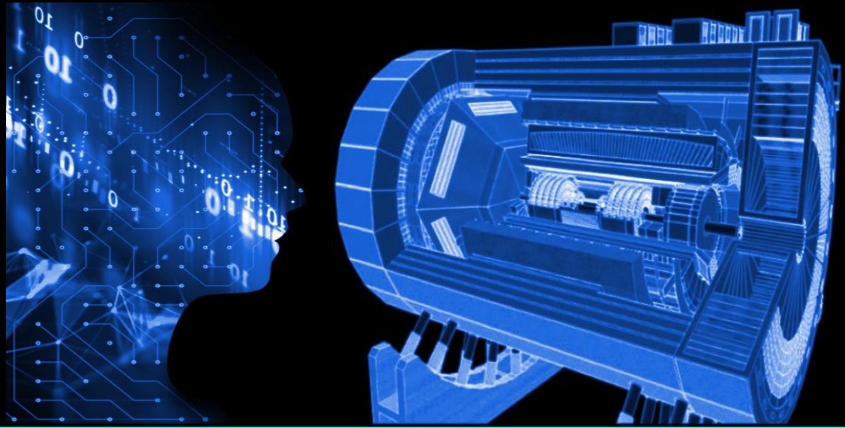


Adaptive Experimentation to assist the detector design of the future EIC

Cristiano Fanelli

WILLIAM & MARY
CHARTERED 1693

Jefferson Lab
Exploring the Nature of Matter

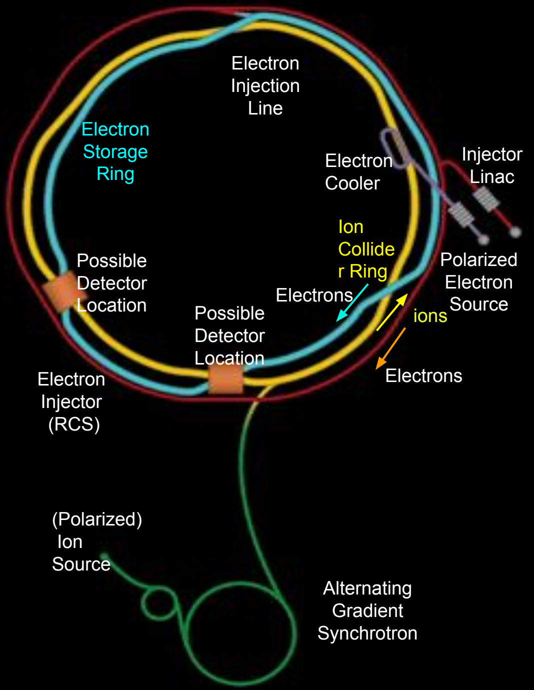
AI4EIC

EIC²
EIC Center at Jefferson Lab

Second MODE Workshop on Differentiable Programming for Experiment Design – Sep 12-16, 2022

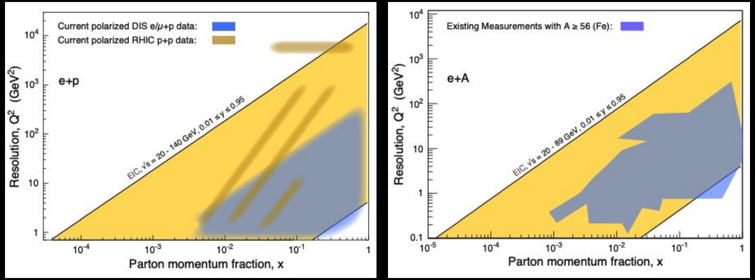
Electron Ion Collider (EIC)

A precision tool to study the glue that binds visible matter



polarized electron - polarized protons/ions

uncovered x-Q^2 range



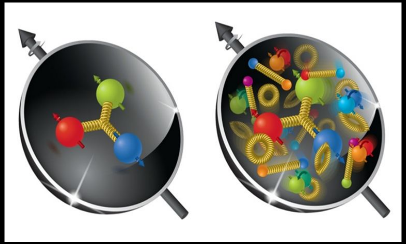
constructed over ten years
estimated cost
between \$1.6 and \$2.6 billion

https://www.bnl.gov/newsroom/news.php?a=219454

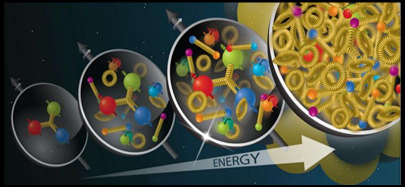
address 3 profound questions:

How does the mass of the nucleon arise?

How does the spin of the nucleon arise?



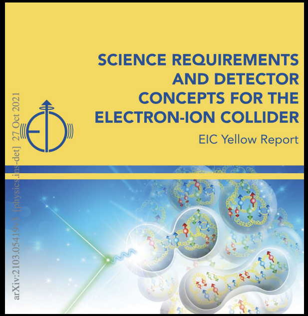
What are the emergent properties of dense systems of gluons?



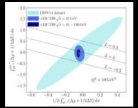
EIC Science

EIC Yellow Report (2021)

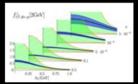
arXiv:2103.05419, Nuclear Physics A 1026, 122447



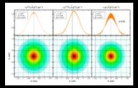
- Origin of Nucleon Spin



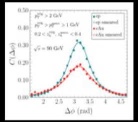
- Confined motion of partons



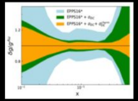
- 3D imaging quarks and gluons



- Nucleon mass

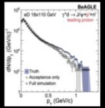


- High gluon densities in nuclei

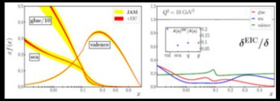


- Quarks and gluons in the nucleus

- Light-ion tagging



- Pion/Kaon structure

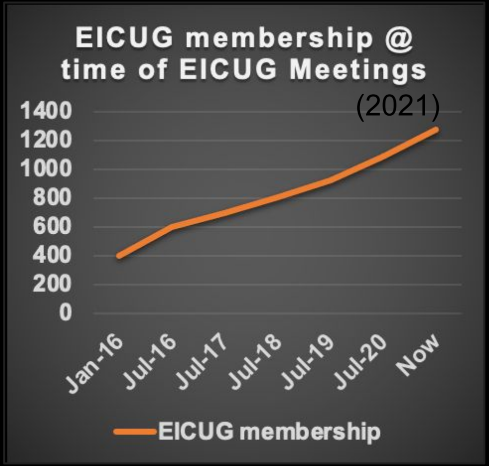


- Diffractive jets?
- Nuclear modifications and in-medium evolution
  - D/D* reconstruction and heavy-flavor in jets

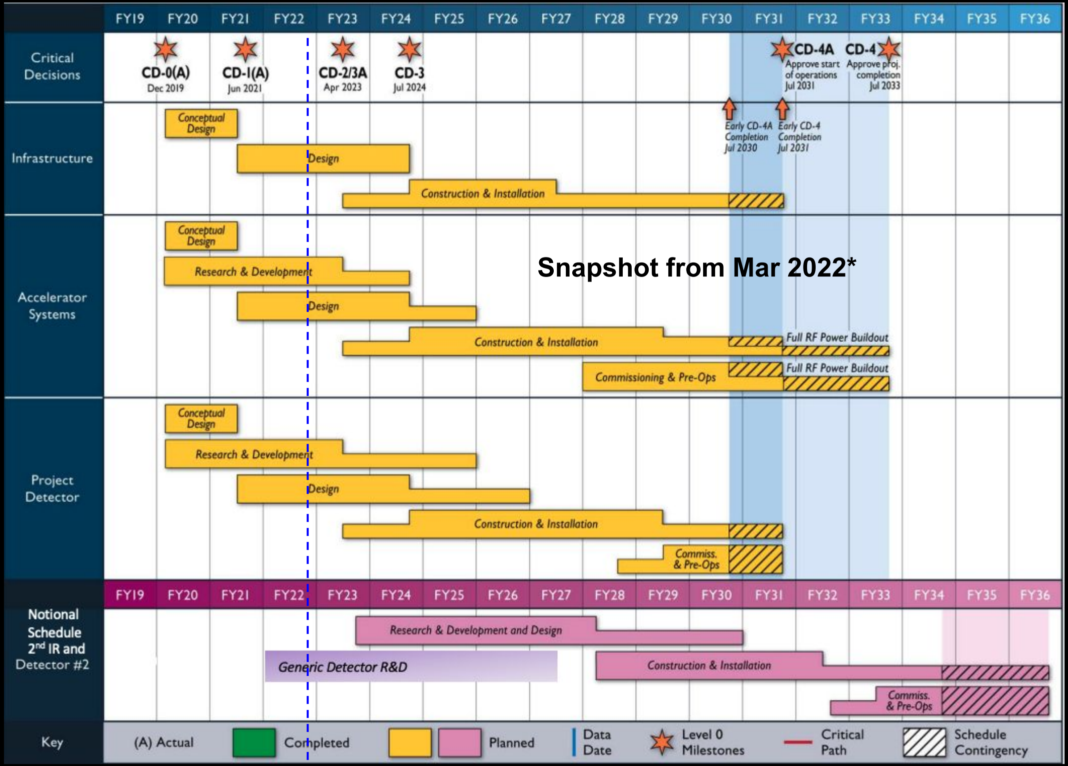
Khalek, R. Abdul, et al. "Science requirements and detector concepts for the electron-ion collider: EIC yellow report." arXiv:2103.05419, 2021

Slide taken from J. Lajoie, The ECCE Experiment, Workshop VIII Streaming Readout, 2021

World-wide interest

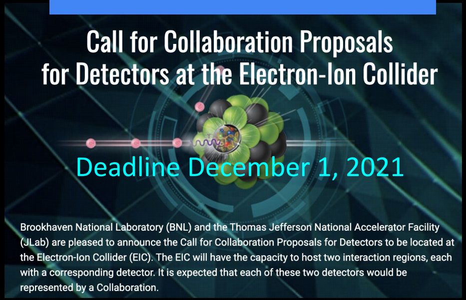


EIC Schedule & Milestones



*EIC Schedule, J. Yeck, Mar 2022

proto-collaborations



⇩

EIC Detector Proposal Advisory Panel Meeting

Process completed on March 21, 2022

Panel Report

6. Recommendations: ECCE Reference Detector

The panel unanimously recommends ECCE as Detector 1. The proto-collaboration is urged to openly accept additional collaborators and quickly consolidate its design so that the Project Detector can advance to CD2/3a in a timely way.

⇩

EIC DETECTOR 1 GENERAL MEETING

Following the DPAP process , the EIC Community is moving towards the formation of a scientific collaboration to support the realization of the EIC project detector - temporarily referred to as "Detector-1".

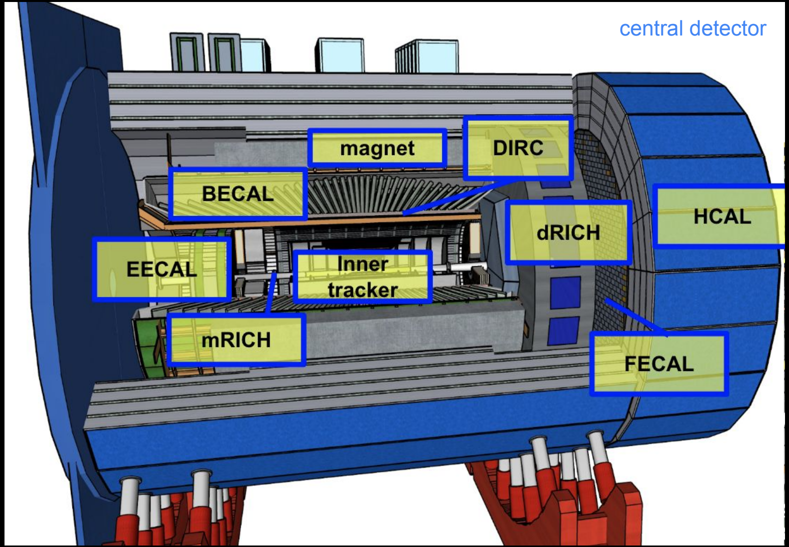
⇩

EPIC Collaboration (July 2022)

The Reference Detector

EIC: large-scale experiment with an integrated detector that extends for ~ ± 35 m to include the central, far-forward, and far-backward regions.

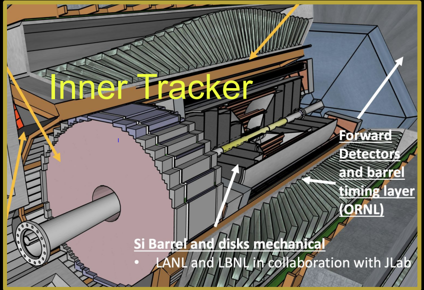
To enable the EIC physics we need a central detector that is:
hermetic and asymmetric



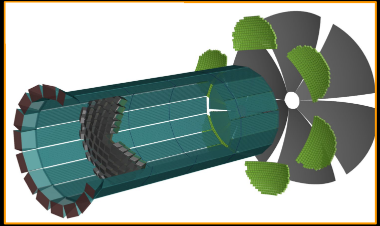
*Tracker

Combines:

- ITS-3 Si technology
- Gaseous detectors
- AC-LGAD ToFs



*Particle Identification (PID) Cherenkov detectors



- dual radiator ring-imaging Cherenkov detector (RICH) in the hadron direction
- DIRC (detection of internally reflected Cherenkov light) in the barrel
- modular RICH in the electron direction.

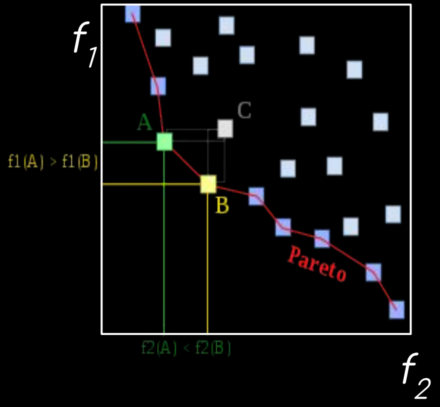
Simulating these detectors is typically compute expensive, involving many photons that need to be tracked through complex surfaces.

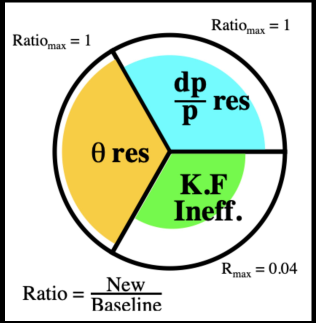
All three rely on pattern recognition of ring images in reconstruction, and the DIRC is the one having the more complex ring patterns!

*Highlighting parts that will be discussed in this talk suitable for optimization

“Complexity” of large-scale detector design

- Need to use advanced simulations which are computationally expensive (Geant).
- For years the full detector design studied after the subsystem prototypes are ready (taking into account the phase constraints from the full detector or outer layers).
    - It is of course desirable to optimize instead all the sub-detectors simultaneously taking into account the constraints in a dynamic way
- Modern complex design are characterized by many parameters (and multiple objective functions) → curse of dimensionality.
    - Objectives can be competing to each other and they can give rise to trade-off solutions, known as Pareto-front.
    - E.g., in the EIC Tracker Design we considered so far: momentum, angular, pointing resolution, Kalman filter efficiency, in addition to mechanical constraints
- AI-assisted strategies can help designing more efficiently and reduce computing resources…

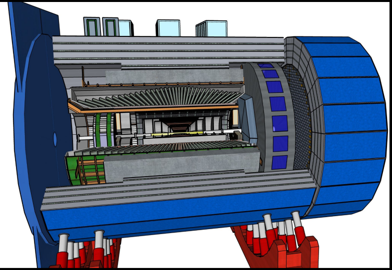




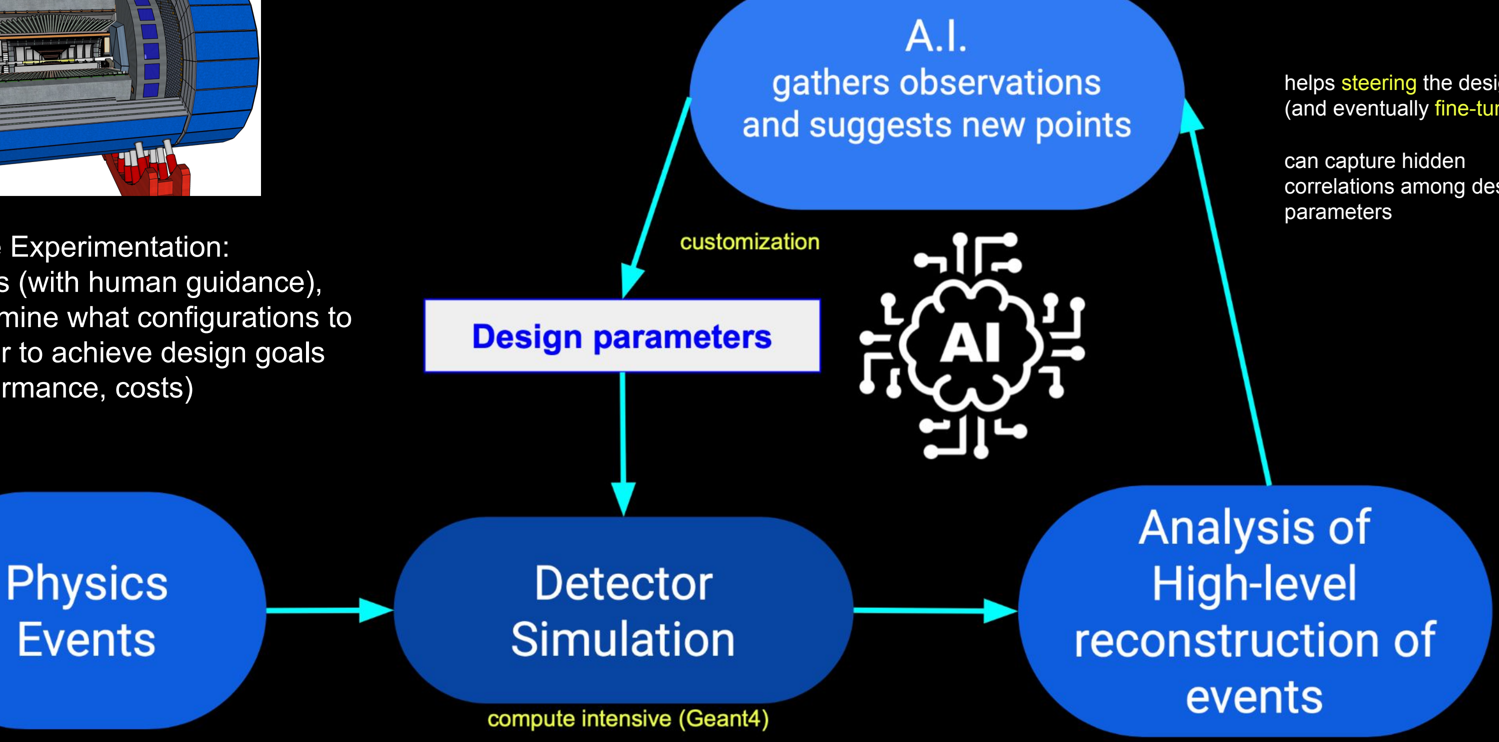
Detector Design Workflow

See talk at IAEA Technical Meeting on AI

IAEA
International Atomic Energy Agency



Adaptive Experimentation:
AI-assisted tools (with human guidance), sequentially determine what configurations to test next in order to achieve design goals (performance, costs)



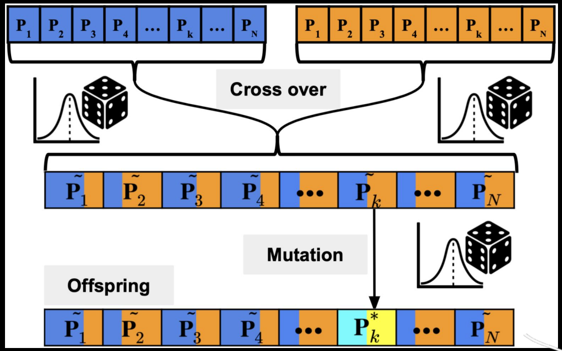
helps steering the design (and eventually fine-tune it)

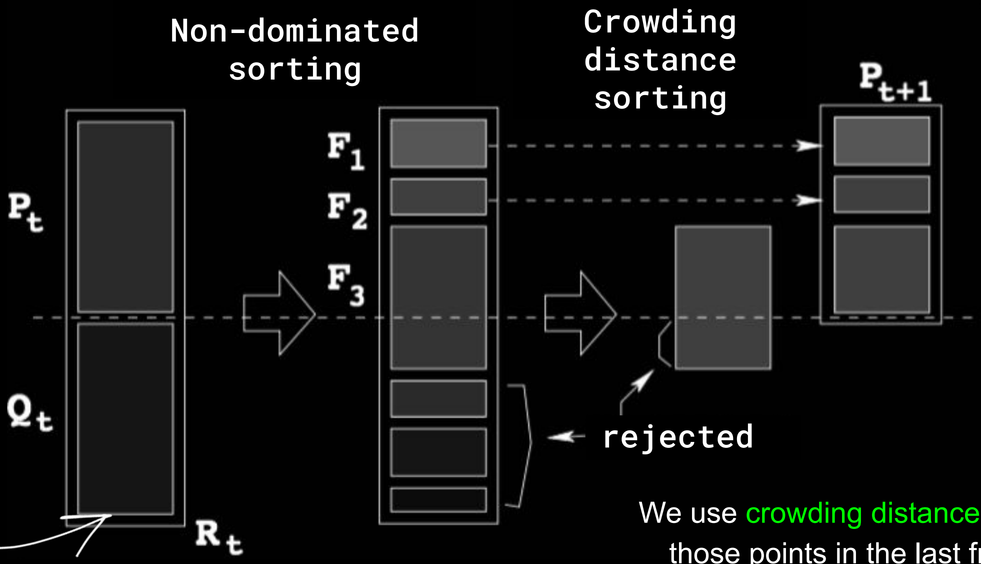
can capture hidden correlations among design parameters

Forward simulations needed to simulate quantum phenomena (interaction of particles with matter)

NSGA-II (ECCE proposal, 2021)

Use Elitist principle
Explicit diversity preserving mechanism
Emphasis in non-dominated solutions





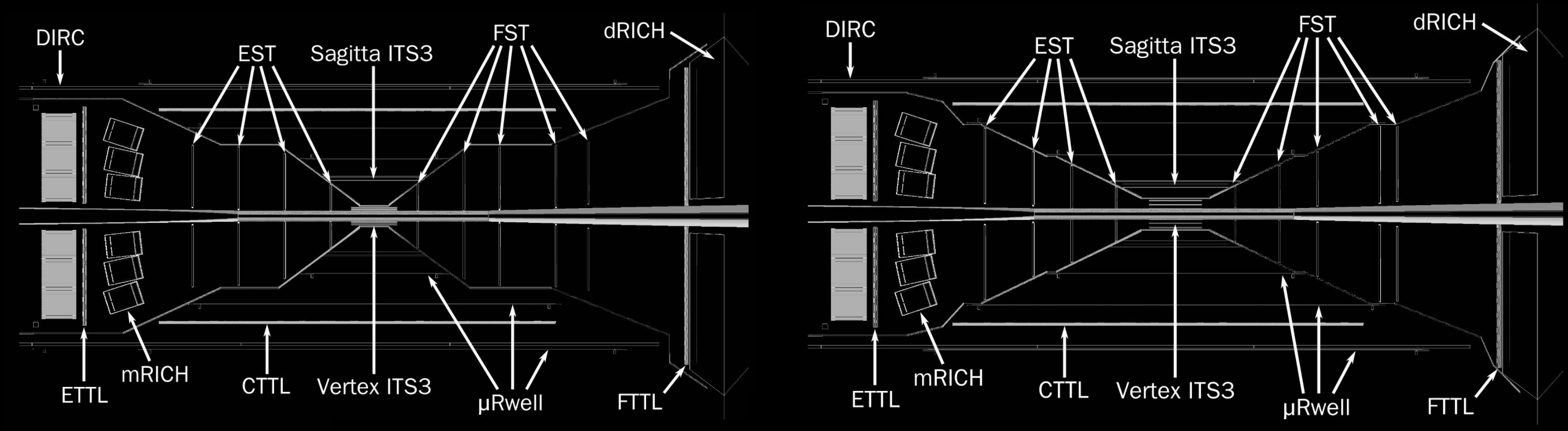
We use crowding distance to keep those points in the last front that contribute to the highest diversity.

The rationale behind this choice instead of, e.g., principled approaches such as Bayesian Optimization, emanated from the ECCE needs at the time of the detector proposal, such as the capability to quickly implement and run multiple parallel optimization pipelines implementing different technology choices and the possibility of dealing with non-differentiable objectives at the exploratory stage.

ECCE Tracker: Reference VS Projective

arXiv:2205.09185

Parametrization underlies the AI-assisted design and can explore non-projective as well as projective



non-projective

projective
(ongoing R&D)

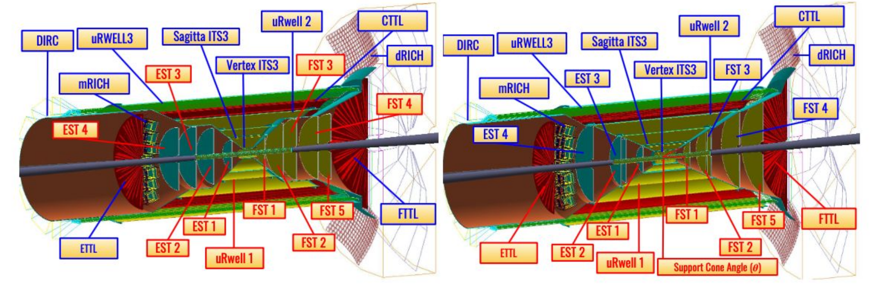


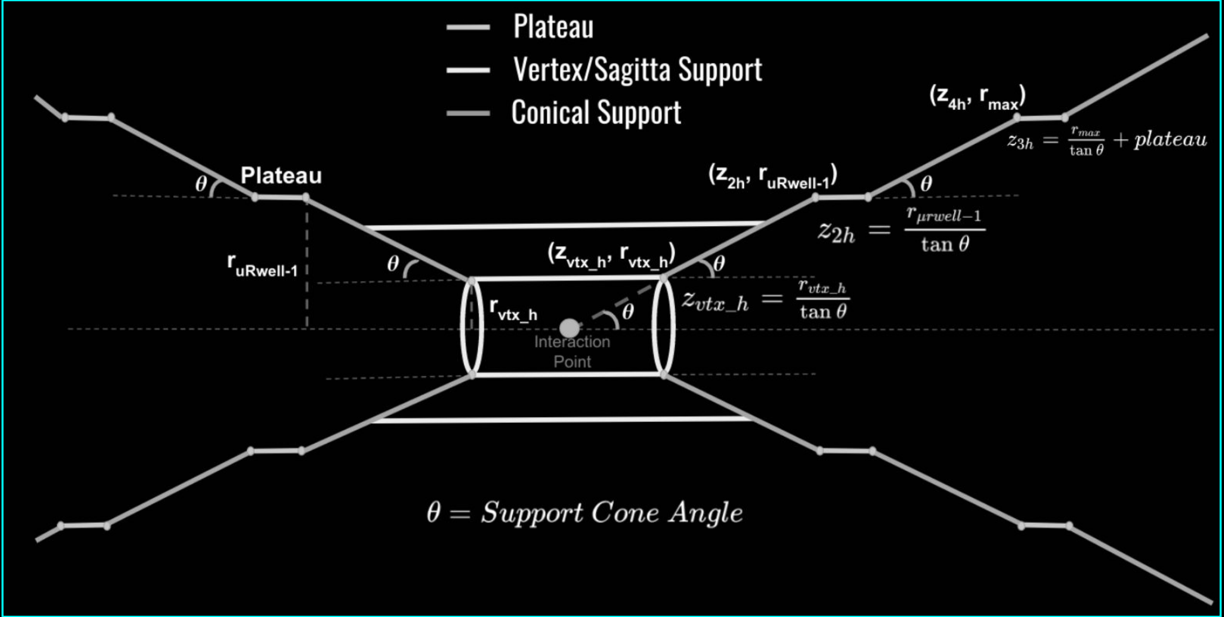
Figure 5: **Tracking and PID system in the non-projective (left) and the ongoing R&D projective (right) designs:** the two figures show the different geometry and parametrization of the ECCE non-projective design (left) and of the ongoing R&D projective design to optimize the support structure (right). Labels in red indicate the sub-detector systems that were optimized, while the labels in blue are the sub-detector systems that were kept fixed due to geometrical constraint. The non-projective geometry (left) is a result of an optimization on the inner tracker layers (labeled in red) while keeping the support structure fixed, The angle made by the support structure to the IP is fixed at about 36.5°. The projective geometry (right) is the result of an ongoing project R&D to reduce the impact of readout and services on tracking resolution.

CF, et al. (ECCE), AI-assisted Optimization of the ECCE Tracking System at the Electron Ion Collider arXiv:2205.09185, 2022

ECCE Tracker: Parametrization

arXiv:2205.09185

Parametrization of the support structure



Parametrization of Disks, tracking layers, TTL

Geometric Constraints

Disks: r_{max} and r_{min} are calculated based on the support structure.

Sagitta: length fixed and radius changed based on the cone angle.

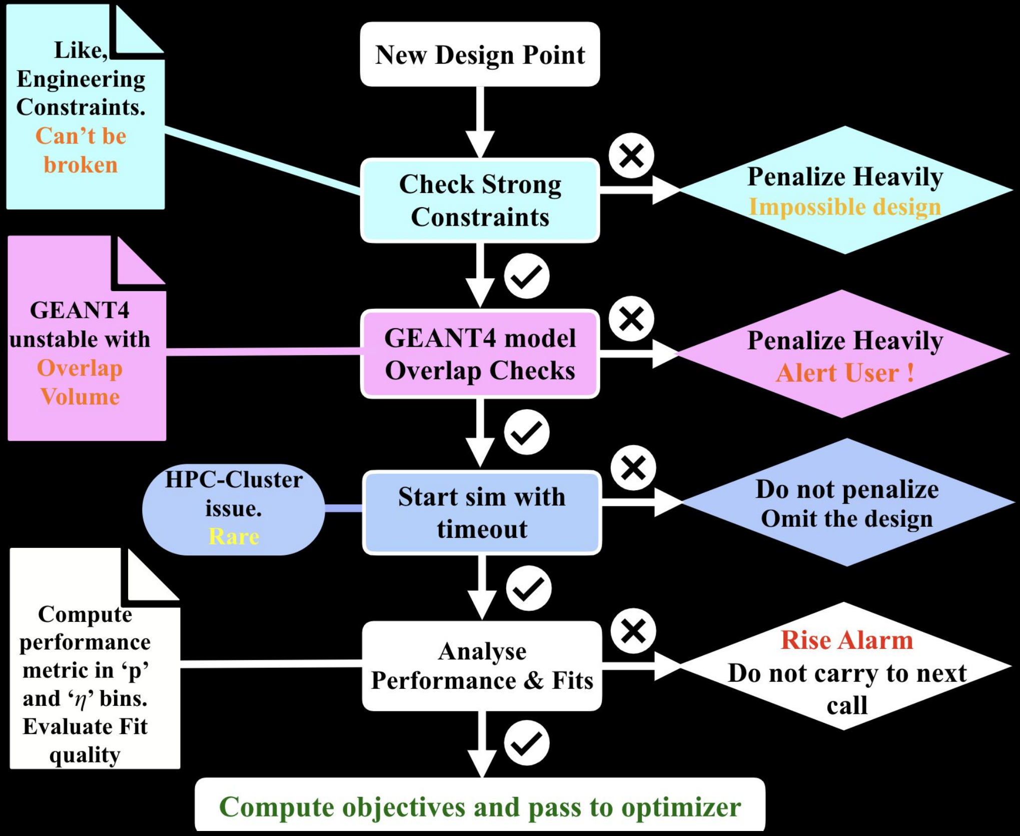
Parametrization underlies the AI-assisted design and can explore non-projective as well as projective

CF, et al. (ECCE), AI-assisted Optimization of the ECCE Tracking System at the Electron Ion Collider arXiv:2205.09185, 2022

"Soft"/"Strong" Constraints and Checks

$$
\begin{aligned}
&\quad min\ \mathbf{f_m}(\mathbf{x}) && m = 1, \cdots, M \\
s.t.\ &\quad \mathbf{g_j}(\mathbf{x}) \le 0, && j = 1, \cdots, J \\
&\quad \mathbf{h_k}(\mathbf{x}) = 0, && k = 1, \cdots, K \\
&\quad x_i^L \le x_i \le x_i^U, && i = 1, \cdots, N
\end{aligned}
$$

sub-detector	constraint	description
EST/FST disks	$min\left\{\sum_i^{disks}\left\lvert\frac{R^i_{out}-R^i_{in}}{d} - \left\lceil\frac{R^i_{out}-R^i_{in}}{d}\right\rceil\right\rvert\right\}$	**soft constraint**: sum of residuals in sensor coverage for disks; sensor dimensions: $d = 17.8$ (30.0) mm
EST/FST disks	$z_{n+1} - z_n >= 10.0$ cm	**strong constraint**: minimum distance between 2 consecutive disks
sagitta layers	$min\left\{\left\lvert\frac{2\pi r_{sagitta}}{w} - \left\lceil\frac{2\pi r_{sagitta}}{w}\right\rceil\right\rvert\right\}$	**soft constraint**: residual in sensor coverage for every layer; sensor strip width: $w = 17.8$ mm
μRWELL	$r_{n+1} - r_n >= 5.0$ cm	**strong constraint**: minimum distance between μRwell barrel layers

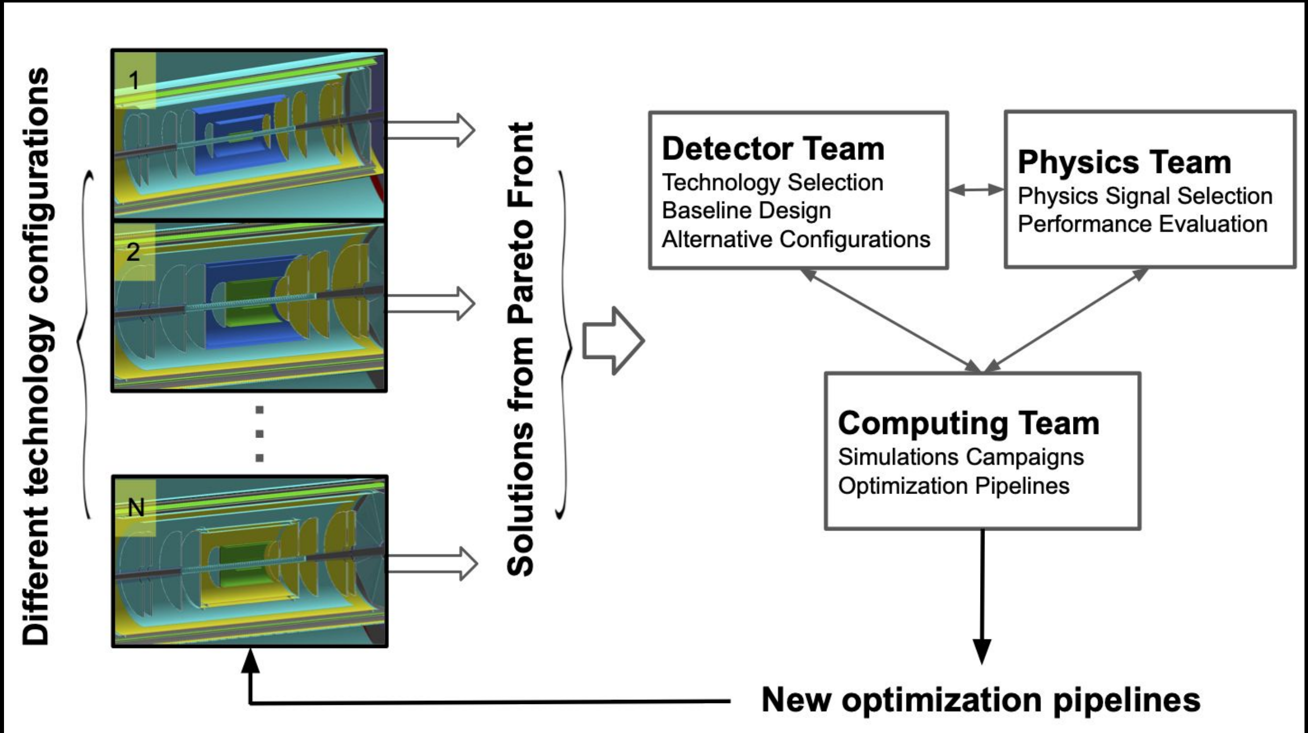


Integration during the EIC Detector Proposal

AI-"Optimization" does not necessarily mean "fine-tuning"

- We want to use these algorithms to: (1) steer the design and suggest parameters that a "manual"/brute-force optimization will likely miss to identify; (2) further optimize some particular detector technology (see d-RICH paper, e.g., optics properties)
- AI allows to capture hidden correlations among the design parameters.
- All "steps" (physics, detector) involved in the AI optimization, strong interplay between working groups

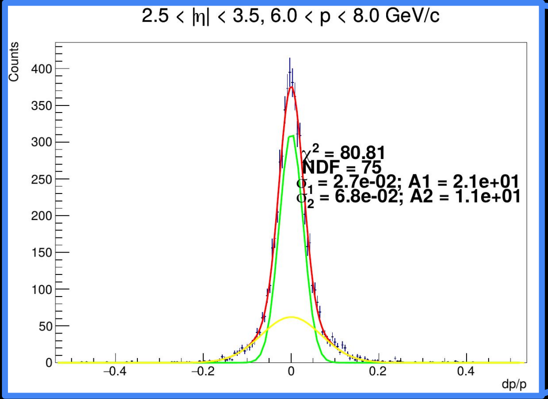
Light/smart optimization pipelines ran during the "explorative" phase of the detector proposal



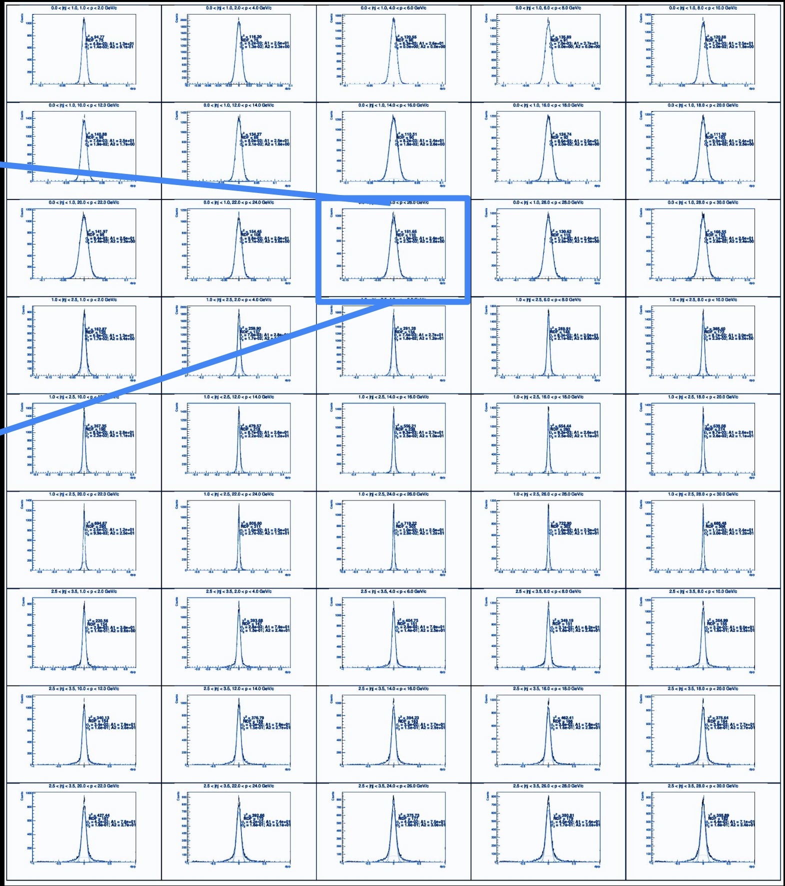
Implementation

- Objectives evaluated in fine-grained phase-space
- Propagate uncertainties from fits

Weighted sum with errors



Weighted sum with errors



$$\bar{x_\eta} = \frac{\sum_p x_p w_p}{\sum_p w_p}$$

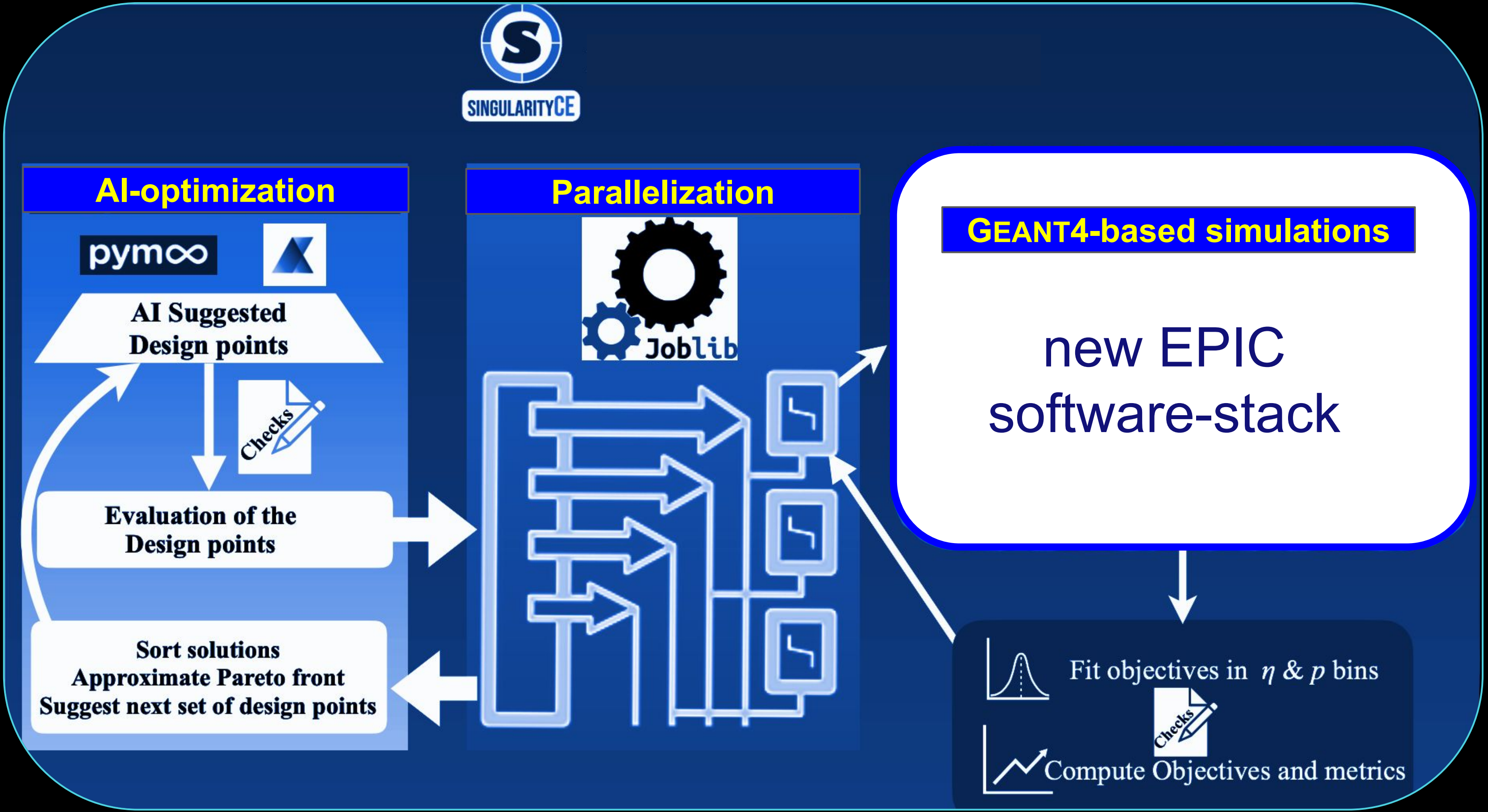
(sum in bins of 14 bins of P)

$$\bar{x} = \frac{\sum_\eta^{N_\eta} \bar{x_\eta}}{N_\eta}$$

(Average objective in a η bin)

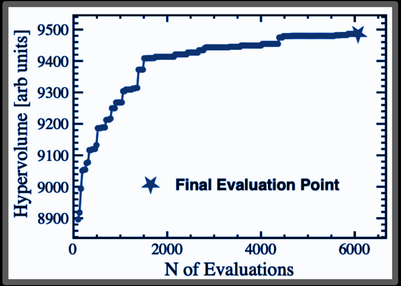
$$\Rightarrow \quad R(f) = \frac{1}{N_\eta} \sum_\eta \left(\frac{\sum_p w_{p,\eta} \cdot R(f)_{p,\eta}}{\sum_p w_{p,\eta}} \right)$$

Workflow during proposal and beyond

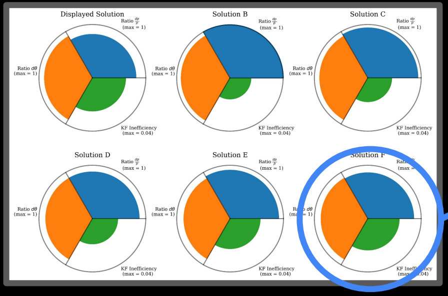


“Navigate” Pareto Front

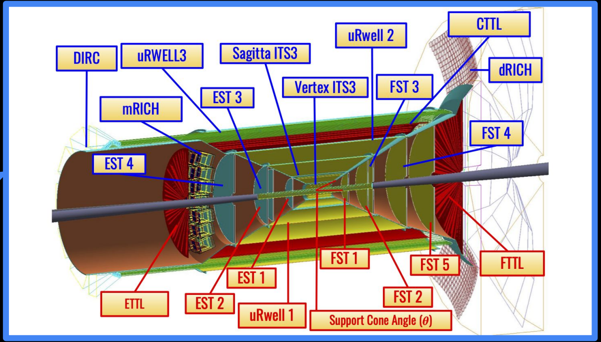
1 Can take a snapshot any time during evaluation



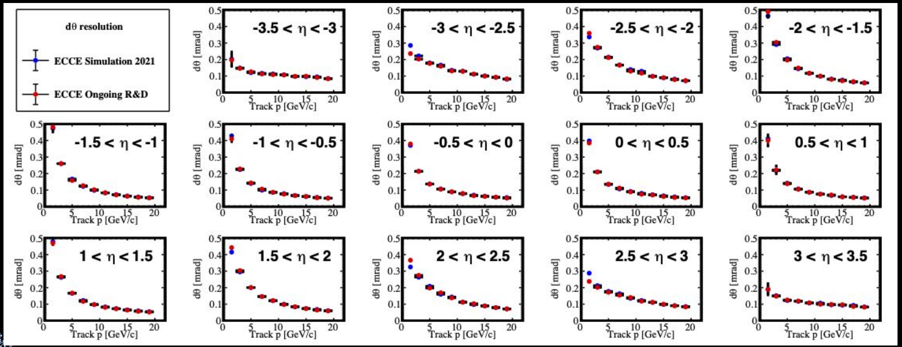
2 Updated Pareto Front at time t

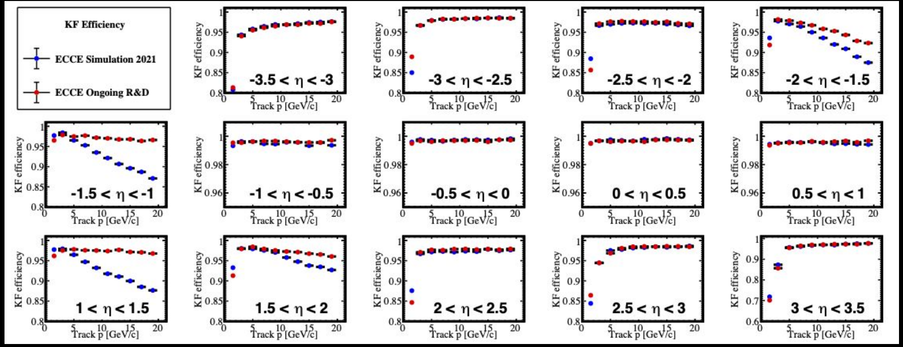


3 At each point in the Pareto front corresponds a design



4 Analysis of Objectives (momentum resolution, angular resolution, KF efficiency)

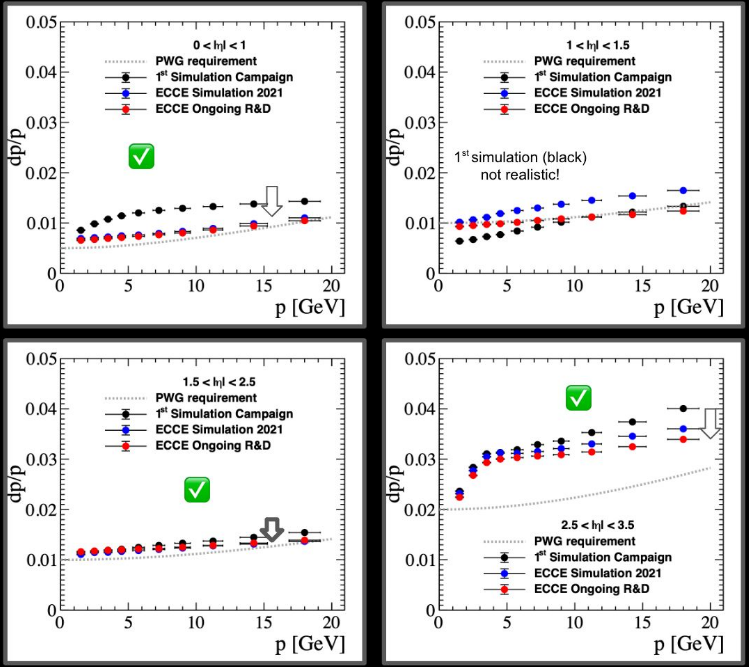




Evolution and Validation

Evolution

- Black points: first simulation campaign, a preliminary detector concept in phase-I optimization with no developed support structure;
- Blue: fully developed simulations for final ECCE detector proposal; Red: the ongoing R&D for the optimization of the support structure.
- There is an improvement in performance in all η bins with the exception of the transition region, an artifact of the fact that black do not include a realistic simulation of the material budget in the transition region!
- In the transition region, it can be also appreciated the improvement provided by the projective design



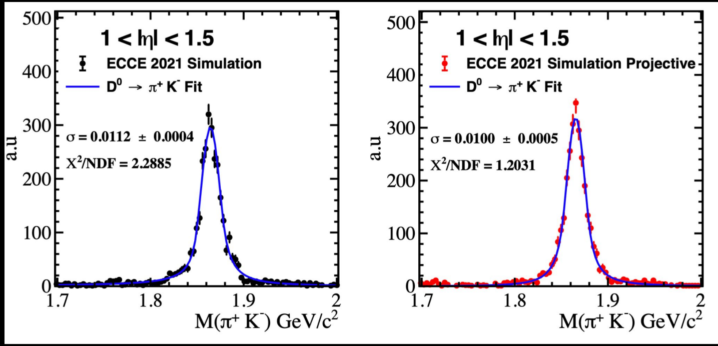
Validation

Observables not directly used in the optimization as objectives

Performance evaluated after optimization process (both designs) using standard analysis procedures

Notice red points are related to an ongoing project R&D with a projective support structure for the ECCE tracker.

E.g., D0 invariant mass from semi-inclusive deep inelastic scattering

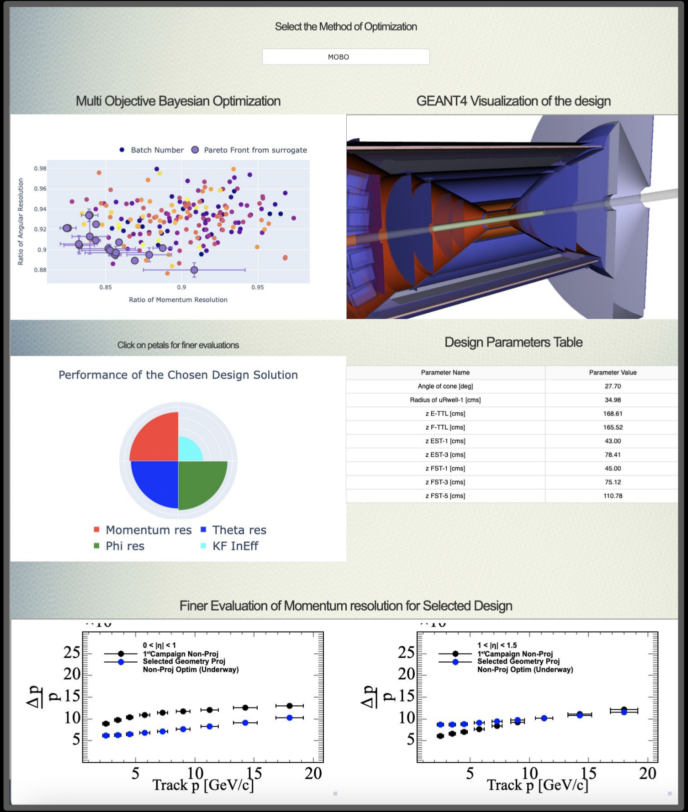


Multi-Objective Bayesian Optimization

- After the proposal stage, we started using a combination of Ax and BoTorch for the EPIC detector:
  - Ax is an accessible, general-purpose platform for understanding, managing, deploying, and automating adaptive experiments
  - BoTorch, built on PyTorch, is a flexible, modern library that advances the SOTA in Bayesian optimization. It leverages features of PyTorch, including auto-differentiation, massive parallelism, and DL.
- These methods enable to solve efficiently larger exploration problems without the need for large quantities of data:
  - Leverage probabilistic approach to model the relationship between limited and potentially noisy observed data and apply principled exploration strategies that are able to meaningfully quantify the costs and benefits of exploring new regions of the problem space
- They have been deployed at scale at Facebook: when used in tandem, Ax and BoTorch significantly accelerate the process of going from research to production

https://ai.facebook.com/blog/open-sourcing-ax-and-botorch-new-ai-tools-for-adaptive-experimentation/

Interactive Navigation of Pareto front



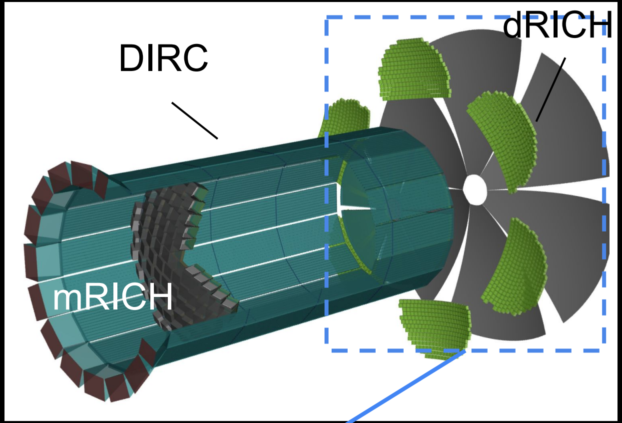
https://ai4eicdetopt.pythonanywhere.com

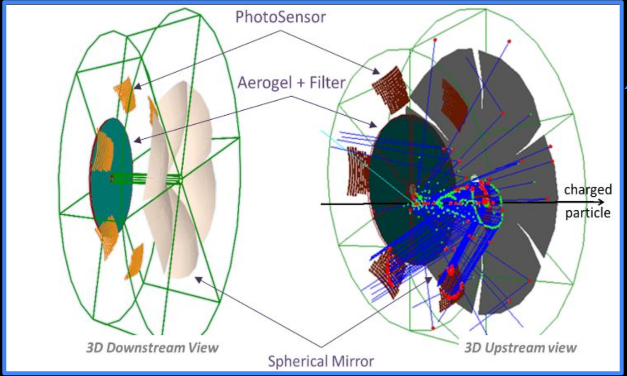
- Use cutting-edge data science tools for visualization of results from approximated Pareto front
- Exploration in a multiple objective space
- Facilitate study/comparison of trade-off solutions
- Here MOBO is implemented using BoTorch/Ax (benefit from strong community support — Meta AI)

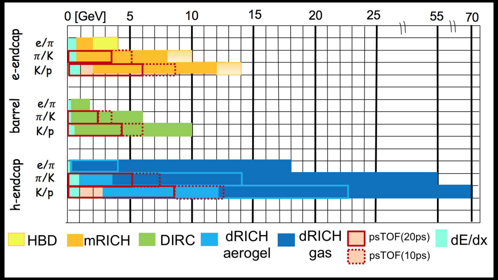
Credits: K. Suresh (U. of Regina)

Extension to larger system of sub-detectors

- Cherenkov detectors are essential part of the PID system of EPIC
  - Simulating these detectors is typically compute expensive, involving many photons that need to be tracked through complex surfaces.
  - All of them rely on pattern recognition of ring images in reconstruction, and the DIRC is the one having the more complex ring patterns!
- Extension of design optimization to tracker + PID system
  - Potential to optimize parameters of the dRICH design in the hadronic endcap
- E.g., dRICH design
  - Large momentum coverage
  - Two radiators: aerogel and gas
  - Legacy design from INFN
    - 6 Identical open sectors
    - Large focusing mirror



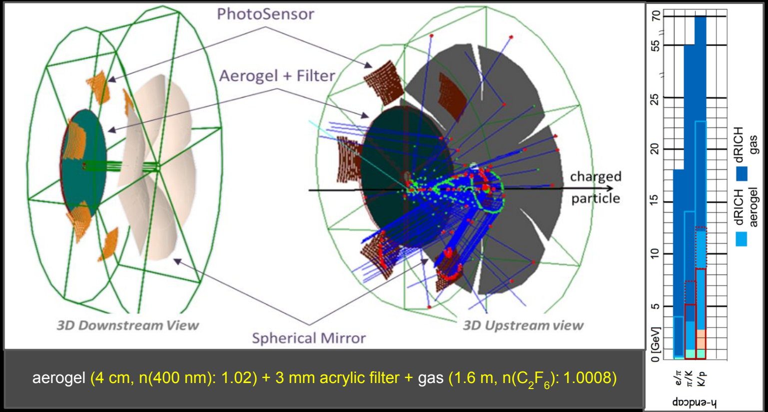




E. Cisbani, A. Del Dotto, CF*, M. Williams et al. "AI-optimized detector design for the future Electron-Ion Collider: the dual-radiator RICH case." *JINST* 15.05 (2020)

Leveraging on work done before the proposal…

- Two radiators with different refractive indices for continuous momentum coverage.
- Simulation of detector and processes is compute-intensive
- Legacy design from INFN (EICUG2017).



aerogel (4 cm, n(400 nm): 1.02) + 3 mm acrylic filter + gas (1.6 m, n(C_2F_6): 1.0008)

1 Define design parametrization and space: optics + geometry

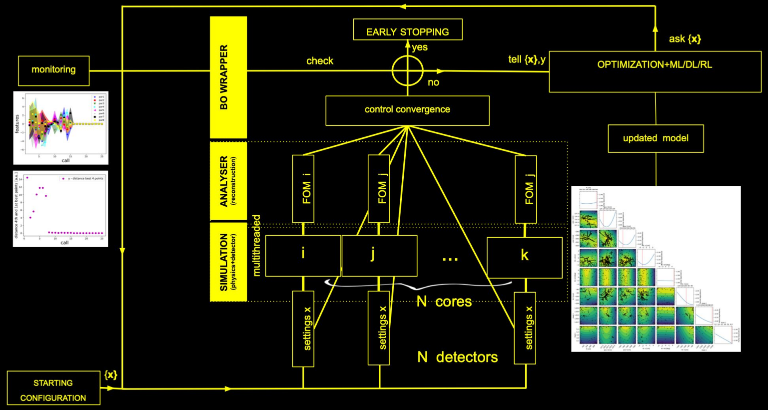
parameter	description	range [units]	tolerance [units]
R	mirror radius	[290,300] [cm]	100 [μm]
pos r	radial position of mirror center	[125,140] [cm]	100 [μm]
pos l	longitudinal position of mirror center	[-305,-295] [cm]	100 [μm]
tiles x	shift along x of tiles center	[-5,5] [cm]	100 [μm]
tiles y	shift along y of tiles center	[-5,5] [cm]	100 [μm]
tiles z	shift along z of tiles center	[-105,-95] [cm]	100 [μm]
$n_{aerogel}$	aerogel refractive index	[1.015,1.030]	0.2%
$t_{aerogel}$	aerogel thickness	[3.0,6.0] [cm]	1 [mm]

2 Come up with a smart objective; study / characterize properties (noise, stats needed etc): simulation + reconstruction

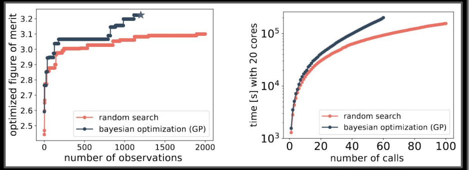
$$N\sigma = \frac{||\langle\theta_K\rangle - \langle\theta_\pi\rangle||\sqrt{N_\gamma}}{\sigma_\theta^{1p.e.}}$$

$$h = 2\cdot\left[\frac{1}{(N\sigma)|_1} + \frac{1}{(N\sigma)|_2}\right]^{-1}$$

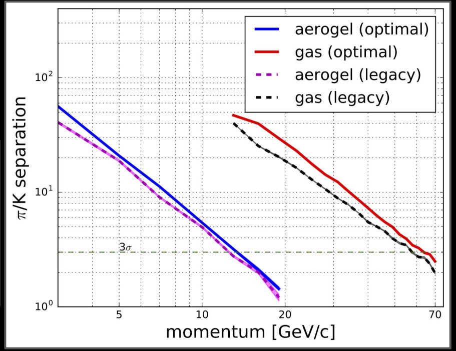
3 Optimization framework (embed convergence criteria)



4 Analysis + Validation



principled vs random



Conclusions

- AI can assist the design and R&D of complex experimental systems by providing more efficient design (considering multiple objectives) utilizing effectively the computing resources needed to achieve that.
- EIC is one of the first experiments to be designed with the support of AI.

  The ECCE reference detector has been already designed taking advantage of a multi-objective optimization approach and a complex parametrization of its design which takes into account constraints.
- This workflow can be further extended for EPIC to optimize the reference detector and to include:
  - More realistic effects in the simulation and reconstruction techniques
  - A larger system of sub-detectors, e.g, detectors like the dRICH

EICUG AI WG (AI4EIC)

Workshop dedicated to AI/ML for the Electron Ion Collider

https://eic.ai

AI4EIC

https://indico.bnl.gov/e/AI4EIC

AI4EIC workshop on October 10-14 2022 at W&M

WILLIAM & MARY
CHARTERED 1693

AI4EIC - October 10-14, 2022

2nd General Workshop on Artificial Intelligence for the Electron Ion Collider
https://indico.bnl.gov/e/AI4EIC
Venue: William and Mary

Registration: https://indico.bnl.gov/e/AI4EIC

Directions to campus: https://mason.wm.edu/about/visiting/directions/index.php
There is a parking lot across Ukrop Way from the business school, and I hope to reserve some parking spots there.

Special hotel rates: https://www.wm.edu/about/visiting/lodging/special-rates/

Contacts:

support@eic.ai

AI4EIC workshop sessions
- Design
- Theory/Experiment connections
- Reconstruction and PID
- Infrastructure and Frontiers
- Streaming
- Tutorials and Hackathon