

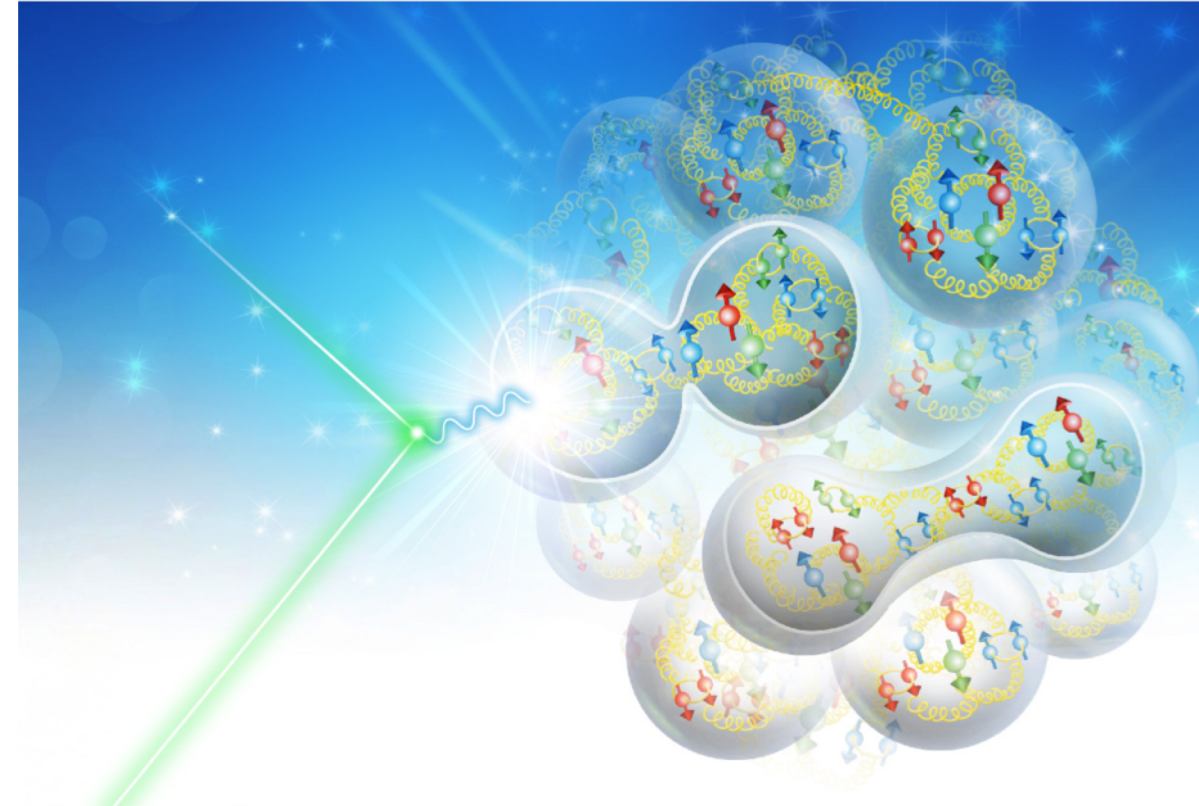
# MCEGs for future ep and eA facilities: Overview

## Electron-Ion Collider

### MCEGs for eA



**EIC<sup>2</sup>**  
EIC Center at Jefferson Lab  
Markus Diefenthaler

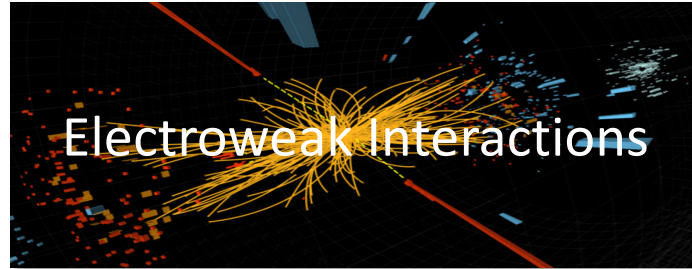


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# **Towards a new frontier in Nuclear Physics**

## **Imaging quarks and gluons**

# The Standard Model of Physics



## Further exploration of the Standard Model

Dark matter searches

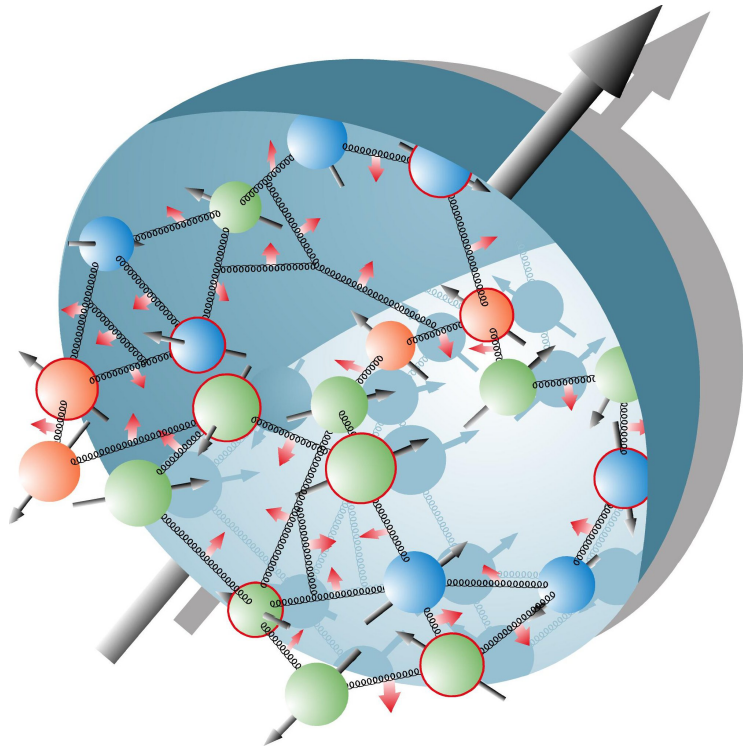
Electroweak symmetry breaking

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.

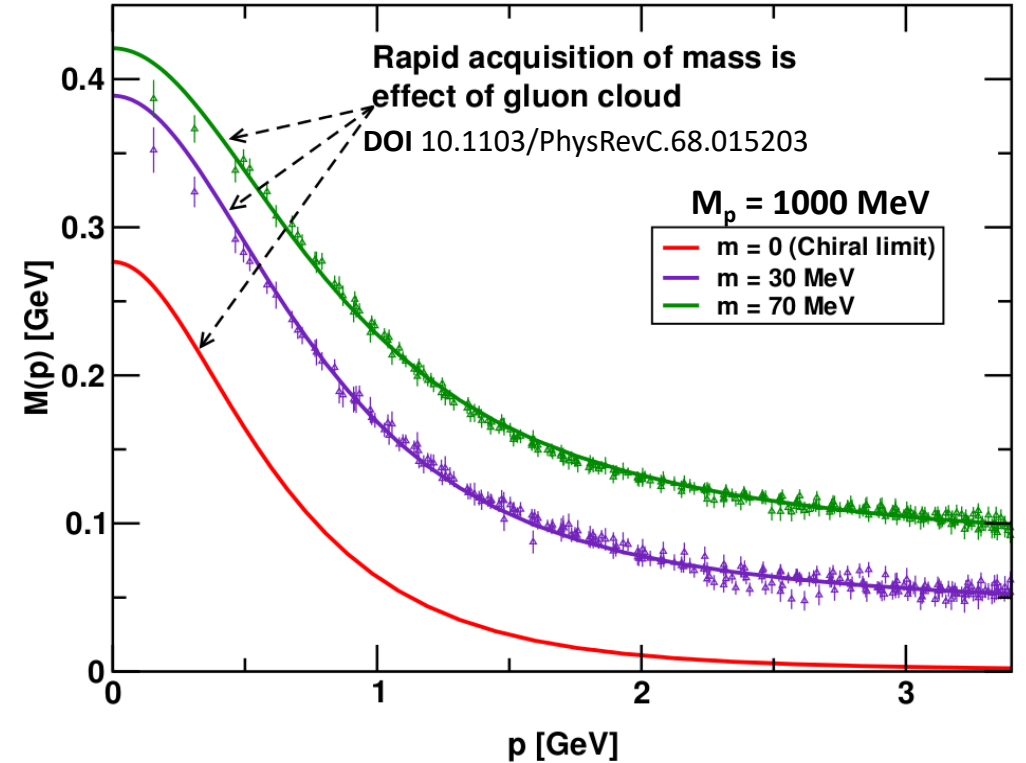
# The dynamical nature of nuclear matter

**Nuclear Matter** Interactions and structures are inextricably mixed up



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

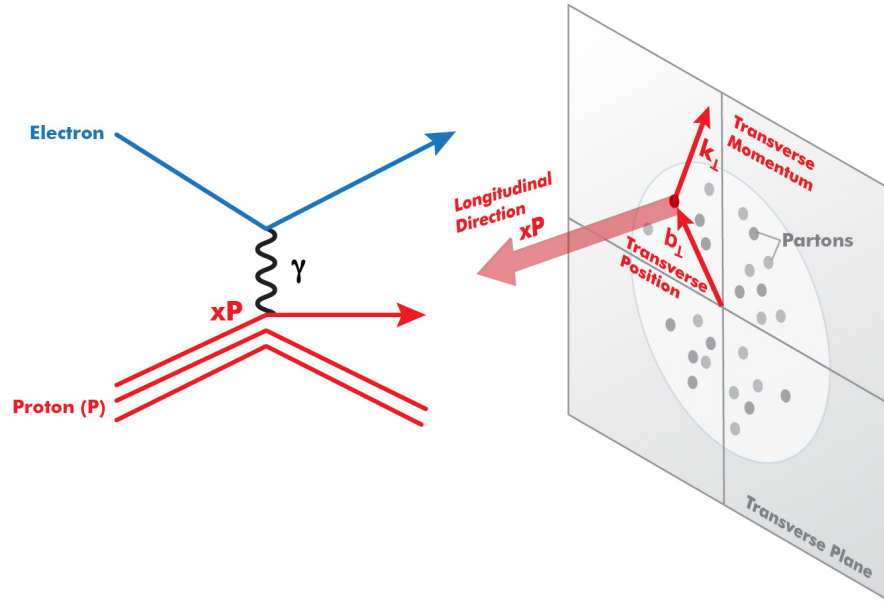
**Observed properties** such as mass and spin emerge out of the complex system



**To reach goal** precisely image quarks and gluons and their interactions

# Imaging quarks and gluons and their interactions

## Novel QCD phenomena



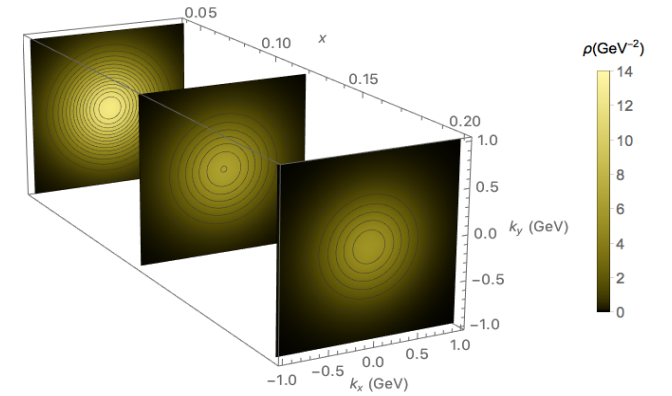
## 3D imaging in space and momentum

longitudinal structure (PDF)  
+ transverse position Information (GPDs)  
+ transverse momentum information (TMDs)  
order of a few hundred MeV

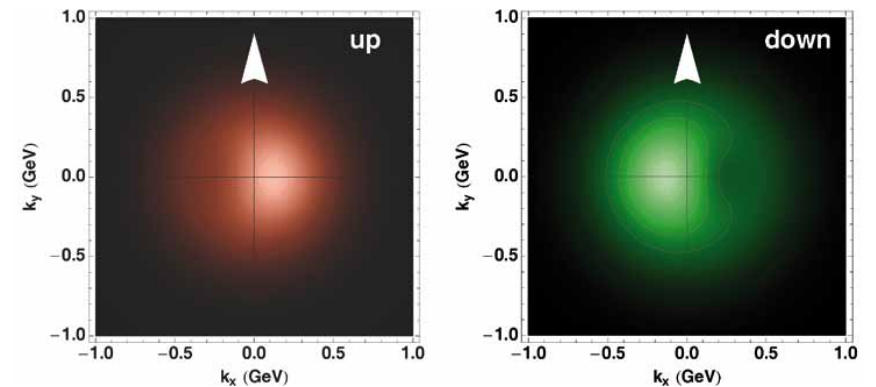
## TMD PDFs

### Unpolarized nucleon

JHEP 1706 (2017) 081



### Transversely polarized nucleon

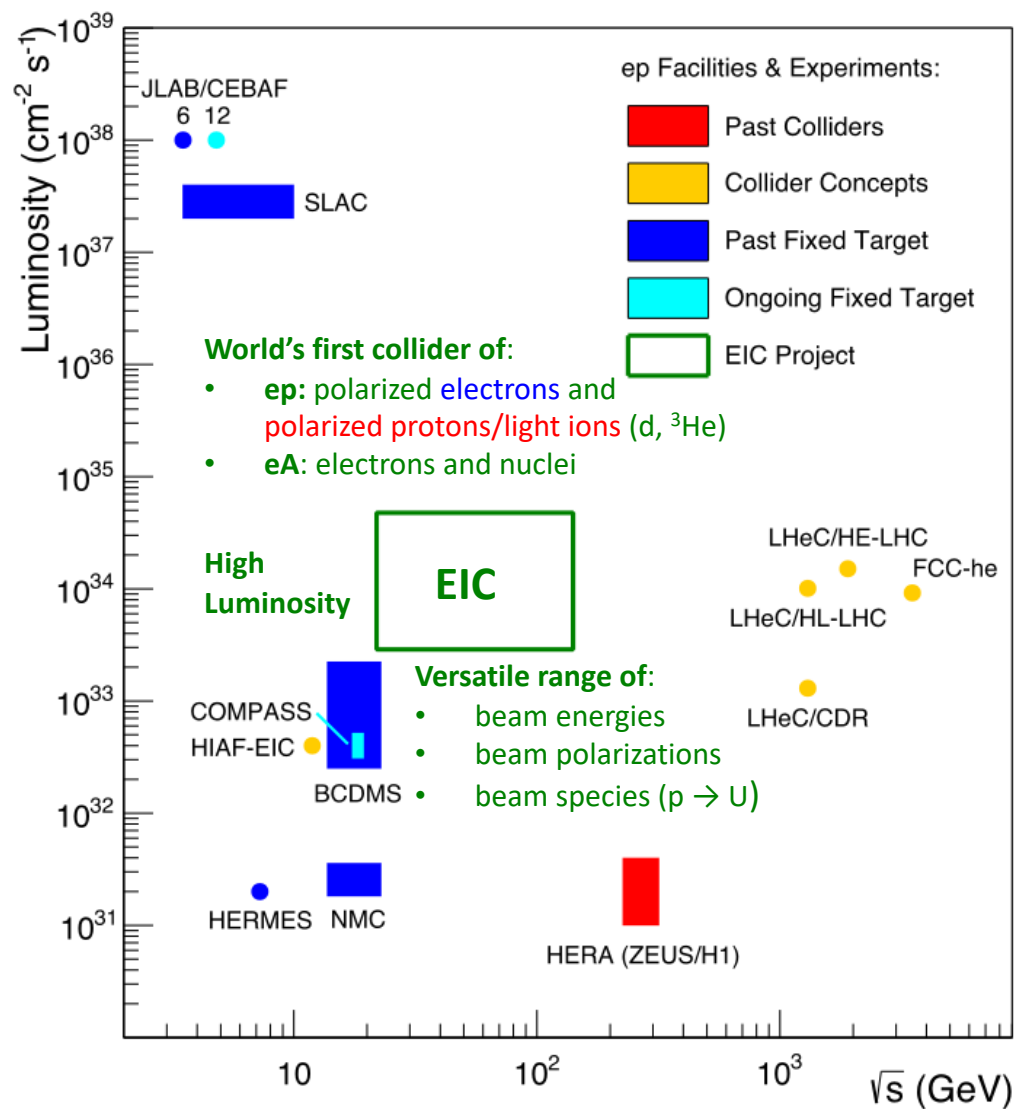


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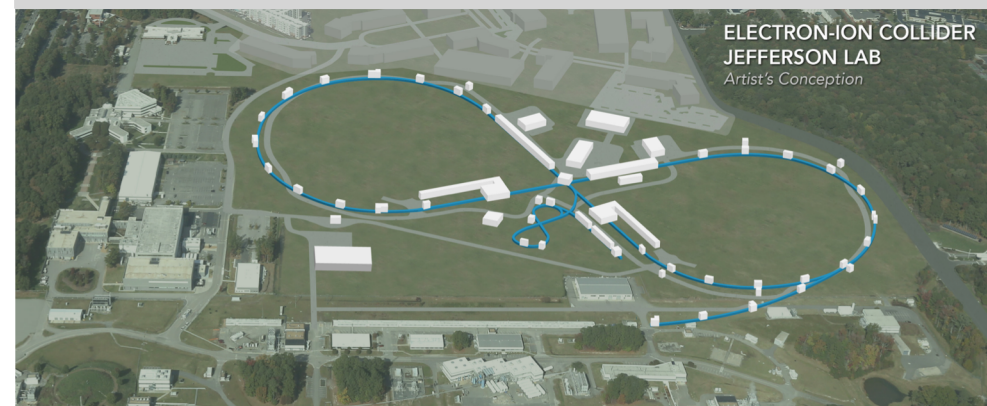
# **Future nuclear physics facility**

## **The Electron-Ion Collider Project**

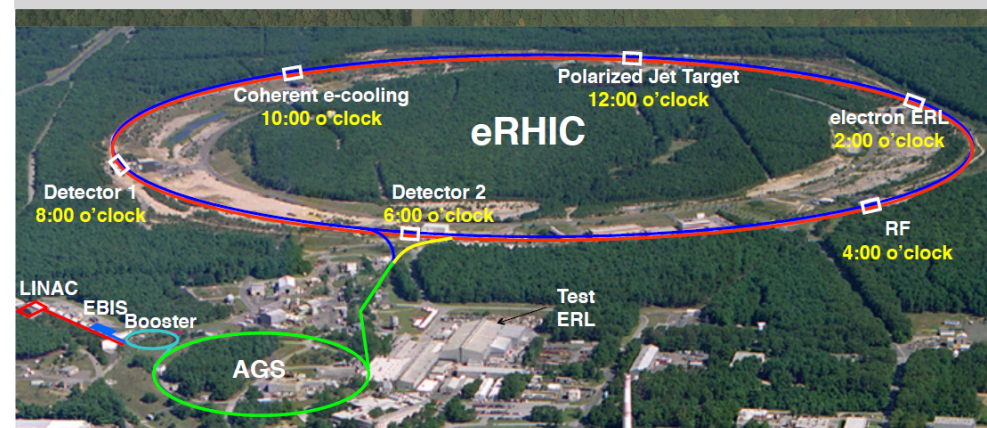
# The Electron-Ion Collider: Frontier accelerator facility in the U.S.



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

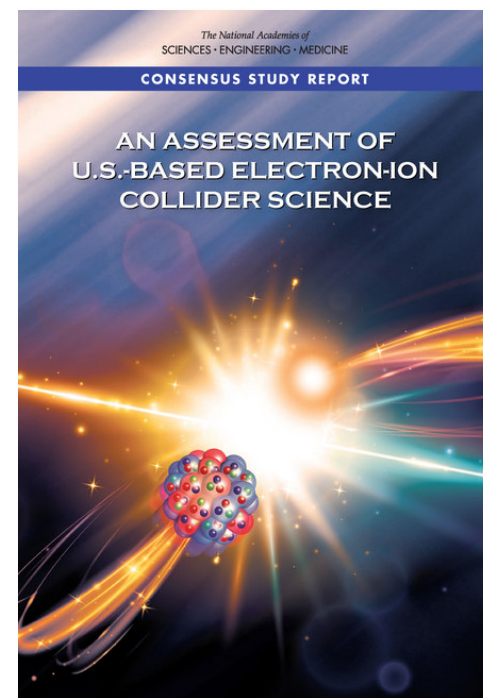
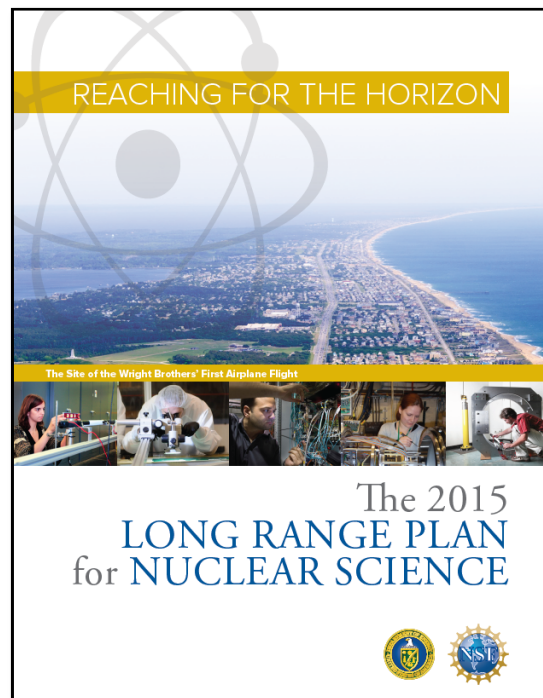
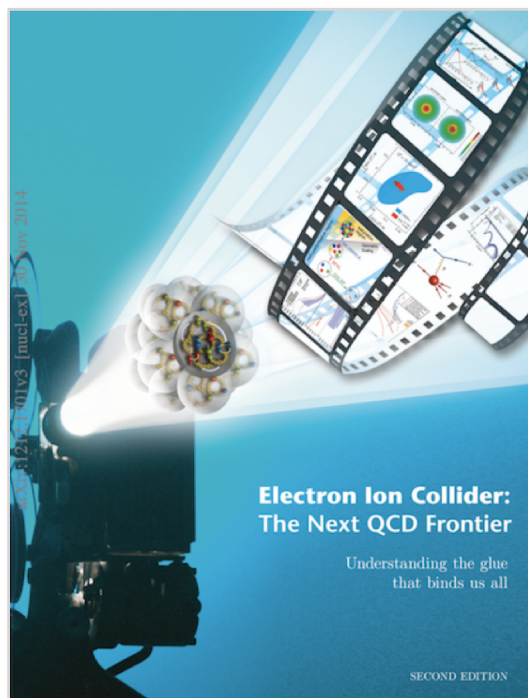


Proposal by Jefferson Lab



Proposal by Brookhaven Lab

# Why an Electron-Ion Collider?



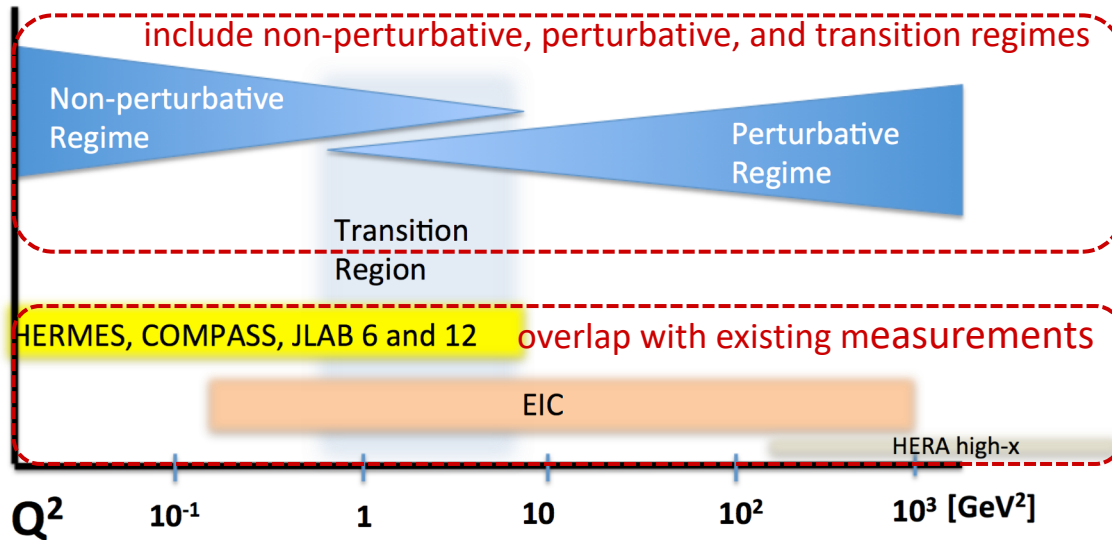
## Right tool

- 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

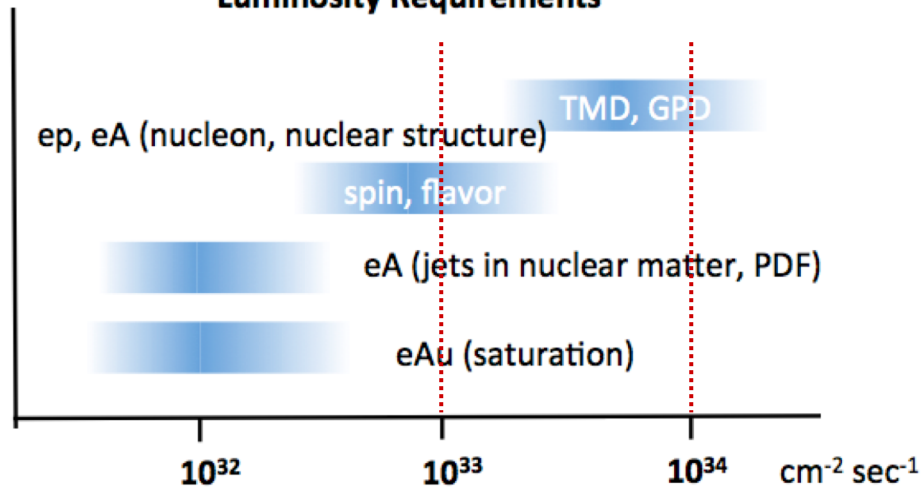


## Various beam energy

broad  $Q^2$  range for

- studying evolution to  $Q^2$  of  $\sim 1000$  GeV<sup>2</sup>
- disentangling non-perturbative and perturbative regimes
- overlap with existing experiments

## Luminosity Requirements

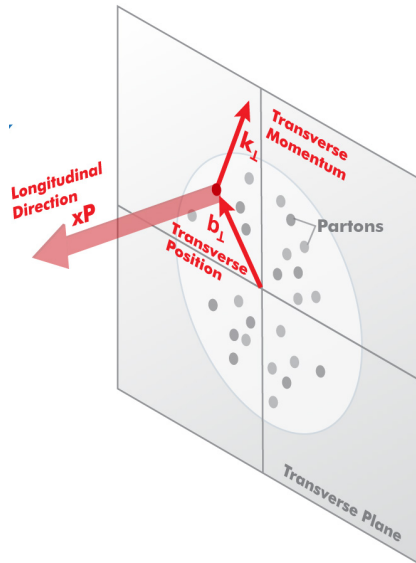
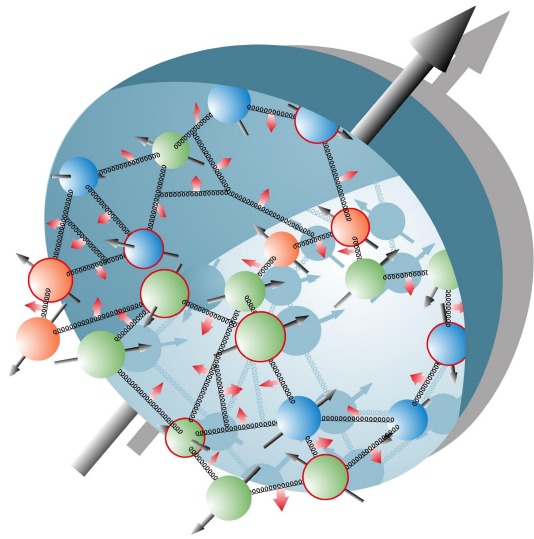


## High luminosity / high precision

### 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

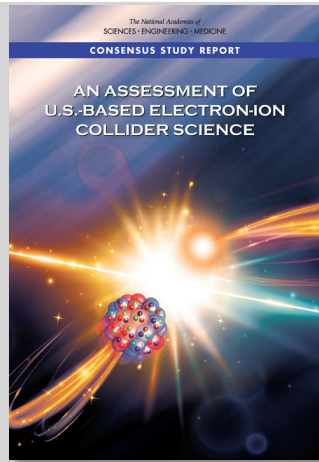
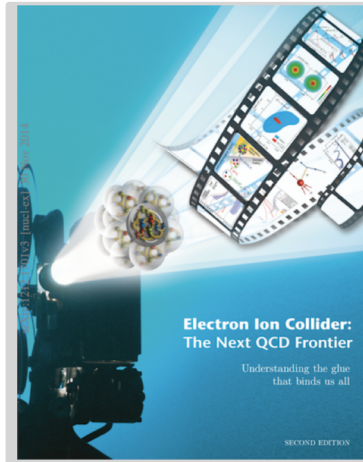
Understanding hadron structure cannot be done without understanding spin:

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

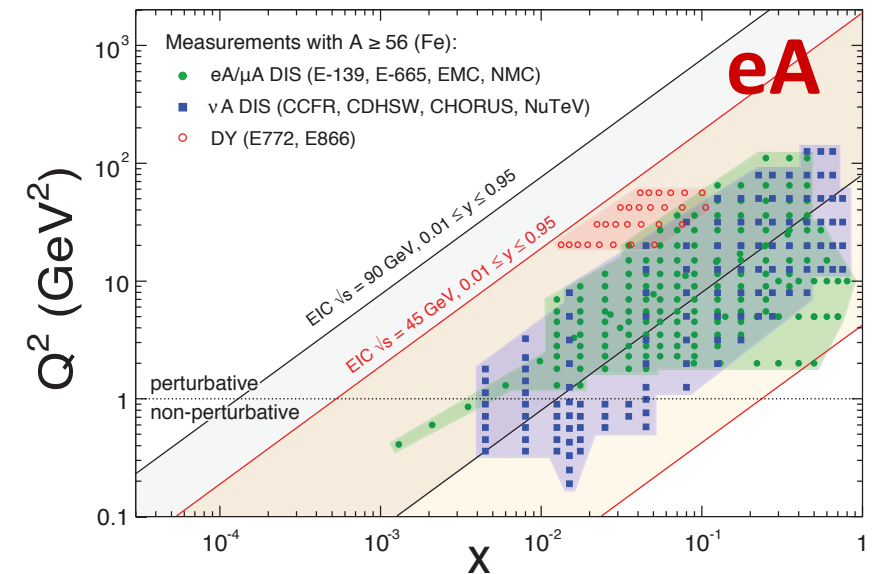
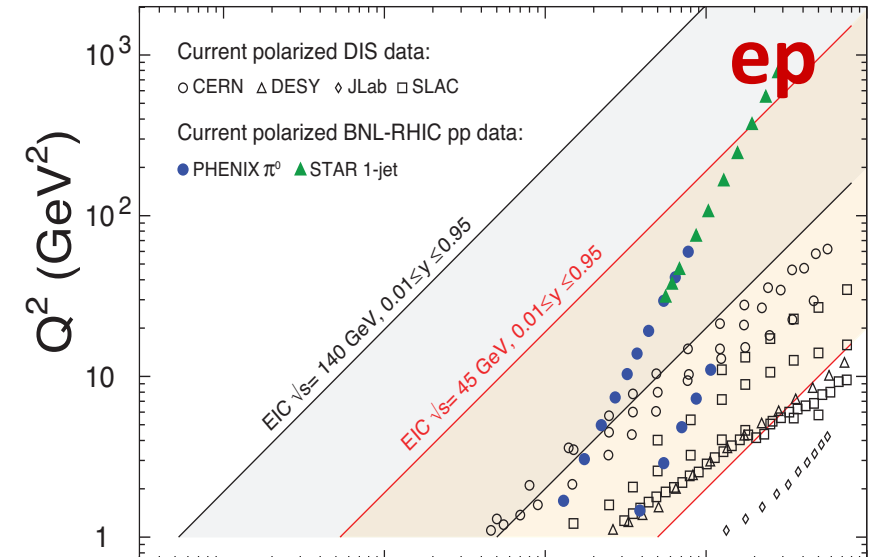
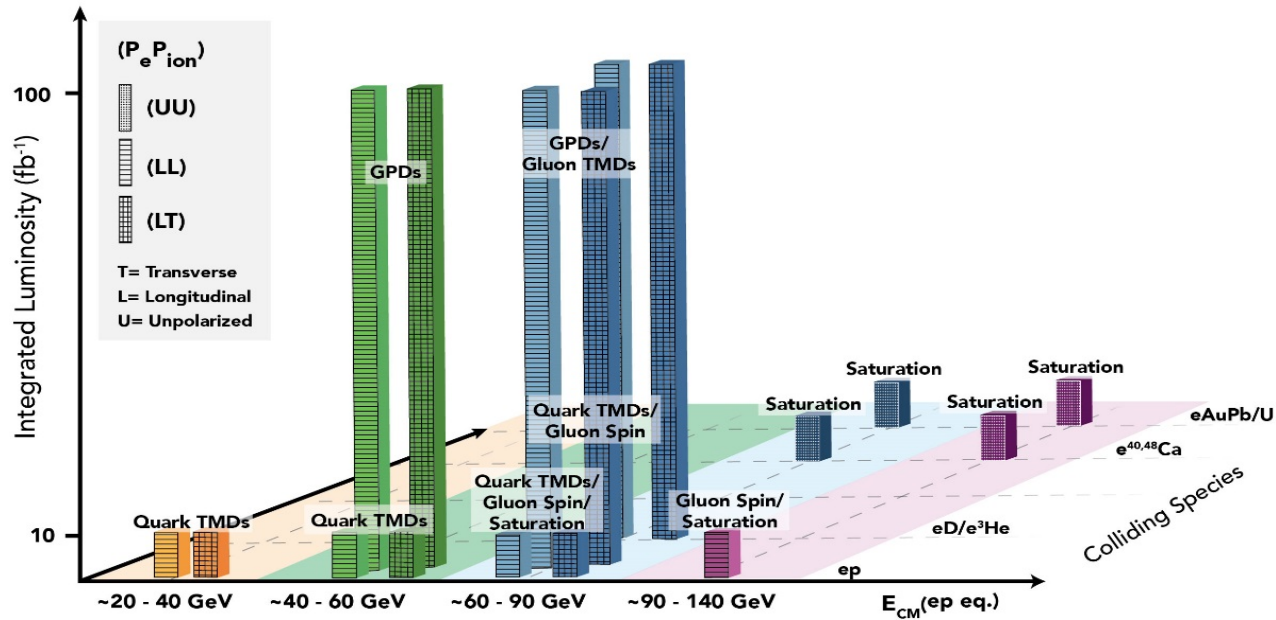
## Longitudinal and transverse and polarization of light ions (d, $^3\text{He}$ )

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

# EIC science program



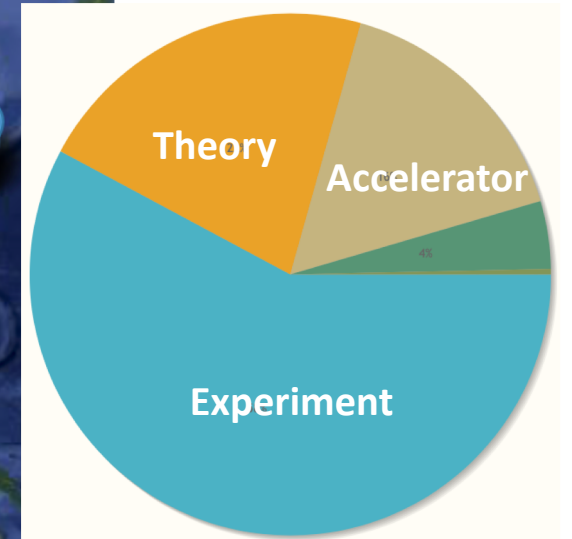
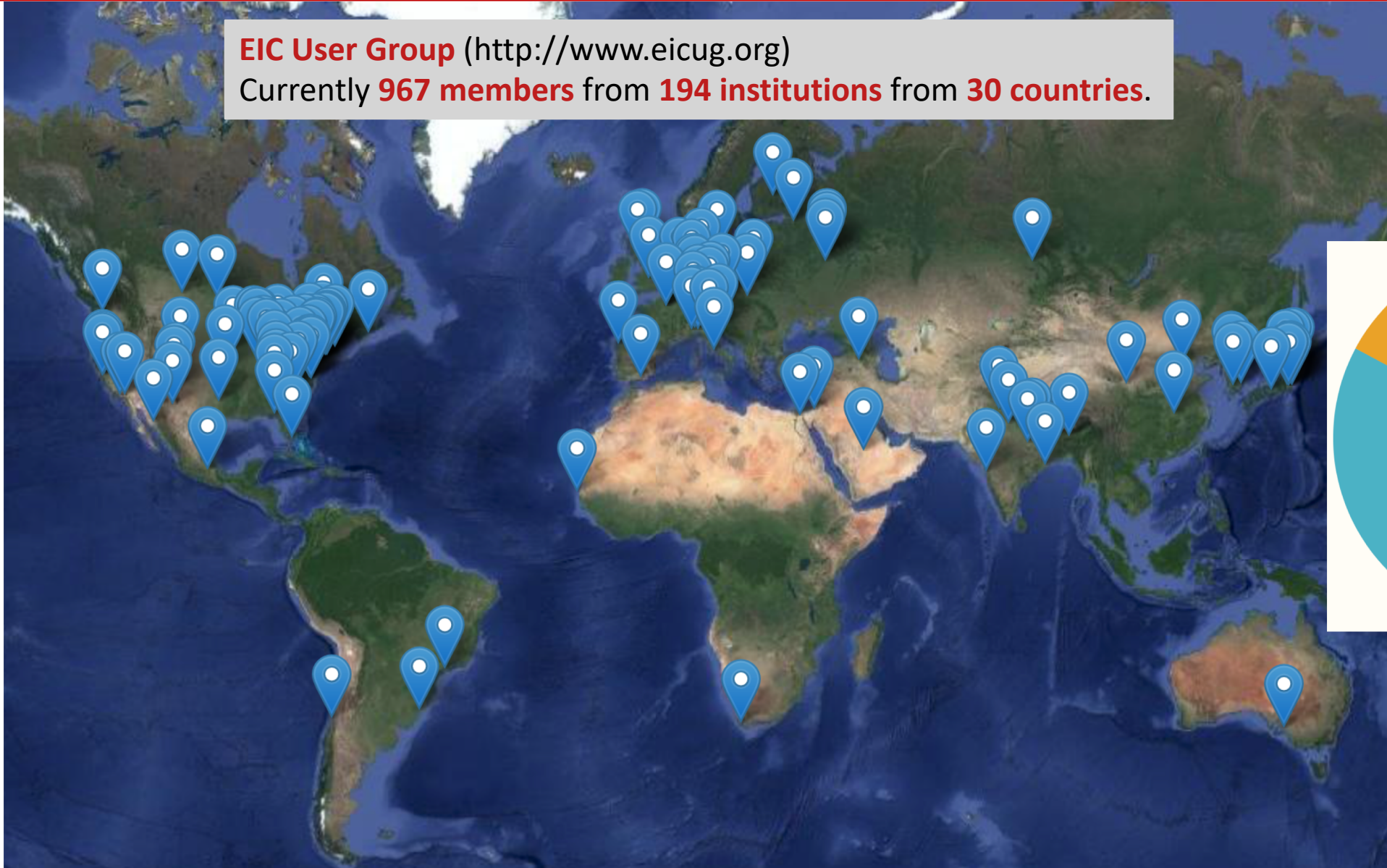
Study **structure** and **dynamics** of **nuclear matter** in **ep** and **eA** collisions with high luminosity and versatile range of beam energies, beam polarizations, and beam species.



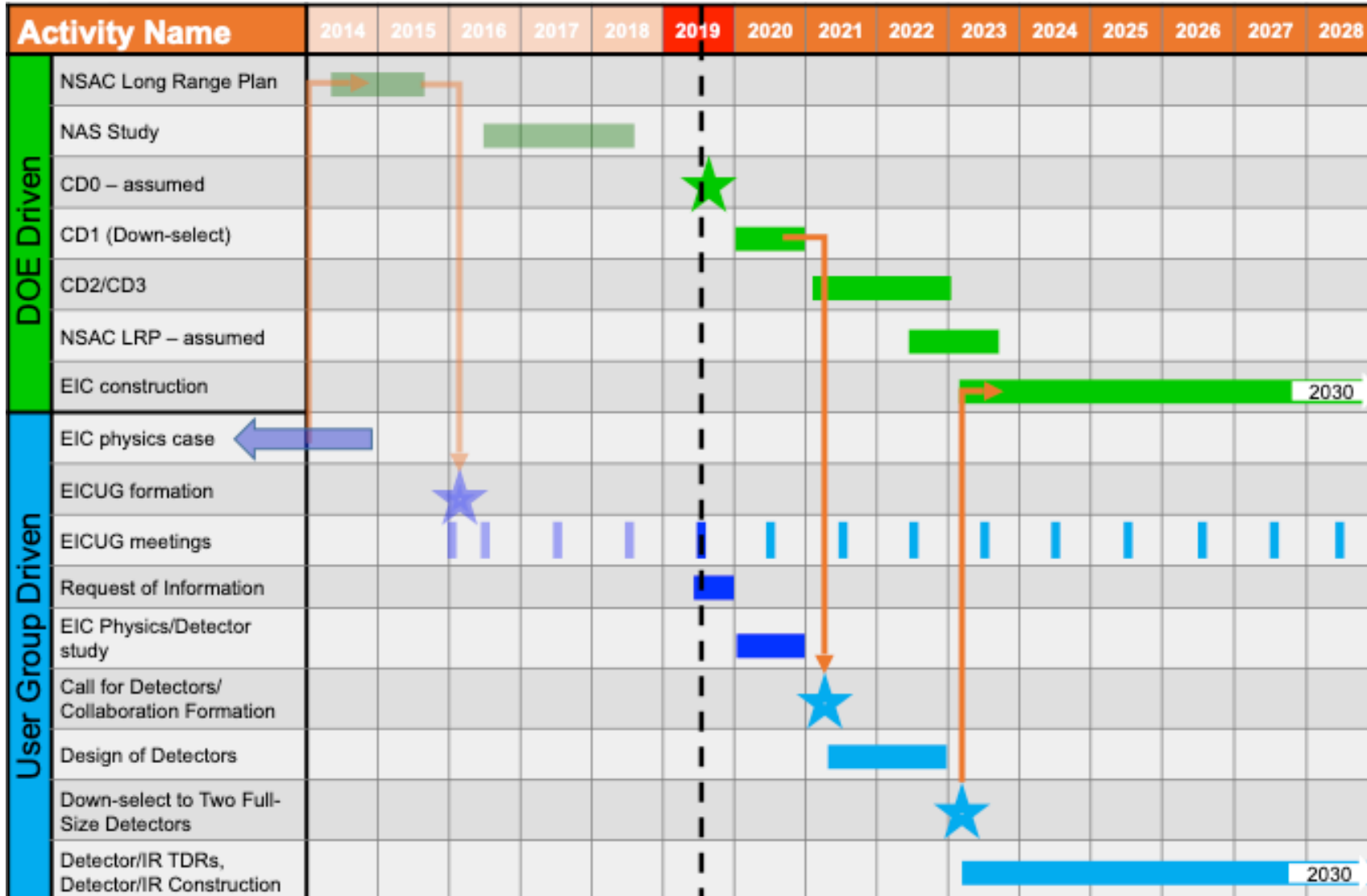
# The worldwide EIC community

**EIC User Group** (<http://www.eicug.org>)

Currently **967 members** from **194 institutions** from **30 countries**.



# Timeline



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# **EIC simulations and analysis**

## **MCEGs for future ep and eA facilities**

# MCEGs for future ep and eA facilities

## P O E T I C 8

8th International Conference on Physics Opportunities at an Electron-Ion Collider  
**19-23 March 2018, University of Regensburg**

**Local Organizing Committee:**

Gunnar Bali  
 Vladimir Braun  
 Falk Bruckmann  
 Sara Collins  
 Andreas Schäfer (chair)  
 Stefan Solbrig

**International Advisory Committee**

Nestor Armesto (Univ. de Santiago de Compostela, Spain)  
 Elke Aschenauer (BNL, USA)  
 Daniel Boer (University of Groningen, Netherlands)  
 Marco Contalbrigo (INFN Ferrara, Italy)  
 Markus Diehl (DESY, Germany)  
 Rolf Ent (JLab, USA)  
 Max Klein (University of Liverpool, UK)  
 Andrzej Sandacz (National Centre for Nuclear Research, Poland)  
 Marco Stratmann (University of Tübingen, Germany)  
 Lech Szymanowski (National Centre for Nuclear Research, Poland)  
 Tony Thomas (University of Adelaide, Australia)  
 Thomas Ullrich (BNL, USA)  
 Raju Venugopalan (BNL, USA)

### Satellite Workshop

**Topics:**

- Structure of hadrons: nuclear parton distribution functions (PDFs, nPDFs), transverse momentum dependent (TMDs) and generalized parton distributions (GPDs), Distribution Amplitudes (DAs), Double Distributions (DDs).
- QCD at high parton densities and small-x: saturation, evolution, Color Glass Condensate
- Fragmentation functions and Jet properties
- Complementarity and connections of EIC physics with p+p, p+A and A+A collisions: high  $p_T$  processes, diffraction, multi-parton interactions, quark-gluon plasma and colored probes in hot nuclear matter.
- Physics beyond the Standard Model and connections to other areas in physics.
- Future DIS facilities: accelerator and detector developments.



**February 20-22, 2019**  
 DESY Hamburg, Germany

EIC User Group and MCnet present

# MCEGs

for future ep and eA facilities

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**PROGRAM**

Updates to general-purpose MCEG for ep/eA  
 Status of NLO simulations for ep/eA  
 GPDs and TMDs in MCEGs  
 QED+QCD effects in ep/eA simulations

**ORGANIZERS**

Elke-Caroline Aschenauer (BNL)    Simon Plätzer (University of Vienna)  
 Andrea Bressan (INFN Trieste)    Stefan Prestel (Lund University)  
 Markus Diefenthaler (JLAB)  
 Hannes Jung (DESY)

[www.desy.de/mceg2019](http://www.desy.de/mceg2019)



**November 20-22, 2019**  
 Erwin-Schrödinger Institute  
 Vienna, Austria

EIC User Group and MCnet present

# MCEGs

for future ep and eA facilities

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**PROGRAM**

MCEGs for eA, including light and heavy ions  
 Validation of HERA data  
 MCEGs for TMDs

**ORGANIZERS**

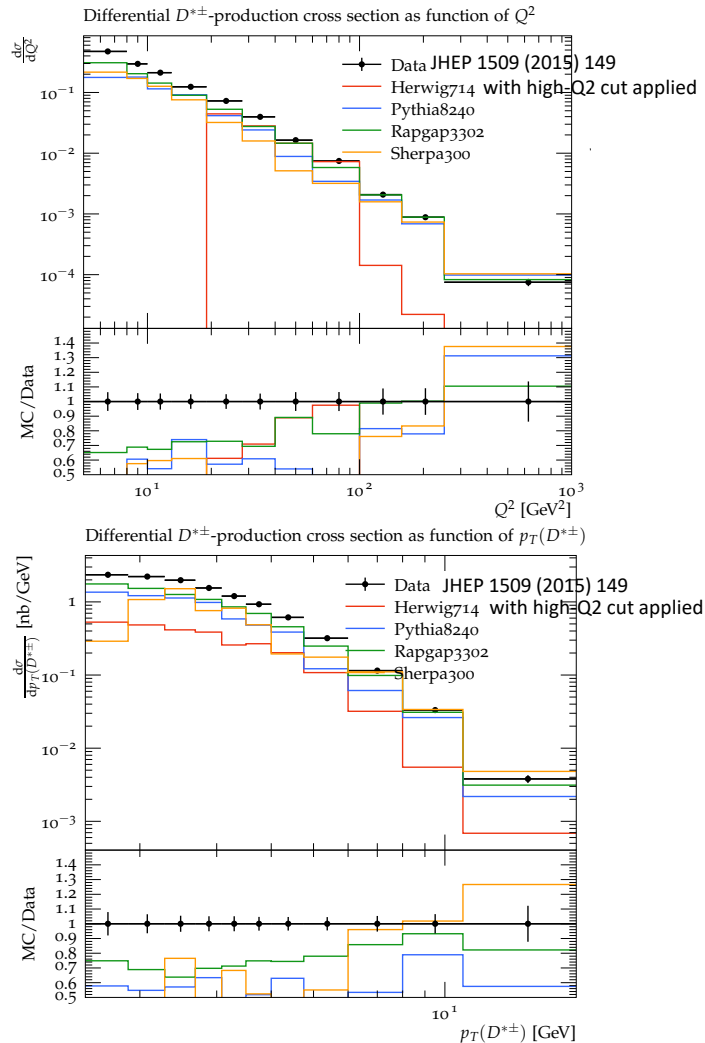
Elke-Caroline Aschenauer (BNL)    Simon Plätzer (Vienna)  
 Andrea Bressan (Trieste)    Stefan Prestel (Lund)  
 Markus Diefenthaler (JLAB)  
 Hannes Jung (DESY)



 Erwin Schrödinger International Institute for Mathematics and Physics
 <https://indico.cern.ch/event/845653/>

Zoran Matic / shutterstock.com

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

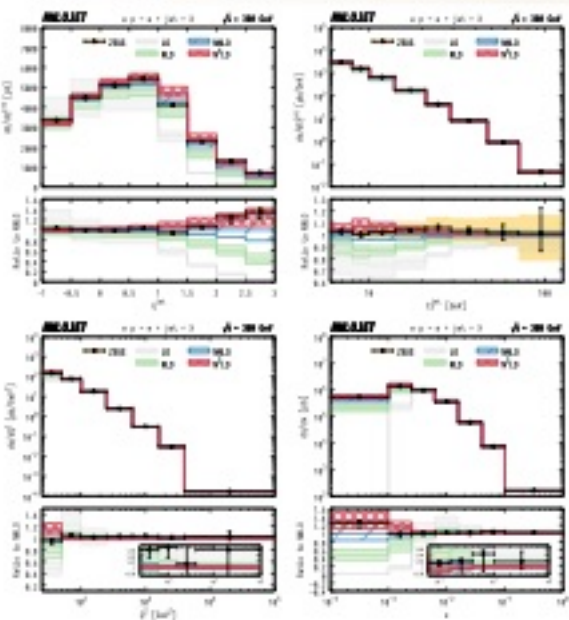
### • Pythia

- 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





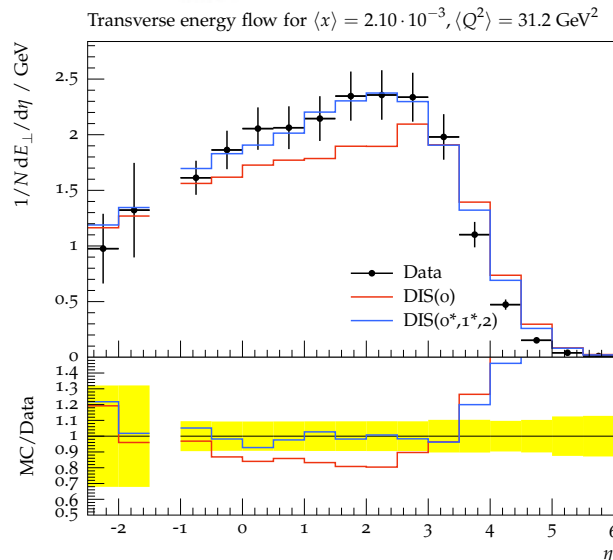
arXiv:1803.09973

## Fixed-order QCD

- QCD calculations available up to N<sup>3</sup>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

```
66 // Extract the particles other than the lepton
67 const FinalState& fs = apply<FinalState>(event, "FS");
68 Particles particles;
69 particles.reserve(fs.particles().size());
70 const GenParticle* dilepGP = dl.out().genParticle();
71 foreach (const Particle& p, fs.particles()) {
72     const GenParticle* loopGP = p.genParticle();
73     if (loopGP == dilepGP)
74         continue;
75     particles.push_back(p);
76 }
77
78 // Apply HERMES cuts.
79 bool validx = (x > 0.023 && x < 0.6);
80 if (q2 < 1. || w2 < 10. || y < 0.1 || y > 0.85 || !validx)
81     vetoEvent;
82
83 // good inclusive event, let's do bookkeeping before we look at the hadrons
84 dis_tot += weight;
85 dis_x->fill(x, weight);
86 dis_Q2->fill(q2, weight);
87
88 for (size_t ip1 = 0; ip1 < particles.size(); ++ip1) {
89     const Particle& p = particles[ip1];
90
91     // get the particle index, check if it is a particle of interest
92     const int part_idx = get_index(p.genParticle()->pdg_id());
93     if (part_idx < 0) {
94         continue;
95     }
96
97     // we have a particle of interest, let's calculate the kinematics
98     // z
99     const double z = (p.momentum() * pProton) / (pProton * q);
100     // pt
101     const double pth = sqrt(p.momentum().pT2());
102
103     // get our z index, if negative, we have a particle outside of [.2, .8]
104     const int z_idx = calc_zslice(z);
105     if (z_idx < 0) {
106         continue;
107     }
108
109     // store the events and make cuts where necessary
110     //
111     // pt cut for variables not binned in pt
112     if (pth > 0 && pth < 1.2) {
113         mult_z[part_idx]->fill(z, weight);
114         mult_zx[part_idx][z_idx]->fill(x, weight);
115         mult_zQ2[part_idx][z_idx]->fill(q2, weight);
116     }
117     mult_zpt[part_idx][z_idx]->fill(pth, weight);
118 }
```

- **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](mailto:rivet-ep-l@lists.bnl.gov)
  - HERA data not (yet) included in MCEG tunes

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



## *n*TMD using PB method

Krzysztof Kutak



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



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.



21<sup>st</sup> 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 + 3PO; good description of Collins and di-hadron asymmetries; Boer-Mulders, jet handedness can be simulated.

# Merging QED and QCD effects

CLASSIFICATION OF  $O(\alpha)$  QED CORRECTIONS

- **Radiation from the lepton**  
model independent (universal),  
dominating by far: enhanced by large logs,  $\ln(Q^2/m_e^2)$
- vacuum polarization (boson self energy)  
universal, photon self energy  $\rightarrow \alpha_{em}(Q^2)$
- **Radiation from the hadronic initial/final state**  
parton model: radiation from quarks  
to be considered as a part of the nucleon structure
- **Interference of leptonic and hadronic radiation**  
 $2\gamma$  exchange  
new structure
- purely weak corrections

Note: for NC-scattering, straightforward separation  
IR divergences: need to combine real and virtual radiation

H. Spiesberger (Mainz) MCEGs, 20. 2. 2019 5 / 20

## 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

Radiative corrections in SIDIS

The Born cross section

Emission of a radiated photon (semi-inclusive processes)

Loop diagrams

Emission of a radiated photon (exclusive processes)

The real polar angle of virtual photon is changing due to radiation of the real photon, introducing azimuthal dependence, coupling to  $\phi$ -dependence of the x-section  
Akushevich, Ilyichev, Osipenko, PL B672 (2009) 35

THE GEORGE WASHINGTON UNIVERSITY Andrei Afanasev, Workshop on MCEGs for Future ep and eA facilities, 20 Feb 2019 4  
WASHINGTON, DC

# 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

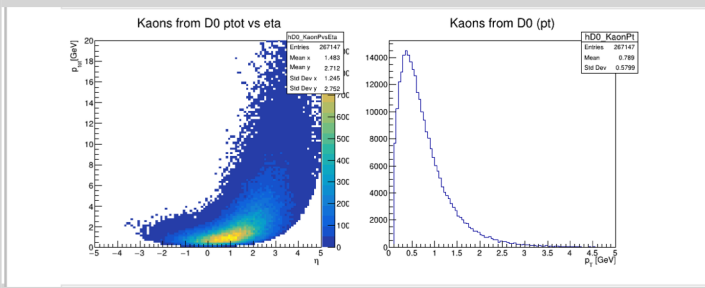
[5]: jana.source('../data/herwig6_20k.hepmc')

[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  $x_B \gg 0.1$  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.

The figure shows four Feynman diagrams illustrating open charm production processes. The diagrams are labeled  $D^0$ ,  $D^+$ ,  $D_s^+$ , and  $D_s^0$ . Each diagram shows a quark line (red) and a gluon line (blue) interacting to produce a charm quark (red) and a gluon (blue), which then combine to form the final state.

## Container for Pythia8+DIRE by Nadine Fischer (Pythia)

The screenshot shows a Jupyter notebook interface with a menu bar (File, Edit, View, Language) and a 'Logout' button. The main content area displays a list of notebooks:

- 1 Welcome to the Jupyter notebooks for Pythia 8 and DIRE!
- 2
- 3
- 4 You have the choice to run the following notebooks:
- 5
- 6 **pythiaPI.ipynb**  
7 Gives a basic idea of the Pythia 8 event generator, by using the Python  
8 interface of Pythia 8. You can adjust a set of parameters and choose  
9 from different different histograms to be plotted.
- 10
- 11 **pythiaRivetPI.ipynb**  
12 Shows how to use the Pythia 8 event generator, together with Rivet,  
13 by using the Python interface of Pythia 8.
- 14
- 15 **pythiaRivet.ipynb**  
16 Shows how to use Pythia 8, together with Rivet, by using an already  
17 compiled executable called pythiaHepMC. You can adjust a set of parameters  
18 and a settings file is created.
- 19
- 20 **pythiaRivetUS.ipynb**  
21 As pythiaRivet.ipynb, but uses a prepared settings file, to be provided  
22 by the user.
- 23
- 24 **direRivet.ipynb**  
25 Shows how to use Pythia 8 with the DIRE parton shower, together with  
26 Rivet, by using the default DIRE executable. You can adjust a set of  
27 parameters and a settings file is created.
- 28
- 29 **direRivetUS.ipynb**  
30 As direRivet.ipynb, but uses a prepared settings file, to be provided  
31 by the user.
- 32
- 33 **direEvent.ipynb**  
34 Pythia 8 with the DIRE parton shower, graphical output of one event  
35 with the default DIRE executable.  
36 The process can be chosen as well as a few basic parameters.
- 37
- 38 **tuning.ipynb**  
39 Tuning with Professor, Rivet, and Pythia 8 / DIRE.
- 40

## Jupyter notebook interface

The screenshot shows a Jupyter notebook interface with the following content:

### Pythia 8 standalone

This notebook 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.

First, lets import all necessary modules.

```
In [1]: import os, sys, pythia8
from plotting import MULTHIST
import py8settings as py8s
```

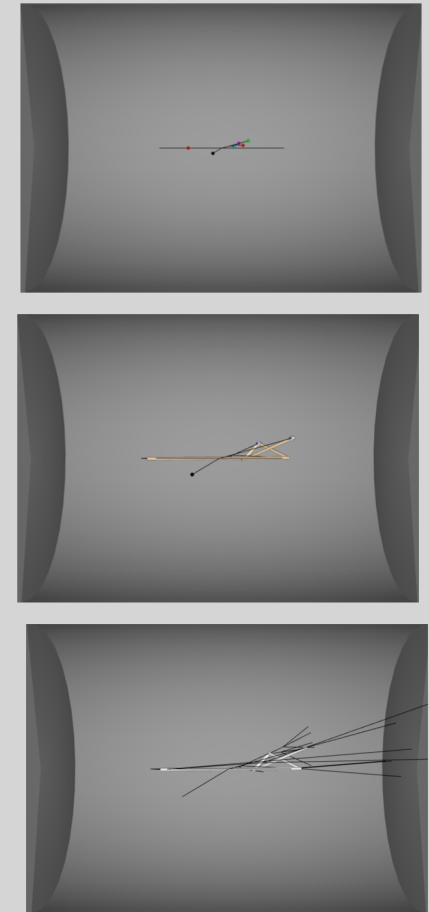
Now we create a Pythia 8 object and apply the settings to define the incoming beams. More settings can be adjusted later.

```
In [2]: # Setup pythia, apply beam settings.
pythia = pythia8.Pythia()
py8s.beam_settings(pythia)
```

You can now set the parameters for the incoming beams:

beam A id [Beams:idA]	e-
beam B id [Beams:idB]	p
beam frame type [Beams:frameType]	2: back-to-back beams with different energies, set Beams:eA and Beams:eB
CMS energy for Beams:frameType = 1 [Beams:eCM]	65.7
beam A energy for Beams:frameType = 2 [Beams:eA]	10.8
beam B energy for Beams:frameType = 2 [Beams:eB]	100

## Visualization of ep collision



# Online catalogue for MCEGs

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- **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](mailto: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  $Q^2 \sim 0$ , 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://estarlightheppforge.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 MCEGs**, 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

November 20-22, 2019  
Erwin-Schrödinger Institute  
Vienna, Austria

EIC User Group and MCnet present

# MCEGs

for future ep and eA facilities

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**PROGRAM**

- MCEGs for eA, including light and heavy ions
- Validation of HERA data
- MCEGs for TMDs

**ORGANIZERS**

Elke-Caroline Aschenauer (BNL)	Simon Plätzer (Vienna)
Andrea Bressan (Trieste)	Stefan Prestel (Lund)
Markus Diefenthaler (JLAB)	
Hannes Jung (DESY)	

  Erwin Schrödinger International Institute for Mathematics and Physics <https://indico.cern.ch/event/845653/>

Zoran Matic / shutterstock.com

## 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 models 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

# Goals

## Build our community

### MCEG R&D for EIC

- eA
- TMDs
- validation

### Common projects?

