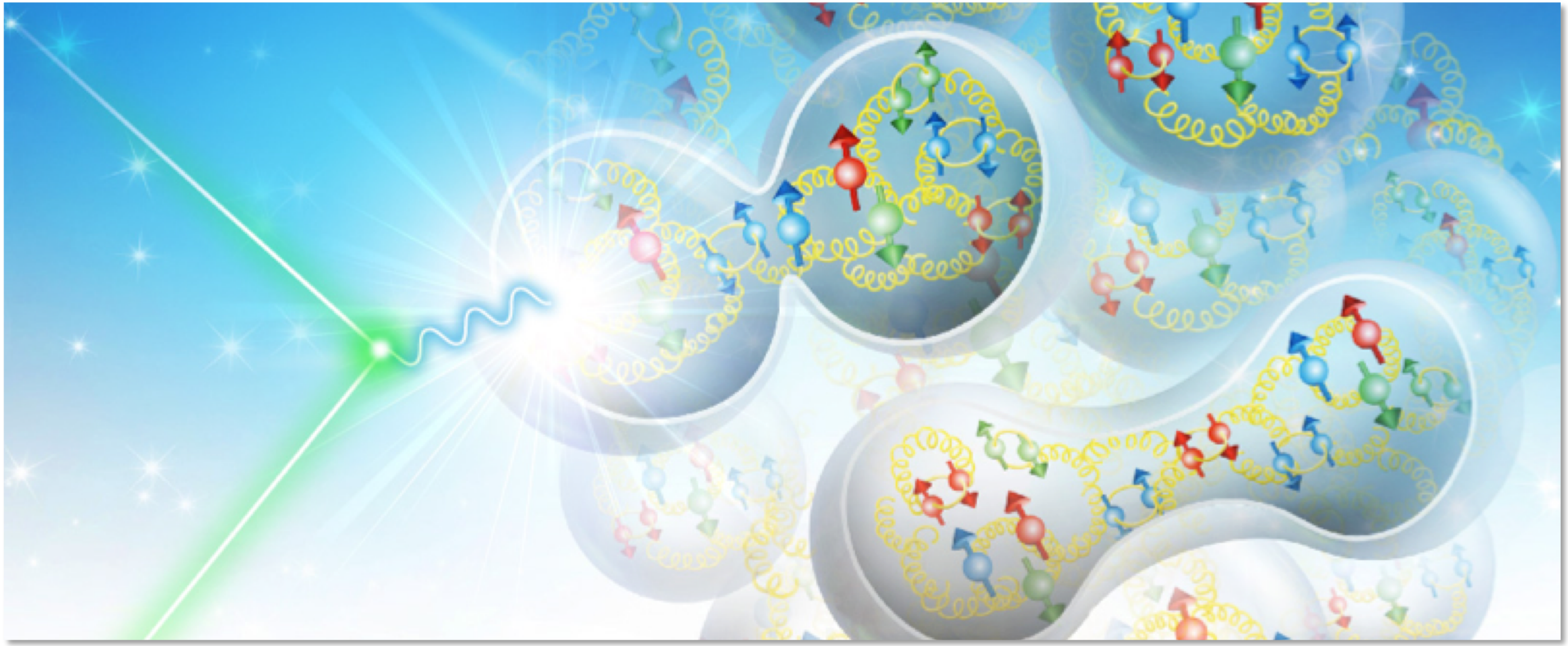
A first look at MCEGs for the Electron-Ion Collider



Markus Diefenthaler

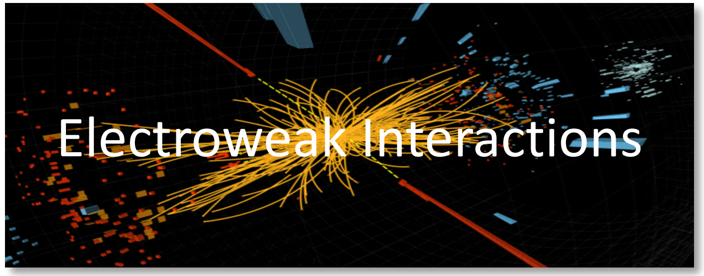
Jefferson Lab

Nuclear Physics

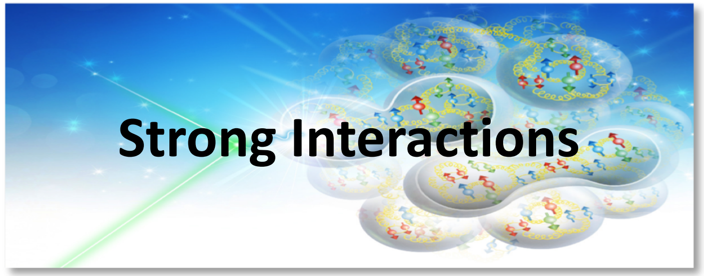
Further exploration of the Standard Model

Dark matter searches

Electroweak symmetry breaking



Deeper understanding of QCD



Mission of Nuclear Physics

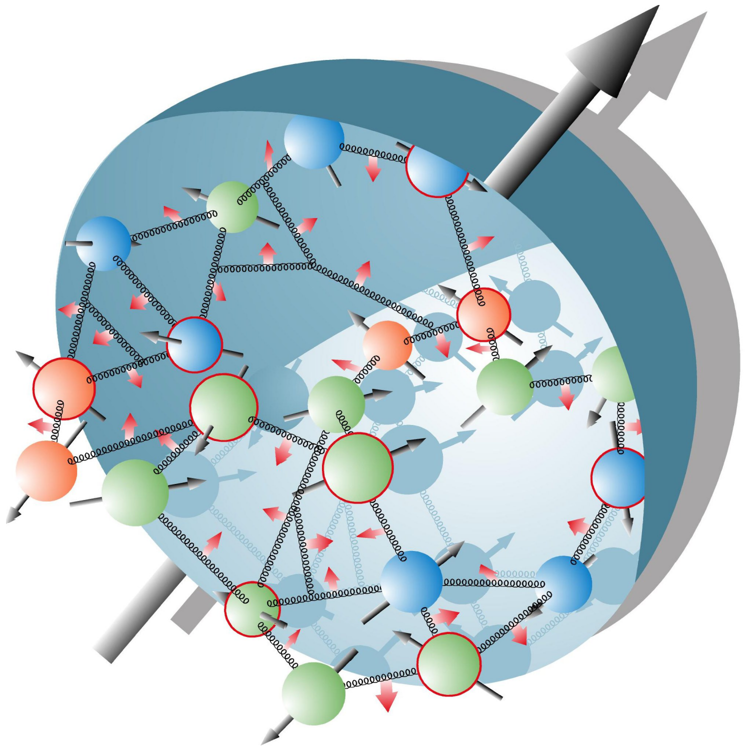
- Discover, explore, and understand all forms of nuclear matter.

Frontiers in Nuclear Physics

- One of the enduring mysteries of the universe is the nature of matter—what are its basic constituents and how do they interact to form the properties we observe? The largest contribution by far to the mass of the matter we are familiar with comes from protons and heavier nuclei.
- Although the fundamental particles that compose nuclear matter—quarks and gluons—are themselves relatively well understood, exactly how they interact and combine to form the different types of matter observed in the universe today and during its evolution remains largely unknown. .

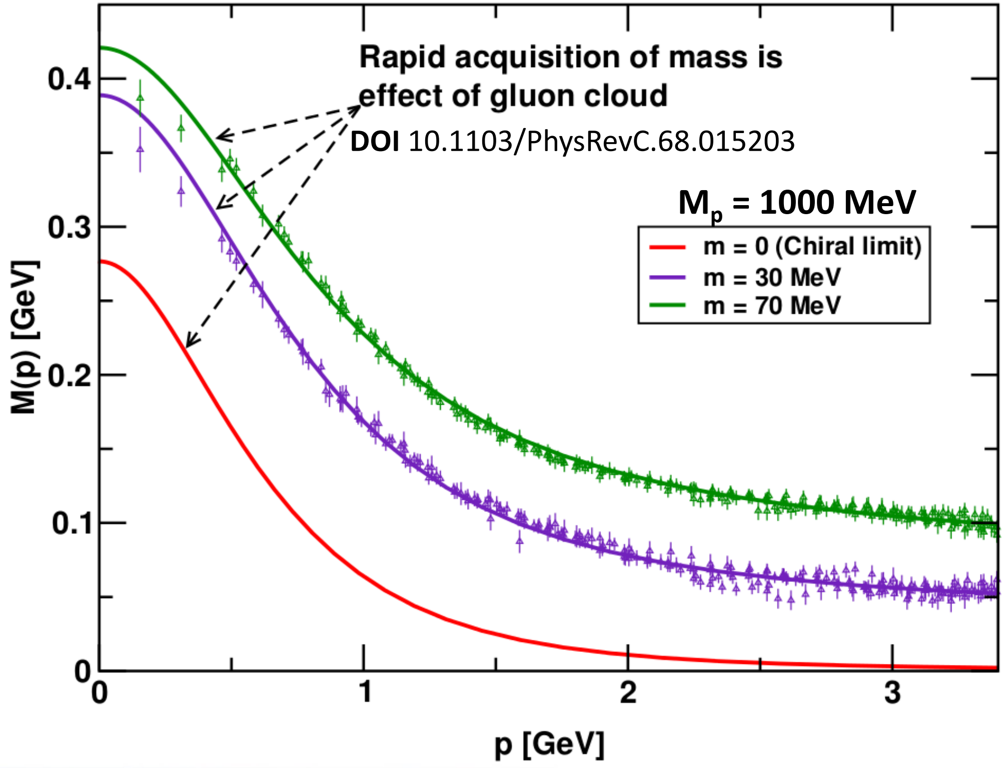
The dynamical nature of nuclear matter

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

Nobel Prizes in Physics related to Nuclear Physics

Hideki Yukawa (1949) "for his prediction of the existence of mesons on the basis of theoretical work on nuclear forces"
But the quark-gluon origin of the nuclear binding force remains unknown.

Robert Hofstadter (1961) "for his pioneering studies of electron scattering in atomic nuclei and for his thereby achieved discoveries concerning the structure of the nucleons"
But the 3D quark-gluon structure of nucleons remains unknown.

Jerome Friedman, Henry Kendall, Richard Taylor (1990) "for their pioneering investigations concerning deep inelastic scattering of electrons on protons and bound neutrons, which have been of essential importance for the development of the quark model in particle physics"
But the role of gluons in protons and bound neutrons remains unknown.

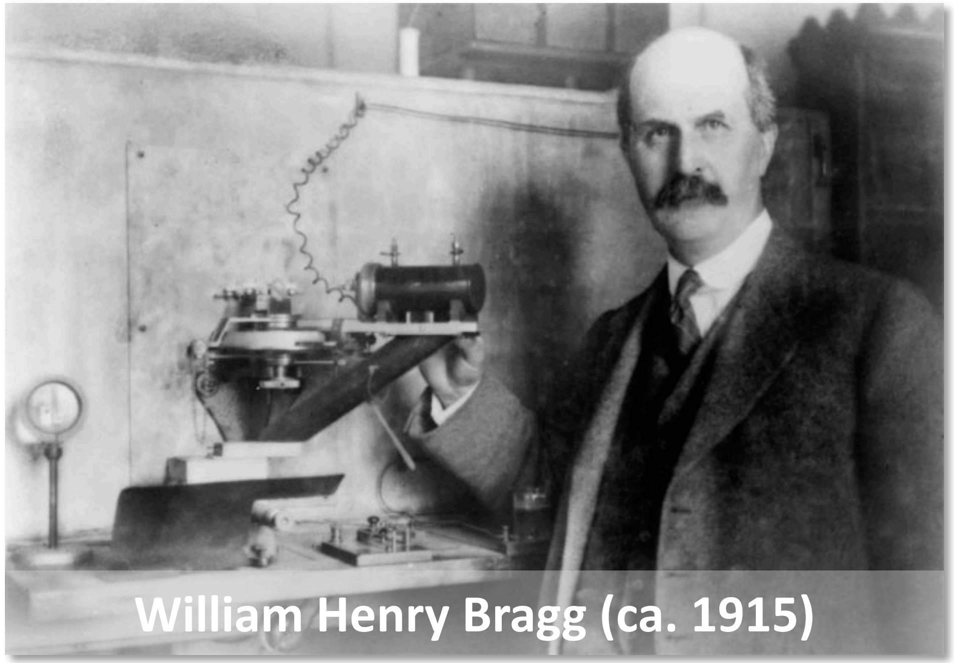
David Gross, David Politzer, Frank Wilczek (2004) "for the discovery of asymptotic freedom in the theory of the strong interaction"
But the confinement aspect of the theory remains unknown.

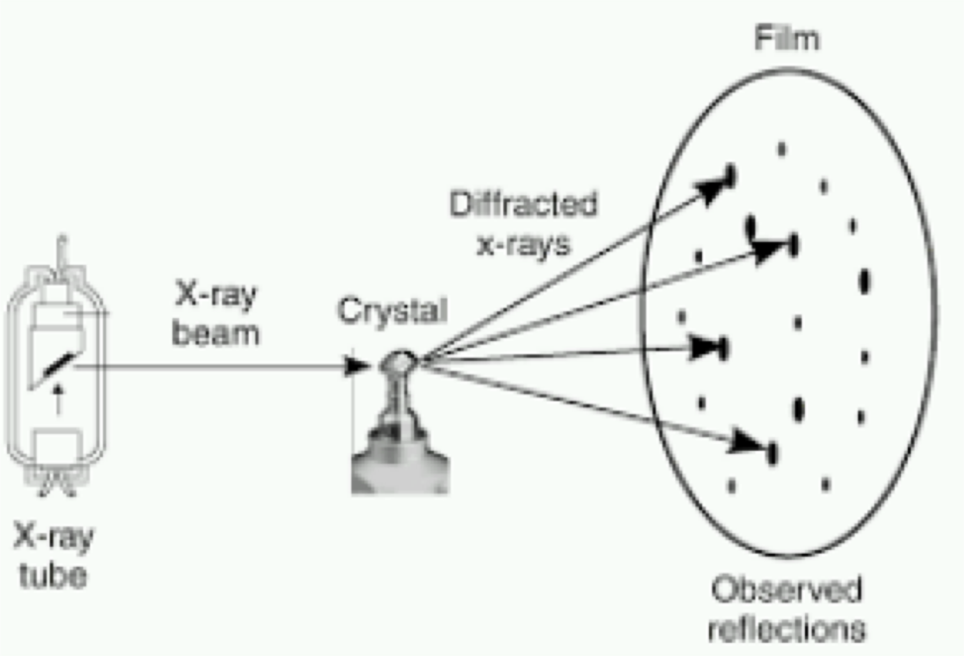
Yoichiro Nambu (2008) "for the discovery of the mechanism of spontaneous broken symmetry in subatomic physics "
But how dynamical chiral symmetry breaking shapes the mass and structure of quark-gluon systems remains unknown.

Electron-Ion Collider

A new frontier in Nuclear Physics

About a century ago… a new frontier in atomic physics

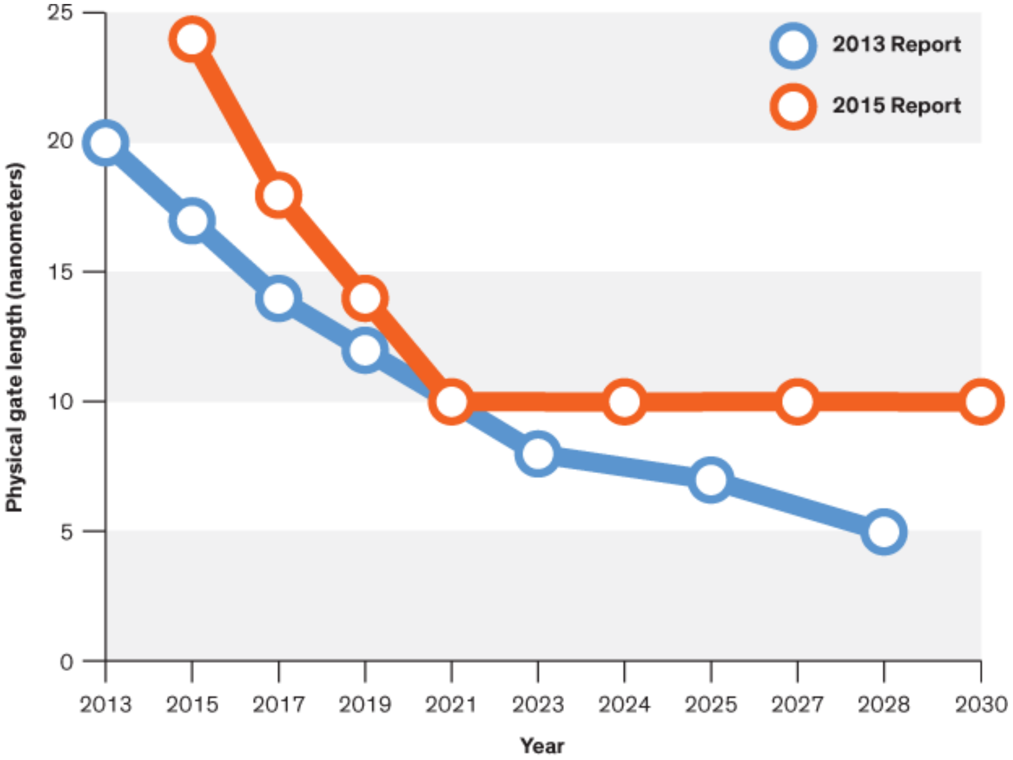




We learned to map atoms inside matter using x-ray crystallography.

The deep knowledge of atomic structures and electromagnetism is the basis of today's technology: Atomic- or nanotechnology

Limits of nanotechnology: Atoms



Microelectronics improve with reduction of the “feature size”.

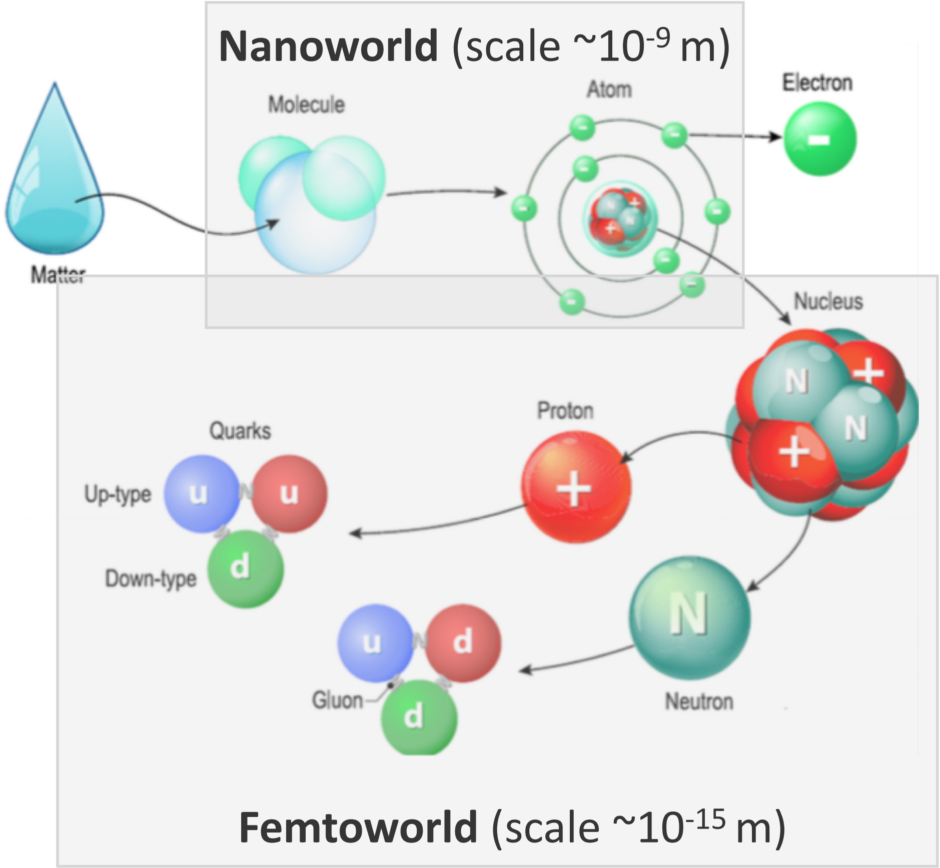
2015 International Technology Roadmap for Semiconductors

We are now down to 10nm (about 100 atoms wide).

Progress becomes more and more difficult.

Can we go smaller?

Structure of matter



Nanoworld

A million times smaller

Femtoworld

Can we manipulate quarks and gluons? We have known for half a century that quarks and gluons and their interactions make up 99% of mass in the visible universe.

However, no way to map quarks and gluons in the nucleus.. till now!

Advances in Nuclear Physics

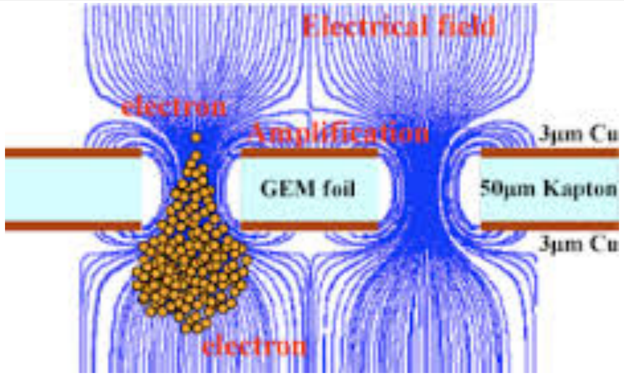
Theory of the strong interaction

$$
\begin{aligned}
\frac{\mathrm{d}\sigma}{\mathrm{d}Q^2\,\mathrm{d}y\,\mathrm{d}q_\mathrm{T}^2} = {} & \frac{4\pi^2\alpha^2}{9Q^2 s} \sum_{j,j_A,j_B} e_j^2 \int \frac{\mathrm{d}^2\boldsymbol{b}_\mathrm{T}}{(2\pi)^2} e^{i\boldsymbol{q}_\mathrm{T}\cdot\boldsymbol{b}_\mathrm{T}} \\
& \times \int_{x_A}^{1} \frac{\mathrm{d}\xi_A}{\xi_A} f_{j_A/A}(\xi_A;\mu_{b_*})\, \tilde{C}^{\mathrm{CSS1,\ DY}}_{j/j_A}\left(\frac{x_A}{\xi_A}, b_*; \mu_{b_*}^2, \mu_{b_*}, C_2, a_s(\mu_{b_*})\right) \\
& \times \int_{x_B}^{1} \frac{\mathrm{d}\xi_B}{\xi_B} f_{j_B/B}(\xi_B;\mu_{b_*})\, \tilde{C}^{\mathrm{CSS1,\ DY}}_{\bar{j}/j_B}\left(\frac{x_B}{\xi_B}, b_*; \mu_{b_*}^2, \mu_{b_*}, C_2, a_s(\mu_{b_*})\right) \\
& \times \exp\left\{ -\int_{\mu_{b_*}^2}^{\mu_Q^2} \frac{\mathrm{d}\mu'^2}{\mu'^2} \left[A_{\mathrm{CSS1}}(a_s(\mu');C_1) \ln\left(\frac{\mu_Q^2}{\mu'^2}\right) + B_{\mathrm{CSS1,\ DY}}(a_s(\mu');C_1,C_2) \right] \right\} \\
& \times \exp\left[-g^{\mathrm{CSS1}}_{j/A}(x_A, b_\mathrm{T}; b_\mathrm{max}) - g^{\mathrm{CSS1}}_{\bar{j}/B}(x_B, b_\mathrm{T}; b_\mathrm{max}) - g^{\mathrm{CSS1}}_{K}(b_\mathrm{T}; b_\mathrm{max}) \ln(Q^2/Q_0^2) \right] \\
& + \text{suppressed corrections.}
\end{aligned}
$$

Quantumchromo-dynamics (QCD)

Accelerator technologies

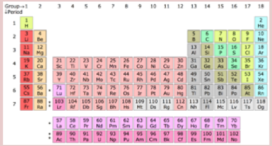
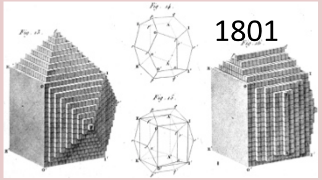
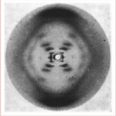
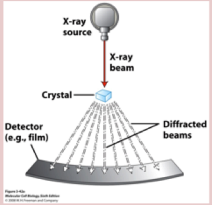
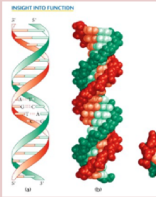
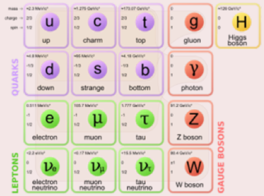
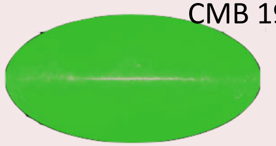
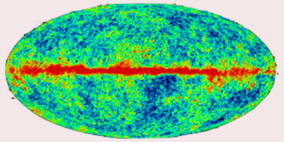
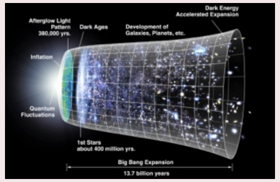
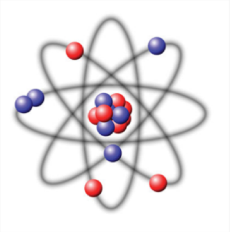
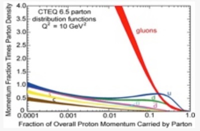
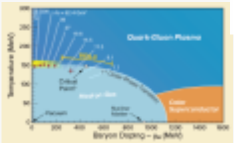
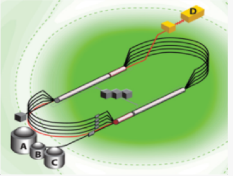
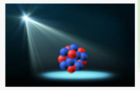
Detector technologies



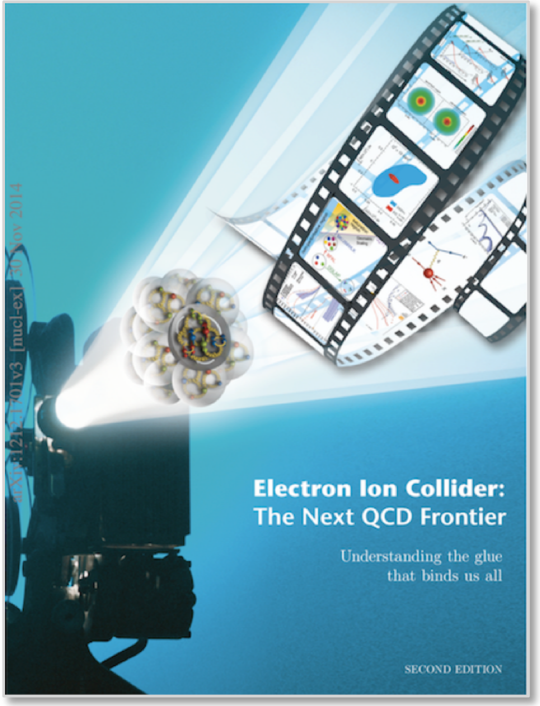
Computer technologies

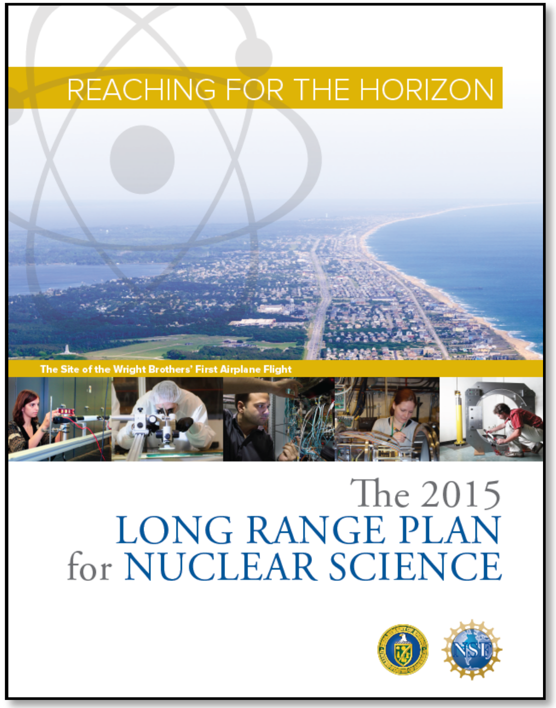
Steady advances in all of these areas mean that →

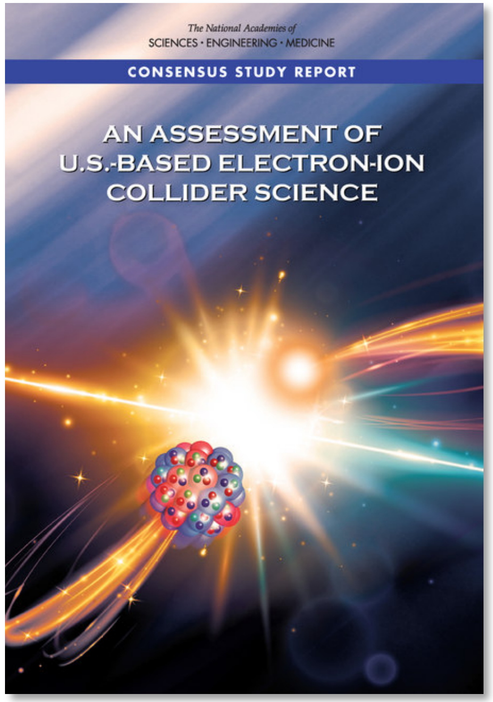
EIC: A new frontier in science

Dynamical System	Fundamental Knowns	Unknowns	Breakthrough Structure Probes (Date)	New Sciences, New Frontiers
Solids 	Electromagnetism Atoms 	Structure  1801	X-ray Diffraction (~1920)  	Solid state physics Molecular biology  DNA
Universe 	General Relativity Standard Model 	Quantum Gravity, Dark matter, Dark energy. Structure CMB 1965 	Large Scale Surveys CMB Probes (~2000)  	Precision Observational Cosmology 
Nuclei and Nucleons 	Perturbative QCD Quarks and Gluons $\mathcal{L}_{QCD} = \overline{\psi}(i\partial\!\!\!/ - gA\!\!\!/)\psi - \frac{1}{2}\mathrm{tr}\,F_{\mu\nu}F^{\mu\nu}$	Non-perturbative QCD Structure 2017   	CEBAF12 (2018)   Electron-Ion Collider (2025+) 	Structure & Dynamics in QCD 

Why an Electron-Ion Collider?





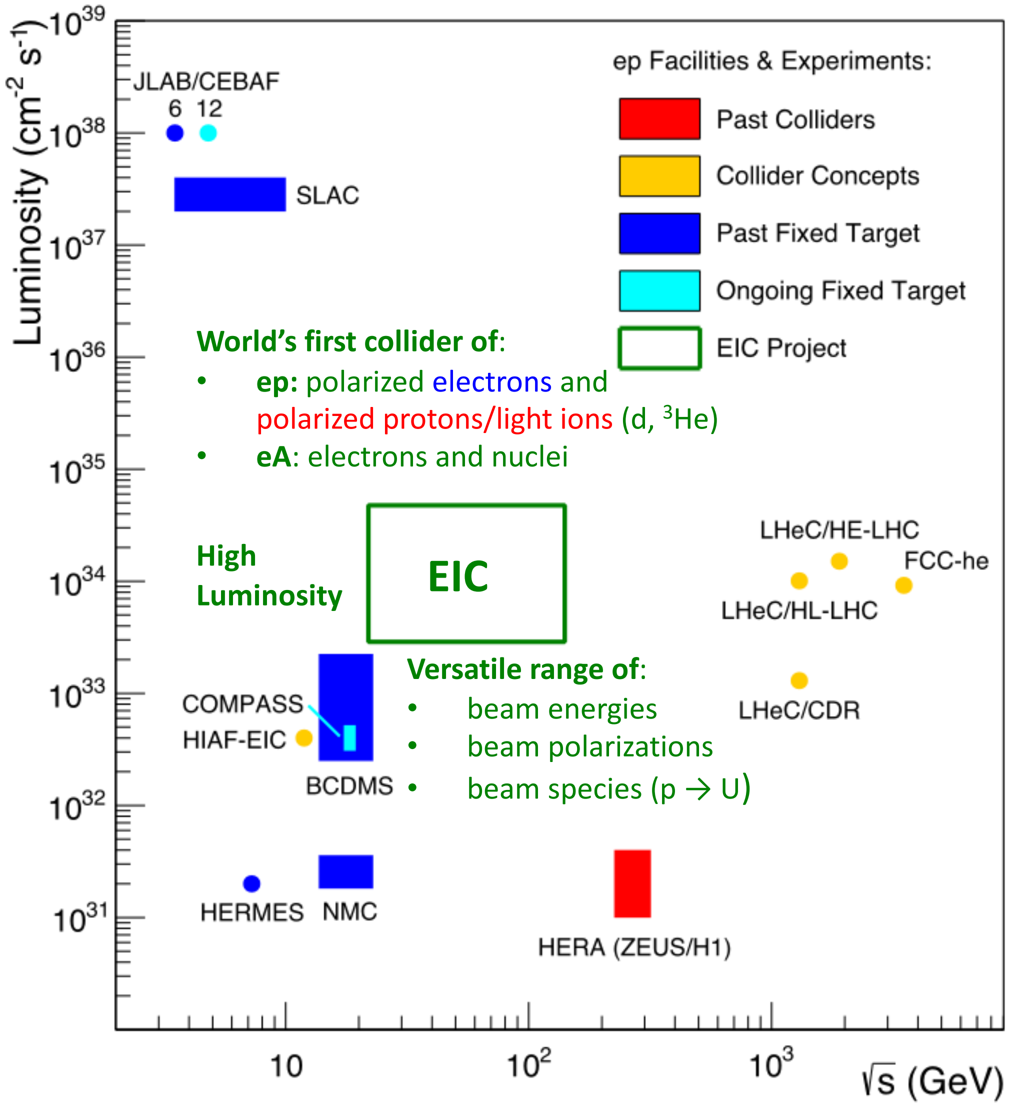


Right tool

- 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.

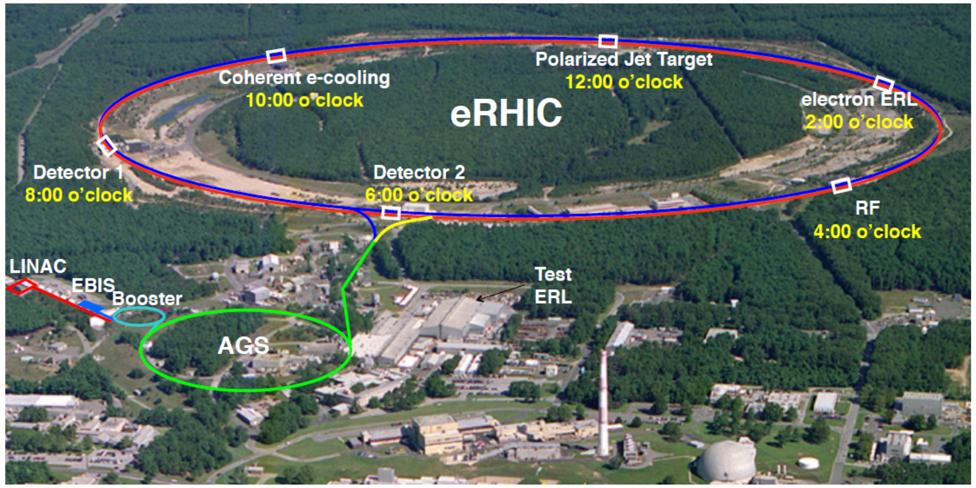
The Electron-Ion Collider: Frontier accelerator facility in the U.S.



Department of Energy

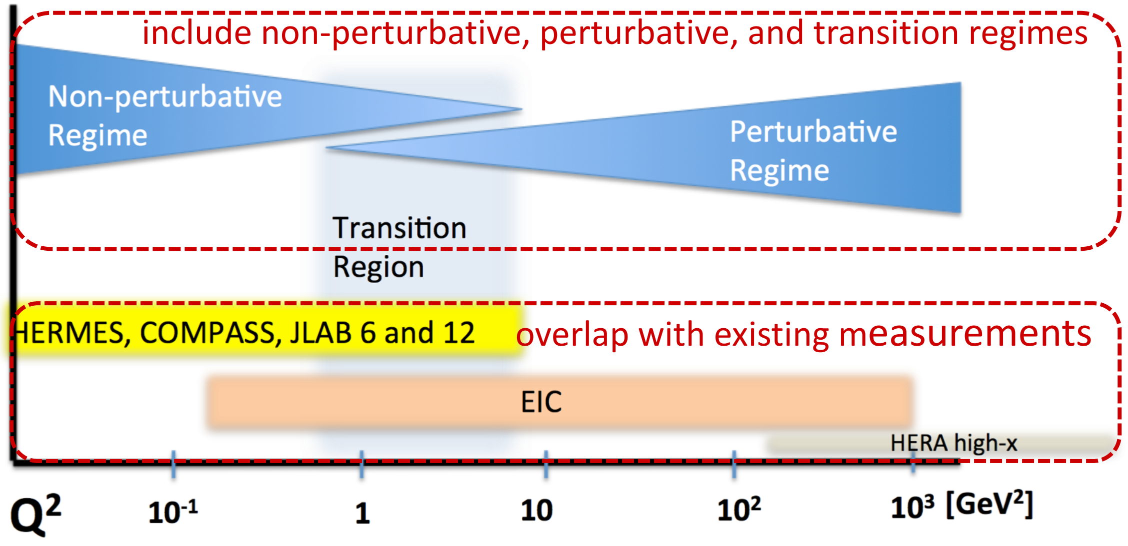
U.S. Department of Energy Selects Brookhaven National Laboratory to Host Major New Nuclear Physics Facility

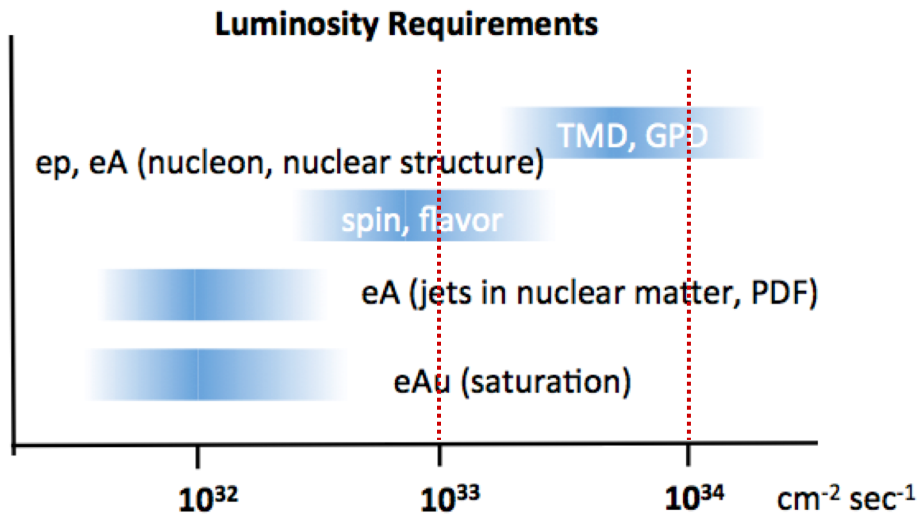
JANUARY 9, 2020



Brookhaven National Laboratory and Jefferson Lab will be host laboratories for the EIC Experimental Program. Leadership roles in the EIC project are shared.

EIC: Ideal facility for studying QCD





Various beam energy

broad Q^2 range for

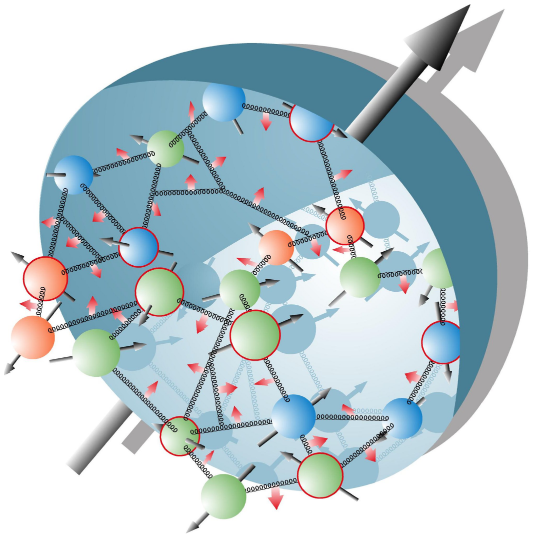
- studying evolution to Q^2 of ~1000 GeV^2
- disentangling non-perturbative and perturbative regimes
- overlap with existing experiments

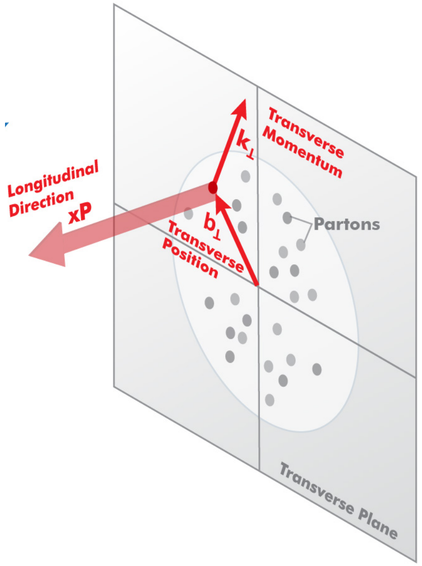
High luminosity

high precision

- for various measurements, e.g., multi-dimensional SIDIS analysis in five or more kinematic dimensions and multiple particles
- in various configurations

EIC: Ideal facility for studying QCD





Polarization

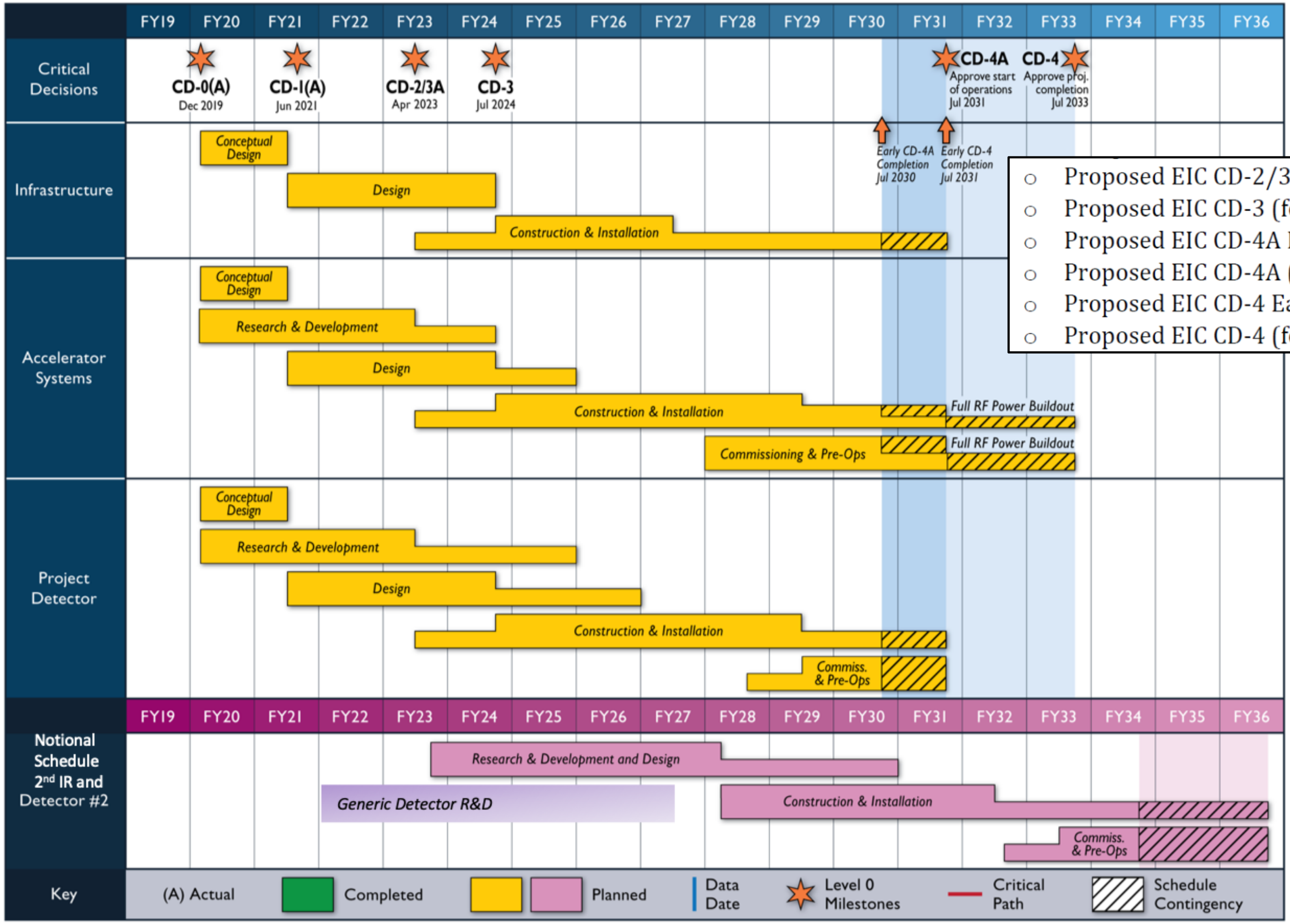
Understanding hadron structure cannot be done without understanding spin:

- 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 Timeline: Operations start a decade from now

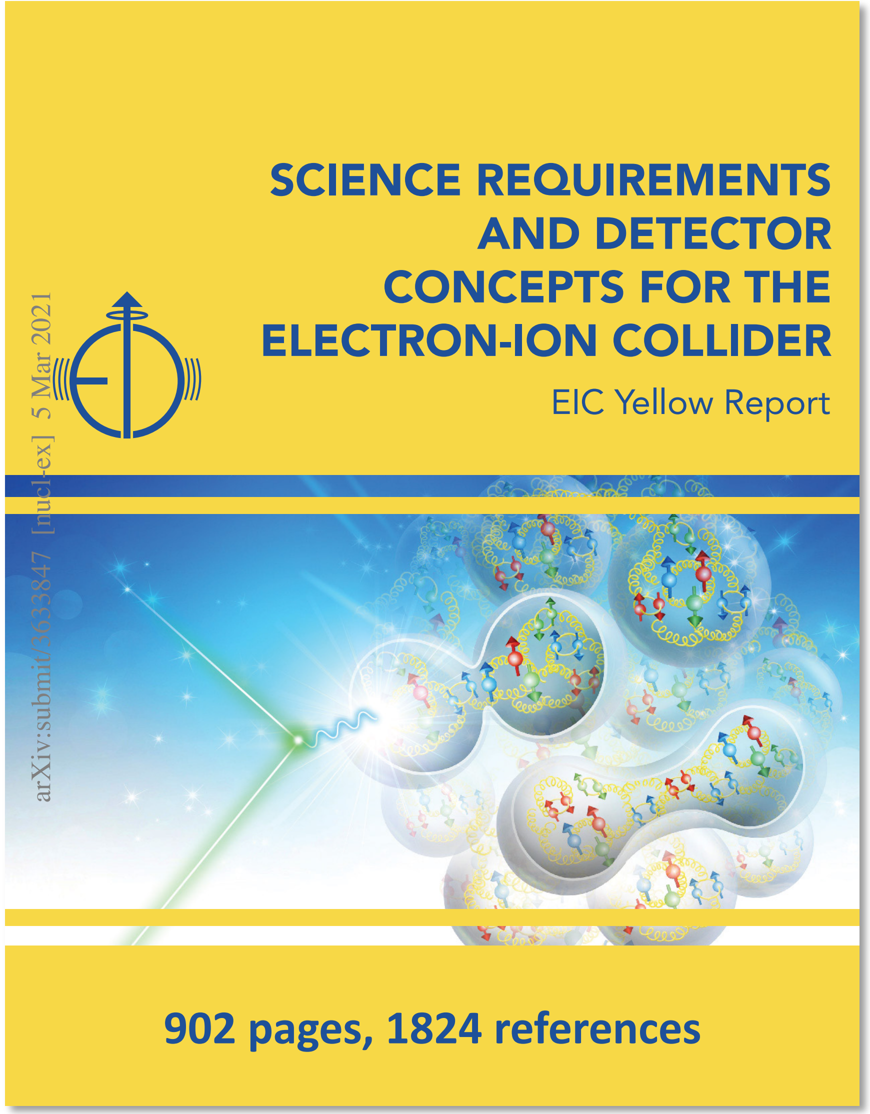


- Proposed EIC CD-2/3A (for EIC planning only) - 2nd Quarter FY2024
- Proposed EIC CD-3 (for EIC planning only) - 3rd Quarter FY2025
- Proposed EIC CD-4A Early Finish (for EIC planning only) - 3rd Quarter FY2031
- Proposed EIC CD-4A (for EIC planning only) - 3rd Quarter FY2032
- Proposed EIC CD-4 Early Finish (for EIC planning only) - 3rd Quarter FY2032
- Proposed EIC CD-4 (for EIC planning only) - 3rd Quarter FY2034

Schedule in flux to take account of FY22 actuals and the FY23 outlook, this will mean an expected 9-month delay of forthcoming CD dates).

EIC User Group (EICUG)

Yellow Report Initiative by the EIC User Group



- The **EIC Yellow Report** describes the physics case, the resulting detector requirements, and the evolving detector concepts for the experimental program at the EIC: arXiv:2103.05419

- The studies leading to the EIC Yellow Report were commissioned and organized by the **EIC User Group**.

- The EIC Yellow Report has been important input to the successful DOE CD-1 review and decision.

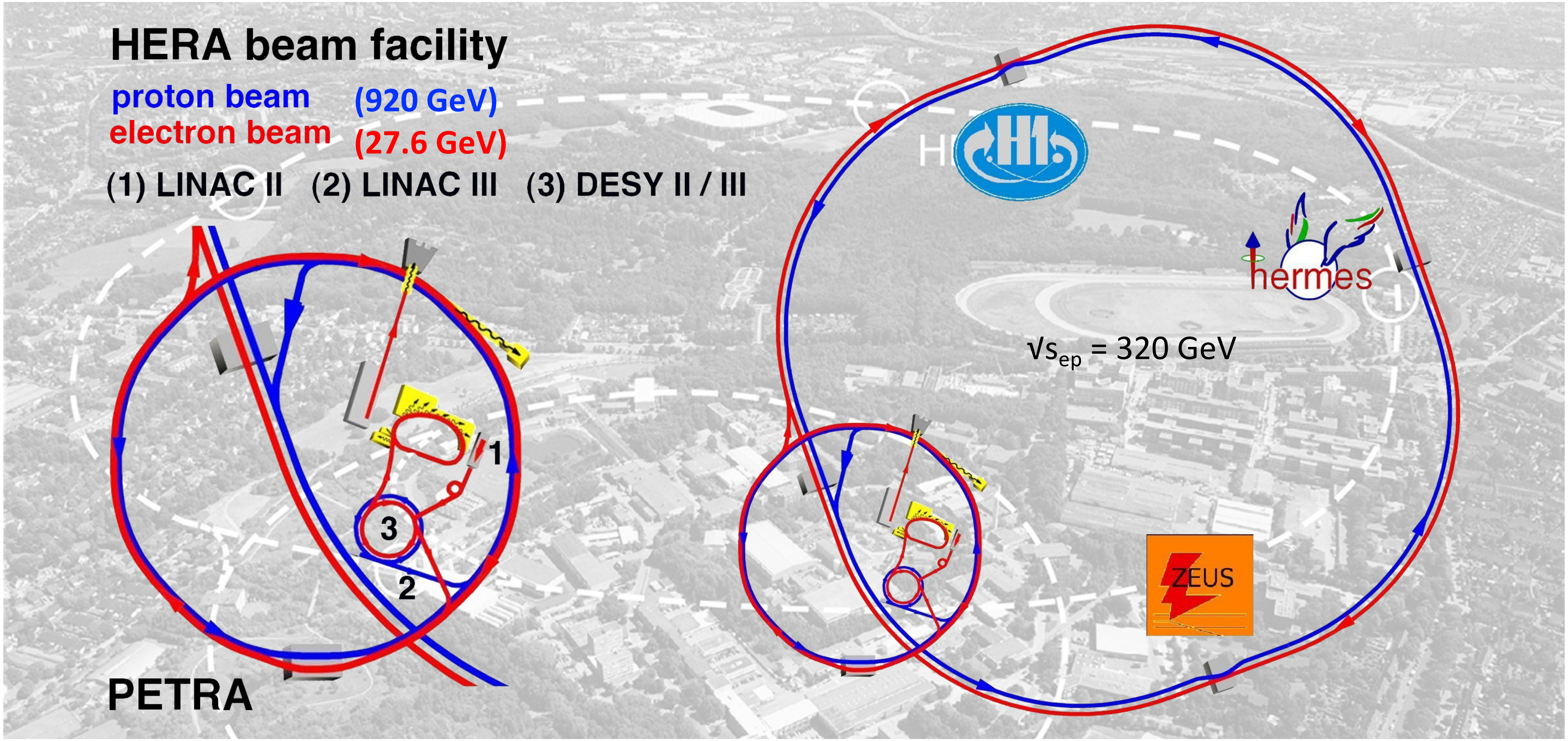
Next Priorities for the EIC User Group

- Formation of the first EIC collaboration.

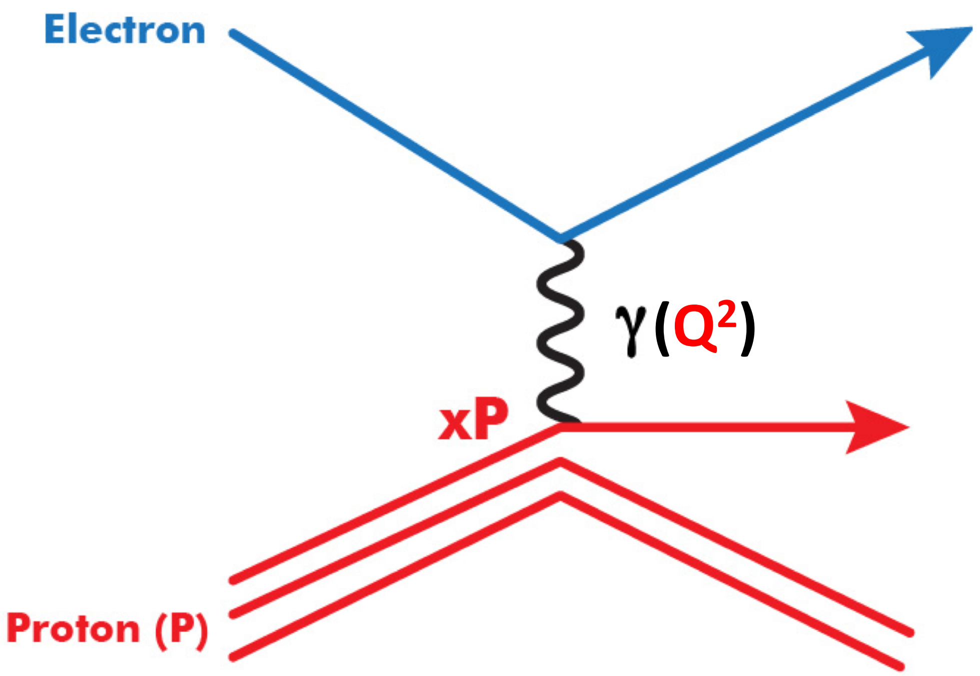
Pioneering measurements

The first Electron-Ion Collider

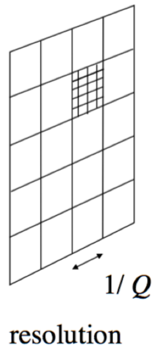
HERA: The first Electron-Ion Collider



Deep-inelastic scattering (DIS) of electrons off protons

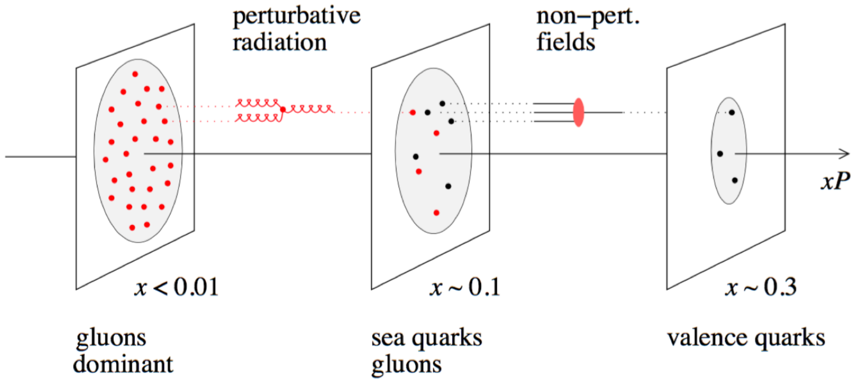


Ability to change **Q^2** changes the resolution scale



$Q^2 = 400\ \text{GeV}^2$
$\Rightarrow 1/Q = 0.01\ \text{fm}$

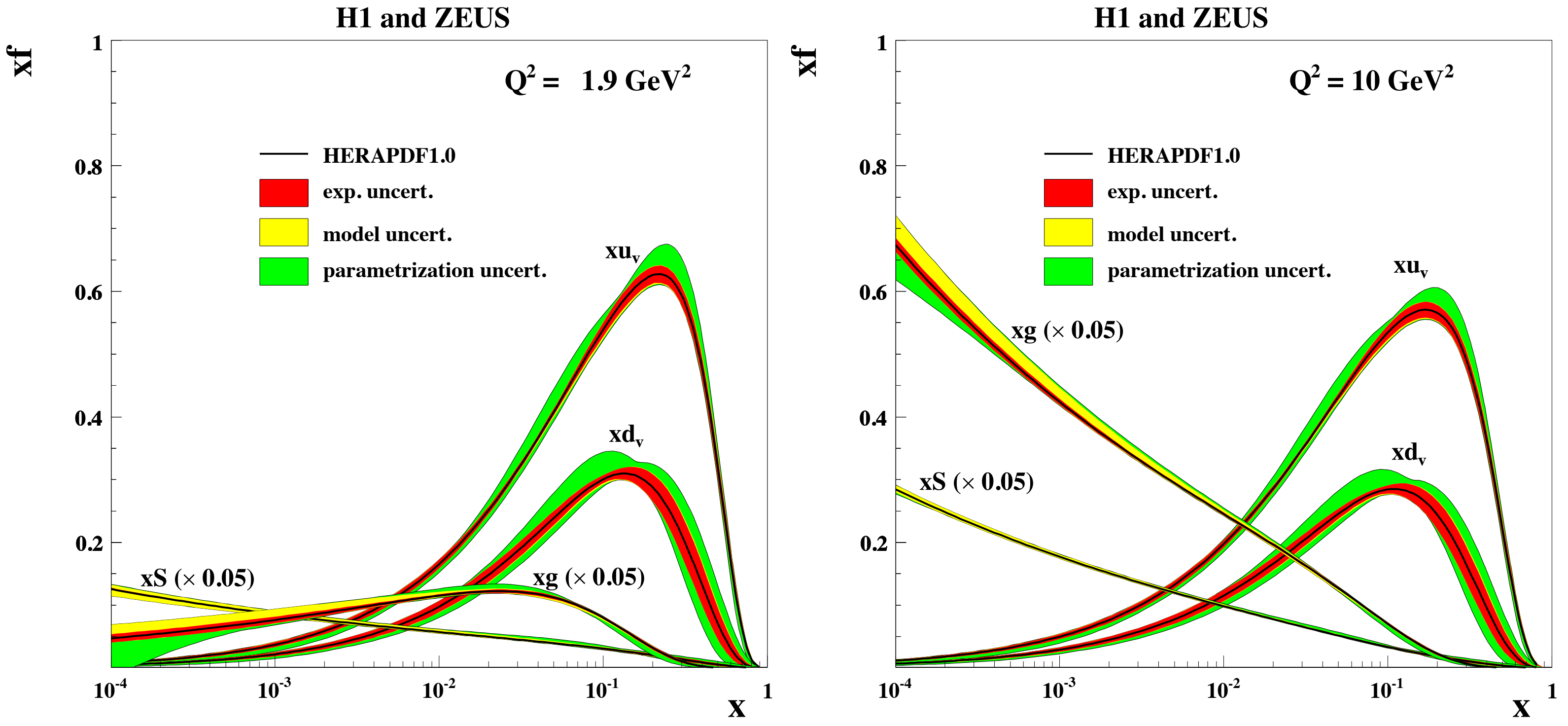
Ability to change **x** projects out different con-figurations where different dynamics dominate



Parton distribution functions (PDF)

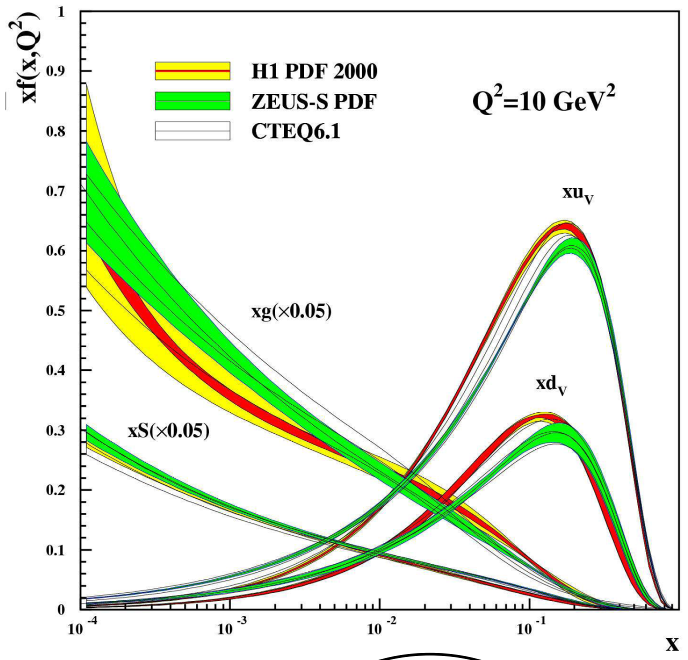
Observable cross section → structure functions → **QCD analysis** PDFs

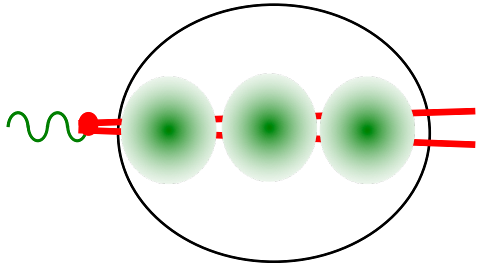
process-dependent → **universal**



QCD at extremes: Parton saturation

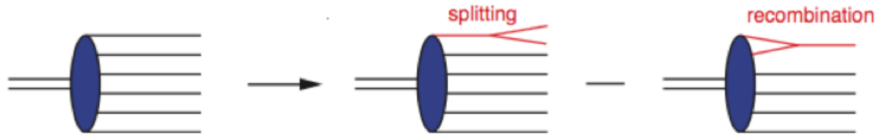
Dramatic rise of gluon PDF



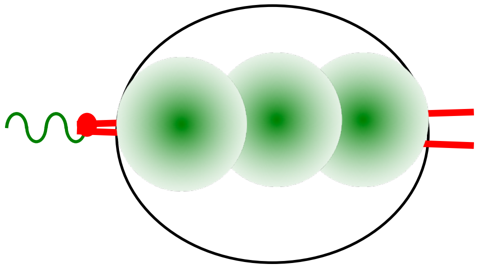


In nuclei, the interaction probability enhanced by A⅓

Parton splitting and recombination



- rise of gluon PDF cannot go on forever as *x* becomes smaller and smaller
- **parton saturation**: parton recombination must balance parton splitting
- unobserved at HERA for a proton and expected at extreme low *x*

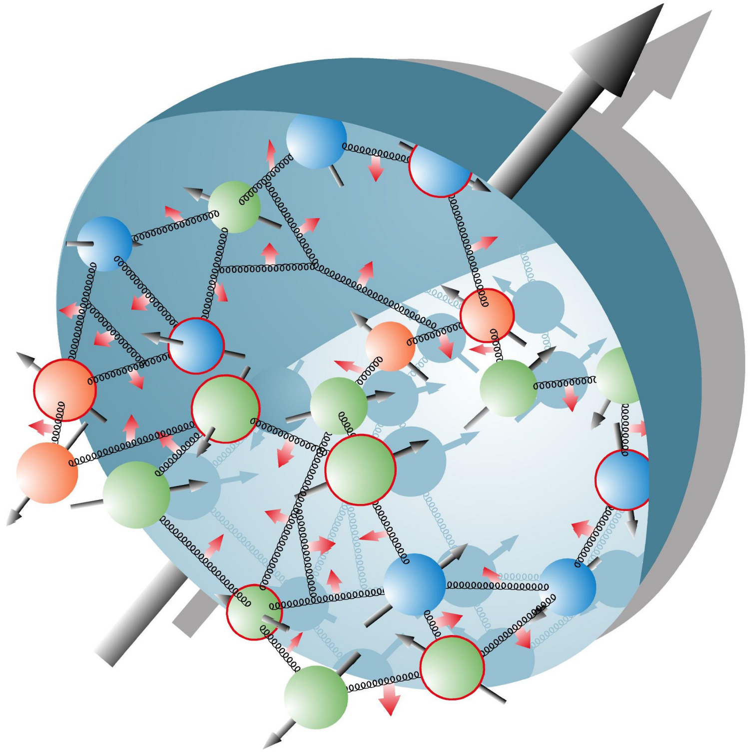


Will nuclei saturate faster as color leaks out of nucleons?

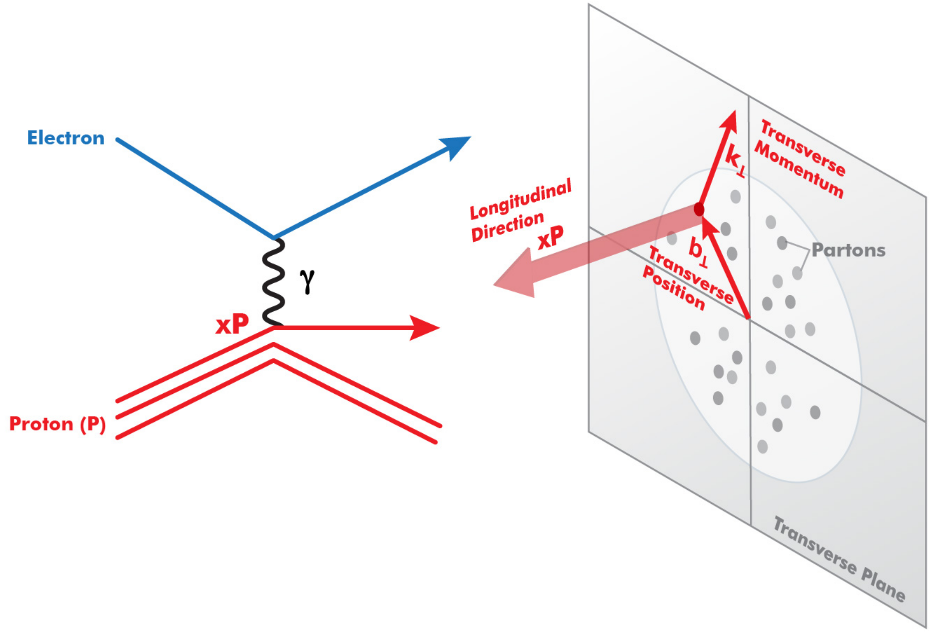
Jefferson Lab

Polarized DIS measurements

Polarization



Novel QCD phenomena



3D imaging in space and momentum

longitudinal structure (PDF)

+ transverse position information (GPDs)

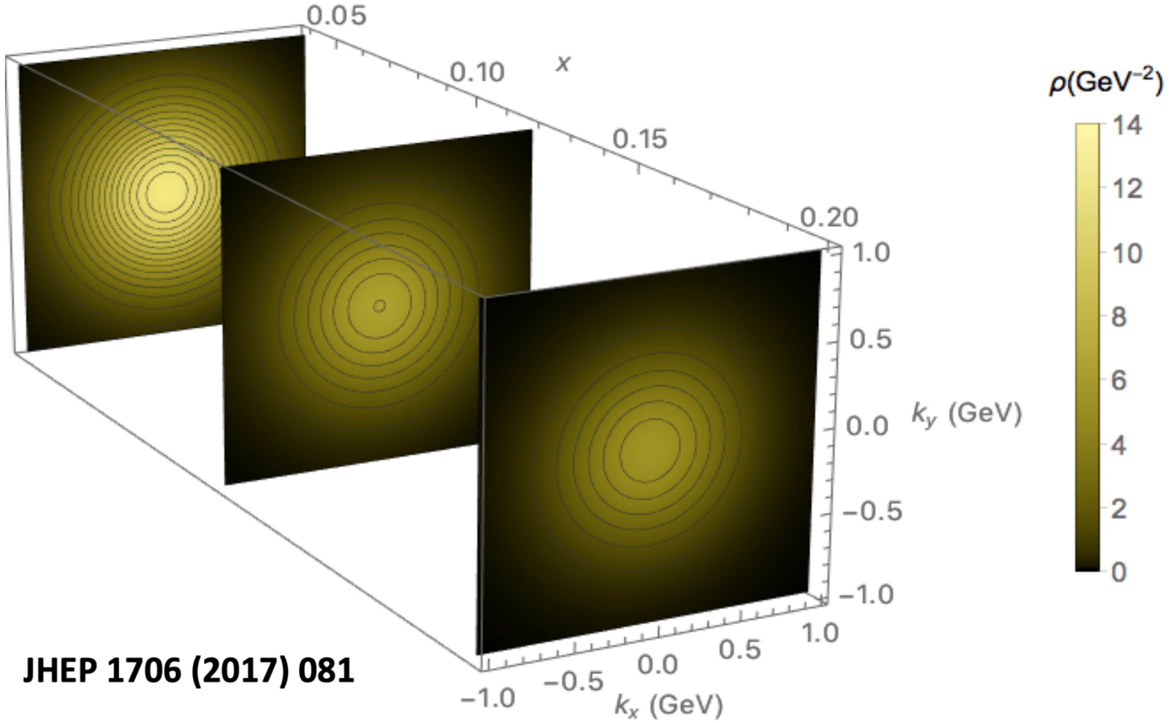
+ transverse momentum information (TMDs)

order of a few hundred MeV

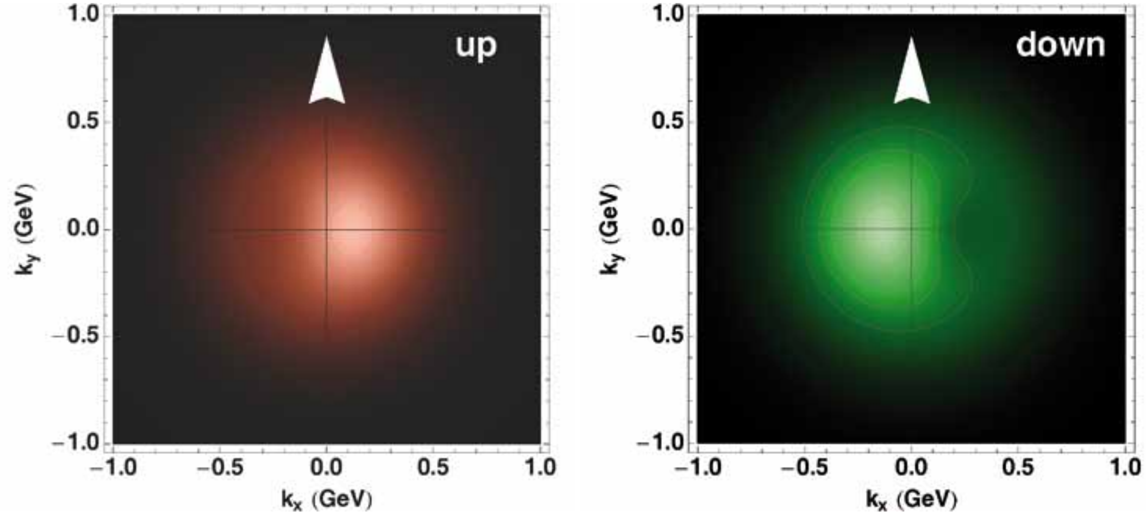
Transverse-momentum dependent PDFs (TMD PDFs or TMDs)

Unpolarized nucleon

Transversely polarized nucleon

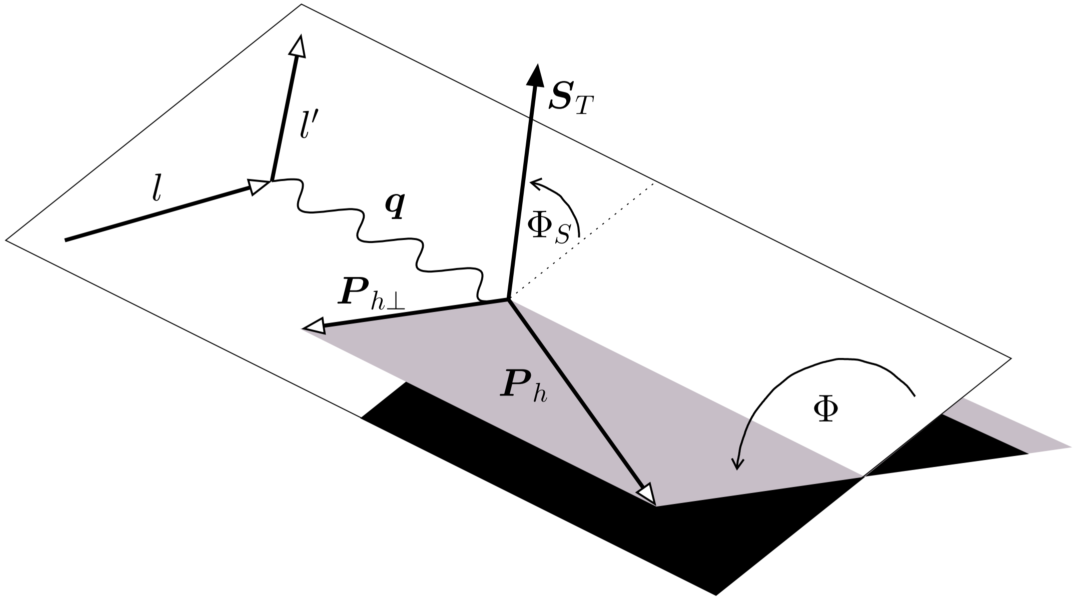


JHEP 1706 (2017) 081



Jefferson Lab

The hard core of Nuclear Physics: Factorization theorems



Semi-inclusive DIS (SIDIS)

Hadron h is detected
in **coincidence** with the scattered lepton l'

Observable

SIDIS cross section

Factorization theorem (perturbative QCD)

Distribution functions (PDF, TMD PDF) empirical description of non-perturbative structure (confinement)

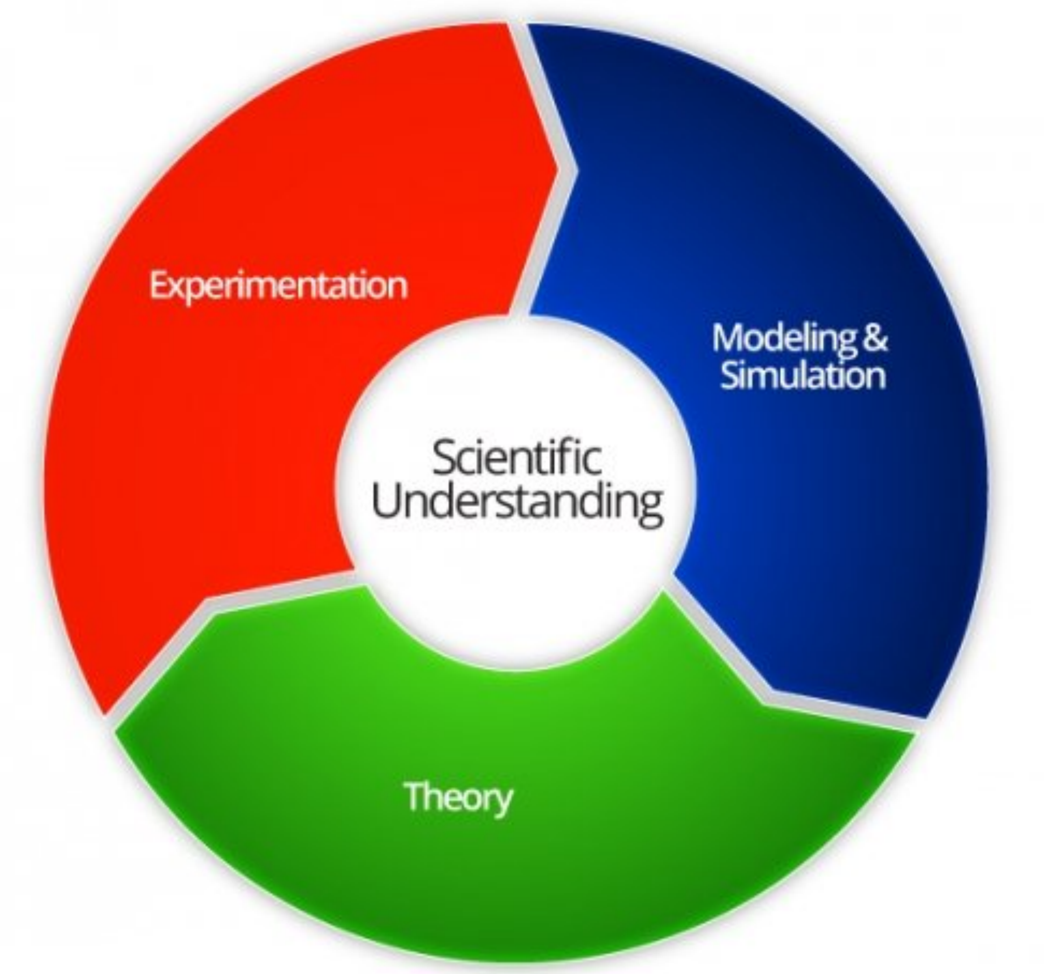
Perturbative part Cross section for elementary photon-quark interaction
Calculable (asymptotic freedom)

Fragmentation functions (FF, TMD FF) empirical description of non-perturbative structure (hadronization)

Physics Event Generation

Monte Carlo Event Generators for the EIC

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.

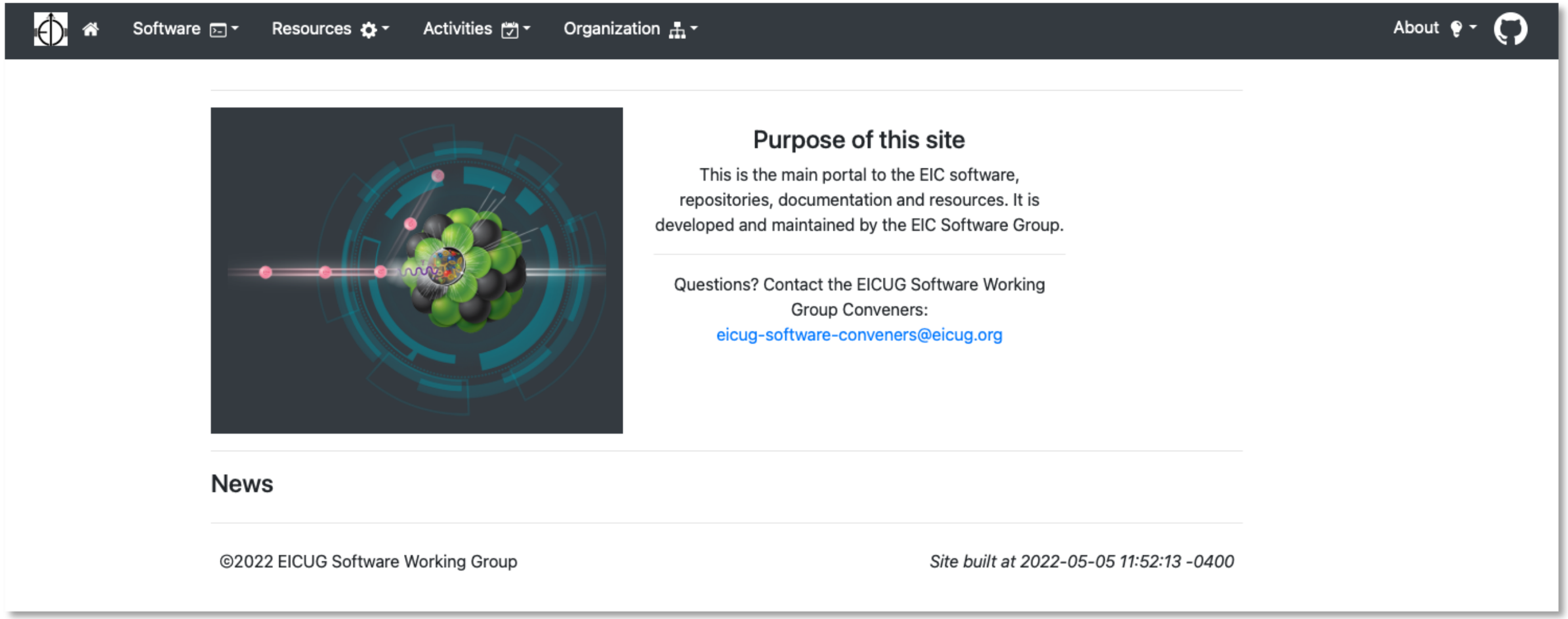
Common challenges, e.g. with HL-LHC: **High-precision QCD measurements require high-precision simulations**.

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

EIC R&D For Software & Computing

EIC Software & Computing is in a very early life stage:

- The current focus is supporting detector design.
- Software Working Group (SWG) within the EIC User Group works with community and the forming EIC collaboration to address software needs and evolving R&D.
- Legacy codes and frameworks are in use.
- Distributed Computing approach to supply resources for physics and detector studies.
- At the pre-requirements stage for production computing and software activities.



MCEG Distribution for the EIC

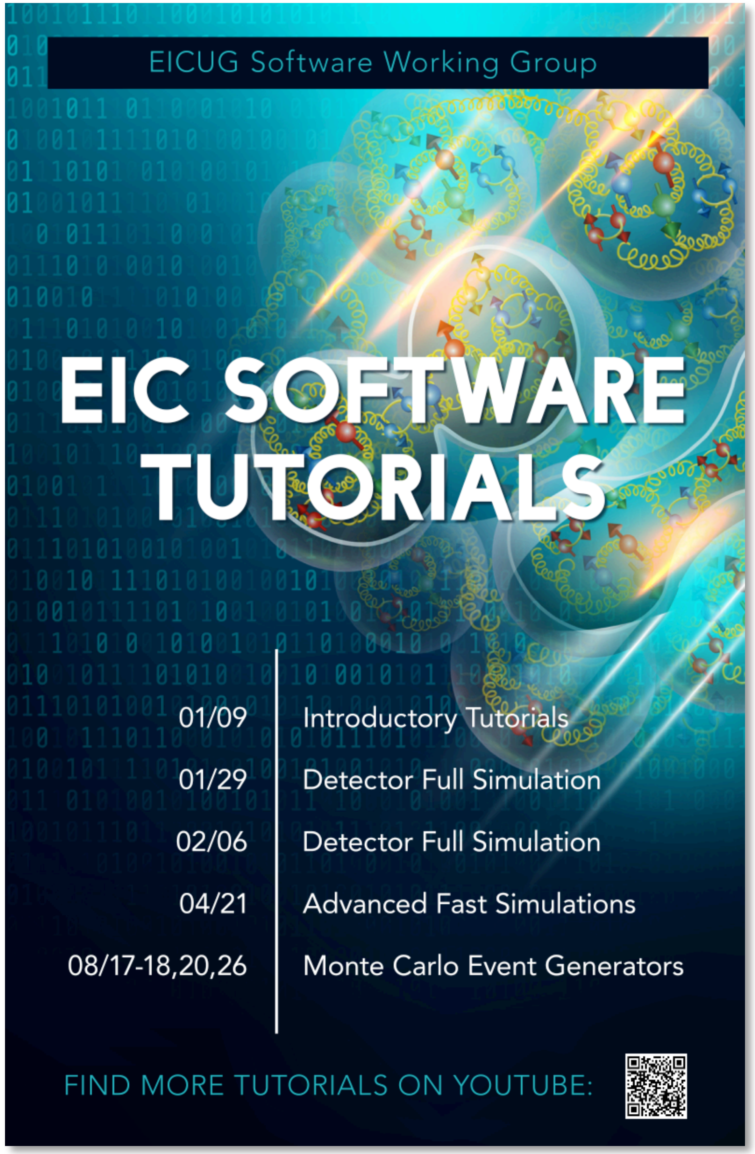
EIC community has been organized around its MCEGs needs already for several years:

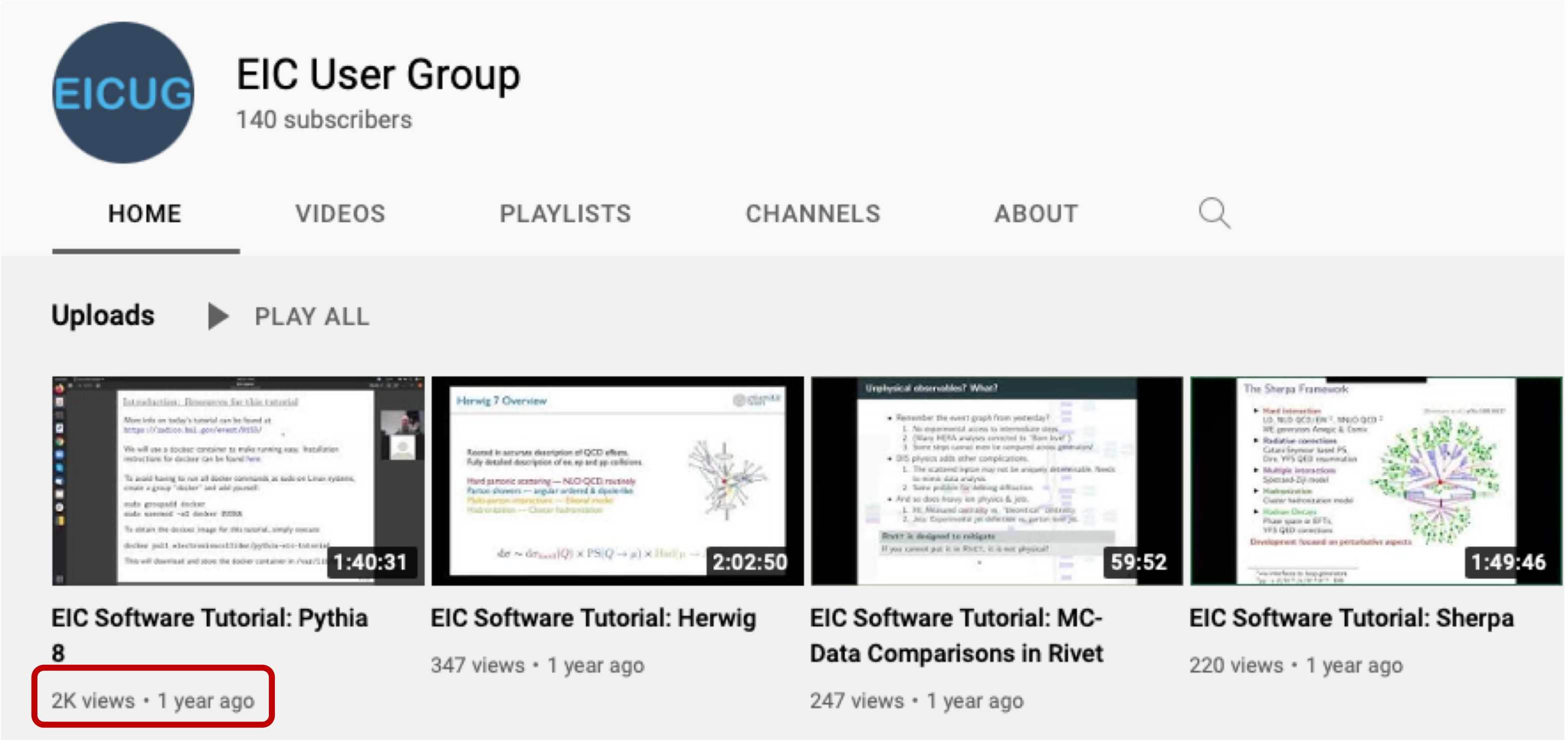
- **PYTHIA6 (modified)** General-purpose MCEG, including unpolarized DIS
- **BeAGLE** Benchmark eA Generator for LEptoproduction
- **DJANGOH** MCEG for (un)Polarized DIS, including higher order QED and QCD effects
- **MILOU** MCEG for deeply virtual Compton scattering (DVCS)
- **PEPSI** MCEG for polarized DIS
- **RAPGAP** MCEG for DIS, including diffraction
- **Sartre** MCEG for exclusive diffractive vector meson production in ep and eA
- And a few others.

Maintained on CVMFS and used for a plethora of EIC studies.

Established HepMC3 as standard in the wider EIC community (thanks to Andrii Verbytskyi (MPP) for support).

Introducing modern general-purpose MCEGs and Rivet





Excellent feedback on online tutorials and their recordings.

Why has DIS been first missing in Pythia8

MCEG community focus of last two decades: **LHC**

Problems with default parton shower for DIS (used in Pythia6)

- The parton shower has been developed for positron-election annihilation and Drell-Yan.
- The parton shower is using a s-hat approach where *s-hat* = $x_1 * x_2 * s$ at all scales. This works well for hadron-hadron collisions, e.g., for preserving the W/Z mass in the parton shower.
- When expanding the parton shower for electron-hadron scattering, one has to replace one incoming parton with an electron at $x=1$. The Bjorken-x value of the event will be not preserved during the reconstruction of the initial state shower, as the introduction of the a transverse momentum will change the value of $P * q$. This also implies that the cross-section is changed.
- This was solved (for a single splitting) by a very specific handling of the initial and final state cascades and limiting the maximum allowed virtuality to W^2 with additional rejection techniques.

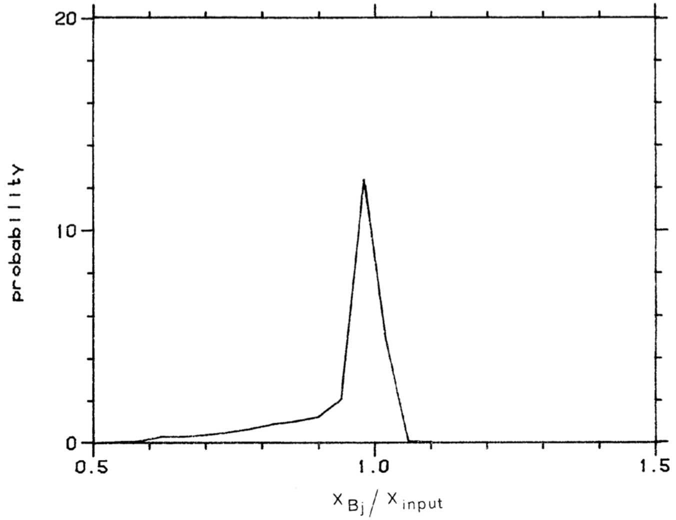


Fig 4

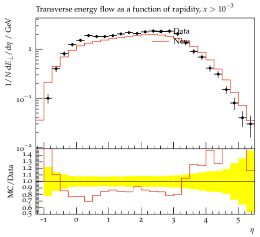
Status of ep simulations in Pythia8 (I. Helenius)

DIS with Pythia

New shower option: `dipoleRecoil`

[B. Cabouat and T. Sjöstrand, EPJC 78 (2018 no.3, 226)]

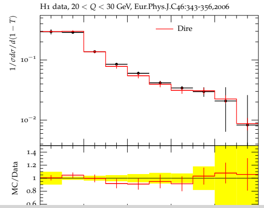
- No PS recoil for the scattered lepton
- Reasonable description of single-particle properties, such as transverse energy flow
- Results based on tune with the default global-recoil shower



DIRE plugin (to be included in PYTHIA 8.3)

[S. Höche, S. Prestel, EPJC 75 (2015) no.9, 461]

- Correct soft-gluon interference at lowest order
- Inclusive NLO corrections to collinear splittings
- Good agreement with HERA data for thrust T



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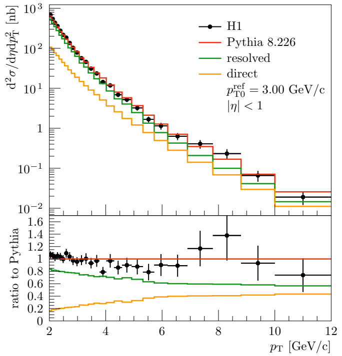
Photoproduction with PYTHIA

Photoproduction in PYTHIA 8

- Hard and soft QCD processes
- Mix of resolved and direct processes
- Photon PDFs from CJKL fit
- MPIs for the resolved processes
  - ⇒ Regulated with p_{T0} as in pp
- Applicable also for UPCs

Inclusive hadron spectra from H1

- Resolved contribution dominates
- Good agreement with the data using $p_{T0}^{ref} = 3.00$ GeV (pp: $p_{T0}^{ref} = 2.28$ GeV)



[H1: Eur.Phys.J. C10 (1999) 363-372]

11

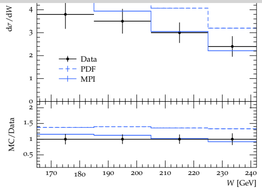
Transition region (1 GeV²<Q²<10 GeV²)

So far no implementation is present for this region. This is something we have made plans to consider in detail later on but so far left as an open question. Note that in Pythia 6, a description of the transition region is available, heavily relying on tweaking parameters. Thus, Pythia 6 cannot provide a predictive model, and is thus dangerous to use.

- Based on dynamical rapidity gap survival

  [C. O. Rasmussen, T. Sjöstrand, JHEP 1602 (2016) 142]

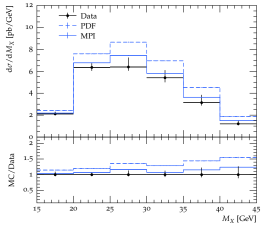
- Begin with factorized approach with diffractive PDFs (Ingelman-Schlein picture)
- Reject events where MPIs between resolved γ and p would destroy the rapidity gap



Comparison to HERA diffractive dijet data

[H1: EPJC 51 (2007) 549, ZEUS: EPJC 55 (2008) 177]

- More MPI suppression towards higher W, M_X
- Natural explanation for observed factorization breaking in pp and γp

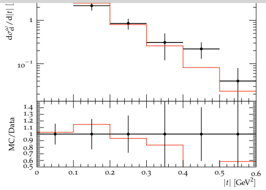


12

- Based on (pre-HERA) SAS parametrizations

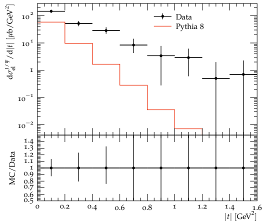
  [G.A. Schuler, T. Sjöstrand, Phys.Rev. D49 (1994) 2257-2267]

- Includes ρ, ω, ϕ and J/Ψ production via elastic scattering



Comparison to HERA data

- Good agreement with low-mass mesons (ω)
- Underestimate heavy-meson (J/Ψ) production
  - ⇒ Require improved parametrizations using HERA data



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Starting with MCEG validation using Rivet

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

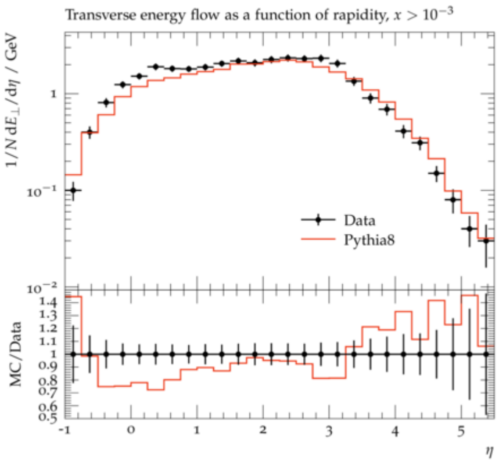
- data := analysis description + data points

HEP existing workflow using Rivet.

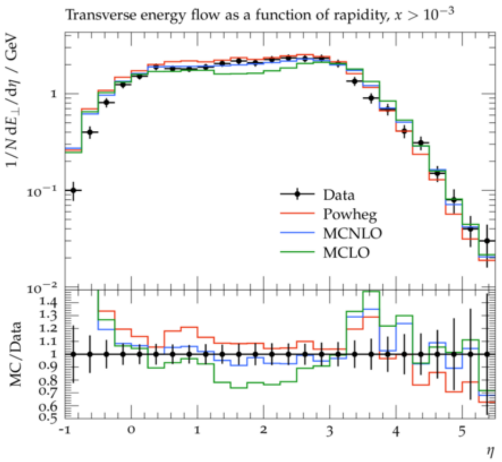
Ongoing activity with EIC-India and MCnet:

- 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.

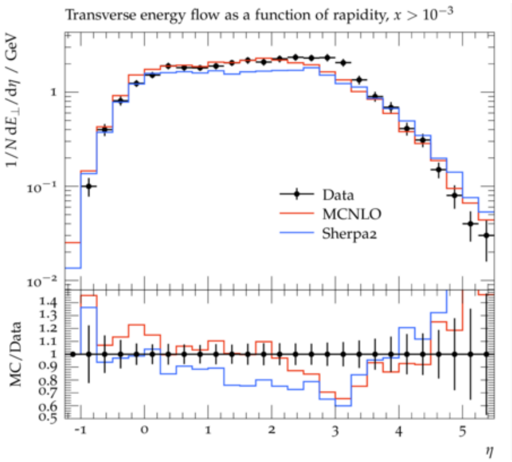
Many thanks for Christian Bierlich, Ilkka Helenius, and Simon Plätzer!



Pythia8

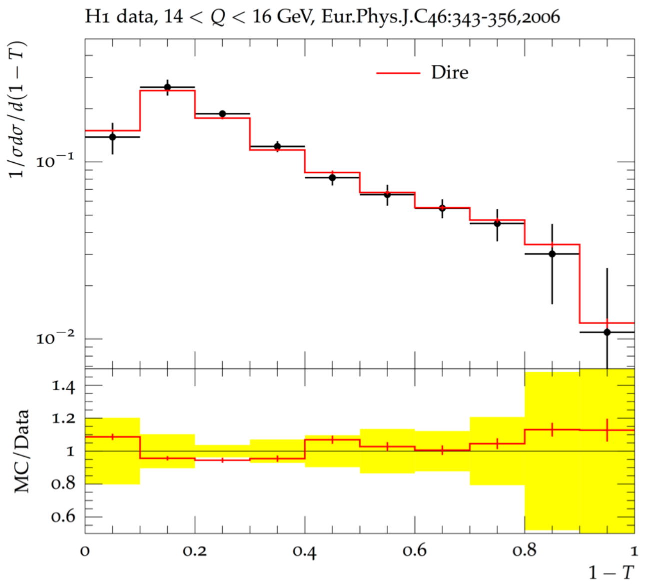


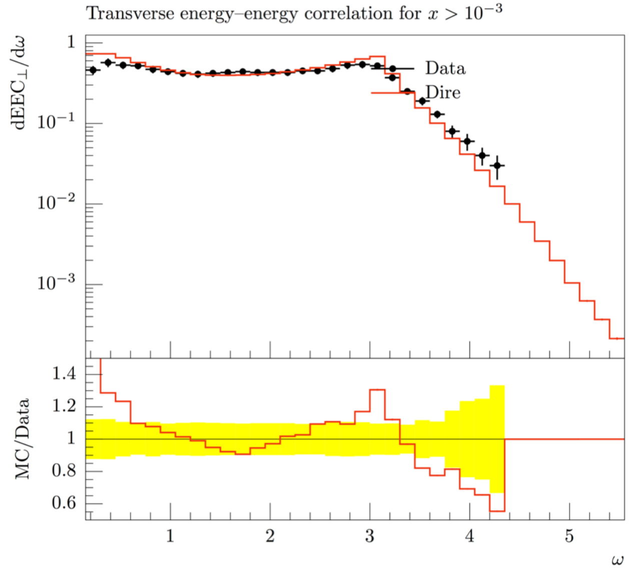
Herwig7

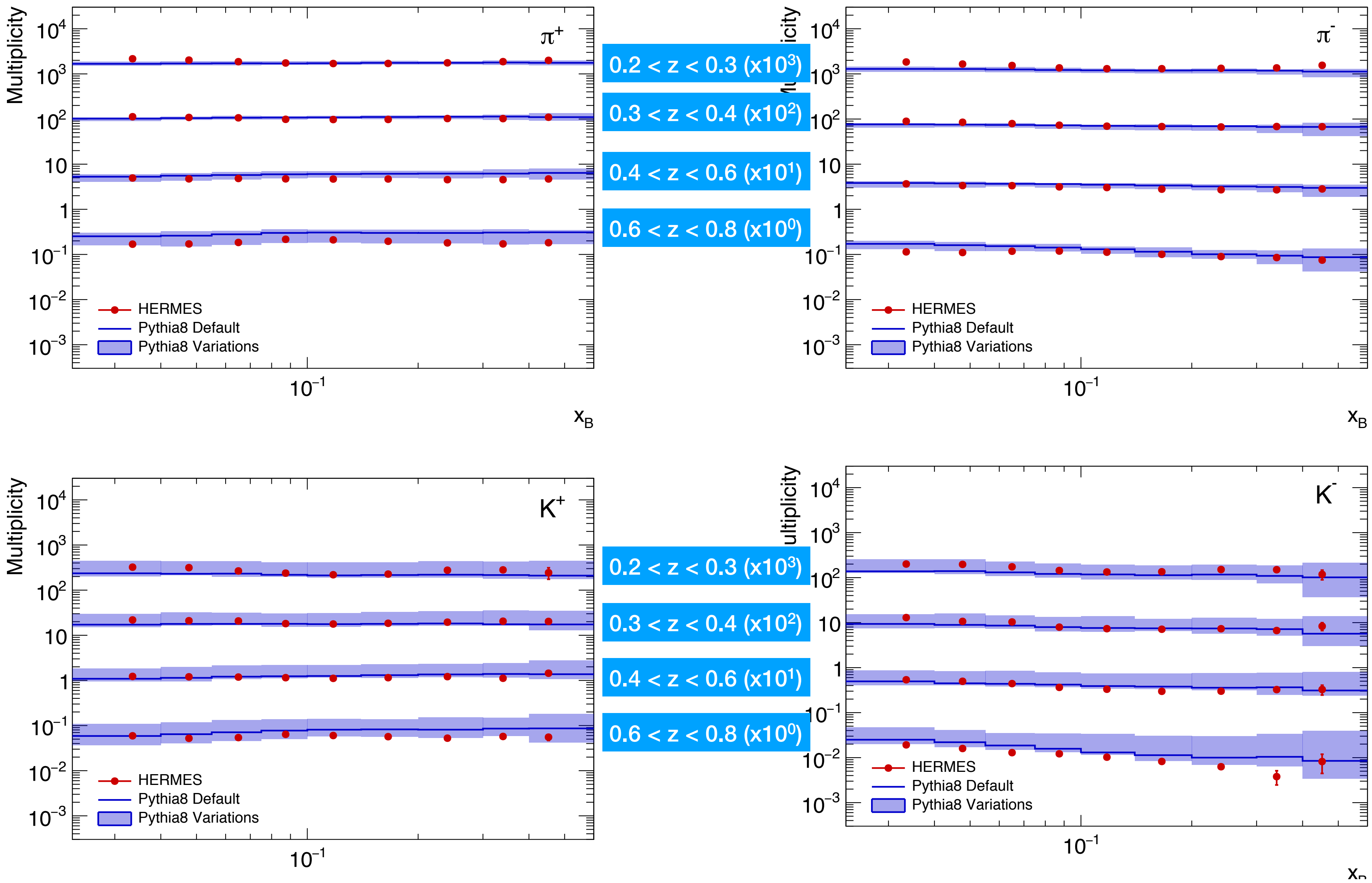


Sherpa2

Pythia8+DIRE at low energy (studies by MD, S. Joosten (ANL), S. Prestel (LUND))



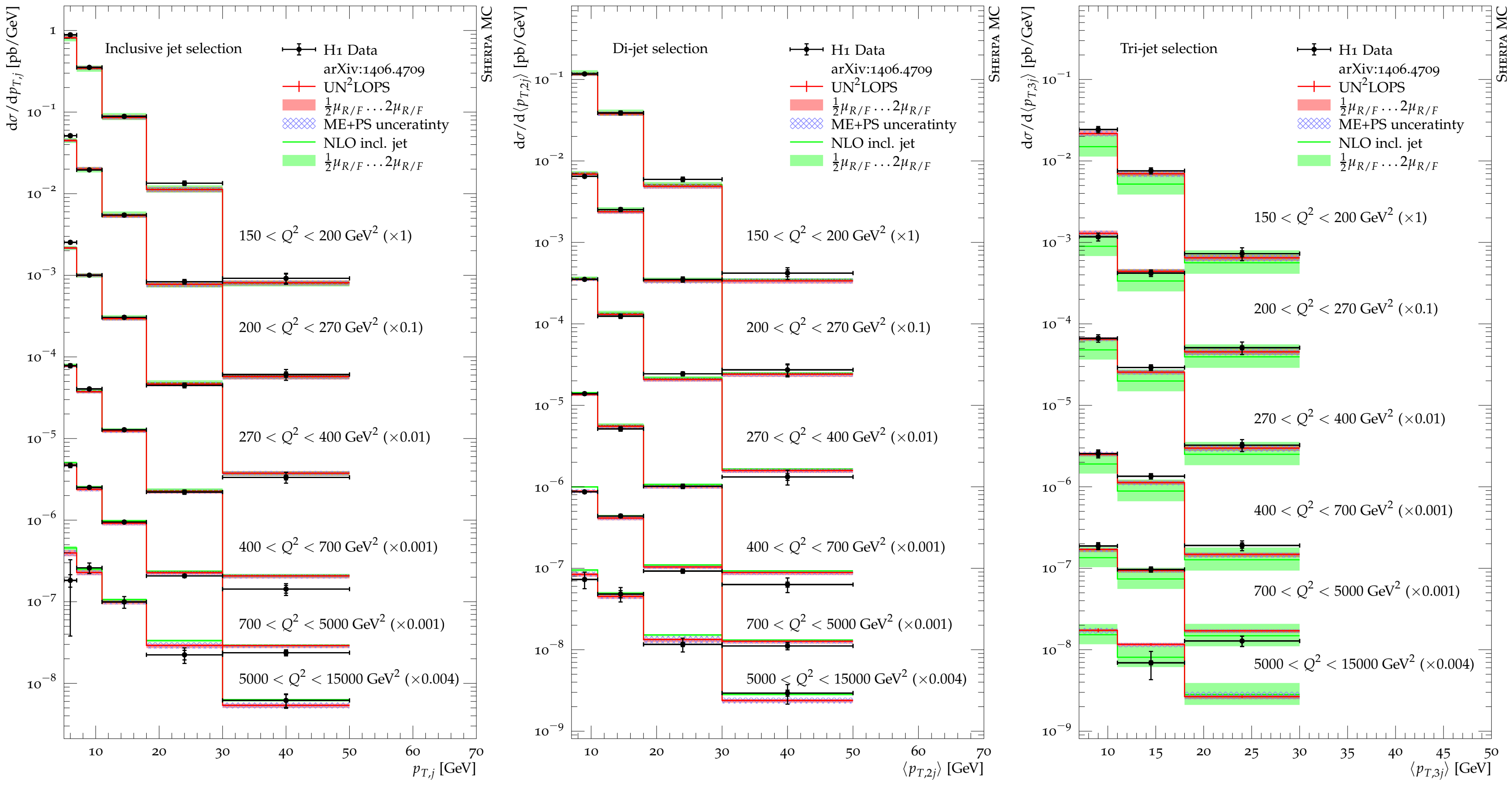




Sherpa NNLO particle-level simulation vs. H1 high-Q^2 data

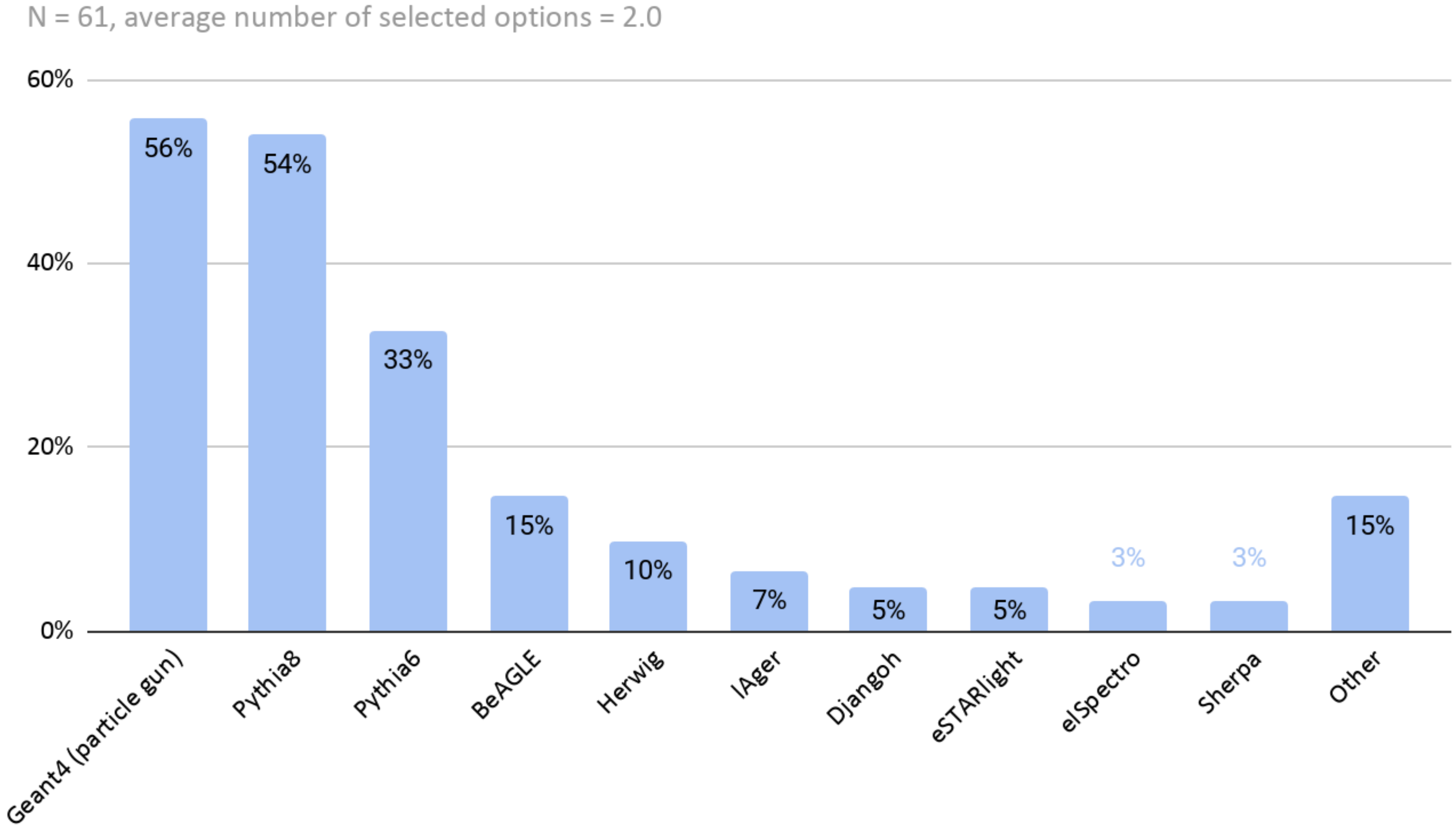
Slide prepared by S. Hoeche (SLAC)

[Höche,Kuttimalai,Li] arXiv:1809.04192



MCEGs used for Yellow Report

Source State of Software Survey

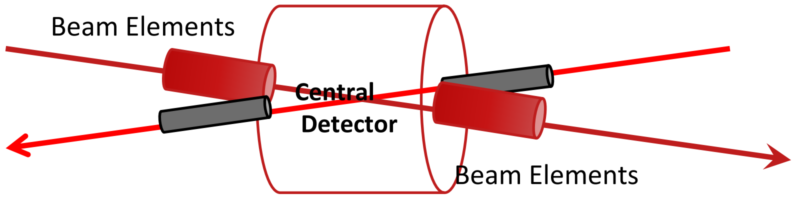


Other (N = 9): personal computer codes (N = 2), ACT, CLASDIS, ComptonRad, GRAPE-DILEPTON, MADX, MILOU, OPERA, RAYTRACE, Sartre, Topeg, ZGOUBI

Machine-Detector interface (MDI)

Integrated interaction region and detector design to optimize physics reach

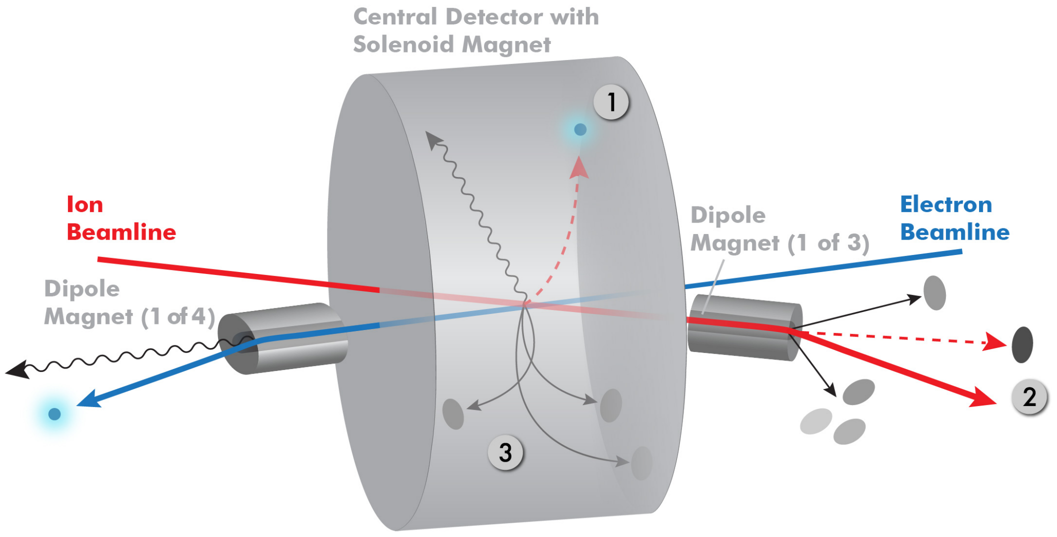
The aim is to get **~100% acceptance** for all final state particles, and measure them with good resolution.



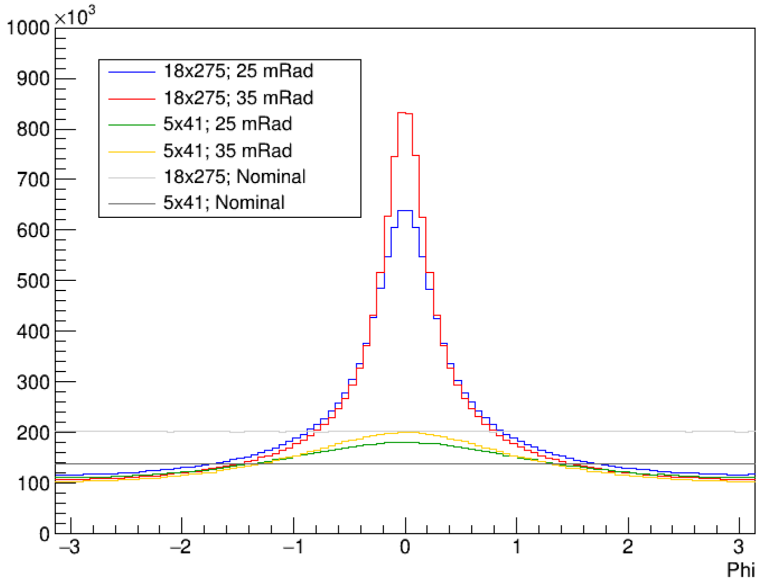
Experimental challenges:

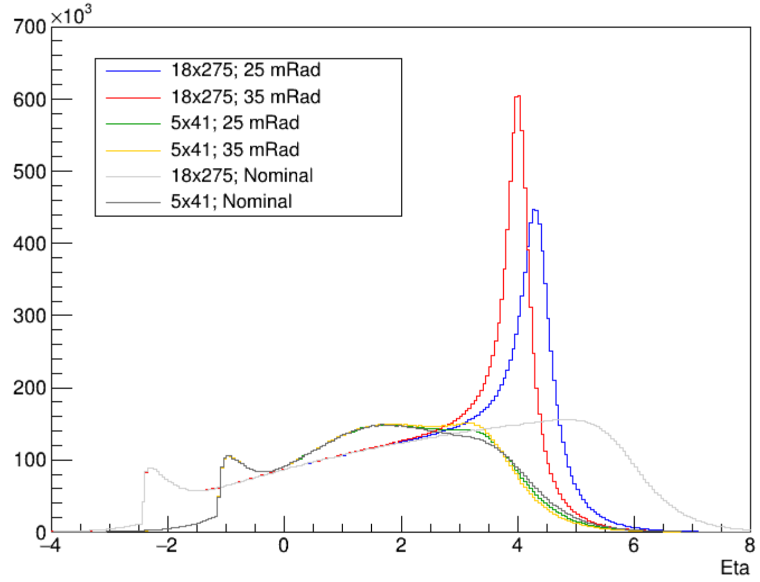
- beam elements limit forward acceptance
- central Solenoid not effective for forward

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



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.

Start building a MCEG community for the EIC

Satellite workshop during POETIC 8

Organized by Elke-Caroline Aschenauer (BNL), Andrea Bressan (Trieste), Markus Diefenthaler (JLab), Hannes Jung (DESY), Simon Plätzer (Vienna), Stefan Prestel (LUND)

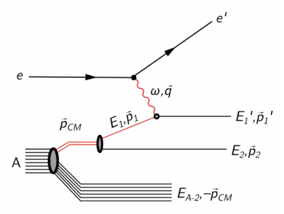
Summary from MCEG workshop series

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).



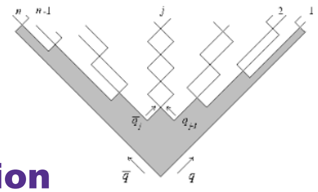
Primary interaction

Primary interaction treated by **PYTHIA6** for the hard collision.

Glauber handled by BeAGLE

PyQM: Nuclear Geometry + optional gluon radiation in medium.

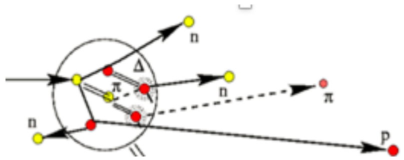
Hadronization handled by **PYTHIA6.**



Hadronization

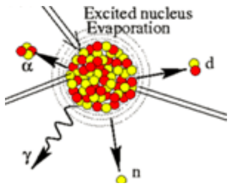
Cascade process handled by **DPMJET.**

Formation time. Stochastic.



Intra-nuclear cascade

Nuclear remnant evaporation and break up by **FLUKA.**



Nuclear remnant evaporation & breakup

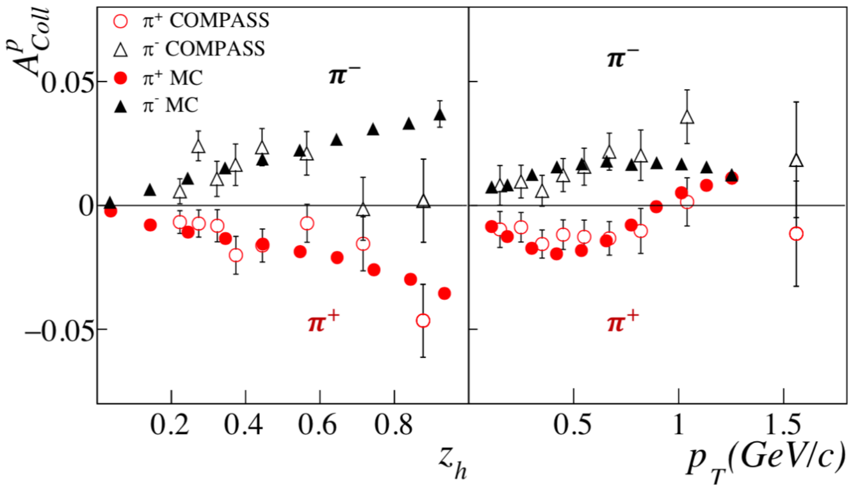
Some Nuclear Effects

	In BeAGLE
Parton distribution functions	✓
Parton saturation (CGC etc.)	
Short-range correlations	✓ (GCF)
"Fermi motion"	✓
Partonic (or "dipole") MS	✓
Partonic gluon radiation	✓
Medium-modified hadronization	
Formation times	✓
Hadronic Cascade	✓
Nuclear evaporation, breakup	✓
Photonic de-excitation of A*	✓

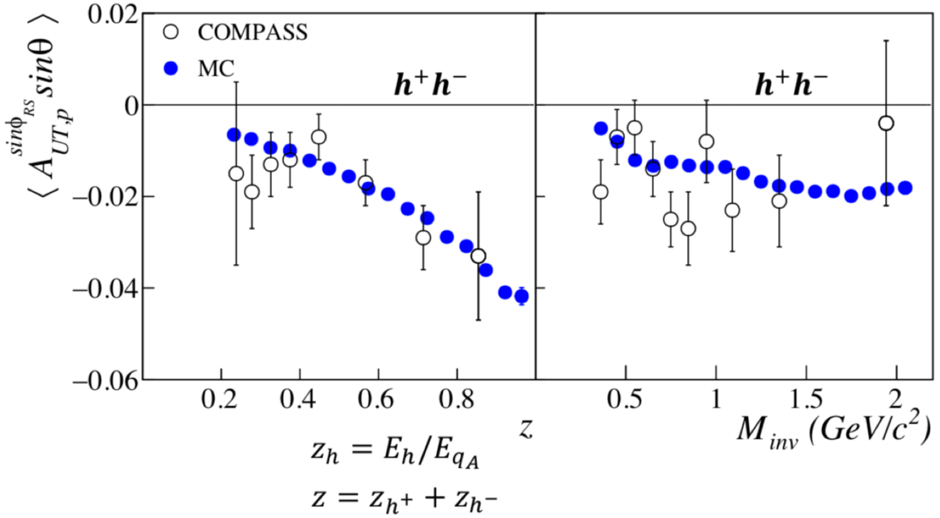
Recursive model for the fragmentation of polarized quarks

Albi Kerbizi (Trieste)

COMPASS Collins SSA



COMPASS di-hadron asymmetry

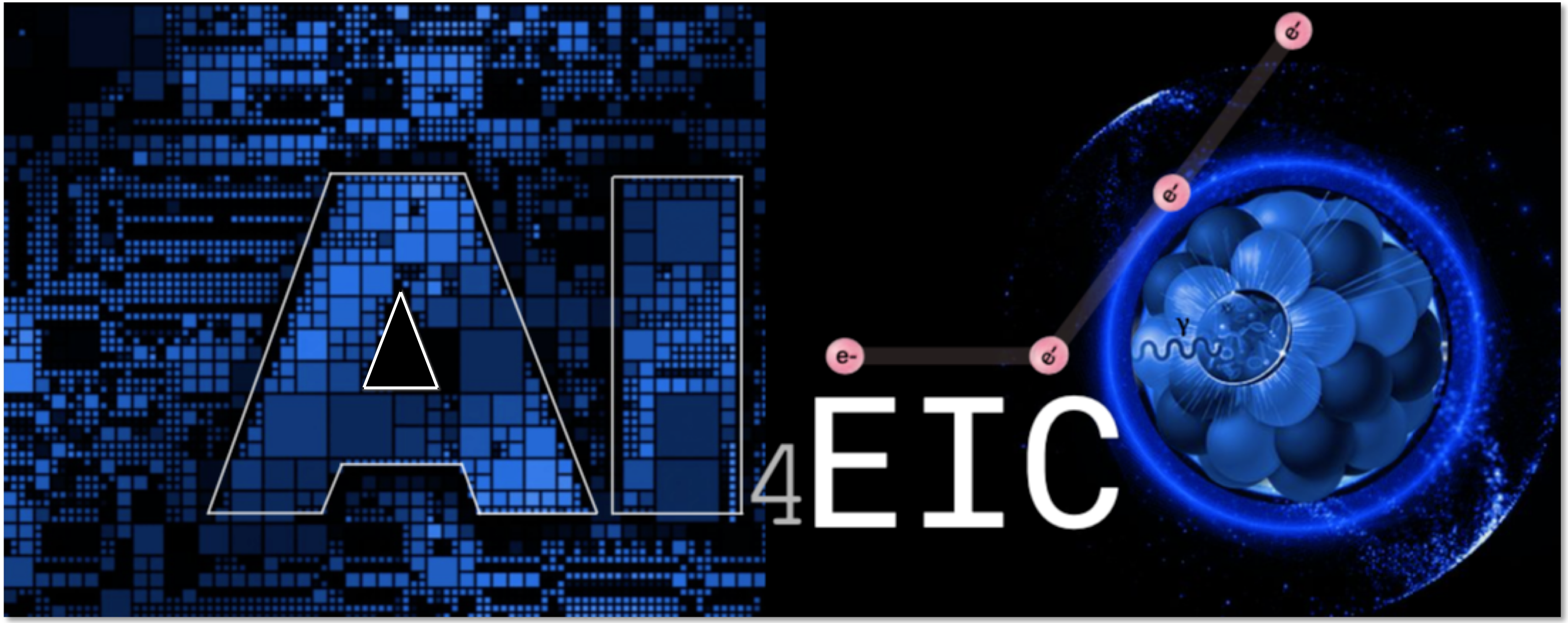


- The string + $^3P_0$ model for pseudo-scalar meson emission has been implemented in a stand alone MC code
- The comparison with experimental data on Collins and di-hadron asymmetries is very promising
- Other effects like Boer-Mulders or jet-handedness can be simulated

- The same results can be obtained with different choices for the $\check{g}$ function acting on the spin-independent correlations between quark transverse momenta
- The choice $\check{g} = 1/\sqrt{N_a(\varepsilon_h^2)}$ guarantees again LR symmetry and allows to simplify
  - the formalism and the analytical calculations
  - **the improvement of the simulations (i.e. adding vector mesons) → ongoing**
  - **the interface with external event generators and in particular with PYTHIA → ongoing**

AI/ML for EIC

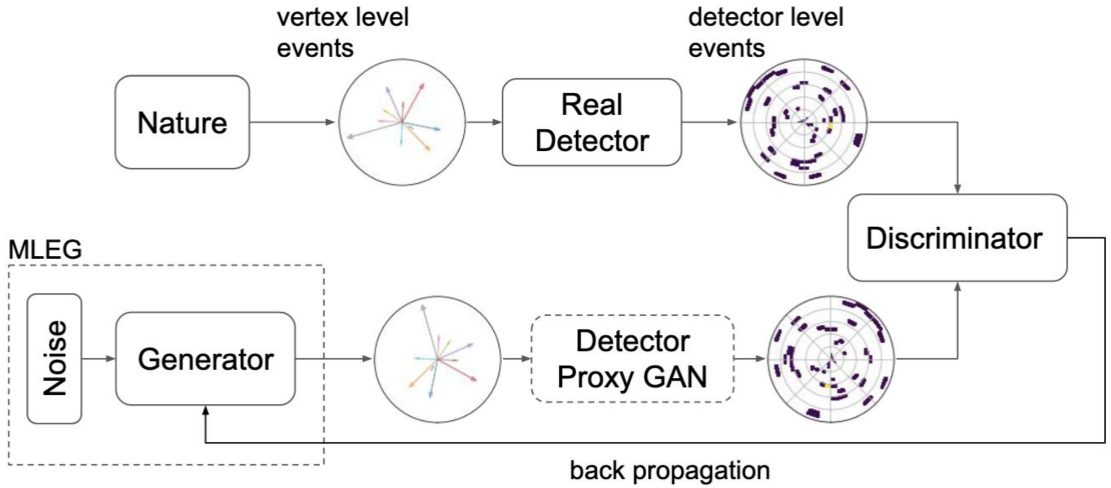
AI/ML already has an important presence in EIC, being applied to detector design optimization, as well as applications such as streaming DAQ, and a **new** AI Working Group as part of SWG to explore and develop AI/ML's potential.

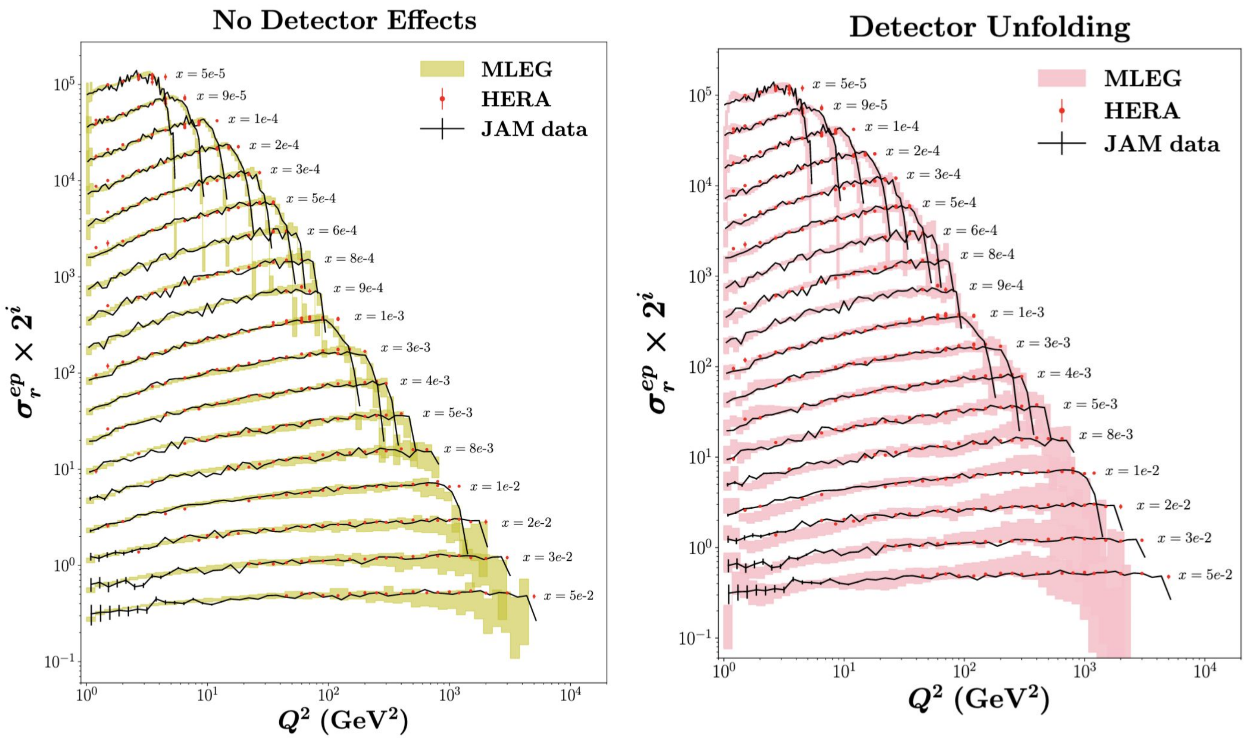


Machine learning-based event generator for ep scattering (N. Sato et al.)

arXiv:2008.03151

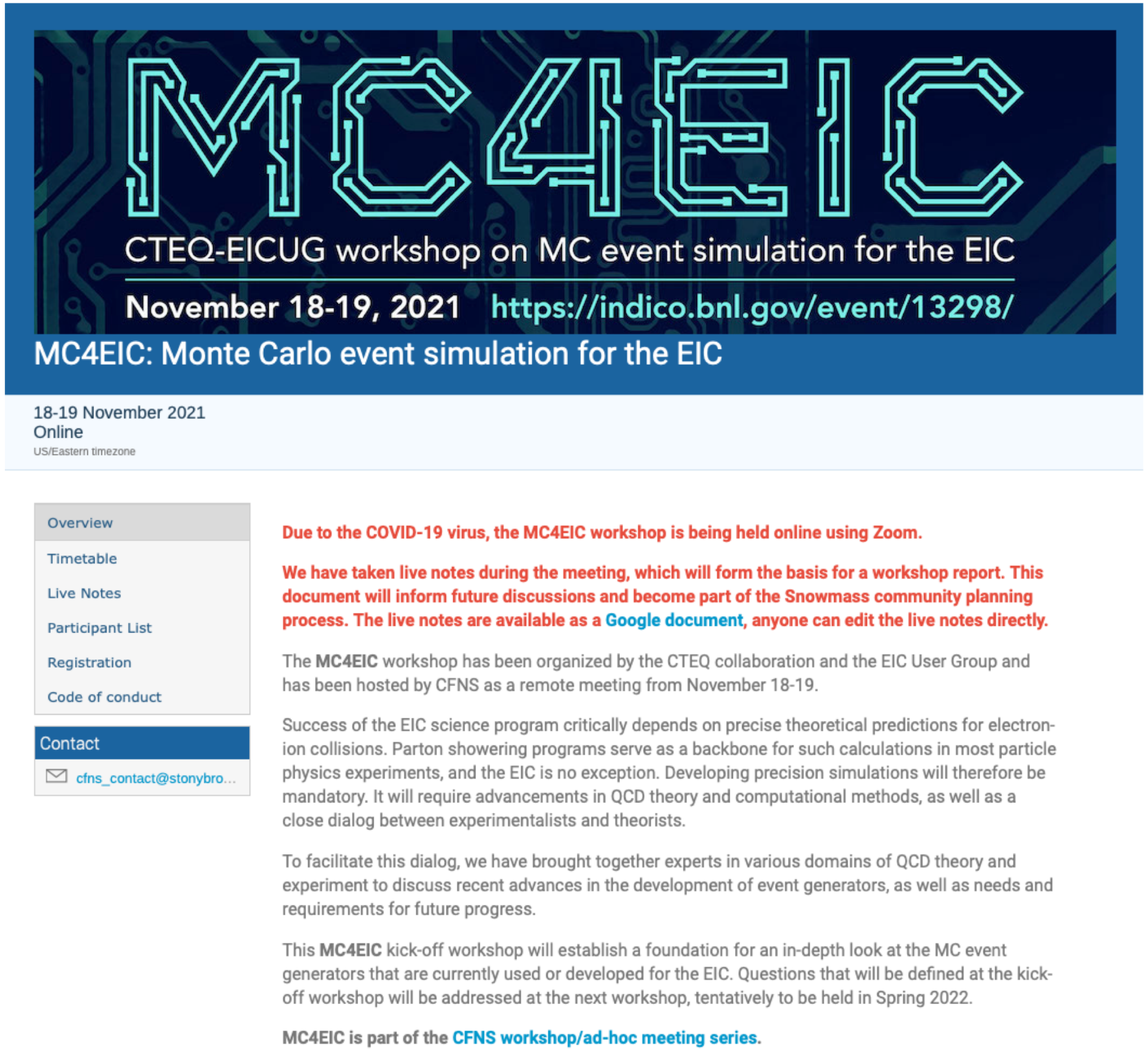
Motivation: Interpolate across many different experiments, in a way that they could never do by stitching all the





Jefferson Lab

MC4EIC



MC4EIC

CTEQ-EICUG workshop on MC event simulation for the EIC

November 18-19, 2021 https://indico.bnl.gov/event/13298/

MC4EIC: Monte Carlo event simulation for the EIC

18-19 November 2021
Online
US/Eastern timezone

Overview
Timetable
Live Notes
Participant List
Registration
Code of conduct

Contact
cfns_contact@stonybro...

Due to the COVID-19 virus, the MC4EIC workshop is being held online using Zoom.

We have taken live notes during the meeting, which will form the basis for a workshop report. This document will inform future discussions and become part of the Snowmass community planning process. The live notes are available as a Google document, anyone can edit the live notes directly.

The **MC4EIC** workshop has been organized by the CTEQ collaboration and the EIC User Group and has been hosted by CFNS as a remote meeting from November 18-19.

Success of the EIC science program critically depends on precise theoretical predictions for electron-ion collisions. Parton showering programs serve as a backbone for such calculations in most particle physics experiments, and the EIC is no exception. Developing precision simulations will therefore be mandatory. It will require advancements in QCD theory and computational methods, as well as a close dialog between experimentalists and theorists.

To facilitate this dialog, we have brought together experts in various domains of QCD theory and experiment to discuss recent advances in the development of event generators, as well as needs and requirements for future progress.

This **MC4EIC** kick-off workshop will establish a foundation for an in-depth look at the MC event generators that are currently used or developed for the EIC. Questions that will be defined at the kick-off workshop will be addressed at the next workshop, tentatively to be held in Spring 2022.

MC4EIC is part of the CFNS workshop/ad-hoc meeting series.

- Establish a foundation for in-depth look at event generators currently used or developed for the EIC.
- Understand precision level to be satisfied by event generators in order to match experimental analysis requirements.
- Highlight areas in need of cross-talk between theory and experiment.
- Establish benchmarks for MCEG development.

210 participants.

Will continue in Fall.

Event Generators for the EIC

arXiv:2203.11110

Submitted to the US Community Study
on the Future of Particle Physics (Snowmass 2021)

Event Generators for High-Energy Physics Experiments

We provide an overview of the status of Monte-Carlo event generators for high-energy particle physics. Guided by the experimental needs and requirements, we highlight areas of active development, and opportunities for future improvements. Particular emphasis is given to physics models and algorithms that are employed across a variety of experiments. These common themes in event generator development lead to a more comprehensive understanding of physics at the highest energies and intensities, and allow models to be tested against a wealth of data that have been accumulated over the past decades. A cohesive approach to event generator development will allow these models to be further improved and systematic uncertainties to be reduced, directly contributing to future experimental success. Event generators are part of a much larger ecosystem of computational tools. They typically involve a number of unknown model parameters that must be tuned to experimental data, while maintaining the integrity of the underlying physics models. Making both these data, and the analyses with which they have been obtained accessible to future users is an essential aspect of open science and data preservation. It ensures the consistency of physics models across a variety of experiments.

CP3-22-12 DESY-22-042 FERMILAB-PUB-22-116-SCD-T IPPP/21/51
JLAB-PHY-22-3576 KA-TP-04-2022 LA-UR-22-22126 LU-TP-22-12
MCNET-22-04 OUTP-22-03P P3H-22-024 PITT-PACC 2207 UCI-TR-2022-02

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).
Will result in of QCD factorization and evolution, QED radiative corredeeper understanding ctions, hadronization models etc.

Discussion

Common forum for:

- **Discussion** on the physics event generators used by **N**HEP experiments.
- **Technical work** on these physics event generators

Promotes collaboration among:

- Experimental physicists from NHEP experiments
- Theoretical physicists from generator teams
- Software and computing engineers