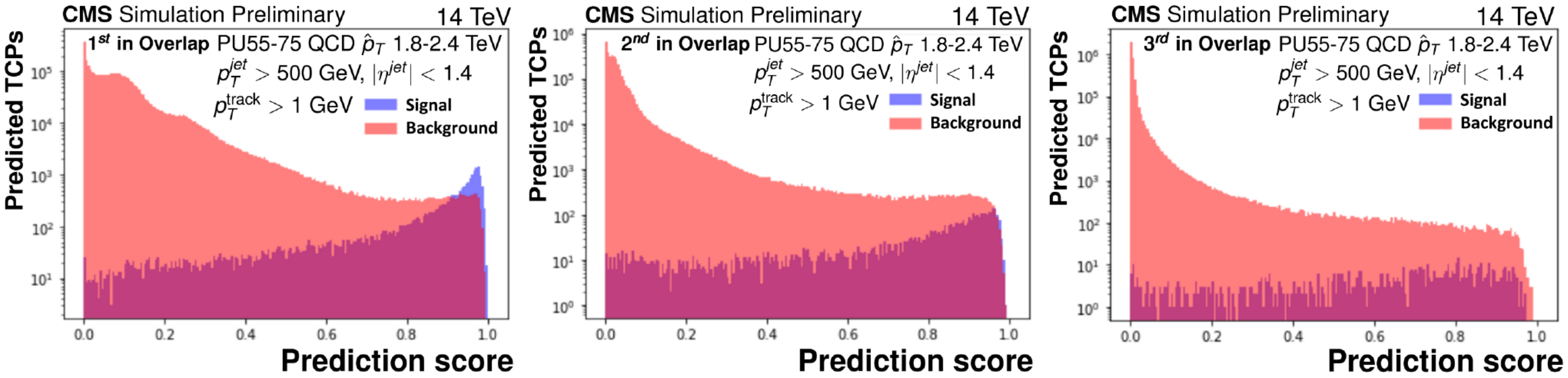

The prediction score distribution for signal (predicted TCP associated to a true TCP) and background (predicted TCP not associated to a true TCP) are shown above for Overlap 1 (left), Overlap 2 (middle) and Overlap 3 (right). There are fewer true TCPs in Overlap 2, which requires a higher threshold to preserve signal efficiency. The number of true TCPs on Overlap 3 is not significant, which warrants disabling Overlap 3 predictions in order to preserve signal efficiency.

- Thus, the following prediction thresholds are used: 0.7/0.85/1(disabled) for the first/second/third particle in Overlap.
- Moreover, the set of prediction thresholds is raised if BPIX1/3/4 are empty (0.8/0.9/1) and if BPIX2 is empty all predictions are disabled (1/1/1).

Merged clusters in dense jet cores in the Phase-2 Inner Tracker

	η_{jet} range					
	Phase-1			Phase-2		
Jet p_T range [GeV]	0.0–0.6	0.6–1.5	1.5–1.8	0.0–0.6	0.6–1.5	1.5–1.8
50–100	9384	12126	3199	9494	12095	3268
100–250	11730	14712	3703	11511	14509	3690
250–500	7679	9135	2106	7759	9129	2037
500–1000	5169	5571	982	5094	5562	959
1000–2000	2162	1775	115	2096	1633	123

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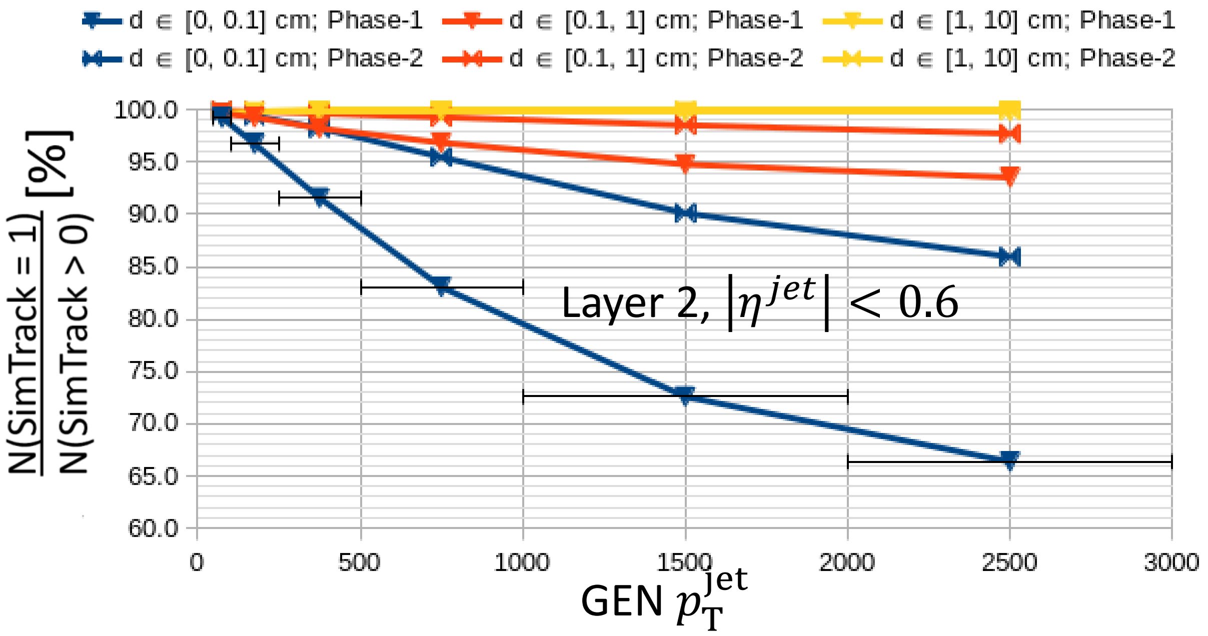

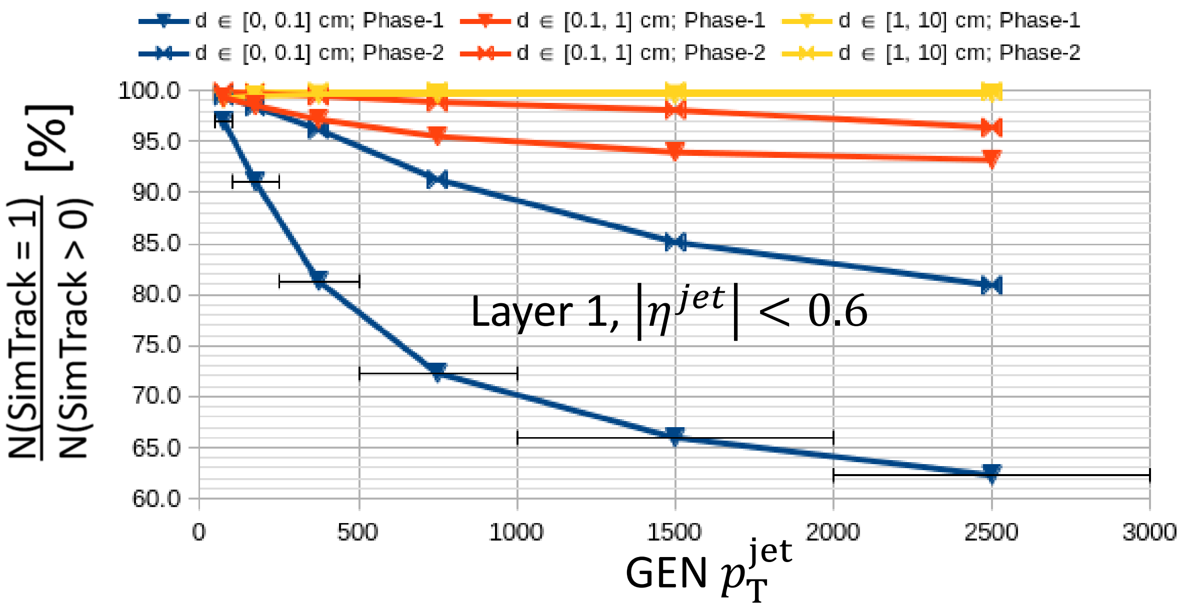

Seagulls & Cowboys (S&C) in Dense Environments

Cristina Giordano,
Robert Schoefbeck

- Object selection
  - Tracks → $dR(j, t)<0.4$ & $|pdgId_{Tracks}|=211$ jetConstituents
  - Jets → MEF < 0.2 slimmedJets
  - Muons → $p_T>20$ slimmedMuons

- Samples (miniAODSIM) →

DYJetsToLL_M50_LO(_ext1)	DYJetsToLL_M50_HT400to600_LO(_ext1)
DYJetsToLL_M50_NLO	DYJetsToLL_M50_HT600to800_LO
DYJetsToLL_M50_HT70to100_LO	DYJetsToLL_M50_HT800to1200_LO
DYJetsToLL_M50_HT100to200_LO(_ext1)	DYJetsToLL_M50_HT1200to2500_LO
DYJetsToLL_M50_HT200to400_LO(_ext1)	DYJetsToLL_M50_HT2500toInf_LO

Pairs →

- Charge requirement → $q_{Track\_1} + q_{Track\_2} = 0$ → Pair of tracks
- If $d\varphi_{Pair} > 0$ → Cowboy; $d\varphi_{Pair} < 0$ → Seagull