Detector and Reconstruction Performance

aka how to deal with Beam Induced Background

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on behalf of many people

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International MUON Collider Collaboration

BERKELEY LAB
Lawrence Berkeley National Laboratory

Snowmass 2022

Our Onion Detector

Details

heavily based on CLIC detector

hadronic calorimeter

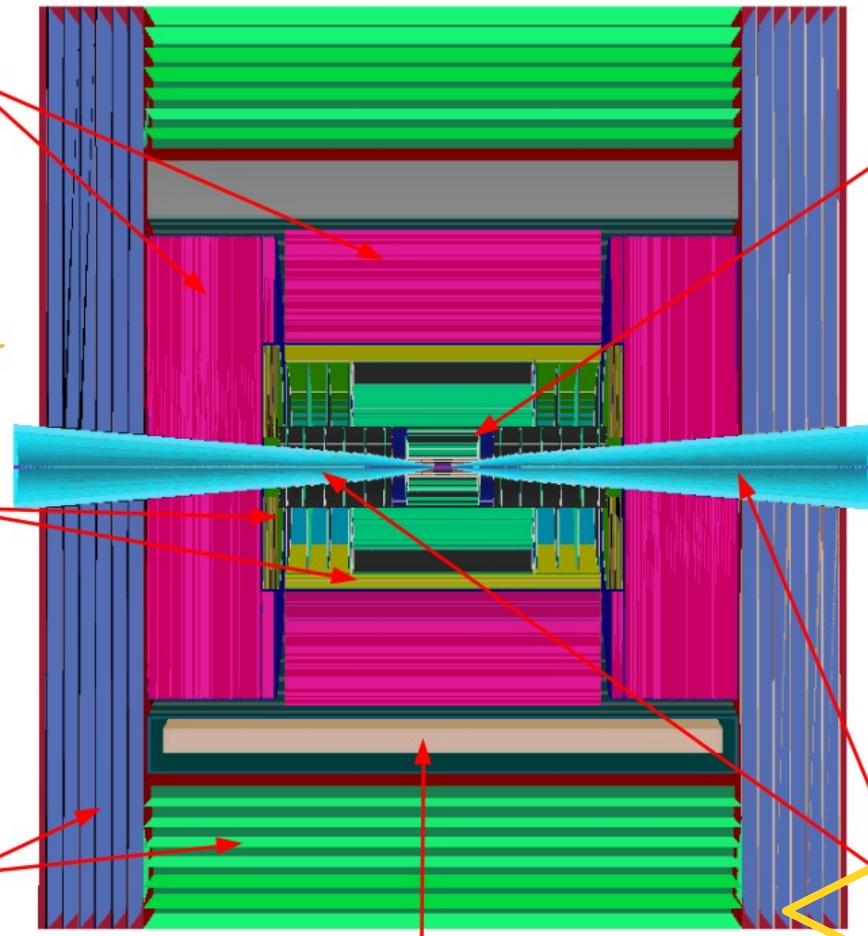
- 60 layers of 19-mm steel absorber + plastic scintillating tiles;
- 30x30 mm^2 cell size;
- 7.5 λ_I.

electromagnetic calorimeter

- 40 layers of 1.9-mm W absorber + silicon pad sensors;
- 5x5 mm^2 cell granularity;
- 22 X_0 + 1 λ_I.

muon detectors

- 7-barrel, 6-endcap RPC layers interleaved in the magnet's iron yoke;
- 30x30 mm^2 cell size.



superconducting solenoid (3.57T)

tracking system

- Vertex Detector:
  - double-sensor layers (4 barrel cylinders and 4+4 endcap disks);
  - 25x25 μm^2 pixel Si sensors.
- Inner Tracker:
  - 3 barrel layers and 7+7 endcap disks;
  - 50 µm x 1 mm macro-pixel Si sensors.
- Outer Tracker:
  - 3 barrel layers and 4+4 endcap disks;
  - 50 µm x 10 mm micro-strip Si sensors.

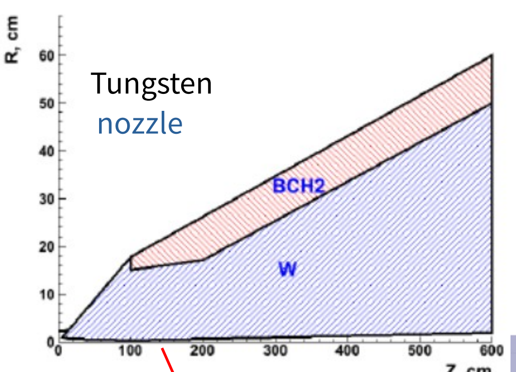
shielding nozzles

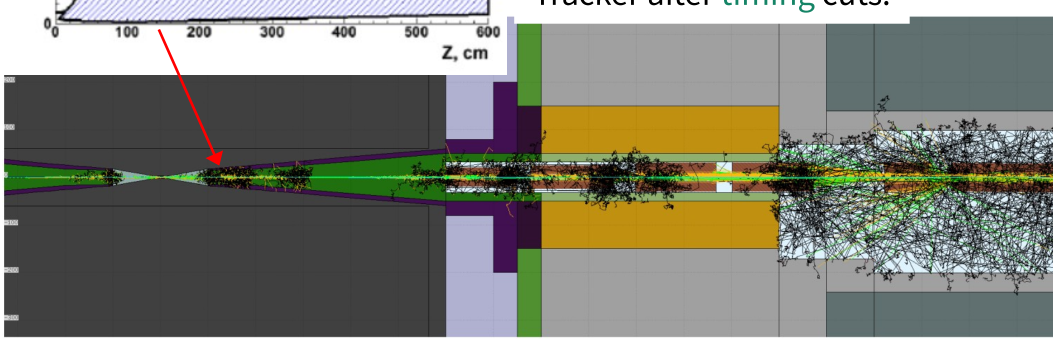
- Tungsten cones + borated polyethylene cladding.

Beam Induced Background

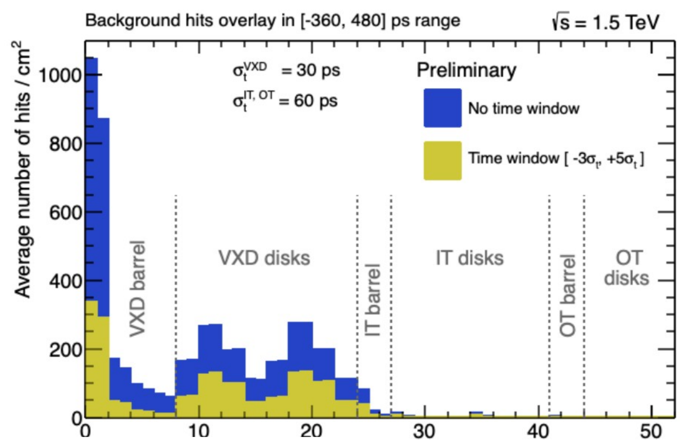
arxiv:2105.09116

- **BIB = muon beam decay and strike the detector**
- **Several main mitigation**
  - 10° tungsten nozzle to shield from beam decay products
  - Precision timing information from detectors

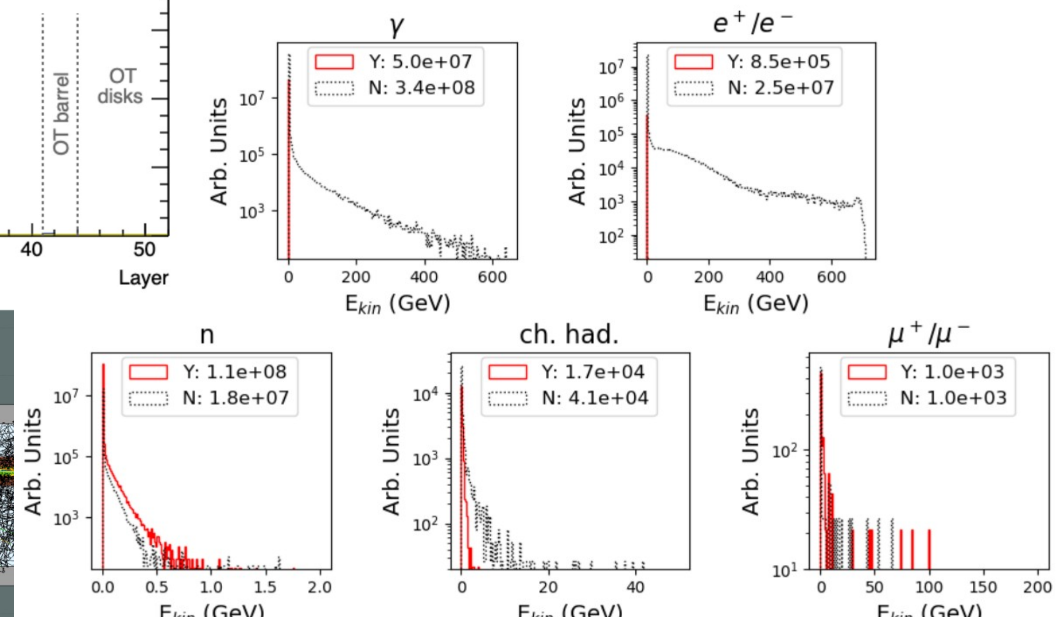




FLUKA simulation of BIB before reaching the detector.



Tracker after timing cuts.



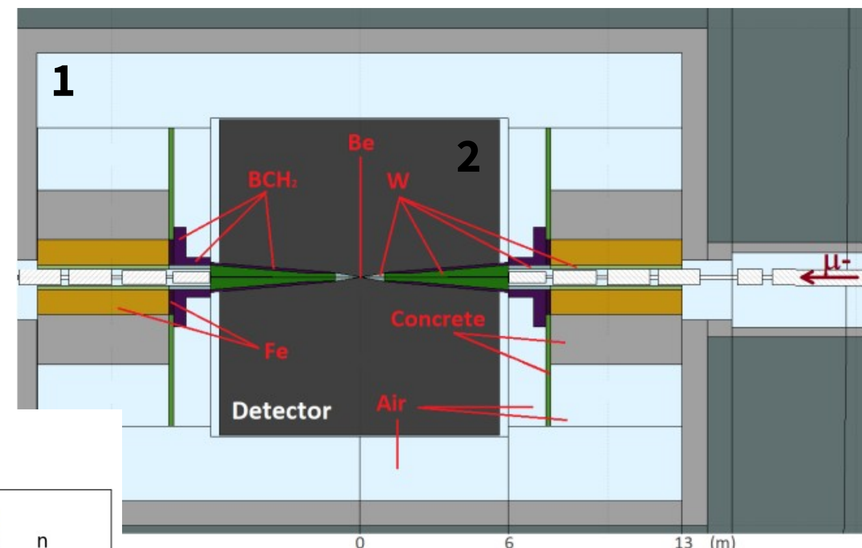
Particle energy spectra with (Y) and without (N) nozzle.

Simulating Beam Induced Background

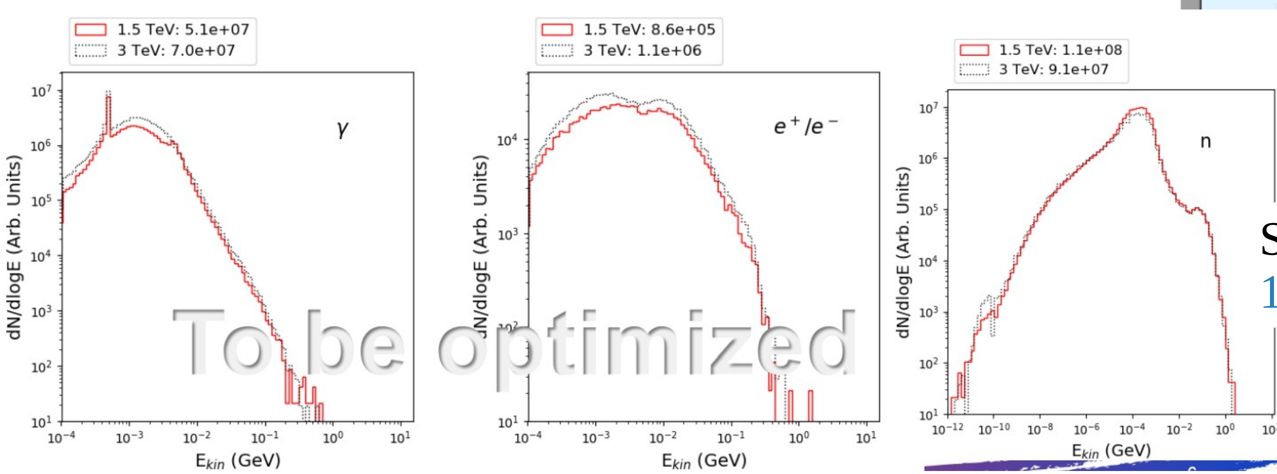
1)Muon trajectory, decay and transport of products via FLUKA*

- Full beam optics present through LineBuilder Interface

2)GEANT simulation of particles entering the detector



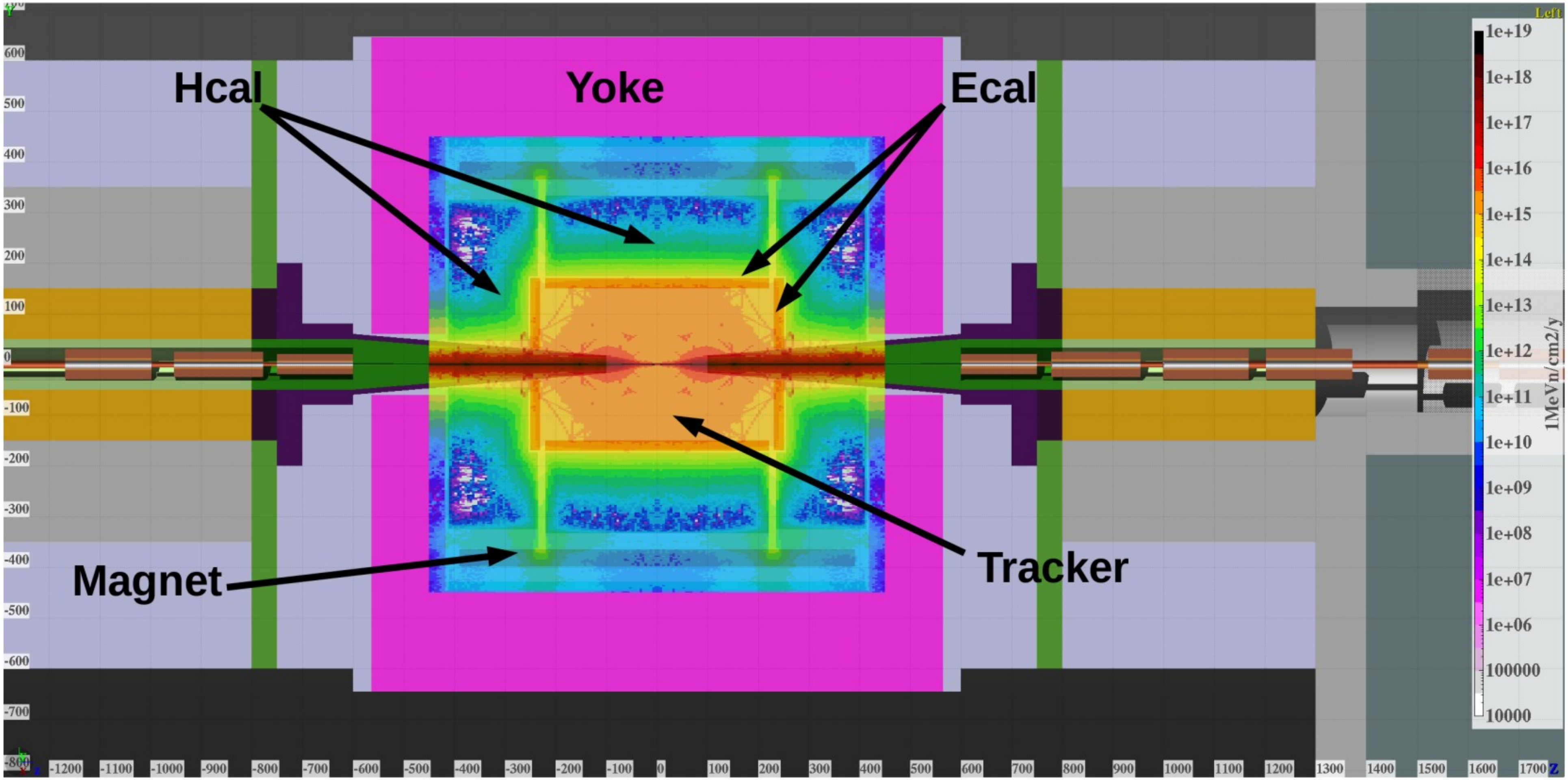
1.5 TeV used to develop setup, more energy points becoming available



Source:
1.5 vs 3 TeV

* validated against an older model from MARS15

Radiation Damage From BIB

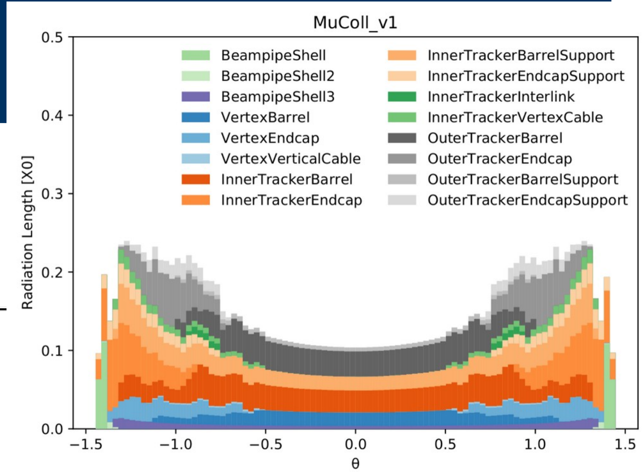


Dose comparable to full HL-LHC luminosity.

source

All-Silicon Tracking Detector

Details



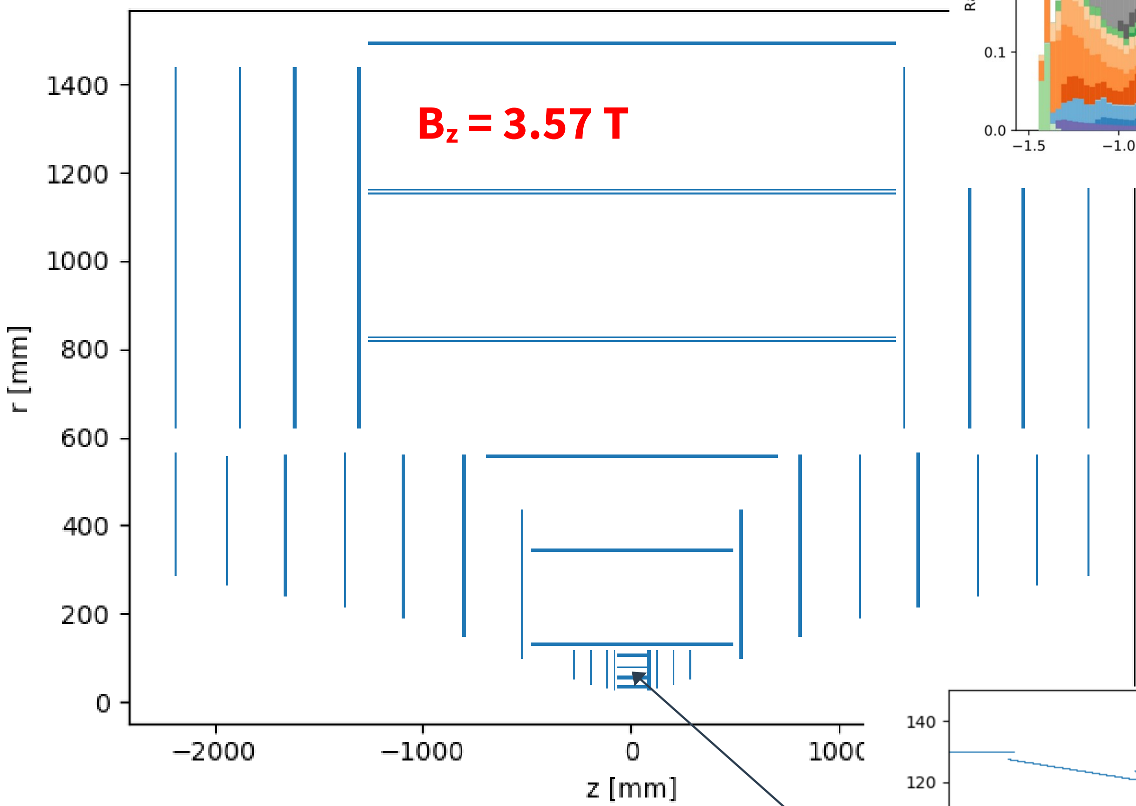
Material description

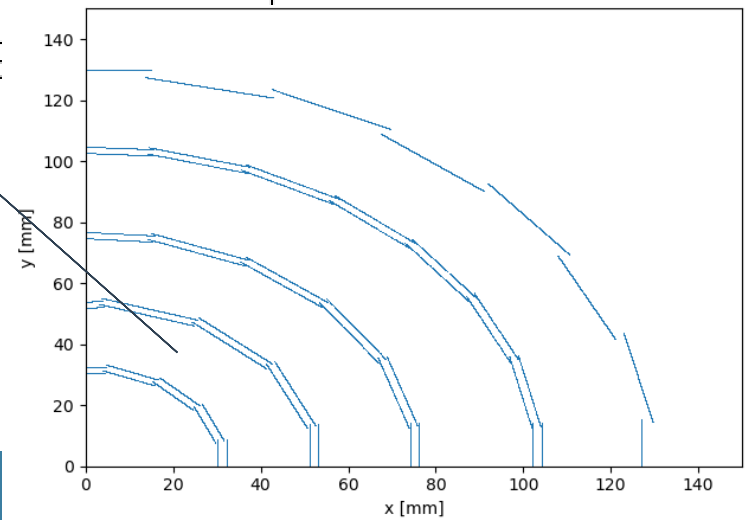
Outer Tracker (OT)

- micro-strips

Inner Tracker (IT)

- macro-pixels



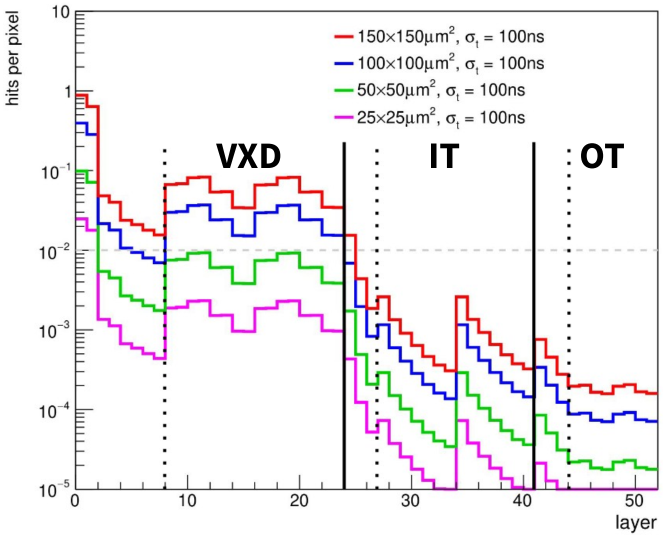


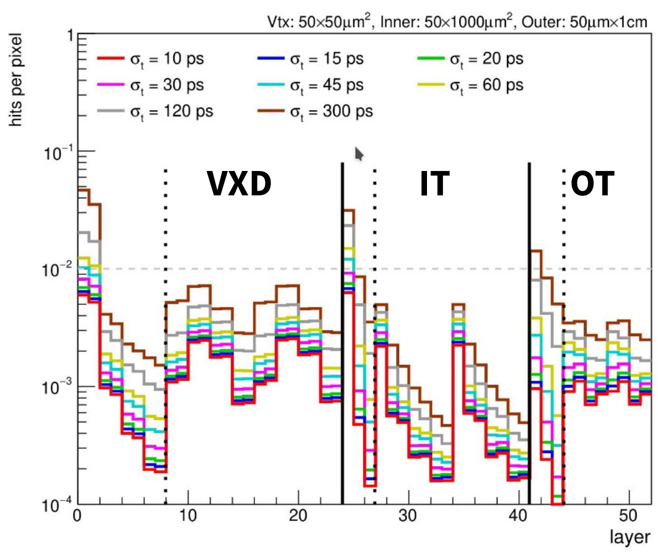
Vertex Detector (VXD)

- pixels
- double layers

Pixel Size and Timing

Details





- **Goal is <1 % occupancy per pixel.**
  - Pixel size optimized to achieve this
  - Precision timing also plays important role
    - Needed for on-detector filtering (for readout)
- **Need to be careful about slow particles**
- **Resolutions are approximated in simulation using Gaussian smearing**

Current Assumptions

	Cell Size	Sensor Thickness	Time Resolution	Spatial Resolution
VXD	25 µm x 25 µm	50 µm	30 ps	5 µm x 25 µm
IT	20 µm x 1 mm	100 µm	60 ps	7 µm x 90 µm
OT	50 µm x 10 mm	100 µm	60 ps	7 µm x 90 µm

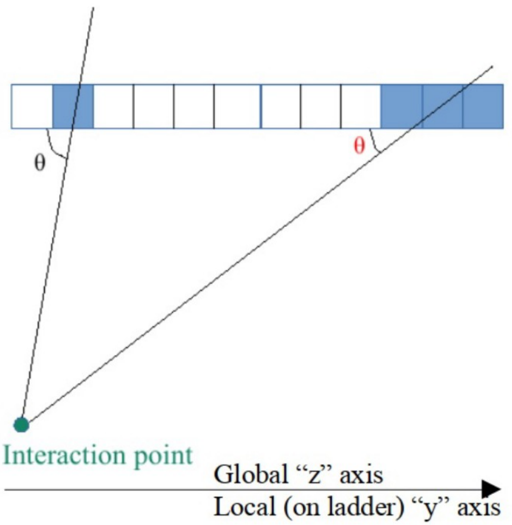
No difference between barrel and endcap.

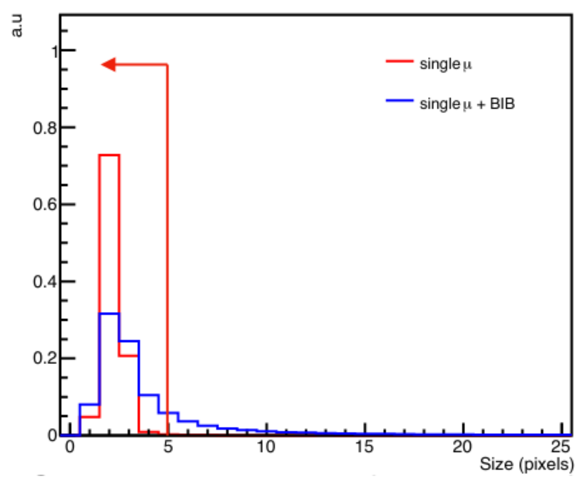
Realistic Digitization

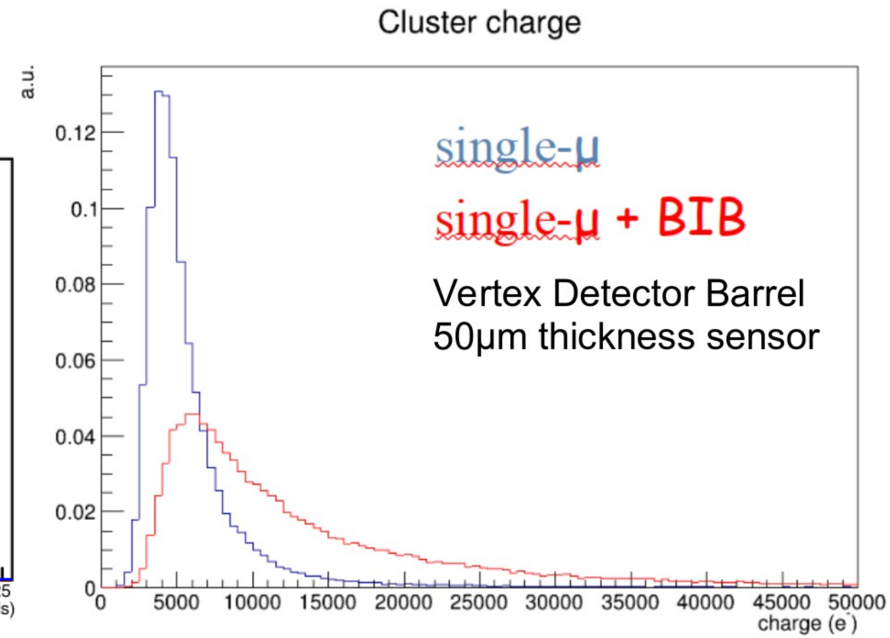
Details

Work In Progress: Currently not part of common workflow

- Provides a more accurate description of hit clusters
- Provides a handle on BIB rejection







Requirement	Cut efficiency	Loose	Tight
Size-y cut vs. θ only	Single-μ	99.8 %	99.6 %
	Single-μ and BIB	55.2 %	43.7 %
Adding pixel size-x < 4	Single-μ	99.3 %	99.1 %
	Single-μ and BIB	37.4 %	30.7 %

Current Track Reconstruction

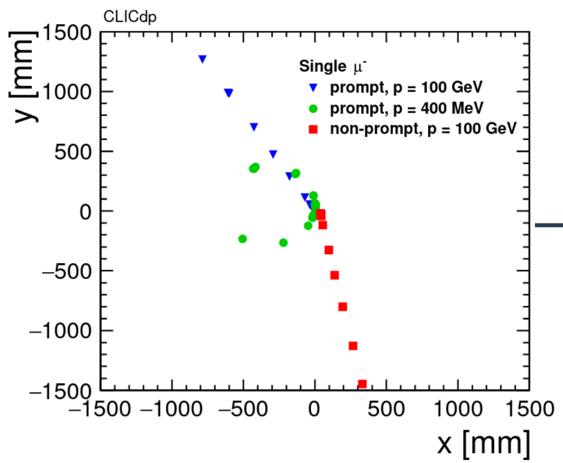
Details

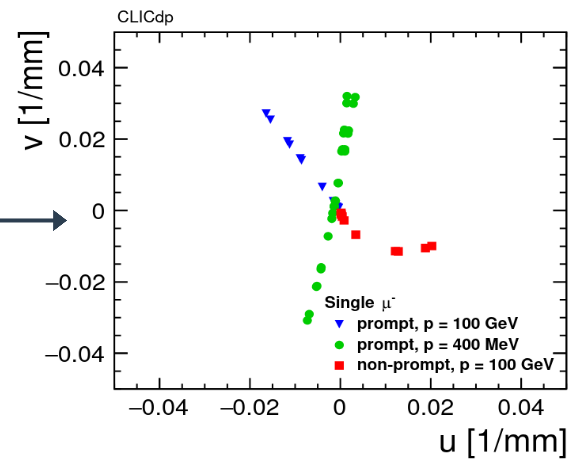
Global Hit Selection
ie: timing or double layers

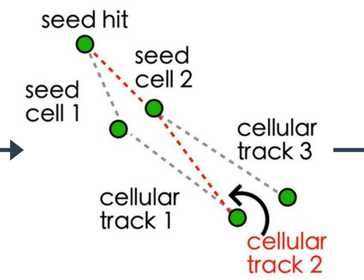
Conformal Transform
circular tracks → straight lines

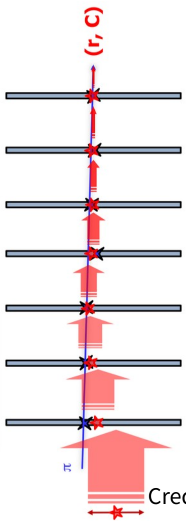
Cellular Automaton
straight “lines” → tracks

Kalman filter
Track fit









Credit: I. Kisel

Remove BIB hits

Pattern Recognition

Track Fit

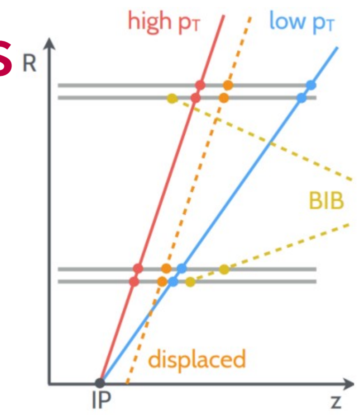
Algorithm + code inherited from CLIC software.

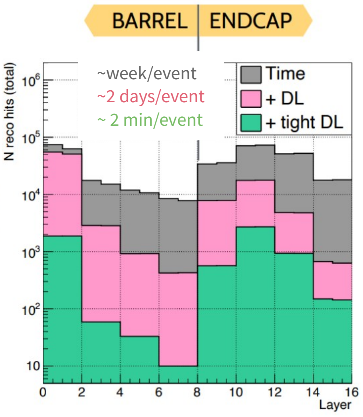
aka optimized for clean e^+e^- environment

Current Tracking Performance

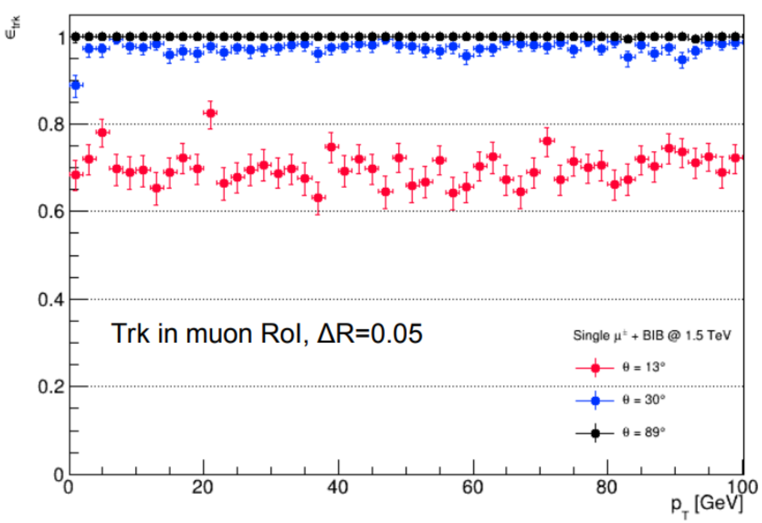
Details

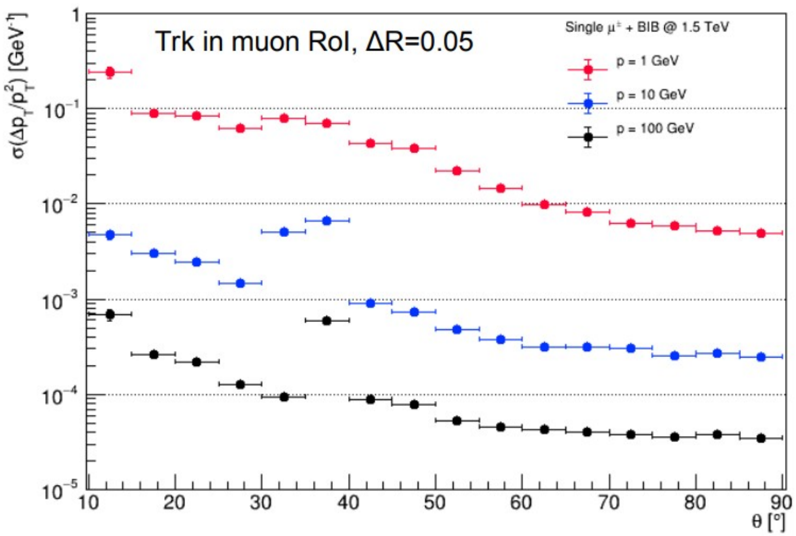
- **Employ hit multiplicity reduction strategies**
  - Region of Interest seeded tracking
  - Directional information from double layers
- **Require tight filtering for practical tracking**





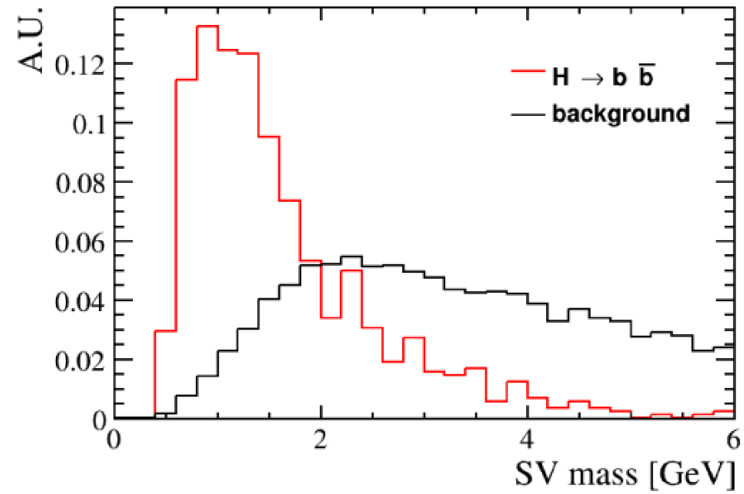
- **Good track reconstruction once algorithm completes**





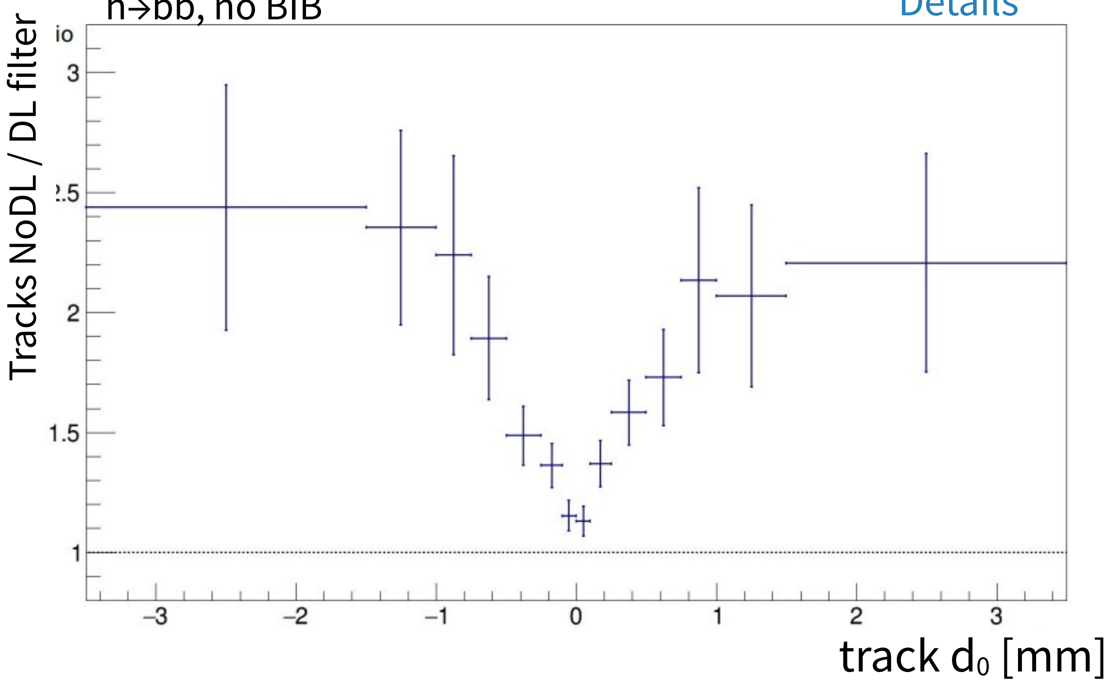
Flavour Tagging

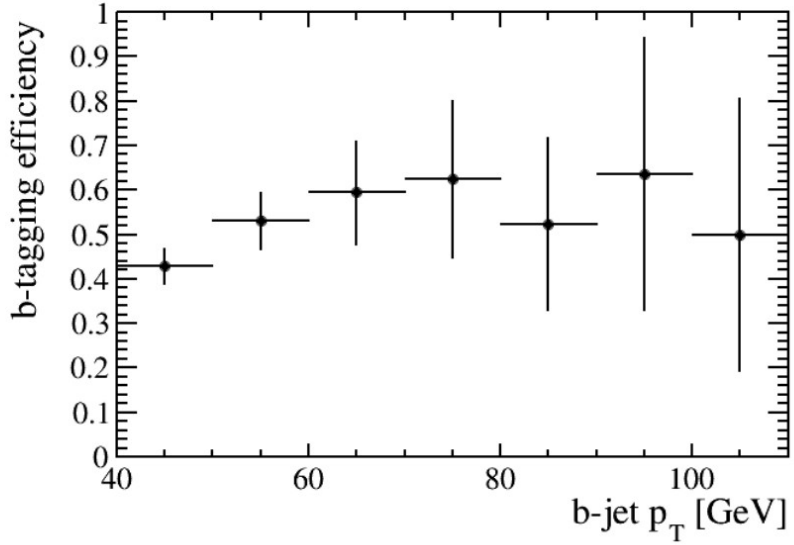
- **Secondary vertex reconstruction possible with BIB**
  - Caveat: using a very loose hit filter
- **Work ongoing on multivariate tagger**
- **Double layer filtering → possible bias**



h→bb, no BIB

Details





A Common Tracking Software

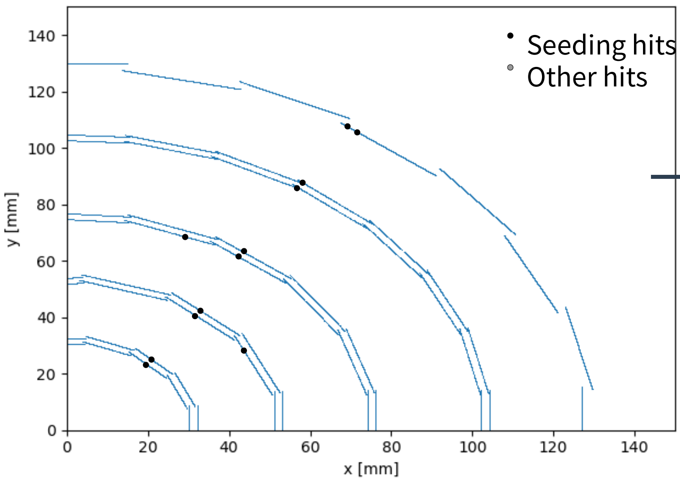
- **ACTS is a standalone library for tracking algorithms**
- **Dedicated team working on advancing tracking algorithms**
  - Tracking is hard!
- **Allows us explore alternate algorithms**
  - Triplet-based seeding optimized for high multiplicity environments
  - Ongoing work to incorporate ML-based algorithms
- **Code optimization come for free**
  - Good software is even harder than tracking!
  - Also explores modern computing architectures (ie: GPU’s)

https://github.com/acts-project/acts

Fit Library	Kalman Filter Execution Time
ACTS	0.5 ms / track
iLCsoft	100 ms / track

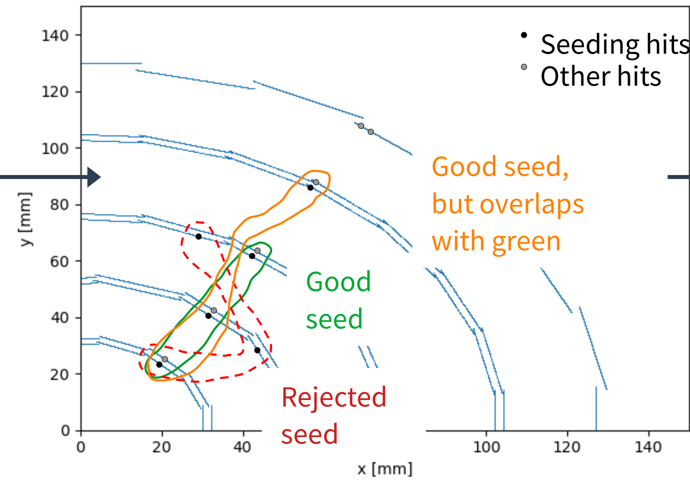
Triplet Seeded CKF

Global Hit Selection
ie: timing, *

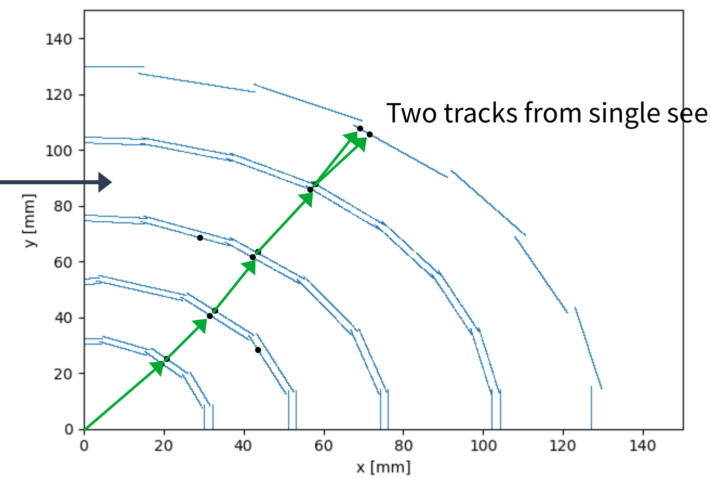


* Currently not leveraging double layers.

Seed Finding
Initial parameters for CKF



Combinatorial Kalman filter
Track fit



Remove BIB hits

Pattern Recognition

Track Fit

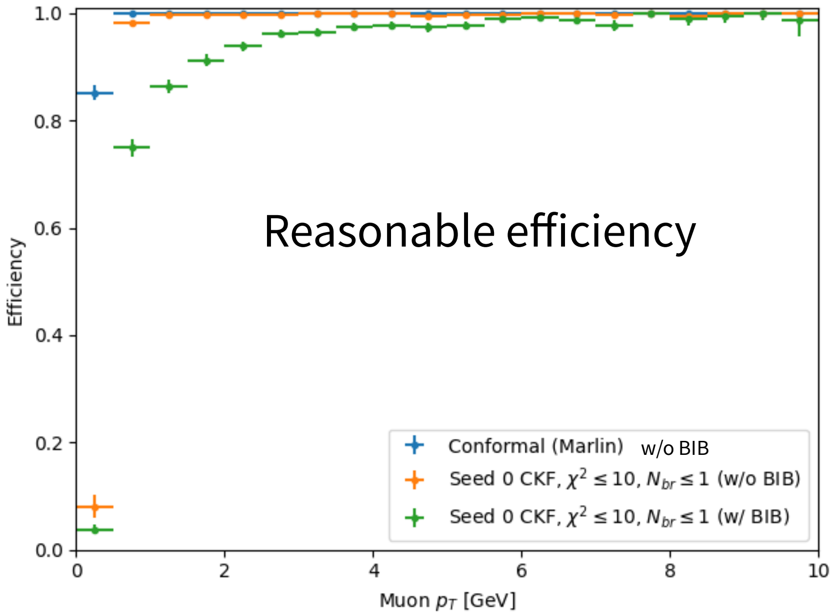
Similar algorithm used by ATLAS.

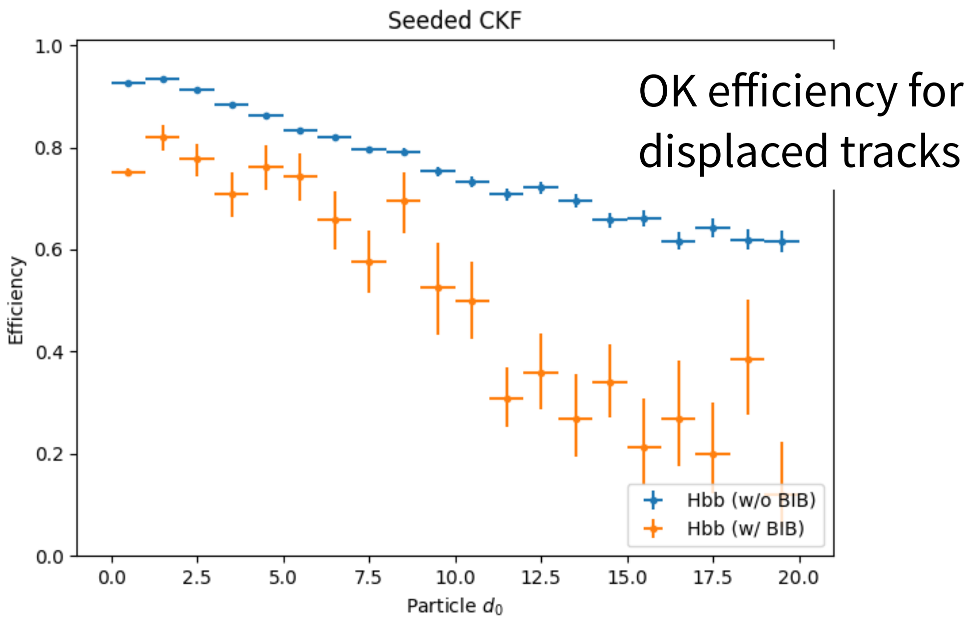
aka optimized for high hit multiplicity

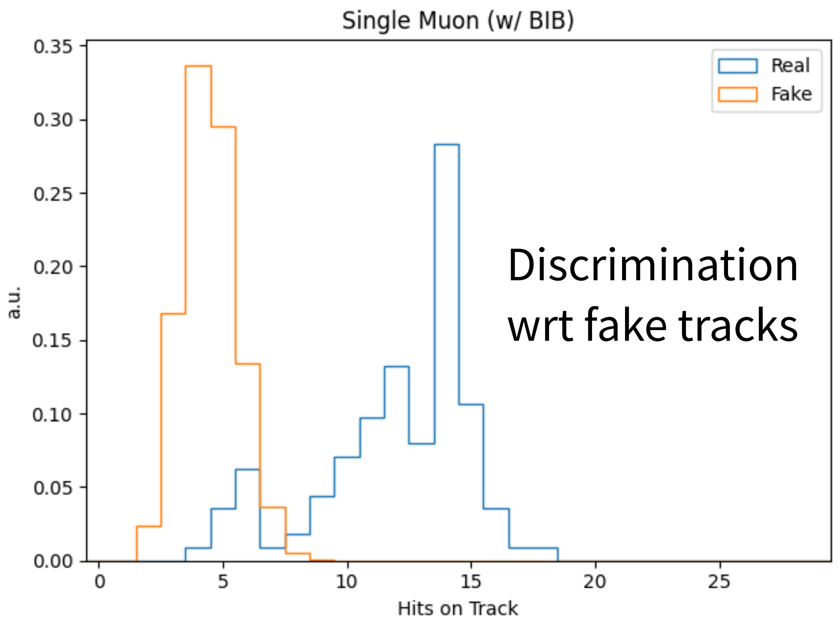
ACTS Track Finding

Details

- **Seeded CKF runs in ~4 min / event.**
- **Parameters need to be optimized.**
  - Seeding: very narrow collision region
  - CKF: No branching allowed

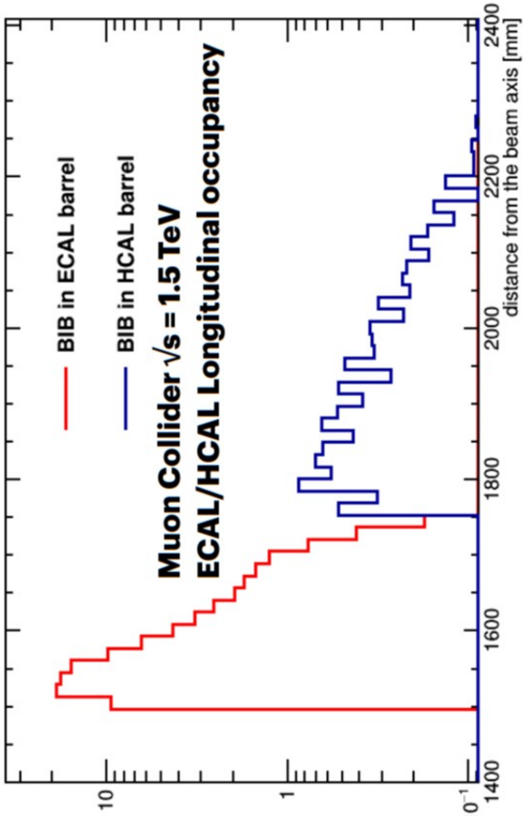






Calorimeters

Details



[longitudinal calorimeter occupancy [hits / mm^2]

Hadronic Calorimeter

- 40 layers
- W absorber
- Silicon pad sensors, 5x5 mm^2

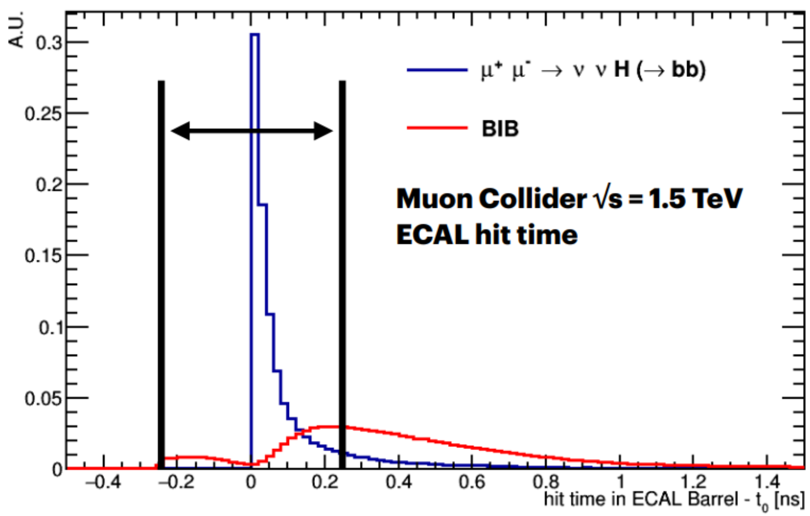
Electromagnetic Calorimeter

- 60 layers
- steel absorber
- Plastic scintillating tiles, 30x30 mm^2

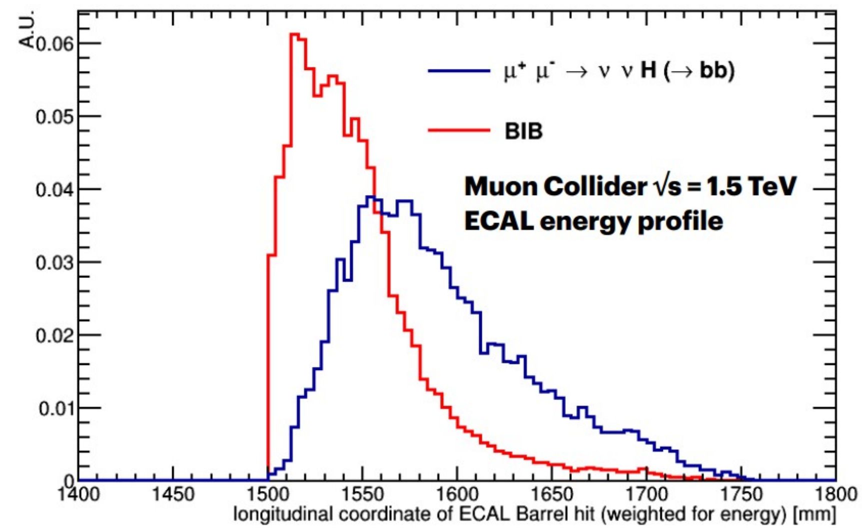
BIB in Calorimeter

Details

- **Timing is important**



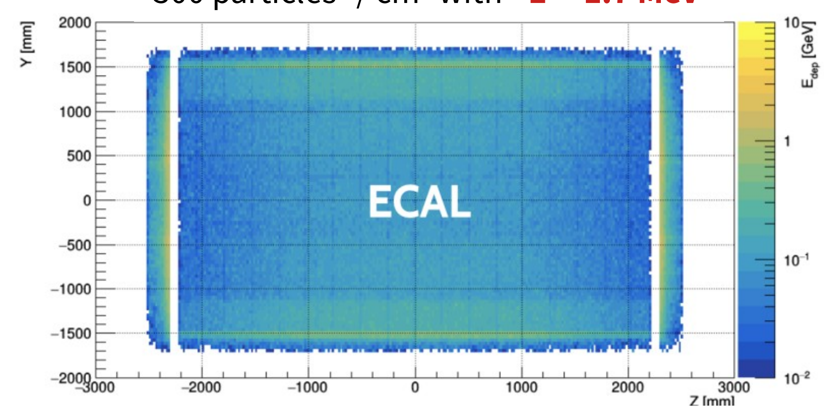
- **Shower shape another handle**



- **Remaining BIB is removed by subtraction**
  - Accept ECal hit if $E_{HIT} > \langle E_{BIB} \rangle + 2\sigma_{BIB}$
  - Correct remaining ECal hits $E_{HIT} \rightarrow E_{HIT} - \langle E_{BIB} \rangle$

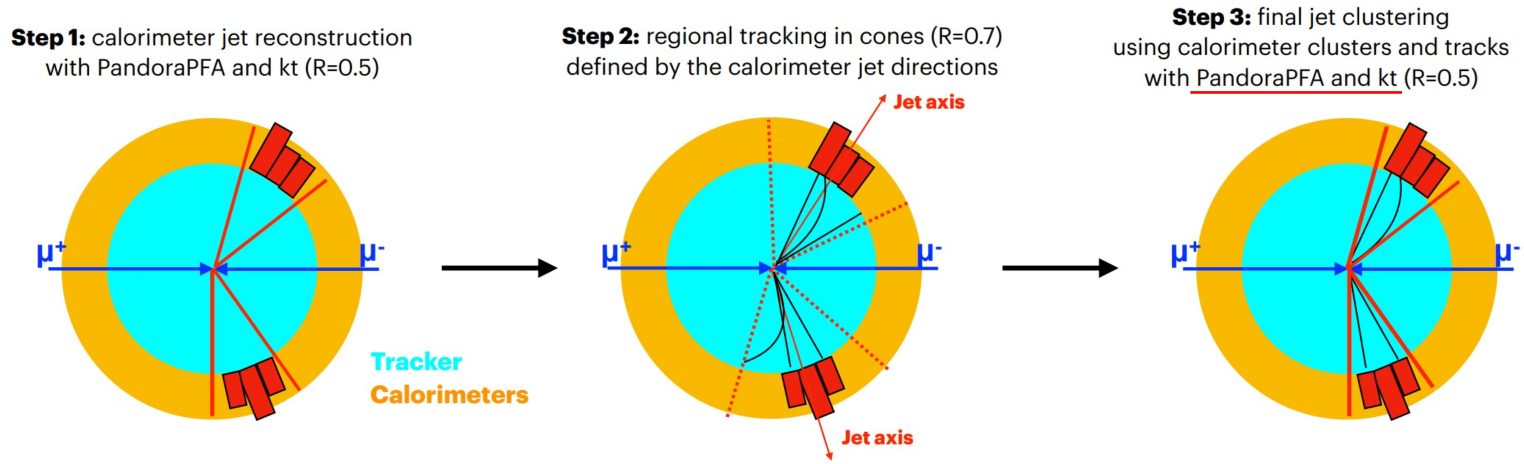
* mostly photons

300 particles* / cm² with **<E>=1.7 MeV**

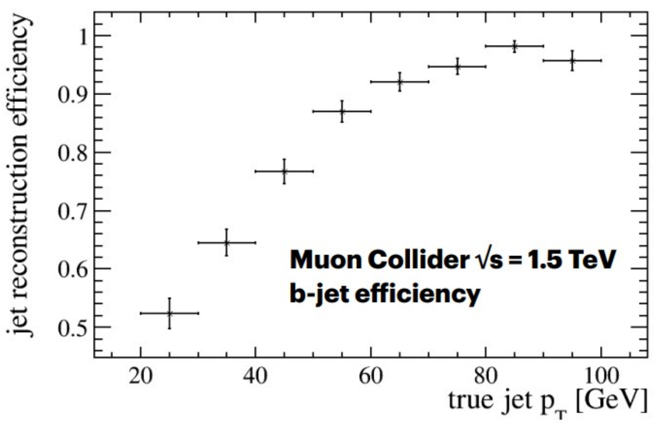


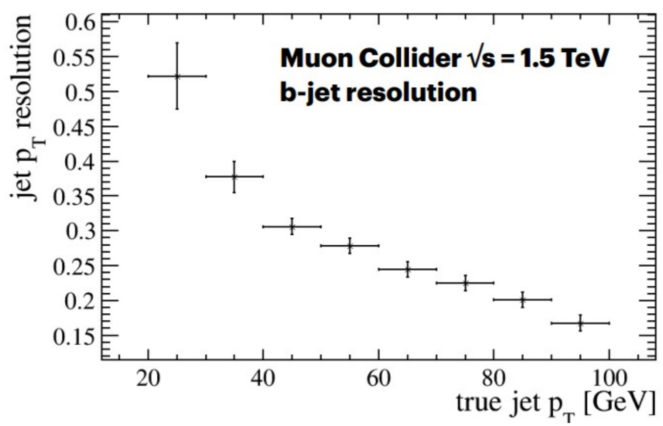
ECal energy deposition in one bunch crossing.

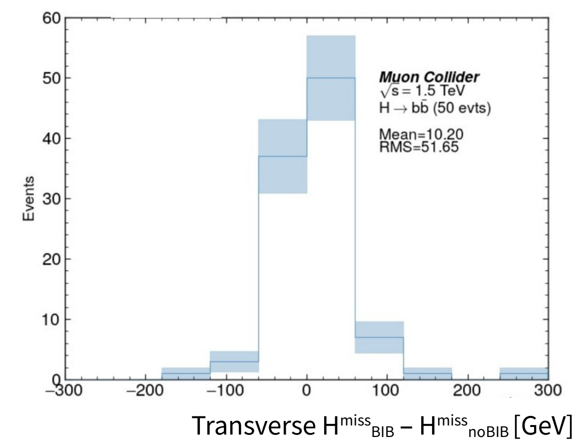
Jet Reconstruction



Fully efficient for p_T>80 GeV with ~20% resolution



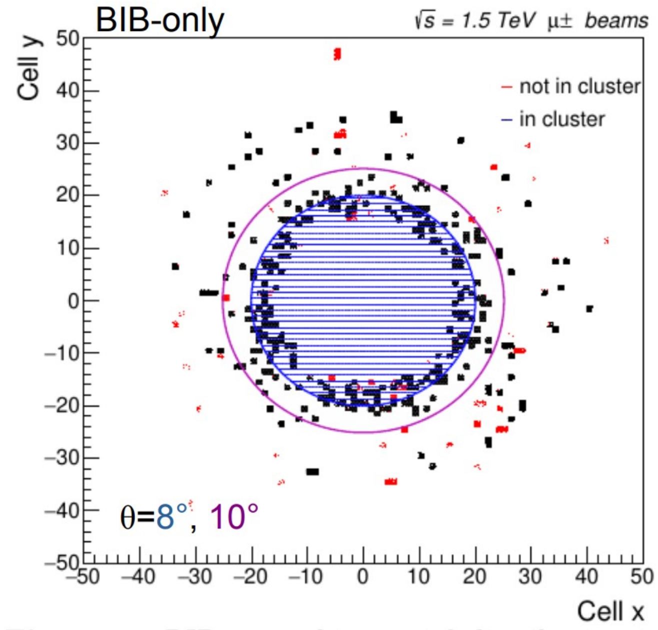


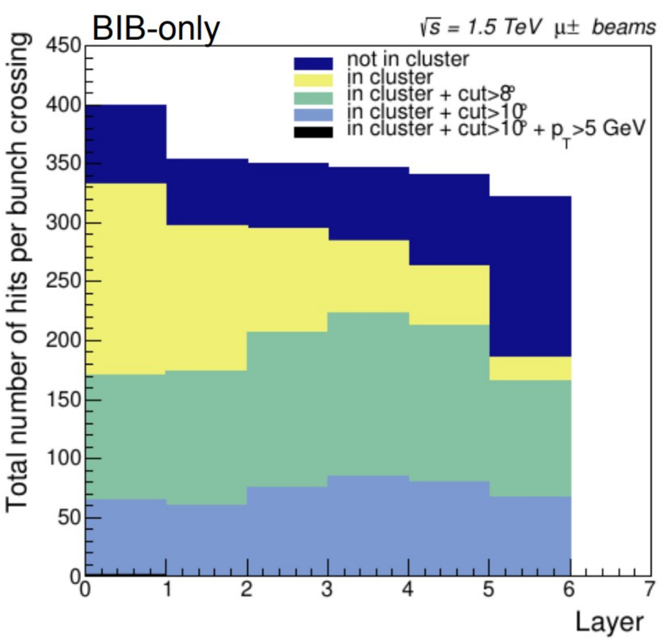


Plenty of room to *optimize* and *innovate*!

Muon Spectrometer

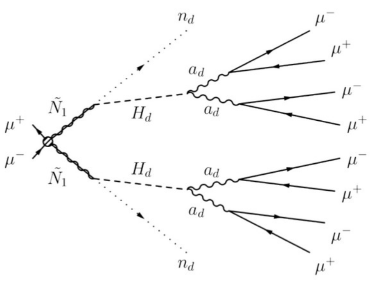
- **RPC cells of 30x30 mm²**
  - 7 barrel layers, 6 endcap layers
- **BIB not a major problem**
  - Mostly in endcap tips (close to beamline)
  - Suppressed via geometrical cuts (<10°)

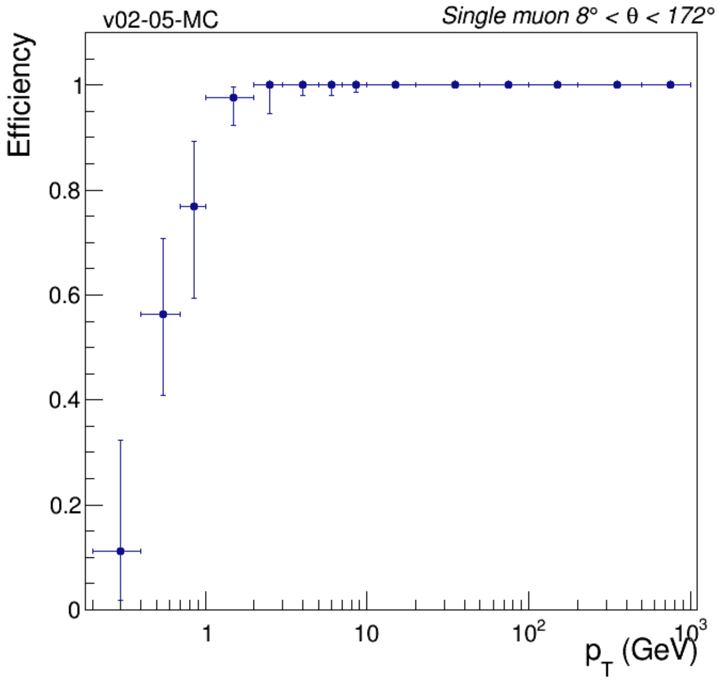


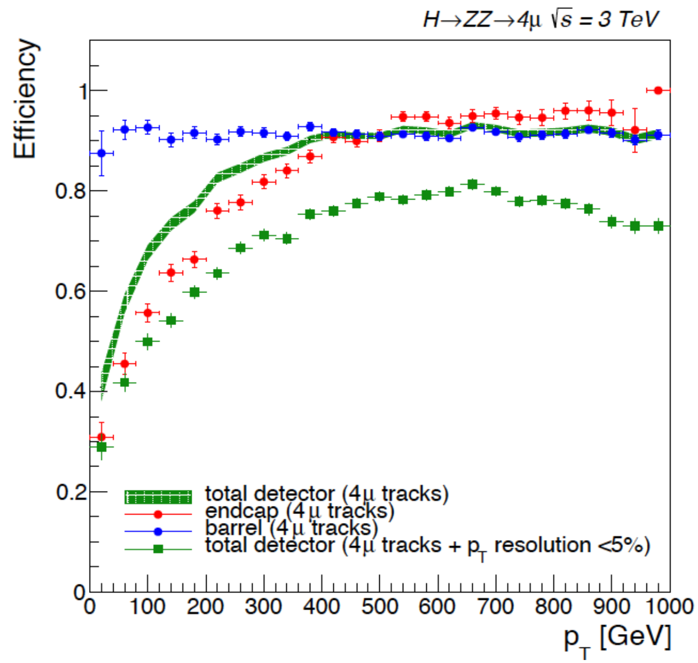


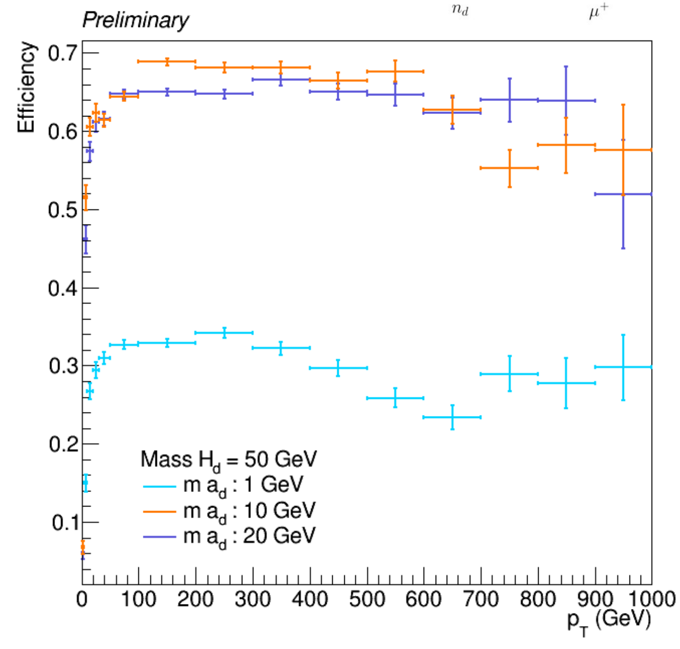
Muon Reconstruction

- Muons reconstructed with high efficiency
- Can seed extension to inner tracker





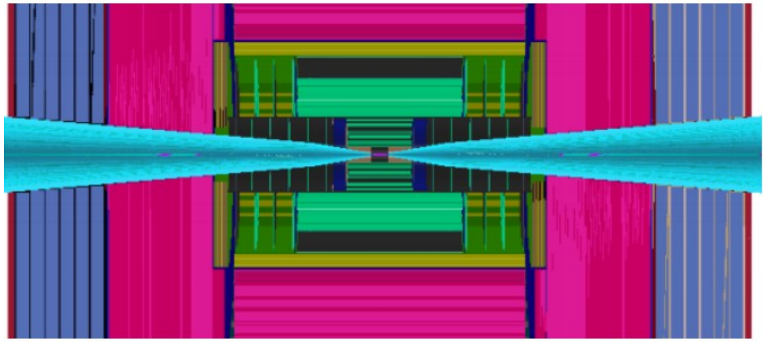




Luminosity Measurements

Problem:

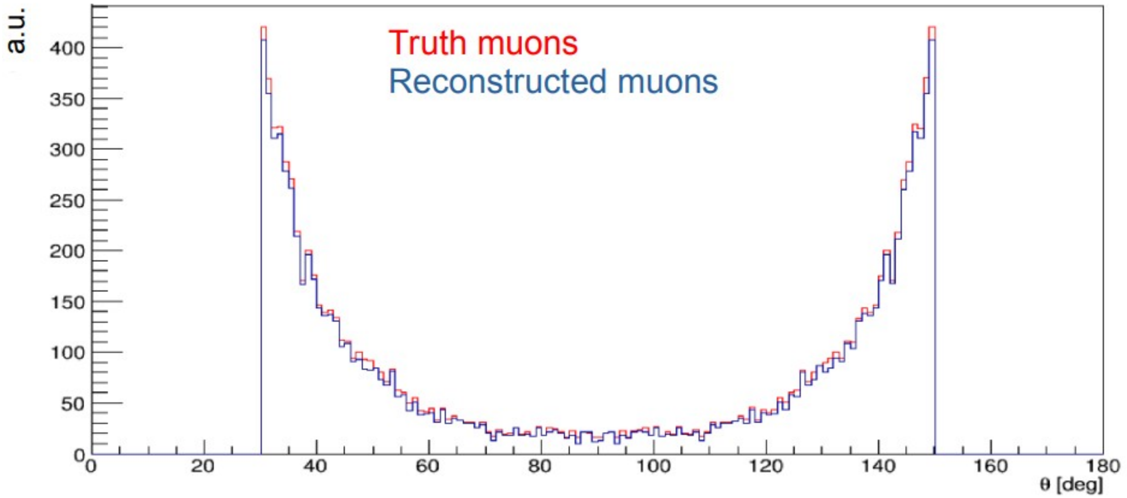
- Nozzle prevents placement of forward luminometers
- Direct methods (vdM scans) difficult due to short muon lifetime



Possible Solution:

- Measure via μμ → μμ scattering
  - $m_{\mu\mu} \sim \sqrt{s}$
- Limited statistics due to detector acceptance

$$\delta L / L \approx 0.2\%$$



Conclusions

- **Baseline detector for muon collider in place**
  - Useful tool for understanding event reconstruction in this environment
- **Largest issue is Beam Induced Background**
  - Precision timing will plan an important role
- **Tracking: biggest challenge is pattern recognition**
  - Modern algorithms offer a potential solution
- **Calorimeter: huge diffuse background**
  - Plenty of room for new ideas
- **Muons: No major problems seen**

SUBJECT TO CHANGE!

Expect plenty of innovation

in years to come.

BACKUP

Truth Tracking

Pattern Recognition

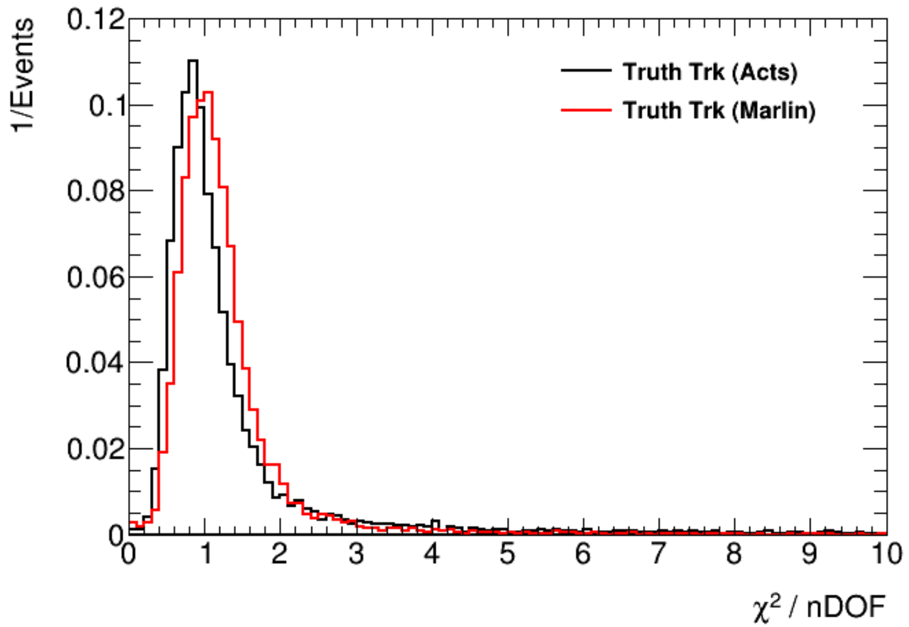
- Use hits associated to MC particle (100% efficiency)
- Same code for Marlin and ACTS

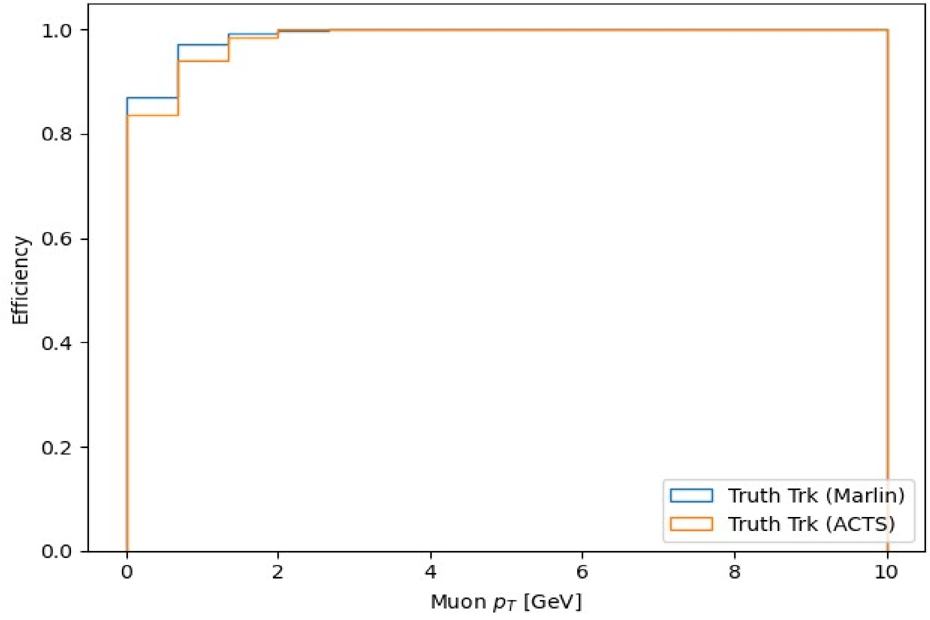
Track Fit

- Kalman Filter, but ACTS vs Marlin implementation

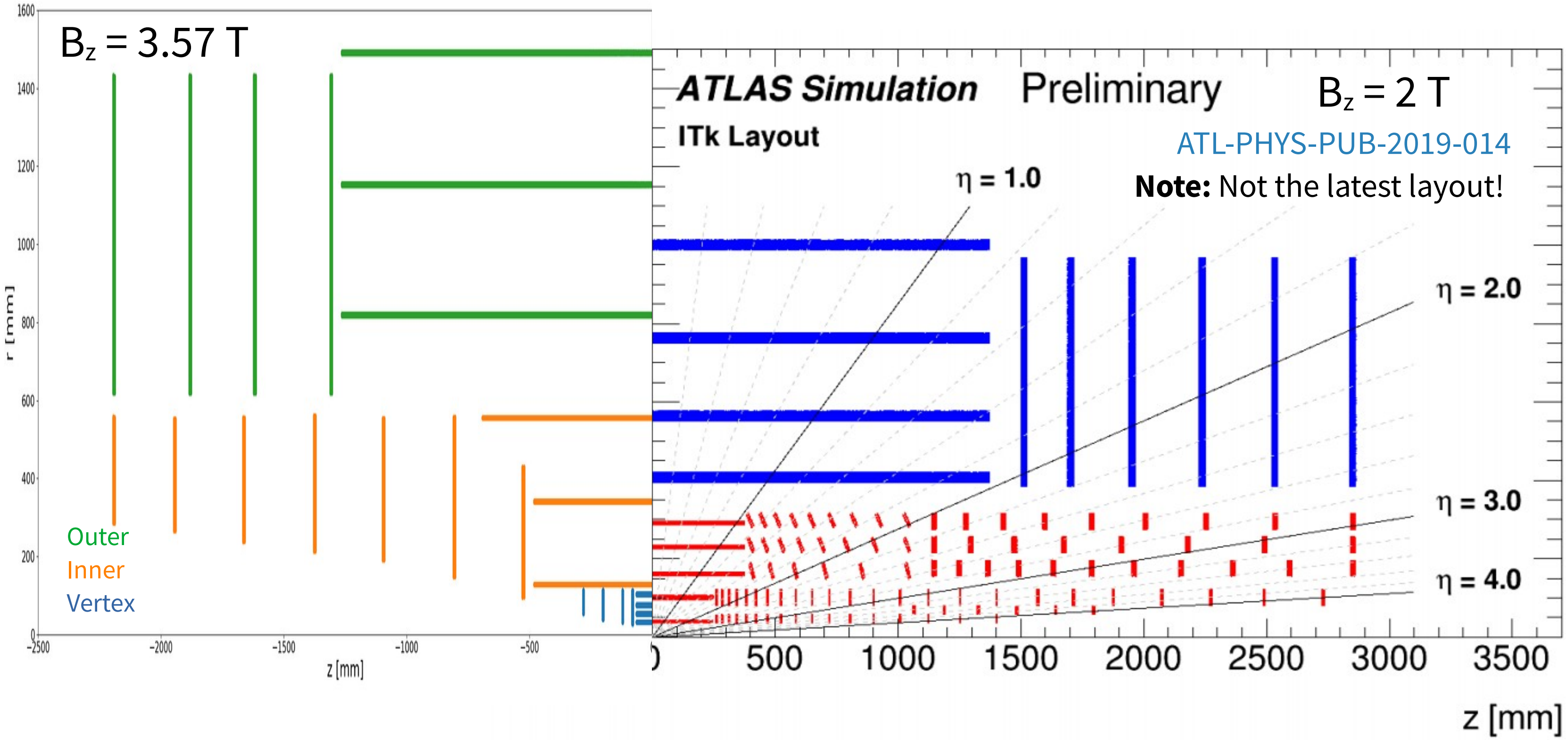
Same inputs, same algorithm, but different programmer.

Fit Library	Execution Time
ACTS	0.5 ms / evt
iLCsoft	100 ms / evt





The Scale of BIB



	ITk Hit Density [mm^{-2}]	MCC Equiv. Hit Density [mm^{-2}]
Pix Lay 0	0.643	3.68
Pix Lay 1	0.022	0.51
Str Lay 1	0.003	0.03

ITk Pixels TDR, ITk Strips TDR

BIB in Calorimeter