Monte Carlo for the EIC

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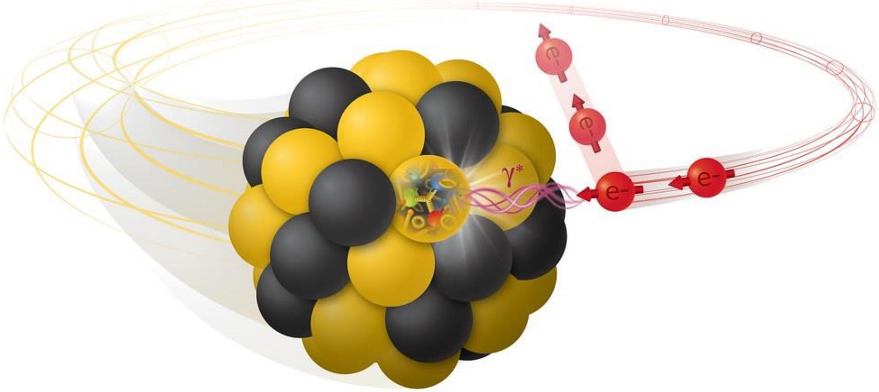
Uncovering New Laws of Nature at the EIC

November 20, 2024



Introduction

- ☐ Physics simulations utilizing Monte Carlo Event Generators (MCEGs) are an essential component of the process linking experimentation and theory to broader scientific understanding
- ☐ What unique challenges will the EIC science program place on MCEGs?
- ☐ What new MCEG features need to be developed in order to maximize the scientific output of the EIC?
- ☐ How can MCEGs aid in the design of the EIC collider and detectors?
- ☐ How can we take advantage of synergies with the wider HEP and MCEG developer communities?

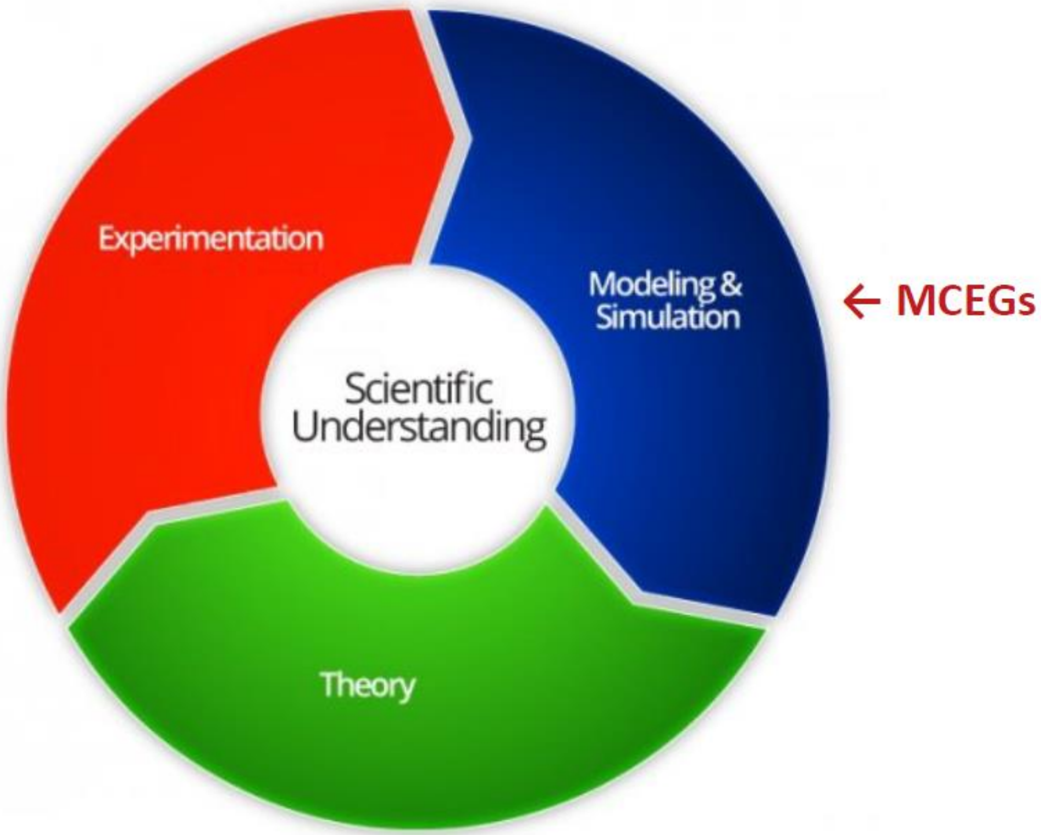
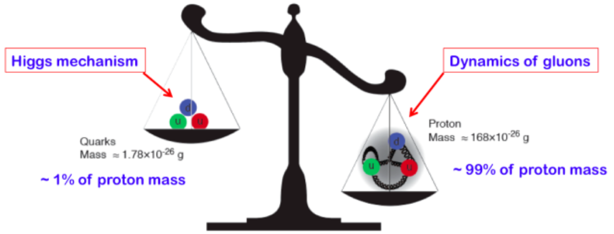


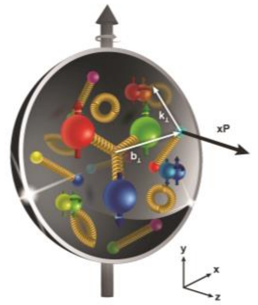
Figure by M. Diefenthaler

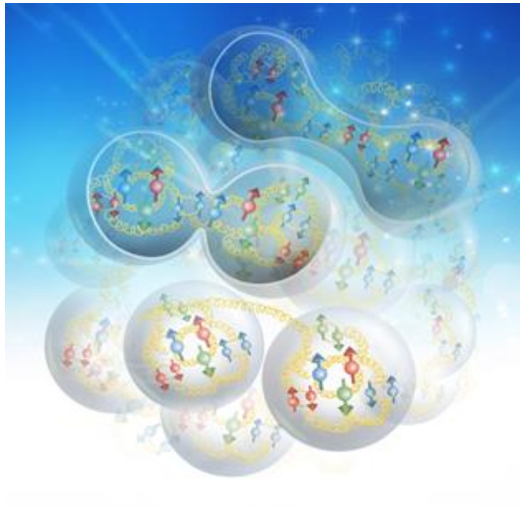
The EIC: An Extensive Science Program

How are the sea quarks and gluons, and their spins, distributed in space and momentum inside the nucleon?

How do the nucleon properties emerge from them and their interactions?







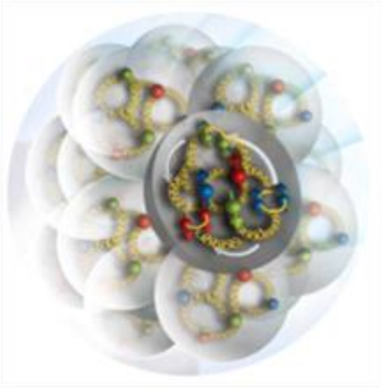
How do color-charged quarks and gluons, and colorless jets, interact with a nuclear medium?

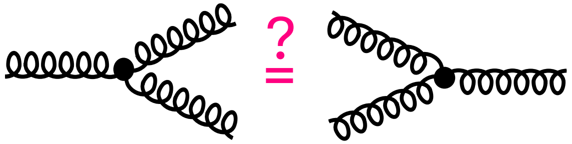
How do the confined hadronic states emerge from these quarks and gluons?

How do the quark-gluon interactions create nuclear binding?

How does a dense nuclear environment affect the quarks and gluons, their correlations, and their interactions?

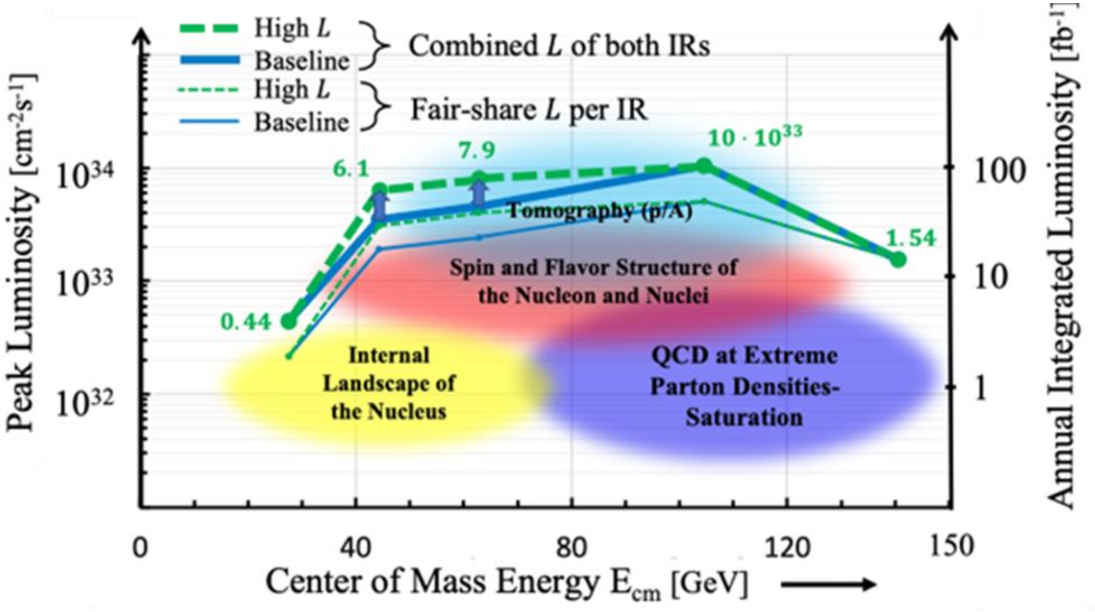
What happens to the gluon density in nuclei? Does it saturate at high energy, giving rise to a gluonic matter with universal properties in all nuclei, even the proton?

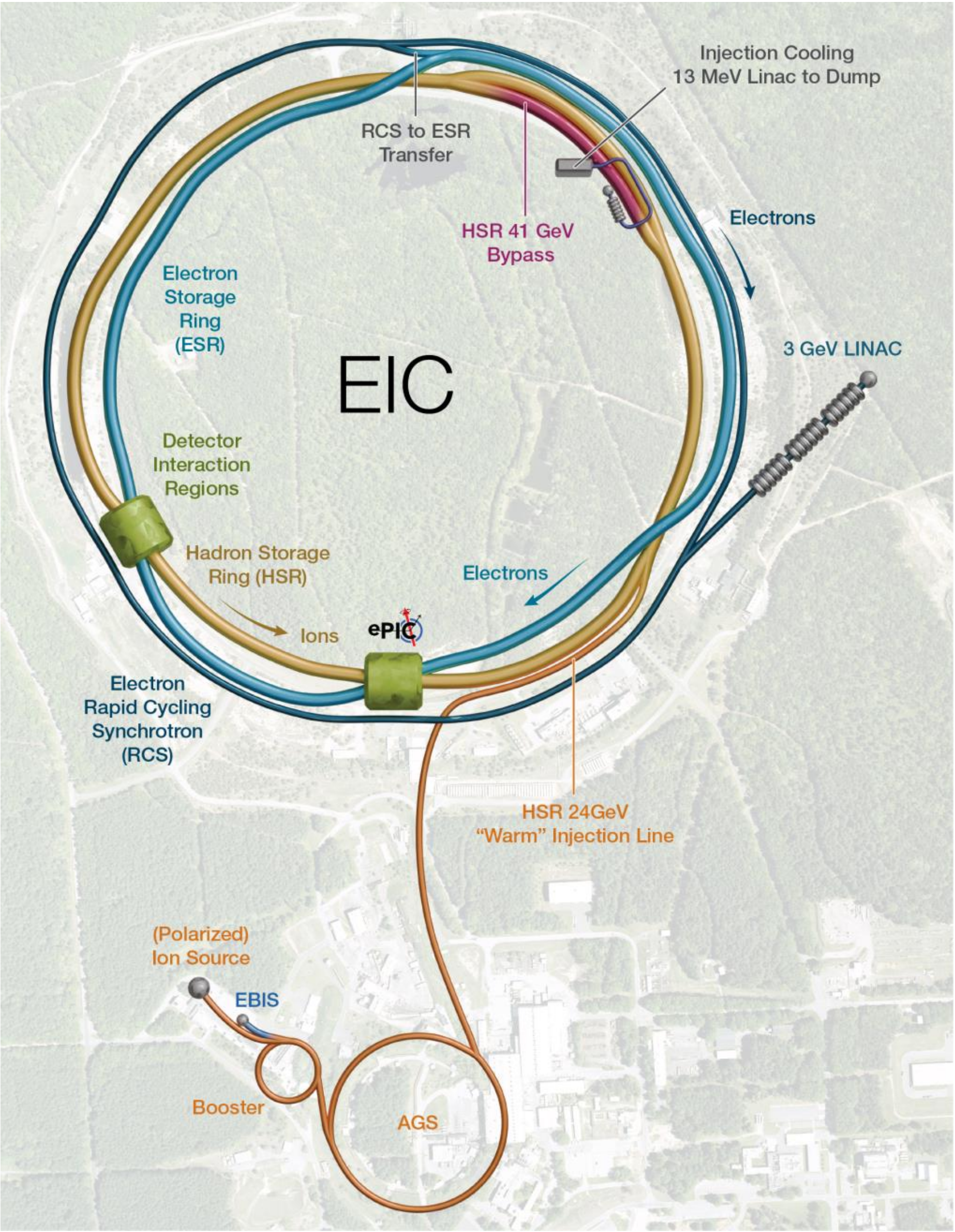




The EIC: A Versatile Machine

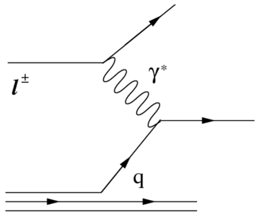
- ☐ High Luminosity: L = 10^{33} – 10^{34} cm^{-2}/s
  - ☐ 10 – 100 fb^{-1}/year
- ☐ Polarization of electron and proton (and light ion) beams up to 70%
- ☐ Large center of mass energy range: E_{cm} = 29 – 140 GeV
- ☐ Large ion species range: protons - Uranium





The EIC: A Large and Varied Phase Space

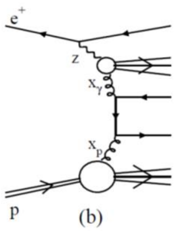
- ☐ Center of mass energies available at the EIC will give access to a large phase space
- ☐ Phase space includes different dominant subprocesses and relevant hadronic dynamics
- ☐ Need MCEGs which can consistently describe physics across this landscape and interpolate smoothly between different regions

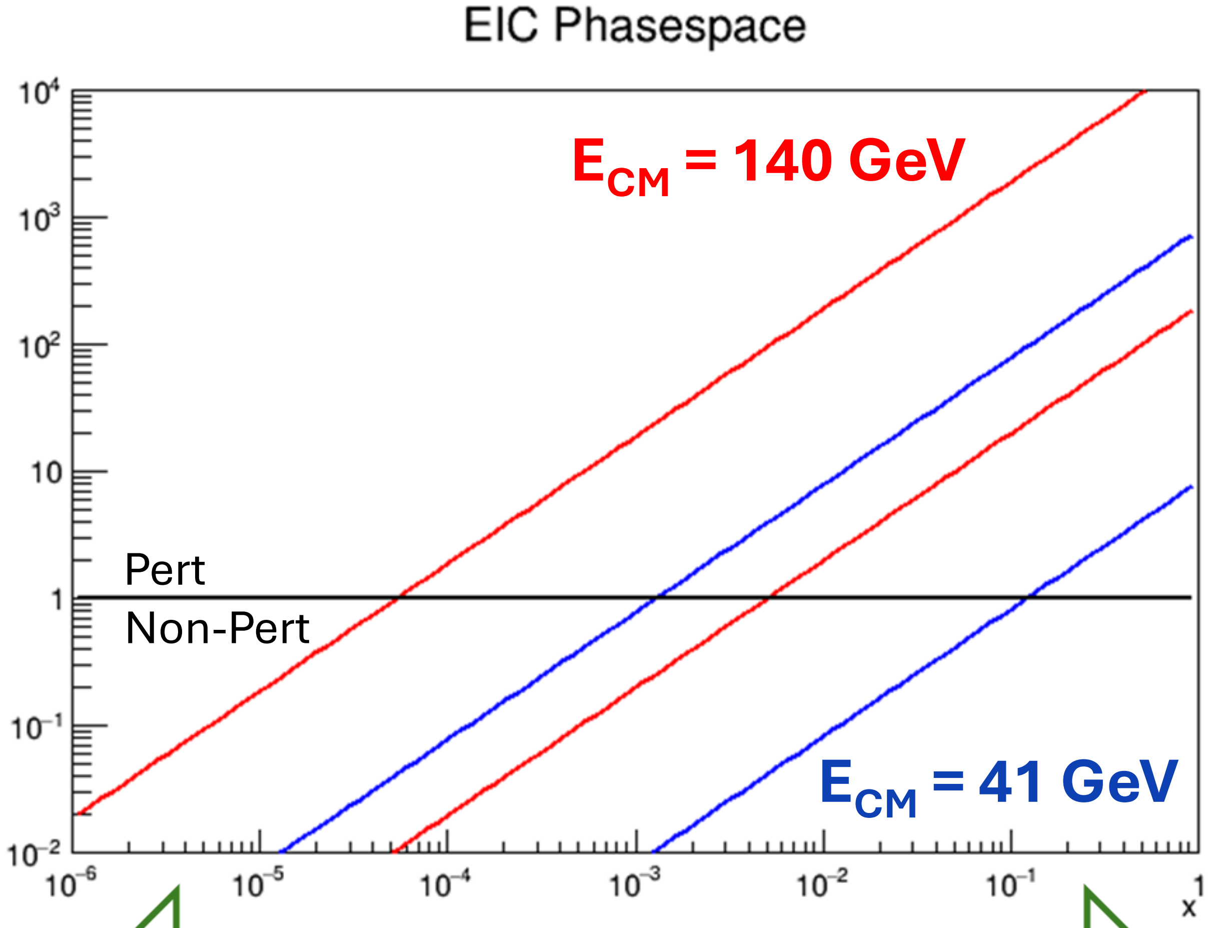


DIS

Q^2

Photo-Production

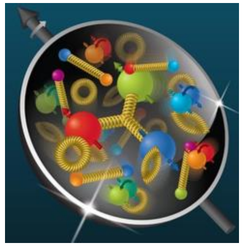


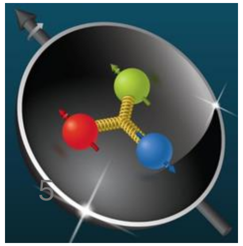


Gluonic

X

Valence





The EIC Monte Carlo Landscape (Not Exhaustive)

Legacy Monte Carlos

- ❑ RAPGAP
  - ➢ https://rapgap.hepforge.org/
  - ➢ DIS and diffractive ep
- ❑ DJANGOH
  - ➢ https://www.desy.de/~hspiesb/mcp.html
  - ➢ NC and CC DIS with radiative effects
  - ➢ Polarized DIS
- ❑ PEPSI
  - ➢ Comp. Phys. Comm. 71, 305-318 (1992)
  - ➢ Polarized DIS

General Purpose Monte Carlos

- ❑ PYTHIA 8
  - ➢ https://pythia.org/
  - ➢ DIS: Dipole shower, Vincia, DIRE
  - ➢ Photoproduction with PS and MPI
- ❑ Sherpa 2
  - ➢ https://sherpa-team.gitlab.io/
  - ➢ DIS with matching/merging
  - ➢ Photoproduction at NLO
- ❑ Herwig 7
  - ➢ https://herwig.hepforge.org/index.html
  - ➢ DIS with NLO merging
  - ➢ No photoproduction yet

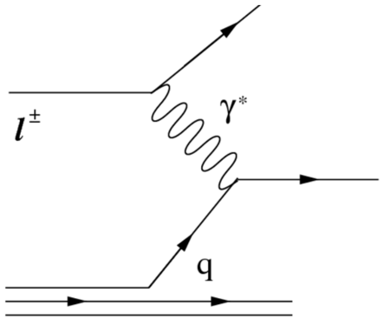
Specialized Monte Carlos

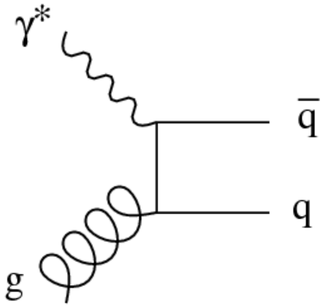
- ❑ CASCADE
  - ➢ *Eur.Phys.J.C* 81 (2021) 5, 425
  - ➢ TMDs
- ❑ Milou
  - ➢ arXiv:hep-ph/0411389
  - ➢ Older GPD generator
- ❑ ePIC
  - ➢ arXiv:2205.01762
  - ➢ Modern GPD generator
- ❑ BeAGLE
  - ➢ arXiv:2204.11998
  - ➢ eA generator with nuclear breakup
- ❑ SARTRE
  - ➢ https://sartre.hepforge.org/
  - ➢ DVCS and DVMP

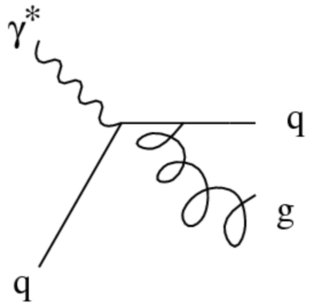
Needs for General Purpose MCEGs

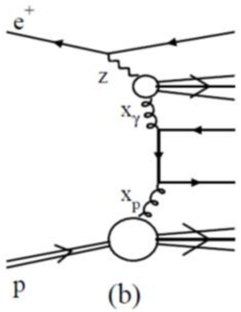
- EIC measurements will cover both the photoproduction and electroproduction regions
- Many different subprocesses (DIS, H.O., diffractive) will be relevant for different measurements in different kinematic regions

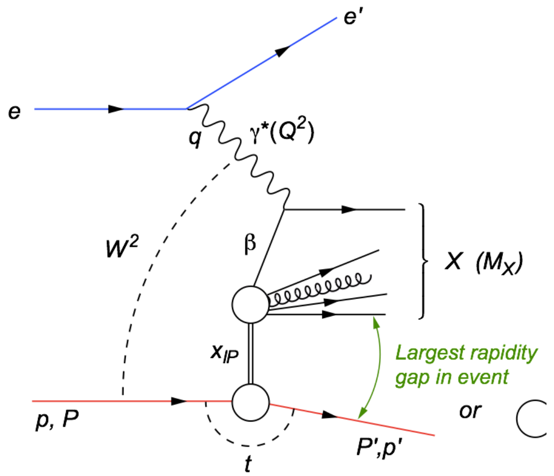
General purpose MCEGs need to be able to ‘smoothly’ move between photoproduction and electroproduction regimes with consistent subprocess cross section behavior. A ‘min-bias’ setting that automatically incorporates all subprocesses in a given Q^2 range in the appropriate ratios would be very useful.





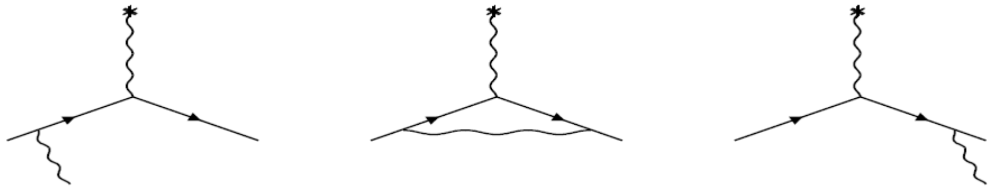




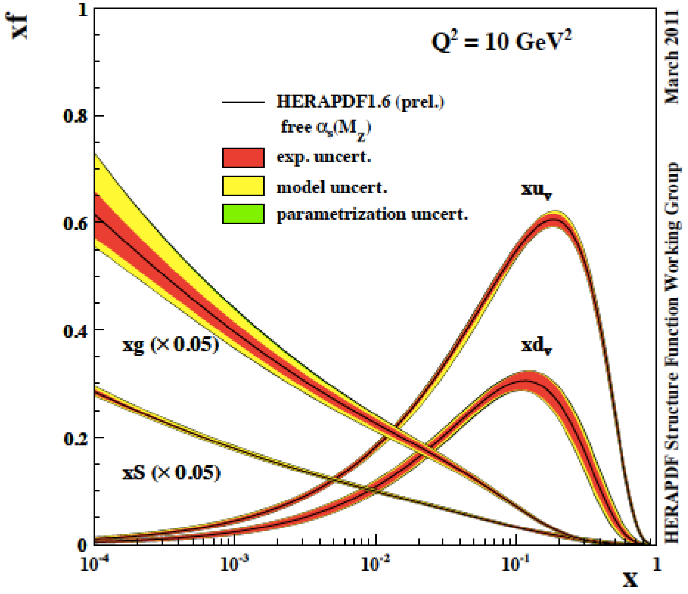


Collinear Structure

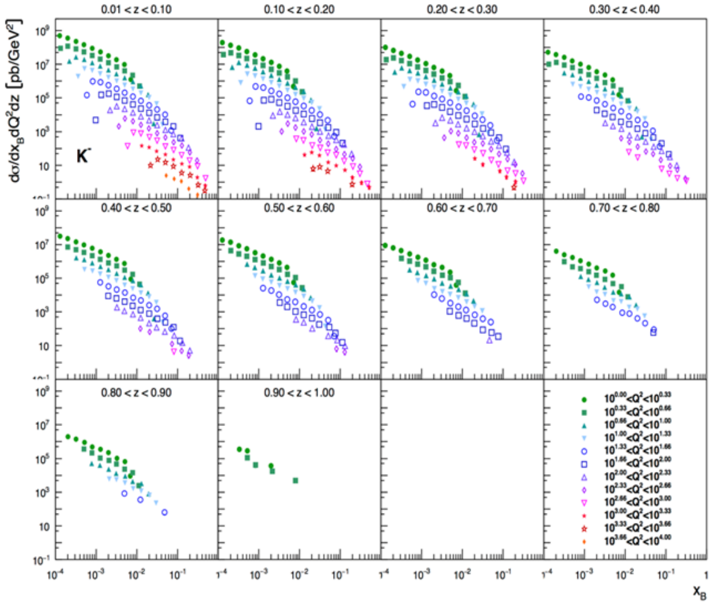
- ❑ Nearly every measurement at the EIC will require precise knowledge of event kinematics (x, Q^2, etc)
- ❑ This is especially true of measurements to constrain PDFs/FFs



MCEGs should incorporate precise QED radiative corrections so impacts on kinematics can be determined and correction / mitigation strategies developed



Phys.Rev.D 99 (2019) 9, 094004



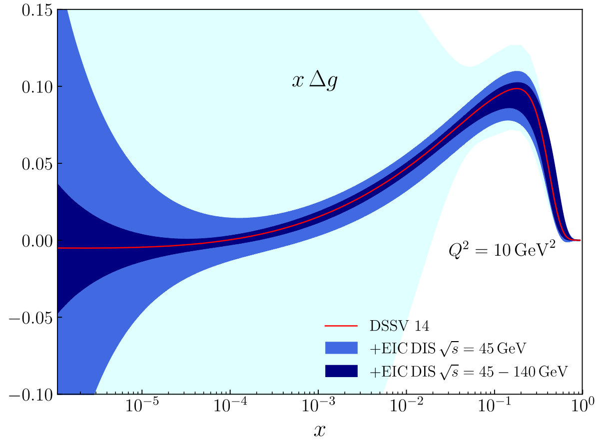
- ❑ Consider newer RC techniques like those proposed in *Phys.Rev.D* 104 (2021) 9, 094033 which treat QED and QCD radiation on equal footing
- ❑ Should move toward simultaneous extraction of PDFs and FFs

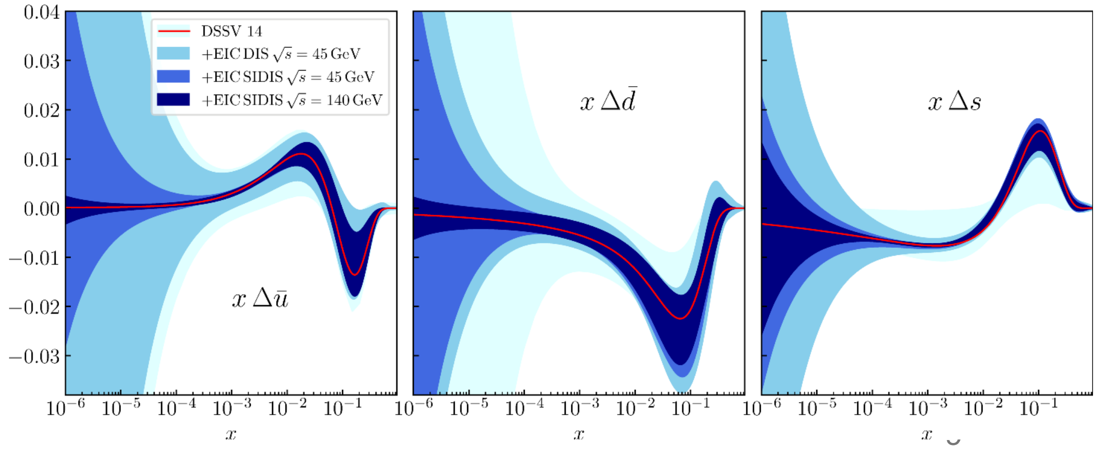
Nucleon Structure: Helicity

- EIC will allow measurements of the (un)polarized structure of the nucleon with unparalleled precision over a wide kinematic range
  - Helicity PDFs
  - TMDs
  - GPDs

MCEGs should incorporate polarization into all stages of simulation: initial state, hard-scattering, and shower / hadronization to reduce biases and systematic effects in measurements

Phys.Rev.D 102 (2020) 9, 094018

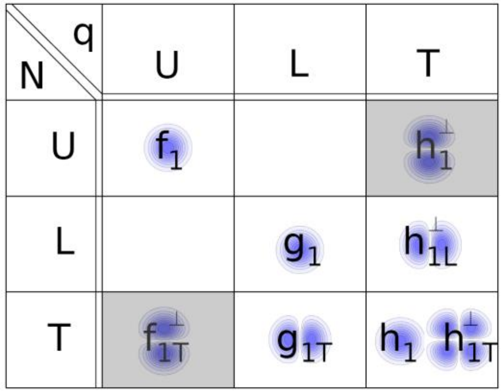




- Legacy polarized generators exist (e.g. PEPSI and DJANGOH)

- New MCEGs should also include:
  - NLO descriptions of NC and CC (SI)DIS
  - Access to modern (un)polarized PDFs
  - Polarized radiative corrections

Nucleon Structure: TMDs



N \ q	U	L	T
U	f_1		$h_1^\perp$
L		g_1	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1 $h_{1T}^\perp$

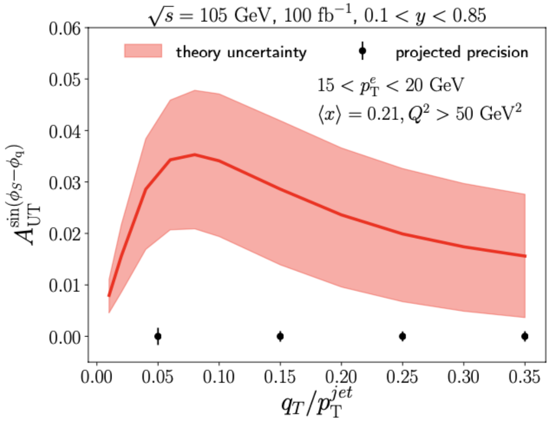
- ☐ EIC will allow measurements of the (un)polarized structure of the nucleon with unparalleled precision over a wide kinematic range
  - ➢ Helicity PDFs
  - ➢ TMDs
  - ➢ GPDs

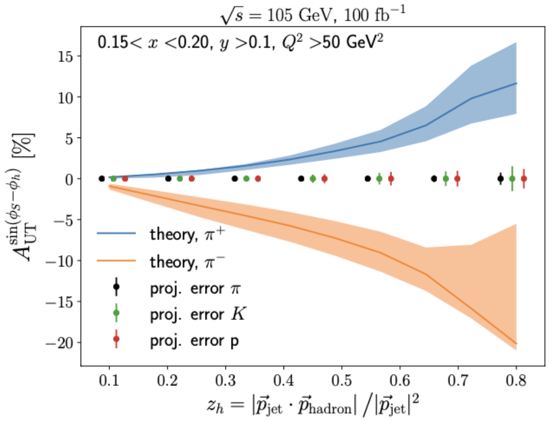
Including transverse momentum dependence into initial and final states and PS will reduce biases in TMD measurements

- ☐ CASCADE: Add transverse momentum dependance to initial partons from collinear generators and apply TMD showers and hadronization

- ☐ Extend to include polarization and radiative corrections?

- ☐ Can this approach be integrated with existing general purpose MCEGs?





Nucleon Structure: GPDs

☐ EIC will allow measurements of the (un)polarized structure of the nucleon with unparalleled precision over a wide kinematic range

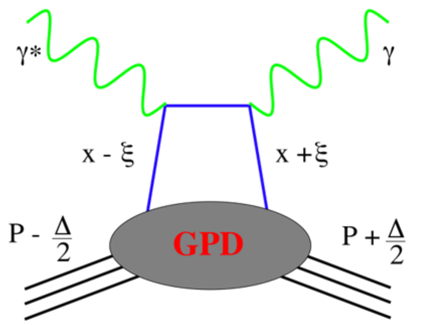
- Helicity PDFs
- TMDs
- GPDs

☐ MILOU (arXiv:hep-ph/0411389)

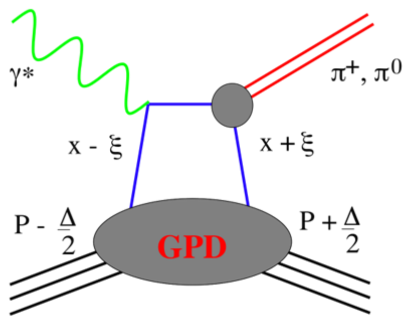
- Simulate amplitudes for DVCS, BH and interference term – old GPD models
- Radiative corrections and NLO included

☐ ePIC (arXiv:2205.01762)

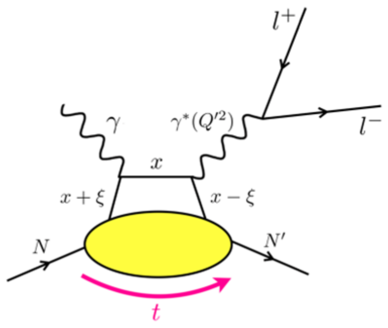
- New GPD models -> linked to PARTON
- Radiative corrections
- TCS and DVCS processes



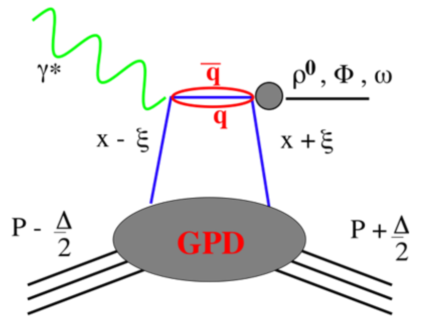
DVCS



Pseudo-scaler mesons



TCS



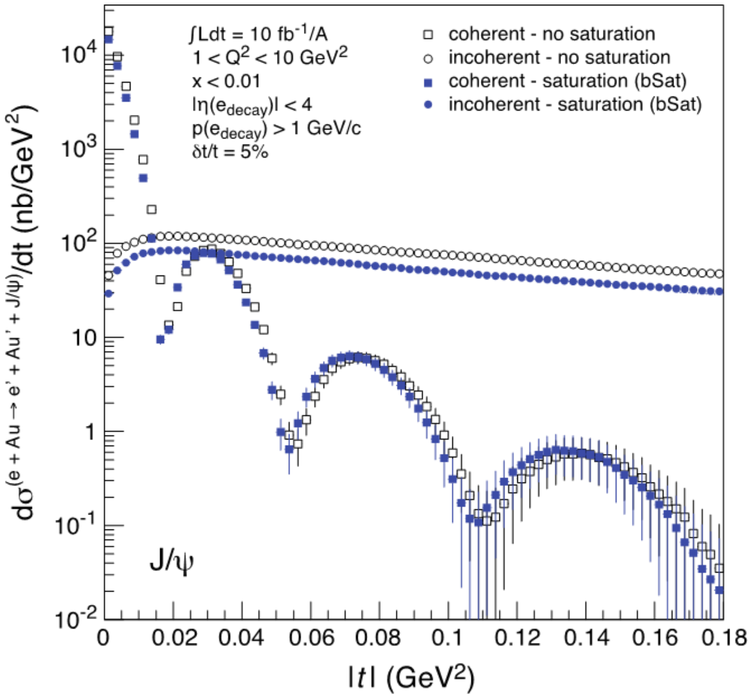
Vector mesons

Simulation of exclusive processes relevant for GPDs will require dedicated MCEGs – try to make as general as possible while including features such as radiative corrections

Nuclear Targets

- The EIC will provide the first electron – nucleus collisions
- Cold nuclear matter properties, color interactions with medium, hadronization, and saturation will all be pillars of the EIC program

General purpose eA monte carlo will be critical to the EIC. Need tunable energy loss and transport properties as well as nuclear breakup effects and different hadronization models. Modeling of collective effects and transition to saturated regime will also be important.



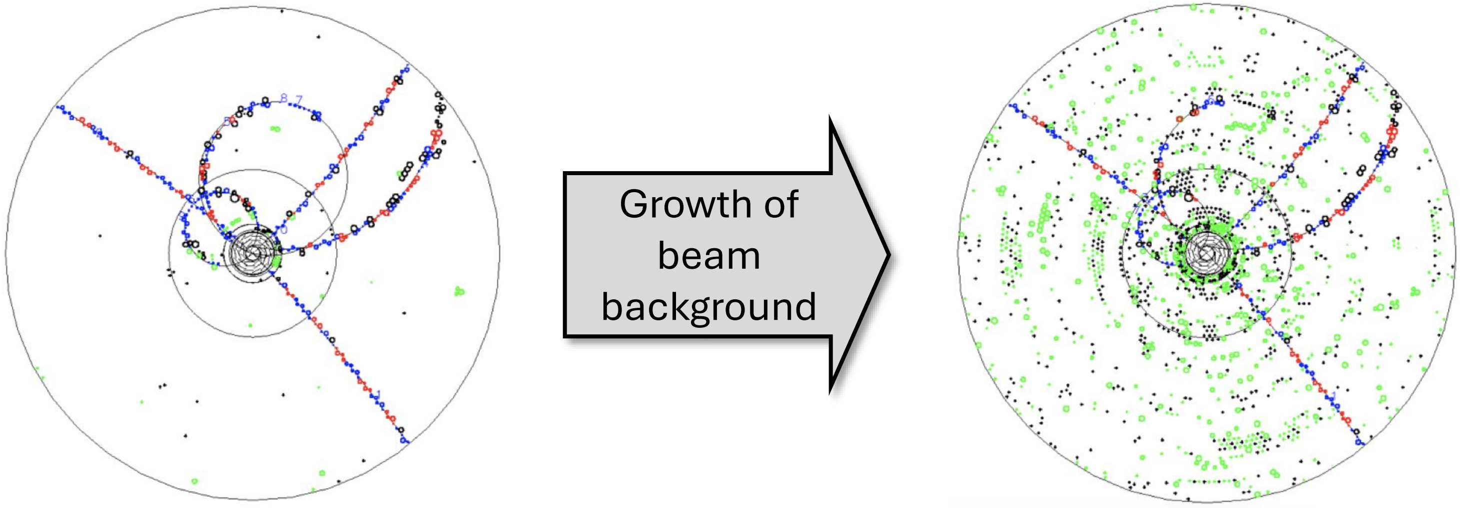
PRC 87 (2013) 024913

- BeAGLE: based on PYTHIA-6 merged with DPMJET-III
  - No radiative corrections
  - Good model for nuclear breakup
  - Has been critical for evaluation of ability to experimentally identify diffractive and coherent scattering
- SARTRE: Exclusive diffractive vector meson production in ep and eA
  - Uses dipole models bSat and bNonSat
  - Gemini++ for nuclear breakup
- PYTHIA-8 + Angantyr: Nuclear beams and breakup in Pythia
  - Wounded nucleon model
  - Takes advantage of extensive MPI machinery

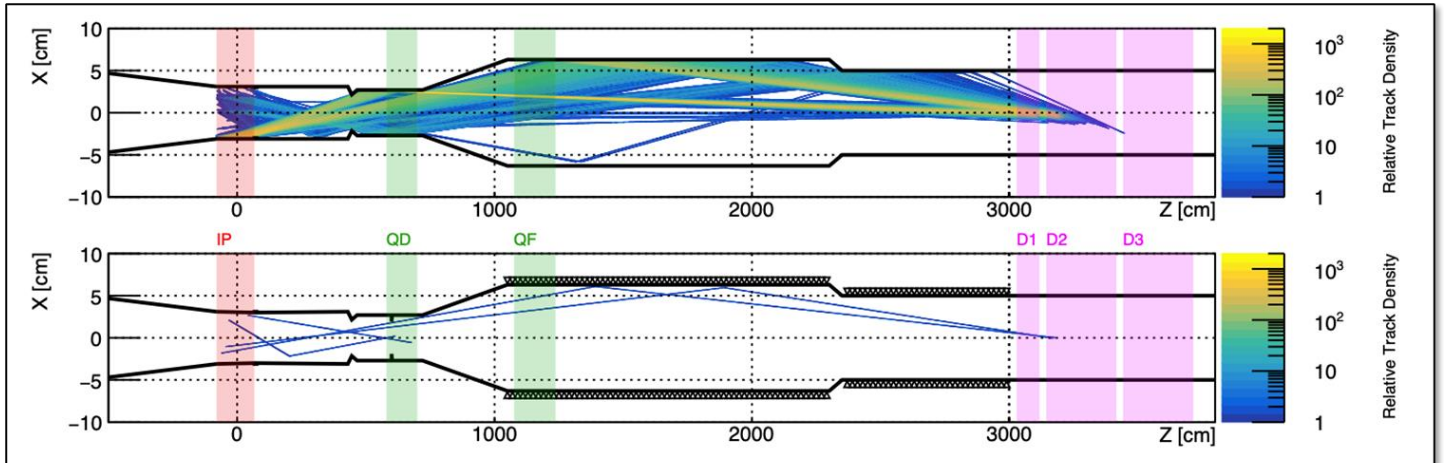
MC For Machine and Detector Design

- ☐ In addition to physics analysis driven needs, MCEGs play a critical role in machine and detector design
- ☐ Experience from HERA and KEK shows that understanding sources of beam background is critical for the realizing the EIC physics program
- ☐ SynradG4 framework (arxiv.org/abs/2408.11709), new tool implementing all features to describe SR in Geant-4, used to track synchrotron radiation in the EIC electron storage ring
- ☐ Allow development of masks which reduce the SR load in the IR by more than 3 orders of magnitude

Figure adapted from Belle/Belle II



SR Flux Without Shielding

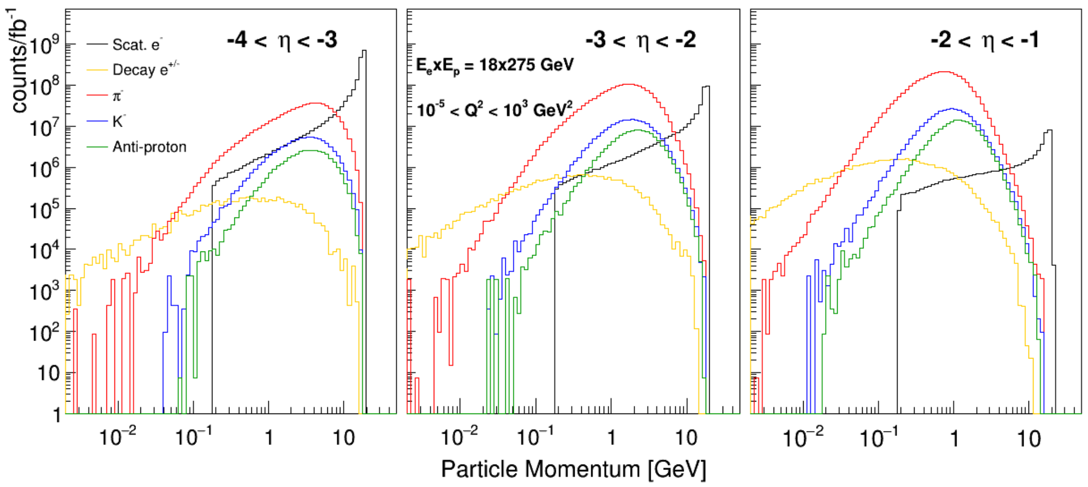


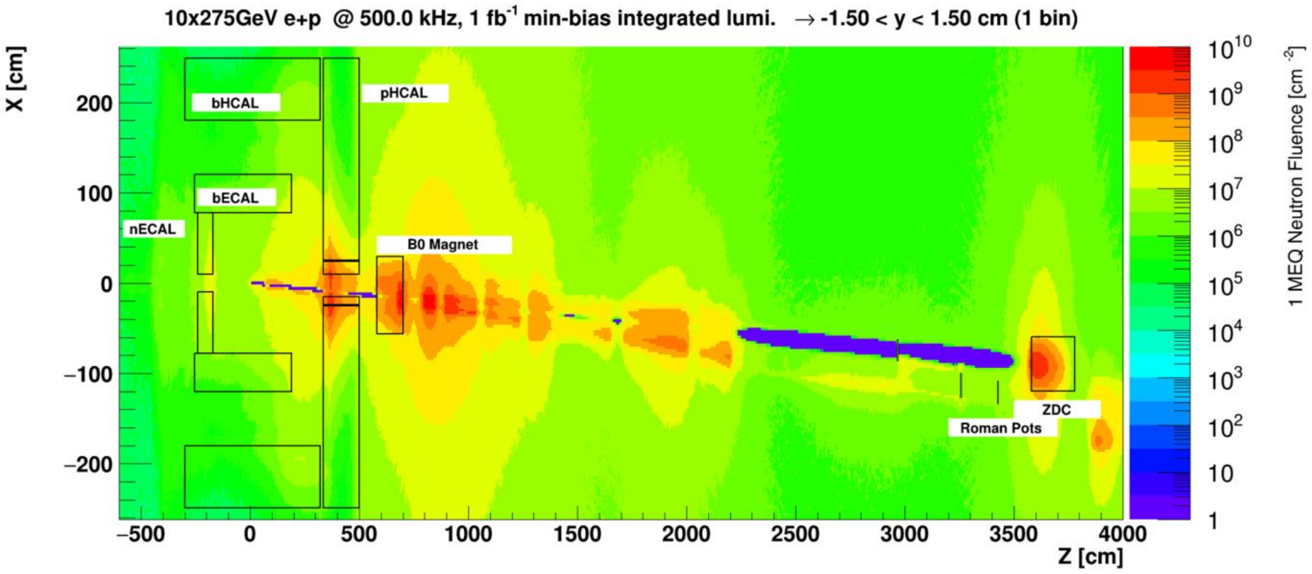
SR Flux With Shielding

Figures and work by A. Natochii (BNL)

MC For Machine and Detector Design

- On the detector side, need to understand physics and beam induced backgrounds to determine detector performance requirements
- Need to understand detector occupancies for DAQ and FEE design
- General purpose MCEGs like PYTHIA which can provide ‘min-bias’ event information are critical for getting an accurate picture of backgrounds and rates





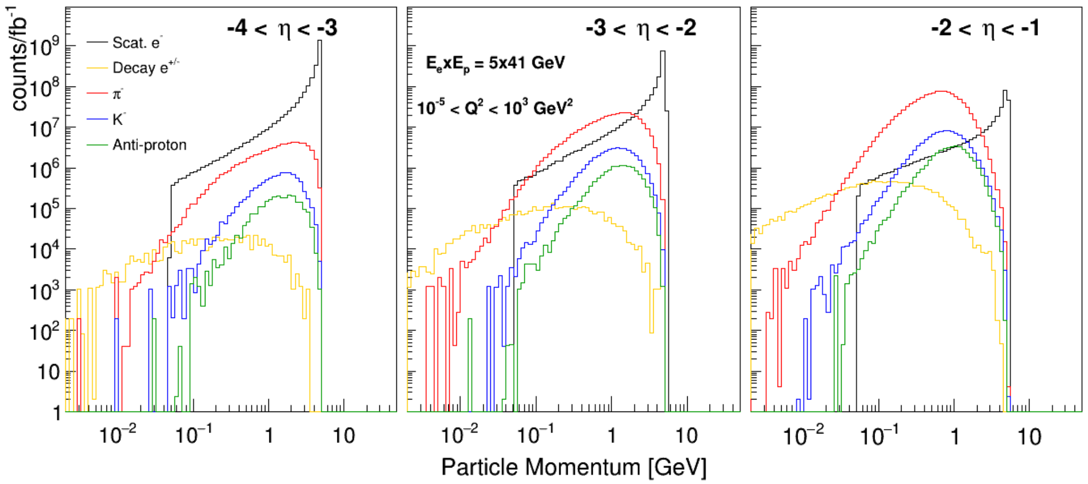
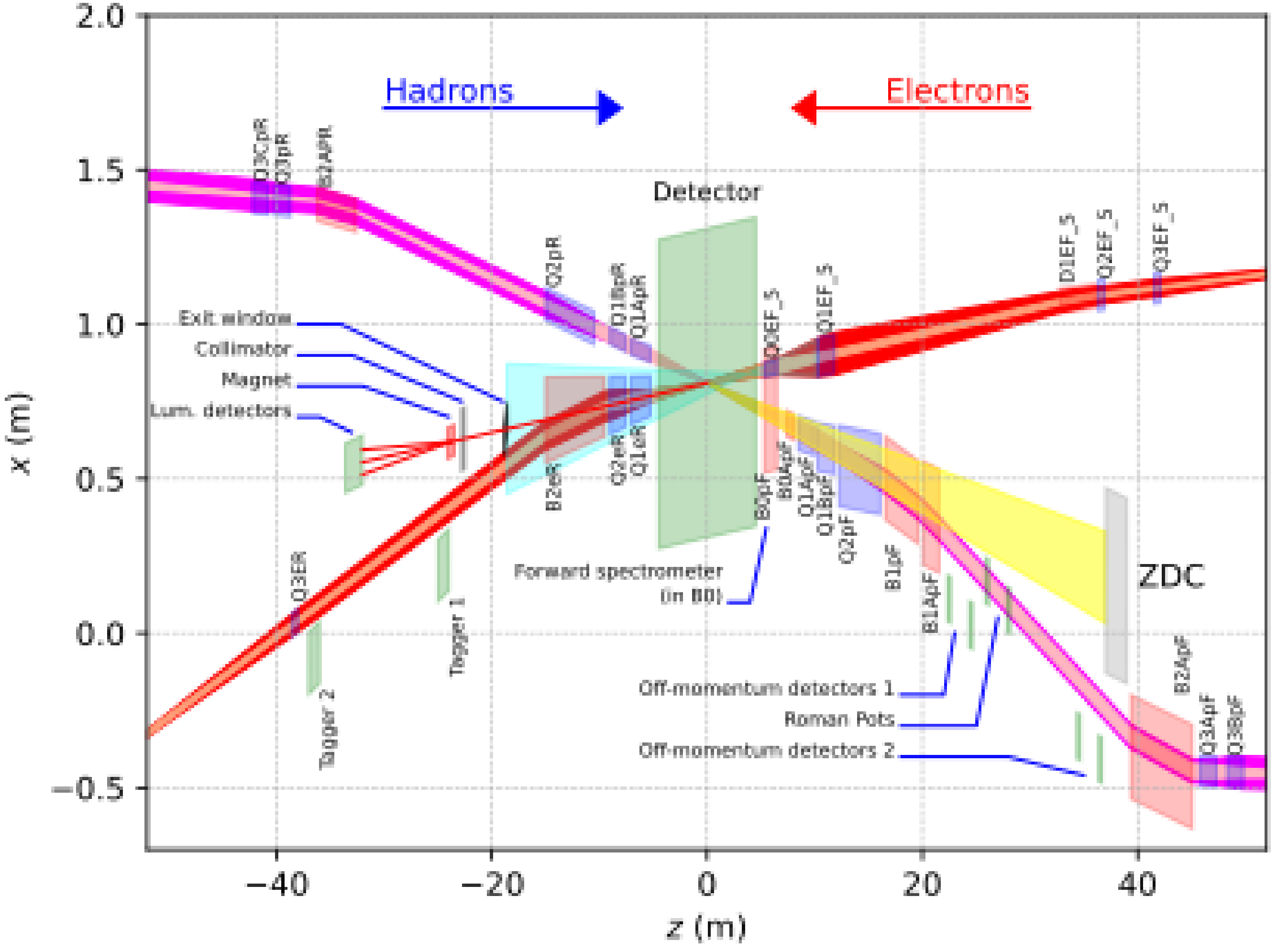


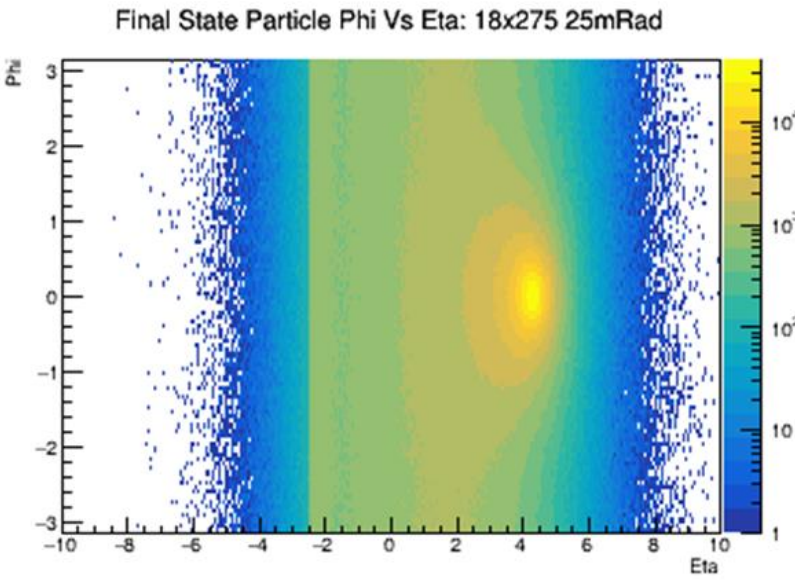
Fig. by A. Jentsch

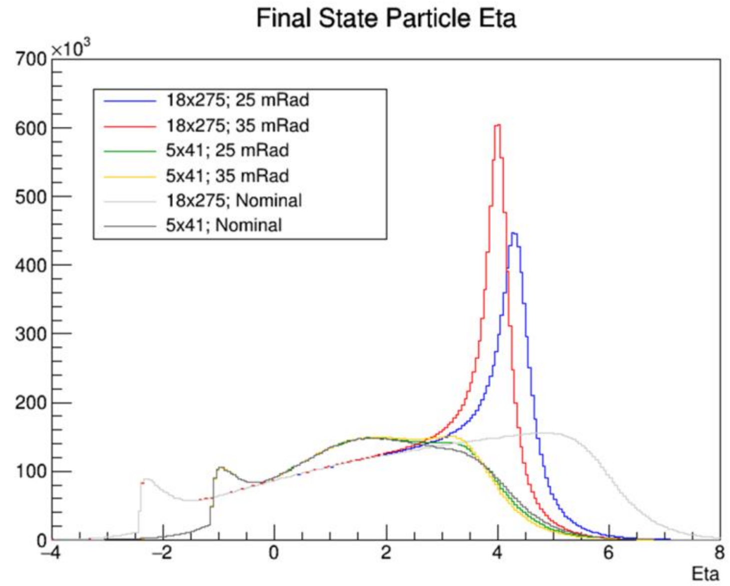
Simulating Beam Effects

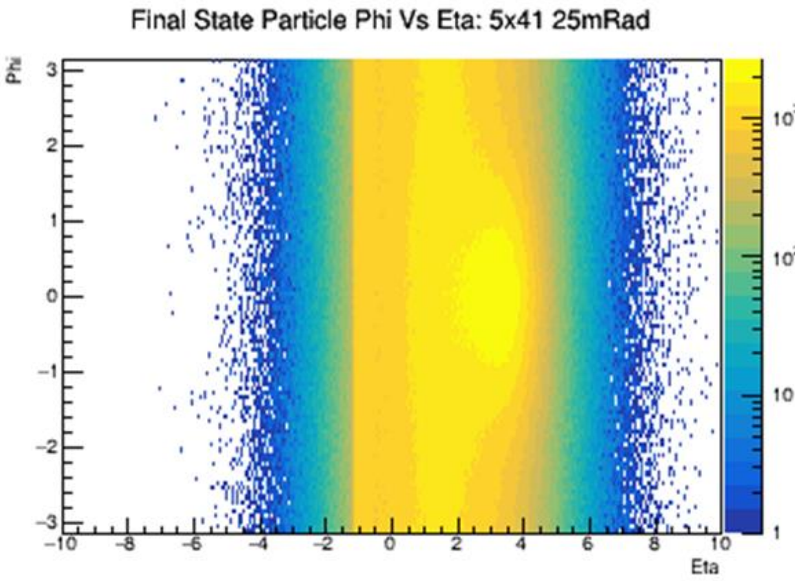


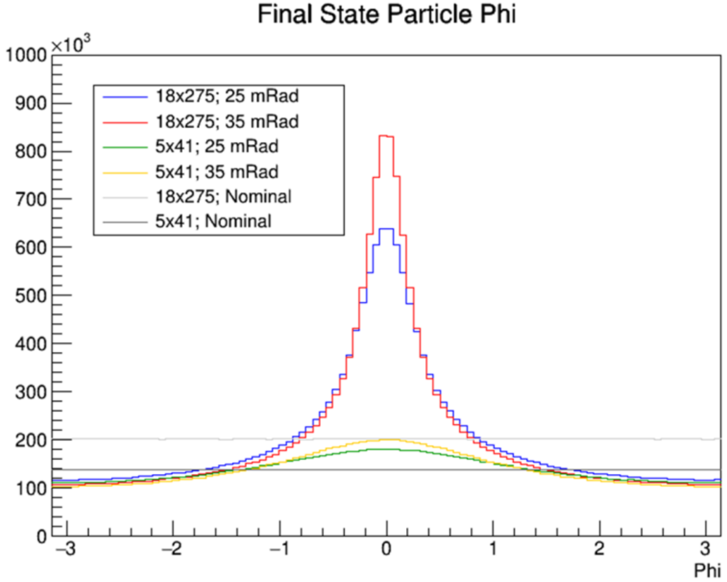
- Both interaction regions at the EIC will feature significant beam crossing angles (25 mRad for IP6 and 35 mRad for IP8)
- Presence of crossing angle will affect acceptance and detector design in the proton-going endcap
- Other beam properties like angular divergence and crab cavity kicks can have large impacts in far-forward region
- A summary of beam effects and methods for simulating these can be found in the technical note here: https://zenodo.org/record/6514605#.ZETiIOzMJAY
- Beam effects included either natively in Pythia8 using the BeamShape functionality or via a dedicated ‘afterburner’

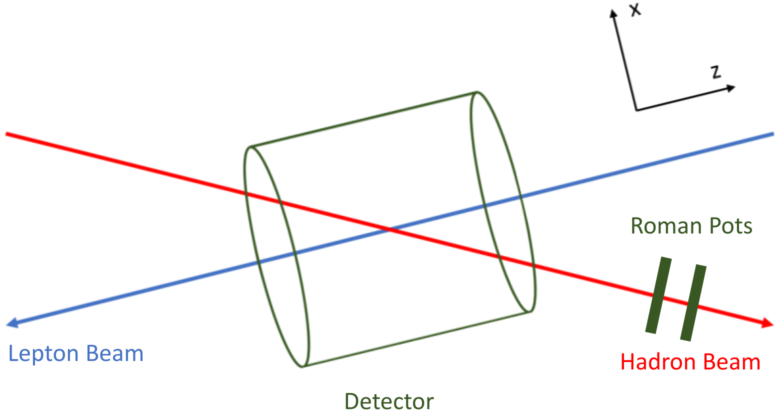
Simulating Beam Effects


Final State Particle Phi Vs Eta: 18x275 25mRad


Final State Particle Eta


Final State Particle Phi Vs Eta: 5x41 25mRad


Final State Particle Phi



- ☐ Detector solenoid must align with electron beam to minimize synchrotron radiation: “lab frame” -> electron beam = z-axis
- ☐ When measuring in lab frame coordinates – see a hot spot in eta/phi corresponding to the beam direction
- ☐ More pronounced for more relativistic beams
- ☐ How do we mitigate these features?

Monte Carlo "Ecosystem"

- ☐ In addition to the Monte Carlo Event Generators themselves, there are a number of associated tools which increase the practical functionality of simulations

- ☐ LHAPDF
  - ☐ Utility for representing and sharing PDFs and their error sets between MCEGs

- ☐ HepMC3
  - ☐ Standard for storing output of MCEGs

- ☐ Rivet
  - ☐ Common framework for storing analyses and validating/tuning MCEGs

- ☐ Professor/Apprentice Toolkits
  - ☐ Utilities for tuning the many free parameters in MCEGs to best match data

- ☐ The EIC community needs to take advantage of the extensive set of tools developed by the HEP community – both to take advantage of synergies and to interface with MCEG developers

Summary

- ☐ Monte Carlo Event Generators are a vital component of any modern collider physics program – serving as an interface between experiment and theory
- ☐ The versatility of the EIC machine and depth/breadth of the science program poses unique challenges for Monte Carlos
- ☐ Both general purpose generators – capable of simulating a large number of processes over a wide kinematic range – and specialty generators focused on a few processes will be needed
- ☐ New features, such as comprehensive treatment of polarization, and radiative corrections will be needed
- ☐ MCEGs also play a vital role in the planning and design of the collider and detector
- ☐ Interface with the HEP and MCEG developer community will be essential to the success of the EIC MC program – MC4EIC series of workshops