AI-assisted Optimization of the ECCE Tracking System at the Electron Ion Collider

https://arxiv.org/abs/2205.09185

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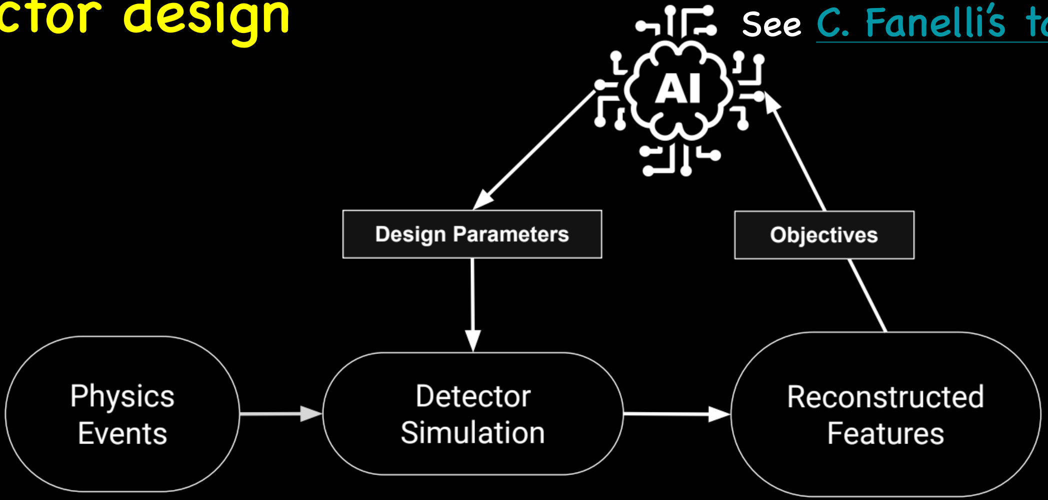
Outline

- This talk leverages on many concepts discussed in the previous talk by C. Fanelli.
- Key concepts
  - Why AI in detector design
  - AI assisted EIC tracker
  - Walk through of developed Modular framework
  - Results
- See arXiv: 2205.09185:
  - Design parameters
  - Objectives
  - Constraints
  - Extension

Optimization of EIC detector design

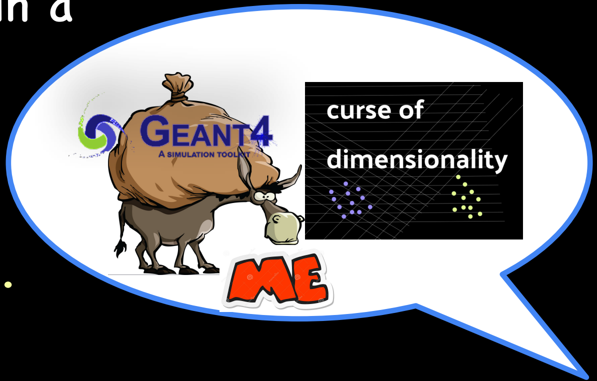
See C. Fanelli's talk



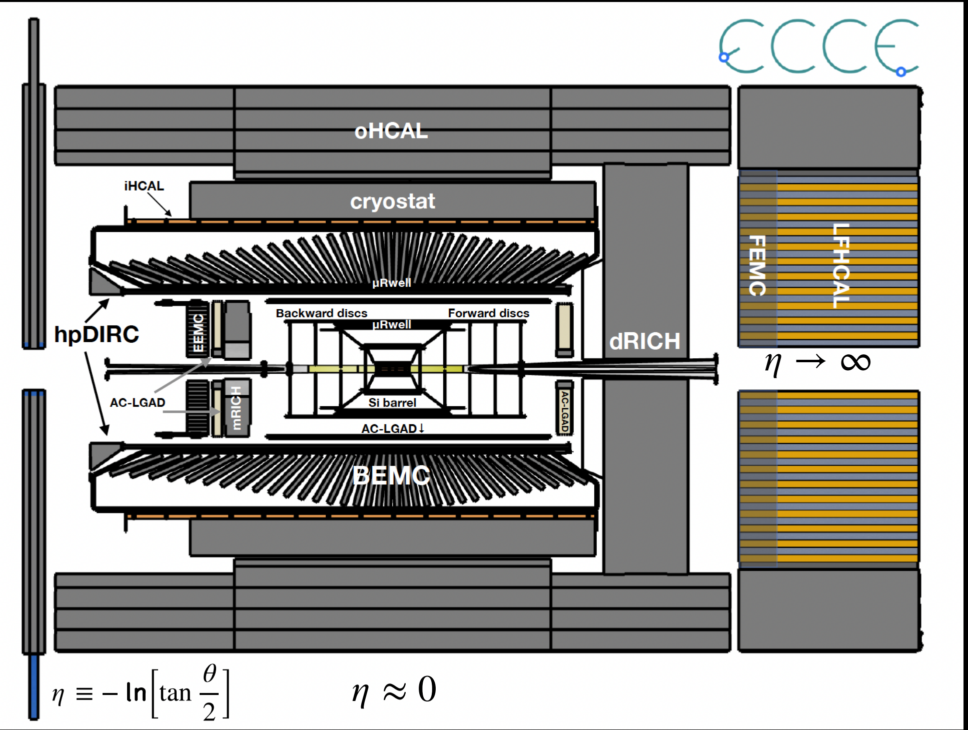
GEANT4 simulations are typically compute-intensive.

In order to explore a multi-dimensional parameter space in a multi-objective space, AI can assist our design in a more efficient way.

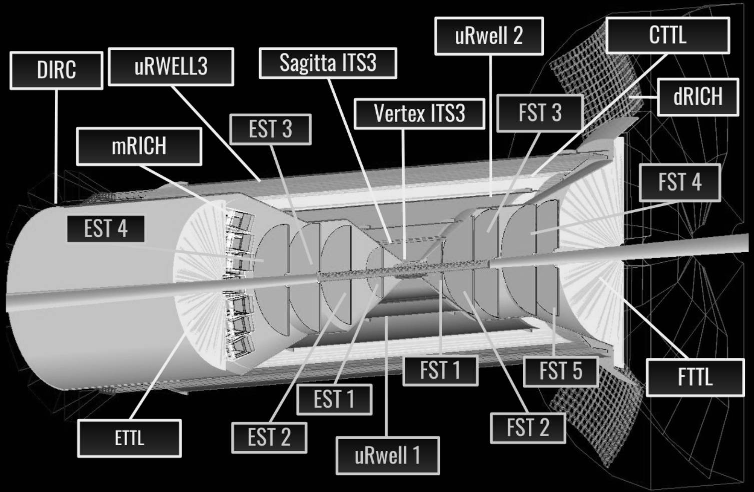
AI assist in designing.
NOT "just" fine tuning.



The Reference Detector: the Tracking System



AI assisted
Tracker System



★ Si technology inner tracker ★ Gas detectors (μRWELL) ★ AC-LGAD ToF
Check out Elke's talk

- ❑ The tracking system reconstructs charged particle tracks. It combines different technologies.
- ❑ Goal : Optimal combination of choice of tech & optimal geometric parameters.
- ❑ Optimization Phases of optimization

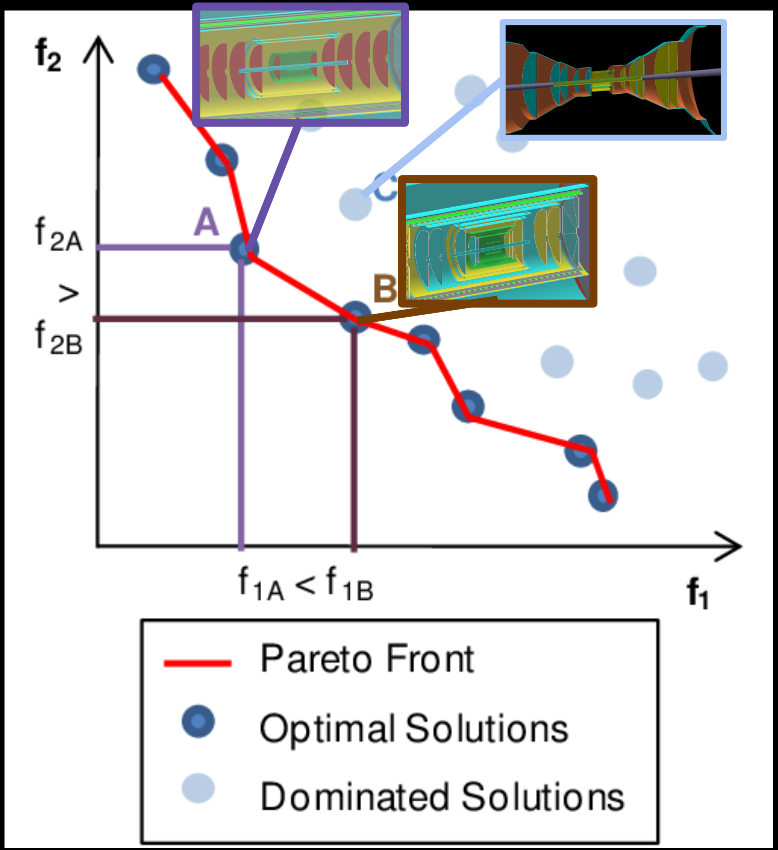
Multi Objective Optimization

- Multiple "objectives", e.g., weighted avg momentum resolution, θ resolution, KF efficiency, projected θ resolution at PID location. Objectives could be conflicting. (This can be extended to other objectives, e.g., physics)

- Pareto-optimal solutions. Locus of points in Objective Space which are non-dominating to one another. Check out Cristiano Fanelli's talk.

- Developed a pipeline for optimization with MOGA/MOBO to optimize and "Fun4All" (GEANT4 based framework) to simulate and analyze the detector response. The approach is agnostic to the simulation framework.

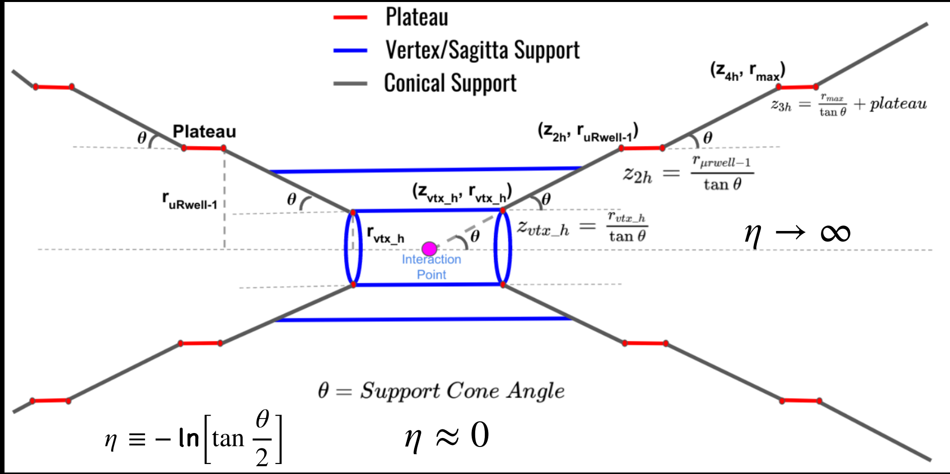
$$
\begin{aligned}
& min\ \mathbf{f_m}(\mathbf{x}) && m = 1, \cdots, M \\
s.t.\ \ & \mathbf{g_j}(\mathbf{x}) \leq 0, && j = 1, \cdots, J \\
& \mathbf{h_k}(\mathbf{x}) = 0, && k = 1, \cdots, K \\
& x_i^L \leq x_i \leq x_i^U, && i = 1, \cdots, N
\end{aligned}
$$

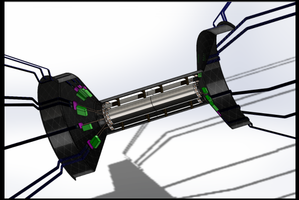


The Tracker Parametrization

Parametrization is an essential part of the optimization:

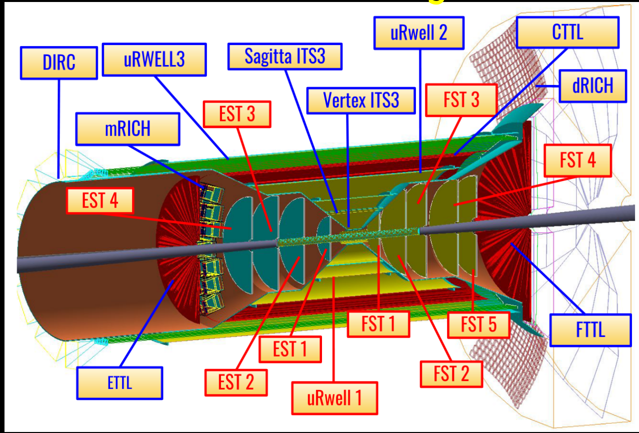
- explores different designs
- avoids overlaps of volumes
- encodes constraints



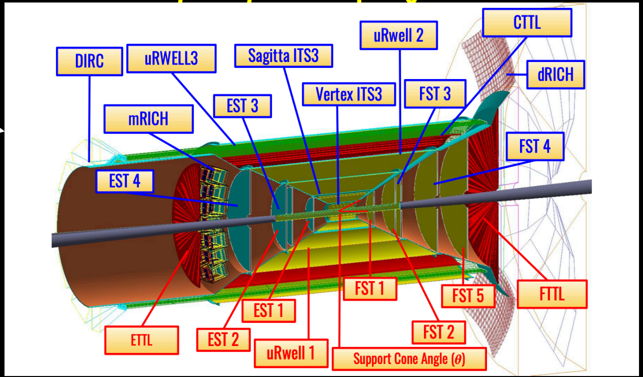


Implementation of support structures with realistic material budgets

Reference design



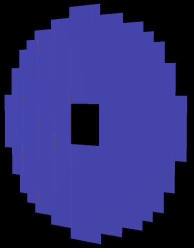
Ongoing R&D projective



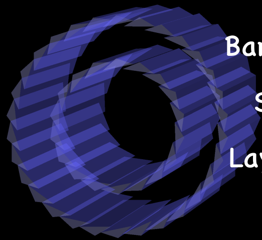
Variable pars; Fixed pars

Constraints

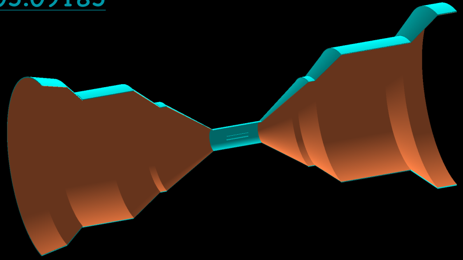
Extensive details at arXiv:2205.09185



FST/ EST Disks



Barrel Si Layer



- **Design Parameters** (n_pars ≥ 9)
  - Based on an parameterization.
- **Constraints** being used (n_const ≥ 3)
  - STRONG The minimum distance between any 2 disks should be >= 10 cm (giving room for services)
  - SOFT The Rmax-Rmin for the disks have to be multiple of 3.00 cms and 1.8 cms (Tiling of pixels)
- **Overlaps checked**
  - GEANT4 unstable when overlaps are detected in volumes.
  - Overlaps are checked for every design explored and penalized.

sub-detector	constraint	description
EST/FST disks	$min\left\{\sum_{i}^{disks}\left\|\frac{R^{i}_{out}-R^{i}_{in}}{d}-\left\lfloor\frac{R^{i}_{out}-R^{i}_{in}}{d}\right\rfloor\right\|\right\}$	**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	$min\left\{\left\|\frac{2\pi r_{sagitta}}{w}-\left\lfloor\frac{2\pi r_{sagitta}}{w}\right\rfloor\right\|\right\}$	**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

ECCE design (non-projective)	
Design Parameter	**Range**
μRWELL 1 (Inner) (r) Radius	[17.0, 51.0 cm]
μRWELL 2 (Inner) (r) Radius	[18.0, 51.0 cm]
EST 4 z position	[-110.0, -50.0 cm]
EST 3 z position	[-110.0, -40.0 cm]
EST 2 z position	[-80.0, -30.0 cm]
EST 1 z position	[-50.0, -20.0 cm]
FST 1 z position	[20.0, 50.0 cm]
FST 2 z position	[30.0, 80.0 cm]
FST 3 z position	[40.0, 110.0 cm]
FST 4 z position	[50.0, 125.0 cm]
FST 5 z position	[60.0, 125.0 cm]
ECCE ongoing R&D (projective)	
Design Parameter	**Range**
Angle (Support Cone)	[25.0°, 30.0°]
μRWELL 1 (Inner) Radius	[25.0, 45.0 cm]
ETTL z position	[-171.0, -161.0 cm]
EST 2 z position	[45, 100 cm]
EST 1 z position	[35, 50 cm]
FST 1 z position	[35, 50 cm]
FST 2 z position	[45, 100 cm]
FST 5 z position	[100, 150 cm]
FTTL z postion	[156, 183 cm]

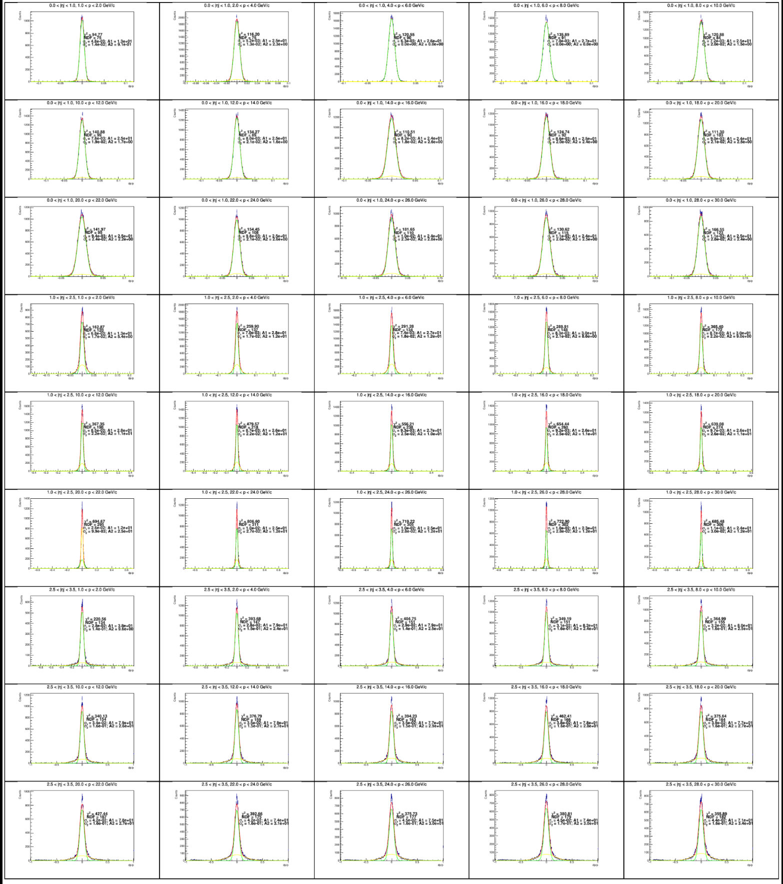
Implementation

- **Objective functions** Average of Weighted Averages (n_obj ≥ 3)
  - Momentum resolution dp/p
  - Theta resolution $d\theta$
  - Projected $d\theta$ at PID location.
  - Kalman Filtering inefficiency (improving the tracking reconstruction ability of the algorithm)

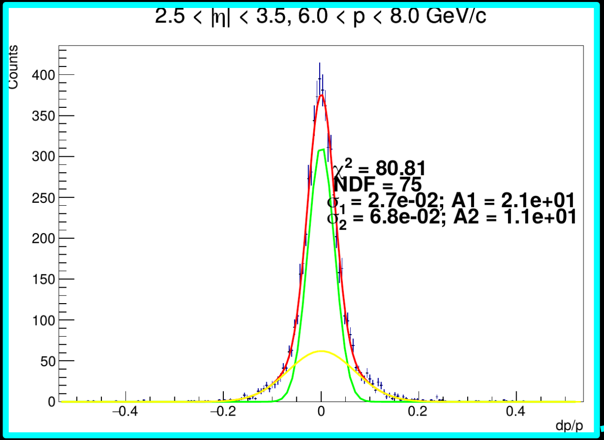
- **Validation** of the solutions
  - Validate by comparing optimal vs baseline $d\varphi$ resolution, vertex resolution and reconstruction efficiency

Weighted sum with errors

Weighted sum with errors



Implementation



Propagate uncertainties from fits

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

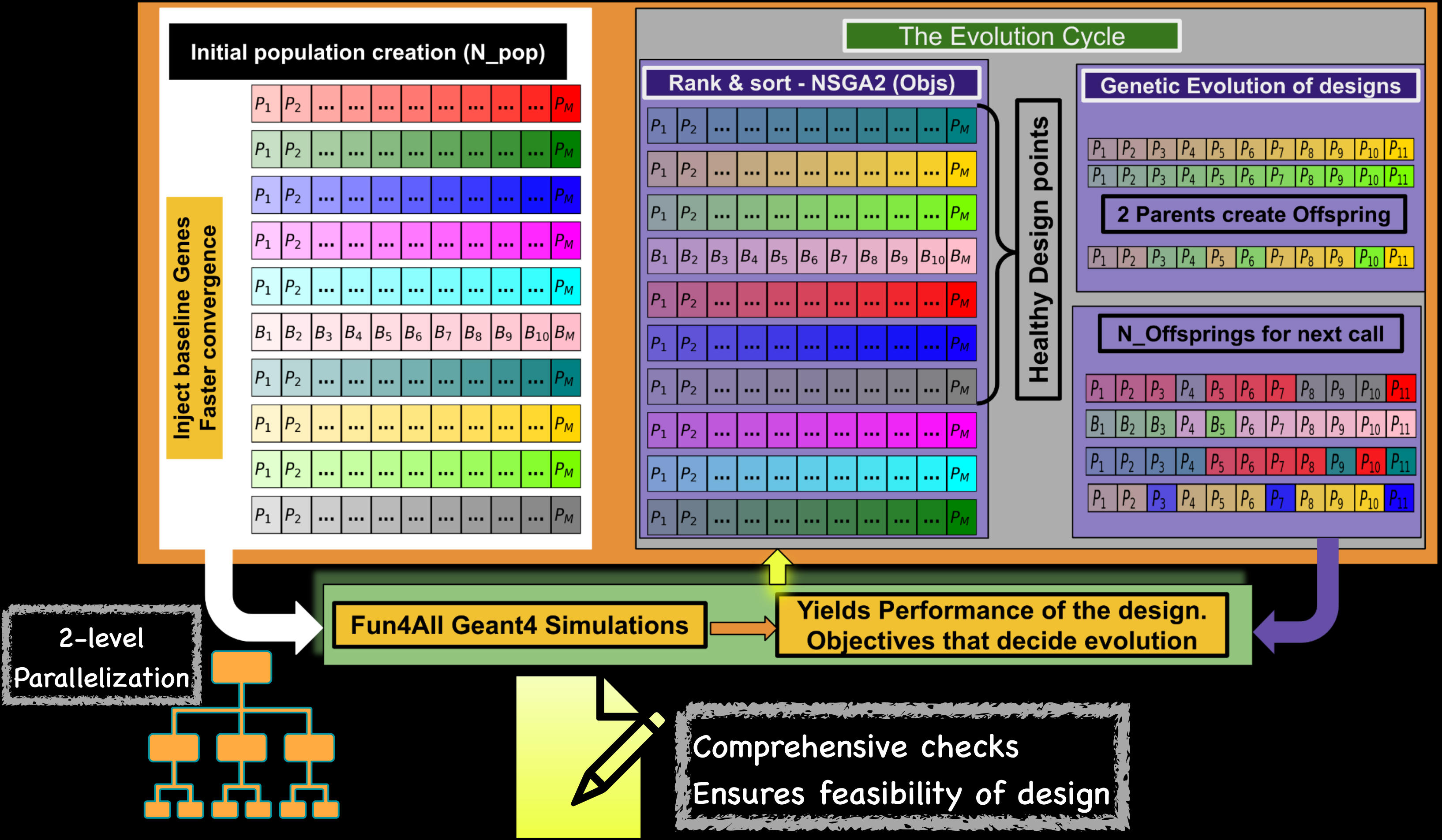
Average objective in a η bin

Sum in bins of p 14 bins

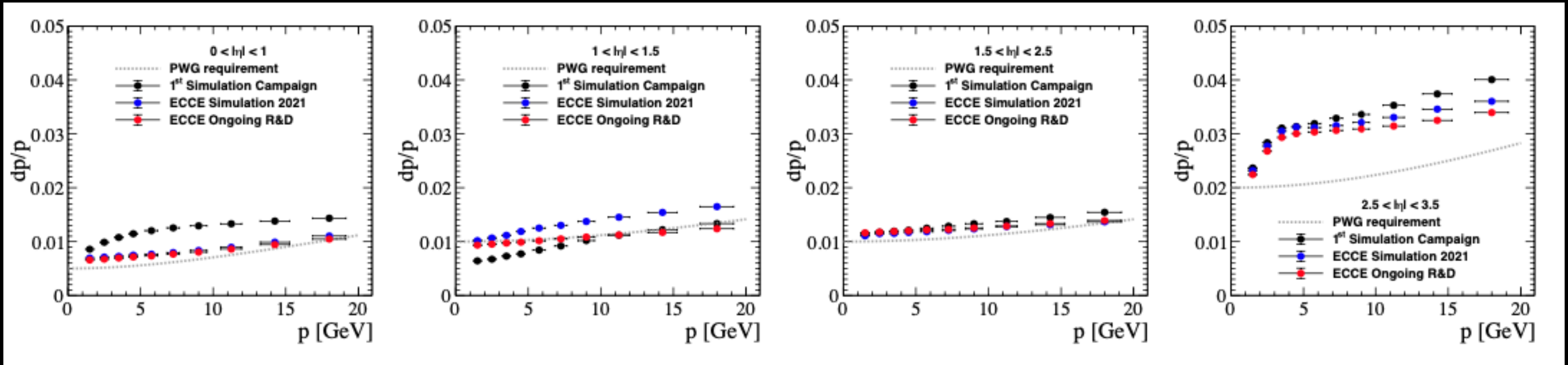
$$\bar{x} = \frac{\sum_\eta^{N_\eta} \bar{x_\eta}}{N_\eta}$$

6 η bins

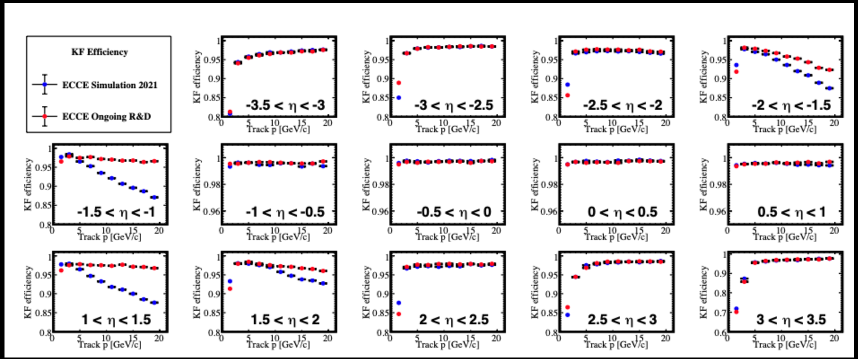
Summarizing the MOGA pipeline

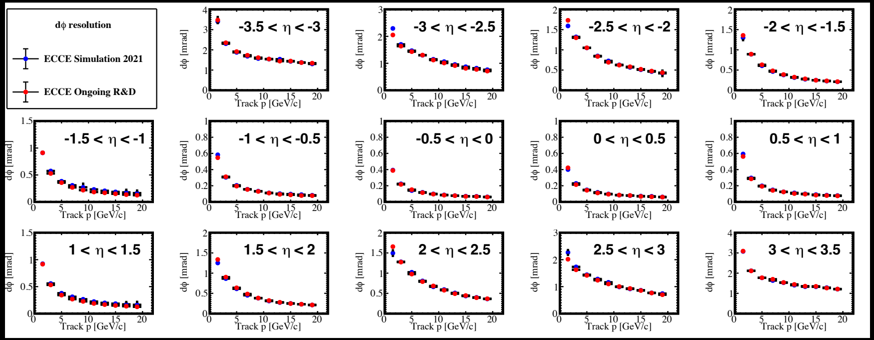


Evolution of Detector Performance



Momentum Resolution

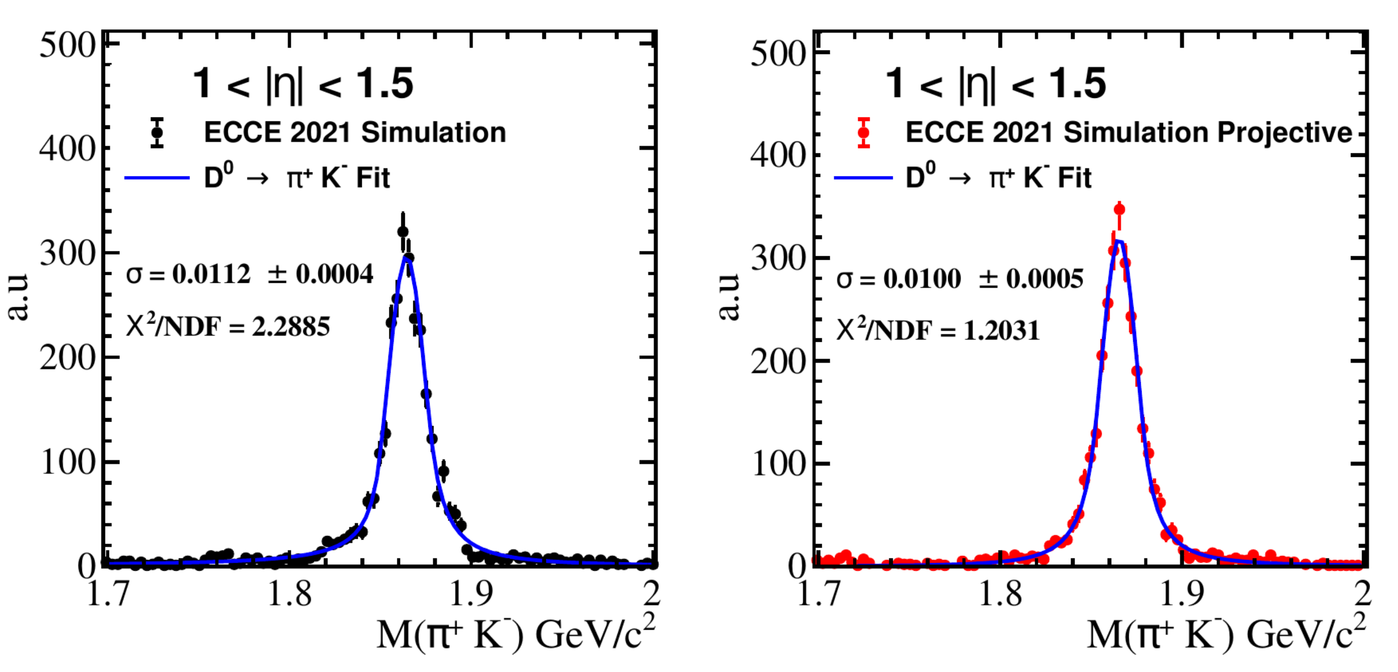




KF Efficiency

θ resolution

Post-hoc validation on physics observables

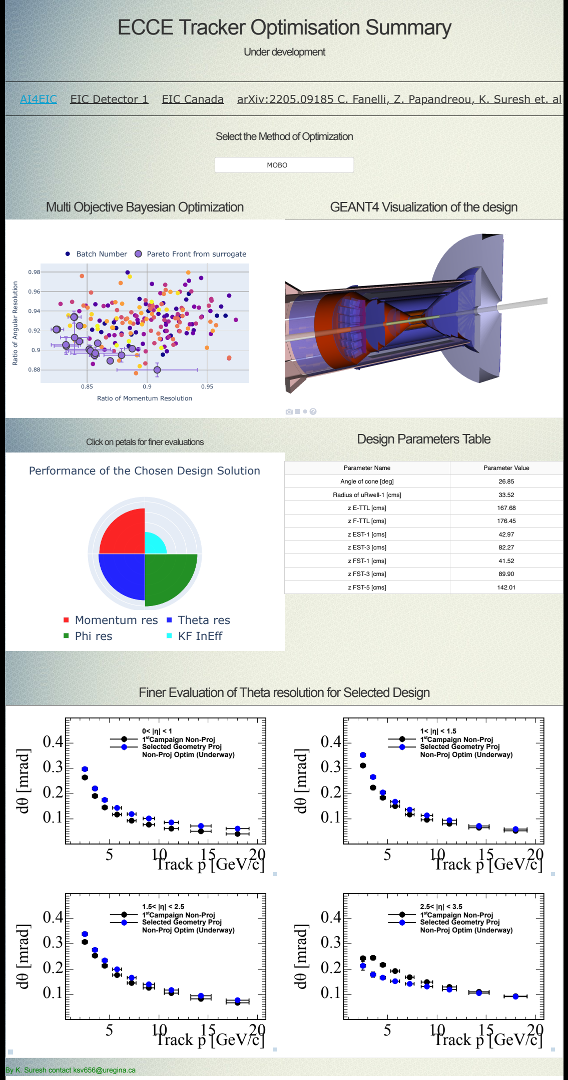


The π+K− invariant mass obtained from the SIDIS events with updated baseline and recent version of optimized projective geometry.

A region of eta sensitive due to materials for support structure is considered for optimization.

Summary

- EIC is one of the first experiments to be designed with the support of AI
- Optimization is continuous and iterative. The current tracking system is an AI-assisted design. arXiv:2205.09185
- For the "first" time -> framework integrating the GEANT4 based simulation coupled to MOO has been developed with massive parallelization.
  - Modular framework : applicable to EIC Detector-1. Ongoing work to optimize tracker + PID detectors.
  - Pareto solutions can be explored post hoc and decision making can be done based on cost, engineering, physics realization etc.



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