2nd Annual US Muon Collider Meeting

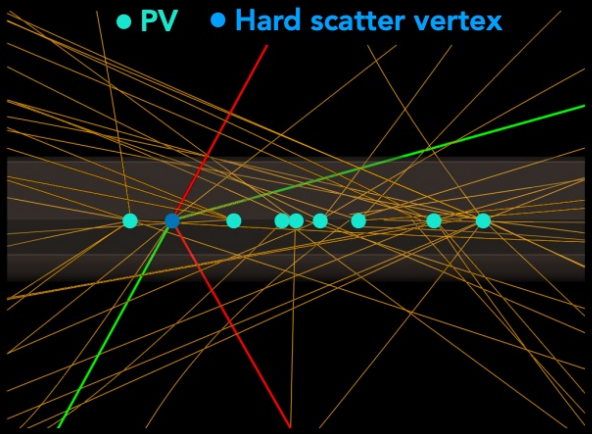
August 7-8, 2025

USMCC

Tracking Software and ML Tracking

Rocky Bala Garg
Stanford University

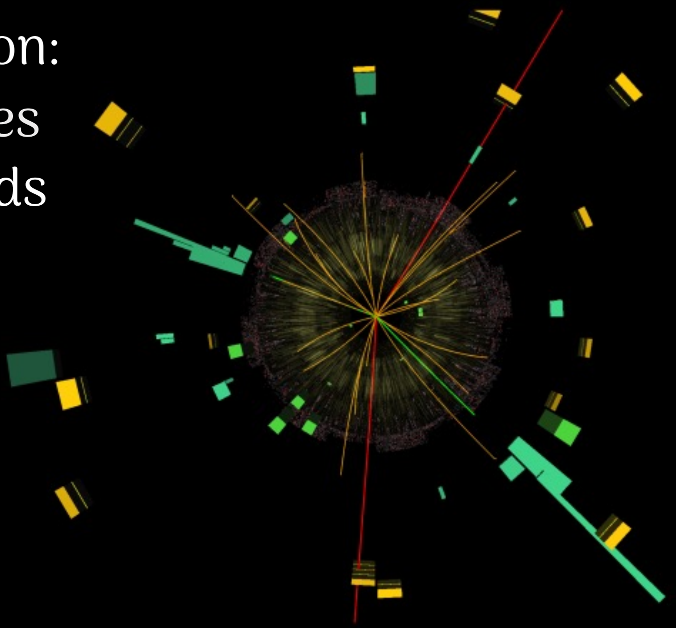
Tracking

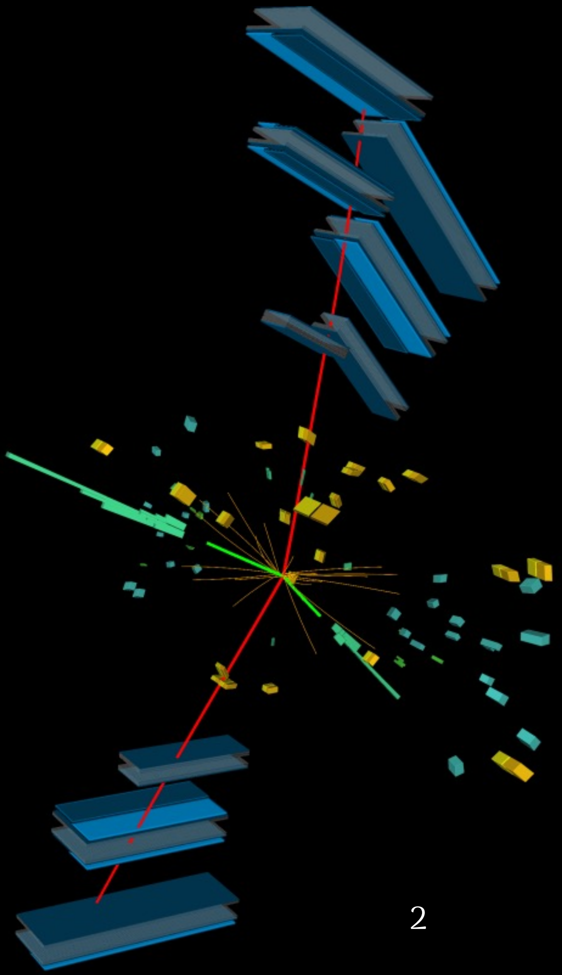


Reconstructing trajectories of charged particles through the detector

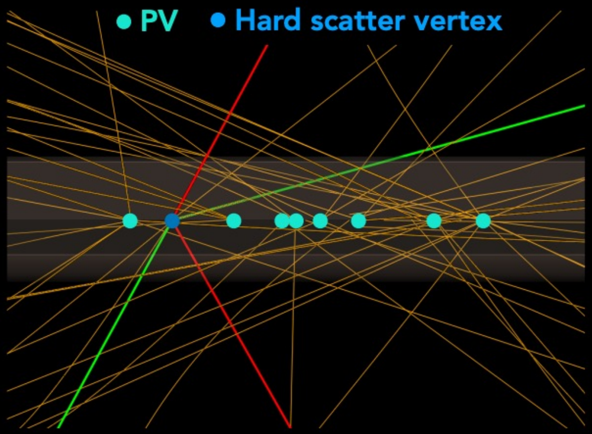
An essential component of event reconstruction:

- Identify primary and secondary vertices
- Suppress pile-up and other backgrounds
- Identify particle type
- Measure their charge and momenta





Tracking



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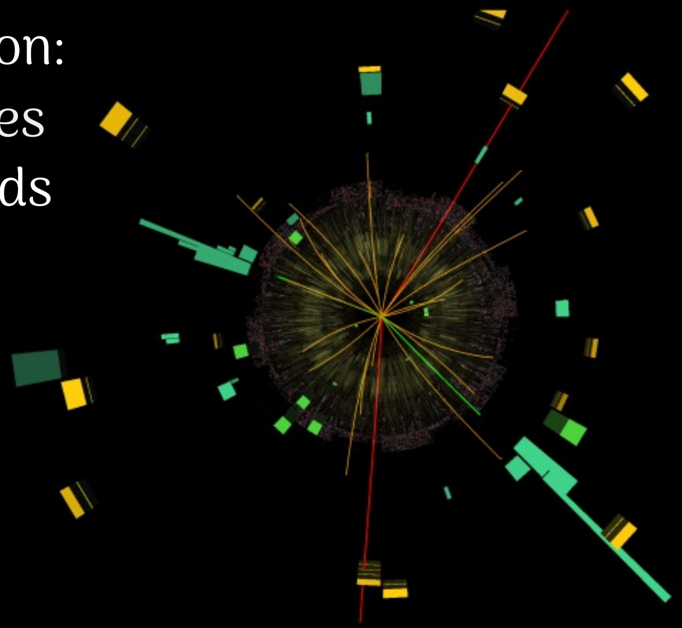
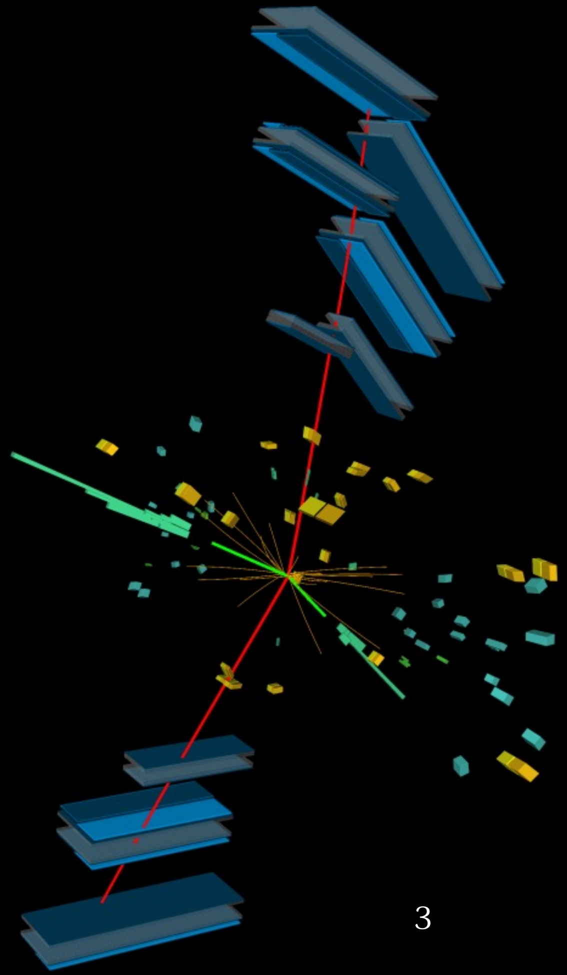




In short: Tracking helps in identifying

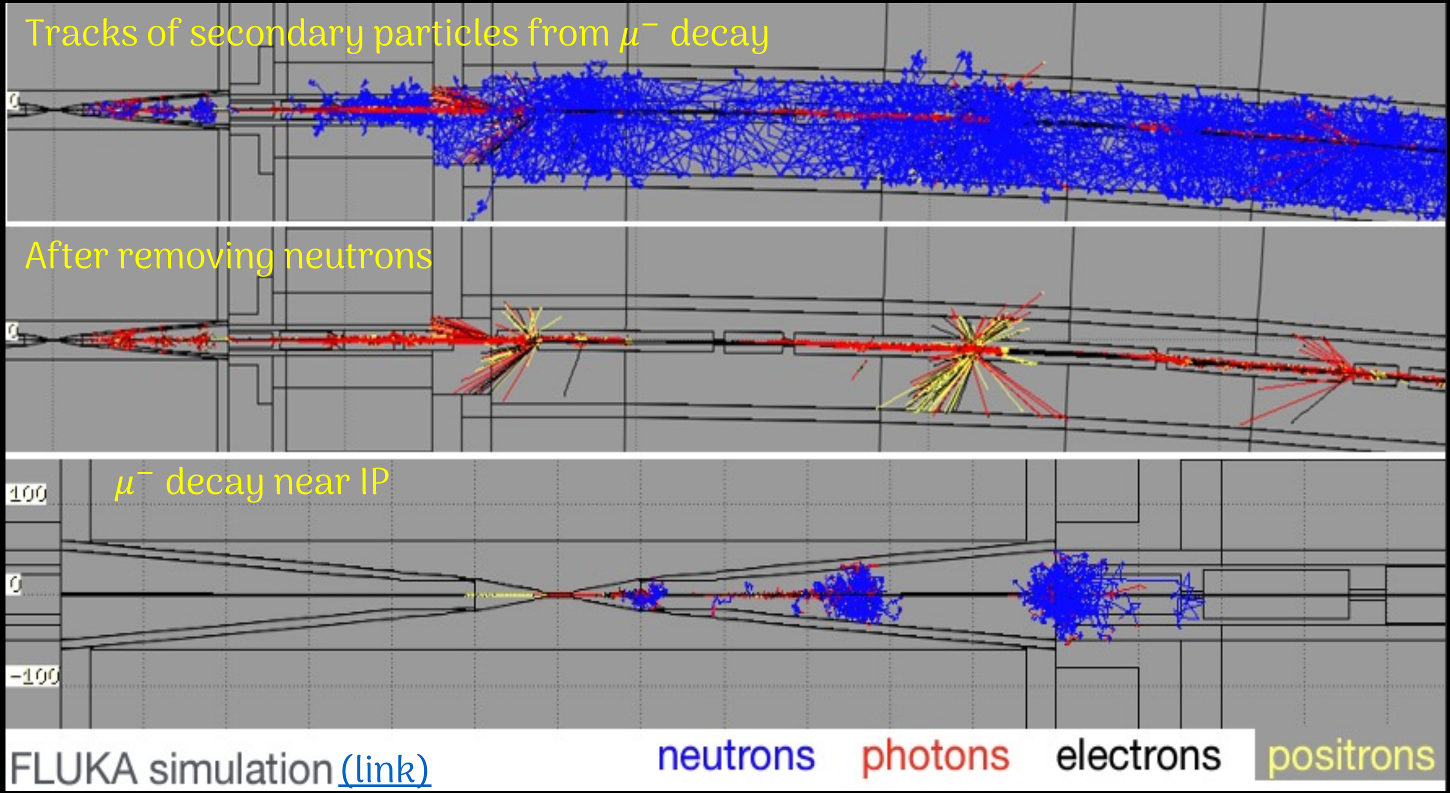
- what particles were produced
- where they came from
- how fast they were moving
- and whether they belong to rare or interesting processes

Unique tracking challenges at a Muon Collider

Beam-Induced Background

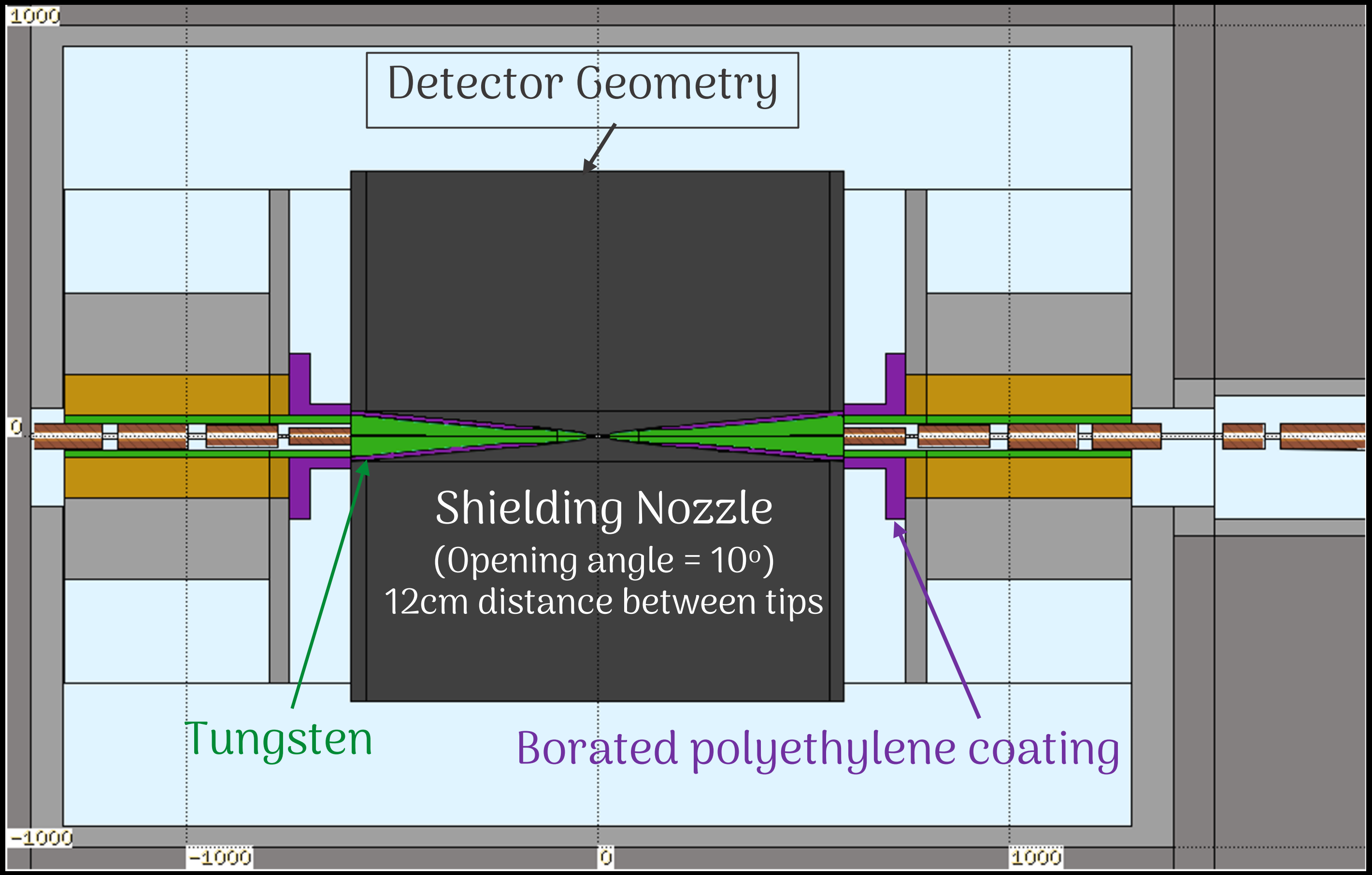
- Muons decay with a short lifetime (τ_μ = 2.2 μs at rest)
- Secondary and tertiary interactions of the decay products with the accelerator lattice results into significant beam-induced background (BIB)
- BIB composition
  - Dominated by high rates of e^+/e^-, γ and neutrons
  - Smaller contributions from charge hadrons and secondary muons

arxiv:2203.07964



Beam-Induced Background with Nozzle Shielding

- A shielding nozzle to suppress BIB in the forward region
- Reduces BIB by over three orders of magnitude

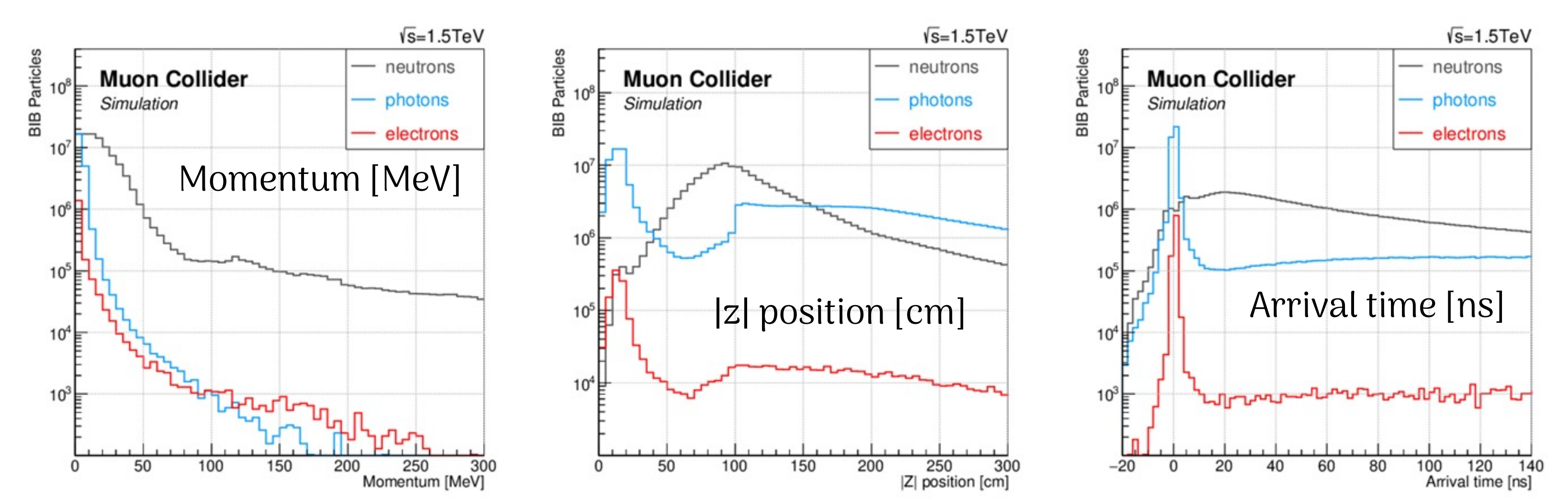


Beam-Induced Background with Nozzle Shielding

- A shielding nozzle to suppress BIB in the forward region
- Reduces BIB by over three orders of magnitude
- However, a significant fraction of BIB remains in the transverse region

BIB particle rates in the transverse direction at different CoM energies (showing moderate energy dependence)

Monte Carlo simulator	FLUKA	FLUKA	FLUKA
Beam energy [GeV]	750	1500	5000
μ decay length [m]	$46.7 \cdot 10^5$	$93.5 \cdot 10^5$	$311.7 \cdot 10^5$
μ decay/m/bunch	$4.3 \cdot 10^5$	$2.1 \cdot 10^5$	$0.64 \cdot 10^5$
Photons ($E_\gamma > 0.1$ MeV)	$51 \cdot 10^6$	$70 \cdot 10^6$	$107 \cdot 10^6$
Neutrons ($E_n > 1$ MeV)	$110 \cdot 10^6$	$91 \cdot 10^6$	$101 \cdot 10^6$
Electrons & positrons ($E_{e^\pm} > 0.1$ MeV)	$0.86 \cdot 10^6$	$1.1 \cdot 10^6$	$0.92 \cdot 10^6$
Charged hadrons ($E_{h^\pm} > 0.1$ MeV)	$0.017 \cdot 10^6$	$0.020 \cdot 10^6$	$0.044 \cdot 10^6$
Muons ($E_{\mu^\pm} > 0.1$ MeV)	$0.0031 \cdot 10^6$	$0.0033 \cdot 10^6$	$0.0048 \cdot 10^6$



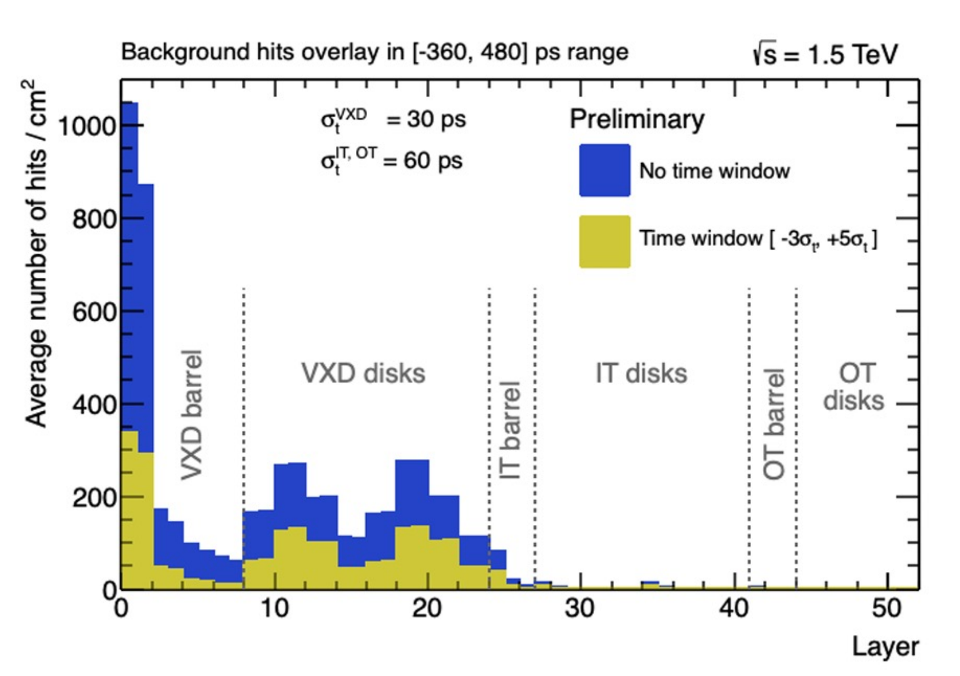
Key BIB characteristics

- Low Momentum
- Longitudinal spread
- Broad arrival time distribution

Severe Hit Density

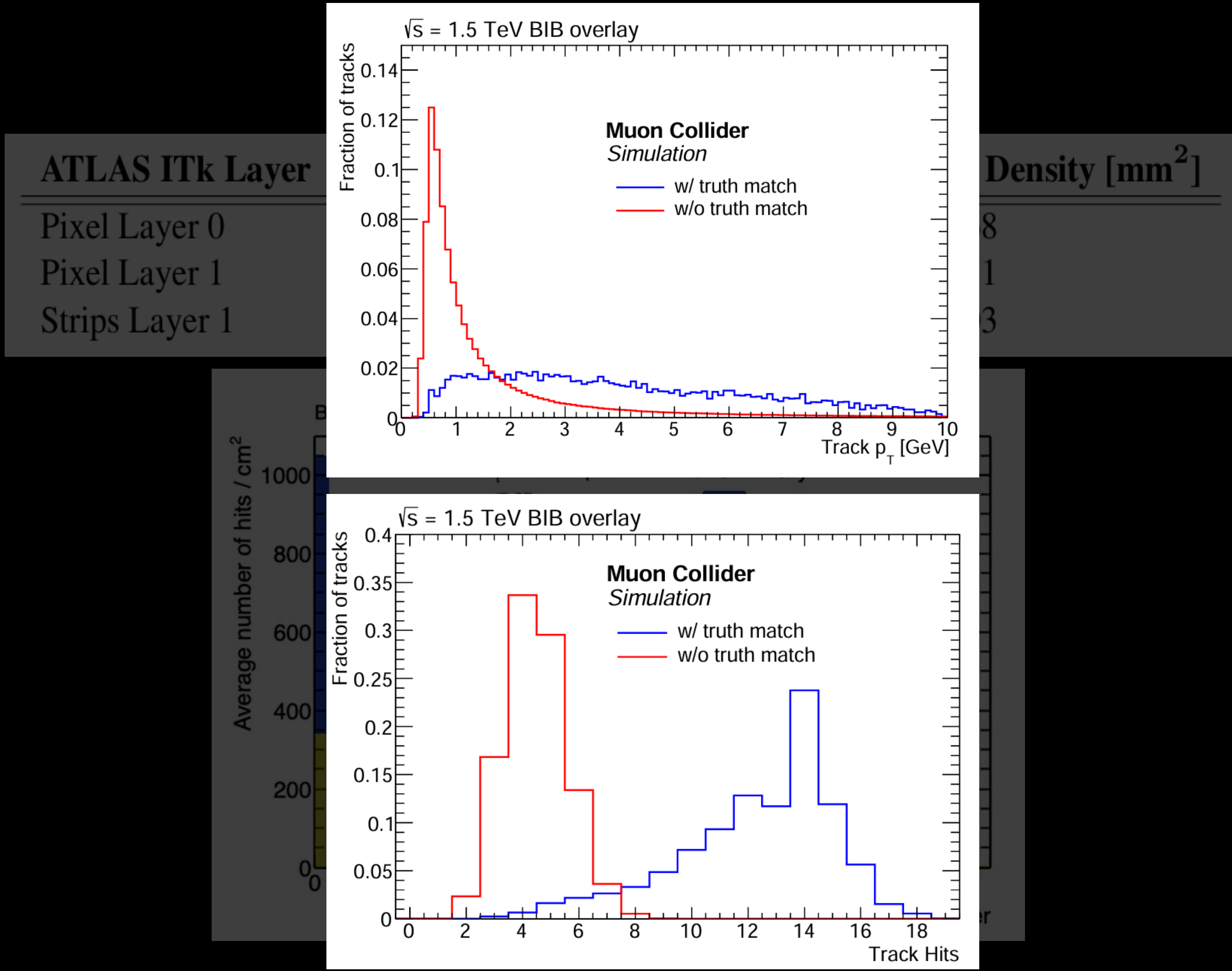
- BIB hit density in the Muon tracker ~10× higher than expected HL-LHC pile-up
- Around 1000 hits/cm^2 in the innermost layers
- Combinatorial explosion in the track reconstruction

ATLAS ITk Layer	ITk Hit Density [mm^2]	MCD Equiv. Hit Density [mm^2]
Pixel Layer 0	0.643	3.68
Pixel Layer 1	0.022	0.51
Strips Layer 1	0.003	0.03



Severe Hit Density and fake tracks

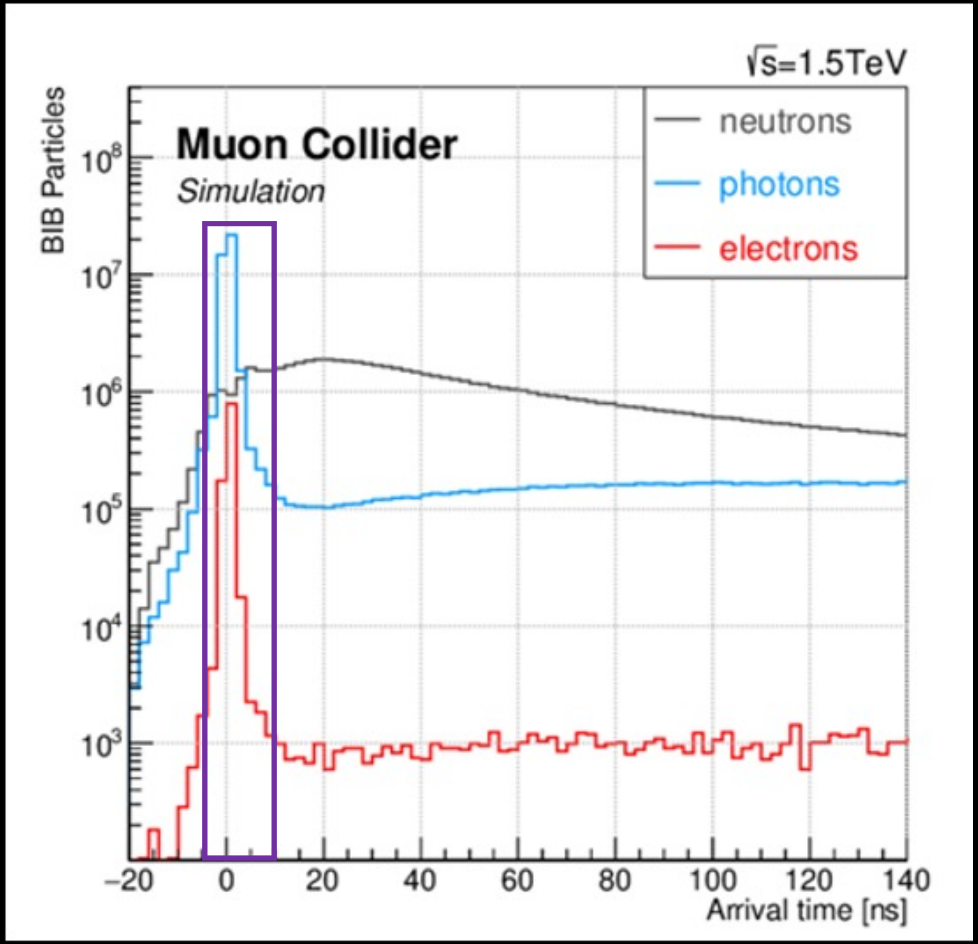
- BIB hit density in the Muon tracker ~10× higher than expected HL-LHC pile-up
- Around 1000 hits/cm^2 in the innermost layers
- Combinatorial explosion in the track reconstruction
- Around 150,000 track seeds per event, around 100,000 of these are fake
- Fake tracks are characterized by low pT and small number of associated hits



From Challenges to Solutions

Incorporating timing information

Timing cut to mitigate out-of-time BIB



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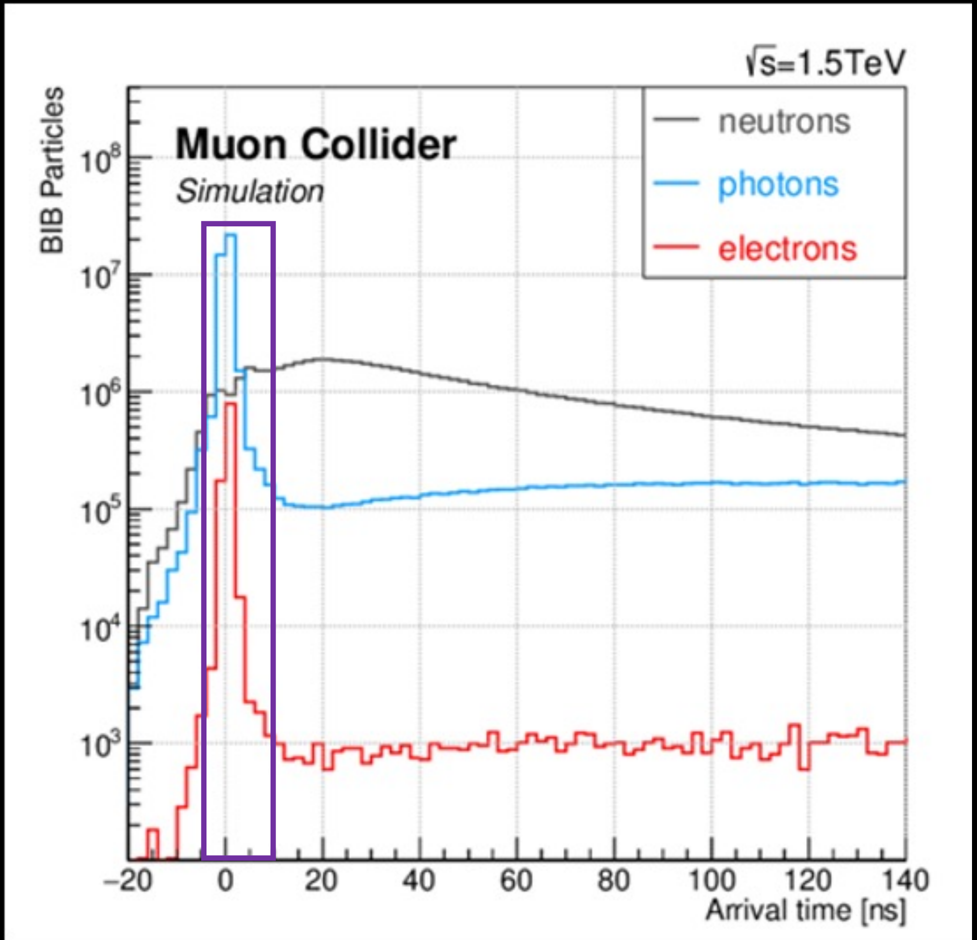
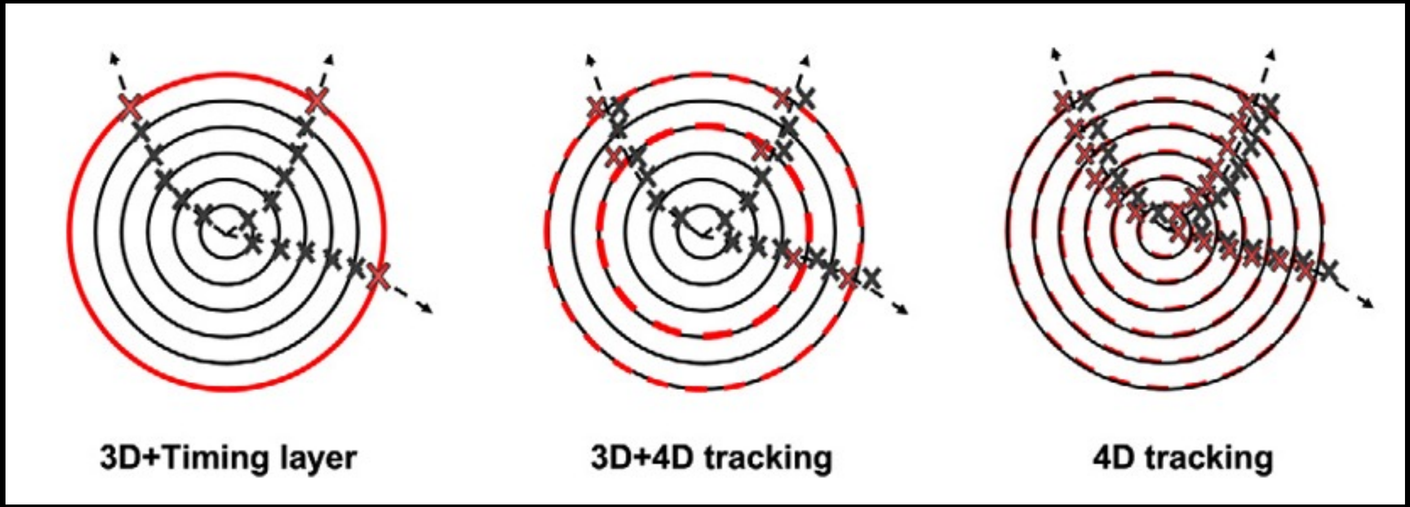


Ways to Implement Timing in Detector Systems



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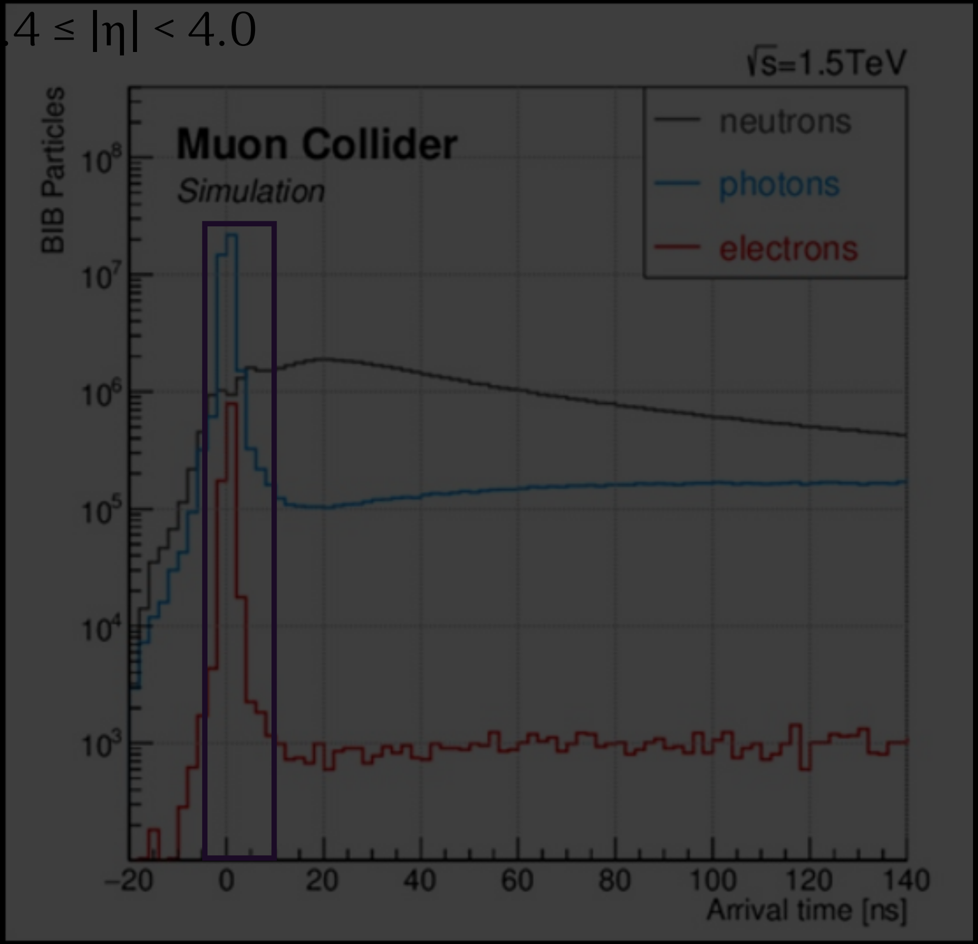
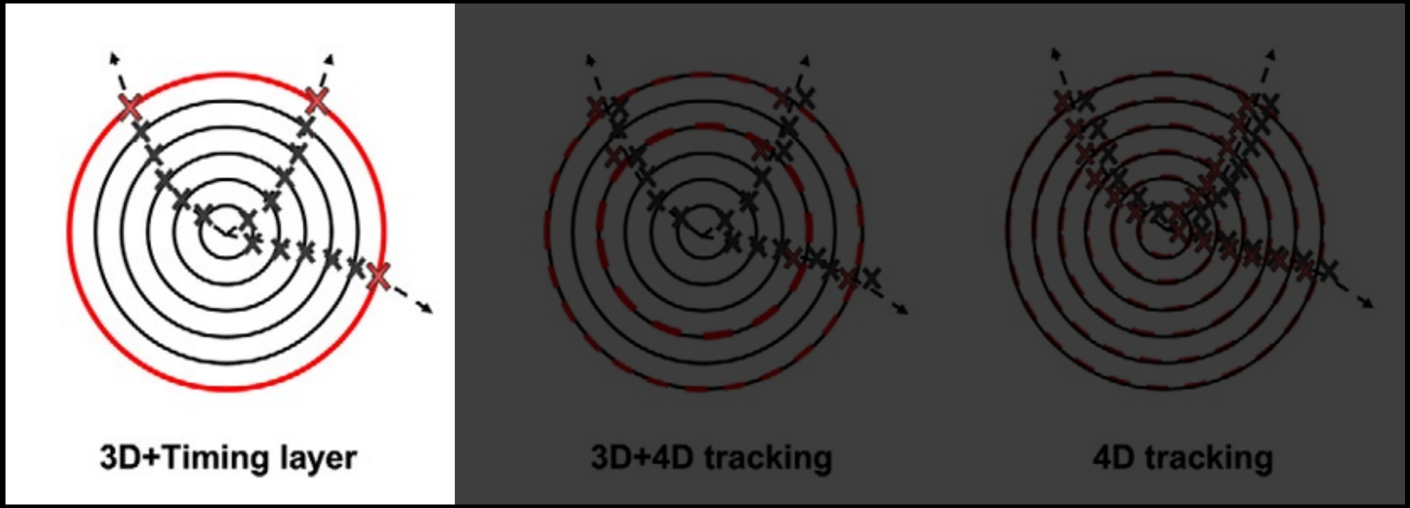
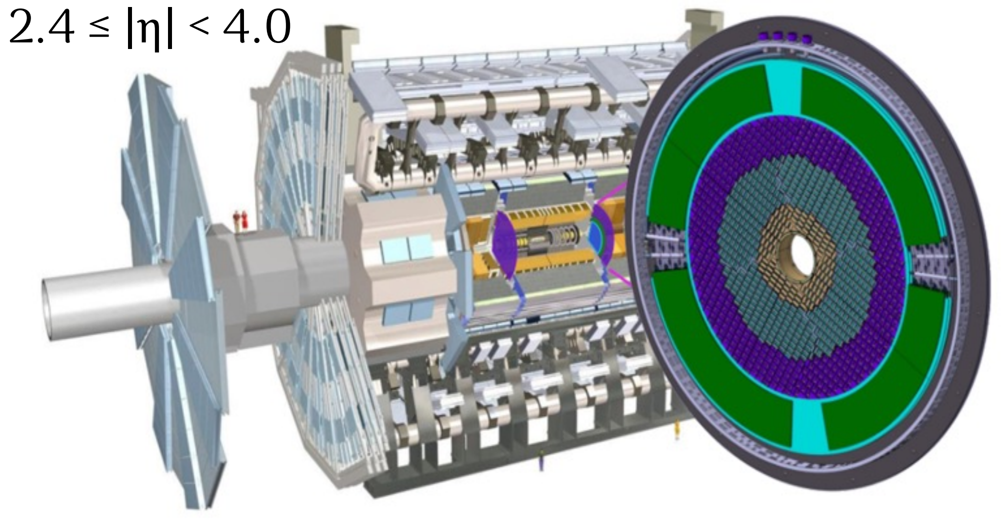


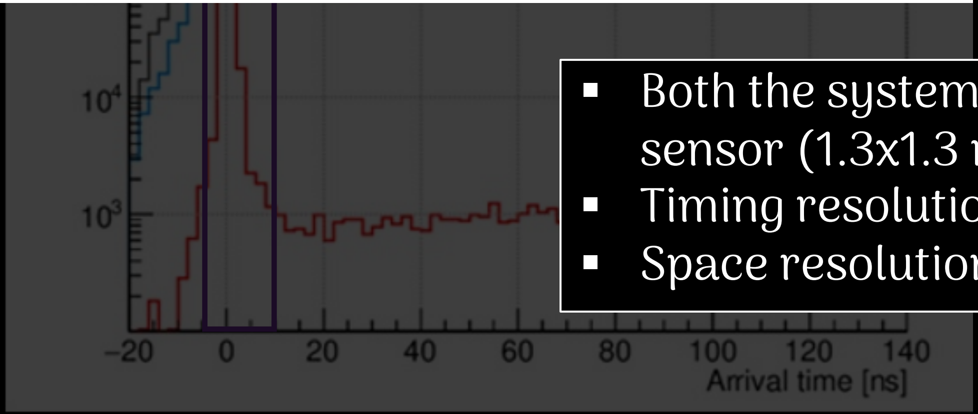
Strategy adopted by ATLAS and CMS for HL-LHC



Incorporating timing information

ATLAS HGTD





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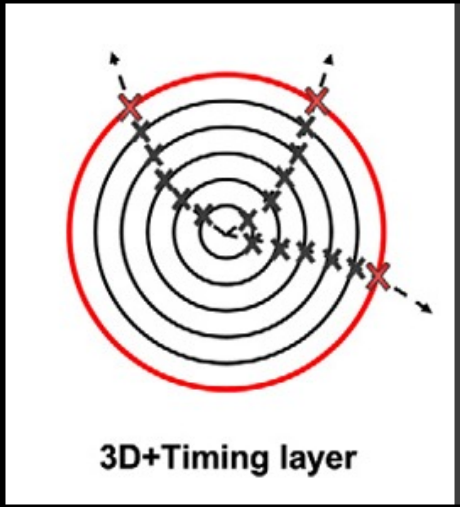
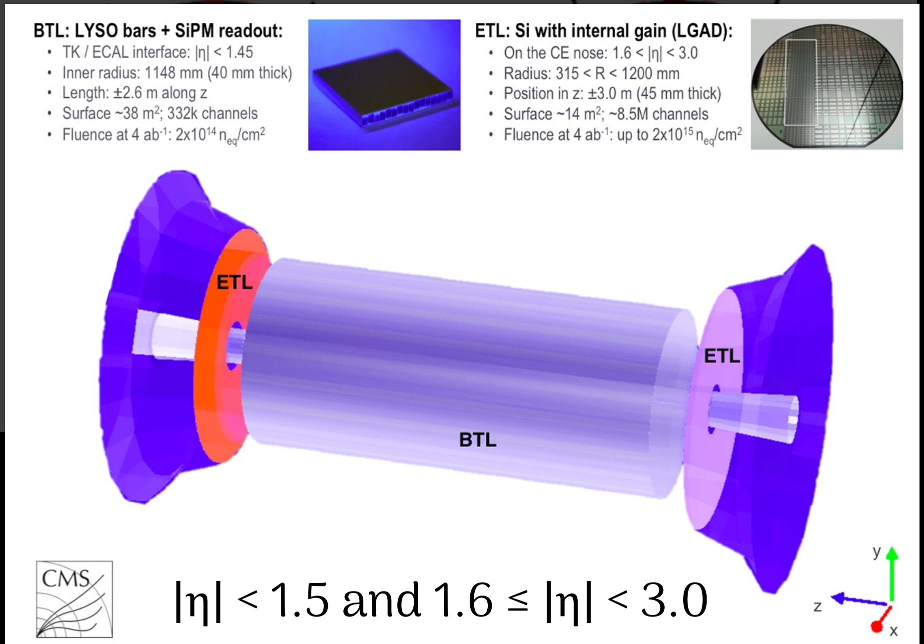


CMS MTD



- Both the systems are based on LGAD sensor (1.3x1.3 mm^2) technology
- Timing resolution ~ 30-50 ps
- Space resolution ~ mm

Incorporating timing information: Muon Collider

Timing cut to mitigate out-of-time BIB

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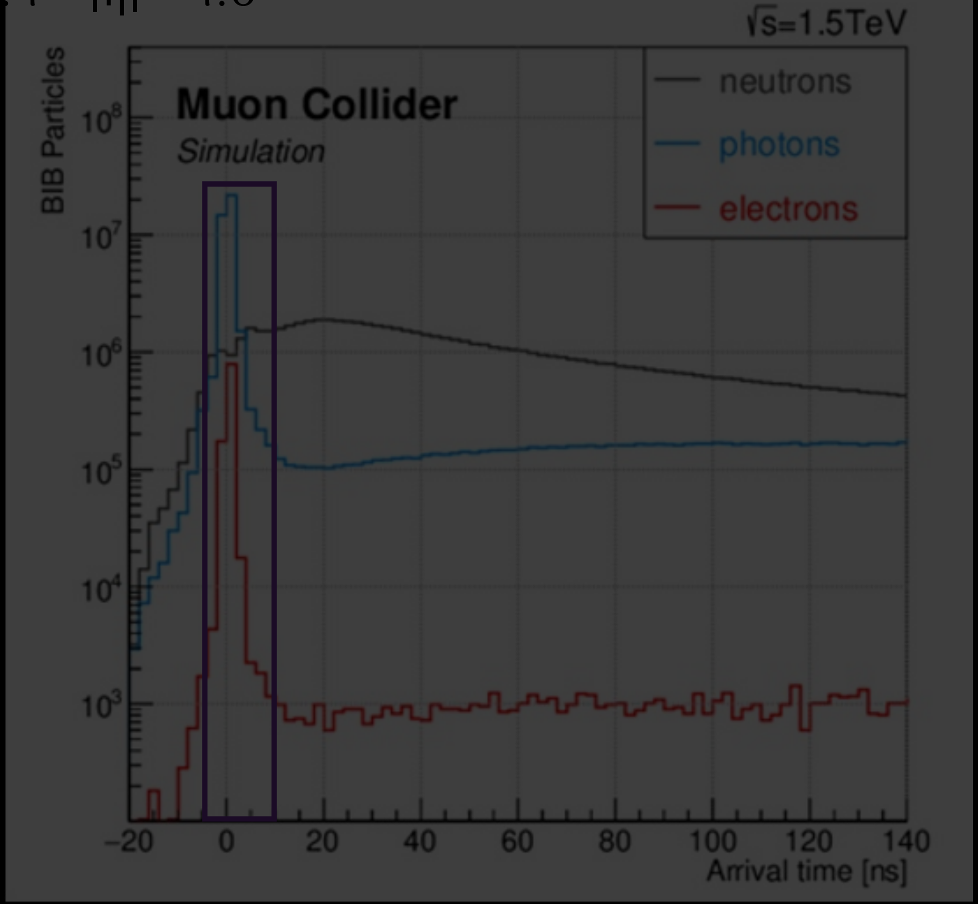
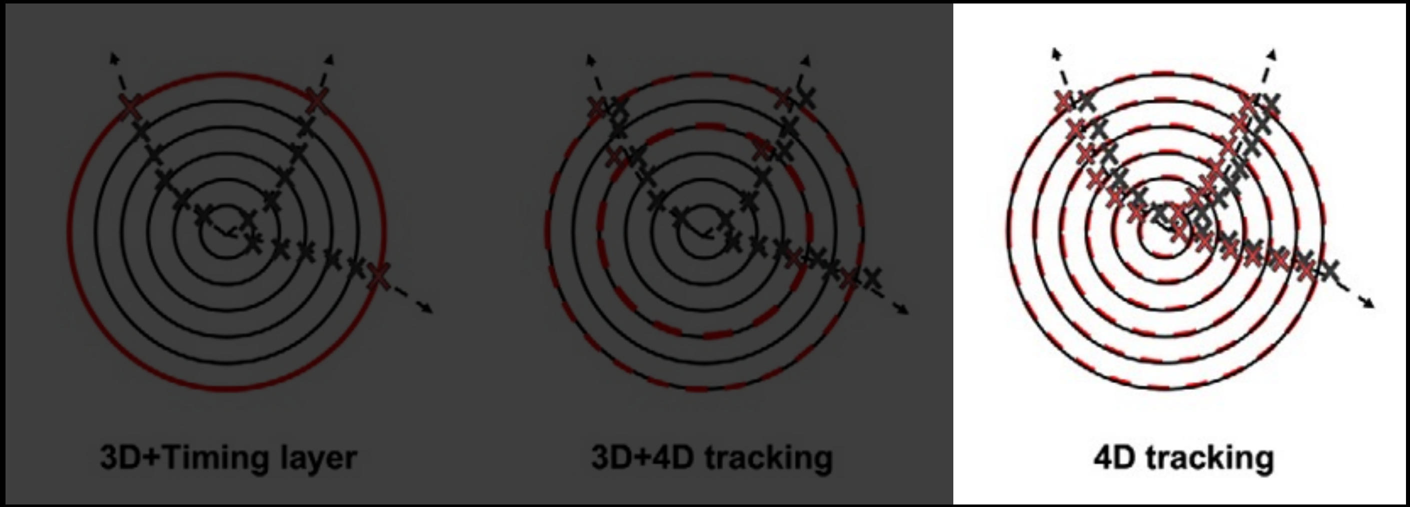


Per-hit timing (30-50ps) information:
Critical Requirement for the Muon Collider



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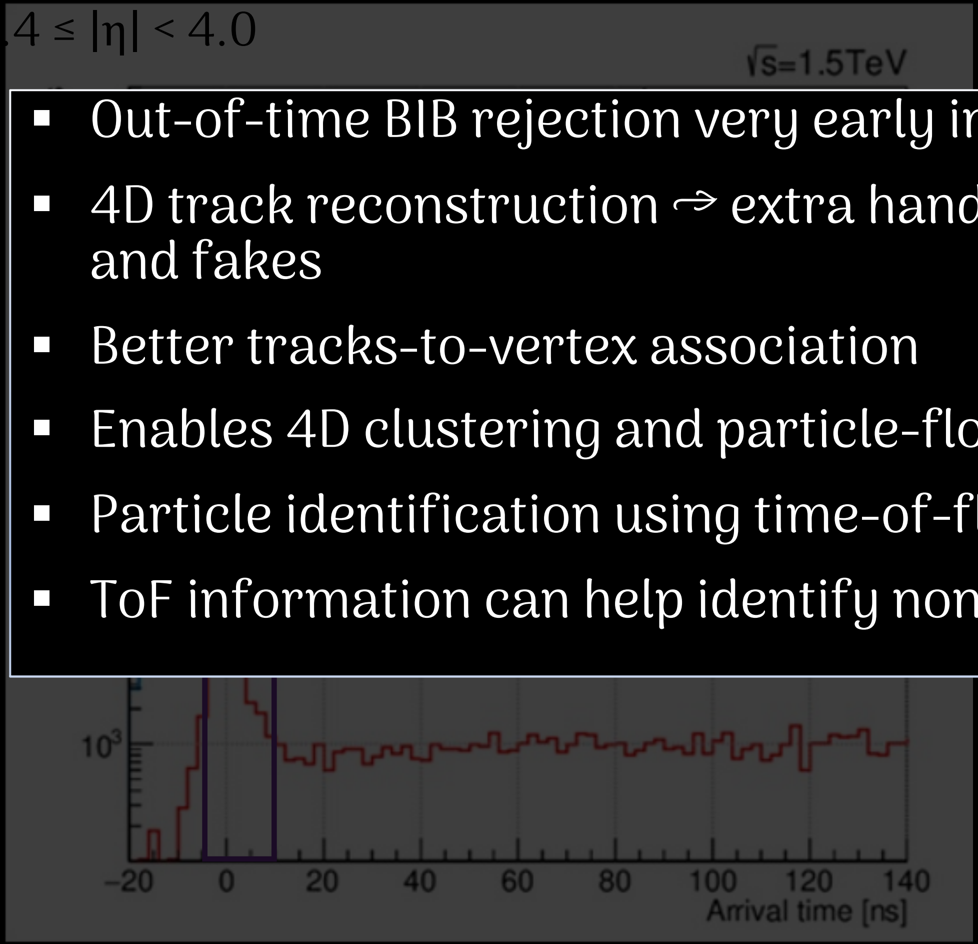

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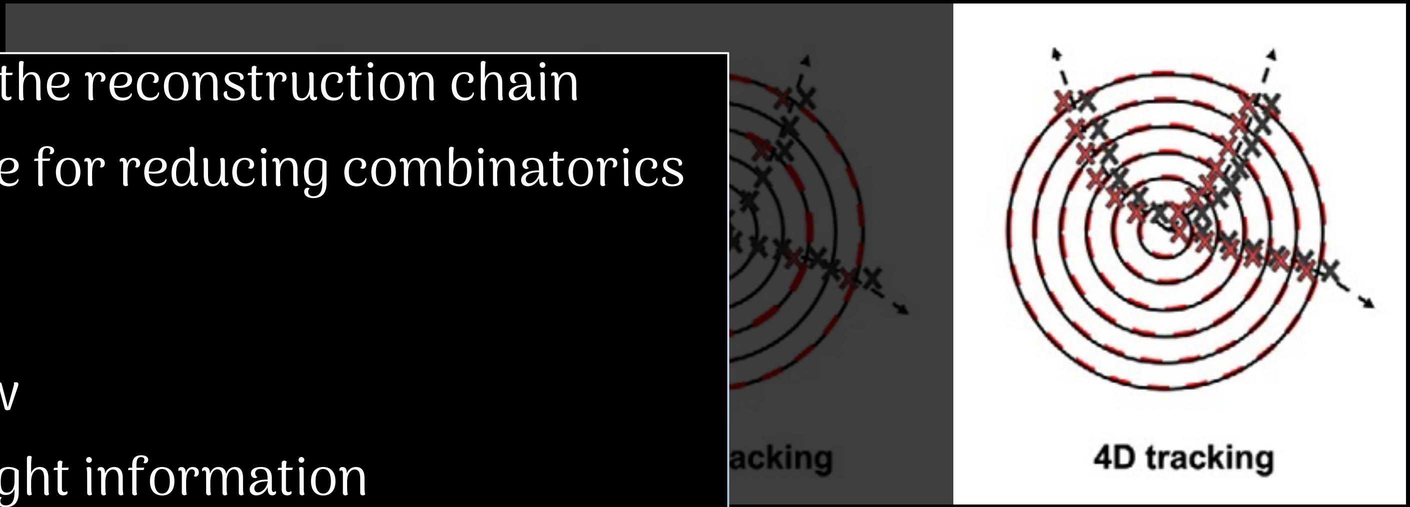
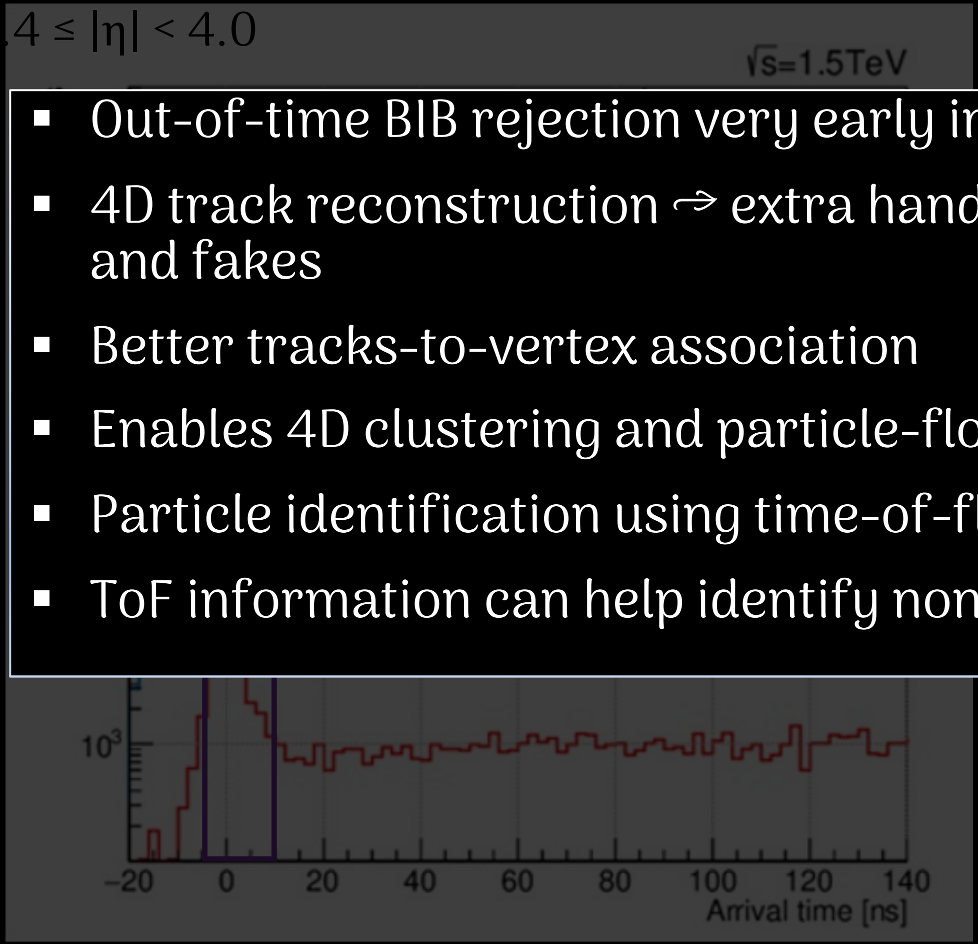


- Out-of-time BIB rejection very early in the reconstruction chain
- 4D track reconstruction → extra handle for reducing combinatorics and fakes
- Better tracks-to-vertex association
- Enables 4D clustering and particle-flow
- Particle identification using time-of-flight information
- ToF information can help identify non-prompt signatures

More in talks by Jennifer Ott and Artur Apreysan

Incorporating timing information: Muon Collider

Timing cut to mitigate out-of-time BIB



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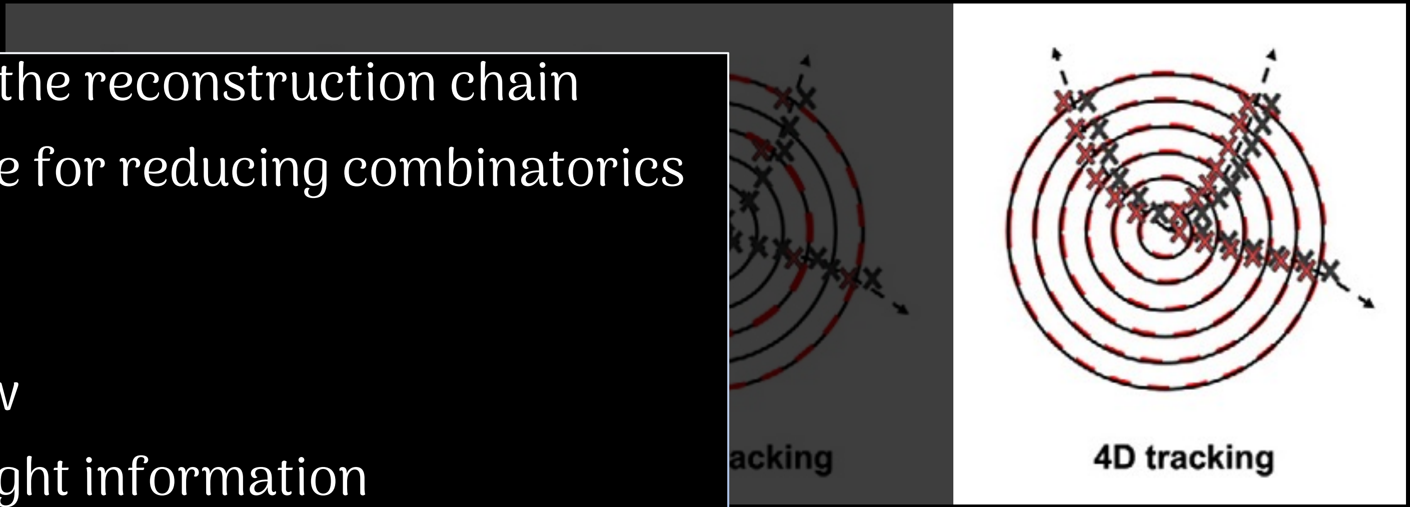

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Intensive R&D efforts underway to develop detectors with ps-level timing and μm-level spatial resolution
(Talks by Cristian Pena and Murtaza Safdari)
(4D tracking workshop 2024, SLAC)

Tracking with Machine Learning

Tracking with Machine Learning

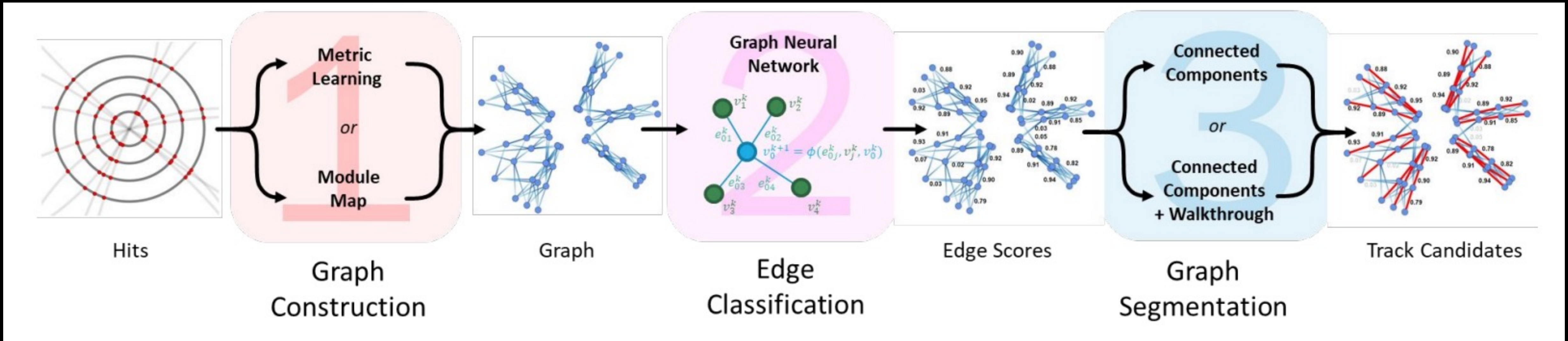
&

Tracking with time-aware Machine Learning

Track reconstruction using GNN / time-aware GNN

- GNNs naturally fits for tracking as a graph problem
  - Hits → nodes, Potential connections → edges
  - and tracking is essentially about identifying the correct relationship between hits
- Timing information **can add a powerful new dimension**

GNN4ITk Pipeline



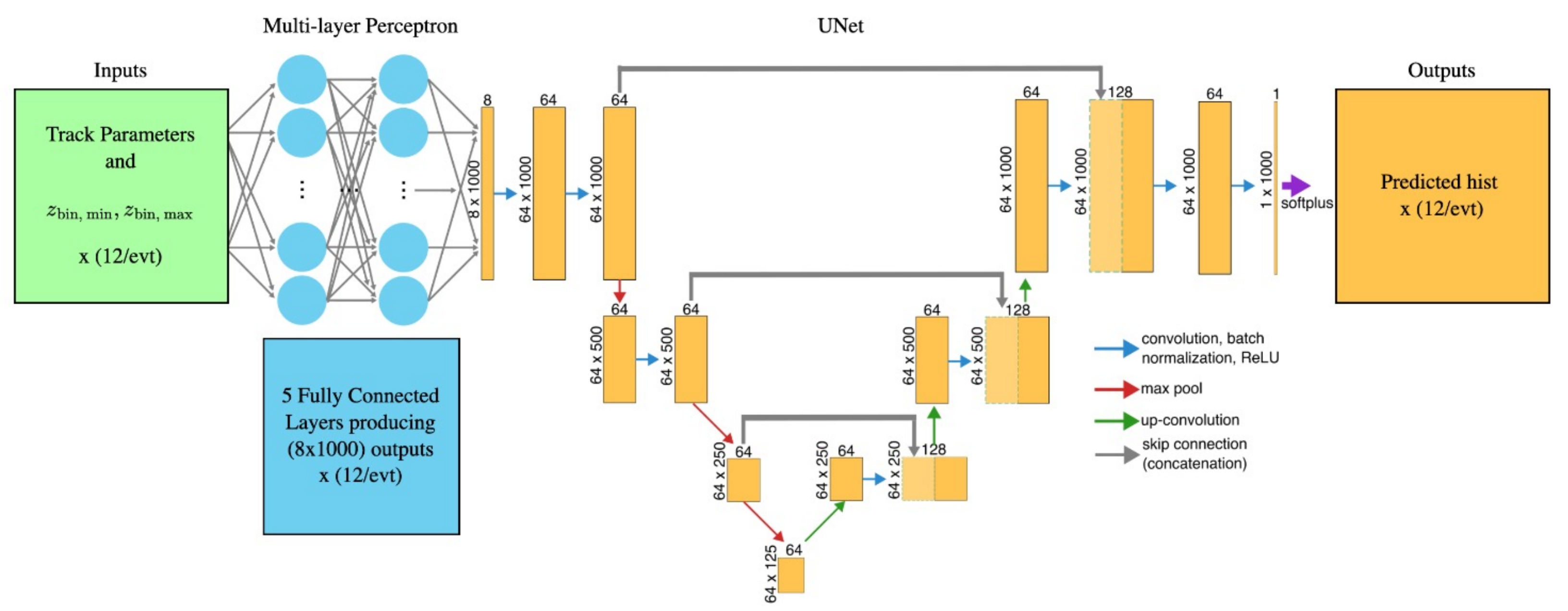
Link to paper

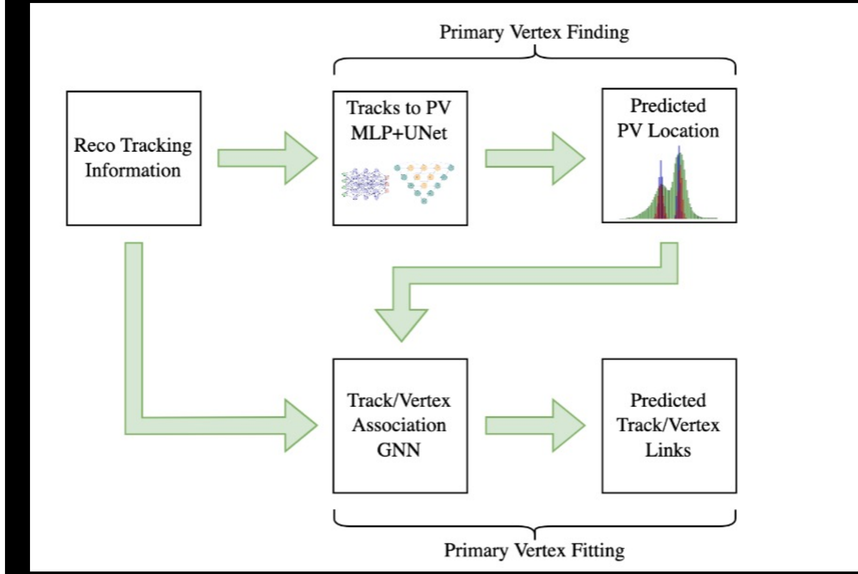
Primary vertex finding using CNN+GNN

Paper

- Primary vertices are essentially collision points on the z-axis ⇾ 1-D image ⇾ CNNs
- Tracks-to-vertex association ⇾ Node-edge connections ⇾ GNNs

ATLAS PV-Finder Pipeline

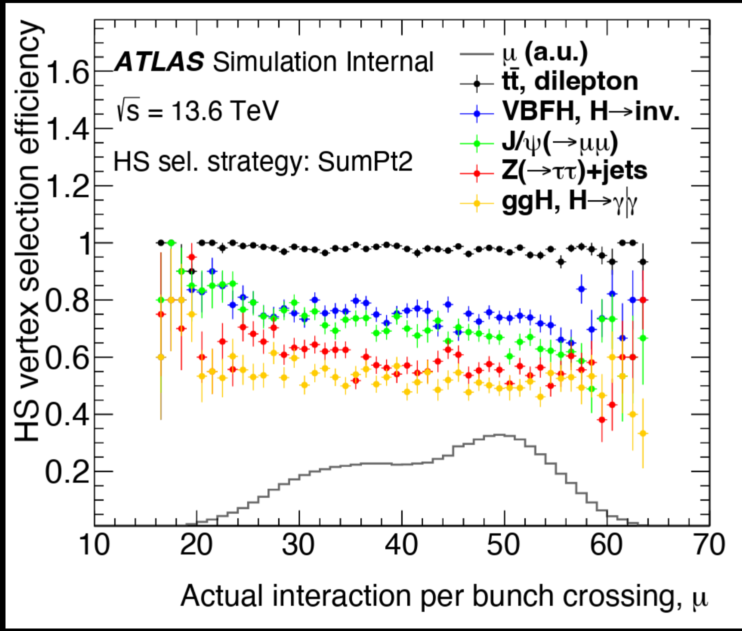




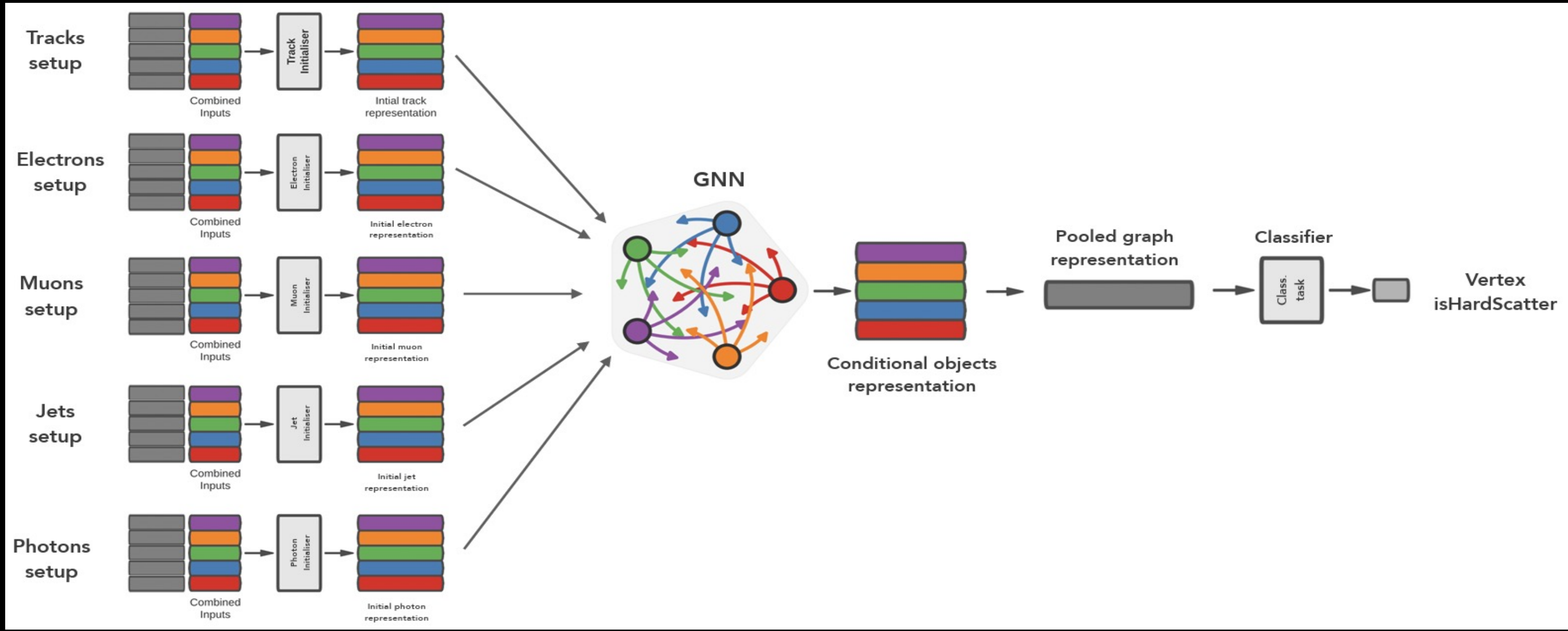
Hard Scatter Vertex selection using GNN

- SumPT2 is not the best metric for many physics processes
- A GNN trained on physics objects information can provide better handle for HS selection
- Timing information may provide new dimensions

Motivation



ATLAS HSGN2 Pipeline

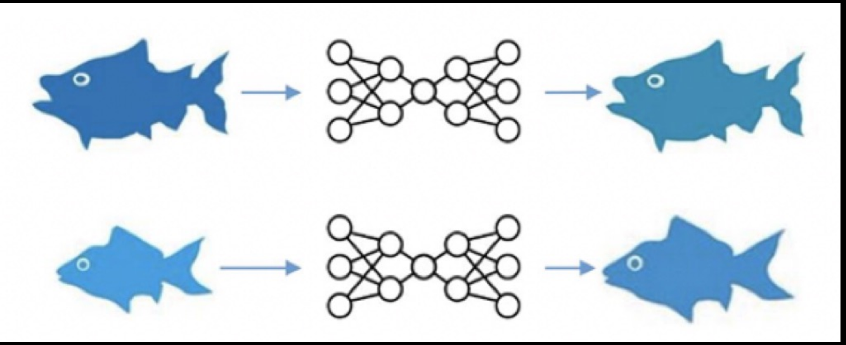


Anomaly detection and other tools for hit clustering and BIB suppression

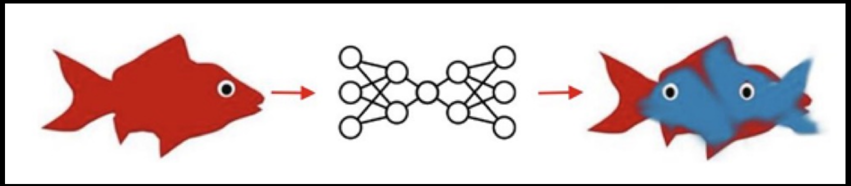
- Suppress non-signal-like hit clusters or energy deposits in **tracking and calorimeters**
- Anomaly detection models can learn typical signal patterns and flag **out-of-time**, **diffuse**, or **isolated activity** characteristic of BIB
- This allows **early filtering** of background before reconstruction, improving both **efficiency** and **accuracy**

- **Other deep learning based supervised ML models** combined with **precision timing information** can also **predict hit cluster shapes** and **discriminate against BIB hits**

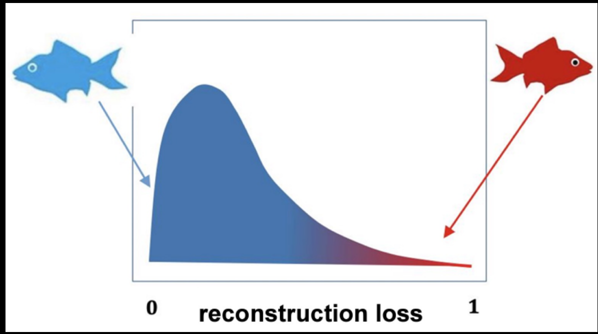
Train the model on non-anomalous samples



Test the model on real data samples to look for anomalies

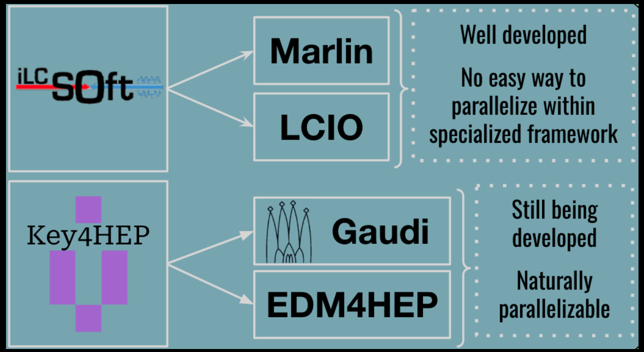


Anomaly score



Muon Collider Software Framework

Muon Collider Software Framework



Software Environment

- MUONCOLLIDERSOFT software stack built on top of key4HEP stack
- Reproducible, source-based builds managed through **Spack package manager**

Event Data Models

- EDM4hep: key4hep native (Default for Gaudi based workflows)
- LCIO: Legacy EDM used in Marlin based processors

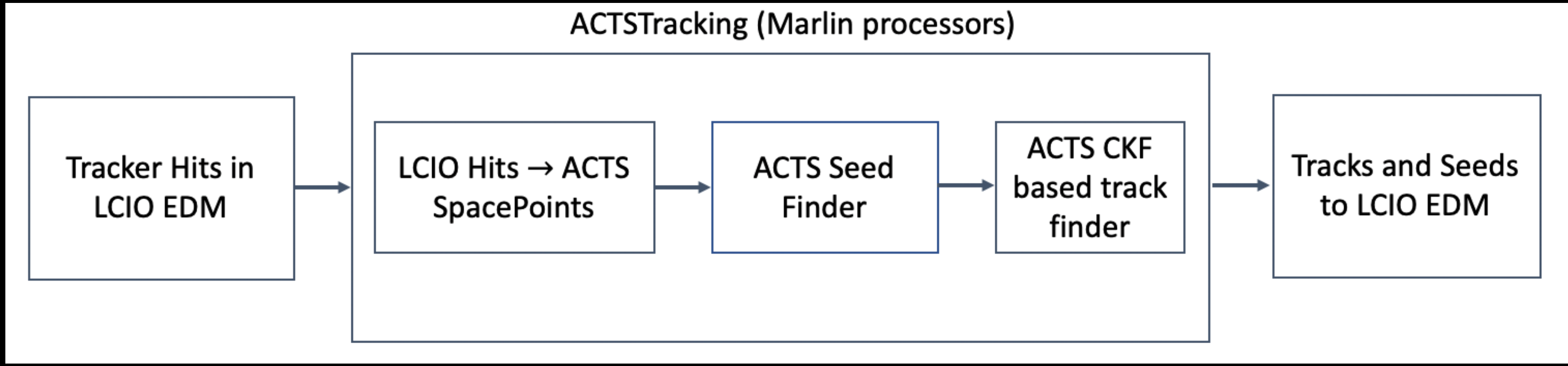
Frameworks & Infrastructure

- **Gaudi:** Primary application framework for simulation and reconstruction
- **Marlin:** Legacy framework from iLCSoft still used for many reconstruction algorithms (MarlinTrkProcessors)
- k4MarlinWrapper: Enables use of Marlin processors inside Gaudi-based workflows
- **DD4hep**: Unified geometry & detector description system
- **Geant4, Delphes**: Full and fast simulation supported
- **ACTS**: Track reconstruction software

ACTS based Tracking

Paper

- What is ACTS?
  - Short for ‘A Common Tracking Software’
  - open-source track reconstruction software
  - Detector agnostic: can be configured with different geometries
  - Based on latest C++: inherently parallelizable and fast
  - Already supports 4D track measurements
- ACTS integration into Muon Collider Software Framework: through a wrapper around ACTS algorithms called ACTSTracking
    - Convert MuCol-specific LCIO EDM to the ACTS EDM format
    - Perform track reconstruction using ACTS algorithms
    - Convert reconstructed data back from ACTS EDM to LCIO EDM to be used downstream



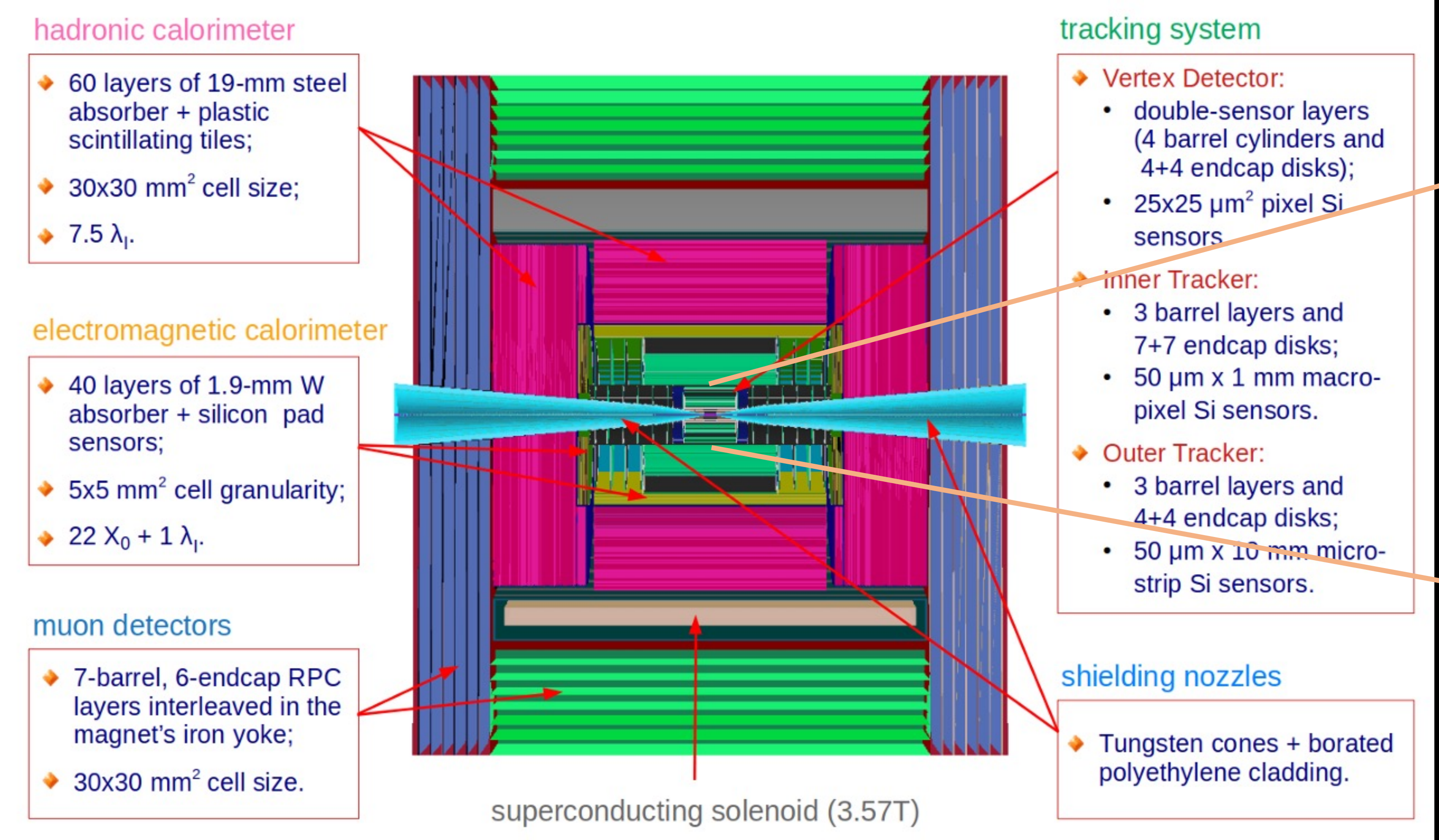
Conclusion

- Tracking at Muon Colliders poses challenges unseen at previous colliders
- **4D tracking** is **not just desirable but critical** for the **Muon Collider**
- **Machine Learning** offers promising tools to address complex pattern recognition and background suppression tasks
- Progress will require **tight integration of detector R&D, software development, and reconstruction algorithms**
- The Muon Collider is not just a challenge — it's an **opportunity to redefine tracking**

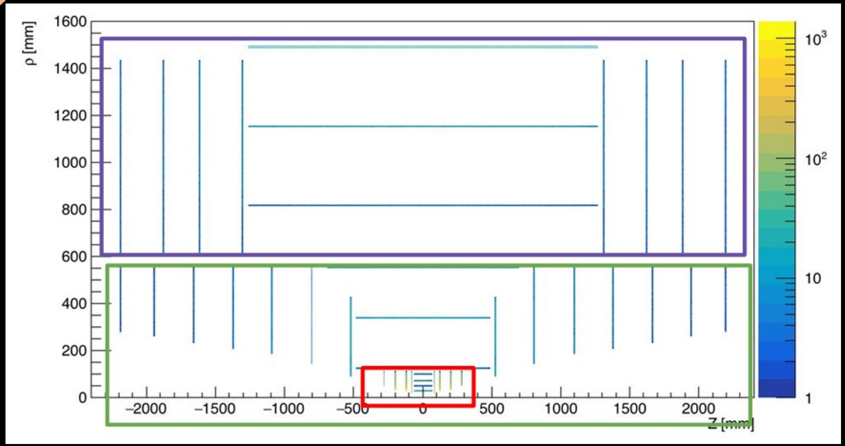
Back-up

Muon Collider Detector Concepts

Three geometries into consideration: MuColl_v1 ($\sqrt{s}$ = 3TeV, B = 3.57T), MuSiC and MAIA ($\sqrt{s}$ = 10TeV, B = 5.0T)



All-Silicon based Tracking system

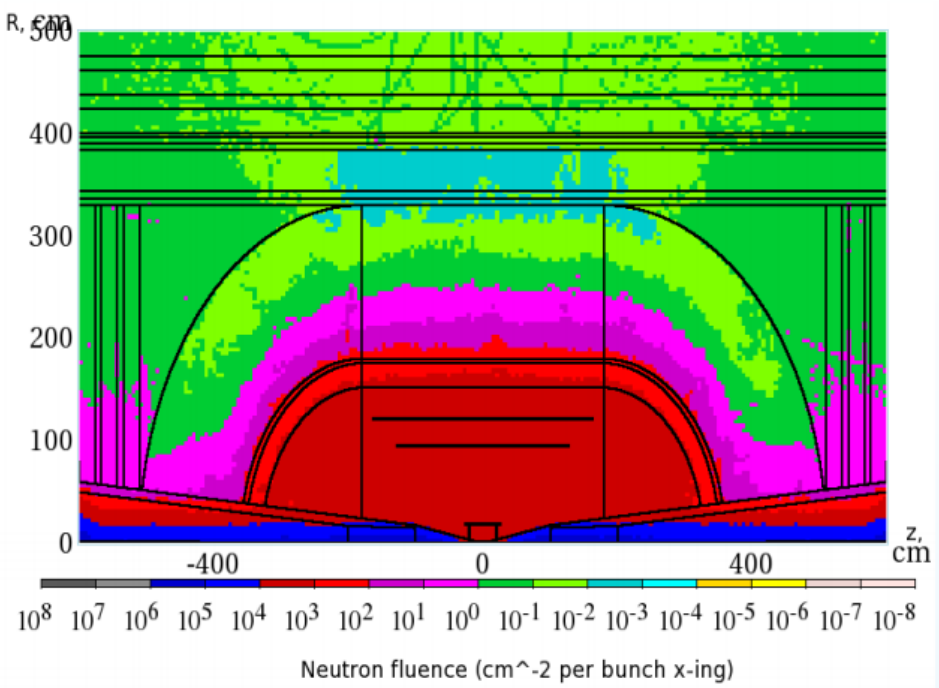


	Vertex Detector	Inner Tracker	Outer Tracker
Cell type	pixels	macropixels	microstrips
Cell Size	$25\mu m \times 25\mu m$	$50\mu m \times 1mm$	$50\mu m \times 10mm$
Sensor Thickness	$50\mu m$	$100\mu m$	$100\mu m$
Time Resolution	30ps	60ps	60ps
Spatial Resolution	$5\mu m \times 5\mu m$	$7\mu m \times 90\mu m$	$7\mu m \times 90\mu m$

S. Jindariani

Severe Radiation Environment

10 TeV Muon Collider



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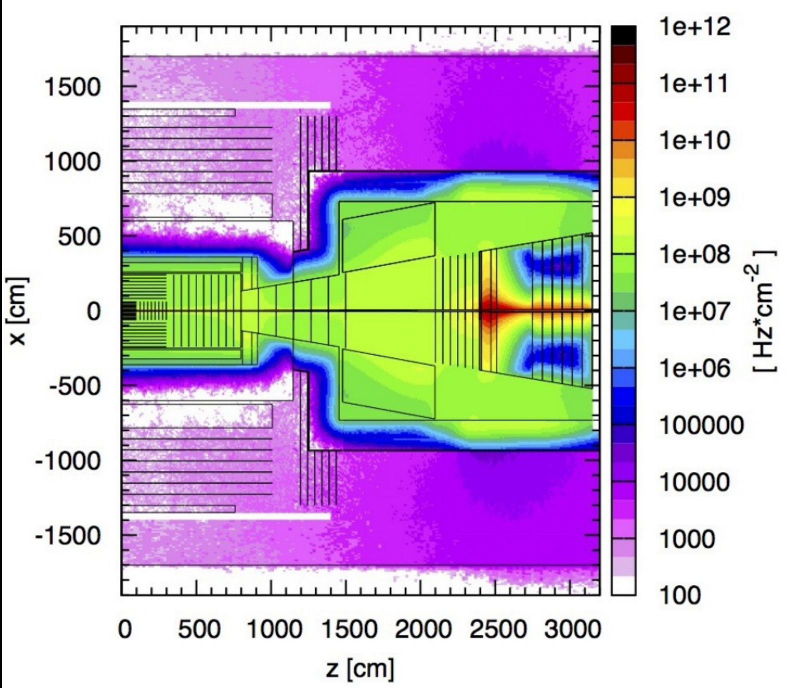
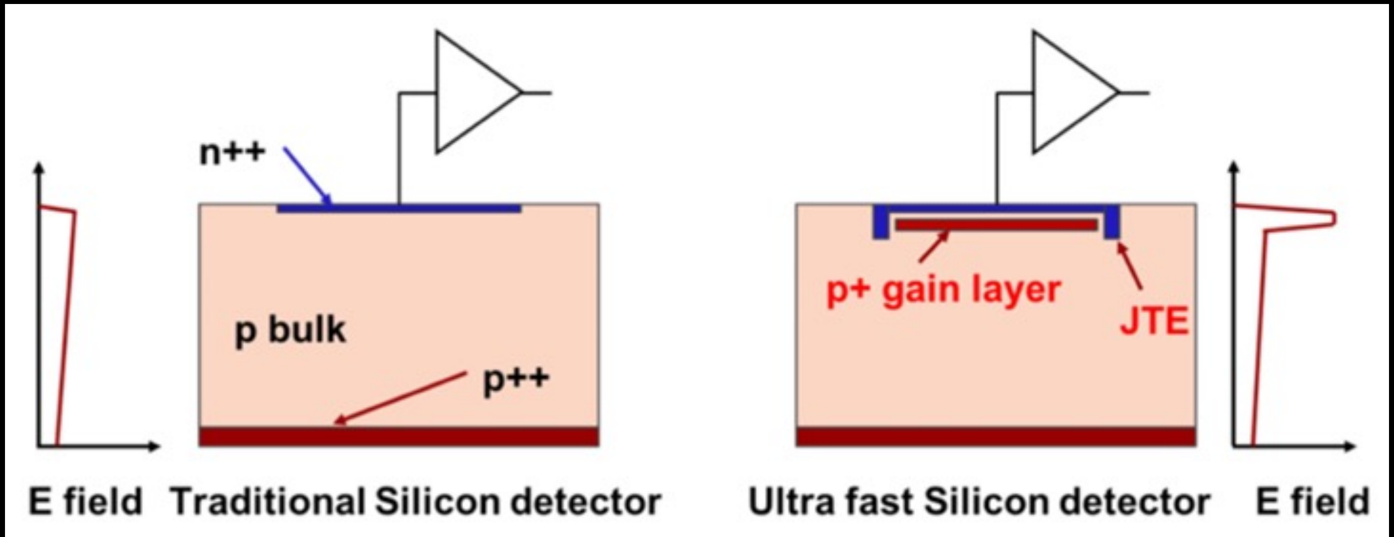


Neutron fluence per cm^2 per bunch x-ing

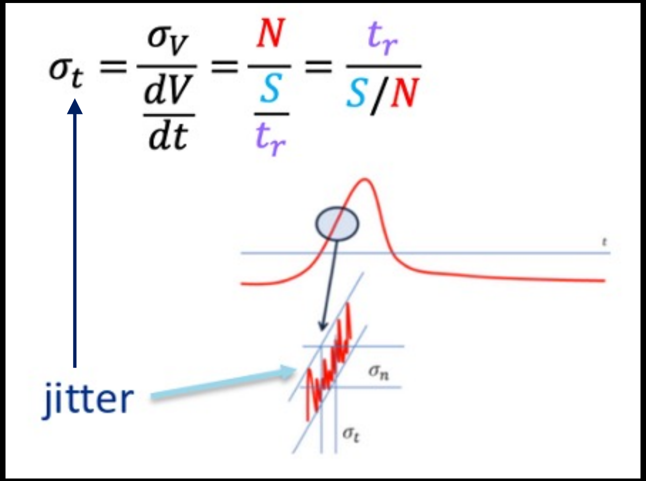
LGAD (Low Gain Avalanche Diodes)

- LGADs are silicon sensors that use an internal gain layer to induce controlled avalanche multiplication, boosting charge signals
- Fast rise time and high signal-to-noise ratio enable precise timing measurements with resolutions as low as 30-50ps
- However, achieving sufficient charge collection requires larger sensor pads, reducing spatial resolution to ~mm



Small Pixel size → Better spatial resolution

Small Pixel size → Less charge collection → large S/N → worse timing resolution



Why a single timing layer like CMS/ATLAS not enough for Muon Collider?

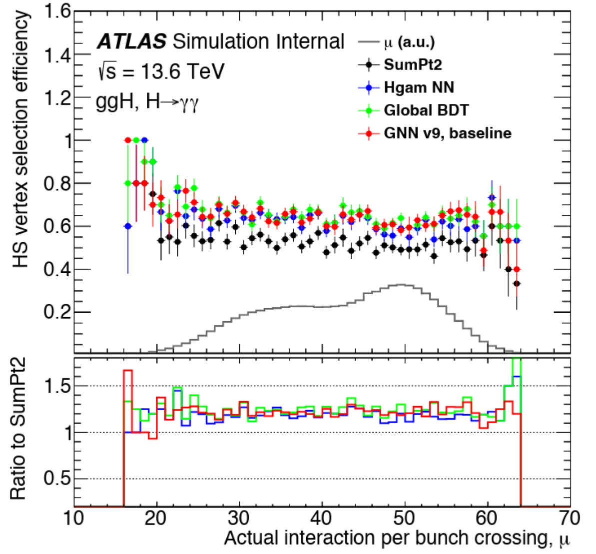
- No hit-level BIB rejection → tracking faces unmanageable combinatorics and fake tracks
- BIB hits can appear correlated across layers, mimicking real tracks
- Upstream tracking may already be compromised by the time timing information is available
- Late-arriving BIB can resemble non-prompt physics signatures
- BIB must be filtered out as early as possible in the reconstruction chain
- Poor tracking cascades into degraded particle flow, calorimetry, and object ID
- One time-stamp per track offers little help in rejecting BIB hits

How Particle-flow can help surpass BIB

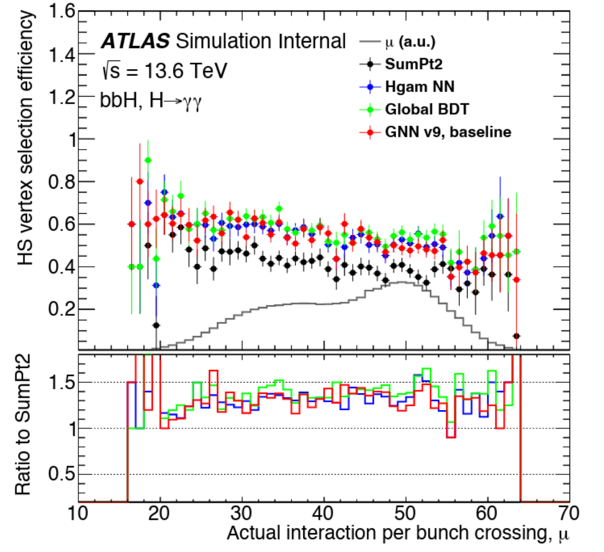
- Particle-flow algorithms aim to **reconstruct each particle** by combining data from all subdetectors—tracking, calorimetry, and muon systems.
- **How PF helps suppress BIB:**
  - Tracks genuine **charged particles** using the tracker, then **match them with calorimeter clusters**
  - **Clusters without matching tracks** can be scrutinized more carefully or suppressed—many BIB particles do not produce quality tracks
  - By identifying and separating **charged and neutral components**, PF algorithms can isolate unphysical patterns typical of BIB (e.g., isolated low-energy deposits without track correlation)
- PF enables more **fine-grained association**, helping reject BIB-induced deposits that do not align with expected physics object topologies

HSGN2 Performance

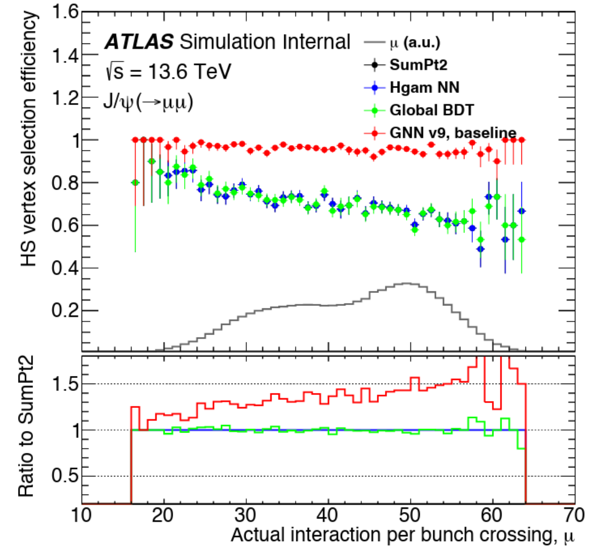
ggH, H→γγ



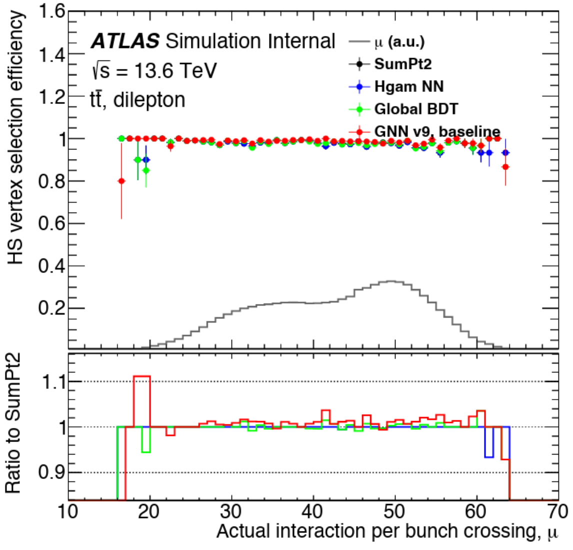
bbH, H→γγ



J/ψ→μμ



ttbar dilepton



Geometry dimensions

MuColl_V1: Solenoid after ECAL and HCAL

Subsystem	Region	R dimensions [cm]	|Z| dimensions [cm]	Material
Vertex Detector	Barrel	3.0 – 10.4	65.0	Si
	Endcap	2.5 – 11.2	8.0 – 28.2	Si
Inner Tracker	Barrel	12.7 – 55.4	48.2 – 69.2	Si
	Endcap	40.5 – 55.5	52.4 – 219.0	Si
Outer Tracker	Barrel	81.9 – 148.6	124.9	Si
	Endcap	61.8 – 143.0	131.0 – 219.0	Si
ECAL	Barrel	150.0 – 170.2	221.0	W + Si
	Endcap	31.0 – 170.0	230.7 – 250.9	W + Si
HCAL	Barrel	174.0 – 333.0	221.0	Fe + PS
	Endcap	307.0 – 324.6	235.4 – 412.9	Fe + PS
Solenoid	Barrel	348.3 – 429.0	412.9	Al
Muon Detector	Barrel	446.1 – 645.0	417.9	Fe + RPC
	Endcap	57.5 – 645.0	417.9 – 563.8	Fe + RPC

MAIA: Solenoid before ECAL

Subsystem	Region	R dimensions [cm]	|Z| dimensions [cm]	Material
Vertex Detector	Barrel	3.0 – 10.4	65.0	Si
	Endcap	2.5 – 11.2	8.0 – 28.2	Si
Inner Tracker	Barrel	12.7 – 55.4	48.2 – 69.2	Si
	Endcap	40.5 – 55.5	52.4 – 219.0	Si
Outer Tracker	Barrel	81.9 – 148.6	124.9	Si
	Endcap	61.8 – 143.0	131.0 – 219.0	Si
Solenoid	Barrel	150.0 – 185.7	230.7	Al
ECAL	Barrel	185.7 – 212.5	230.7	W + Si
	Endcap	31.0 – 212.5	230.7 – 257.5	W + Si
HCAL	Barrel	212.5 – 411.3	257.5	Fe + PS
	Endcap	30.7 – 411.3	257.5 – 456.2	Fe + PS
Muon Detector	Barrel	415.0 – 715.0	456.5	Air + RPC
	Endcap	44.6 – 715.0	456.5 – 602.5	Air + RPC