USMCC

Fermilab

Machine Learning + Muon Collider

Abhijith Gandrakota

(Based on discussions with Sergo. J, Nhan. T, Nick. S and many more)

Expectations from Muon Collider

- Muon collider is an innovative machine with incredible physics potential.
  - Energy reach of hadron collider + Precision of a lepton collider

- What are the expectations ?

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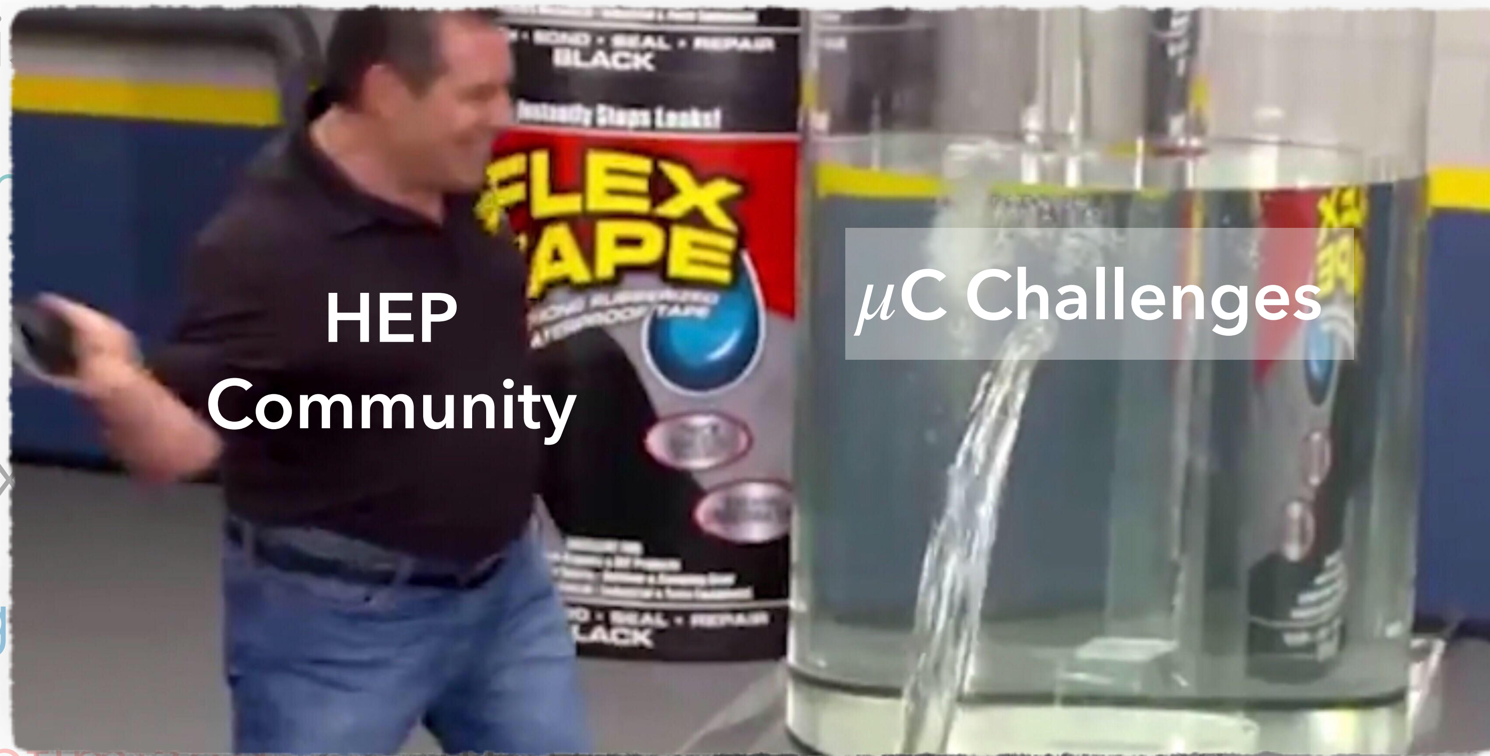

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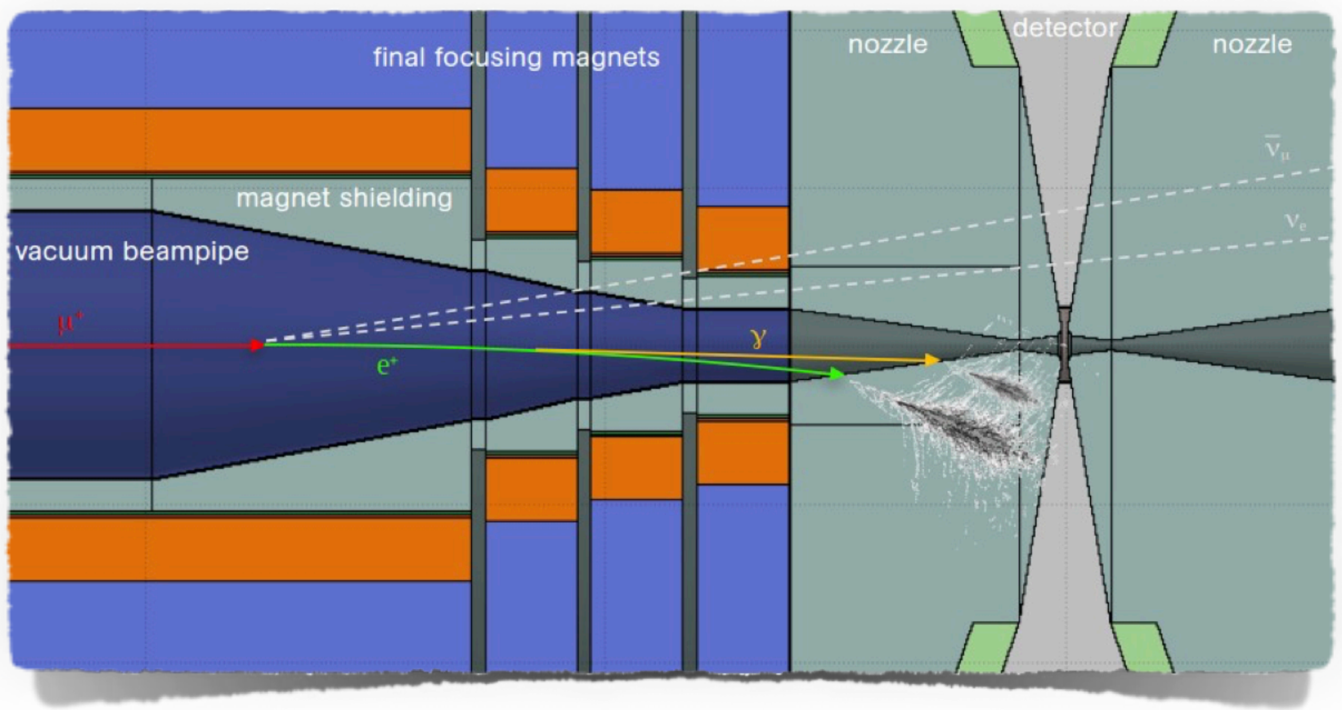
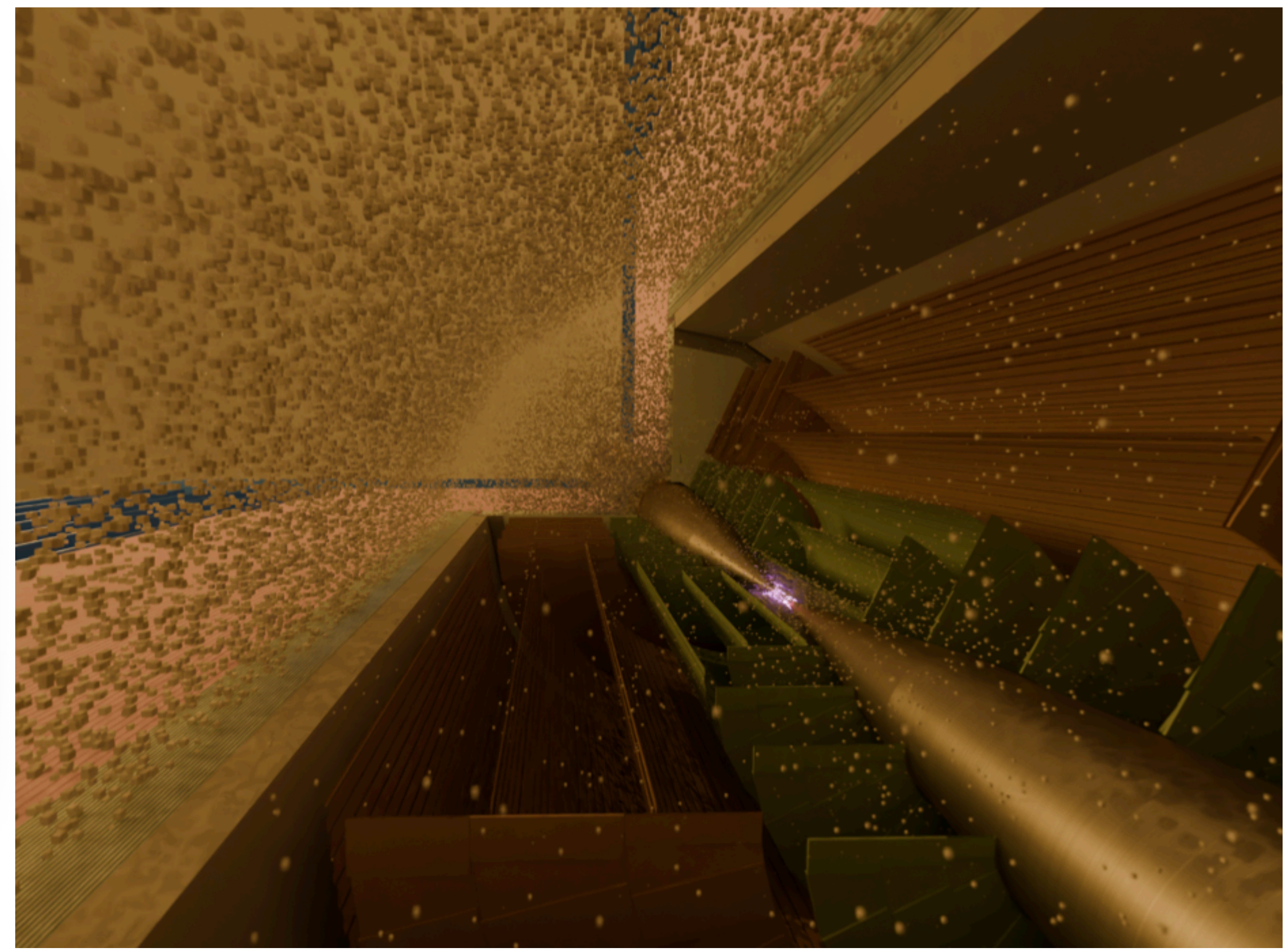
Mitigating Beam Induced Background

- BIB is the biggest challenge for physics performance
  - Arising from the decay of muons in the beam





Eric. Y, Karri. D.P + Samrt pixels collab.

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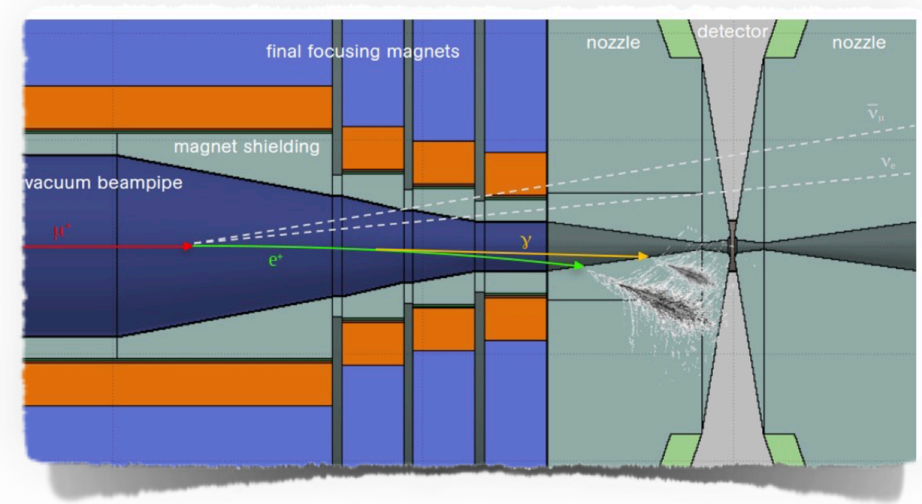
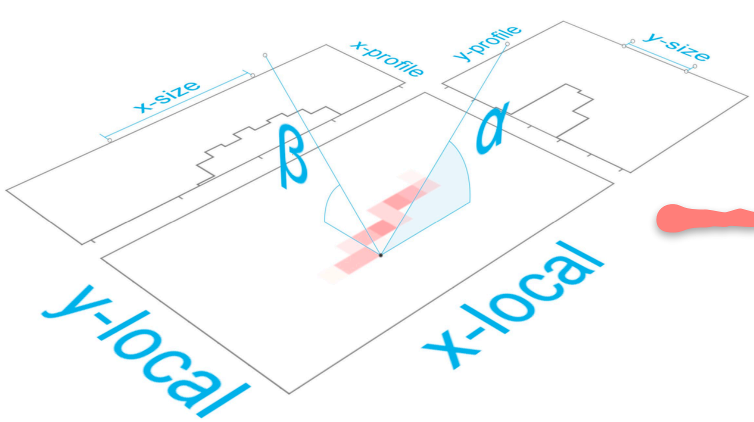
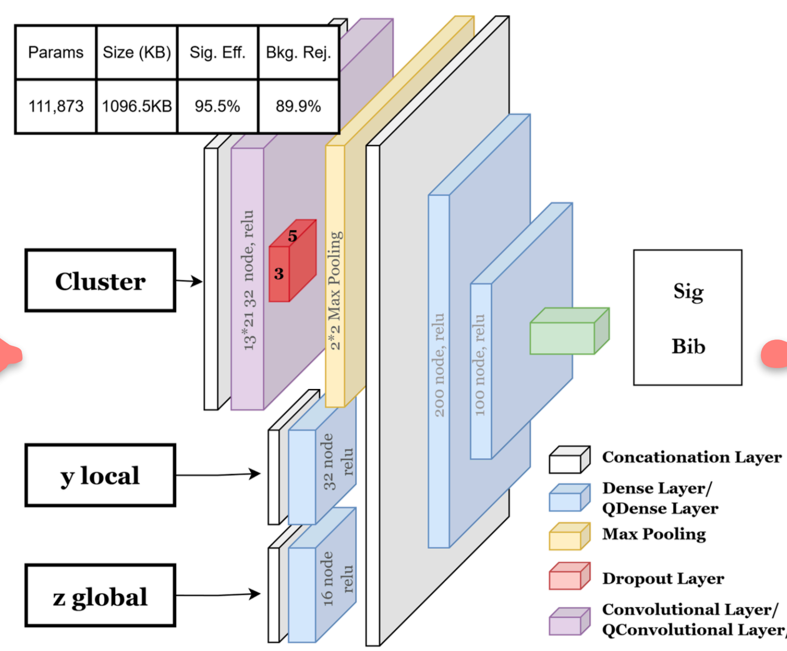
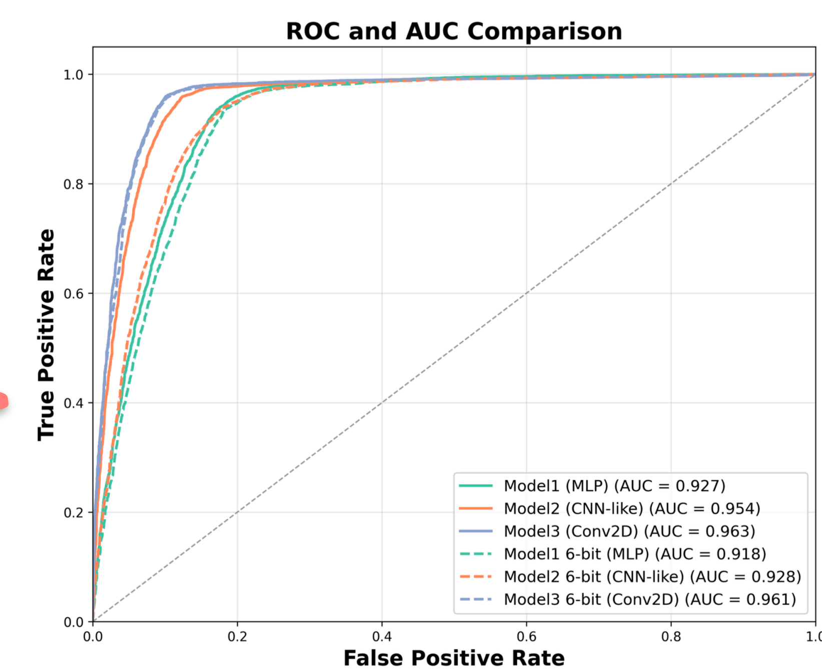


- Mitigate using **on-detector readout and filtering**
  - **Smart pixels**: Pixel sensors w/ ML on chip





Params	Size (KB)	Sig. Eff.	Bkg. Rej.
111,873	1096.5KB	95.5%	89.9%



From Eric's poster on Smart Pixels for Muon Collider

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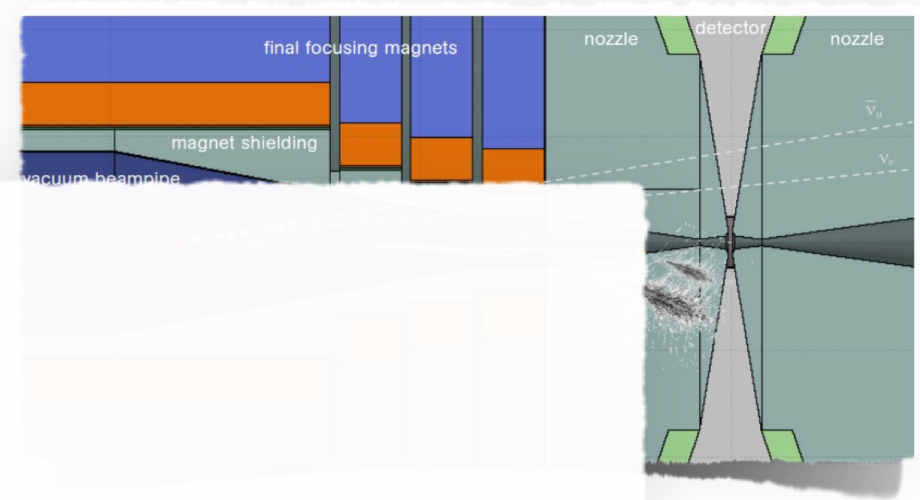

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Step 0: Simulating BIB ; Computationally expensive !

How do we do that ?

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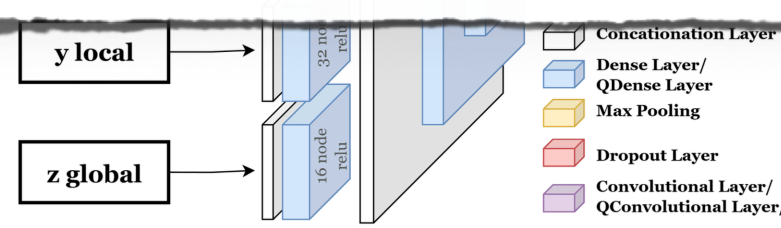

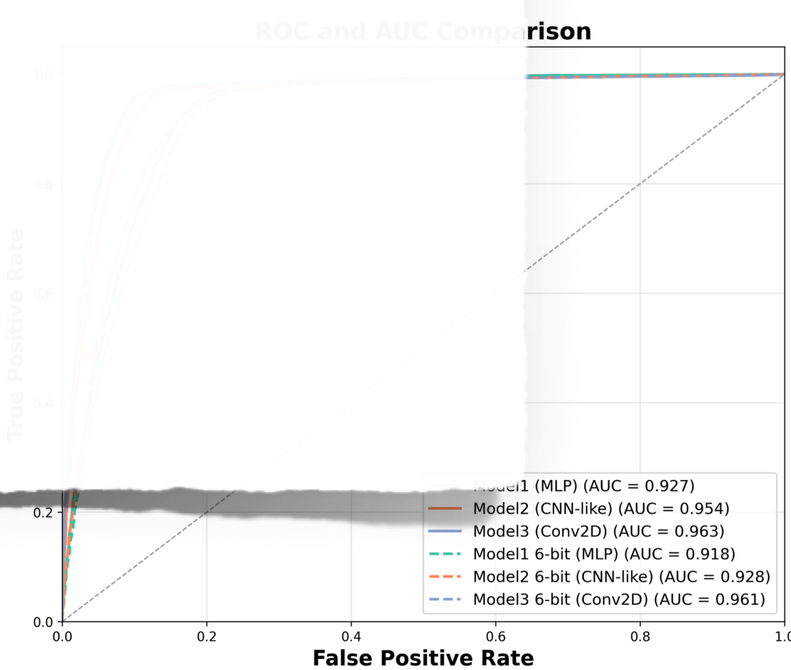

Eric. Y, Karri. D.P + Samrt pixels collab.

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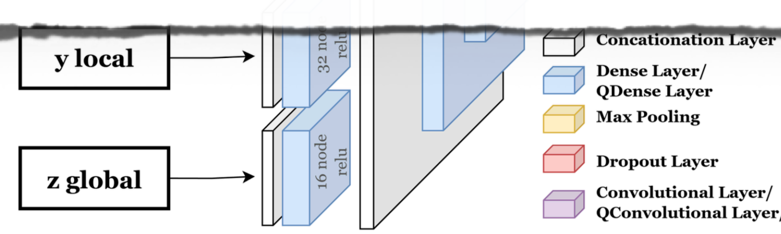

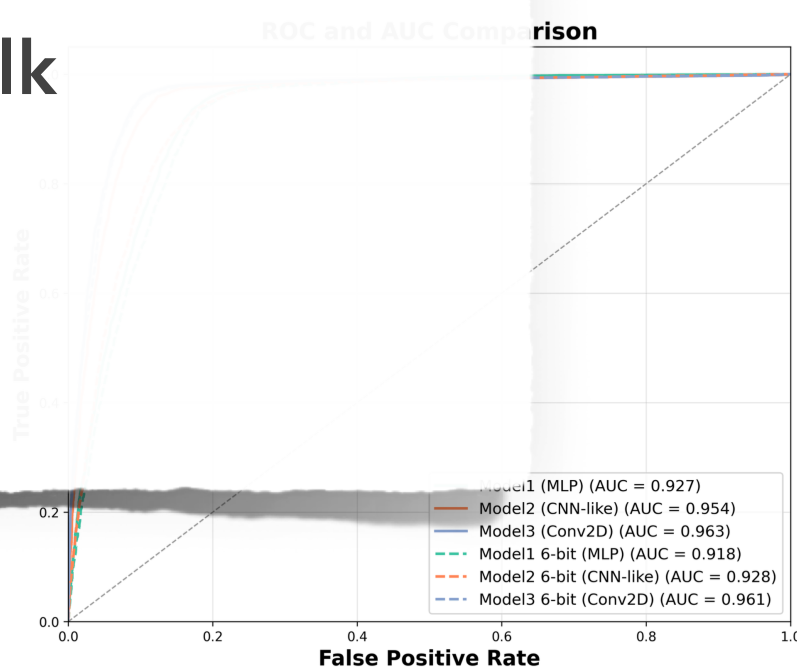

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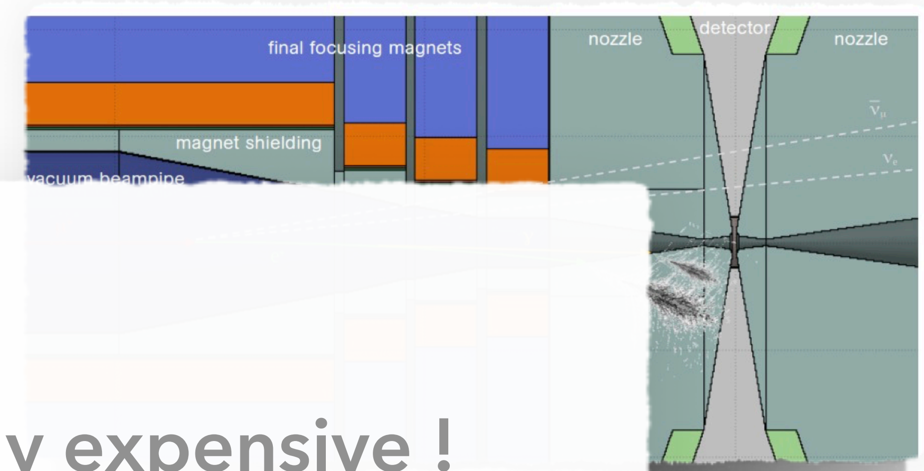

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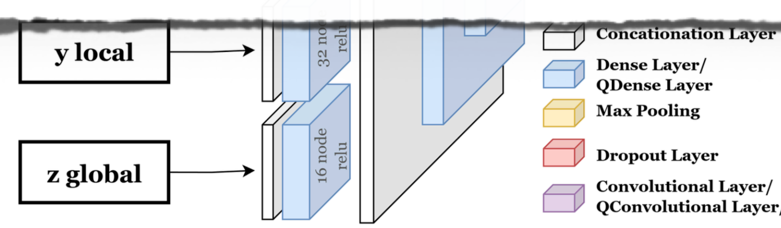
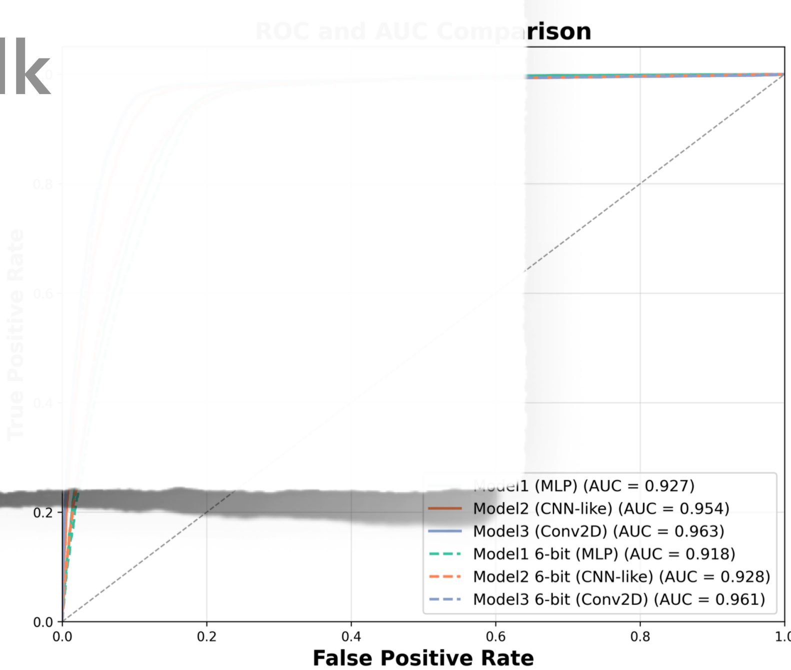
But **can we do more with this ?**





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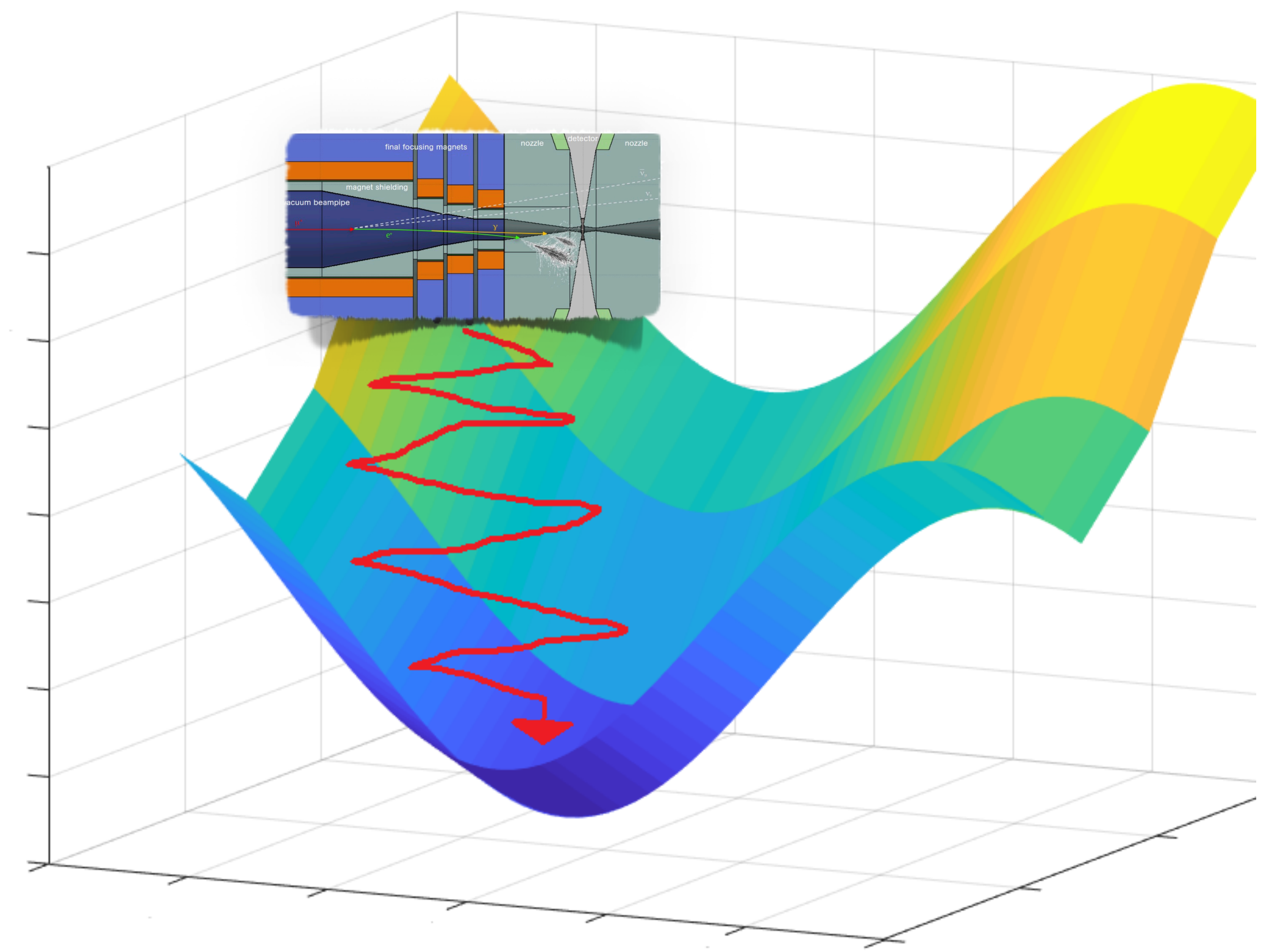
Mitigating Beam Induced Background

- Optimized nozzle design, can greatly reduce noise BIB
  - We can use the core principle of ML: **Gradient decent** to achieve this !
    - But FLUKA / GEANT 4 are not differentiable !



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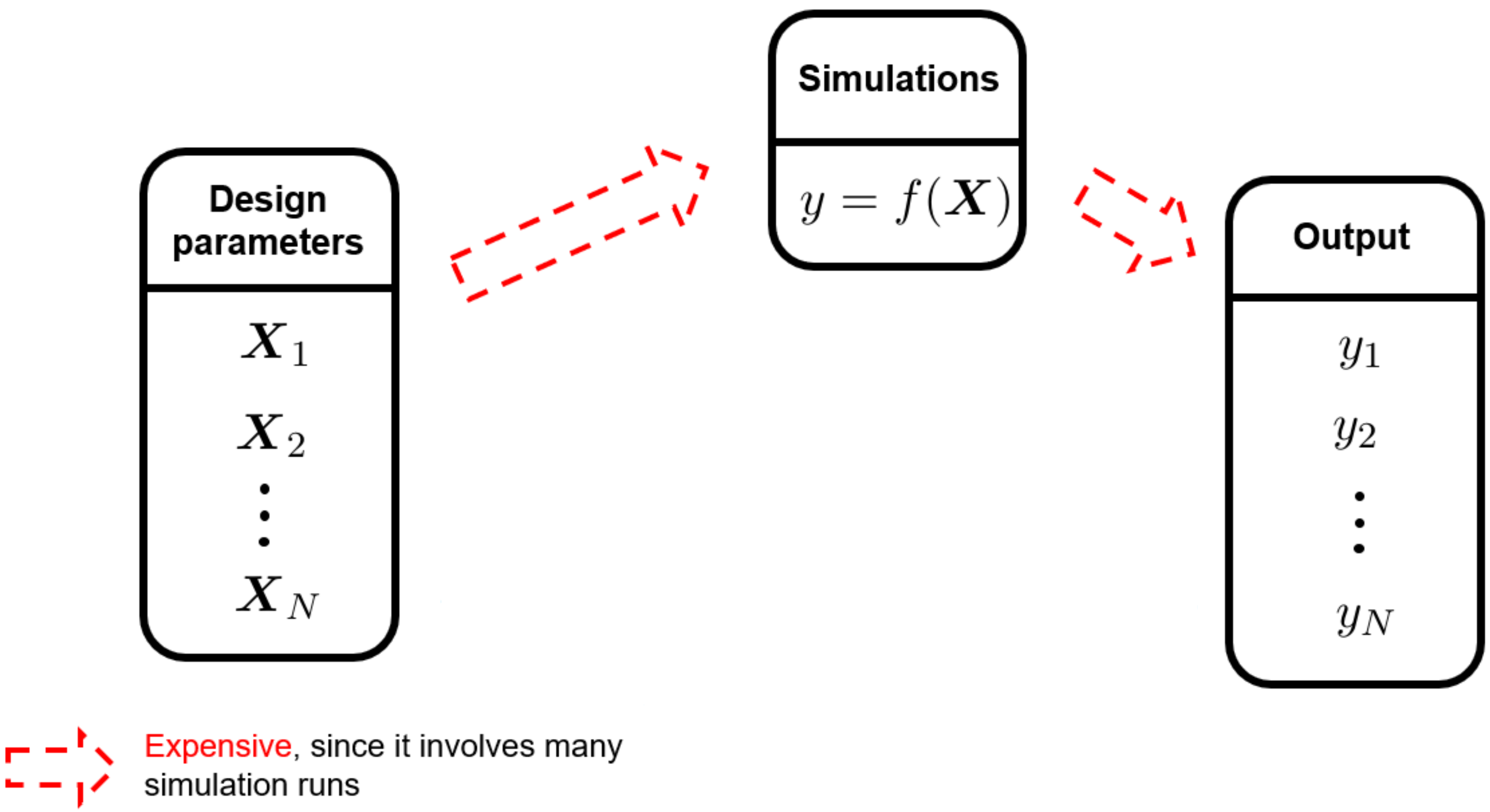
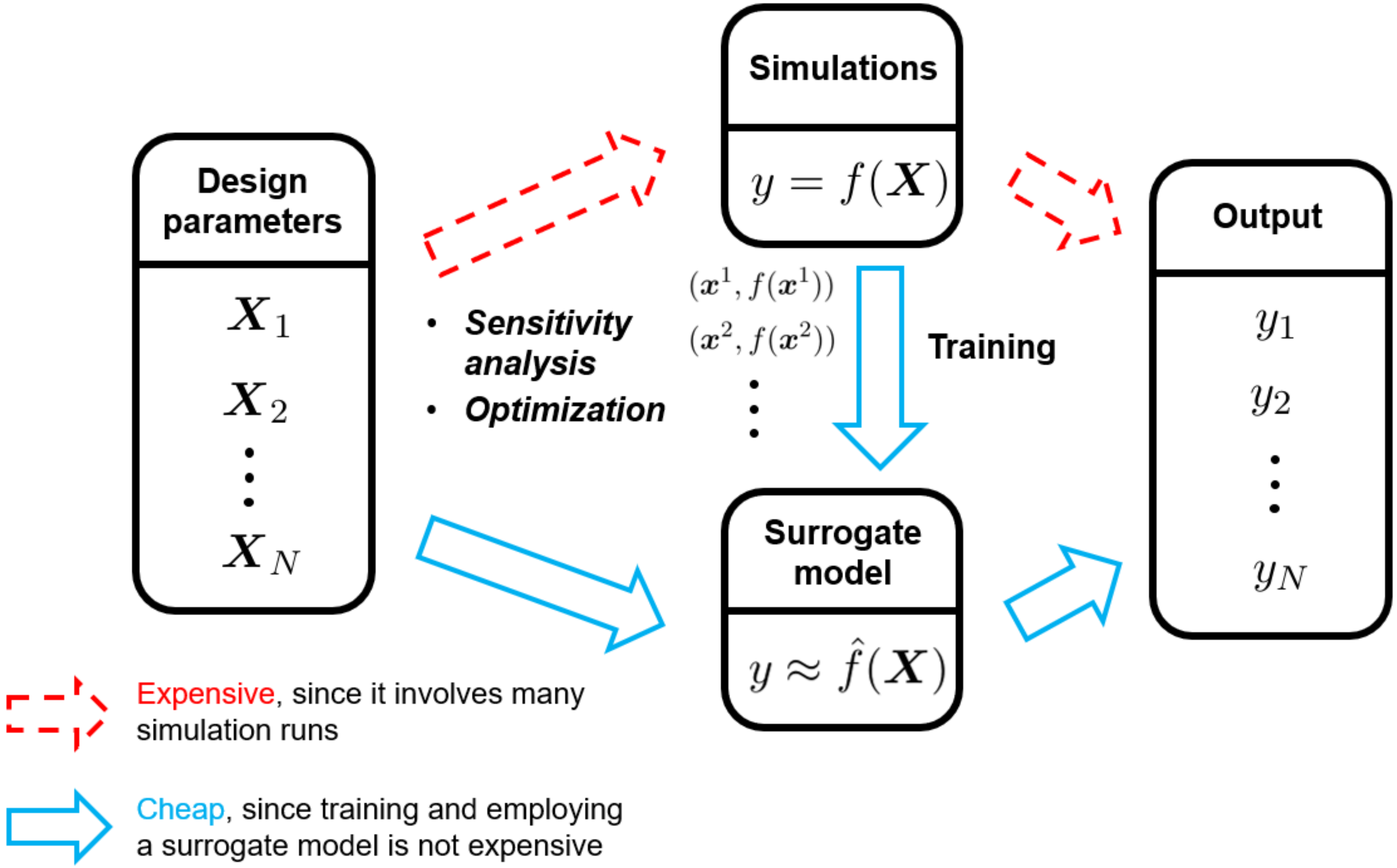


source

Mitigating Beam Induced Background

- Optimized nozzle / MDI design, can greatly reduce noise BIB
  - **Surrogate Models / Generative ML** to rescue !
    - With a differentiable Twin, We can fully tune and optimize MDI



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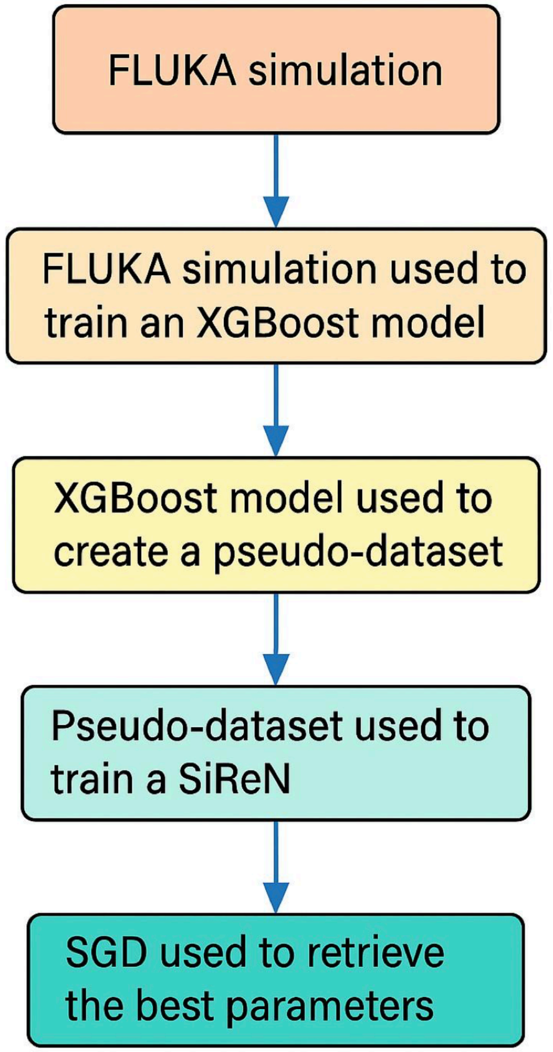
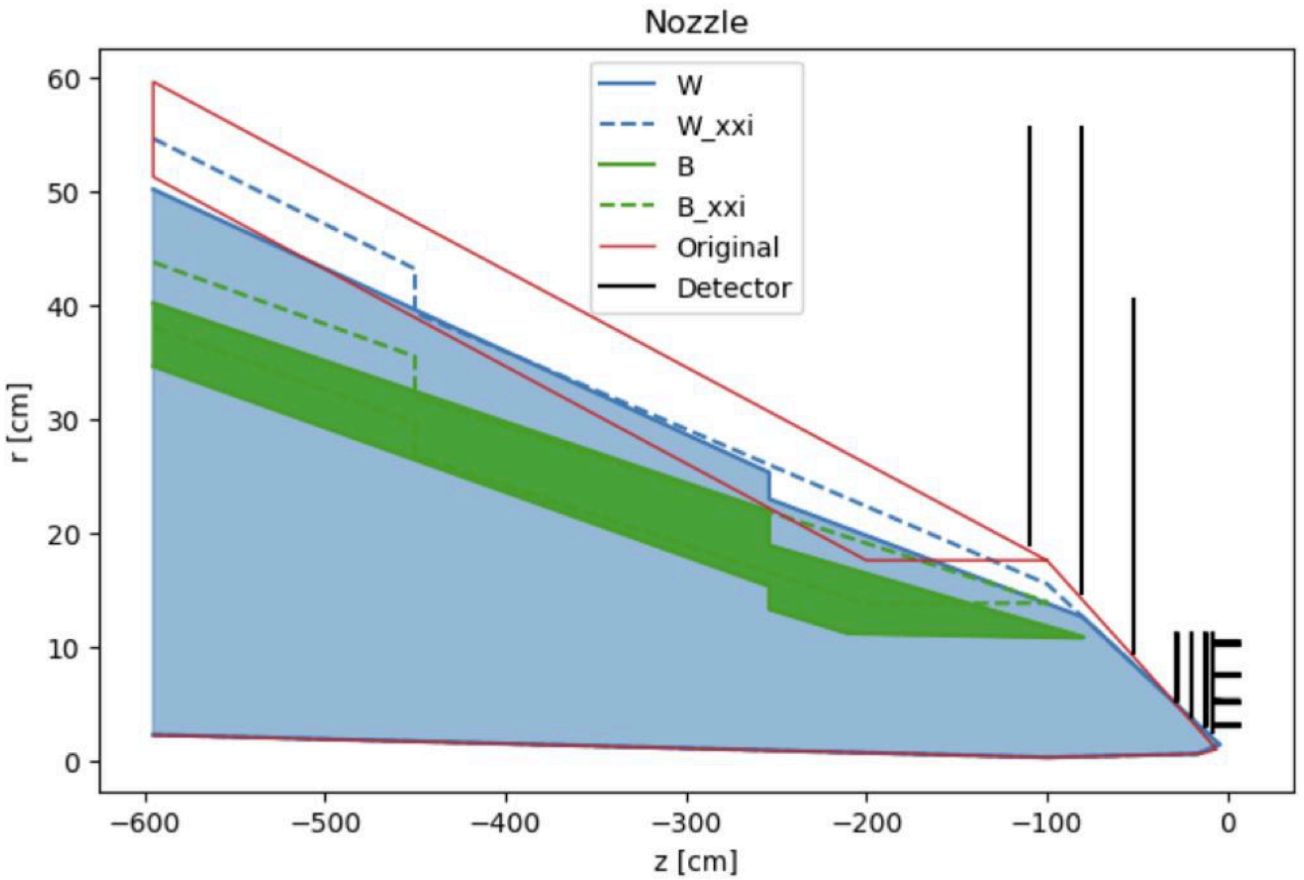


Talk by L. Castelli at IMCC workshop



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Talk by Jeff. K, Micheal. K ; arxiv:2405.07944

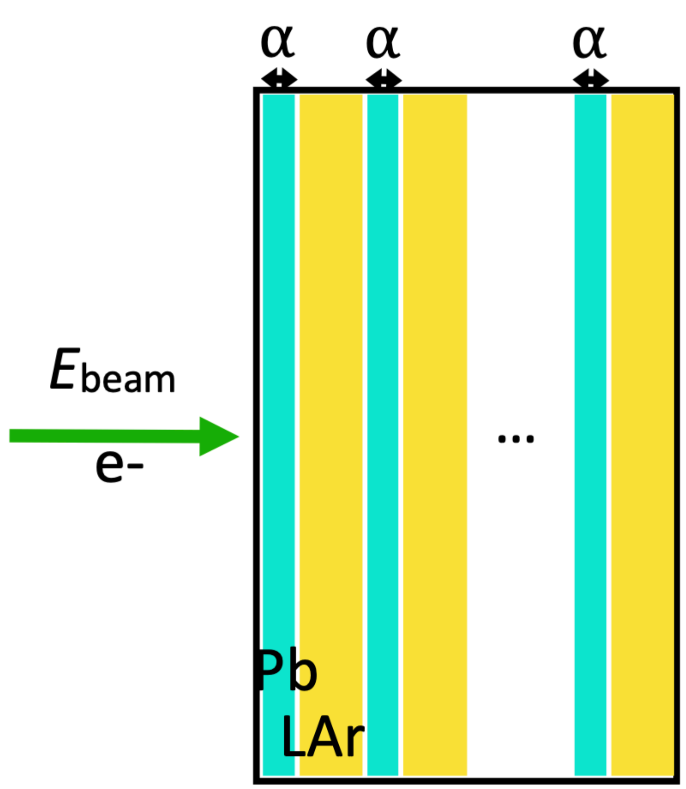
Optimizing μC detectors

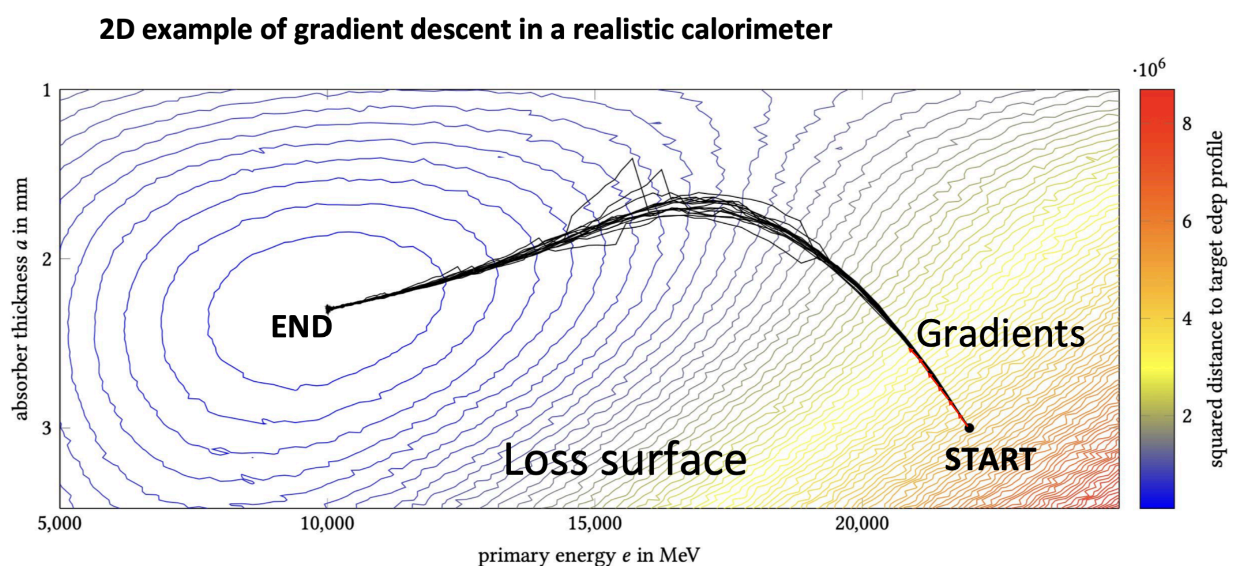
- We can use ML to optimize the entire detector design !
  - Existing effort to optimize geometry of CRILIN for MUSIC detector

- First principled effort to make **GEANT differentiable** w/ multiple scattering

tune $\theta \in (E_{beam}, \alpha)$

optimize an energy deposition profile





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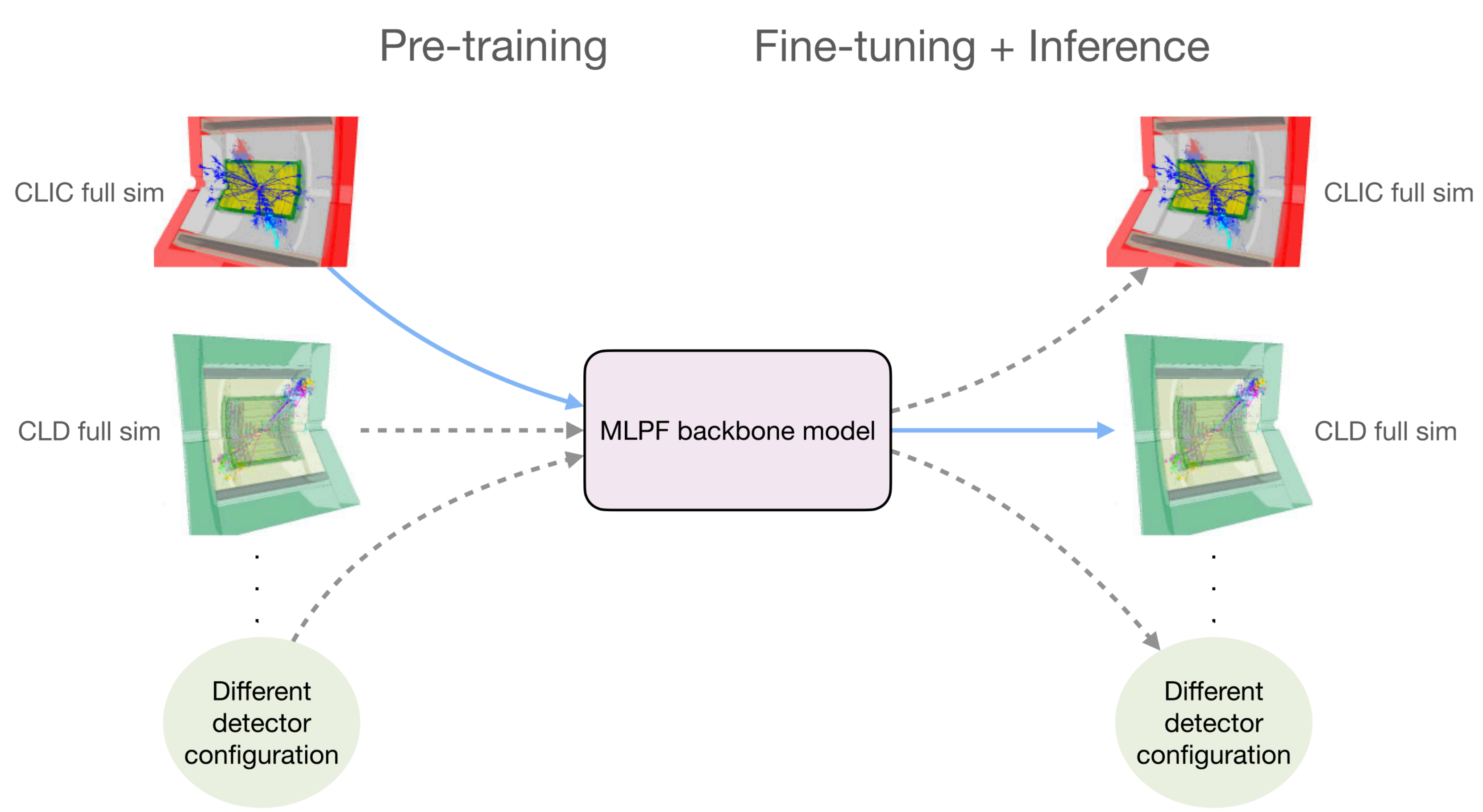
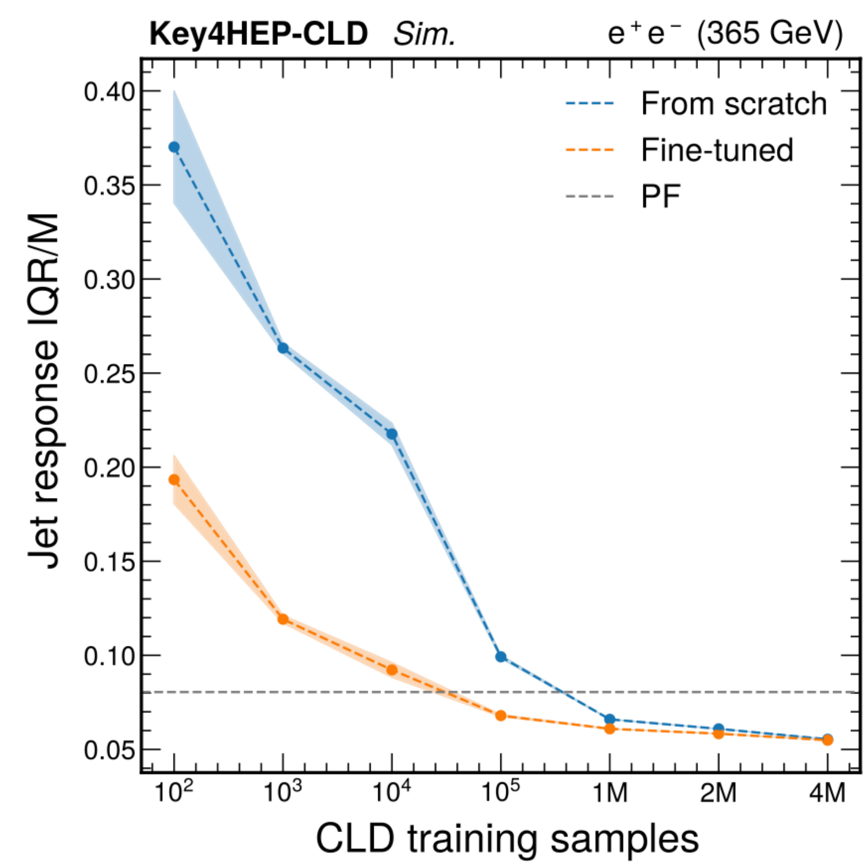
Reconstruction for Optimized Detectors

- Efforts to develop "cross-detector" ML Particle Flow backbone model
  - Train on one detector design → Adapt it on another detector desgin
- Can serve as Ideal surrogate model to optimize entire detector geometry

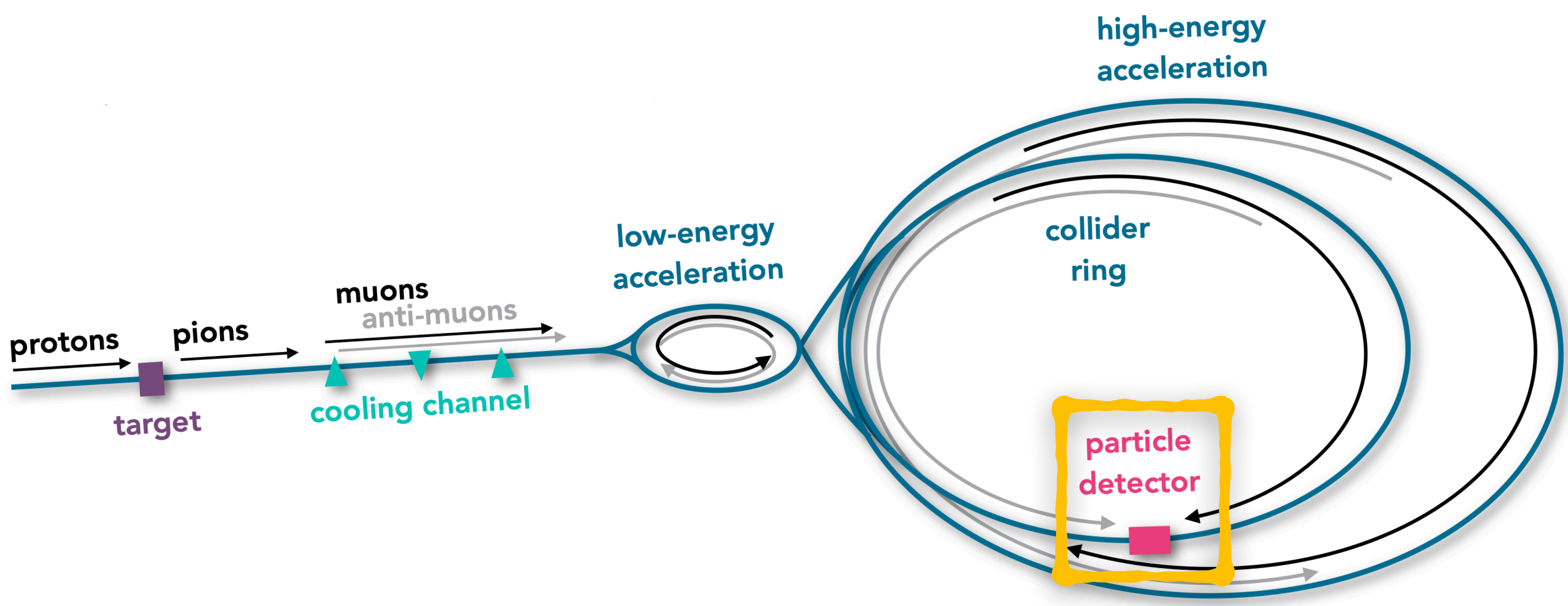
Work by Faoruk. M et. al





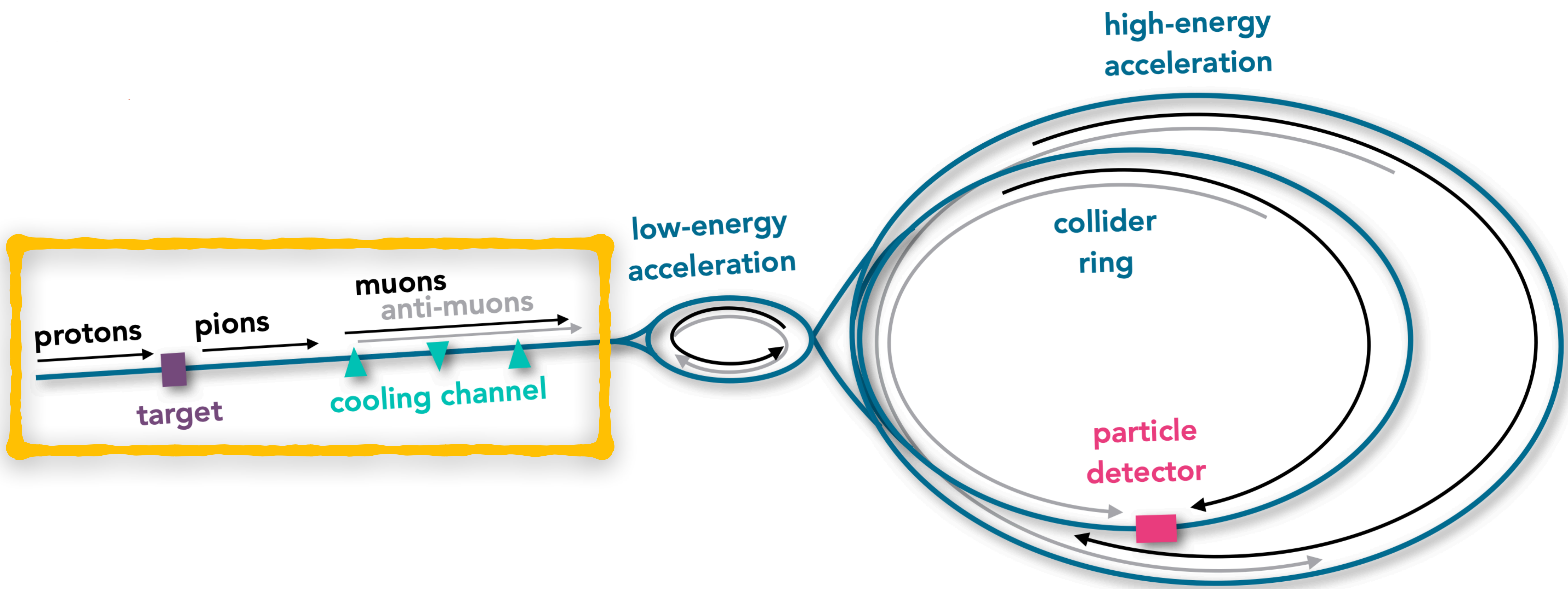
The big picture

- So far, explored applications of **AI/ML to improve detectors**



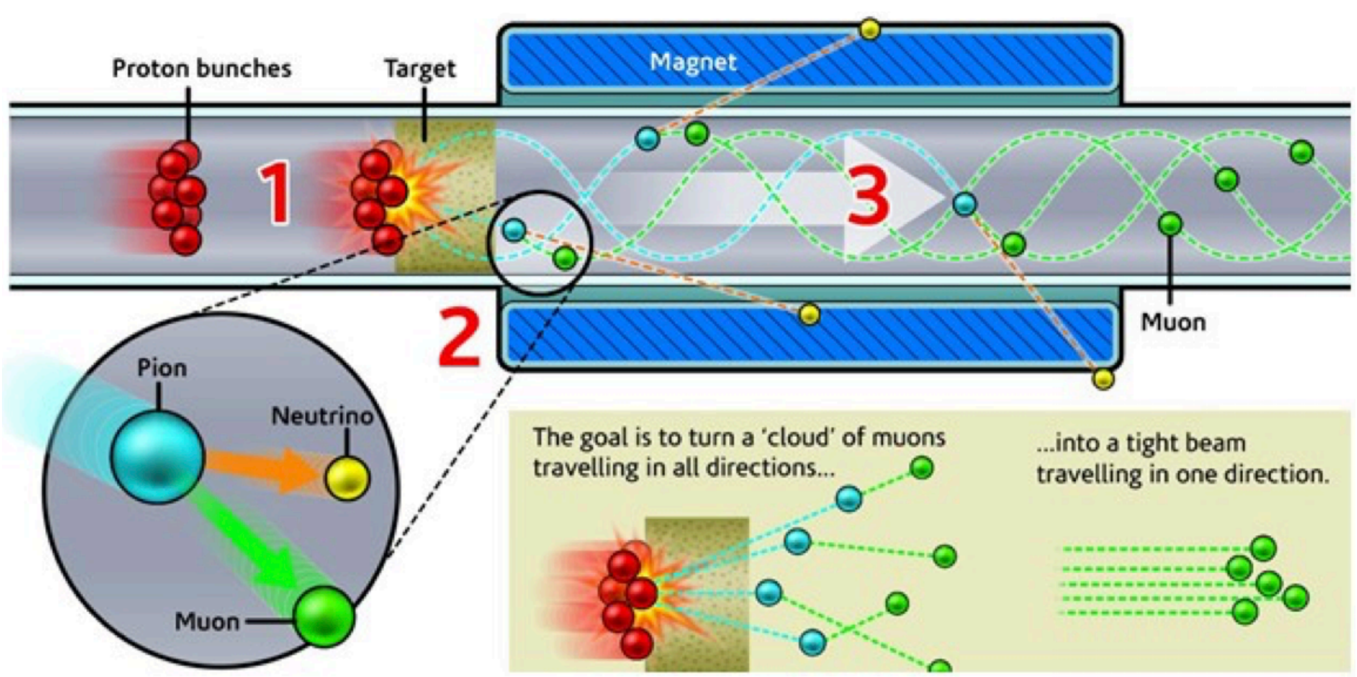
The big picture

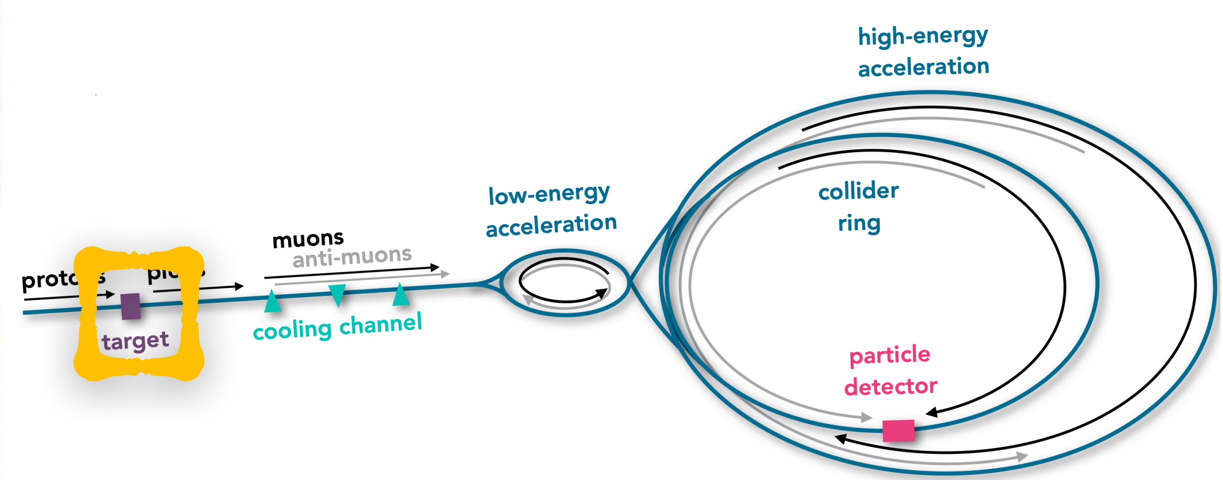
- So far, explored applications of **AI/ML to improve detectors**
  - But, what is the **most critical system for the next 5**+ years ?



Optimizing Target & Capture

- Target should **sustain high power & Intensity + Powerful Magnets**
- Use ML models to find and test optimal target configurations
- We are developing differentiable Geant 4
  - Why not extend this to differentiable g4beamline !





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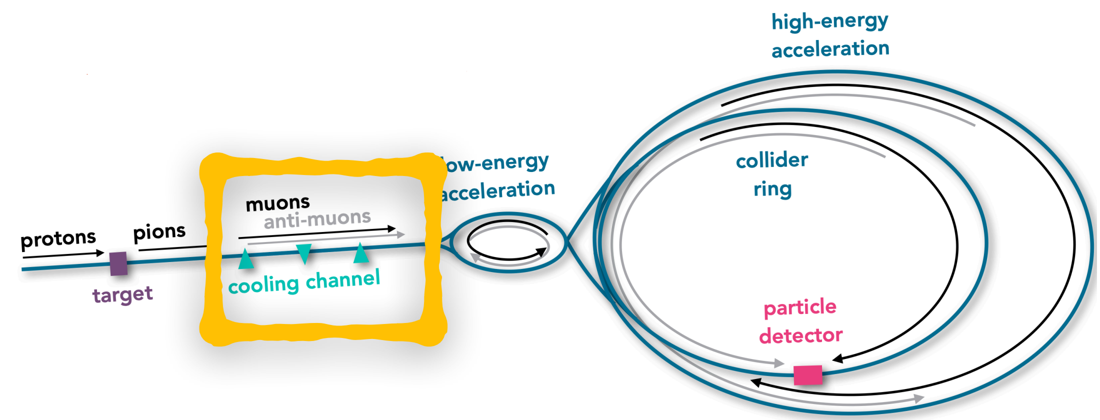
Nick.S, et. al

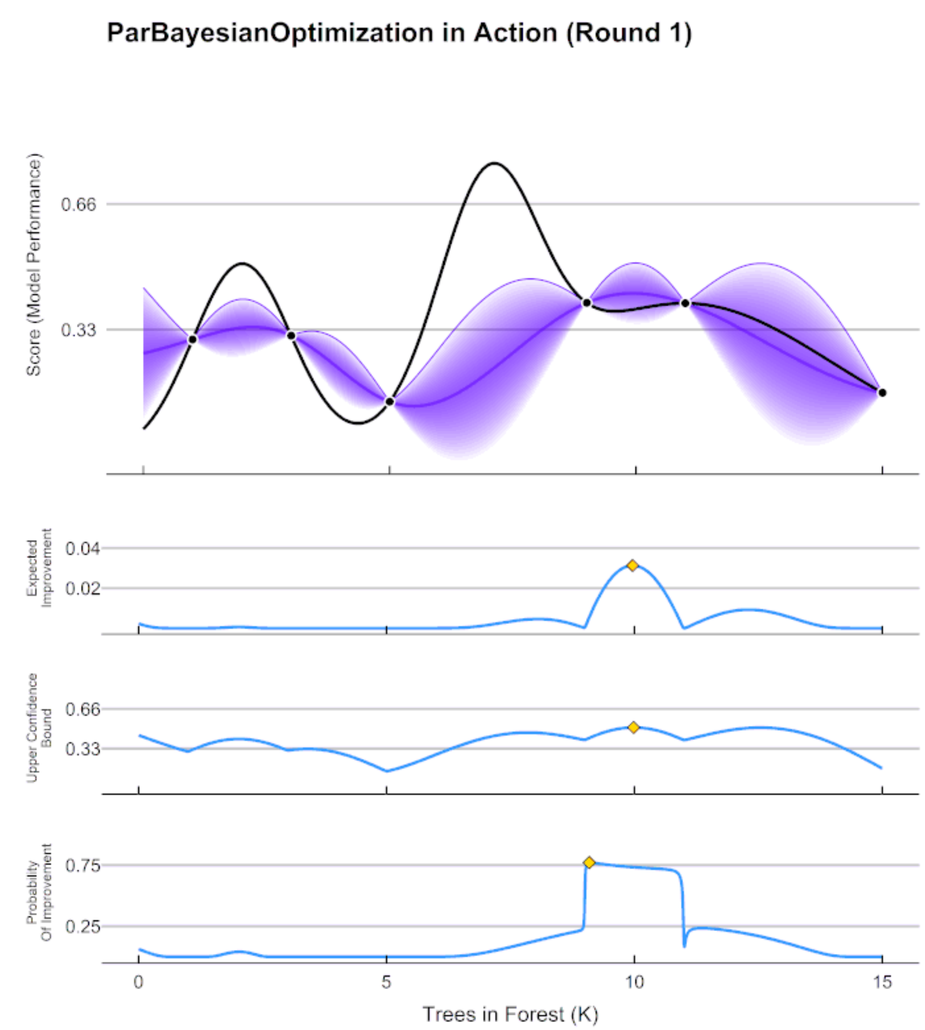
Optimization for the Demonstrator

- Muon cooling is critical and challenging
  - Design choices strongly effect luminosity



- Muon cooling systems has $\mathcal{O}(100)$ parameters to optimize
  - Time consuming to try each configuration

- Use Bayesian optimization /+ Surrogate Model
  - Used for optimizing ML hyper parameters

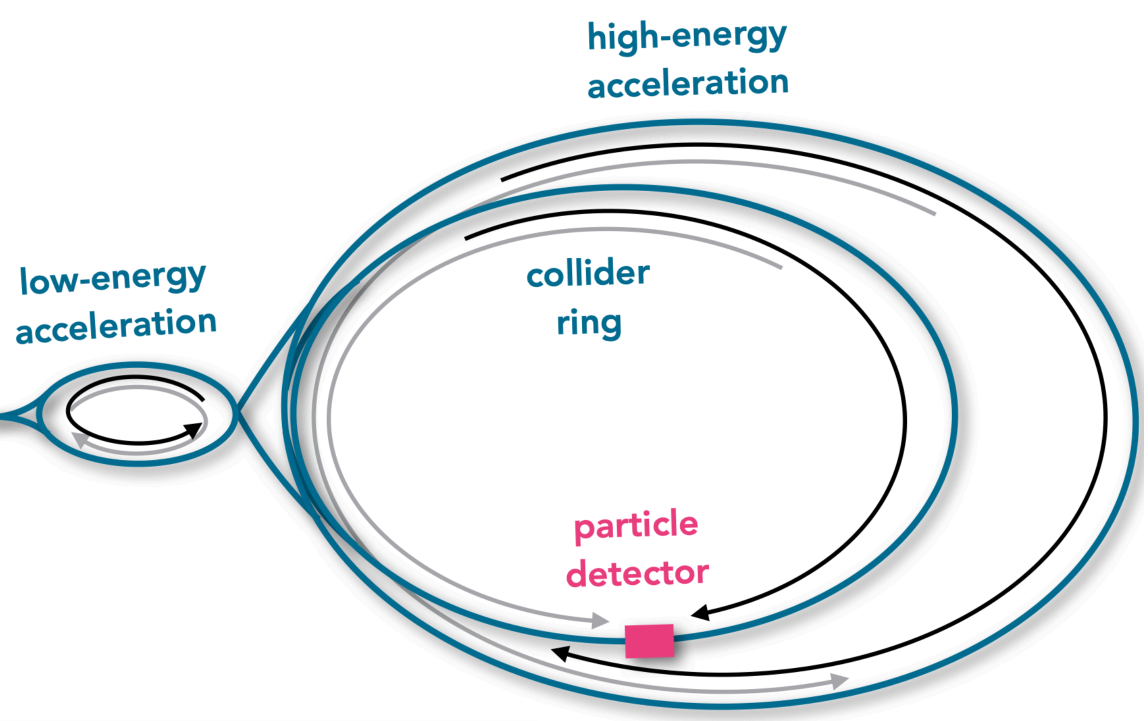


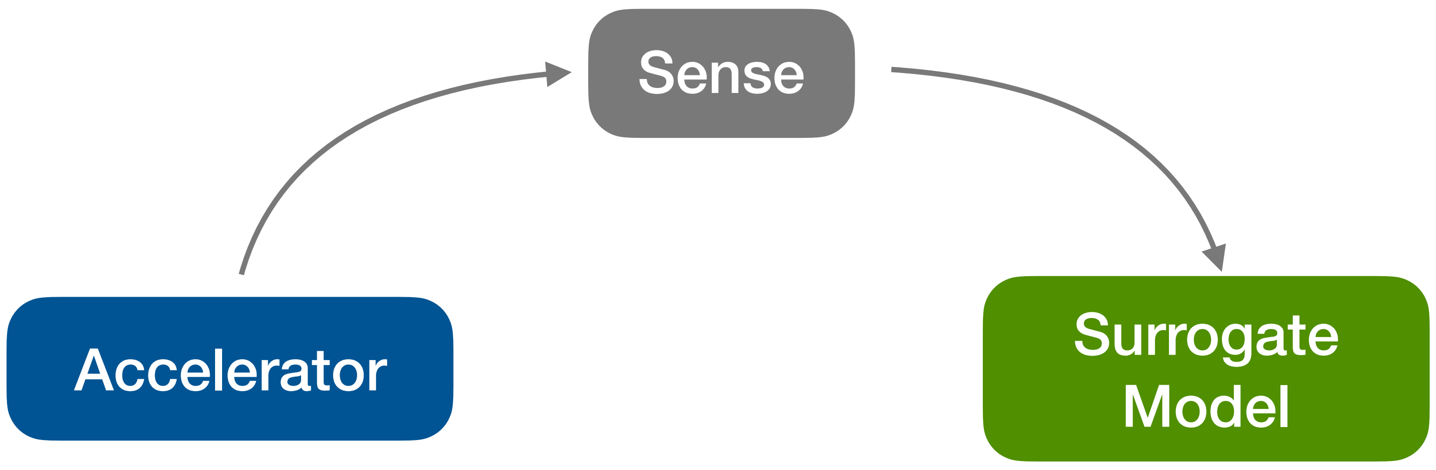
$$\frac{d\epsilon_T}{ds} = -\frac{1}{\beta^2 E}\frac{dE}{ds}\epsilon_T + \frac{\beta_\gamma \beta_T}{2}\frac{d\theta_0^2}{ds}$$

- Can be used to reduce overall cost !

Real-time Beam Control

- Unlike traditional colliders, muons can't stay for long in the ring
  - Really important to have a full control on the beam dynamics





Real-time Beam Control

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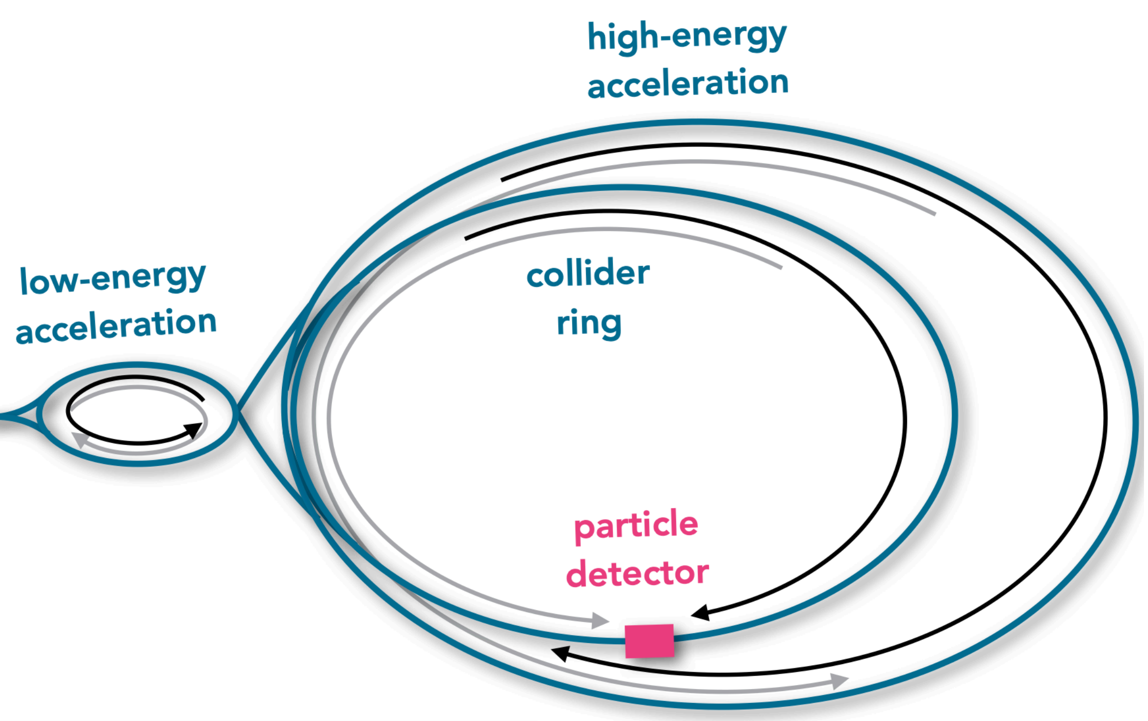
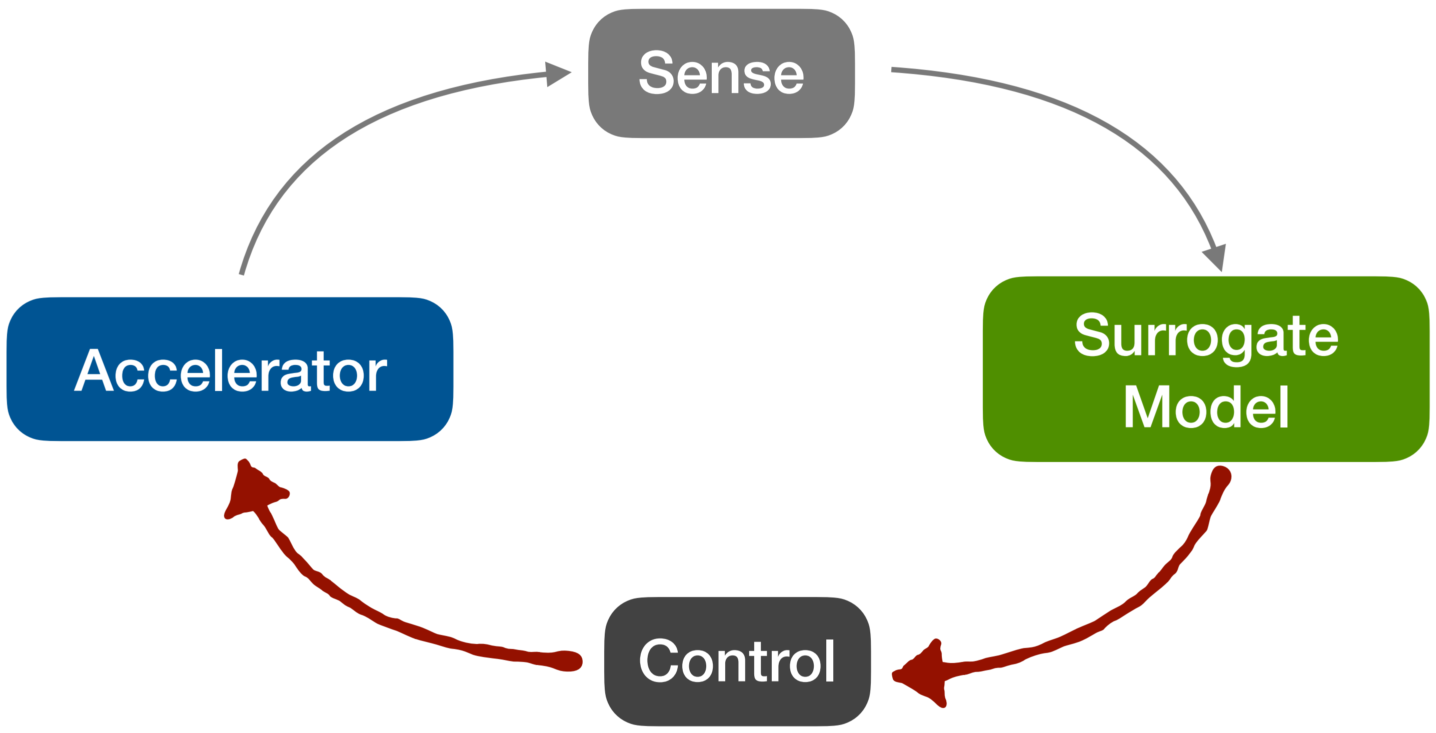
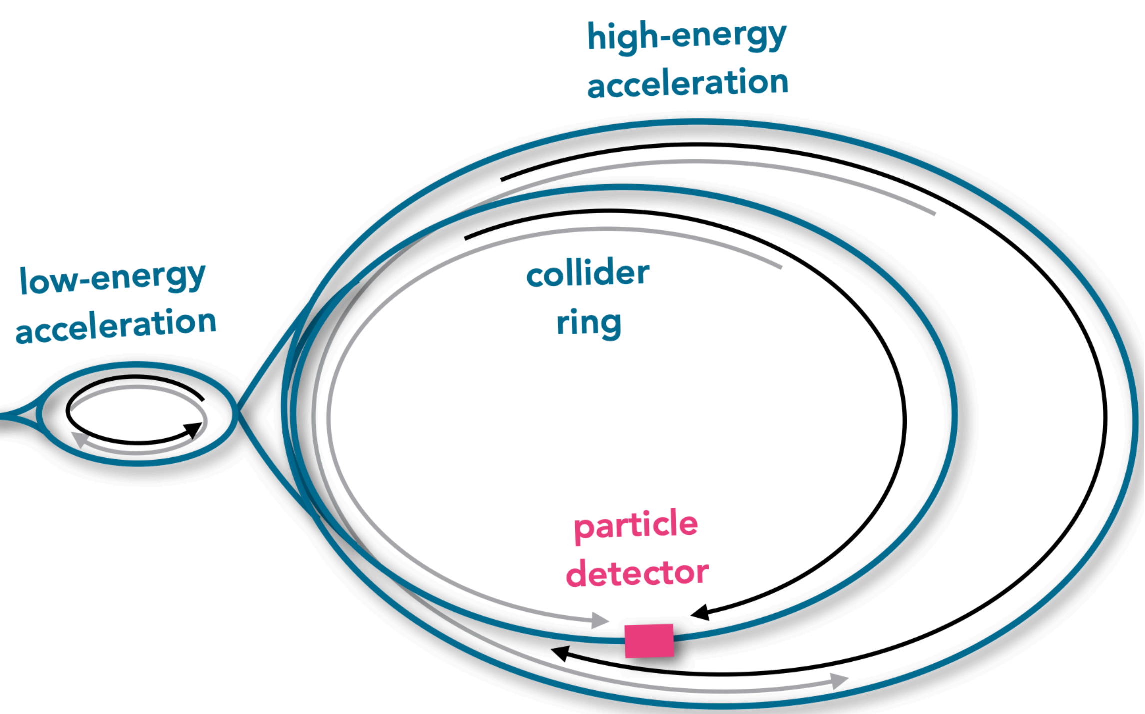
  - Really important to have a full control on the beam dynamics
- Is it feasible to implement this system ?

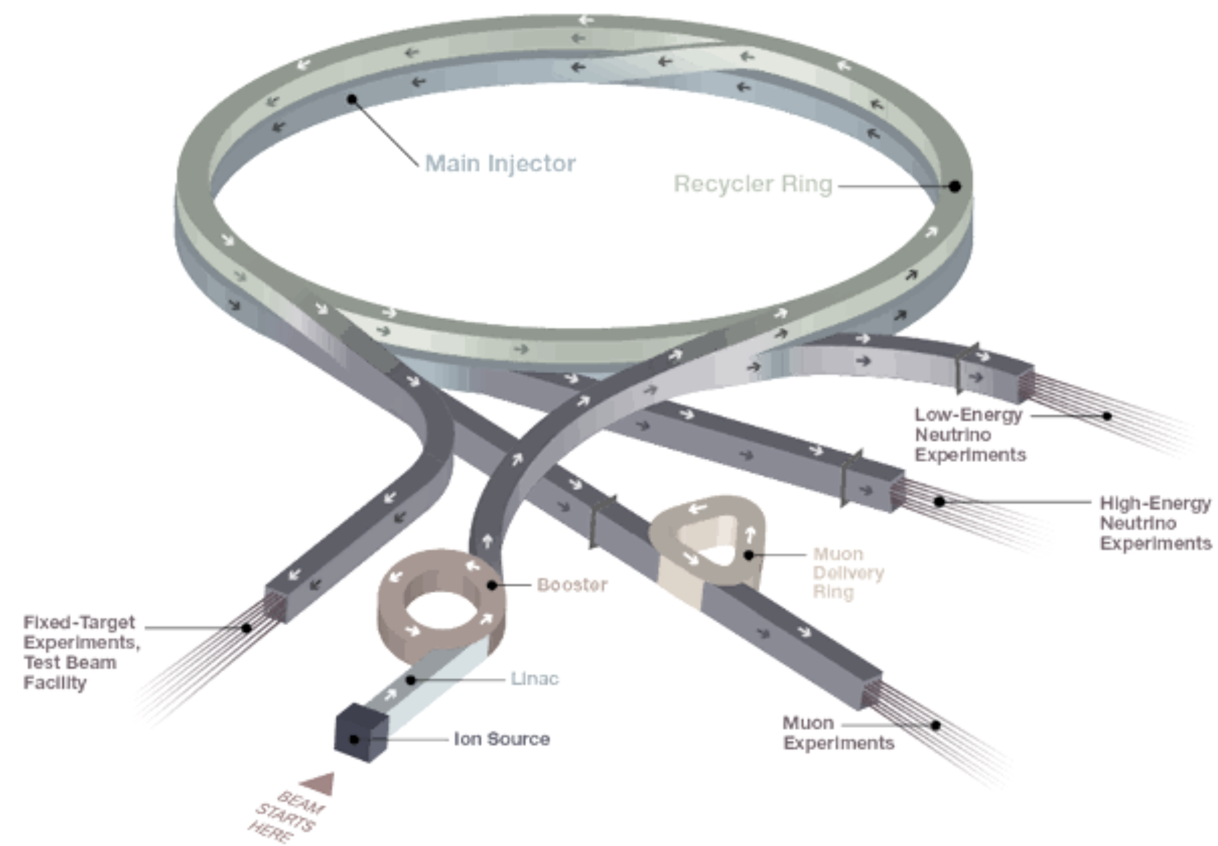




Real-time Beam Control

- Current approaches for realtime-beam control





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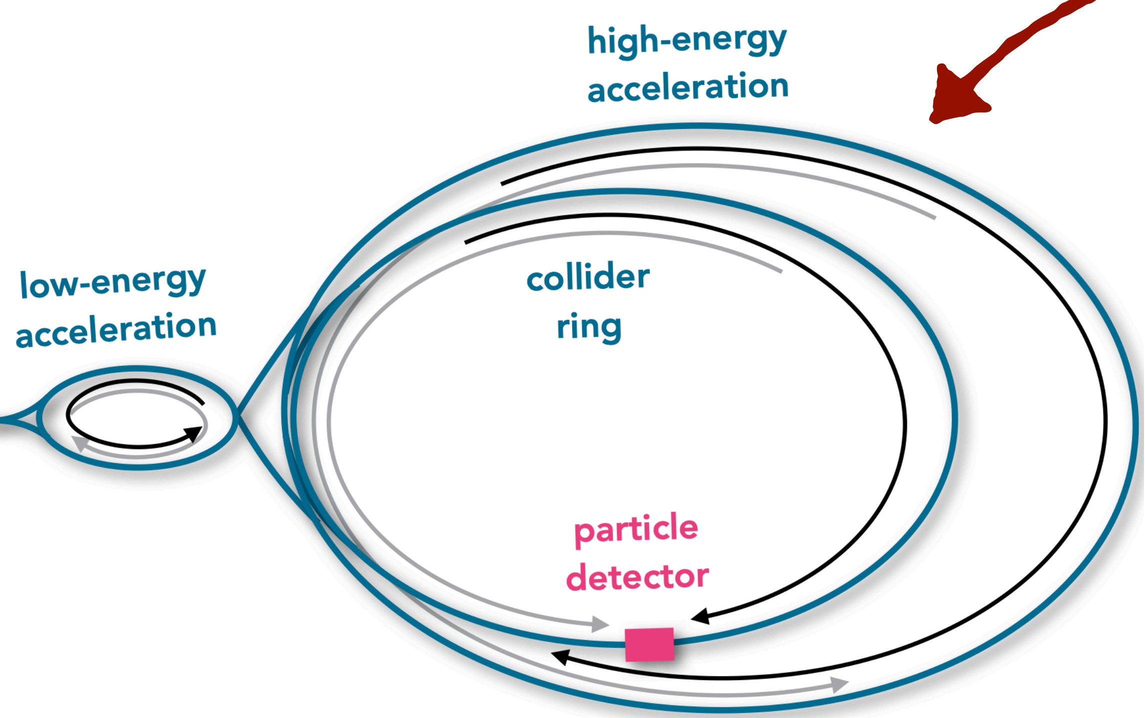
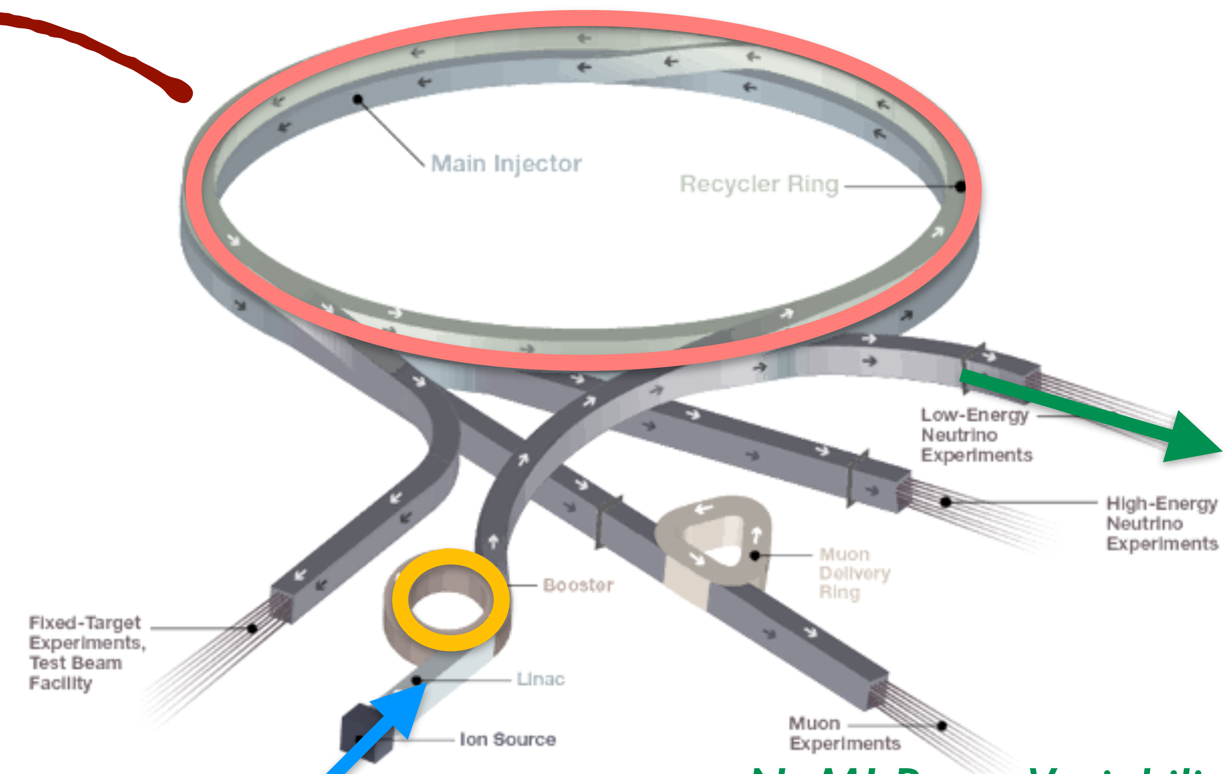
Real-time Beam Control

- We can adapt real-time AI approaches to μC accelerators
  - Reduce / eliminate down time to tune the machine

Real-time Edge AI Distributed System

Differentiate beam loss monitor signals around the ring; Identify if main injector or recycler ring is the source





Linac RF Optimization

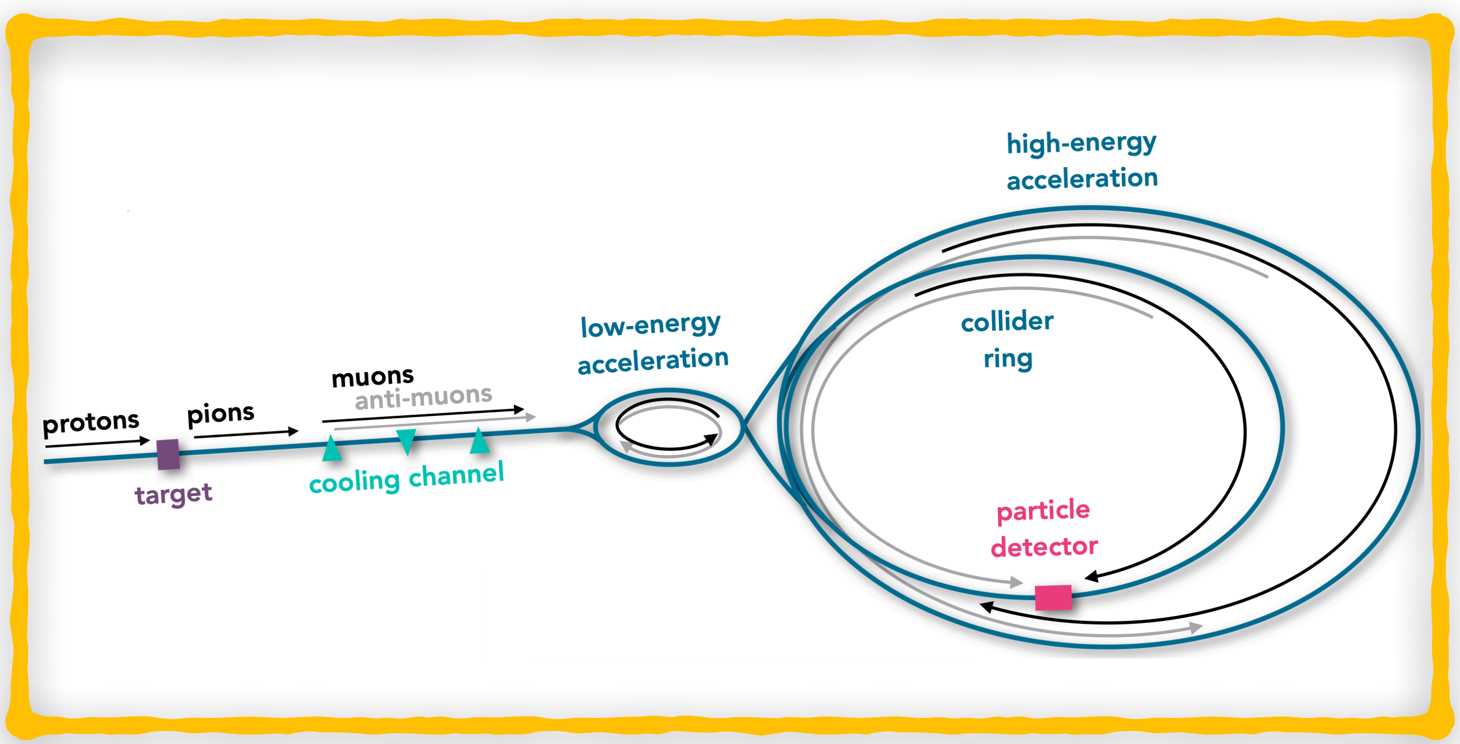
Predict PF parameters to keep beam energy constant and minimize eminence

NuMI Beam Variability Prediction & LBNF monitoring

Predict NuMI proton beam position, intensity and horn current

What's left for us to solve ?

What is the **most critical component** in the μC apparatus ?



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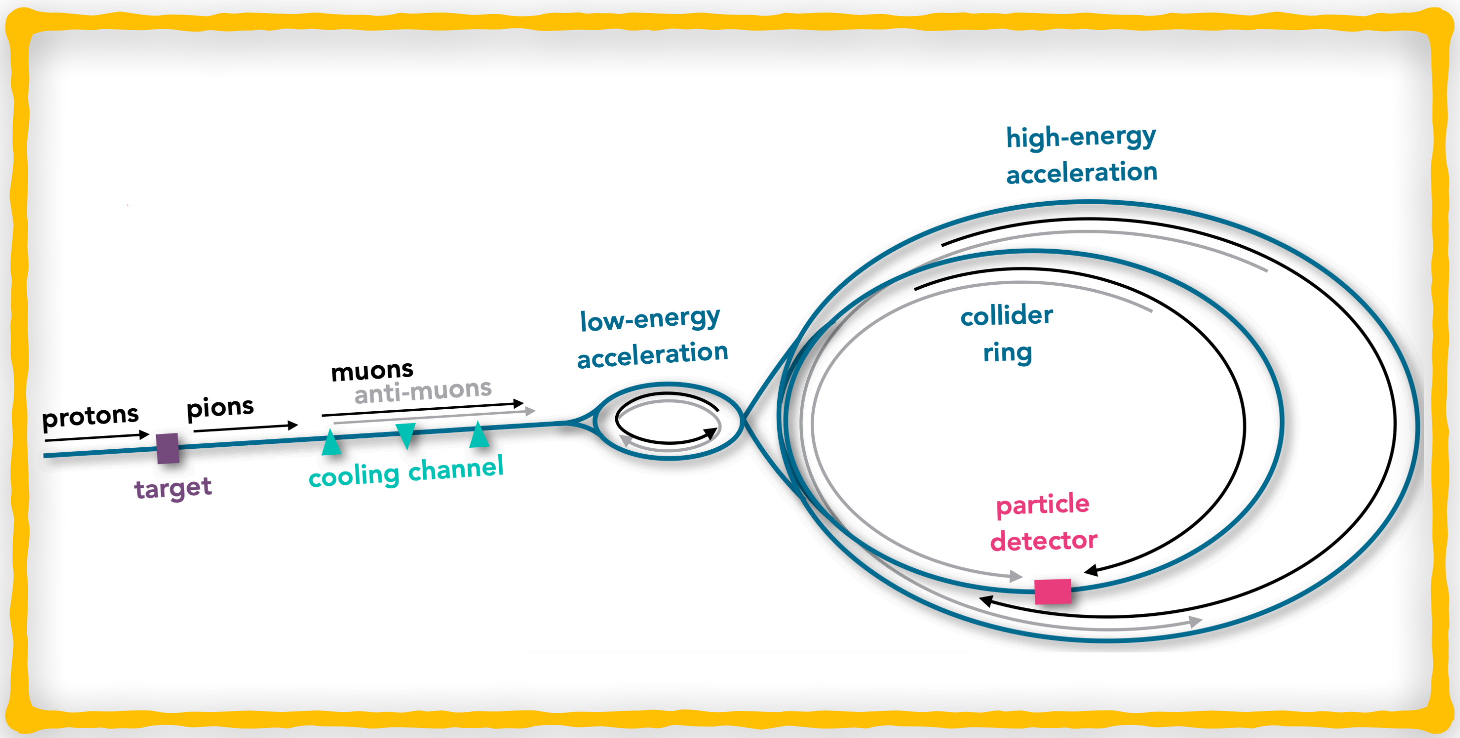

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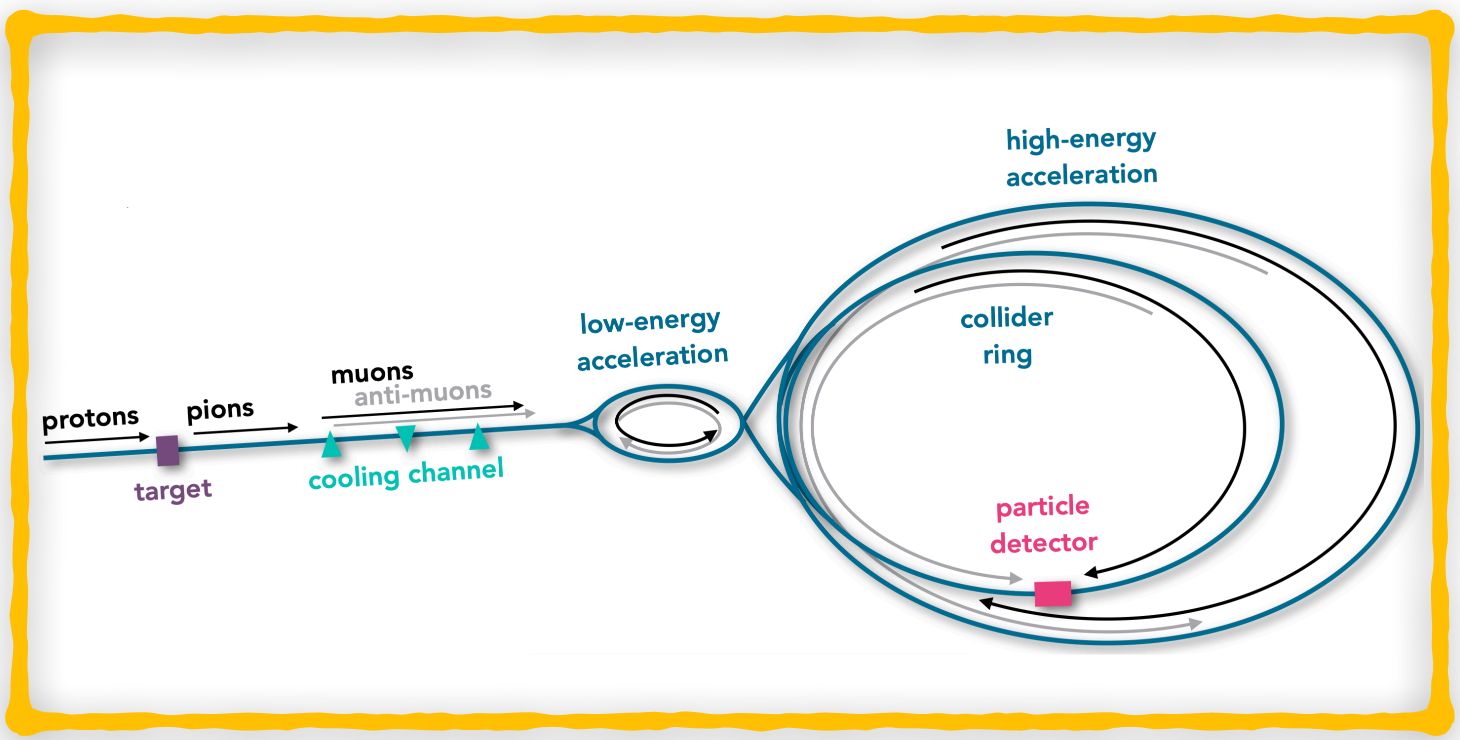
What is the **most critical component** in the μC apparatus ?

What do they do if you **ramp up current** ?



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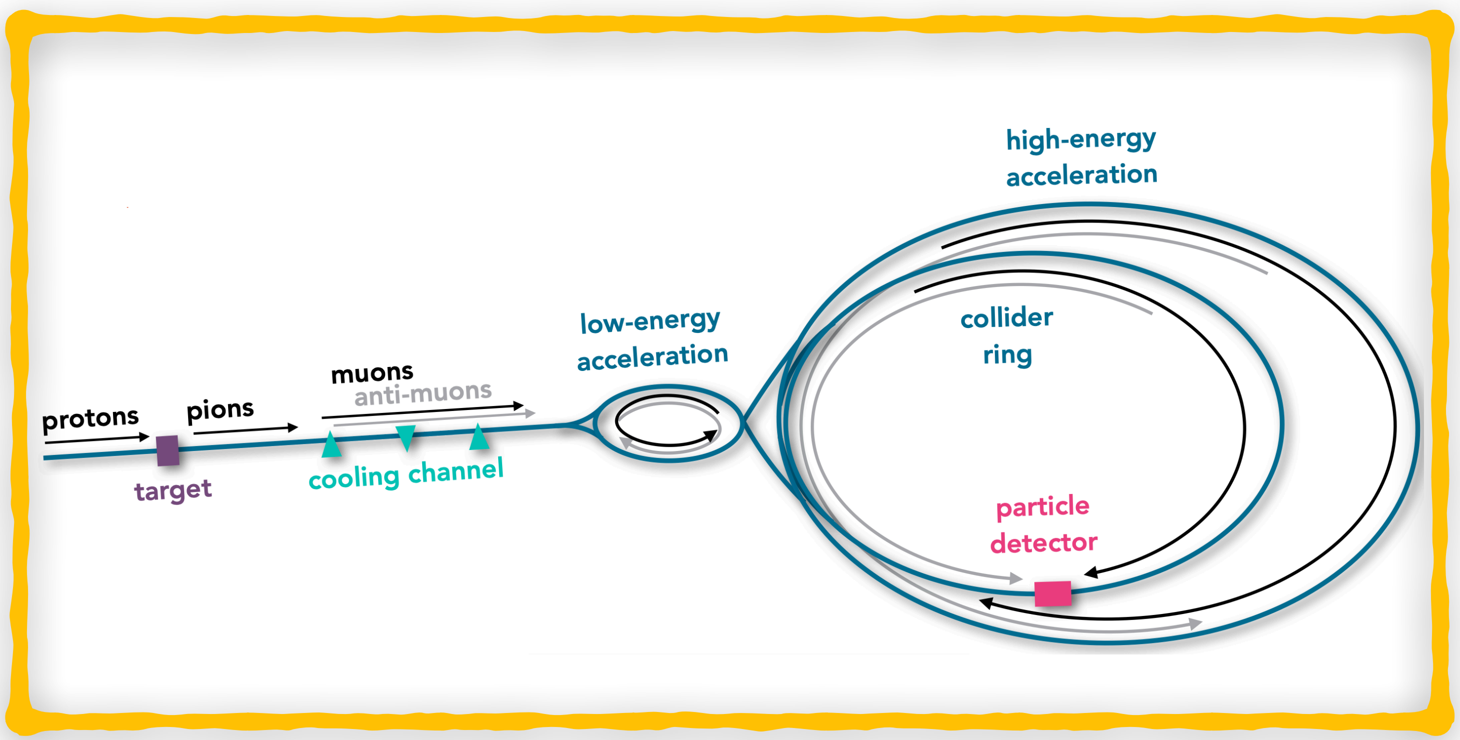
What is the **most critical component** in the μC apparatus ?

What do they do if you **ramp up current** ?

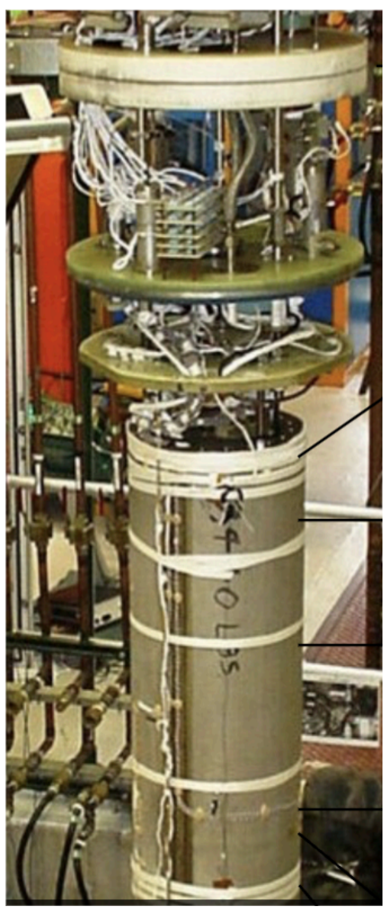
How do we mitigate this ?

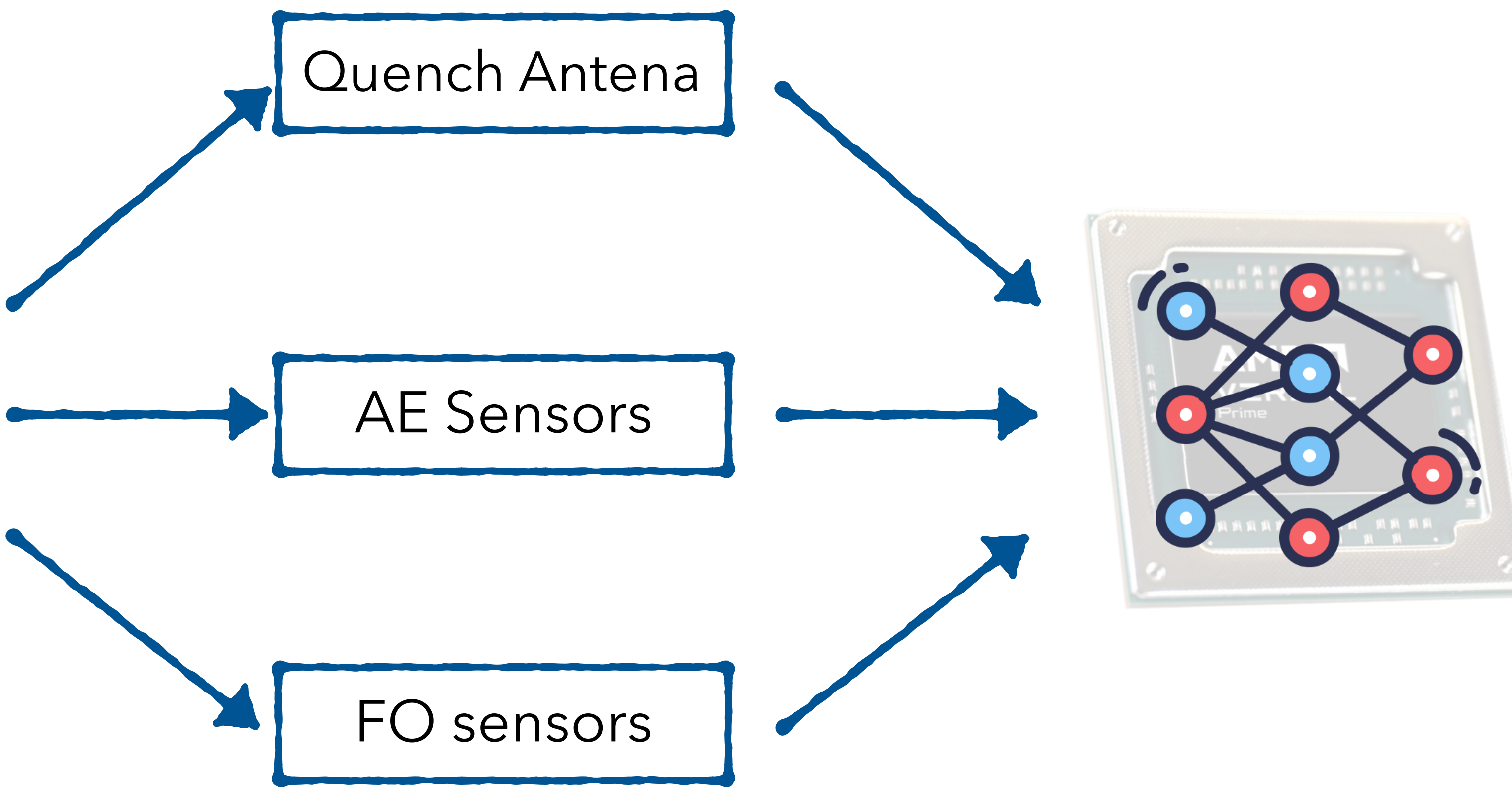


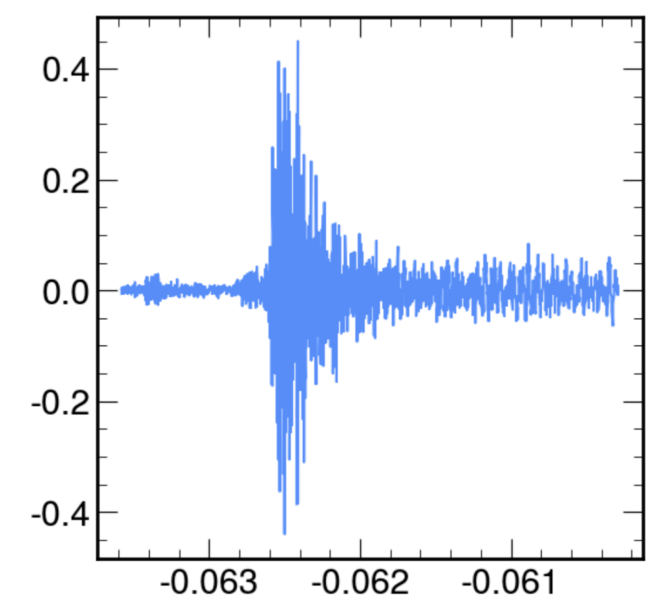
Real-time quench protection

- For field strength, magnets must operate at high current
  - Need to flag precursors before the quench occurs
- Using SSMs with various data streams for Quench prediction
  - Targeting sub milliseconds latency

Maira.K, Abhijith. G, et. Al
Funded by LDRD







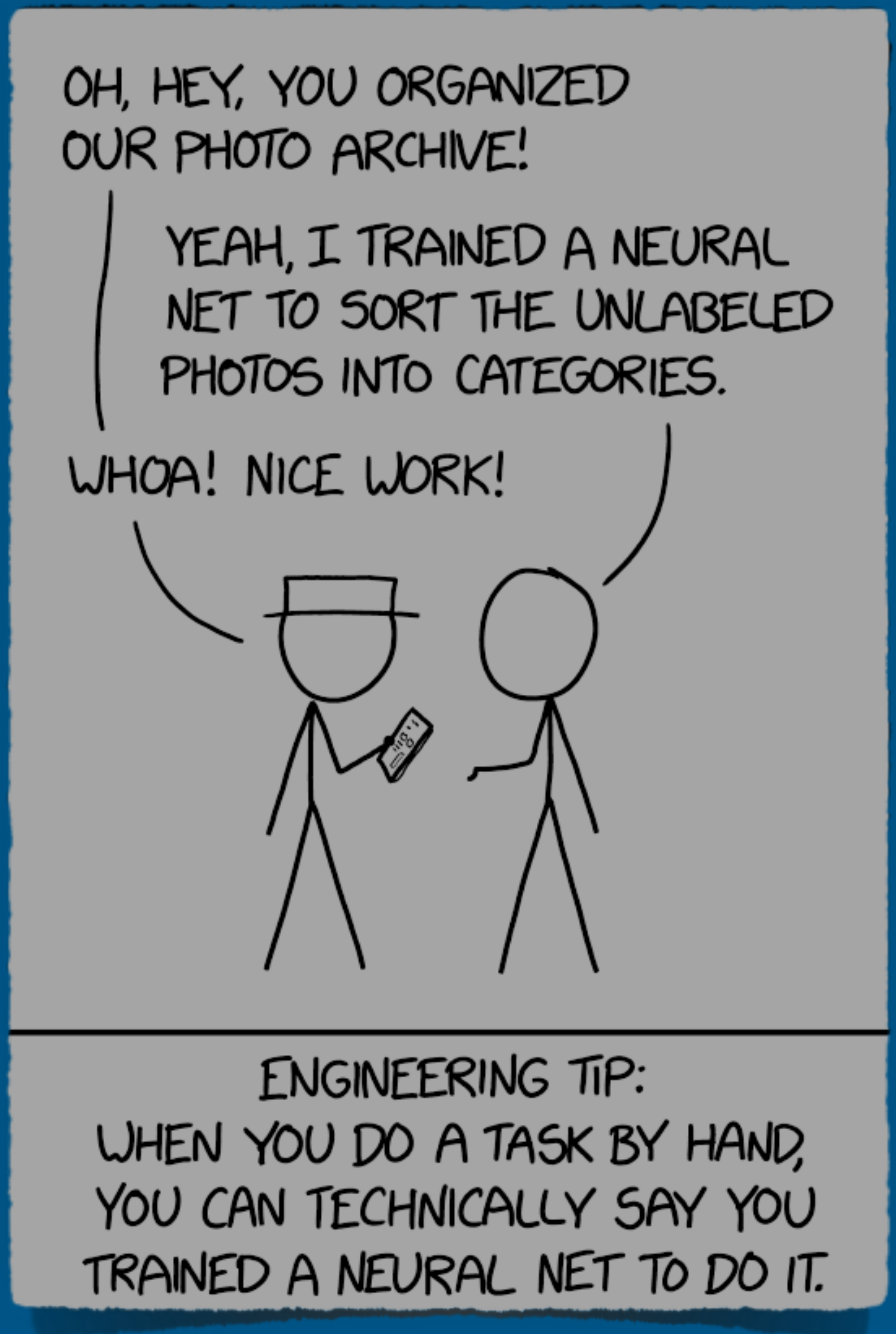
Conclusion

- Not a full list of ML opportunities / efforts in Muon collider
  - Personal take on where ML could be impactful in near future

- Muon Collider is an **exiting and challenging program**
  - We need **bold and unconventional solutions** to solve them

"AI/ML approaches are our best bet for making significant and rapid progress"

-N. Tran


OH, HEY, YOU ORGANIZED OUR PHOTO ARCHIVE!
YEAH, I TRAINED A NEURAL NET TO SORT THE UNLABELED PHOTOS INTO CATEGORIES.
WHOA! NICE WORK!
ENGINEERING TIP:
WHEN YOU DO A TASK BY HAND, YOU CAN TECHNICALLY SAY YOU TRAINED A NEURAL NET TO DO IT.

Thank you!