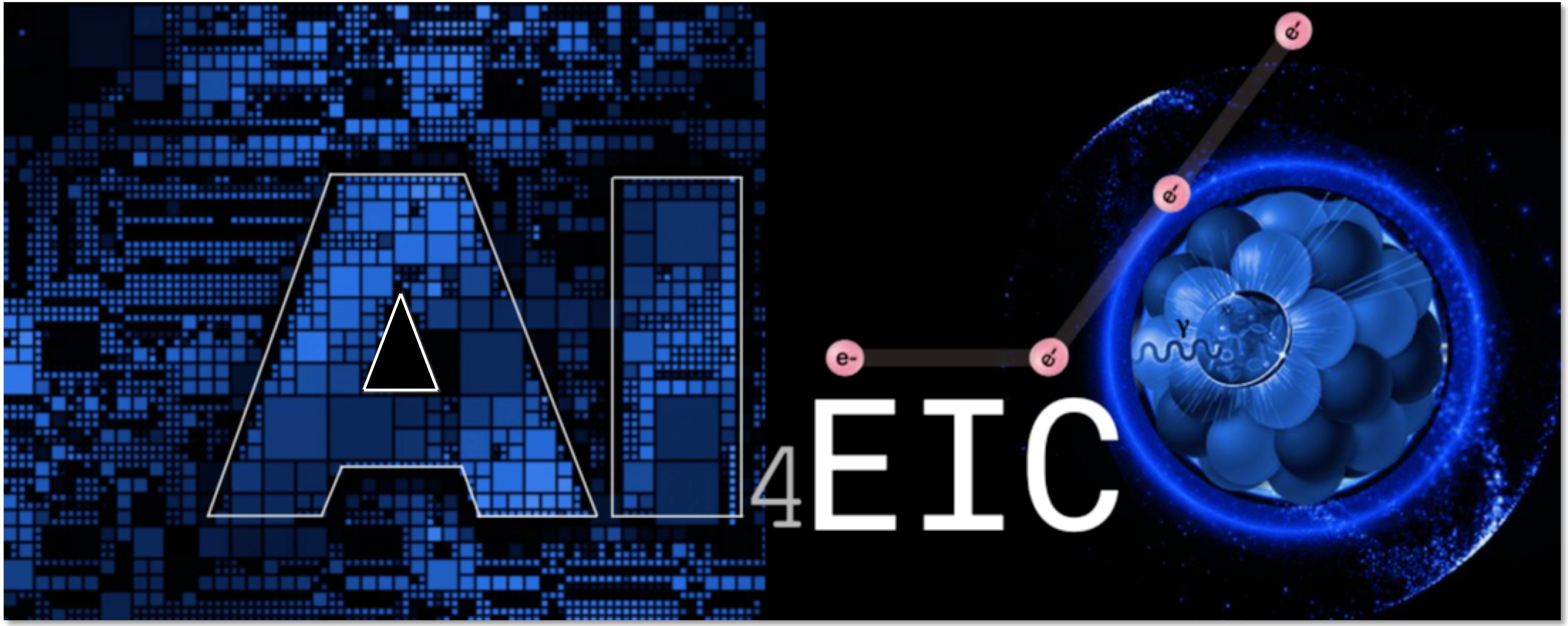
Event Generation and Simulation Needs for the EIC



Markus Diefenthaler

EIC²
EIC Center at Jefferson Lab

Jefferson Lab

Role of simulations in experimental Nuclear Physics

Design Experiments Design and develop detectors and large-scale detector systems. Optimize the design.

Analysis Develop and verify analysis methods and tools as well as analyses of experimental data. Estimate systematic uncertainties.

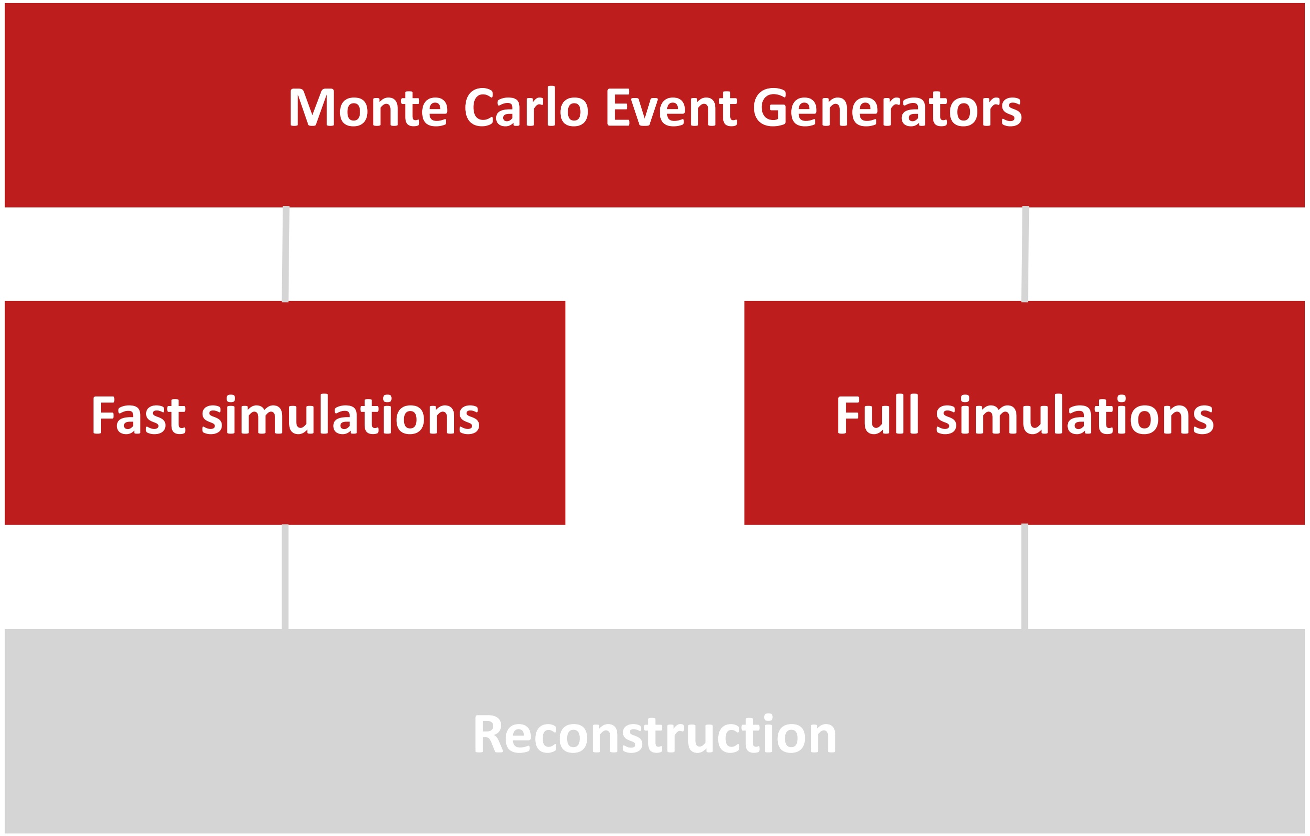
Verify Measurements Detailed simulations essential for commissioning experiments and verify analyses.

Discussion of Event Generation and Simulation Needs

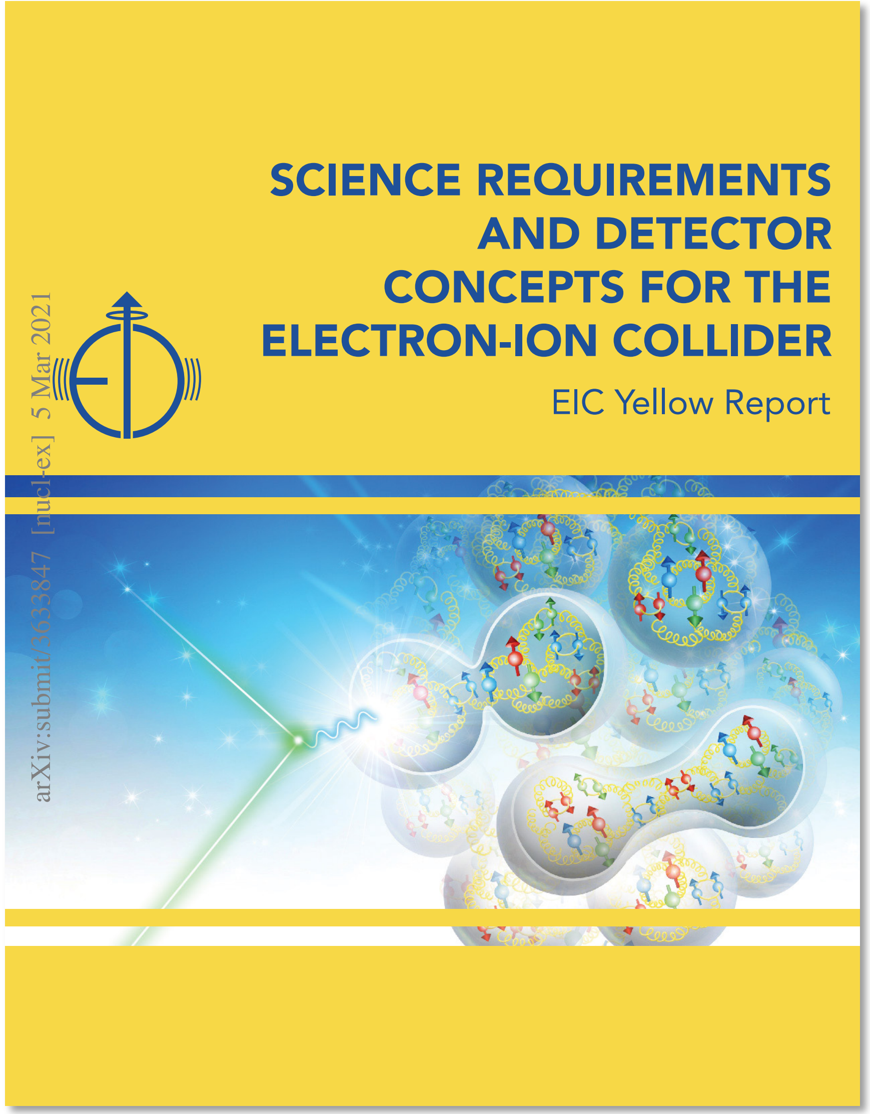
Simulation of physics processes

Simulation of detector responses

Analysis of simulated data



Event Generators for the EIC



Monte Carlo Simulation of

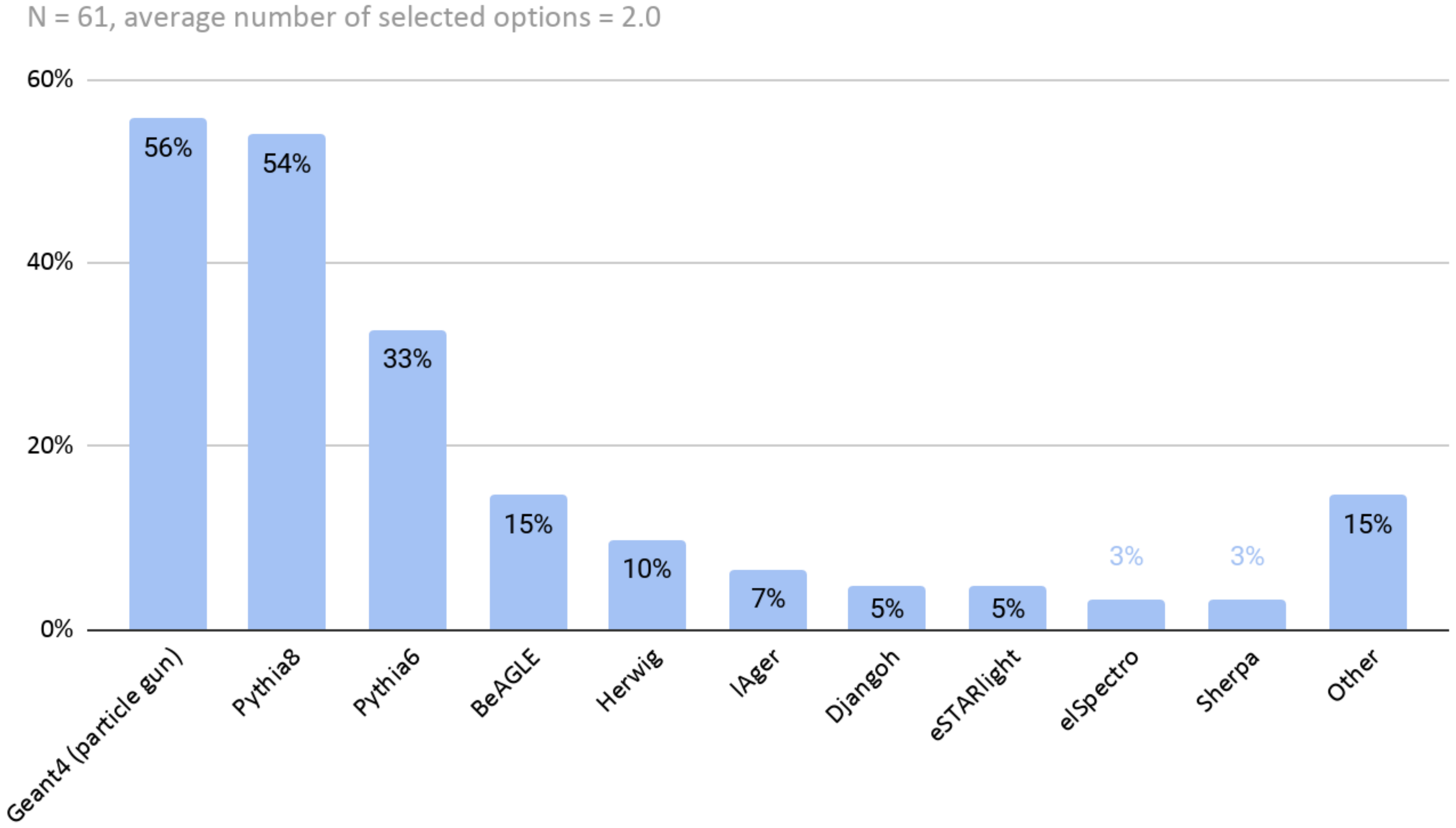
- electron-proton (ep) collisions,
- electron-ion (eA) collisions, both light and heavy ions,
- including higher order QED and QCD effects,
- including a plethora of spin-dependent effects.

Common challenges, e.g. with HL-LHC: High-precision QCD measurements require high-precision simulations.

Unique challenges MCEGs for electron-**ion** collisions and **spin-dependent** measurements, including novel QCD phenomena (e.g., GPDs or TMDs).

MCEGs used for Yellow Report

Source State of Software Survey



Other (N = 9): personal computer codes (N = 2), ACT, CLASDIS, ComptonRad, GRAPE-DILEPTON, MADX, MILOU, OPERA, RAYTRACE, Sartre, Topeg, ZGOUBI

MCEG R&D for EIC

MCEG for ep On a good path, but still a lot of work ahead.

- **General-purpose MCEG**s, HERWIG, PYTHIA, and SHERPA, will be significantly improved w.r.t. MCEGs at HERA time:
- Comparisons with HERA data and QCD predictions critical:
  - To learn where physics models need to be improved,
  - To complement MC standard tunes with first DIS/HERA tune.
- The existing general-purpose MCEG should be able to simulate NC and CC unpolarized observables also for eA. A precise treatment of the nucleus and, e.g., its breakup is needed.
- First parton showers and hadronization models for ep with spin effects, but far more work needed for polarized ep / eA simulations.
- Need to clarify the details about merging higher QED+QCD effects (in particular for eA).

MCEG for eA Less clear situation about theory and MCEG.

- **Pioneering projects**, e.g., BeAGLE, spectator tagging in ed, Sartre.
- **Active development,** e.g., eA adaptation of JETSCAPE, Mueller dipole formalism in Pythia8 (ala DIPSY).

Example Project: Compare MCEGs Results with HERA Data

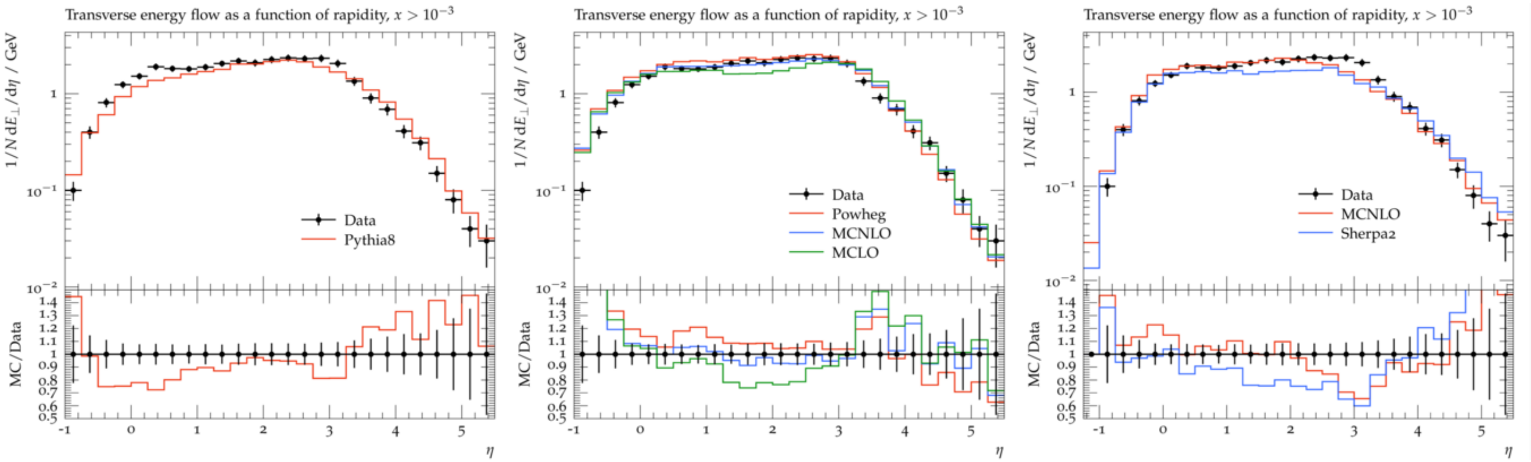
MCEG R&D requires *easy* access to *data:*

- data := analysis description + data points

HEP existing workflow using Rivet.

Ongoing activity with EIC-India and MCnet:

- Comparison to published results using RIVET and understand differences.
- **Provide initial findings and results in publication (work in progress)::**
  - Overview of where we stand in understanding HERA data with current physics and models implement in MCEGs.



Pythia8 Herwig7 Sherpa2

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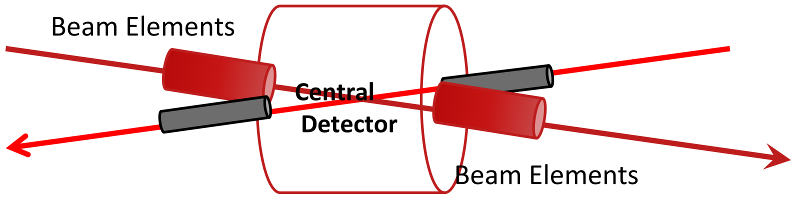
Machine-Detector interface (MDI)

Integrated interaction region and detector design to optimize physics reach

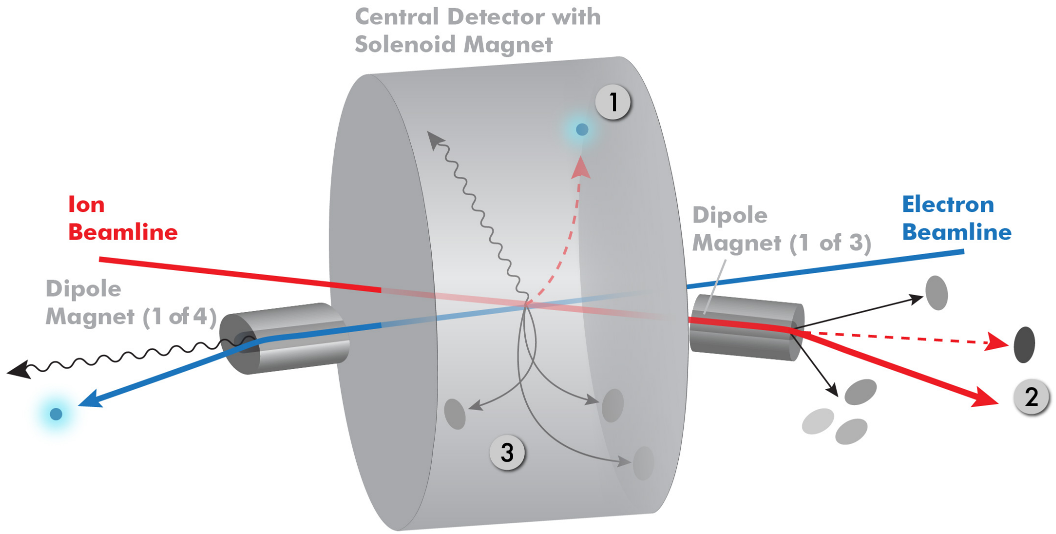
The aim is to get **~100% acceptance** for all final state particles, and measure them with good resolution.



Experimental challenges:

- beam elements limit forward acceptance
- central Solenoid not effective for forward

Possible to get ~100% acceptance for the whole event.



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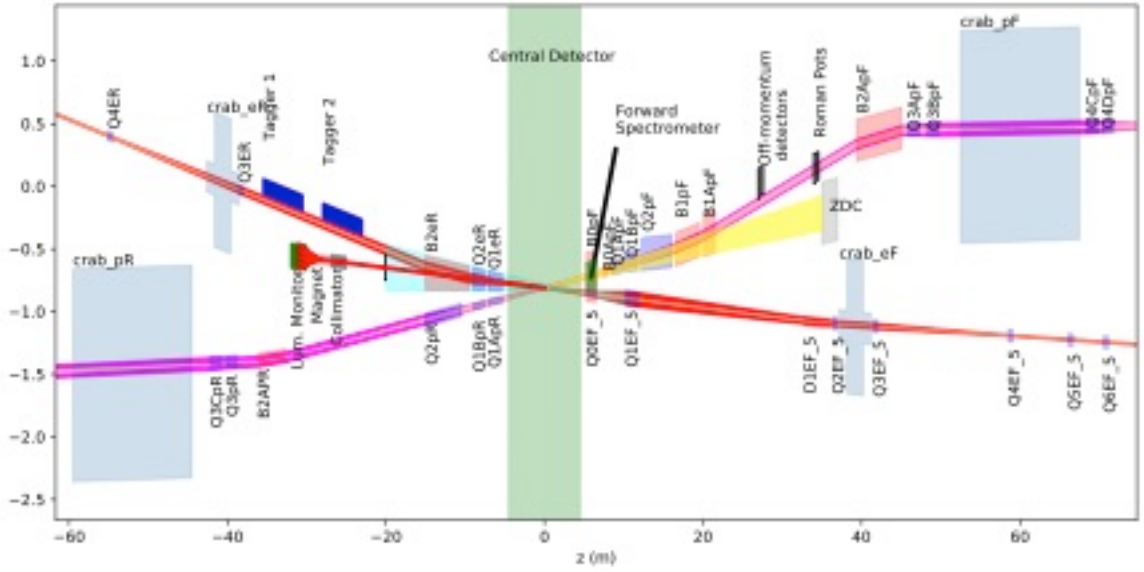
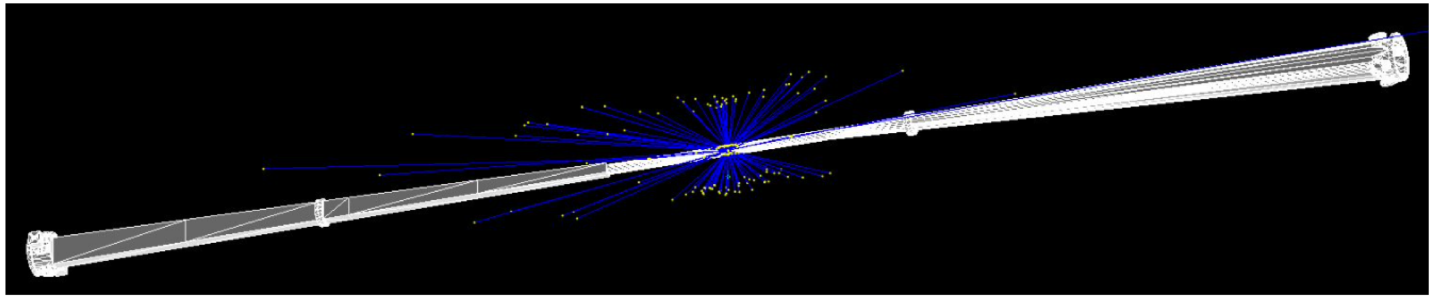
MDI in Simulations

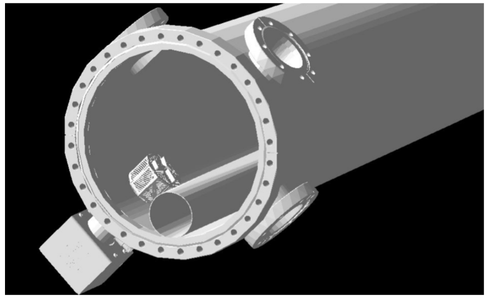
IR Layout



Unprecedented integration of IR and detector (shown here for IP6).

CAD Interface (accelerator elements and service structures)

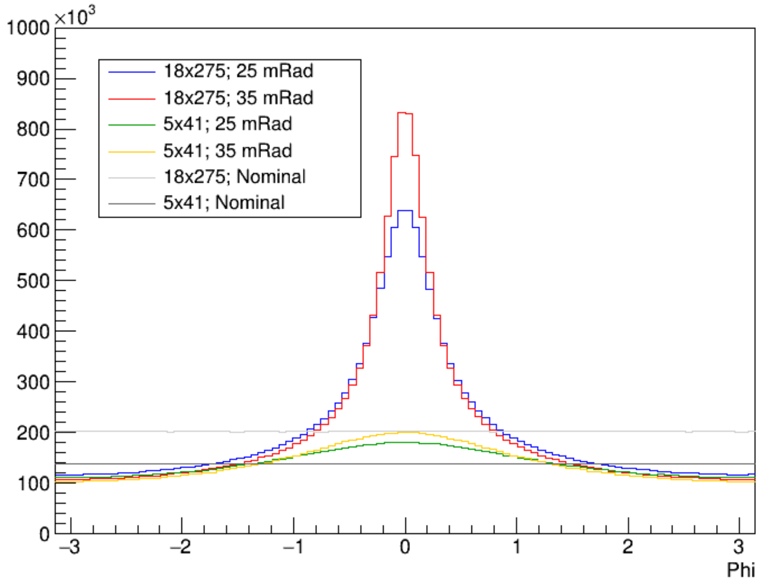


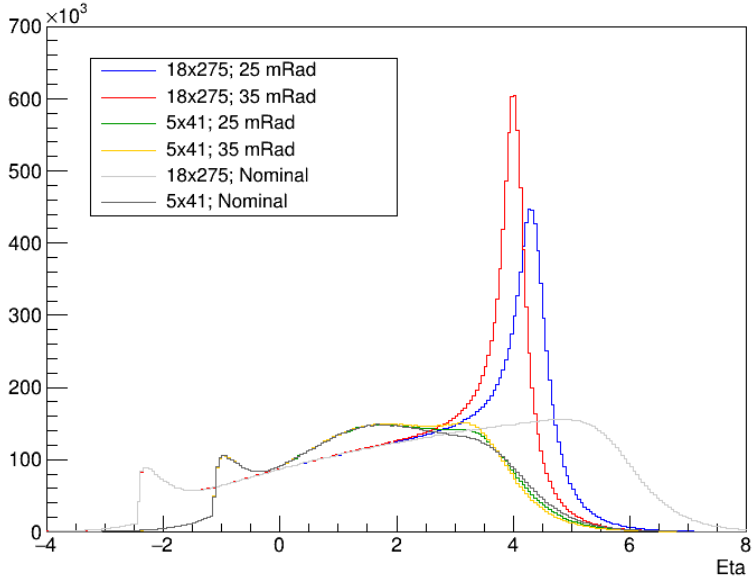


EIC Project

Simulation based (in part) on CAD files provided by EIC project engineering teams, rather than a bottoms-up reliance on constructive solid geometry (Screenshots from **eAST**)

Accelerator and Beam Conditions Critical for EIC Simulations





- **Accelerator and beam effects that influence EIC measurements**
  - Beam crossing angle,
  - Crabbing rotation,
  - Beam energy spread,
  - Angular beam divergence,
  - Beam vertex spread.

- **Note for EIC Community** https://eic.github.io/resources/simulations.html
  - Profound consequences on measurement capabilities of the EIC and layout of the detectors,
  - How to integrate these effects in EIC simulations.
  - **Authors** J. Adam, E.-C.Aschenauer, M. Diefenthaler, Y. Furletova, J. Huang, A. Jentsch, B. Page.

Beyond that Include beam background estimates in simulations.

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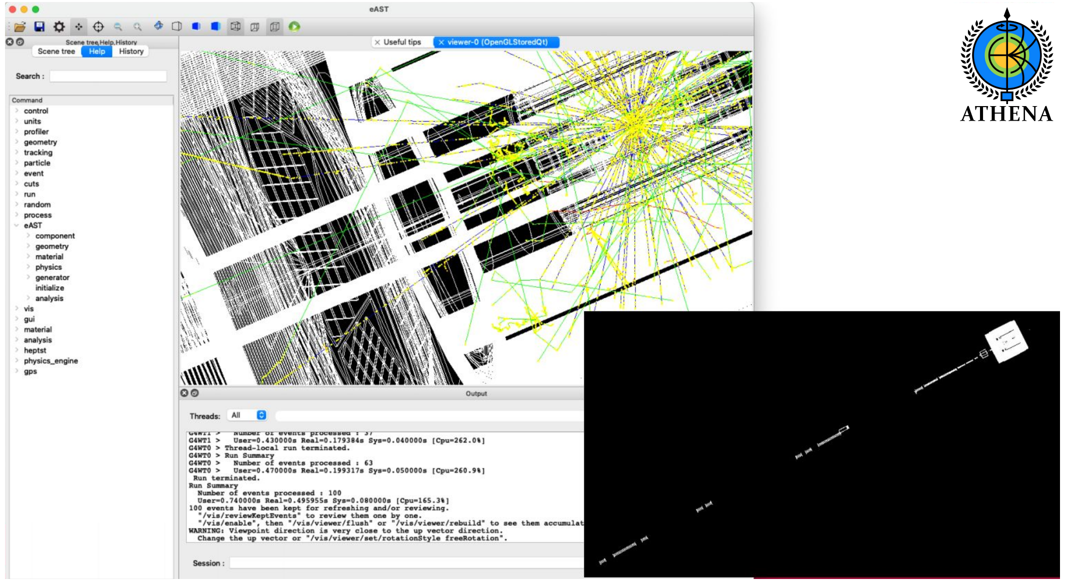
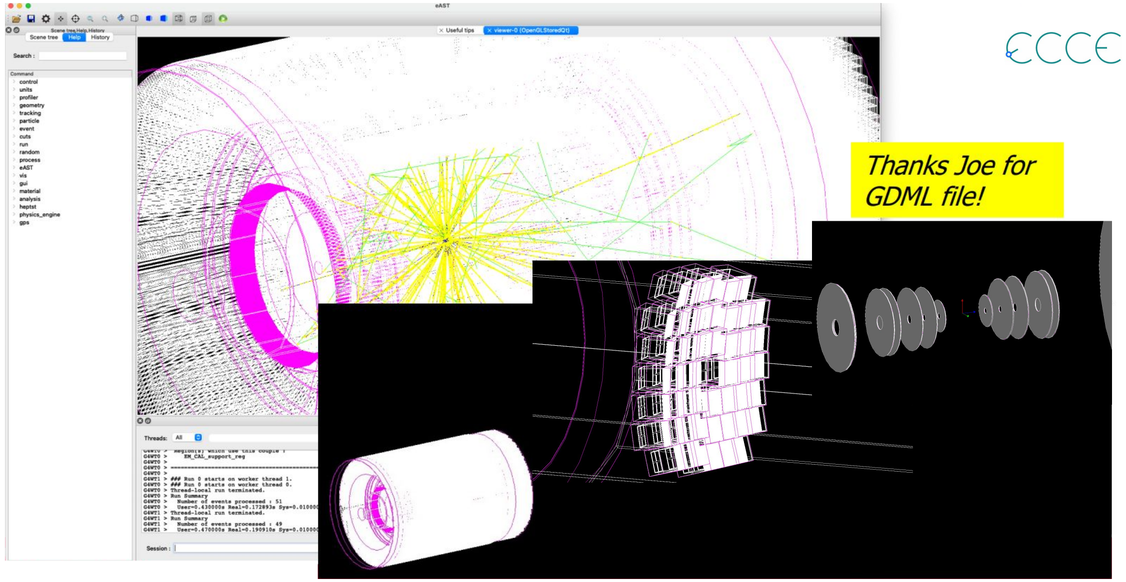
Detector simulations and Geant4

(Screenshots from **eAST**)

EIC

- Detector (and physics) simulations rely on **Geant4,** the **(!)** detector simulation toolkit for HEP and NP:
    - Detector full simulations for ATHENA and ECCE detector concepts based on **Geant4**.
    - As GeantV comes up at times:
        - Project concluded: no performance gain from the vectorization of the individual software components,
        - Modular software packages such as VecGeom integrated into **Geant4**.
- Energy range is different from LHC,
- validation, tuning and extension including test beam studies required.
- Ongoing collaboration with international Geant4 collaboration, including Technical Forum on NP/EIC.





Thanks Joe for GDML file!

The role of AI/ML in simulations

Lesson learned High-precision QCD measurements require high-precision simulations

Statistical accuracy for precise hypothesis testing

- up to trillion of simulated events required (HL-LHC)
- often computationally intensive, in particular calorimeter simulations

Common alternatives

- fast simulations with computationally efficient approximations, e.g., parameterizations or look-up tables
- **still** insufficient accuracy for high-precision measurements

Promising alternatives

- fast generative models, e.g., GANs or VAEs
- AI driven design, e.g., Bayesian optimization

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THE EUROPEAN PHYSICAL JOURNAL A

Review

A.I. for nuclear physics

Paulo Bedaque[1], **Amber Boehnlein**[2,a], **Mario Cromaz**[3], **Markus Diefenthaler**[2], **Latifa Elouadrhiri**[2], **Tanja Horn**[4], **Michelle Kuchera**[5], **David Lawrence**[2], **Dean Lee**[6], **Steven Lidia**[6], **Robert McKeown**[2], **Wally Melnitchouk**[2], **Witold Nazarewicz**[6], **Kostas Orginos**[2,7], **Yves Roblin**[2], **Michael Scott Smith**[8], **Malachi Schram**[9], **Xin-Nian Wang**[3]

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Communicated by Ulf Meissner

Abstract This report is an outcome of the workshop AI for Nuclear Physics held at Thomas Jefferson National Accelerator Facility on March 4–6, 2020

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This report is an outcome of the workshop *AI for Nuclear Physics* held at Thomas Jefferson National Accelerator Facility on March 4–6, 2020. The workshop brought together 184 scientists to explore opportunities for Nuclear Physics in the area of Artificial Intelligence. The workshop consisted of plenary talks, as well as six working groups.

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Springer

Jefferson Lab

Common Software Effort

EIC User Group

Steering Committee

Software Working Group

Proto-Collaborations

ATHENA

CORE*

ECCE

Simulation Working Groups

liaisons

* CORE adapts existing software for their needs and has a far smaller software effort than other proto-collaborations.

HEP Community

Collaboration with **Geant4** and **HEP Software Foundation**

Data Science Community

- EIC as a driver for research in CS and applied math
- scientific, systematic approach to AI / ML approaches to NP
- activation functions, DNN design particular for NP
- building efficient DNNs no more complex than necessary

EICUG Software Working Group

127 members

Electron-Ion Collider User Group

The world's most powerful microscope for studying the "glue" that binds the building blocks of visible matter.

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EIC Software

Software Working Group

The Software Working Group (SWG) is open to all members of the EICUG to work on EICUG related software tasks. It communicates via its mailing list and organizes regular online and in-person meetings that enable broad and active participation from within the EICUG as a whole.

The SWG has participated in the call for Expressions of Interest (EoI) and intends to carry its EoI for Software forward as a living document that will evolve towards a work plan for the SWG, setting priorities for the next years and goals for the next decade.

In addition to that, it will support the work on the simulation efforts for the collaboration proposals for detectors at the EIC.

For questions about the Software Working Group, please contact the conveners (Andrea Bressan (Trieste), Markus Diefenthaler (JLab), and Torre Wenaus (BNL)).

Important links

Mailing list	eicug-software@eicug.org (subscribe via Google Group)
EIC organization on GitHub	https://github.com/eic
Website	https://eic.github.io

Common Projects: Expression of Interest for Software

https://eic.github.io/activities/eoi.html

Expression of Interest (EOI) for Software

Please indicate the name of the contact person for this submission:

Conveners of the Software Working Group:
- A. Bressan, M. Diefenthaler, and T. Wenaus
- eicug-software-conveners@eicug.org

Please indicate all institutions collectively involved in this submission of interest:

29 institutions

ANL	Argonne National Laboratory
BNL	Brookhaven National Laboratory
CEA/Irfu	IRFU at CEA /Saclay institute
EIC-India	Akal University, Central University of Karnataka, DAV College Chandigarh, Goa University, Indian Institute of Technology Bombay, Indian Institute of Technology Delhi, Indian Institute of Technology Indore, Indian Institute of Technology Patna, Indian Institute of Technology Madras, Malaviya National Institute of Technology Jaipur, Panjab University, Ramkrishna Mission Residential College Kolkata
IMP-CAS	Institute of Modern Physics - Chinese Academy of Sciences
INFN	Istituto Nazionale di Fisica Nucleare
JLab	Thomas Jefferson National Accelerator Facility
LANL	Los Alamos National Laboratory
LBNL and UC Berkeley	Lawrence Berkeley National Laboratory and University of California, Berkeley
NCBJ	National Centre for Nuclear Research
OhioU	Ohio University
ORNL	Oak Ridge National Laboratory
SBU	Stony Brook University
SLAC	SLAC National Accelerator Laboratory
SU	Shandong University

https://indico.bnl.gov/event/8552/contributions/43221/

- **Software Tools for Simulations and Reconstruction**
  - **Monte Carlo Event Generators** focus on validation
  - **Detector Simulations**
  - **Reconstruction**
  - **Validation**
- **Middleware and Preservation**
  - **Workflows** Simple examples for job submission
  - **Data and Analysis Preservation** REANA
- **Interaction with the Software Tools**
  - **Explore User-Centered Design**
  - **Discoverable Software** cvmfs/spack
  - **Data Model** Common data format
- **Future Technologies**
  - Artificial Intelligence
  - Heterogeneous computing
  - New languages and tools
  - Collaborative software

Towards a Next-Generation Simulations

ELECTRON ION COLLIDER USER GROUP
STATE OF SOFTWARE SURVEY

Survey from February 16 – 23, 2021. report

There are **too many generators and simulation tools** used at the moment.

Unify the Simulation Effort

- The SWG is preparing to launch a **common effort on next-generation simulations**:
  - building on the work done in the existing simulations,
  - unify the software community behind one common effort,
  - a requirement for the common framework is that it integrate the existing detector simulations in a modular way.

Project eAST in a nutshell

18 developers and growing

Detector Simulation

- **comprehensive, centrally maintained application**
- **based on Geant4 for fast and full simulations**
- **with library of potential detector options**

Requirements

- ability to **reuse existing simulation work**
- ease of **switching detector options**
- ease of switching between **detailed and coarse** detector descriptions
- ease of **leveraging new and rapidly evolving** technologies,
  - AI/ML to accelerate simulations
  - computing hardware, e.g., heterogeneous architectures
    - AI/ML is the best near term prospect for using LCF/Exascale effectively

Project Leader

- Makoto Asai, Geant4 project leader and deep technical expert for >20yrs.

Markus Diefenthaler

mdiefent@jlab.org

Summary

- **Simulations** essential for design of experiments, data analysis, and verification of measurements.
- **Simulations** for the **EIC**, i.e. MCEGs and fast and full detector simulations for the EIC, require **R&D**. We miss core capabilities and we need to work towards accuracy and precision.
- **Simulation R&D** is most efficiently done in common projects and in collaboration with other fields, e.g., HEP or data science.
- Many opportunities for AI/ML to complement and improve **simulations**. While AI/ML approaches will substitute part of **simulation workflows**, they will not replace core tools, e.g., general-purpose MCEGs or Geant4.