The way to an Electron-Ion Collider

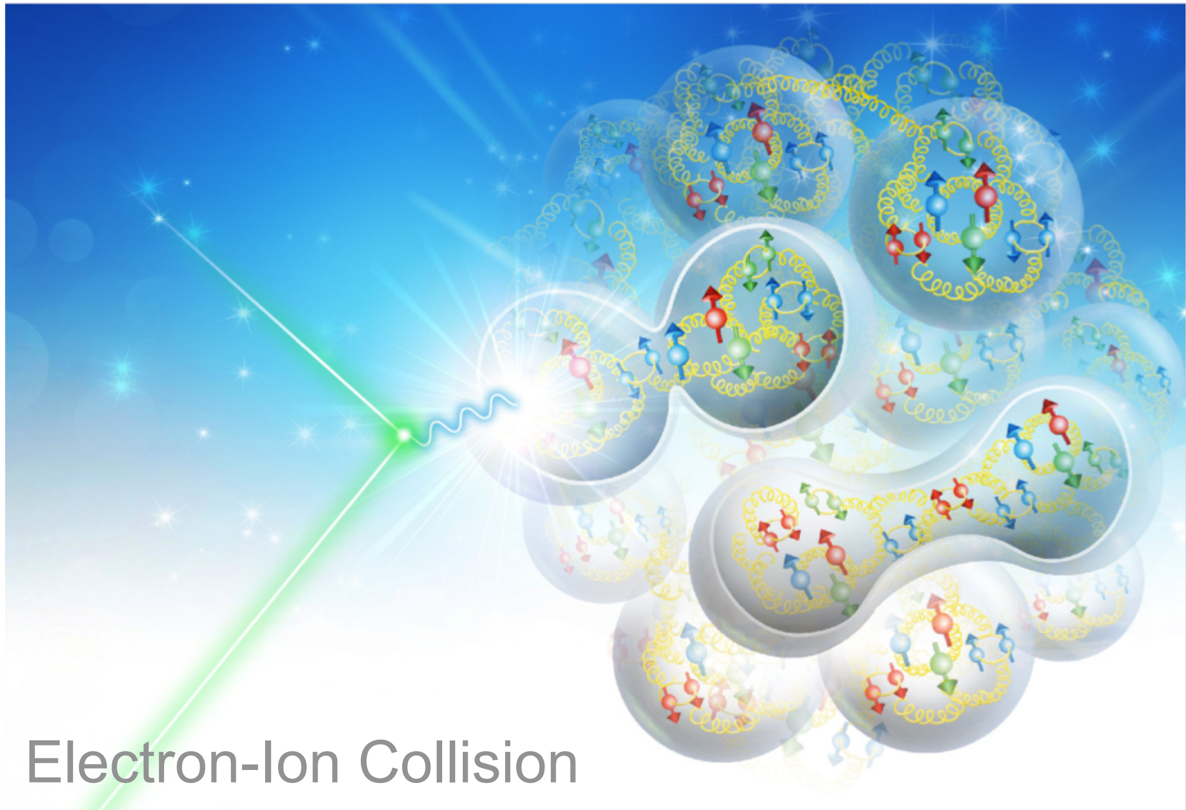
EIC A new frontier in Nuclear Physics

TMDs Imaging quarks and gluons in nuclear matter

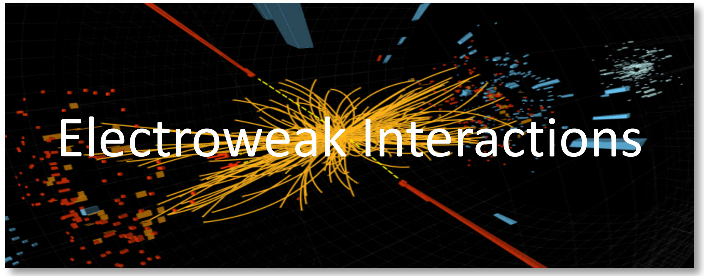
EIC^2

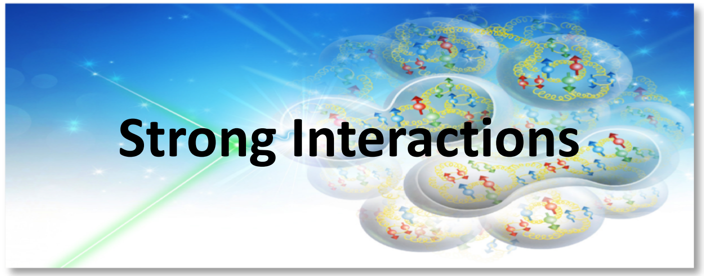
EIC Center at Jefferson Lab

Markus Diefenthaler



The Standard Model of Physics



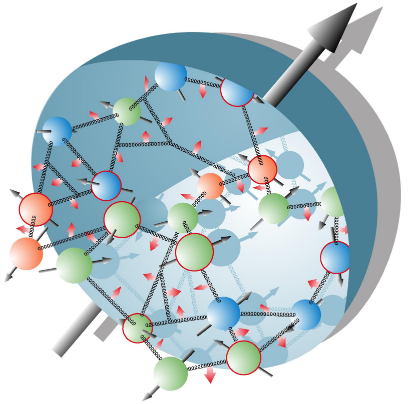


Further exploration of the Standard Model

Dark matter searches

Electroweak symmetry breaking

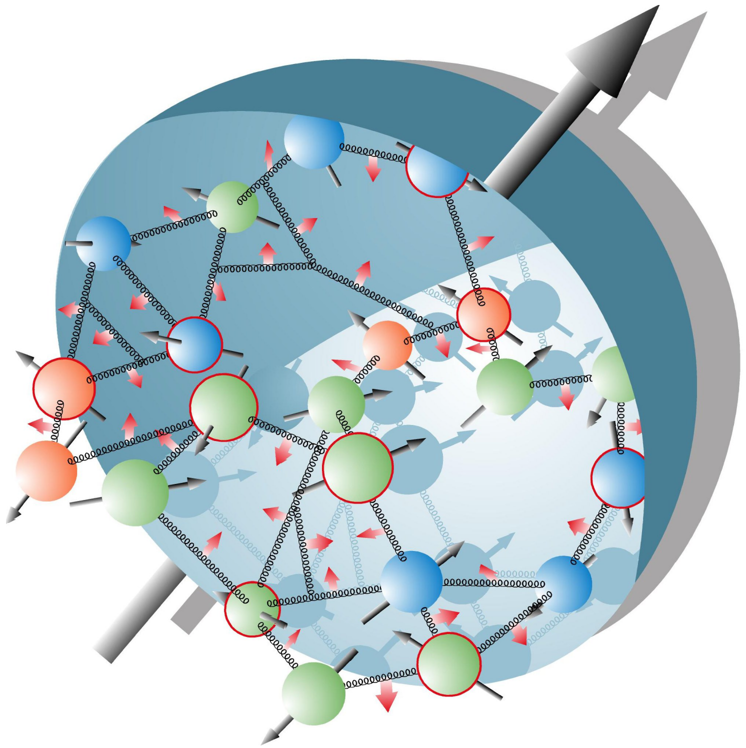
Deeper understanding of QCD:



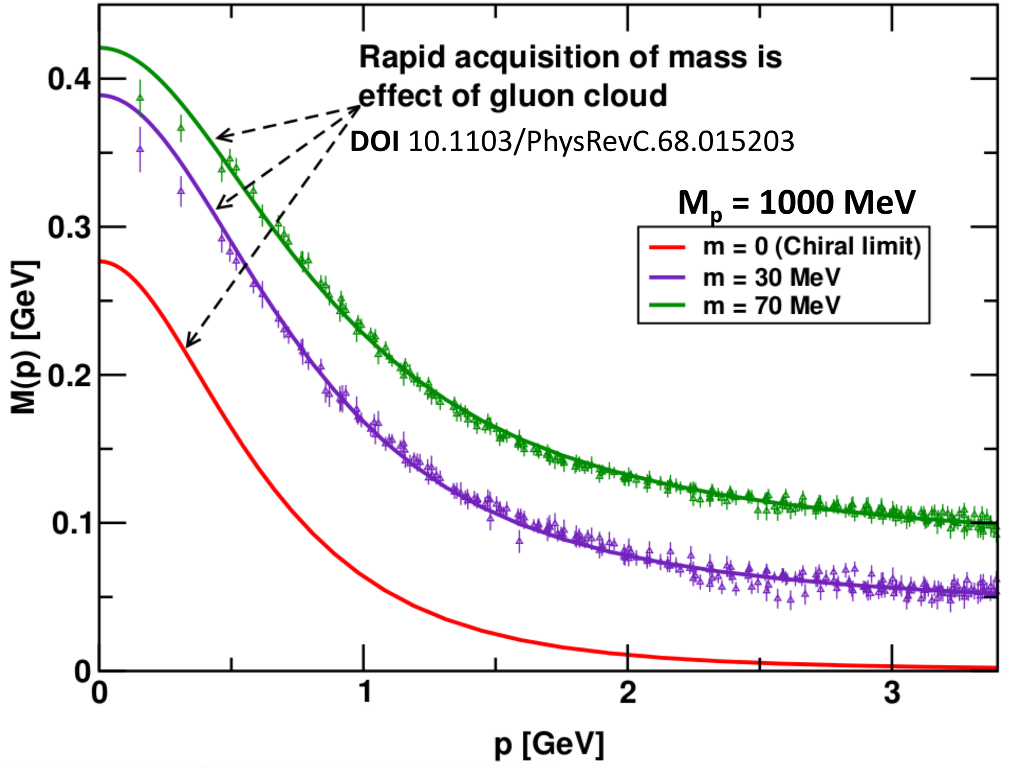
Study of nuclear matter

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



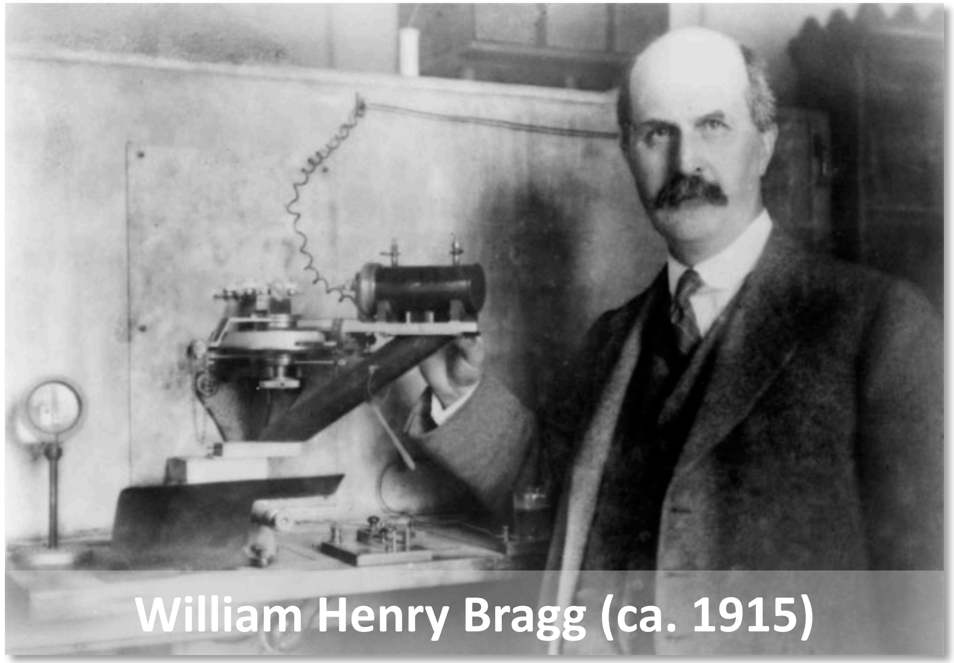
Ultimate goal Understand how matter at its most fundamental level is made

To reach goal precisely image quarks and gluons and their interactions

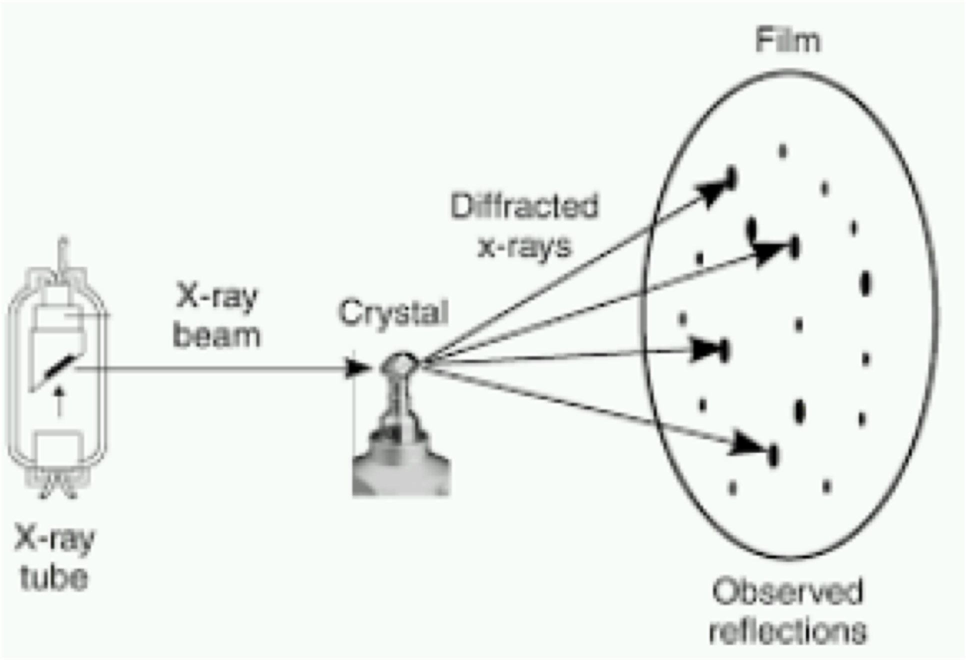
Introduction

A new frontier in Nuclear Physics

About a century ago… a new frontier in atomic physics



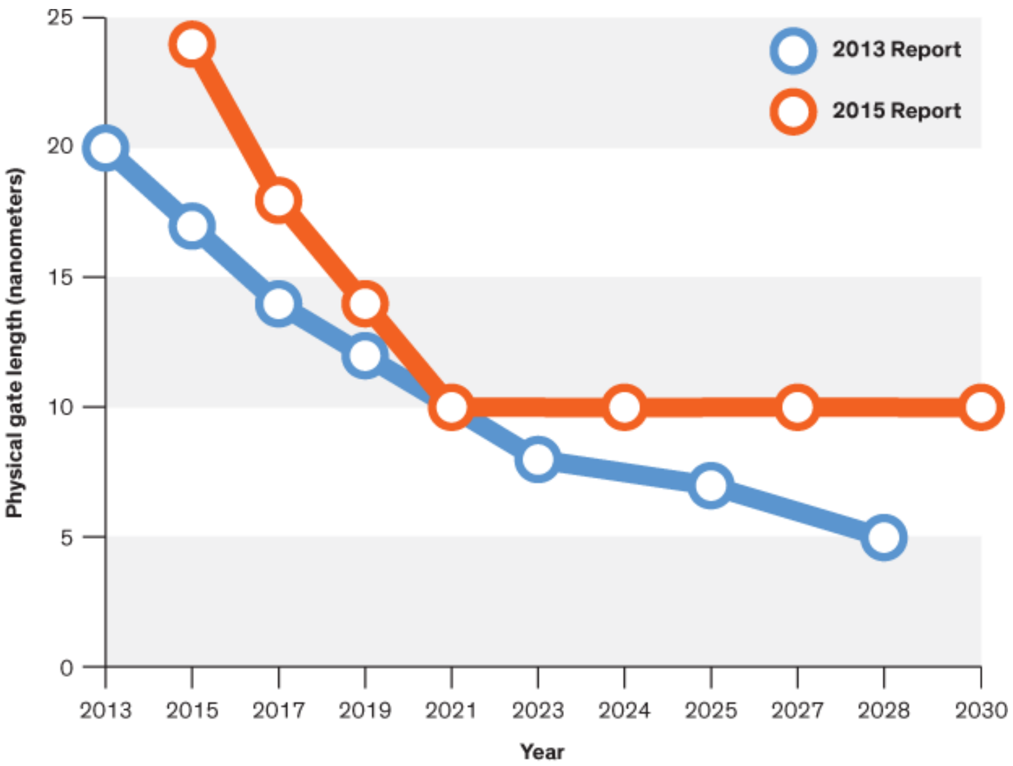
William Henry Bragg (ca. 1915)



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?

Quarks (and gluons)

Nobel Prize in Physics 1990

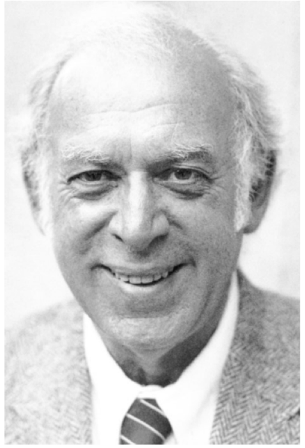


Photo from the Nobel Foundation archive.

Jerome I. Friedman

Prize share: 1/3

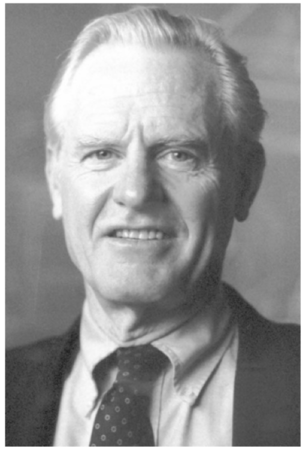


Photo from the Nobel Foundation archive.

Henry W. Kendall

Prize share: 1/3

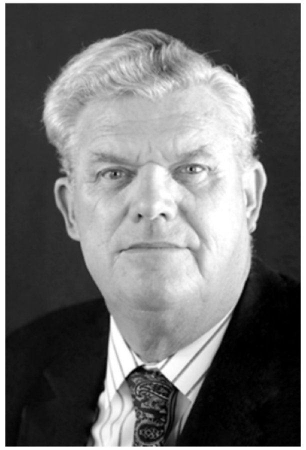


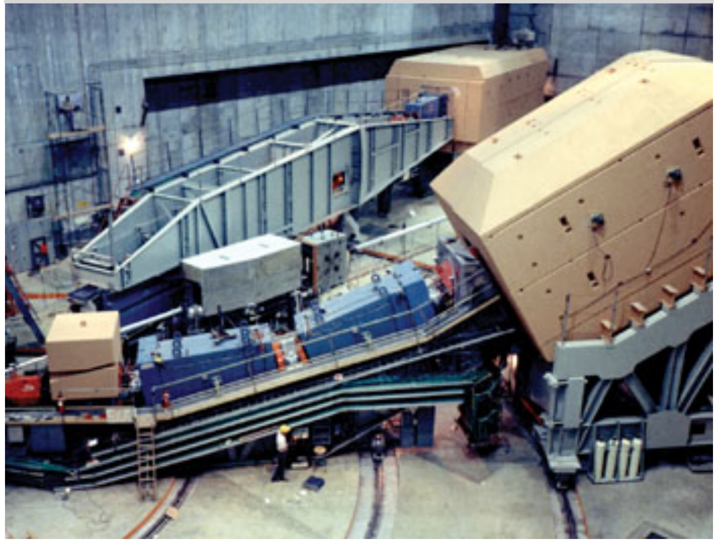
Photo: T. Nakashima

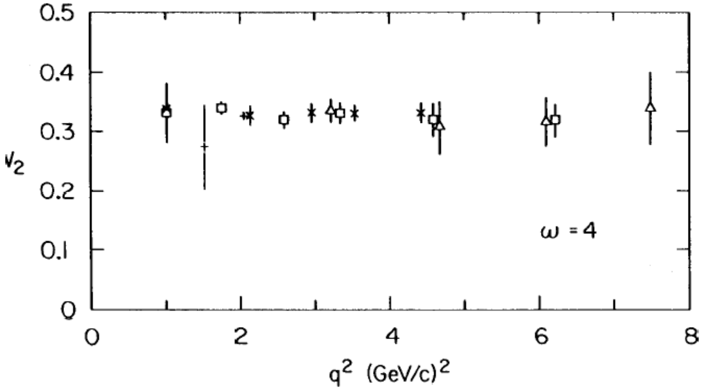
Richard E. Taylor

Prize share: 1/3

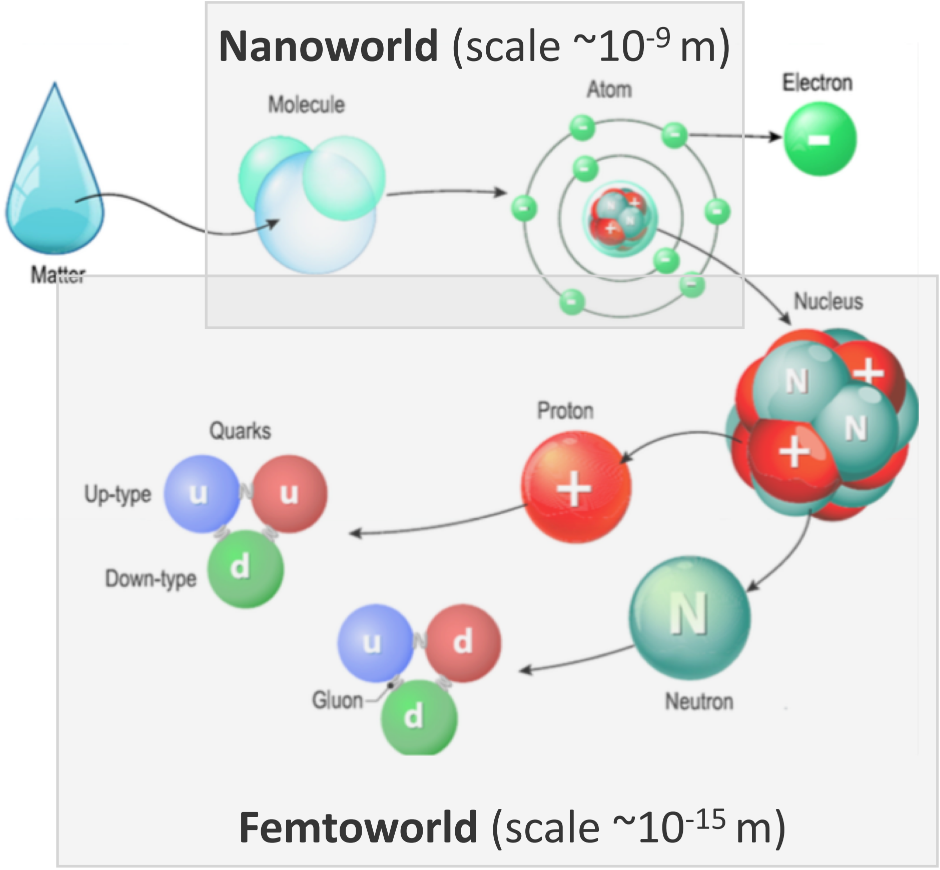
Discovery of quarks The Nobel Prize in Physics 1990 was awarded "for their pioneering investigations concerning deep inelastic scattering of electrons on protons and bound neutrons, which have been of essential importance for the **development of the quark model in particle physics**."

SLAC-MIT Experiment 1969





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

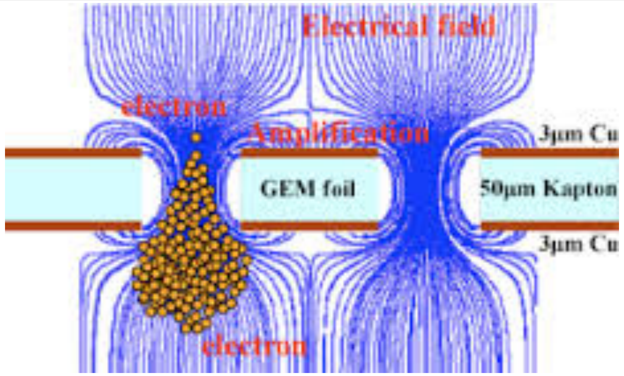
Theory of the strong interaction

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

Quantumchromo-dynamics (QCD)

Accelerator technologies

Detector technologies

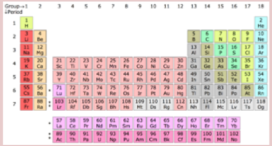
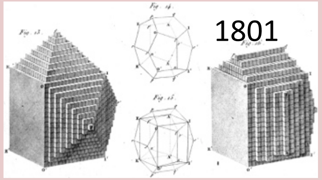
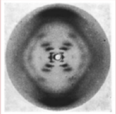
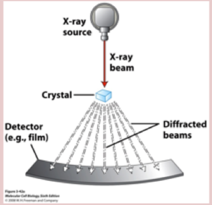
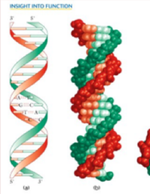
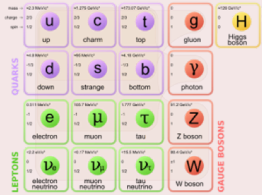
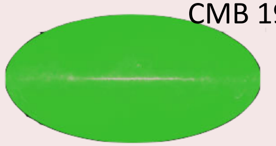
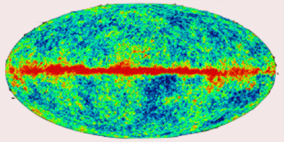
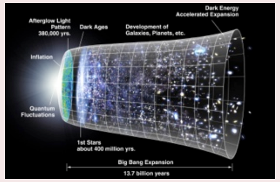
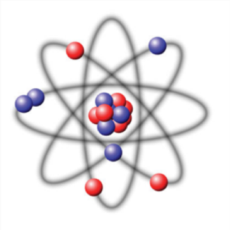
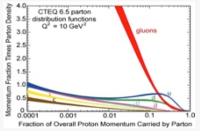
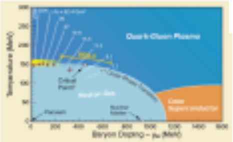
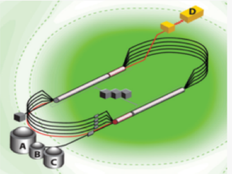
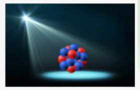
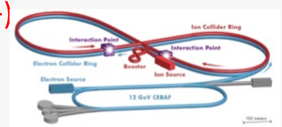


Computer technologies

Steady advances in all of these areas mean that →

Jefferson Lab

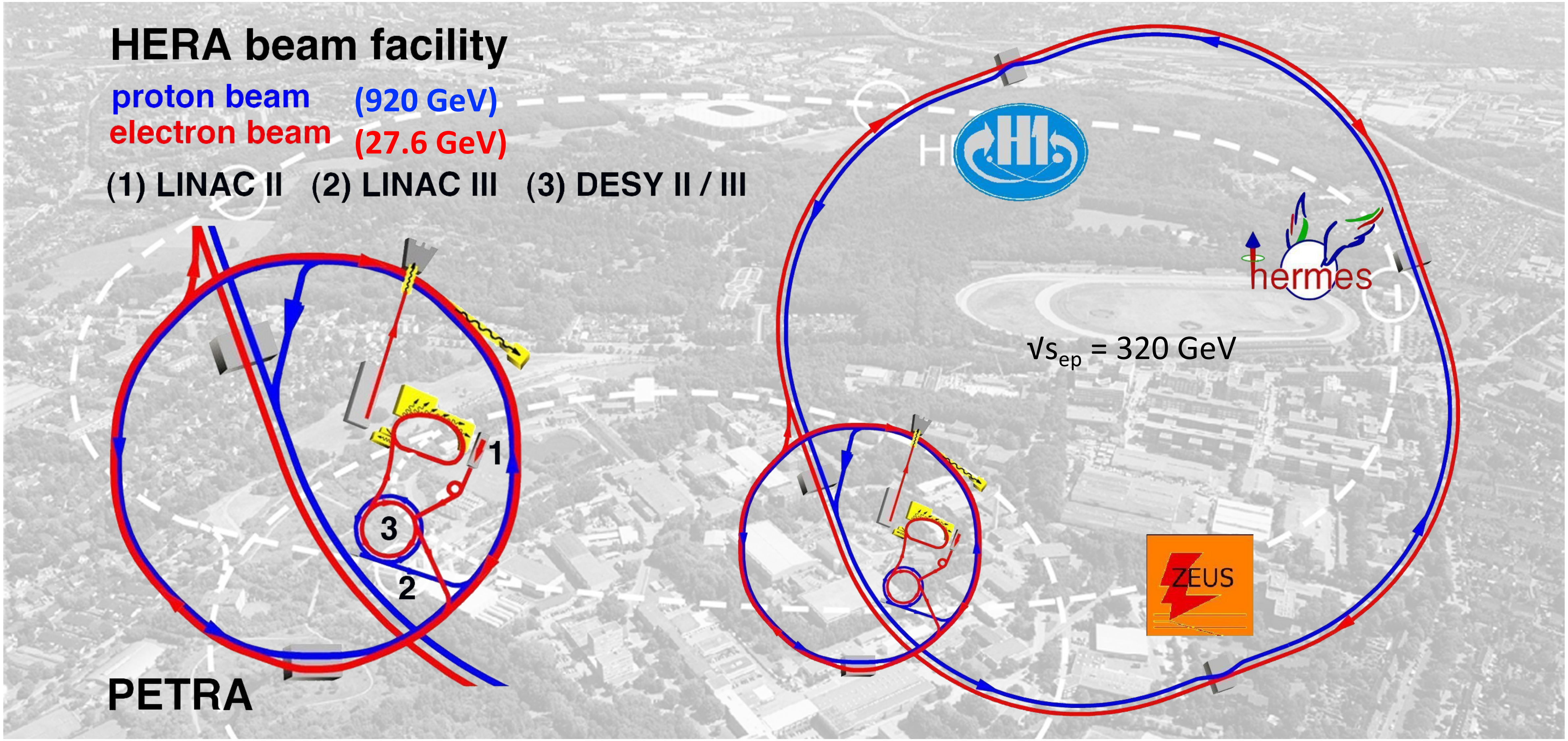
EIC: A new frontier in science

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 $\mathcal{L}_{QCD} = \overline{\psi}(i\not{\partial} - g\not{A})\psi - \frac{1}{2}\mathrm{tr}\, F_{\mu\nu}F^{\mu\nu}$	Non-perturbative QCD Structure 2017   	CEBAF12 (2018)   Electron-Ion Collider (2025+) 	Structure & Dynamics in QCD 

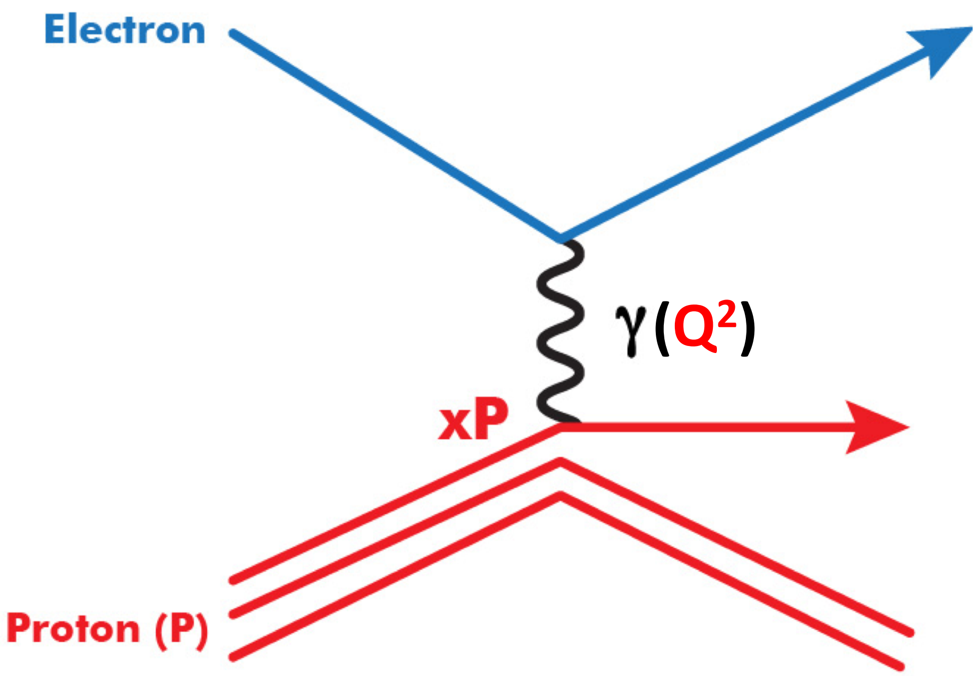
Pioneering measurements

The first Electron-Ion Collider

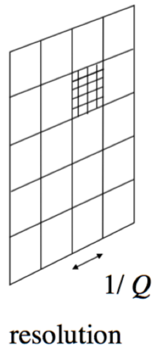
HERA: The first Electron-Ion Collider



Deep-inelastic scattering (DIS) of electrons off protons

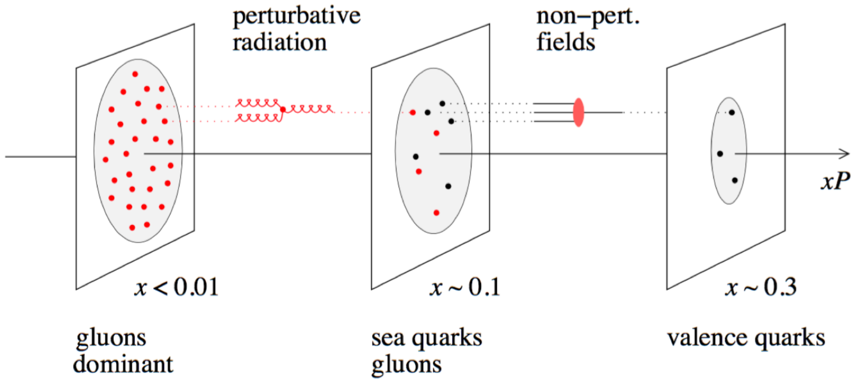


Ability to change Q^2 changes the resolution scale



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

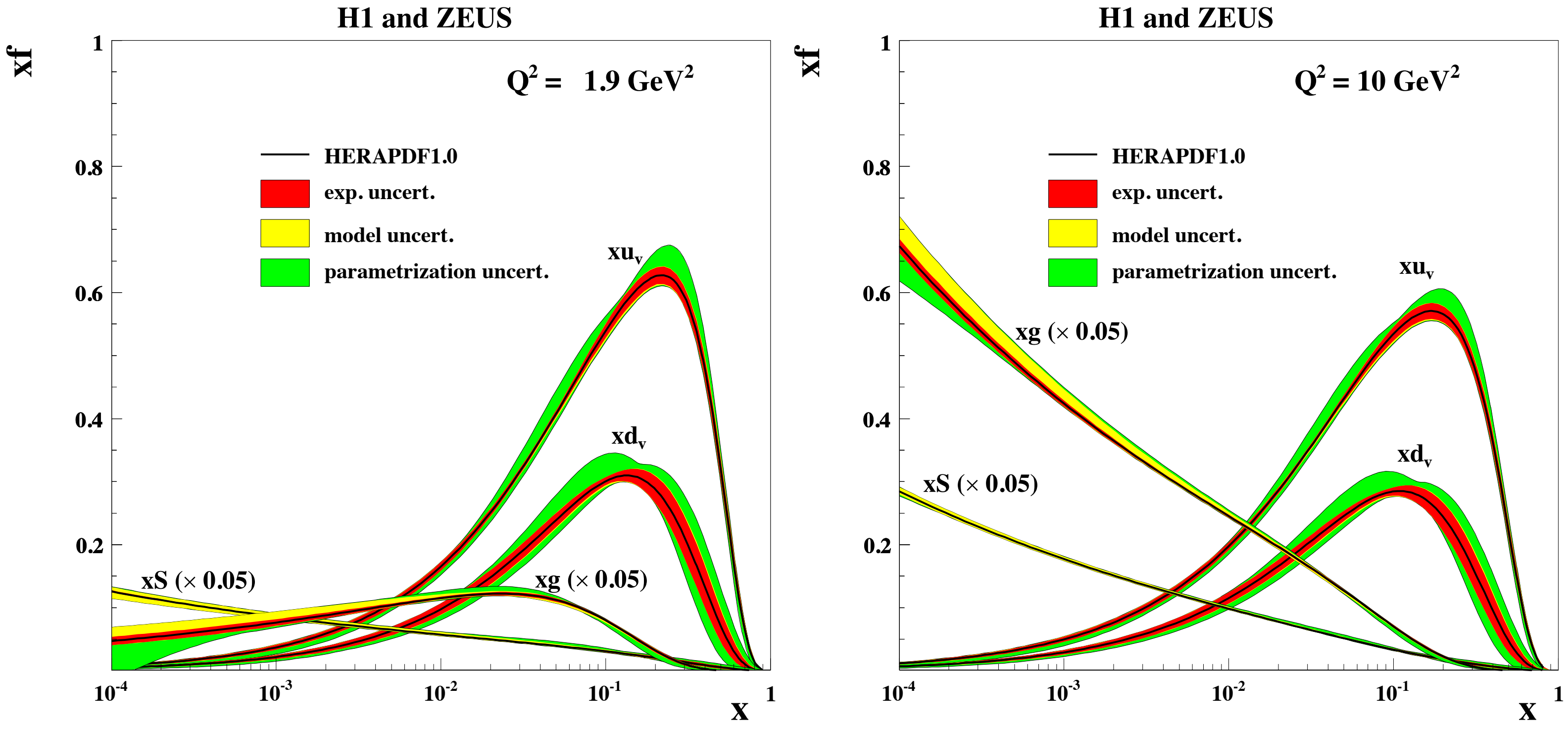
Ability to change x projects out different con-figurations where different dynamics dominate



Parton distribution functions (PDF)

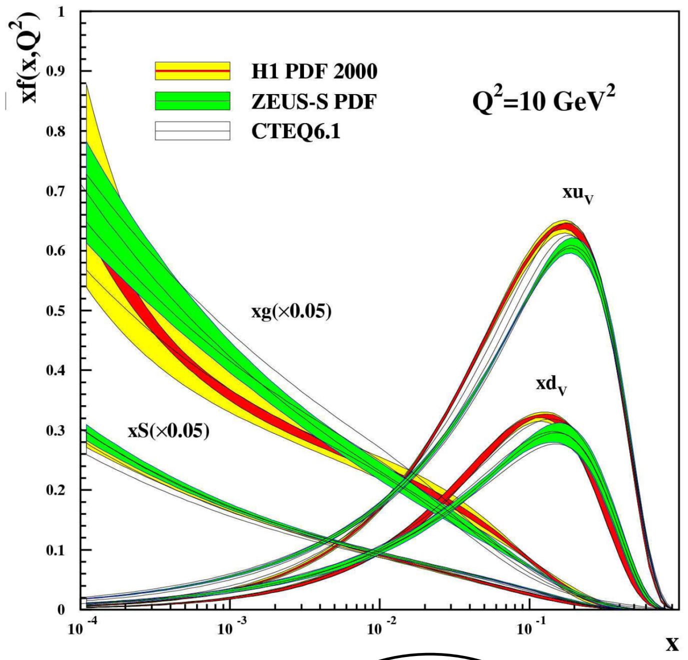
Observable cross section → structure functions → QCD analysis PDFs

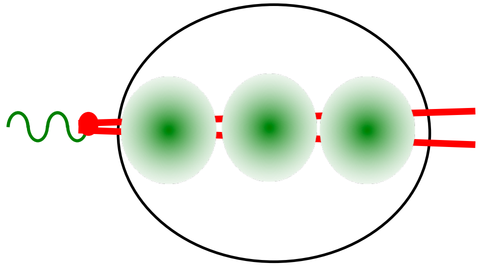
process-dependent | universal



QCD at extremes: Parton saturation

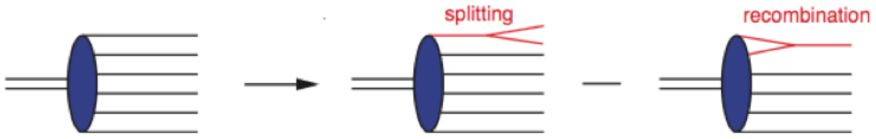
Dramatic rise of gluon PDF



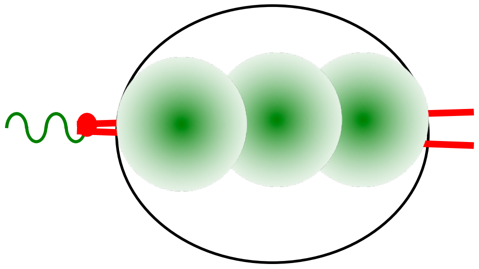


In nuclei, the interaction probability enhanced by A⅓

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*

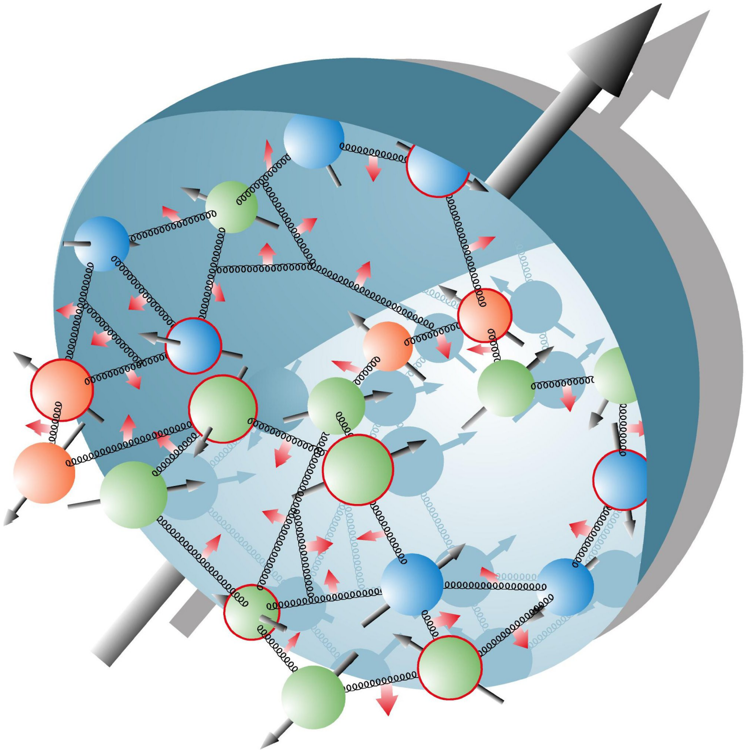


Will nuclei saturate faster as color leaks out of nucleons?

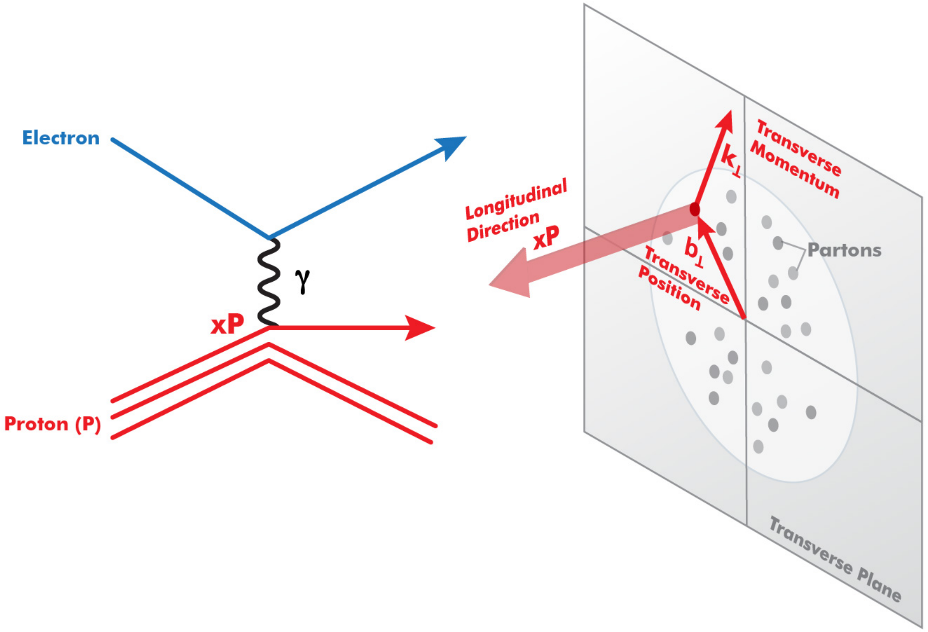
Polarized DIS measurements

hermes

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

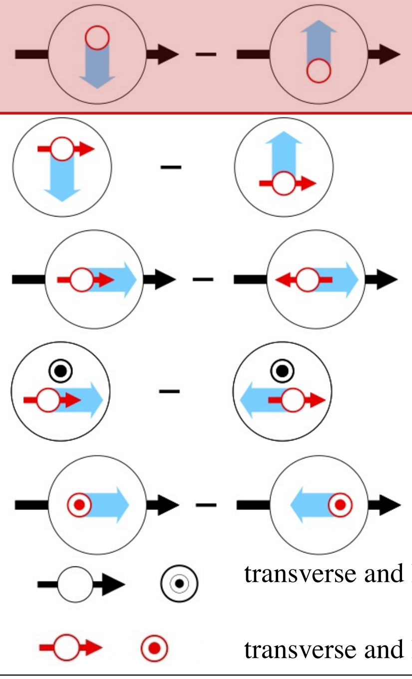
Transverse-momentum dependent PDFs

Dirac decomposition of the quark-quark correlator

$$\frac{1}{2}\mathrm{Tr}\left[\left(\gamma^+ + \lambda\gamma^+\gamma_5\right)\Phi\left(x,\mathbf{p}_T\right)\right] = \frac{1}{2}\Big[f_1^q\left(x,\mathbf{p}_T^2\right) + S_T^i\varepsilon^{ij}p_T^j\frac{1}{M}\,f_{1T}^{\perp,q}\left(x,\mathbf{p}_T^2\right) + \lambda\Lambda\,g_1^q\left(x,\mathbf{p}_T^2\right) + \lambda S_T^i p_T^i\frac{1}{M}\,g_{1T}^{\perp,q}\left(x,\mathbf{p}_T^2\right)\Big],$$

$$\frac{1}{2}\mathrm{Tr}\left[\left(\gamma^+ - s_T^j i\sigma^{+j}\gamma_5\right)\Phi\left(x,\mathbf{p}_T\right)\right] = \frac{1}{2}\Big[f_1^q\left(x,\mathbf{p}_T^2\right) + \boxed{S_T^i\varepsilon^{ij}p_T^j\frac{1}{M}\,f_{1T}^{\perp,q}\left(x,\mathbf{p}_T^2\right)} + s_T^i\varepsilon^{ij}p_T^j\frac{1}{M}\,h_1^{\perp,q}\left(x,\mathbf{p}_T^2\right) + s_T^i S_T^i\,h_1^q\left(x,\mathbf{p}_T^2\right) + s_T^i\left(2p_T^i p_T^j - \mathbf{p}_T^2\delta^{ij}\right)S_T^j\frac{1}{2M^2}\,h_{1T}^{\perp,q}\left(x,\mathbf{p}_T^2\right) + \Lambda s_T^i p_T^i\frac{1}{M}\,h_{1L}^{\perp,q}\left(x,\mathbf{p}_T^2\right)\Big].$$

TMD	probabilistic interpretation	chiral properties	naive-T properties
$f_{1T}^{\perp,q}\left(x,\mathbf{p}_T^2\right)$	–	chiral-even	naive-T-odd
$h_1^{\perp,q}\left(x,\mathbf{p}_T^2\right)$	–	chiral-odd	naive-T-odd
$h_{1T}^{\perp,q}\left(x,\mathbf{p}_T^2\right)$	–	chiral-odd	naive-T-even
$h_{1L}^{\perp,q}\left(x,\mathbf{p}_T^2\right)$	–	chiral-odd	naive-T-even
$g_{1T}^{\perp,q}\left(x,\mathbf{p}_T^2\right)$	–	chiral-even	naive-T-even



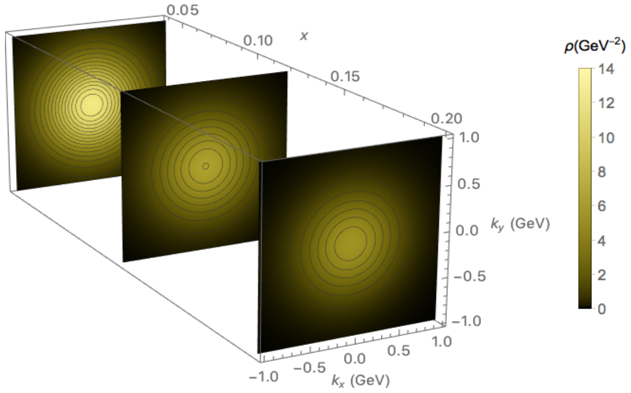
legend

transverse and longitudinal nucleon polarisation

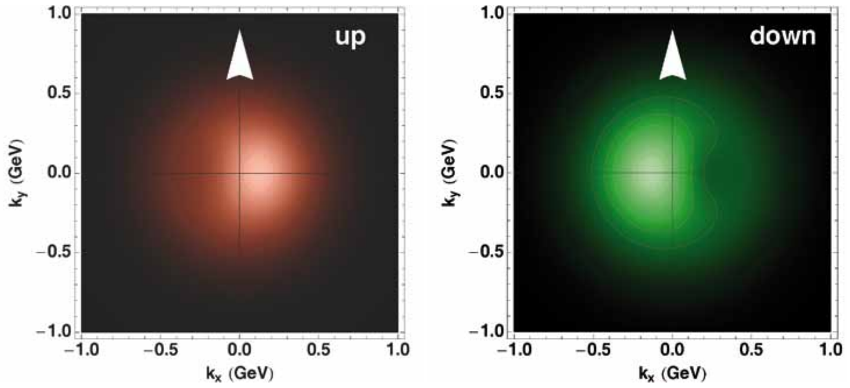
transverse and longitudinal quark polarisation

Unpolarized nucleon

JHEP 1706 (2017) 081



Transversely polarized nucleon



Single-spin asymmetries (SSA) at high energies

E704 at Fermilab

$$p^{\Uparrow} p \to hX$$

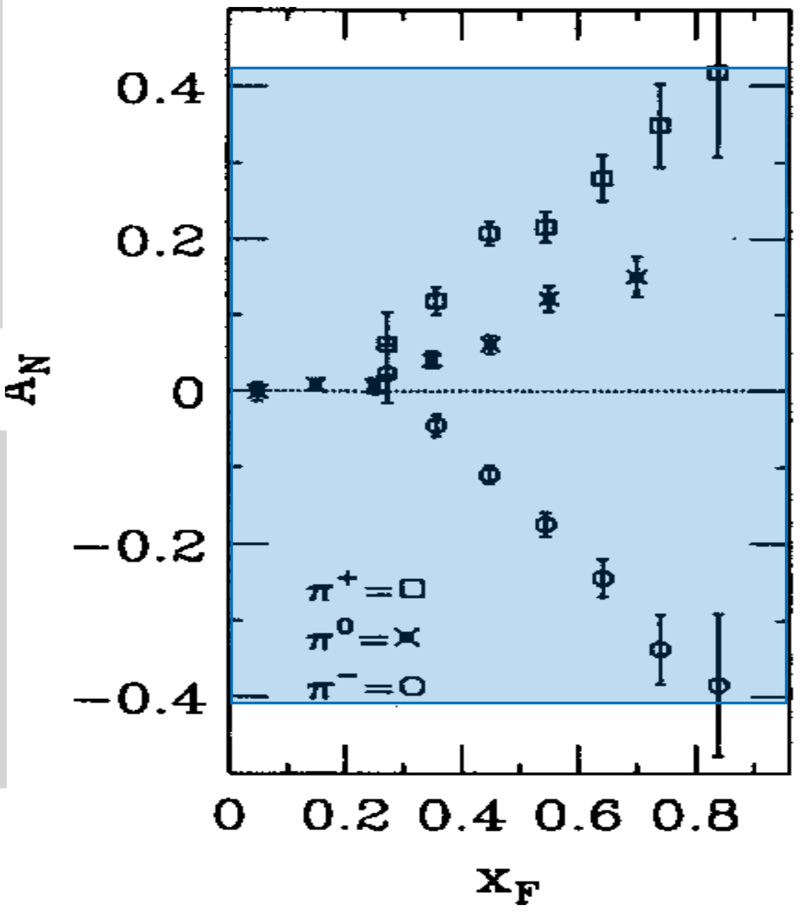
$$A_N = \frac{1}{P_{\text{beam}}} \frac{N^{\pi}_{\text{left}} - N^{\pi}_{\text{right}}}{N^{\pi}_{\text{left}} + N^{\pi}_{\text{right}}}$$

QCD prediction

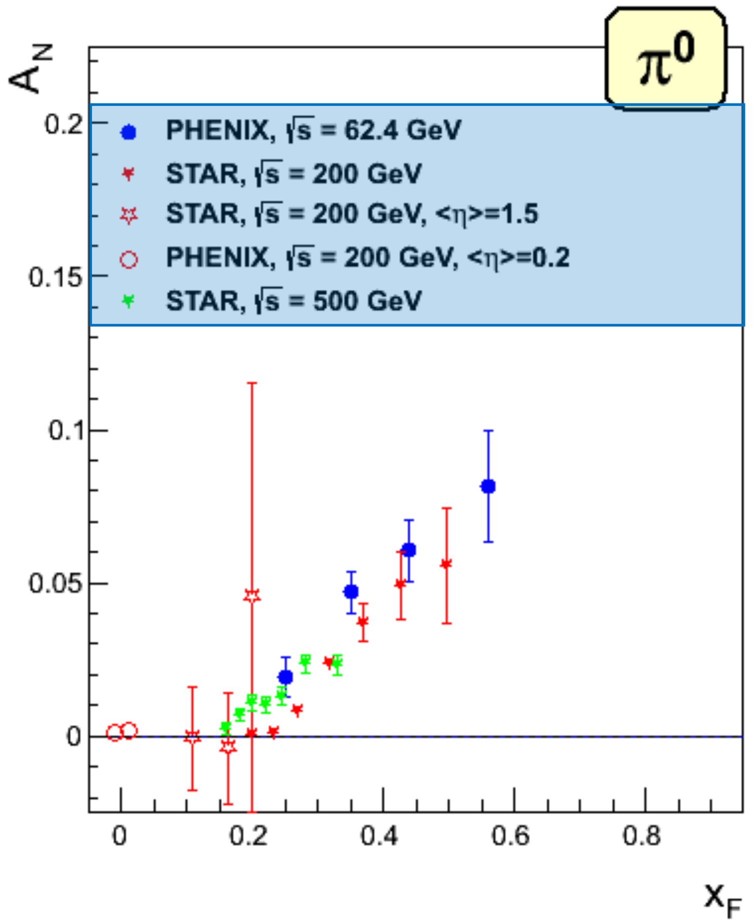
$$A_N \propto \alpha_s m_q / P_T \to 0$$

Kane, Pumplin, Repko [KPR78]

E704 SSA at √s ≈ 20 GeV



Confirmed at √s up to 500 GeV



SSA at HERMES

SSA in QCD

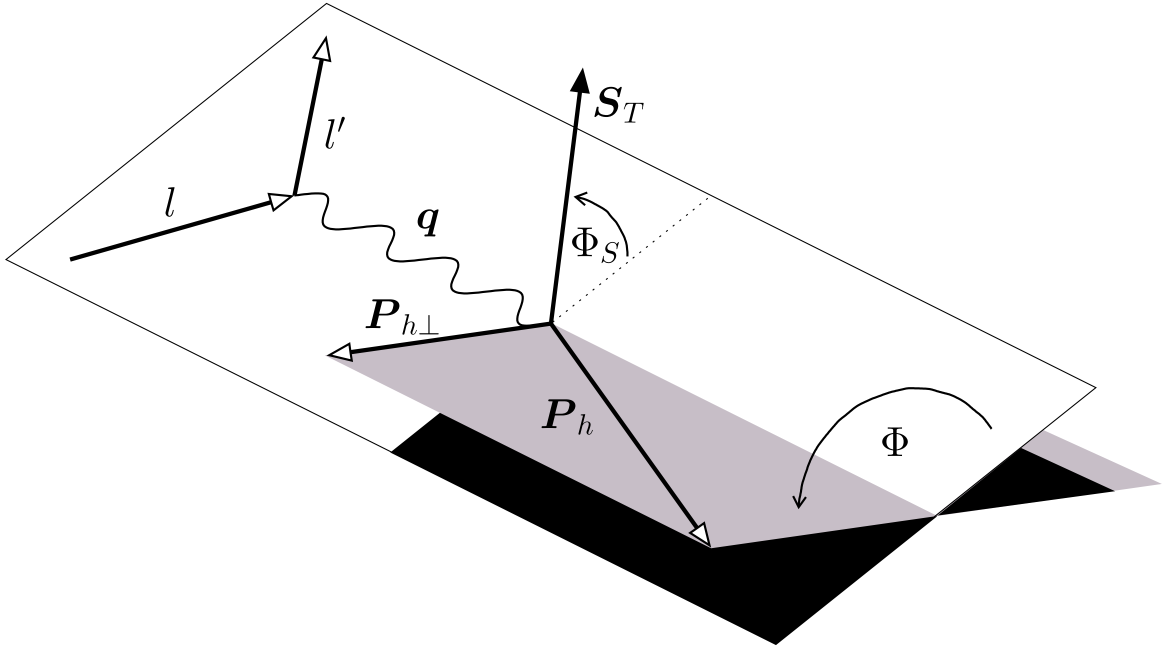
- spin-orbit correlations

  $$\mathbf{S}\cdot(\mathbf{p}_1\times\mathbf{p}_2) \qquad \textbf{E704}\quad \vec{S}_{\text{beam}}\cdot(\vec{p}_{\text{beam}}\times\vec{p}_{\pi})$$

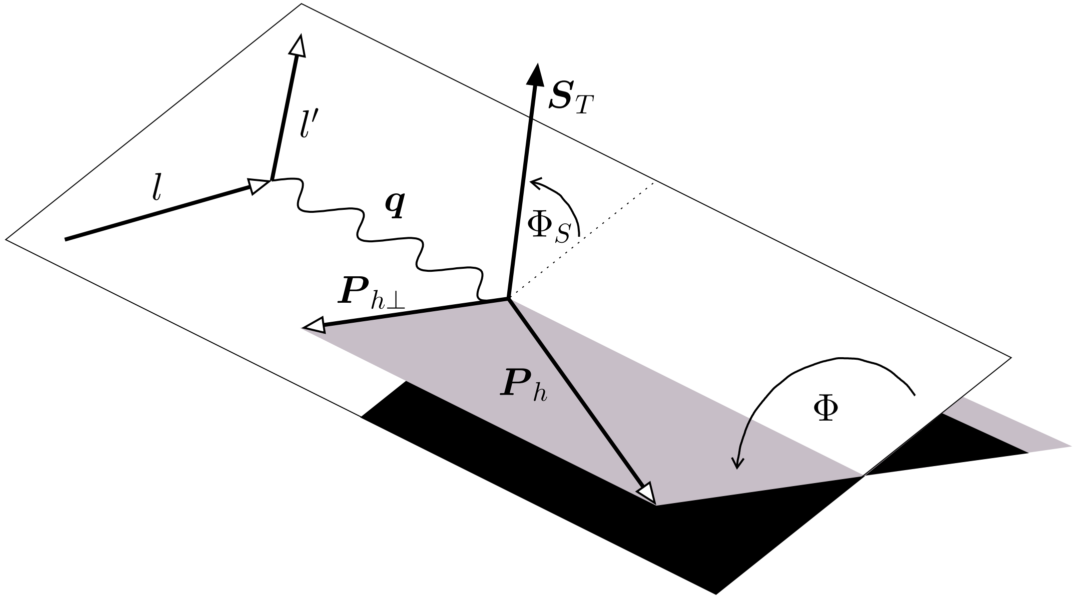
- **Brodsky, Hwang, Schmidt [BHS02]** caused by the interference of scattering amplitudes with different complex phases coupling to the same final state
- **Transverse SSA** related to the interference of scattering amplitudes with different hadron helicities:
  - **[KPR78]** suppressed in hard scattering processes
  - **[BHS02]** caused by initial- or final-state interactions
- **naive-*T*-odd** function with the property to induce SSA

TSSA at HERMES

- two naive-*T*-odd functions at leading twist:
  - Sivers TMD: **Sivers effect** $\mathbf{S}_N\cdot(\mathbf{q}\times\mathbf{P}_h)$
  - Collins FF: **Collins effect** $\mathbf{s}_q\cdot(\mathbf{p}_q\times\mathbf{P}_h)$



Semi-inclusive deep-inelastic scattering (SIDIS)



SIDIS

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

Observable

SIDIS cross section (asymmetry)

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)

Signals for TMD PDFs and TMD FFs

Differential cross section

Cross section decomposition in terms of structure functions

$$\frac{d\sigma^h}{dx\,dy\,d\phi_S\,dz\,d\phi\,d\mathbf{P}_{h\perp}^2} = \frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)$$

$$\Big\{ \Big[F_{\mathrm{UU,T}} + \varepsilon F_{\mathrm{UU,L}} + \sqrt{2\varepsilon(1+\varepsilon)}\cos(\phi)F_{\mathrm{UU}}^{\cos(\phi)} + \varepsilon\cos(2\phi)F_{\mathrm{UU}}^{\cos(2\phi)}\Big]$$

Sivers effect

$$+\ S_T\ \Big[\sin(\phi-\phi_S)\left(F_{\mathrm{UT,T}}^{\sin(\phi-\phi_S)} + \varepsilon F_{\mathrm{UT,L}}^{\sin(\phi-\phi_S)}\right)$$

Collins effect

$$+\varepsilon\sin(\phi+\phi_S)F_{\mathrm{UT}}^{\sin(\phi+\phi_S)} + \varepsilon\sin(3\phi-\phi_S)F_{\mathrm{UT}}^{\sin(3\phi-\phi_S)}$$
$$+\sqrt{2\varepsilon(1+\varepsilon)}\sin(\phi_S)F_{\mathrm{UT}}^{\sin(\phi_S)}$$
$$+\sqrt{2\varepsilon(1+\varepsilon)}\sin(2\phi-\phi_S)F_{\mathrm{UT}}^{\sin(2\phi-\phi_S)}\Big]$$

Factorized results in terms of TMD PDFs and TMD FFs

at tree-level and twist-2 and twist-3 accuracy

Assuming one-photon exchange, current fragmentation only, TMD factorization hold, small transverse momenta, Gaussian Ansatz valid

Sivers TMD and spin-independent FF

$$F_{\mathrm{UT,T}}^{\sin(\phi-\phi_S)} = \mathscr{C}\left[-\frac{\hat{\mathbf{h}}\cdot\mathbf{p}_T}{M}f_{1T}^{\perp}D_1\right]$$

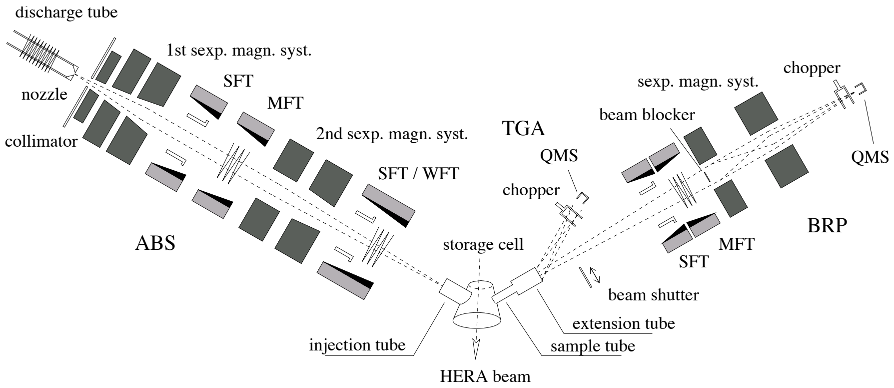
Transversity PDF and Collins FF

$$F_{\mathrm{UT}}^{\sin(\phi+\phi_S)} = \mathscr{C}\left[-\frac{\hat{\mathbf{h}}\cdot\mathbf{k}_T}{M_h}h_1 H_1^{\perp}\right]$$

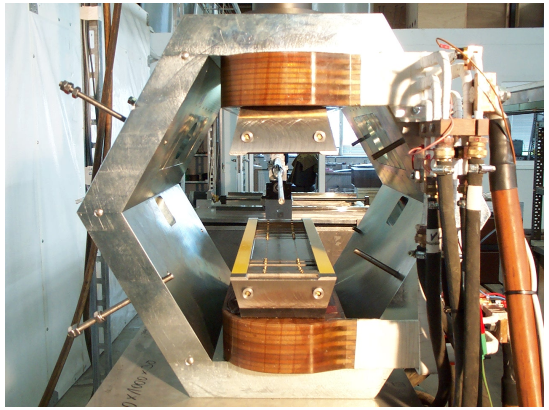
Jefferson Lab

HERMES experiment

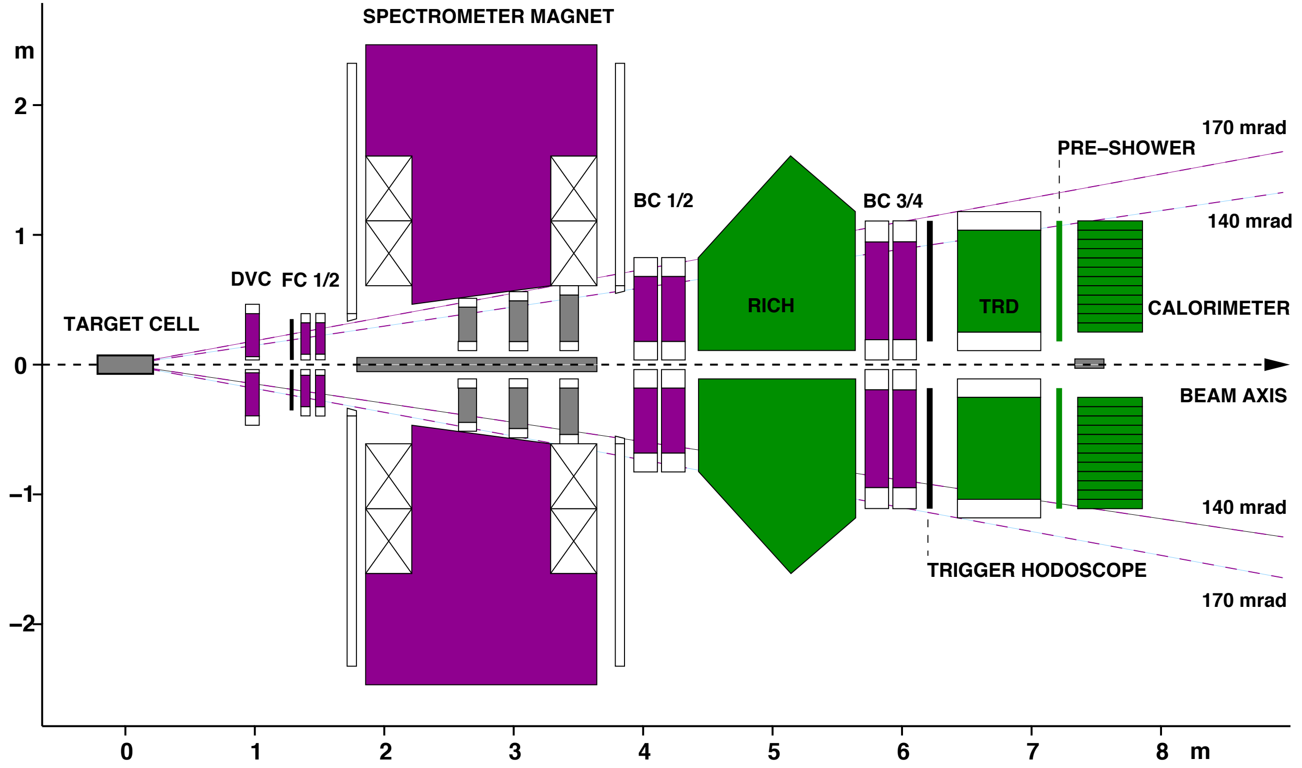
Internal gas target



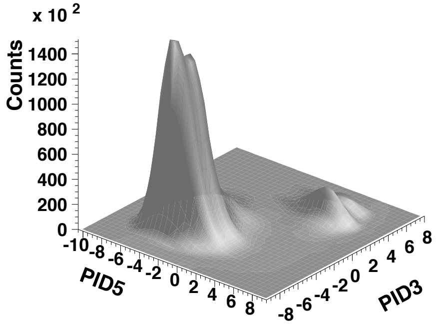
Transverse target magnet

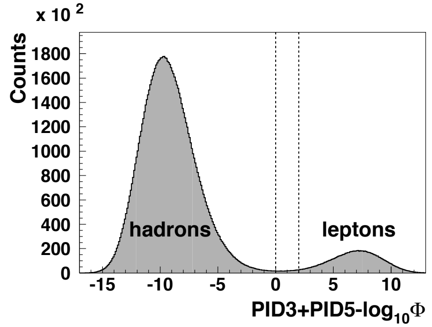


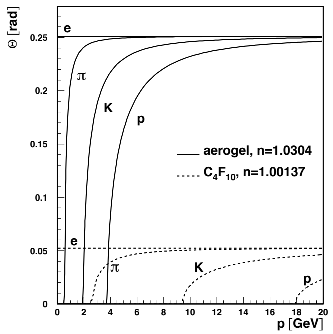
Spectrometer



PID

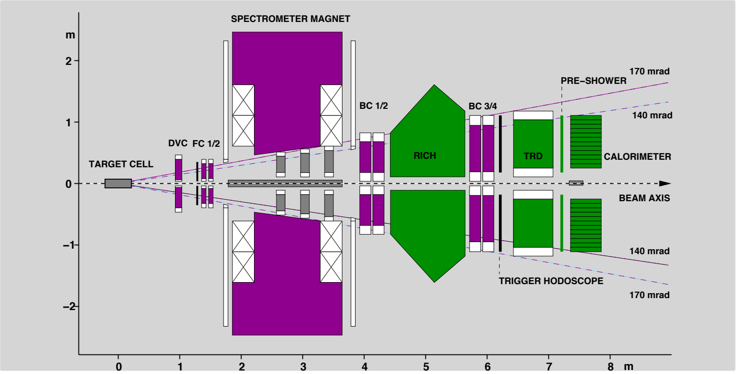


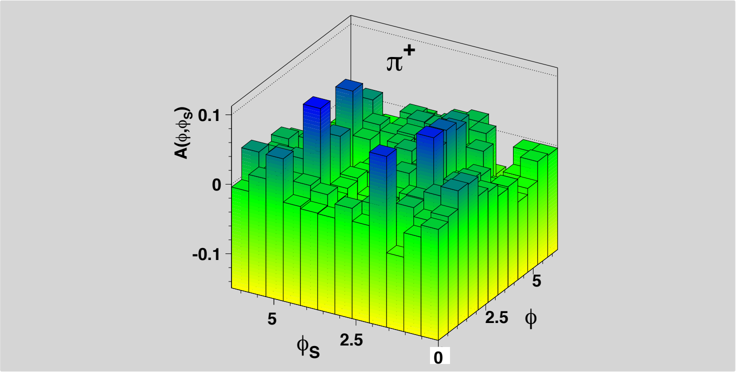




Jefferson Lab

Hermes measurement of TSSA





$$\frac{d\sigma^h}{dx\,dy\,d\phi_S\,dz\,d\phi\,d\mathbf{P}_{h\perp}^2} = \frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)$$
$$\Big\{ \Big[F_{\mathrm{UU,T}}+\varepsilon F_{\mathrm{UU,L}} + \sqrt{2\varepsilon(1+\varepsilon)}\cos(\phi)F_{\mathrm{UU}}^{\cos(\phi)} + \varepsilon\cos(2\phi)F_{\mathrm{UU}}^{\cos(2\phi)}\Big]$$
$$+\; S_T \Big[\sin(\phi-\phi_S)\left(F_{\mathrm{UT,T}}^{\sin(\phi-\phi_S)}+\varepsilon F_{\mathrm{UT,L}}^{\sin(\phi-\phi_S)}\right) + \varepsilon\sin(\phi+\phi_S)F_{\mathrm{UT}}^{\sin(\phi+\phi_S)} + \varepsilon\sin(3\phi-\phi_S)F_{\mathrm{UT}}^{\sin(3\phi-\phi_S)} + \sqrt{2\varepsilon(1+\varepsilon)}\sin(\phi_S)F_{\mathrm{UT}}^{\sin(\phi_S)} + \sqrt{2\varepsilon(1+\varepsilon)}\sin(2\phi-\phi_S)F_{\mathrm{UT}}^{\sin(2\phi-\phi_S)}\Big]$$

Measurement of SIDIS

- **transversely polarized proton target**
- detect π-mesons and charged K-mesons in coincidence with scattered lepton in:

$$0.023 < x < 0.4, \quad 0.2 < z < 0.7, \quad 0.0\,\mathrm{GeV} < |\mathbf{P}_{h\perp}| < 2.0\,\mathrm{GeV}$$

Measurement of SSA

- HERMES was designed to measure cross section asymmetries not absolute cross sections

$$A^h_{\mathrm{U}\perp}(\phi,\phi_S) = \frac{1}{|S_\perp|}\frac{L_{\Downarrow}N^h_{\Uparrow}(\phi,\phi_S) - L_{\Uparrow}N^h_{\Downarrow}(\phi,\phi_S)}{L_{\Downarrow}N^h_{\Uparrow}(\phi,\phi_S) + L_{\Uparrow}N^h_{\Downarrow}(\phi,\phi_S)}$$

Fourier decomposition of SSA

$$\mathscr{L}\left(2\langle\sin(\phi-\phi_S)\rangle^h_{\mathrm{U}\perp}\right) = \prod_{n=1}^{N^h} P(x_n, Q^2_n, z_n, P_{h\perp,n}, \phi_n, \phi_{S,n}; 2\langle\sin(\phi-\phi_S)\rangle^h_{\mathrm{U}\perp})$$

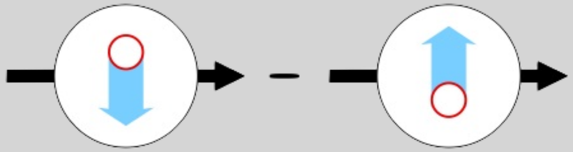
HERMES results on Sivers effect

PRL103 (2009) 152002

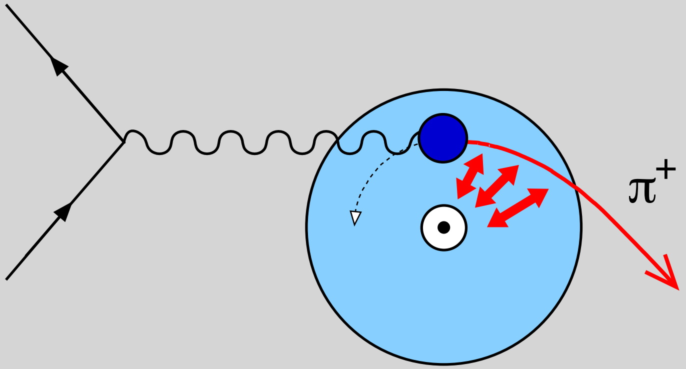
SSA amplitude

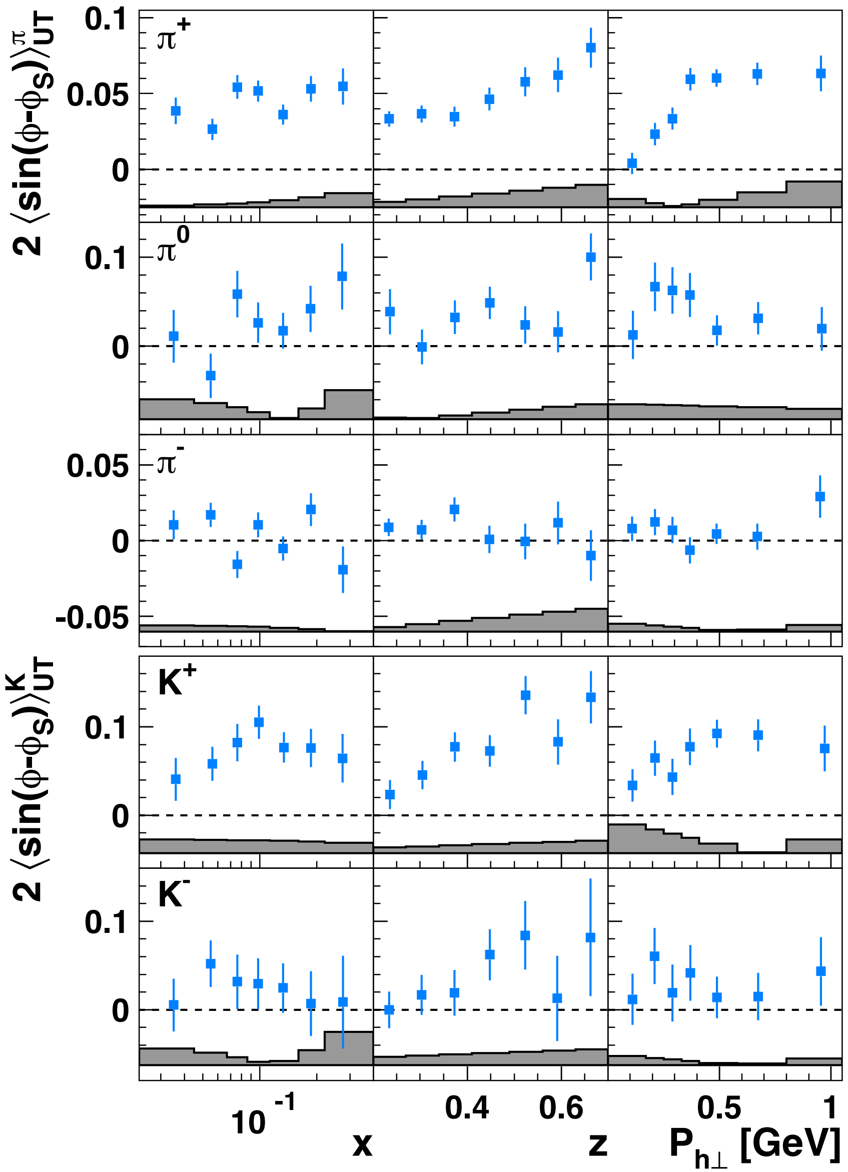
$$2\left\langle \sin(\phi-\phi_S)\right\rangle_{\mathrm{UT}}^{h} = -\frac{\mathscr{C}\left[\frac{\hat{\mathbf{h}}\cdot\mathbf{p}_T}{M} f_{1T}^{\perp,q}\left(x,\mathbf{p}_T^2\right) D_1^q\left(z,z^2\mathbf{k}_T^2\right)\right]}{\mathscr{C}\left[f_1^q\left(x,\mathbf{p}_T^2\right) D_1^q\left(z,z^2\mathbf{k}_T^2\right)\right]}$$

Sivers TMD



Semi-classical picture





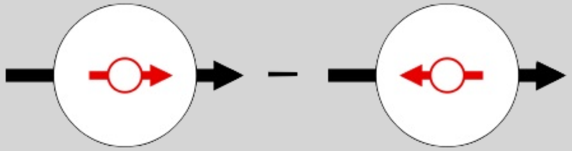
HERMES results on Collins effect

JHEP 0806 (2008) 017

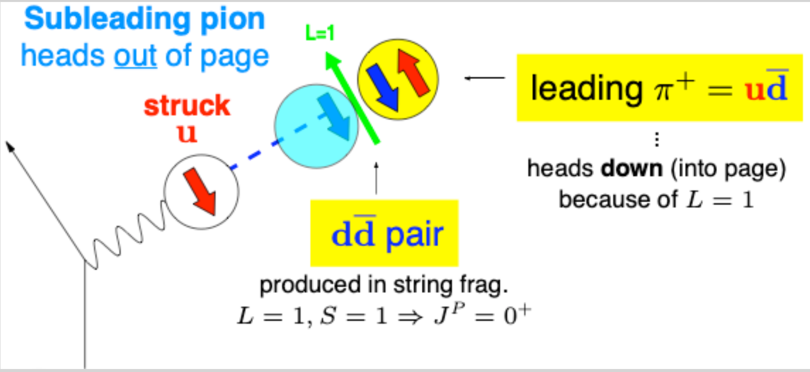
SSA amplitude

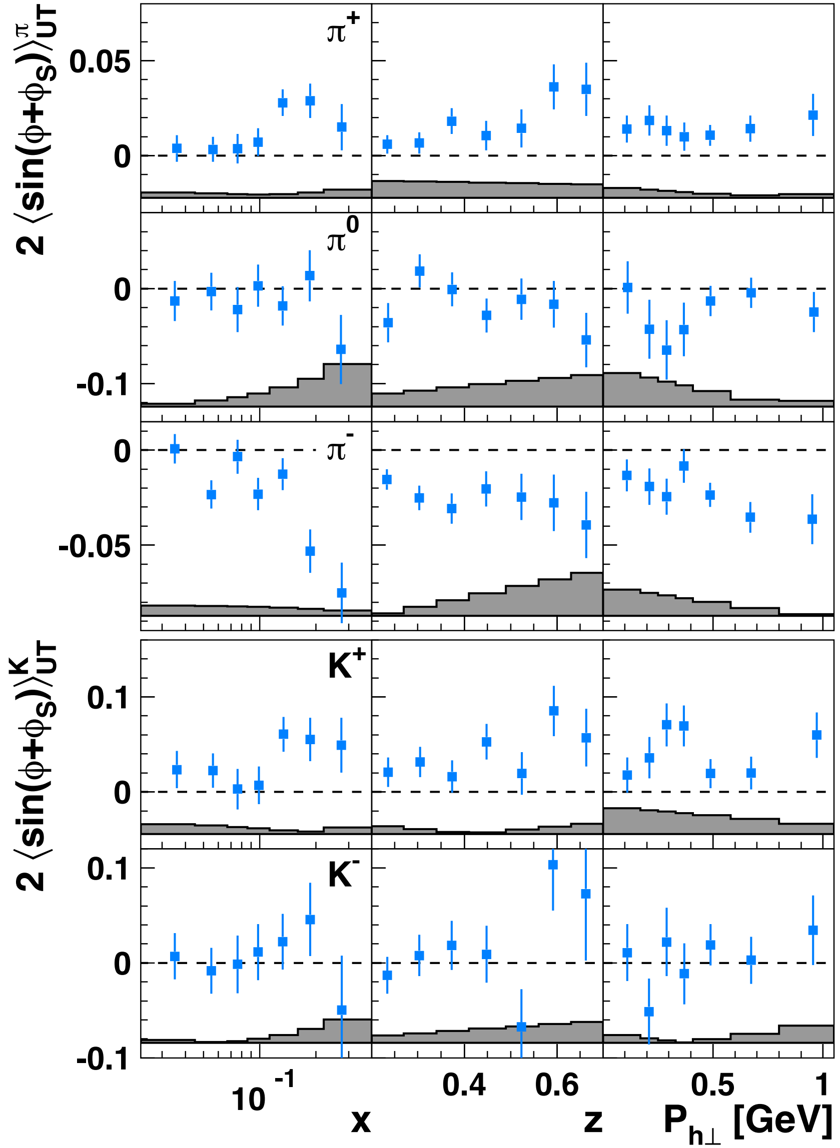
$$2\langle\sin(\phi+\phi_S)\rangle^h_{\mathrm{UT}} = \frac{\mathscr{C}\left[-\frac{\hat{\mathbf{h}}\cdot\mathbf{k}_T}{M_h} h_1^q\left(x,\mathbf{p}_T^2\right) H_1^{\perp,q}\left(z,z^2\mathbf{k}_T^2\right)\right]}{\mathscr{C}\left[f_1^q\left(x,\mathbf{p}_T^2\right) D_1^q\left(z,z^2\mathbf{k}_T^2\right)\right]}$$

Transversity PDF

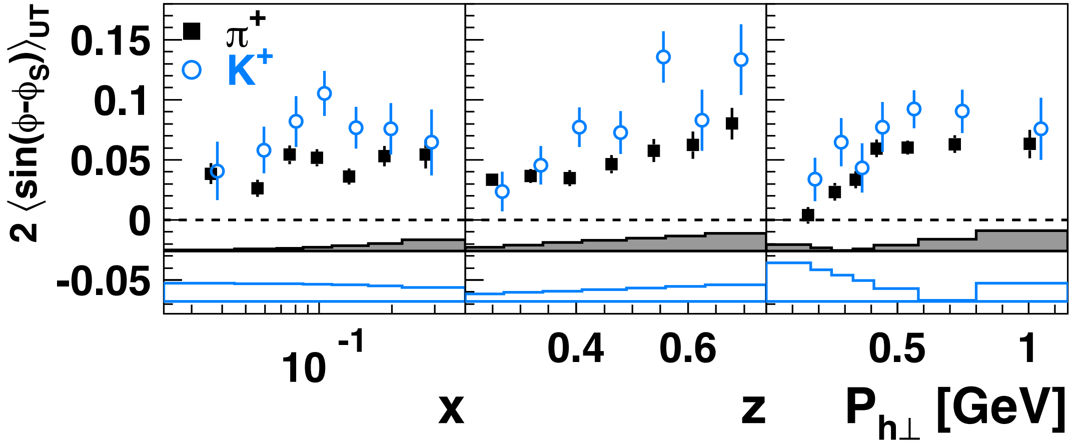


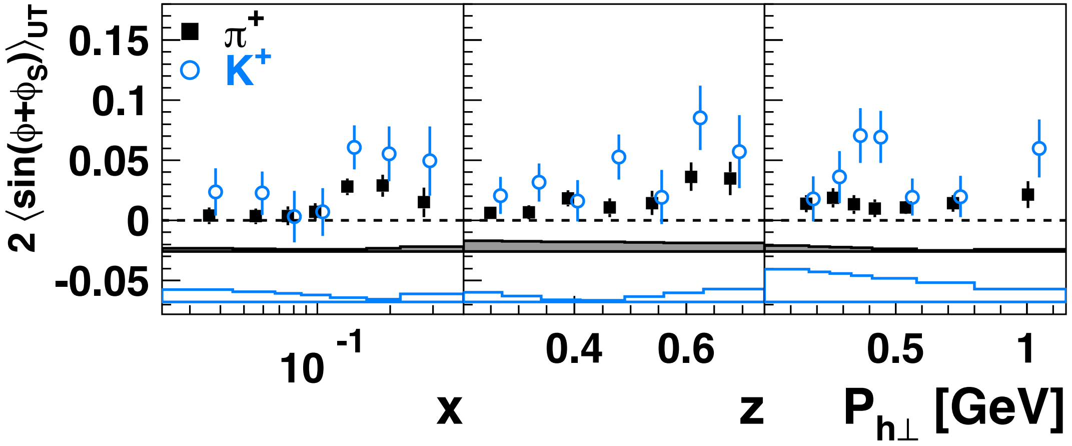
Lund model and $^3P_0$ hypothesis

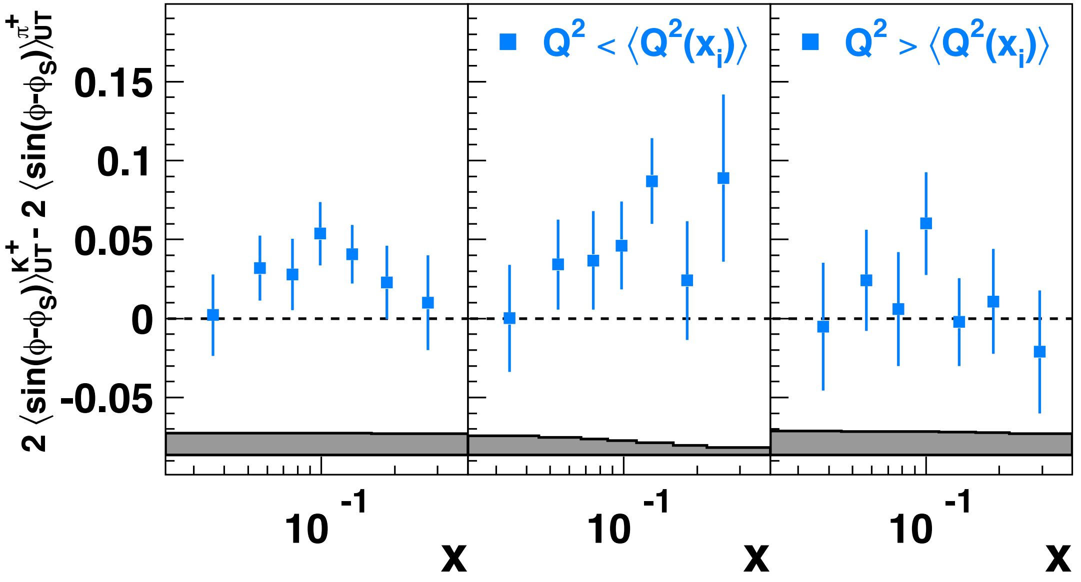


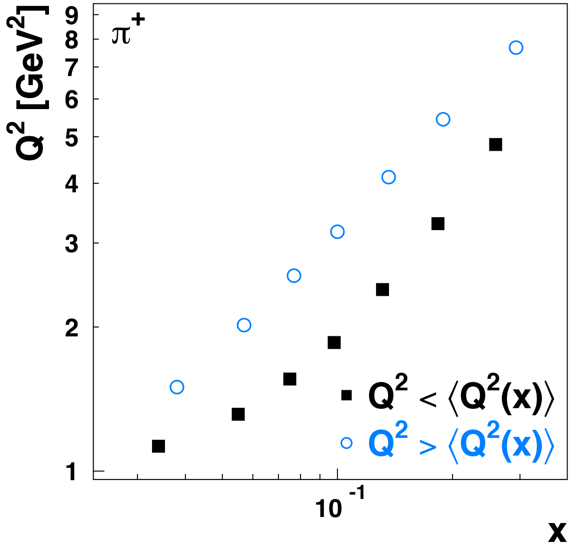


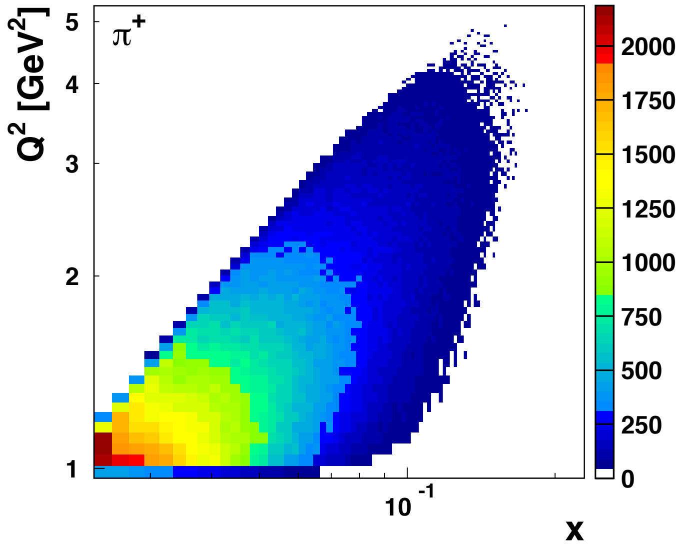
The picture of u-quark dominance and the role of higher twist



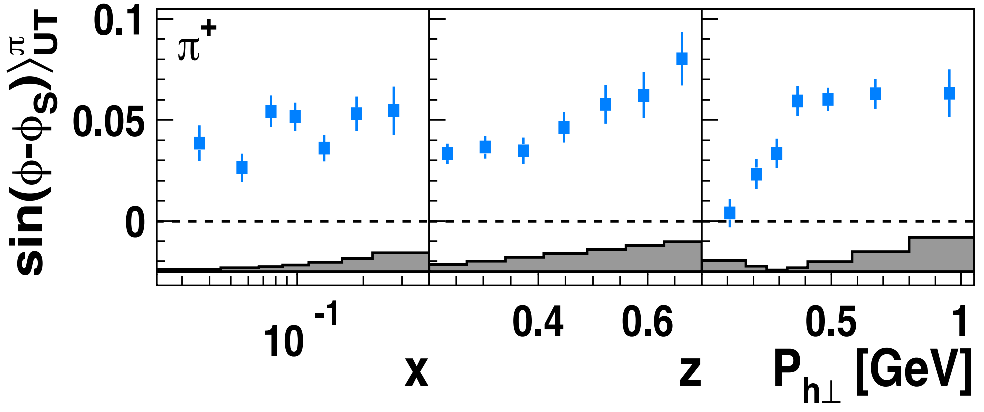


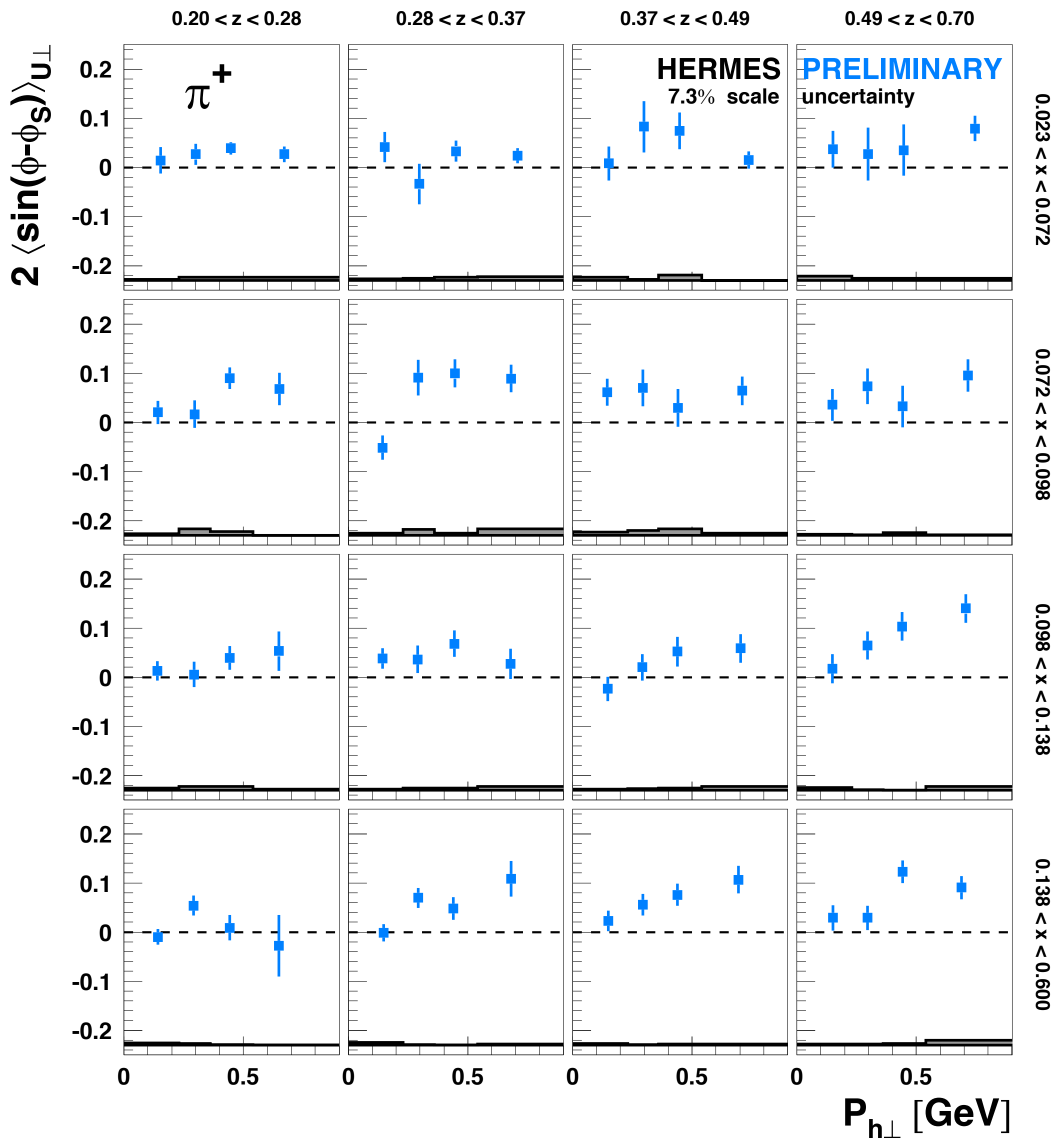






Multi-dimensional analysis



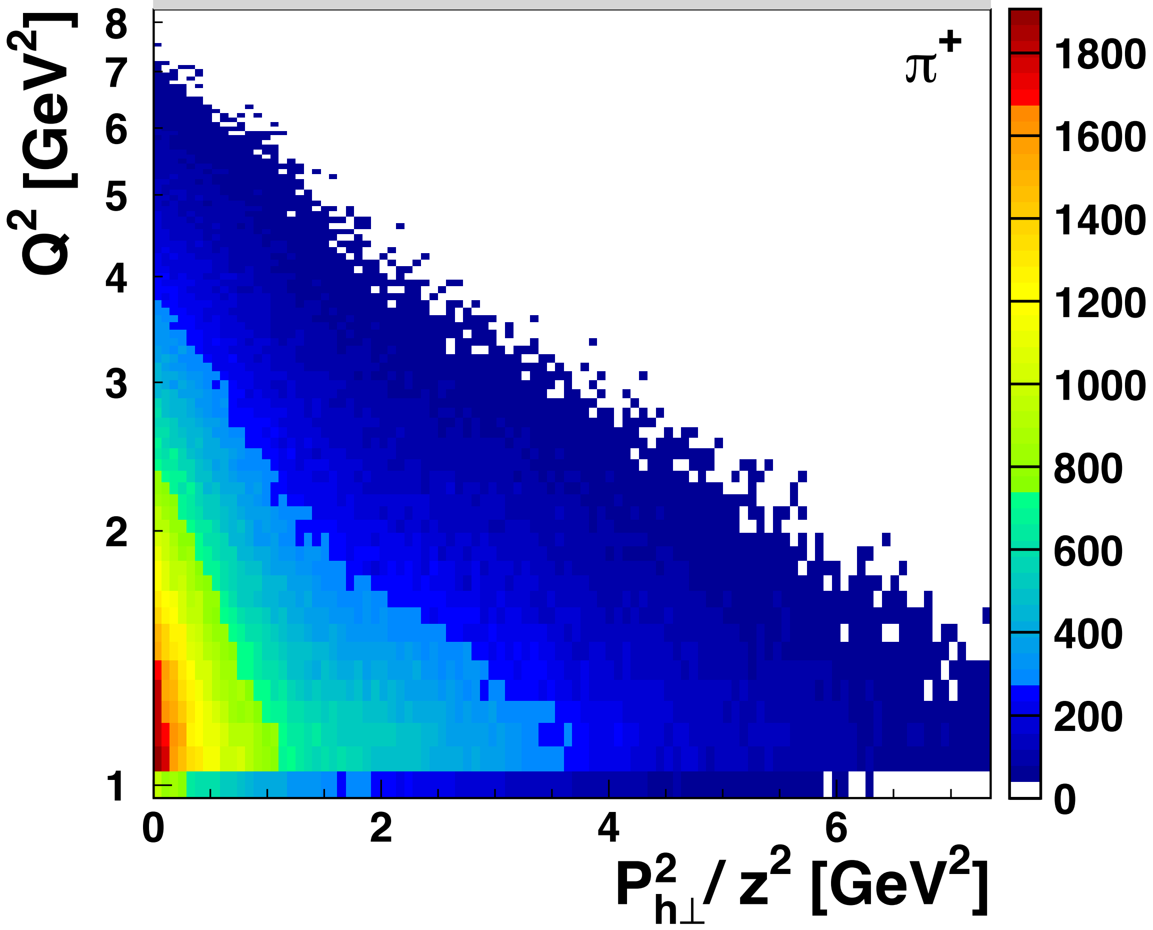


Goal: Fully differential approach with small bin-sizes (similar to this analysis):

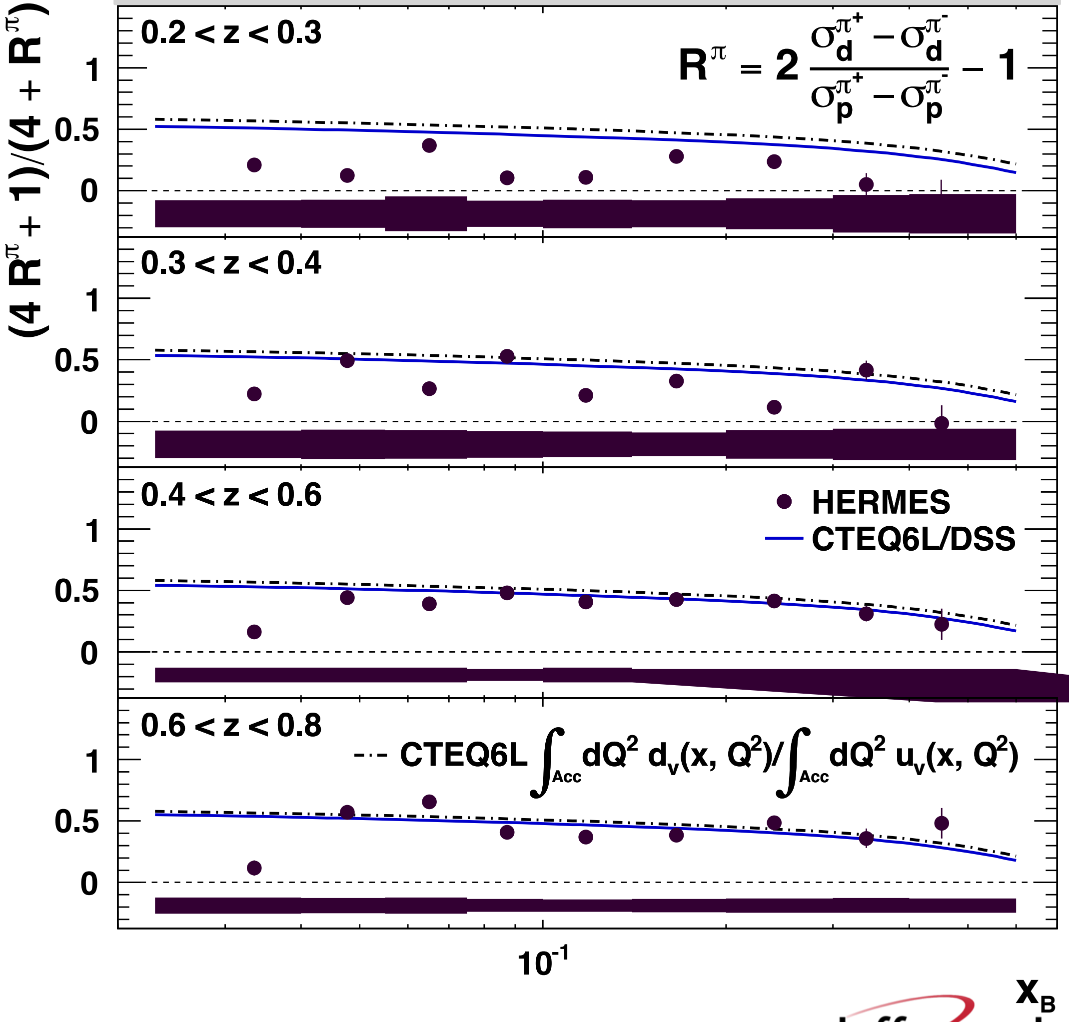
- minimizes the dominant contributions to the systematic uncertainty, and therefore maximizes the attainable experimental precision
- maximize information for QCD analysis

Factorization scales and breaking

TMD factorization partonic scale << hard-scattering scale



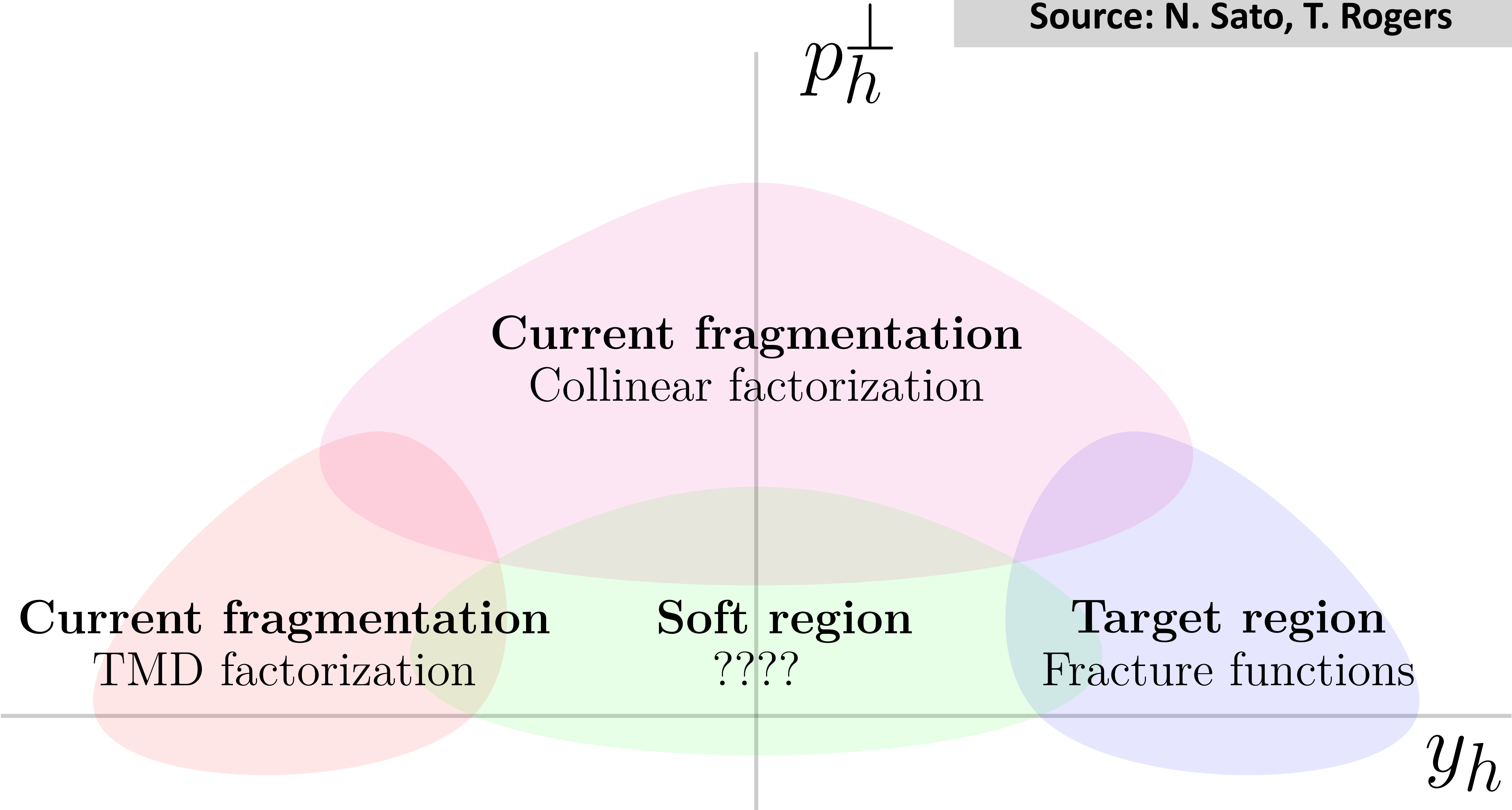
HERMES multiplicities from unpolarized SIDIS sample



Jefferson Lab

Exploring SIDIS regions

Source: N. Sato, T. Rogers



Exploring the nature of matter

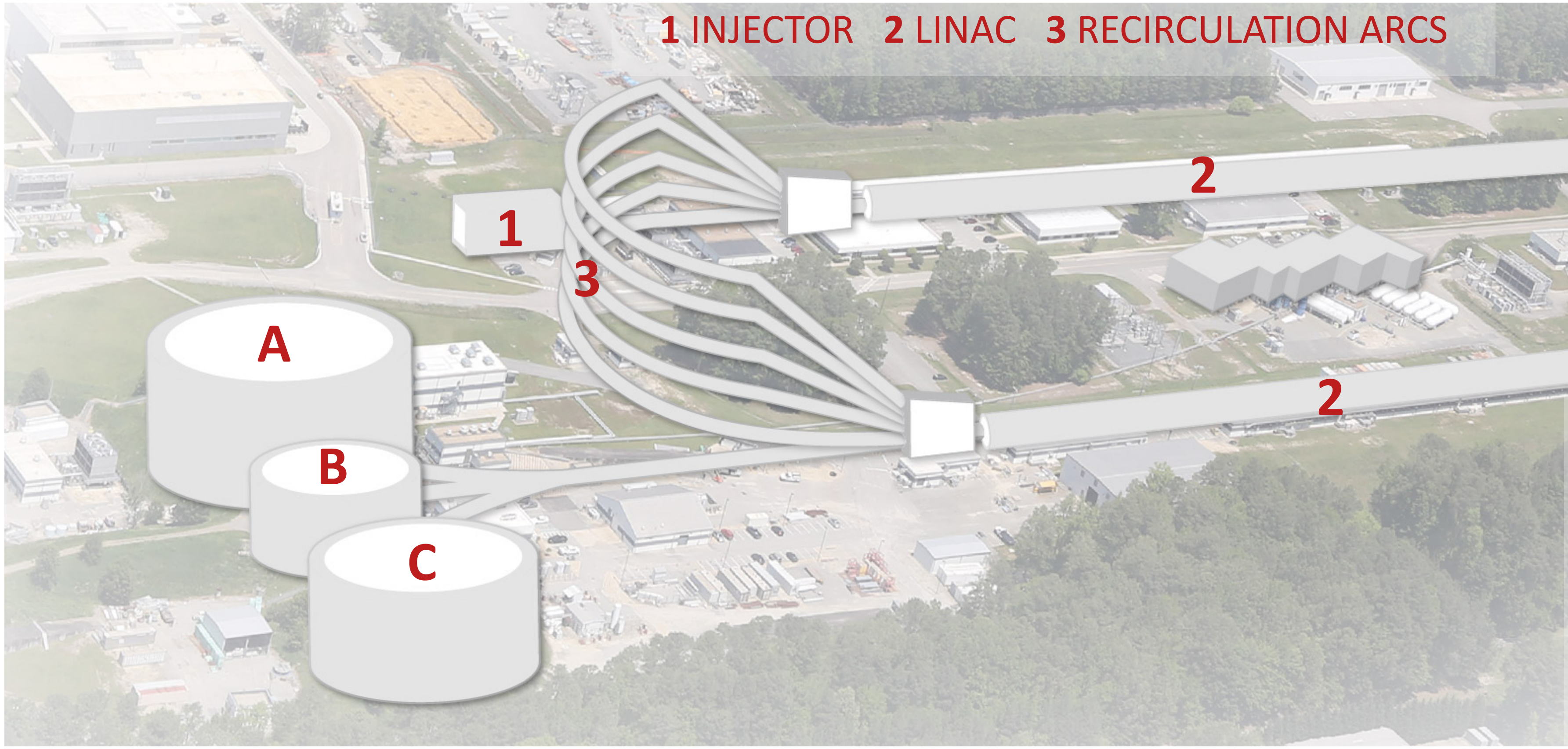
The 12 GeV Science Program at Jefferson Lab

Exploring the nature of matter

Thomas Jefferson National Accelerator Facility is a U.S. Department of Energy Office of Science national laboratory.

Jefferson Lab's unique and exciting mission is to expand humankind's knowledge of the universe by **studying the fundamental building blocks of matter** within the nucleus: subatomic particles known as **quarks and gluons**.

CEBAF at Jefferson Lab



CEBAF upgrade

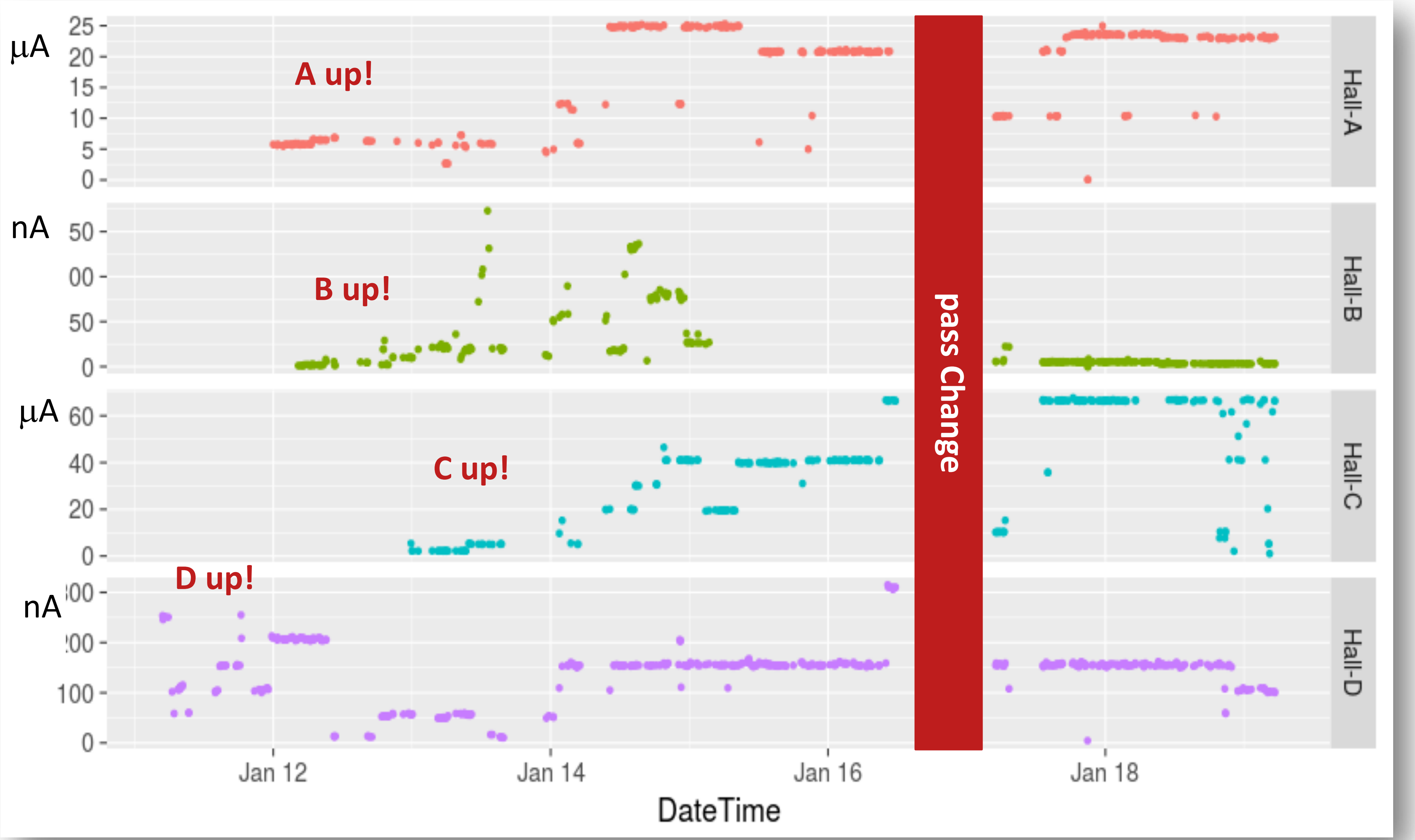
- completed in 09/2017
- CW electron beam
- E_{max} = 12 GeV
- I_{max} = 90 mA
- Pol_{max} = 90%

CEBAF

- ultra-high luminosities: up to 10^{39} electrons-nucleons /cm^2/ s
- world-record polarized electron beams
- highest intensity tagged photon beam at 9 GeV
- versatile: deliver range of beam energies and currents to multiple halls simultaneously

Jefferson Lab

Simultaneous Hall operation



Jefferson Lab

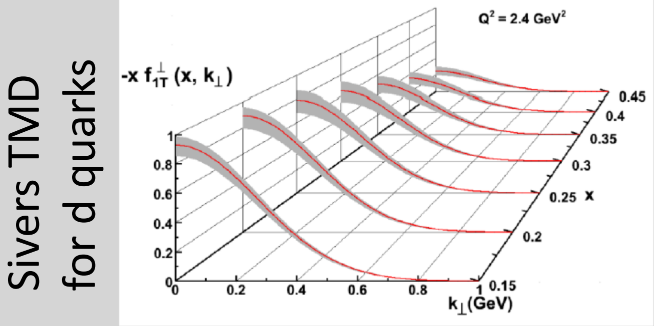
Approved experiments of the 12 GeV Science Program

Topic	Hall A	Hall B	Hall C	Hall D	Other	Total
The Hadron spectra as probes of QCD	0	2	1	3	0	**6**
The transverse structure of the hadrons	**6**	**3**	**3**	**1**	**0**	**13**
The longitudinal structure of the hadrons	**2**	**3**	**6**	**0**	**0**	**11**
The 3D structure of the hadrons	**5**	**9**	**6**	**0**	**0**	**20**
Hadrons and cold nuclear matter	8	5	7	0	1	**21**
Low-energy tests of the Standard Model and Fundamental Symmetries	3	1	0	1	2	**7**
Total	**24**	**23**	**23**	**5**	**3**	**78**

TMD studies at the 12 GeV Science Program

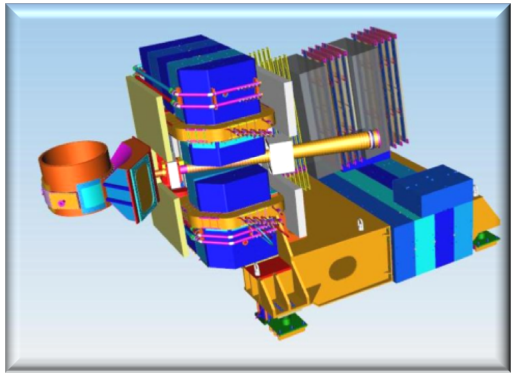
Goal

- Precision in 3D imaging in (space and) momentum for x > 0.1 (valence quark region)



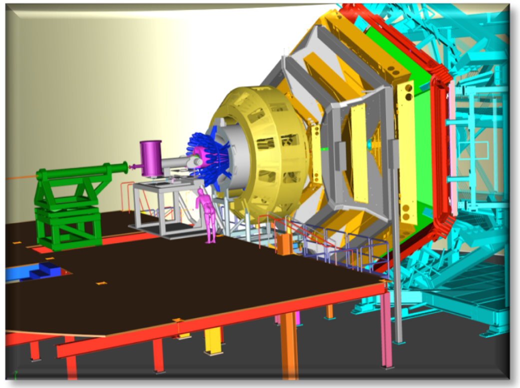
Experimental techniques enabling TMD experiments

- high luminosity
- polarized beams
- polarized targets
- large acceptance experiments with good PID capabilities



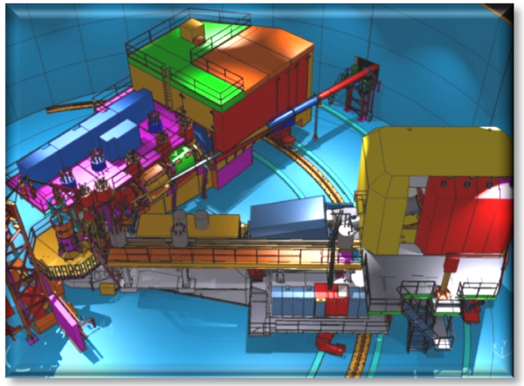
Hall A

Super Bigbite Spectrometer (SBS): dedicated large-*x* TMD study with medium acceptance and high luminosity



Hall B

CEBAF Large Acceptance Spectrometer (CLAS12): general survey experiments, large acceptance and medium luminosity



Hall C

HMS, SHMS, and Neutral-Particle Spectrometer (NPS): precision cross sections for L-T studies and ratios, small acceptance and high luminosity

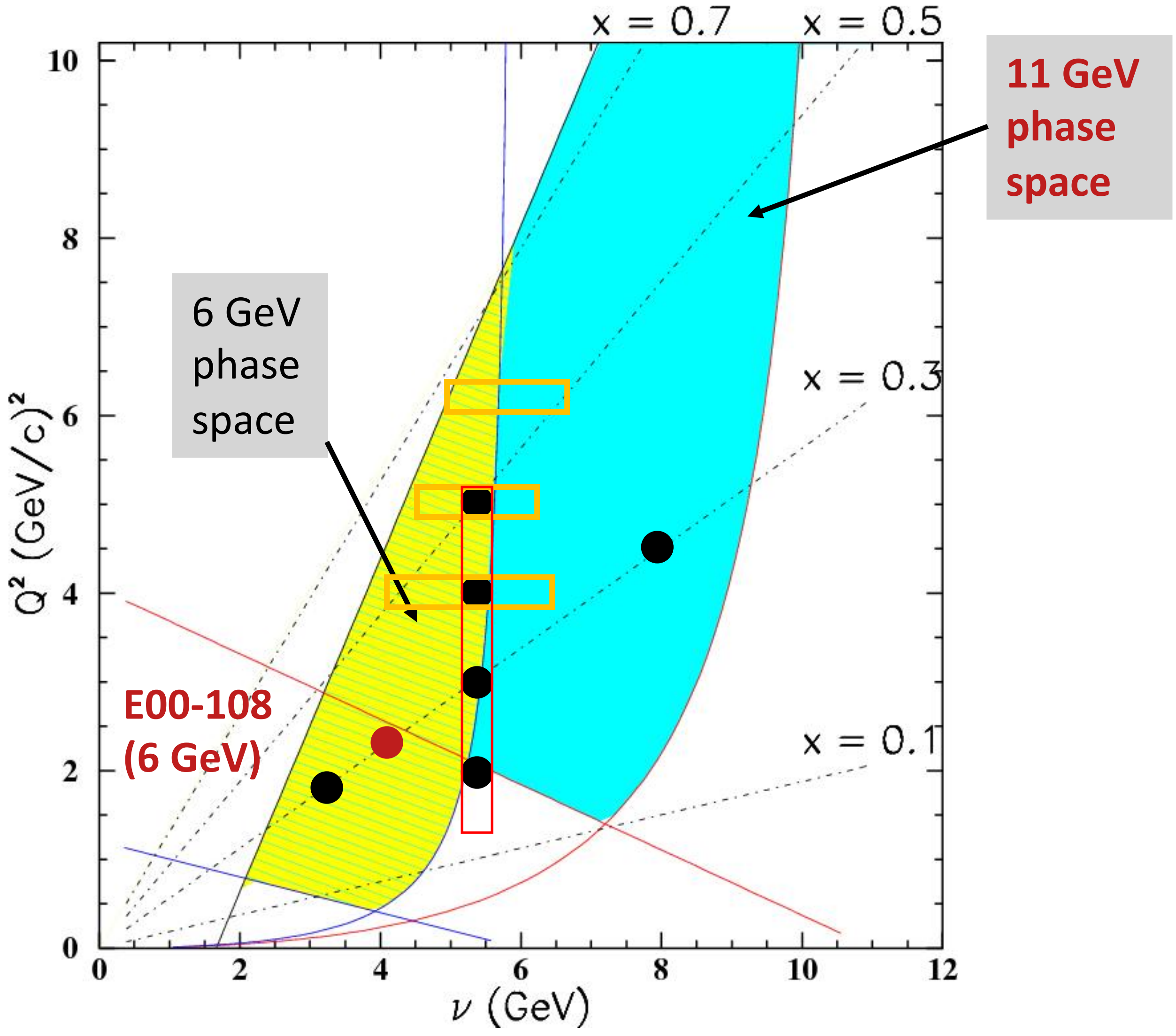
Hall C SIDIS Program (HMS+SHMS)

Accurate cross section measurements for

- validation of SIDIS factorization framework
- L/T separations

Experiments Spring / Fall 2018

- ● E12-09-017 Scan in (x,z,P_T) + scan in Q^2 at fixed x
- ▭ E12-09-002 + scans in z
- ▯ E12-06-104 L/T scan in (z,P_T)

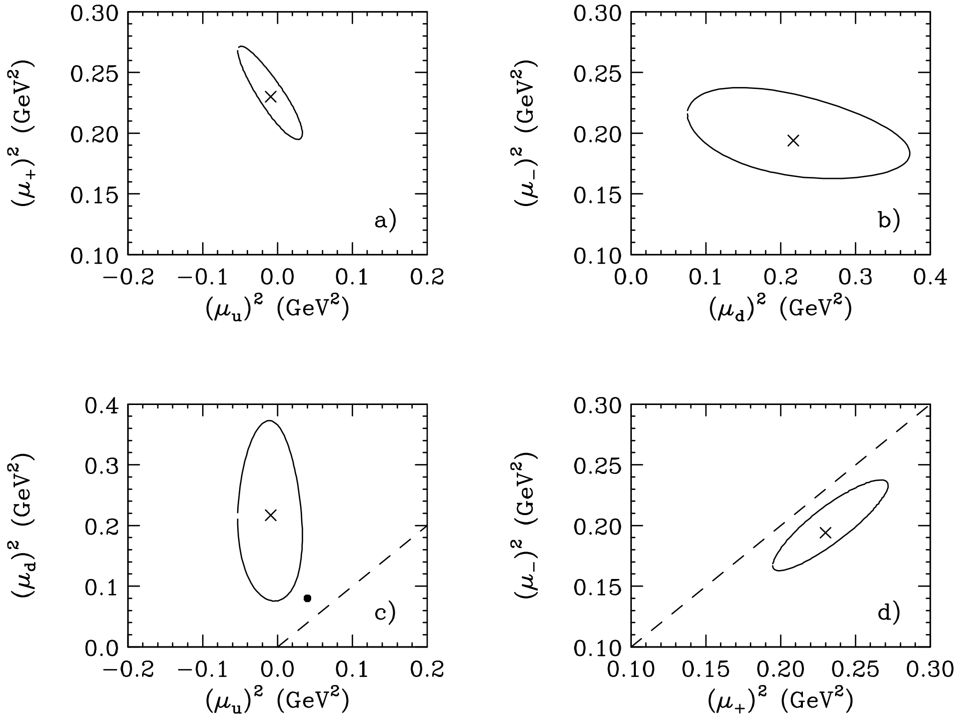


E12-09-017: Transverse Momentum Dependence of Semi-Inclusive Pion Production

Experiment goal Extract information about transverse distribution of quarks by measuring π^+/π^- cross sections and ratios from LH2 and LD2
→ Need to make measurements over a range of transverse momentum at fixed x and Q^2

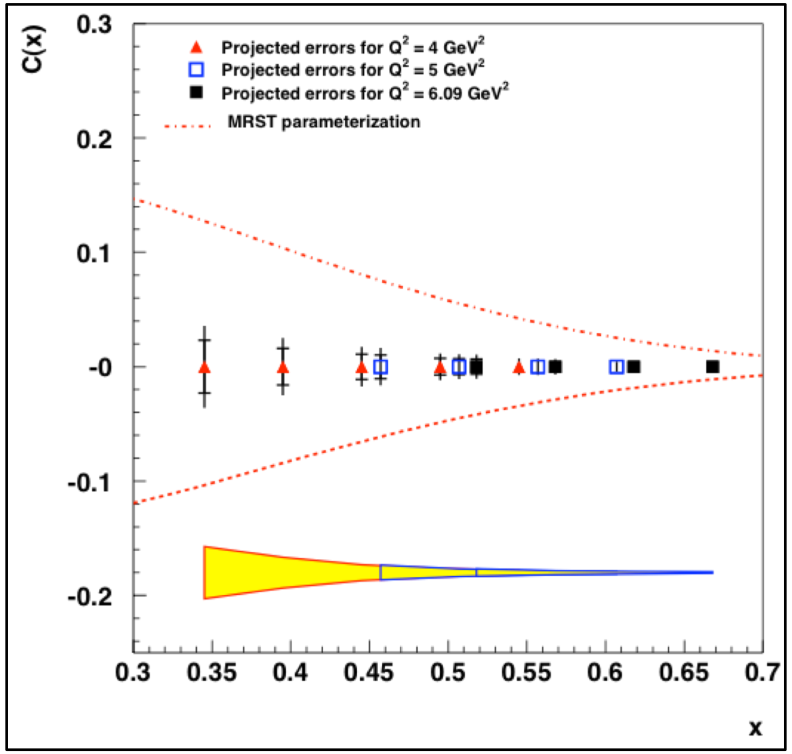
- Ran for about 28 days in Spring 2018
- Ran for another 2 weeks in Fall 2018 to complete experiment

Kinematics:
1. $x=0.31$, $Q^2=3.1$ GeV^2
   → $z=0.9-0.45$ at $P_T=0$, $P_T=0-0.6$ at $z=0.35$
2. $x=0.3$, $Q^2=4.1$ GeV^2
   → $z=0.9-0.45$ at $P_T=0$, $P_T=0-0.6$ at $z=0.35$
3. $x=0.45$, $Q^2=4.5$ GeV^2
   → $z=0.9-0.45$ at $P_T=0$, $P_T=0-0.6$ at $z=0.35$



Results from Hall C 6 GeV data

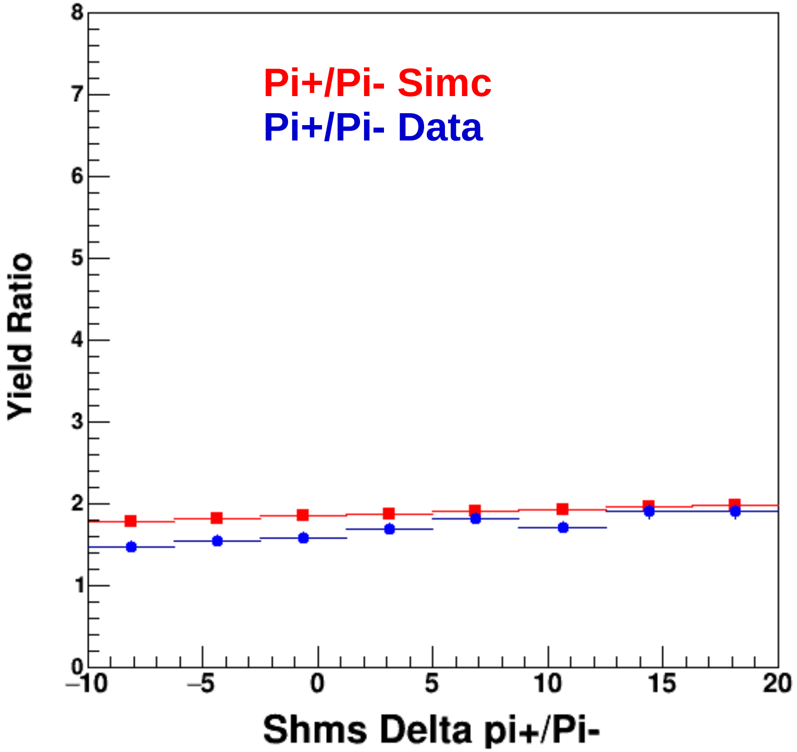
E12-09-002: Charge Symmetry Violating Quark Distributions via π^+/π^- in SIDIS



Experiment goal: place constraints on charge symmetry violation in quark distributions using by making precise measurements of π^+/π^- ratios from LD2

Fall 2018 Ran for 19 days, finished measurements at 2 lowest Q^2 values
Spring 2019: Will run for another 15 days to finish largest Q^2

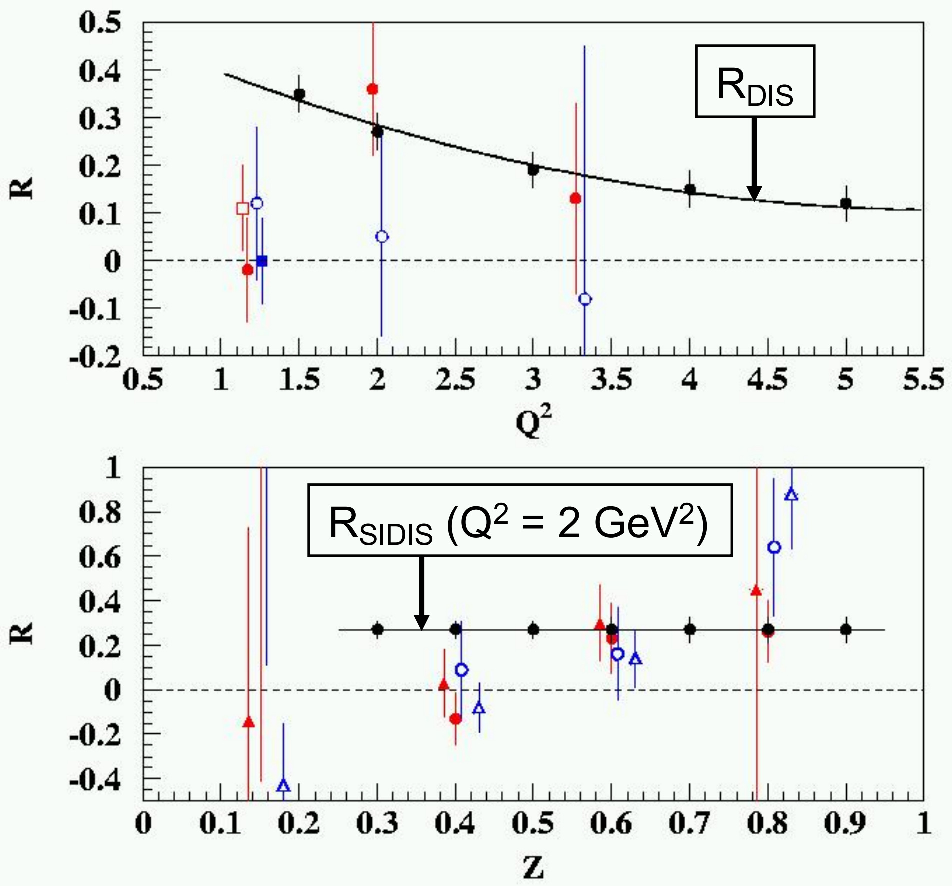
Piplus_Piminus_Ratio_Delta



Kinematics: $P_T \sim 0$ ***z=0.4, 0.5, 0.6, and 0.7***
$Q^2 = 4.0$ GeV^2 *x=0.35, 0.40, 0.45, 0.50*
$Q^2 = 4.75$ GeV^2 *x=0.45, 0.50, 0.55, 0.60*
$Q^2 = 5.5$ GeV^2 *x=0.50, 0.55, 0.60, 0.65*

Raw, barely offline ratios
- 1 out 8 settings taken in Fall 2018
- roughly consistent with MC expectation

$R = \sigma_L/\sigma_T$ in SIDIS



R_{DIS}

- R_{DIS} is in the naïve parton model related to the parton's transverse momentum:

$$R = 4(M^2x^2 + \langle k_T^2\rangle)/(Q^2 + 2\langle k_T^2\rangle)$$

- $R_{DIS} \rightarrow 0$ at $Q^2 \rightarrow \infty$ is a consequence of scattering from free spin-½ constituents

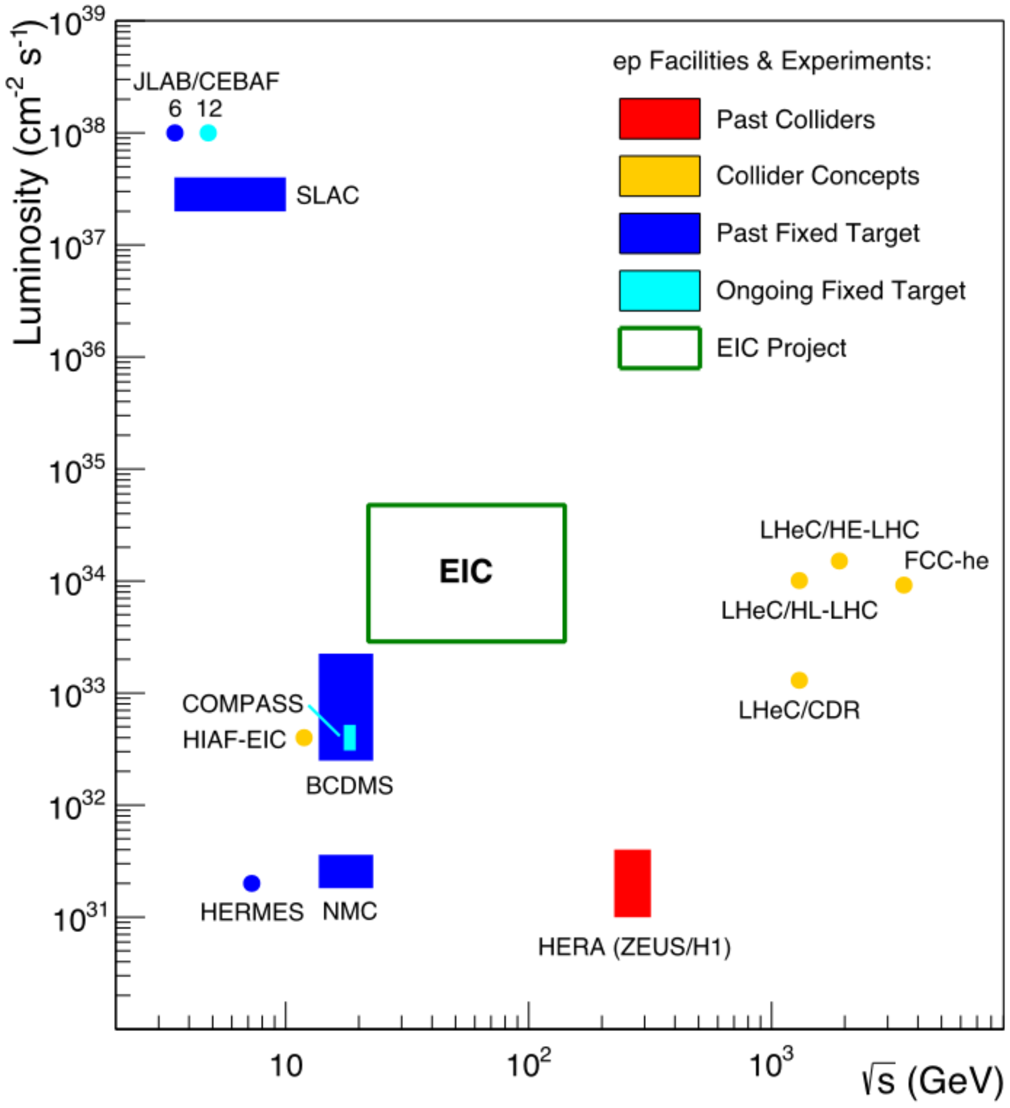
R_{SIDIS}

- knowledge on R_{SIDIS} is non-existing
- R_{SIDIS} may vary with z and with p_T
- knowledge on R_{SIDIS} needed for any TMD-related measurement, requirement for TMD program at EIC

A new frontier in Nuclear Physics

The Electron-Ion Collider Project

The Electron-Ion Collider (EIC)



Frontier accelerator facility in the U.S.

World's first collider of

- polarized electrons and polarized protons/light ions (d, ^{3}He)
- electrons and nuclei

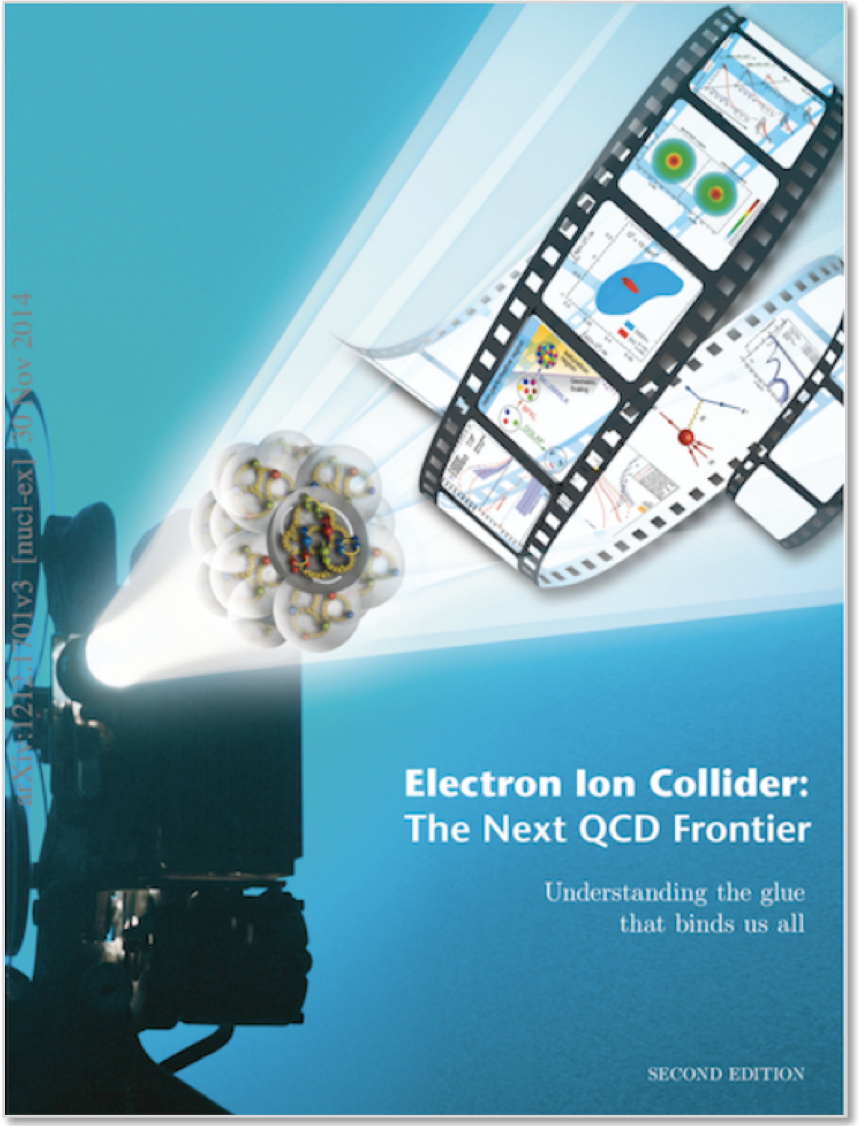
Versatile range of

- beam energies: $\sqrt{s_{ep}}$ range ~20 to ~100 GeV upgradable to ~140 GeV
- beam polarizations for electrons, protons and light ions (longitudinal, transverse, tensor), at least ~70% polarization
- ion beam species: D to heaviest stable nuclei

High luminosity

- 100 to 1000 times HERA luminosity

EIC White Paper



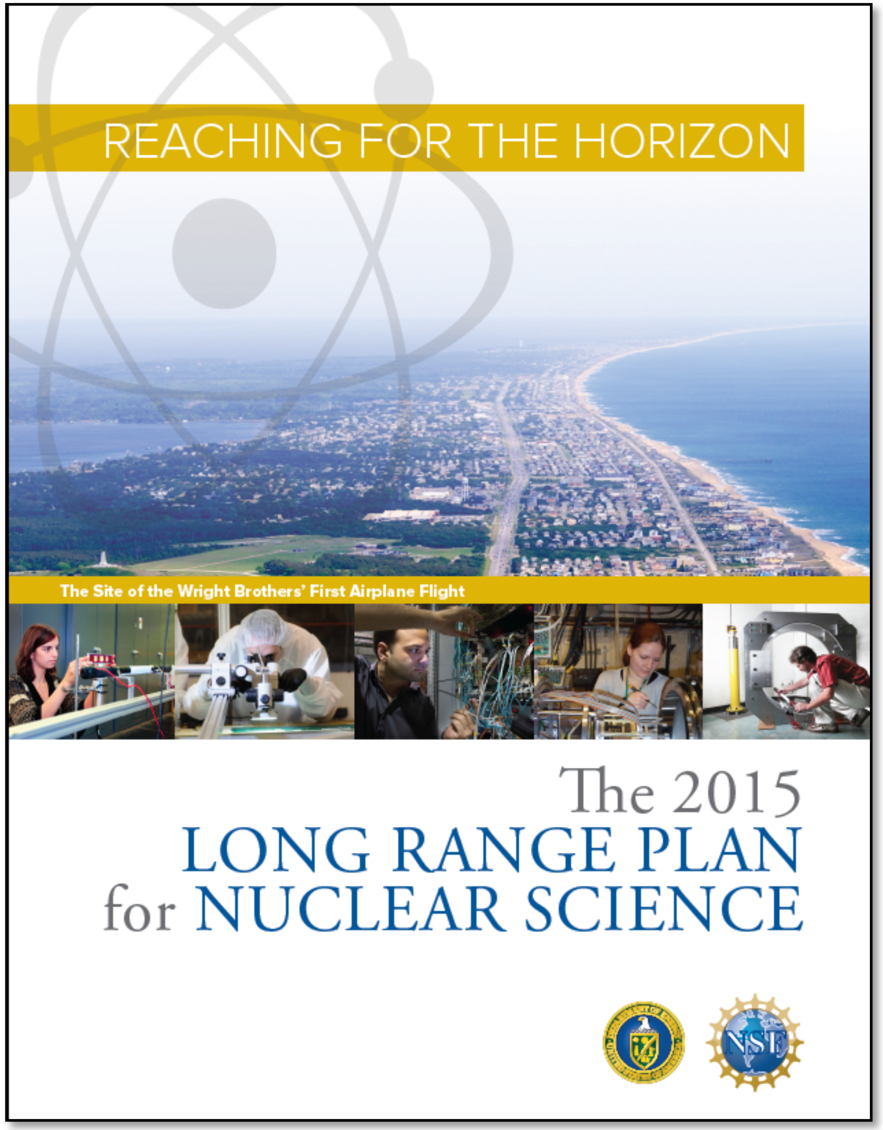
A **white paper** is an authoritative report or guide that informs readers concisely about a complex issue and presents the issuing body's philosophy on the matter.

Spin and Three-Dimensional Structure of the Nucleon
The Longitudinal Spin of the Nucleon
Confined Motion of Partons in Nucleons: TMDs
Spatial Imaging of Quarks and Gluons: GPDs

The Nucleus: A Laboratory for QCD
Physics of High Gluon Densities in Nuclei
Quarks and Gluons in the Nucleus
Connections to pA, AA and Cosmic Ray Physics

Possibilities at the Luminosity Frontier:
Physics Beyond the Standard Model

2015 Nuclear Science Long-Range Plan



1. **The highest priority in this 2015 Plan is to capitalize on the investments made.**
   - **12 GeV** – unfold quark & gluon structure of hadrons and nuclei
   - **FRIB** – understanding of nuclei and their role in the cosmos
   - **Fundamental Symmetries Initiative** – physics beyond the SM
   - **RHIC** – properties and phases of quark and gluon matter
2. We recommend the timely development and deployment of a U.S.-led ton-scale neutrinoless double beta decay experiment.
3. **We recommend a high-energy high-luminosity polarized Electron Ion Collider as the highest priority for new facility construction following the completion of FRIB.**
4. We recommend increasing investment in small and mid-scale projects and initiatives that enable forefront research at universities and laboratories.

NAS: EIC Science Assessment

THE NATIONAL ACADEMIES OF SCIENCES, ENGINEERING, AND MEDICINE
next formal step on EIC science case (before CD0)

NAS committee

Ani Aprahamian, Co-Chair (University of Notre Dame)
Gordon Baym, Co-Chair (U. Illinois at Urbana-Champaign)
Christine Aidala (University of Michigan)
Richard Milner (MIT)
Ernst Sichtermann (LBNL)
Zein-Eddine Meziani (Temple University)
Thomas Schaefer (NC State University)
Michael Turner (University of Chicago)
Wick Haxton (University of California-Berkeley)
Kawtar Hafidi (Argonne)
Peter Braun-Munzinger (GSI)
Larry McLerran (University of Washington)
Haiyan Gao (Duke)
John Jowett (CERN)

Meetings in Feb., Apr., Sept. 2017
Report released in July 2018

NAS charge

1 What is the **merit and significance of the science** that could be addressed by an EIC facility and what is its **importance in the overall context of research in nuclear physics** and the physical sciences in general?

2 What are the **capabilities of other facilities, existing and planned, domestic and abroad**, to address the science opportunities afforded by an EIC? What **unique scientific role** could be played by a domestic EIC that is complementary to existing and planned facilities at home and abroad?

3 What are the **benefits of US leadership** in nuclear physics if a domestic EIC were constructed?

4 What are the **benefits to other fields of science and to society** of establishing such a facility in the US?

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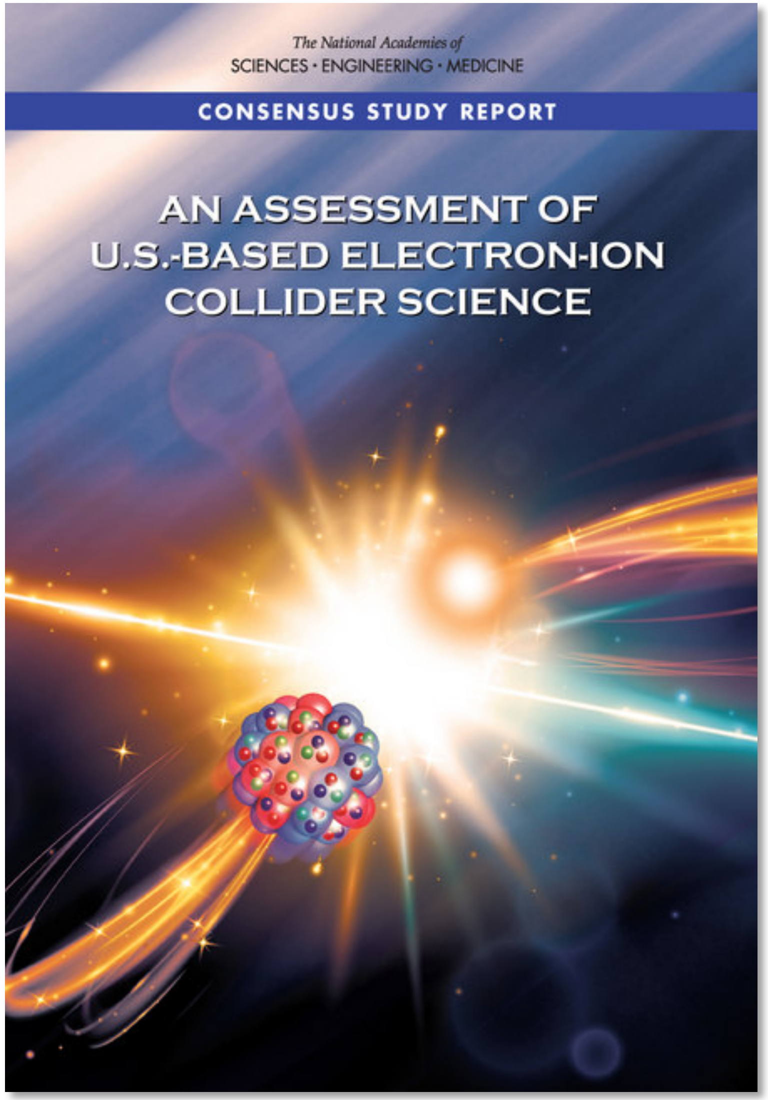
NAS report

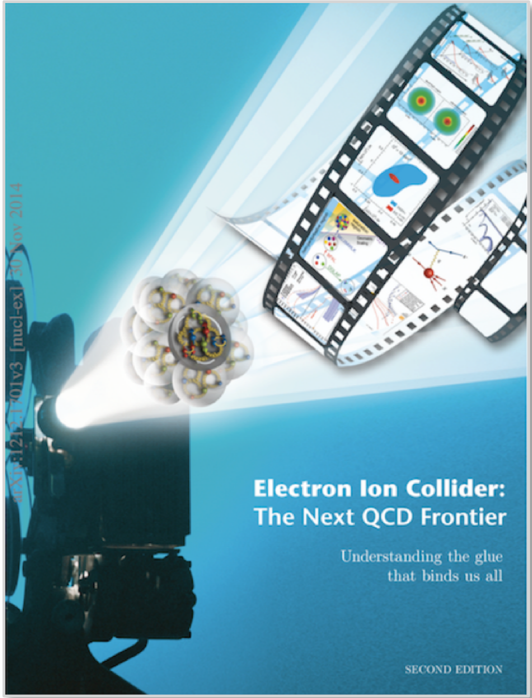


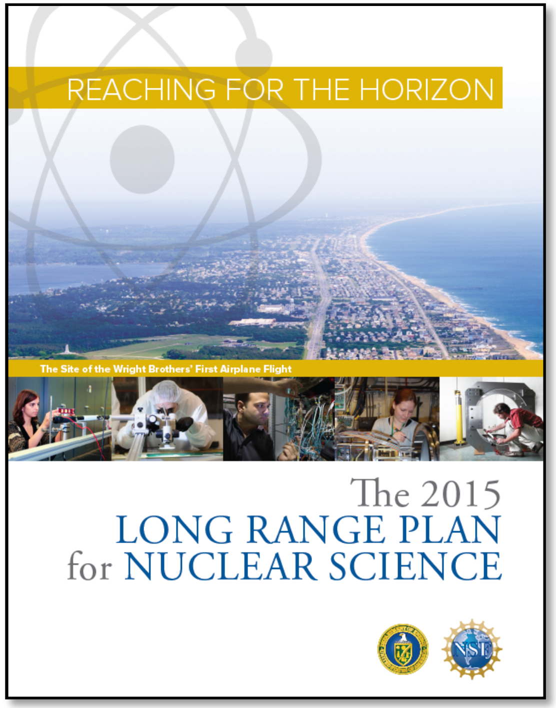
"In summary, the committee finds a compelling scientific case for such a facility. The science questions that an EIC will answer are central to completing an understanding of atoms as well as being integral to the agenda of nuclear physics today. In addition, the development of an EIC would advance accelerator science and technology in nuclear science; it would as well benefit other fields of accelerator based science and society, from medicine through materials science to elementary particle physics."

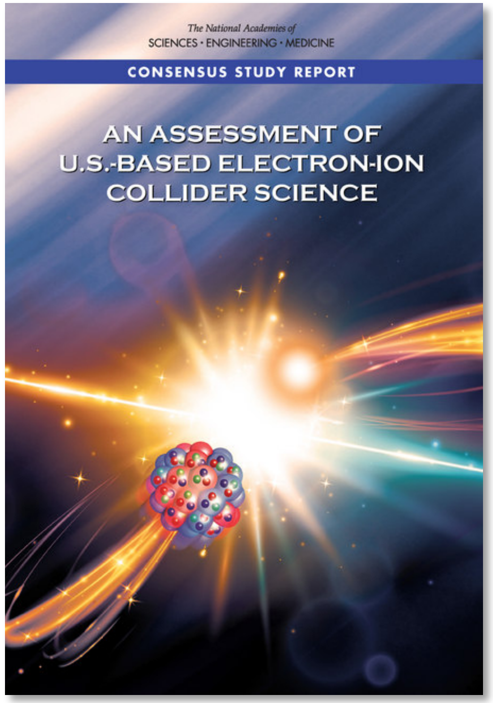
Why an Electron-Ion Collider?

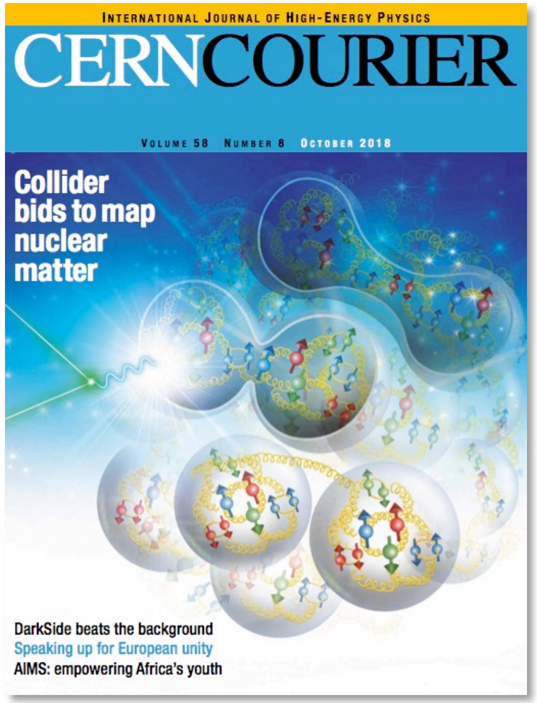
Right tool:
- to precisely **image quarks and gluons** and their interactions
- to explore the new **QCD frontier of strong color fields in nuclei**
- to understand **how matter at its most fundamental level is made**.

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.

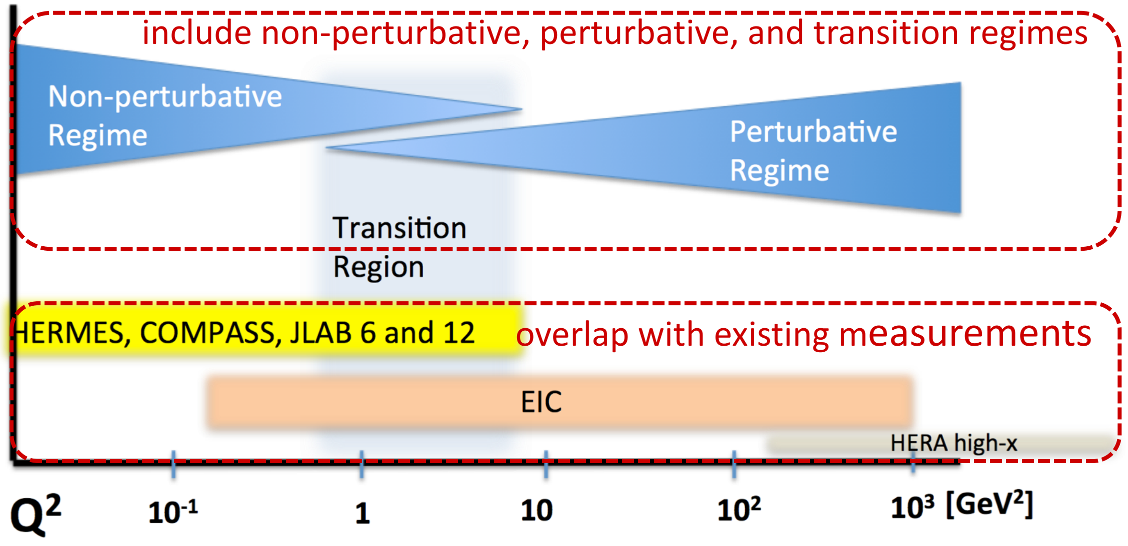


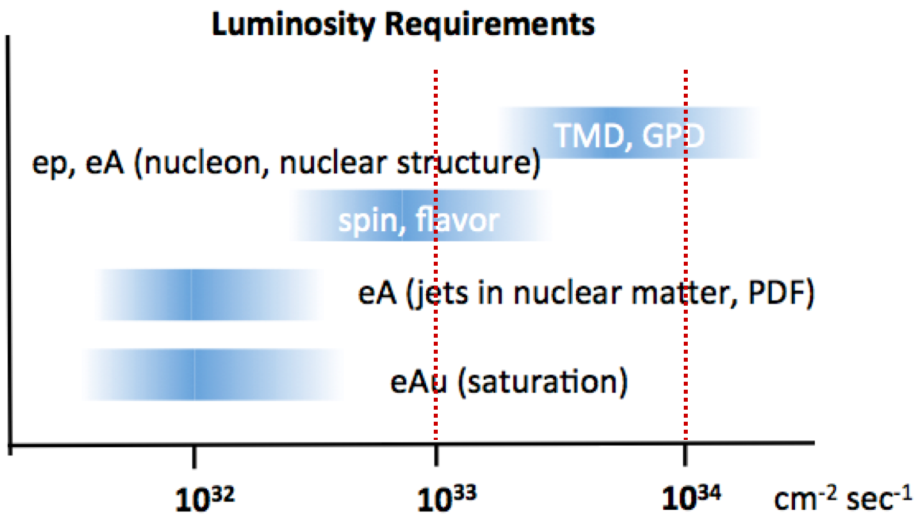






EIC: Ideal facility for studying QCD





Various beam energy

broad Q^2 range for

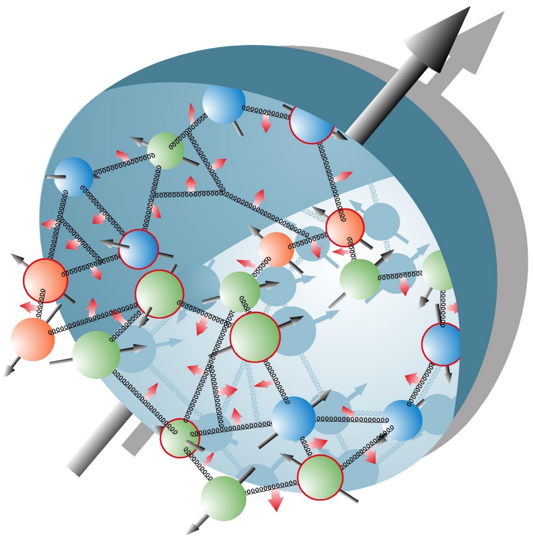
- studying evolution to Q^2 of ~1000 GeV^2
- disentangling non-perturbative and perturbative regimes
- overlap with existing experiments

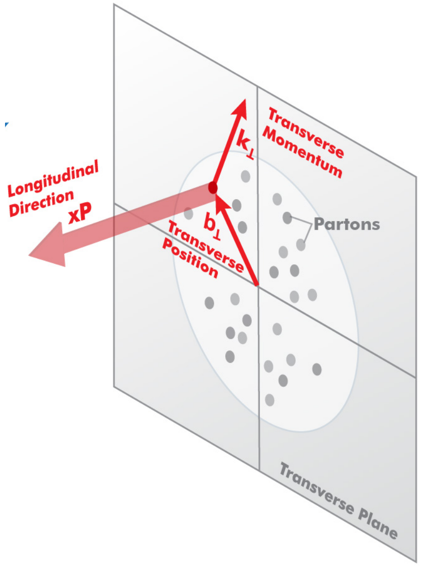
High luminosity

high precision

- 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

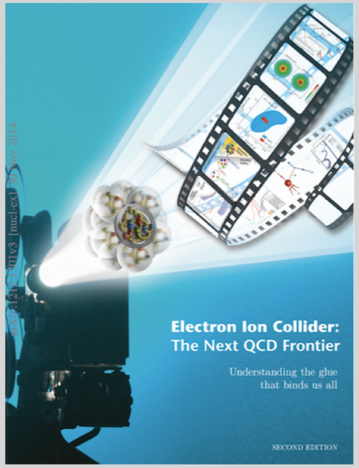
Understanding hadron structure cannot be done without understanding spin:

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

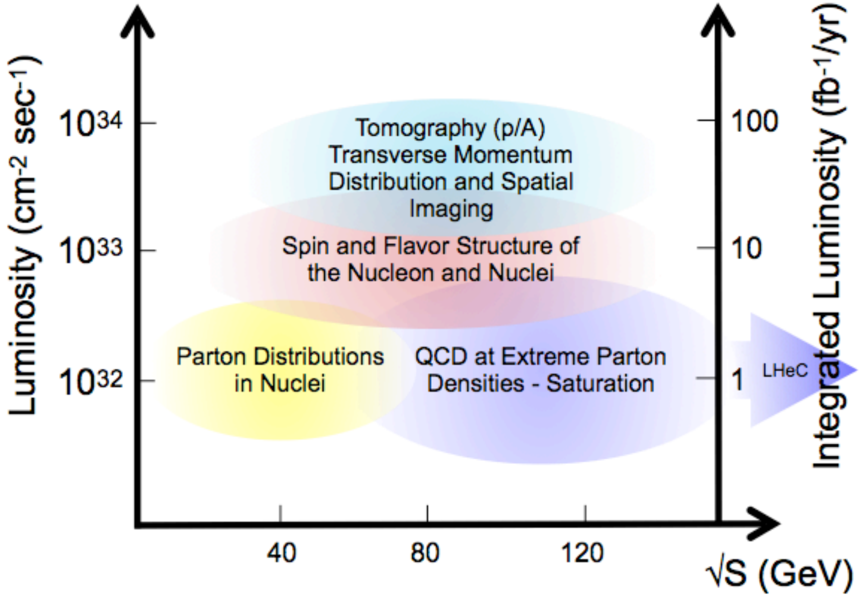
Longitudinal and transverse and polarization of light ions (d, ^{3}He)

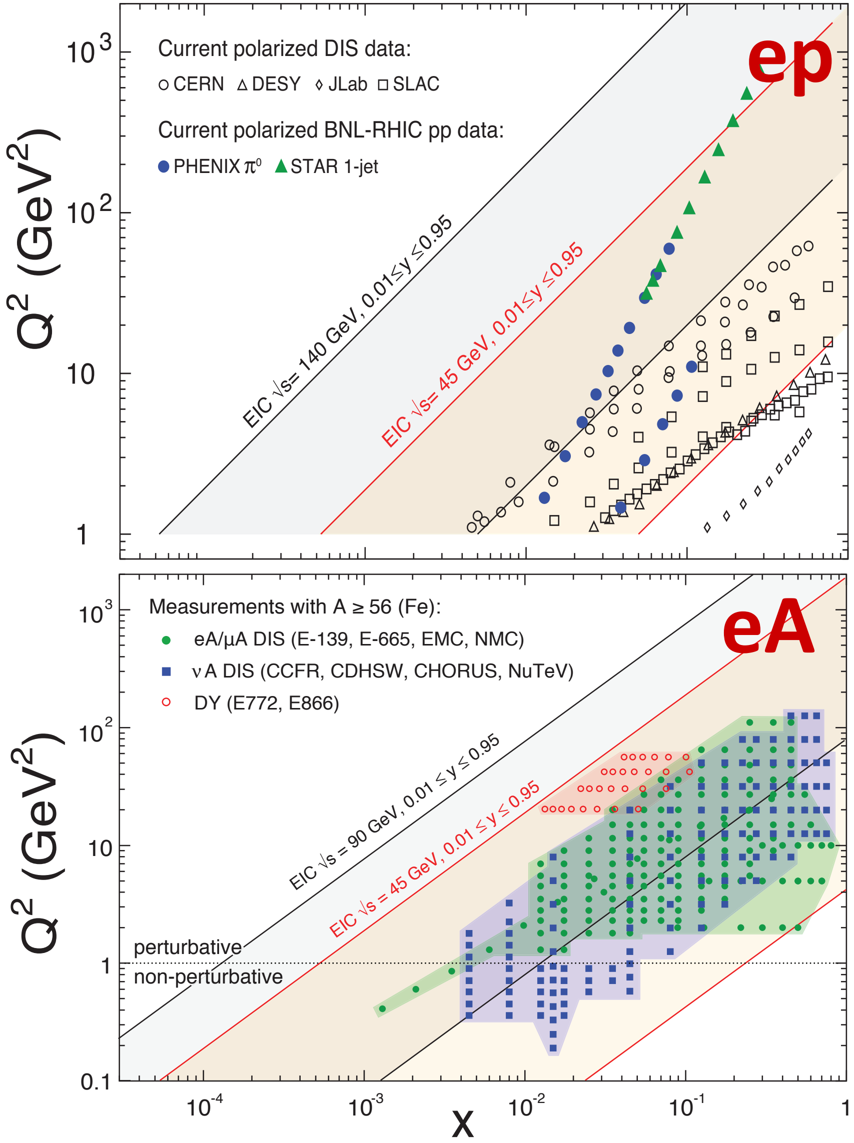
- 3D imaging in space and momentum
- spin-orbit correlations

EIC science program

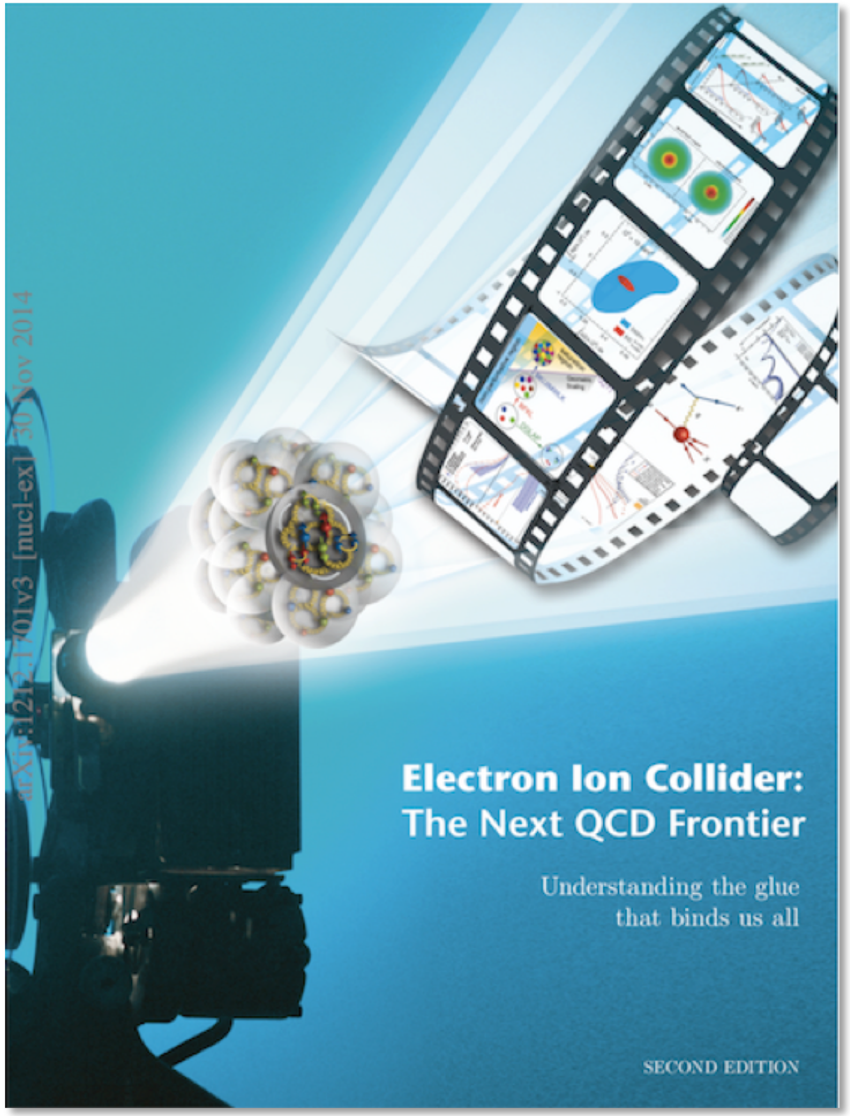


Study **structure** and **dynamics** of **nuclear matter** in **ep** and **eA collisions** with high luminosity and versatile range of beam energies, beam polarizations, and beam species.





TMD program in EIC White Paper



Ultimate measurement of TMDs for quarks

- **high luminosity**
  - high-precision measurement
  - multi-dimensional analysis (x, Q^2, ϕ_S, z, P_t, ϕ_h)
- **broad *x* coverage** $0.01 < x < 0.9$
- **broad Q^2 range** disentangling non-perturbative / perturbative regimes

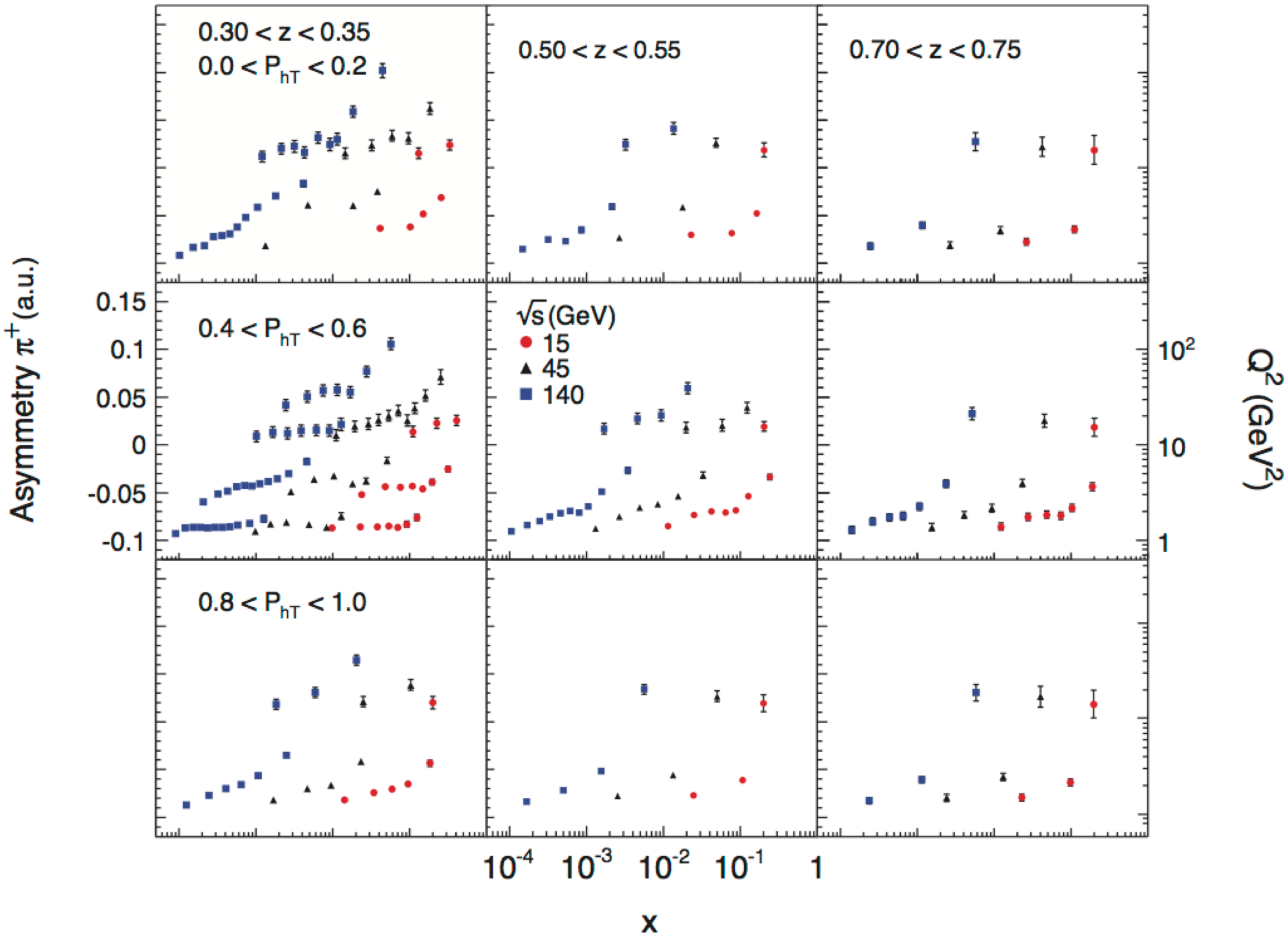
First (?) measurement of TMDs for sea quarks

First (?) measurement of TMDs for gluons

Nuclear dependence of TMDs

Systematic factorization studies

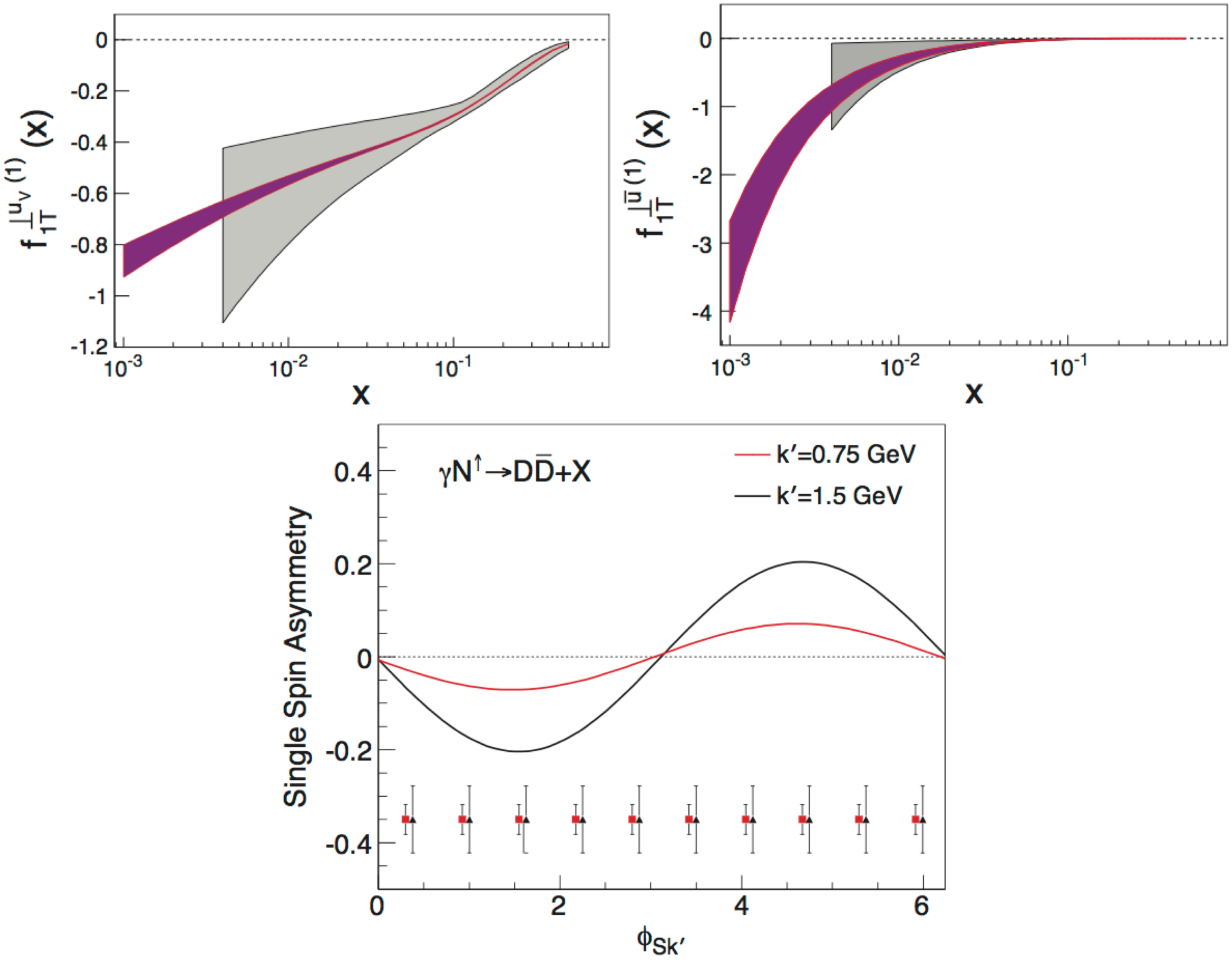
Ultimate measurement for TMDs



multidimensional binning

$\mathcal{L}$ = 10 fb^{-1}

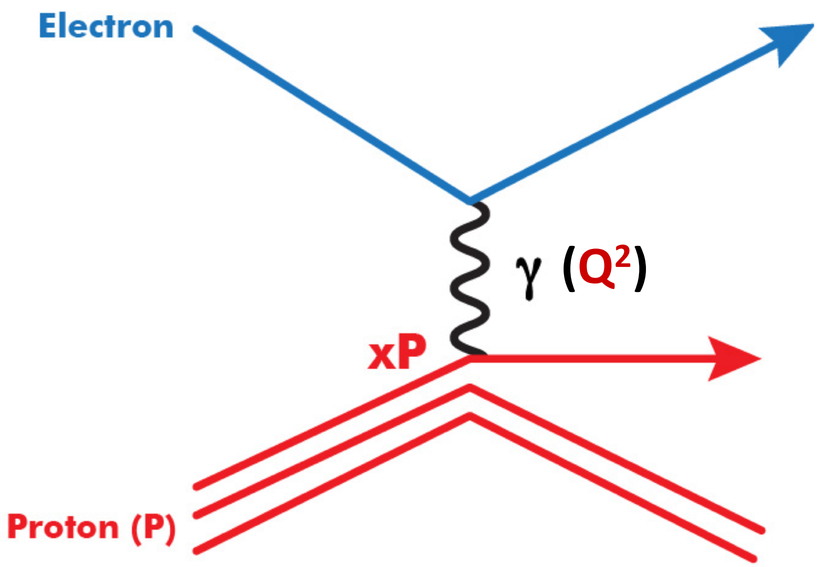
TMDs for sea quarks and gluons



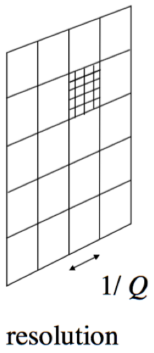
Accelerator design

Designing the right probe

Electron-Proton Scattering

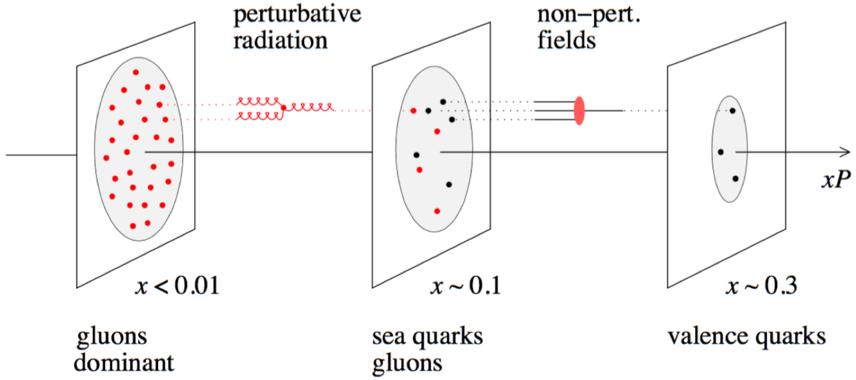


Ability to change Q^2 changes the resolution scale



Q^2 = 400 GeV^2
=> 1/Q = 0.01 fm

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



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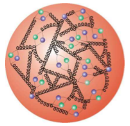
Where EIC Needs to be in x (nucleon)

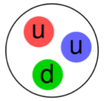
Saturation Regime:
Needs to be Accessed via Ions

Collective Regime



Many-body Regime

Few-body Regime



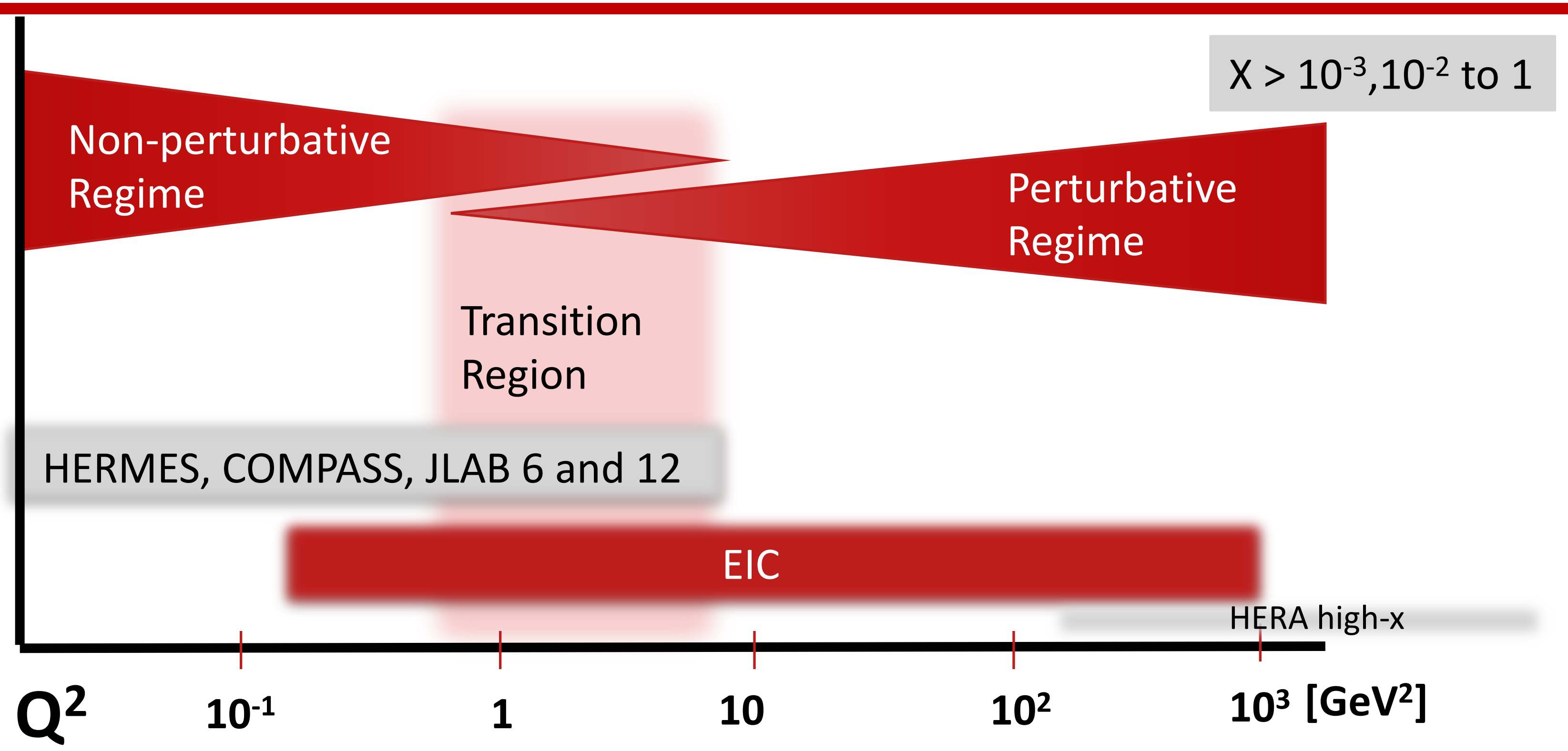
10^{-4} 10^{-3} 10^{-2} 10^{-1} 1 X (for proton)

QCD Radiation Dominated
(Studied at HERA)

Hadron Structure Dominated

Main interest for EIC Nucleon/Nuclear Program

Where EIC needs to be in Q^2



- Include non-perturbative, perturbative and transition regimes
- Provide long evolution length and up to Q^2 of ~1000 GeV^2 (~.005 fm)
- Overlap with existing measurements

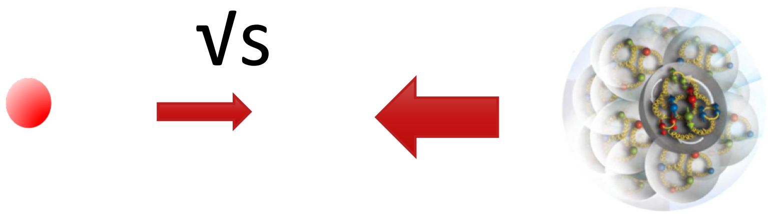
Disentangle Pert./Non-pert., Leading Twist/Higher Twist

Designing The Right Probe: √s

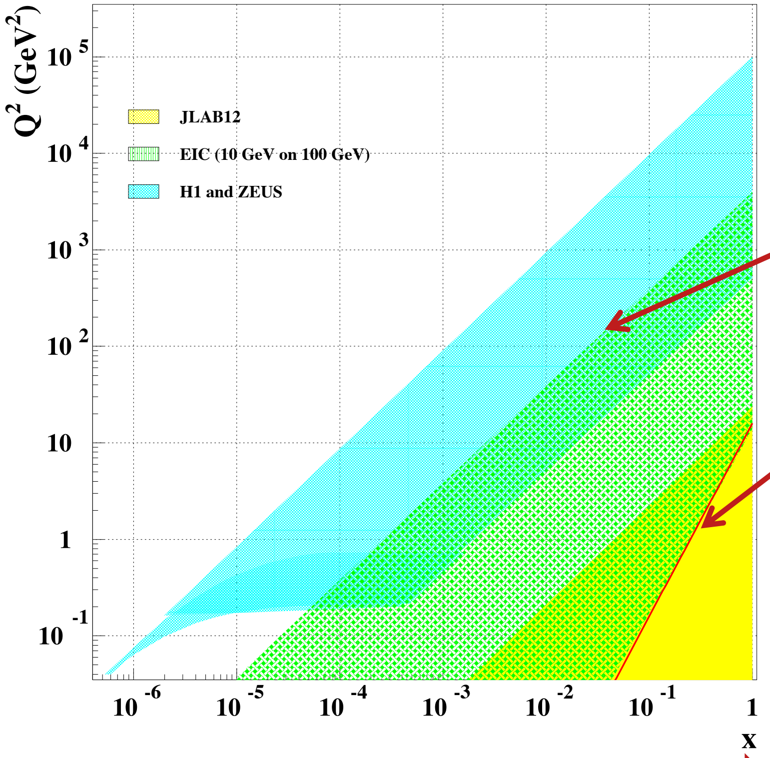
What are the right parameters for the collider for the EIC science program?

We know the x range: down to ~ 10^{-3-4}
We know the Q^2 range: up to ~1000 GeV^2

$Q^2 = sxy$, $s = 4E_eE_{hadron}$
→ energies we need.



JLEIC parameters (nucleon)



Cross section decreases rapidly with higher X

This edge determined by √s:
√s = 65 GeV

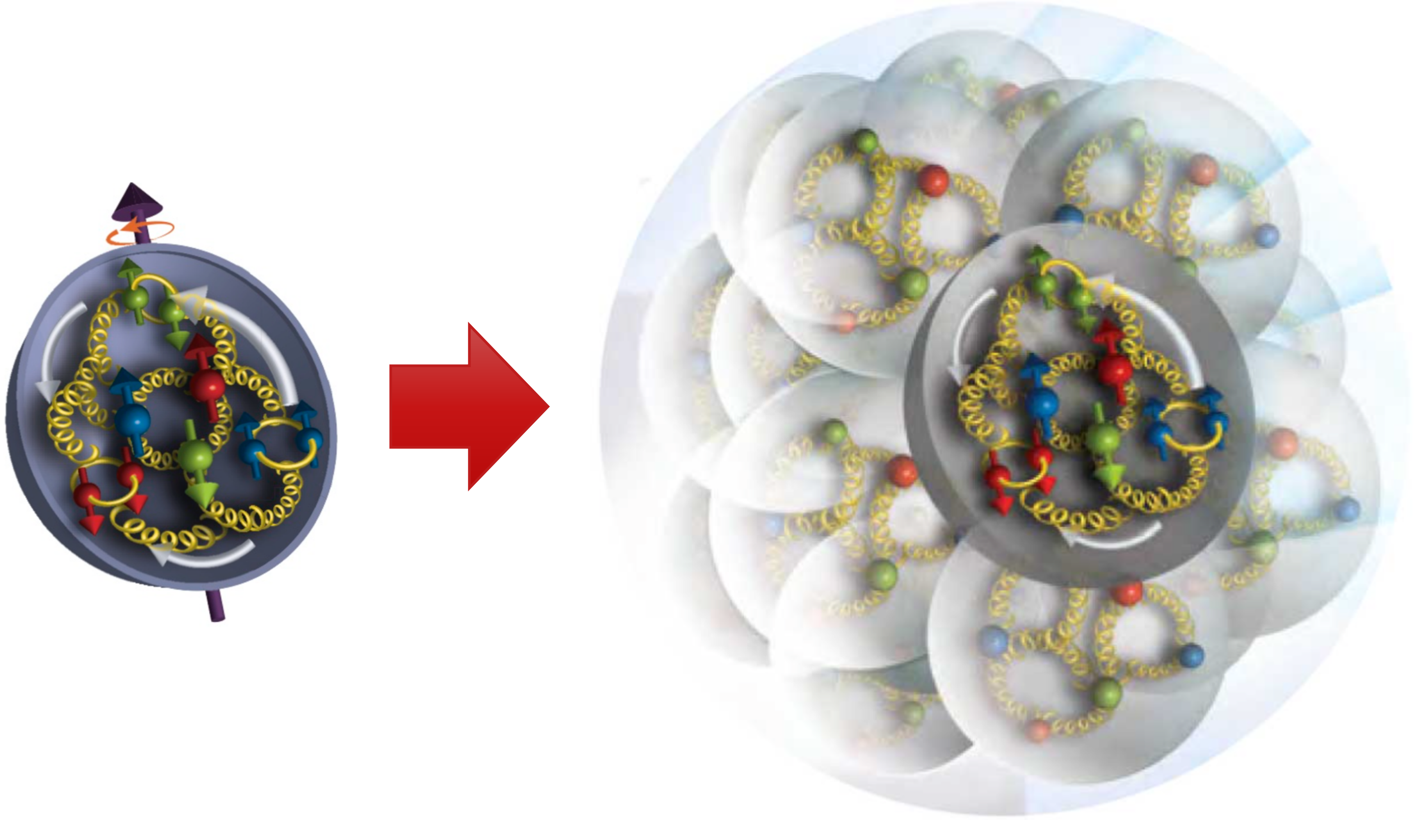
This edge determined by proton beam energy:
E_{proton} < 100 GeV -> $E_{electron}$ = 10 GeV^2

Measure at x of 10^{-3} to 1, exclusive processes
Luminosity: x 10 to 100 that of HERA

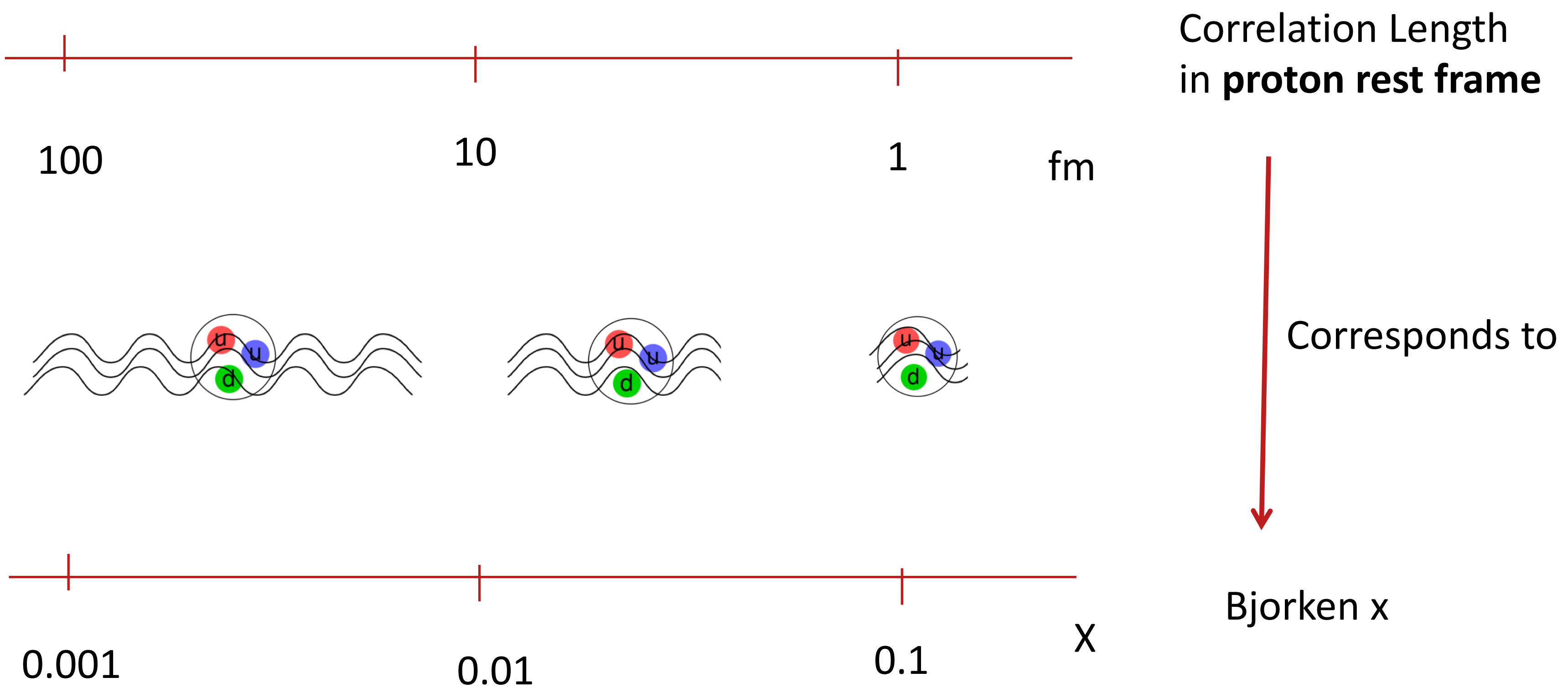
Sets some of the basic parameters of the JLEIC design

Higher beam energies required for eA measurements, e.g., nuclear PDFs

Understanding the nuclei at the next level

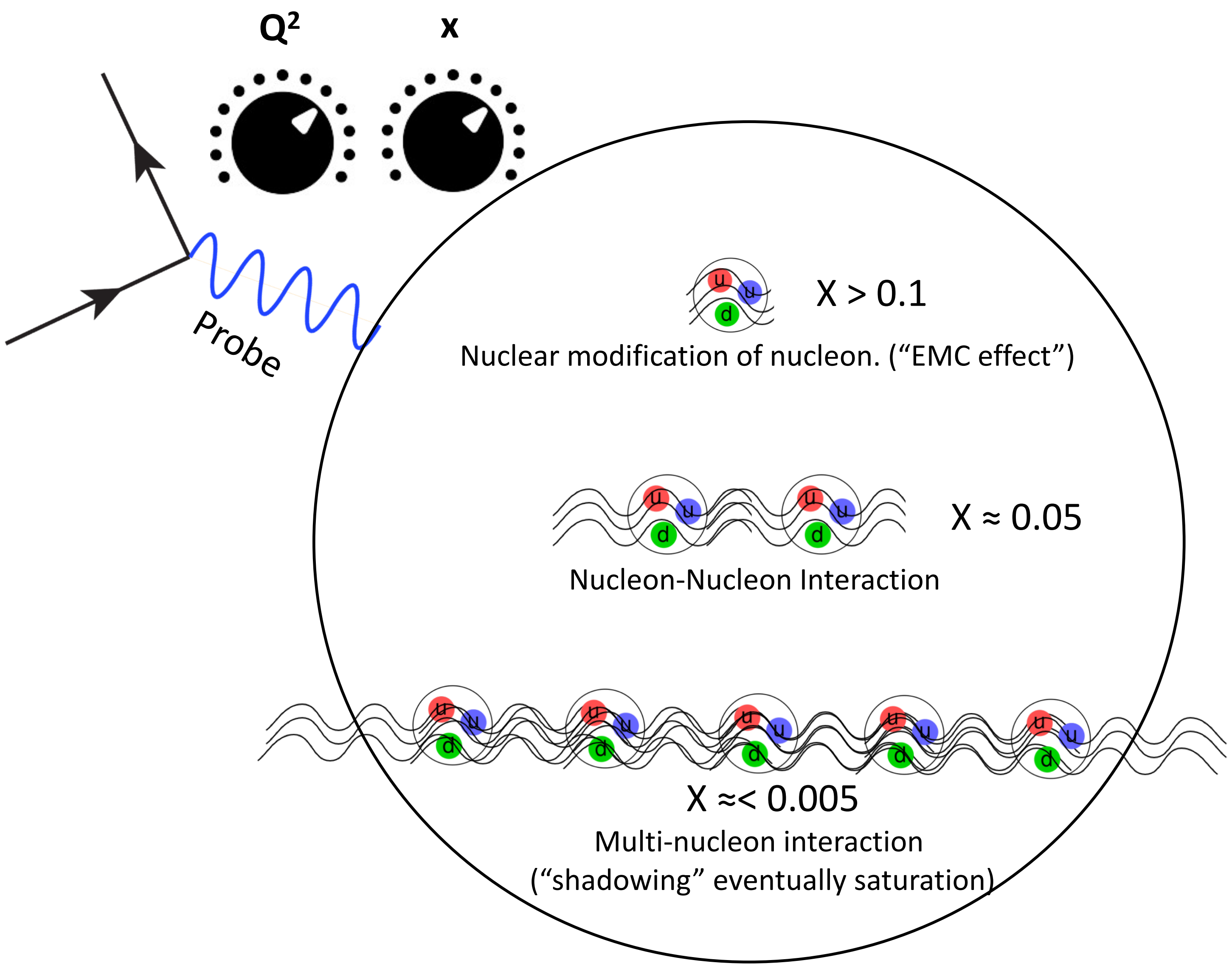


Bjorken x and length scale

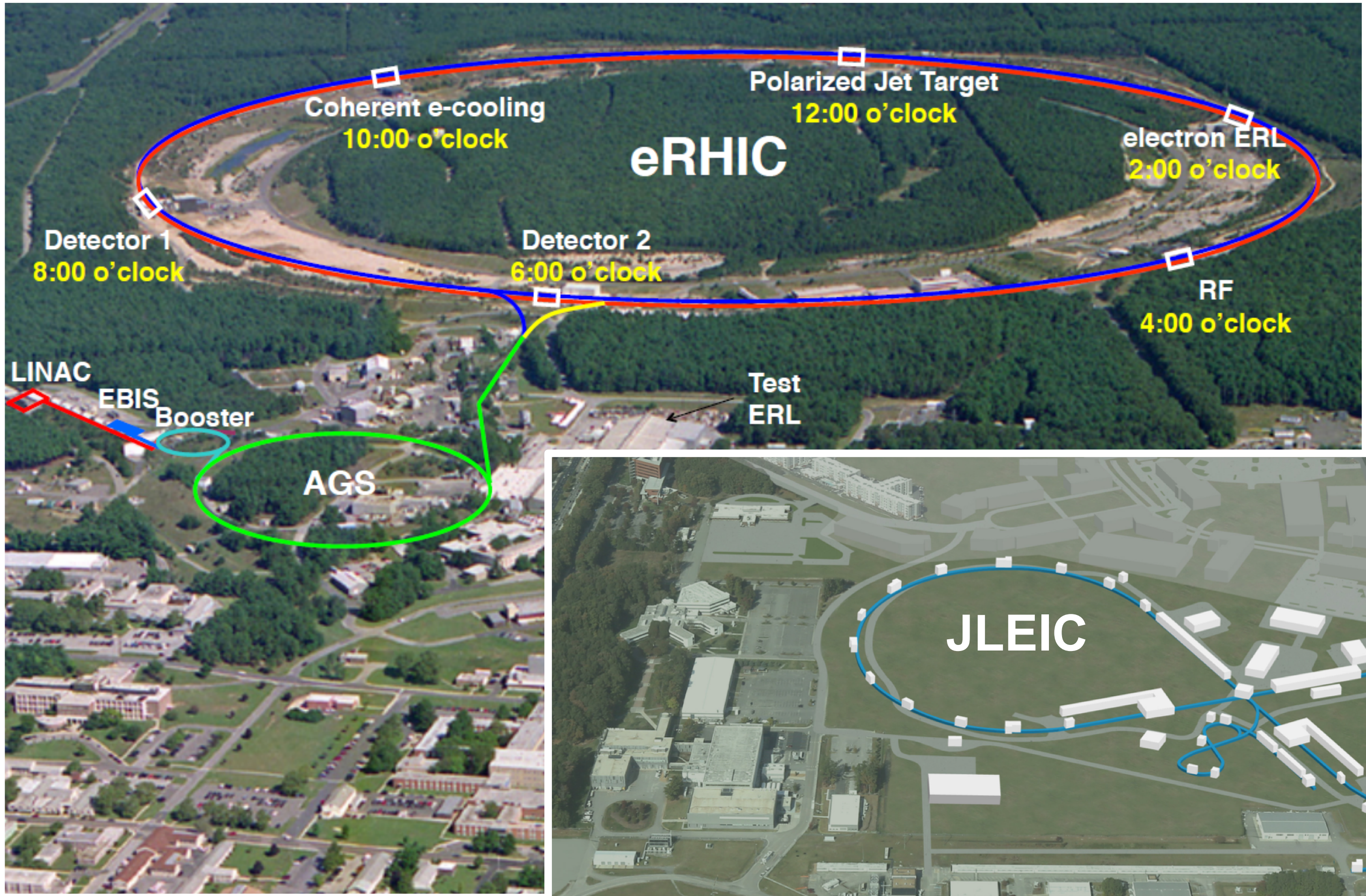


In the proton rest frame, QCD field (x < 0.1) extends far beyond the proton charge radius

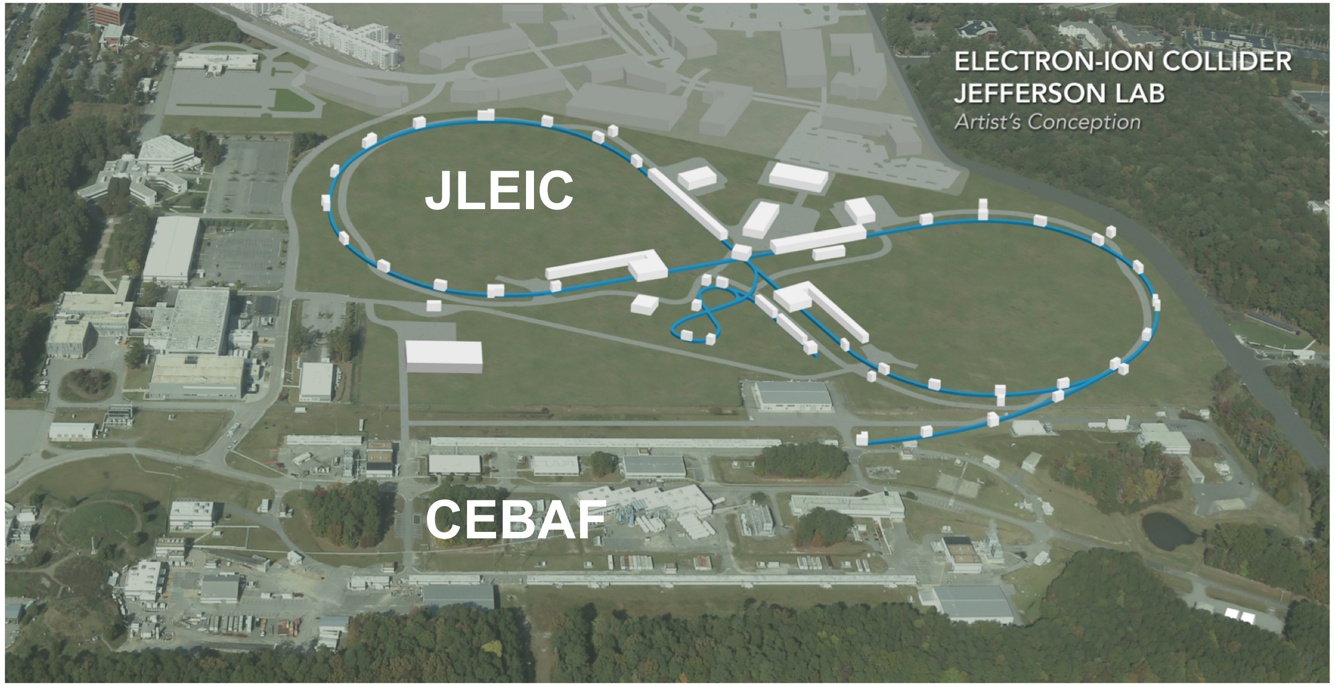
Probing the nucleon interaction in the nuclei



Realization of the science case



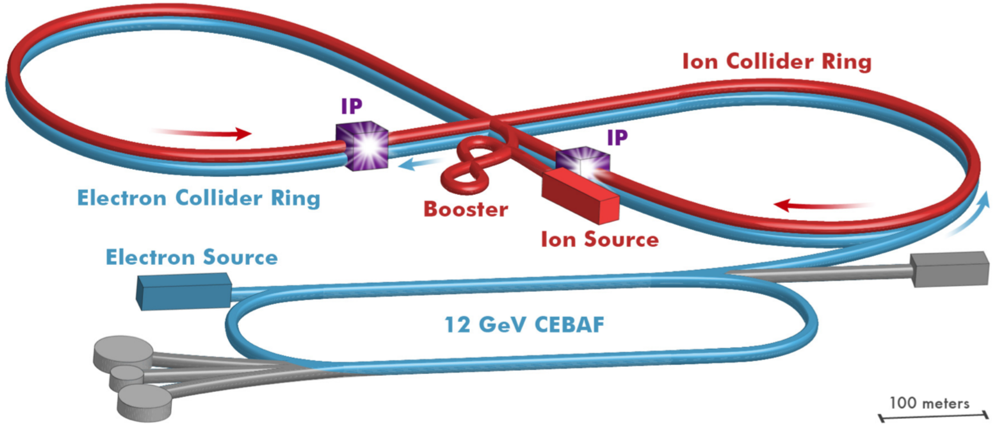
Brookhaven Lab
Long Island, NY

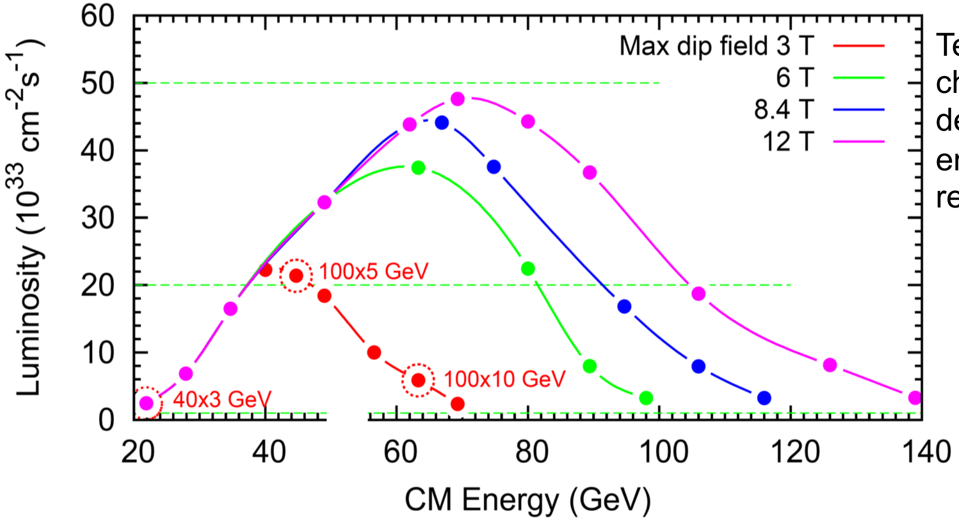


Jefferson Lab
Newport News, VA

JLEIC design strategy: High luminosity and polarization

>80% polarization for both **electrons** and **light ions**





Technology choice determines energy reach.

Figure-8 shaped ring-ring collider

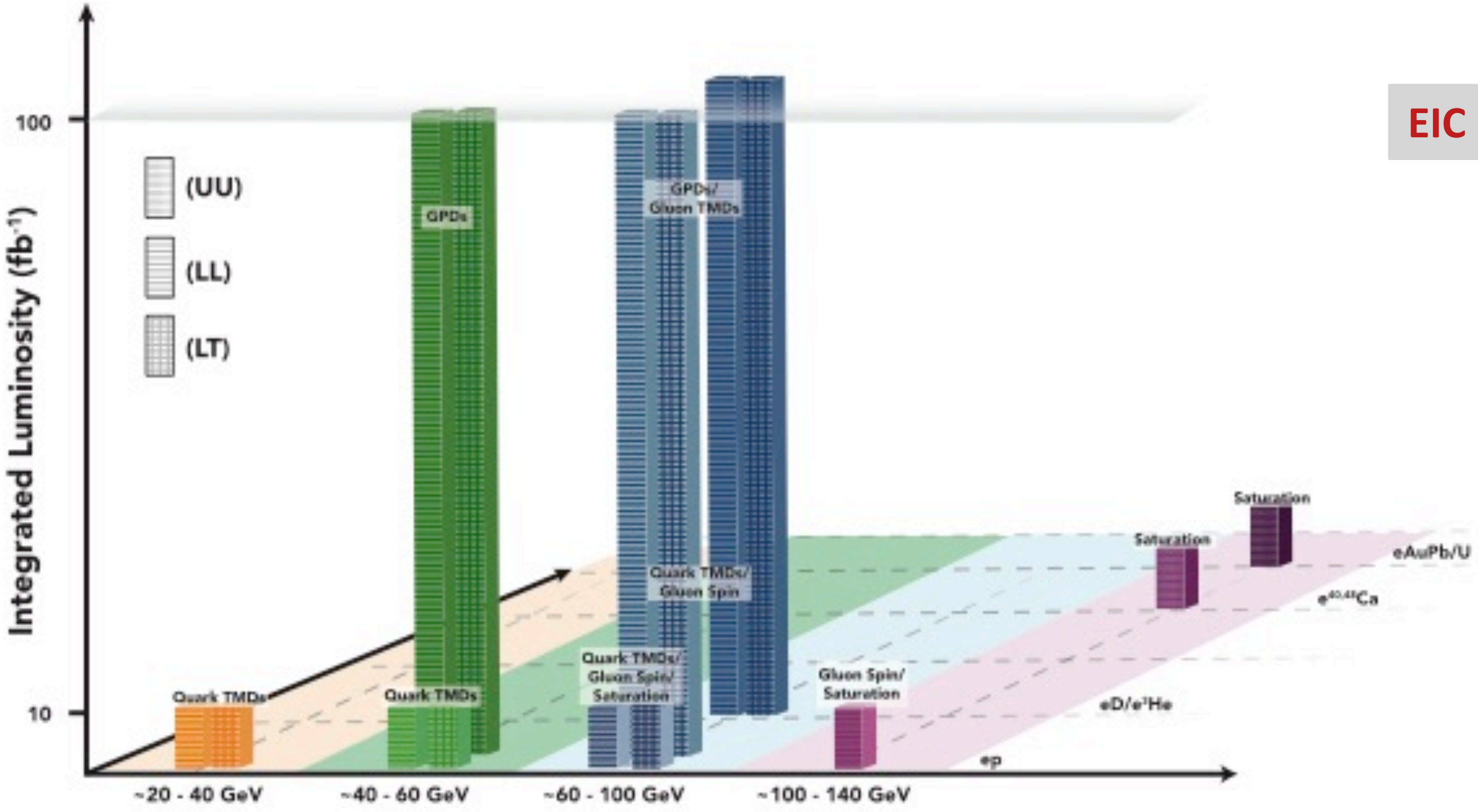
- zero **spin tune** (net spin precession)
- energy-independent **spin tune**
- **polarization** easily preserved and manipulated:
  - by small solenoids
  - by other compact spin rotators

High luminosity

- high-rate collision of short bunches
  - with small emittance
  - with low charge
- **ion beam:** high-energy electron cooling (R&D)
- **electron beam:** synchrotron radiation damping

JLEIC energy reach √s =**20 –100 GeV**, upgradable to **140 GeV** using 12 T magnets (HE-LHC, FCC)

Projected luminosity needs (EIC Whitepaper)



EIC luminosity ~650 fb^{-1}

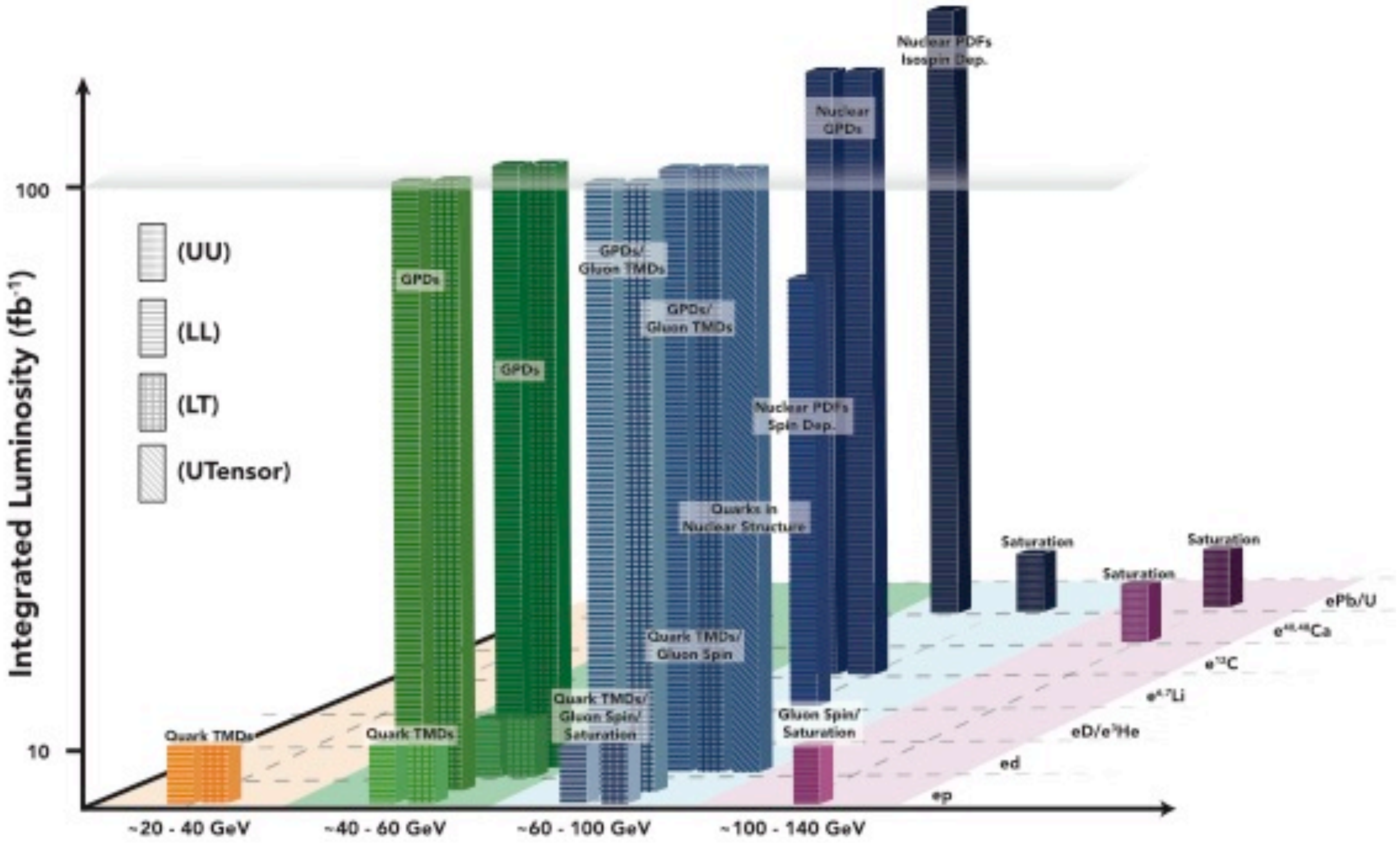
EIC luminosity 100 – 1000 times HERA luminosity:

- **0.6 fb^{-1} to 6 fb^{-1}/week** of running or
- **average luminosity** (while running) **of 10^{33} to 10^{34} cm^{-2} s^{-1}**

6 fb^{-1}/week ➔ 100 fb^{-1}/year assuming 10^7 s in year (running ~1/3 of the year or a *snowmass* year)

Projected luminosity needs (beyond EIC Whitepaper)

as discussed by EIC community



We cannot start the TMD program without high luminosity.
We need high-luminosity at the start of physics running at the EIC.

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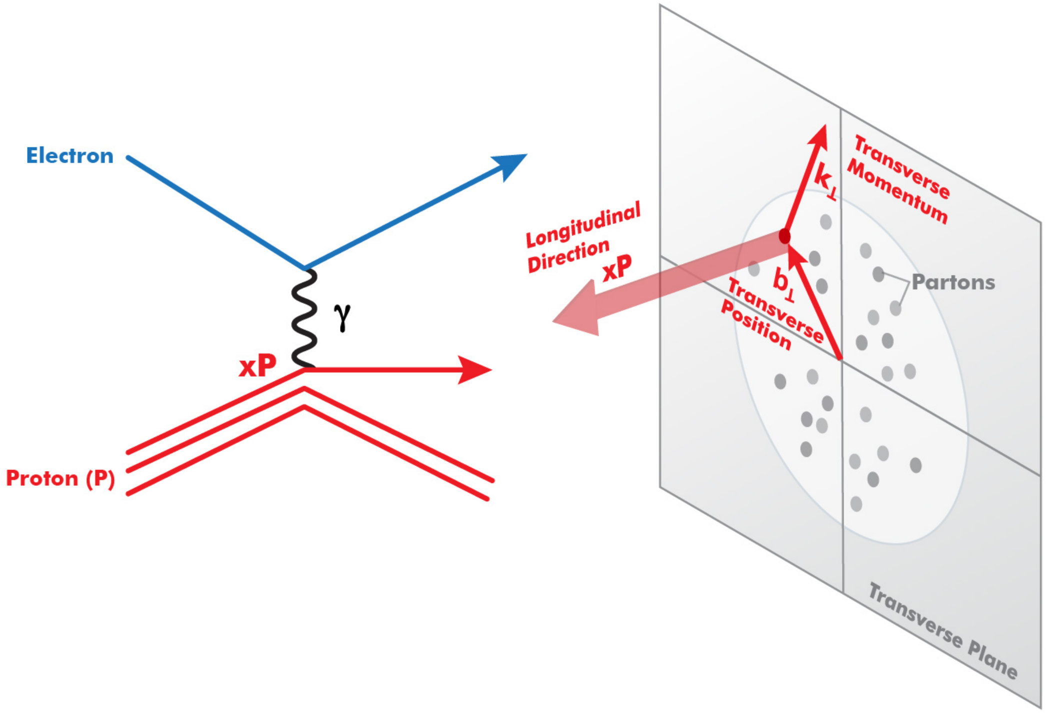
Detector design

General design considerations

Mapping position and motion of quarks and gluons

Study nuclear matter **beyond longitudinal description** makes the **requirements for IR and detector design different** from all previous colliders including HERA.

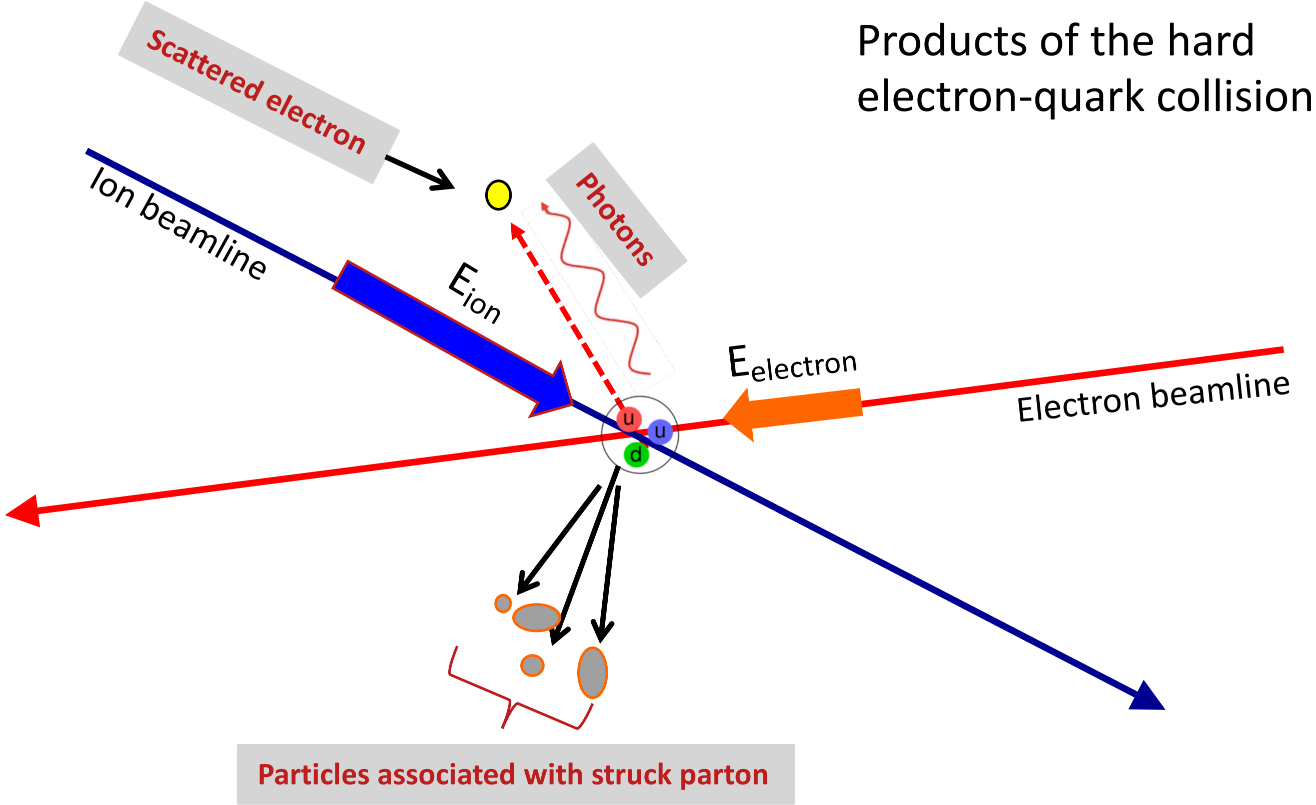


3D imaging in space and momentum

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

order of a few hundred MeV **measurement**

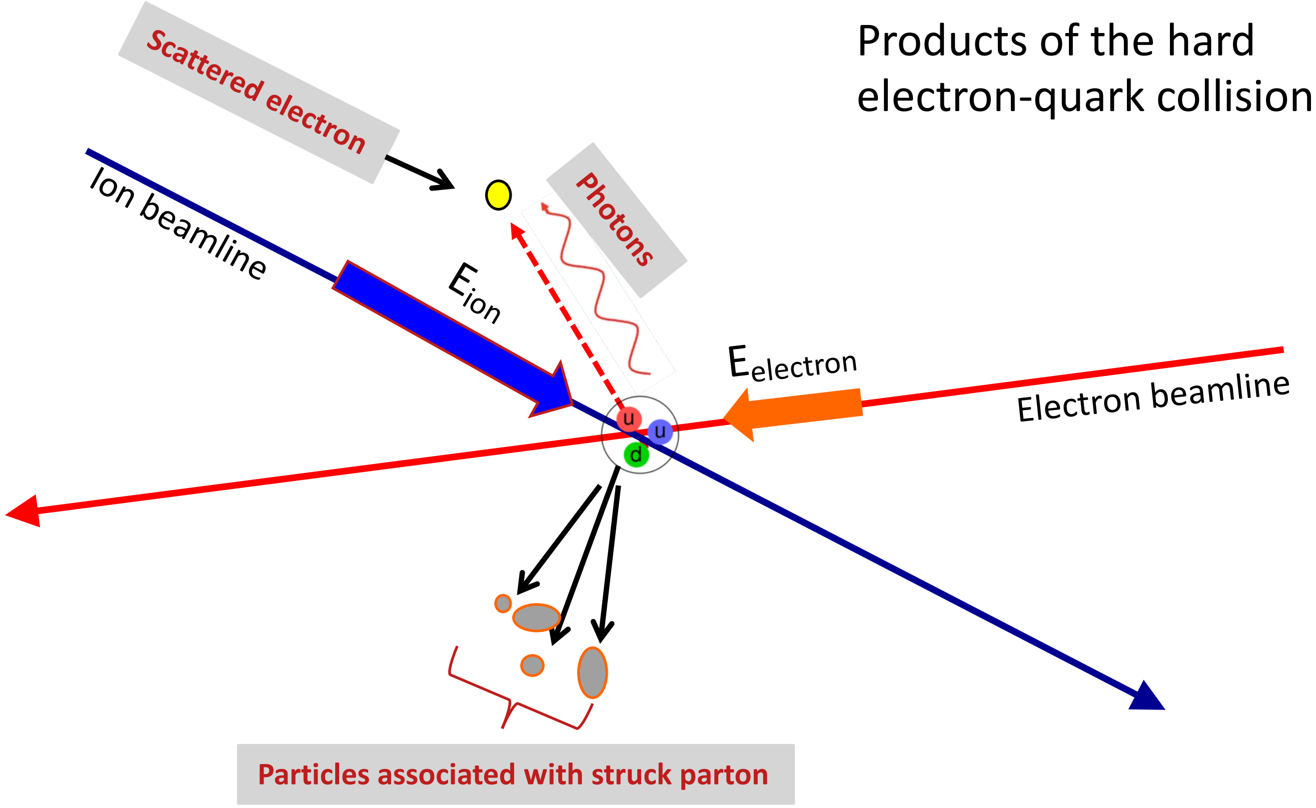
Particle Identification



Products of the hard electron-quark collision

Transverse and flavor structure measurement of the nucleon and nuclei: The particles associated with struck parton must have its species identified and measured. **Particle ID much more important than at HERA** colliders.

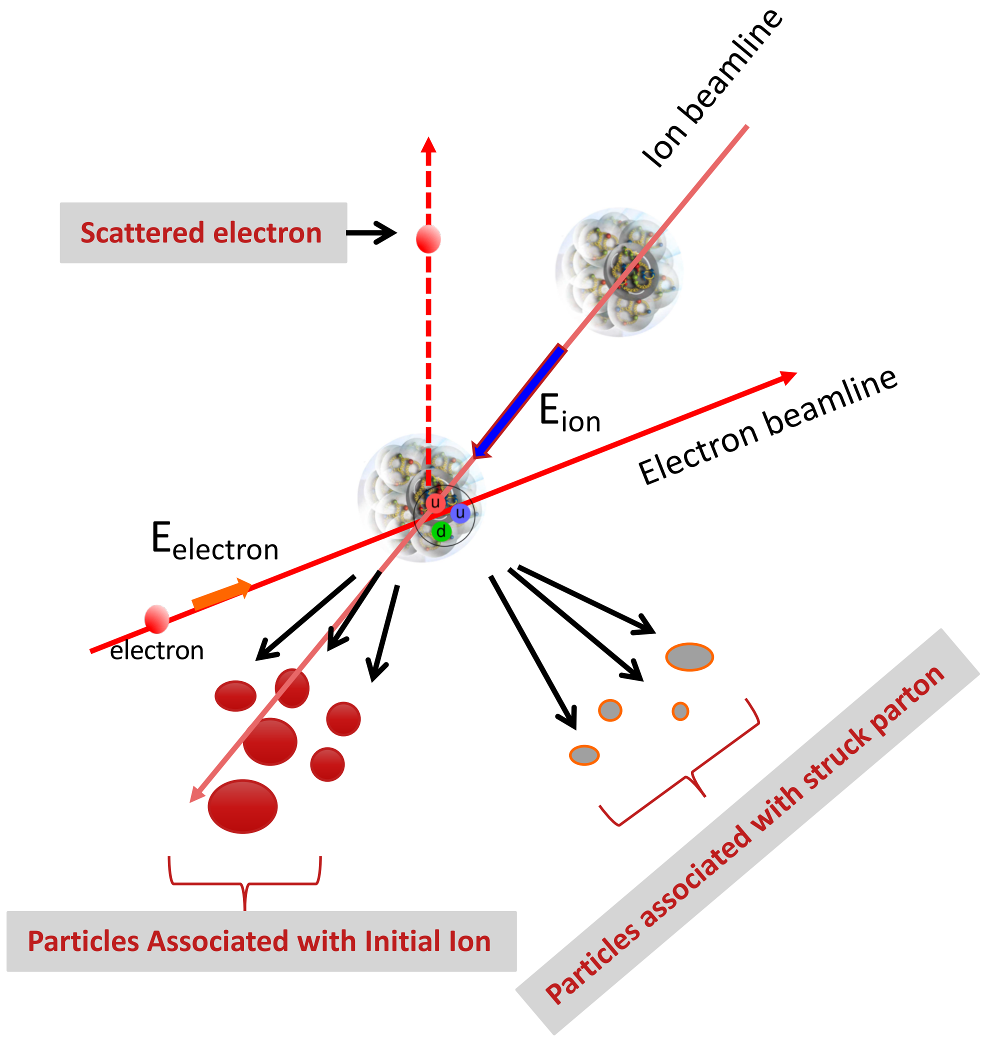
Final-state particles in the central rapidity



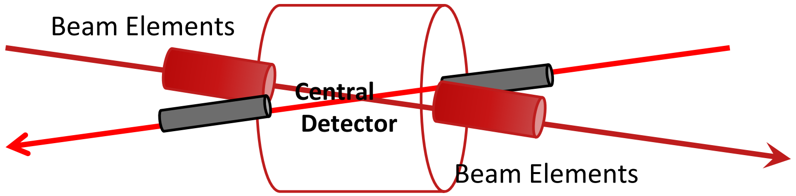
Products of the hard electron-quark collision

Asymmetric collision energies will boost the final state particles in the ion beam direction: **Detector requirements change as a function of rapidity.**

Final-state particles



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

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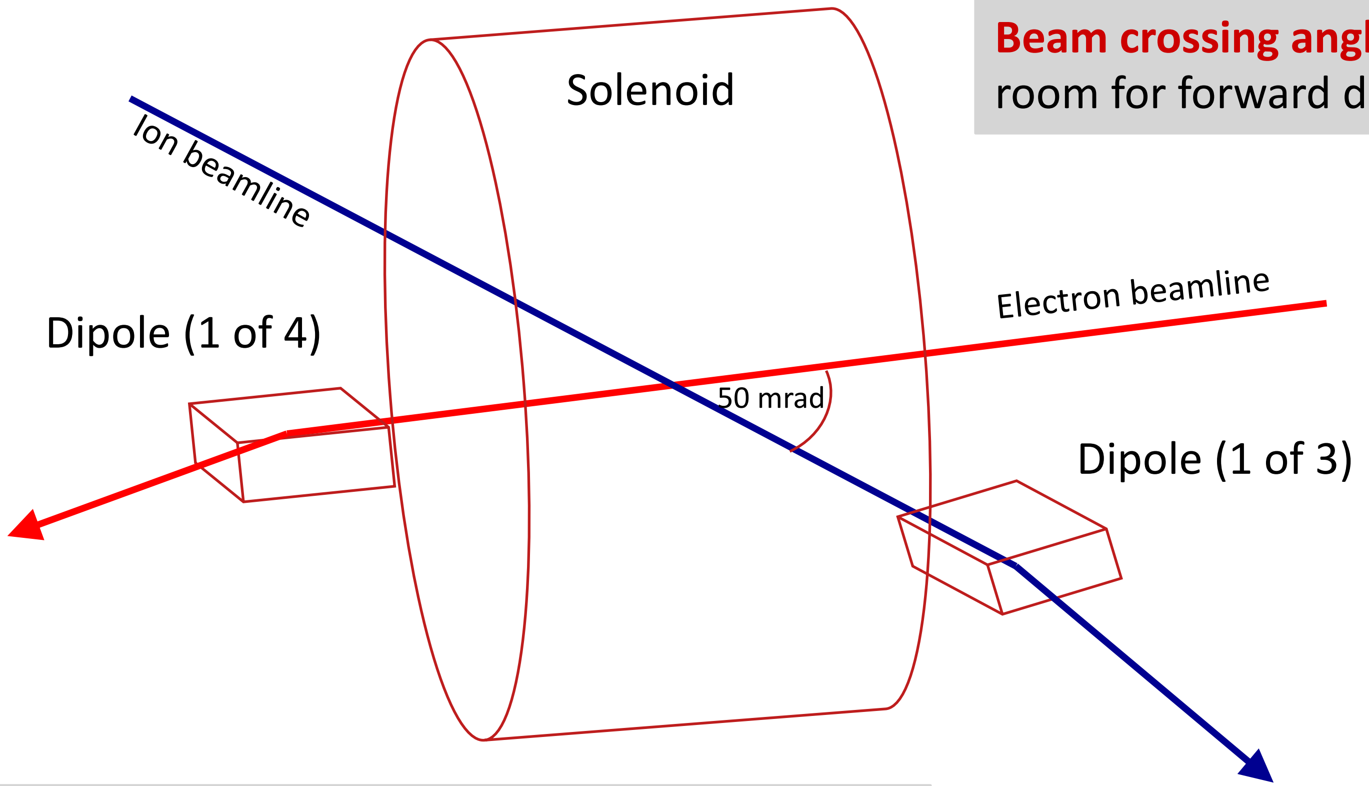
Interaction region concept

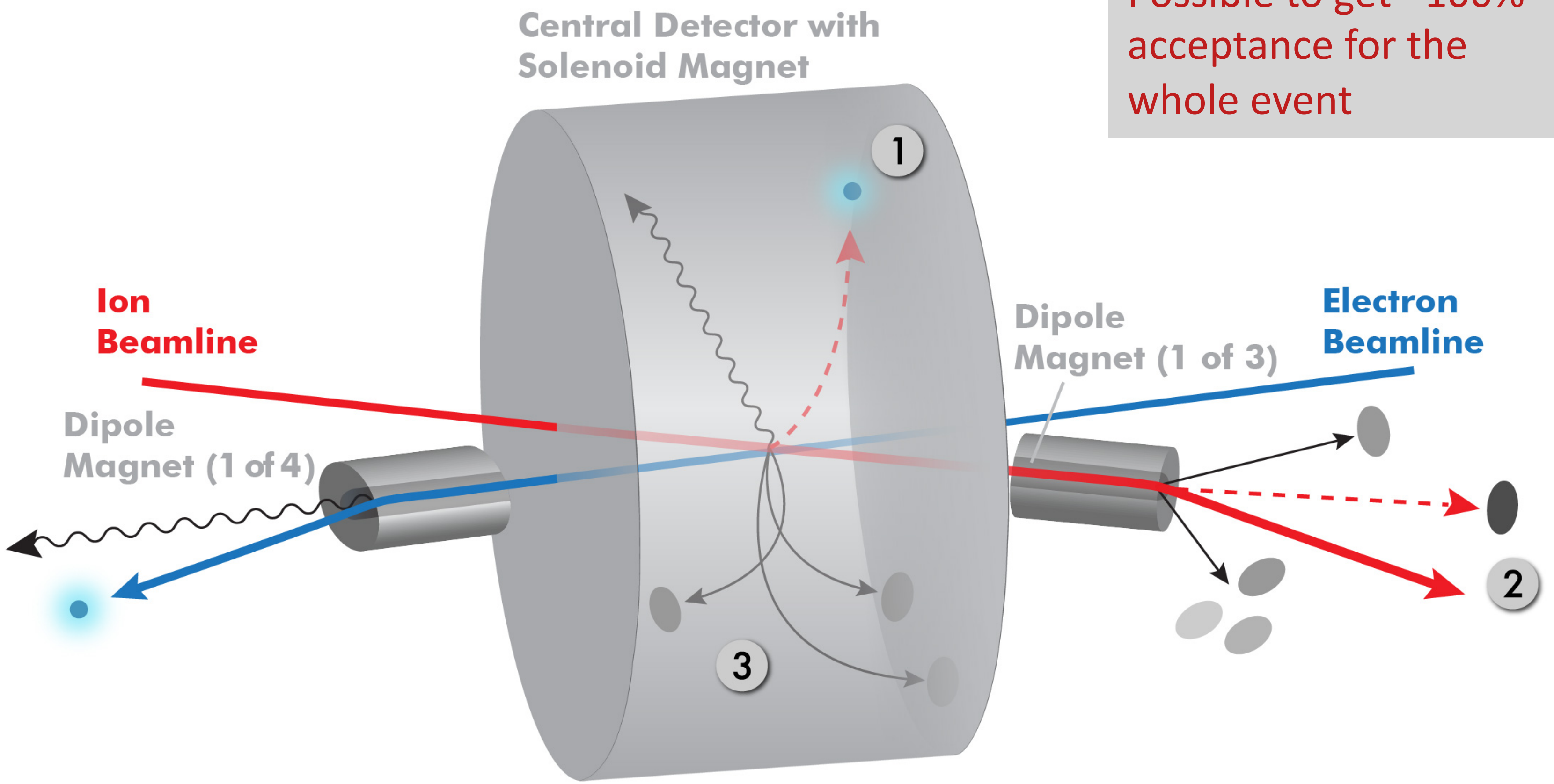
NOT TO SCALE!

Beam crossing angle creates room for forward dipoles



Dipoles analyze the forward particles
and create space for detectors in the forward direction

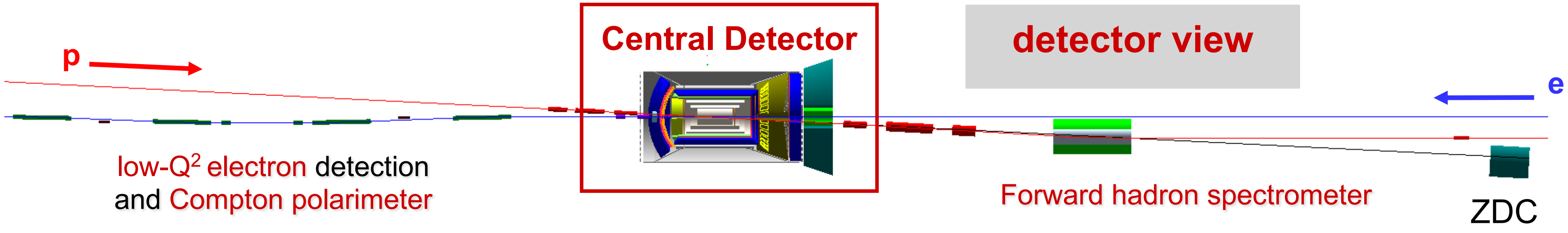
Interaction region concept



Possible to get ~100% acceptance for the whole event

Total acceptance detector (and IR)

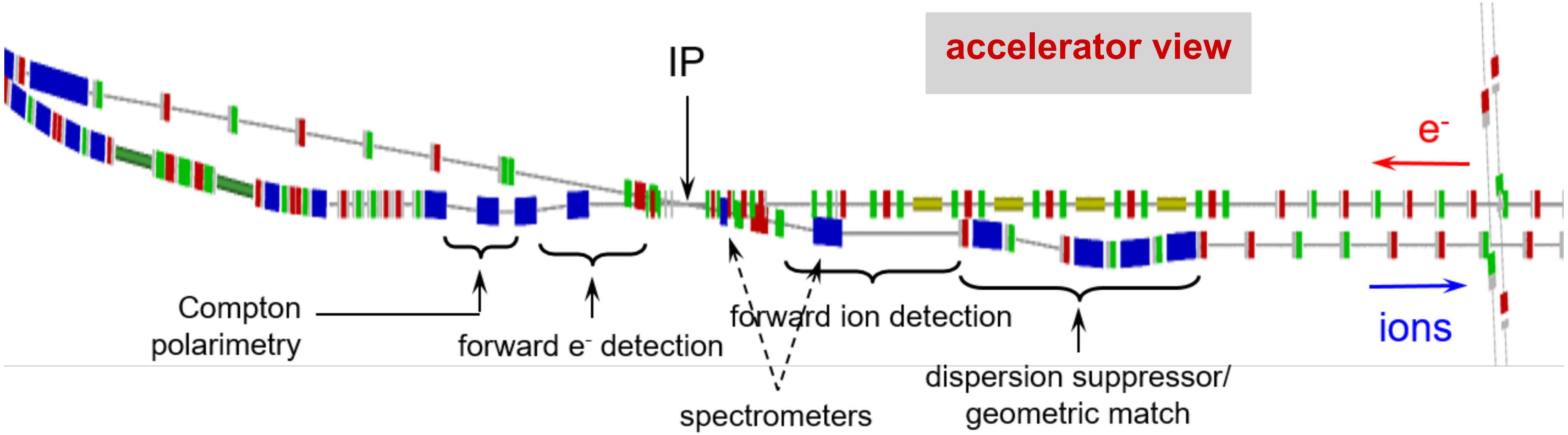
Detector and interaction region (for JLEIC)



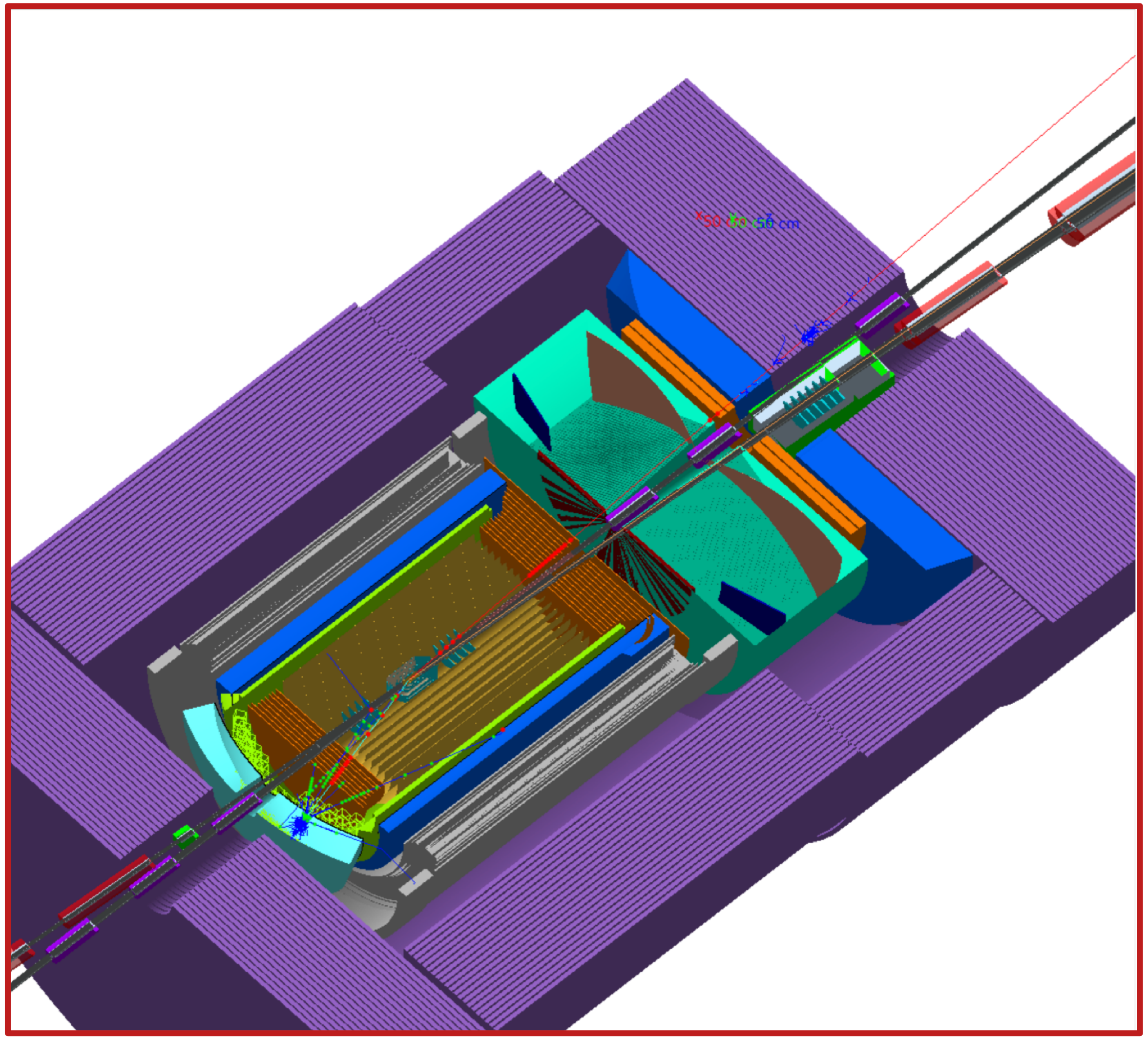
Extended detector: 80m

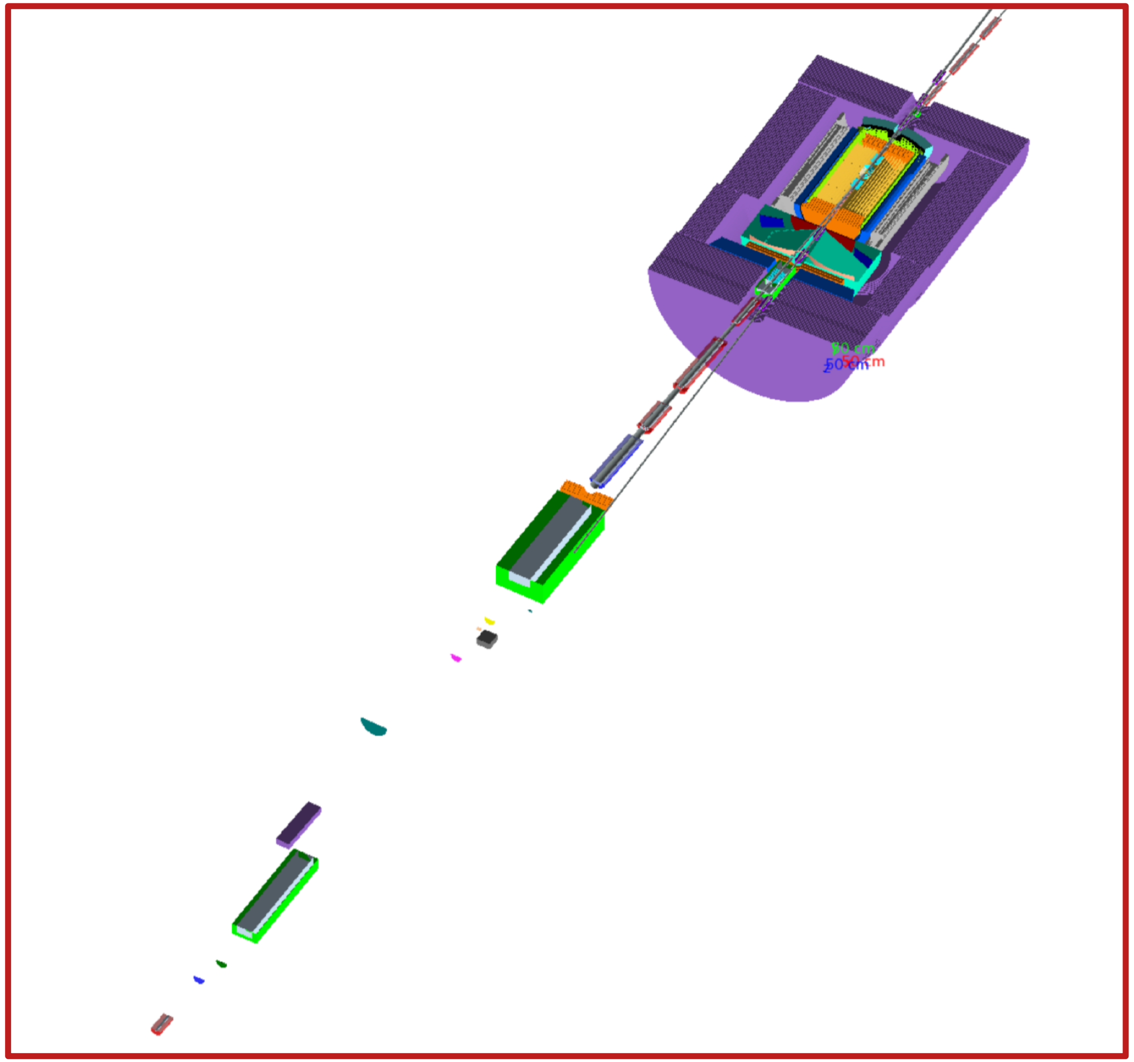
30m for multi-purpose chicane, 10m for central detector, 40m for the forward hadron spectrometer

fully integrated with accelerator lattice



Simulation of the JLEIC Detector





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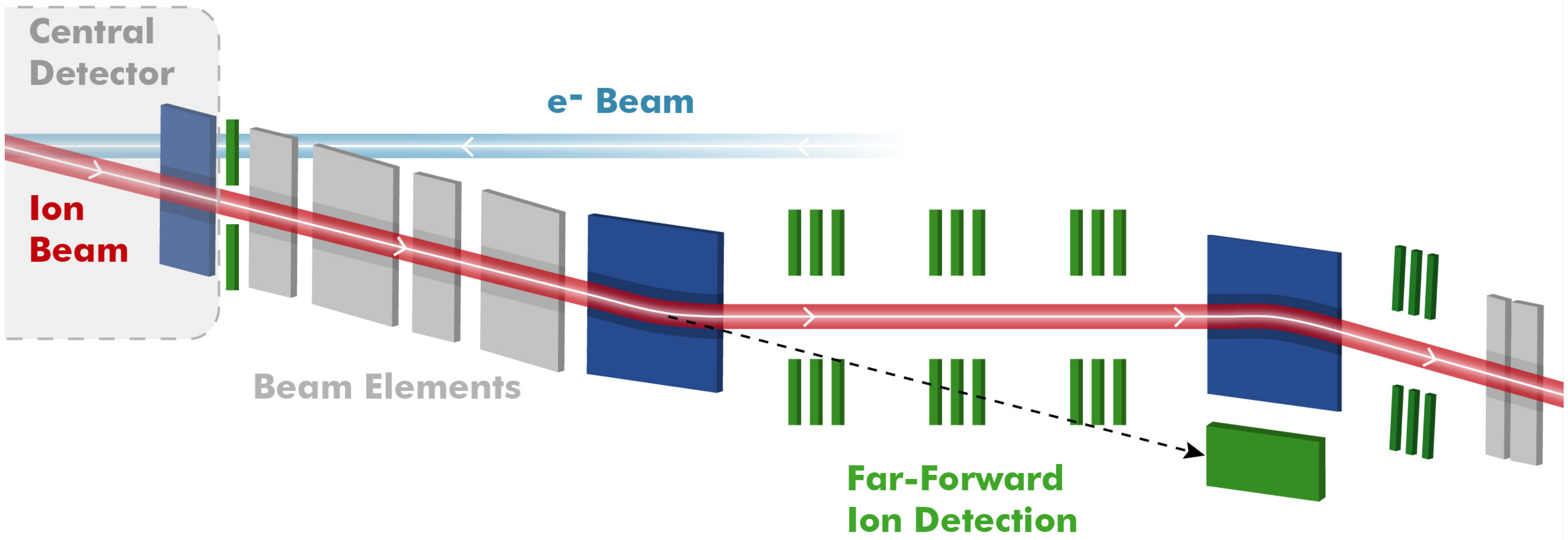
Far-forward ion detection

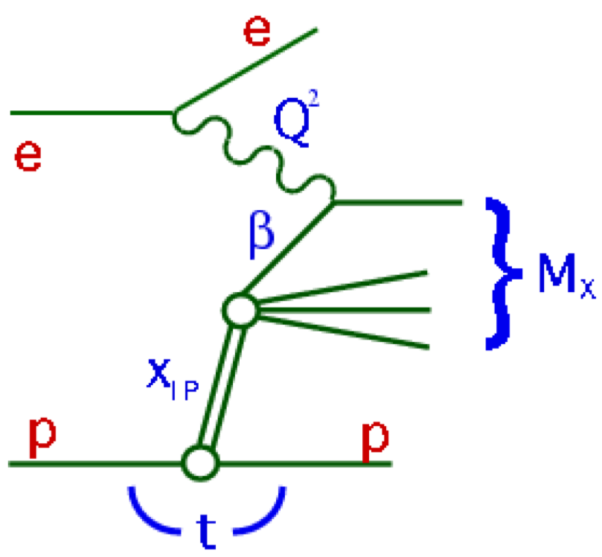


Forward detection requirements
- good acceptance for recoils nucleons (rigidity close to beam)
- good acceptance for fragments (rigidity different than beam)

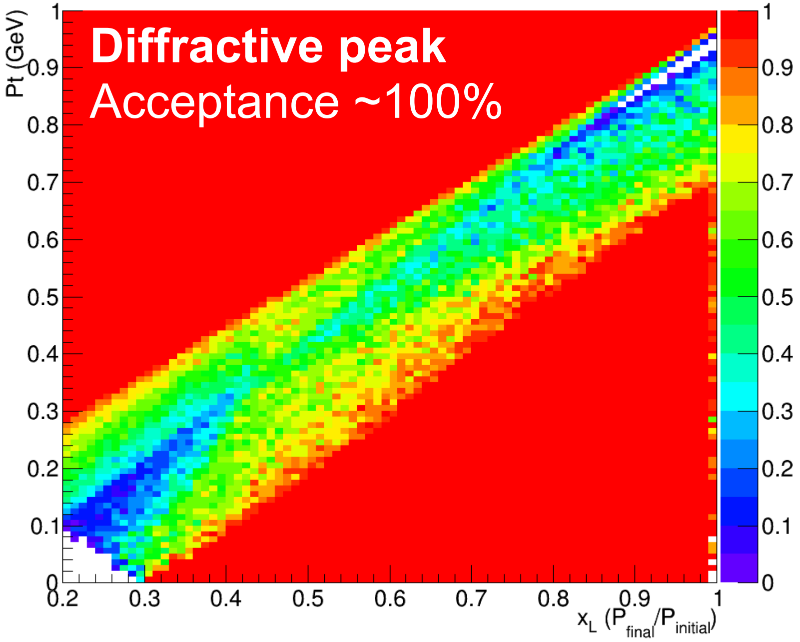
Example for far-forward detection: Diffractive DIS

Diffractive DIS

Signature for saturation

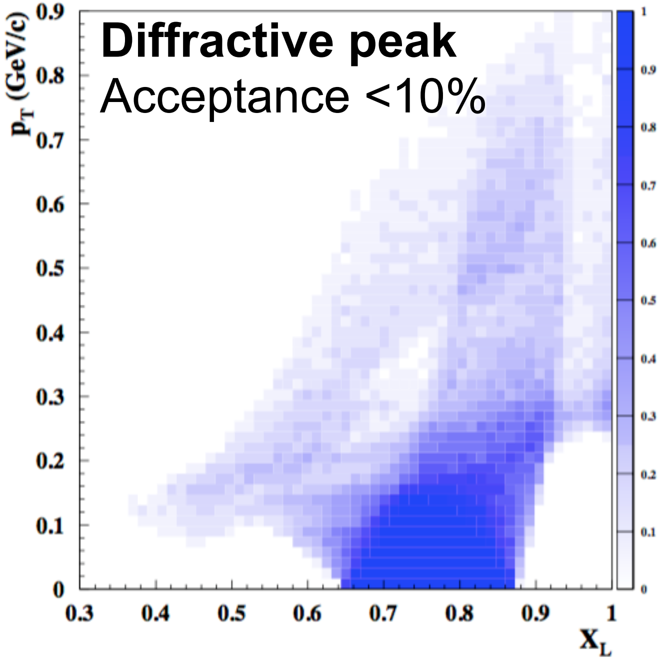


JLEIC



ZEUS

Leading Proton Spectrometer



Identify the scattered proton p'

- distinguish from proton dissociation
- measure $X_L = E_p'/E_p$, and P_t (or t)

Measurement for p' in DDIS

diffractive peak X_L>~.98

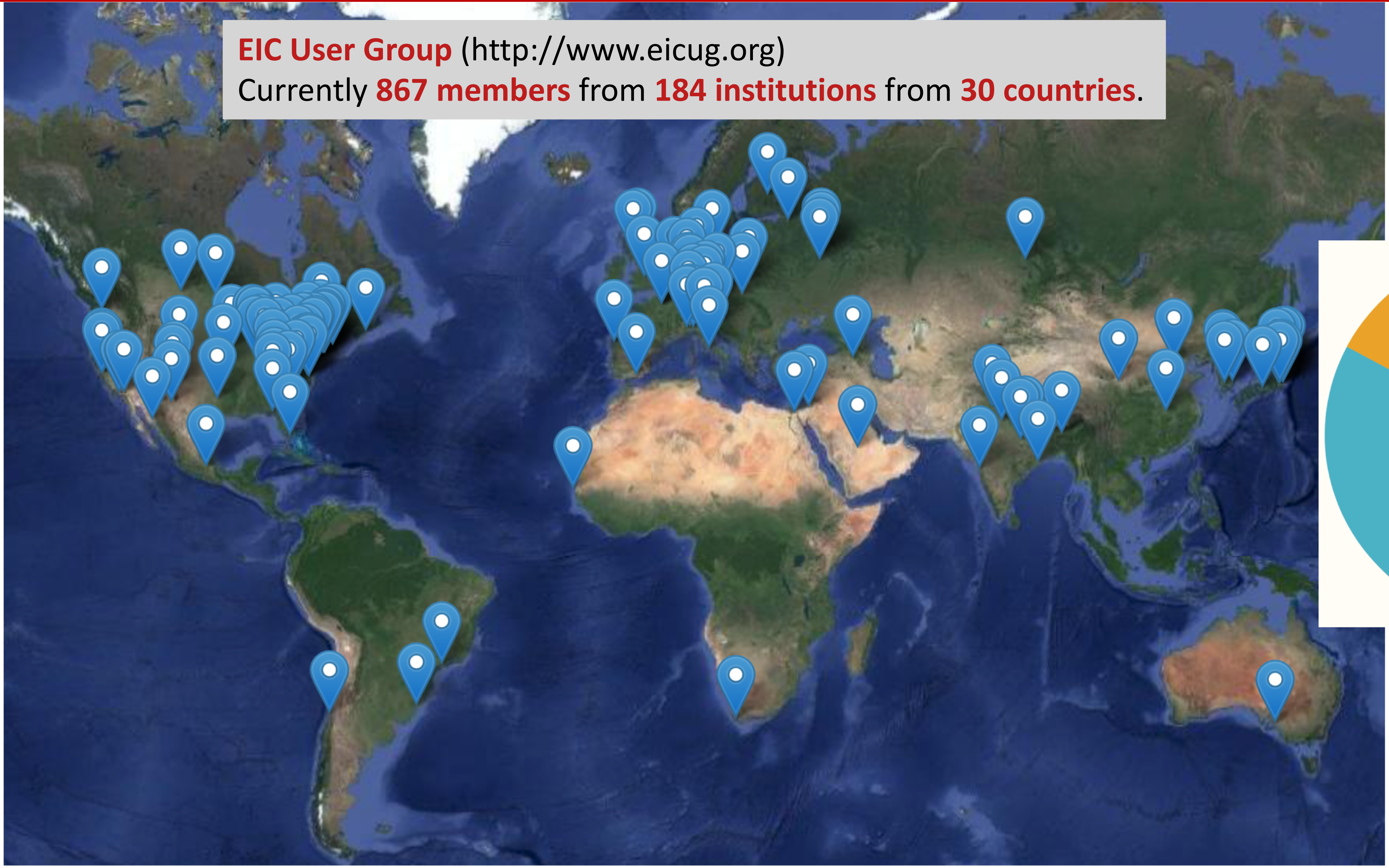
Jefferson Lab

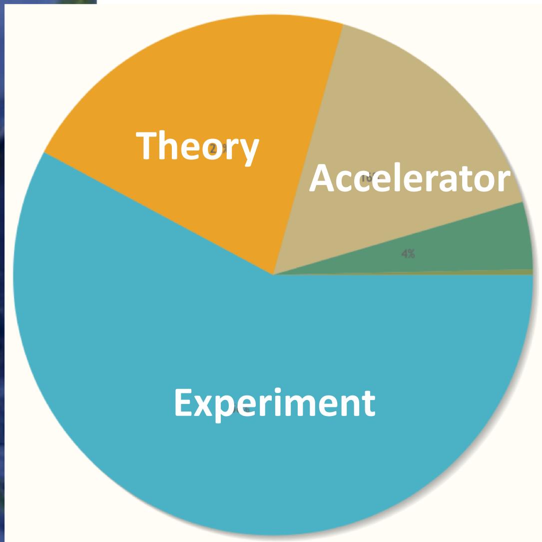
DOE and the EIC User Group

The realization of the EIC project

The worldwide EIC community

EIC User Group (http://www.eicug.org)
Currently **867 members** from **184 institutions** from **30 countries**.





Status of the EIC project

President's Budget FY 2020 Budget Justification

See Volume 4 – Science, pages 269-326 for Nuclear Physics

Page 270

"The 2015 NSAC LRP for Nuclear Science recommended a high-energy, high-luminosity polarized Electron-Ion Collider (EIC) as the highest priority for new facility construction following the completion of FRIB. Consistent with that vision, in 2016 NP commissioned a National Academy of Sciences (NAS) study by an independent panel of external experts to assess the uniqueness and scientific merit of such a facility. The report, released in July 2018, **strongly supports the scientific case for building a U.S.-based EIC, documenting that an EIC will advance the understanding of the origins of nucleon mass, the origin of the spin properties of nucleons, and the behavior of gluons**."

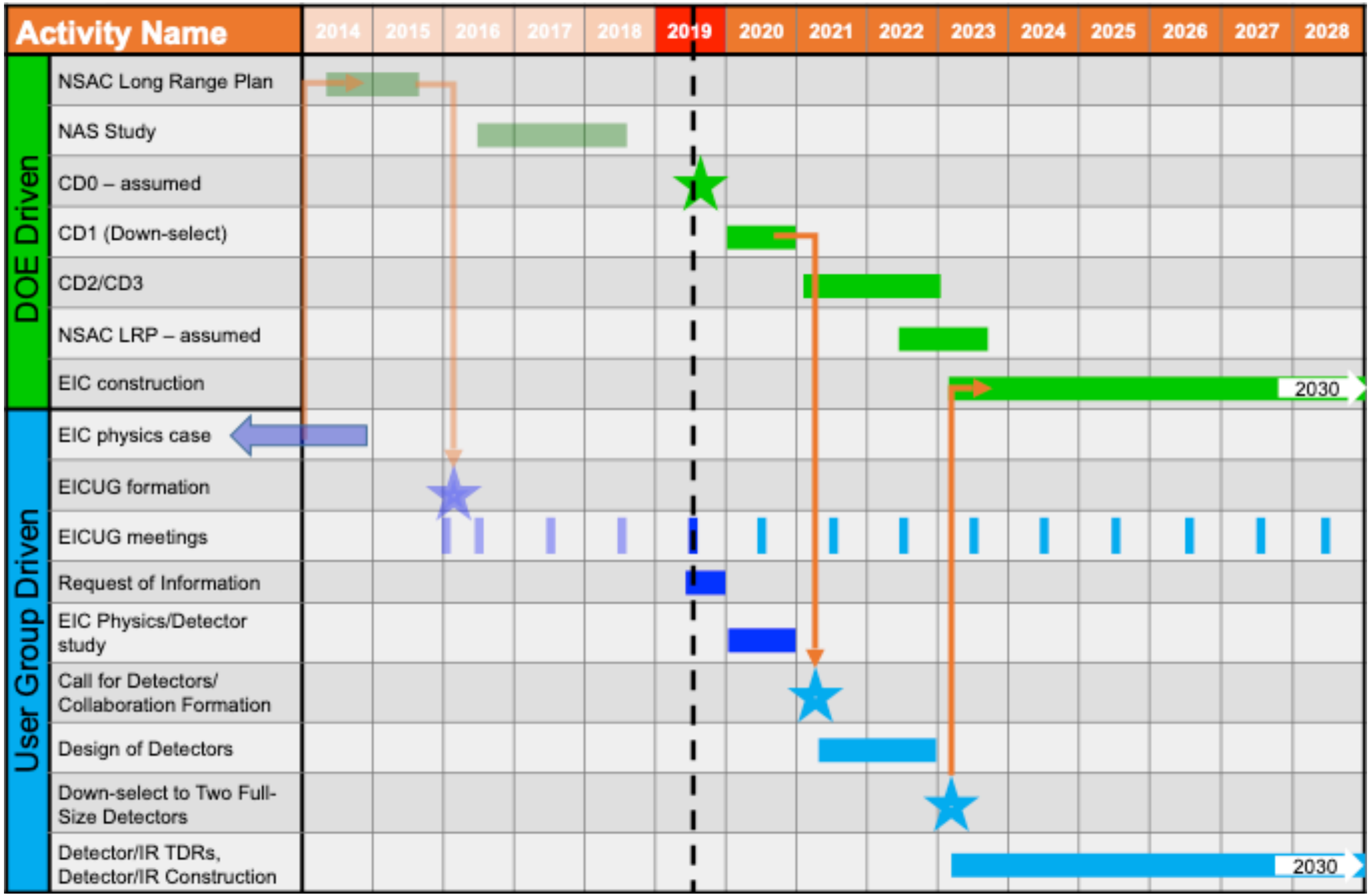
Page 272

"The Request for Construction and Major Items of Equipment (MIEs) includes:"

(…)

Other Project Costs (OPC) funding to support high priority, critically needed accelerator R&D to retire high risk technical challenges for the proposed U.S.-based EIC. Subsequent to the FY 2018 National Academy of Science Report confirming the importance of a domestic EIC to sustain U.S. world leadership in nuclear science and accelerator R&D core competencies. **Critical Decision-0, Approve Mission Need, is planned for FY 2019**."

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

Markus Diefenthaler

mdiefent@jlab.org

Summary

- The Electron-Ion Collider (EIC) 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.
- **TMDs** Imaging quarks and gluons
  - **HERMES** Pioneering TMD measurements
  - **Precision TMD studies** The 12 GeV Science Program at Jefferson Lab
  - **EIC** A new frontier in Nuclear Physics
- What we learn at JLAB 12 and later EIC, together with advances enabled by FRIB and LQCD studies, will open the door to **a transformation of Nuclear Physics**.