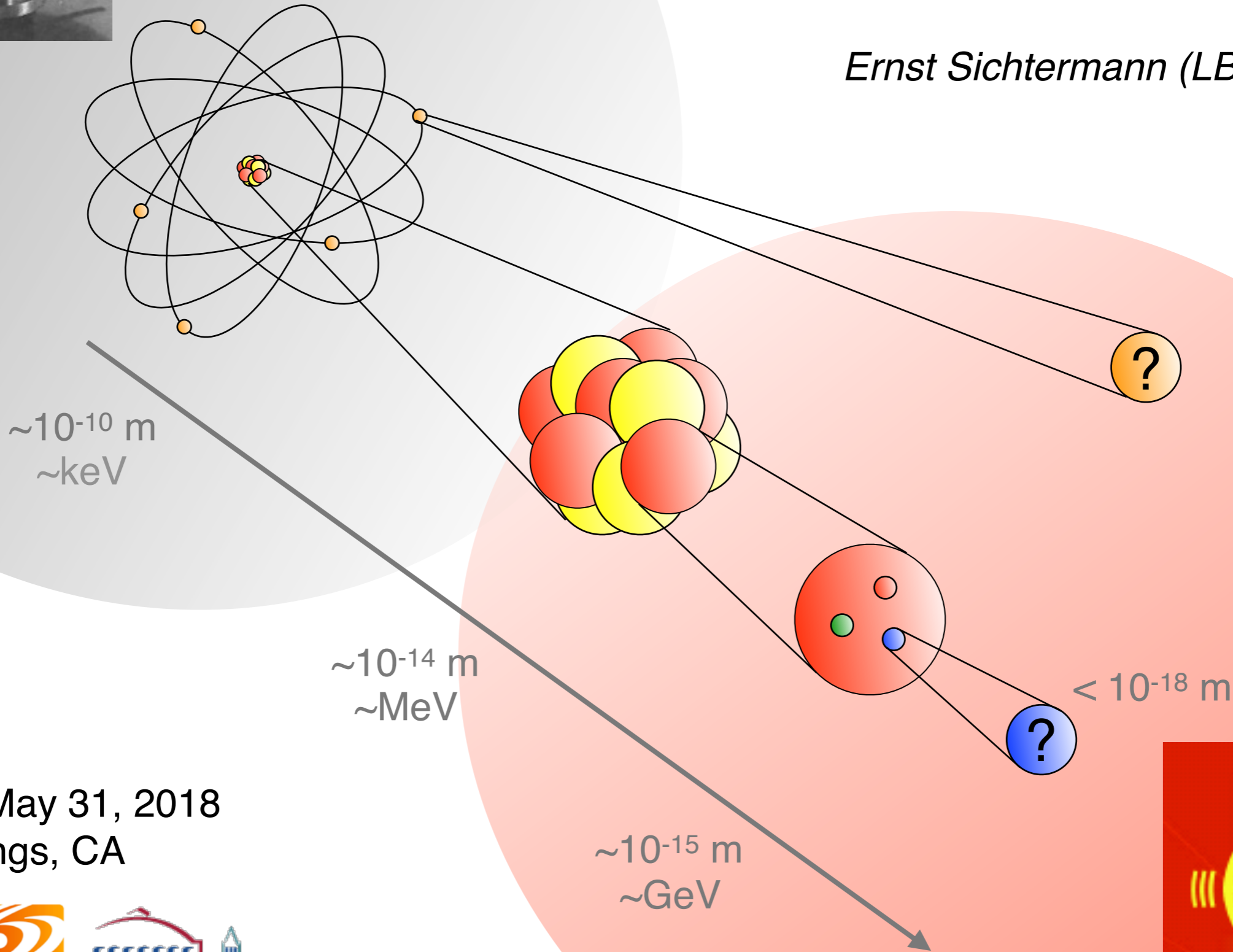


Physics with an Electron-Ion Collider

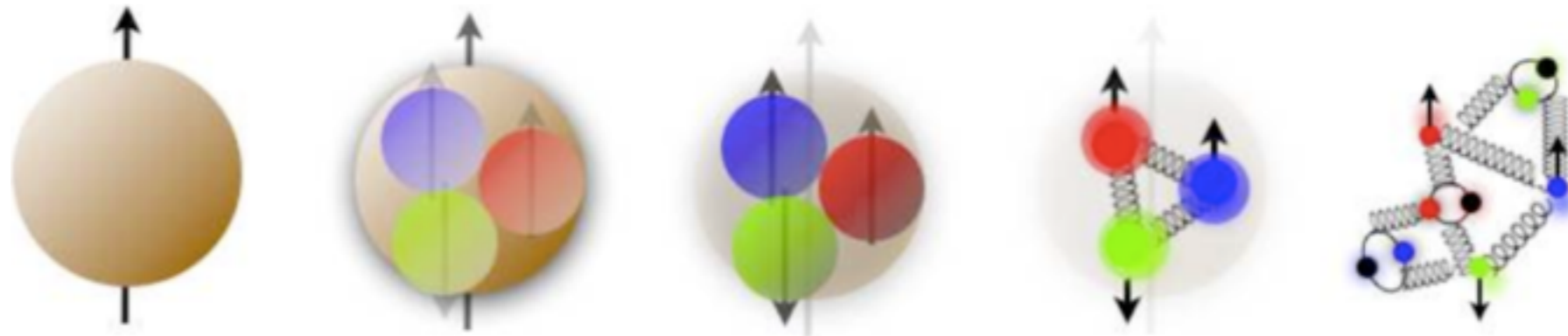
Ernst Sichter (LBNL)



CIPANP- May 31, 2018
Palm Springs, CA



What *is* a proton, neutron, nucleus?



Why and what about an Electron-Ion Collider*?

*I will focus mostly on a U.S.-based EIC and efforts in this talk.

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}	1×10^{-5}	5×10^{-7}	$7 \times 10^{-3} - 3 \times 10^{-4}$	5×10^{-3}	1×10^{-4}	5×10^{-5}
ion	p	p to Pb	p to U	p to $\sim^{40}\text{Ca}$	p to Pb	p to U
polarization	-	-	p, d, ^3He	p, d	p, d, ^3He (^6Li)	p, ^3He
L [$\text{cm}^{-2}\text{s}^{-1}$]	2×10^{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

Past

Possible Future

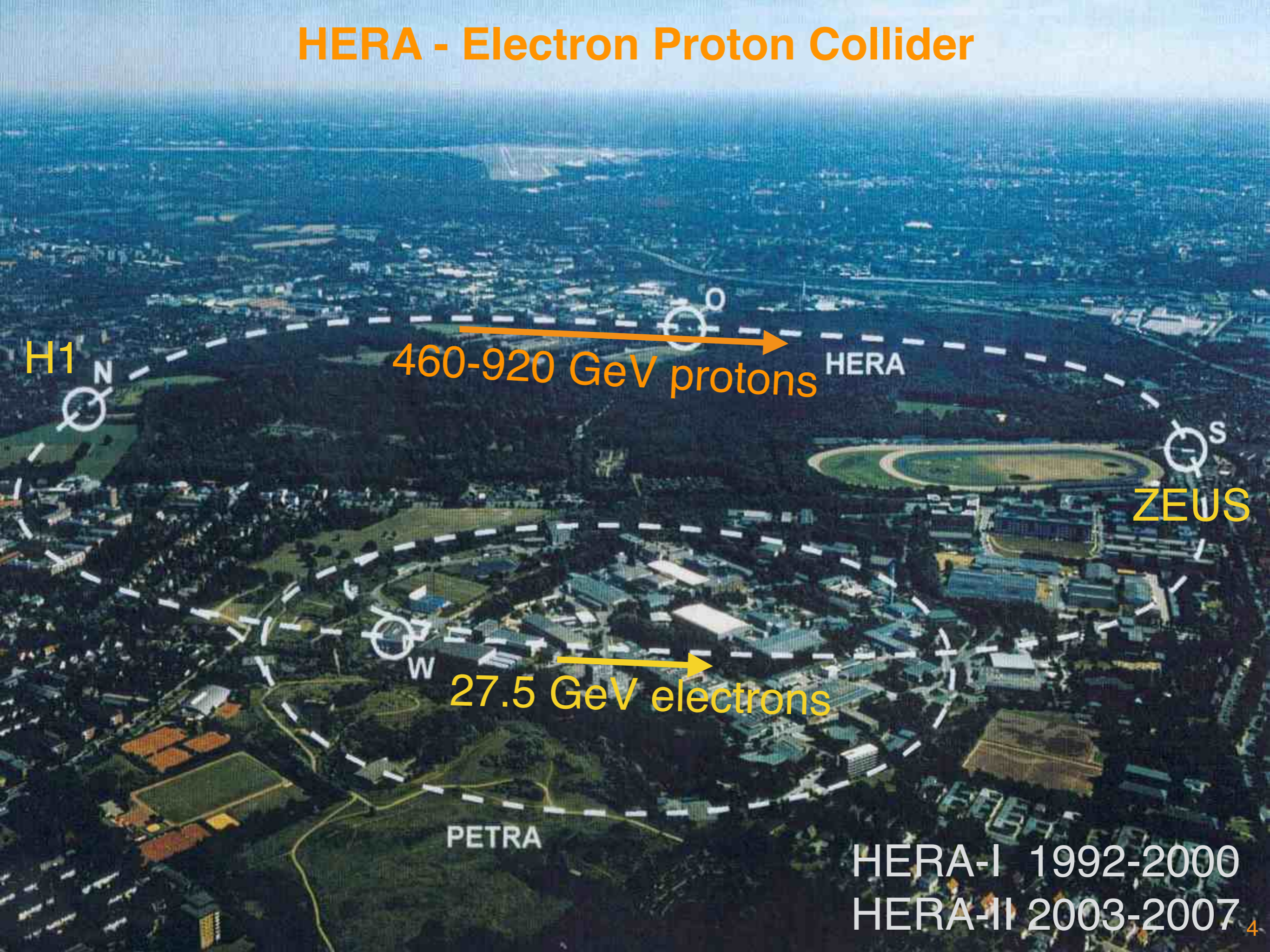
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High-Energy Physics

Nuclear Physics

World Wide Interest

HERA - Electron Proton Collider



H1

460-920 GeV protons

HERA

ZEUS

27.5 GeV electrons

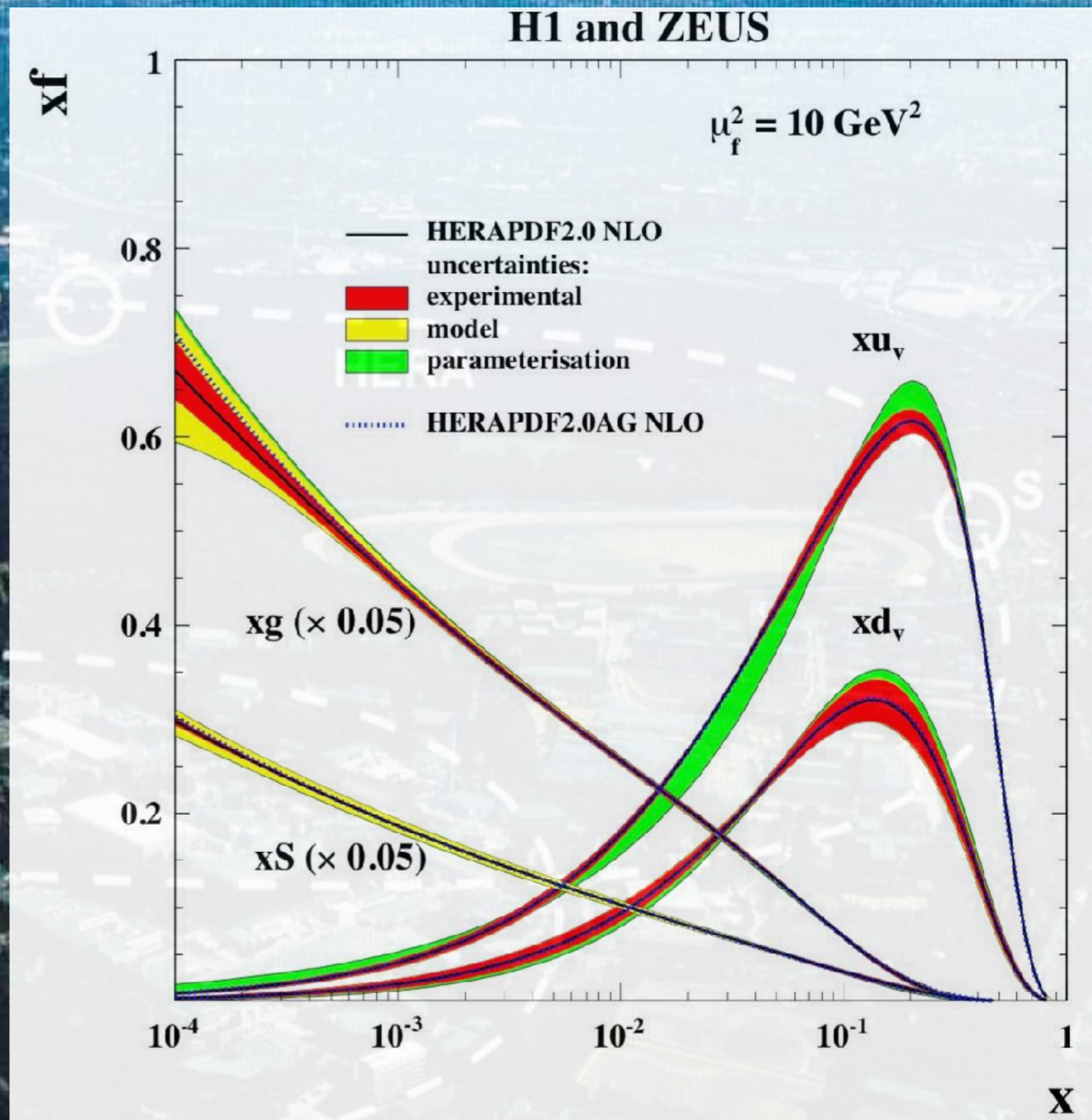
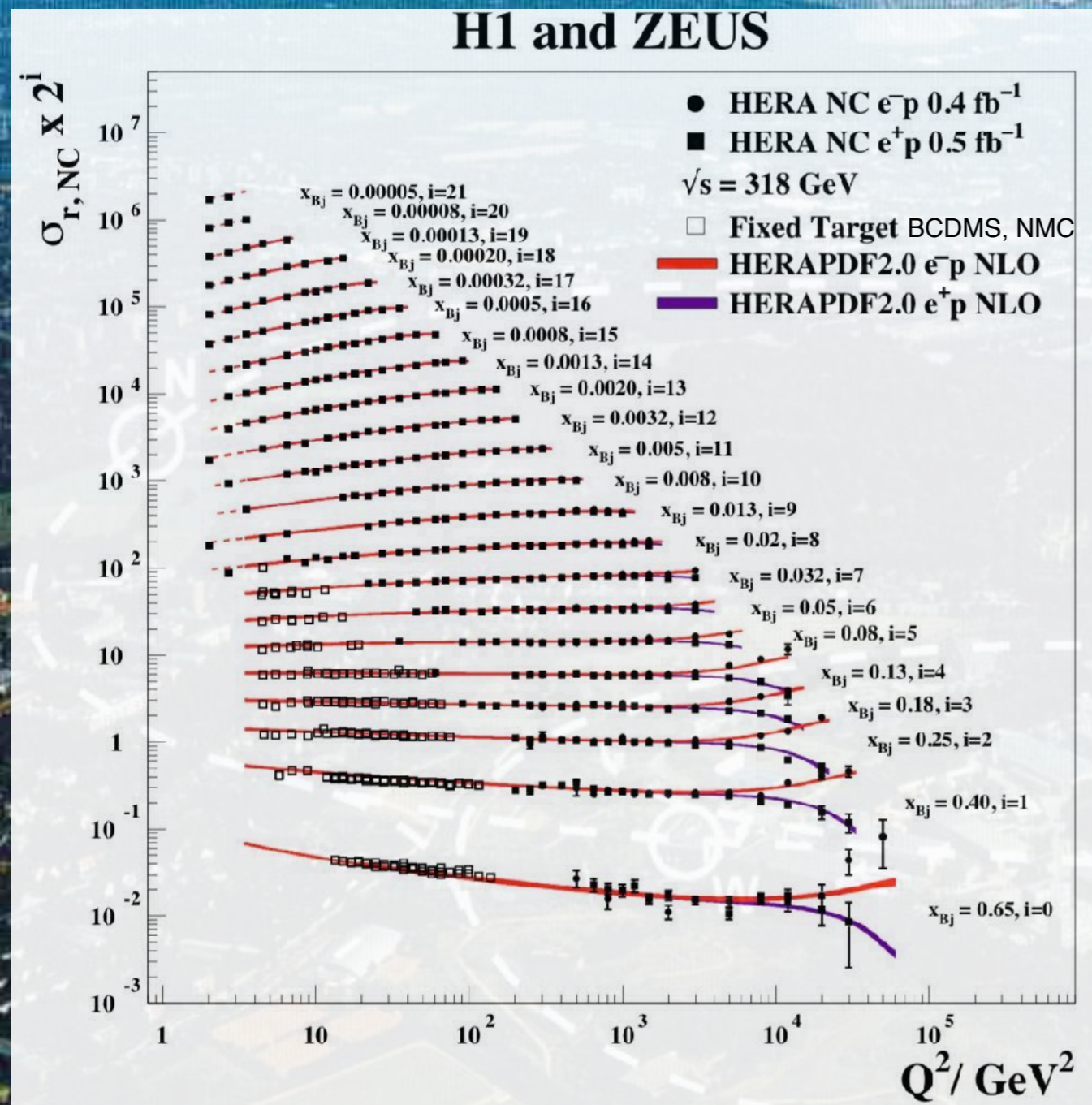
PETRA

HERA-I 1992-2000

HERA-II 2003-2007

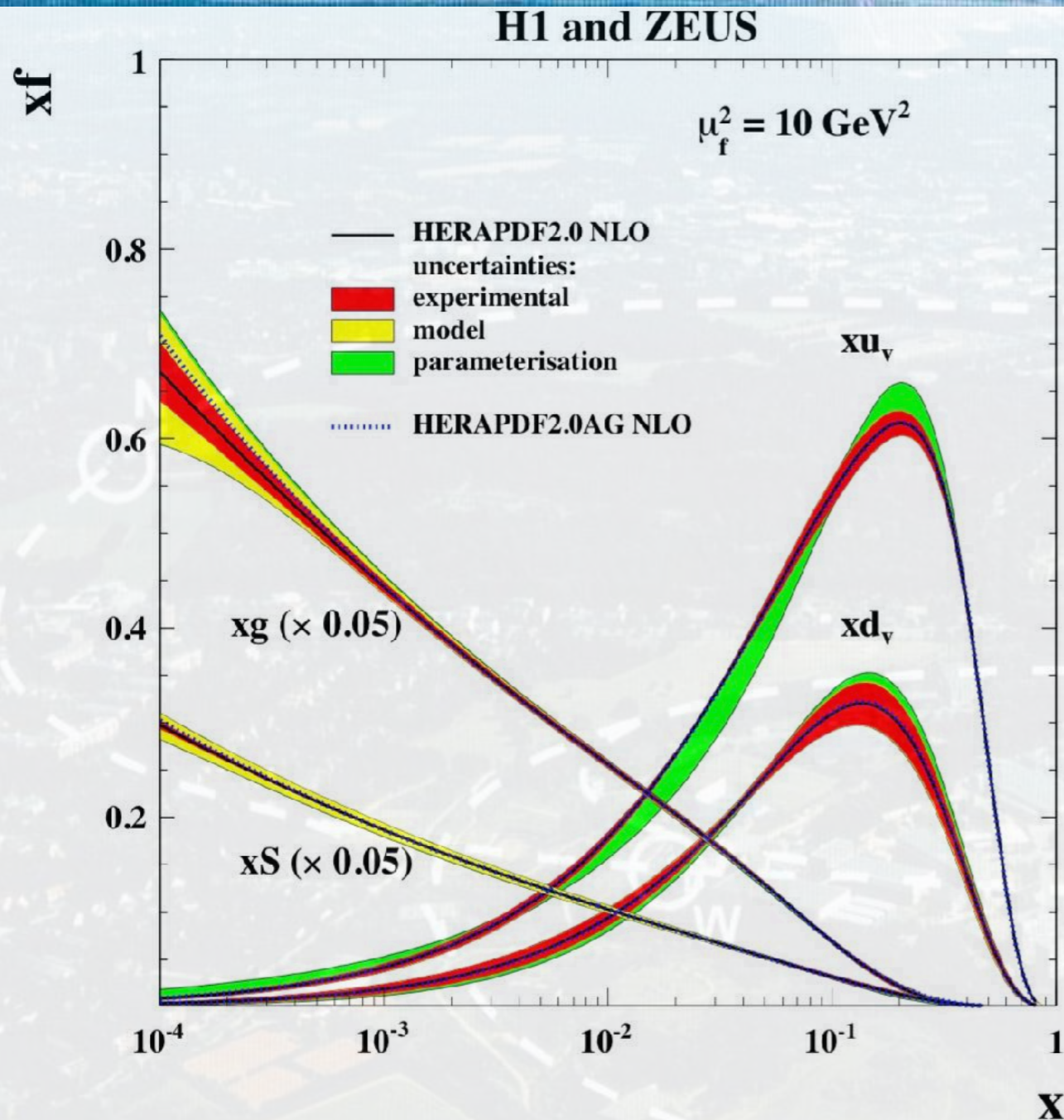
HERA's Legacy

H1 and ZEUS Coll., EPJ C75 (2015) 580



Vast body of *precision* measurements over a wide kinematic range,
 Best possible insight in high-energy proton structure to date.

HERA's Legacy



Proton structure at high-energy is:

- *far* from elementary,
- gluon-dominated for $x < 0.1$,

Gluon content increases with decreasing x ,

Gluons pose a number of questions, e.g. saturation

HERAPDF2.0:

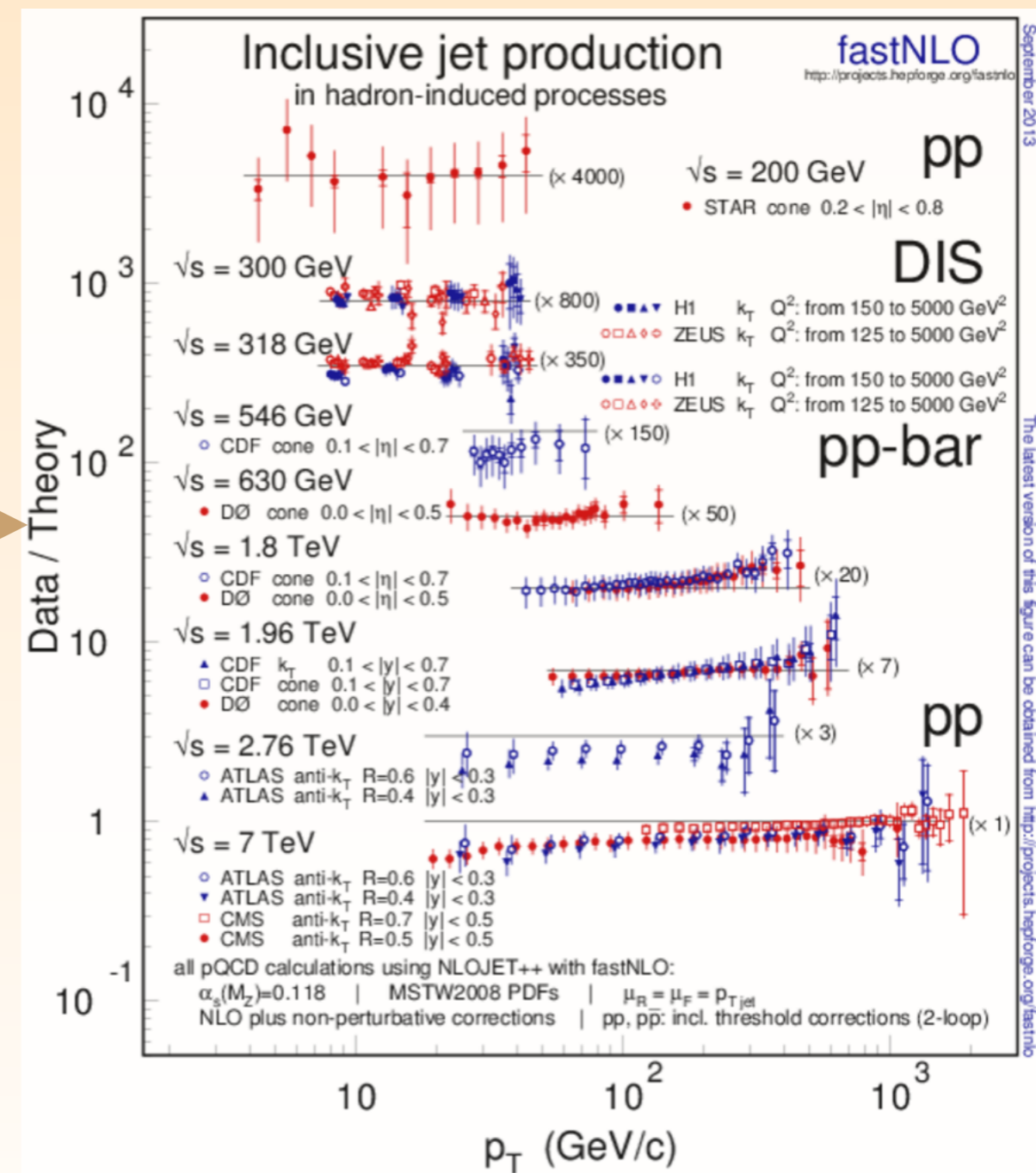
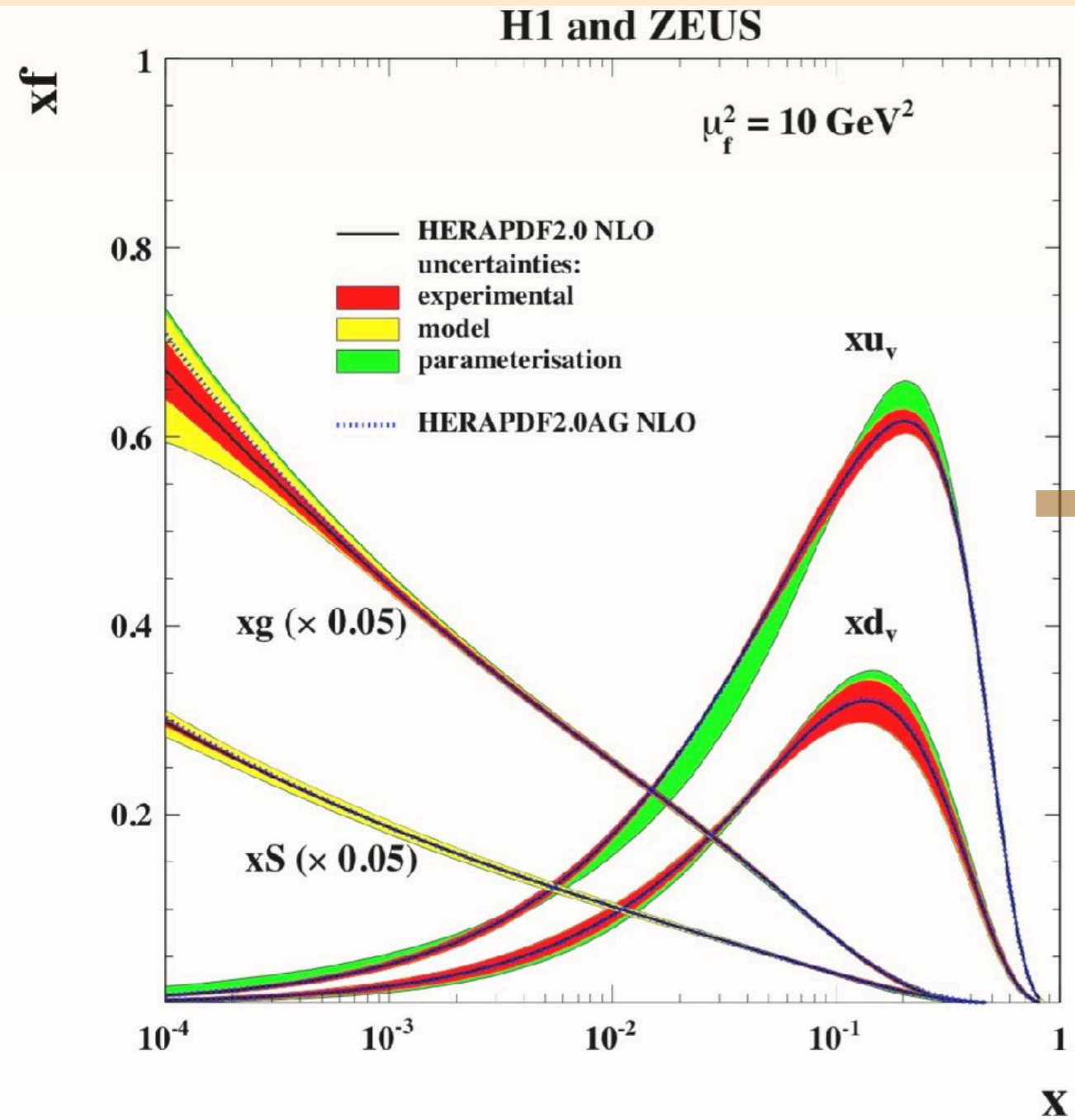
- 14 parameters,
- ~ 1400 combined data points,

PETRA

HERA's Legacy

The proton in terms of gluons and quarks

pQCD at work...

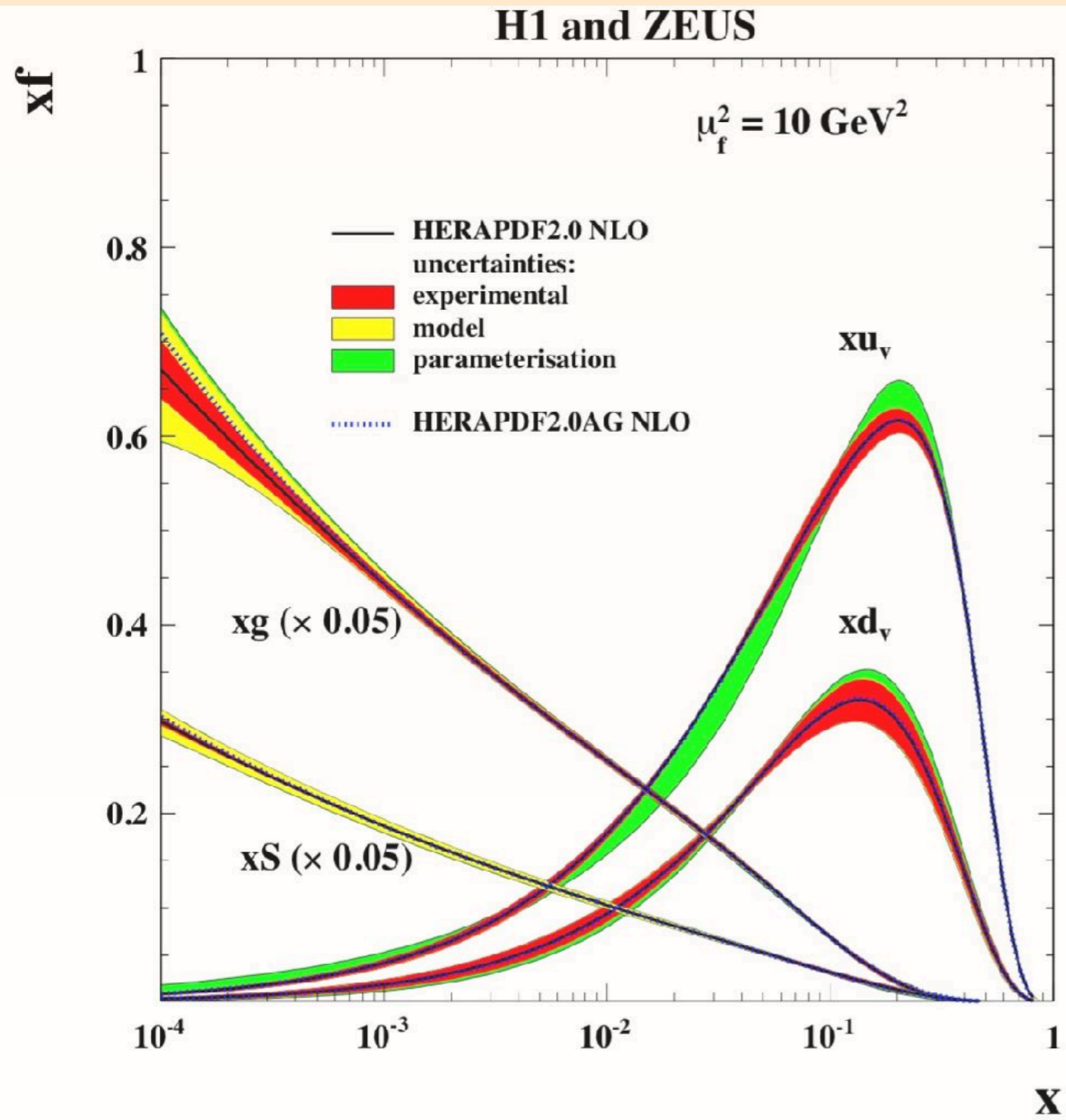


Factorization, the separation of short distance and long distance physics, combined with PDFs are 'universally invaluable' in hard scattering processes.

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,

Spin puzzle - no hadron beam polarization,

Imaging - polarization, luminosity,

Quark-gluon dynamics in nuclei - no nuclei,

Saturation - insufficient \sqrt{s} / no nuclei,

...

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*

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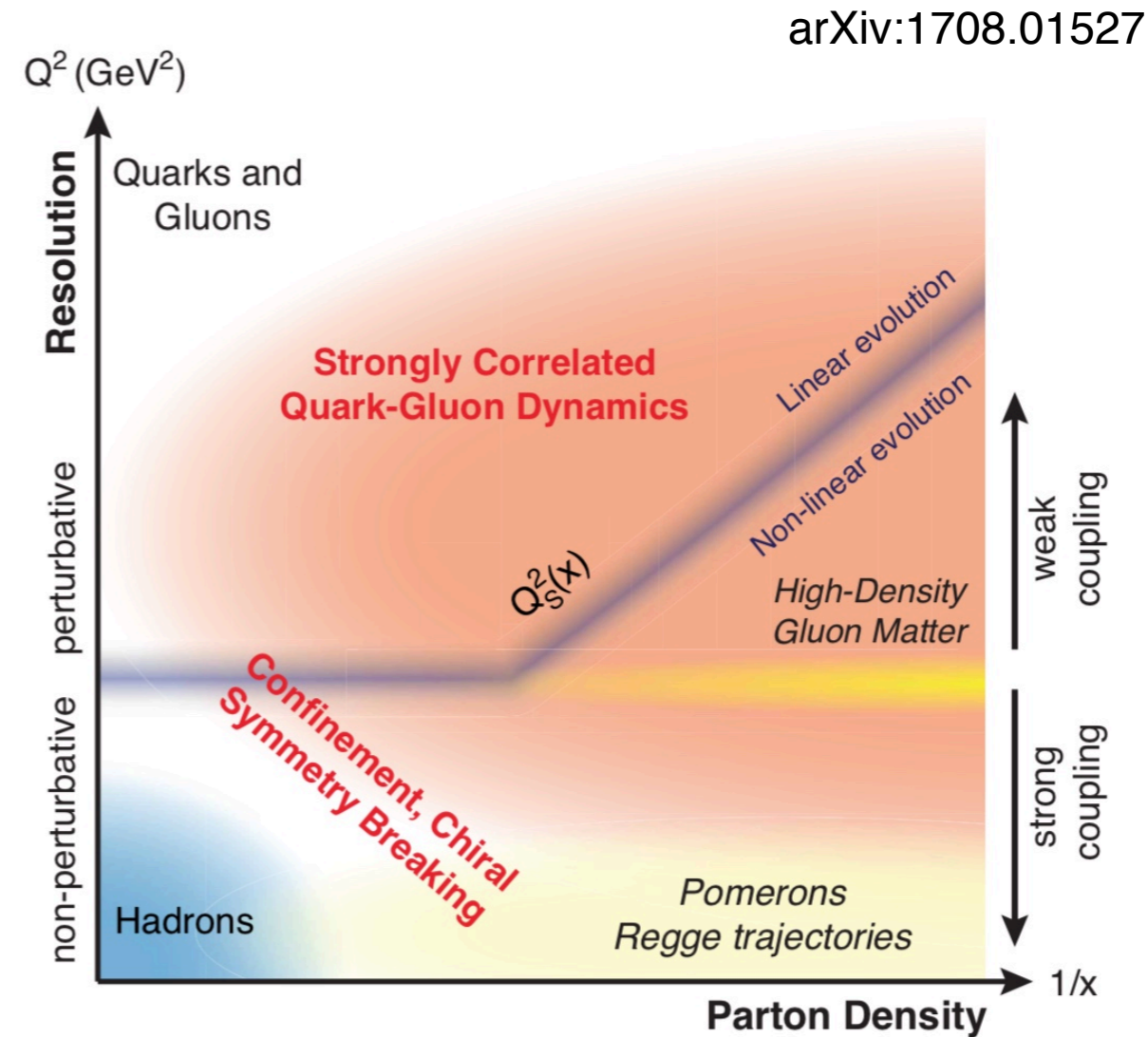
*Factorization theorem(s) + one-dimensional parton distributions,
no correlations among the partons*

***Really? More than a few of our high-energy observations are actually different
Essential to separate intrinsic structure from interaction dynamics,
push the envelope beyond the theoretically established,
obtain meaningful accuracy.***

HERA

Saturation:

- geometric scaling of the cross section,
- diffractive cross-section independent of W and Q^2 ,
- evidence for BFKL dynamics (Ball et al., arXiv:1710.05935)



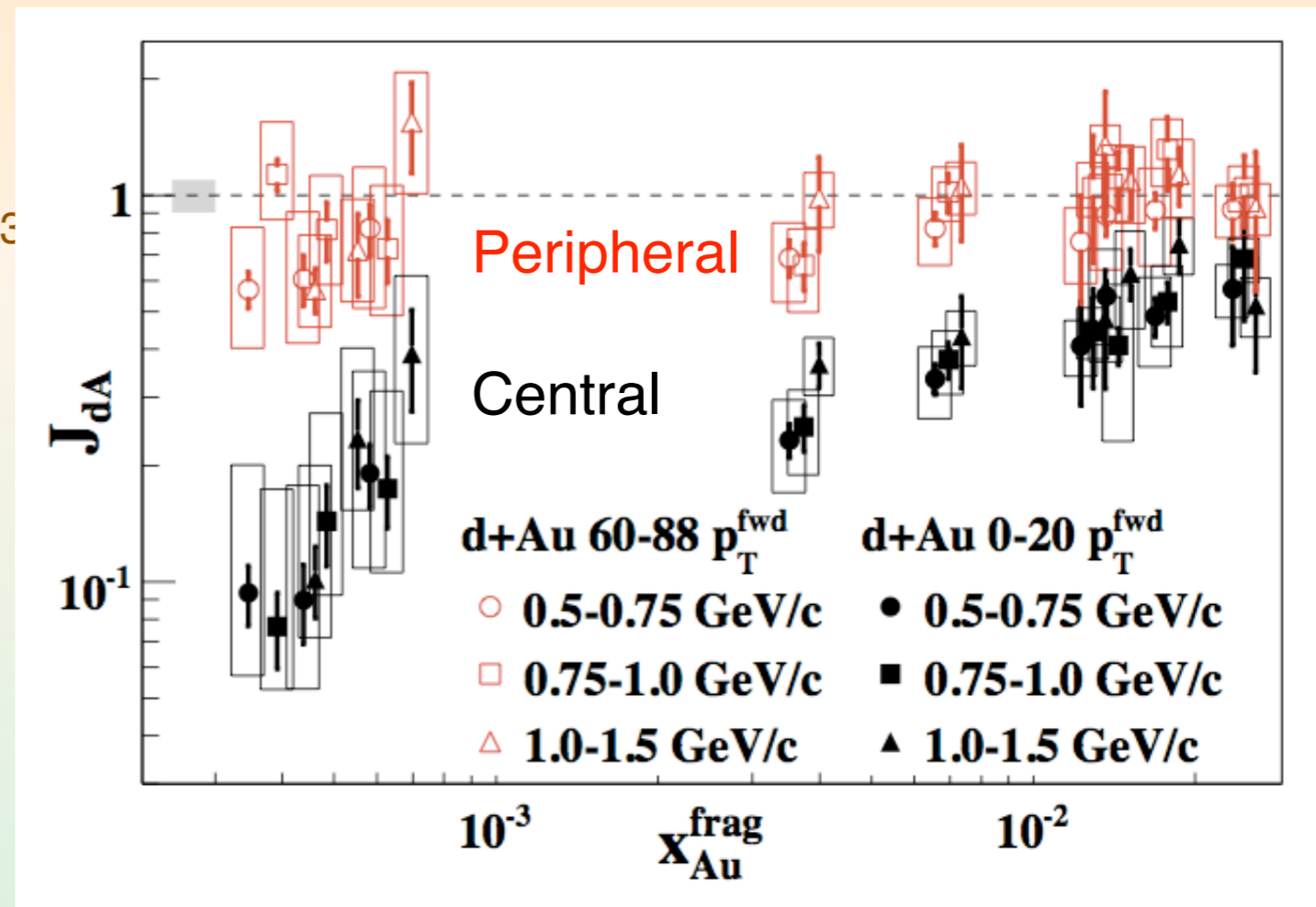
HERA - RHIC

Saturation:

- geometric scaling of the cross section,
- diffractive cross-section independent of W and Q^2 ,
- evidence for BFKL dynamics (Ball, arXiv:1710.05933)
- forward multiplicities and correlations at RHIC,

Forward-Forward

Mid-forward correlation



Phenix, Phys.Rev.Lett. 107 (2011) 172301

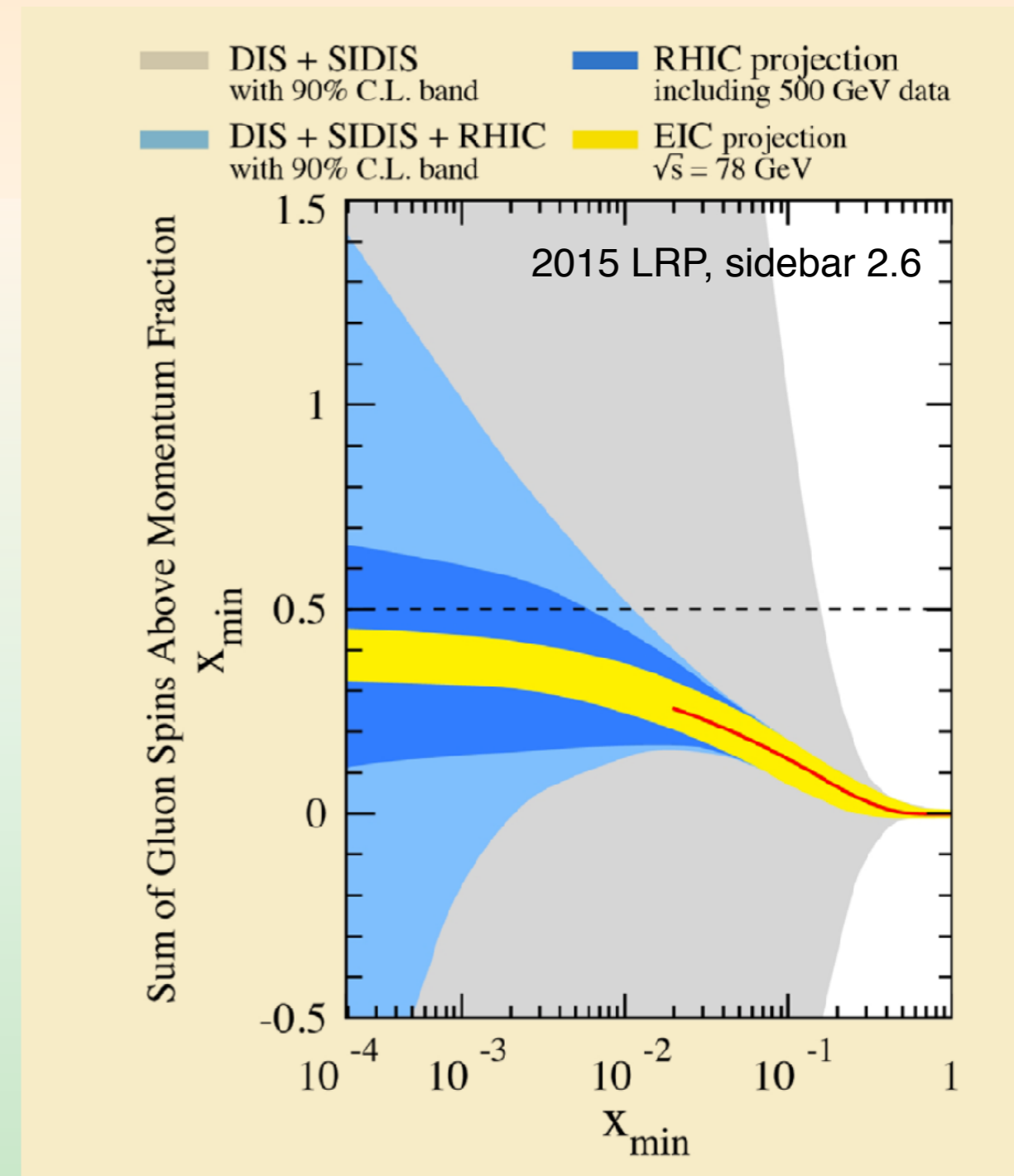
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Spin puzzle:

- defining constraint on $\Delta G(x)$ for $x > 0.05$,
smaller x is terra-icognita,
- fragmentation-free insight in Δu , Δd , $\Delta \bar{u}$, $\Delta \bar{d}$
strange (anti-)quarks?
- large forward transverse-spin phenomena



HERA - RHIC, JLab

Saturation:

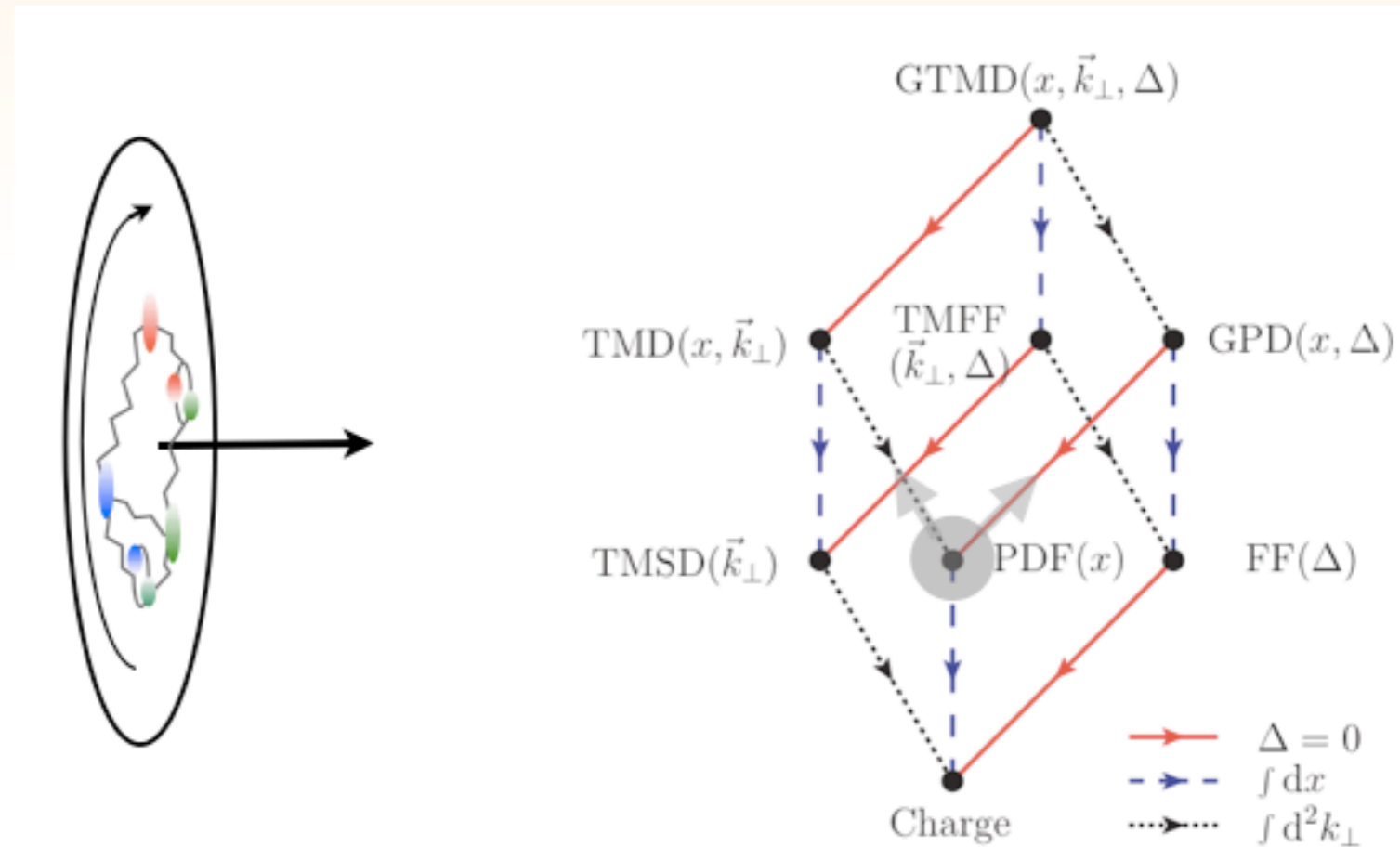
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Imaging / tomography:

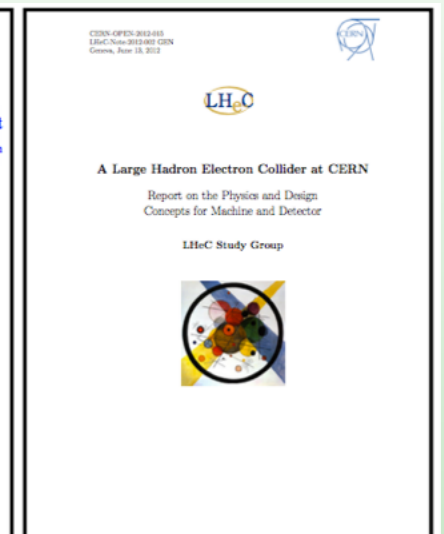
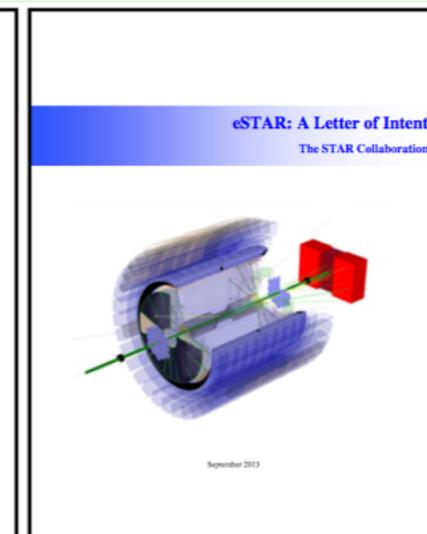
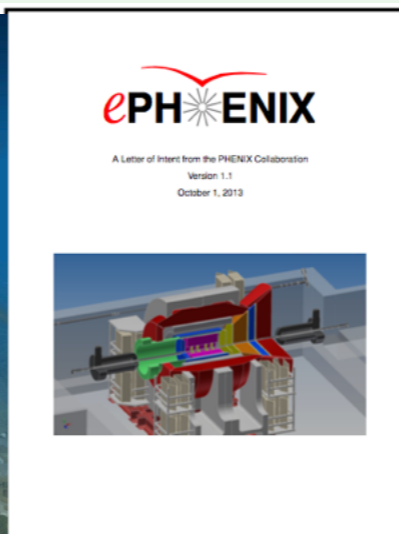
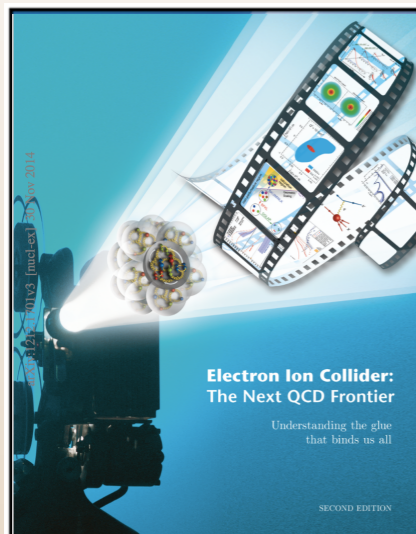
- valence quark region,



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
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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**.

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

Independent NAS science assessment being finalized.

U.S.-based EIC - Two Facility Concepts

eRHIC:

- upgrade to existing RHIC hadron beam,



JLEIC:

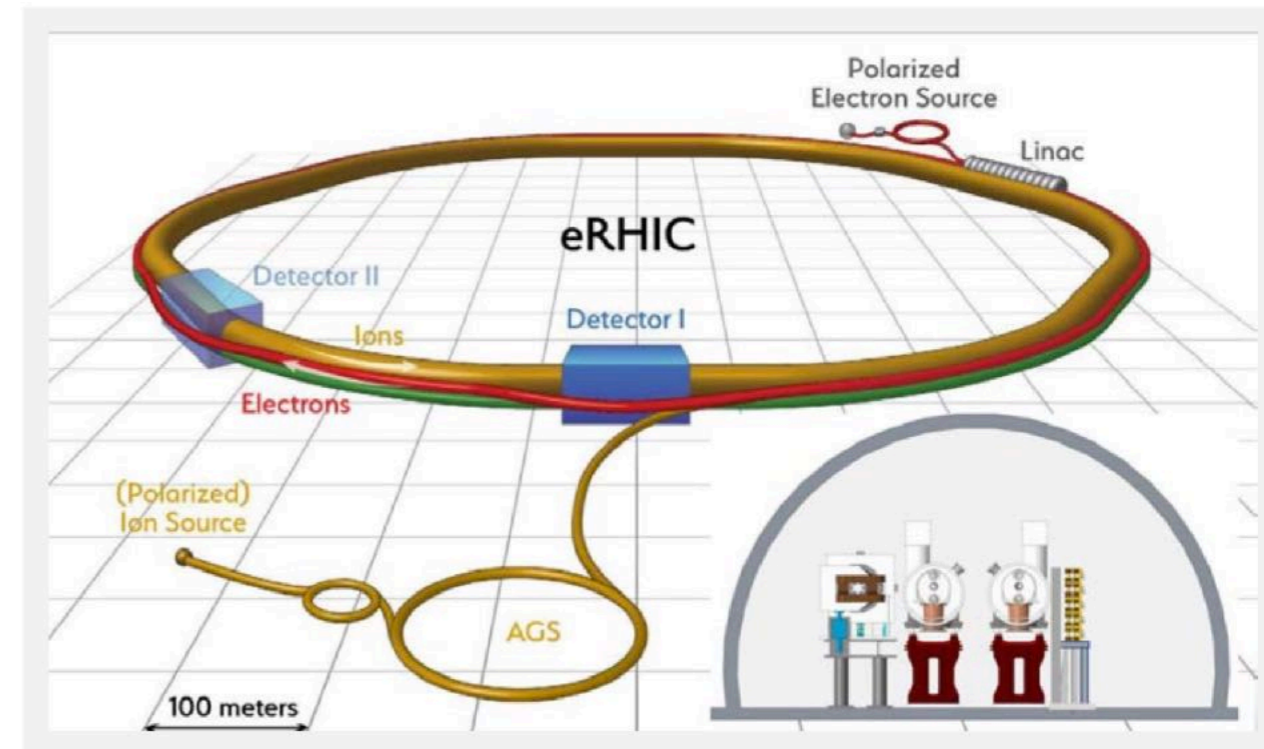
- upgrade to existing CEBAF 12 GeV electron beam,



U.S.-based EIC - Two Facility Concepts

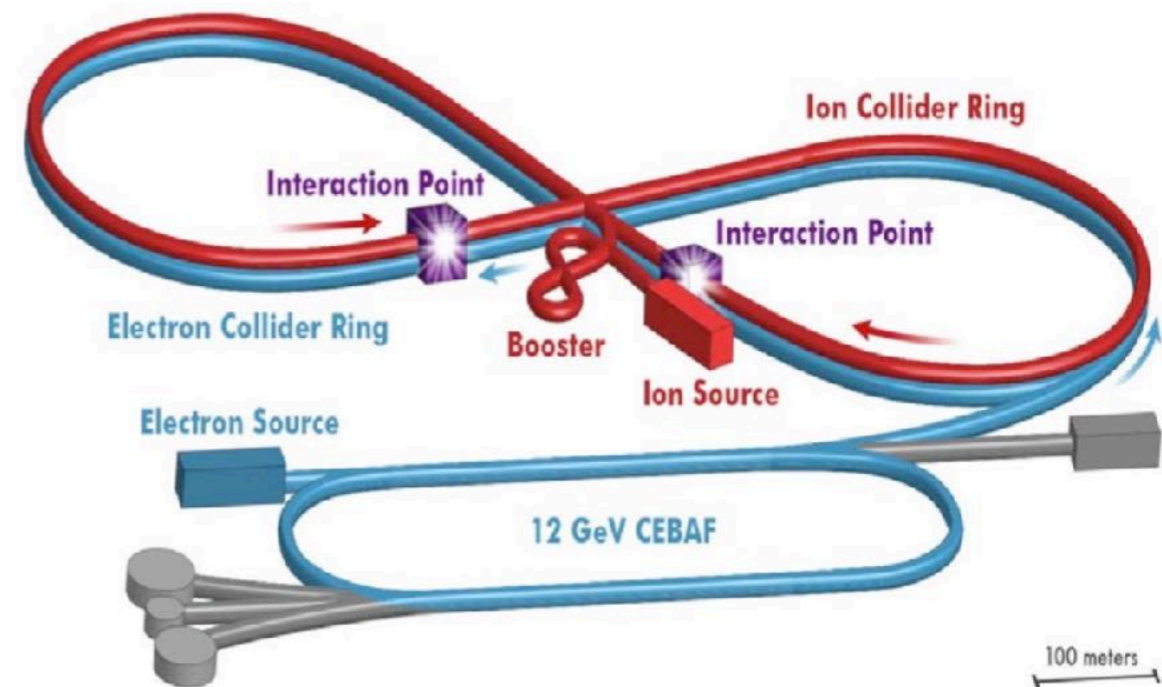
eRHIC:

- 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 93 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:

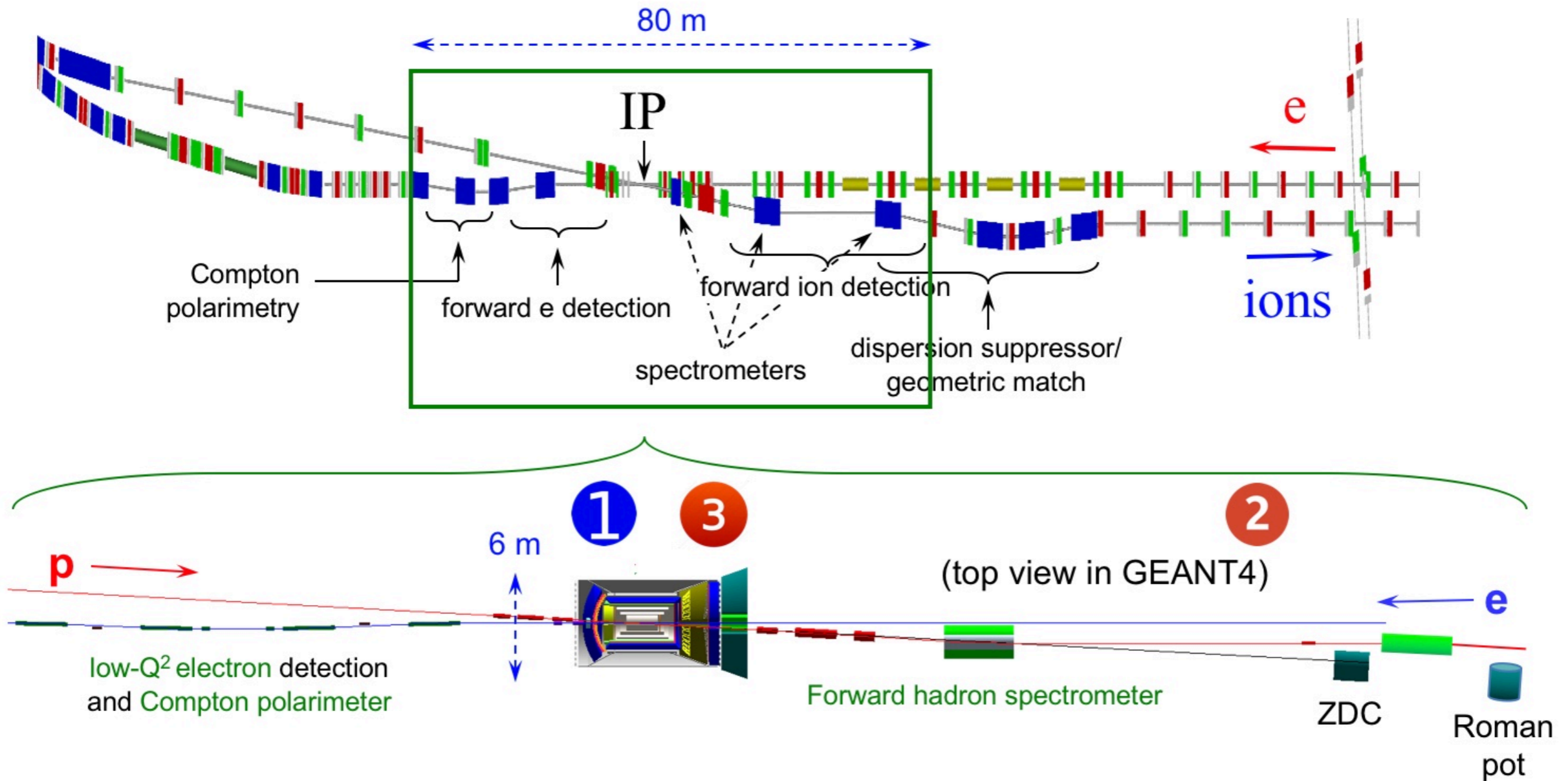
- upgrade to CEBAF 12 GeV electron beam facility,
- new hadron injector,
- new figure-8 collider configuration,
- 3-10 GeV electron energy,
- 12-40 GeV/u Heavy Ion energy,
upgradable (ion arc dipole)
- $L \sim 10^{34} \text{ cm}^{-2}\text{s}^{-1}/\text{A}$



Science cases by themselves!

U.S.-based EIC - Two Facility Concepts

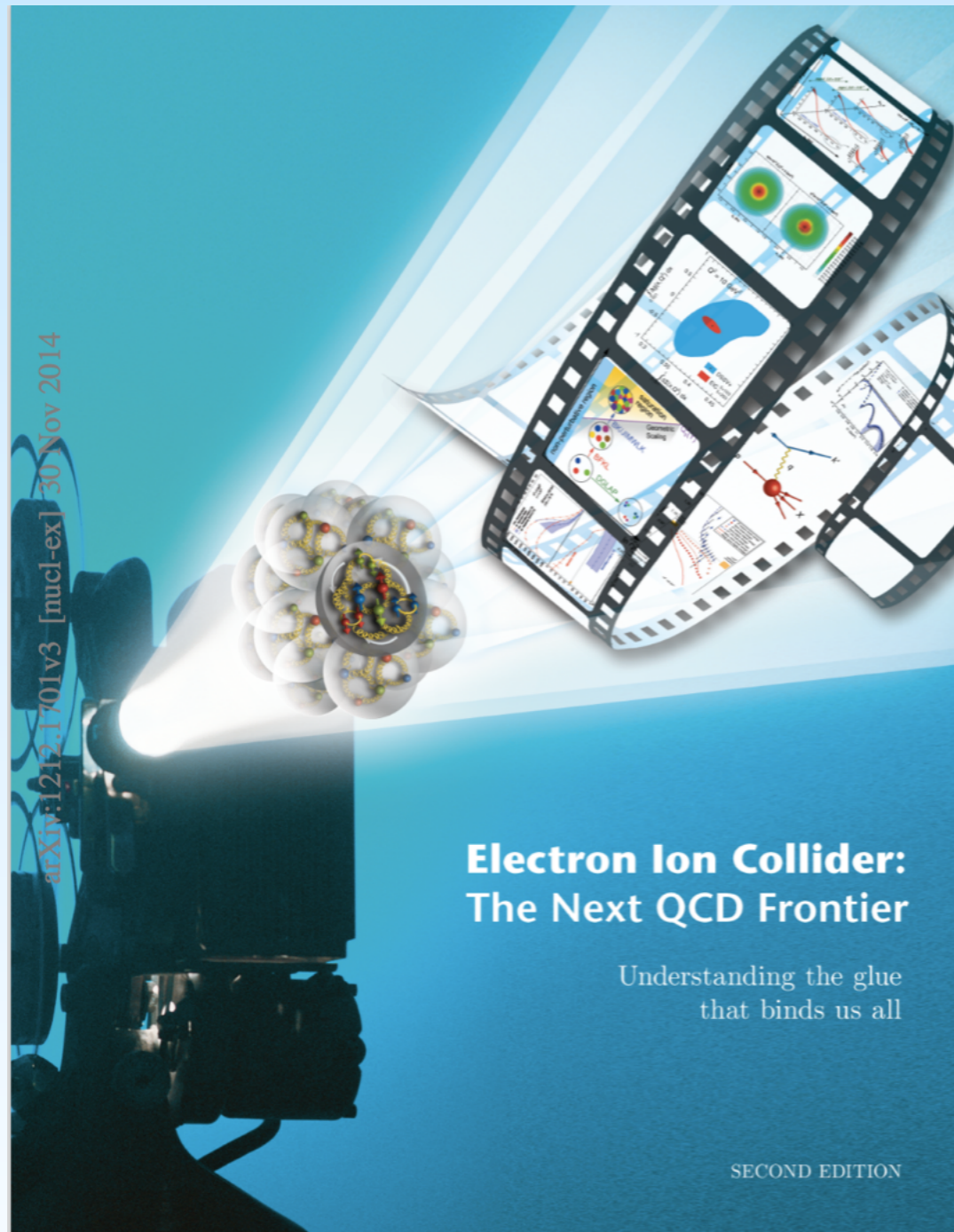
Science cases by themselves requiring, for example, tight integration with detectors



courtesy V. Morozov (JLab)

Multiple (central) detector concepts are being pursued within the EIC community.

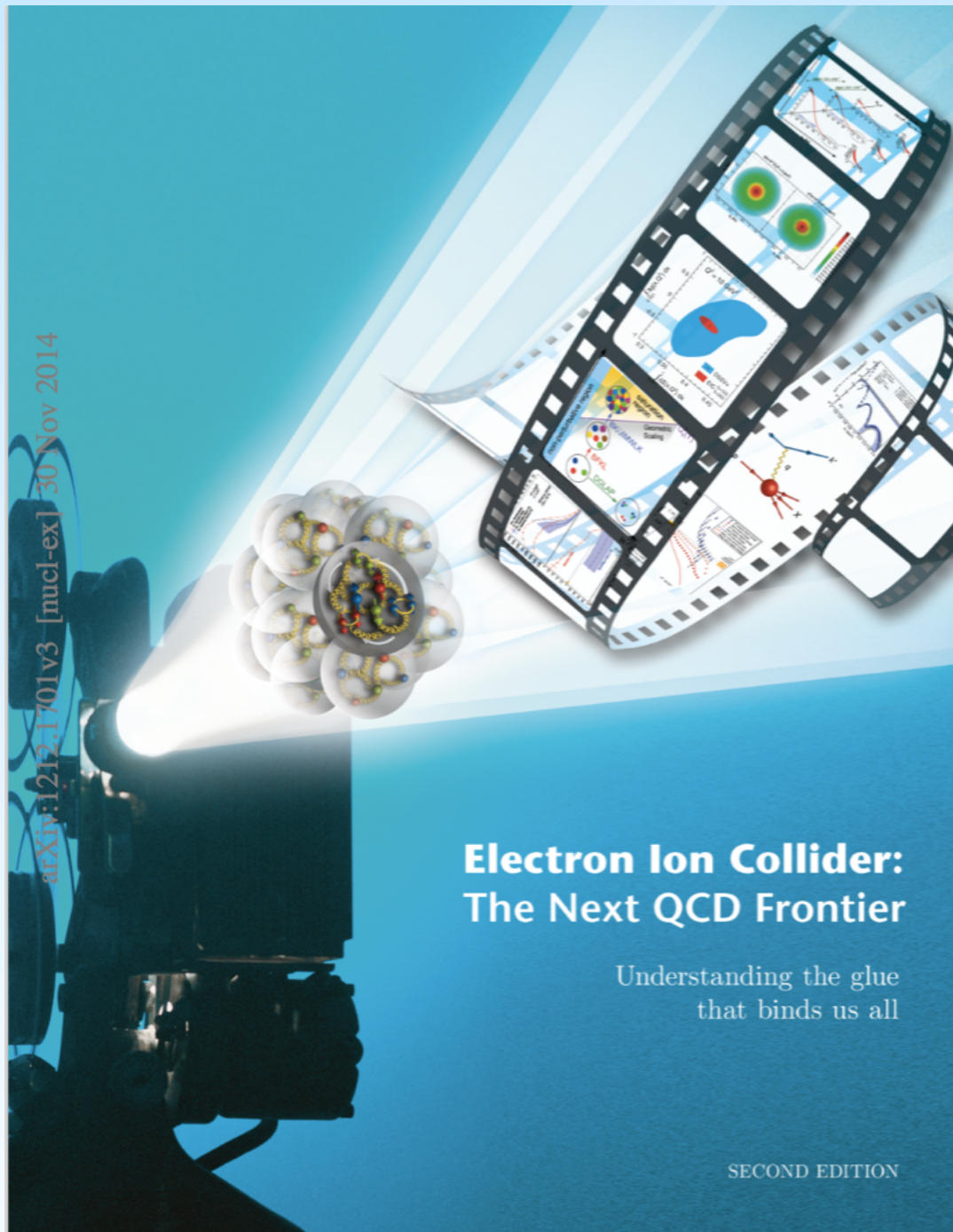
U.S. EIC Capabilities



Eur. Phys. J. A52 (2016) no.9, 268 - 441 citations

- *A collider to provide kinematic reach well into the gluon dominated regime,*
- *Electron beams provide the unmatched precision of the electromagnetic interaction as a probe,*
- *Polarized nucleon beams to determine the correlations of sea quark and gluon distributions with the nucleon spin,*
- *Heavy Ion beams to access the gluon-saturated regime and as a precise dial to study propagation of color charges in nuclear matter.*
- *Facility concepts (upgrades) at RHIC and at Jefferson Laboratory.*

U.S. EIC Science Case



Eur. Phys. J. A52 (2016) no.9, 268 - 441 citations

See also arXiv:1708.01527

- *How are the sea quarks and gluons, and their spins, distributed in space and momentum inside the nucleus?*
- *Where does the saturation of gluon densities set in?*
- *How does the nuclear environment affect the distribution of quarks and gluons and their interactions in nuclei?*

U.S.-based EIC - Observables

Key questions:

- How are the sea quarks and gluons, and their spins, distributed in space and momentum inside the nucleus?
- Where does the saturation of gluon densities set in?
- How does the nuclear environment affect the distribution of quarks and gluons and their interactions in nuclei?

Key measurements:

- Inclusive Deep-Inelastic Scattering,
- Semi-inclusive deep-inelastic scattering with one or two of the particles in the final state,
- Exclusive deep-inelastic scattering,
- Diffraction.

coherent contributions from many nucleons effectively amplify the gluon density being probed.

The EIC was designated in the 2007 Nuclear Physics Long Range Plan as "embodying the vision for reaching the next QCD frontier" [1]. It would extend the QCD sci-

ence programs in the U.S. established at both the CEBAF accelerator at JLab and RHIC at BNL in dramatic and fundamentally important ways. The most intellectually pressing questions that an EIC will address that relate to our detailed and fundamental understanding of QCD in this frontier environment are:

- How are the sea quarks and gluons, and their spins, distributed in space and momentum inside the nucleon? How are these quark and gluon distributions correlated with overall nucleon properties, such as spin direction? What is the role of the orbital motion of sea quarks and gluons in building the nucleon spin?

- Where does the saturation of gluon densities set in? Is there a simple boundary between the saturation and non-saturation regimes? If so, how does the distribution of quarks and gluons change at this boundary? Does this saturation produce matter of universal properties in the nucleon and all nuclei viewed at nearly the speed of light?

- How does the nuclear environment affect the distribution of quarks and gluons and their interactions in nuclei? How does the transverse spatial distribution of quarks and gluons change in nuclei? How does the nuclear environment affect the distribution of quarks and gluons and their interactions in nuclei?

Answers to these questions are essential for understanding the nature of visible matter. An EIC is the ultimate machine to provide answers to these questions for the following reasons:

- A collider is needed to provide kinematic reach well into the gluon-dominated regime;
- Polarized nucleon beams are needed to determine the correlations of sea quark and gluon distributions with the nucleon spin;
- Heavy ion beams are needed to provide precocious access to the regime of saturated gluon densities and offer a precise dial in the study of propagation-length for color charge in nuclear matter.

The EIC would be distinguished from all past, current, and contemplated facilities around the world by being at the intensity frontier with a versatile range of kinematics and beam polarizations, as well as beam species, allowing the above questions to be tackled at one facility. In particular, the EIC design exceeds the capabilities of HERA, the only electron-proton collider

to date, by adding a) polarized proton and light-ion beams; b) a wide variety of heavy-ion beams; c) two to three orders of magnitude increase in luminosity to facilitate tomographic imaging; and d) wide energy variability to enhance the sensitivity to gluon distributions. Achieving these challenging technical improvements in a single facility will extend U.S. leadership in accelerator sci-

U.S.-based EIC - Observables

Key requirements:

- *Electron identification - scattered lepton*
- *Momentum and angular resolution - x, Q^2*
- *$\pi^+, \pi^-, K^+, K^-, p^+, p^-, \dots$ identification, acceptance*
- *Rapidity coverage, t -resolution*

Key measurements:

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- *Semi-inclusive deep-inelastic scattering with one or two of the particles in the final state,*
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- How does the nuclear environment affect the distribution of quarks and gluons and their interactions in nuclei? How does the transverse spatial distribution of quarks and gluons change as a function of the nuclear size?

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The EIC would be distinguished from all past, current, and contemplated facilities around the world by being at the intensity frontier with a versatile range of kinematics and beam polarizations, as well as beam species, allowing the above questions to be tackled at one facility. In particular, the EIC design needs the capabilities of a collider, including electron-proton collider

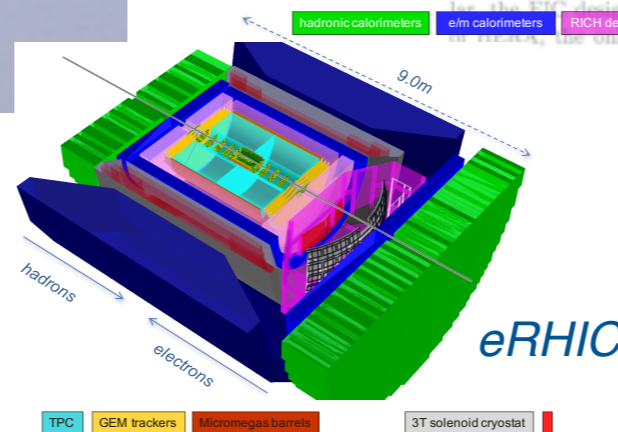
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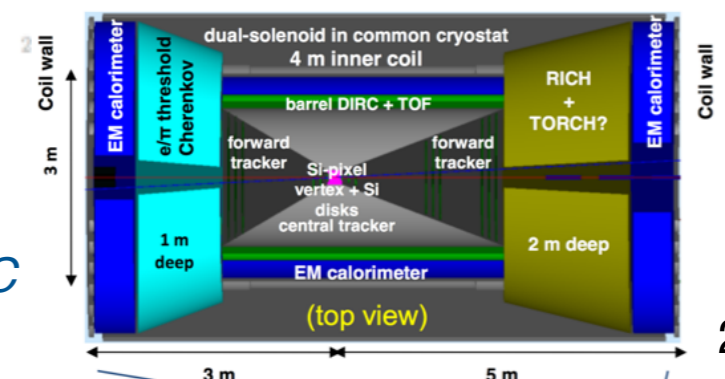
Electron Ion Collider:
The Next QCD Frontier

Understanding the glue
that binds us all

Green-field detector concepts:



JLEIC



U.S.-based EIC - Core Science

The Next QCD Frontier
Understanding the glue that binds us all

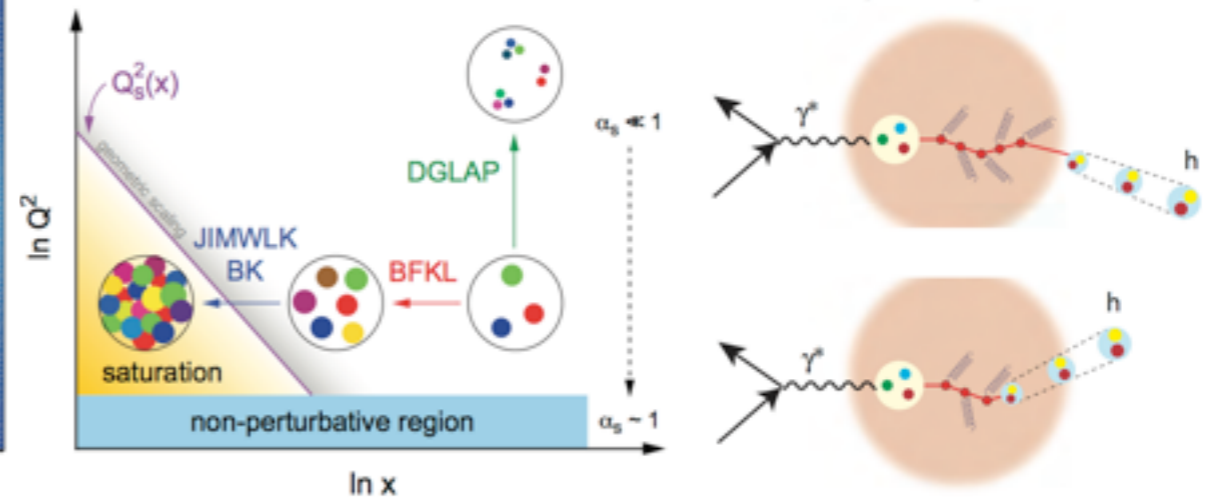
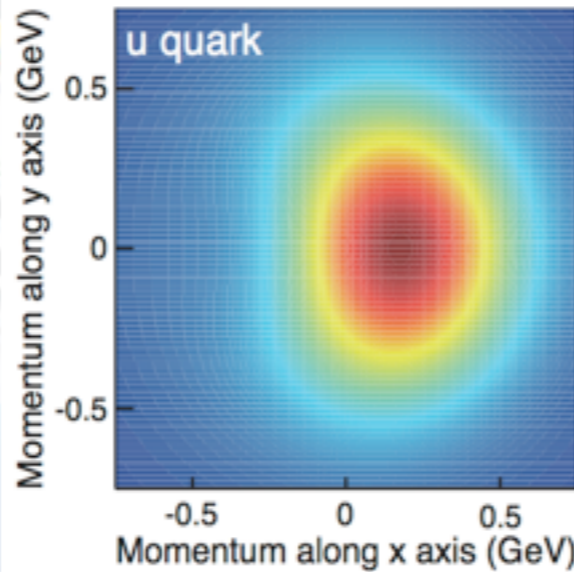


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- Heavy ion beams are needed to provide precocious access to the regime of saturated gluon densities and offer a precise dial in the study of propagation-length for color charges in nuclear matter.

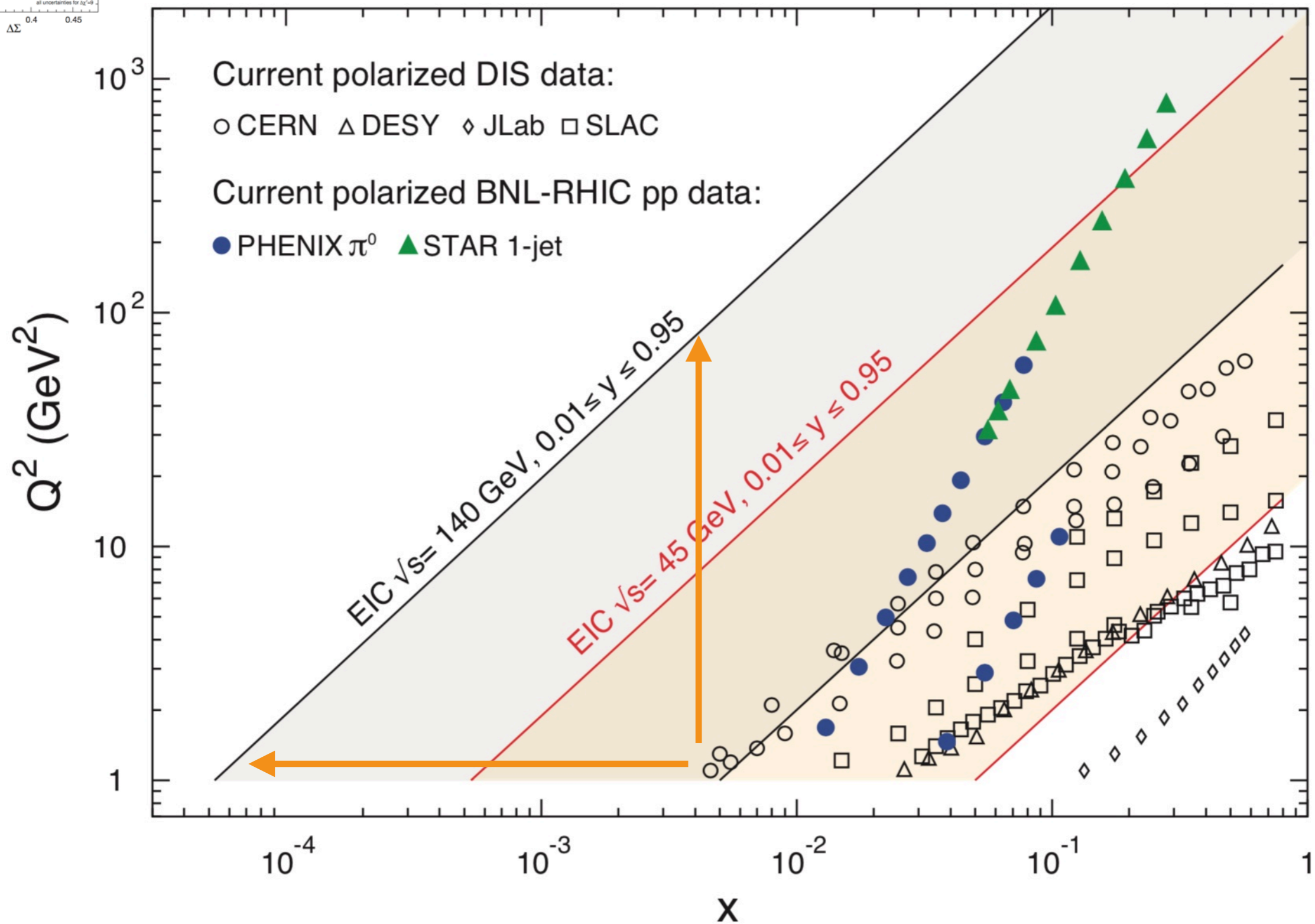
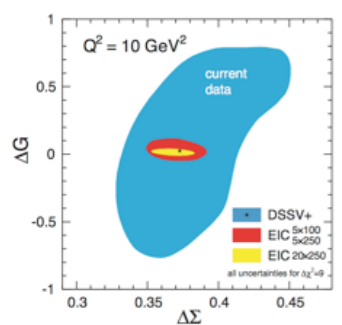
The EIC would be distinguished from all past, current, and contemplated facilities around the world by being at the intensity frontier with a versatile range of kinematics and beam polarizations, as well as beam species, allowing the above questions to be tackled at one facility. In particular, the EIC design exceeds the capabilities of HERA, the only electron-proton collider

to date, by adding a) polarized proton and light-ion beams; b) a wide variety of heavy-ion beams; c) two to three orders of magnitude increase in luminosity to facilitate tomographic imaging; and d) wide energy variability to enhance the sensitivity to gluon distributions. Achieving these challenging technical improvements in a single facility will extend U.S. leadership in accelerator sci-

Nuclear Physics enabled by EIC **beam** energy, intensity, polarization, and species, **detector** capabilities,

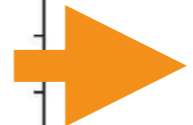
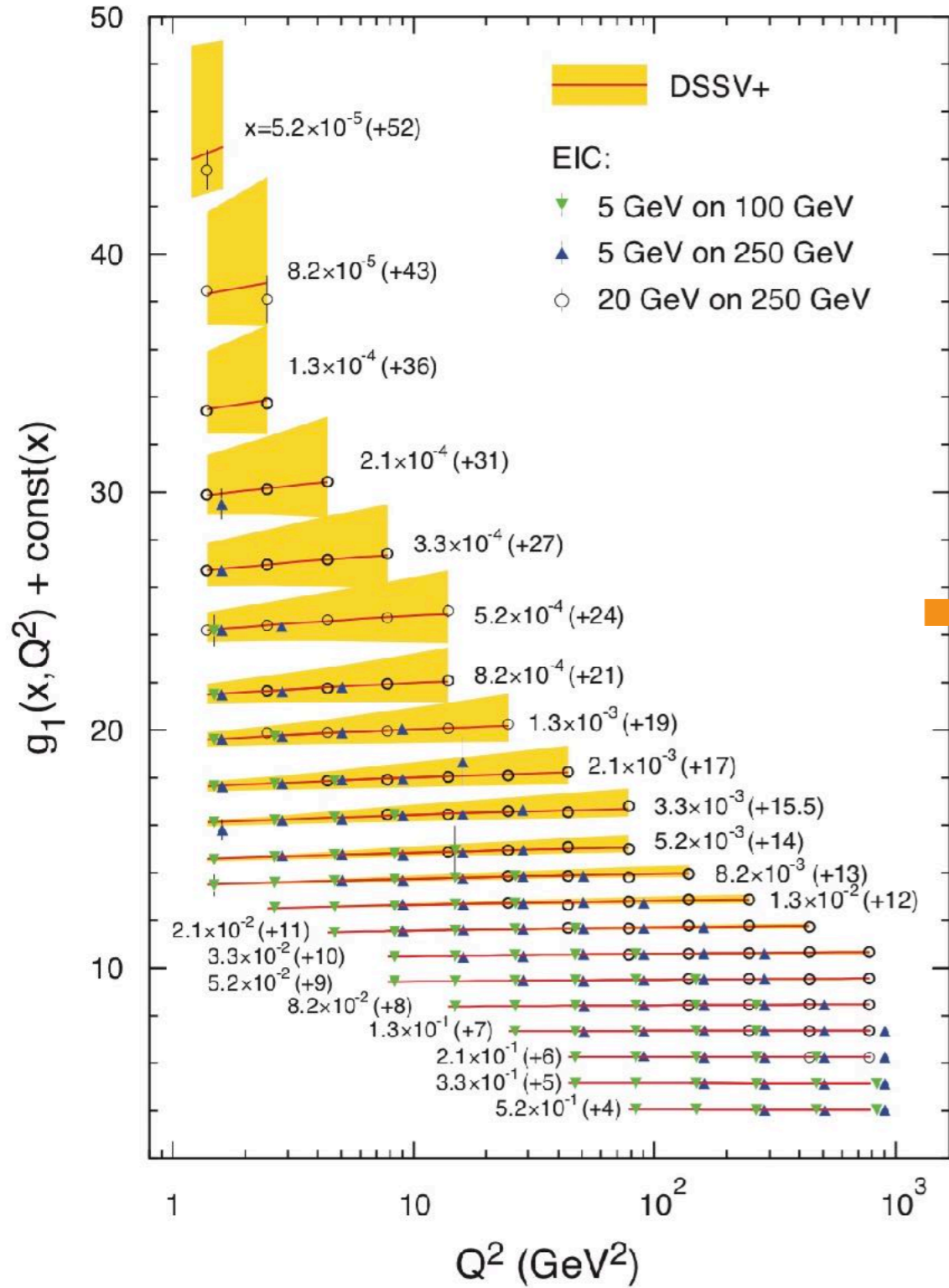
Theory

U.S.-based EIC - Proton Spin

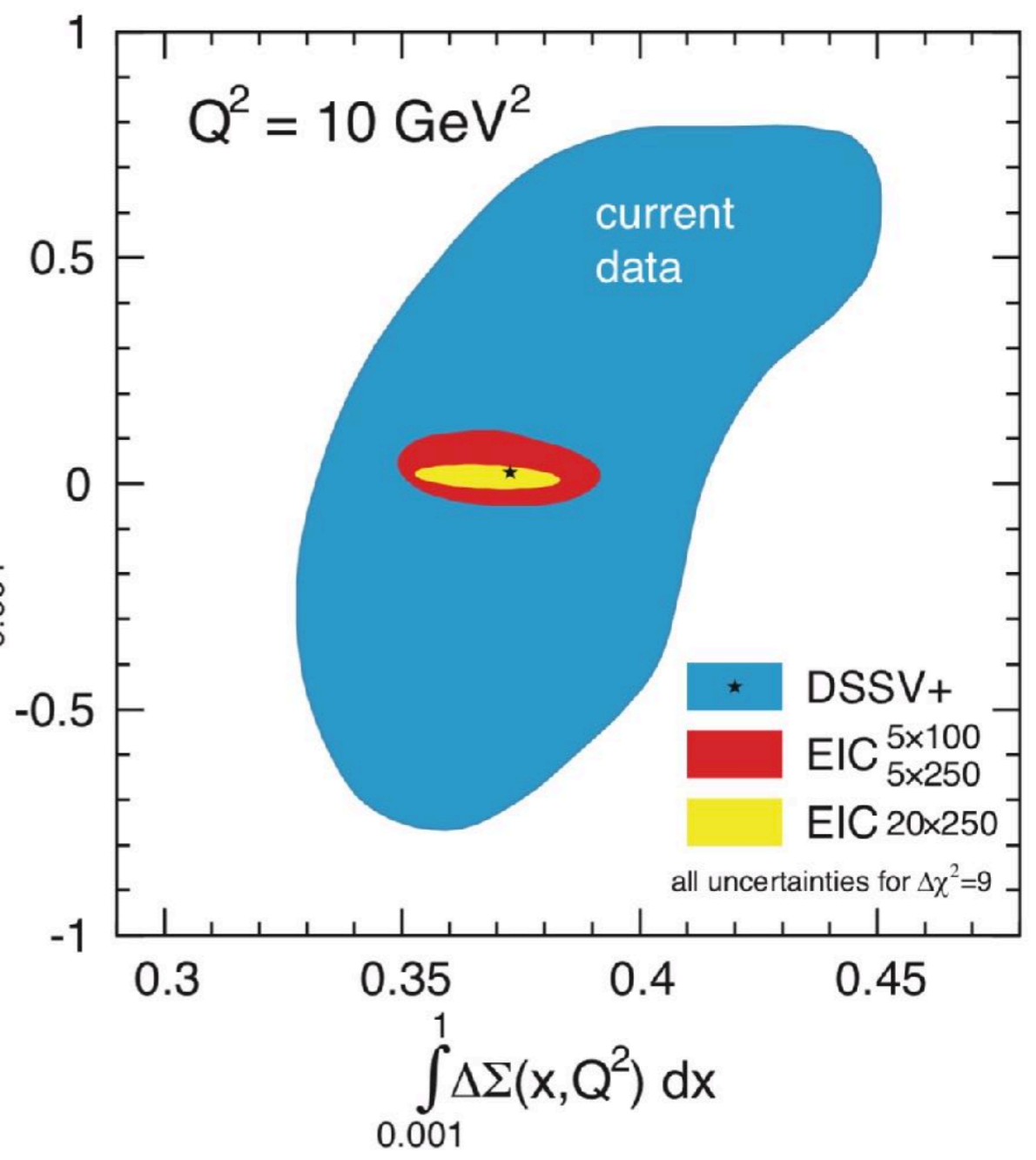


Two orders in x and Q^2 compared to existing data; few, if any, alternatives.

U.S.-based EIC - Proton Spin



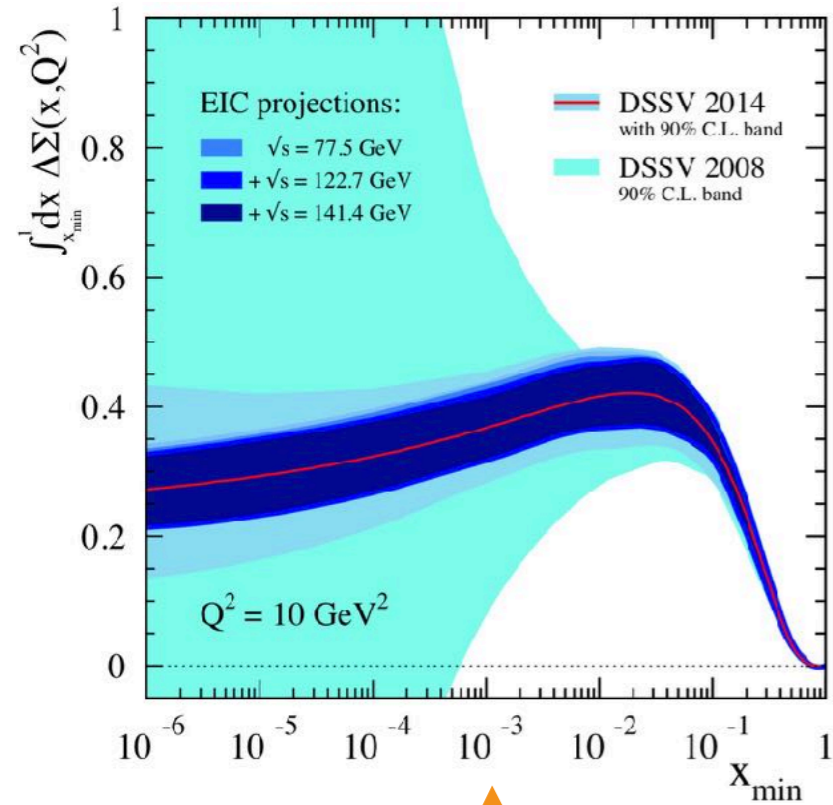
$$\int_{0.001}^1 \Delta g(x, Q^2) dx$$



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

U.S.-based EIC - Proton Spin

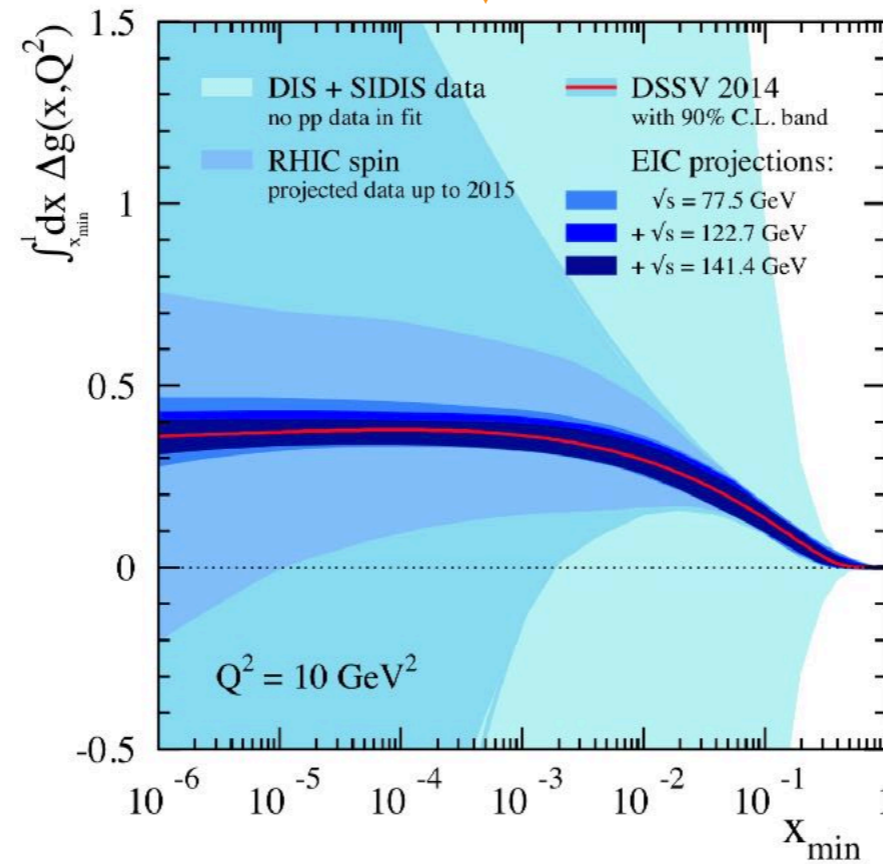
A more up-to-date view; E. Aschenauer et al.
PRD 92 (2015) 094030



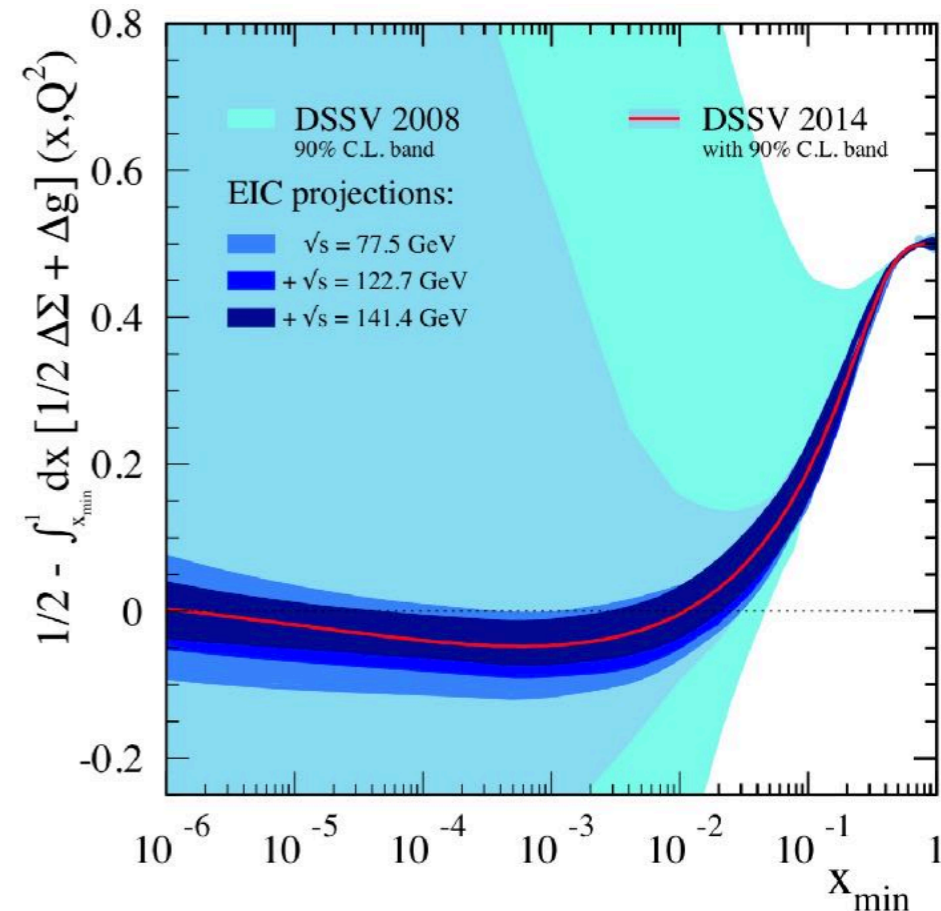
(anti-)quark helicity

Clearly requires EIC

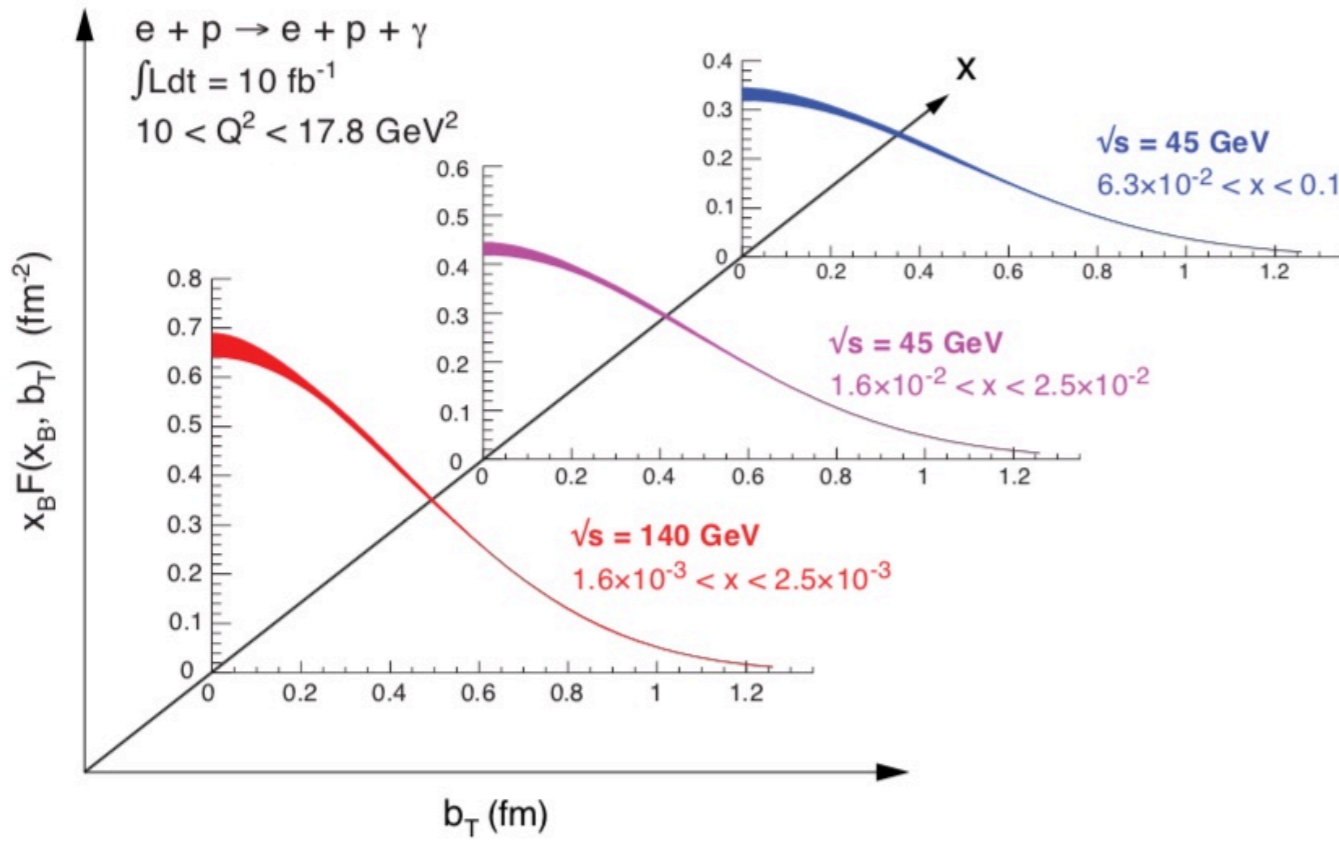
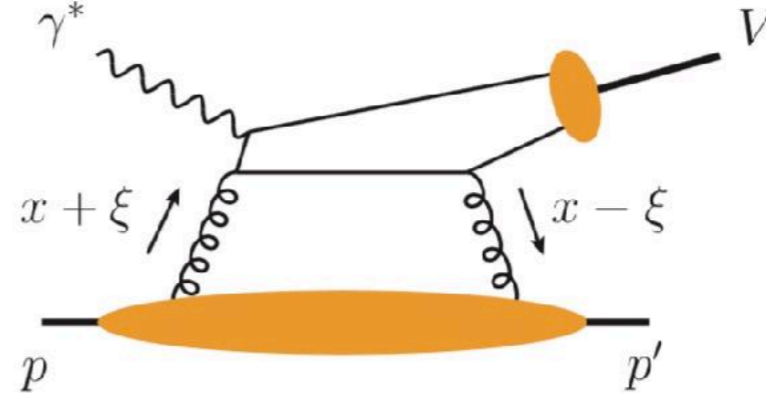
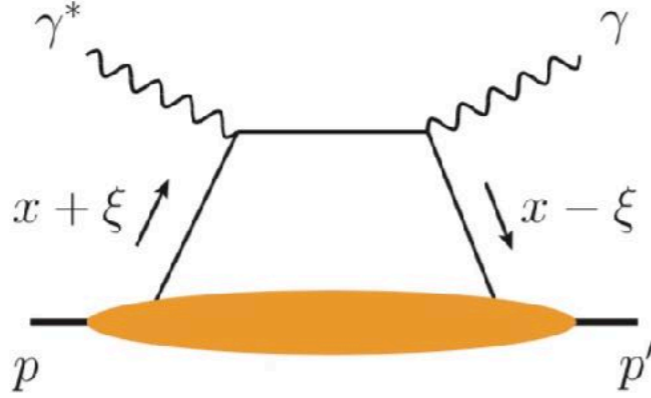
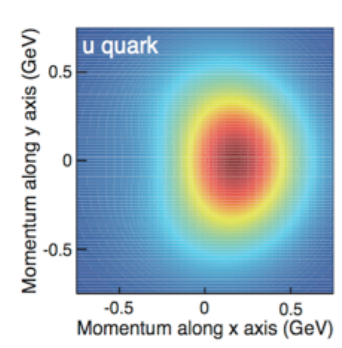
gluon helicity



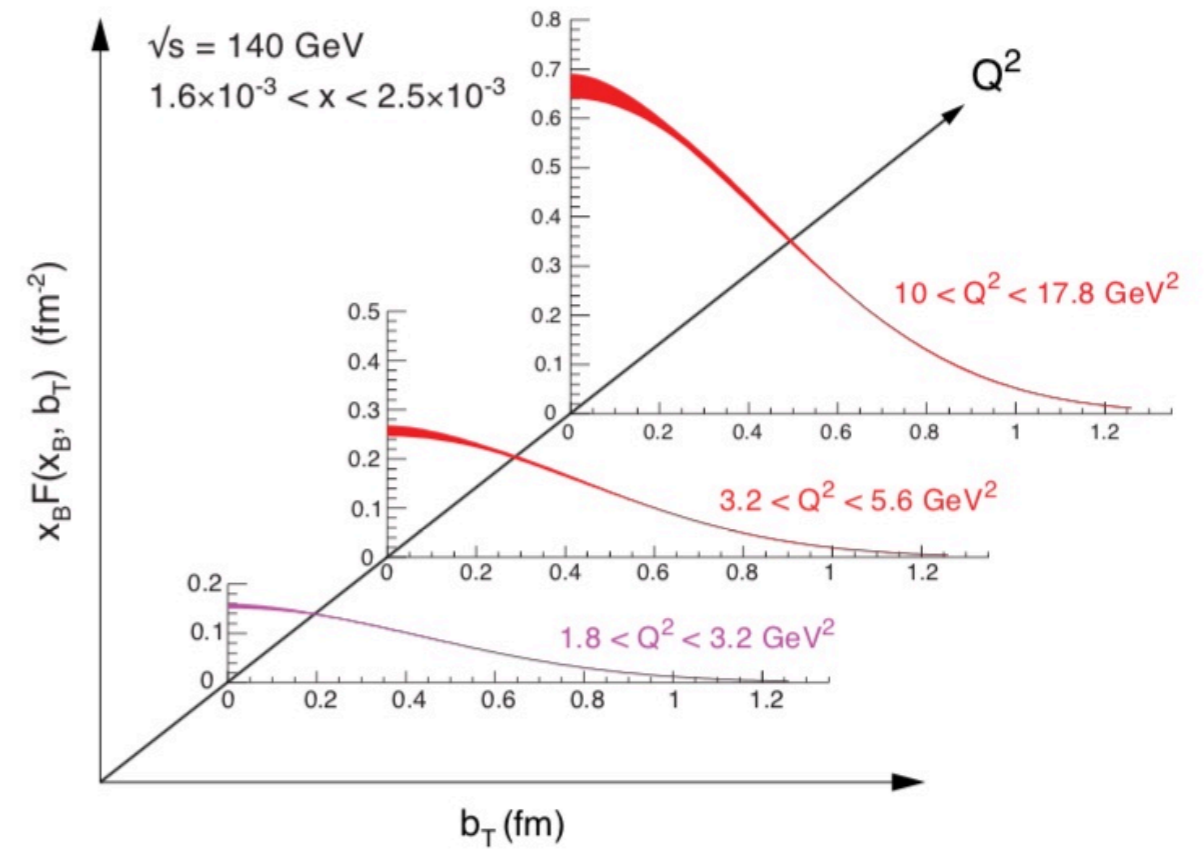
orbital momenta



EIC - DVCS, DVMP, and Imaging

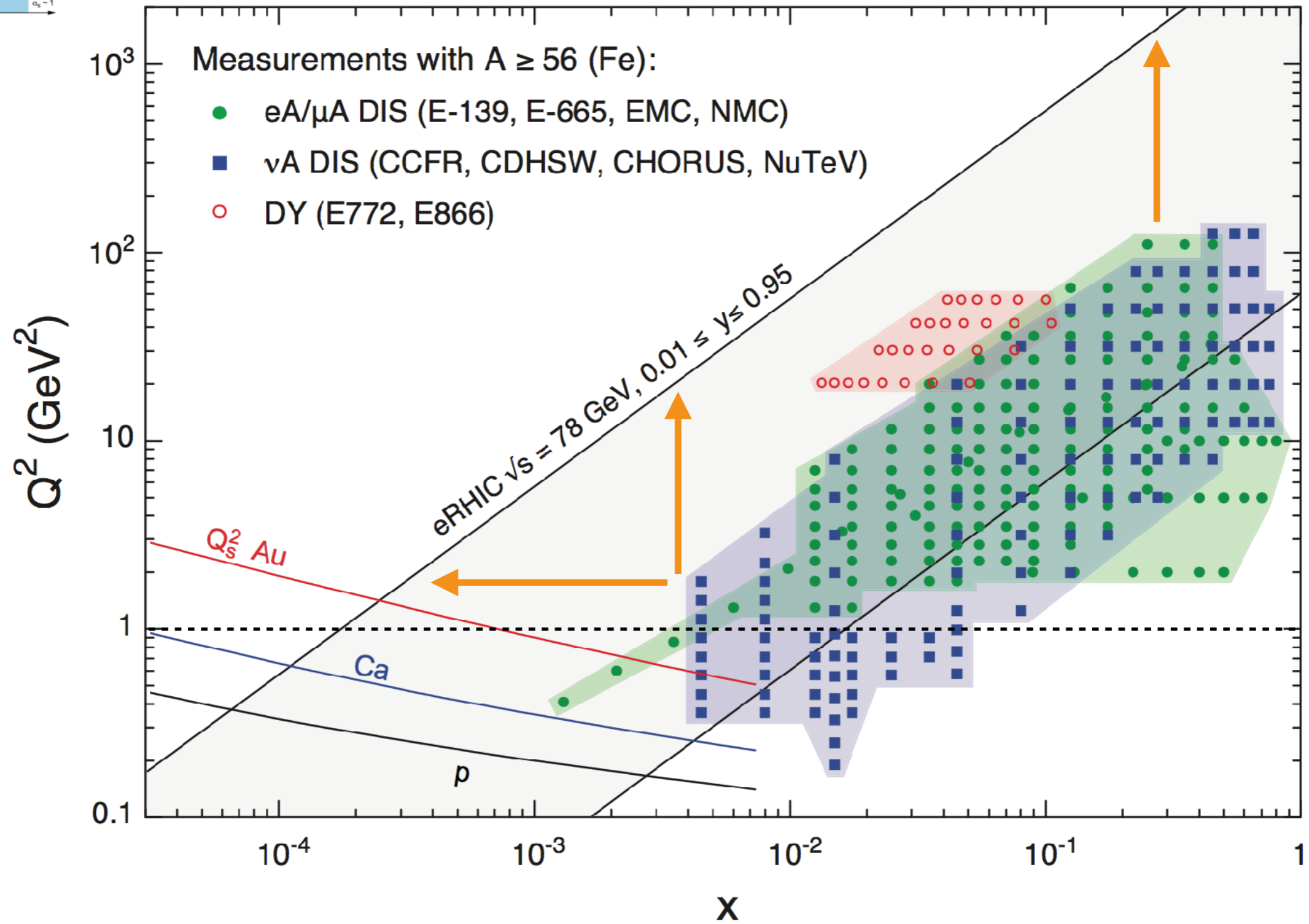
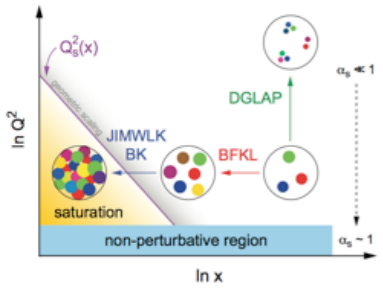


x-dependence at fixed Q^2

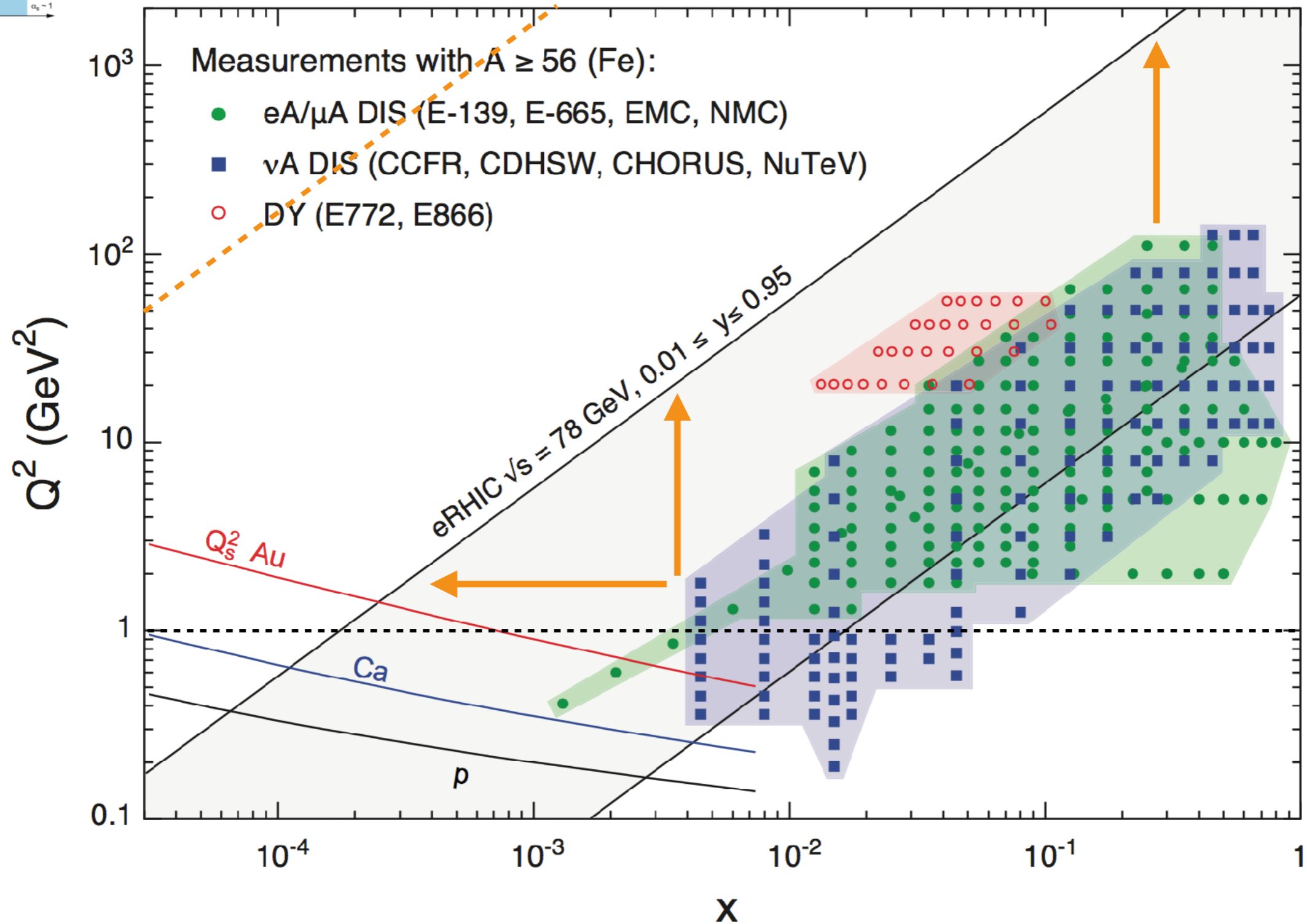
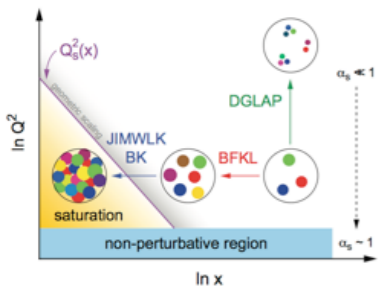


Q^2 -dependence at fixed x

U.S.-based EIC - The Nuclear Landscape

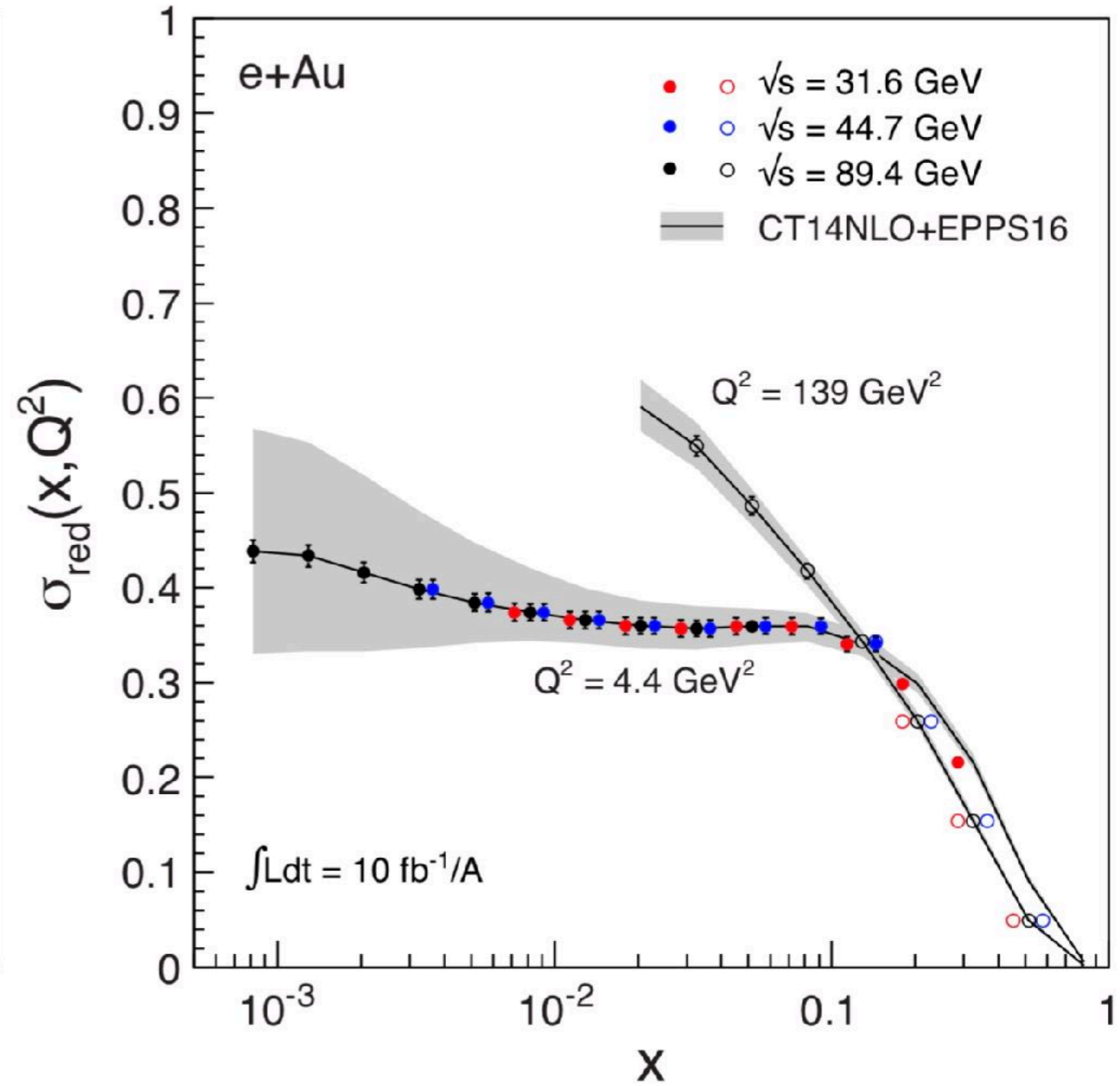
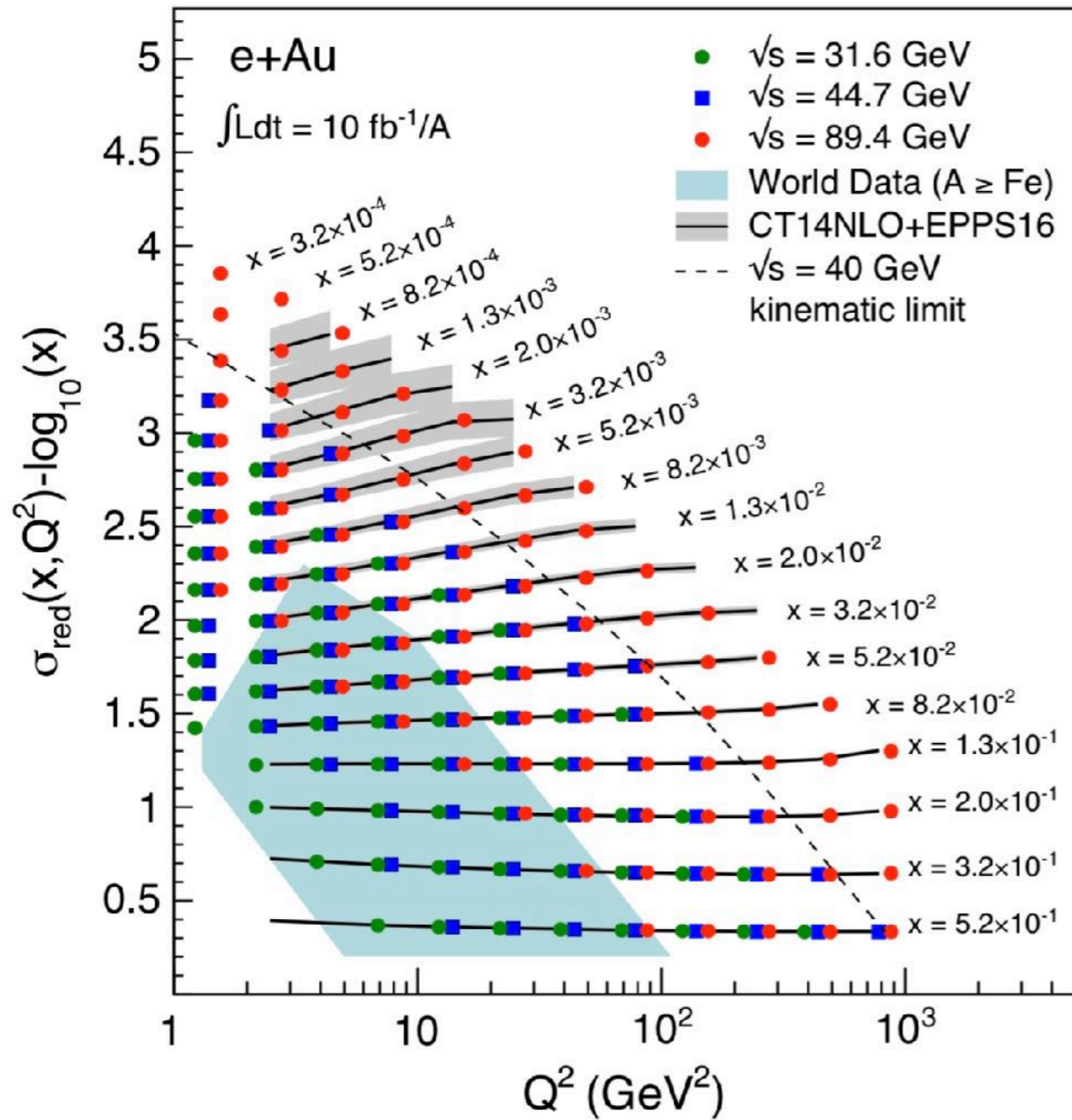


U.S.-based EIC - The Nuclear Landscape



LHeC, if realized, will obviously provide unprecedented kinematic reach, complementarity in polarization, A capabilities.

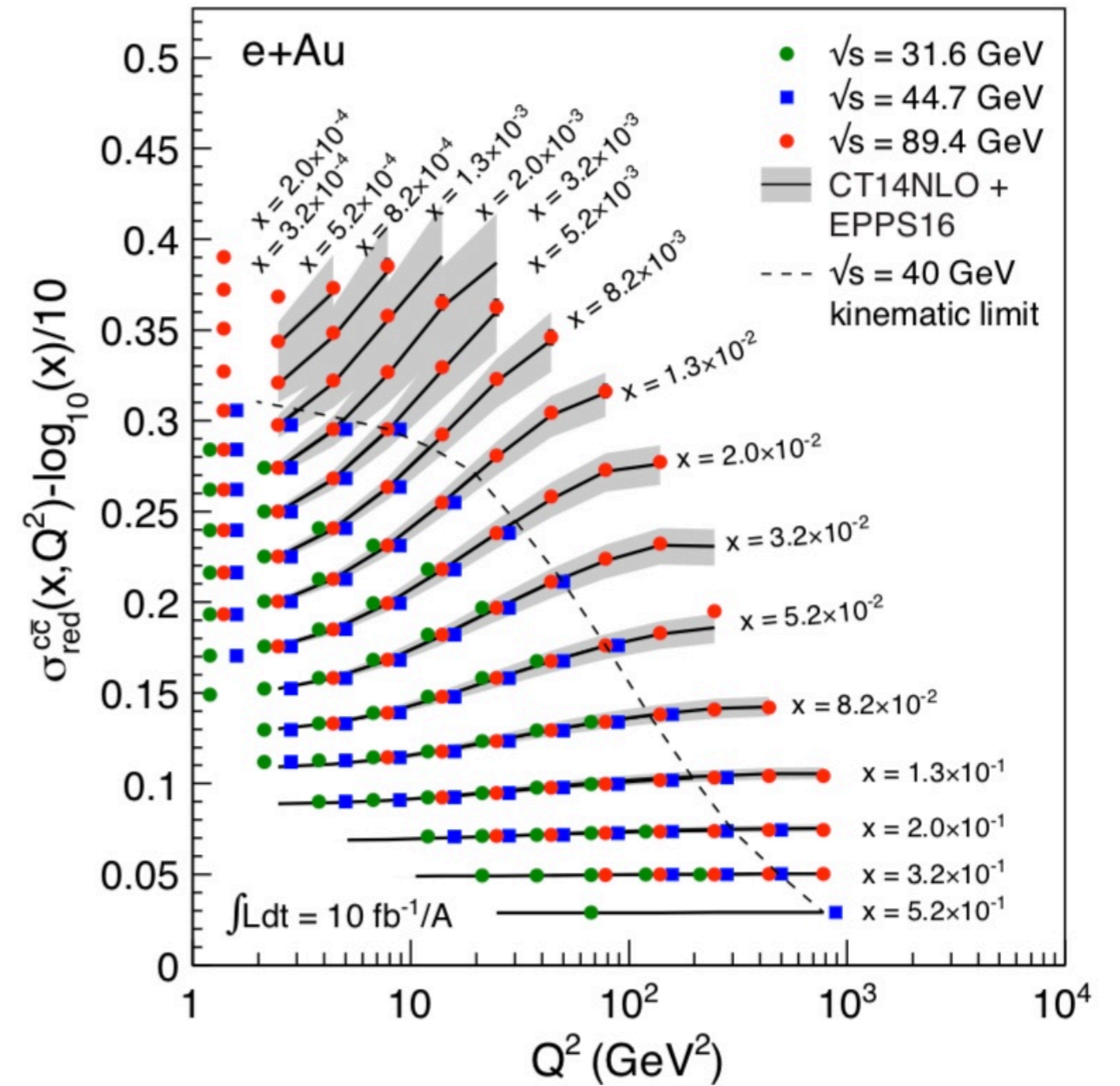
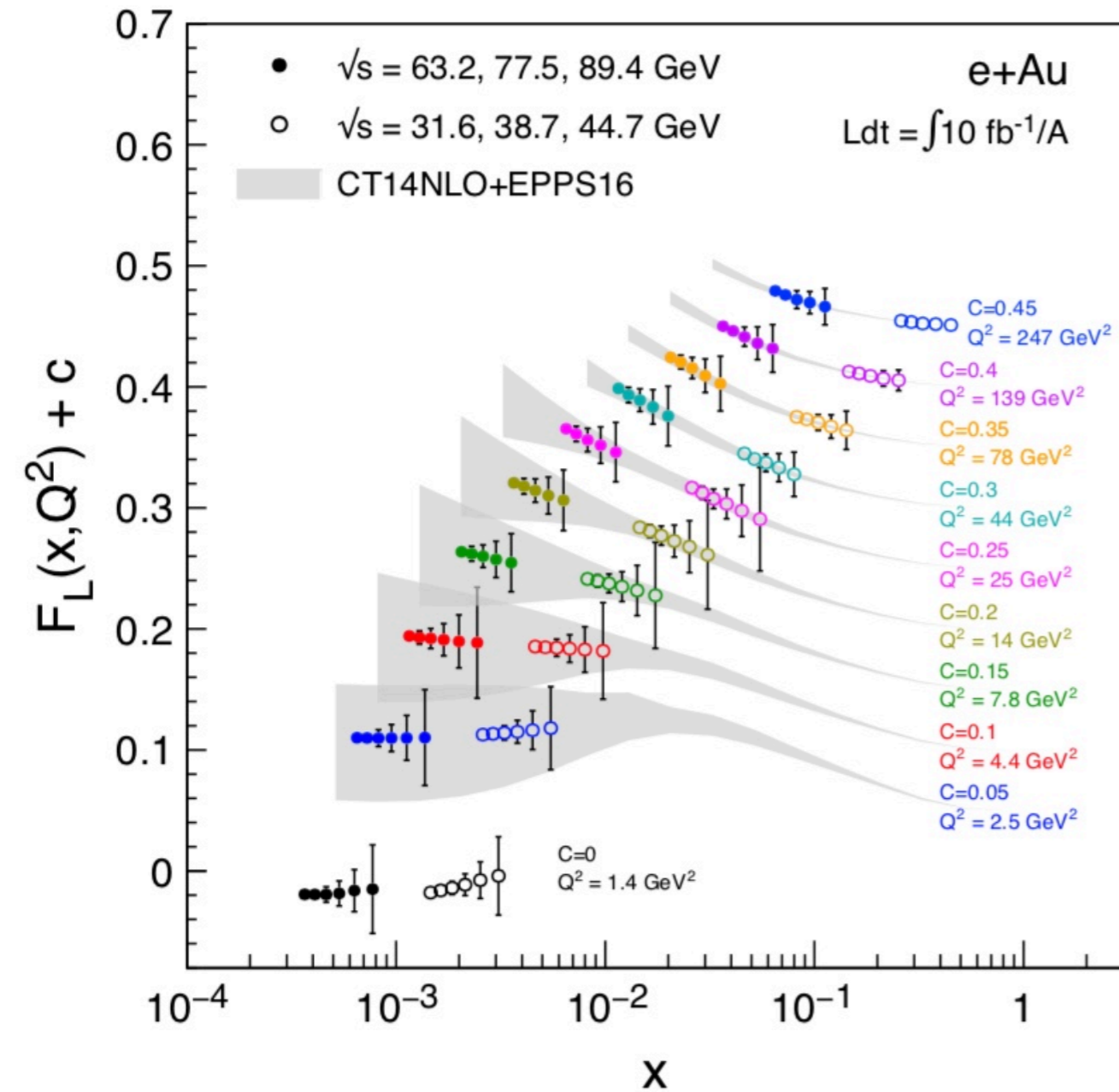
U.S.-based EIC - The Nuclear Landscape



$$\sigma_{\text{reduced}} = F_2(x, Q^2) - \frac{y}{1 + (1 - y)^2} F_L(x, Q^2)$$

Impactful baseline inclusive measurements.

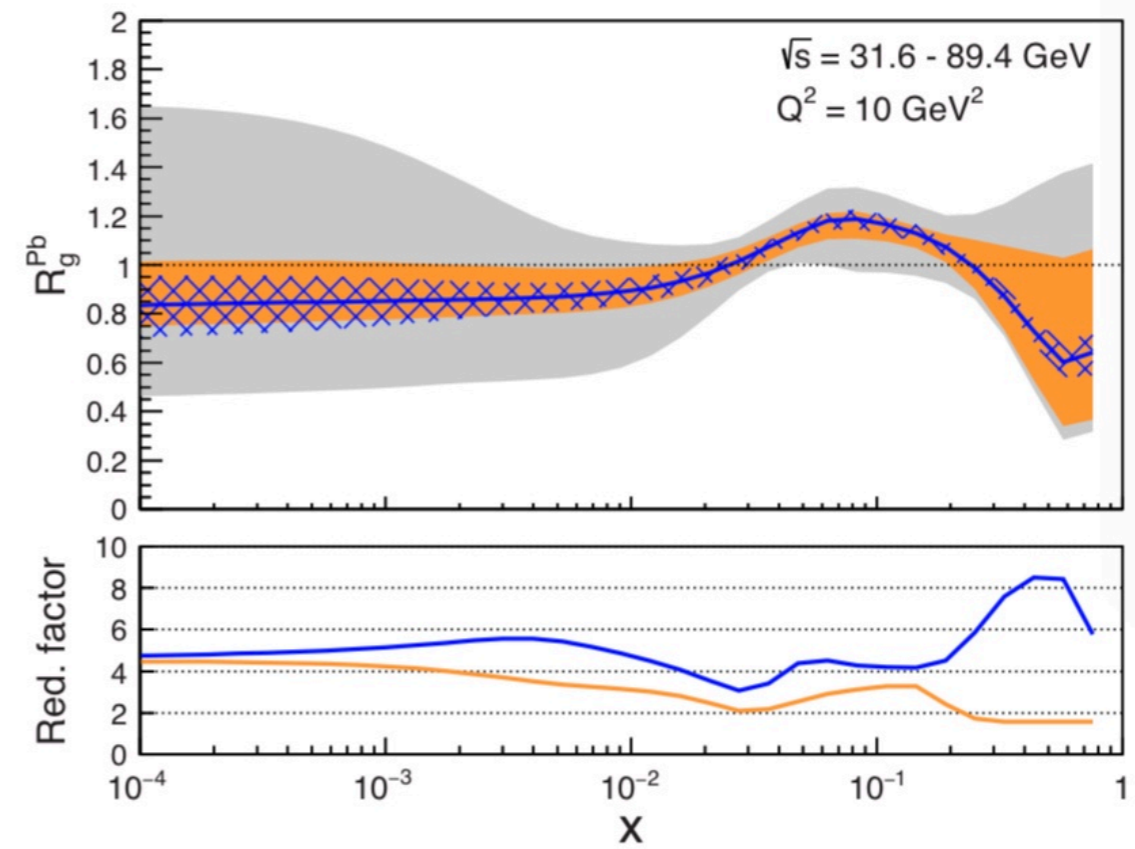
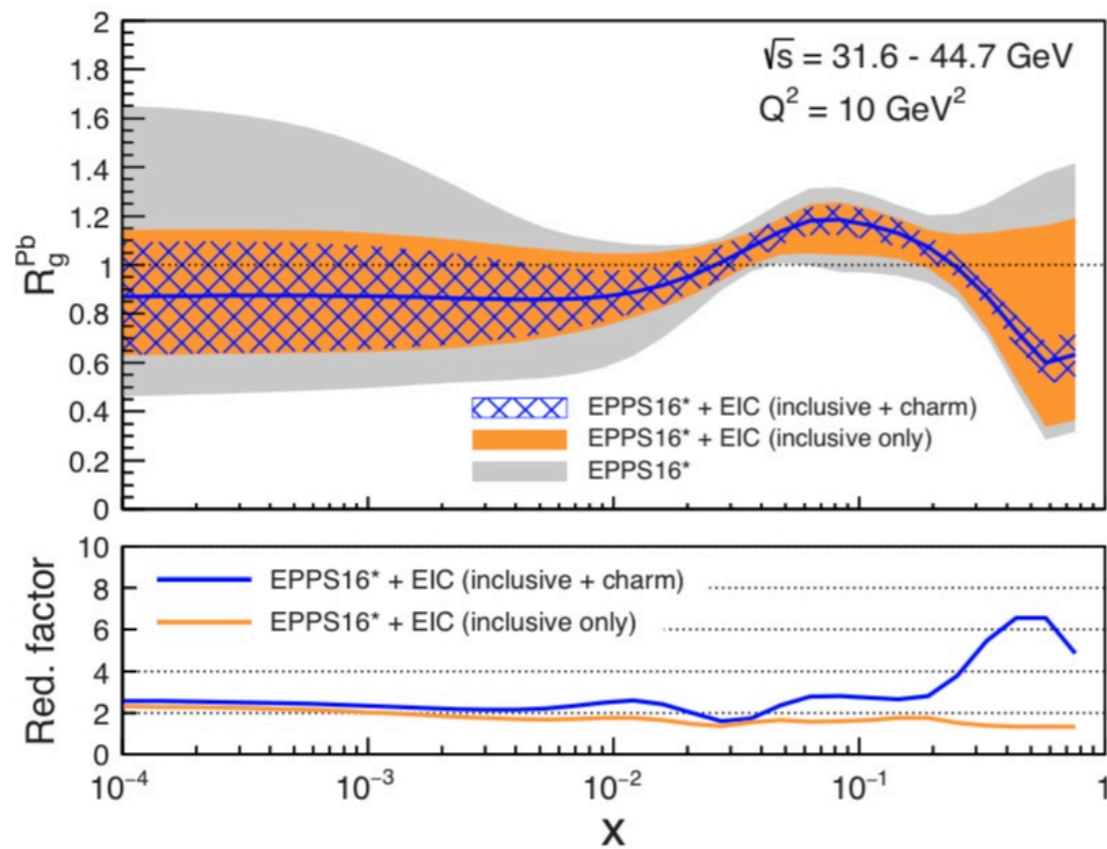
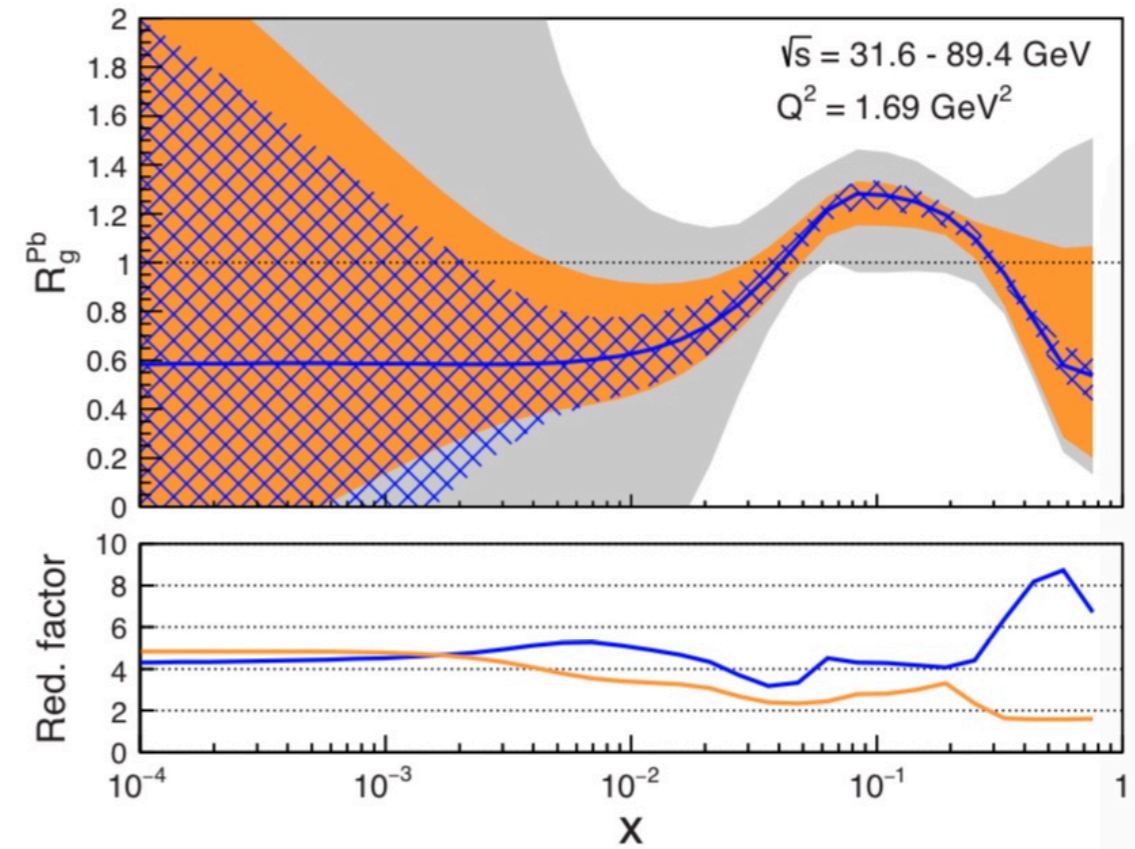
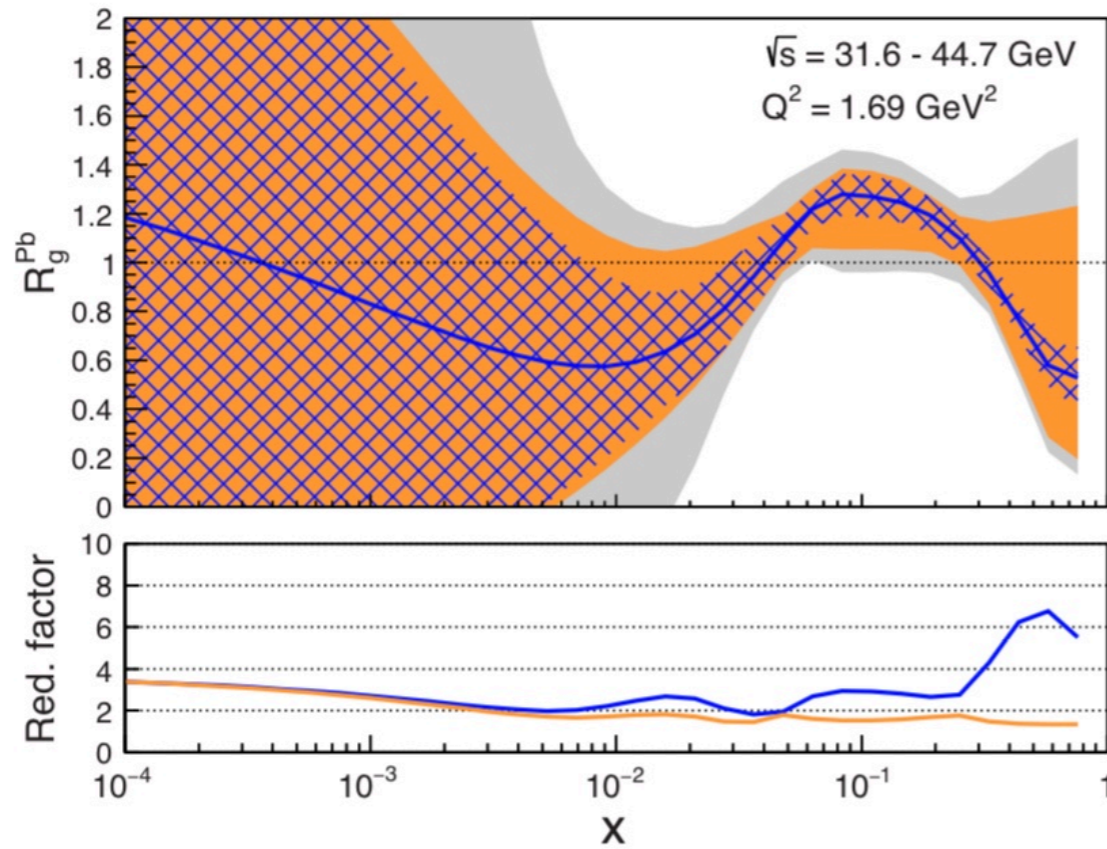
U.S.-based EIC - The Nuclear Landscape



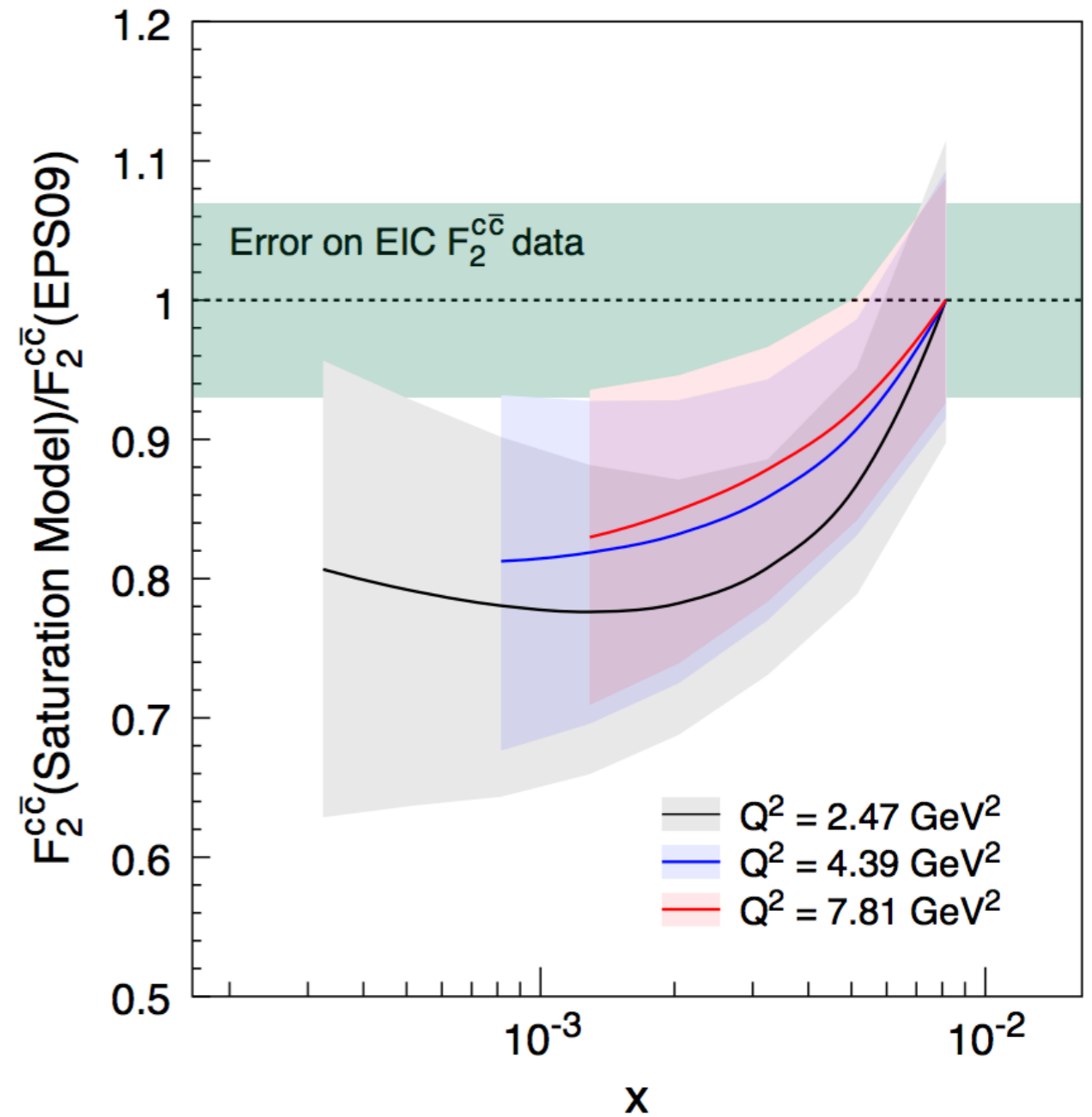
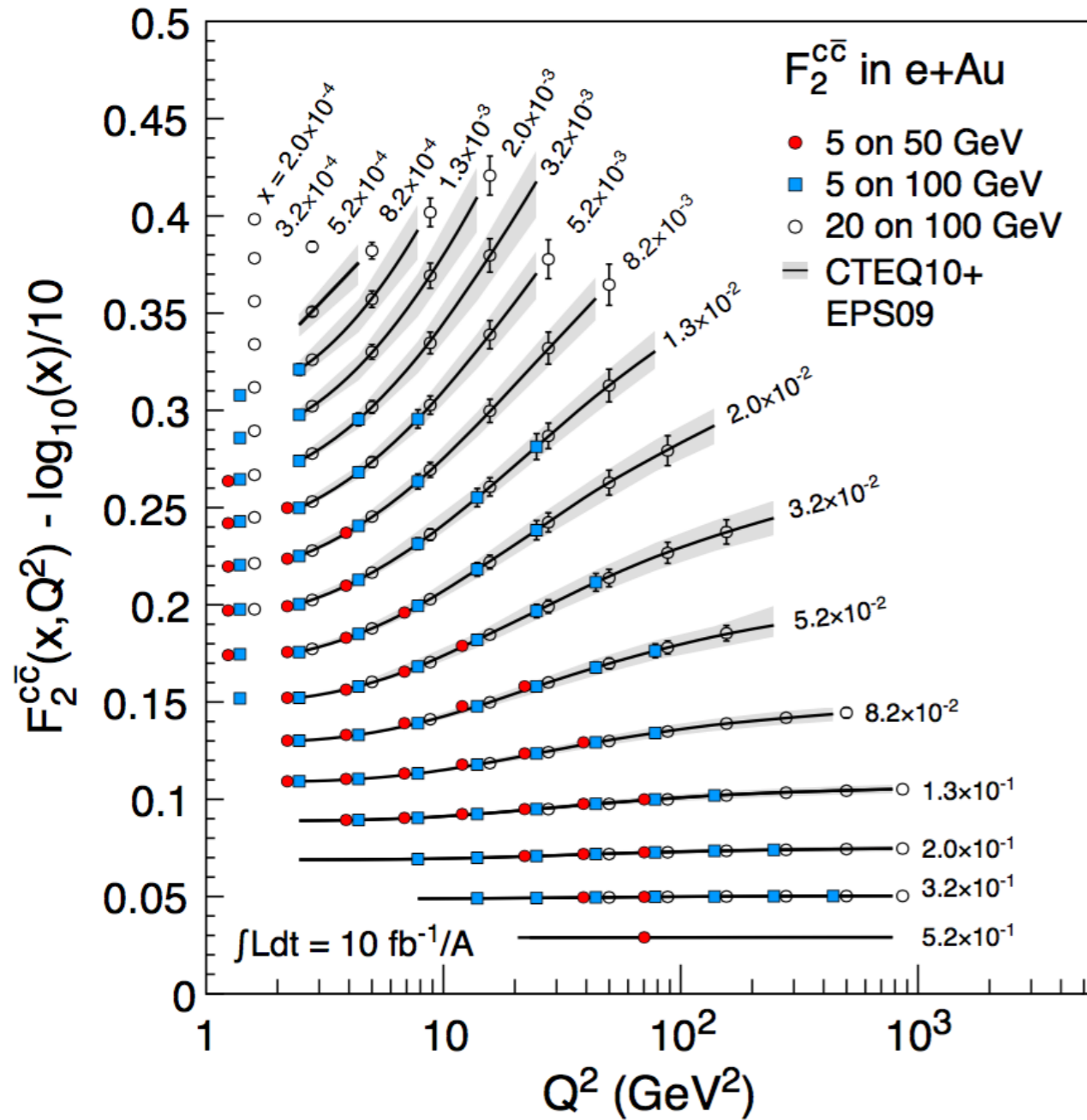
Clearly visible impact also beyond baseline inclusive measurements with “Rosenbluth separation” and semi-inclusive measurements.

Nuclear gluon will be probed sensitively with complementary channels.

U.S.-based EIC - The Nuclear Landscape

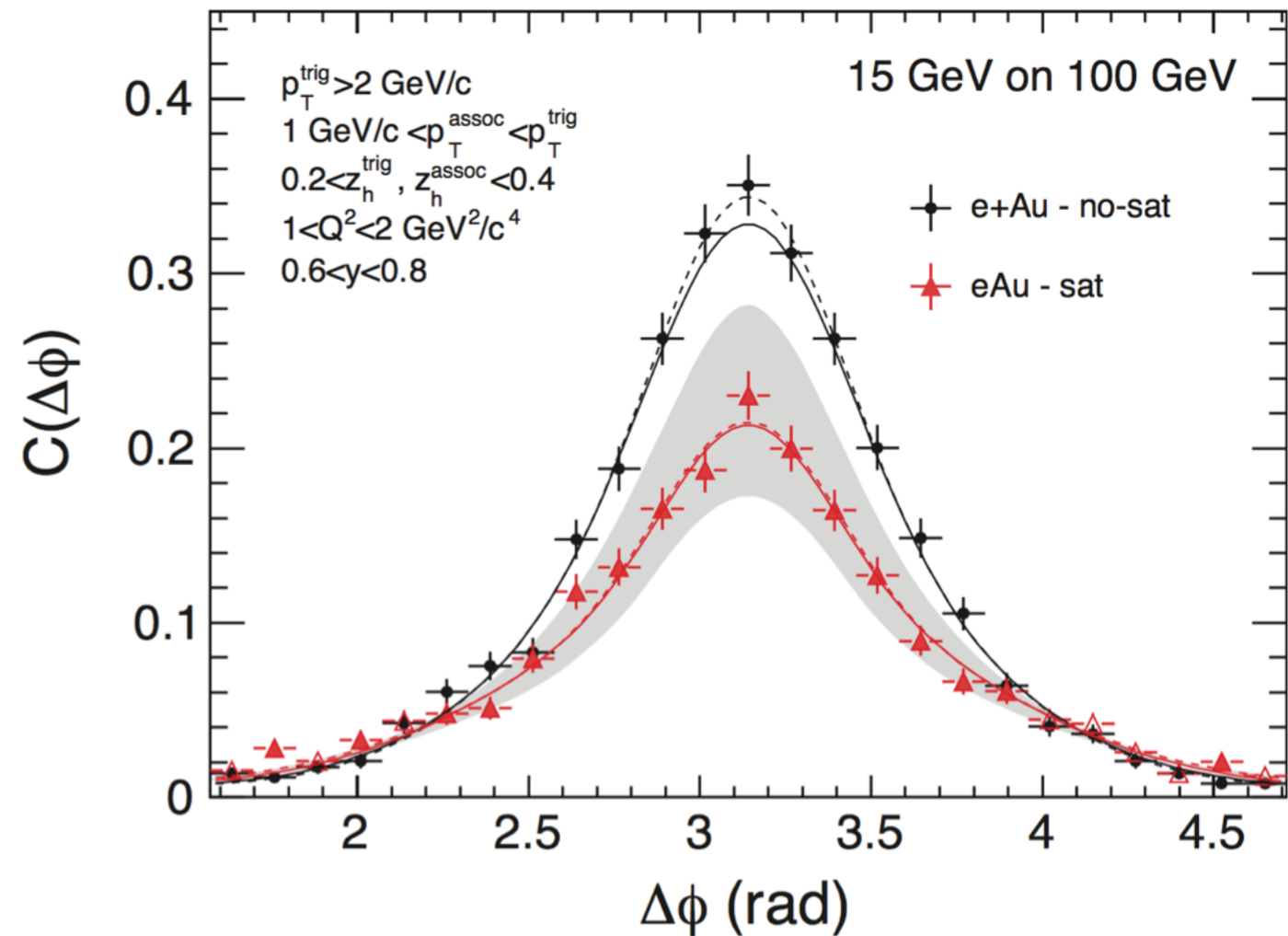
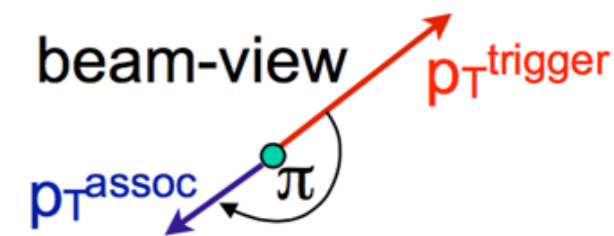
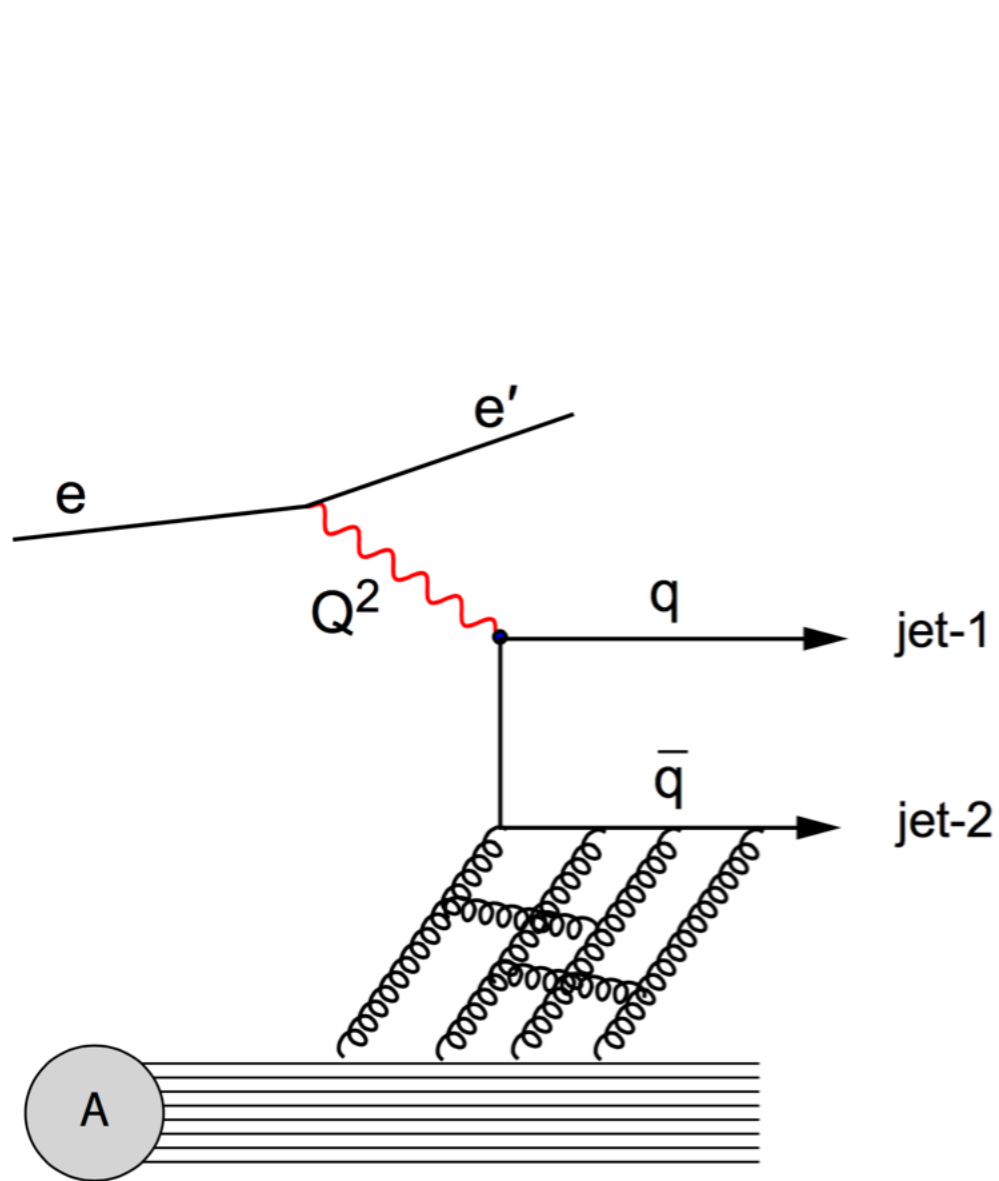


EIC - Saturation from within the PDF?



Improbable and certainly no substitute for thinking outside the PDF!

EIC - Dihadrons to probe Saturation



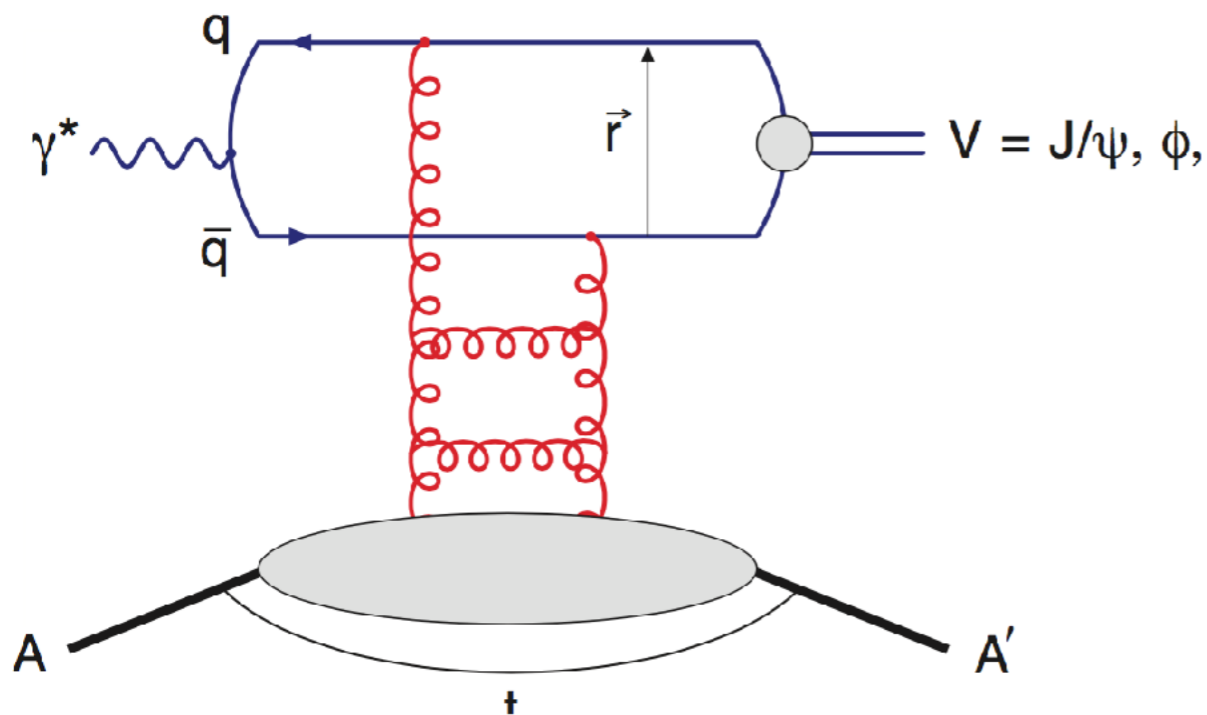
Dominguez, Xiao, Yuan (2011)

Zheng et al (2014)

Suppression of back-to-back hadron or jet correlation directly probes the (un-)saturated gluon distributions in nuclei,

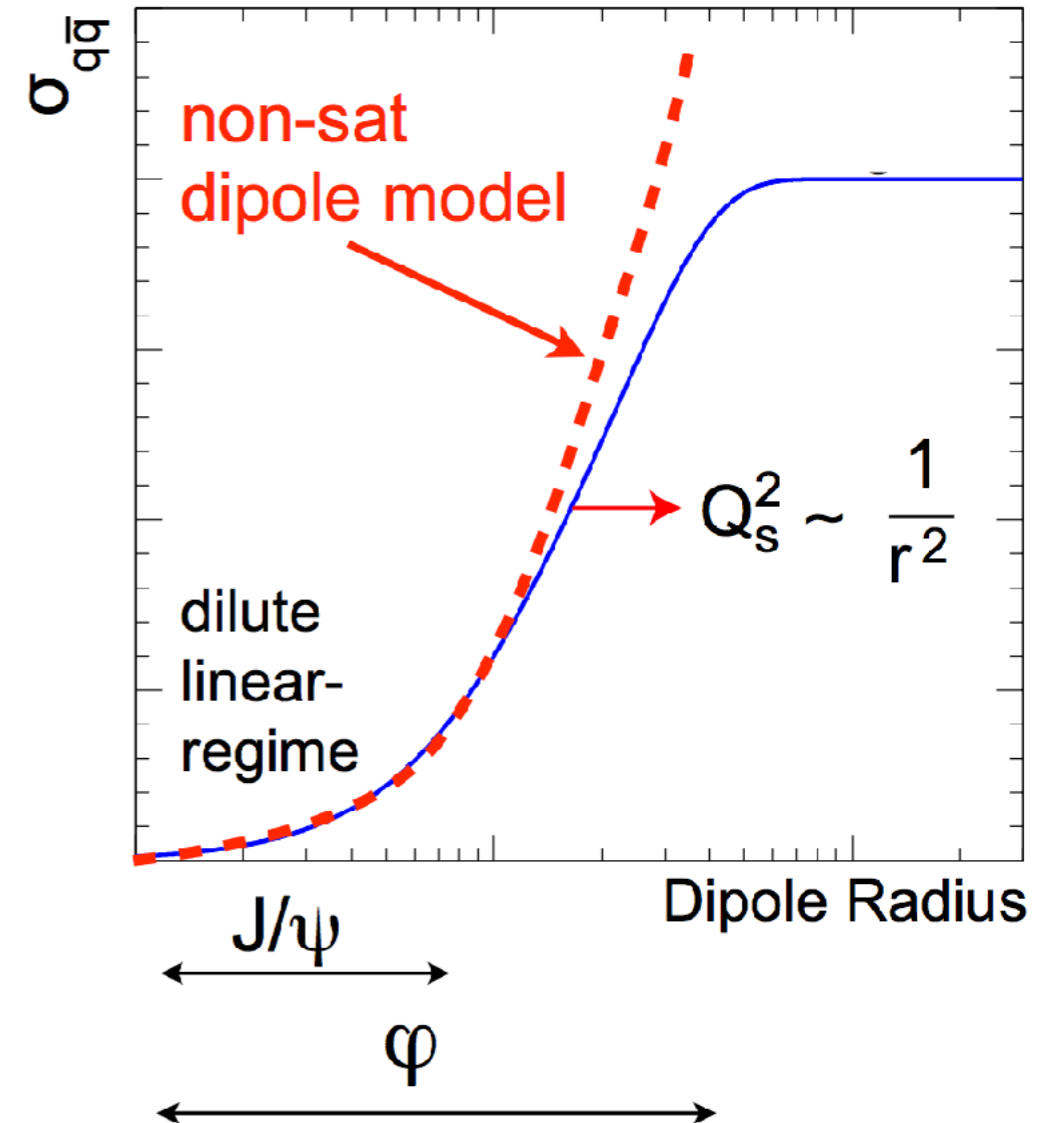
EIC - Exclusive Vector Mesons to probe Saturation

$$t = (\mathbf{p}_A - \mathbf{p}_{A'})^2 = (\mathbf{p}_{\text{VM}} + \mathbf{p}_{e'} - \mathbf{p}_e)^2$$

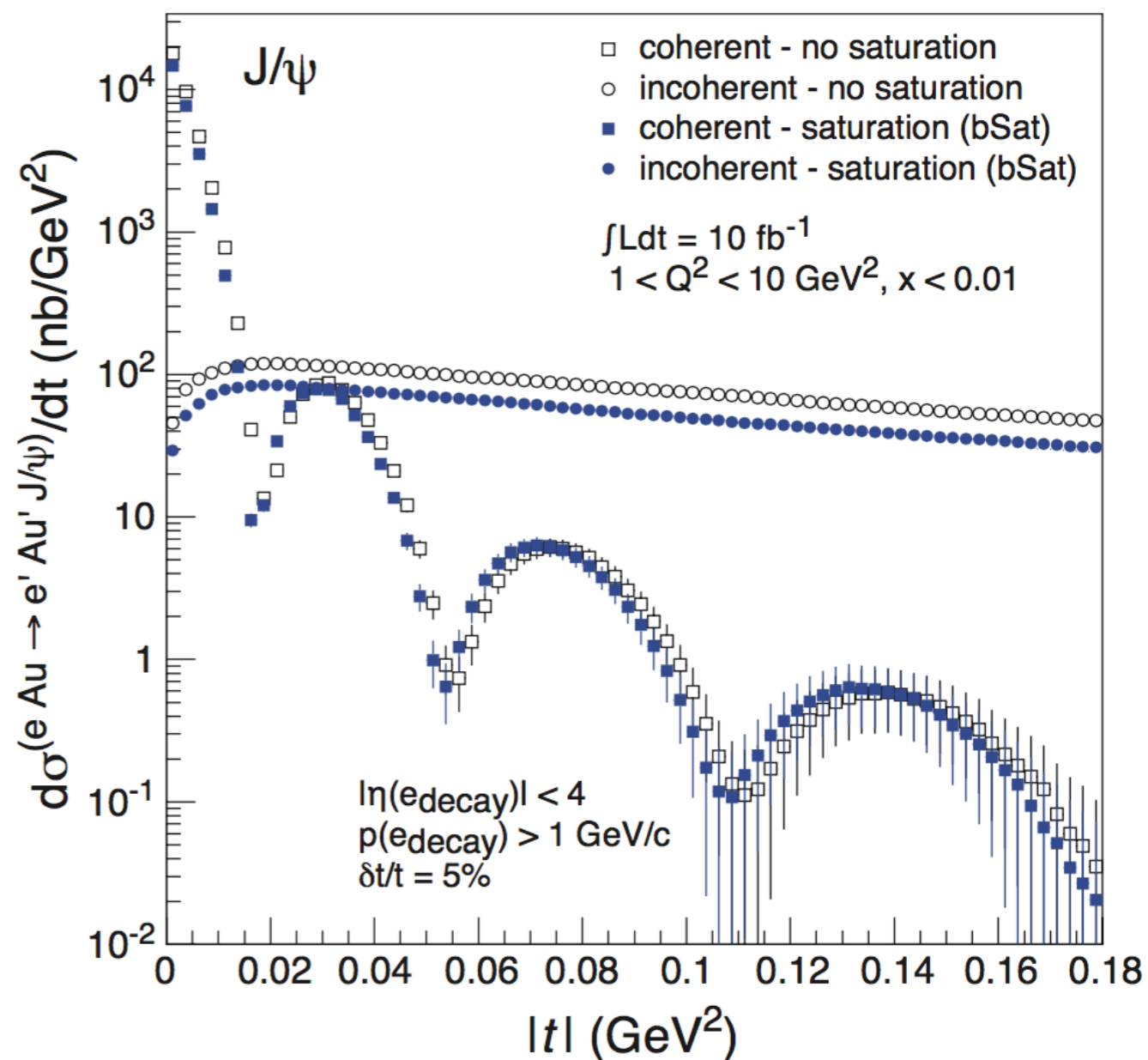
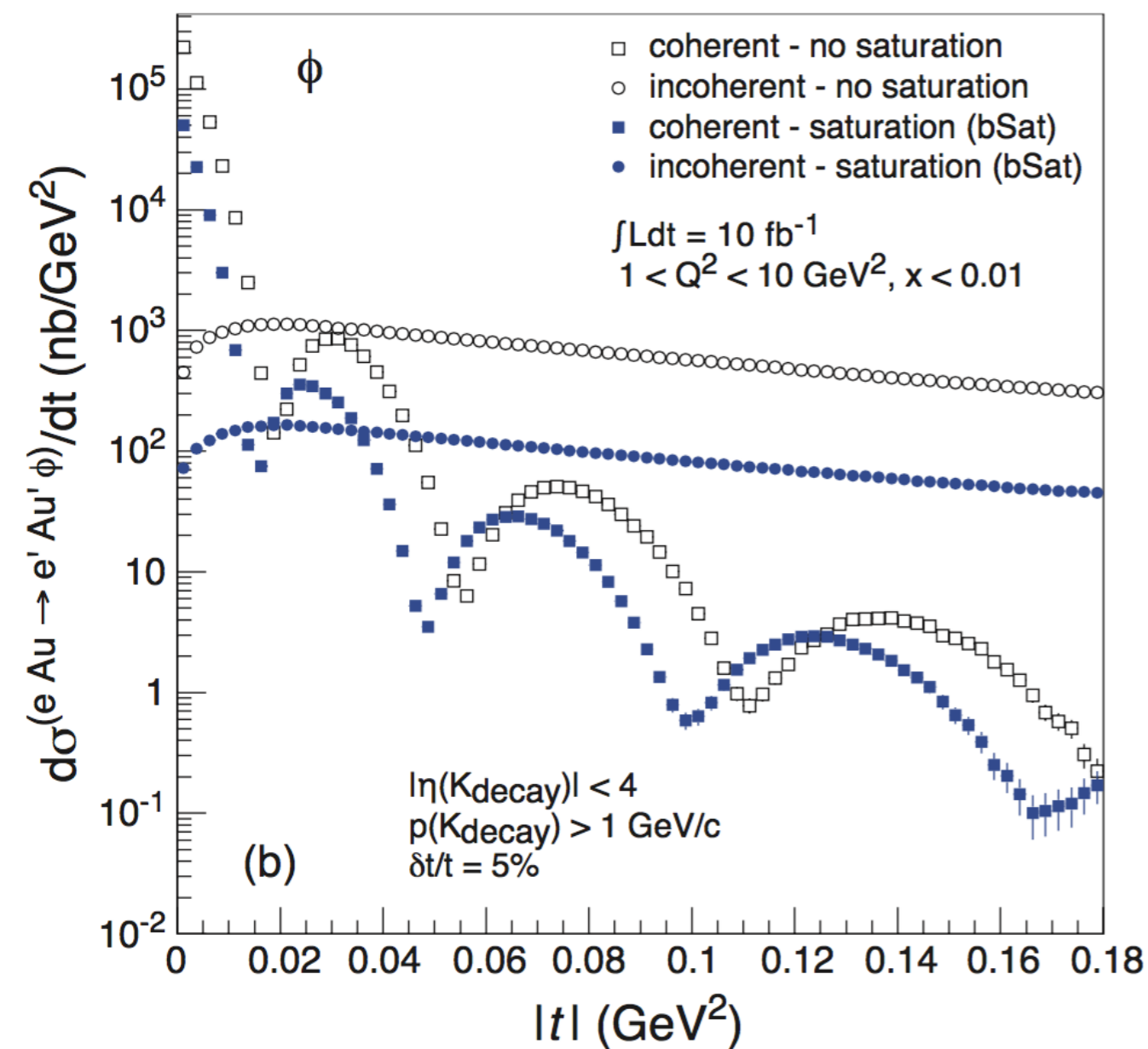


Nucleus escapes down the beampipe
(In)coherence tagged with ZDC

Dipole Cross-Section:

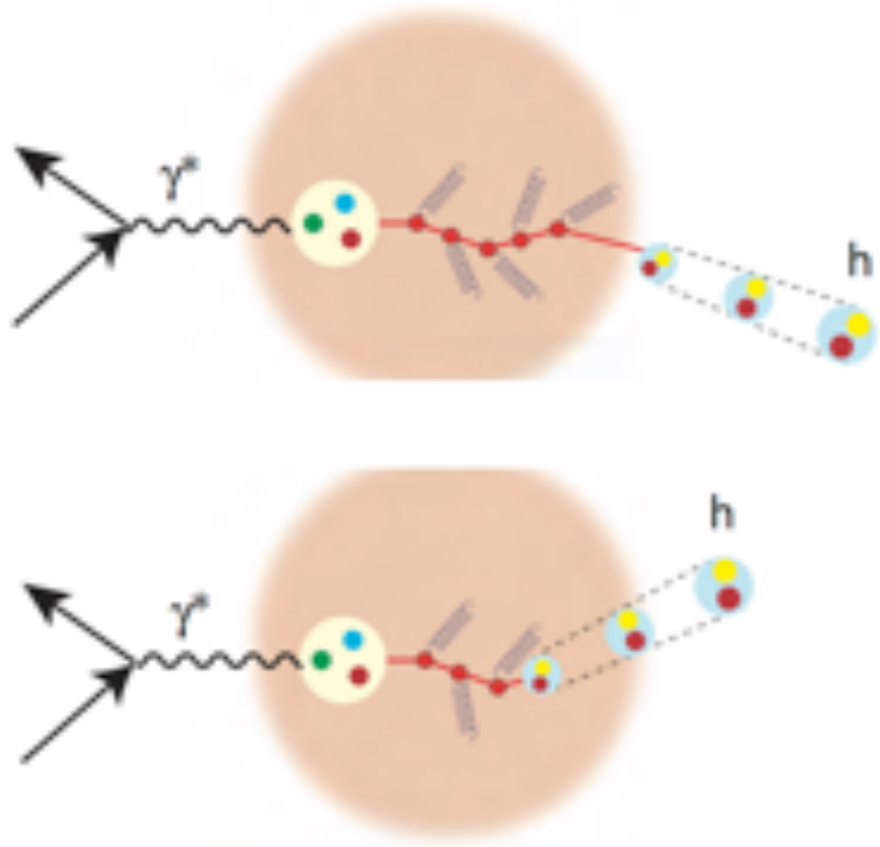


EIC - Exclusive Vector Mesons to probe Saturation



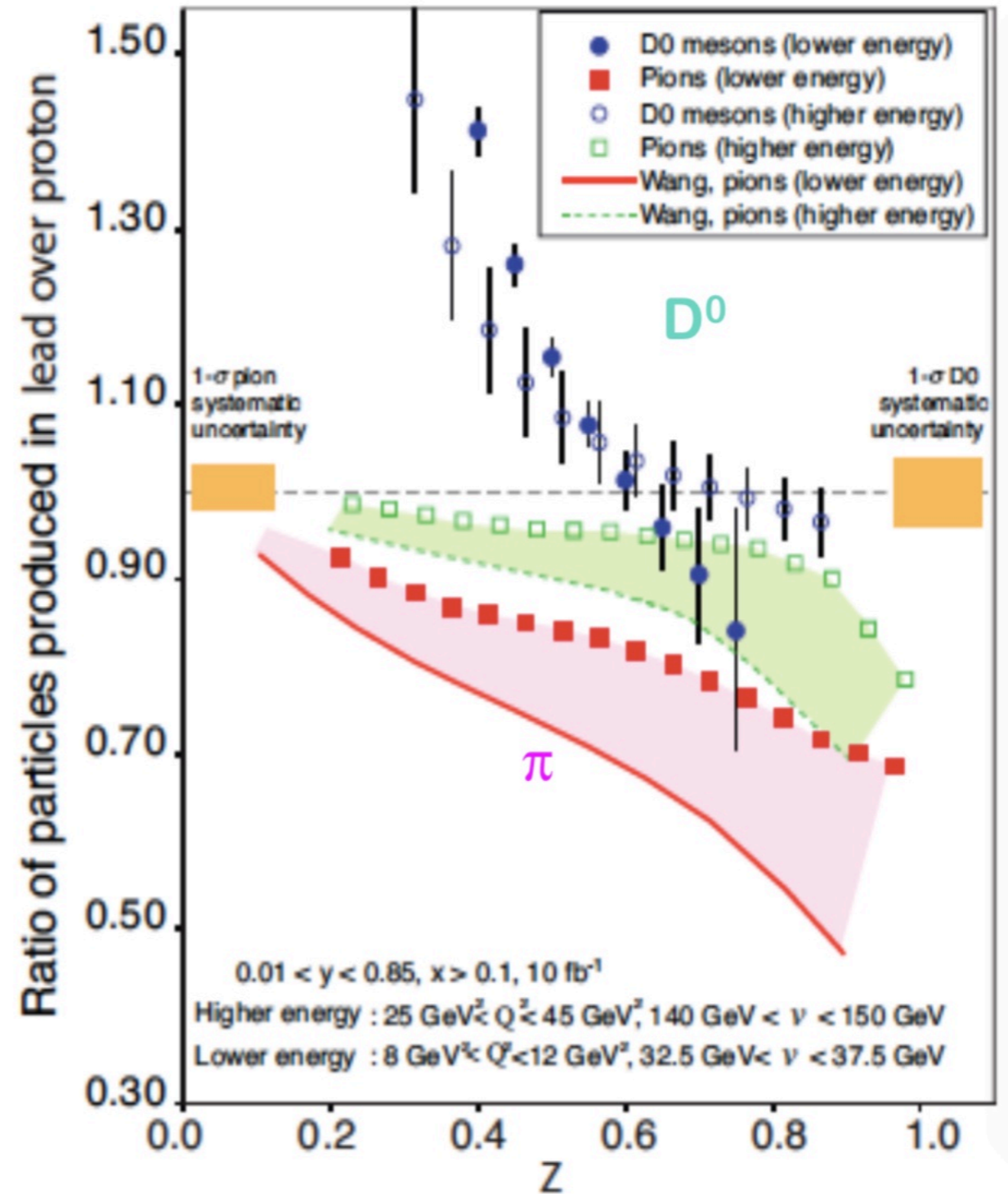
*Exclusive vector meson production is key to (all) imaging,
as is deeply virtual Compton scattering*

EIC - SIDIS to study Emergence of Hadrons

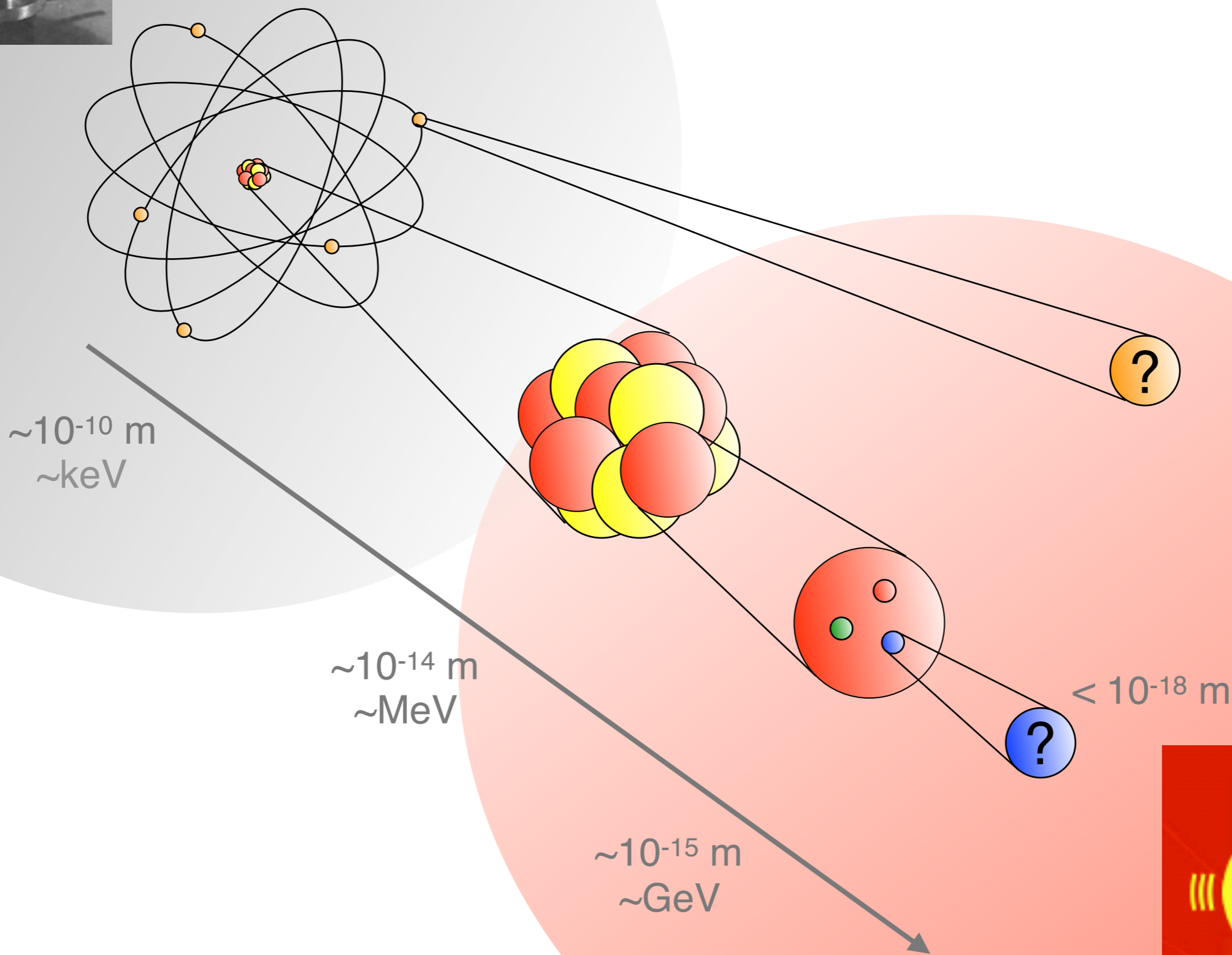
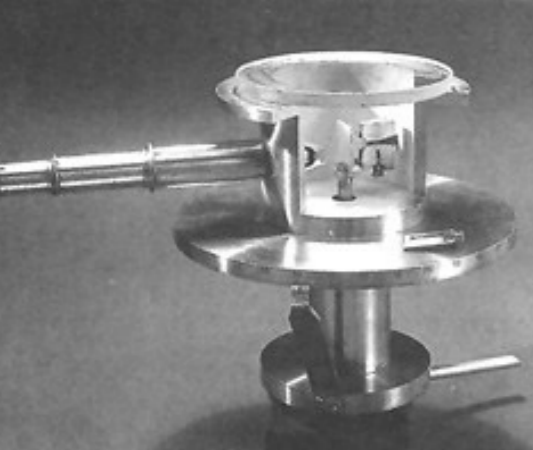


Control of $\nu = \frac{Q^2}{2mx}$ and
medium length

Study mass-dependence via
charmed hadrons.



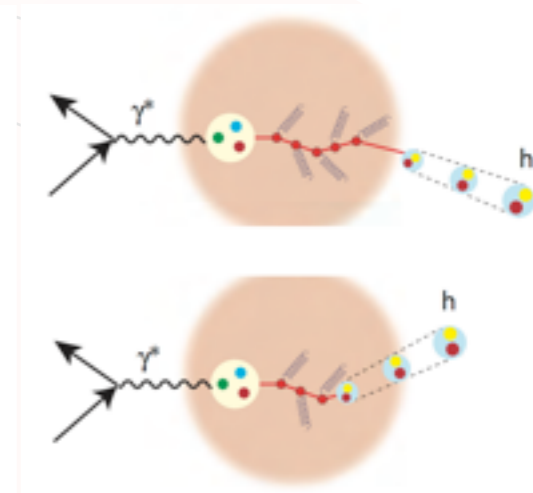
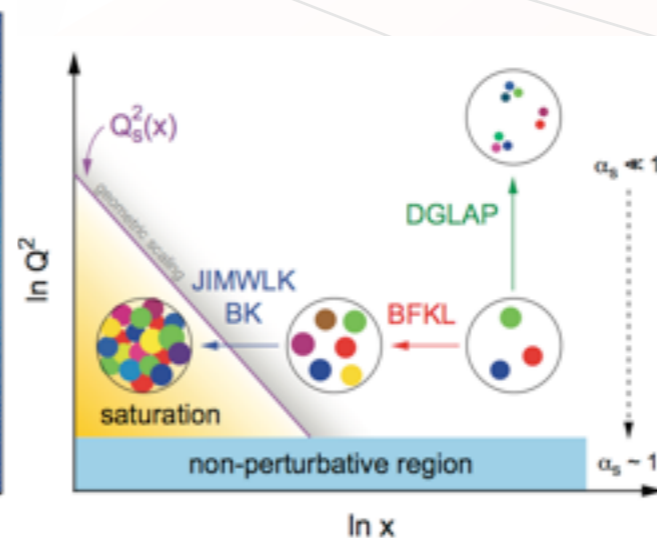
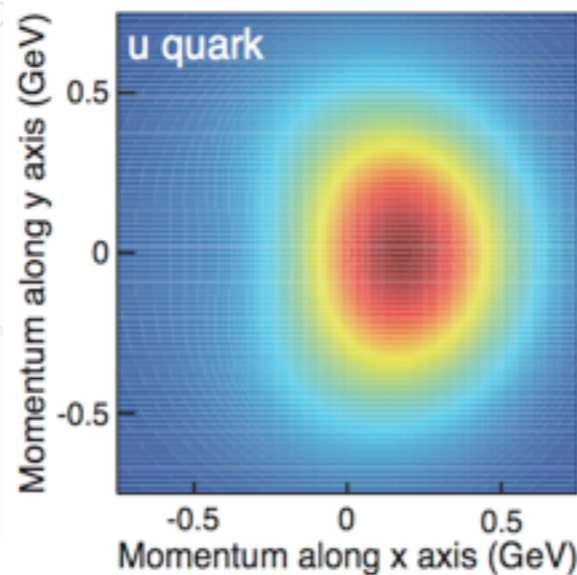
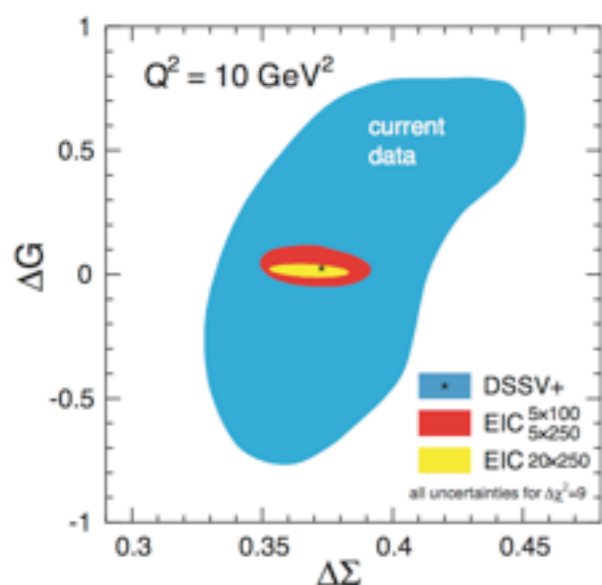
Closing Comments



Closing Comments

EIC will address profound questions:

- *How are the sea quarks and gluons, and their spins, distributed in space and momentum inside the nucleus?*
- *How does the nuclear environment affect the distribution of quarks and gluons and their interactions in nuclei?*
- *Where does the saturation of gluon densities set in?*



ArXiv:1212.17010

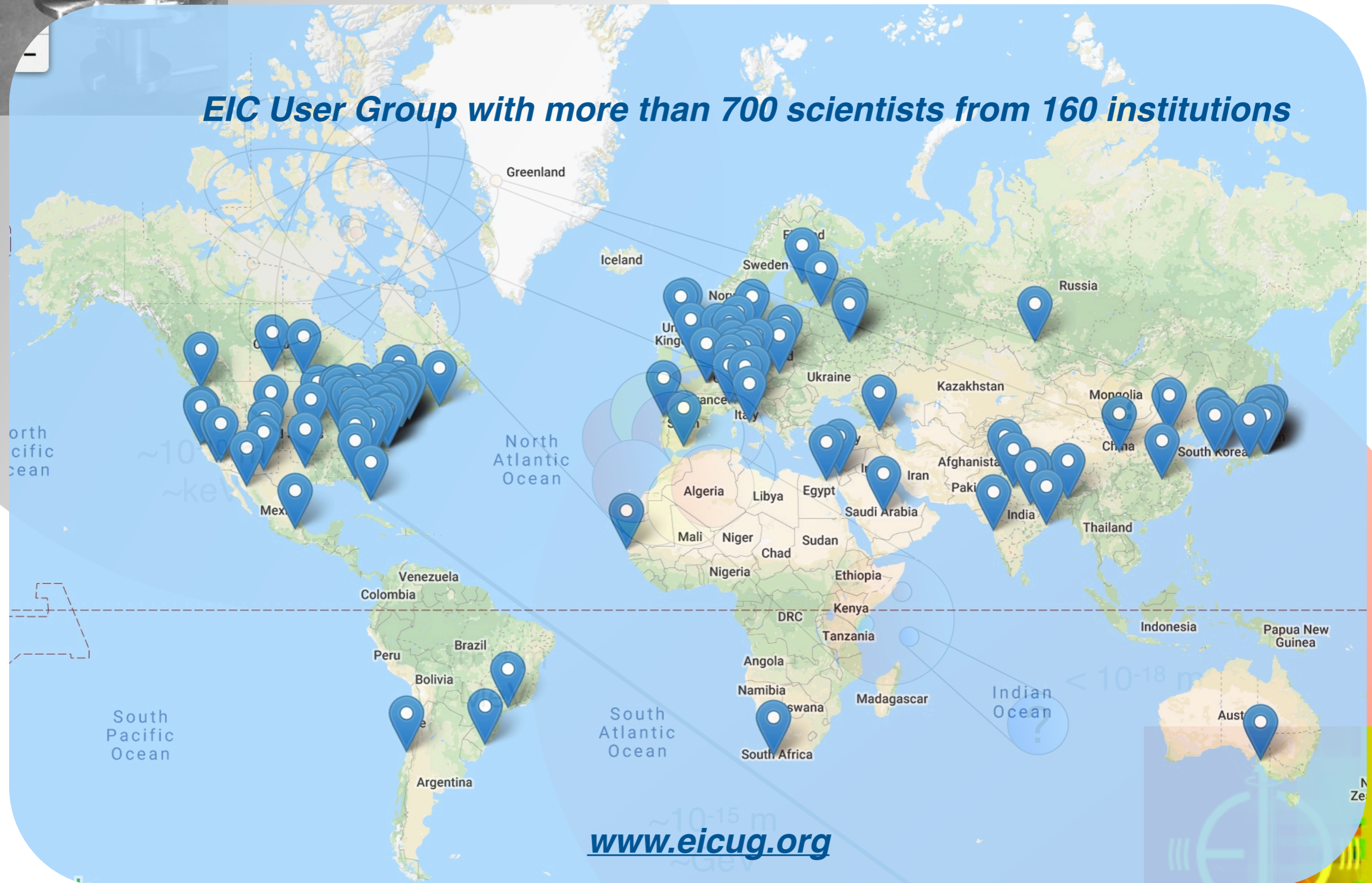
through **identified** measurements - inclusive, semi-inclusive, exclusive and diffractive - with quantified **impact**.

Relies crucially on theory and experiment,
combined strengths of the JLab and BNL communities,

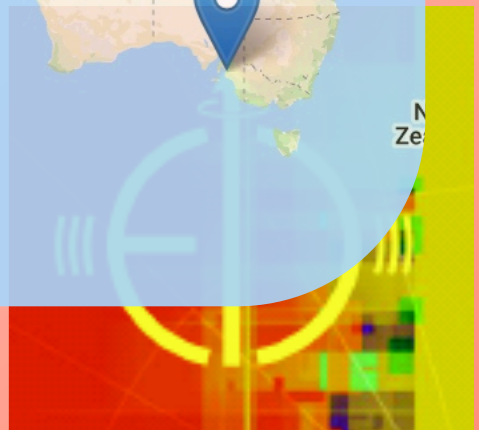
There is precedent for surprises in nature, provided you look.



EIC User Group with more than 700 scientists from 160 institutions



www.eicug.org



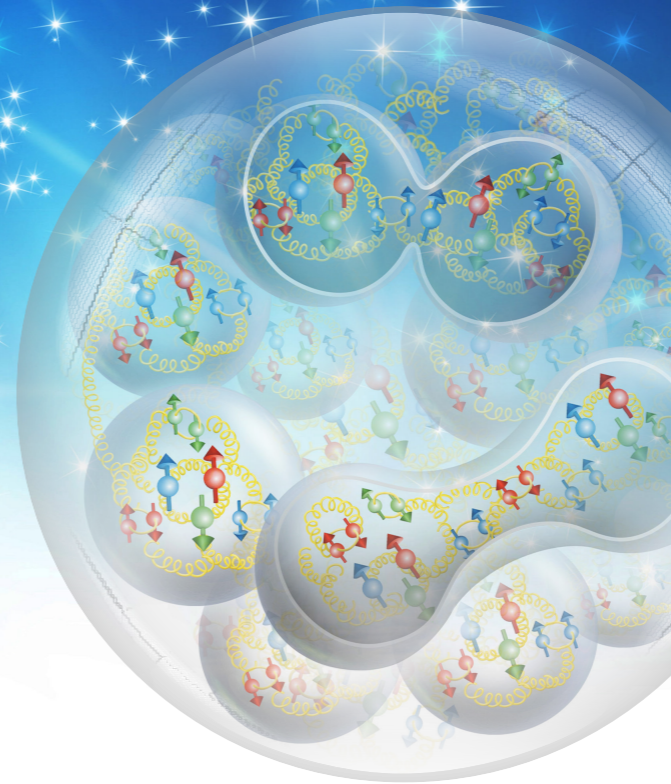
EICUG 2018

Electron Ion Collider User Group Meeting 2018

July 29 – August 2, 2018

Catholic University of America
Washington, DC

The Electron Ion Collider (EIC) is a proposed facility to study hadron physics at high energy recommended by the 2015 Long Range Plan for Nuclear Science by the NSAC. The EIC User Group (EICUG) promotes the realization of the EIC and its science, and consists of over 700 scientists. The meeting will discuss the outcome of the National Academic of Science study and the path forward for the Electron Ion Collider, as well as recent developments and progress on novel physics ideas and technical plans for the collider and detectors.



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LOCAL ORGANIZING COMMITTEE

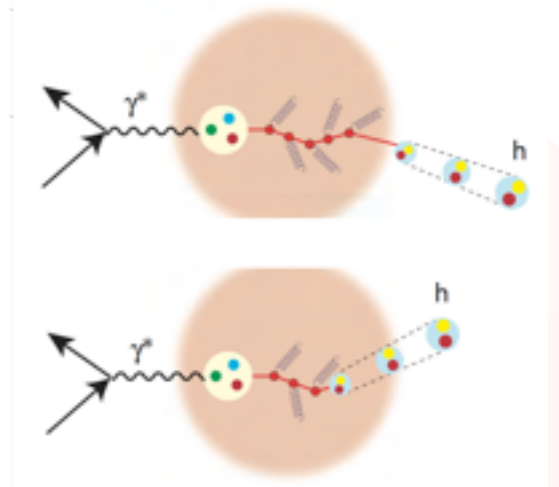
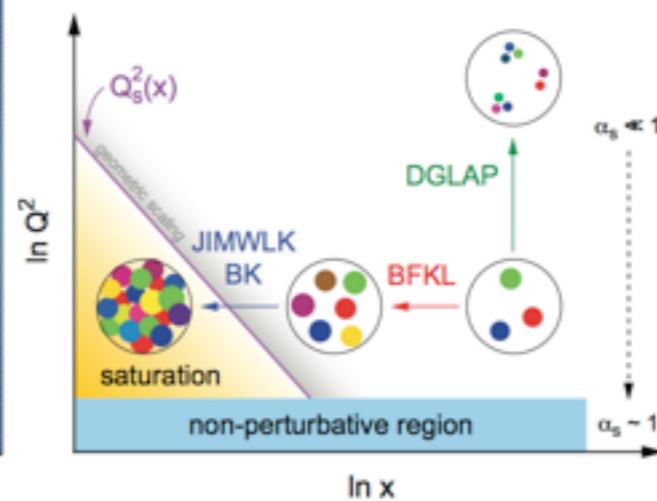
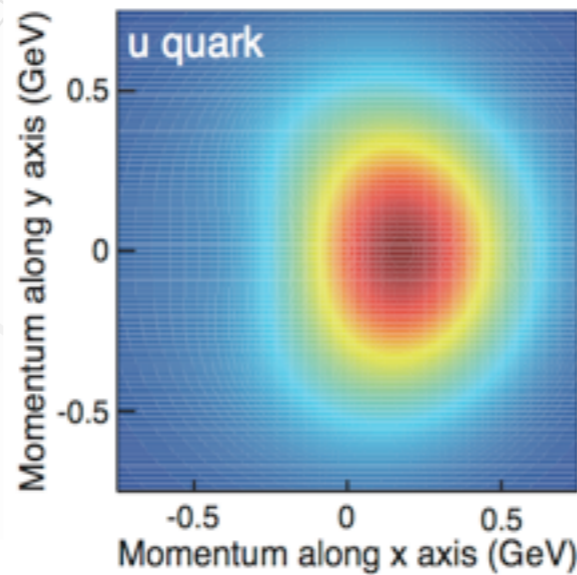
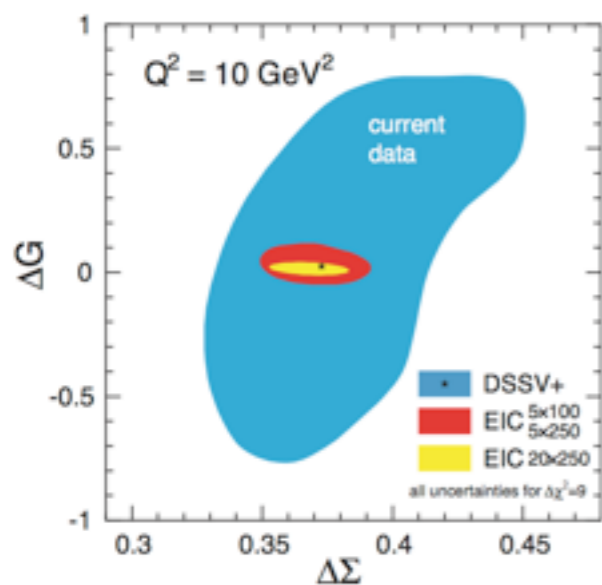
Fatiha Benmokhtar (Duquesne U.)
Tanja Horn (CUA)
Greg Kalicy (CUA)
Ian Pegg (CUA)
Alexei Prokudin (Penn State Berks)



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Thank you