Detector design at a Muon Collider

AI to solve a constrained, multi-objective optimization problem

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AI4MuC Mini-workshop
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HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

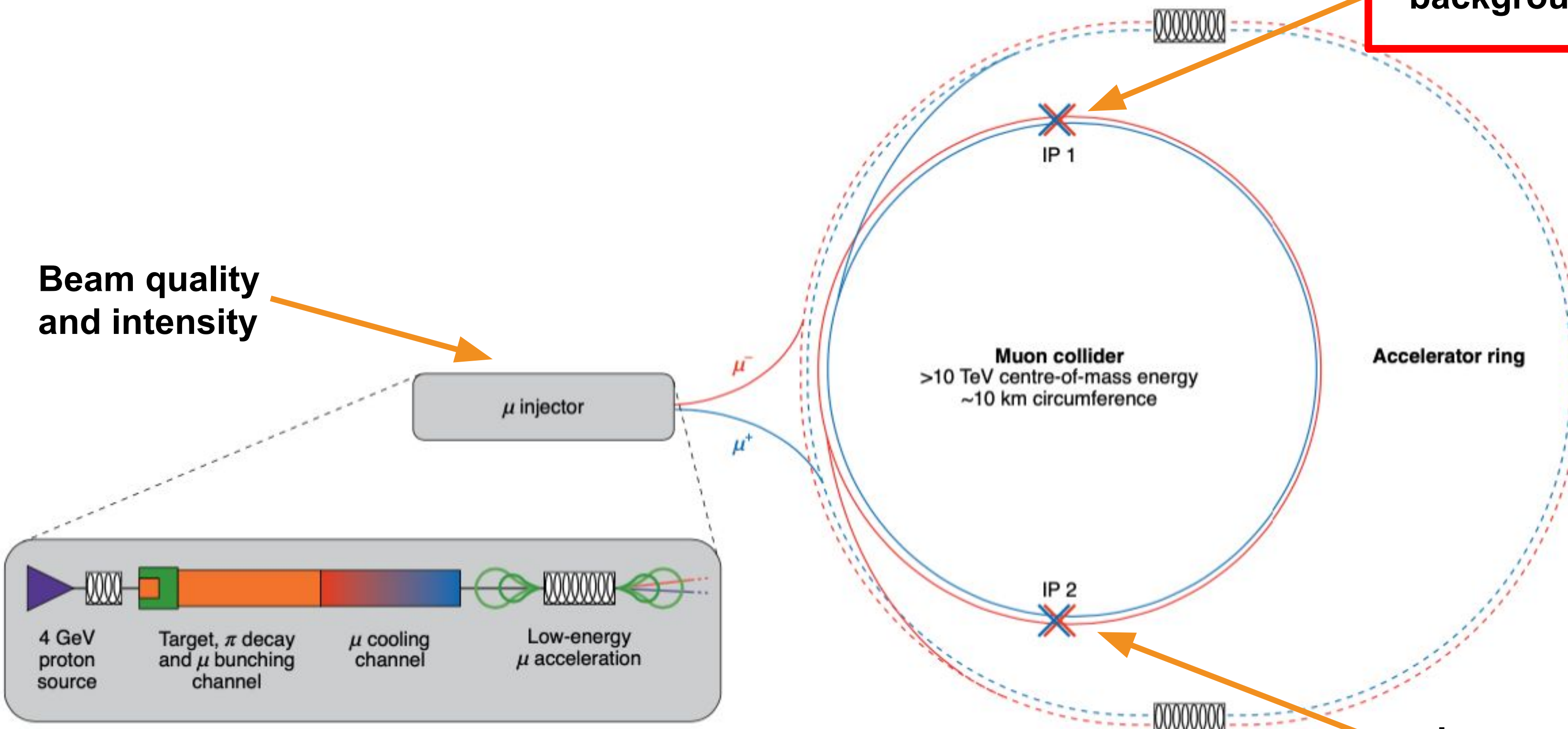
DESY.

Key detector challenge

Muons have a **limited lifetime**: 2.2 μs at rest

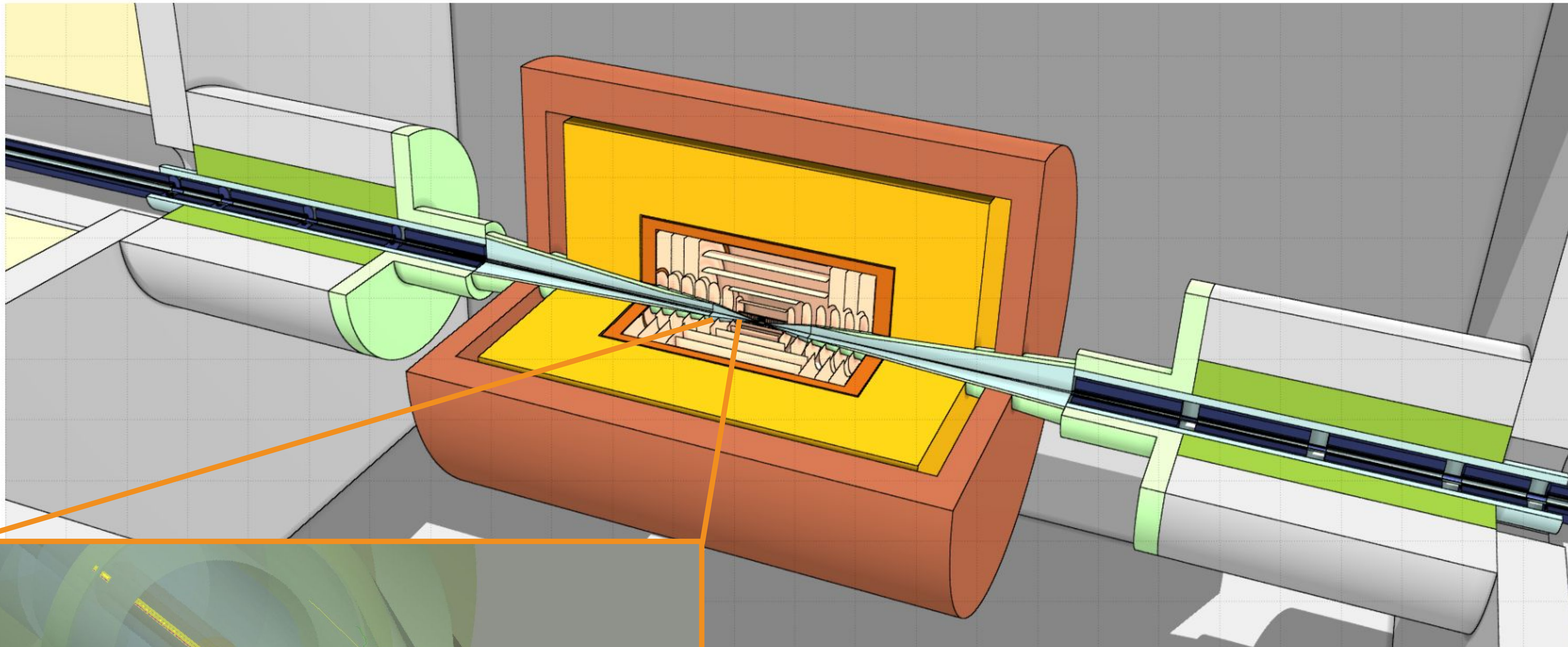
Beam induced backgrounds

Beam quality and intensity



Large neutrino flux

Beam-induced backgrounds (BIB)

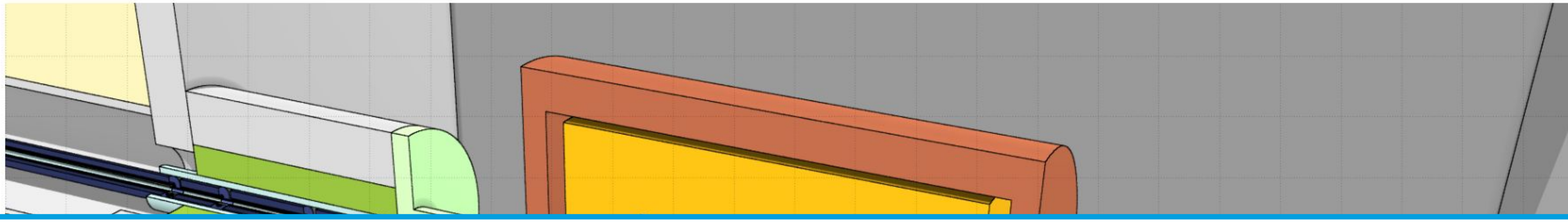


Huge number of particles from muon decays (up to 4×10^5 per metre of lattice) and their byproducts

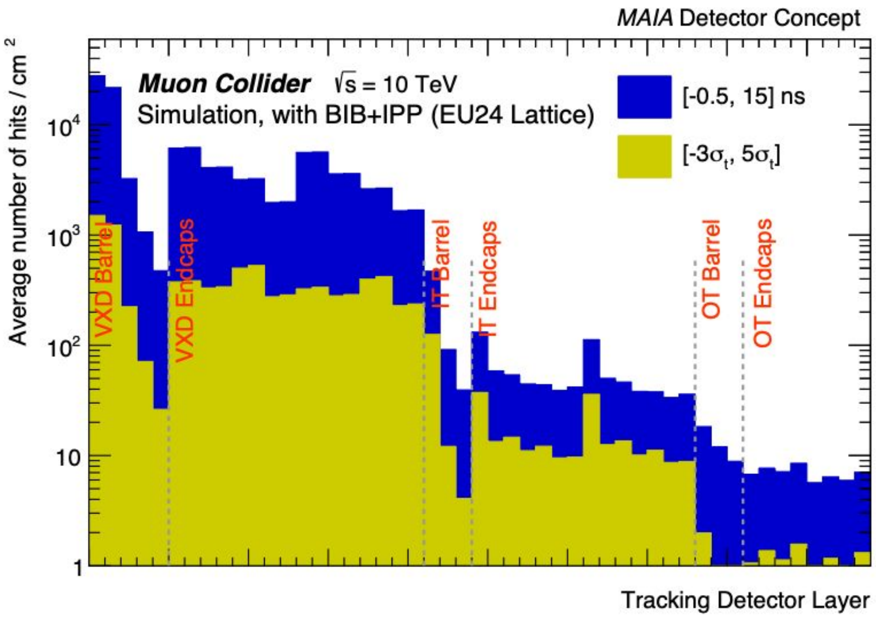
- Shielding with absorbing nozzles

Unique challenge of Muon Colliders

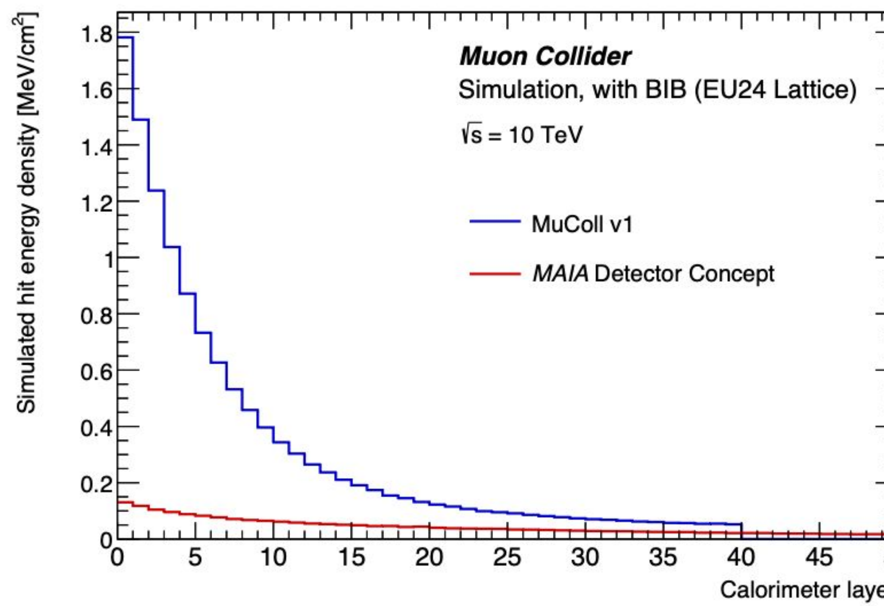
Beam-induced backgrounds (BIB)



Large tracker occupancies



Sizeable "pile-up" in calorimeters

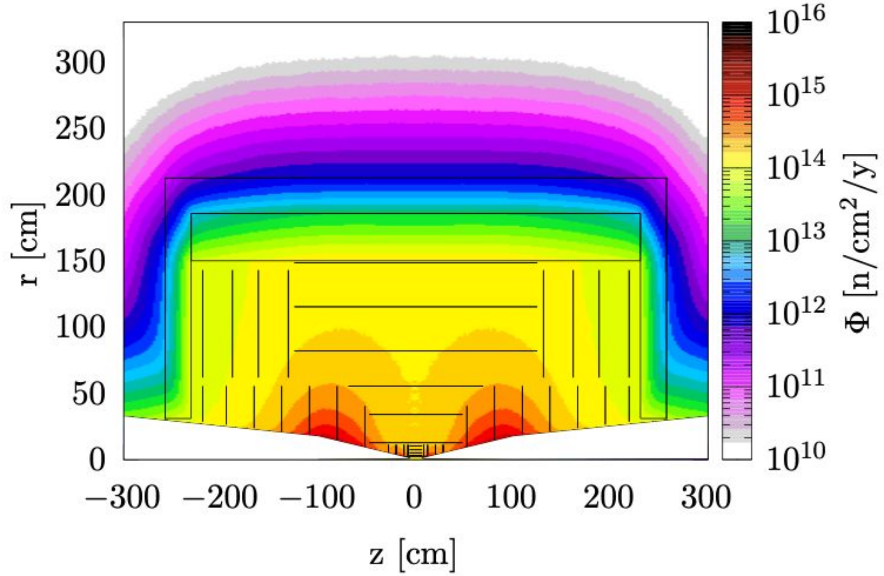


Shower from single muon decay, 25m from IP

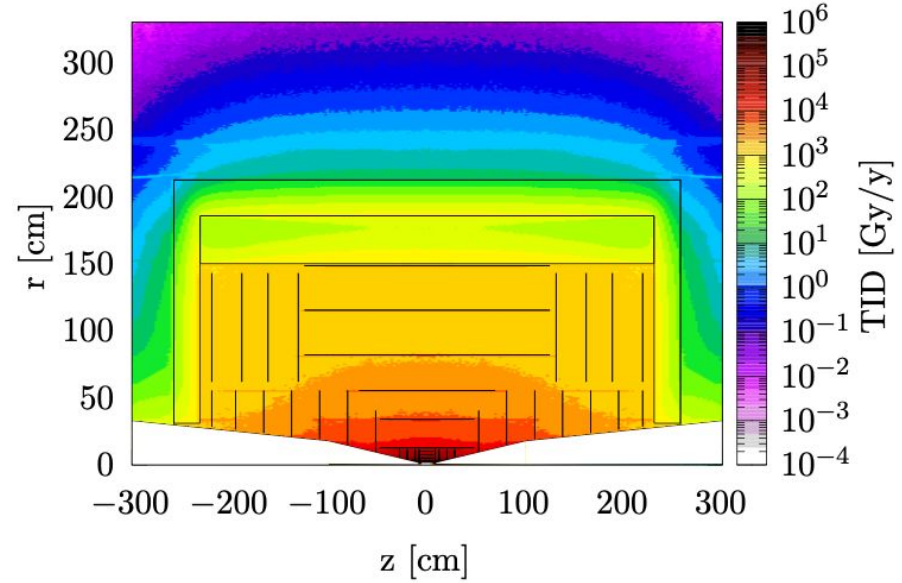
Unique challenge of Muon Colliders

Detection Environment

FLUKA simulation



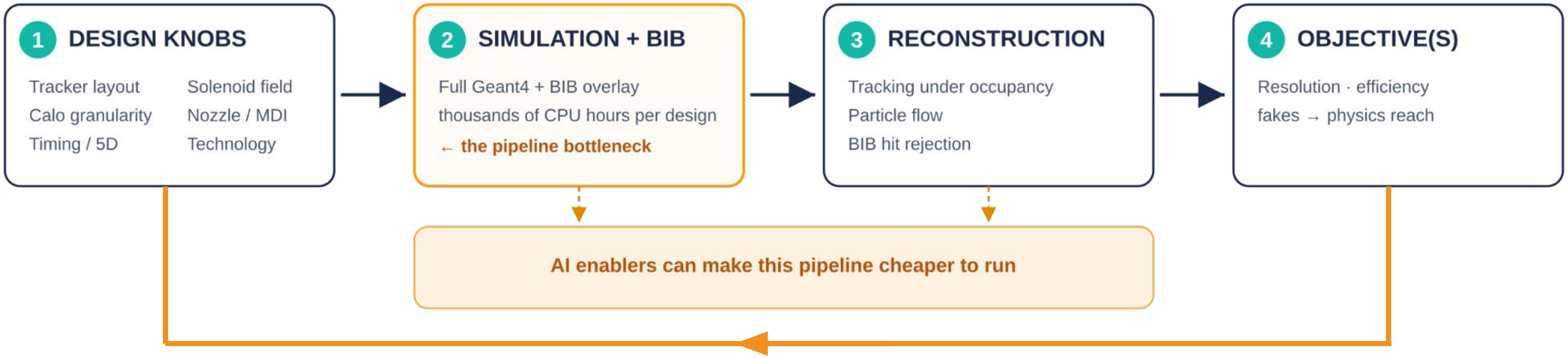
1-MeV-n_{eq}/cm^2 fluence for 200 days of operation



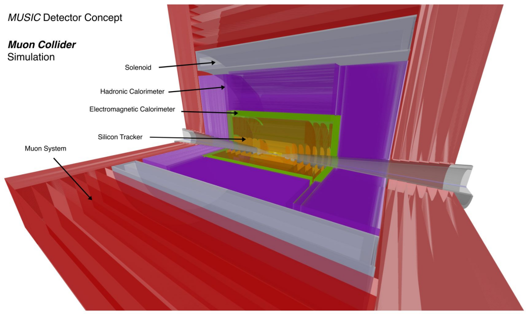
Total Ionising Dose for 200 days of operation

	Maximum Dose (Mrad)		Maximum Fluence (1 MeV-neq/cm^2)	
	R= 22 mm	R= 1500 mm	R= 22 mm	R= 1500 mm
Muon Collider (3 TeV)	10	0.1	10^{15}	10^{14}
HL-LHC	100	0.1	10^{15}	10^{13}
Muon Collider (10 TeV)	20	0.2	3×10^{14}	10^{14}

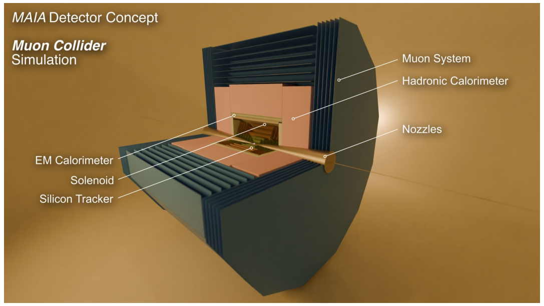
Detector design as an optimisation problem



Landscape of possibilities limited by resources and expert person power



MUSIC - MUon System for Interesting Collisions



MAIA - Muon Accelerator Instrumented Apparatus

Detector design as an optimisation problem

1 DESIGN KNOBS
- Tracker layout
- Calo granularity
- Timing / 5D
- Solenoid field
- Nozzle / MDI
- Technology

→

2 SIMULATION + BIB
- Full Geant4 + BIB overlay
- thousands of CPU hours per design
- ← **the pipeline bottleneck**

→

3 RECONSTRUCTION
- Tracking under occupancy
- Particle flow
- BIB hit rejection

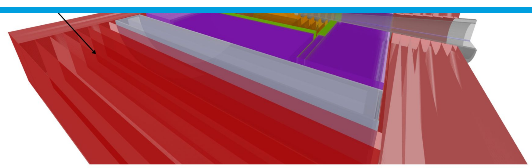
→

4 OBJECTIVE(S)
- Resolution · efficiency
- fakes → physics reach

AI enablers can make this pipeline cheaper to run

Landscape

AI tools could automate and significantly speed up the iterative process



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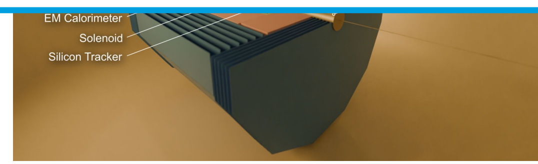


MAIA - Muon Accelerator Instrumented Apparatus

Design knobs

Tracking layout

Radii, number of layers, double-layer / p_T filtering, per-hit timing — reject BIB by geometry before reconstruction even runs.

Calorimeter granularity

Transverse and longitudinal cell size to separate diffuse BIB from real showers — drives channel count and cost

Technology vs radiation-hardness

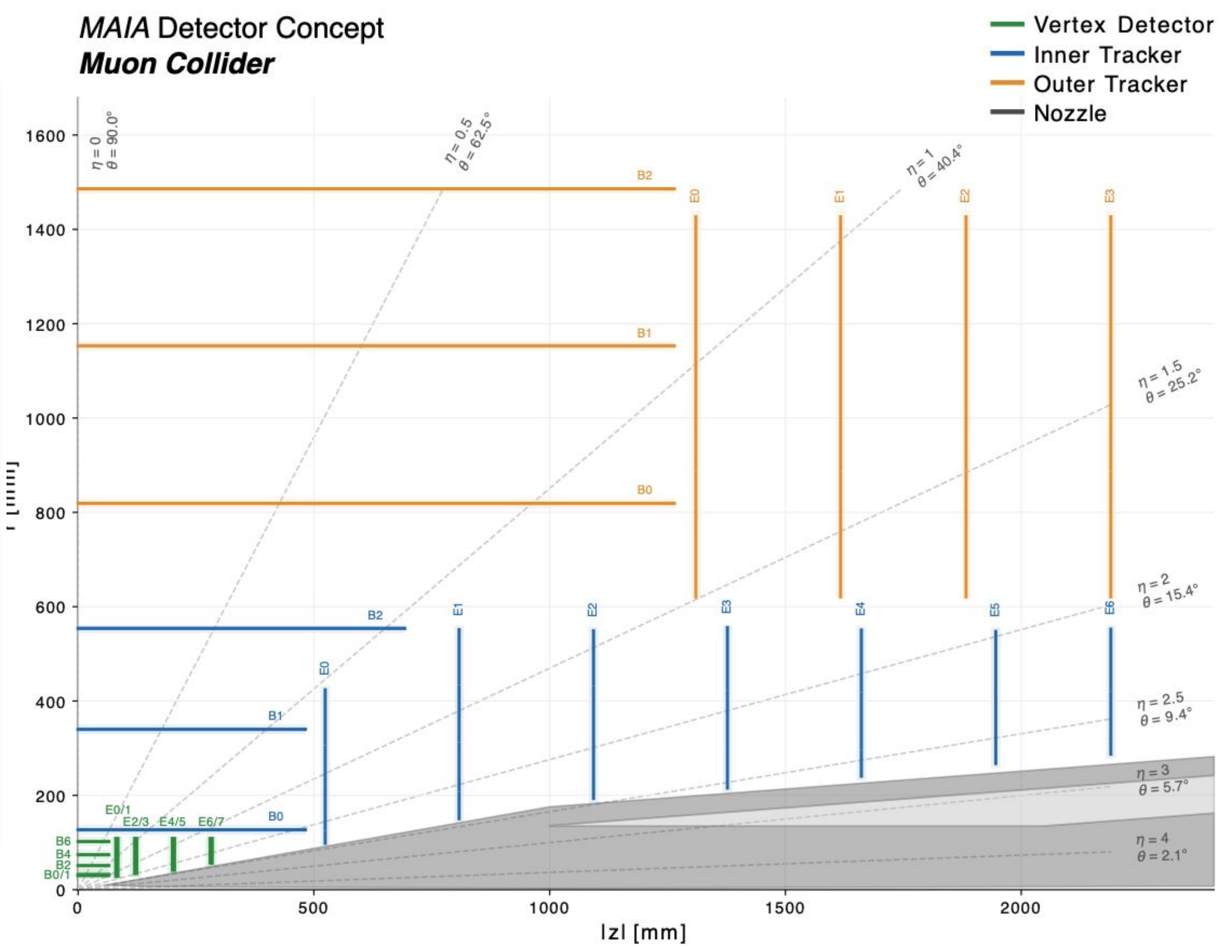
Sensor choice: performance vs survivability vs cost

Design knobs

Deeper dive into tracking

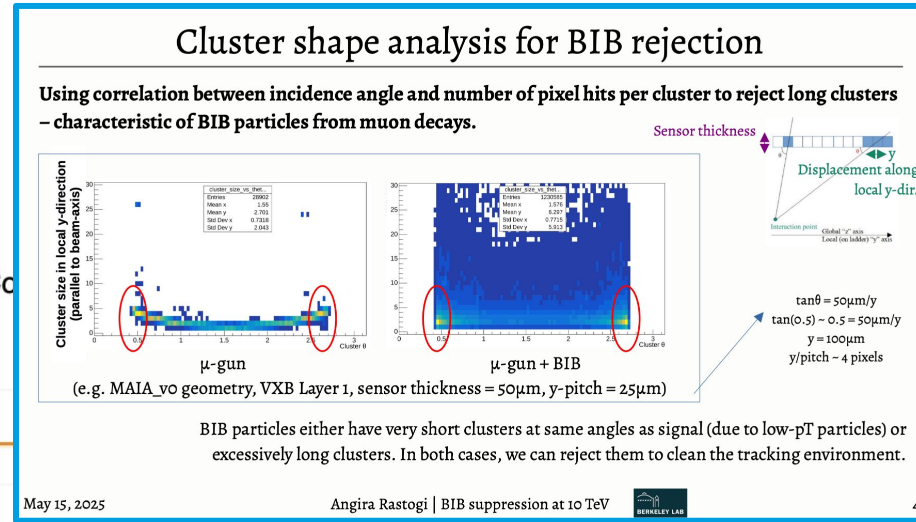
Tracking layout

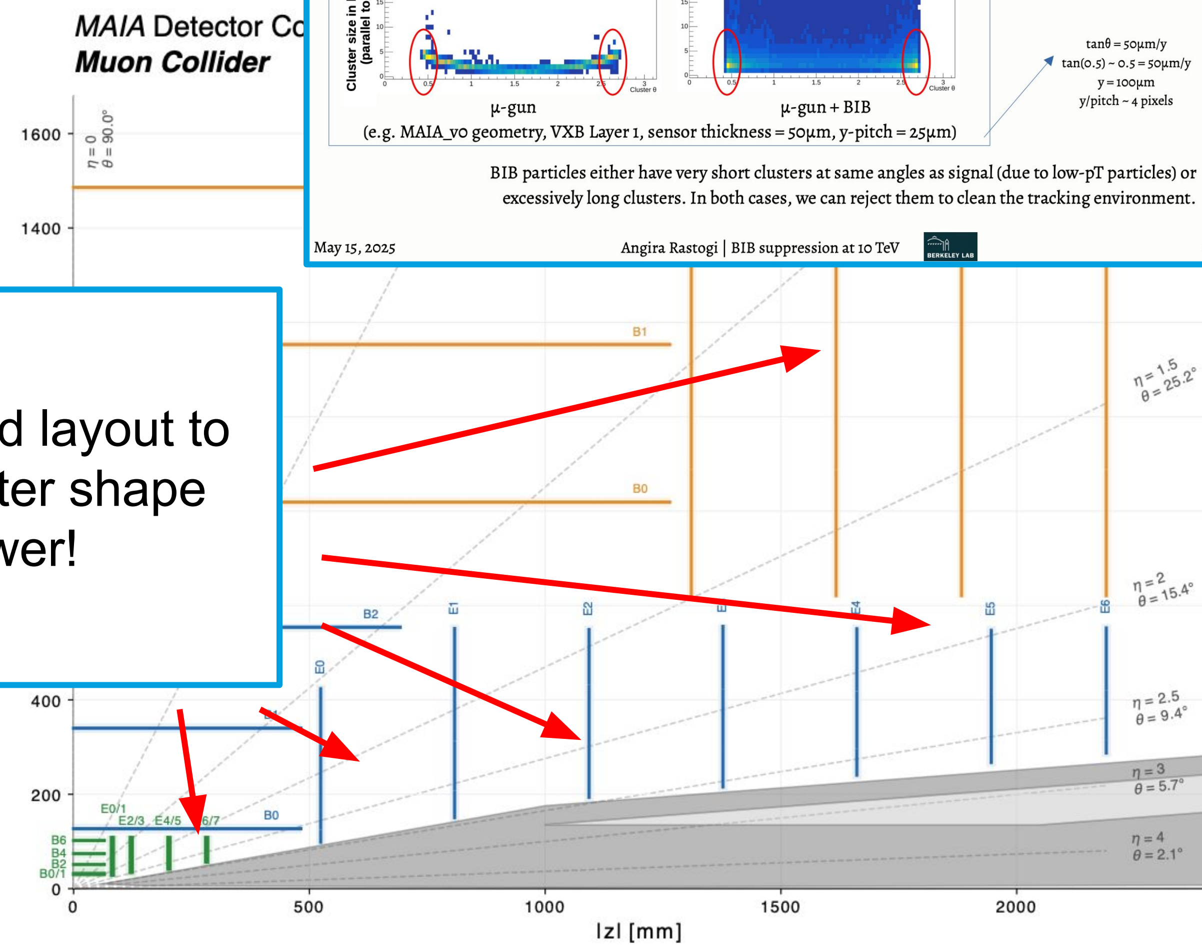
Radii, number of layers, double-layer / p_T filtering, per-hit timing — reject BIB by geometry before reconstruction even runs.



Design knobs

Deeper dive into tracking





Optimise an inclined layout to maximise the cluster shape rejection power!

More design knobs: the system-level ones

Nozzle / MDI geometry

Tungsten cones set BIB and forward acceptance at once and sit on the accelerator-detector boundary.

Timing / 5D

ps-level timing is a strong handle on out-of-time BIB. Placement, resolution and cost are open choices.

Solenoid field

Strength and shape sweep soft loopers (from **incoherent pair production**) and set momentum resolution and the whole detector envelope.

Material budget

Minimise scattering and BIB secondaries under cooling and support constraints.

AI as (automated) exploration tool

Each of the (knob, objective) combinations I touched upon so far is a differentiable problem that AI (in its old “ML” form) can help with

- Better results, but still bound by expert person power

AI can enable more ambitious approaches: spawn a **team of agents** that runs the design-and-evaluate pipeline and reports back

- Nest optimisation agents into a Bayesian (or name your preferred method) search for the optimum combination of parameters
- Can limit scope to desired “detector design targets” or extend up to “physics performance”
- Allow to explore unconventional designs
- Still bound by computing resources…

What do we optimise for?

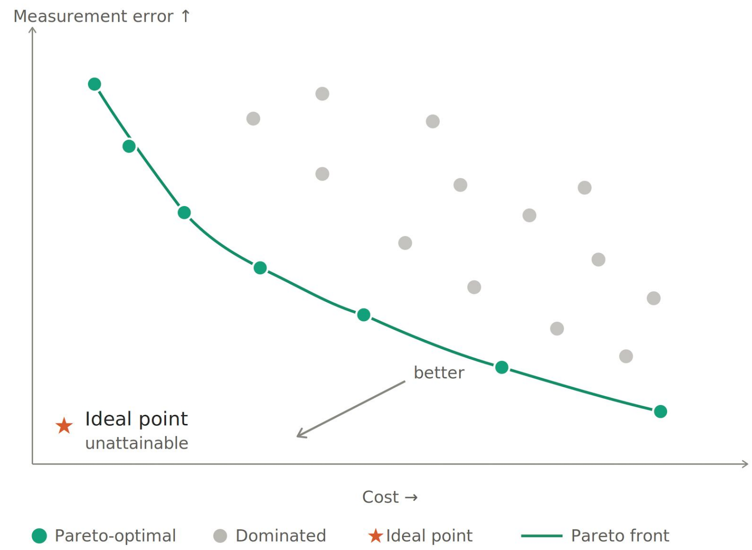
With a broad physics programme, the objective is itself a design choice.

Higgs measurements, precision EW physics, searches for new phenomena, neutrino physics, … all pull in different directions

- No single figure of merit captures all of them

AI explorative value: map the Pareto front and make the trade-offs explicit, rather than pre-baking one objective

- Humans then choose where to sit



Summary

In detector design at Muon Colliders, BIB is the unifying driver

- Every choice made is aimed at delivering excellent physics while rejecting BIB

AI/ML will be key in designing optimal detectors

- Several optimisation problems up for grabs differing in scope and complexity
- Potential as a multiplier of expert effort

The frontier opportunity: end-to-end optimisation of the whole detector, from knobs to physics output

Thank you!

Contact

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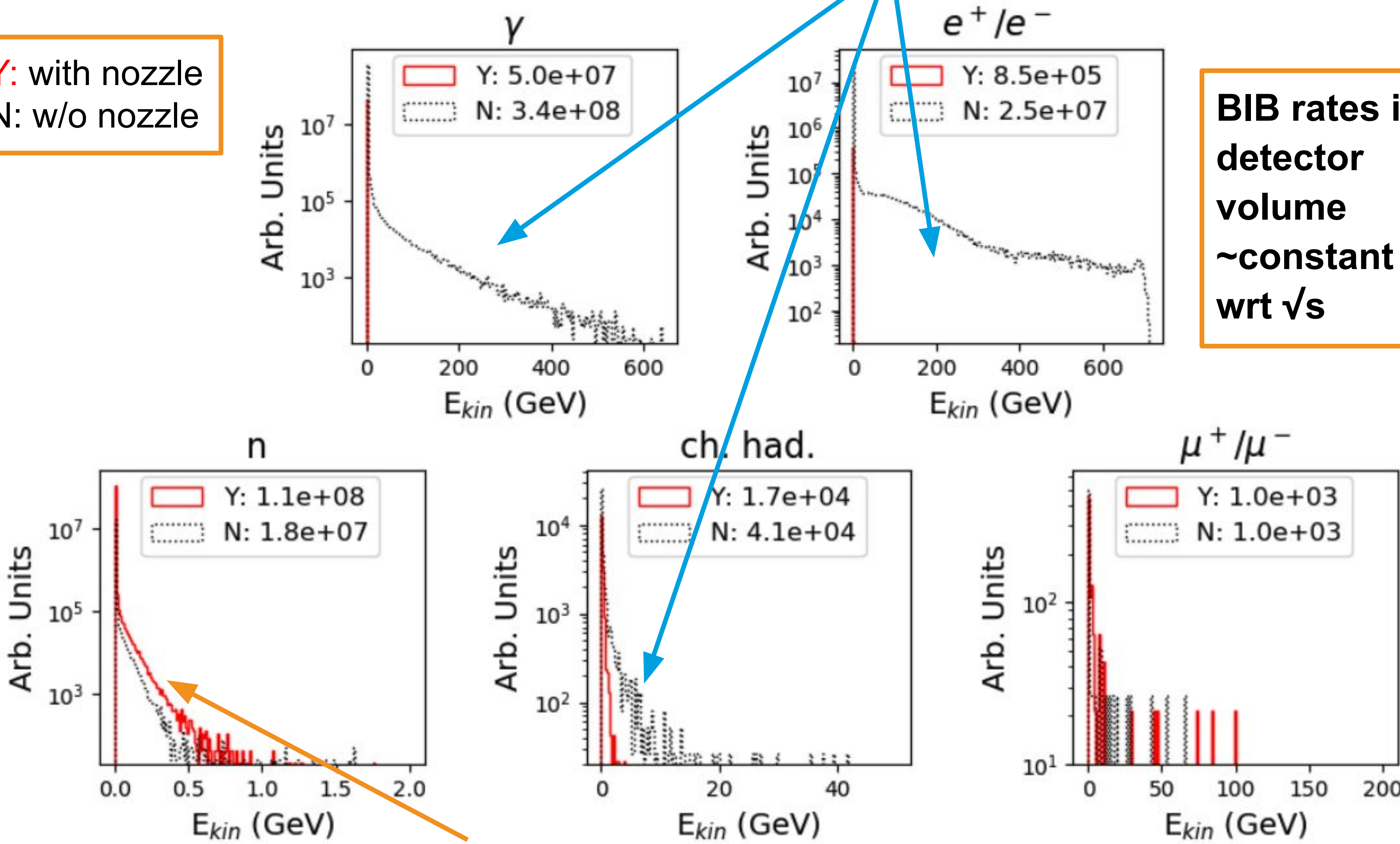
Detector design targets

Requirement	Baseline	Aspirational
Angular acceptance $\eta = -\log(\tan(\theta/2))$	$\|\eta\| < 2.5$	$\|\eta\| < 4$
Minimum tracking distance [cm]	~ 3	< 3
Forward muons ($\eta > 5$)	tag	$\sigma_p/p \sim 10\%$
Track σ_{p_T}/p_T^2 [GeV^{-1}]	4×10^{-5}	1×10^{-5}
Photon energy resolution	$0.2/\sqrt{E}$	$0.1/\sqrt{E}$
Neutral hadron energy resolution	$0.4/\sqrt{E}$	$0.2/\sqrt{E}$
Timing resolution (tracker) [ps]	$\sim 30-60$	$\sim 10-30$
Timing resolution (calorimeters) [ps]	100	10
Timing resolution (muon system) [ps]	~ 50 for $\|\eta\| > 2.5$	< 50 for $\|\eta\| > 2.5$
Flavour tagging	b vs c	b vs c, s-tagging
Boosted hadronic resonance ID	h vs W/Z	W vs Z

Impact of nozzles

High-energy component absorbed

Y: with nozzle
N: w/o nozzle



BIB rates in detector volume ~constant wrt √s

Increase in neutron flux