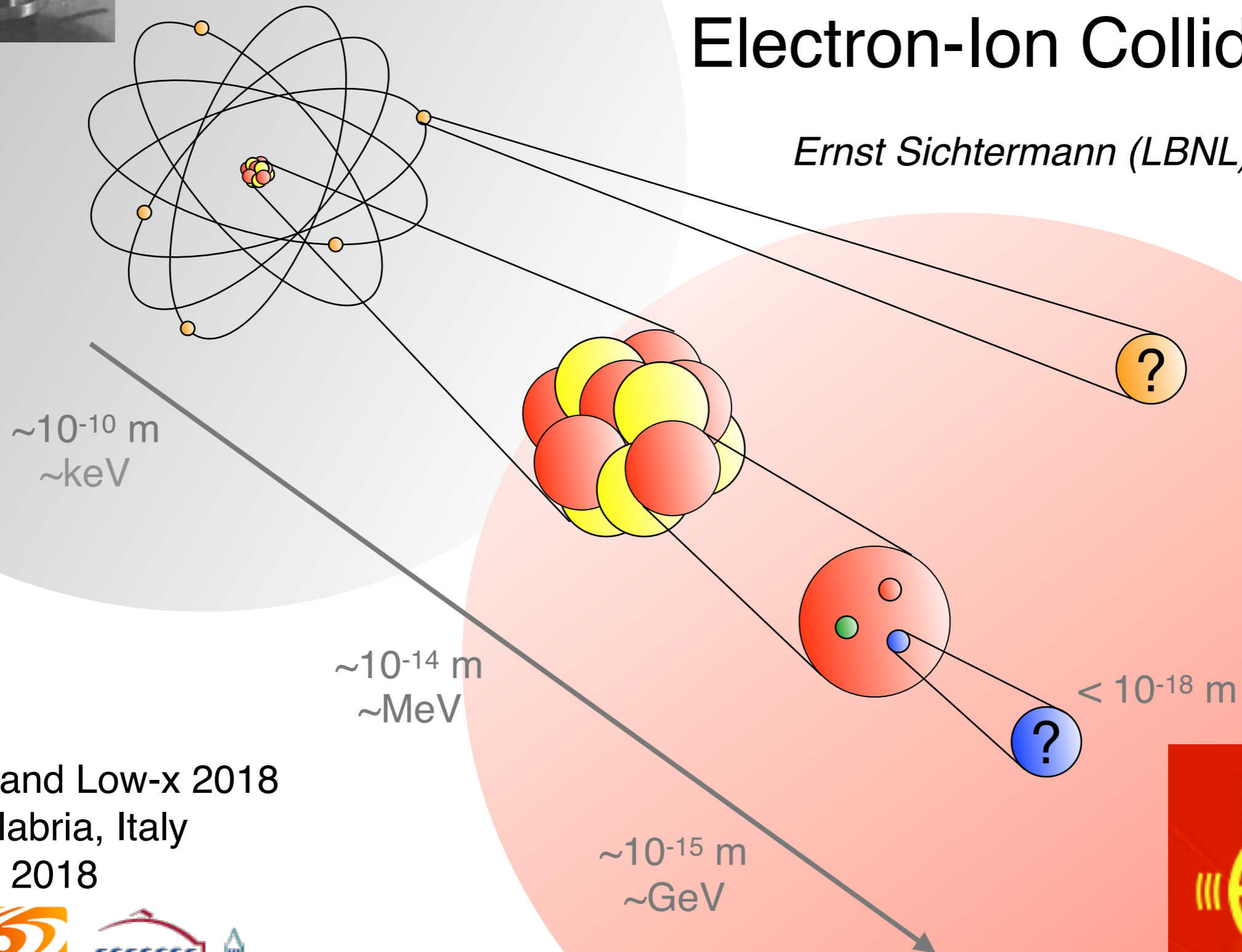


# Spin Physics Opportunities at an Electron-Ion Collider

*Ernst Sichteremann (LBNL)*



Diffraction and Low-x 2018  
Reggio Calabria, Italy  
August 29, 2018



# Electron Ion Collider Initiatives

Past

Possible Future

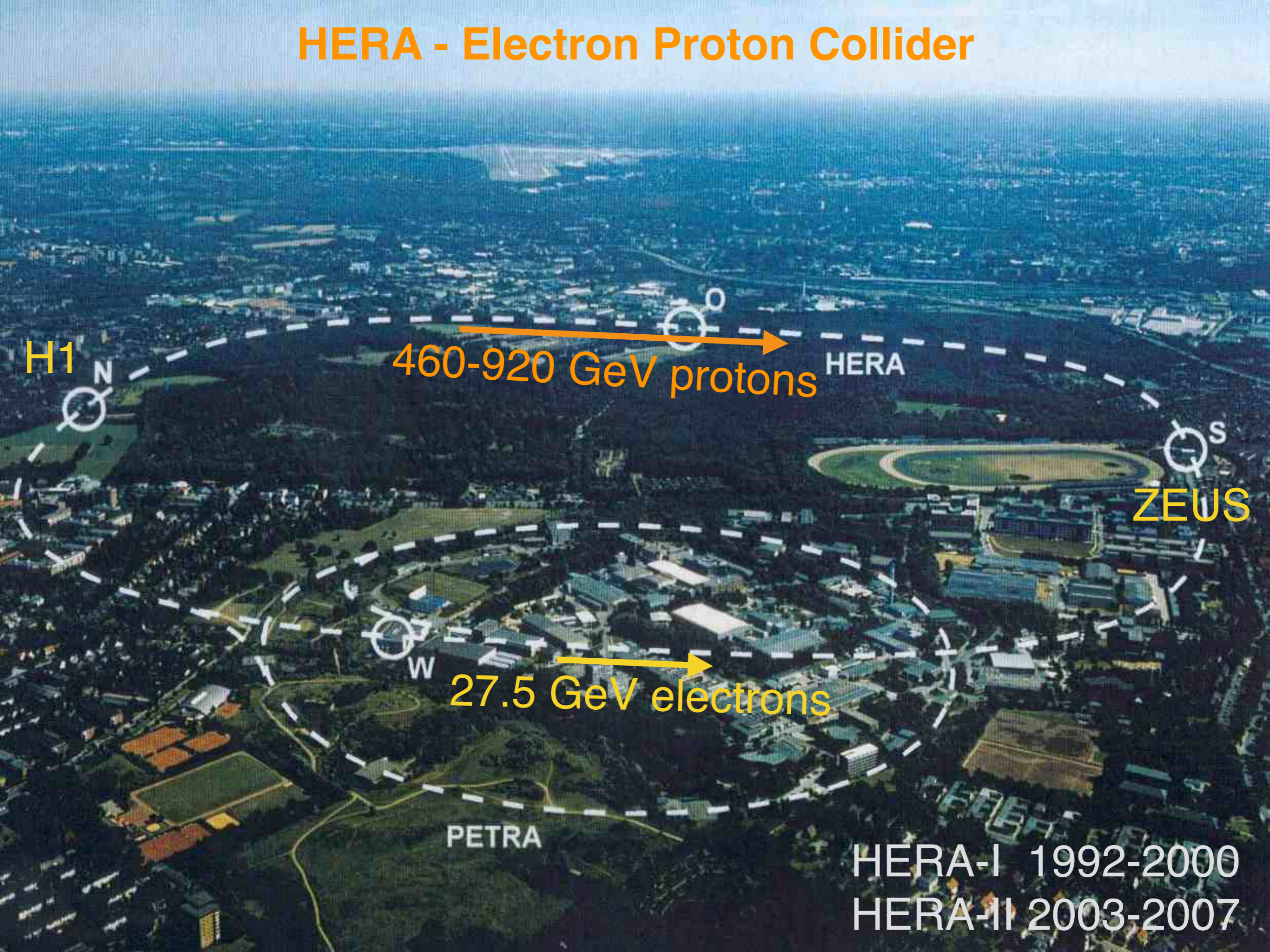
	HERA @ DESY	LHeC @ CERN	HIAF @ CAS	ENC @ GSI	JLEIC @ JLab	eRHIC @ BNL
$\sqrt{s}$ [GeV]	320	800 - 1300	12 - 65	14	20 - 140	78 - 145
proton $x_{min}$	$1 \times 10^{-5}$	$5 \times 10^{-7}$	$7 \times 10^{-3} - 3 \times 10^{-4}$	$5 \times 10^{-3}$	$1 \times 10^{-4}$	$5 \times 10^{-5}$
ion	p	p to Pb	p to U	p to $\sim^{40}\text{Ca}$	p to Pb	p to U
polarization	-	-	p, d, $^3\text{He}$	p, d	p, d, $^3\text{He}$ ( $^6\text{Li}$ )	p, $^3\text{He}$
L [ $\text{cm}^{-2}\text{s}^{-1}$ ]	$2 \times 10^{31}$	$10^{34}$	$10^{32-33} - 10^{35}$	$10^{32}$	$10^{33-34}$	$10^{33}$
Interaction Points	2	1 (?)	1	1	2+	1-2
Year	1992 - 2007	post ALICE	2019 - 2030	upgrade to FAIR	post 12 GeV	2025+

High-Energy Physics

Nuclear Physics

World Wide Interest

# HERA - Electron Proton Collider



H1

460-920 GeV protons

HERA

ZEUS

27.5 GeV electrons

PETRA

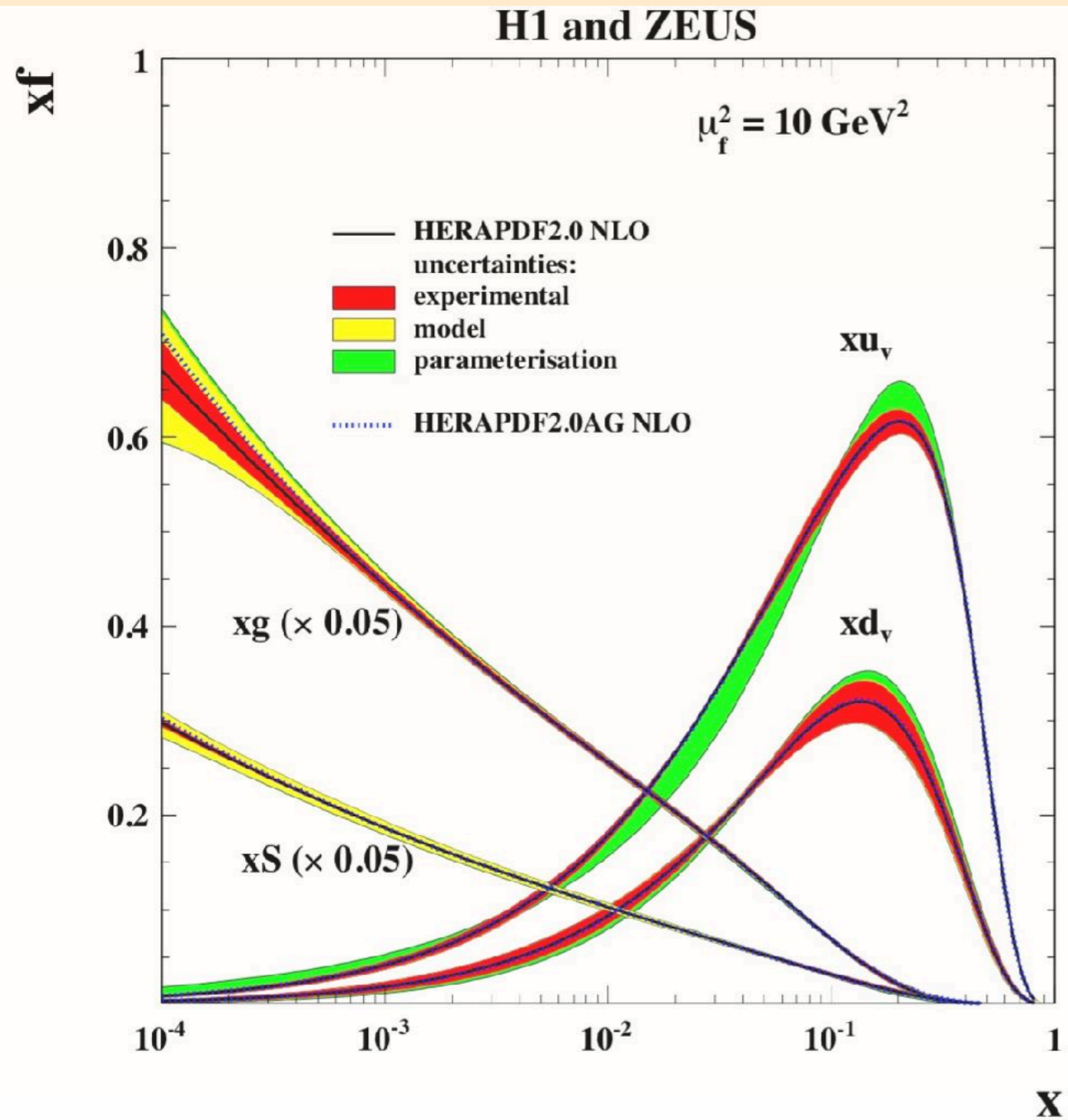
HERA-I 1992-2000

HERA-II 2003-2007

# HERA's Legacy

The proton in terms of gluons and quarks

... and quite remarkable voids:



Precision  $F_L$  - insufficient time,  
Test isospin, u-d, - no deuterons,  
d/u at large x - luminosity,  
Strange quark distributions - luminosity,  
Quark-gluon dynamics in nuclei - no nuclei,  
Saturation - insufficient  $\sqrt{s}$  / no nuclei,  
To BFKL or not to BFKL?

...

Spin puzzle - no hadron beam polarization,  
Imaging - polarization, luminosity,

# What *is* a proton, neutron, nucleus?



*At high energy: an unseparated, broadband beam of quarks, anti-quarks, and gauge bosons (primarily gluons), and perhaps other constituents, yet unknown.*

*40 years of an amazingly robust idealization:  
Renormalization group-improved Parton Model*

*Factorization theorem(s) + one-dimensional parton distributions,  
no correlations among the partons*

# What *is* a proton, neutron, nucleus?



*At high energy: an unseparated, broadband beam of quarks, anti-quarks, and gauge bosons (primarily gluons), and perhaps other constituents, yet unknown.*

*40 years of an amazingly robust idealization:  
Renormalization group-improved Parton Model*

*Factorization theorem(s) + one-dimensional parton distributions,  
no correlations among the partons*

***Really? More than a few of our high-energy observations are actually different  
How does nucleon spin emerge from quarks and gluons?***

# Electron Ion Collider Initiatives

Past

Possible Future

	HERA @ DESY	LHeC @ CERN	HIAF @ CAS	ENC @ GSI	JLEIC @ JLab	eRHIC @ BNL
$\sqrt{s}$ [GeV]	320	800 - 1300	12 - 65	14	20 - 140	78 - 145
proton $x_{min}$	$1 \times 10^{-5}$	$5 \times 10^{-7}$	$7 \times 10^{-3} - 3 \times 10^{-4}$	$5 \times 10^{-3}$	$1 \times 10^{-4}$	$5 \times 10^{-5}$
ion	p	p to Pb	p to U	p to $\sim^{40}\text{Ca}$	p to Pb	p to U
polarization	-	-	p, d, $^3\text{He}$	p, d	p, d, $^3\text{He}$ ( $^6\text{Li}$ )	p, $^3\text{He}$
L [ $\text{cm}^{-2}\text{s}^{-1}$ ]	$2 \times 10^{31}$	$10^{34}$	$10^{32-33} - 10^{35}$	$10^{32}$	$10^{33-34}$	$10^{33}$
Interaction Points	2	1 (?)	1	1	2+	1-2
Year	1992 - 2007	post ALICE	2019 - 2030	upgrade to FAIR	post 12 GeV	2025+

High-Energy Physics

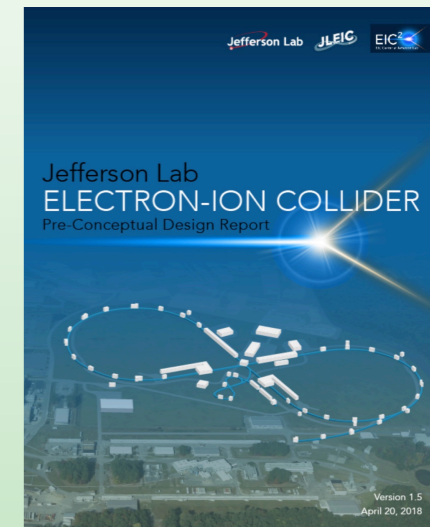
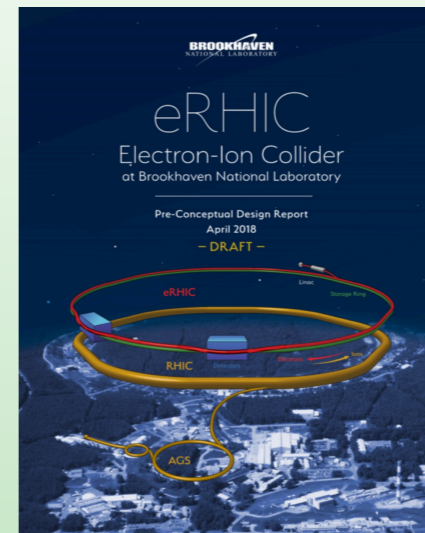
Nuclear Physics

World Wide Interest

# Electron Ion Collider Initiatives

Strategy: combine strengths  
 optimally use existing investments,  
 pursue luminosity; 100x - 1000x HERA  
 nuclei and *polarization* (eRHIC, JLEIC),  
 nuclei and *energy* (LHeC),  
 optimized instrumentation.

	HERA @ DESY	LHeC @ CERN	HIAF @ CAS	ENC @ GSI	JLEIC @ JLab	eRHIC @ BNL
$\sqrt{s}$ [GeV]	320	800 - 1300	12 - 65	14	20 - 140	78 - 145
proton $x_{min}$	$1 \times 10^{-5}$	$5 \times 10^{-7}$	$7 \times 10^{-3} - 3 \times 10^{-4}$	$5 \times 10^{-3}$	$1 \times 10^{-4}$	$5 \times 10^{-5}$
ion	p	p to Pb	p to U	p to $\sim^{40}\text{Ca}$	p to Pb	p to U
polarization	-	-	p, d, $^3\text{He}$	p, d	p, d, $^3\text{He}$ ( $^6\text{Li}$ )	p, $^3\text{He}$
L [ $\text{cm}^{-2}\text{s}^{-1}$ ]	$2 \times 10^{31}$	$10^{34}$	$10^{32-33} - 10^{35}$	$10^{32}$	$10^{33-34}$	$10^{33}$
Interaction Points	2	1 (?)	1	1	2+	1-2
Year	1992 - 2007	post ALICE	2019 - 2030	upgrade to FAIR	post 12 GeV	2025+



See also J.H. Lee's talk yesterday





# U.S.-based EIC - Context

REACHING FOR THE HORIZON

The Site of the Wright Brothers' First Airplane Flight

The 2015  
LONG RANGE PLAN  
for NUCLEAR SCIENCE



## RECOMMENDATION I

The progress achieved under the guidance of the 2007 Long Range Plan has reinforced U.S. world leadership in nuclear science. The highest priority in this 2015 Plan is to **capitalize on the investments made**.

## RECOMMENDATION II

We recommend the timely development and deployment of a U.S.-led **ton-scale neutrinoless double beta decay experiment**.

## RECOMMENDATION III

We recommend a **high-energy high-luminosity polarized EIC** as the highest priority for new facility construction following the completion of FRIB. [Q3 FY22]

## RECOMMENDATION IV

We recommend increasing investment in **small-scale and mid-scale projects and initiatives** that enable **forefront research at universities and laboratories**.

BOARD ON PHYSICS AND ASTRONOMY (BPA)

# An Assessment of U.S.-Based Electron-Ion Collider Science

*A study under the auspices of the  
U.S. National Academies of Sciences, Engineering, and Medicine*

*Gordon Baym and Ani Aprahamian, Co-Chairs*

*The study is supported by funding from the DOE Office of Science.  
(Further information can be found at: <https://www.nap.edu/25171>)*

# Committee - U.S.-Based Electron Ion Collider Science Assessment



The National Academies of Sciences, Medicine, and Engineering work together to provide **independent, objective analysis and advice** to the nation,

### Statement of Task for this study:

The committee will **assess the scientific justification** for a U.S. domestic electron ion collider facility, taking into account current international plans and existing domestic facility infrastructure.

In preparing its report, the committee will address the role that such a facility could play in the **future of nuclear physics**, considering the field broadly, but placing emphasis on its potential **scientific impact on quantum chromodynamics**.

## Bottom Line

The committee *unanimously* finds that the science that can be addressed by an EIC is *compelling, fundamental, and timely*.

The unanimous conclusion of the Committee is that an EIC, as envisioned in this report, would be a *unique facility in the world* that would boost the U.S. STEM workforce and help maintain U.S. scientific leadership in nuclear physics.

The project is *strongly supported by the nuclear physics community*.

The technological *benefits of meeting the accelerator challenges are enormous*, both for basic science and for applied areas that use accelerators, including material science and medicine.

# U.S.-based EIC - Two Facility Concepts

eRHIC:

- upgrade to existing RHIC hadron beam,



JLEIC:

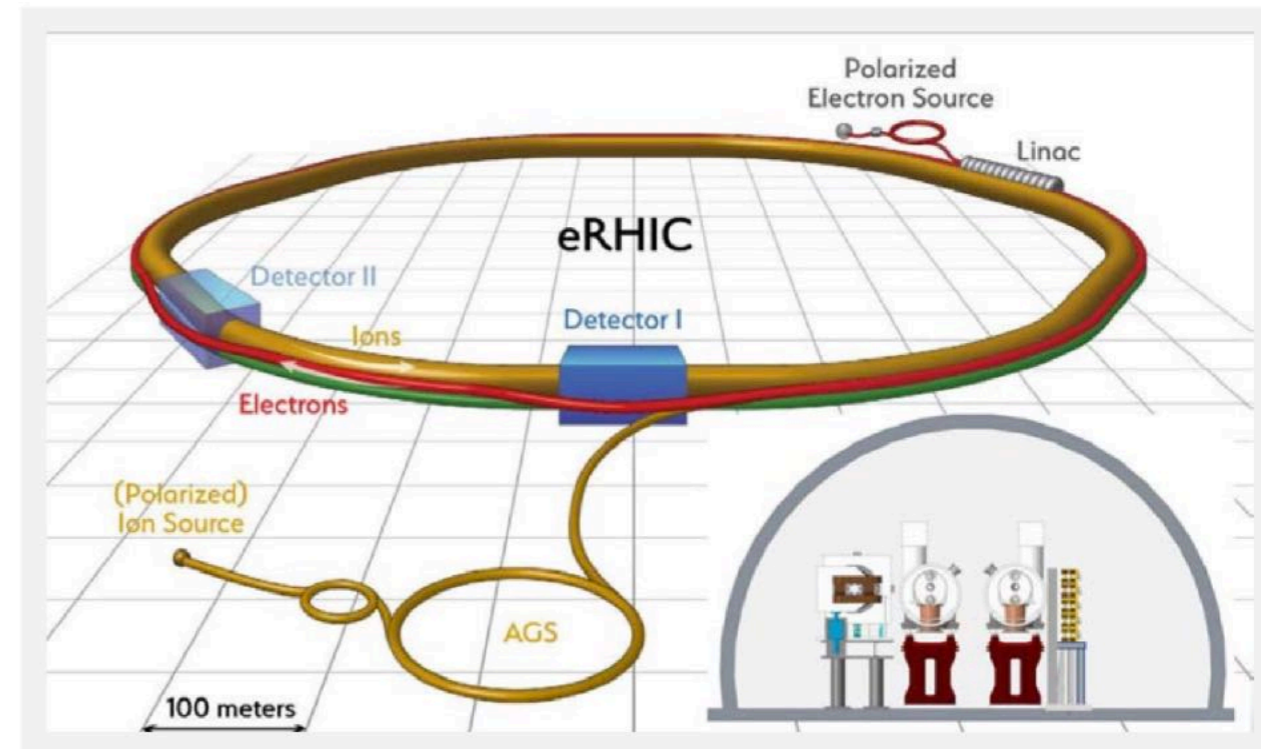
- upgrade to existing CEBAF 12 GeV electron beam,



# U.S.-based EIC - Two Facility Concepts

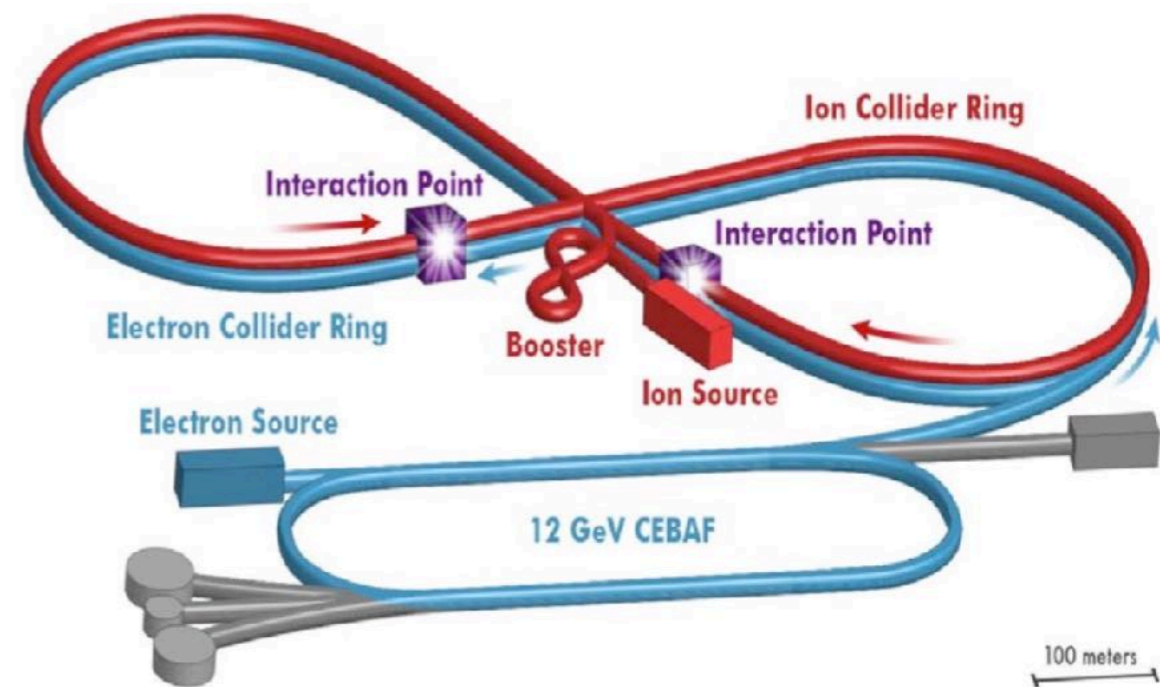
## eRHIC:

- upgrade to RHIC hadron beam,
- new electron storage ring,
- 5 - 18 GeV e energy,
- Heavy Ions up to 100 GeV/u
- $\sqrt{s}$  up to 140 GeV
- $L \sim 0.4 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}/\text{A}$  base design,  
 $1.0 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}/\text{A}$  w. strong cooling



## JLEIC:

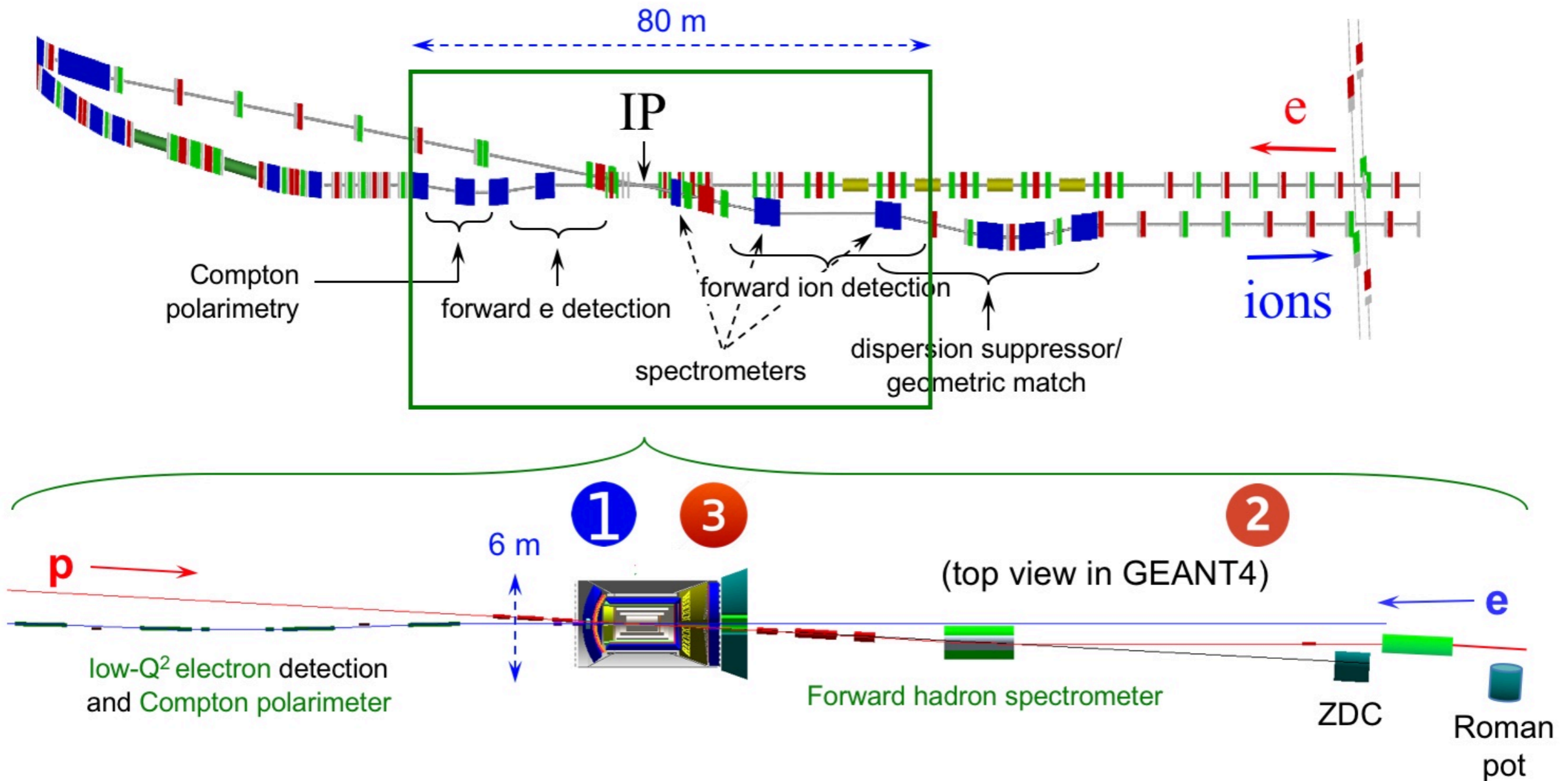
- upgrade to CEBAF 12 GeV electron beam facility,
- new hadron injector,
- new figure-8 collider configuration,
- 3 - 10 GeV electron energy,
- 12-40 GeV/u Heavy Ion energy,  
upgradable (ion arc dipoles)
- $L \sim 10^{34} \text{ cm}^{-2}\text{s}^{-1}/\text{A}$



*Science cases by themselves!*

# U.S.-based EIC - Two Facility Concepts

Science cases by themselves requiring, for example, tight integration with detectors



See J.H. Lee's talk yesterday

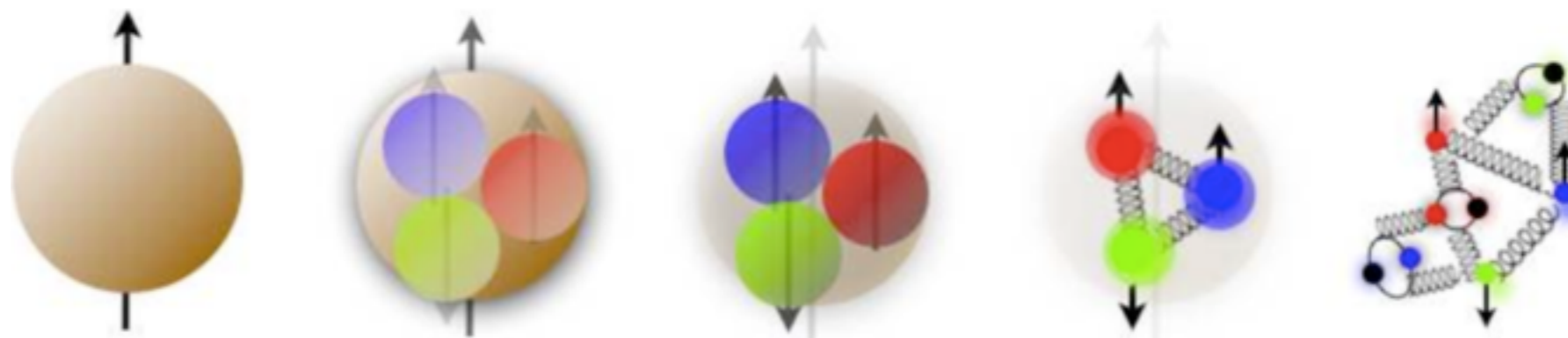
courtesy V. Morozov (JLab)

EIC User Group has just formed a IR working group, c.f. <http://eicug.org>

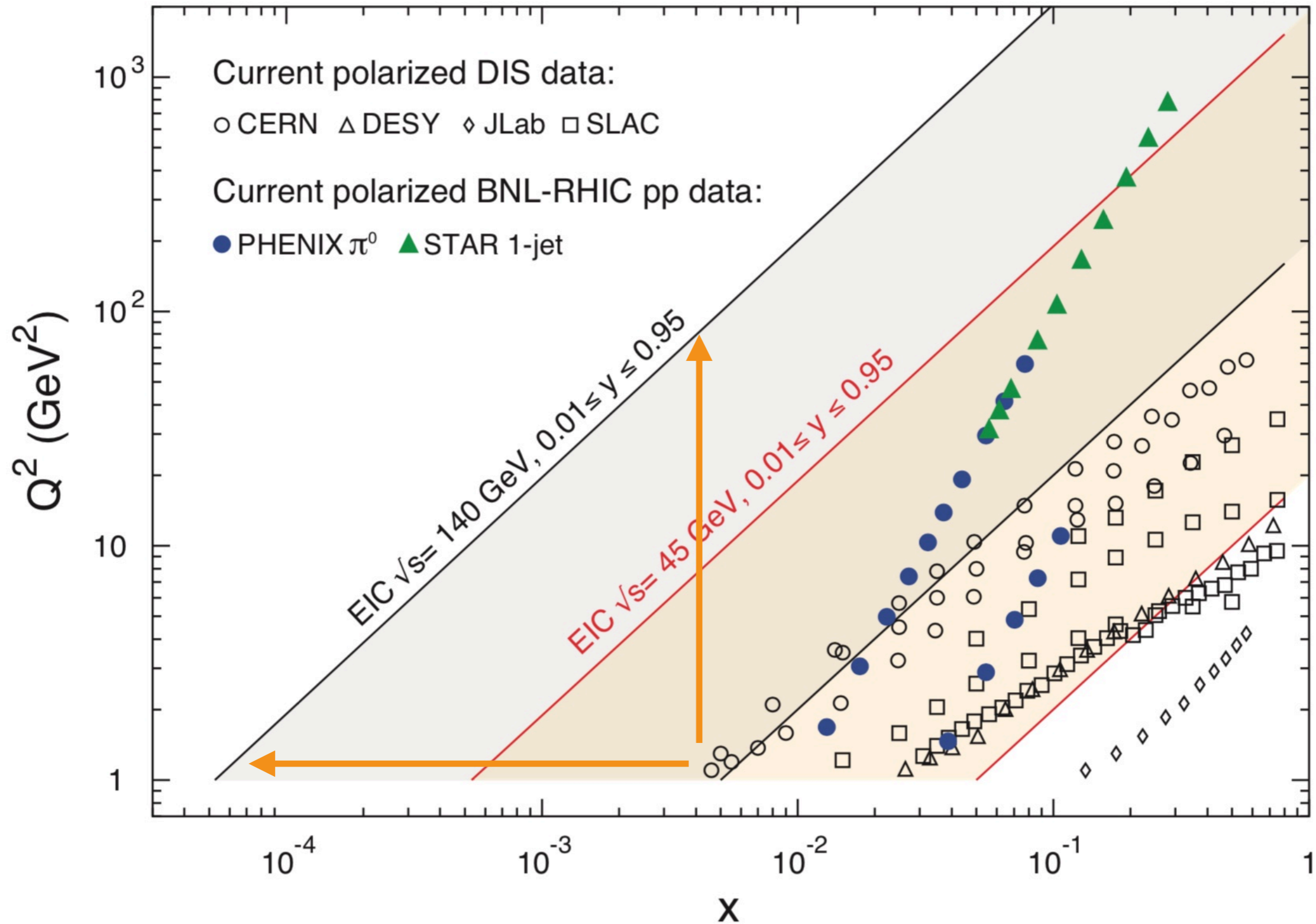
Multiple (central) detector concepts are being pursued within the EIC community, c.f. [https://wiki.bnl.gov/conferences/index.php/EIC\\_R%25D](https://wiki.bnl.gov/conferences/index.php/EIC_R%25D) - generic detector R&D



# U.S.-based EIC - Spin Physics Opportunities



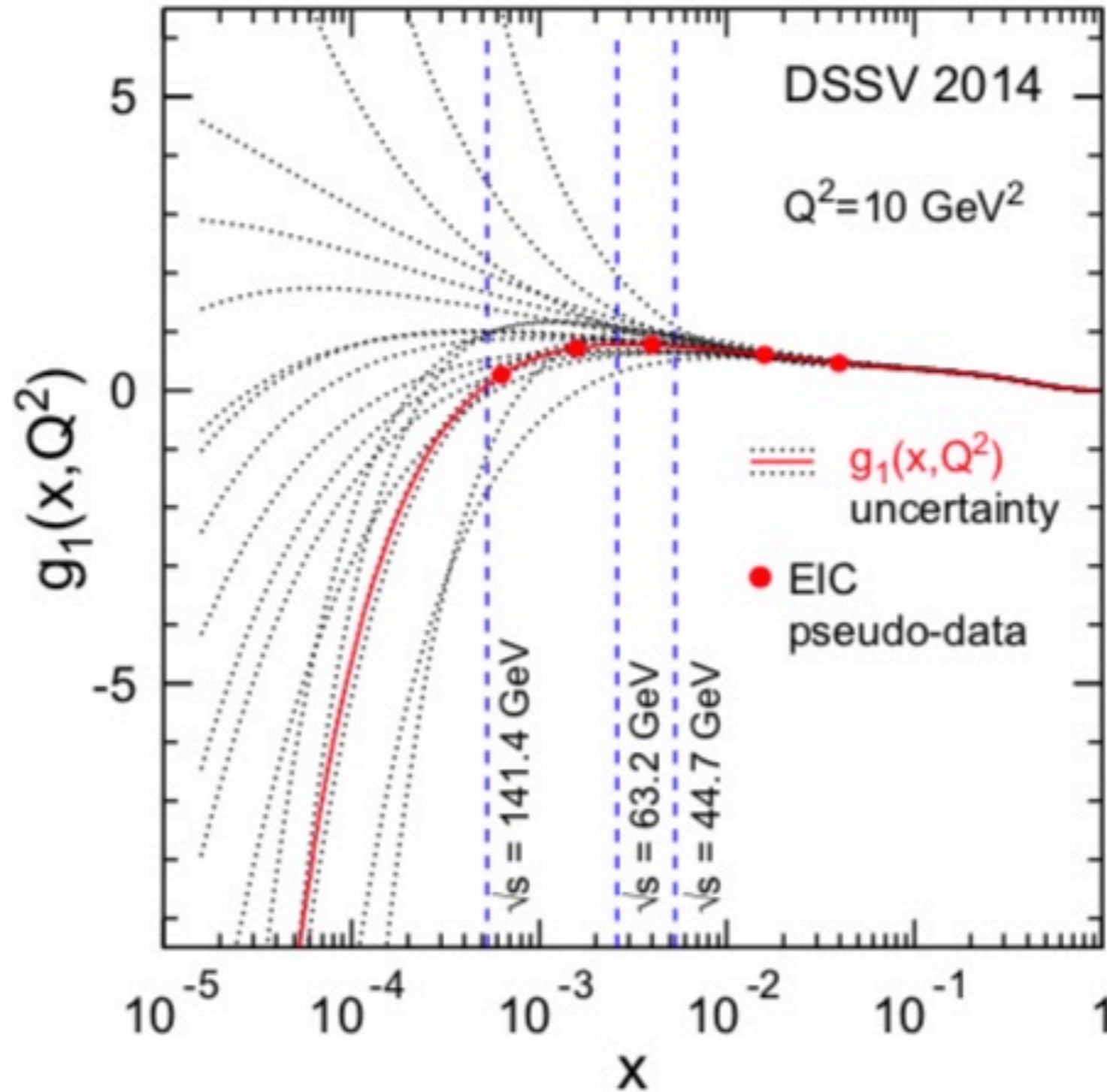
# U.S.-based EIC - Proton Spin



Two orders in  $x$  and  $Q^2$  compared to existing data; few, if any, alternatives.

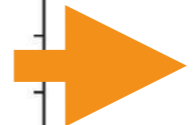
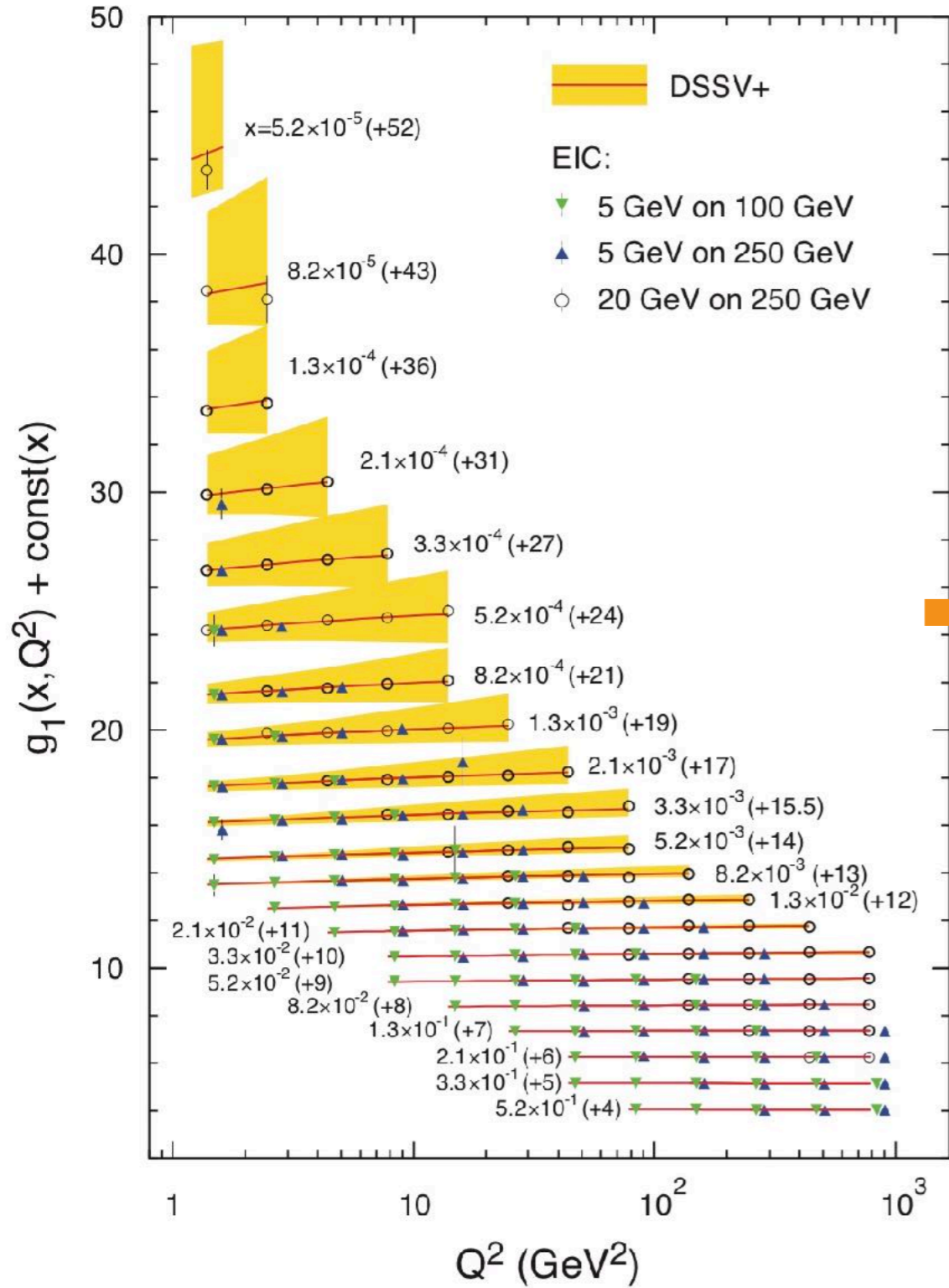
# U.S.-based EIC - Helicity

arXiv:1708.01527

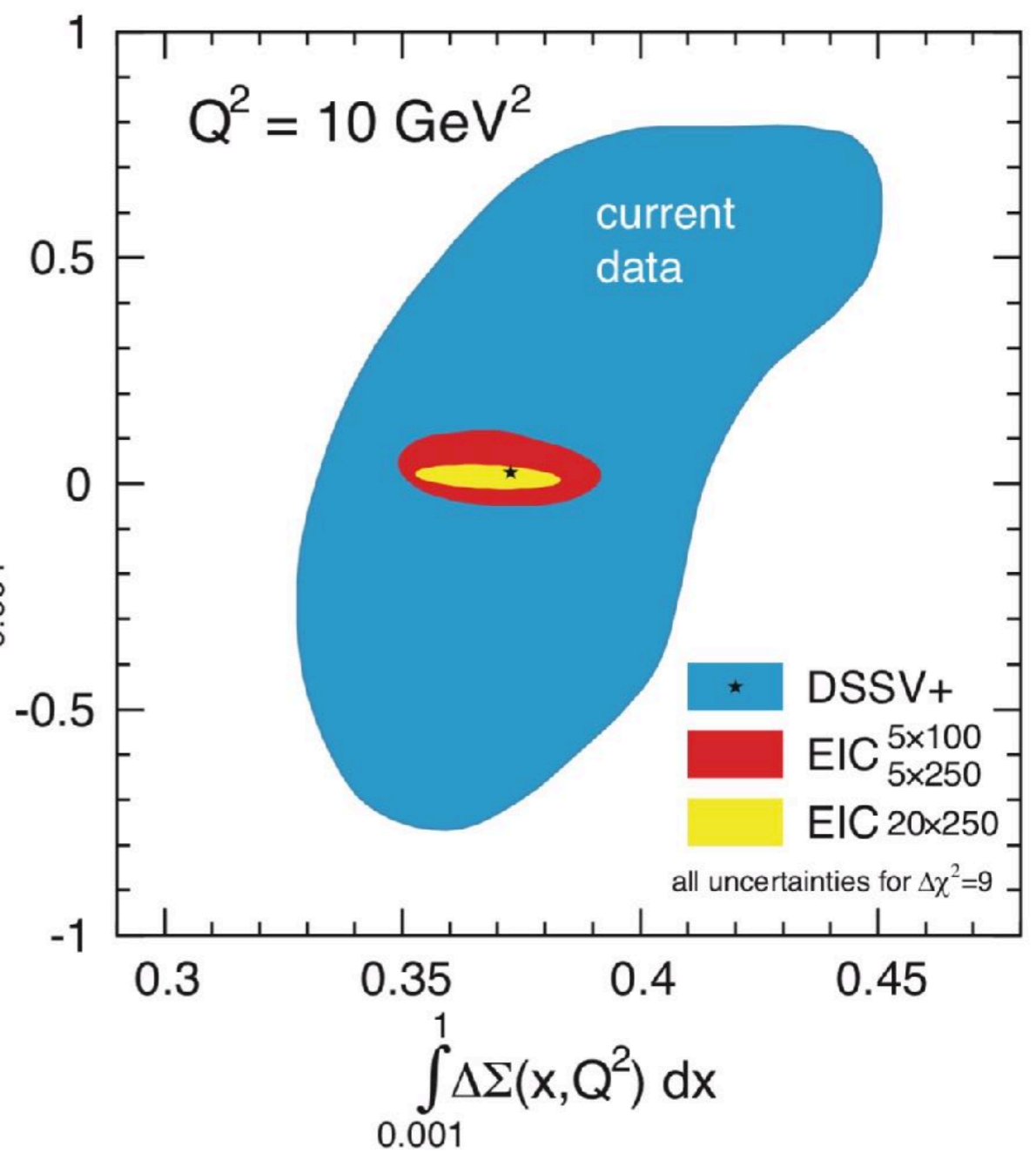


$$\frac{1}{2} \left[ \frac{d^2 \sigma^{\leftarrow}}{dx dQ^2} - \frac{d^2 \sigma^{\rightarrow}}{dx dQ^2} \right] \simeq \frac{4\pi\alpha^2}{Q^4} y(2-y) g_1(x, Q^2)$$

# U.S.-based EIC - Helicity



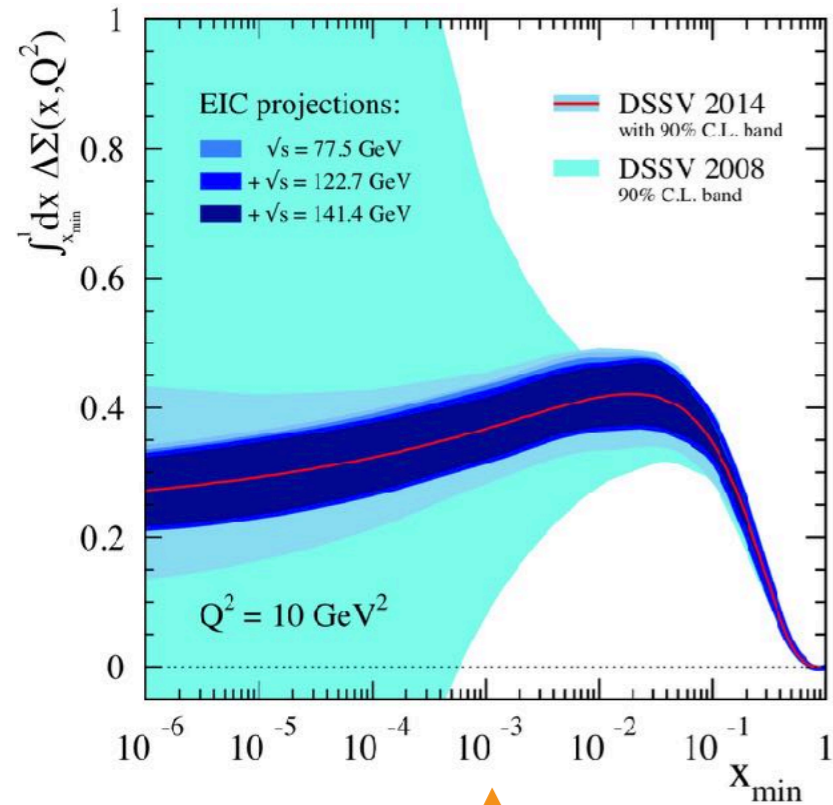
$$\int_{0.001}^1 \Delta g(x, Q^2) dx$$



Conclusive insights in quark and gluon helicity from inclusive measurements, and orbital momentum by subtraction (!)

# U.S.-based EIC - Helicity

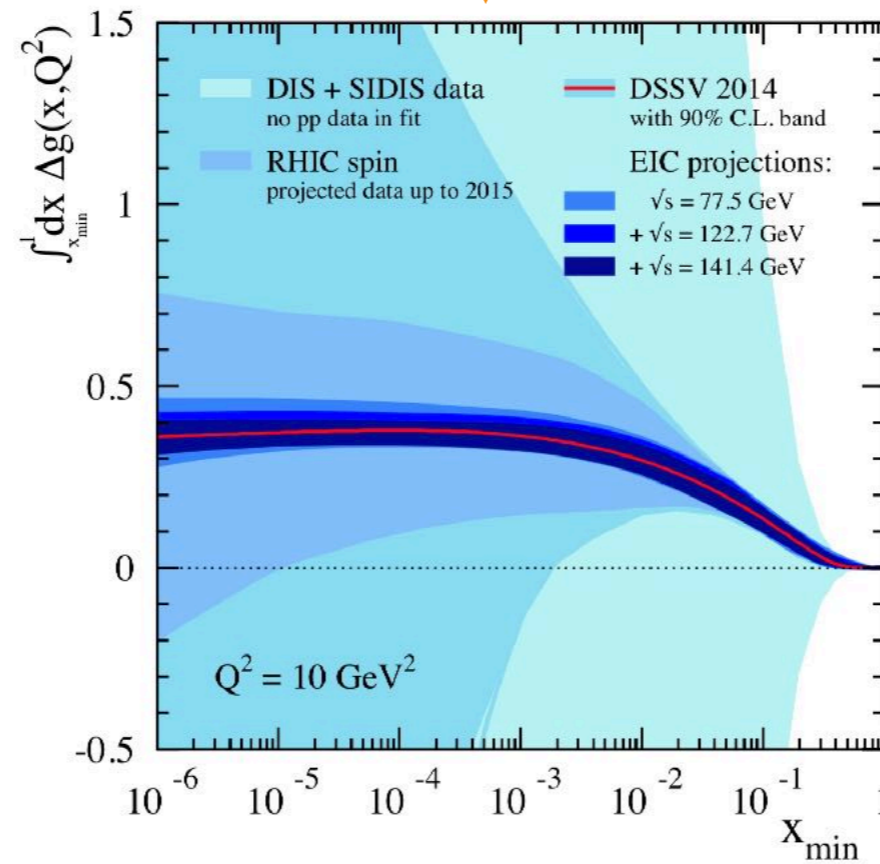
A more up-to-date view; E. Aschenauer et al.  
PRD 92 (2015) 094030



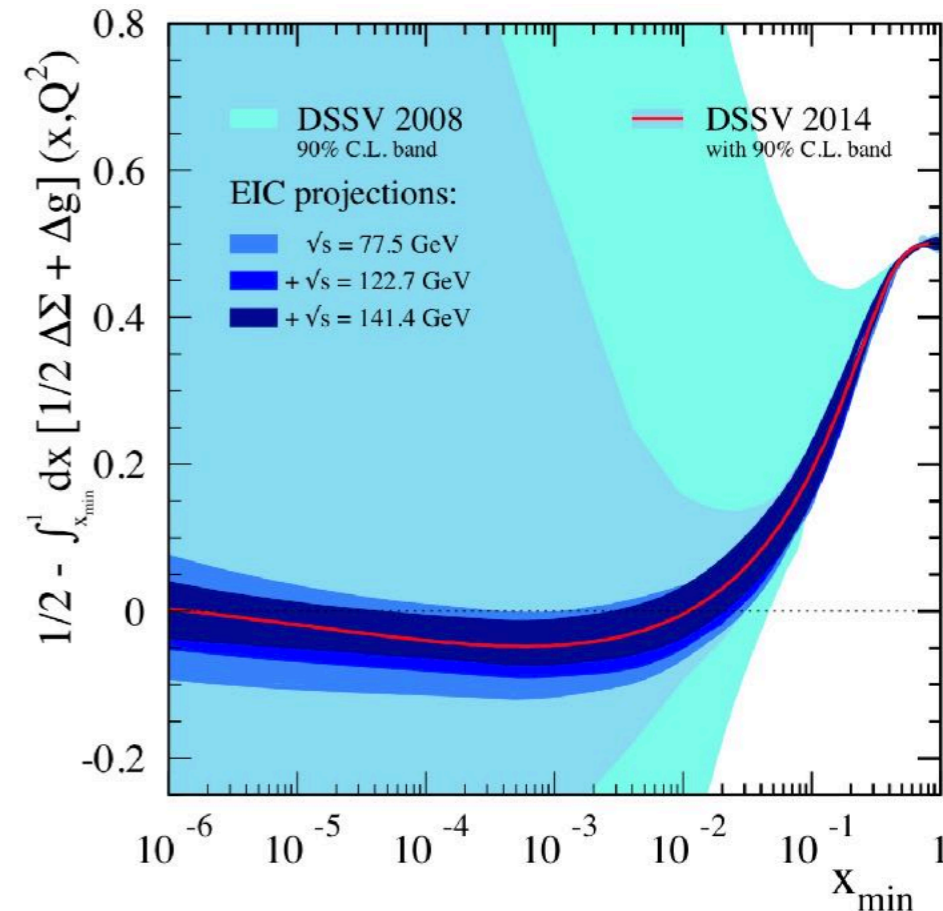
(anti-)quark helicity

Clearly requires EIC

gluon helicity



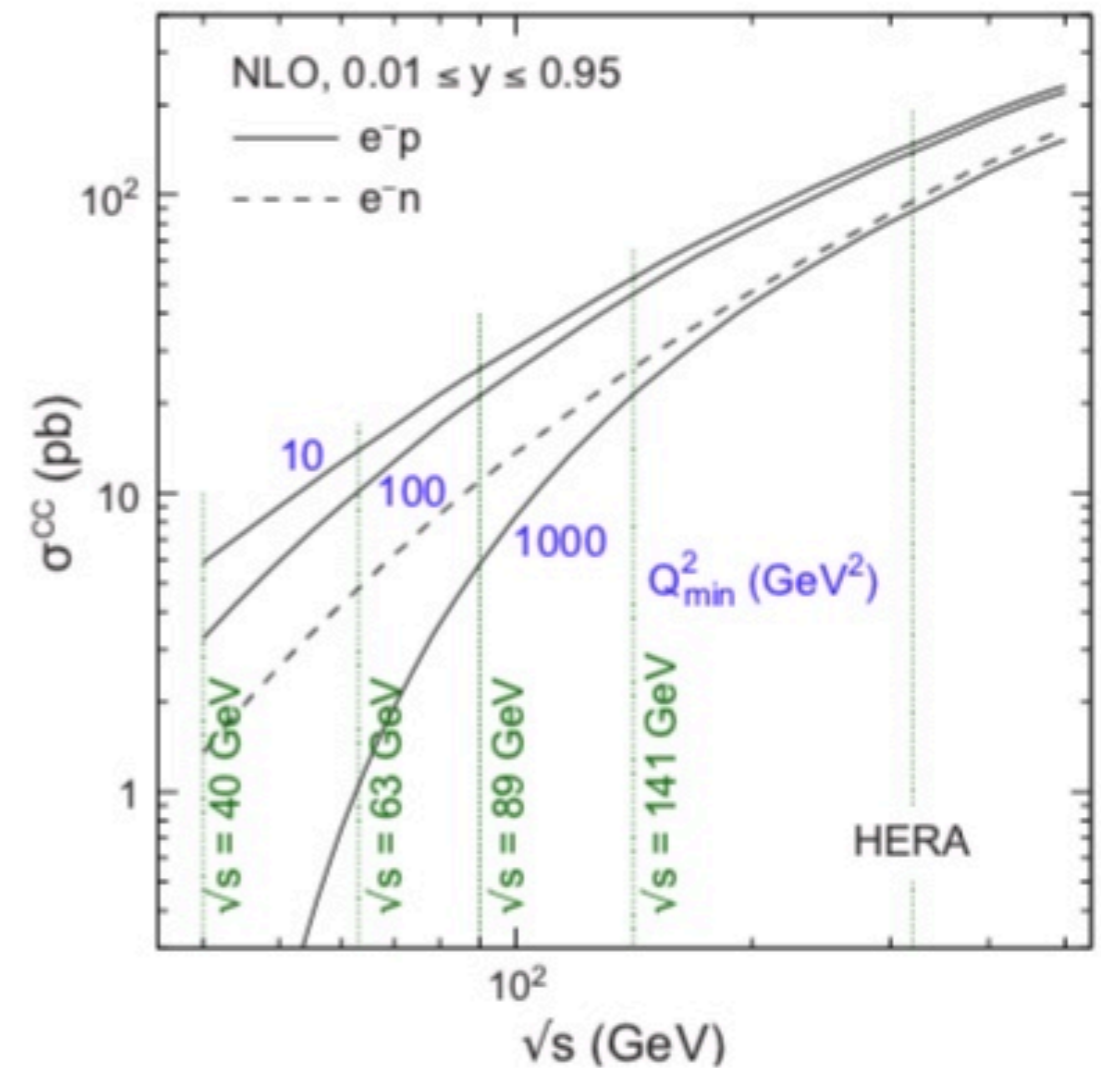
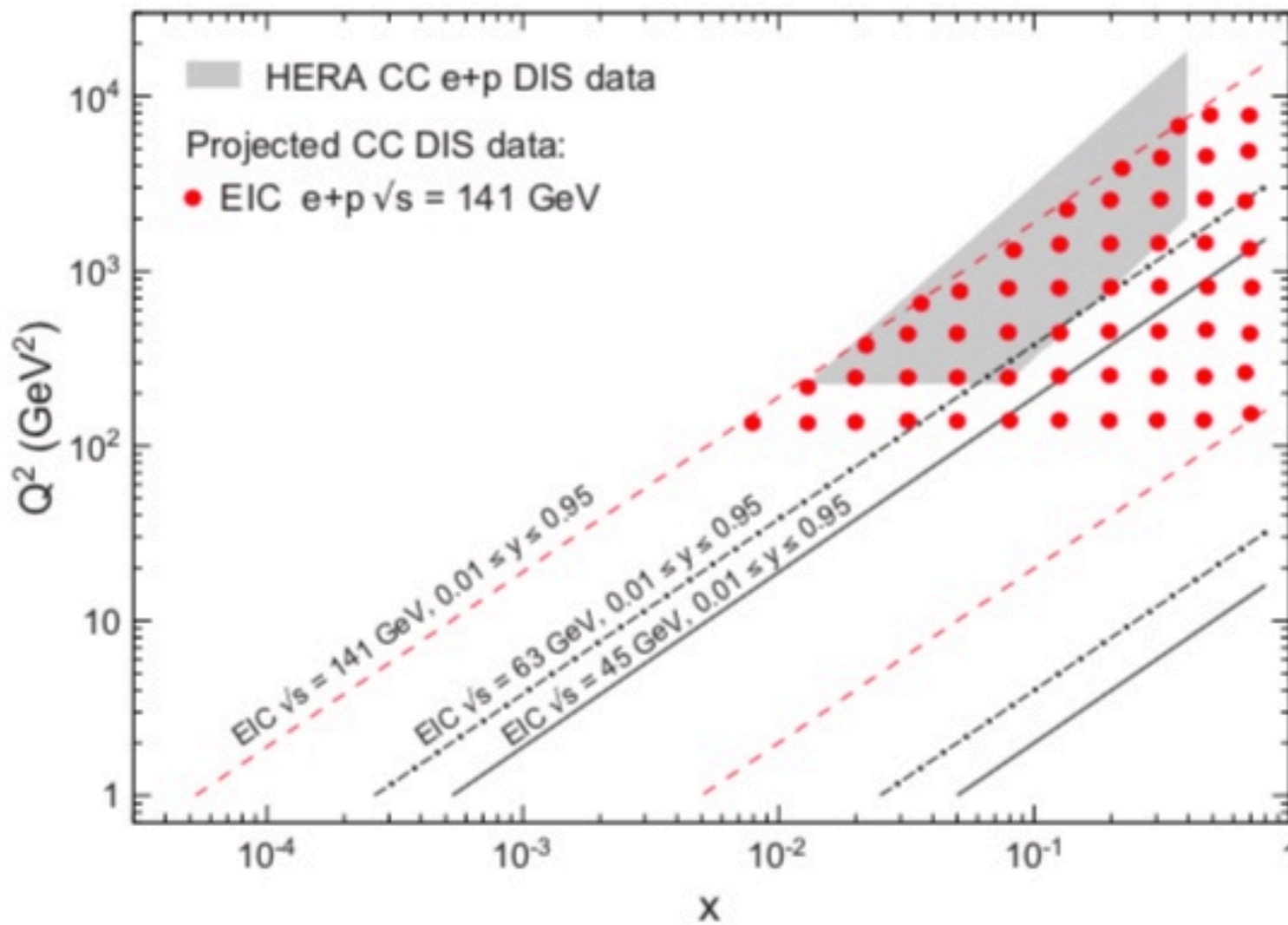
orbital momenta



# U.S.-based EIC - Helicity

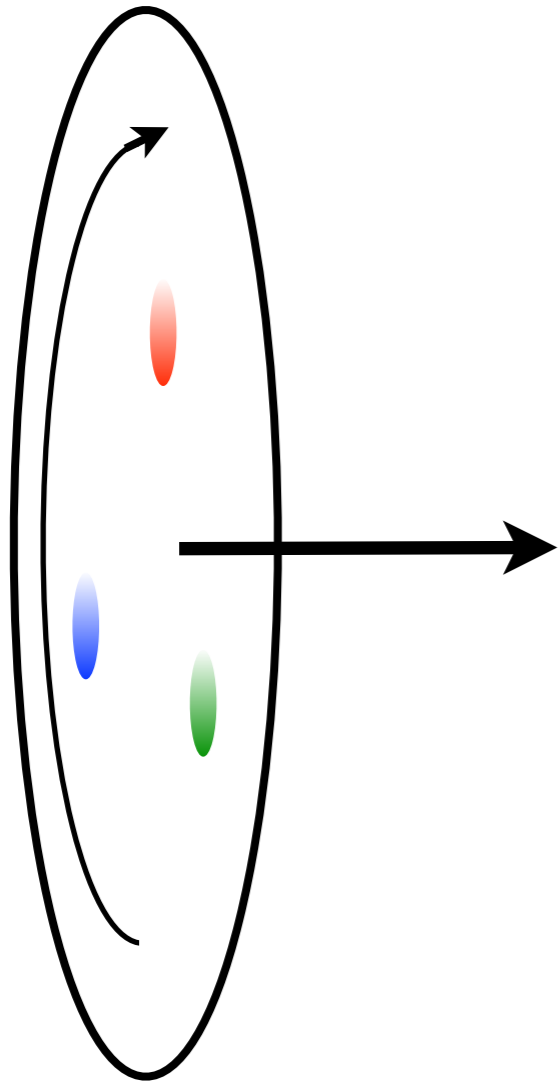
$$g_1^{W^-}(x, Q^2) = [\Delta u + \Delta \bar{d} + \Delta c + \Delta \bar{s}](x, Q^2),$$

$$g_5^{W^-}(x, Q^2) = [-\Delta u + \Delta \bar{d} - \Delta c + \Delta \bar{s}](x, Q^2),$$



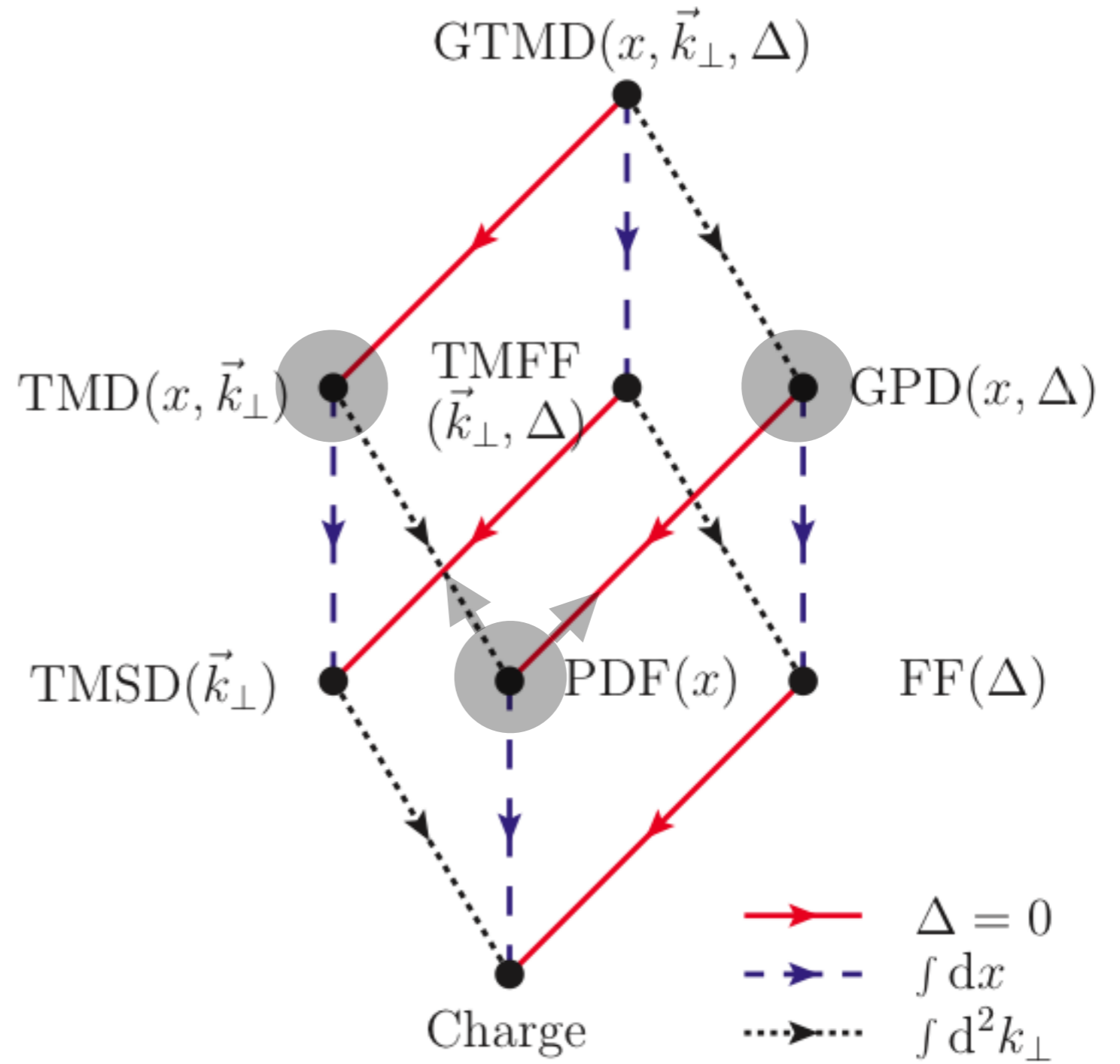
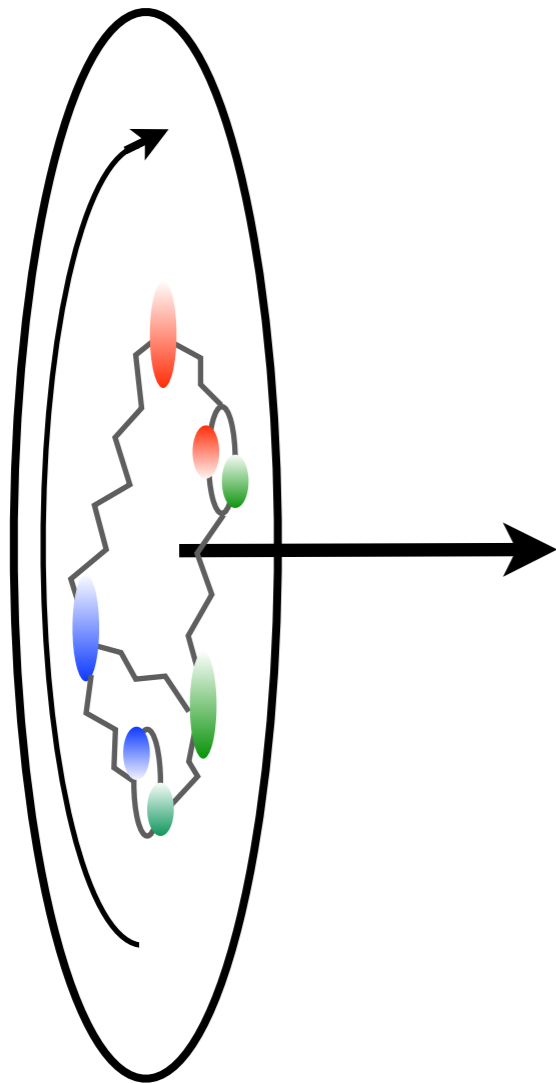
Fragmentation-free insights in flavor structure via NC and CC measurements

# *Intermezzo* - Beyond Helicity Distributions...



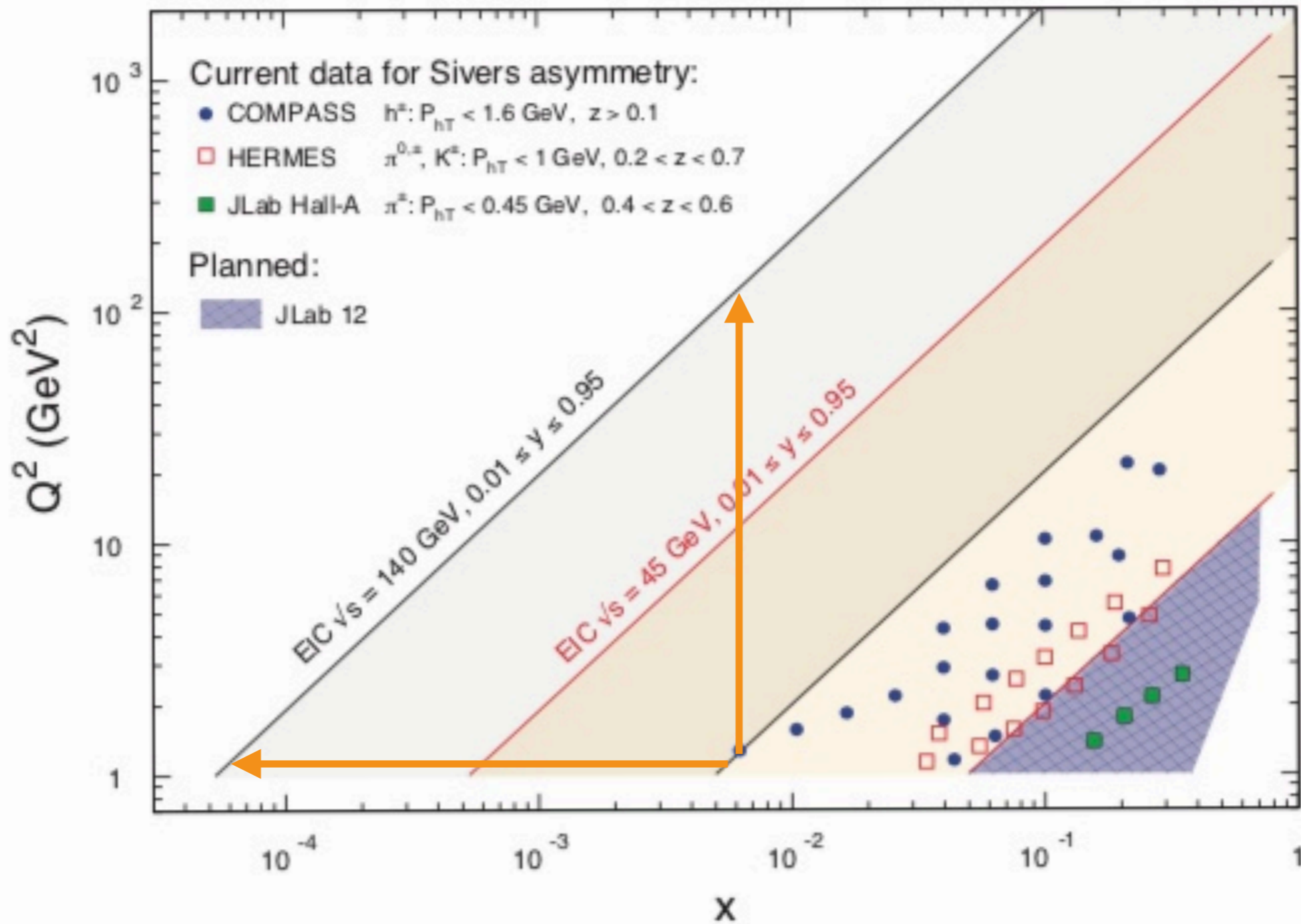
*Simple concepts become involved...*

# Intermezzo - Beyond Helicity Distributions...





# U.S.-based EIC - TMDs

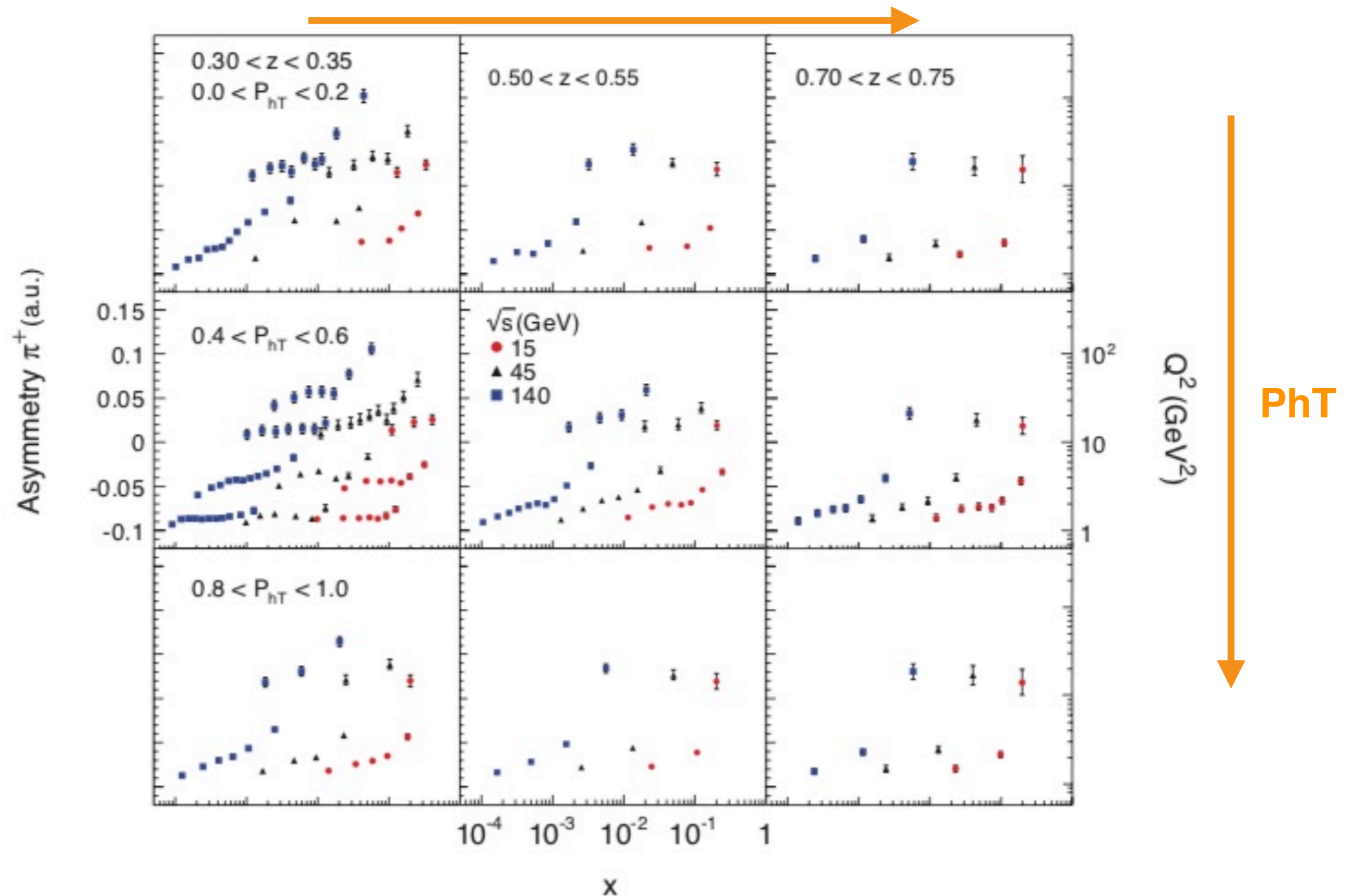


Two orders in  $x$  and  $Q^2$  compared to existing or planned SIDIS data,

Aside, polarized hadroproduction programs essential e.g. to Sivers' sign chg.

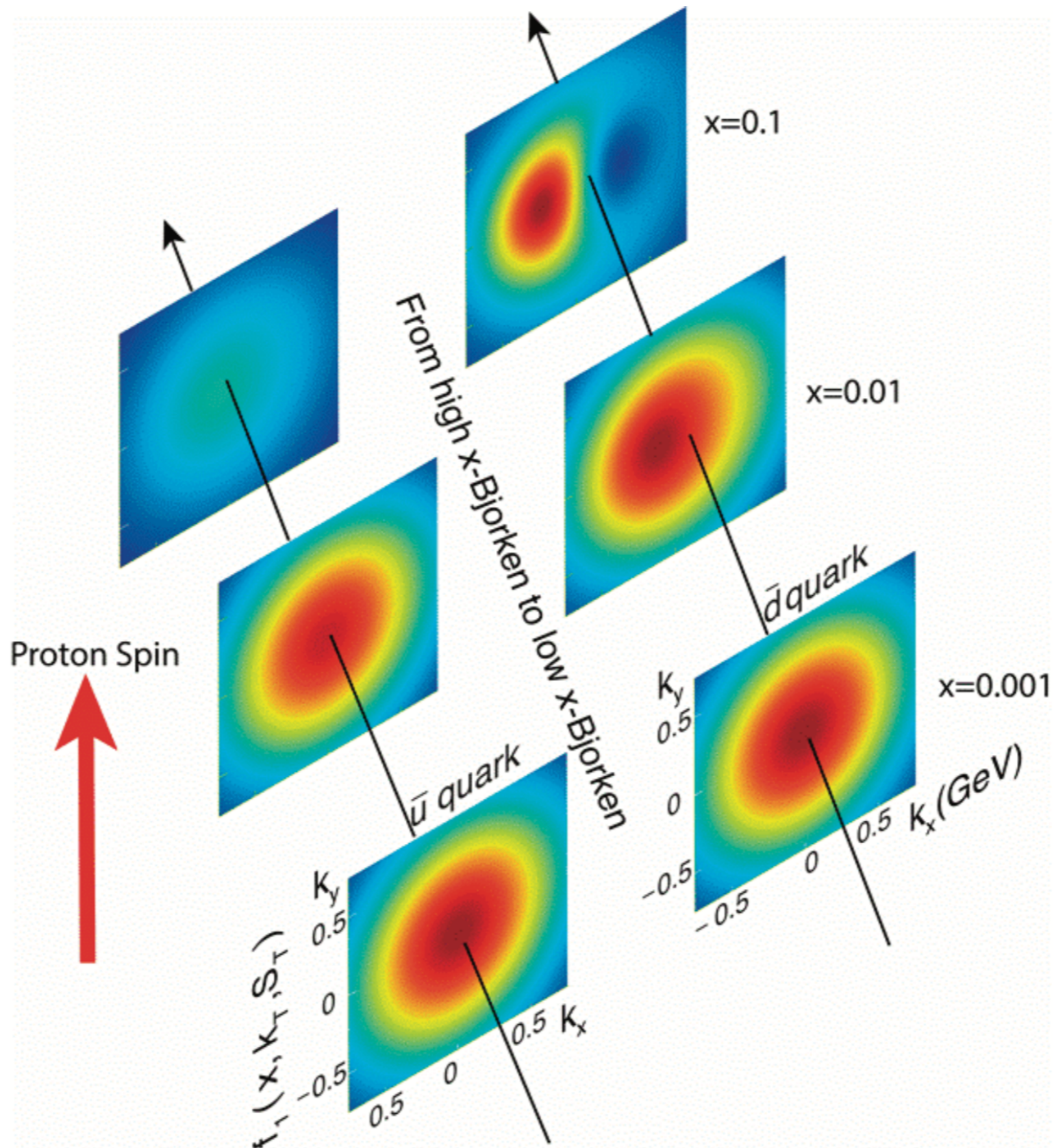
# U.S.-based EIC - TMDs

Increasing fragmentation  $z$



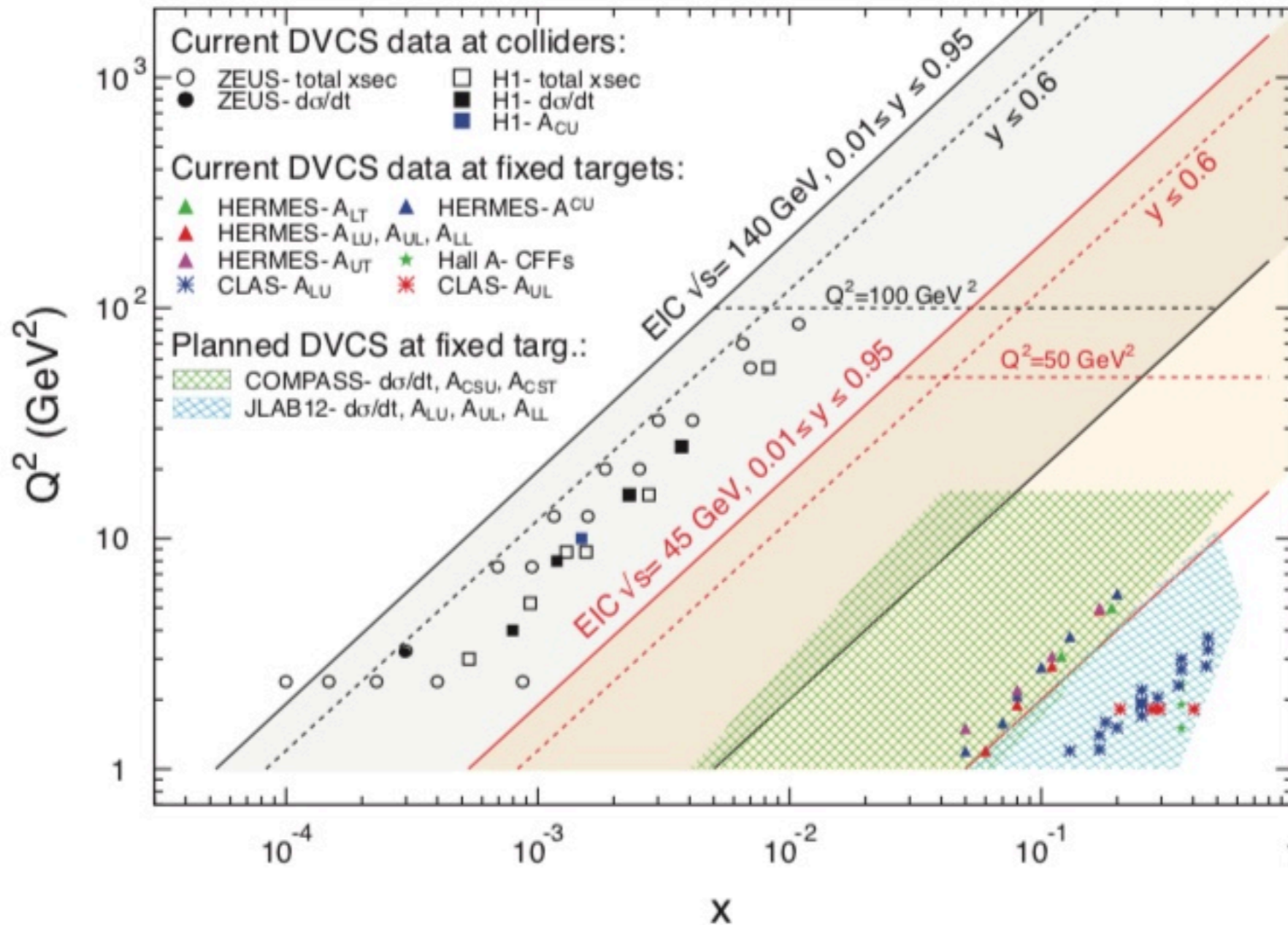
Representative charged pion measurements; positive PID essential  
10 inv. fb, points at indicated  $x$  and  $Q^2$ , uncertainties as indicated

# U.S.-based EIC - TMDs (goal)



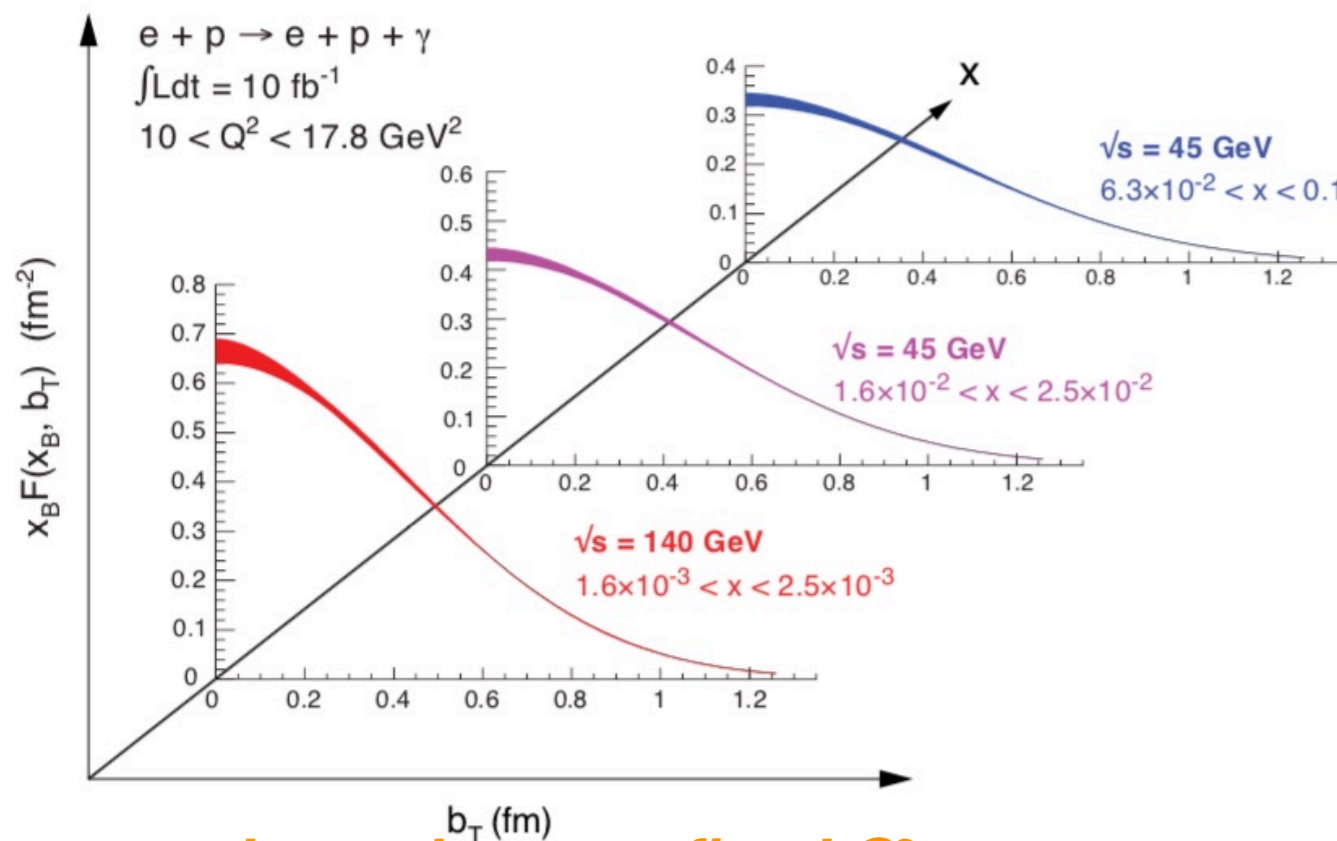
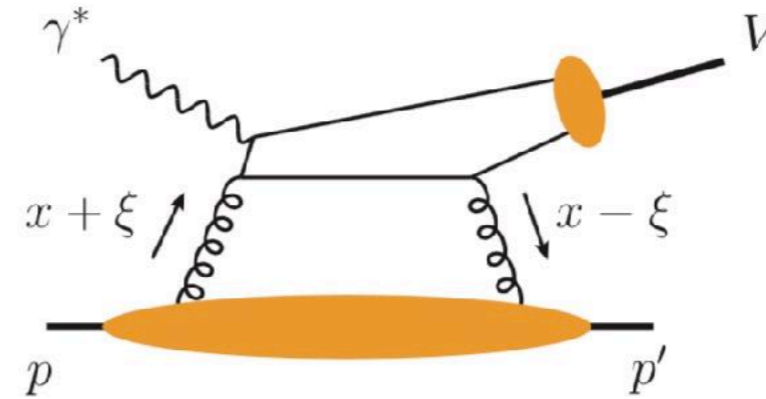
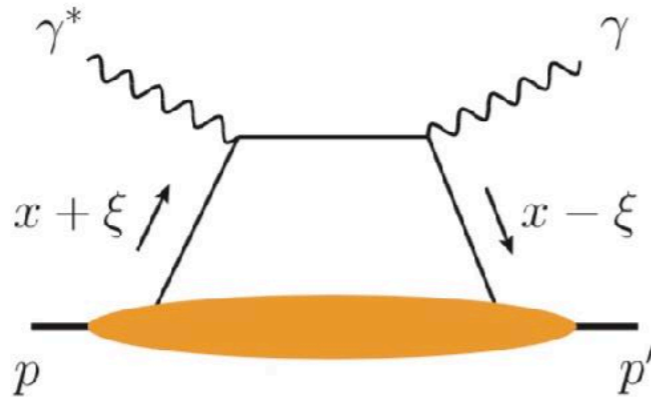
Tomographic insight in the fundamental structure down to low- $x$

# U.S.-based EIC - GPDs

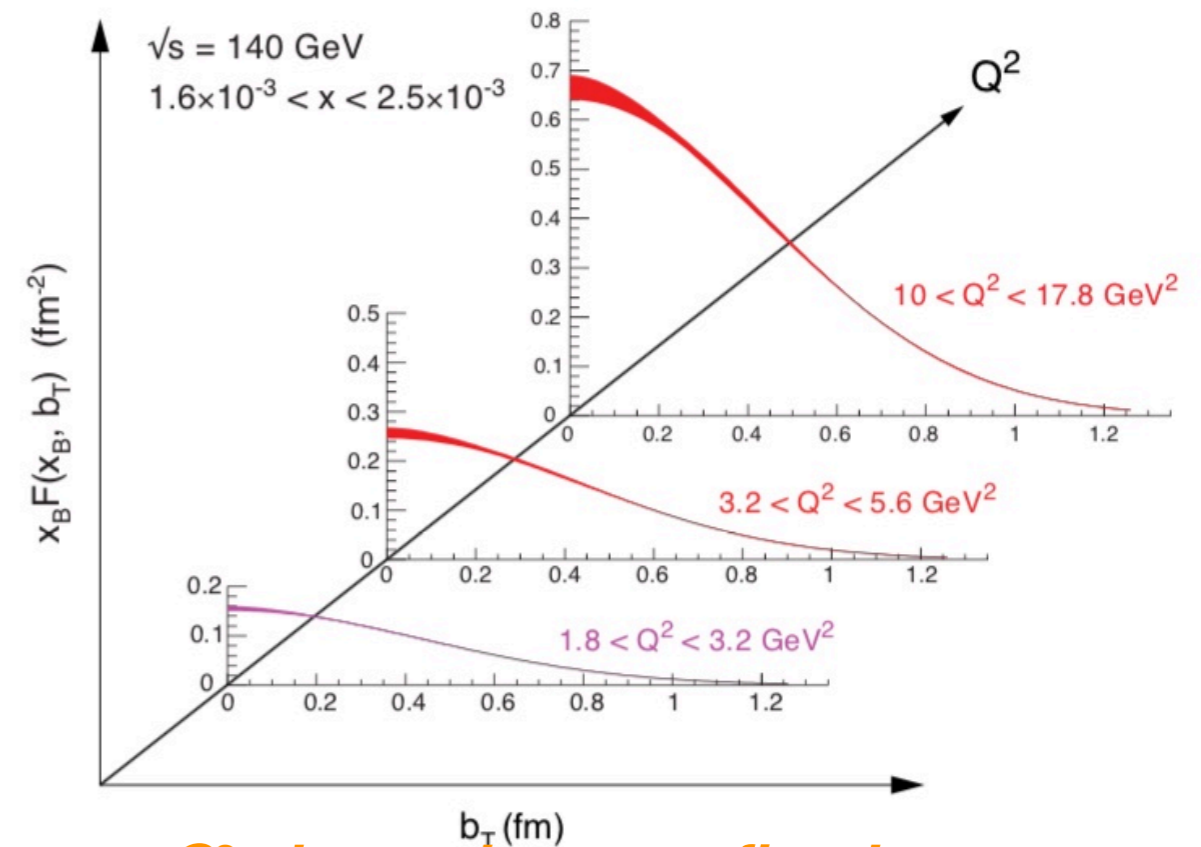


Two orders in  $x$  and  $Q^2$  compared to existing or planned *polarized* data,  
 Two to three orders of magnitude in luminosity for *unpolarized* data.

# U.S.-based EIC - DVCS, DVMP, and Imaging

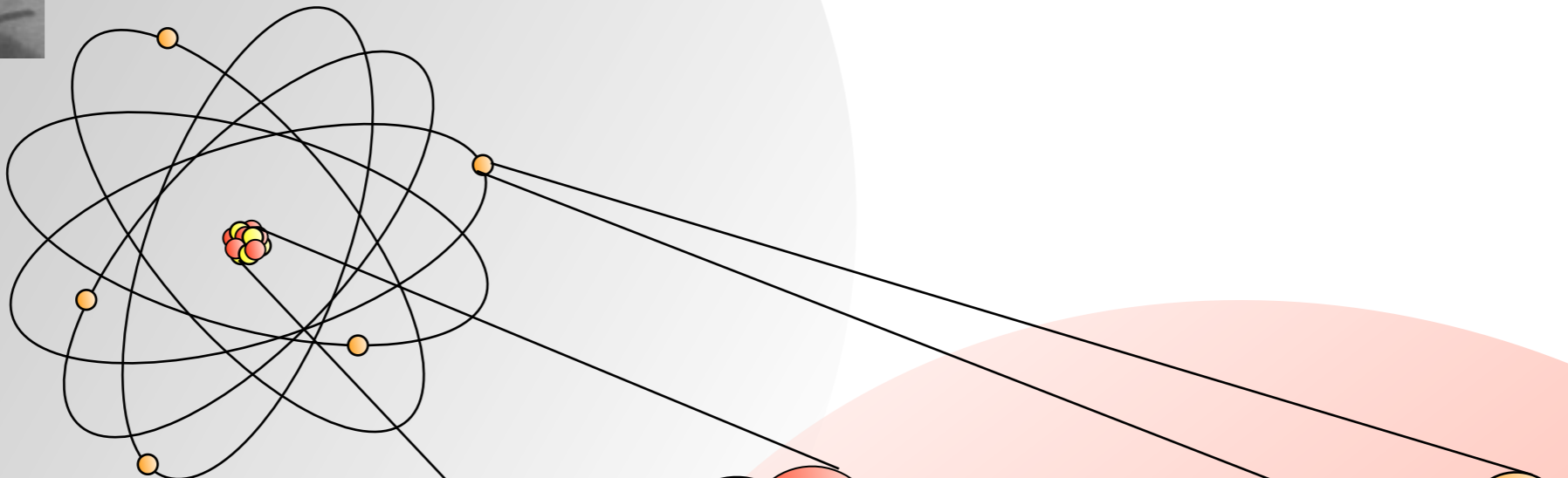
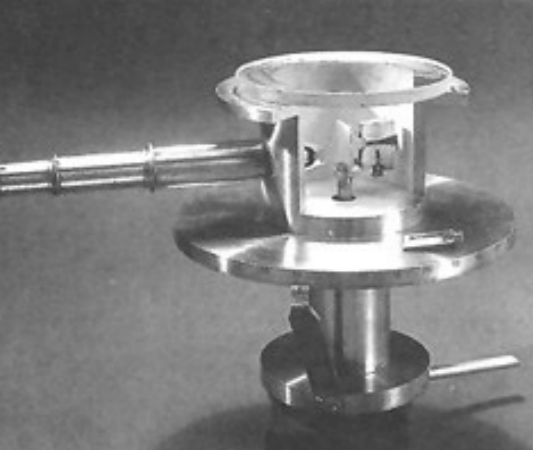


*$x$ -dependence at fixed  $Q^2$*

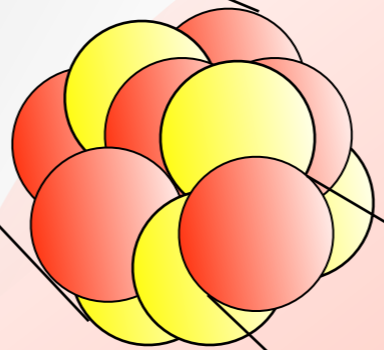


*$Q^2$ -dependence at fixed  $x$*

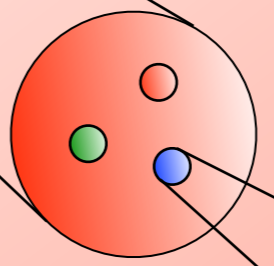
# Closing Comments



$\sim 10^{-10}$  m  
 $\sim$ keV



$\sim 10^{-14}$  m  
 $\sim$ MeV



$< 10^{-18}$  m

$\sim 10^{-15}$  m  
 $\sim$ GeV



# Closing Comments

Significant steps towards future realization of a U.S.-based EIC:

- 2015 Long Range Plan for Nuclear Physics recommendation, and
- 2018 Independent science assessment by the National Academies

$\sim 10^{-10}$  m  
 $\sim \text{keV}$

$\sim 10^{-14}$  m  
 $\sim \text{MeV}$

$\sim 10^{-15}$  m  
 $\sim \text{GeV}$

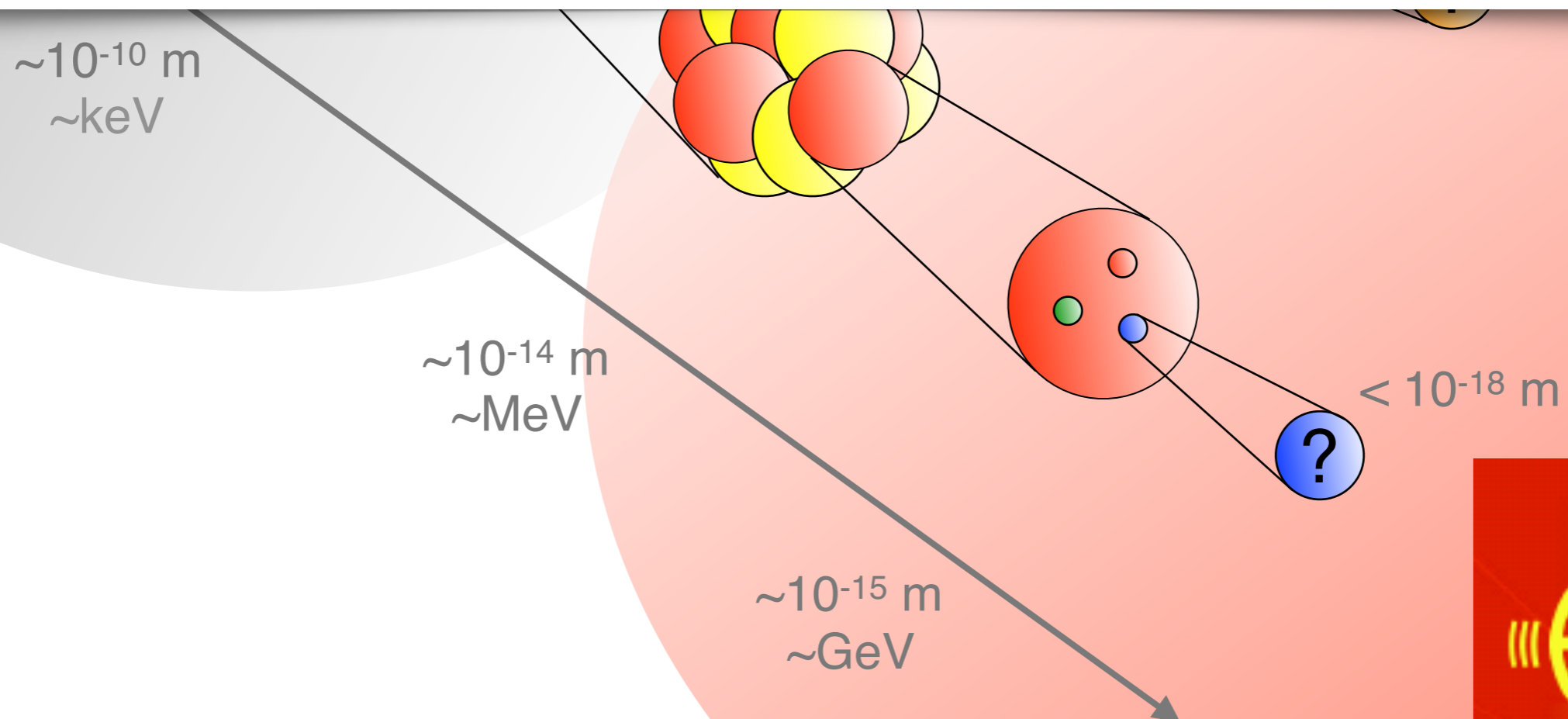
$< 10^{-18}$  m



# Closing Comments

**Finding 1:** An EIC can uniquely address three profound questions about nucleons—neutrons and protons—and how they are assembled to form the nuclei of atoms:

- How does the mass of the nucleon arise?
- How does the spin of the nucleon arise?
- What are the emergent properties of dense systems of gluons?



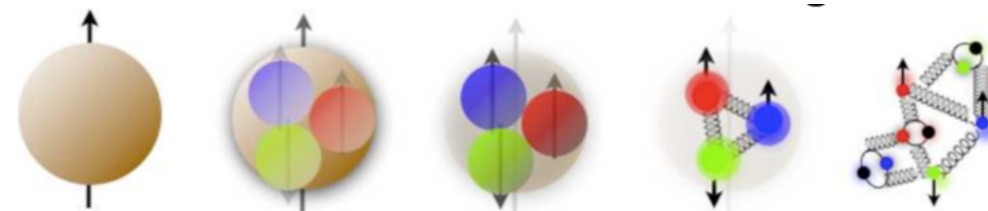


# Closing Comments

Significant steps towards future realization of a U.S.-based EIC:

- 2015 Long Range Plan for Nuclear Physics recommendation, and
- 2018 Independent science assessment by the National Academies

Unique opportunities to study spin structure and spin in QCD,



enabled by energy, luminosity, and polarization, exp. & theory,

Upcoming INT 18-3 program this Fall will look beyond the baseline.

$\sim 10^{-15}$  m  
 $\sim \text{GeV}$

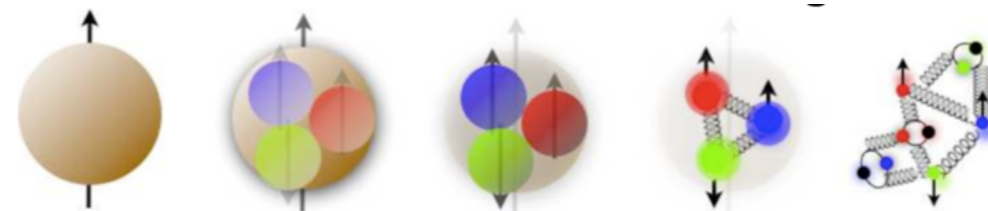


# Closing Comments

Significant steps towards future realization of a U.S.-based EIC:

- 2015 Long Range Plan for Nuclear Physics recommendation, and
- 2018 Independent science assessment by the National Academies

Unique opportunities to study spin structure and spin in QCD,



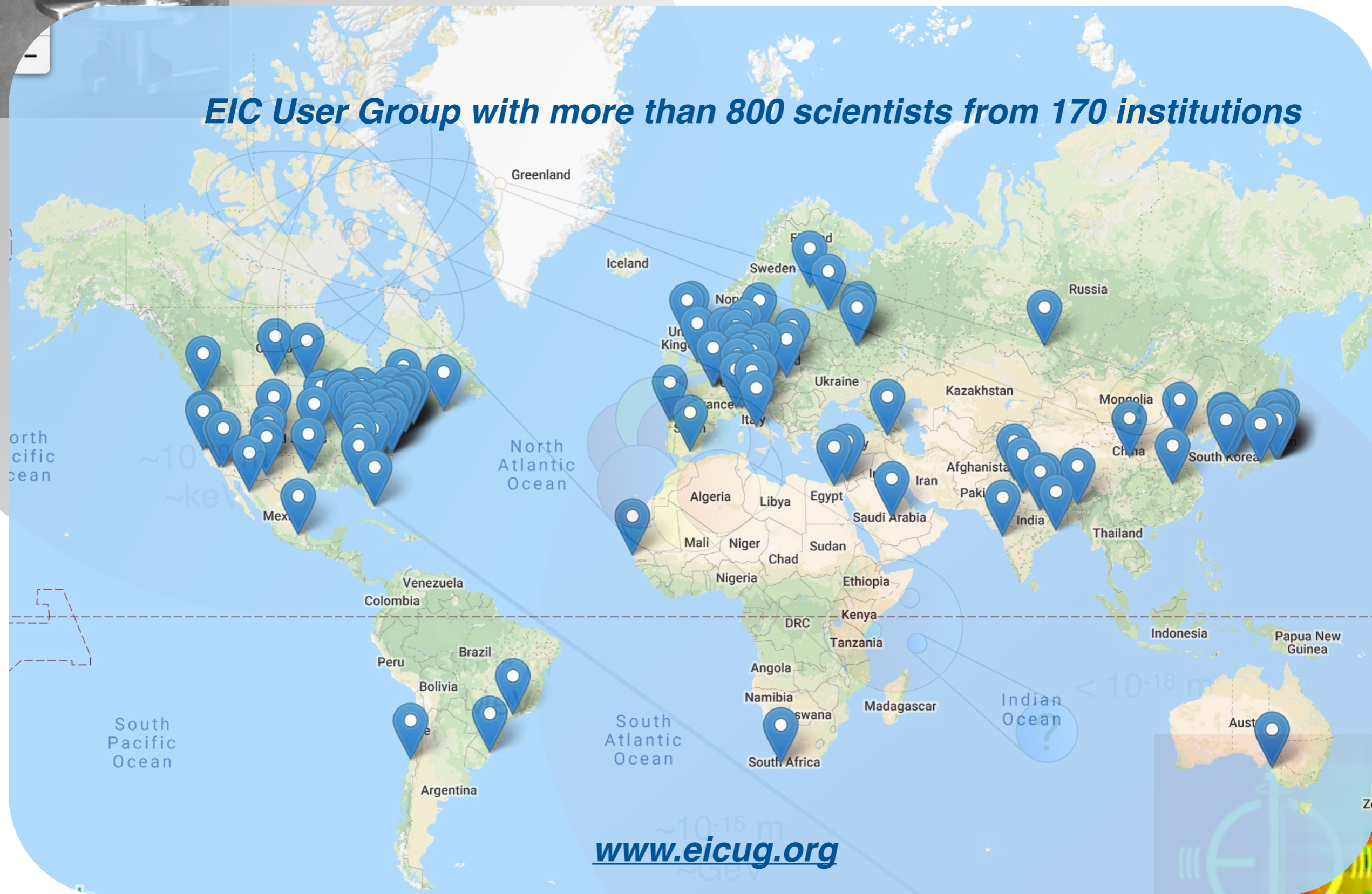
enabled by energy, luminosity, and polarization, exp. & theory,

Upcoming INT 18-3 program this Fall will look beyond the baseline.

EIC realization relies on joint efforts from multiple communities.

# Thank you!

***EIC User Group with more than 800 scientists from 170 institutions***



[www.eicug.org](http://www.eicug.org)