Vertex and tracking detector developments for Muon Collider

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on behalf of the International Muon Collider Collaboration

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International MUON Collider Collaboration

UNIVERSITY OF BIRMINGHAM

VERTEX2023

Physics Case For Muon Collider

Higgs Program

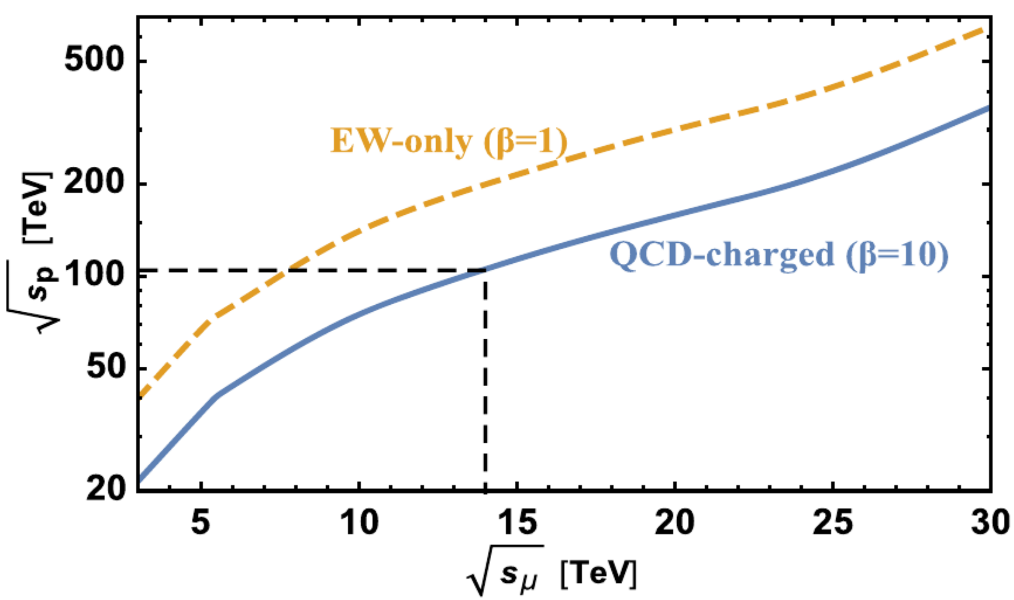
Clean nature of EW collisions allows for precision measurements.

	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**

Goal at future facilities is <1% precision.

High Energy Program

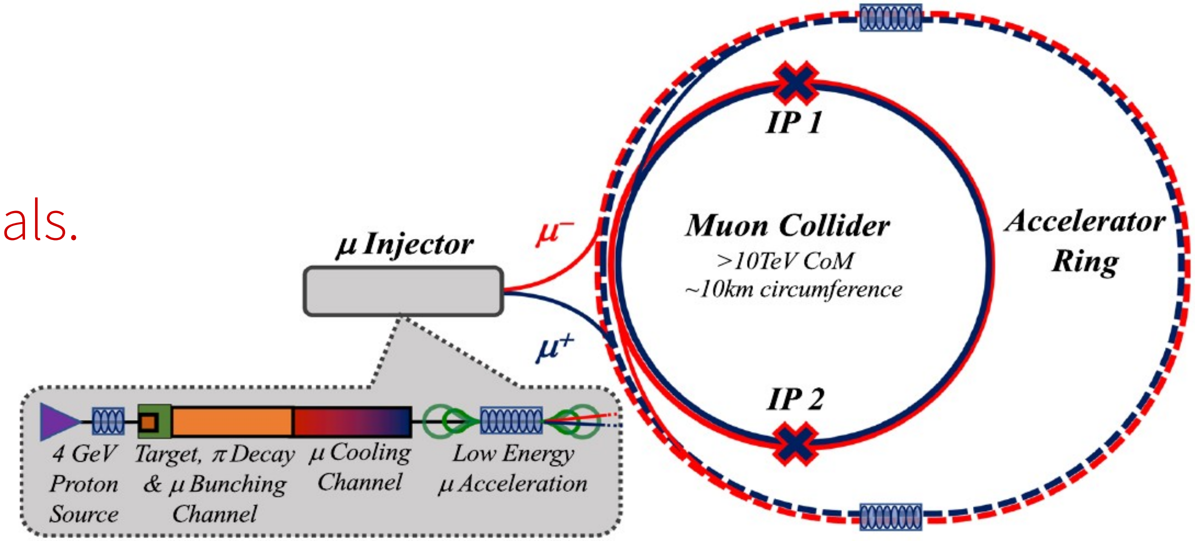
Elementary particles have a higher energy reach per collision.

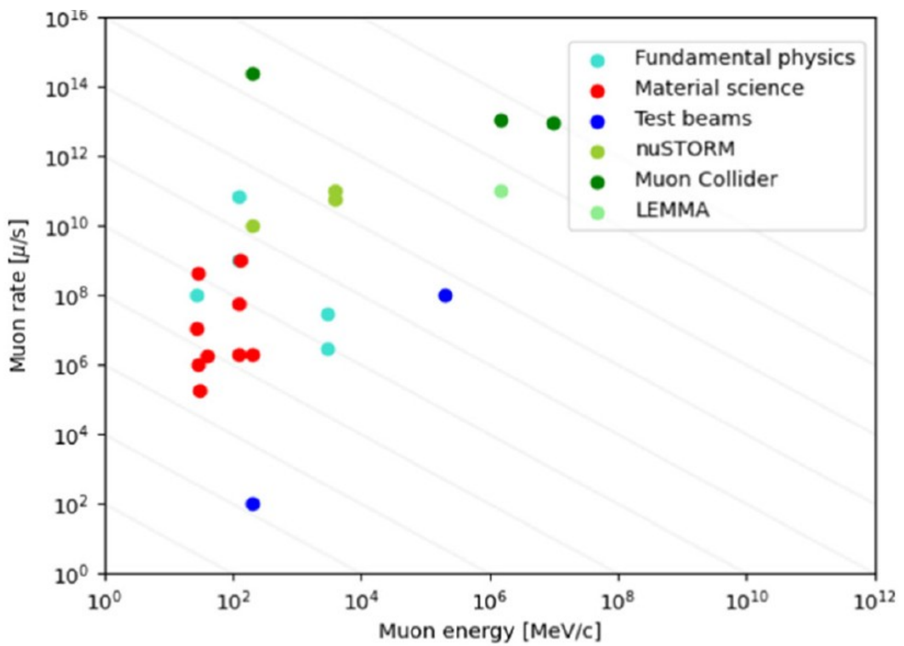


More details about the physics program in the Muon Smasher's Guide.

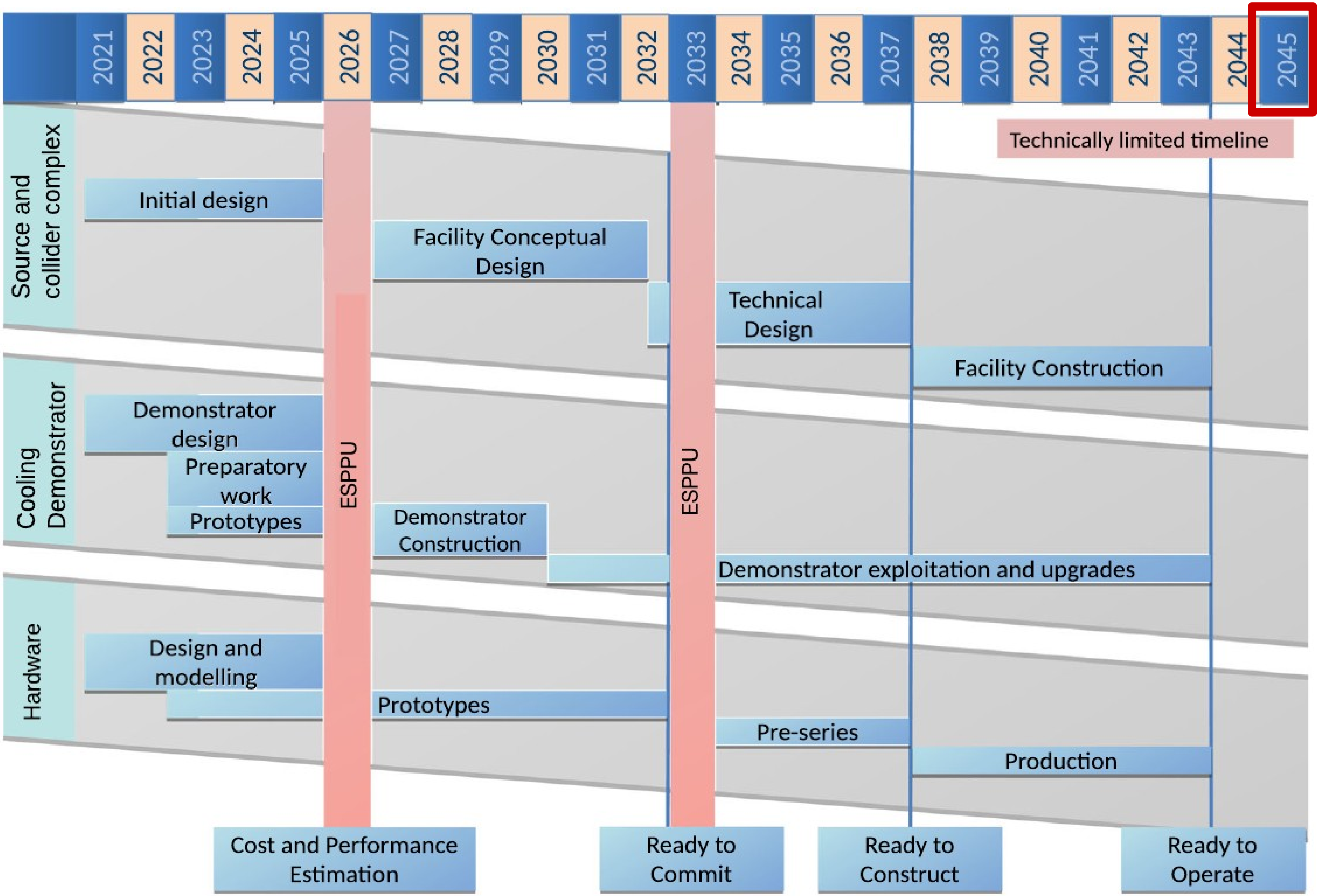
Collider Concept

- **Targeting 10 TeV CoM**
  - Minimum energy for physics goals.
- **Two main challenges:**
  - Target being to withstand high intensities.
  - Rapid transverse cooling of beam.
- **Demonstrator of muon cooling funded via MuCol.**
- **Synergies with other physics program targeting muons.**





Timelines



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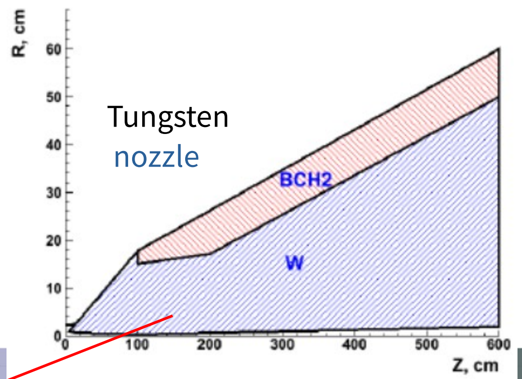
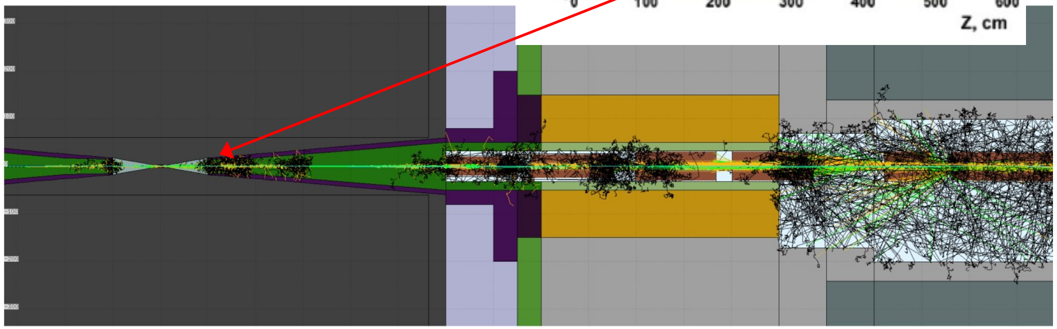
Technically limited timeline
Source and collider complex
Initial design
Facility Conceptual Design
Technical Design
Facility Construction
Cooling Demonstrator
Demonstrator design
Preparatory work
Prototypes
Demonstrator Construction
Demonstrator exploitation and upgrades
Hardware
Design and modelling
Prototypes
Pre-series
Production
ESPPU
ESPPU
Cost and Performance Estimation
Ready to Commit
Ready to Construct
Ready to Operate

Beam Induced Background

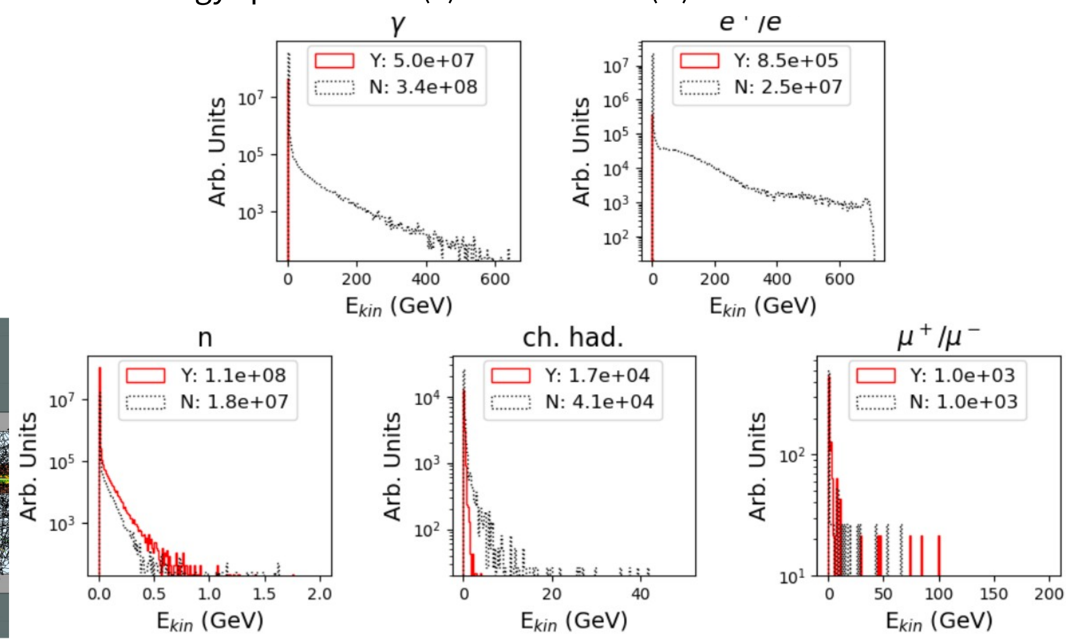
- **BIB = muon beam decays and strikes the detector**
  - Around 2 x 10^5 muon decays per meter!
- **Two main mitigations:**
  - 10° tungsten nozzle to shield from beam decay products
  - Precision timing information from detectors

FLUKA simulation of BIB before reaching the detector.





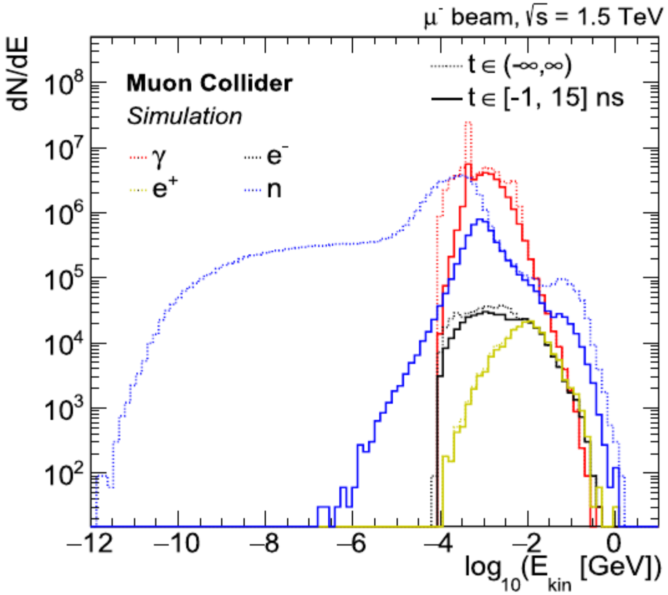
Particle energy spectra with (Y) and without (N) nozzle.

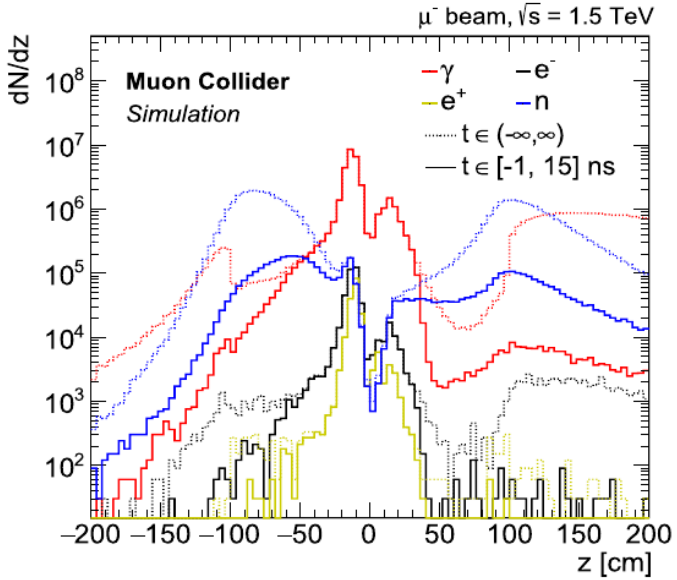


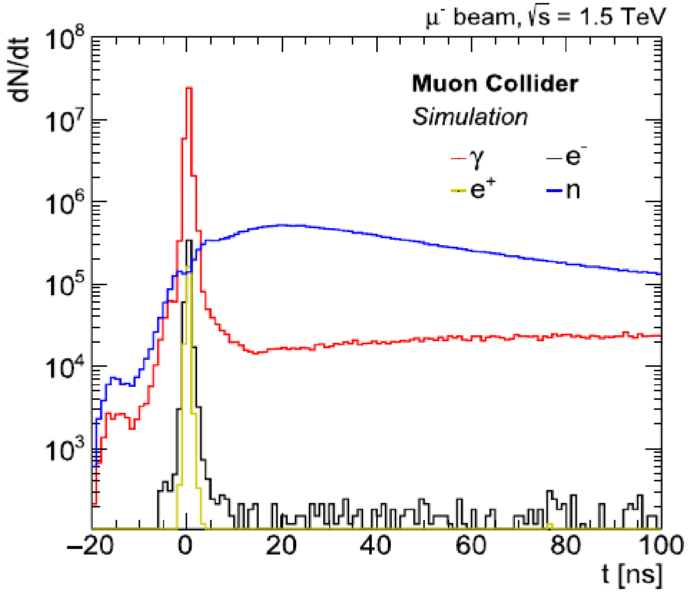
Properties of BIB

BIB is very different from pile-up at LHC.

- Very soft, uniformly distributed, particles.
- Do not originate from the collision region.
- Out of time with collisions.







Our Onion Detector

heavily based on CLIC detector

hadronic calorimeter

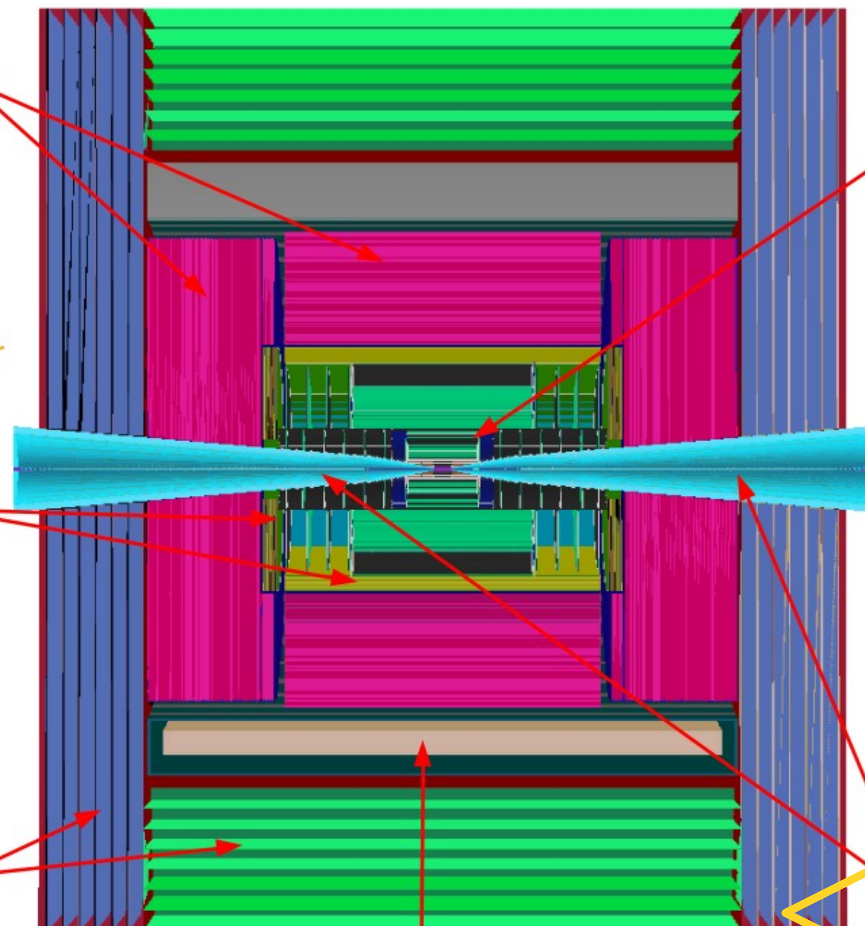
- 60 layers of 19-mm steel absorber + plastic scintillating tiles;
- 30x30 mm^2 cell size;
- 7.5 λ_I.

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.

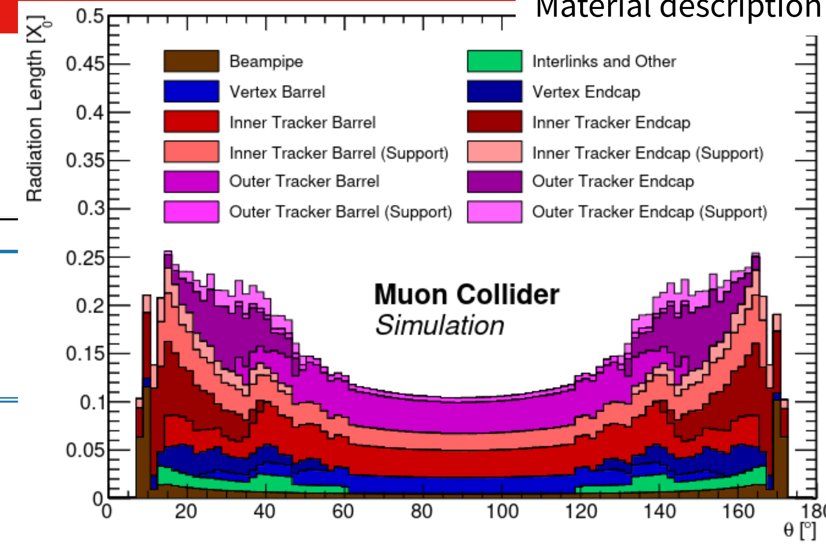
shielding nozzles

- Tungsten cones + borated polyethylene cladding.

TDAQ: Targeting a LHCb-style *trigger-less* readout at 100 kHz.

All-Silicon Tracking Detector

Material description

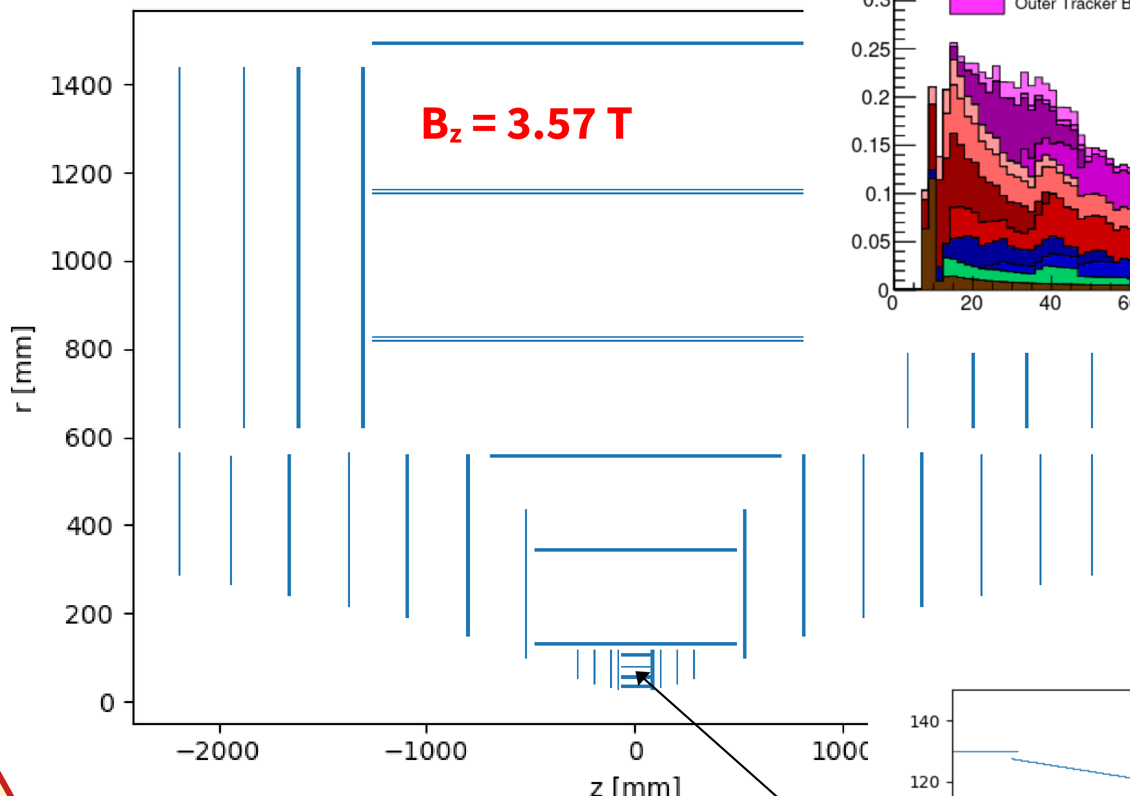


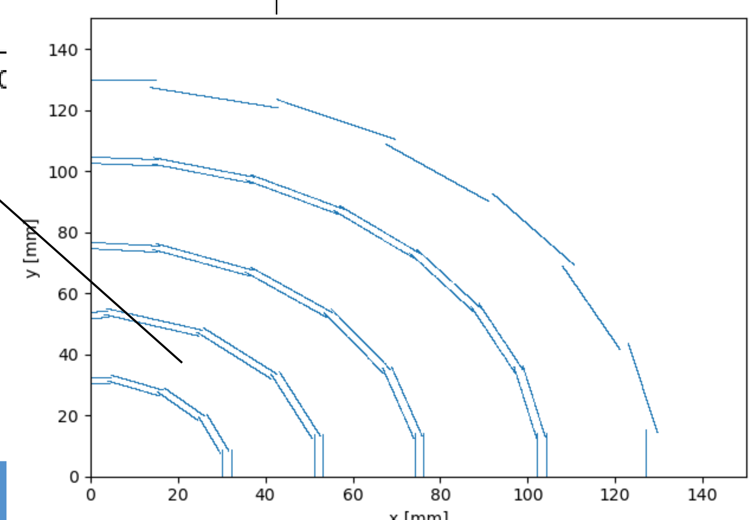
Outer Tracker (OT)

- 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



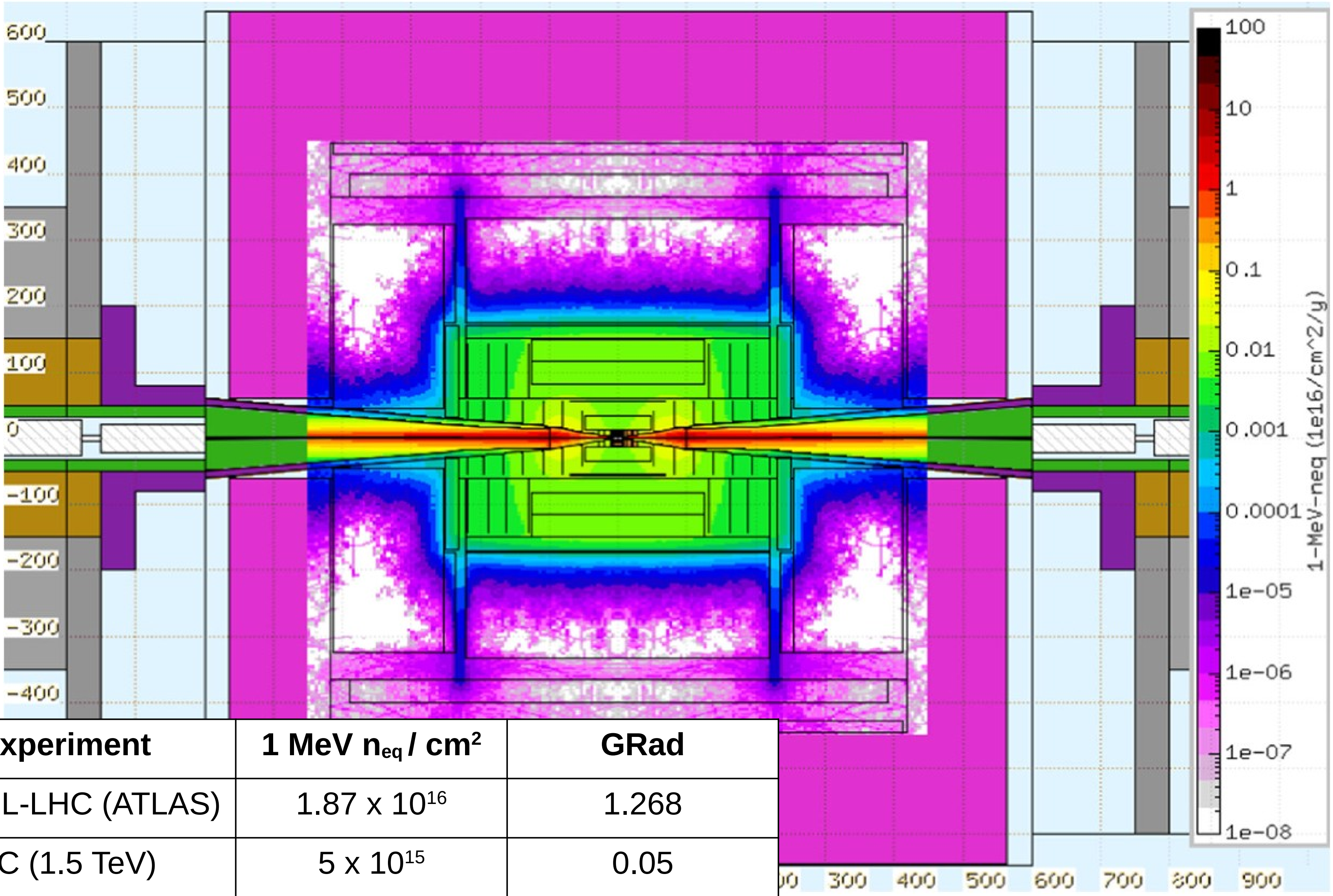


Vertex Detector (VXD)

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

4D tracking critical

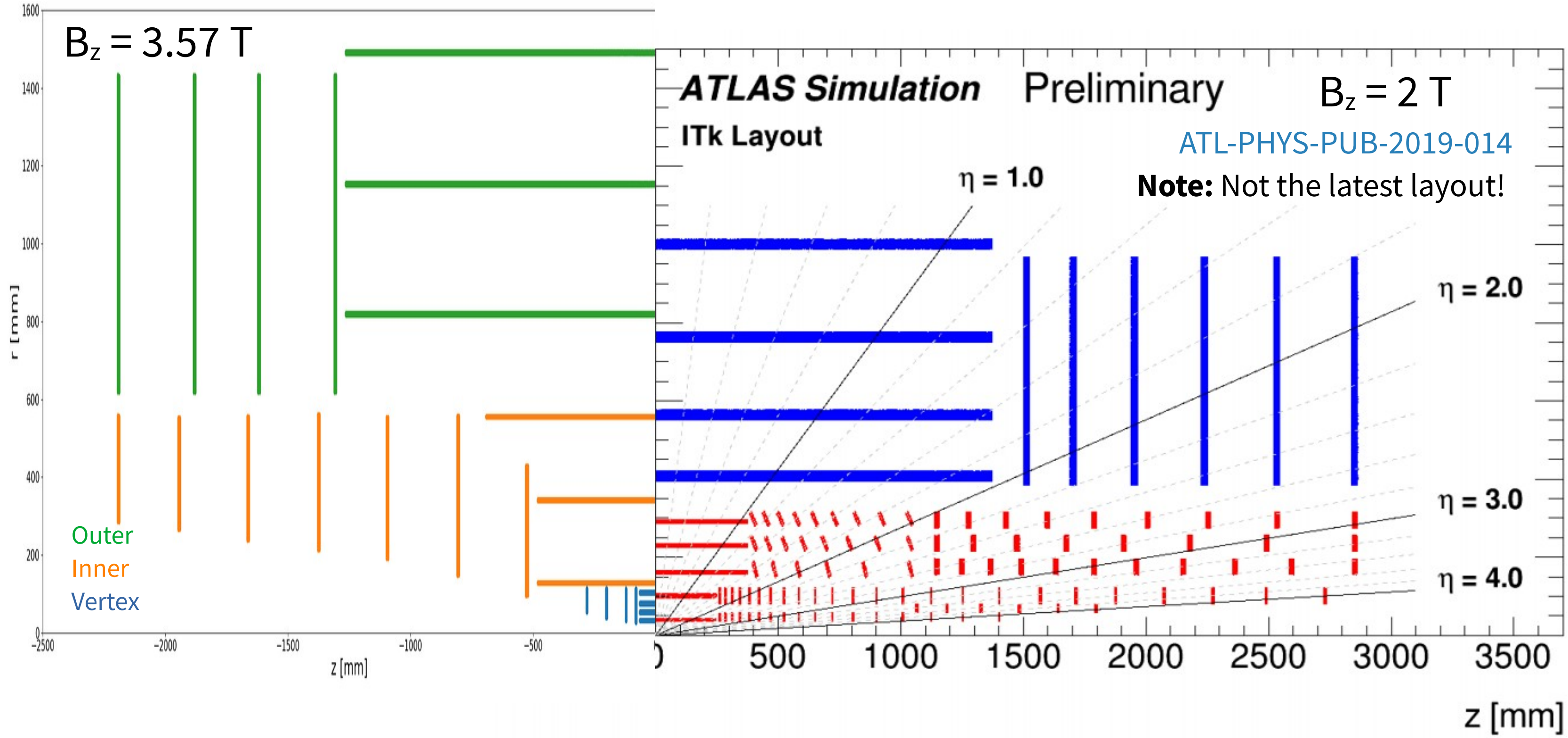
Radiation Damage From BIB



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

Expected dose in innermost tracking layer.

Hit Occupancy From BIB

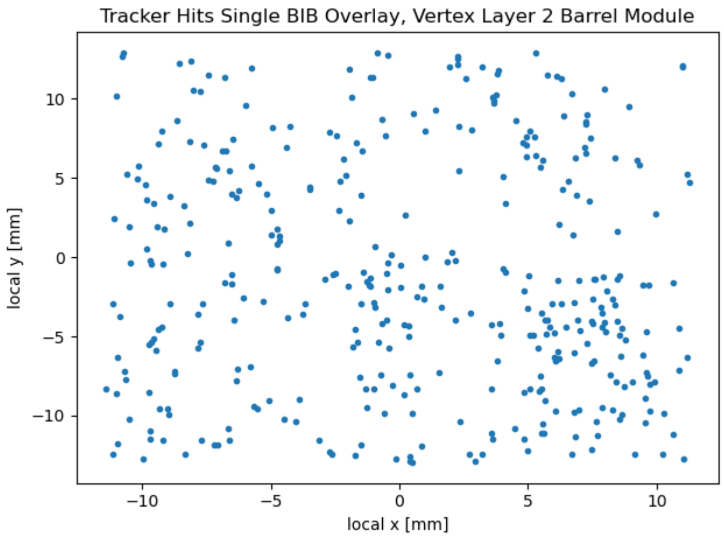


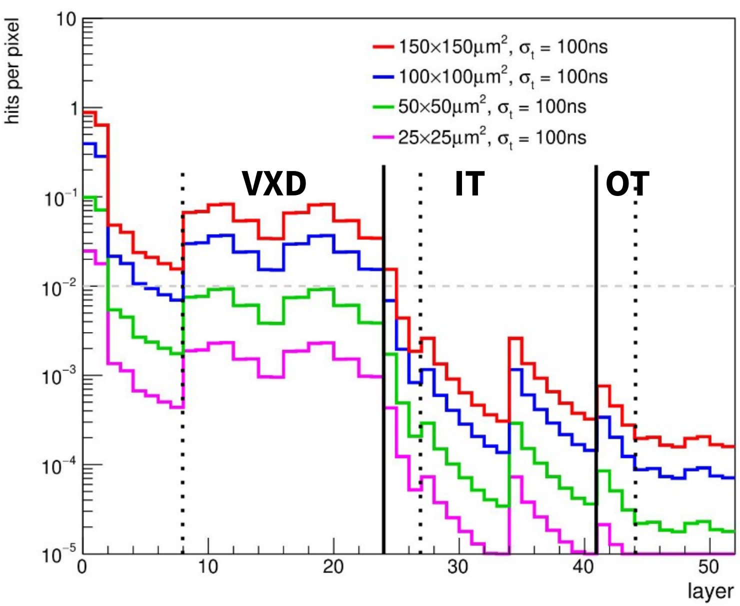
Hit density
after timing cuts
10x HL-LHC

	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

Pixel Size





- **Goal is <1 % occupancy per pixel.**
  - Pixel size optimized to achieve this
  - Precision timing also plays important role
- **Resolutions are approximated in simulation using Gaussian smearing**

Current Assumptions

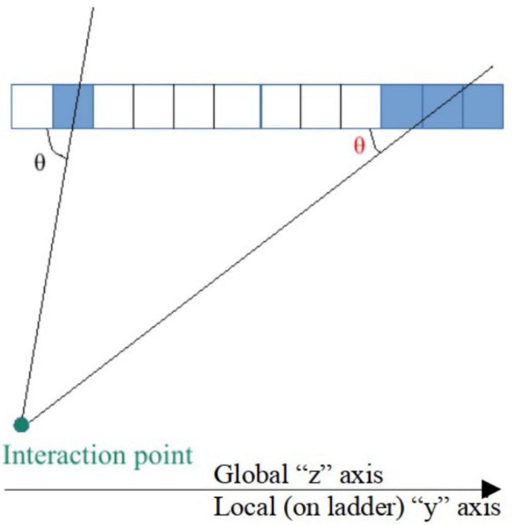
	Cell Size	Sensor Thickness	Spatial Resolution
VXD	25 μm x 25 μm	50 μm	5 μm x 5 μm
IT	50 μm x 1 mm	100 μm	7 μm x 90 μm
OT	50 μm x 10 mm	100 μm	7 μm x 90 μm

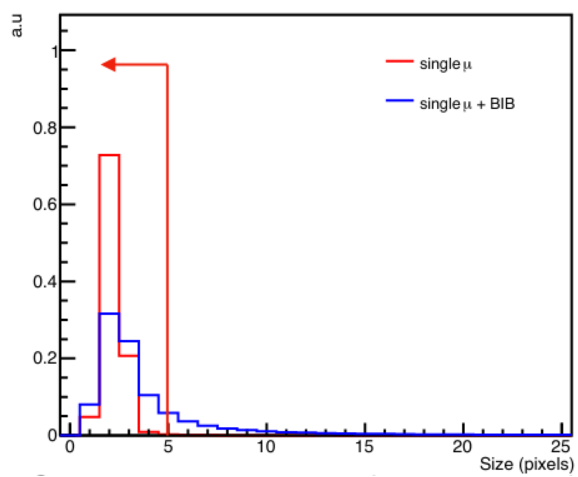
No difference between barrel and endcap.

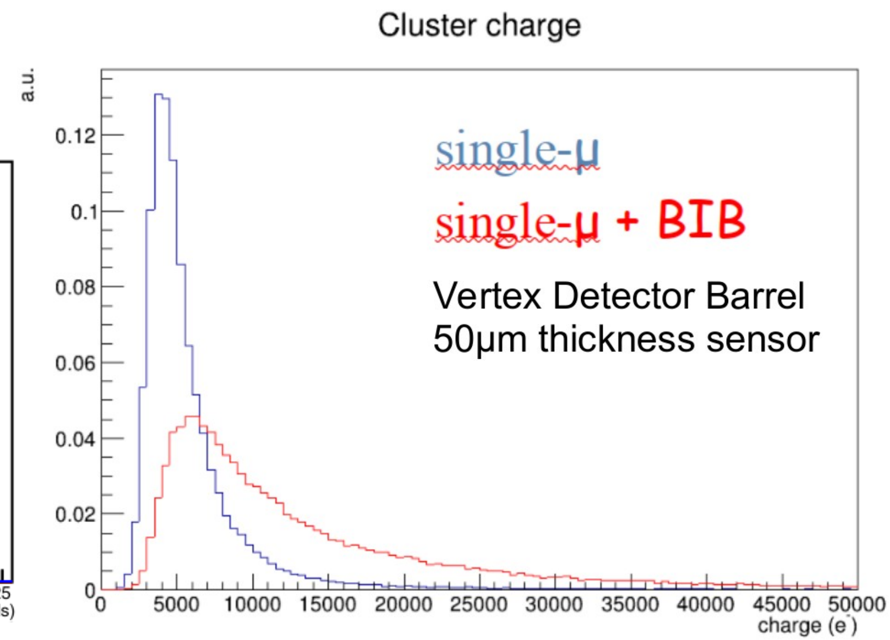
Advantages of Realistic Digitization

Work In Progress: Currently not part of common workflow

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

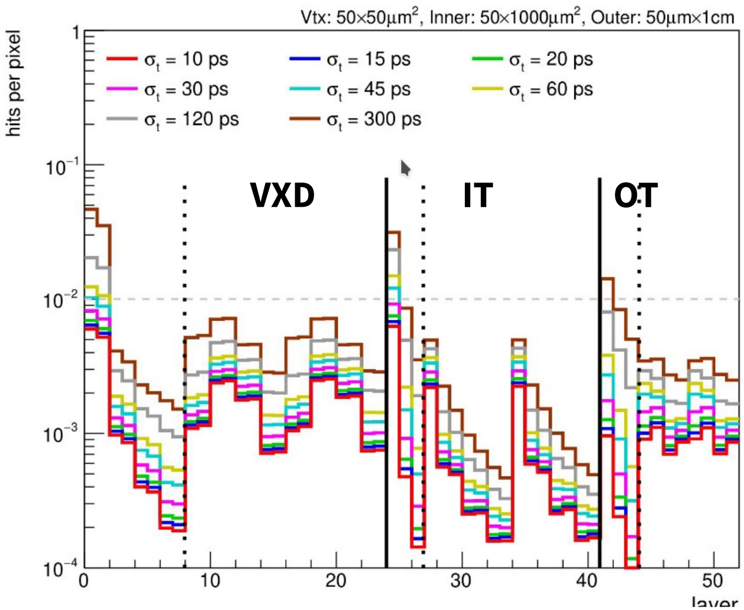




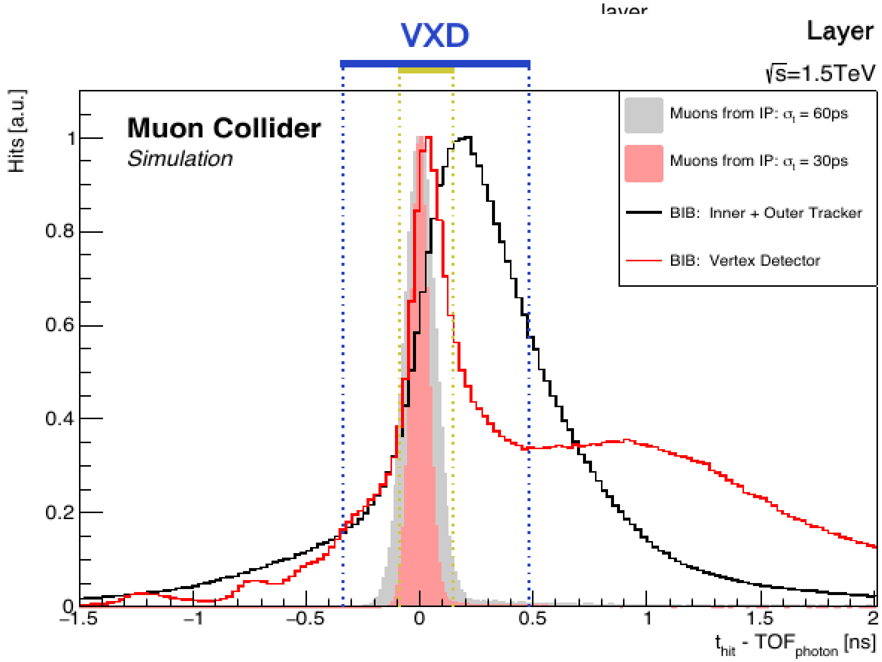


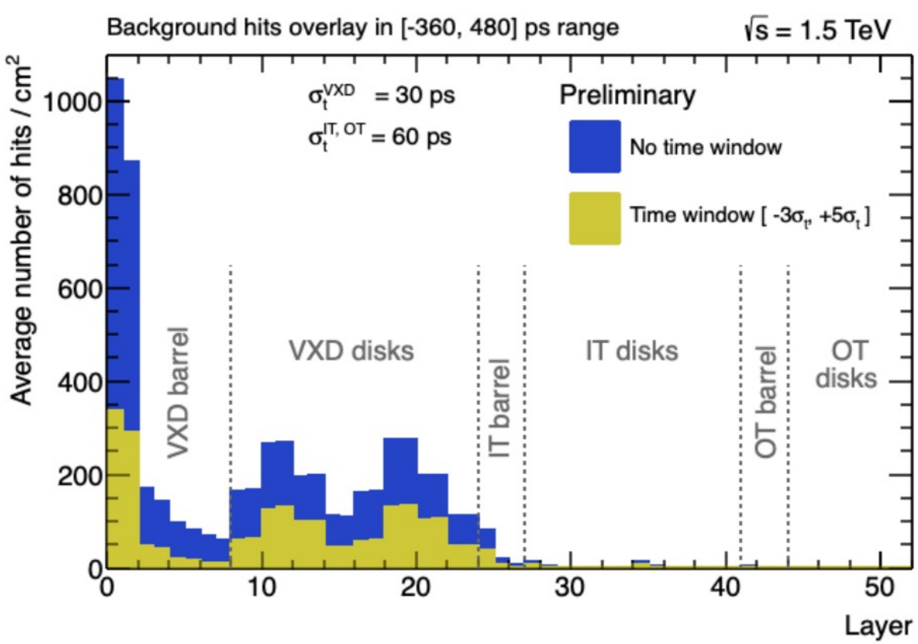
Requirement	Cut efficiency	Loose	Tight
Size-y cut vs. θ only	Single-μ	99.8 %	99.6 %
	Single-μ and BIB	55.2 %	43.7 %
Adding pixel size-x < 4	Single-μ	99.3 %	99.1 %
	Single-μ and BIB	37.4 %	30.7 %

Pixel Timing

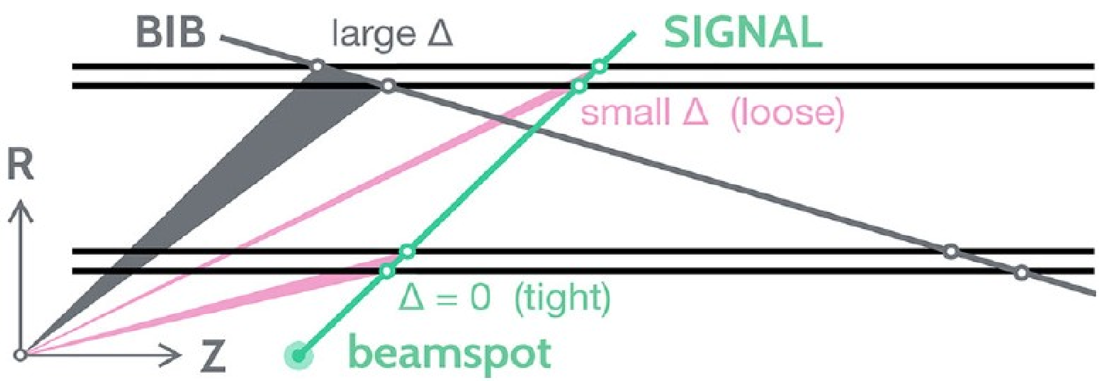


- **Precision ToF is very important.**
  - 30 ps in the VXD reduces occupancy by 50%.
  - Useful for on-detector filtering (for readout).
- **Be careful about long tails.**
- **Be careful about slow particles.**

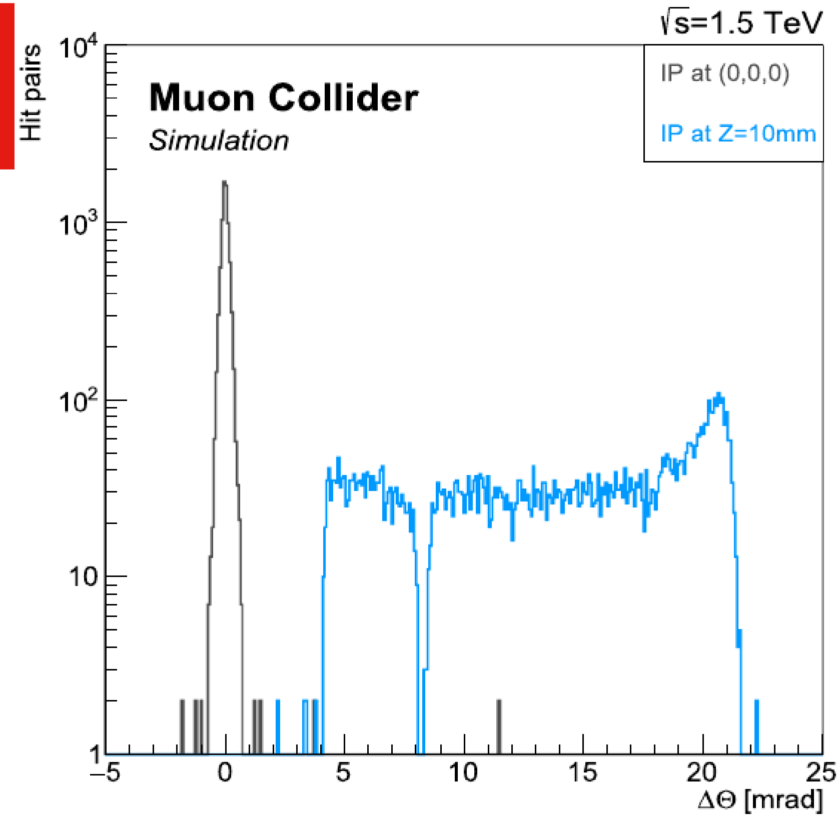


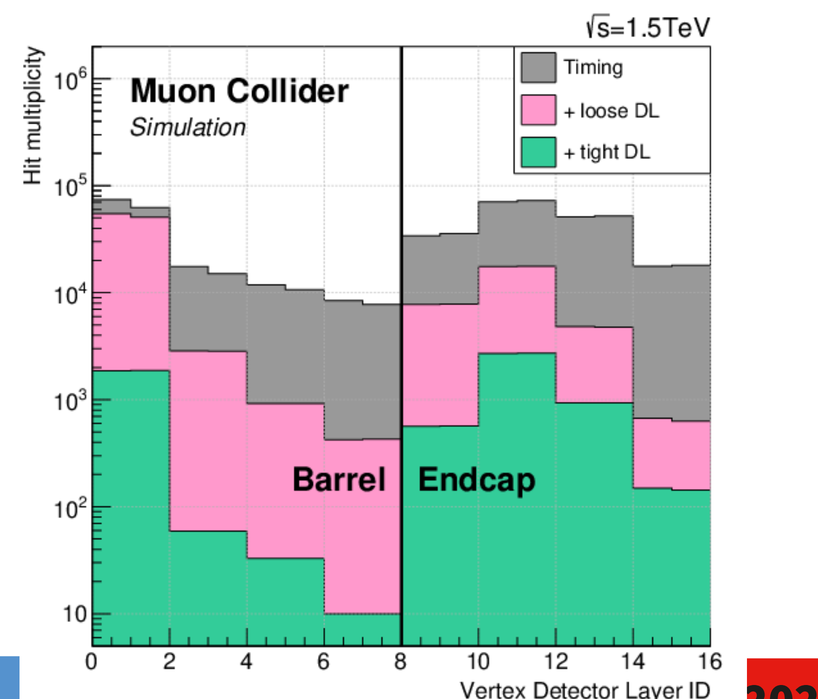


Doublet Layer Filtering



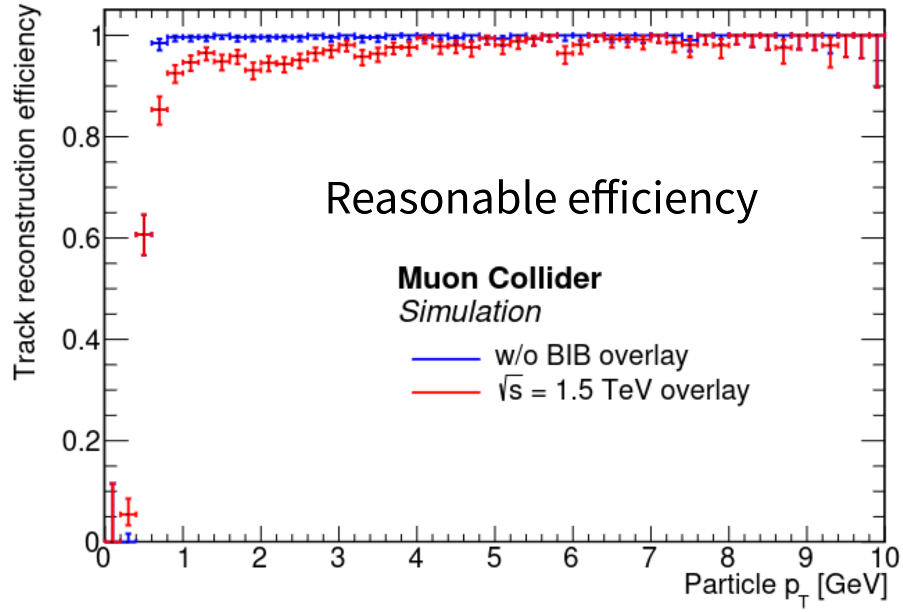
- **Reduce the combinations problem for track reconstruction.**
  - Similar design used by CMS Phase 2 upgrade for track reconstruction inside trigger.
- **There are downsides:**
  - Need to know precise position of pixels.
  - Biased against displaced particles.
  - Construction of layers separated by 2 mm.

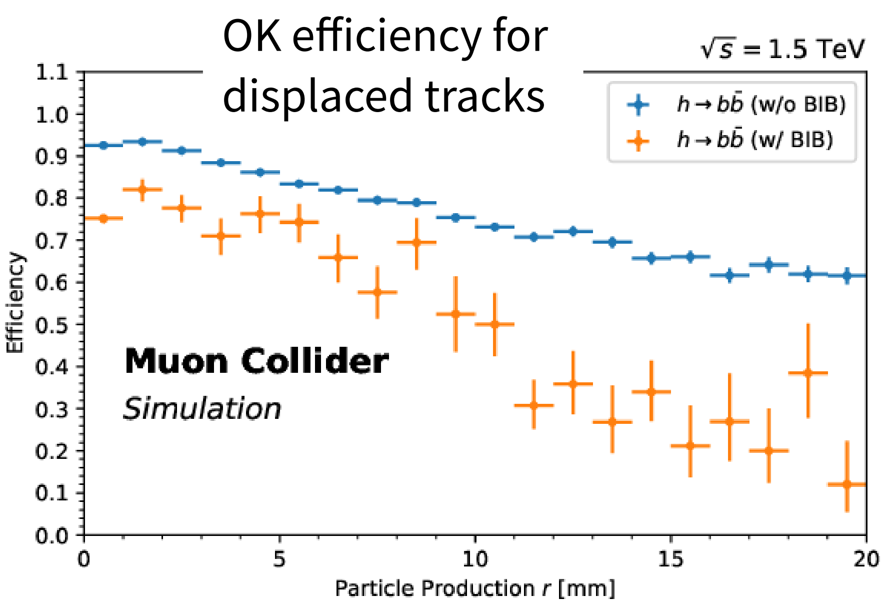




CKF Tracking Performance

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





Fake track removal
(optimized with evolutionary algorithms)

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

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!

How far are we? Outer/Inner Tracker

σ_t = 60 ps, 50μm x O(mm), < 10^{15} 1 MeV neq / cm^2, large area

- **LGAD's satisfy most of these requirements already.**
  - Cheap, rad hard enough…
  - Need improved filling factor.
  - 200 to 2000 times the channel density of ATLAS/CMS timing layers.
- **Good place for monolithic sensors w/ timing?**
  - Wafer scale sensors / stitching to cover large areas.
  - Large "pixels" means more space for front-end circuitry.

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…

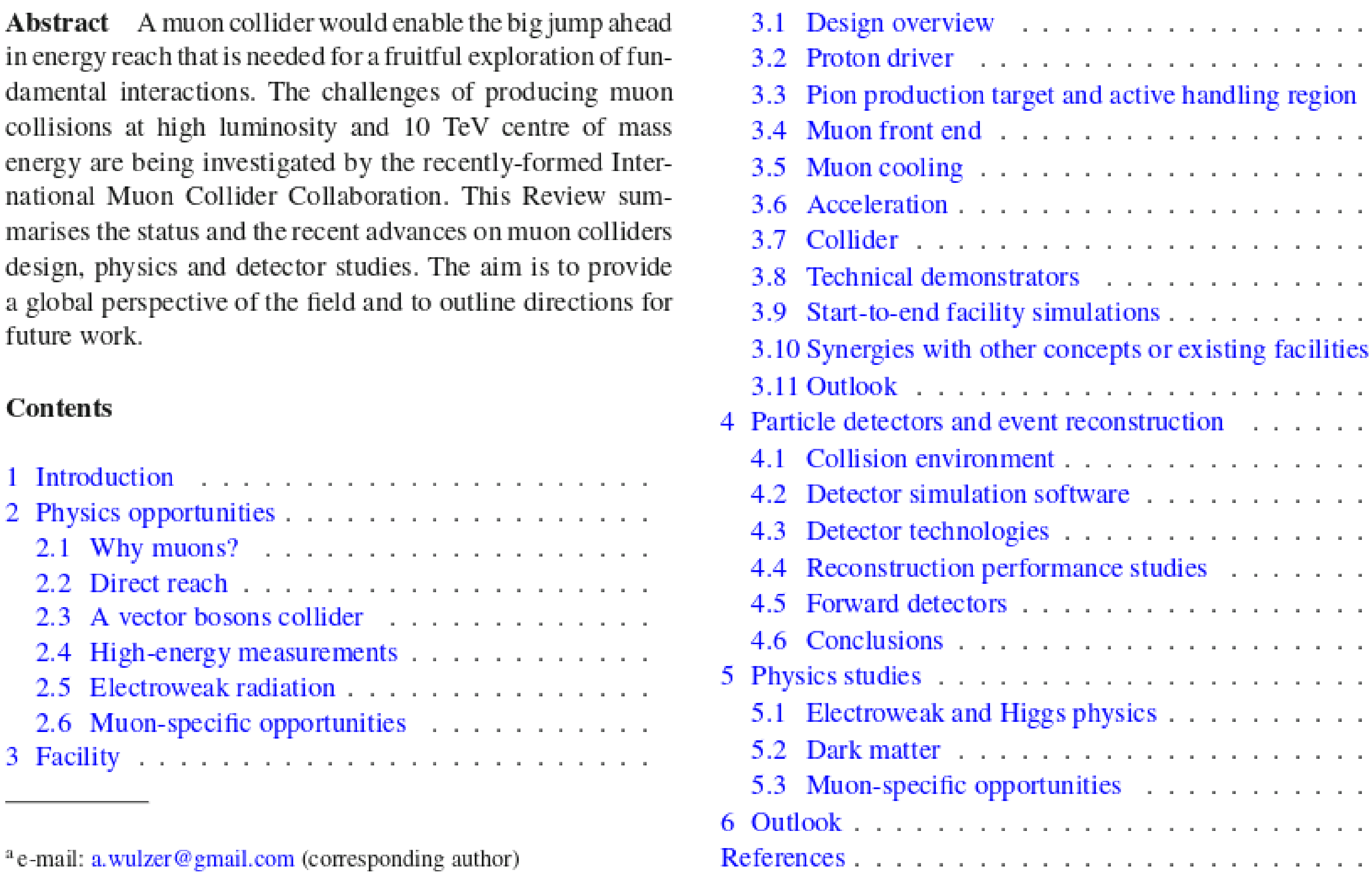
Conclusions

- **Muon Collider is a promising future collider.**
  - "Precision of an electron collider, energy of a hadron collider."
- **Main issue is the Beam Induced Background.**
- **Study of detector requirements well advanced in simulation.**
  - Tracker requirements are understood well.
- **Will benefit from existing R&D into 4D trackers.**
  - "Easier" than FCChh due to lower radiation hardness.
  - Main need is to minituarize pixels.
  - Never forget system-level issues…

Muon Collider Sumary Paper

Accettura, C., Adams, D., Agarwal, R. et al. Towards a muon collider. Eur. Phys. J. C 83, 864 (2023). https://doi.org/10.1140/epjc/s10052-023-11889-x

To learn more about the physics, detector and accelerator challenges: Towards a Muon Collider


Abstract A muon collider would enable the big jump ahead in energy reach that is needed for a fruitful exploration of fundamental interactions. The challenges of producing muon collisions at high luminosity and 10 TeV centre of mass energy are being investigated by the recently-formed International Muon Collider Collaboration. This Review summarises the status and the recent advances on muon colliders design, physics and detector studies. The aim is to provide a global perspective of the field and to outline directions for future work.

Contents

[a] e-mail: a.wulzer@gmail.com (corresponding author)

BACKUP SLIDES

Higgs Self-Coupling (SM DiHiggs)

collider	Indirect-h	hh	combined
HL-LHC [78]	100-200%	50%	50%
ILC_{250}/C^3-250 [51, 52]	49%	–	49%
ILC_{500}/C^3-550 [51, 52]	38%	20%	20%
$CLIC_{380}$ [54]	50%	–	50%
$CLIC_{1500}$ [54]	49%	36%	29%
$CLIC_{3000}$ [54]	49%	9%	9%
FCC-ee [55]	33%	–	33%
FCC-ee (4 IPs) [55]	24%	–	24%
FCC-hh [79]	-	3.4-7.8%	3.4-7.8%
μ(3 TeV) [64]	-	15-30%	15-30%
μ(10 TeV) [64]	-	4%	4%

Multi-TeV collider is required for higgs self-coupling

$$V(\phi) = \mu^2 \phi^\dagger \phi + \lambda(\phi^\dagger \phi)^2$$

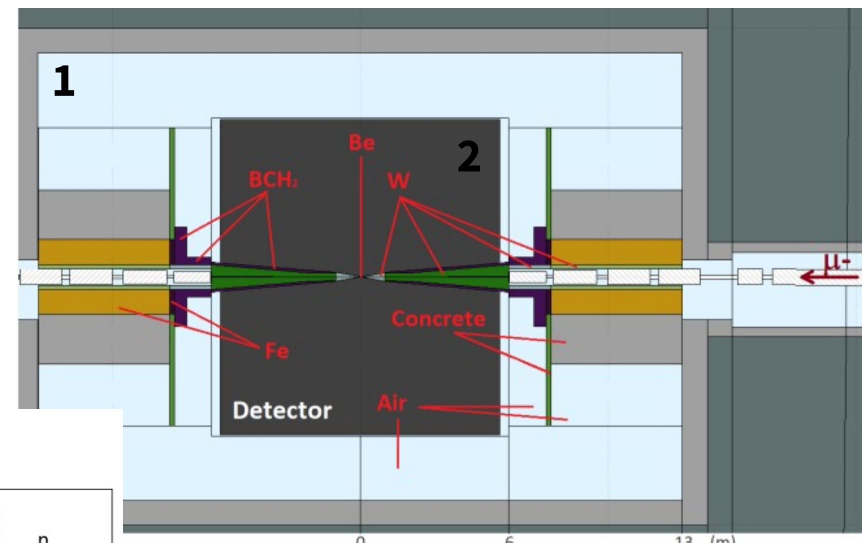
Credit: R. Petrossian-Byrne, N. Craig

Simulating Beam Induced Background

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

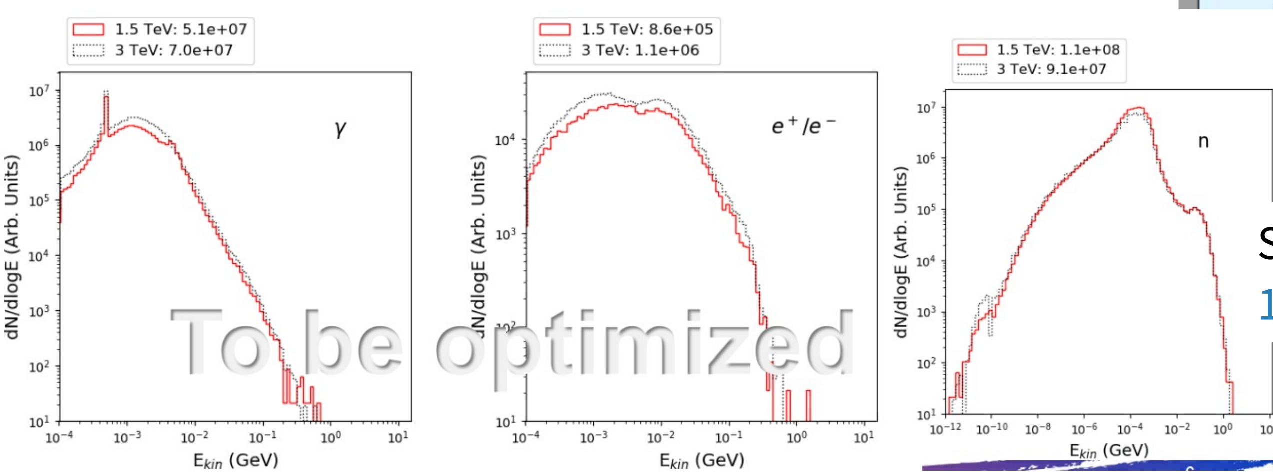
- Full beam optics present through LineBuilder Interface

2)GEANT simulation of particles entering the detector



√s=1.5 TeV used to develop setup,

more energy points being added



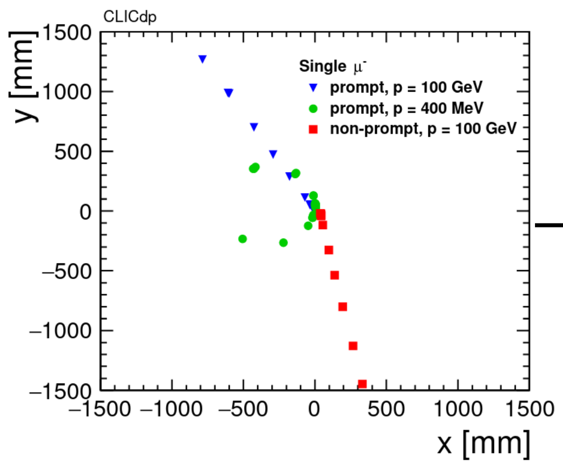
Source:
1.5 vs 3 TeV

* validating against an older model from MARS15

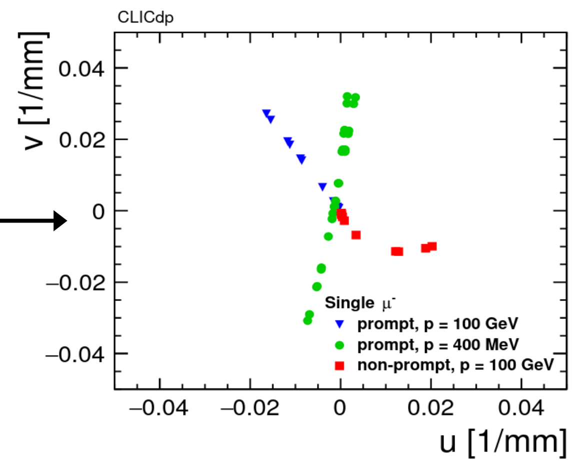
Track Reconstruction Algo #1

Details

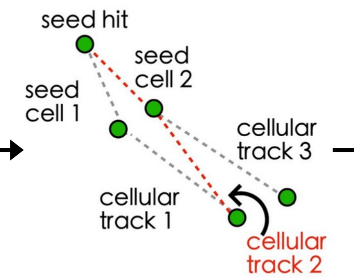
Global Hit Selection
ie: timing or double layers



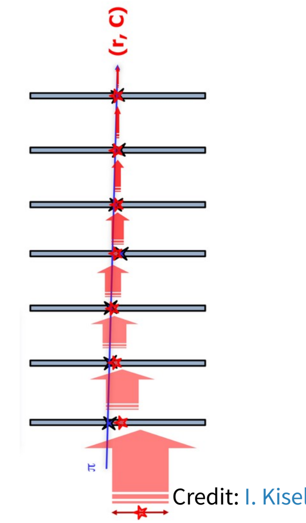
Conformal Transform
circular tracks → straight lines



Cellular Automaton
straight "lines" → tracks



Kalman filter
Track fit



Remove BIB hits

Pattern Recognition

Track Fit

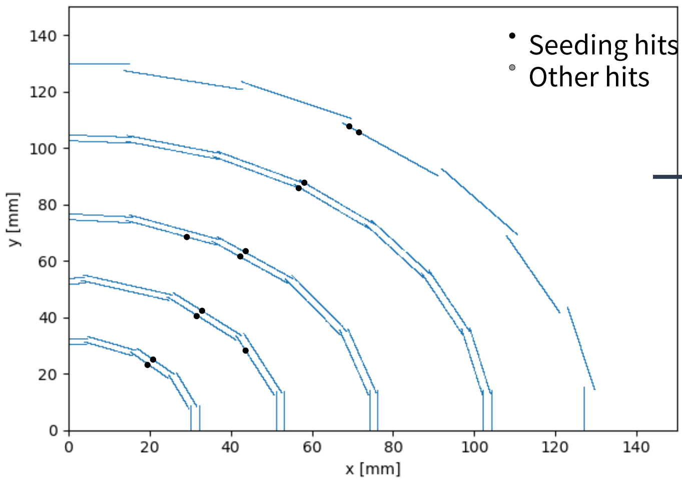
Algorithm + code inherited from CLIC software.

aka optimized for clean e^+e^- environment

Triplet Seeded CKF

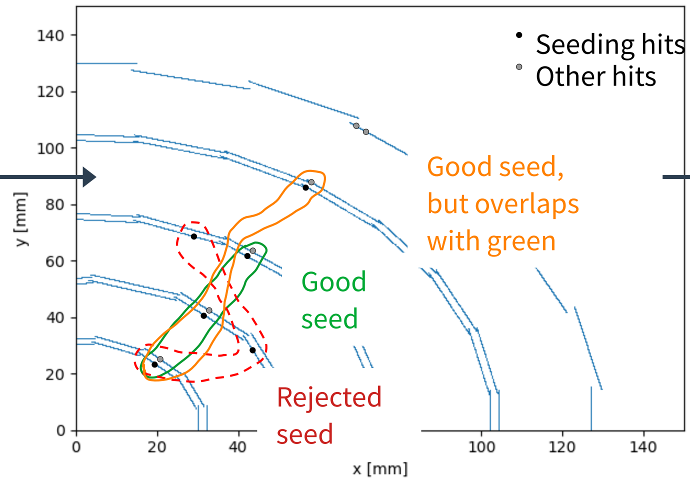
Fit Library	Kalman Filter Execution Time
ACTS	0.5 ms / track
iLCsoft	100 ms / track

Global Hit Selection
ie: timing, *

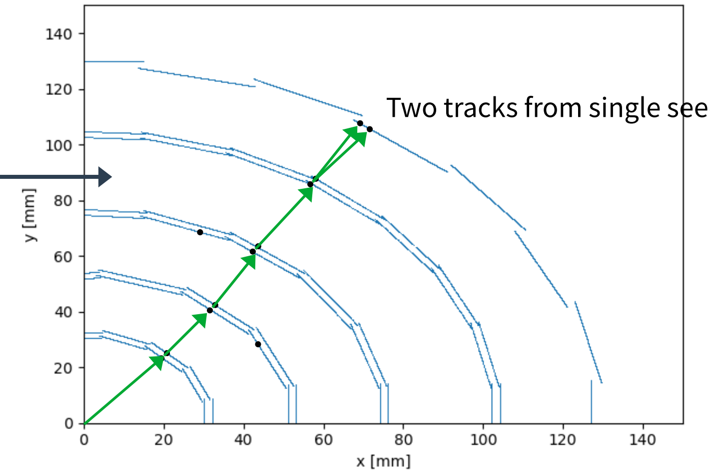


* Currently not leveraging double layers.

Seed Finding
Initial parameters for CKF



Combinatorial Kalman filter
Track fit



Remove BIB hits

Pattern Recognition

Track Fit

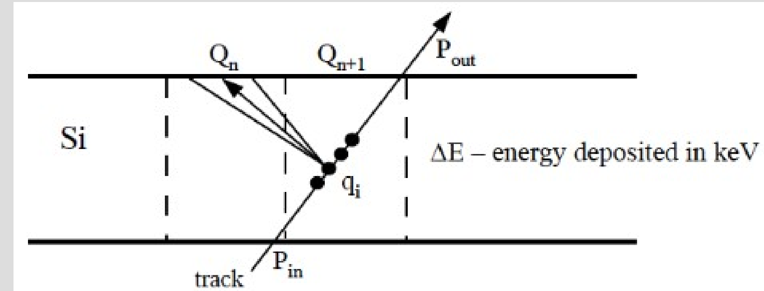
Similar algorithm used by ATLAS.

aka optimized for high hit multiplicity

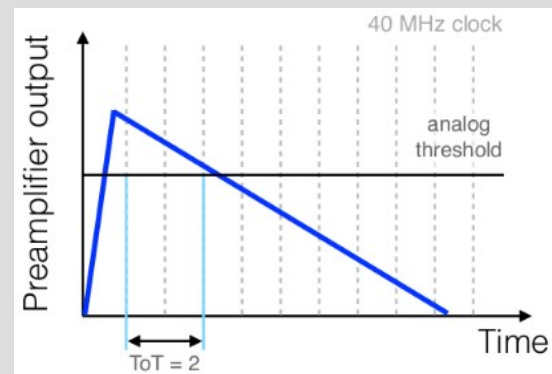
WIP Realistic Digitization

- **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

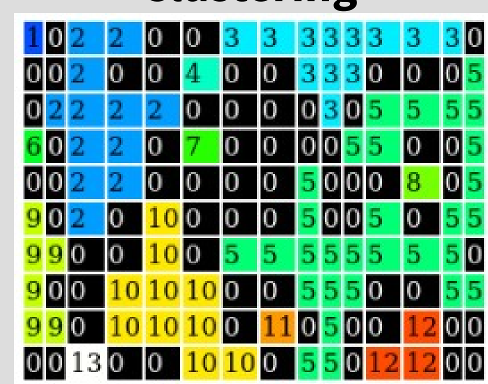
Charge Particle Deposits Details



Sensor Pixelization/Digitization



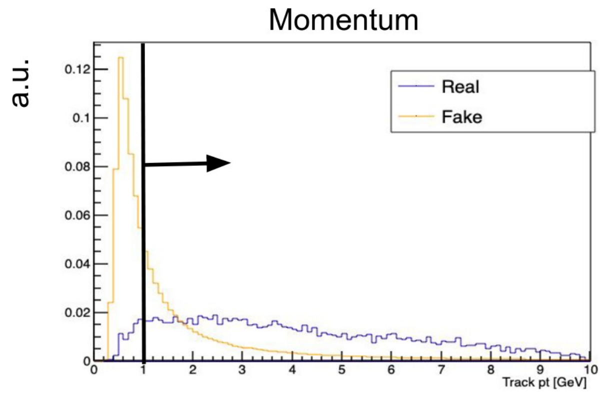
Clustering

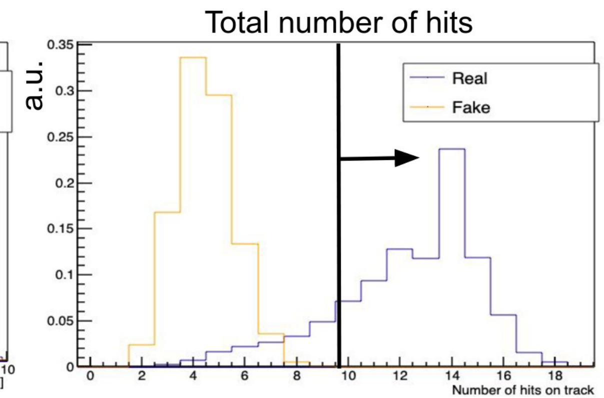


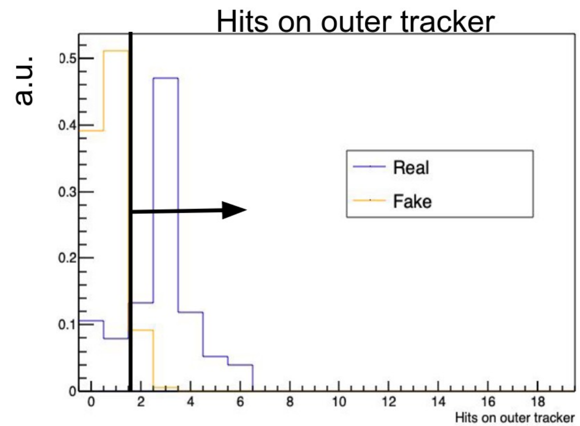
Rejecting Fakes

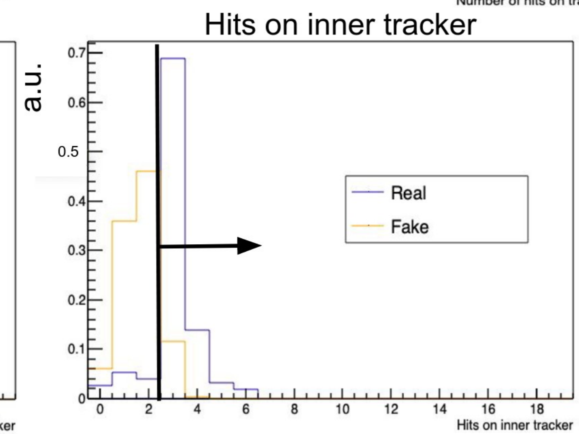
Details

- 100k fake **tracks / event**
- **reduce to < 1 fake / event**
- **Still missing a few handles**
  - χ^2, N_{holes}, timing
- **Implemented as an (unreleased) processor**

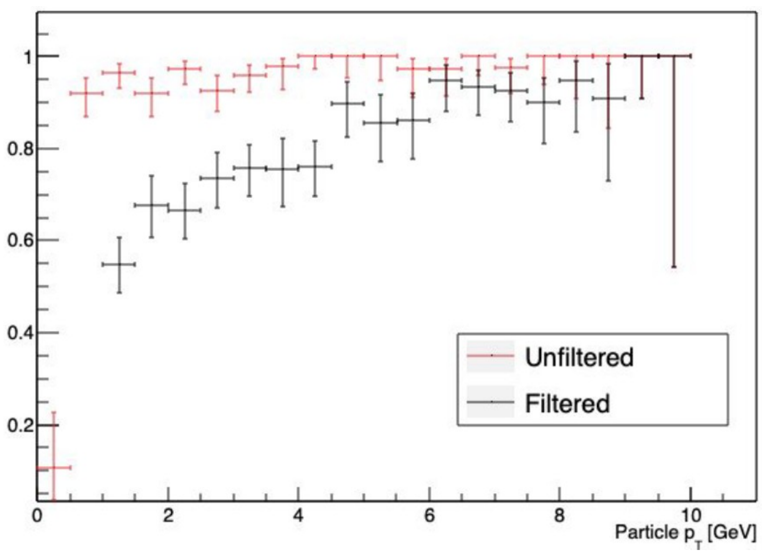


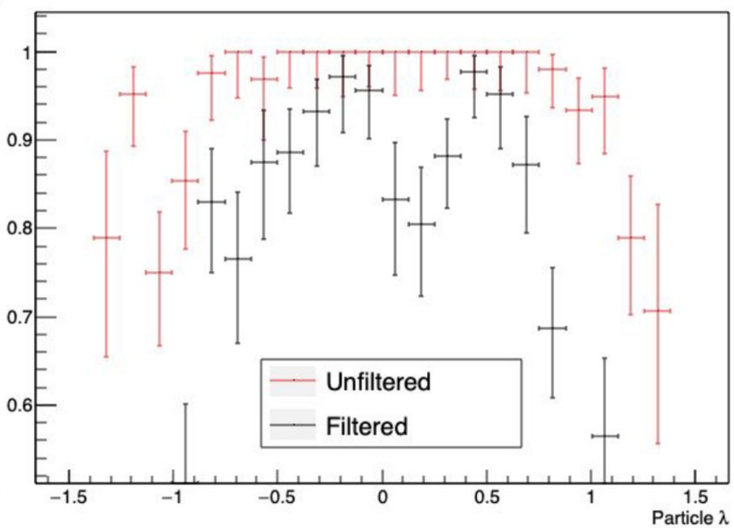


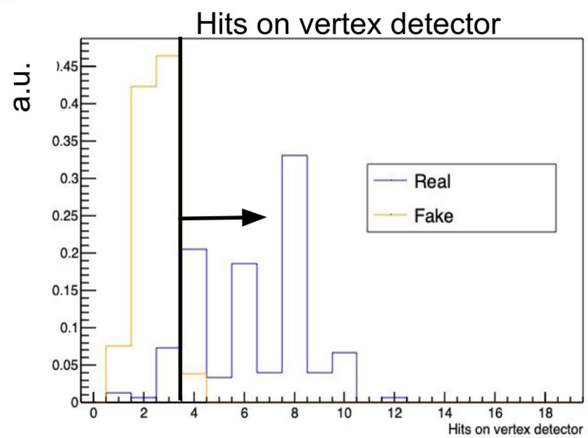




Efficiencies



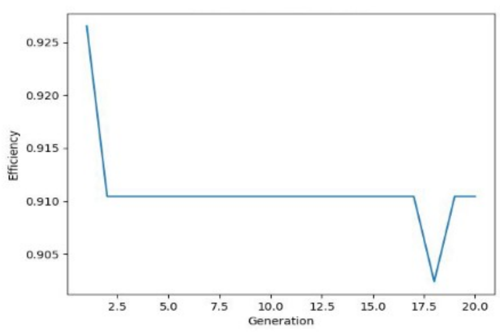
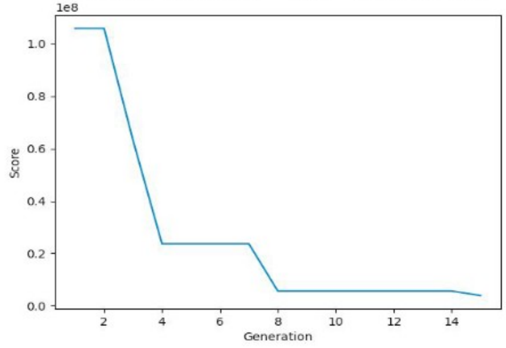
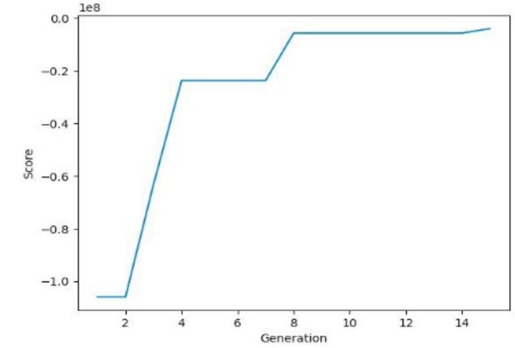




Rejecting Fakes: Optimization

Details

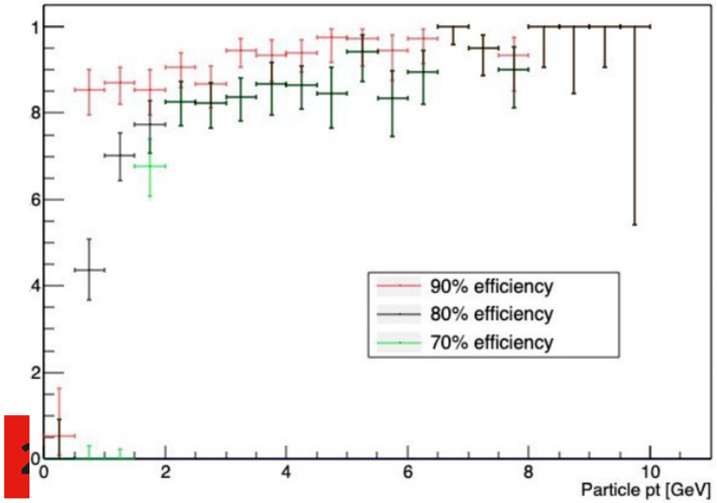
- TrackFilter optimized using evolutionary algorithms

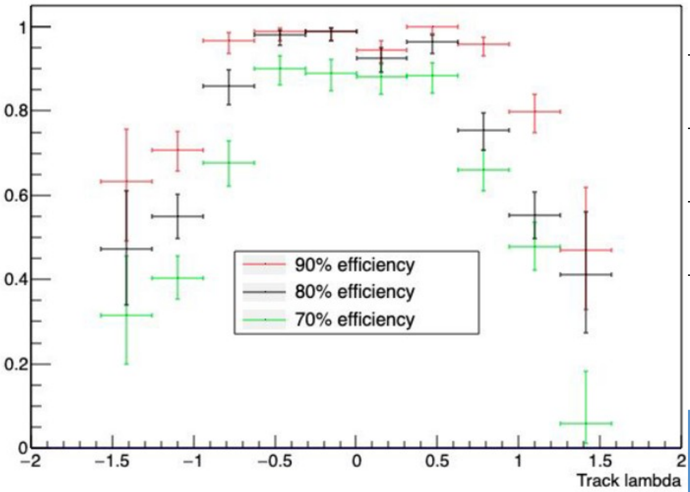
Target efficiency	Efficiency	Number of fakes	Score
90%			

- Studied a few fixed efficiency working points
- For <80% eff, start removing low p_T tracks

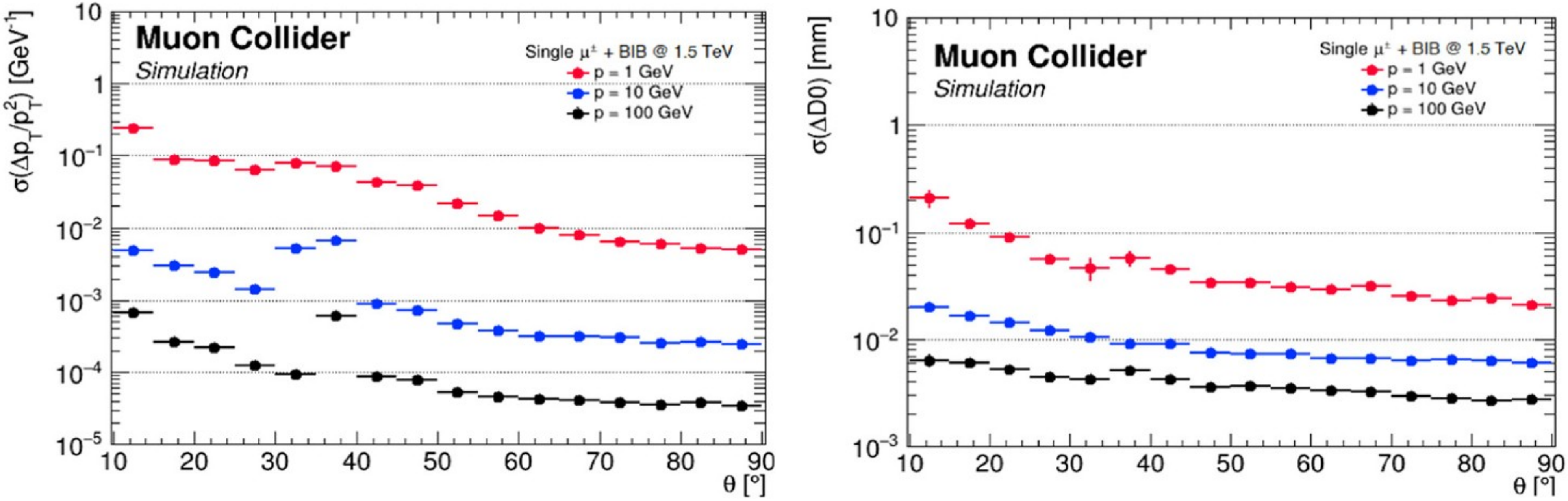
Eff WP	Fakes / event
90%	3900
80%	0.13
70%	0.06
64%*	0.08

* value by hand





Track Resolutions



Track reconstructed with Conformal Tracking and Region of Interests hits.

Next steps: how does this translate into physics results?

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)

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

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