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BOTTLENECKS IN CLASSICAL SIMULATIONS: WHERE CAN AI HELP?

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SIMULATION NEEDS: SHORT TERM

EIC detector design and optimization for proposal and beyond

- EIC is an asymmetric collider
- Detector designs complicated mix of many technologies to address the subtleties of the physics events
- Near-beamline detectors integral part of detectors
- But… want hermetic detector with “seamless” PID, calorimetry and tracking everywhere.
- **Simulation-driven detector design crucial**

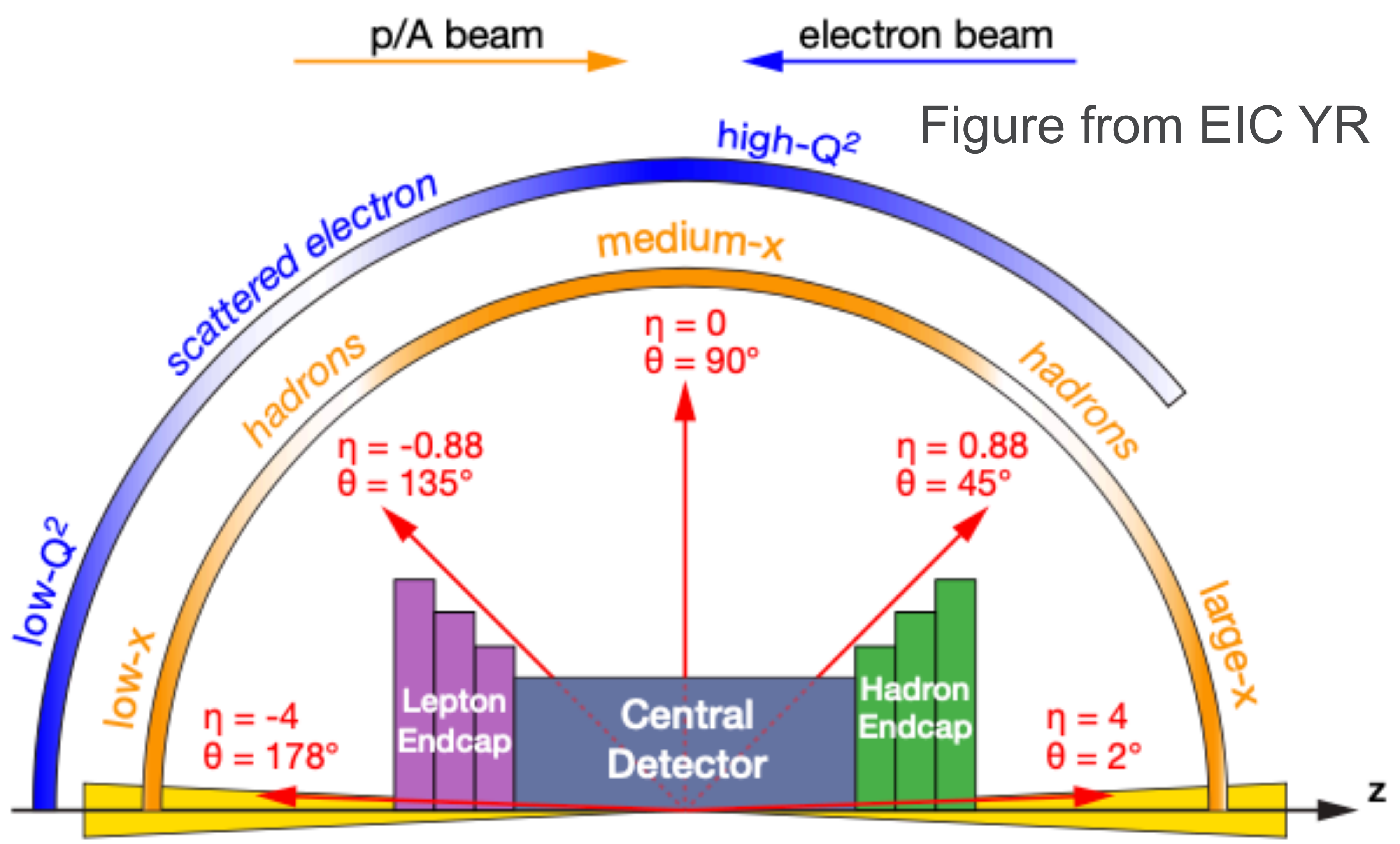


Figure from EIC YR

A NEW DETECTOR FROM SCRATCH?

From the EIC Yellow Report to an optimized EIC detector

η	Nomenclature	Tracking						Electrons and Photons			$\pi/K/p$		HCAL		Muons
		Resolution	Relative Momentun	Allowed X/X_0	Minimum-p_T (MeV/c)	Transverse Pointing Res.	Longitudinal Pointing Res.	Resolution σ_E/E	PID	Min E Photon	p-Range	Separation	Resolution σ_E/E	Energy	
< -4.6	Low-Q2 tagger														
-4.6 to -4.0		Not Accessible													
-4.0 to -3.5			Reduced Performance												
-3.5 to -3.0	Backward Detector		$\sigma_p/p \sim 0.1\% \times p \oplus 2\%$	~5% or less	150-300			$1\%/E \oplus 2.5\%/\sqrt{E} \oplus 1\%$	π suppression up to $1:10^4$	20 MeV	≤ 10 GeV/c	$\geq 3\sigma$	$50\%/\sqrt{E} \oplus 10\%$	~500MeV	Muons useful for background suppression and improved resolution
-3.0 to -2.5															
-2.5 to -2.0			$\sigma_p/p \sim 0.02\% \times p \oplus 1\%$												
-2.0 to -1.5						dca(xy) ~ $40/p_T$ μm $\oplus$ 10 μm	dca(z) ~ $100/p_T$ μm $\oplus$ 20 μm	$2\%/E \oplus (4\text{-}8)\%/\sqrt{E} \oplus 2\%$	π suppression up to $1:(10^{-3}\text{-}10^{-2})$	50 MeV					
-1.5 to -1.0															
-1.0 to -0.5	Barrel		$\sigma_p/p \sim 0.02\% \times p \oplus 5\%$		400	dca(xy) ~ $30/p_T$ μm $\oplus$ 5 μm	dca(z) ~ $30/p_T$ μm $\oplus$ 5 μm	$2\%/E \oplus (12\text{-}14)\%/\sqrt{E} \oplus (2\text{-}3)\%$	π suppression up to $1:10^{-2}$	100 MeV	≤ 6 GeV/c		$100\%/\sqrt{E} \oplus 10\%$		
-0.5 to 0.0															
0.0 to 0.5															
0.5 to 1.0															
1.0 to 1.5	Forward Detectors		$\sigma_p/p \sim 0.02\% \times p \oplus 1\%$		150-300	dca(xy) ~ $40/p_T$ μm $\oplus$ 10 μm	dca(z) ~ $100/p_T$ μm $\oplus$ 20 μm	$2\%/E \oplus (4^*\text{-}12)\%/\sqrt{E} \oplus 2\%$	3σ e/π up to 15 GeV/c	50 MeV	≤ 50 GeV/c		$50\%/\sqrt{E} \oplus 10\%$		
1.5 to 2.0															
2.0 to 2.5															
2.5 to 3.0			$\sigma_p/p \sim 0.1\% \times p \oplus 2\%$												
3.0 to 3.5															
3.5 to 4.0	Instrumentation to separate charged particles from photons		Reduced Performance												
4.0 to 4.5		Not Accessible													
> 4.6	Proton Spectrometer Zero Degree Neutral Detection														

+ new developments

Detector & reconstruction requirements

Extensive list of key performance parameters inform detector choices. This table of requirements could be interpreted as a series of automized tests that a detector implementation needs to pass.

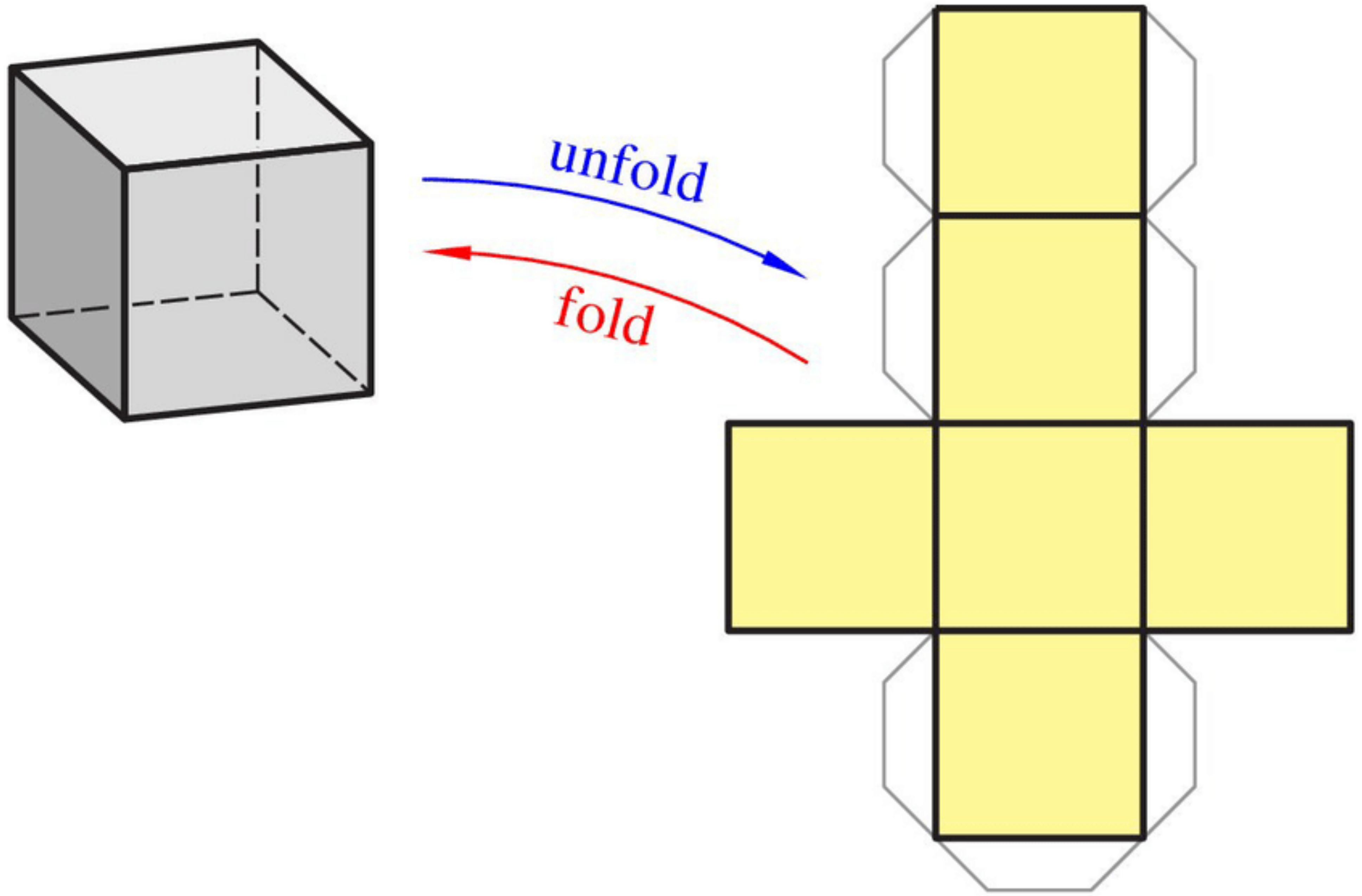
Physics requirements

Detector design has to enable many key physics measurements, while being flexible enough to accommodate new developments through the next 2 decades

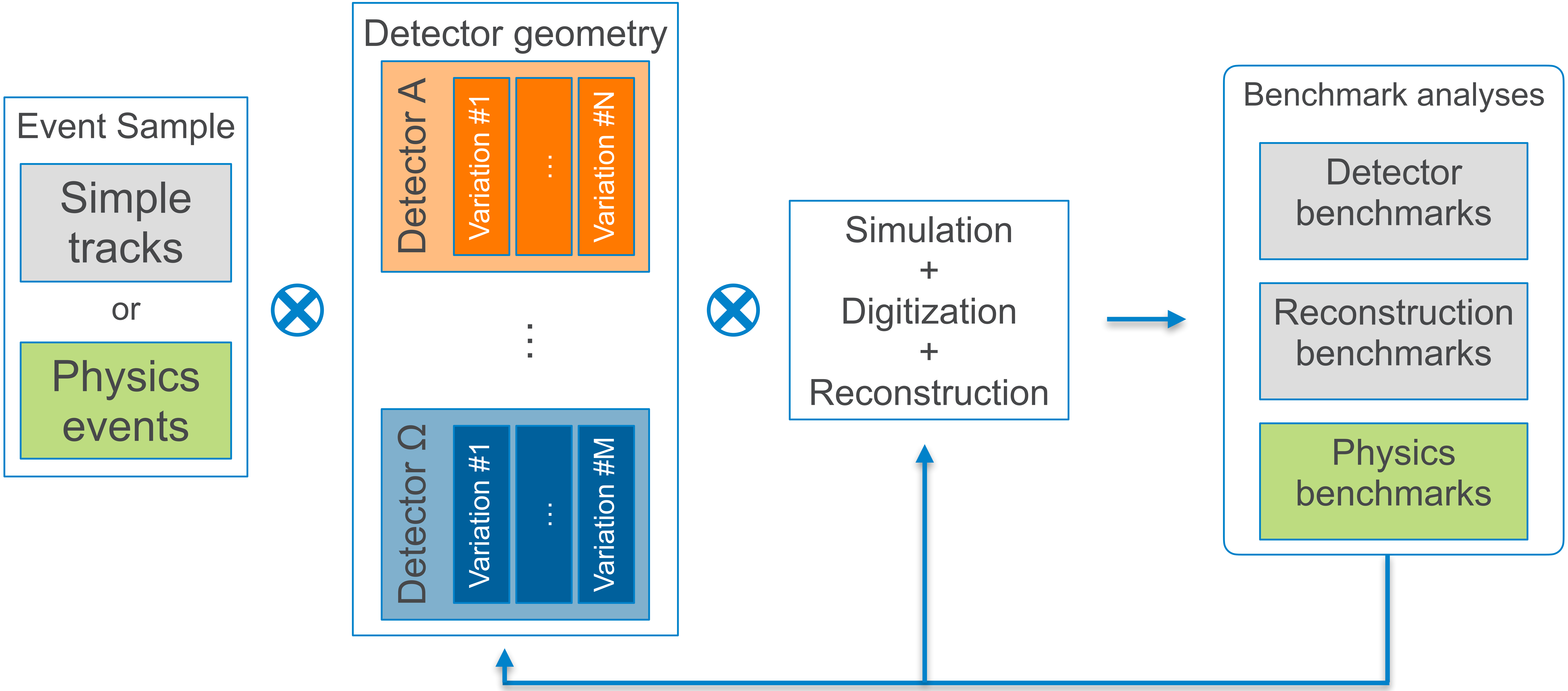
SIMULATION NEEDS: LONG TERM

High-luminosity EIC needs high-luminosity simulations

- EIC is **high-luminosity** collider centered around precision QCD measurements
- At least 10-100x Monte-Carlo statistics/dataset required per measured event-of-interest to properly correct/unfold/analyze data.
- All these Monte-Carlo events need to be propagated through the detector simulation, which is the primary bottleneck for full simulations.
- At this point, the detector itself is essentially static.
- **Prime place to use AI-techniques to “learn” and replace the detector simulation process.**



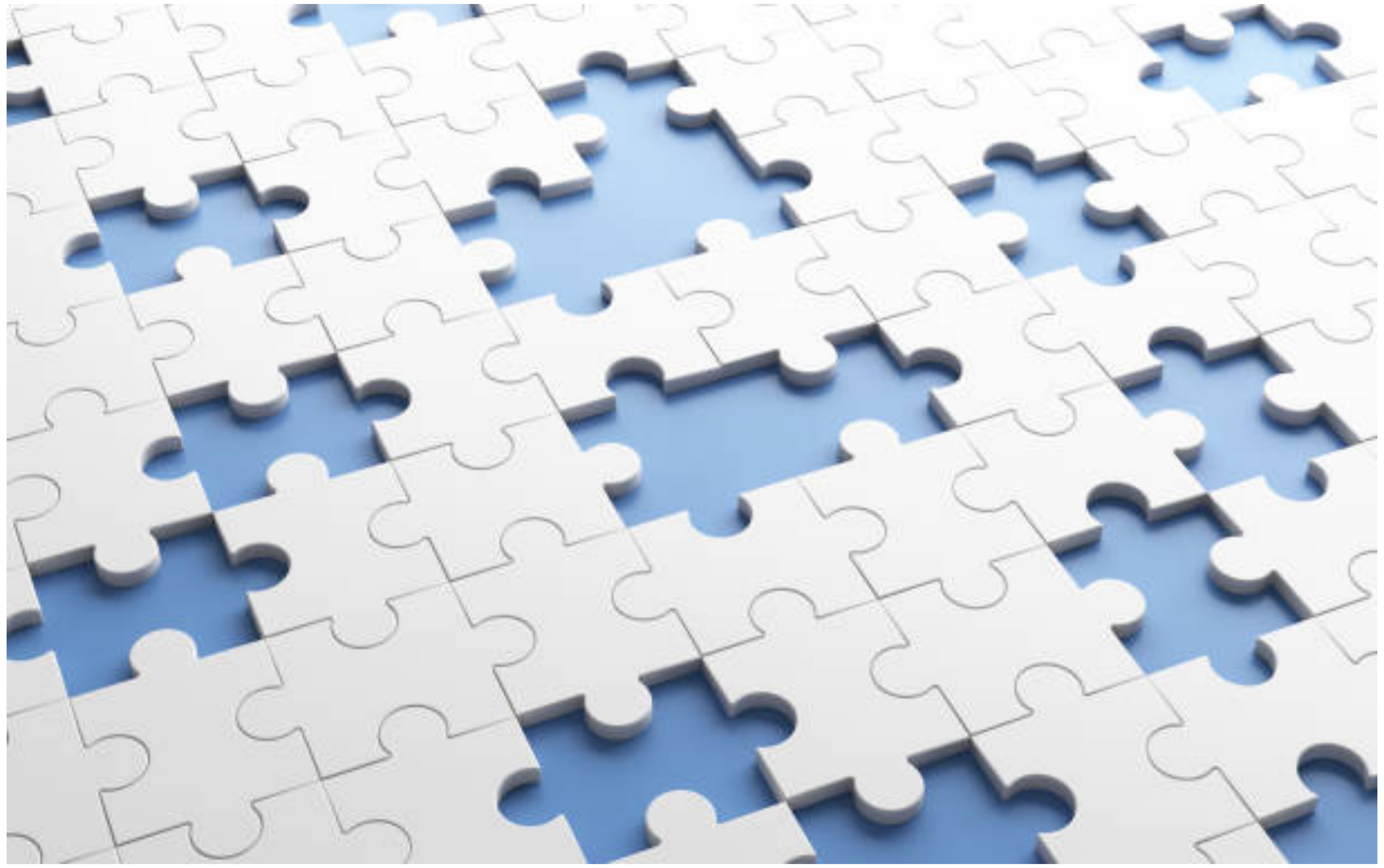
DETECTOR OPTIMIZATION WORKFLOW



ABOUT THIS PRESENTATION

Incomplete overview of bottlenecks in GEANT4 simulations

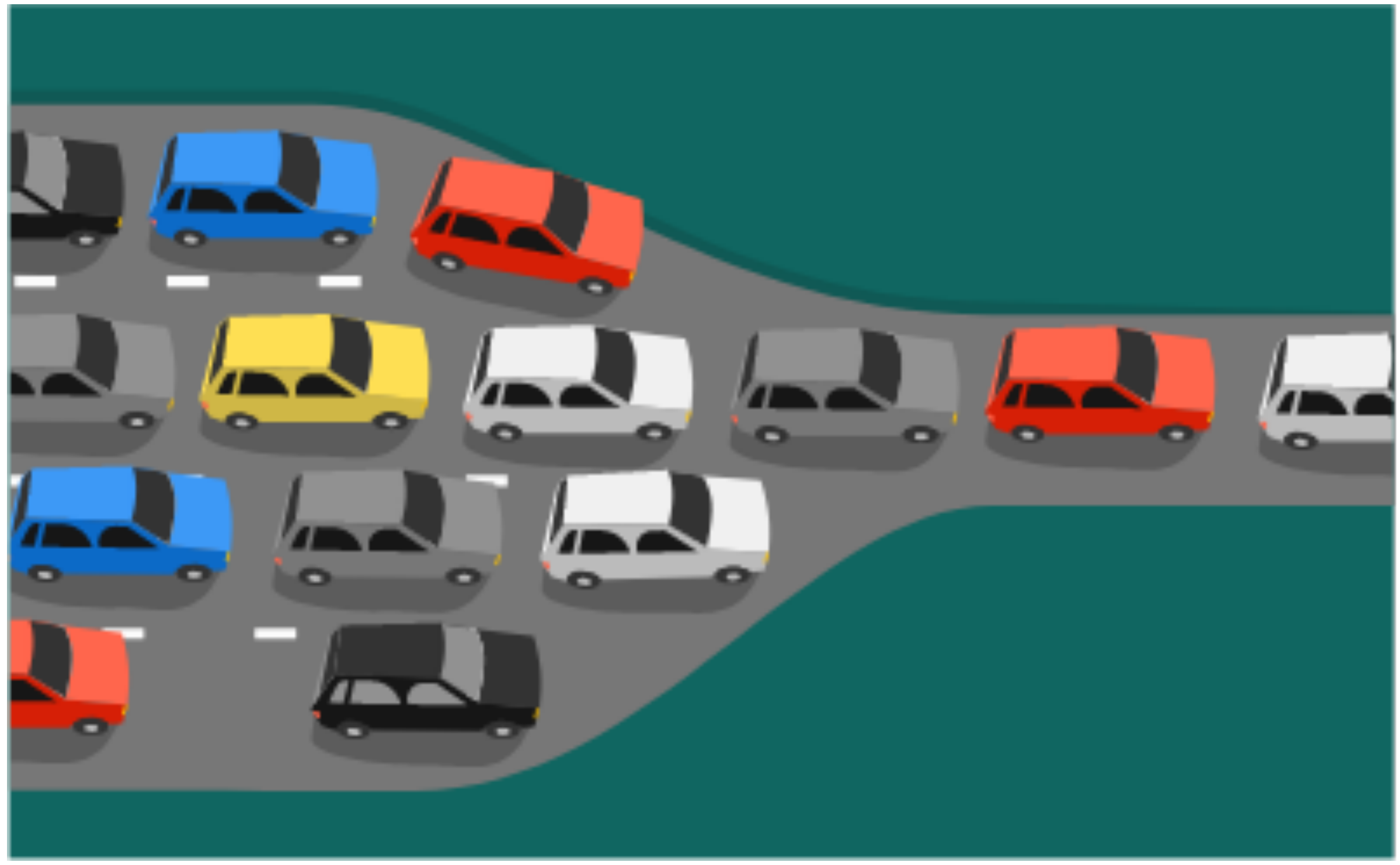
- Based around personal experience with the ATHENA detector proposal (but points applicable to all proposed EIC detectors).
- Aimed to be introductory talk to give a more concrete idea of the problems we can solve
- Mostly centered around piecewise bottlenecks rather than a holistic approach.
- Will **not** focus on solutions to these bottlenecks - see talks by Michele Kuchera, Benjamin Nachman, Lucio Anderlini, and Markus Diefenthaler.



SIMULATION BOTTLENECKS

Many particles, many components, many steps

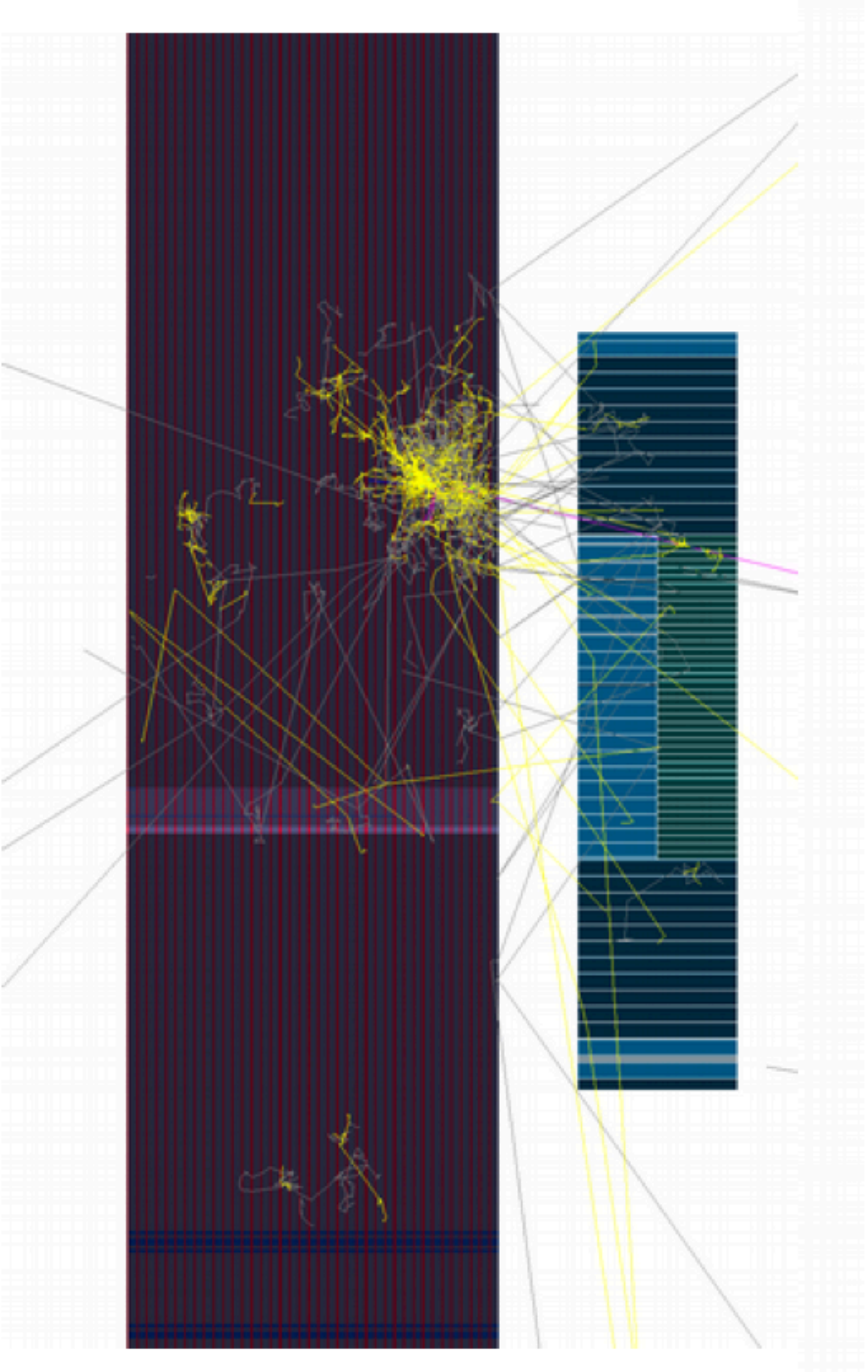
- Usually bottlenecks occur where the particle count is high, e.g. as part of a calorimeter shower, or optical photons in a RICH.
- Bottlenecks can also occur in when navigating very detailed geometries (e.g. fiber calorimeters with millions of fibers).
- Finally, scenarios where we need many precise steps through a magnetic field (for upstream & downstream near-beamline detection) is relatively expensive.
- Often multiple bottlenecks at once.

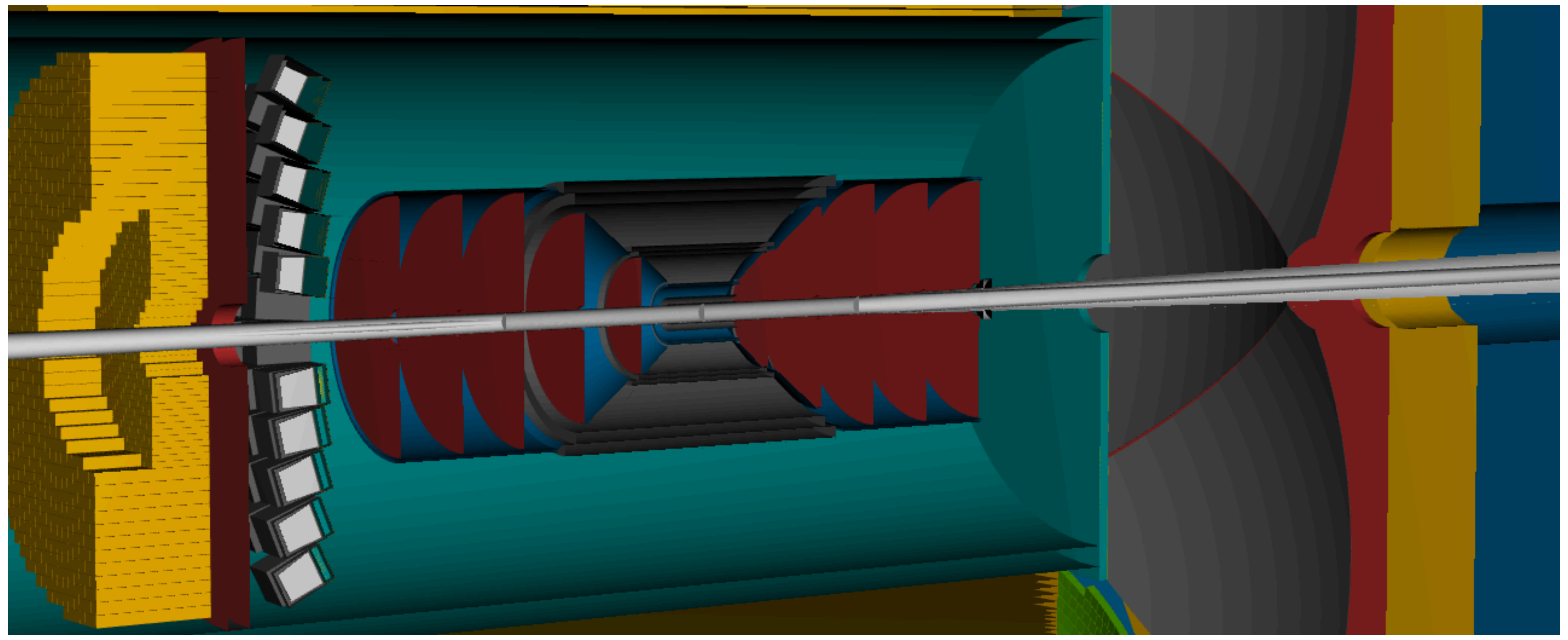


TRADITIONAL CALORIMETRY

From many particles to a 2D image

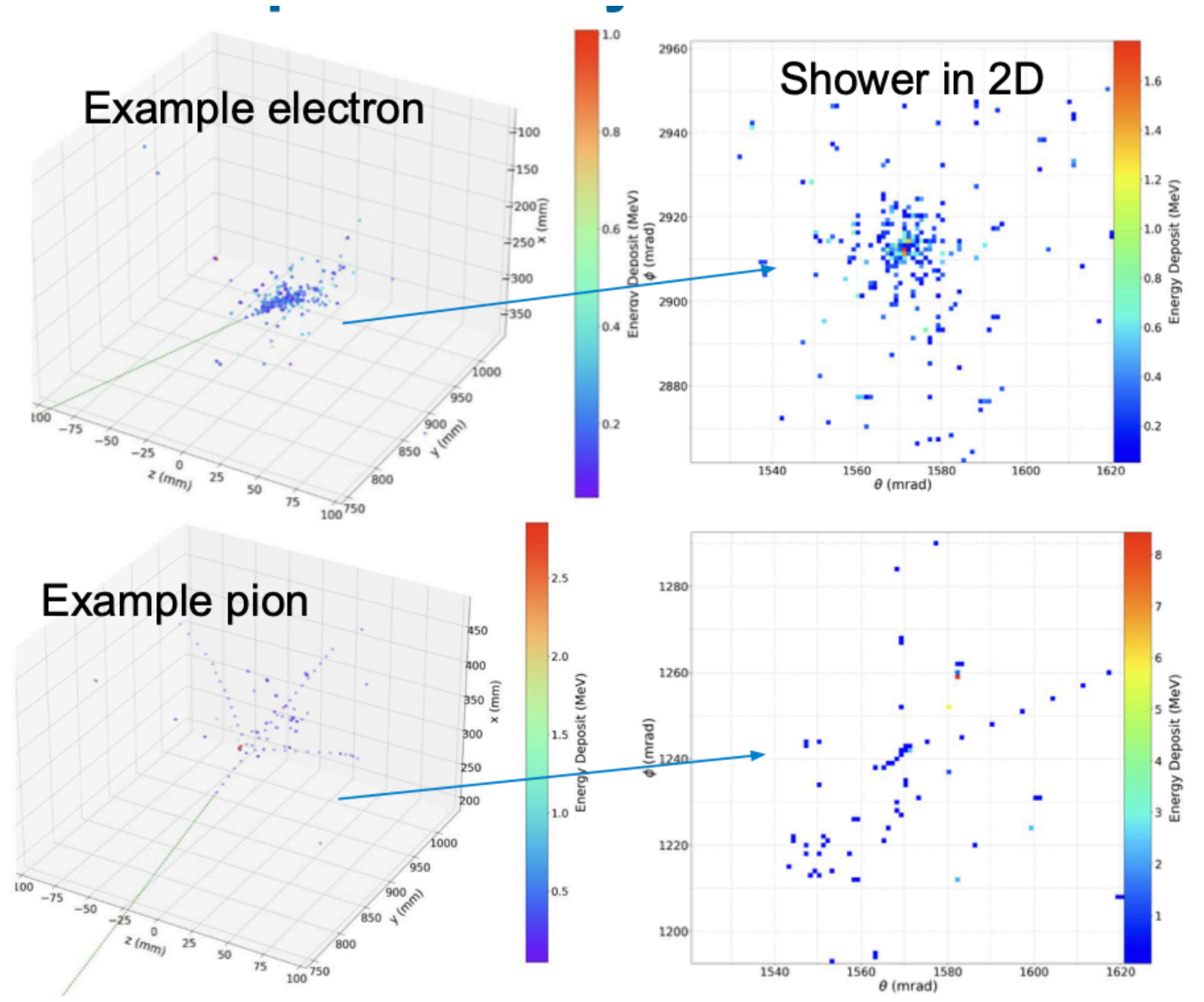
- Calorimeter simulation is computationally intensive due to amount of shower particles.
- Typically, precise particle transport necessary up to calorimeter (to get good handle on actual incident particles).
- Even high-granularity calorimeters have resolution below the single-particle level - calorimeter hits are an aggregate quantity.
- **Describing a traditional calorimeter as a transformation of incident particles into a 2D image prime target for generative models.**



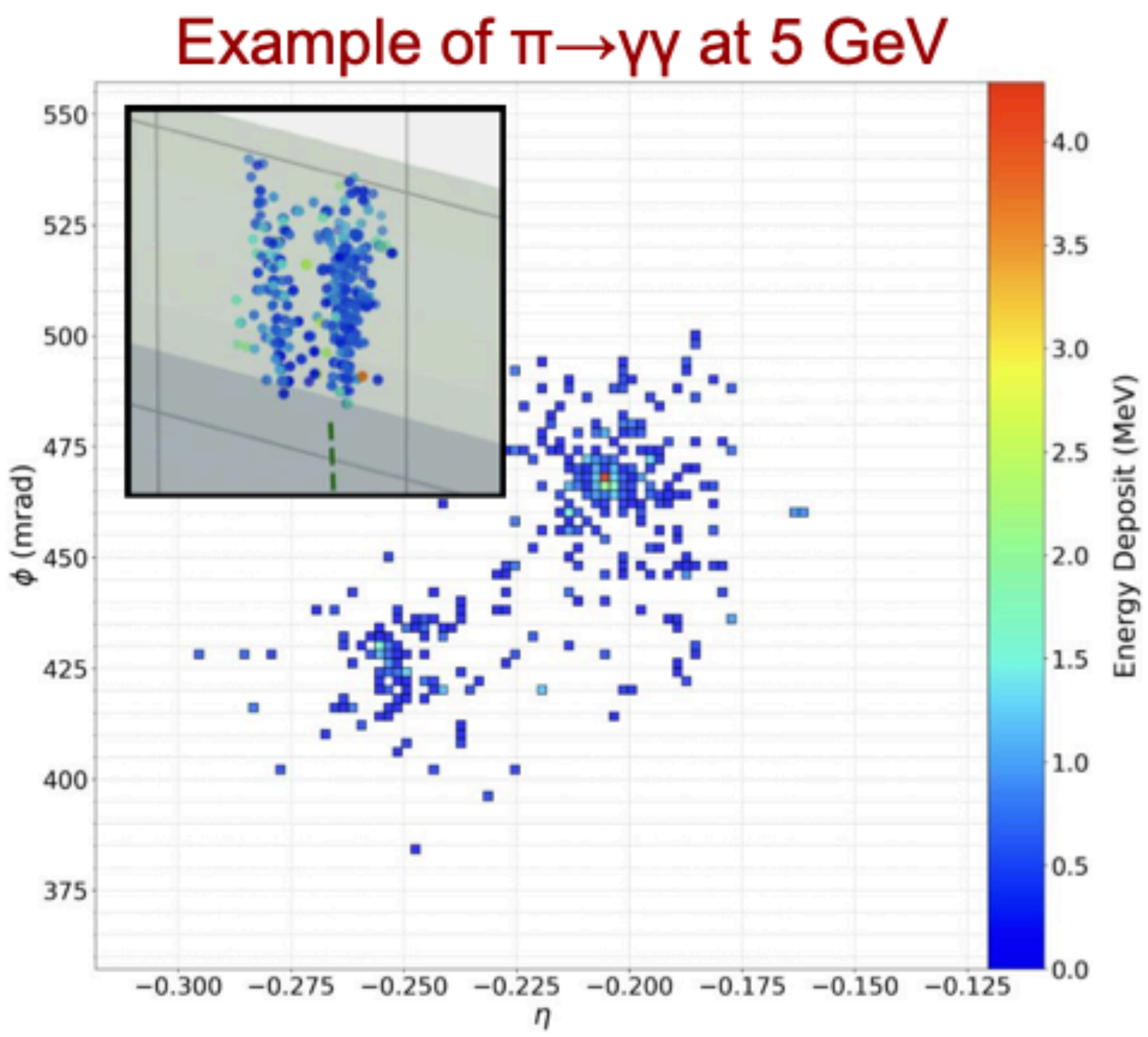


IMAGING CALORIMETRY

From 2D to 3D calorimetry and increasing role of noise

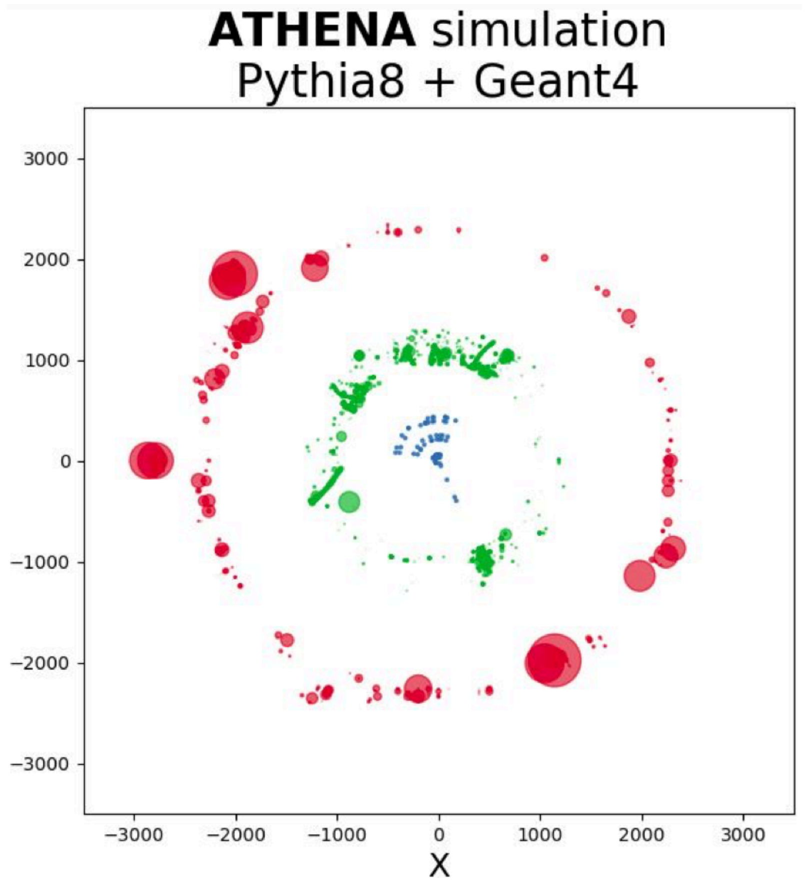


- Problem becomes more pronounced when going to 3D imaging calorimetry (many particles x many sensors).
- For example, hybrid silicon and PbScFi barrel calorimeter in ATHENA can have over 100k hits for high Q^2 events, mostly in scintillating fiber elements.
- Harder problem than the 2D case.
- Granularity levels for 3D calorimetry more susceptible to detector noise. Could be accounted during digitization, or something that can be naturally present with AI.



HOLISTIC CALORIMETRY

Integrating multiple calorimetry systems



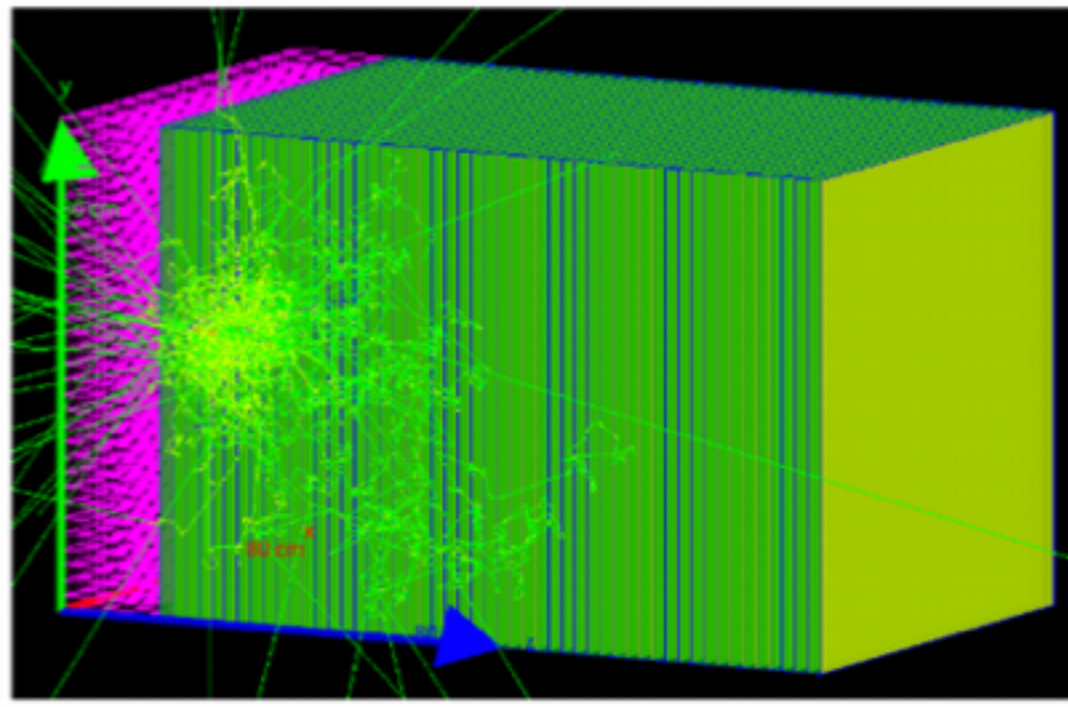
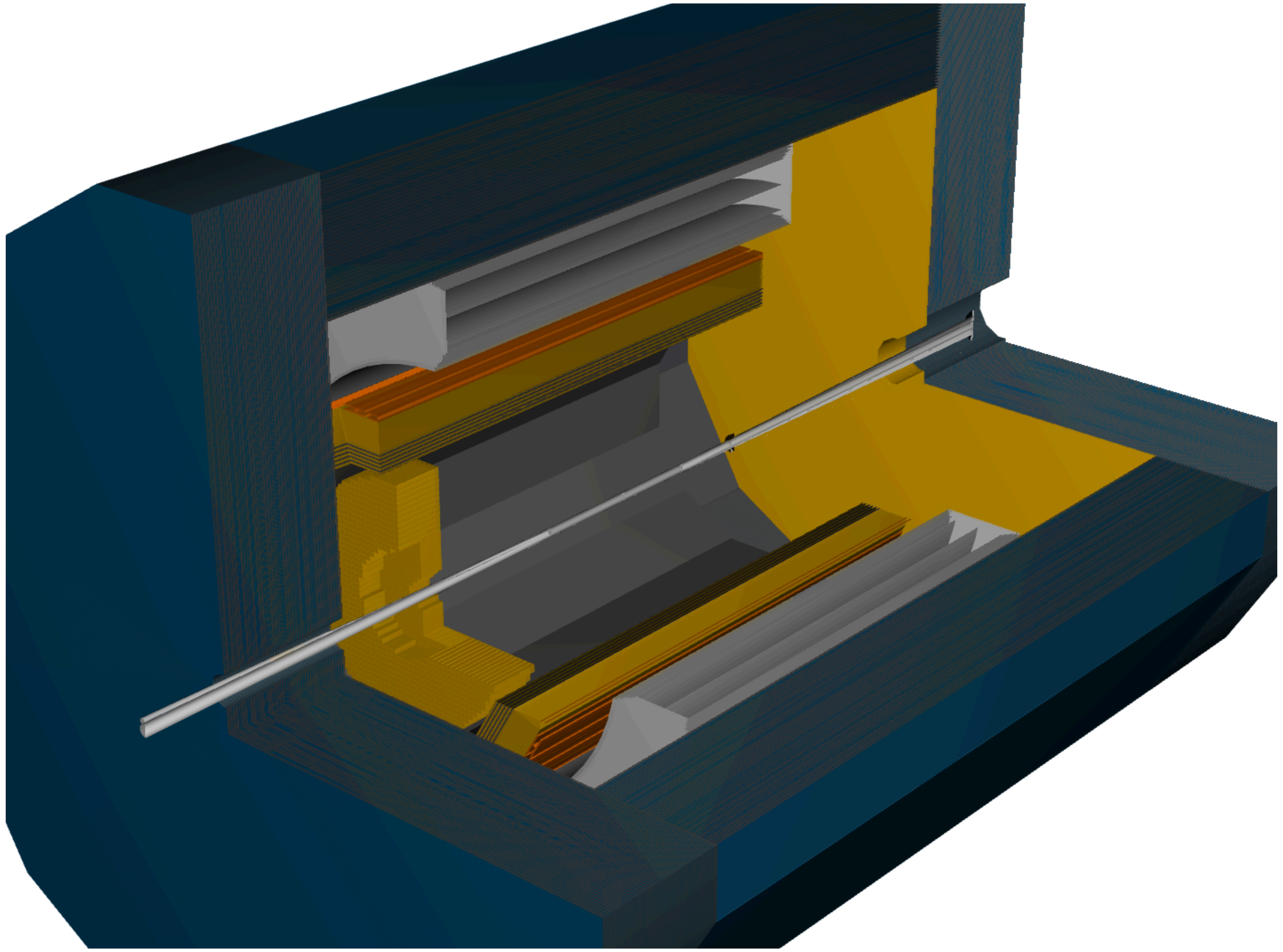


Figure: Event of π^+ at 20 GeV in EM (magenta) and HAD and yellow) parts

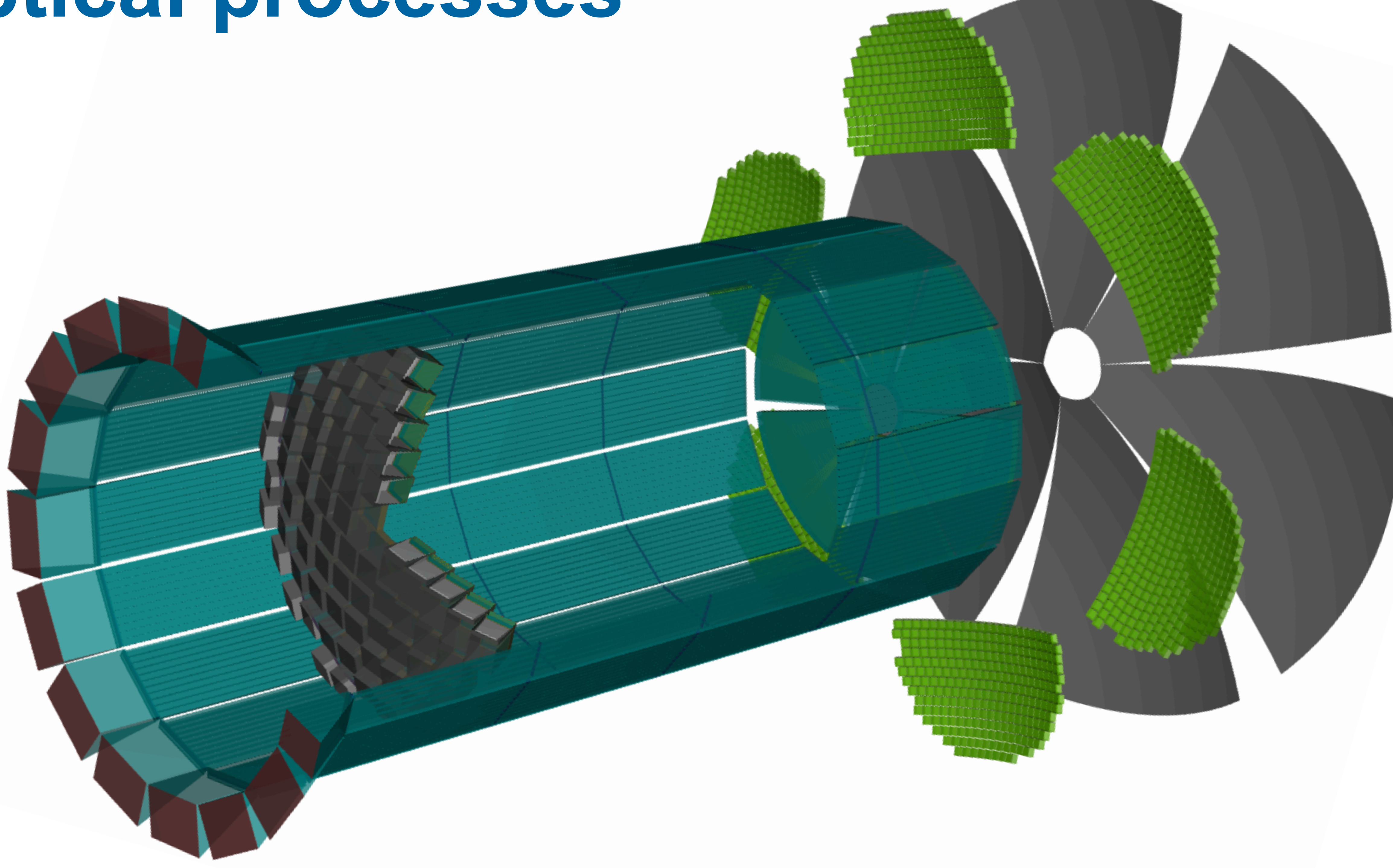
- Of course, dangerous to treat calorimeters as isolated systems. Electromagnetic calorimeters at EIC sit in front of material (e.g. magnet), followed by hadronic calorimeters.
- Hadronic showers that punch through the EMCAL need to be tracked through material and propagated in the the HCAL.
- In principle requires a holistic approach to calorimetry, could be seen as an extension to 3D imaging calorimetry.



BOTTLENECK: OPTICAL PHOTONS DETECTORS

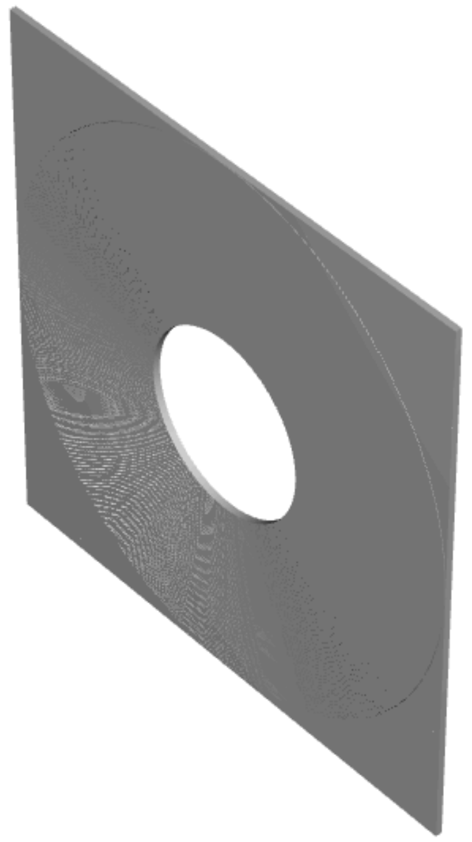
Hadron PID at the EIC based around optical processes

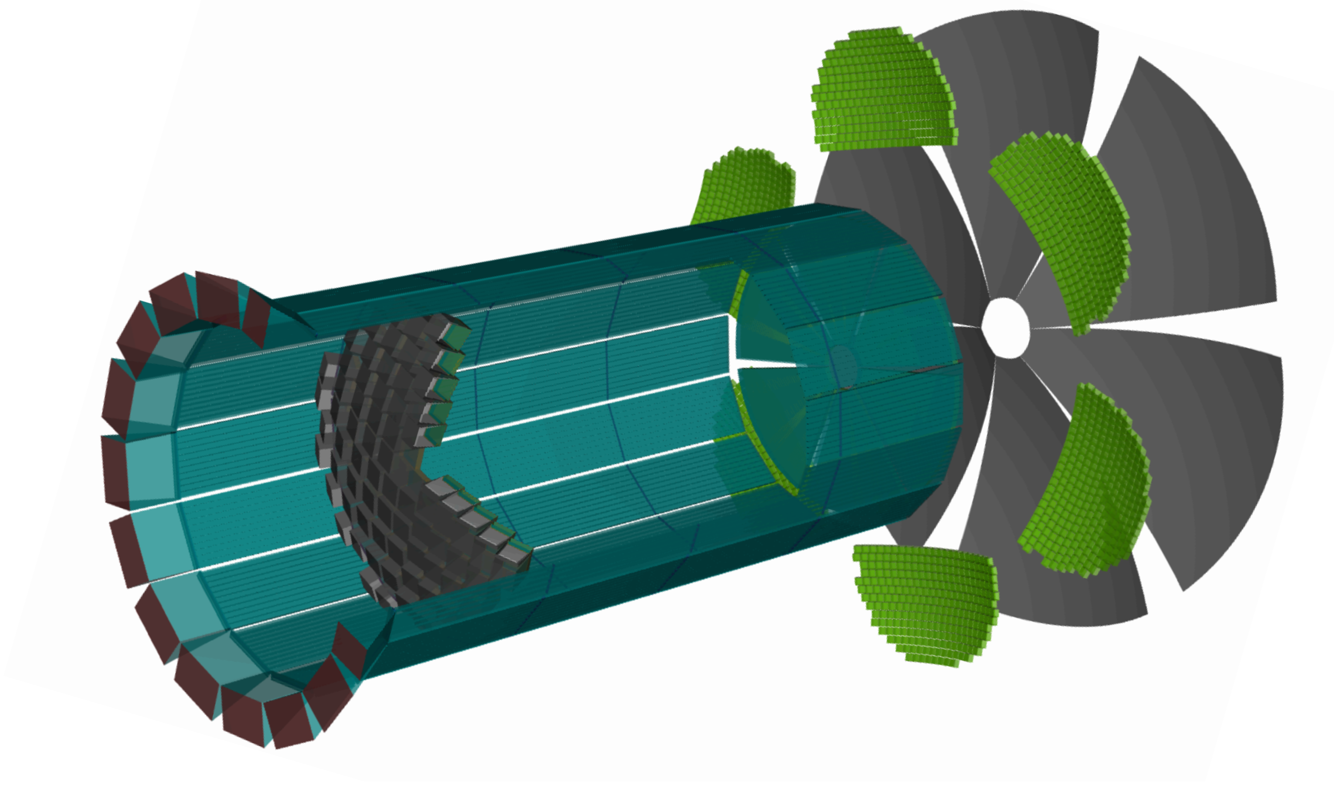
- Cherenkov detectors form the backbone of particle identification at EIC.
- Currently, all EIC detector designs use a dual radiator ring-imaging Cherenkov detector (RICH) in the hadron direction, a DIRC (detection of internally reflected Cherenkov light) in the barrel, and a modular RICH in the electron direction.
- These optical processes involve many photons that need to be tracked through complex surfaces.
- All three detectors rely on pattern-recognition of ring images in the reconstruction.



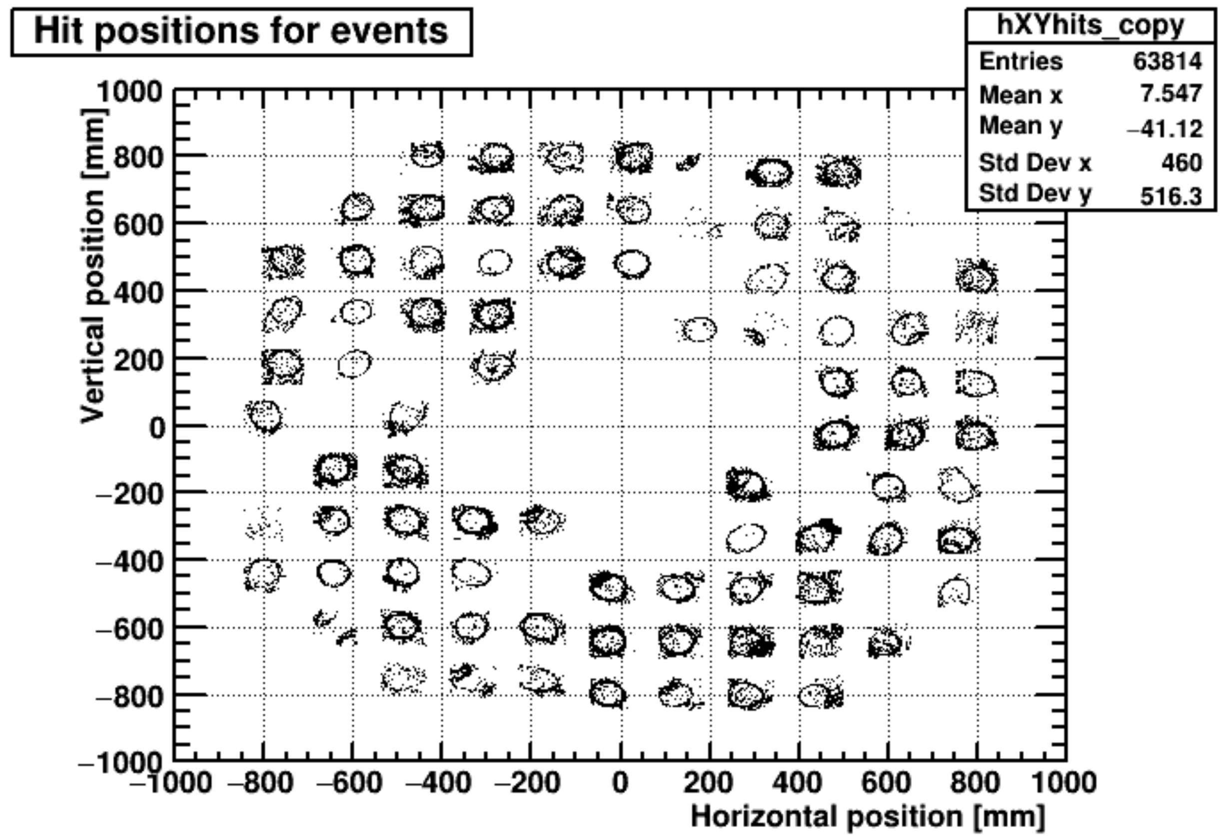
EXAMPLE: THE MRICH

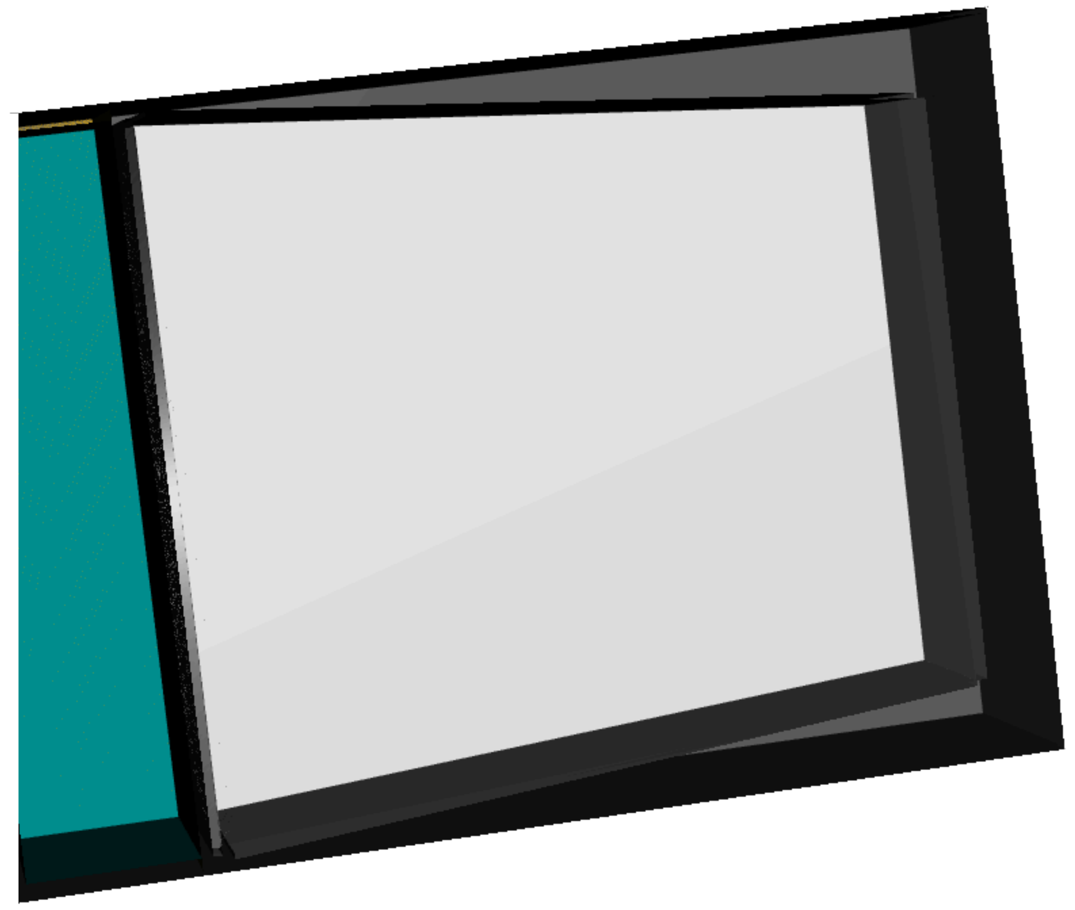
MRICH: Aerogel + fresnel lens + pixel sensor

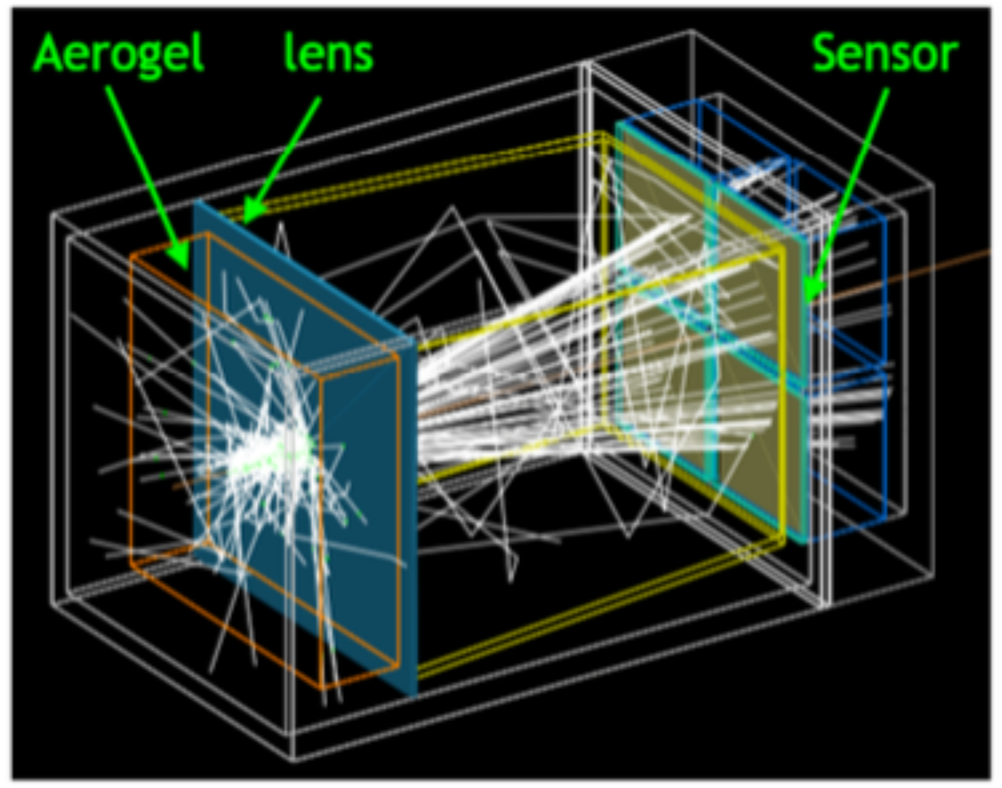


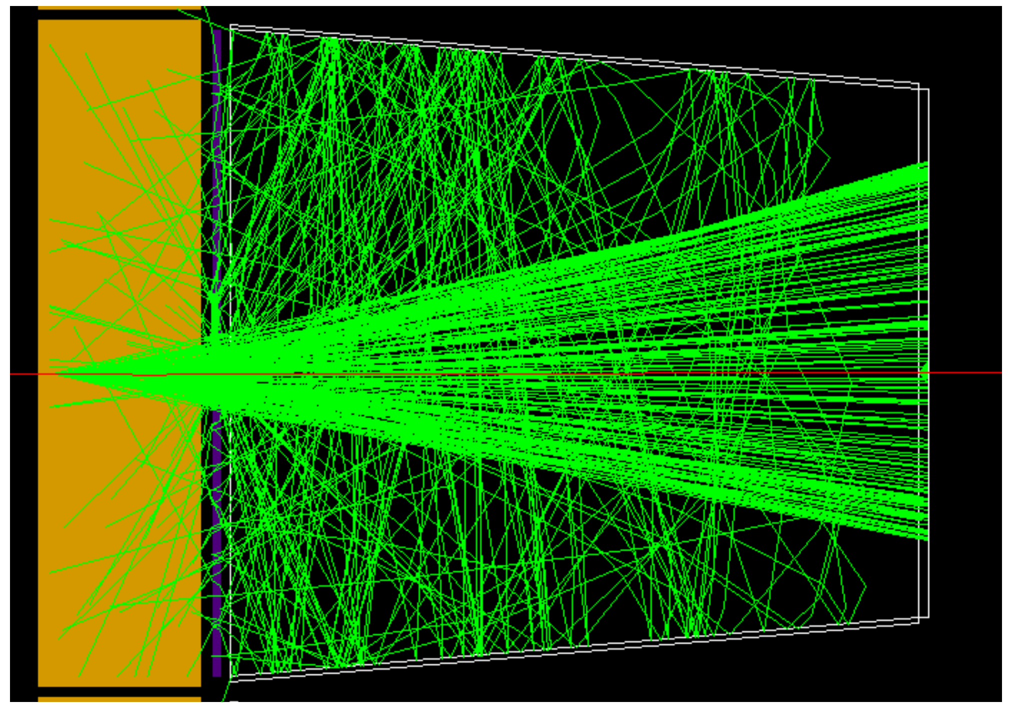


- Photons originate in the aerogel, pass through Fresnel lens (many 100s of grooves!).
- Sides of box mirror to optimize light collection.
- Impact of Fresnel lens on simulation performance non-negligible.
- Ring patterns observed by pixel sensor (e.g. LAPPD). Need to overlay with noise.

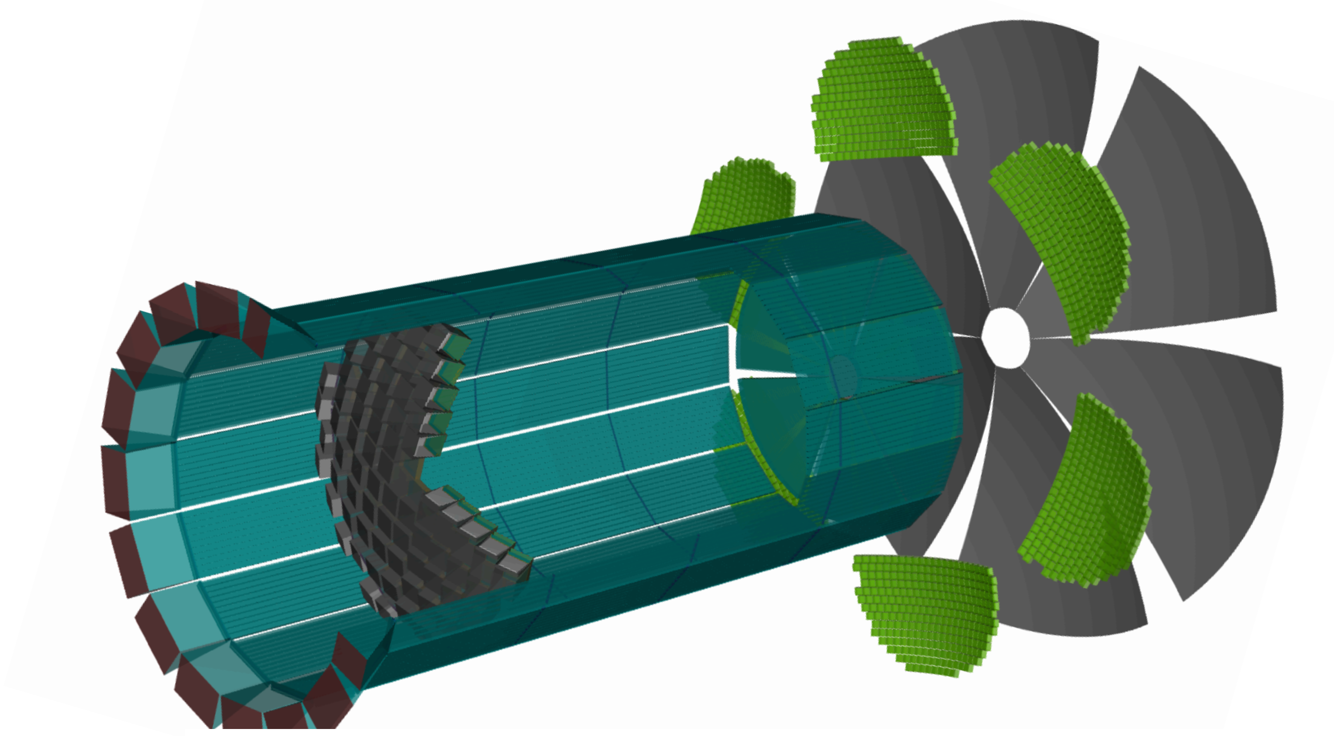






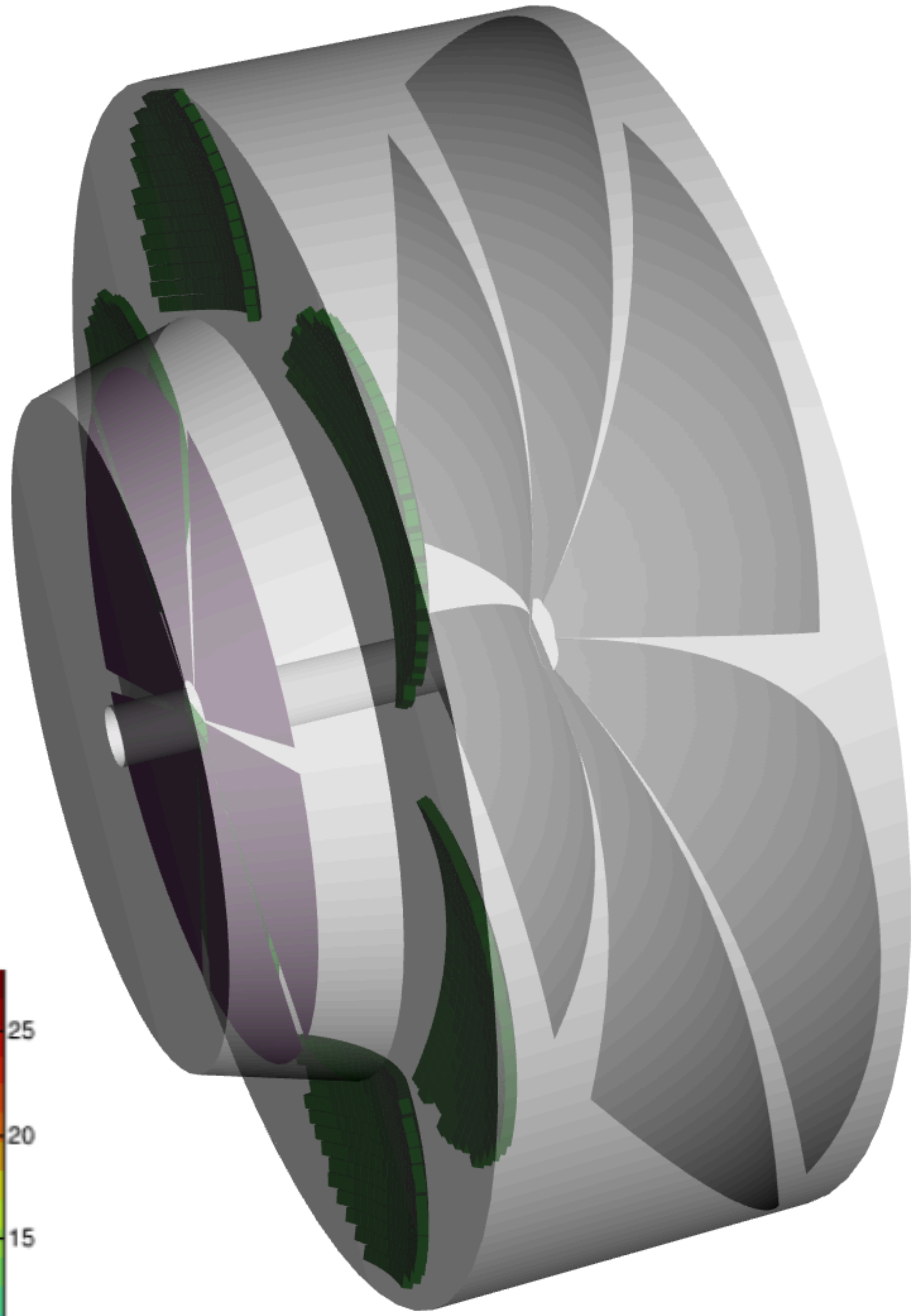


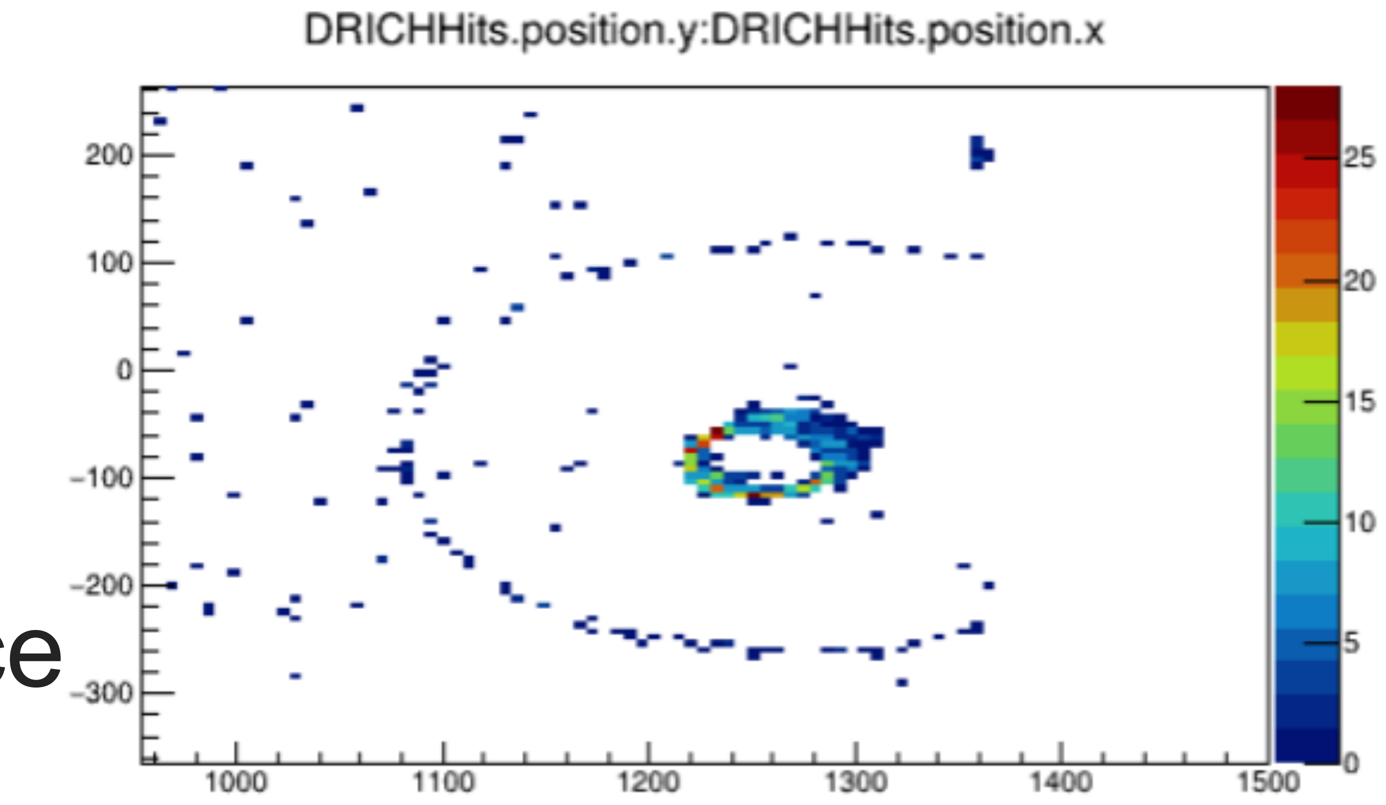
EXAMPLE: THE DRICH



DRICH: Aerogel + heavy gas + mirror + pixel sensor

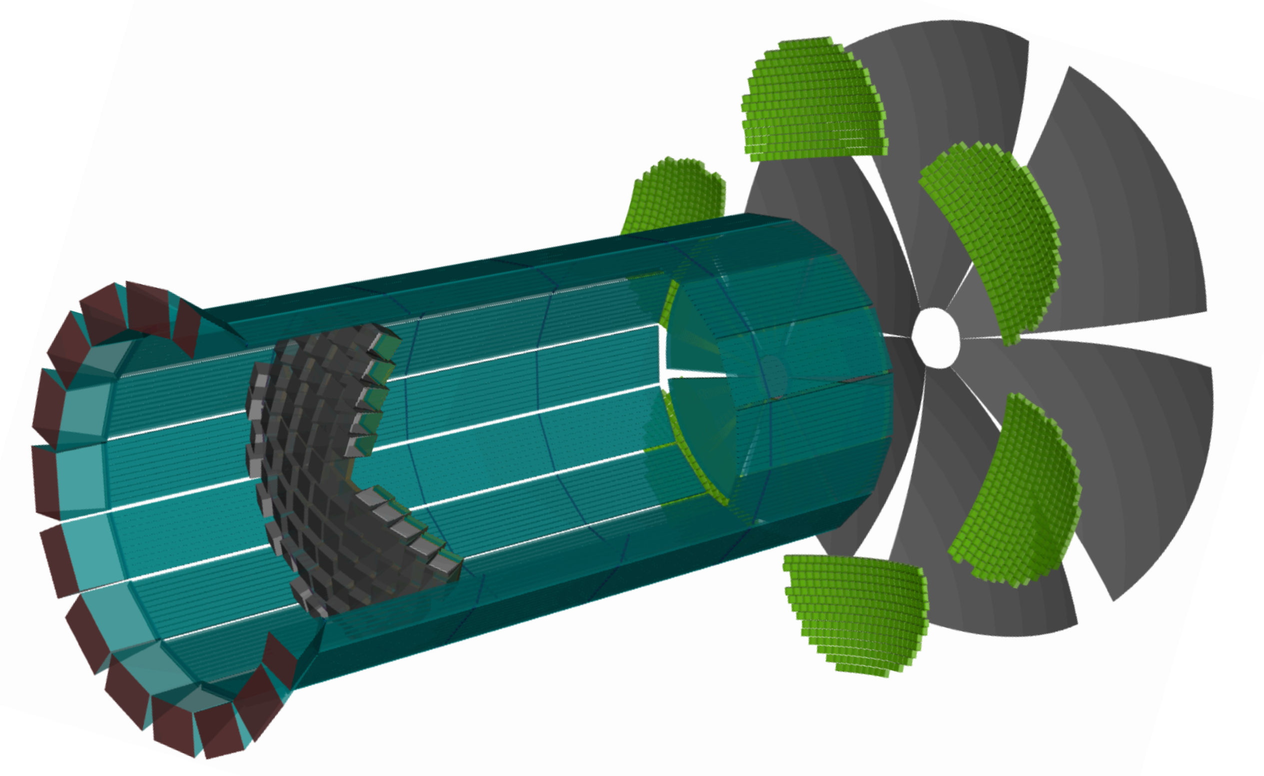
- DRICH uses aerogel radiator + gas radiator (large volume O~1.5m).
- Needs to propagate light to mirrors, and then to light sensors (e.g. SiPMs).
- Geometry optimization can be done with AI (see Cristiano Fanelli’s talk).
- Noise treatment crucial to properly mirror real-live detector performance.
- DRICH essentially translates particles into a nested ring pattern (with noise)
- Replacing this part with a generative network can improve simulation performance.
- Note that the reconstruction end is also a prime place to use AI.



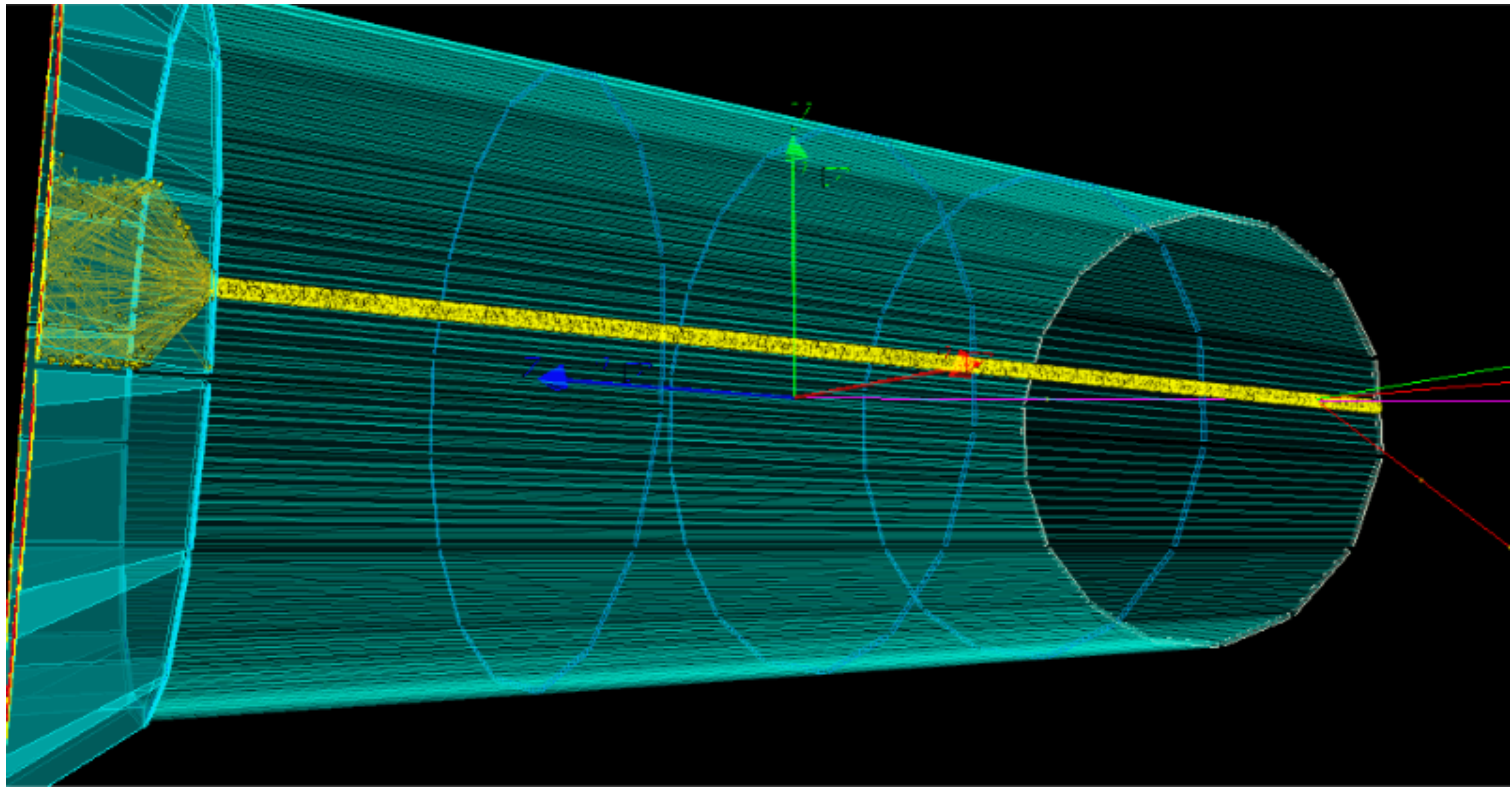


EXAMPLE: THE DIRC

DIRC: Quartz + glue + lenses + expansion volume + pixel sensor



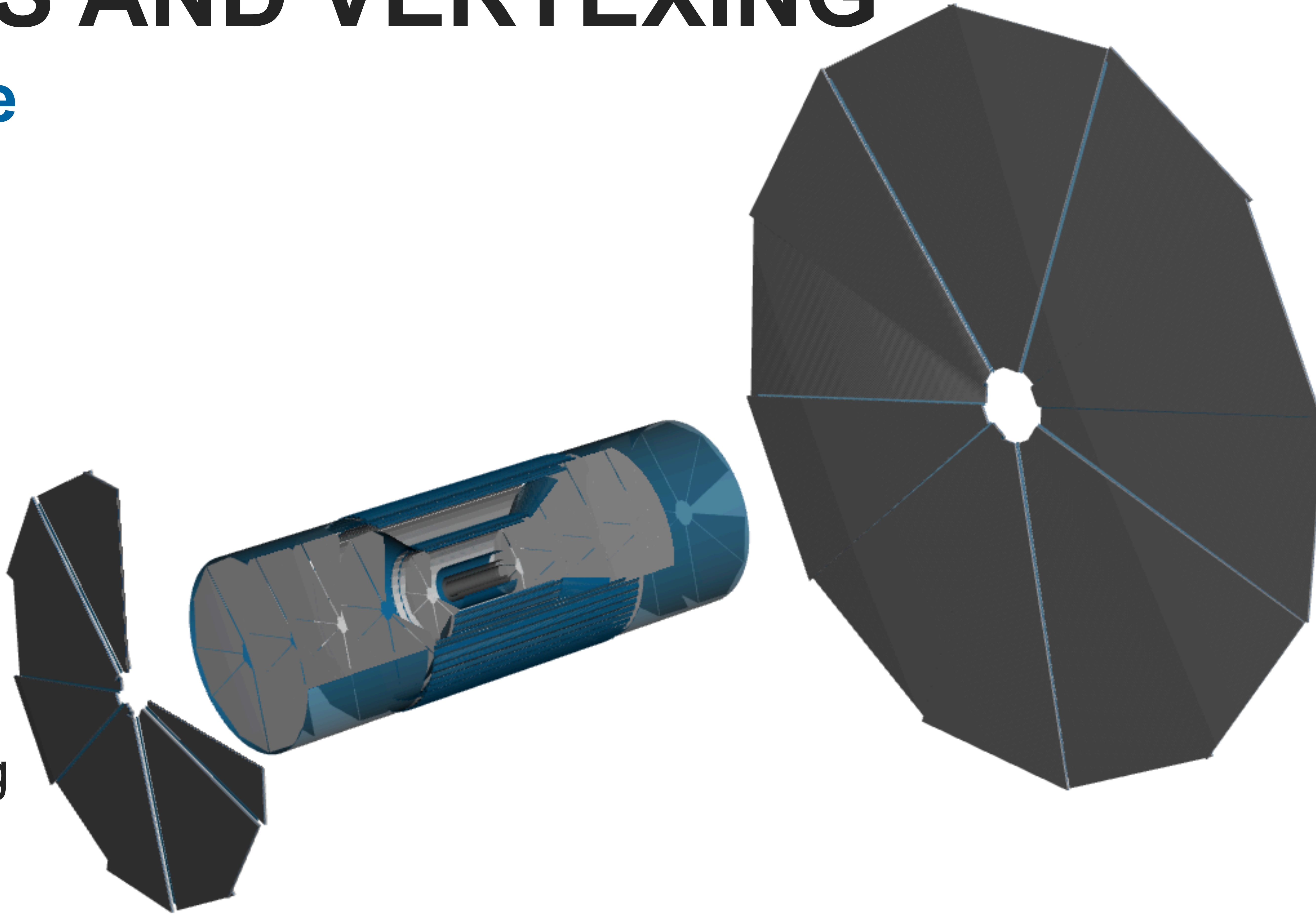
- DIRC has similar challenges (but a much more complex optics system - much more complex ring patterns!).
- Similar argument to the MRICH and DRICH, a natural place to use generative networks.



TRACKING DETECTORS AND VERTEXING

Realistic noise near the beampipe

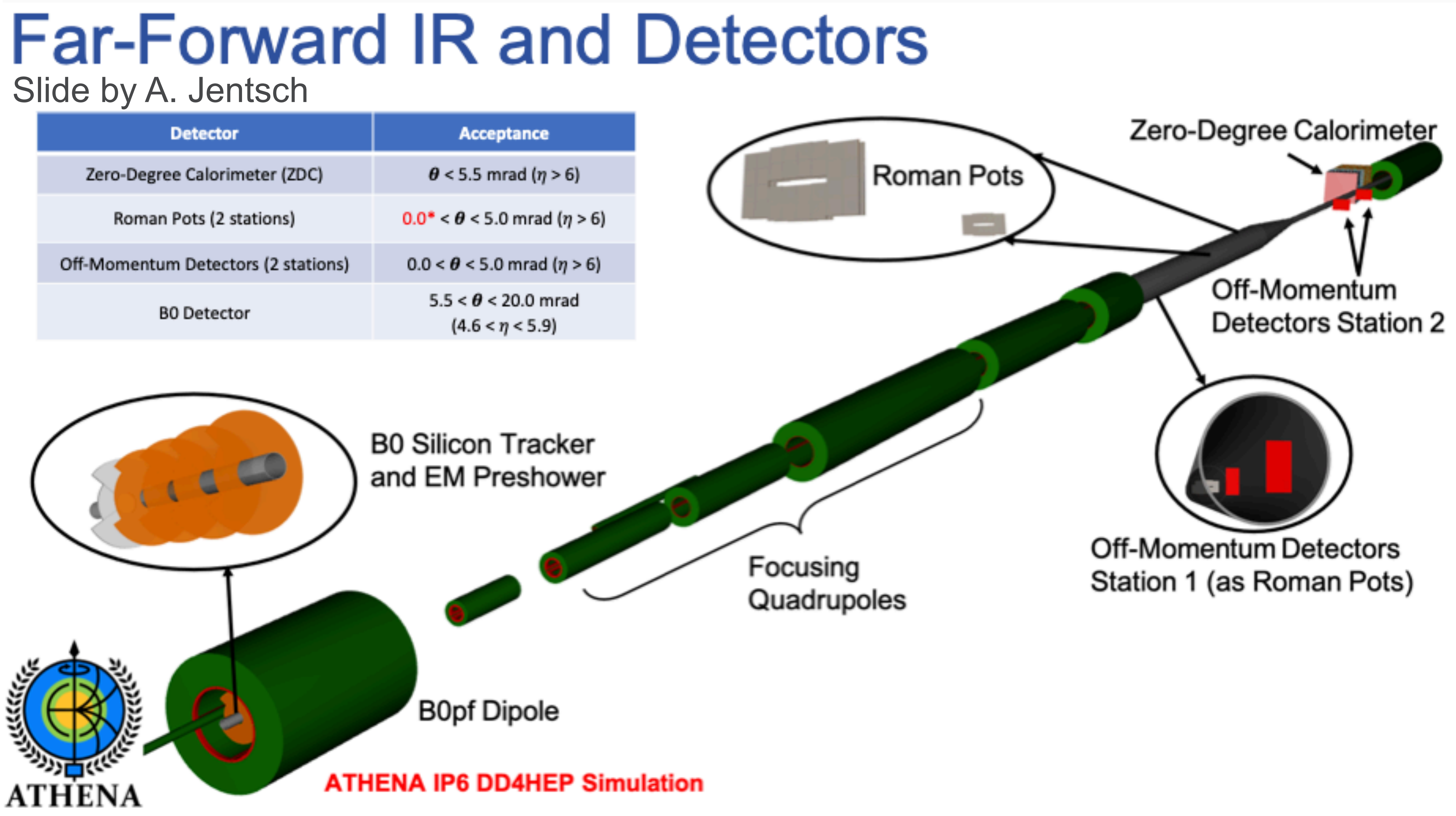
- Tracking detectors only see relatively low numbers of hits (compared to typical HEP scenarios).
- Classical GEANT approach works well here.
- One caveat is the treatment of accelerator effects (beam-gas events, synchrotron radiation, …) impacting in particular the vertex tracker.
- This is currently treated by manually injecting events in the digitization stage.
- It seems that this is another target where we could use AI to inject realistic background noise at the simulation level.



BEAMLINE DETECTOR SYSTEMS

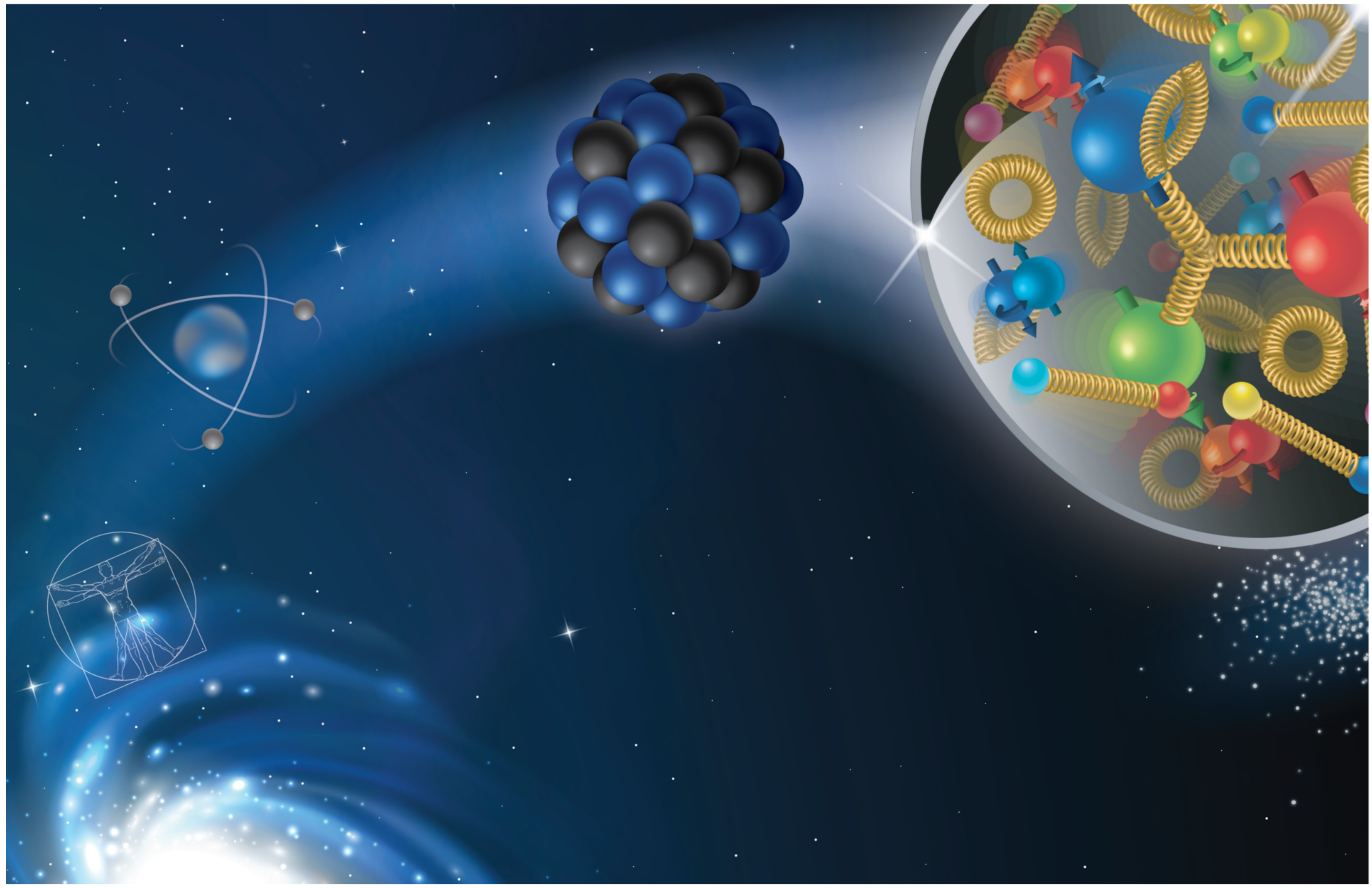
Precision magnet transport over extended distance

- Example: IP6 far-forward detection elements, consisting of Roman Pots, Off-Momentum Detectors and Zero-Degree Calorimeter
- Particle transport through the extended magnet system needs to be done with small step size to get the optics right.
- This important component to EIC events is relatively expensive. A factorized description of the far-forward region (either particle transport or holistic) could significantly speed up simulations.



SUMMARY

- Short-term: need large-scale simulations for optimization of a complex detector system.
- Long-term: need (even larger)-scale simulations to properly analyze high-luminosity/high-precision measurements.
- Bottlenecks usually a combination between many particles, many geometry elements and/or many simulation steps.
- Calorimetry, Cherenkov detectors and the far-forward/far-backward regions are prime targets for AI-driven acceleration.



THE END