AI/ML-based Optimisation Services for Detector Ensembles in Hadron Physics Experiments

A.Belias (GSI)

Town Meeting, Hadron Physics in Horizon Europe
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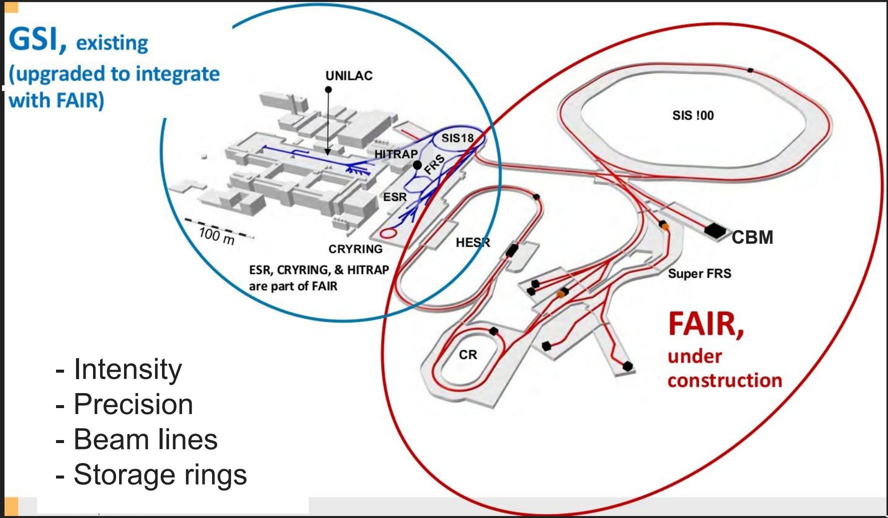
AI/ML-based Optimisation Services for Detector Ensembles in Hadron Physics Experiments



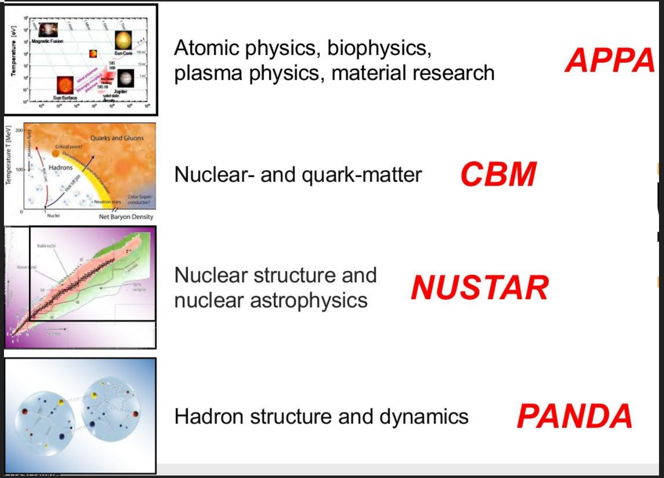
- Intensity
- Precision
- Beam lines
- Storage rings

At GSI and FAIR (under construction), a wide range of particle beams, from protons to ions, are available for fundamental research in hadron physics, heavy-ion physics, nuclear physics, atomic-, bio- and plasma physics and a wide range of materials research.

Many users from different physics communities are eager to use the primary and secondary beam lines, to perform experiments utilizing various different detector systems.

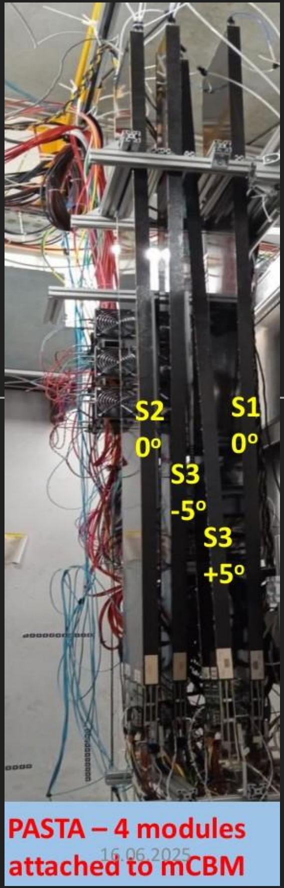
In some experiments the detector systems are deployed as a large permanent installation, in other experiments detector systems are of moderate size with installations for movable configurations.

Typically, each specific detector is optimised individually, however, the combined performances of detector ensembles as intended to be used remain as commissioning tasks with first beams.



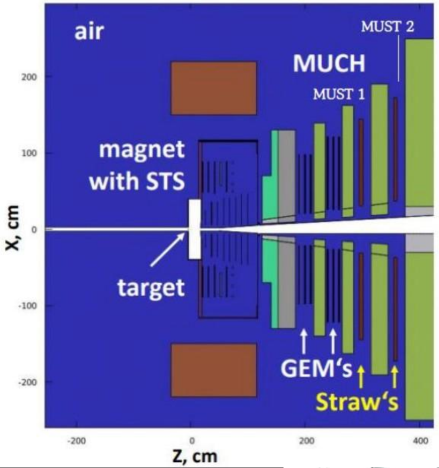
Experimental Commissioning
- Costly
- Beam Time Consuming
- Inefficient
- High human resource costs
- Not optimal

	Examples - Detectors in beam lines @GSI	Examples - Detectors in beam lines @FAIR
C B M	**mCBM detectors & LHCb straws** (Beam times with ions energy scans & various targets)	**CBM detectors incl. LHCb straws** (Detectors-Absorbers) Various beam+target: p+p, p+Au, Au+Au
N U S T A R		



mCBM detectors & LHCb straws

(Beam times with ions energy scans & various targets)



CBM detectors incl. LHCb straws

(Detectors-Absorbers)

Various beam+target:

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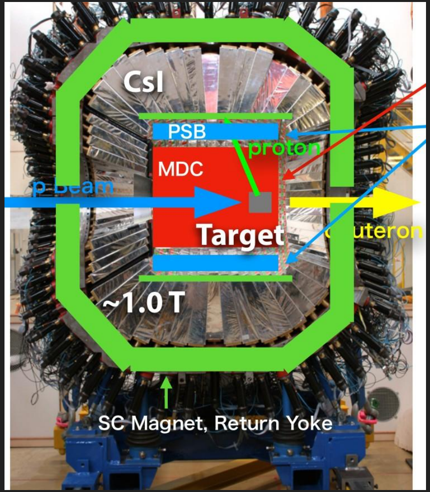
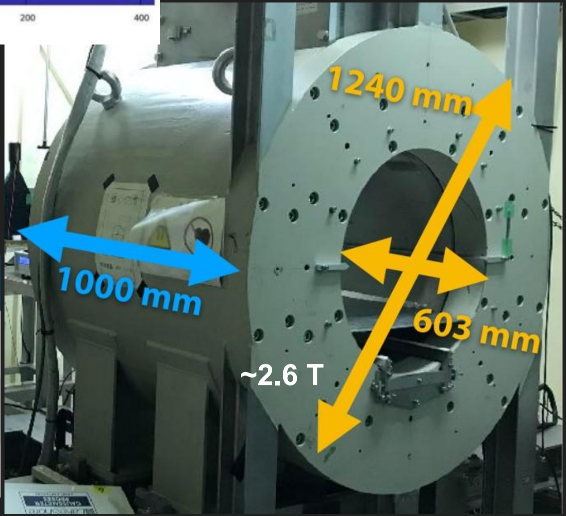


Same detectors - different magnets

	WASA	WASA2
Bore	43 cm	60 cm
Length	55 cm	100 cm
B	1 T	2.6 T



Proposal

We propose the development of an AI/ML-powered optimisation framework that transforms how ensembles of detectors are designed, tuned, and operated under different beam line conditions.

The core idea is to move from individual detector tuning toward a predictive and service-based model that integrates multiple detector responses into ensemble performance maps.

This enables data-driven optimisation of ensemble configurations for specific physics goals, for efficient tasks of particle identification, hadron/electron separation, timing, and spatial resolution, under different beam energies and intensities.

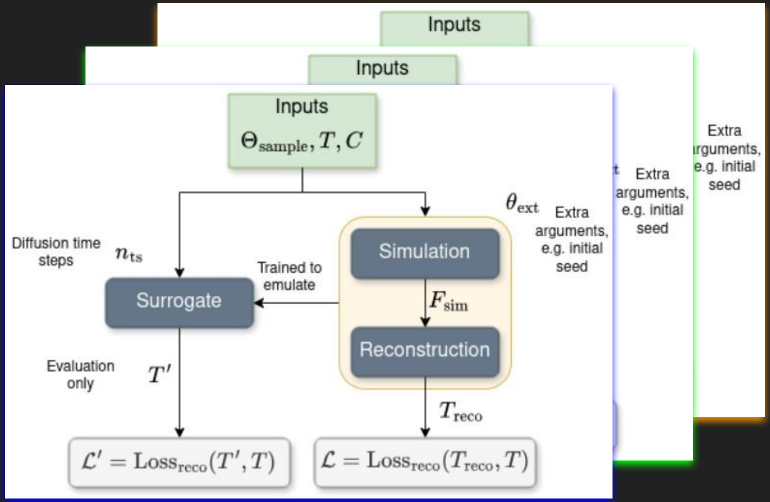
The goal is to provide experimental users with a service that allows them to evaluate and optimise ensemble configurations in advance, based on real detector descriptors and beam conditions.

The proposed AI/ML system

The proposed system operates in two main phases:

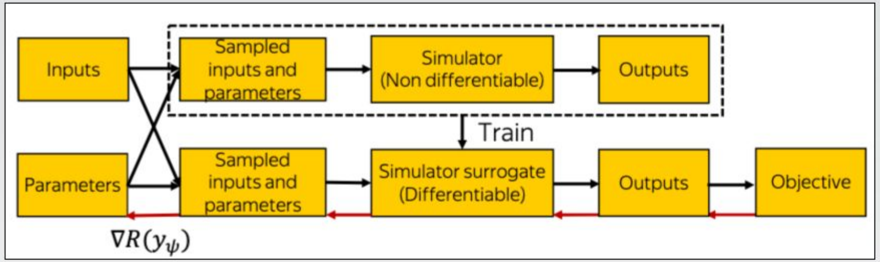
Descriptor Encoding and Mapping: Surrogate models
Using AI/ML techniques, individual detector characteristics (such as geometry, material layers, resolution, response functions) are encoded into an ensemble description. These are then mapped into a high-dimensional parameter space that captures both the beamline phase space and the spatial-temporal interactions of the detector setup. This mapping acts as a surrogate model for ensemble performance.

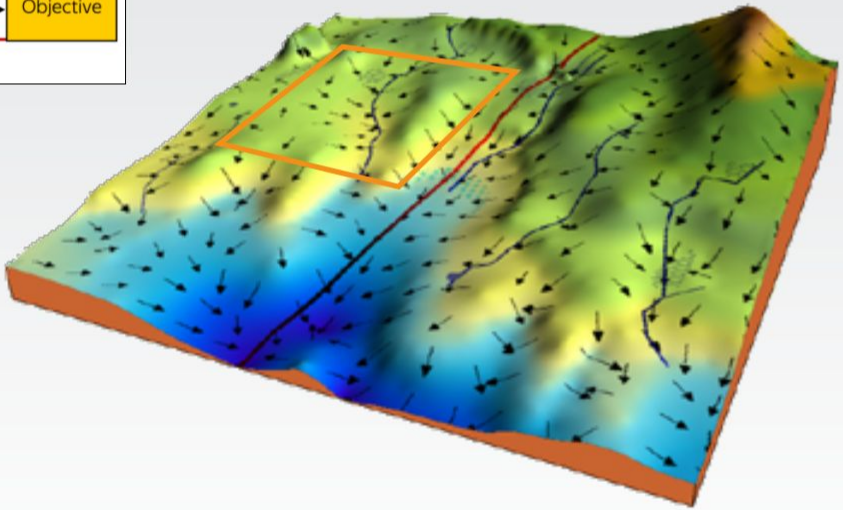
https://arxiv.org/pdf/2502.02152



Optimisation of surrogate ensembles: Optimization pipelines

A Local Surrogate





https://ml-cheatsheet.readthedocs.io/en/latest/gradient_descent.html

S. Shirobokov, et al., arXiv:2002.04632

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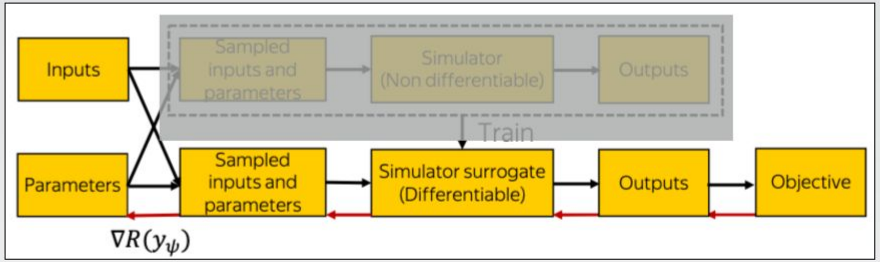

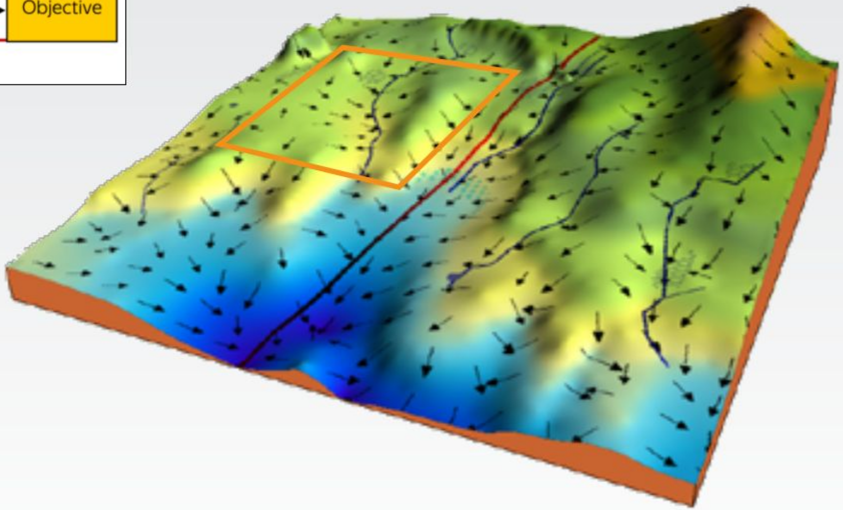

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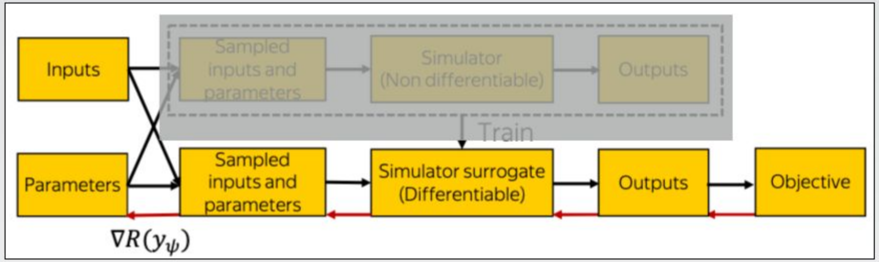

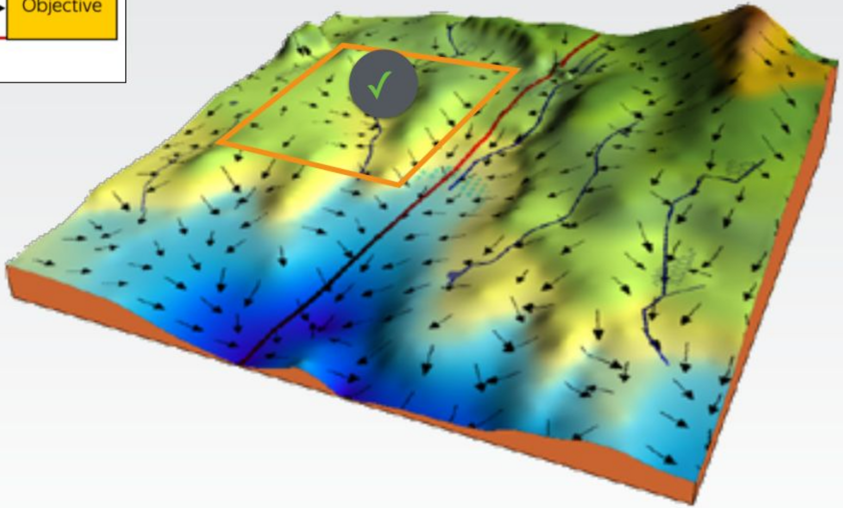

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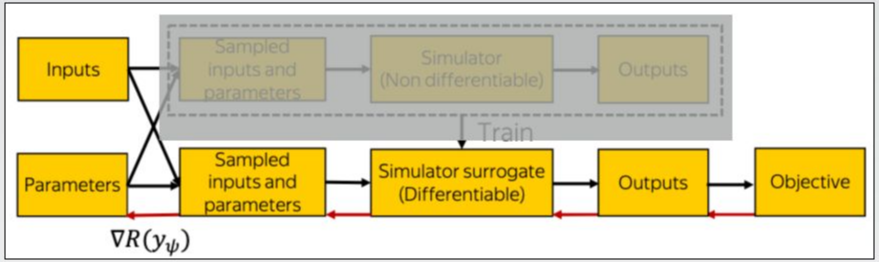

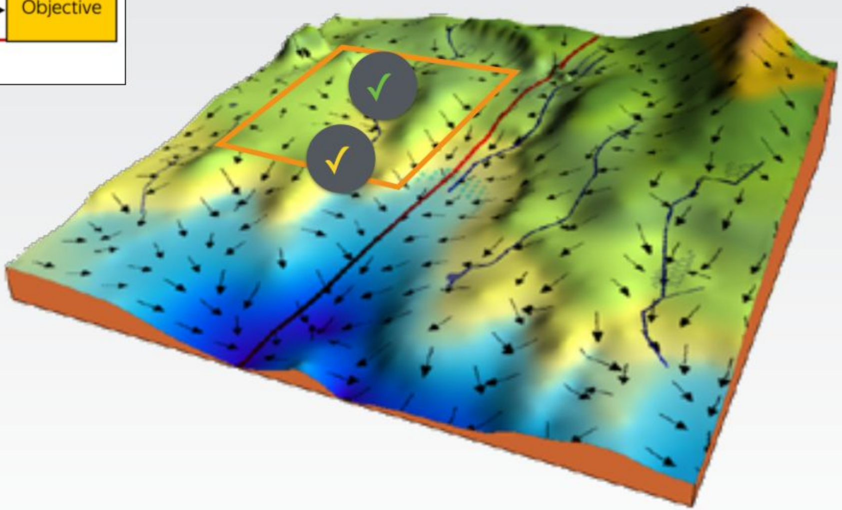

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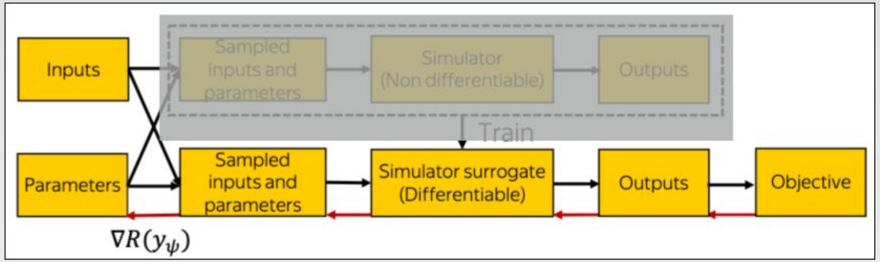

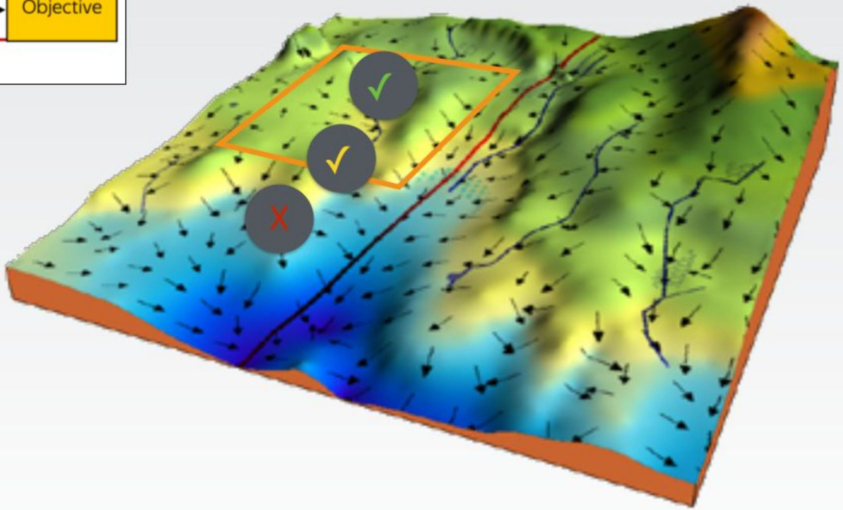

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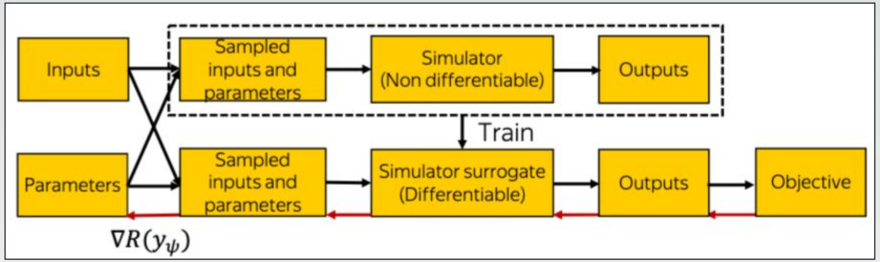

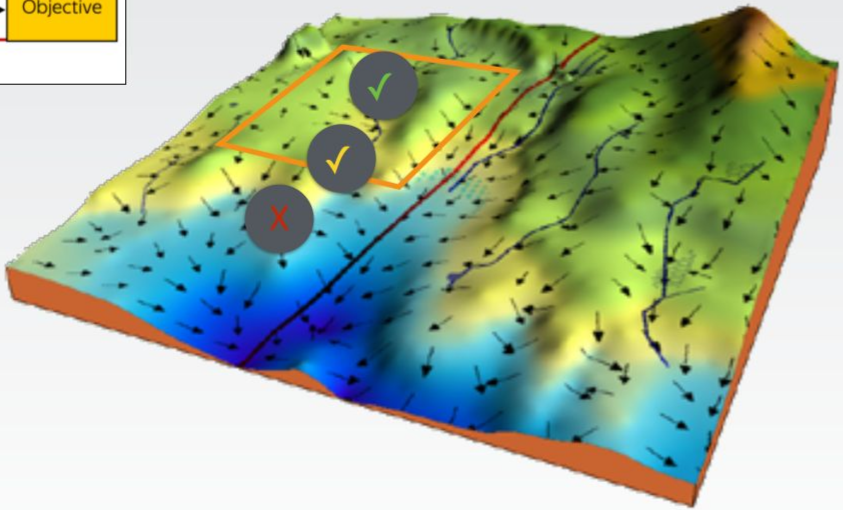

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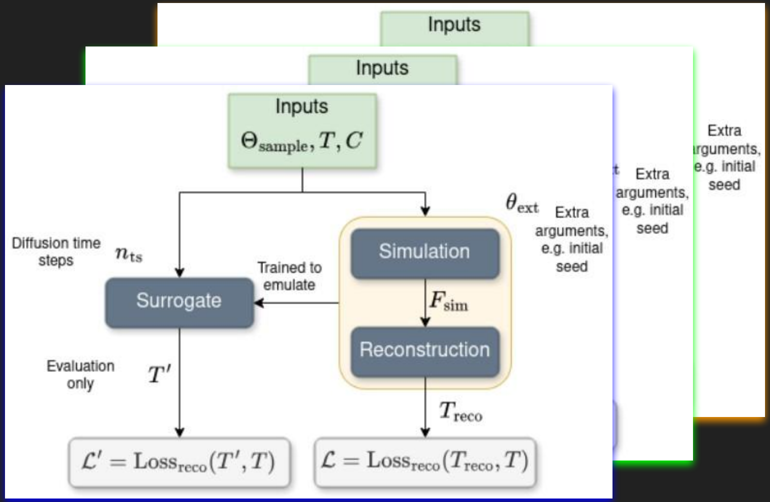
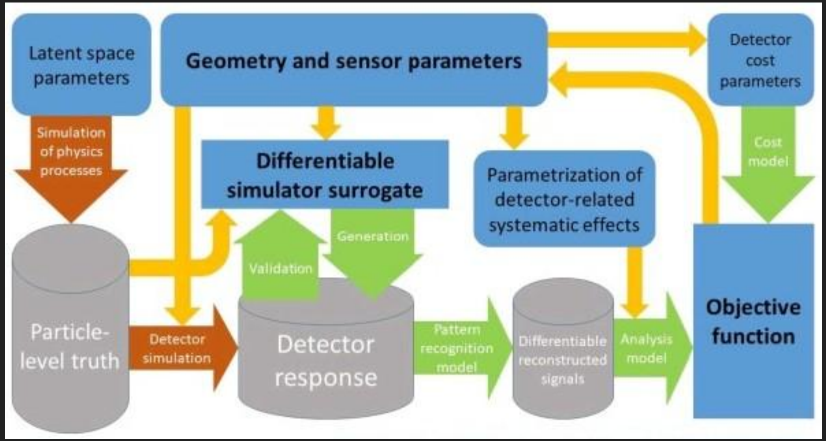


Optimisation of surrogate ensembles: Optimization pipelines
Based on the generated performance maps, an optimisation engine searches for configurations that maximise figures of merit (FOMs) relevant to the experiment. These may include signal-to-noise ratios, detection efficiency, separation power, even beam time and cost constraints, depending on user-defined physics goals.

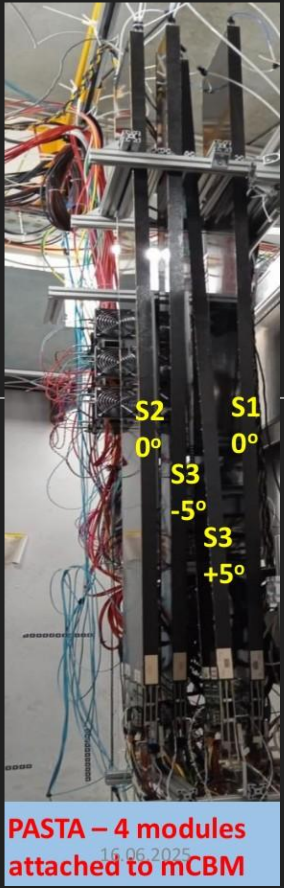


Review in Physics 13 (2025) 100120
Review in Physics 10 (2023) 100085

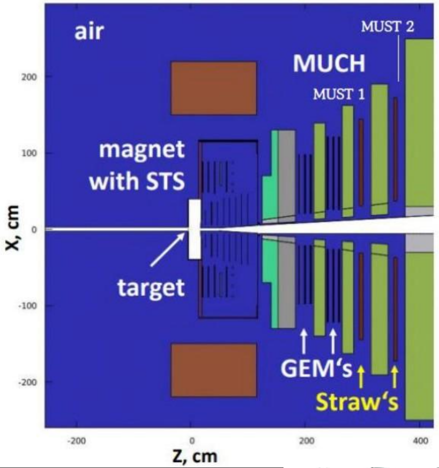
Examples - Detectors in beam lines @GSI

Examples - Detectors in beam lines @FAIR

CBM

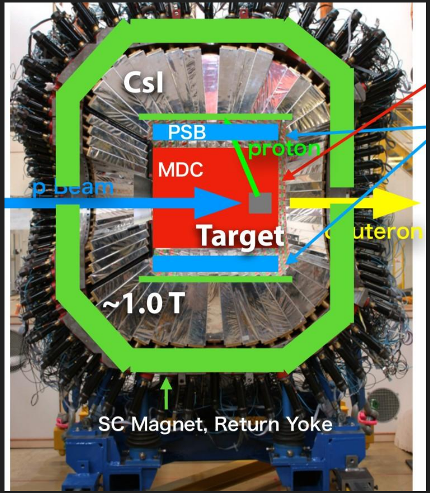


mCBM detectors & LHCb straws
(Beam times with ions energy scans & various targets)
- Derive surrogate models

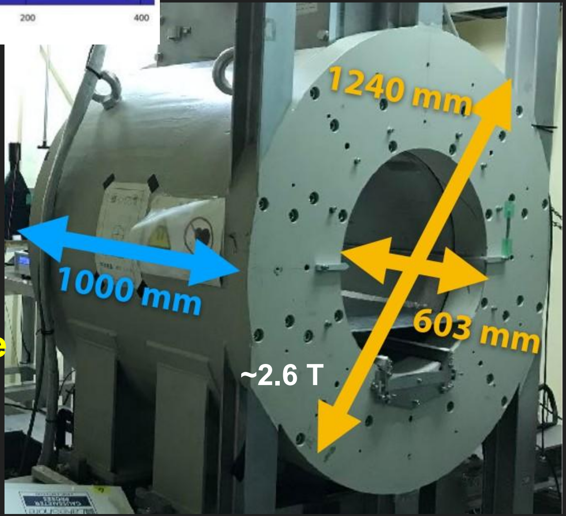


CBM detectors incl. LHCb straws
(Detectors-Absorbers)
Various beam+target:
p+p, p+Au, Au+Au
- Optimize ensemble surrogates

NUSTAR



Same detectors in different magnets
- Derive surrogate models
- Optimize ensemble surrogates



The Plan

- This short term project exploits AI/ML techniques & methods, some already being developed in Particle and Nuclear Physics with great potential
-
- Participants:
- Anastasios Belias (GSI)
- Jan Kieseler (KIT)
- Associated partners:
- Maxim Mai (U. Bern)
-
- Requested budget (over 3 years): 550 kEuro
  - Two PhD positions + 0.5 FTE Staff: 508
  - Networking and conference travels: 30000
  - Moderate AI/ML hardware access support: 12000

Machine-Learning Optimized Design of Experiments

MODE Collaboration

https://mode-collaboration.github.io

At INFN and Università of Padova Dr. Tommaso Dorigo, Dr. Pablo De Castro Manzano, Dr. Federica Fanzago, Dr. Giles Strong, and Dr. Mia Tosi
At Université catholique de Louvain Dr. Andrea Giammanco, Ms. Zahraa Daher, and Mr. Maxime Lagrange
At Universidad de Oviedo and ICTEA Dr. Pietro Vischia
At Université Clermont Auvergne, Prof. Julien Donini, and Mr. Federico Nardi (joint with Universitá di Padova)
At the Higher School of Economics of Moscow, Prof. Andrey Ustyuzhanin, Dr. Alexey Boldyrev, Dr. Denis Derkach, and Dr. Fedor Ratnikov
At the Instituto de Fisica de Cantabria, Dr. Pablo Martinez Ruiz del Árbol
At Karlsruher Institut für Technologie, Dr. Jan Kieseler
At University of Oxford Dr. Atilim Gunes Baydin
At New York University Prof. Kyle Cranmer
At Université de Liège Prof. Gilles Louppe
At GSI/FAIR Dr. Anastasios Belias
At HEPHY Vienna (OeAW) Dr. Claudius Krause
At Uppsala Universitet Prof. Christian Glaser
At TU-München, Prof. Lukas Heinrich
At Sheffield University Dr. Patrick Stowell
At Lebanese University Prof. Haitham Zaraket
At University of Kaiserslautern-Landau Prof. Nicolas Gauger, Mr. Max Aehle, Dr. Long Chen, Prof. Ralf Keidel
At Eindhoven University of Technology, Prof. Lisa Kusch
At Princeton University Prof. Peter Elmer
At University of Washington Prof. Gordon Watts
At SLAC Dr. Ryan Roussel
At Lulea University of Technology Prof. Fredrik Sandin and Prof. Marcus Liwicki
At IGFAE and Universidad de Santiago de Compostela Prof. Xabier Cid Vidal and Ms. Maria Pereira Martinez
At ISER Ms. Sarjeeta Gami
At Carnegie Mellon University Prof. Ann Lee and Mr. Luca Masserano
At IISER Kolkata Dr. Tousik Samoui
At Sofia University, Kalina Dimitrova, Prof. Venelin Kozhuharov, Prof. Peicho Petkov
At ECAP - FAU Erlangen-Nürnberg, Dr. Christian Haack
At NASA, Dr. Stephen M. Casey

- Anastasios Belias (GSI)

- Jan Kieseler (KIT)

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Outlook

The system proposed is envisioned as a virtual access service, enabling experimental users to remotely:

- Pre-configure and simulate detector ensembles before beam time
- Explore performance trade-offs across a range of beam-target conditions
- Receive guidance on optimal placements and combinations of detector systems

Such capabilities are expected to significantly:

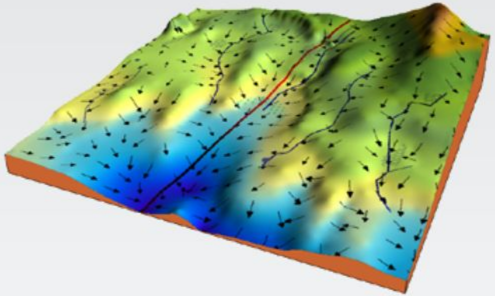
- Reduce in-beam setup times
- Increase the efficiency of data-taking periods
- Improve the quality and reproducibility of results for hadron physics experiments.

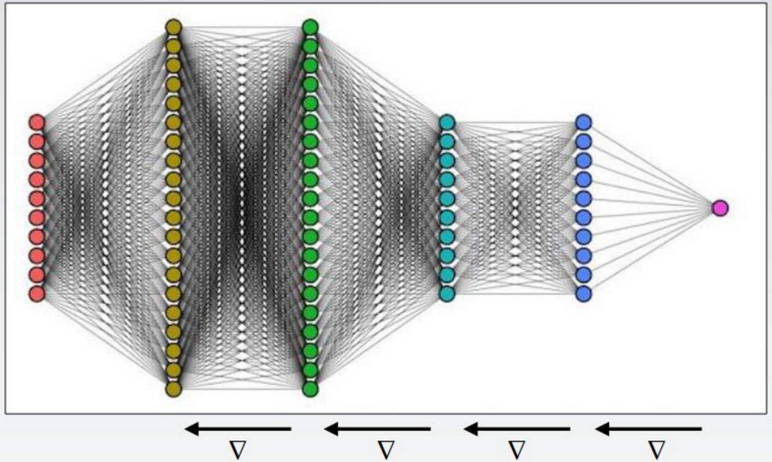
In addition, it is intended to serve as:

- training tools for new users and young investigators
- tools for feasibility studies of new ideas at GSI and FAIR of future beam lines & storage rings

Potential: Surrogates optimizations → DIGITAL TWINS as a SERVICE

$$\theta^{(s+1)} = \theta^{(s)} - \eta \nabla_{\theta^{(s)}} L\left(\mathrm{C}(\theta^{(s)}, x(P)), P\right)$$





Answer to:

I want to improve the Muon / Hadron ID for the p+p, p+Au, Au+Au beam times - which tracking/absorber configurations are optimal for each of the beam-target configuration?

Answer to:

I want to improve the physics precision with the new solenoid in the beam line - what are the optimal positions of the tracking station 1 wrt to station 2 and the TOF wall?

AIMLOVE

AI ML Optimized Virtual Experiments

Thank you for your attention!!

Anastasios (Tassos) Belias

a.belias@gsi.de