Detector at a Muon Collider

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UNIVERSITY OF BIRMINGHAM

UK Muon Beams 2023

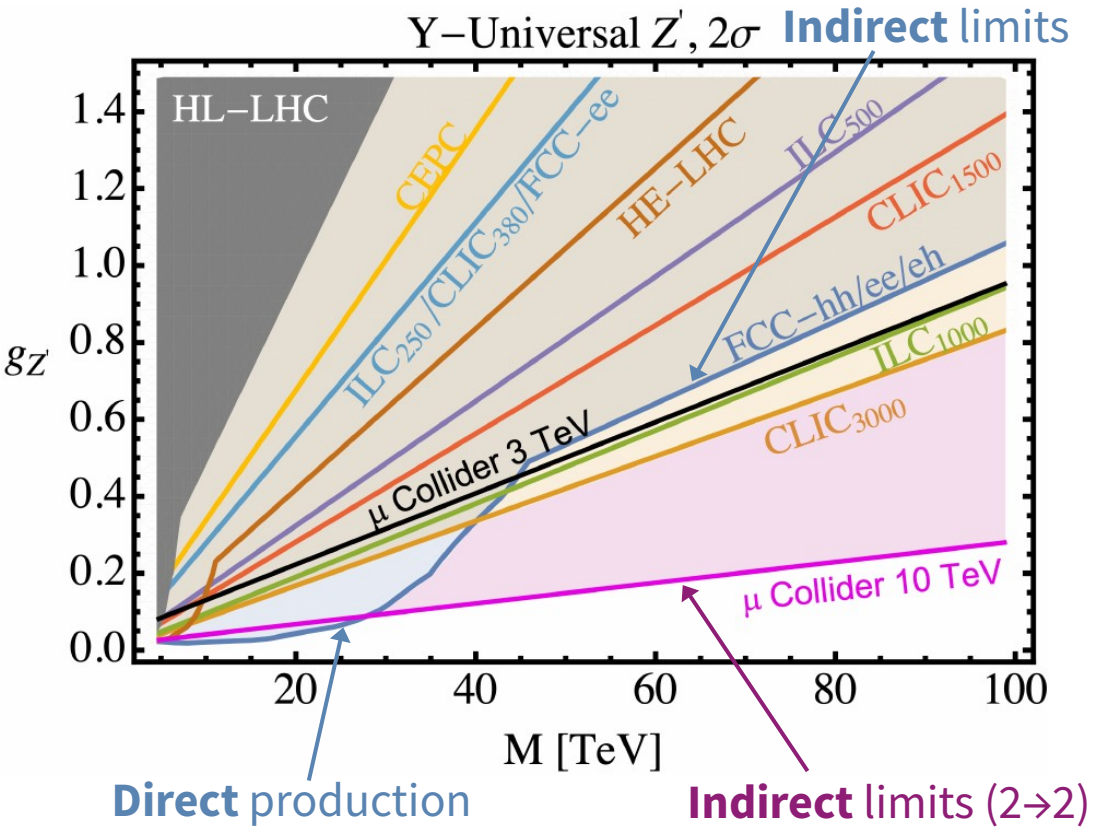
One Slide on Physics

1)Measurements of the Higgs boson targeting <1%

2)Direct searches at high energies to understand any deviations.

Precision is key for both!

	HL-LHC	ILC (500)	FCC-ee/hh	μC (10 TeV)
hZZ	1.5	0.17	**0.12**	0.33
hWW	1.7	0.20	0.14	**0.10**
hbb	3.7	0.50	0.43	**0.23**
hγγ	3.4	0.58	**0.44**	0.55
hgg	2.5	0.82	0.49	**0.44**
hcc	-	1.22	**0.95**	1.8
hττ	1.8	1.22	**0.29**	0.71
hγZ	9.8	10.2	**0.69**	5.5
hμμ	4.3	3.9	**0.41**	2.5
htt	3.4	2.82	1.0	3.2
Γ_{tot}	5.3	0.63	1.1	**0.5**



3 TeV vs 10 TeV Detectors

- **Historically studies were done assuming √s=1.5 TeV.**
  - Lots of results. Hence the bulk of this presentation.
- **Snowmass2021 suggested √s=10 TeV should be baseline.**
  - Results are only starting to appear now. Bit at end…

Our Onion (1.5 TeV) Detector

heavily based on CLIC detector

hadronic calorimeter

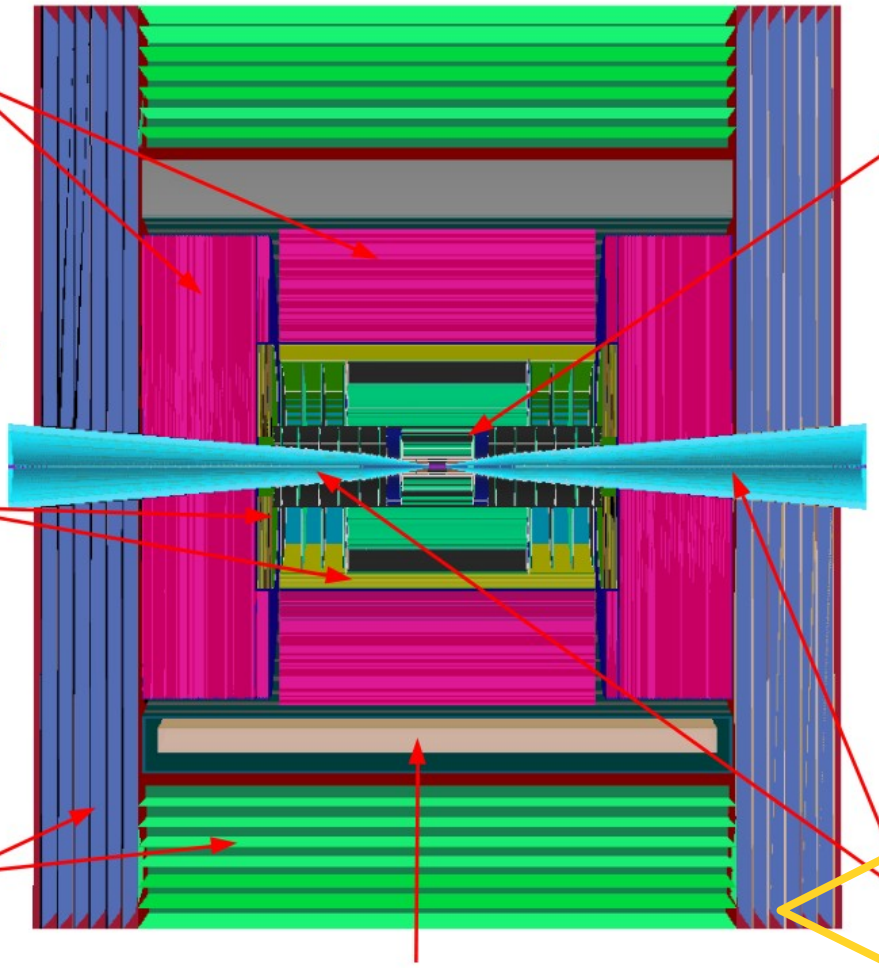
- 60 layers of 19-mm steel absorber + plastic scintillating tiles;
- 30x30 mm^2 cell size;
- 7.5 λ_I.

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

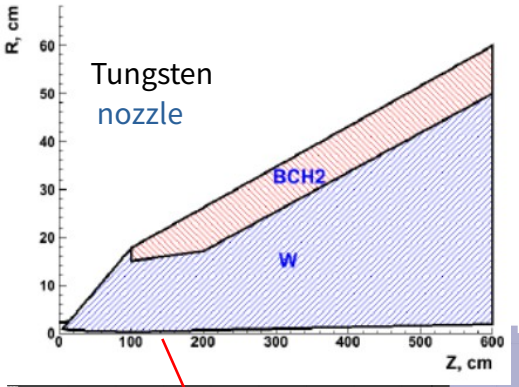
- Vertex Detector:
  - double-sensor layers (4 barrel cylinders and 4+4 endcap disks);
  - 25x25 μm^2 pixel Si sensors.
- Inner Tracker:
  - 3 barrel layers and 7+7 endcap disks;
  - 50 µm x 1 mm macro-pixel Si sensors.
- Outer Tracker:
  - 3 barrel layers and 4+4 endcap disks;
  - 50 µm x 10 mm micro-strip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

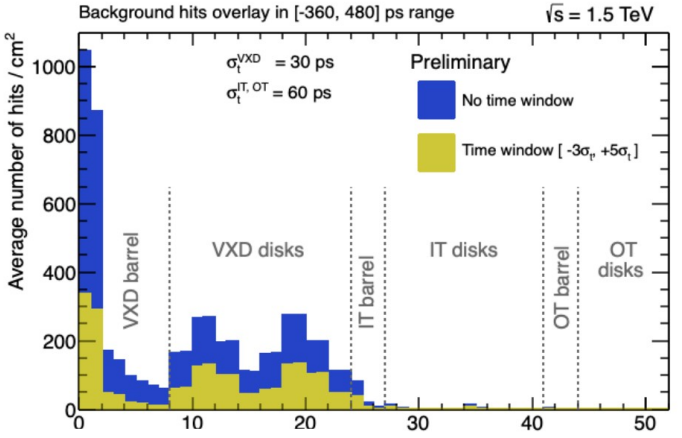
shielding nozzles

- Tungsten cones + borated polyethylene cladding.

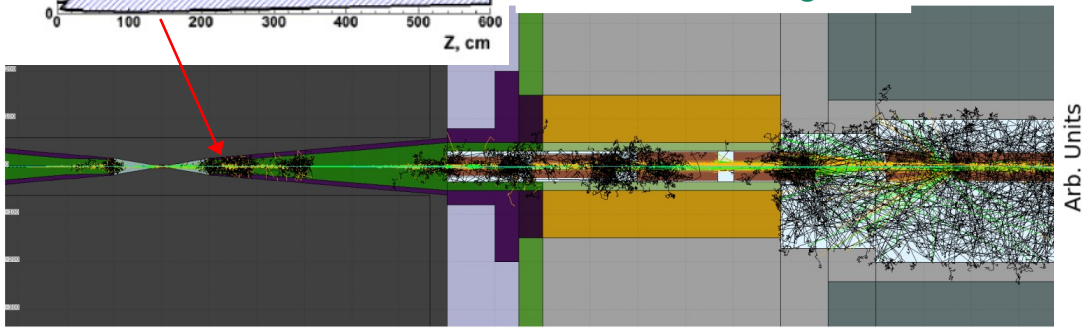
Beam Induced Background

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

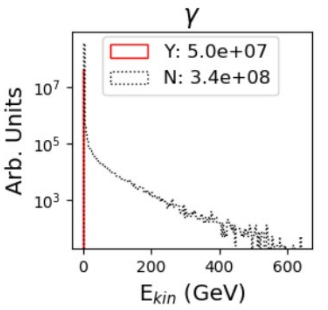


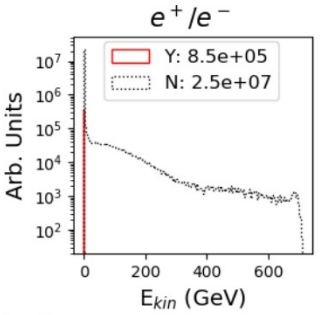


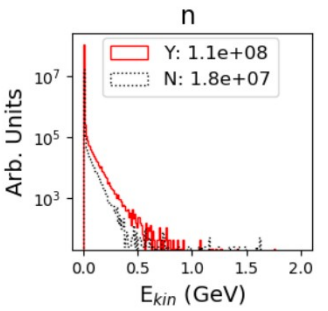
Tracker after timing cuts.

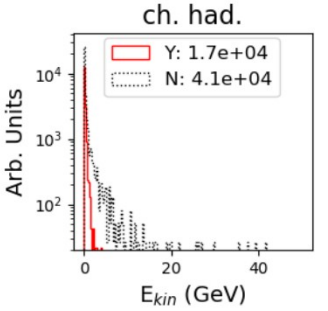


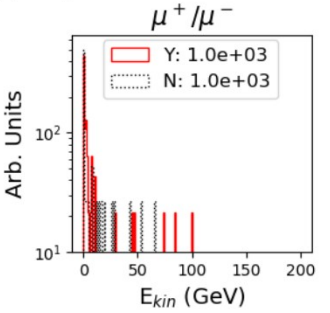
FLUKA simulation of BIB before reaching the detector.











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

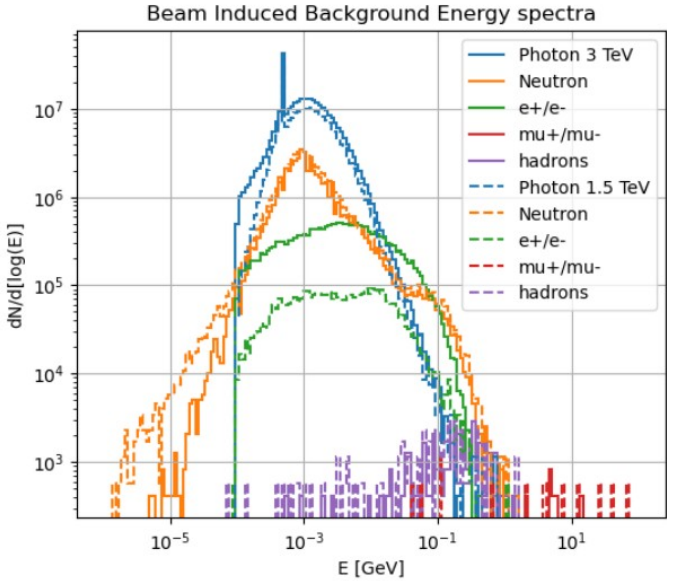
Simulating Beam Induced Background

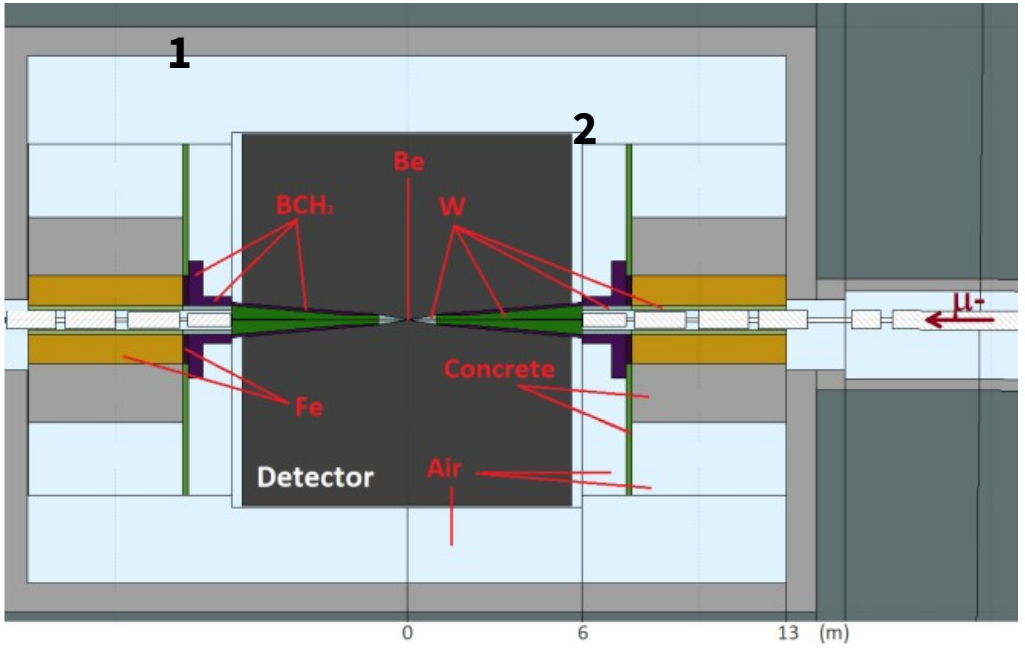
1)Muon trajectory, decay and transport of products via FLUKA*

- Full beam optics present through LineBuilder Interface

2)GEANT simulation of particles entering the detector

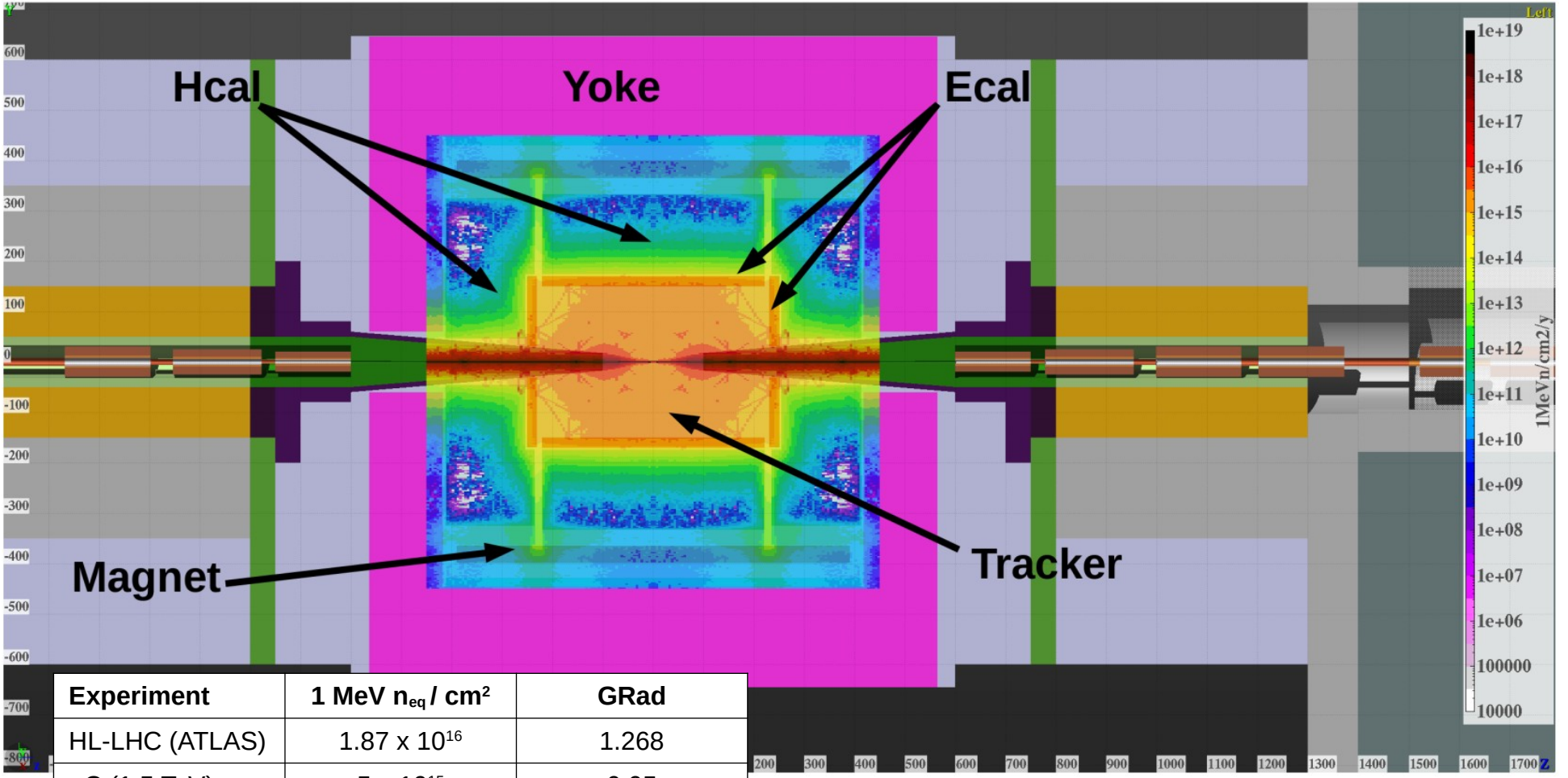
√s=1.5 TeV used to develop setup, more energy points being added.





* validating against an older model from MARS15

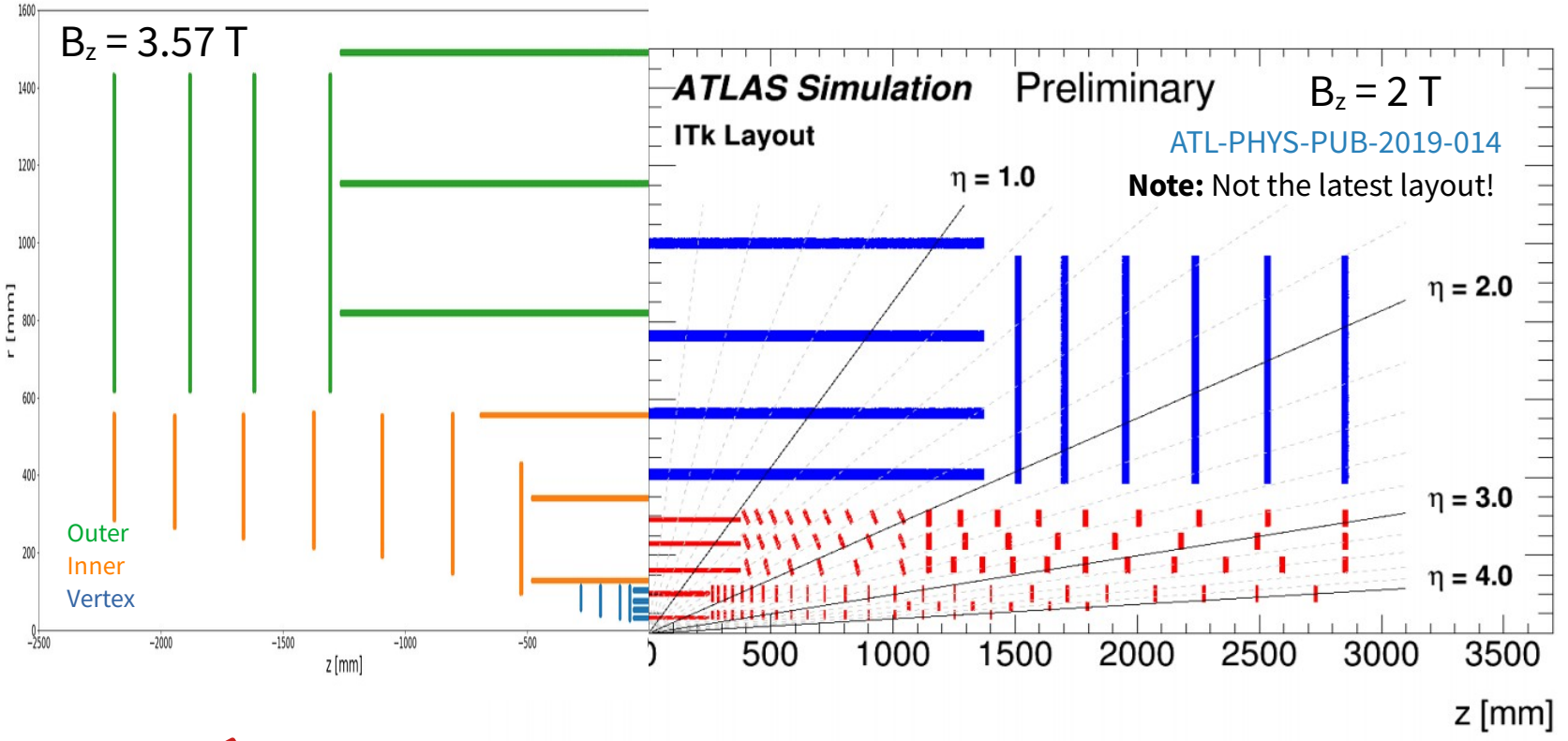
Radiation Damage From BIB



Experiment	1 MeV n_{eq} / cm^2	GRad
HL-LHC (ATLAS)	1.87 x 10^{16}	1.268
μC (1.5 TeV)	5 x 10^{15}	0.05
FCChh	8 x 10^{17}	27
FCCee	? not big ?	? not big ?

Expected dose in innermost tracking layer.

The Scale of BIB



Hit density **after timing cuts** **10x HL-LHC**

	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

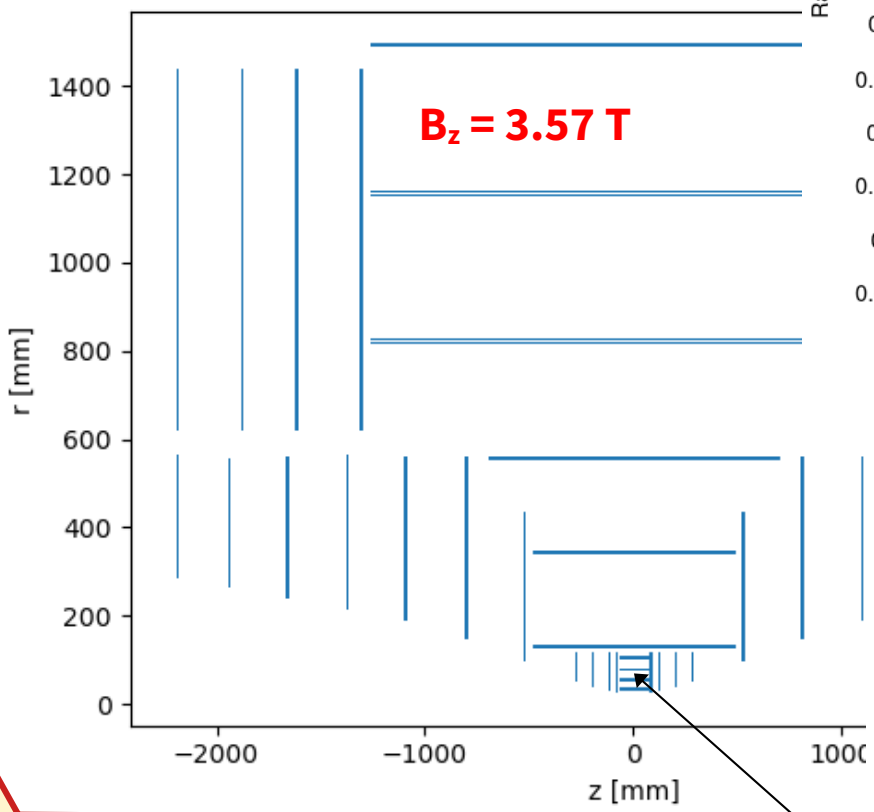
All-Silicon Tracking Detector

Outer Tracker (OT)

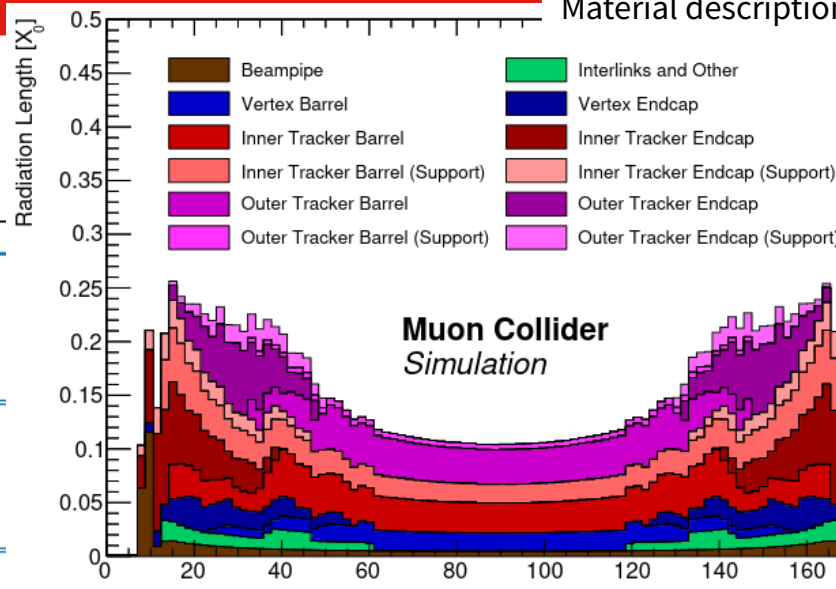
- micro-strips
- 50 µm x 10 mm
- σ_t = 60 ps

Inner Tracker (IT)

- macro-pixels
- 50 µm x 1 mm
- σ_t = 60 ps



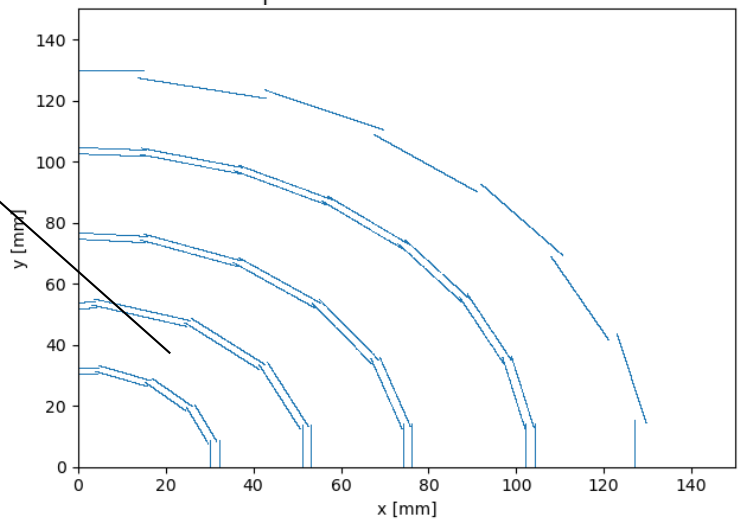
Material description



4D tracking critical

Vertex Detector (VXD)

- pixels
- 25 µm x 25 µm
- σ_t = 30 ps
- double layers



R&D Towards Muon Collider Requirements

The 2021 ECFA detector research and development roadmap (with updates).

"Technical" Start Date of Facility (This means, where the dates are not known, the earliest technically feasible start date is indicated - such that detector R&D readiness is not the delaying factor)				< 2030					2030-2035					2035 - 2040	2040-2045		> 2045		
				Panda 2025	CBM 2025	HIKE 2030	Belle II 2026	ALICE LS3 [1]	ALICE 3	LHCb (≥LS4) [1]	ATLAS/CMS (≥ LS4) [1]	EIC	LHeC	ILC [2]	FCC-ee	CLIC [2]	FCC-hh ~2070	FCC-eh	Muon Collider ~2045
Vertex Detector [3]	MAPS Planar/3D/Passive CMOS LGADs	DRDT 3.1 DRDT 3.4	Position precision σ_{hit} (μm)		≈ 5		≲ 5	≈ 3	≲ 3	≲ 10	≲ 15	≲ 3	≈ 5	≲ 3	≲ 3	≲ 3	≈ 7	≈ 5	≲ 5
			X/X_0 (%/layer)	≲ 0.1	≈ 0.5	≈ 0.5	≲ 0.1	≈ 0.05	≈ 0.05	≈ 1		≈ 0.05	≲ 0.1	≈ 0.05	≈ 0.05	≲ 0.2	≈ 1	≲ 0.1	≲ 0.2
			Power (mW/cm^2)		≈ 60			≈ 20	≈ 20			≈ 20		≈ 20	≈ 20	≈ 50			
			Rates (GHz/cm^2)		≈ 0.1	≈ 1	≲ 0.1		≲ 0.1	≈ 6		≲ 0.1	≈ 0.1	≈ 0.05	≈ 0.05	≈ 5	≈ 30	≈ 0.1	50
			Wafers area (") [4]					12	12			12			12		12		12
		DRDT 3.2	Timing precision σ_t (ns) [5]	10		≲ 0.05	100		25	≲ 0.05	≲ 0.05	25	25	500	25	≈ 5	≲ 0.02	25	≲ 0.02
		DRDT3.3	Radiation tolerance NIEL (x 10^{16} neq/cm^2)			1				≈ 6	≈ 2						≈ 10^2		0.5
			Radiation tolerance TID (Grad)							≈ 1	≈ 0.5						≈ 30		0.05

Same pathway as for many experiments!

There are attempts to start a generic R&D program in UK (Liverpool 2023)

How far are we? Vertex Detector

σ_t = 30 ps, 25µm x 25µm, 5 x 10^{15} 1 MeV neq / cm^2

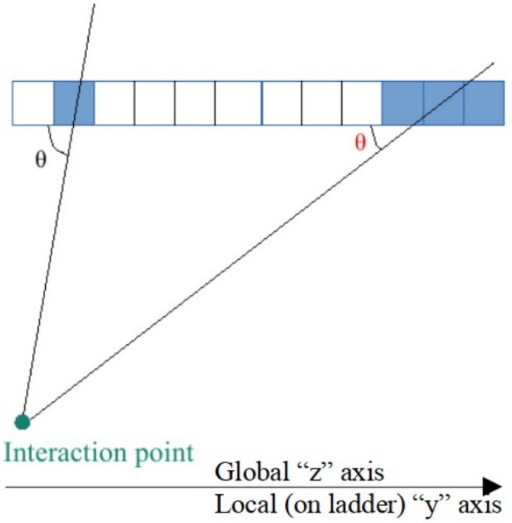
Technology	Pitch [μm^2]	Rad Hard [neq/cm^2]	Timing Res. [ps]
AC/TI/DC LGAD	~100 x 100	2.5 x 10^{15}	20-30
3D (TIMESPOT)	55 x 55	2.5 x 10^{16}	10
Planar (TimePix4)	55 x 55	??	50
Planar (NA62)	300 x 300	1.3 x 10^{14}	130

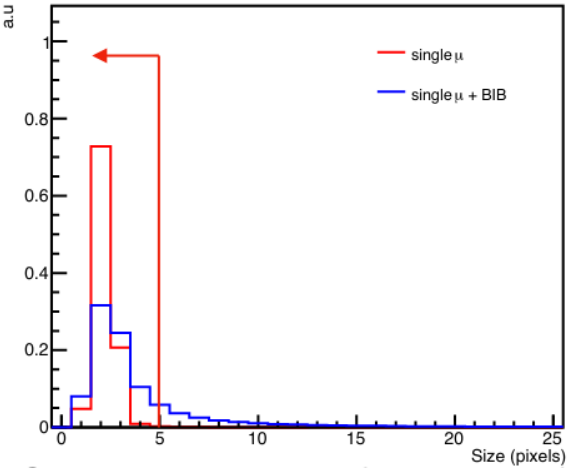
- **Missing ingredient is large scale ASIC with TDCs**
  - IGNITE, PicoPix…
- **Don't forget system level issues!**
  - Scaling up, power, mechanics…

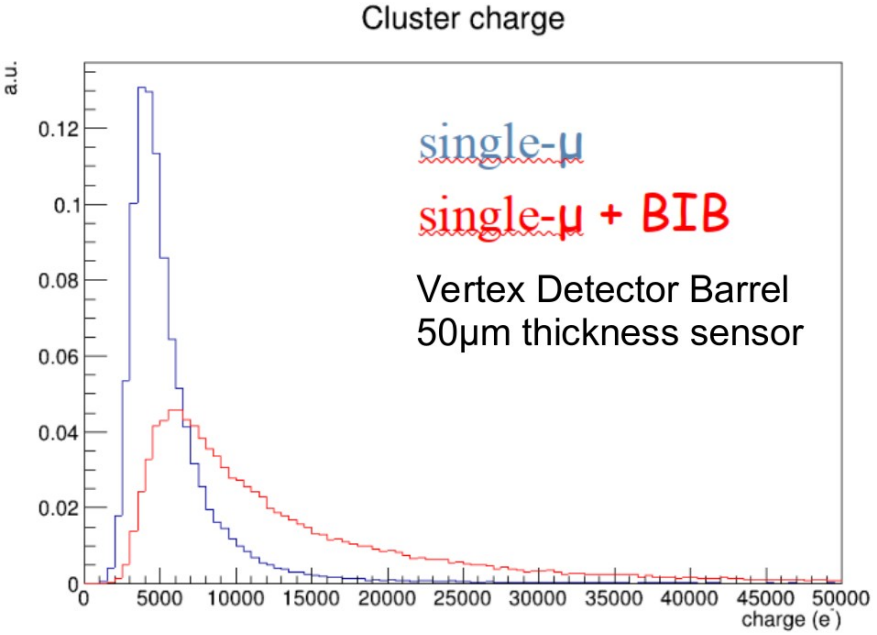
Advantages of Realistic Digitization

Work In Progress: Currently not part of common workflow

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



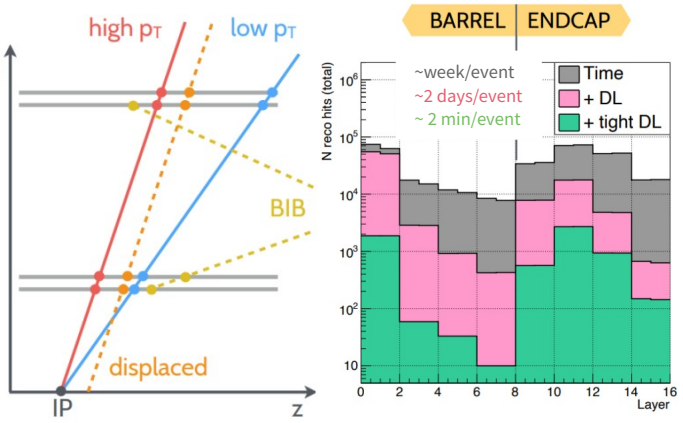


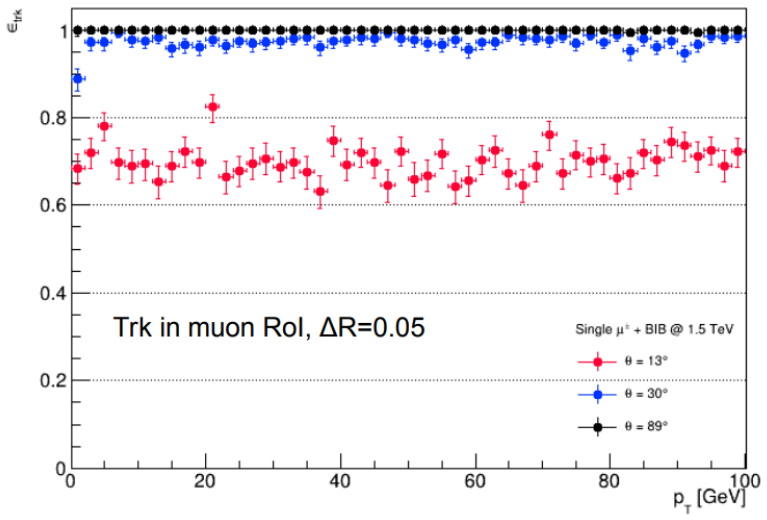


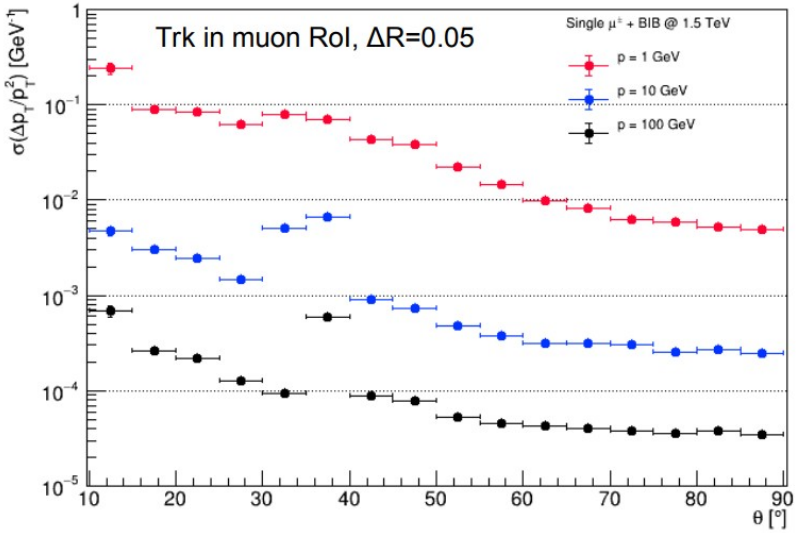
Requirement	Cut efficiency	Loose	Tight
Size-y cut vs. θ only	Single-μ	99.8 %	99.6 %
	Single-μ and BIB	55.2 %	43.7 %
Adding pixel size-x < 4	Single-μ	99.3 %	99.1 %
	Single-μ and BIB	37.4 %	30.7 %

Old Algo: Conformal Transform

- **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**



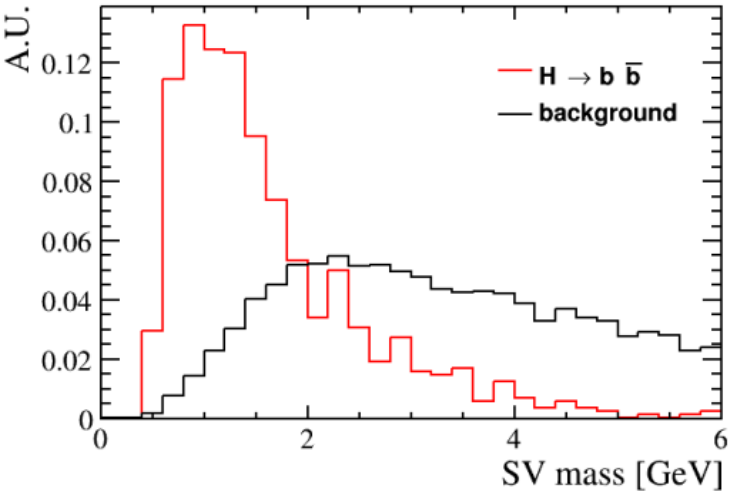




Flavour Tagging

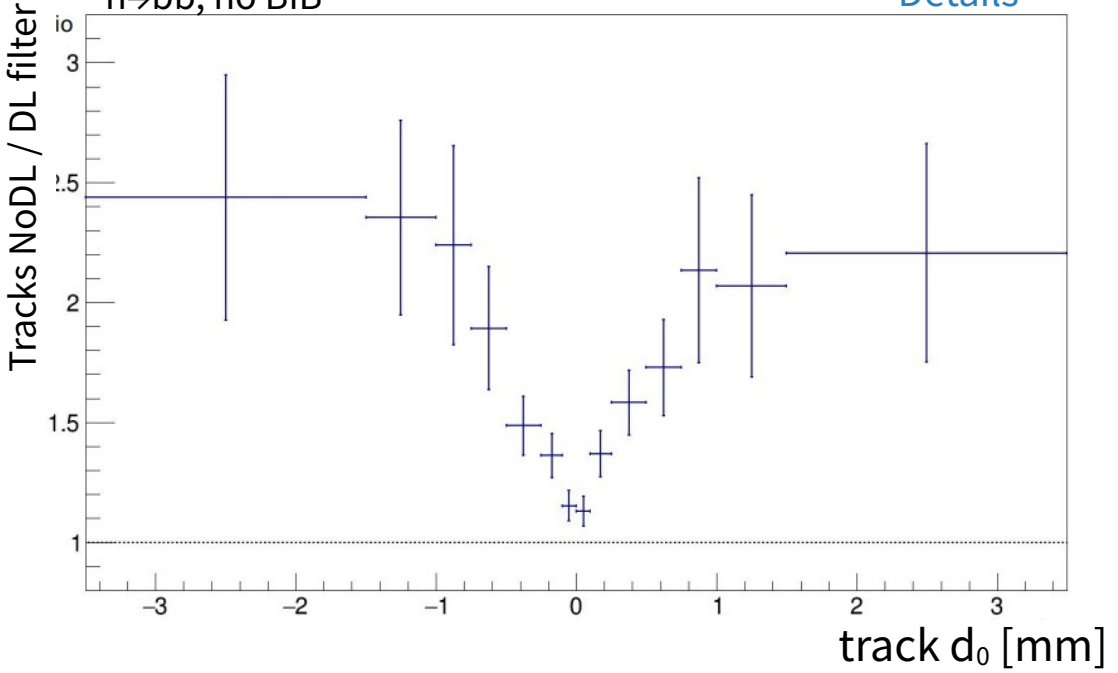
Details

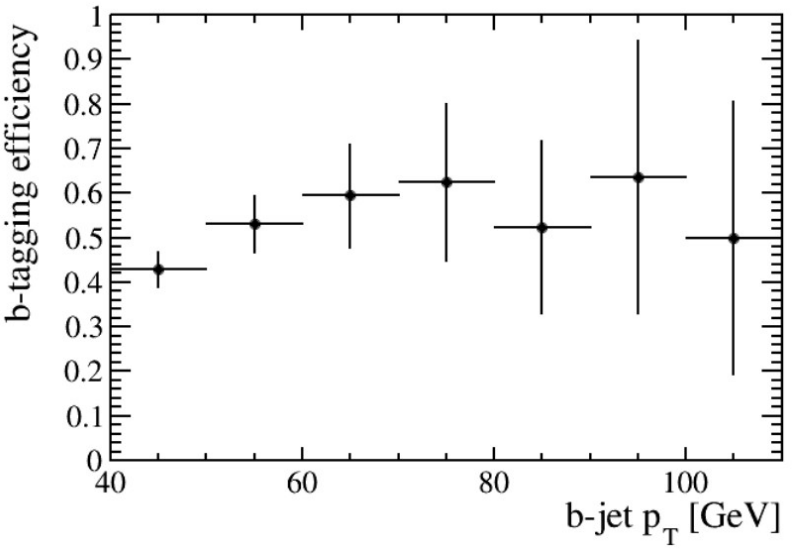
- **Secondary vertex reconstruction possible with BIB**
  - Caveat: using a very loose hit filter
- **Work ongoing on multivariate tagger**
- **Double layer filtering → possible bias**



h→bb, no BIB

Details

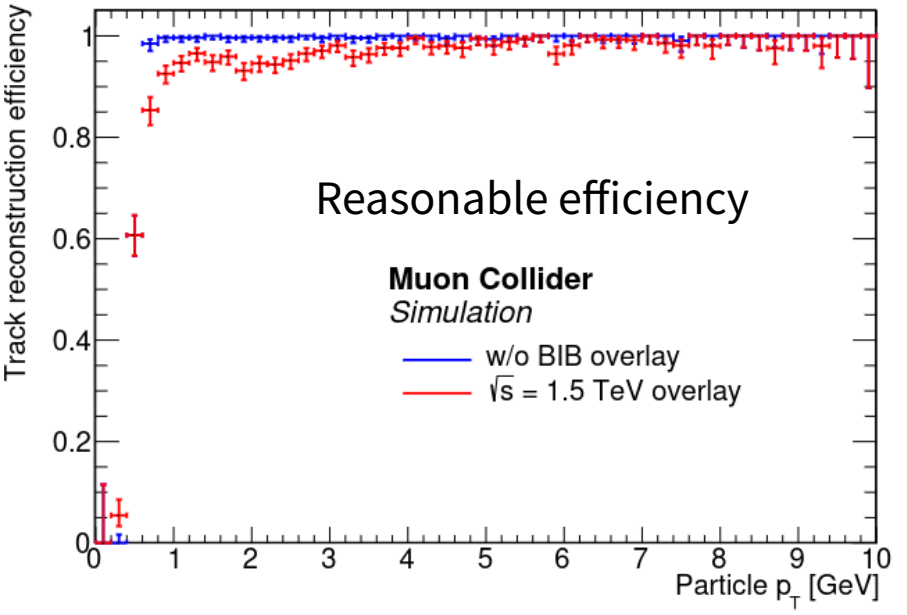




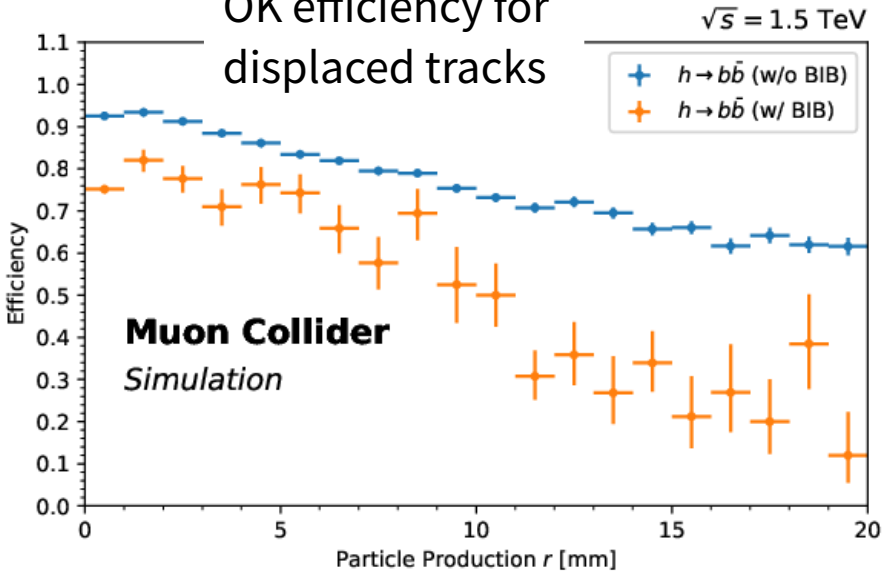
New Algo: CKF Tracking

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

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



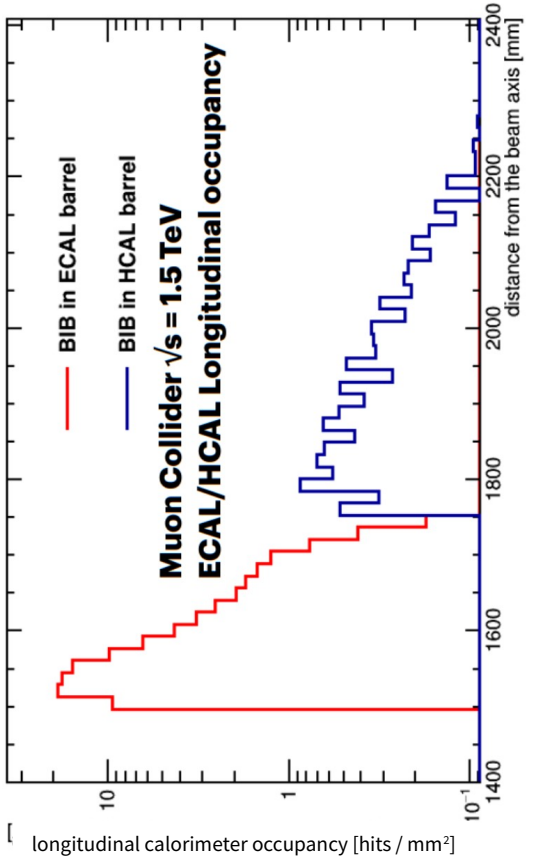
OK efficiency for displaced tracks



Fake track removal
(optimized with evolutionary algorithms)

Eff WP	Fakes / event
90%	3900
80%	0.13
70%	0.06

Calorimeters



Hadronic Calorimeter

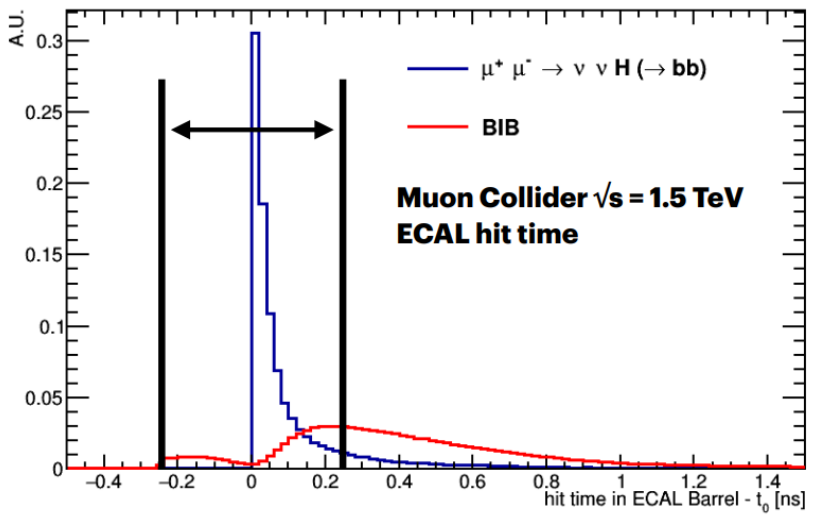
- 60 layers
- steel absorber
- Plastic scintillating tiles, 30x30 mm^2

Electromagnetic Calorimeter

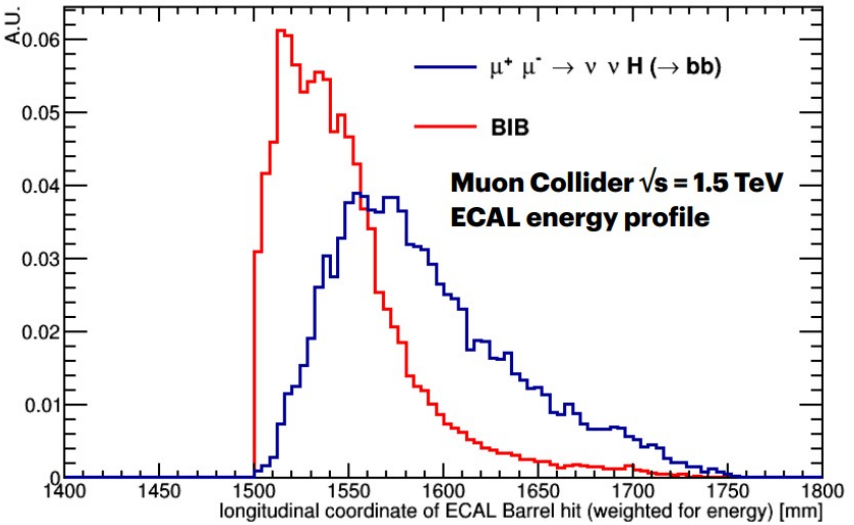
- 40 layers
- W absorber
- Silicon pad sensors, 5x5 mm^2

BIB in Calorimeter

- Timing is important



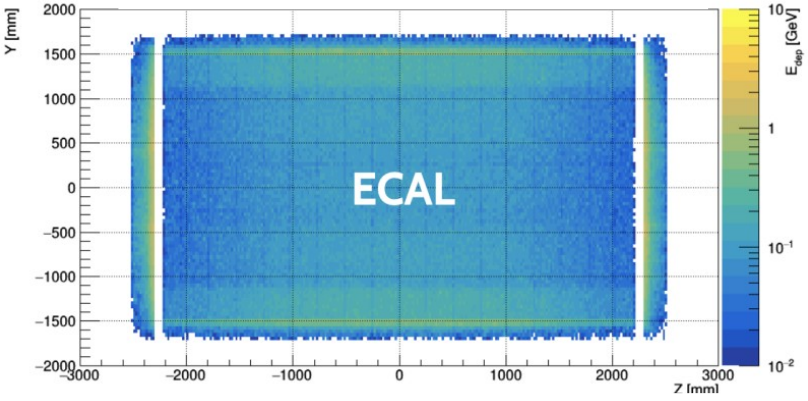
- Shower shape another handle



- 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**

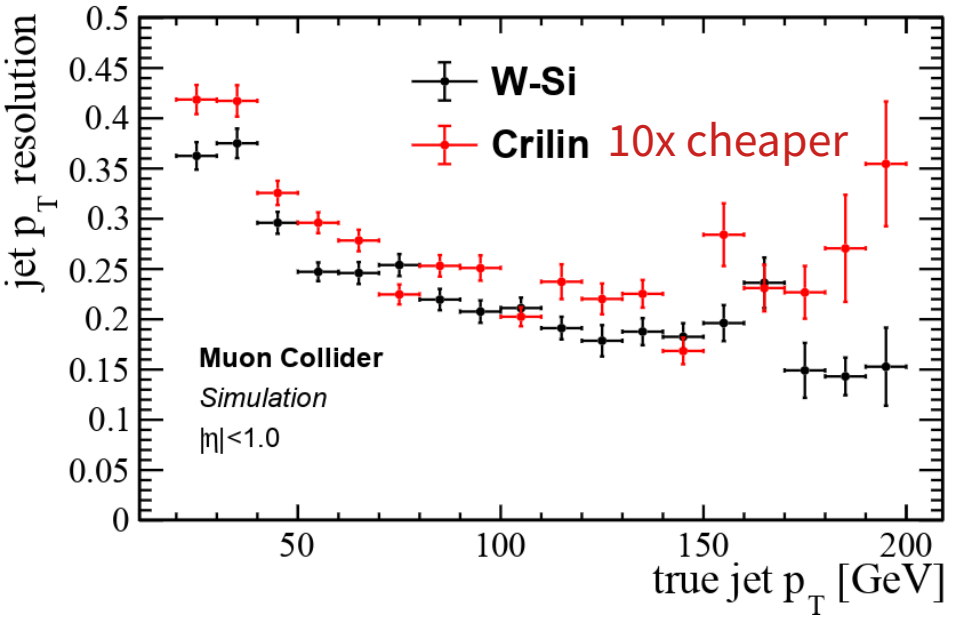


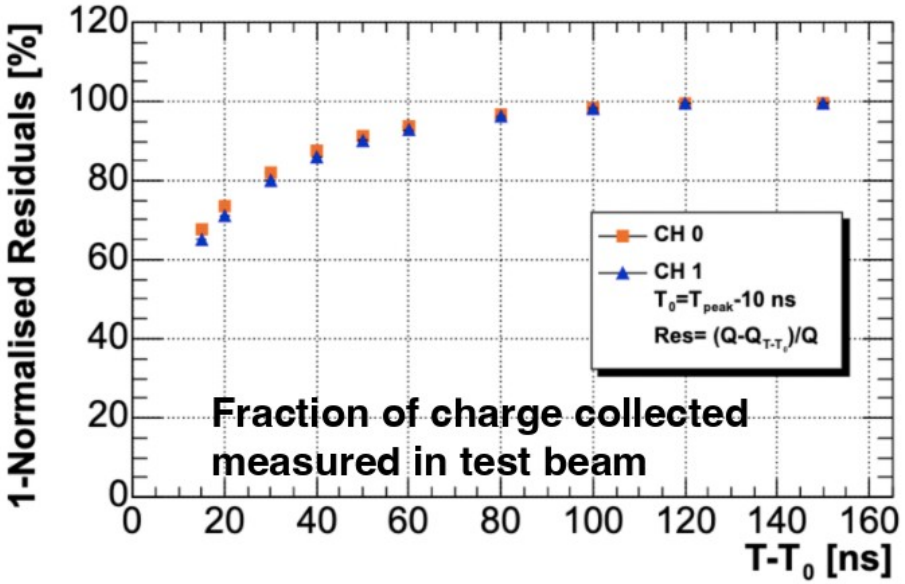
ECal energy deposition in one bunch crossing.

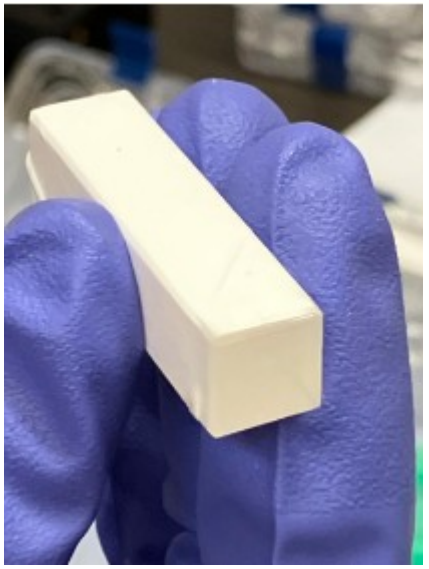
Crilin Calorimeter (ECAL)

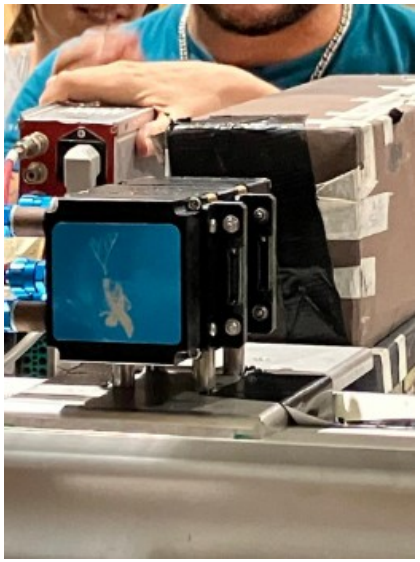
= CRystal calorImeter with Longitudinal INformation

- <u>Segmented</u> homogeneous calorimeter
  - 10 x 10 x 40 mm^3 PbF_2 crystals
  - 4 x 4 mm^2 SiPMs
- Time resolution <100 ps
- Prototypes being built and tested









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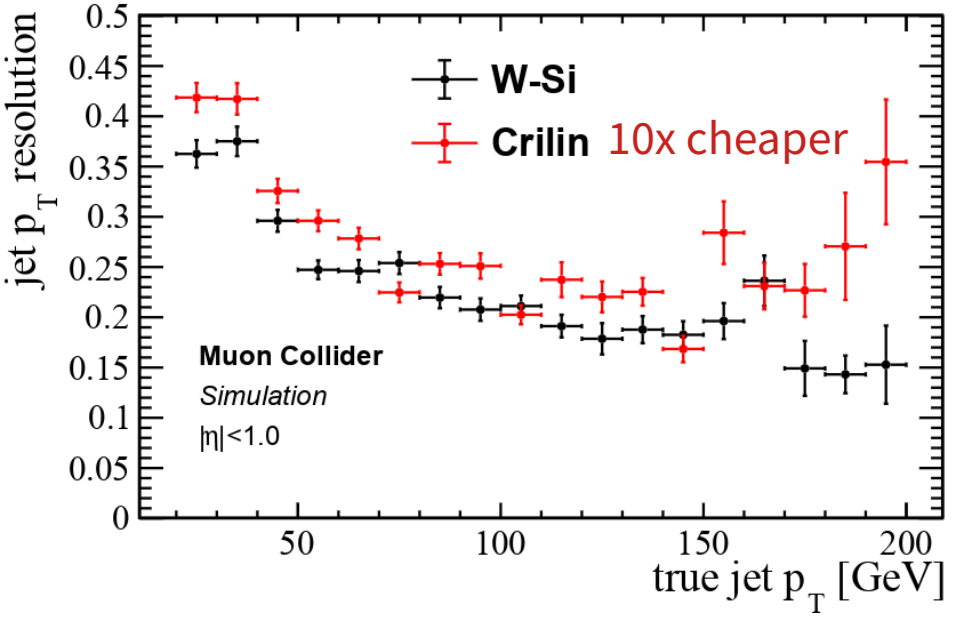
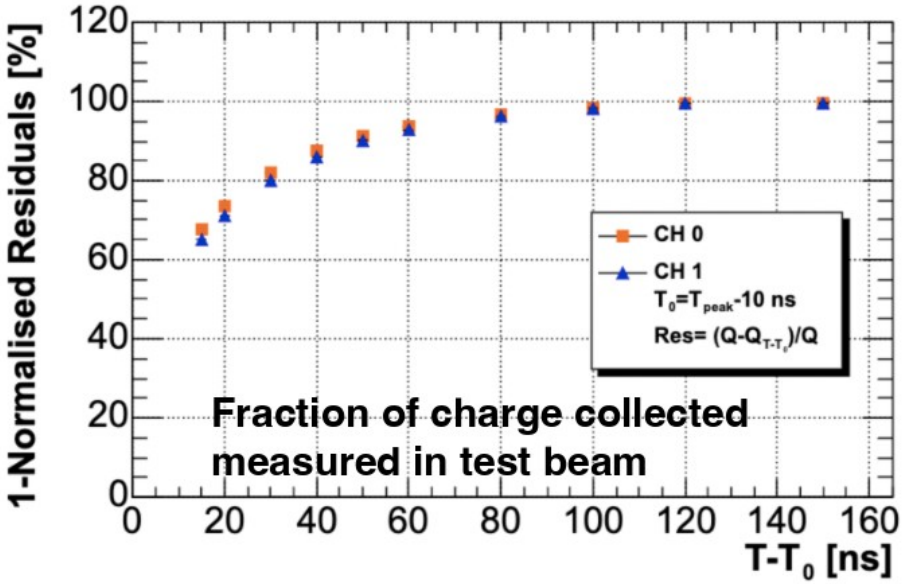
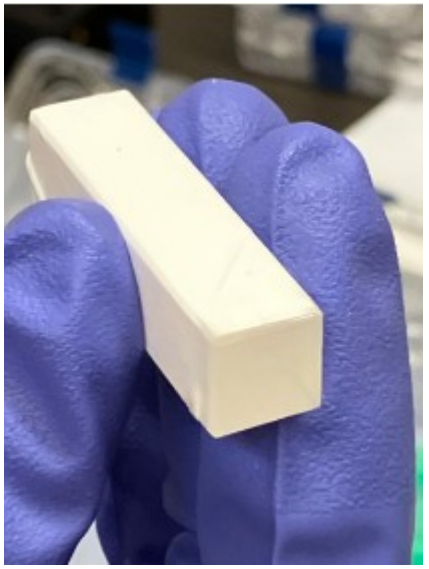
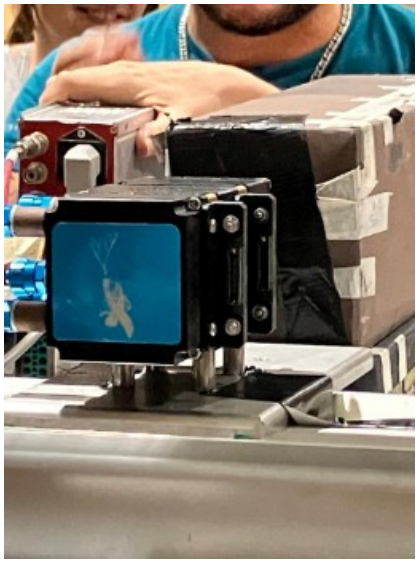
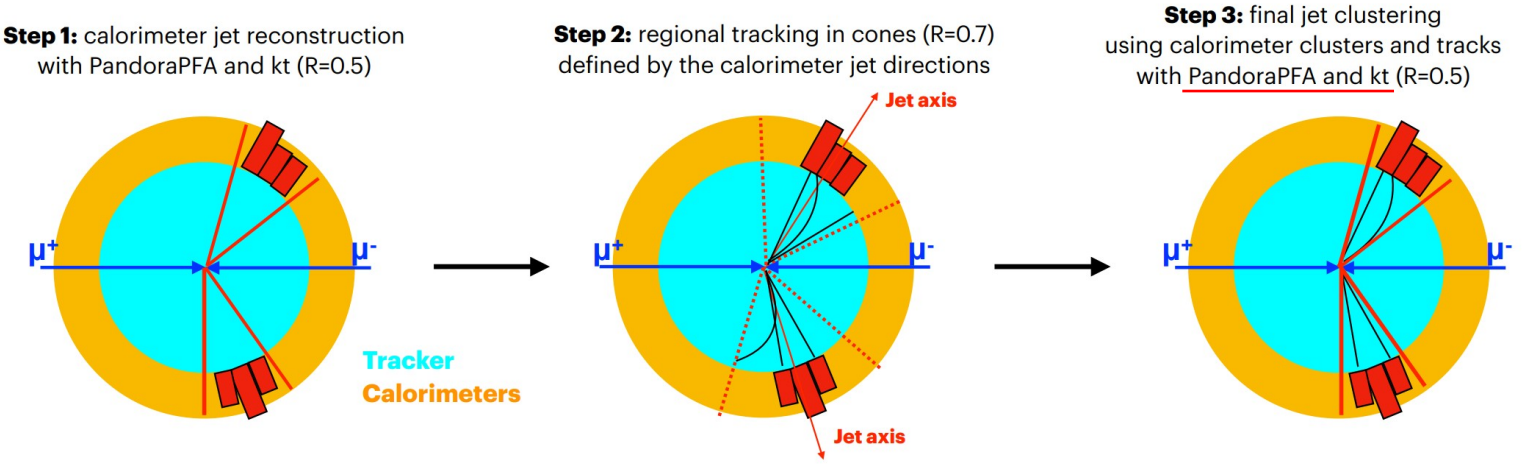




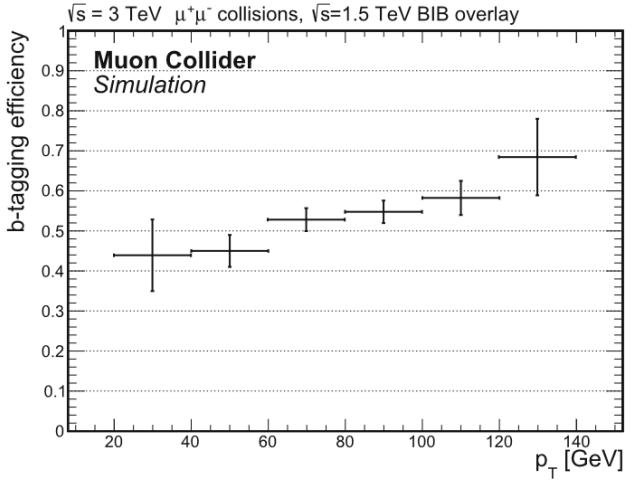


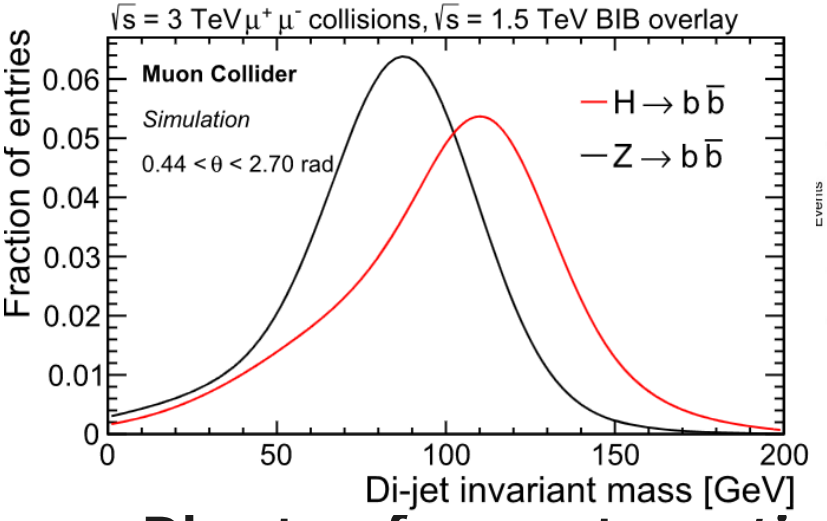


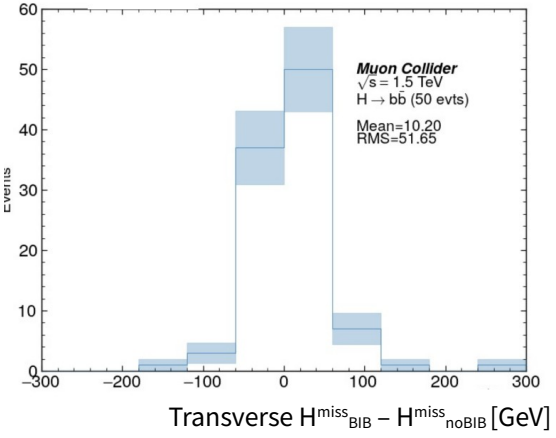
Jet Reconstruction



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

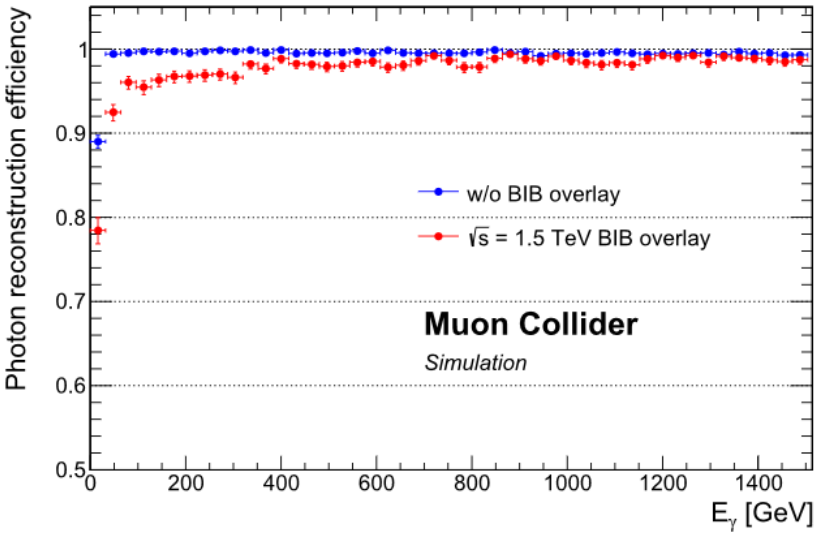


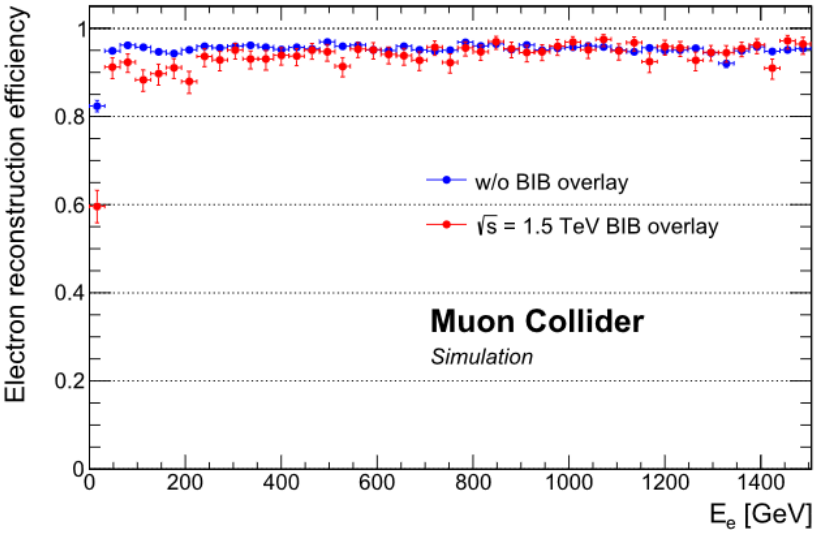


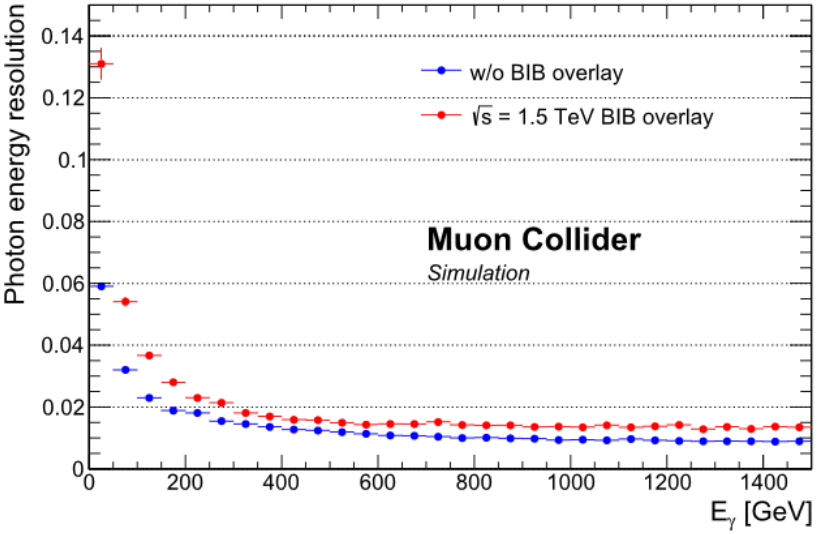


Plenty of room to *optimize* and *innovate*!

Electrons and Photons



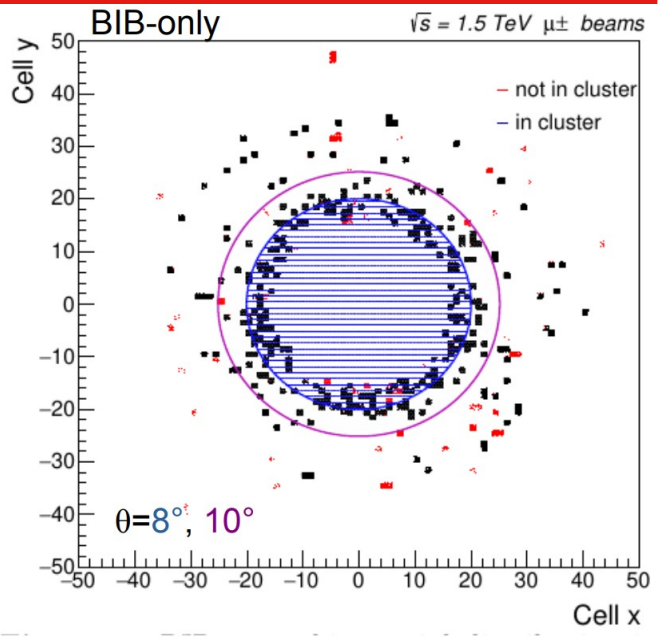


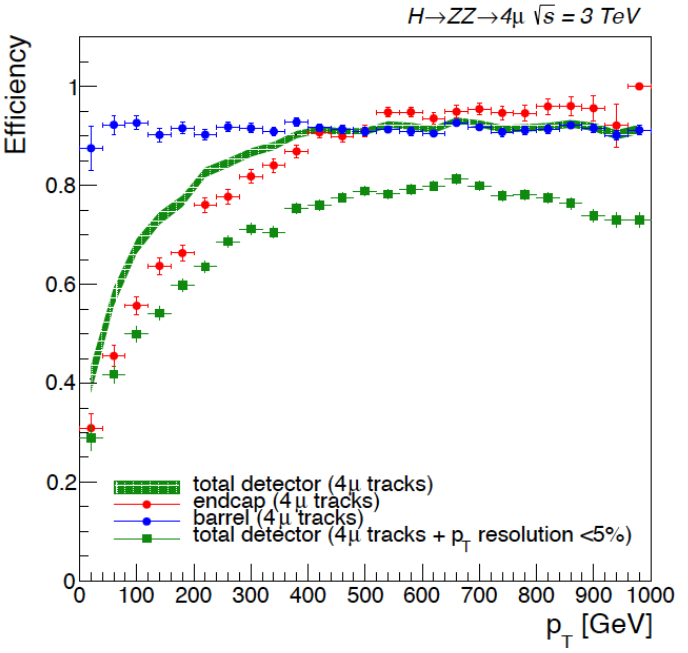


- Good performance.
- Minimal impact from BIB.

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°)

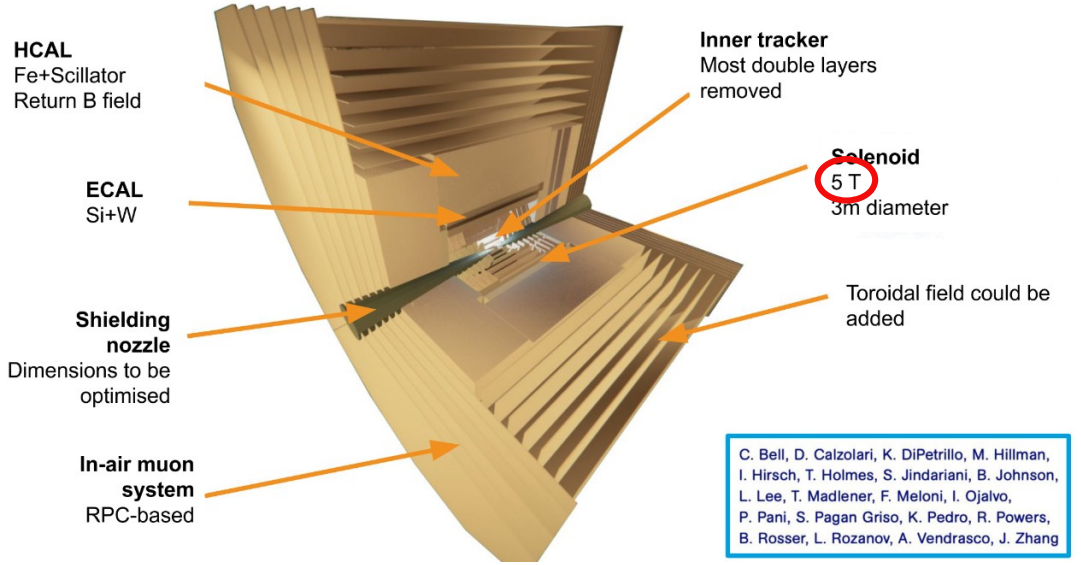




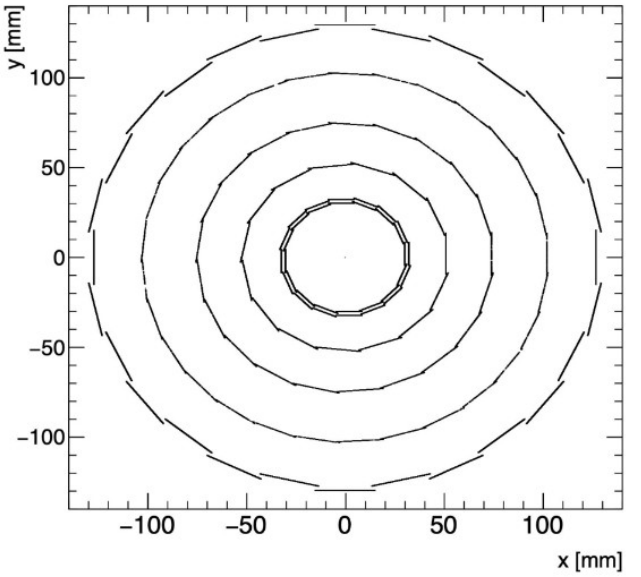
1.5 TeV vs 10 TeV

Summary by B. Rosser

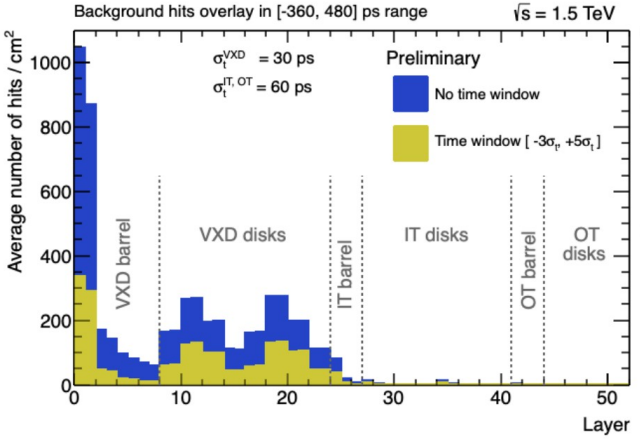
Concept developed at KITP workshop at Santa Barbara

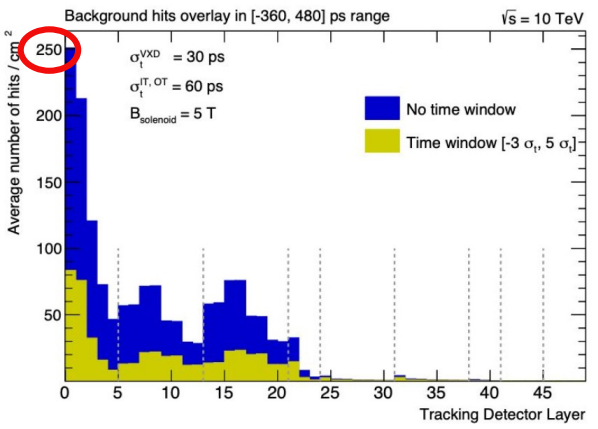


Removed double layers in tracker

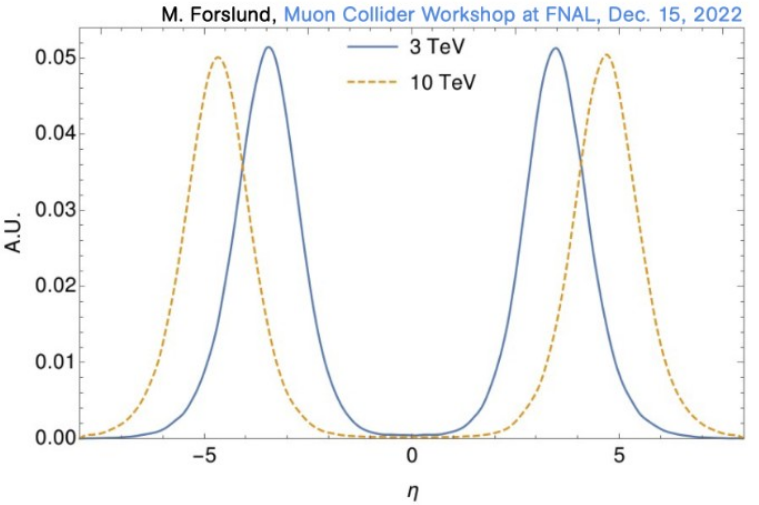


BIB is less of an issue.





But scattered muons from ZZh are more forward (nozzle)



Conclusions

- **Name of the game is reducing hits from BIB.**
  - Timing plans an important role.
- **Advanced simulation and reconstruction of detector available.**
  - Big progress during Snowmass2021 towards improving software.
  - Important to update sensitivity studies with detector simulation.
- **Progress being made towards 10 TeV studies.**
  - BIB is less of an issue.

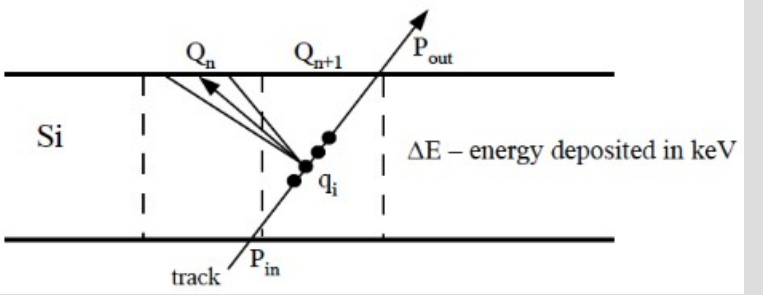
(New) UK Mailing List: UK-MUON-DETECTOR@JISCMAIL.AC.UK
Catch-ups *first Monday of Month* at 3pm

BACKUP SLIDES

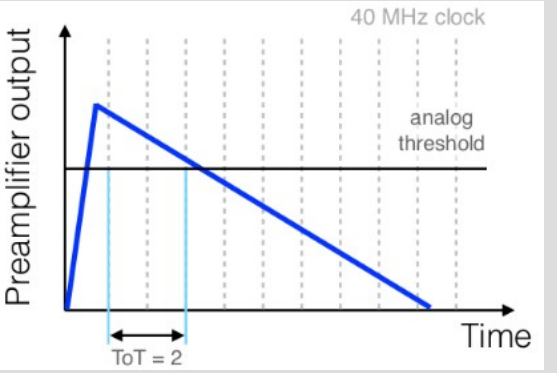
WIP Realistic Digitization

- **Two models for vertex modules**
  - Trivial (collect charge in pixel)
  - RD53A (complete simulation, ref)
- **Hoshen-Kopelman for clustering**
  - Eval alternatives as future development
- **Performance tested with full BIB**
  - Trivial: 100 s / evt
  - RD53A: 5000 s / evt

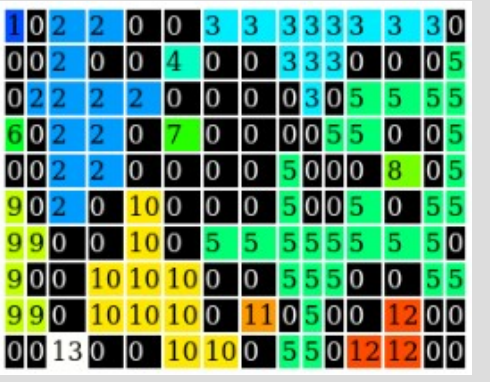
Charge Particle Deposits Details



Sensor Pixelization/Digitization



Clustering



Track Reconstruction Algo #1

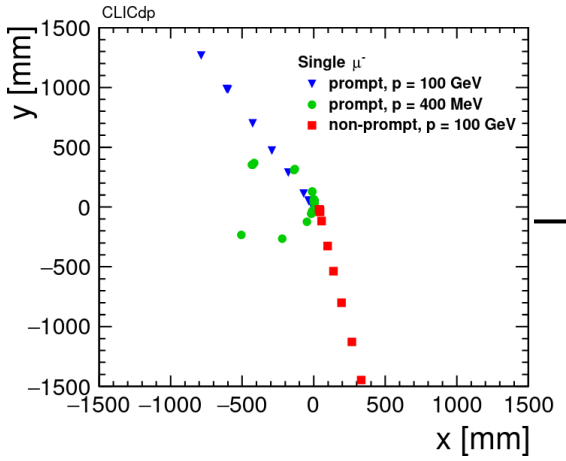
Details

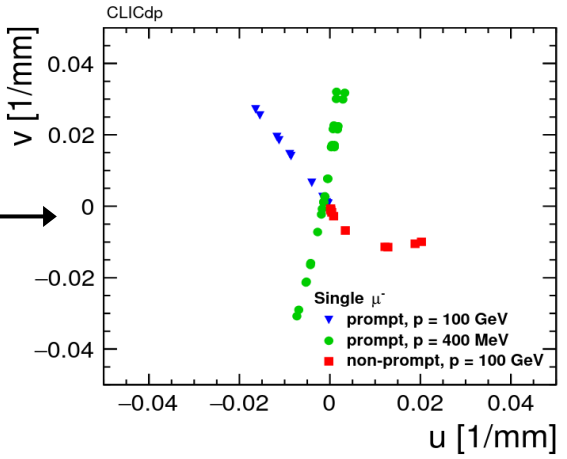
Global Hit Selection
ie: timing or double layers

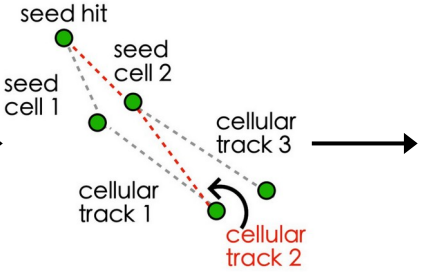
Conformal Transform
circular tracks → straight lines

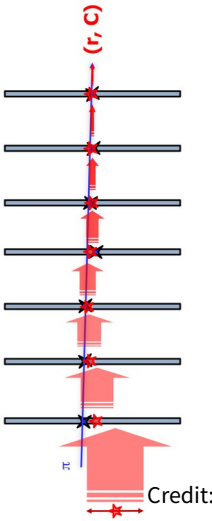
Cellular Automaton
straight "lines" → tracks

Kalman filter
Track fit









Credit: I. Kisel

Remove BIB hits

Pattern Recognition

Track Fit

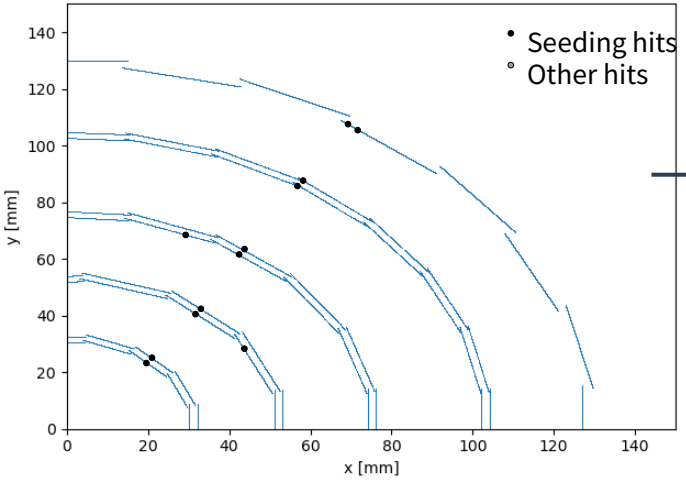
Algorithm + code inherited from CLIC software.

aka optimized for clean e^+e^- environment

Triplet Seeded CKF

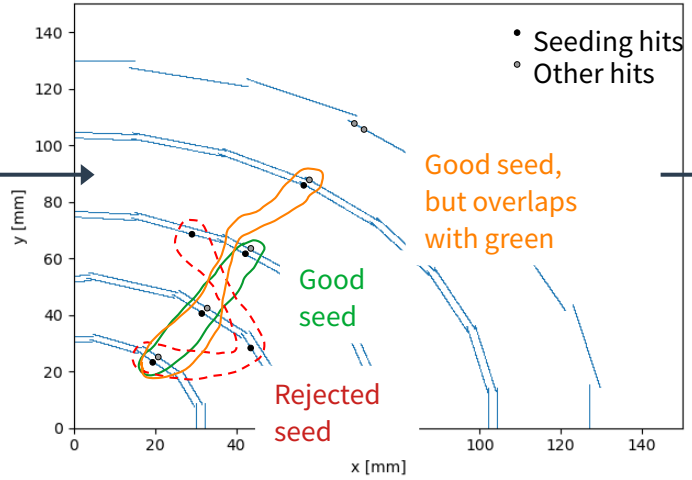
Fit Library	Kalman Filter Execution Time
ACTS	0.5 ms / track
iLCsoft	100 ms / track

Global Hit Selection
ie: timing, *

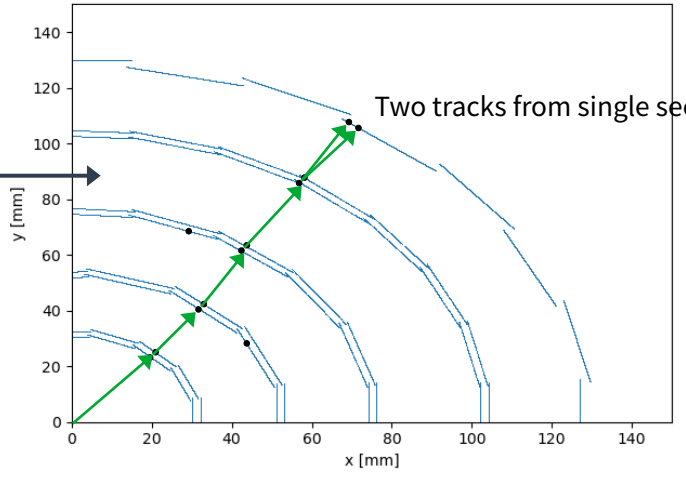


* Currently not leveraging double layers.

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