Software and Reconstruction at a Muon Collider

AI4MuC Workshop, 29-30 June 2026

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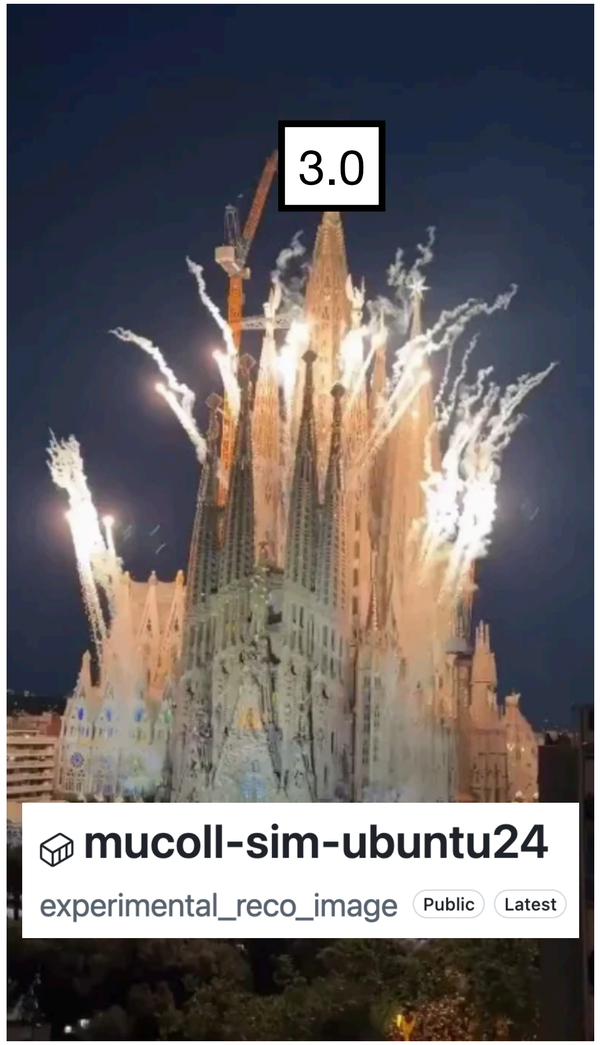
USMCC

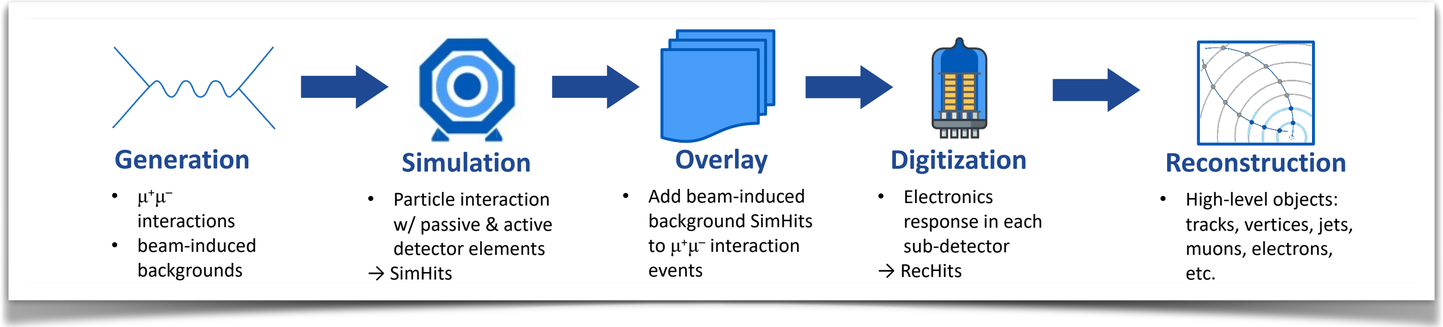
Overview / Executive Summary

- Muon collider core reco software **substantially modernized** in the last two years.
  - **Rel. 3.0 tagged last week!**
    - The first release supporting a **fully Gaudi-native workflow,** within Key4hep/EDM4hep.
      - μC developments are advancing common tools for entire community.
  - Plenty of room for new contributors: try out the ***updated software tutorial!*** https://mcd-wiki.web.cern.ch/software/howto/gaudi/
- **Significant developments and R&D for tracking, BIB simulation & more:** *I'll share highlights, you heard others from **R. Roberts & R. Mastandrea**!*
  - AI/ML is starting to influence every step of the reconstruction chain, most developments currently focused on BIB simulation & overlay.
- For much more detail, see **F. Meloni**'s reflections on the 2024 IMCC Software Task Force goals last week @ IMCC 2026



MuonColliderSoft

https://github.com/MuonColliderSoft



- **Public software hosted on GitHub**
  - "Micro-services" approach
  - PR review by humans is recommended
  - Discussions via **gh issues**
    Repo-specific
  - Detector concept-specific steering configs
    MAIAConfig, MuSICConfig
- Integration into Key4hep
- Recent migration to **Gaudi/EDM4hep**
  - Digitizers & overlay ported
  - **EDM4hep** is now the default output format

Muon Collider

mucoll-spack Public
Muon Collider software repository for Spack
Python ☆ 2 3

MAIAConfig Public
Package for Gaudi configuration files related to the MAIA detector concept
Python ☆ 1

mucoll-benchmarks Public
Collection of tools for producing the Muon Collider benchmark plots
Python ☆ 2 16

MuCollConfig Public
Package for Gaudi configuration files related to the MuColl 3 TeV detector concept
Python ☆ 1

MuSICConfig Public
Package for configuration files related to the MuSIC detector concept
Python ☆ 2 1

Distribution & Automation

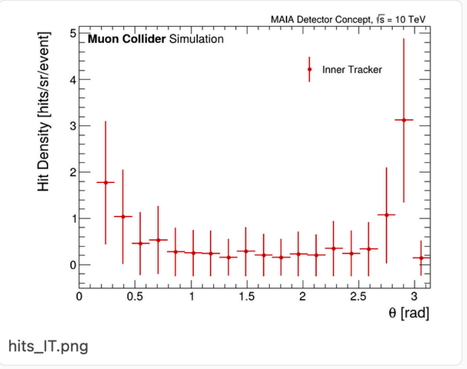
F. Meloni @ IMCC26

https://github.com/MuonColliderSoft/mucoll-spack

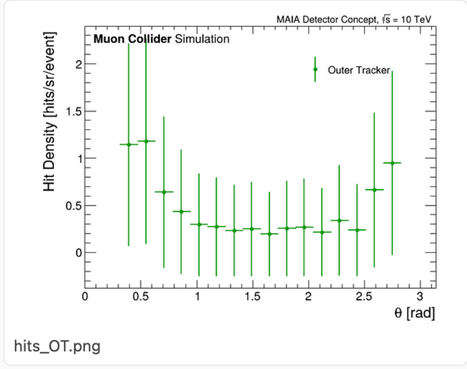
- Releases are **CI-built**, pushed to **ghcr.io** and replicated to **cvmfs unpacked**
- All releases ship in both **native amd64 & arm64 flavors!**
- v3.0 introduces **layered images** for different applications: mucoll-analysis, -sim, -ml

pion performance plots

29 plots generated from `reco.edm4hep.root`.



hits_IT.png



hits_OT.png

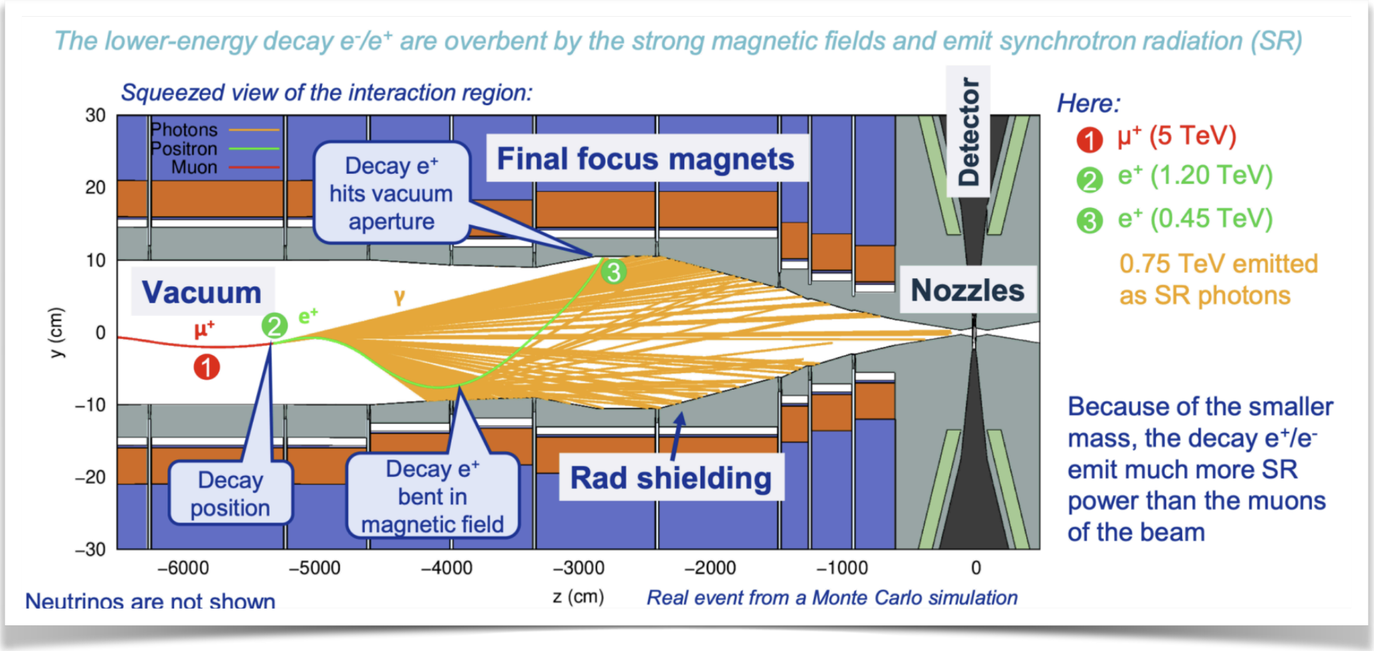
Automated physics validation in CI!

Image	Baseline	Additional	Deprecated
mucoll-analysis	edm4hep, podio, ROOT cmake, ninja, ccache, pelican, py-h5py, py-matplotlib, py-pandas, py-particle, py-pip, py-scipy, py-uproot, py-cppy + compilers (c/cxx/fortran)		
mucoll-sim	edm4hep, podio, ROOT cmake, ninja, ccache, pelican, py-h5py, py-matplotlib, py-pandas, py-particle, py-pip, py-scipy, py-uproot, py-cppy + compilers (c/cxx/fortran)	dd4hep (+ddg4), geant4 (+data), delphes, k4geo, k4reco, k4gaudipandora, k4actstracking, k4simgeant4, k4marlinwrapper muoncvxddigitiser, mybibutils	marlin, marlinutil, marlindd4hep, marlinreco, marlinfastjet, marlinkinfit, marlinkinfitprocessors, marlintrk, aidatt, raida, sio, ced, cedviewer, garlic, generalbrokenlines, gear, ilcutil, lcfiplus, lcfivertex, kaldet, ddkaltest, kitrackmarlin, kaltest, kitrack, fcalclusterer, pandoraanalysis, pandorapfa, clicperformance
mucoll-ml	edm4hep, podio, ROOT cmake, ninja, ccache, pelican, py-h5py, py-matplotlib, py-pandas, py-particle, py-pip, py-scipy, py-uproot, py-cppy + compilers (c/cxx/fortran)	py-torch, torch-scatter, py-torch-scatter, onnx, py-onnx, py-onnxruntime, xgboost, py-xgboost, py-scikit-learn, acorn	

Simulation & overlay

See J.P. Dervan & R. Mastandrea's talks earlier today!

- BIB simulation (FLUKA) is the dominant computing cost.
  - Accounting challenges with **~10^8 particles**
    - Do LHC algorithms scale to such multiplicities?
- Reconstruction of overlaid events is still a bottleneck, even with **'premixed'** digitized BIB.
  - Premixing library: **~20GB disk footprint**
  - Adding BIB overlay **significantly increases event reco time.**
- Long-term vision: **provide realistic BIB overlay on-the-fly with GenAI.**



Step	CPU	Memory	Disk
BIB simulation	up to 24 hours/event (10^8 particles)	up to 32 GB/event (considering whole chain)	~20 GB/event (BIB)
BIB overlay	5 mins/event (before digitization!)		
Tracking	5 mins/event up to hours/event (depends on lattice)		~1 MB/event (signal, w/o BIB)

- These numbers consider the *current* simulation stack being used for design & physics studies

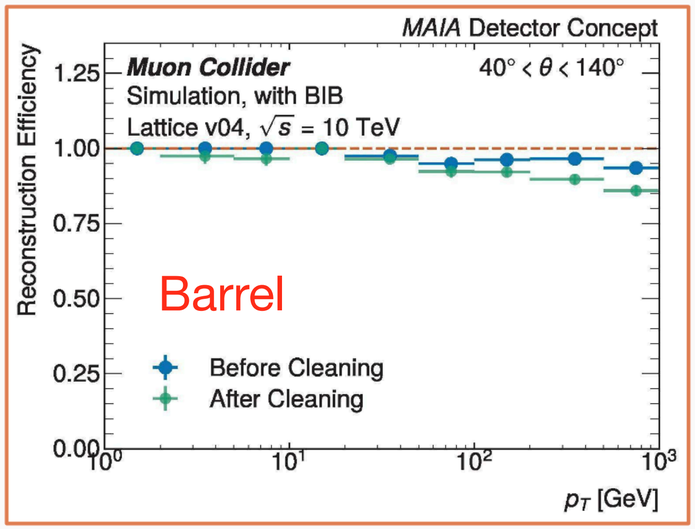
➢ BIB is main driver of computational needs K. Pedro @ USMCC25

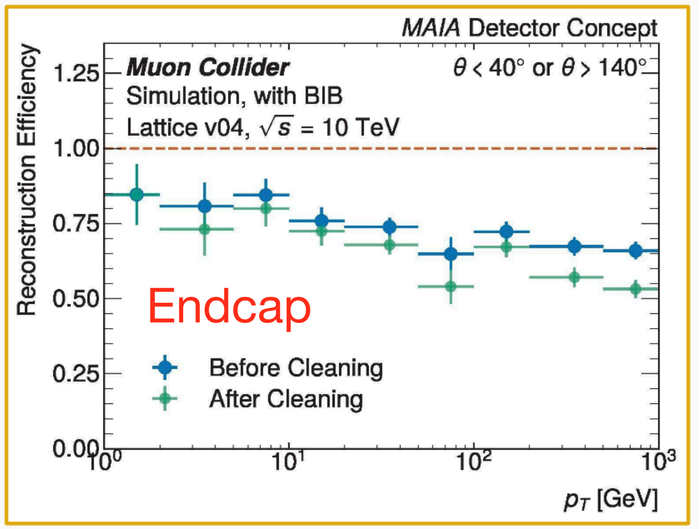
Tracking I: ACTS

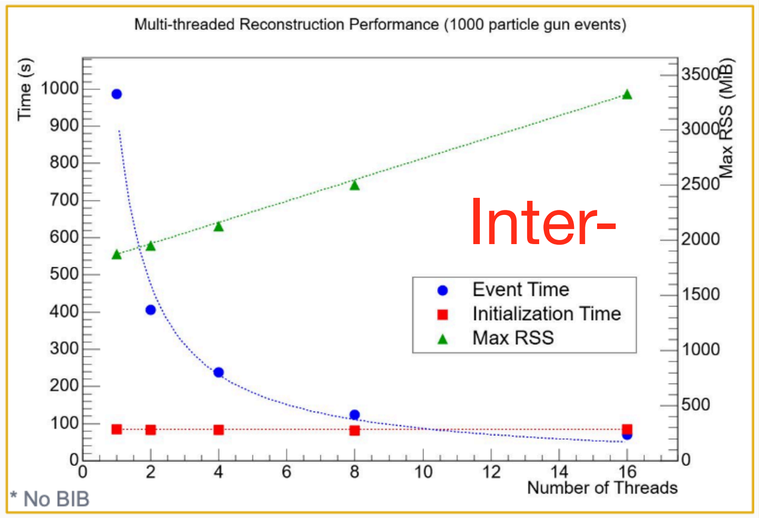
S. Ferraro @ IMCC26

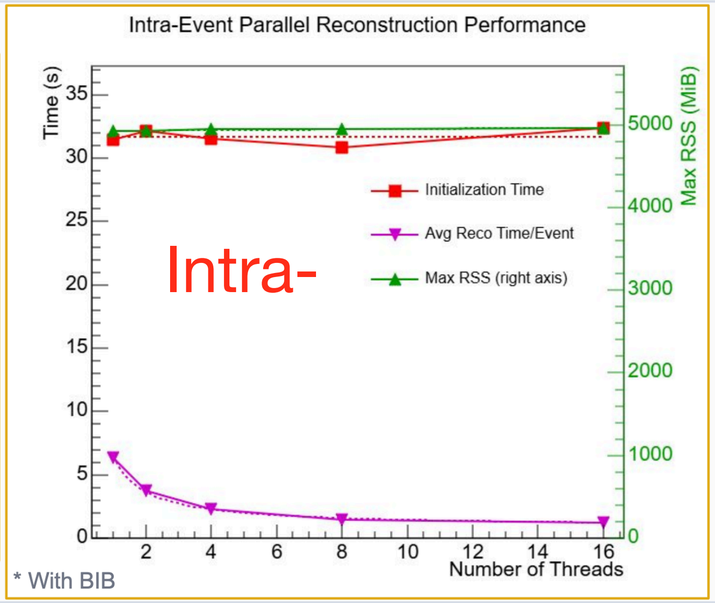
MAIA, 2502.00181

- **ACTS** is a **detector-agnostic, open-source** tracking software.
  - **k4ActsTracking:** generic interface between EDM4hep & ACTS
    - **Implemented within Key4hep by the muon collider community,** now broadly available.
- mucollsoft is currently at **ACTS v42**
  - Room for improvement in forward region: non-uniform **BIB effects endcaps more than barrel.**
  - Gaudi enables **inter- and intra-event multithreading:** significant speedups, ~1/nCPU
  - Plans to study 4D tracking, supported natively in ACTS









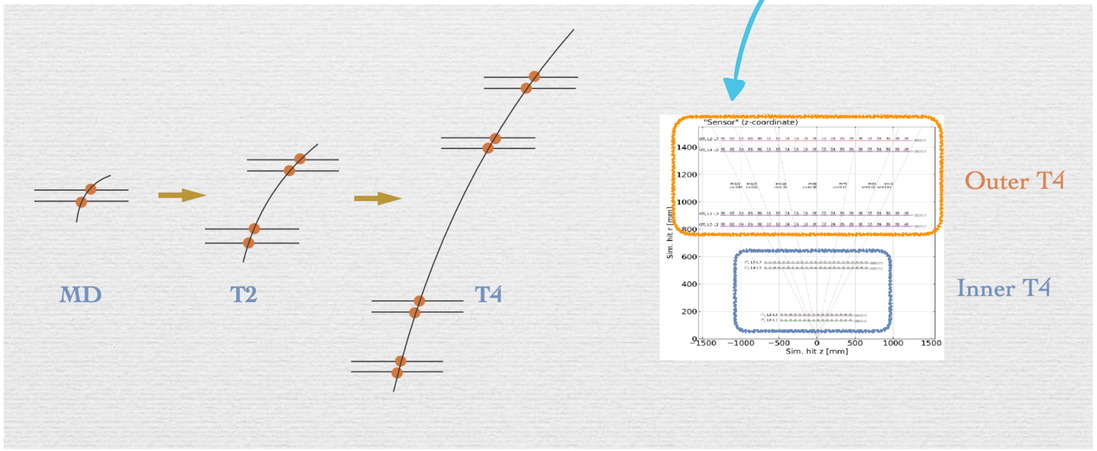
Implies an additional O(N²) de-duping step, not included in estimate.

Tracking II: Line Segment Tracking

Y. Gu @ IMCC 2026

- GPU-native, non-Kalman-Filter track builder,
  CMS baseline for Phase-2
  - hits → doublets → segments → triplets → …
- **μC hit density is 200x higher than CMS HL-LHC** before timing cuts! Some changes …
  - Inverted / “outside-in” approach to avoid BIB-dominated vertex region.
  - Modified inner detector layout w.r.t. MAIA paper
    8 Si layers in each of the inner & outer detectors
  - *2 hits must be in paired layers & pass kinematic cuts*
    ***~99.7%** of signal tracks pass selections*
- **Significant BIB suppression before any timing cuts!**
- Local track building enables GPU parallelization
  34 ms / event for CMS, Masciovecchio @ ACAT 2025

Each ‘layer’ here is a local double-module design



Layer	Hits	MDs	T2s	T4s
L0	2.4M	71k	5k	440
L1	2.7M			
L2	2.2M	77k		
L3	2.5M			
L4	2.1M	180k	30k	
L5	2.3M			
L6	2.0M	205k		
L7	2.3M			

Outer tracker object multiplicities

AI/ML Opportunities in Reco/SW

- **On-detector:** *smart pixels*
  R. Roberts' talk, today
- **Simulation & overlay:** GenAI BIB
  R. Mastandrea's talk, today
- ***Tracking:*** *GNN / time-aware, anomaly detection for BIB hit rejection*
  R. Bala Garg @ USMCC25
- **Particle flow:** MLPF
  J. Duarte et al., à la CMS 2601.17554
- **Computing:** heterogeneous resources will be a baseline requirement (MLPF, LST, GenAI-BIB, *etc.*)

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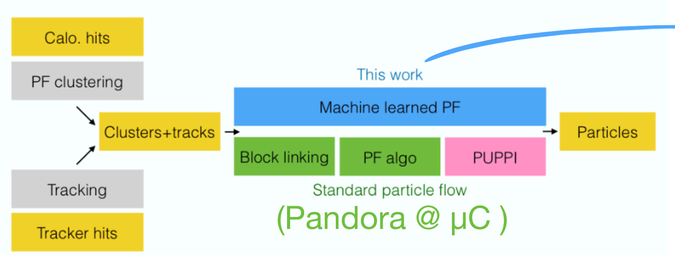
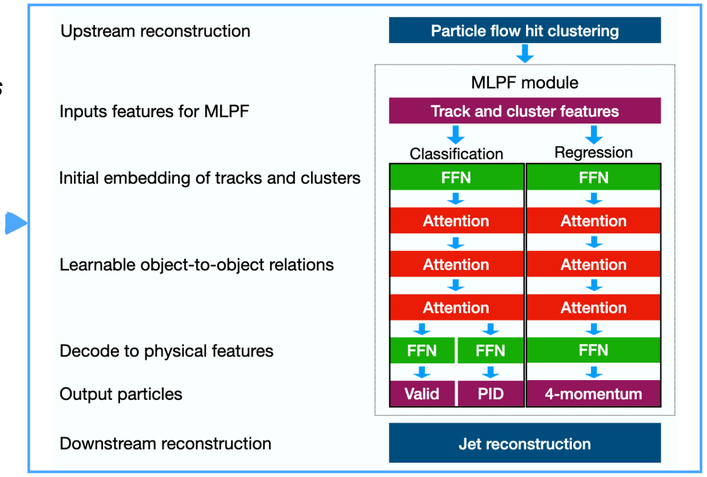
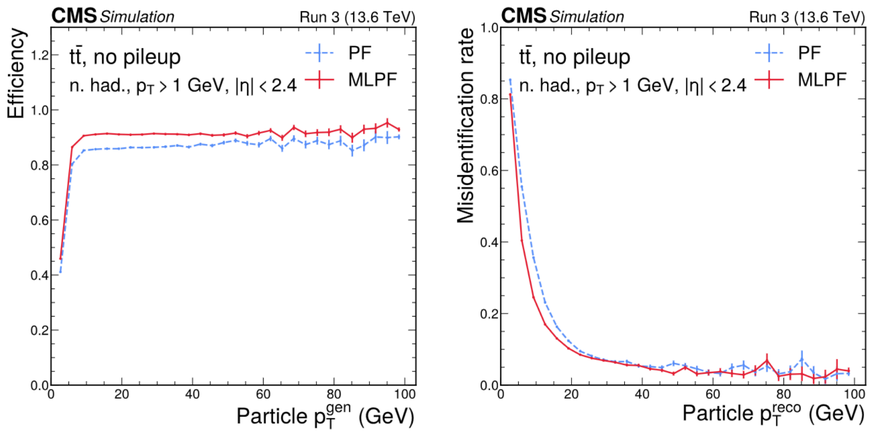
The CMS MLPF algorithm …

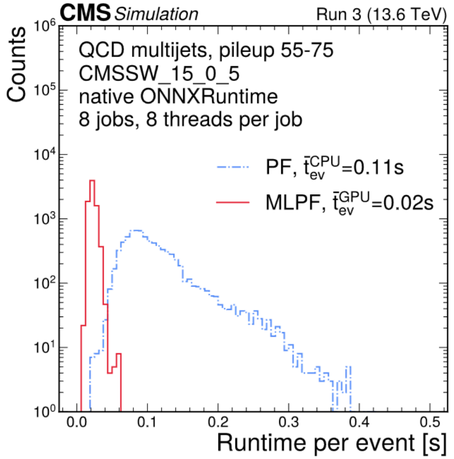
- *performs a **learnable, full-event reconstruction on GPUs***
- *generalizes across **detector conditions and collision energies***
- ***replaces multiple modular reconstruction steps with a single unified model.***







***Comparable or improved performance** w.r.t. CMS PF, depending on the benchmark.*



Significantly reduced runtime!

For more info about MLPF in CMS: K. W. Ho @ BOOST 2025

Thank you!

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