MCEGs for future ep and eA facilities: Overview

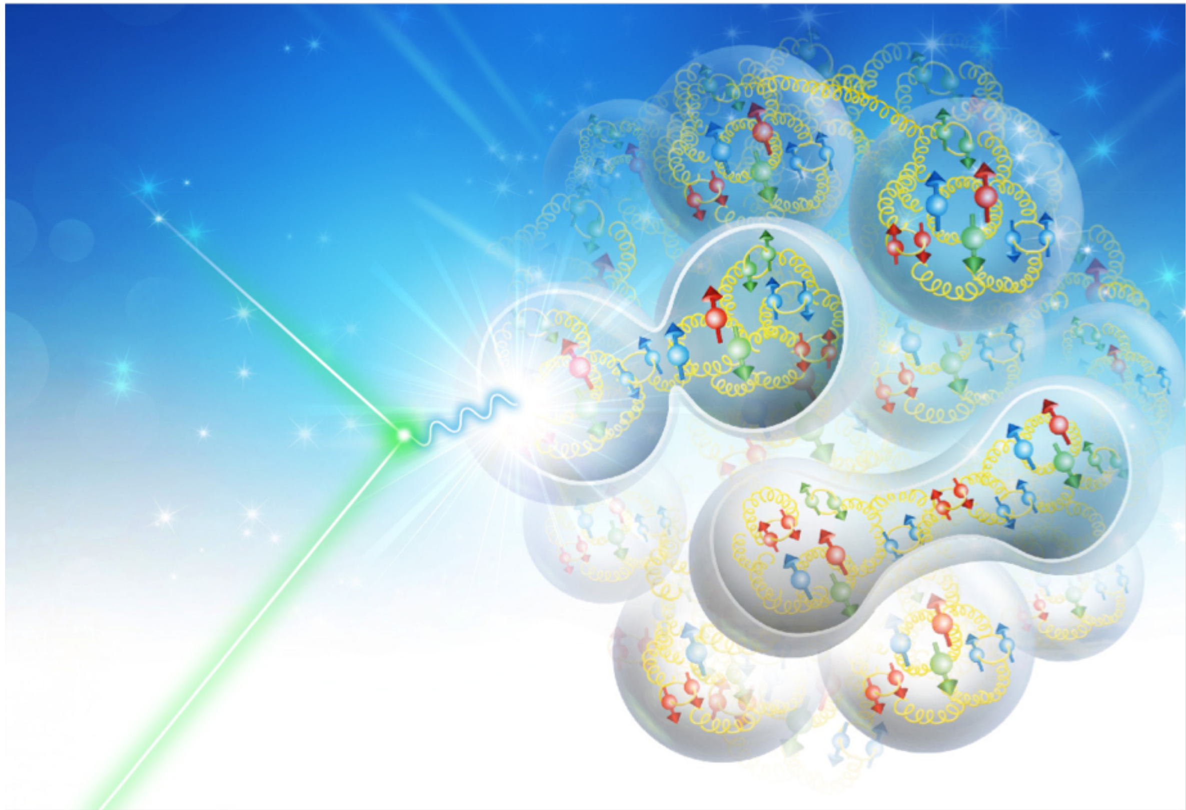
Electron-Ion Collider

MCEGs for eA

EIC²

EIC Center at Jefferson Lab

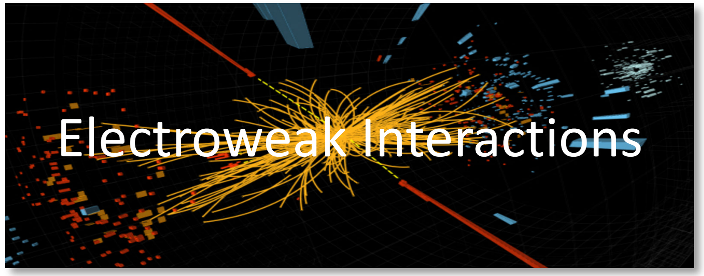
Markus Diefenthaler

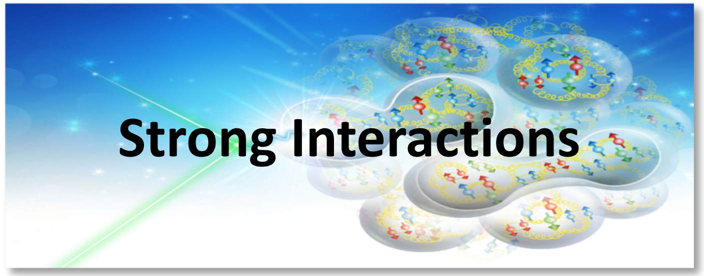


Towards a new frontier in Nuclear Physics

Imaging quarks and gluons

The Standard Model of Physics





Further exploration of the Standard Model

Dark matter searches

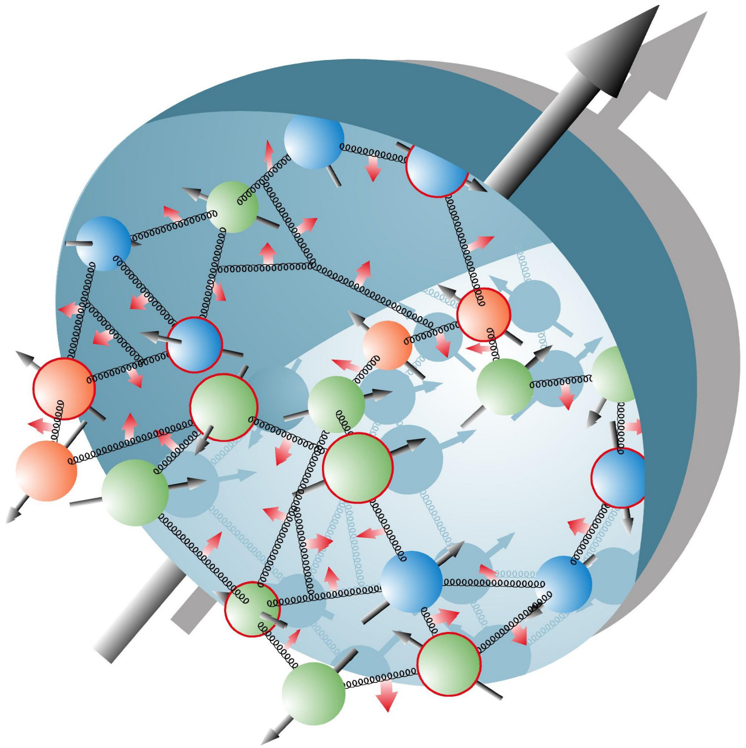
Electroweak symmetry breaking

Deeper understanding of QCD:

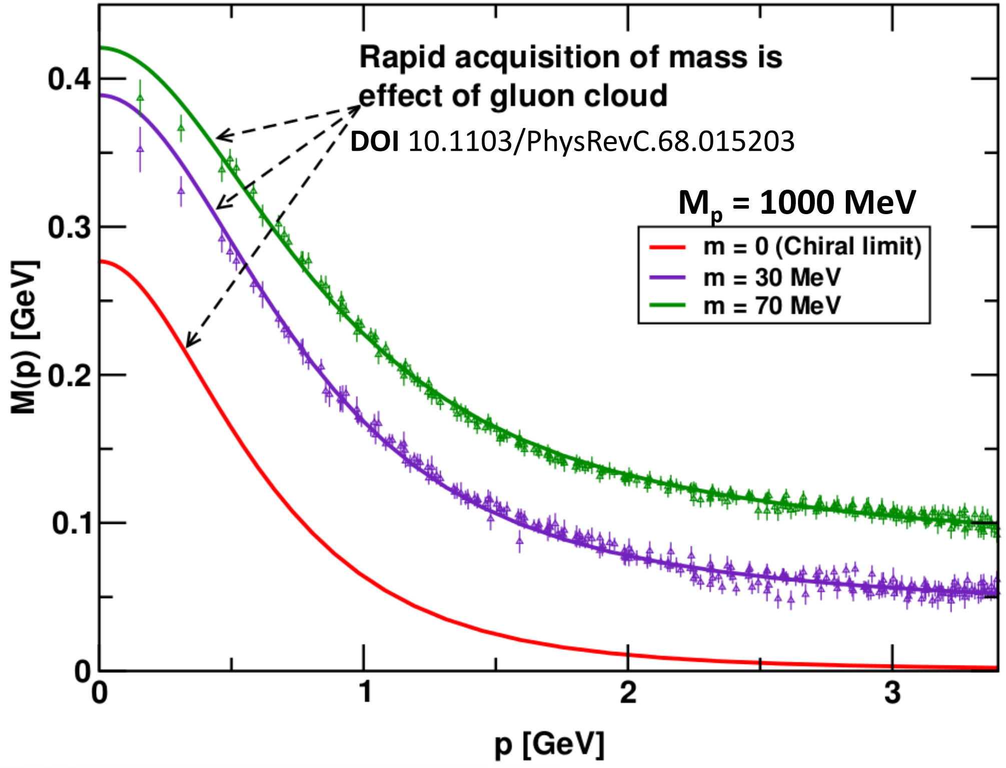
The **Electron-Ion Collider** will enable us to embark on a **precision study of the nucleon and the nucleus at the scale of sea quarks and gluons**, over all of the kinematic range that are relevant.

The dynamical nature of nuclear matter

Nuclear Matter Interactions and structures are inextricably mixed up



Observed properties such as mass and spin emerge out of the complex system

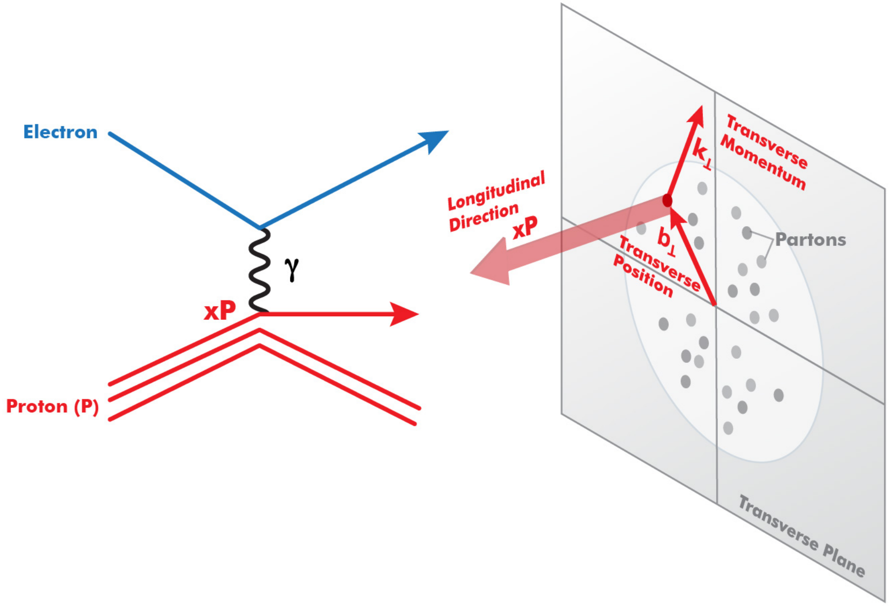


Ultimate goal Understand how matter at its most fundamental level is made

To reach goal precisely image quarks and gluons and their interactions

Imaging quarks and gluons and their interactions

Novel QCD phenomena



3D imaging in space and momentum

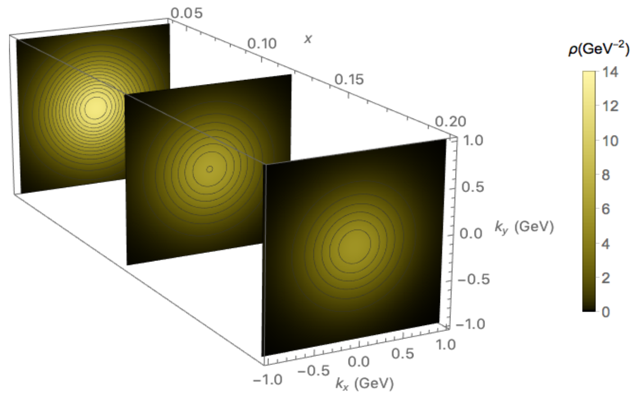
longitudinal structure (PDF)
+ transverse position Information (GPDs)
+ transverse momentum information (TMDs)

order of a few hundred MeV

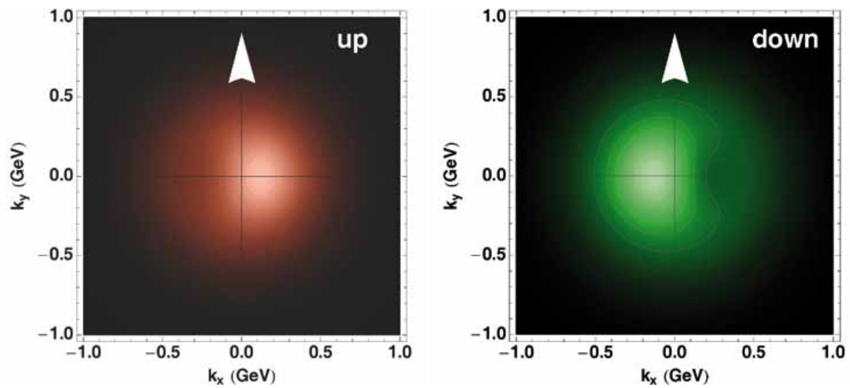
TMD PDFs

Unpolarized nucleon

JHEP 1706 (2017) 081



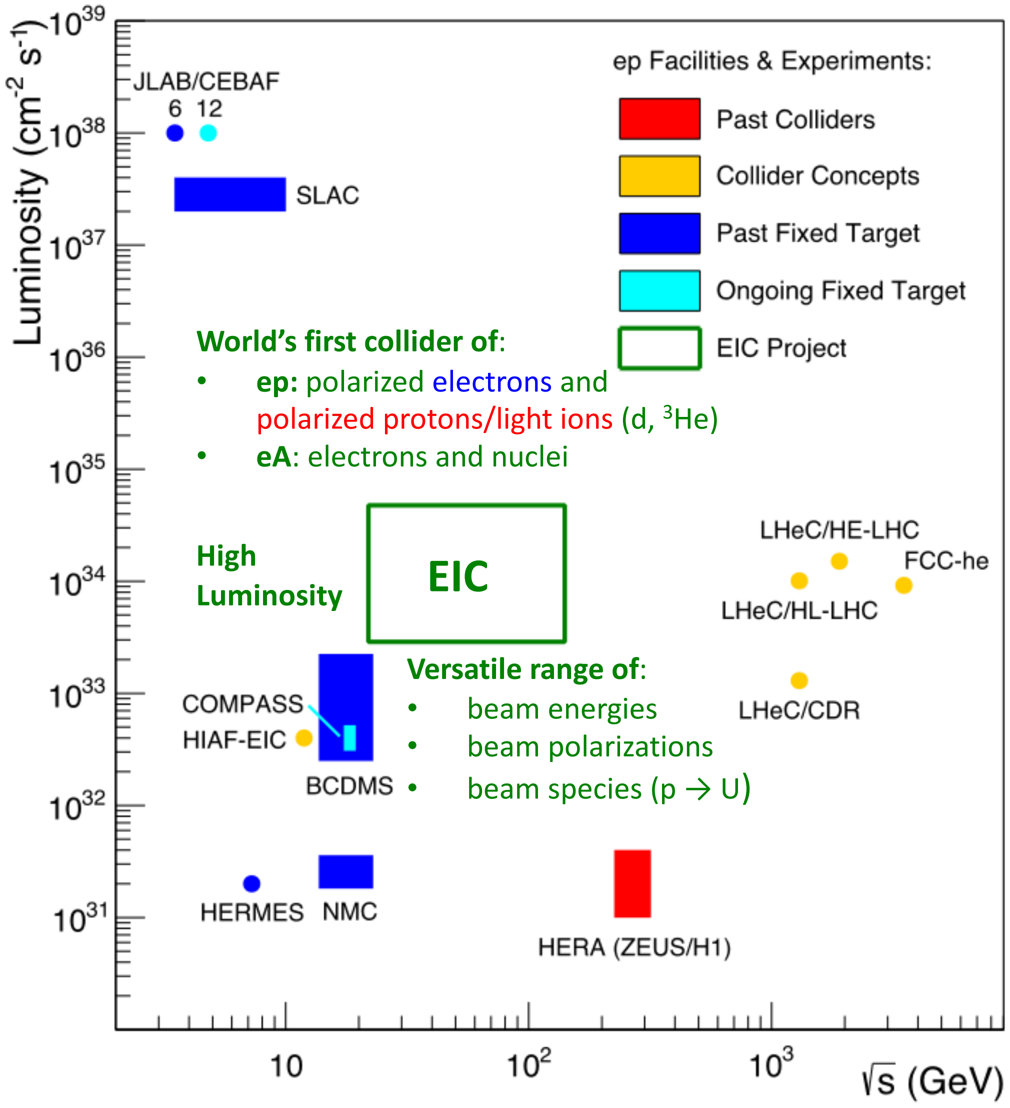
Transversely polarized nucleon



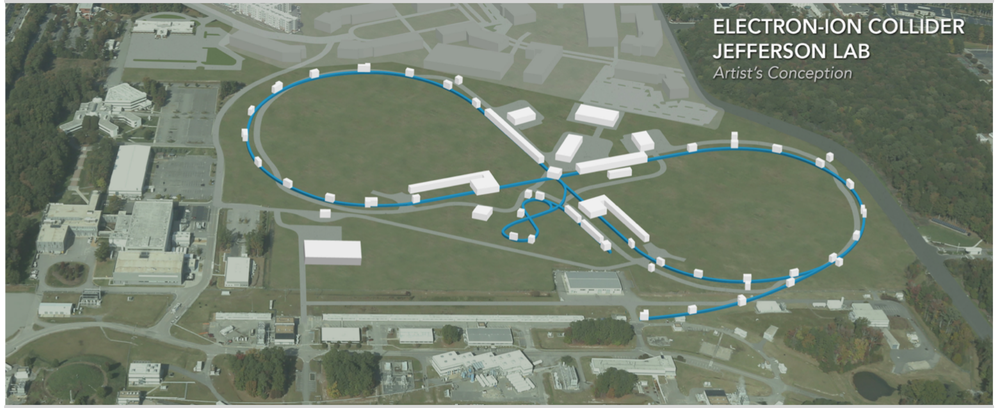
Future nuclear physics facility

The Electron-Ion Collider Project

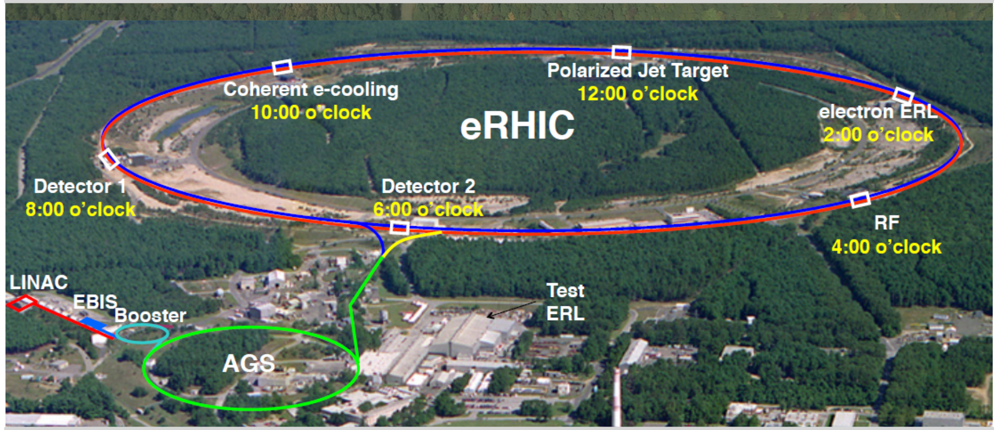
The Electron-Ion Collider: Frontier accelerator facility in the U.S.



Highest priority for new construction
for the U.S. Nuclear Physics program

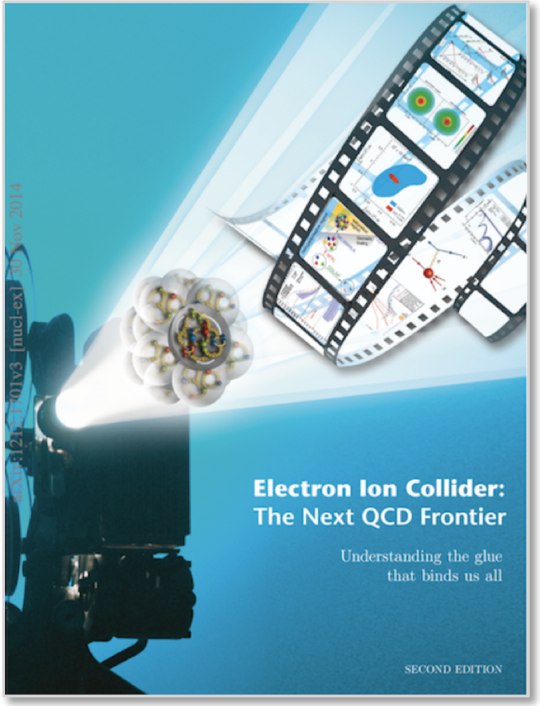


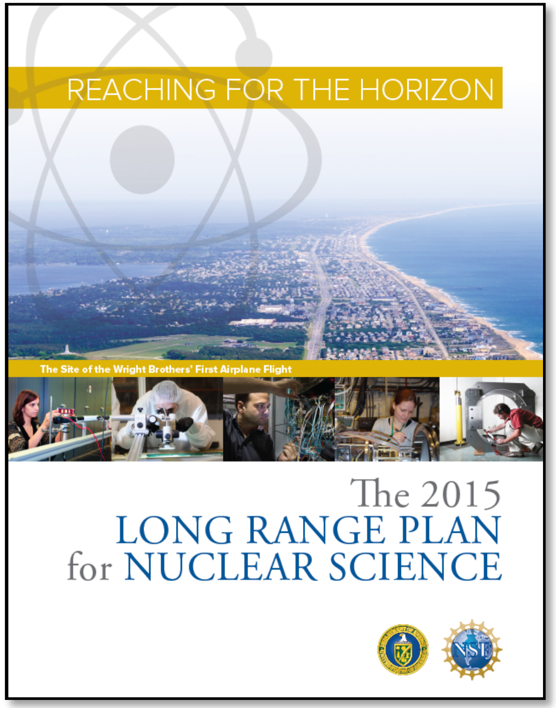
Proposal by Jefferson Lab

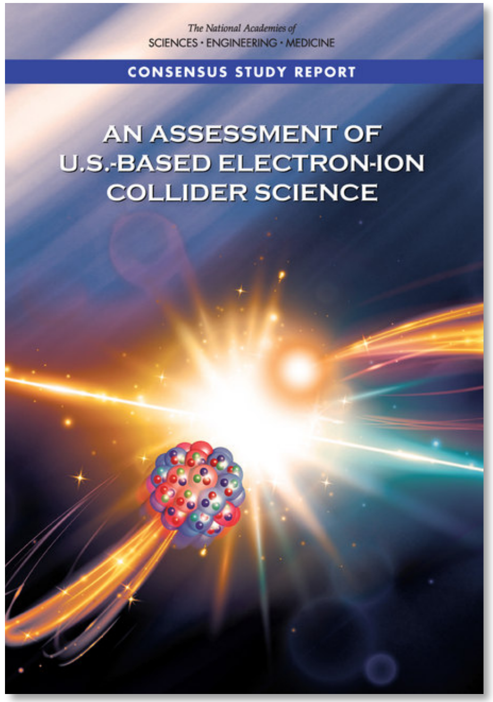


Proposal by Brookhaven Lab

Why an Electron-Ion Collider?





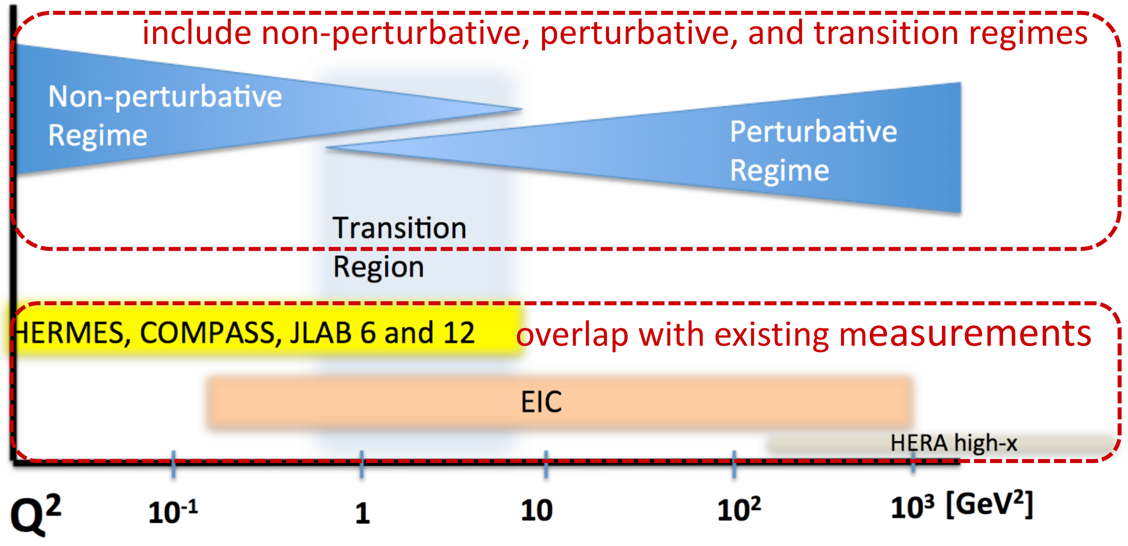


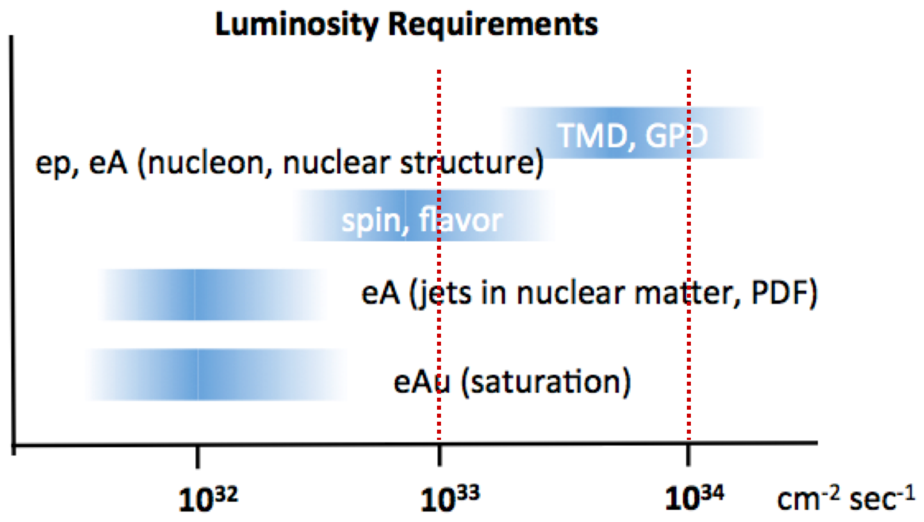
Right tool

- to precisely **image quarks and gluons** and their interactions
- to explore the new **QCD frontier of strong color fields in nuclei**
- to understand **how matter at its most fundamental level is made**.

Understanding of nuclear matter is **transformational**,
perhaps in an even more dramatic way than how the understanding of the atomic and molecular structure of matter led to new frontiers, new sciences and new technologies.

EIC: Ideal facility for studying QCD





Various beam energy

broad Q^2 range for

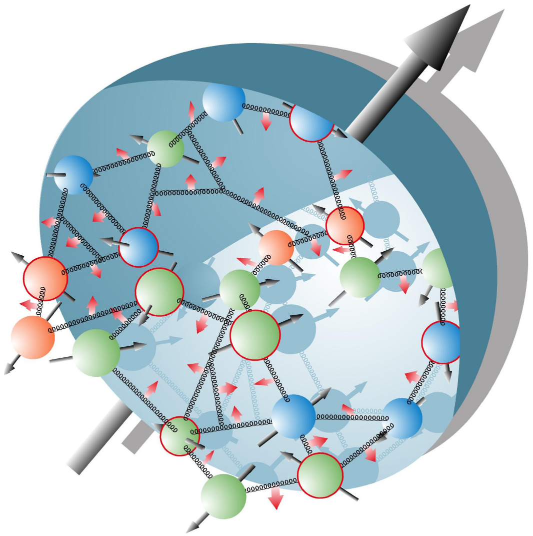
- studying evolution to Q^2 of ~1000 GeV^2
- disentangling non-perturbative and perturbative regimes
- overlap with existing experiments

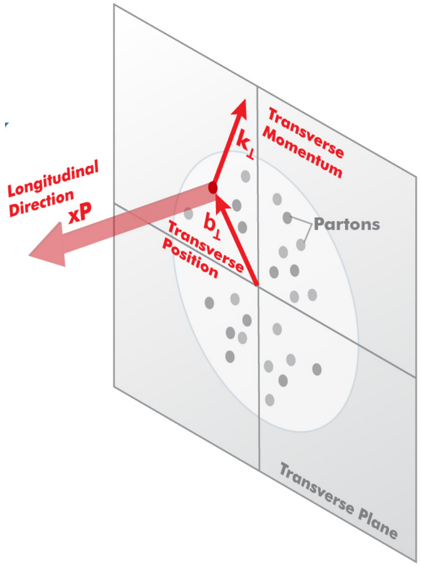
High luminosity / high precision

E.g.: TMD program

- multi-dimensional SIDIS analysis (in five or more kinematic dimensions and multiple particles)
- in various configurations.

EIC: ideal facility for studying QCD





Polarization

Understanding hadron structure cannot be done without understanding spin:

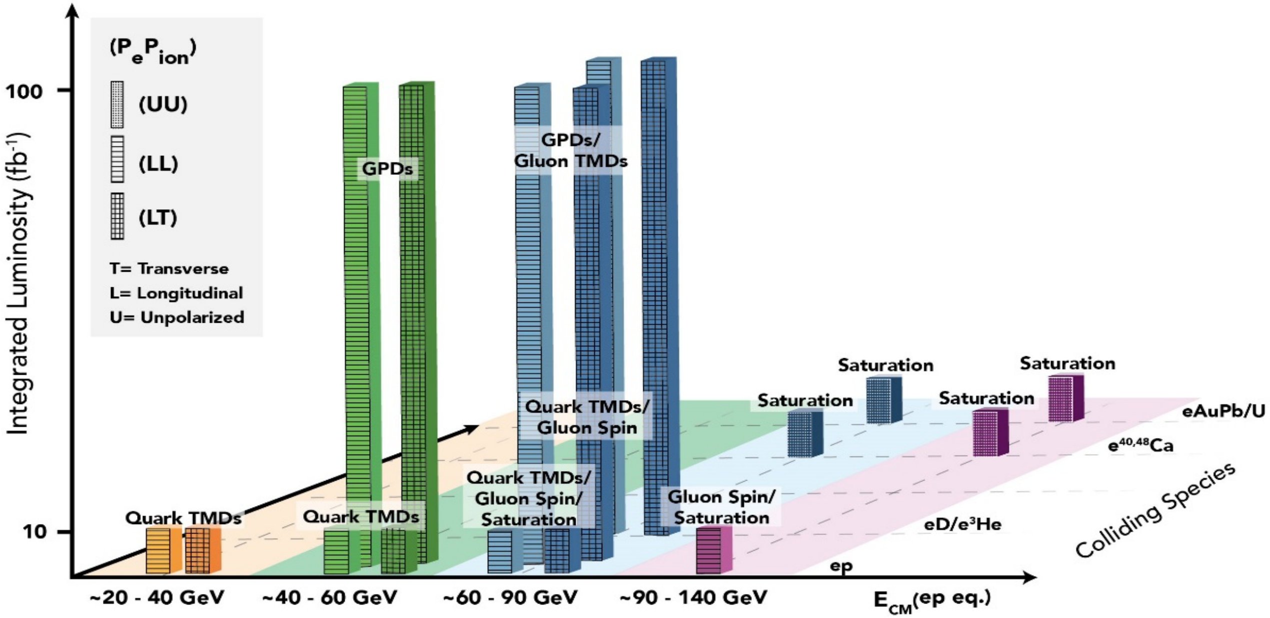
- polarized **electrons** and
- polarized **protons/light ions (d, ^{3}He)** including tensor polarization for d

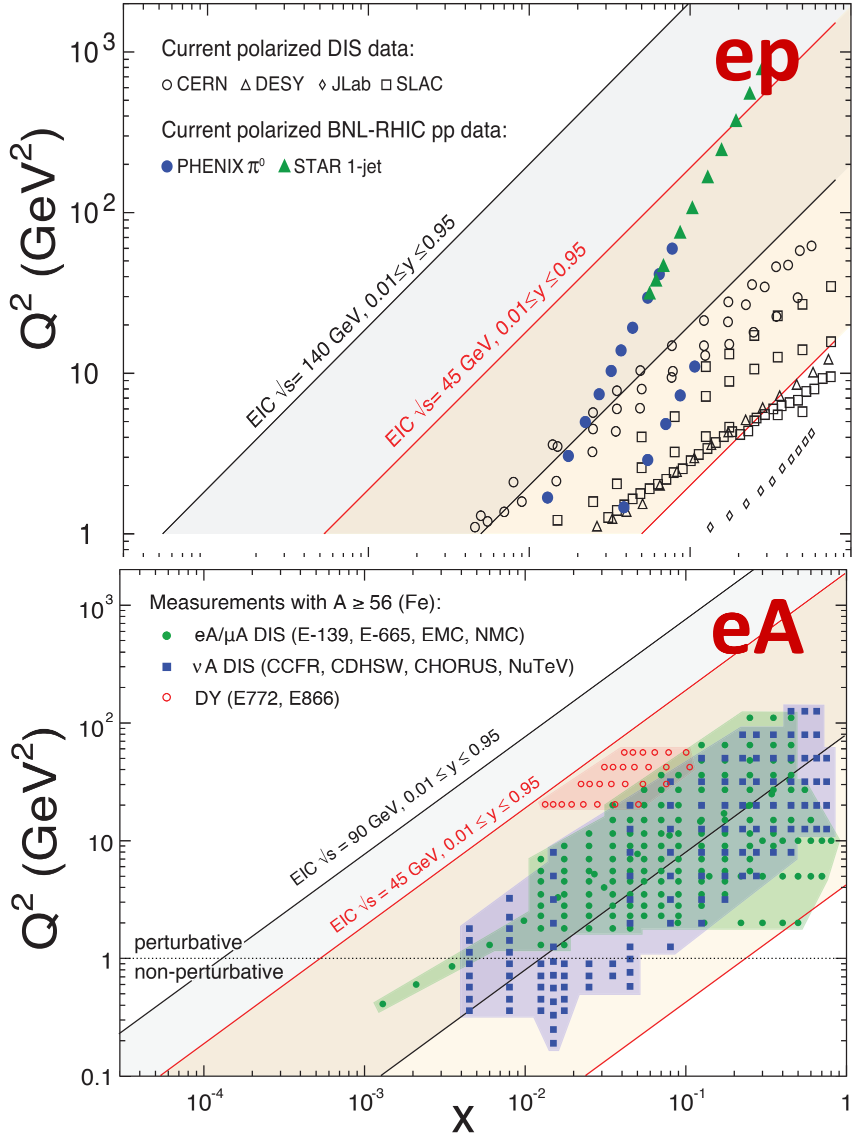
Longitudinal and transverse and polarization of light ions (d, ^{3}He)

- 3D imaging in space and momentum
- spin-orbit correlations

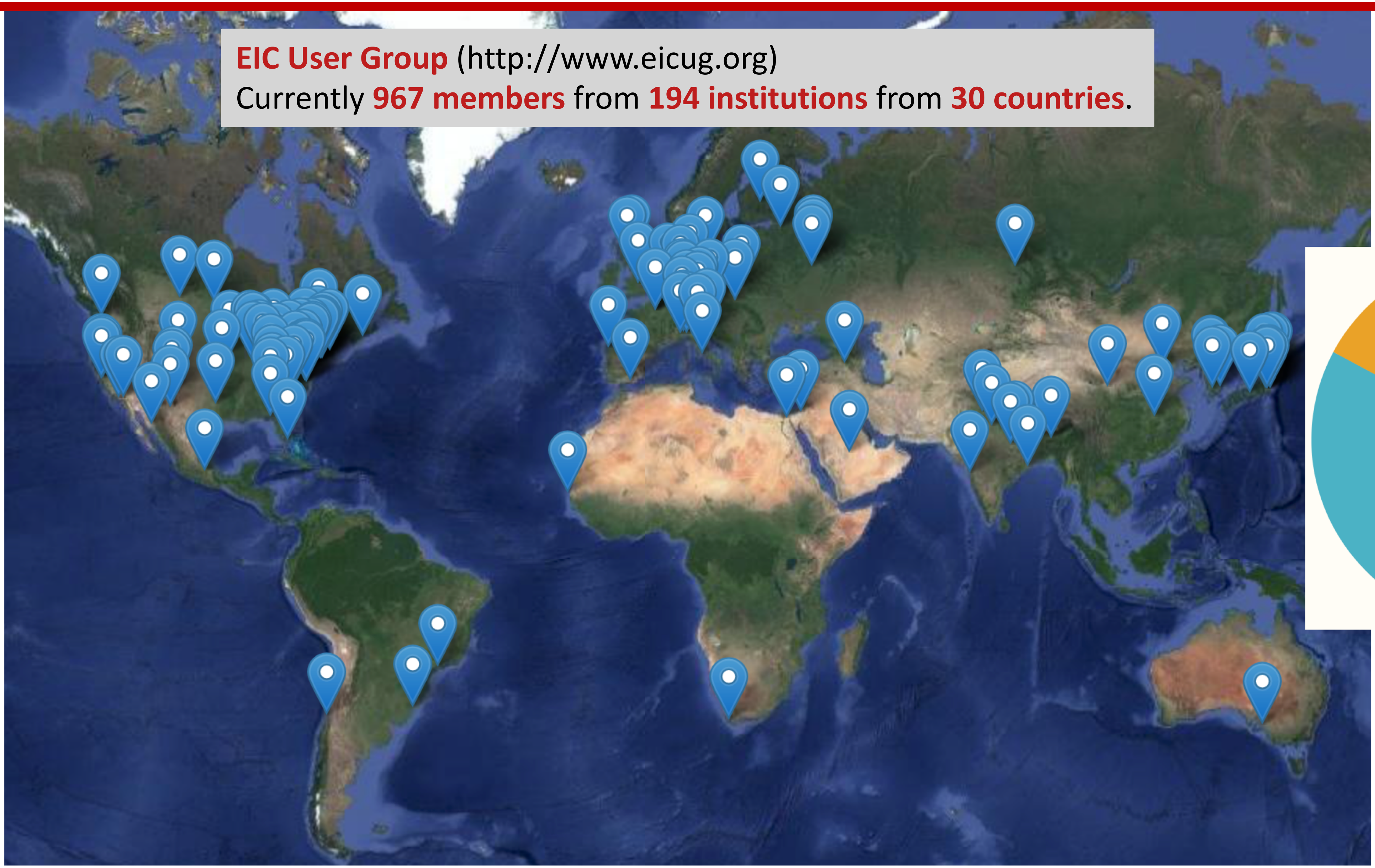
EIC science program

Study **structure** and **dynamics** of **nuclear matter** in **ep** and **eA collisions** with high luminosity and versatile range of beam energies, beam polarizations, and beam species.

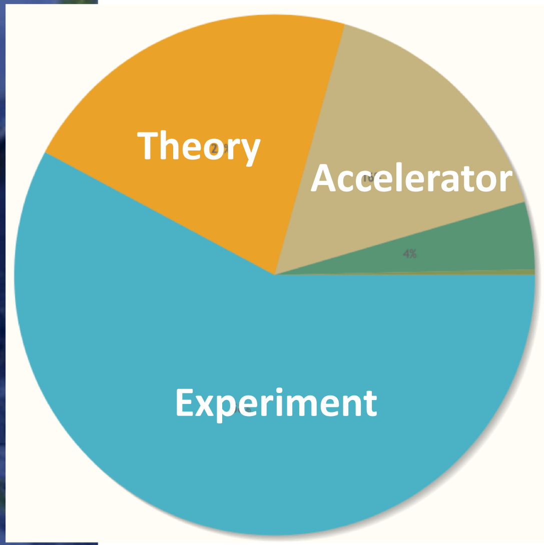




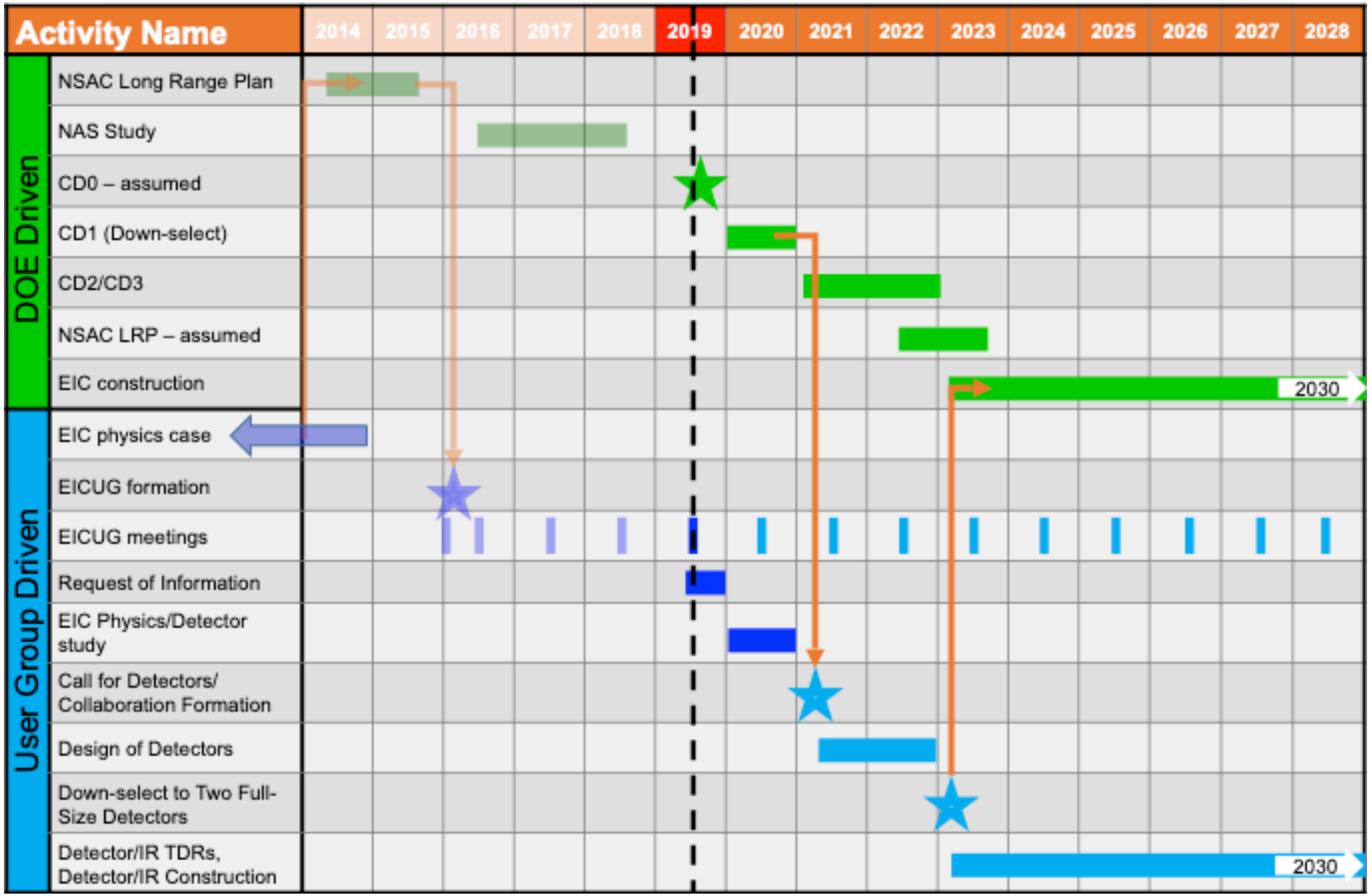
The worldwide EIC community



EIC User Group (http://www.eicug.org)
Currently **967 members** from **194 institutions** from **30 countries**.



Timeline

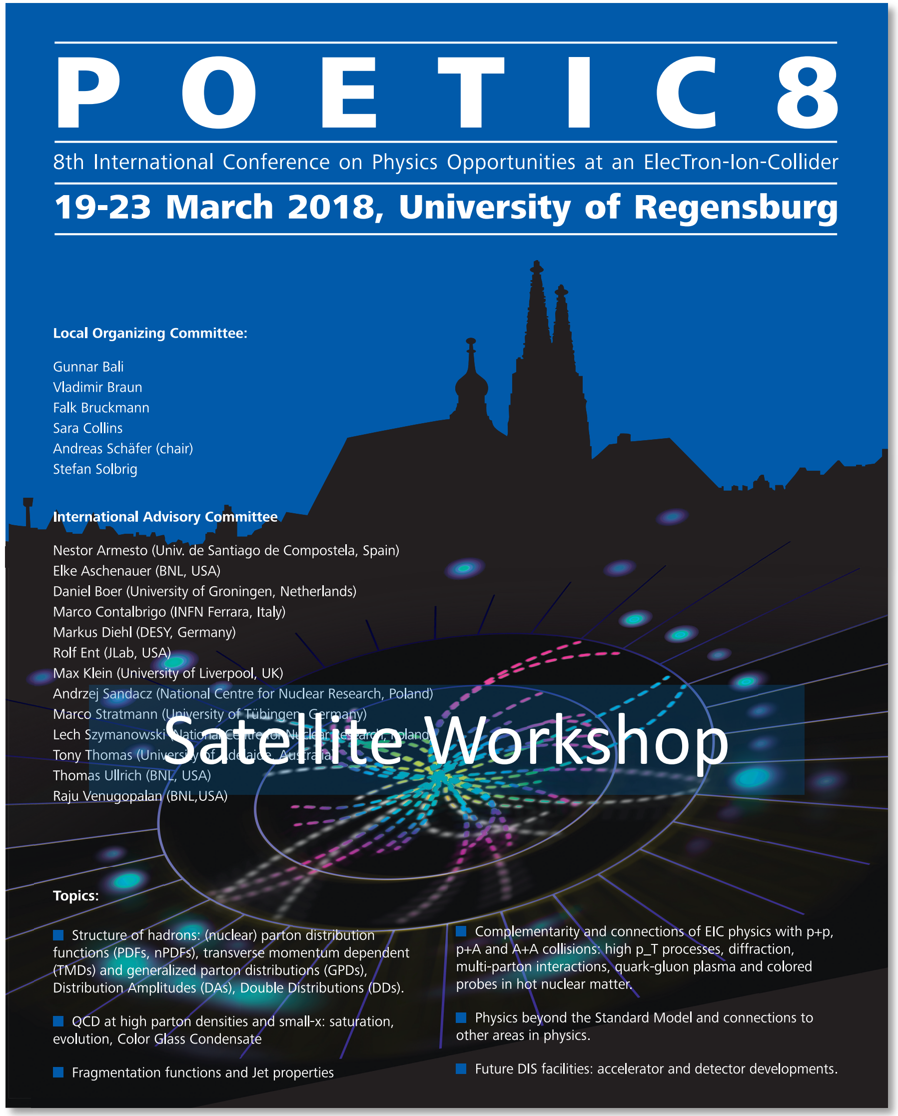


Activity Name
2014
2015
2016
2017
2018
2019
2020
2021
2022
2023
2024
2025
2026
2027
2028
DOE Driven
NSAC Long Range Plan
NAS Study
CD0 – assumed
CD1 (Down-select)
CD2/CD3
NSAC LRP – assumed
EIC construction
2030
User Group Driven
EIC physics case
EICUG formation
EICUG meetings
Request of Information
EIC Physics/Detector study
Call for Detectors/ Collaboration Formation
Design of Detectors
Down-select to Two Full-Size Detectors
Detector/IR TDRs, Detector/IR Construction
2030

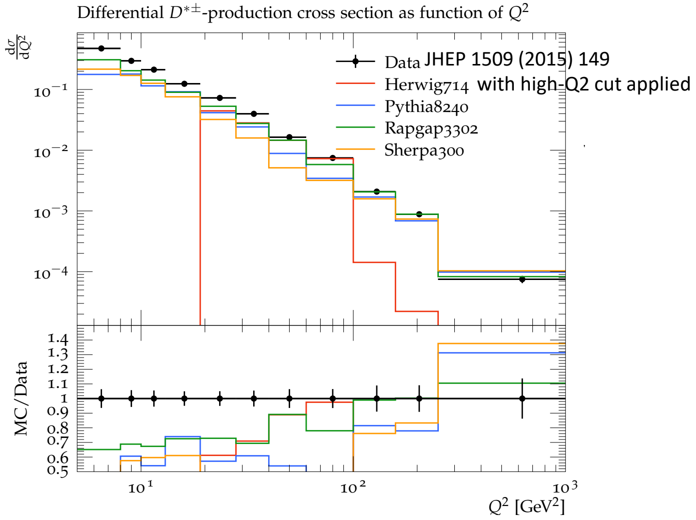
EIC simulations and analysis

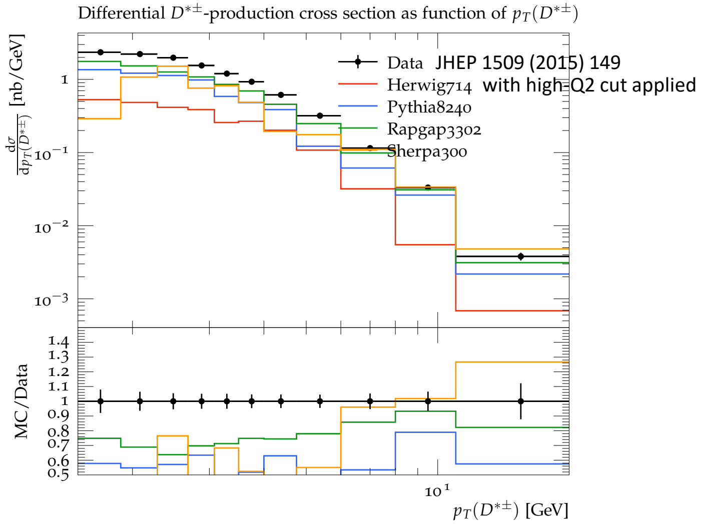
MCEGs for future ep and eA facilities

MCEGs for future ep and eA facilies



Comparisons to combined H1 and ZEUS analysis (A. Verbytskyi)





General-purpose MCEG and ep collisions

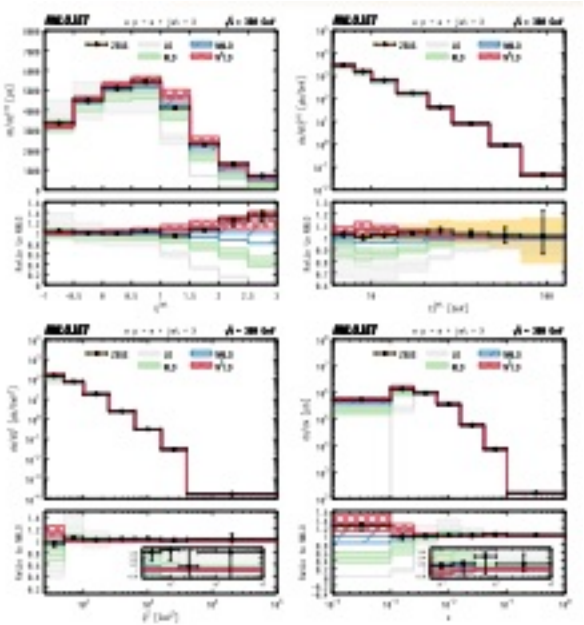
- **Sherpa**
  - DIS with ME corrections and PS merging
  - Good description of jet data at low Q^2 with $\gtrsim 3$ partons in the final state
  - Automated NLO matching with Powheg method, applicable for jets at high-Q^2
- **Herwig**
  - Two shower options with spin correlations and NLO matching
  - Good description for single-particle properties in DIS
  - Also QED radiation for angular-ordered shower
- **Pythia**
  - Possible to generate DIS events with the new dipole shower implementation
  - Higher-order corrections via Dire plugin, soon part of Pythia core
  - Photoproduction for hard and soft QCD processes, also hard diffraction

General-purpose MCEG and eA collisions

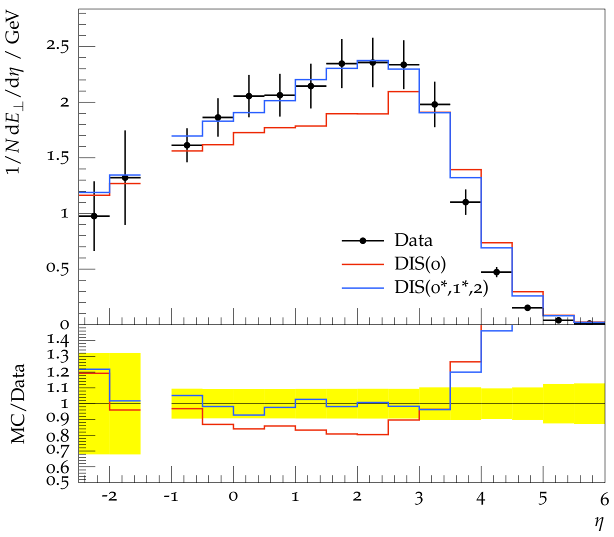
- No strong modifications for DIS (nuclear PDFs, what else?)
- For photoproduction need to include interactions between resolved photon and other nucleons
- Complementary to ultra-peripheral collisions at the LHC and RHIC

Status of NLO simulations for ep

Stefan Hoeche (SLAC)



arXiv:1803.09973



Fixed-order QCD

- QCD calculations available up to N^{3}LO for inclusive DIS
- Peculiarities of DIS require careful selection of scales
- Excellent description of experimental data from HERA

MC event simulation

- DIS simulations available in all three event generation frameworks
- NLO matching & merging standard, NNLO matching available
- Peculiarities of DIS require careful selection of clustering history
- Very good description of wide range of experimental data

MCEG–HERA comparisons and MCEG validation for ep

Rivet example

SIDIS analysis at HERMES

```
// Extract the particles other than the lepton
const FinalState& fs = apply<FinalState>(event, "FS");
Particles particles;
particles.reserve(fs.particles().size());
const GenParticle* dislepGP = dl.out().genParticle();
foreach (const Particle& p, fs.particles()) {
  const GenParticle* loopGP = p.genParticle();
  if (loopGP == dislepGP)
    continue;
  particles.push_back(p);
}

// Apply HERMES cuts.
bool validx = (x > 0.023 && x < 0.6);
if (q2 < 1. || w2 < 10. || y < 0.1 || y > 0.85 || !validx)
  vetoEvent;

// good inclusive event, let's do bookkeeping before we look at the hadrons
dis_tot += weight;
dis_x->fill(x, weight);
dis_Q2->fill(q2, weight);

for (size_t ip1 = 0; ip1 < particles.size(); ++ip1) {
  const Particle& p = particles[ip1];

  // get the particle index, check if it is a particle of interest
  const int part_idx = get_index(p.genParticle()->pdg_id());
  if (part_idx < 0) {
    continue;
  }

  // we have a particle of interest, let's calculate the kinematics
  // z
  const double z = (p.momentum() * pProton) / (pProton * q);
  // pt
  const double pth = sqrt(p.momentum().pT2());

  // get our z index, if negative, we have a particle outside of [.2, .8]
  const int z_idx = calc_zslice(z);
  if (z_idx < 0) {
    continue;
  }

  // store the events and make cuts where necessary
  //
  // pt cut for variables not binned in pt
  if (pth > 0 && pth < 1.2) {
    mult_z[part_idx]->fill(z, weight);
    mult_zx[part_idx][z_idx]->fill(x, weight);
    mult_zQ2[part_idx][z_idx]->fill(q2, weight);
  }
  mult_zpt[part_idx][z_idx]->fill(pth, weight);
}
```

- **MCEG R&D** requires *easy* access to *data*
- data := analysis description + data points

- **HEP** existing workflow for MCEG R&D using tools such as HZTool, Rivet and Professor

- **Detailed comparisons between modern MCEG and HERA data**
  - workshop on Rivet for ep (Feb 18—20 2019)
  - mailing list rivet-ep-l@lists.bnl.gov
  - HERA data not (yet) included in MCEG tunes

TMDs and MCEGs

Vibrant community

MCEG Workshop
DESY, February 2019

F Hautmann
TMDs from Parton Branching

First all flavor. all Q^2, all x and all k_t TMD at NLO determined.

- Introduction
- The Parton Branching (PB) method
- New results and applications

F Hautmann: MCEG Workshop, DESY - February 2019 1

TMD and parton shower: CASCADE-3

Hannes Jung (DESY)

with contributions from
A. van Hameren, K. Kutak, A. Kusina,
A. Bermudez Martinez, P. Connor F. Hautmann, O. Lelek, R. Zlebcik

- From inclusive to exclusive distributions
  - Parton Branching method for TMDs

First TMD parton shower using higher order splitting function.

H. Jung, TMD and Parton Shower CASCADE3 , MCEG for future ep facilities, Hamburg, Feb 2019 1

NCN

nTMD using PB method

Krzysztof Kutak

Instytut Fizyki Jądrowej
im. Henryka Niewodniczańskiego
Polskiej Akademii Nauk

First all Q^2, all x, all k_t TMD at NLO for nuclei. Comparison with DY data (pp, pPb, CMS)

Updates for KaTie

Andreas van Hameren
Institute of Nuclear Physics
Polish Academy of Sciences
Kraków

presented at the
MCEGs for future ep and eA facilities
21-02-2019, DESY, Hamburg

First ever off-shell hard process calculation for ep including all flavors.

Lively discussion: Factorization Theorem and MCEG approaches

To what extent are TMDs a result of a coherent branching evolution as, e.g., implemented in Herwig

Next: Comparison to TMD theory

Extract TMD from the different MCs and compare to analytic results.

UNIVERSITÀ
DEGLI STUDI DI TRIESTE

INFN
Istituto Nazionale di Fisica Nucleare

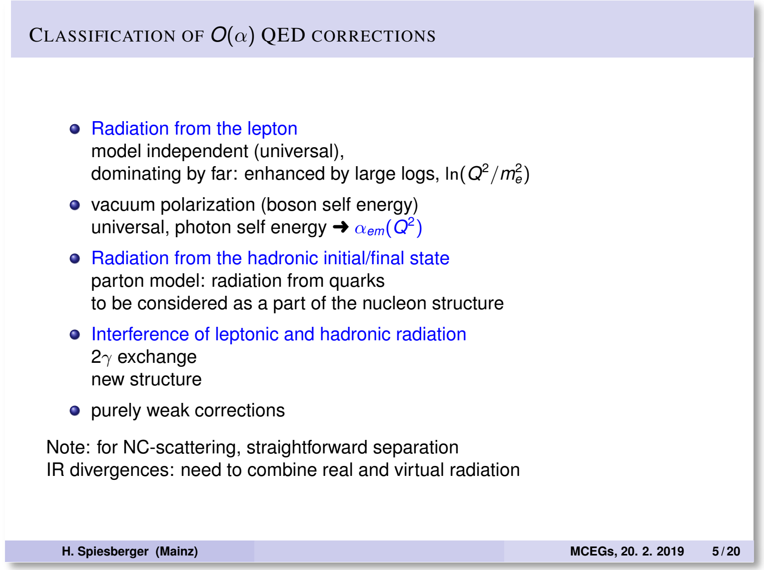
21st February 2019,
DESY,
Hamburg

Revisited version of a recursive model for the fragmentation of polarized quarks

Albi Kerbizi
University of Trieste, Trieste INFN Section

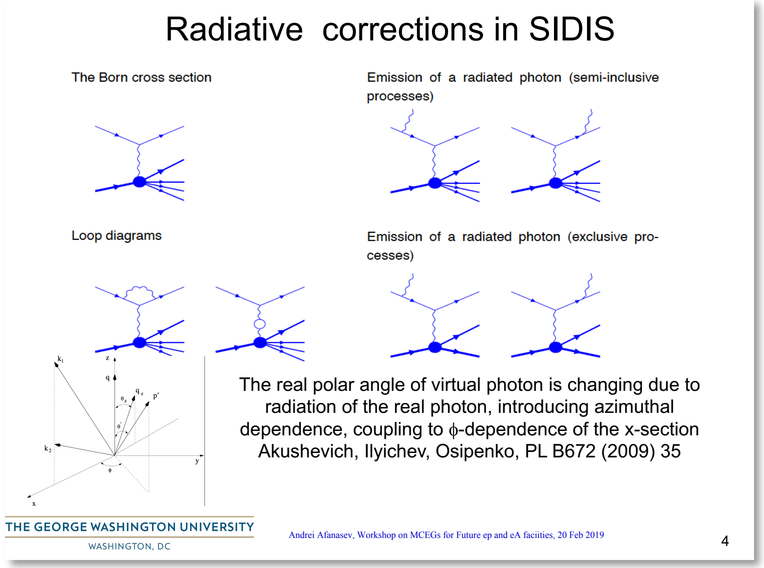
Lund string + 3P0; good description of Collins and di-hadron asymmetries; Boer-Mulders, jet handedness can be simulated.

Merging QED and QCD effects



Hubert Spiesberger (Mainz): QED corrections for electron scattering

- High-precision measurements need careful treatment of radiative corrections.
- Closely related to experimental conditions need full Monte Carlo treatment (Unfolding) including simulation of hadronic final states.
- The basics are known and available …
- … but improvements are needed.



Andrei Afanasev (GWU): Semi-analytic vs. Monte-Carlo Approaches for QED Corrections to SIDIS

- Consistent approach to address RC for SSA in polarized SIDIS
- SSA due to two-photon exchange need to be included in analysis of SSA from strong interaction, of same size at JLAB experiments
- More detailed calculation of the two-photon exchange at quark level required: elastic scattering, inclusive, semi-inclusive, and exclusive DIS

JupyterLab environment for EIC simulations

- **collaborative workspace** to create and share Jupyter Notebooks
- **web-based interactive analysis environment** accessible, consistent, reproducible analyses
- **fully extensible and modular** build a collection of analyses and analysis tools
- **bridge to modern data science**, e.g.,
  - *Nature* **563**, 145-146 (2018): “Why Jupyter is data scientists’ computational notebook of choice”
  - more than three million Jupyter Notebooks publicly available on GitHub

07/23 EIC Software Tutorial

Dmitry Romanov (JLAB) introduced EIC simulations in JupyterLab environment.

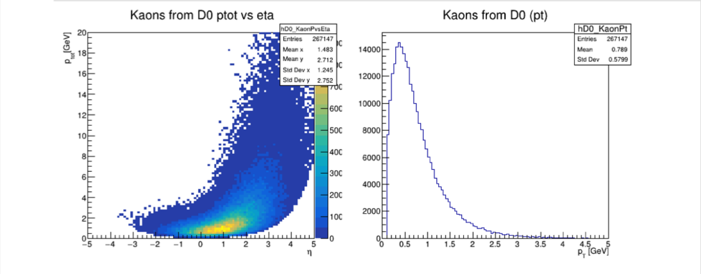
Quickstart https://eic.gitlab.io/documents/quickstart/

Jupyter Notebooks

- **writing analysis code**

```
[4]: jana.plugin('hepmc_reader') \
     .plugin('jana', nevents=10000, output='hepmc_sm.root') \
     .plugin('eic_smear', detector='jleic') \
     .plugin('open_charm')
[4]: eJana configured
     plugins: hepmc_reader,eic_smear,open_charm
[5]: jana.source('../data/herwig6_20k.hepmc')
[5]: eJana configured
     plugins: hepmc_reader,eic_smear,open_charm
     sources:
     ../data/herwig6_20k.hepmc
[6]: jana.run()
     Total events processed: 10001 (~ 10.0 kevt)
```

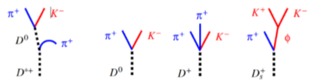
- **visualization of results**



- **narrative of the analysis**

Open charm

The high luminosity at the EIC would allow measurements of open charm production with much higher rates than at HERA and COMPASS, extending the kinematic coverage to large $x_B > \sim 0.1$ and rare processes such as high-p_T jets. Heavy quark production with electromagnetic probes could for the first time be measured on nuclear targets and used to study the gluonic structure of nuclei and the propagation of heavy quarks through cold nuclear matter with full control of the initial state.



Pythia8 on Jupyter

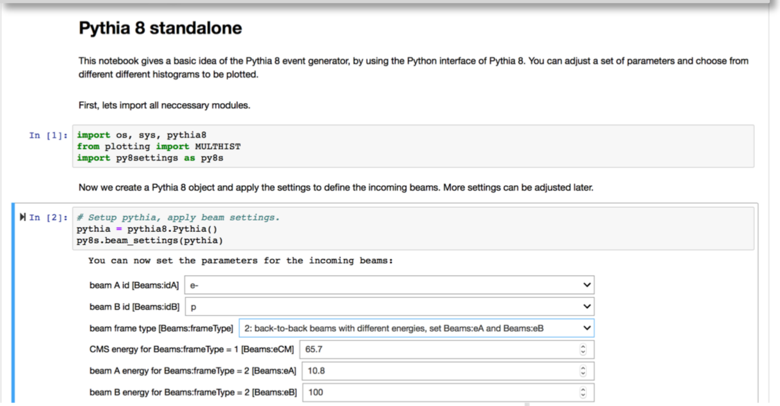
Container for Pythia8+DIRE by Nadine Fischer (Pythia)

jupyter README✔ 8 minutes ago Logout

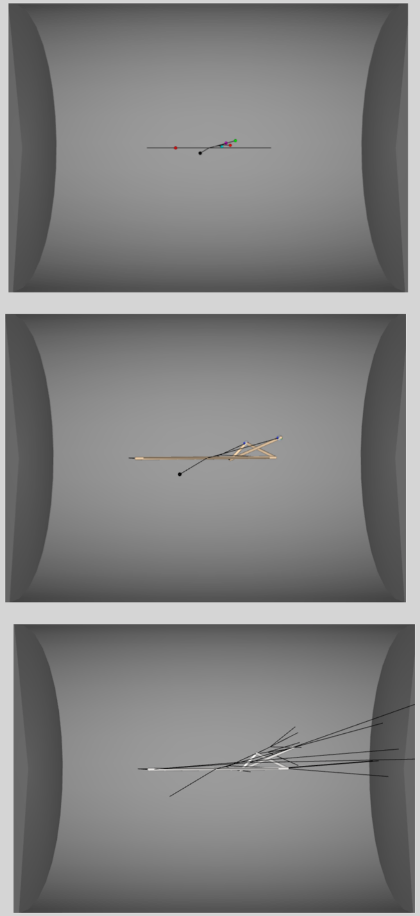
File Edit View Language Plain Text

```
Welcome to the Jupyter notebooks for Pythia 8 and DIRE!


You have the choice to run the following notebooks:

pythiaPI.ipynb
  Gives a basic idea of the Pythia 8 event generator, by using the Python
  interface of Pythia 8. You can adjust a set of parameters and choose
  from different different histograms to be plotted.

pythiaRivetPI.ipynb
  Shows how to use the Pythia 8 event generator, together with Rivet,
  by using the Python interface of Pythia 8.

pythiaRivet.ipynb
  Shows how to use Pythia 8, together with Rivet, by using an already
  compiled executable called pythiaHepMC. You can adjust a set of parameters
  and a settings file is created.

pythiaRivetUS.ipynb
  As pythiaRivet.ipynb, but uses a prepared settings file, to be provided
  by the user.

direRivet.ipynb
  Shows how to use Pythia 8 with the DIRE parton shower, together with
  Rivet, by using the default DIRE executable. You can adjust a set of
  parameters and a settings file is created.

direRivetUS.ipynb
  As direRivet.ipynb, but uses a prepared settings file, to be provided
  by the user.

direEvent.ipynb
  Pythia 8 with the DIRE parton shower, graphical output of one event
  with the default DIRE exectuable.
  The process can be choosen as well as a few basic parameters.

tuning.ipynb
  Tuning with Professor, Rivet, and Pythia 8 / DIRE.
```

Jupyter notebook interface



Visualization of ep collision



Online catalogue for MCEGs

- **Goals** Hosted on http://eicug.org/web/content/eic-software, editable for EIC group on GitLab

- **Proposed fields**
  - **Categories** ep, eA, radiative effects
  - Name
  - Contact information
  - **Brief Description** What processes are described? What is unique about the MCEG? Include version number as reference.
  - **References (links)** website, repository, documentation, container, validation plots

Online catalogue for MCEGs

- **Category** ep, eA, exclusive vector meson production, general photoproduction
- **Name** eSTARlight
- **Contact Information** Spencer Klein, srklein@lbl.gov
- **Brief description** eSTARlight simulates coherent photoproduction and electroproduction of vector mesons in ep and eA collisions. It can simulate a variety of different vector mesons, and it also includes an interface to DPMJET, which allows for general simulation of photonuclear interactions. It internally simulates most simple (2-body) vector meson decays with a correct accounting for the initial photon polarization (transverse for Q^2 ~ 0, with an increasing longitudinal component with increasing Q^2) in the angular distributions of the final state. It can also interface to PYTHIA8 to simulate more complicated decays.
- **References** The code is freely available from https://estarlight.hepforge.org/ The Readme file includes a fairly comprehensive users manual. The physics behind the code is documented in M. Lomnitz and S. Klein, Phys. Rev. C99, 015203 (2019).

Where we ended our discussions at DESY (MCEG2019a)

- **General-purpose MCEG**s, HERWIG, PYTHIA, and SHERPA, will be significantly improved w.r.t. MCEGs at HERA time:
  - MCEG-data comparisons in Rivet will be critical to tune the MCEGs to DIS data and theory predictions.
  - The existing general-purpose MCEG should soon be able to simulate NC and CC unpolarized observables also for eA. A precise treatment of the nucleus and 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 QED+QCD effects (in particular for eA).

- **TMD physics**
  - Vibrant community working on various computational tools for TMDs.
  - CASCADE: MCEG for unpolarized TMDs at high energy.
  - Need more verification of MCEG models with TMD theory / phenomenology.

MCEG for ep We are on a very good path, but still quite some work ahead.

MCEG for eA Less clear situation about theory and MCEG.

Where we will continue our discussions

MCEG for eA

- **eA theory**:
  - Challenges for MCEG for eA
  - eA Theory: Light Ions
  - eA Theory: Heavy Ions
  - Nuclear PDFs and TMDs
- **eA MCEG**: ALICE, Angantyr: Mueller dipole morels for pA and eA, BeAGLE, MCEG for spectator tagging in eD, JETSCAPE and JETSCAPE for EIC, MCEGs for Saturation, Sartre

MCEG validation Rivet/HZTool, Rivet for Heavy Ions

MCEG for TMDs ARTIMIDE, MCEG for (SI)DIS with TMDs, Parton branching TMDs and collider cross sections, TMDs and Coherent Branching

Markus Diefenthaler
mdiefent@jlab.org

Goals

Build our community

MCEG R&D for EIC

- eA
- TMDs
- validation

Common projects?