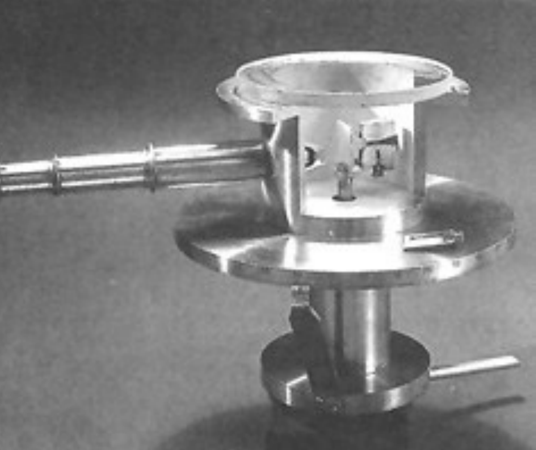
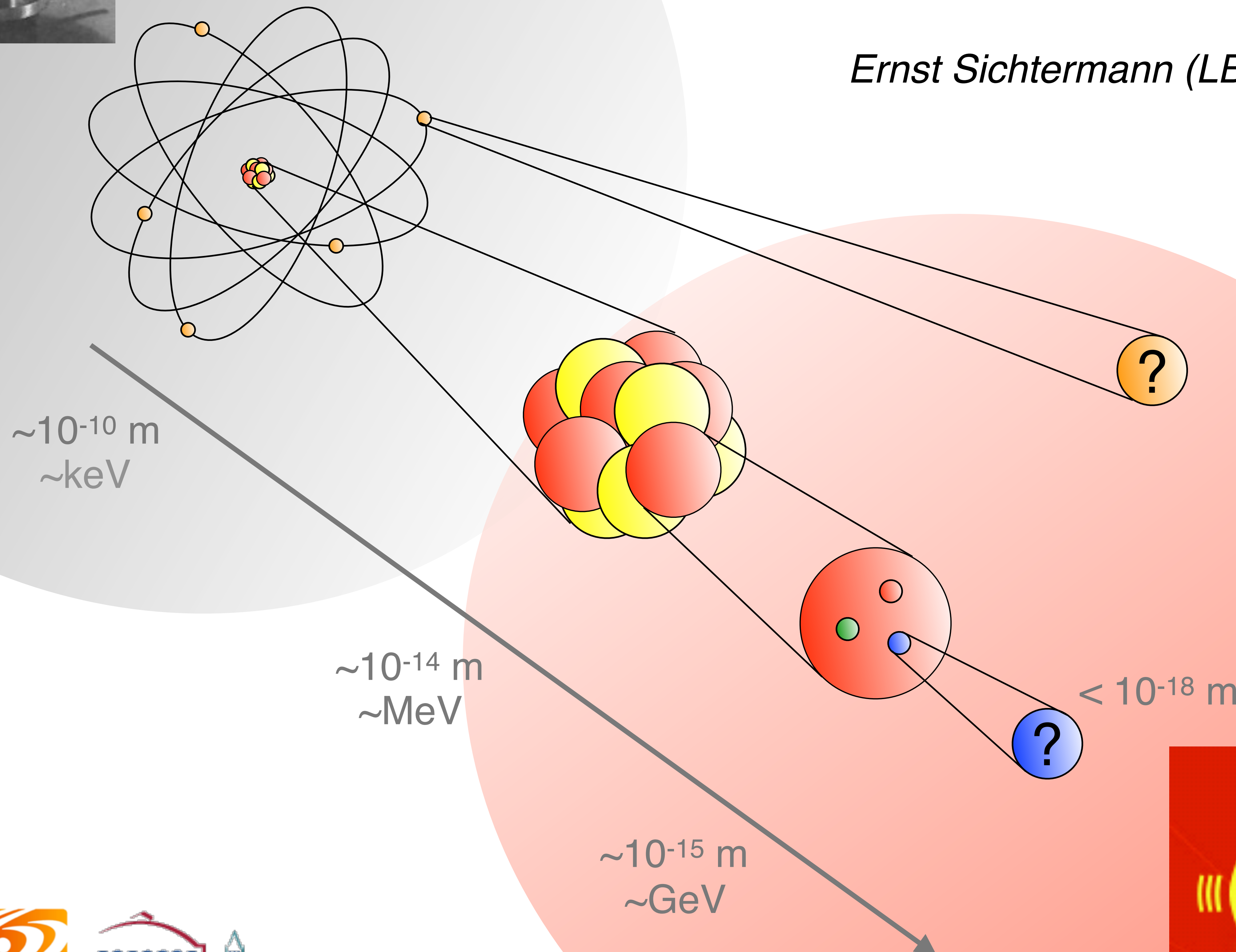


Electron-Ion Collider Perspective

Ernst Sichtermann (LBNL)



Office of Science
U.S. Department of Energy
BERKELEY LAB

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.

EIC is the work of *many* over *more than two decades;* you know who you are - thank you!
this is by no means a comprehensive summary,
any errors are obviously mine.

Electron Ion Collider Initiatives

Past

Possible Future

	HERA @ DESY	LHeC @ CERN	EIC in China	EIC in U.S.
$\sqrt{s_{ep}}$ [GeV]	320	200 - 1300	17	20 - 100 (140)
proton x_{min}	1×10^{-5}	5×10^{-7}	3×10^{-3}	
ion	p	p, Pb, …	p - Pb	p - U
polarization	-	-	p, light nuclei	p, d, ^{3}He, Li
L [$cm^{-2}s^{-1}$]	2×10^{31}	1×10^{34}	5×10^{33}	10^{33} - 10^{34}
Interaction Points	2	1	1	2
Timeline	1992 - 2007	post ALICE	> 2028	> 2028

High-Energy Physics

Nuclear Physics

Several initiatives not listed: HE-LHeC, PEPIC, VHEeP, FCC-eh, c.f. M. Wing's talk

Electron Ion Collider Initiatives

Past

Possible Future

	HERA @ DESY	LHeC @ CERN	EIC in China	EIC in U.S.
$\sqrt{s_{ep}}$ [GeV]	320	200 - 1300	17	20 - 100 (140)
proton x_{min}	1×10^{-5}	5×10^{-7}	3×10^{-3}	
ion	p	p, Pb, …	p - Pb	p - U
polarization	-	-	p, light nuclei	p, d, ^{3}He, Li
L [$cm^{-2}s^{-1}$]	2×10^{31}	1×10^{34}	5×10^{33}	10^{33} - 10^{34}
Interaction Points	2	1	1	2
Timeline	1992 - 2007	post ALICE	> 2028	> 2028

High-Energy Physics

Nuclear Physics

World Wide Interest

Electron Ion Collider Initiatives

Past

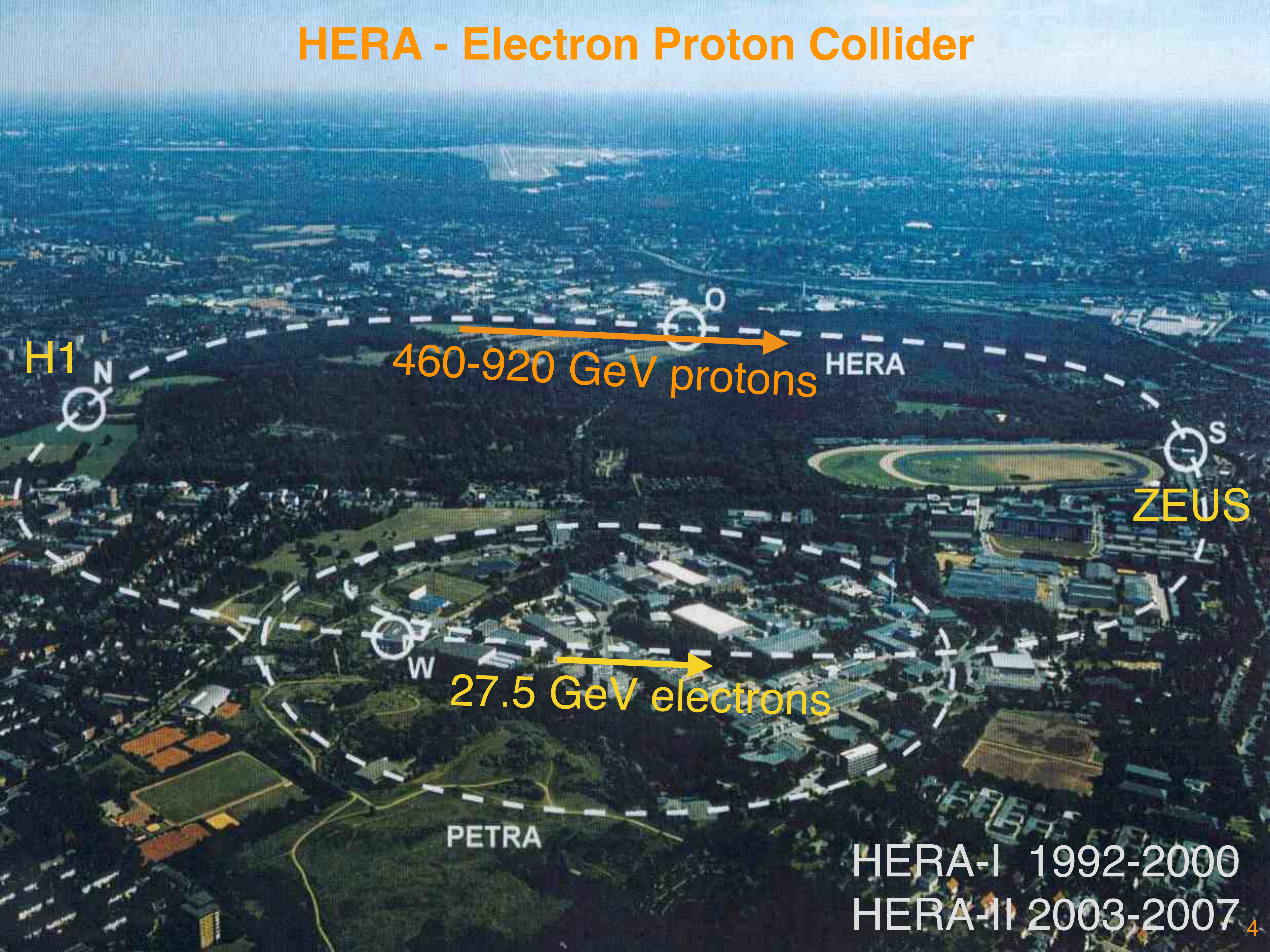
Possible Future

	HERA @ DESY	LHeC @ CERN	EIC in China	EIC in U.S.
$\sqrt{s_{ep}}$ [GeV]	320	200 - 1300	17	20 - 100 (140)
proton x_{min}	1×10^{-5}	5×10^{-7}	3×10^{-3}	
ion	p	p, Pb, …	p - Pb	p - U
polarization	-	-	p, light nuclei	p, d, ^{3}He, Li
L [$cm^{-2}s^{-1}$]	2×10^{31}	1×10^{34}	5×10^{33}	10^{33} - 10^{34}
Interaction Points	2	1	1	2
Timeline	1992 - 2007	post ALICE	> 2028	> 2028

High-Energy Physics

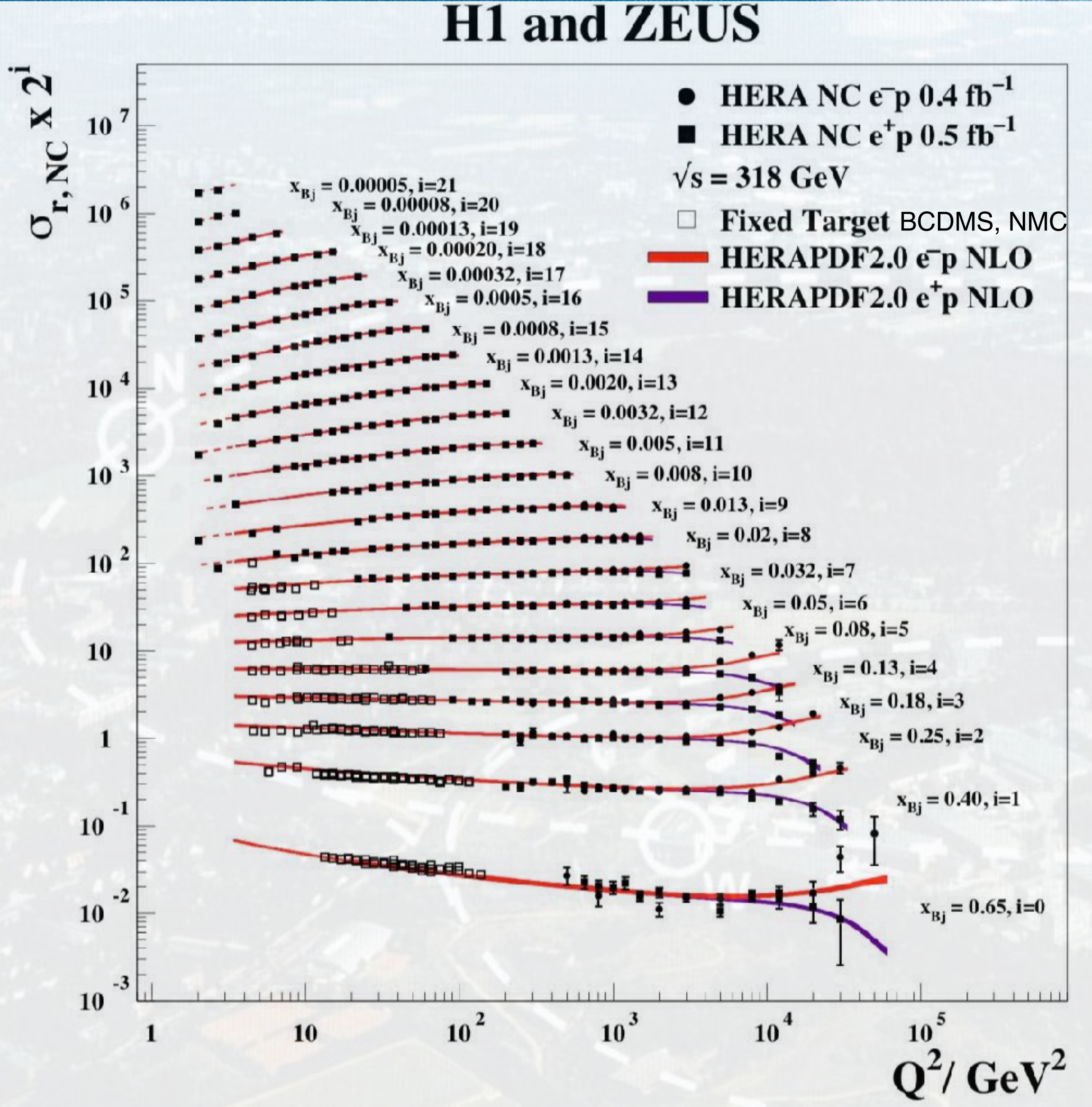
Nuclear Physics

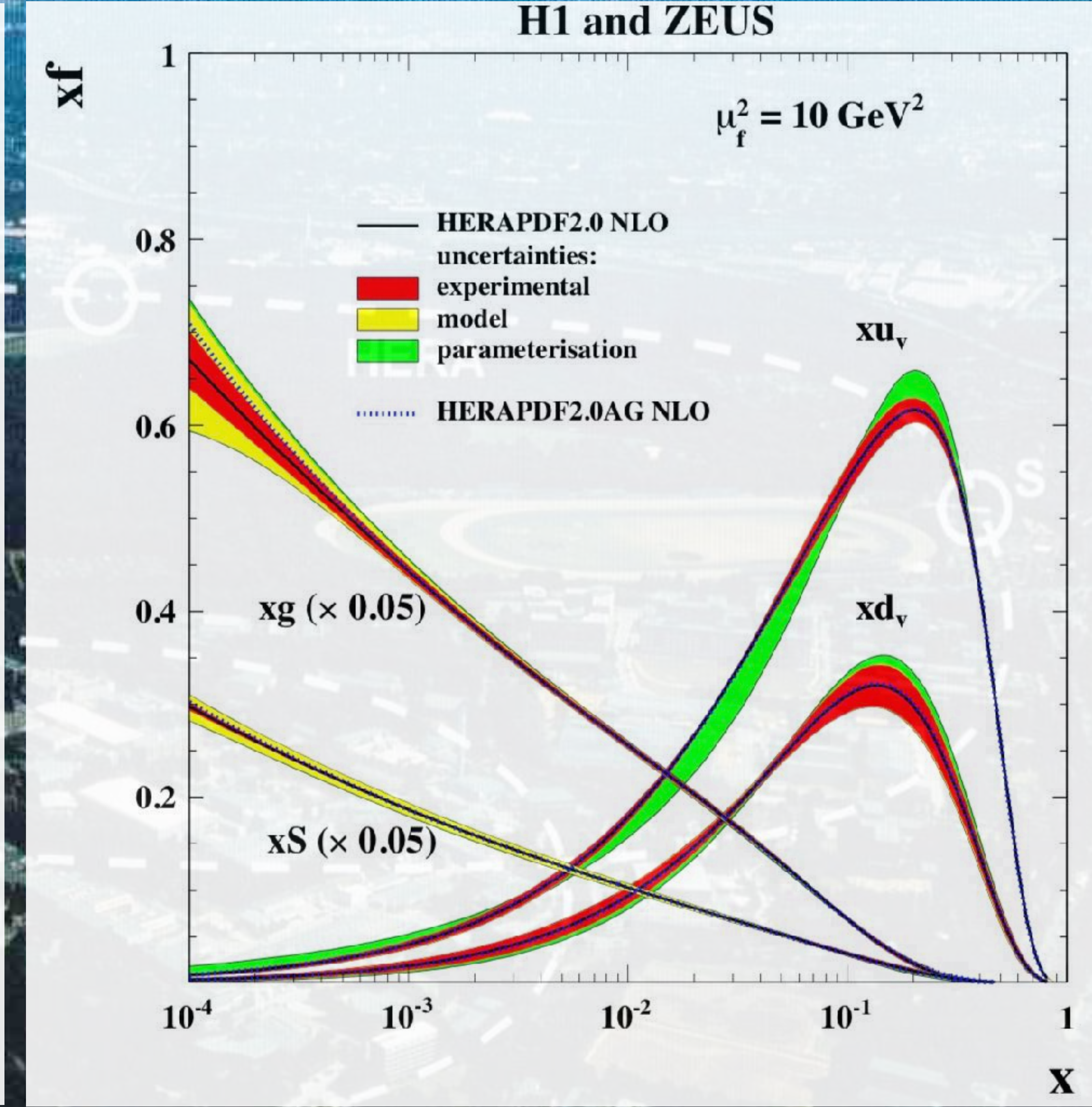
World Wide Interest


HERA - Electron Proton Collider
O
H1
N
460-920 GeV protons
HERA
S
ZEUS
W
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,
Exquisite insight in high-energy proton structure and QCD dynamics.

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

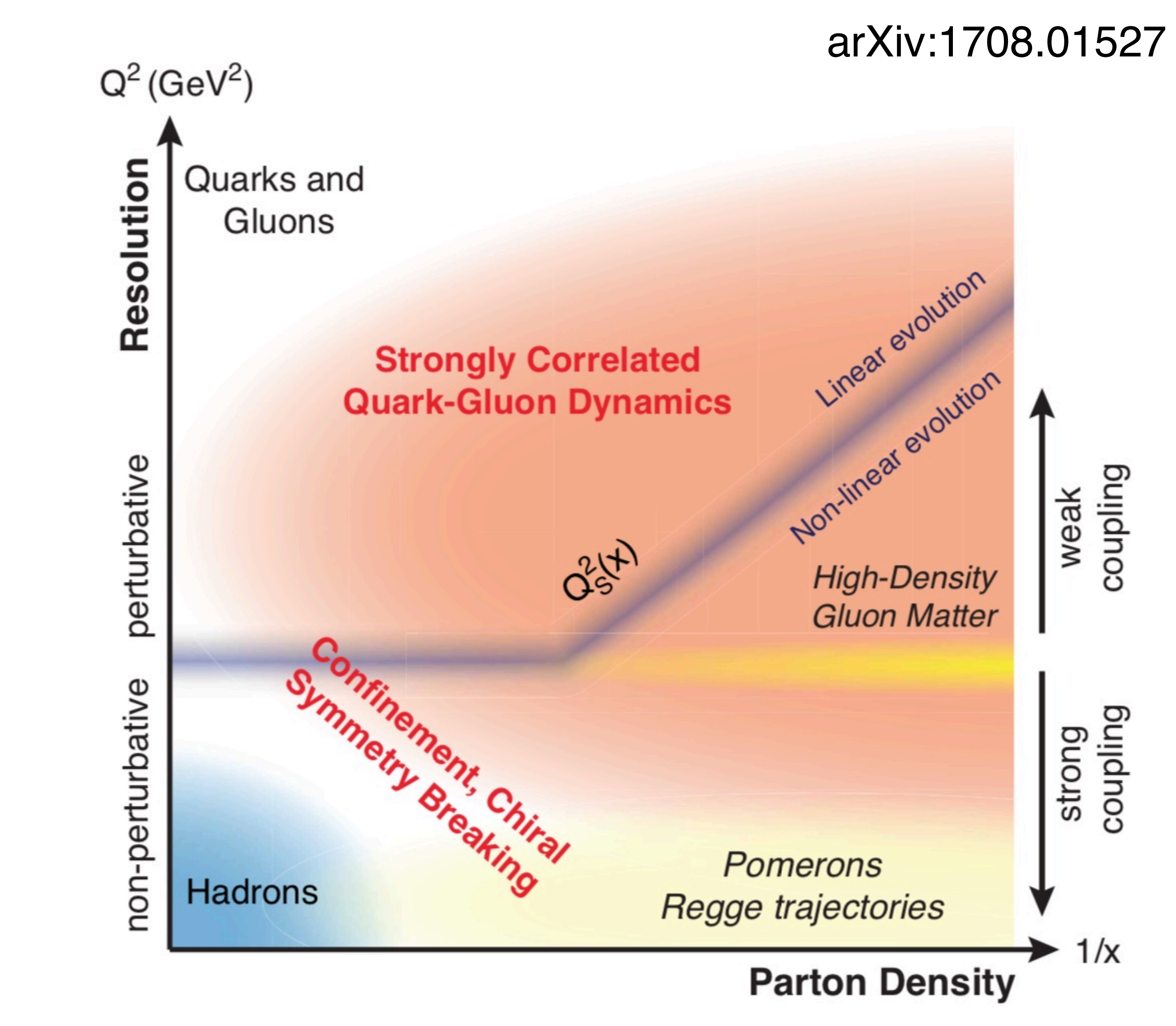
Factorization theorem(s) + one-dimensional parton distributions,
no correlations among the partons

Not quite…. ***more than a few high-energy observations are actually different***
Imperative 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)

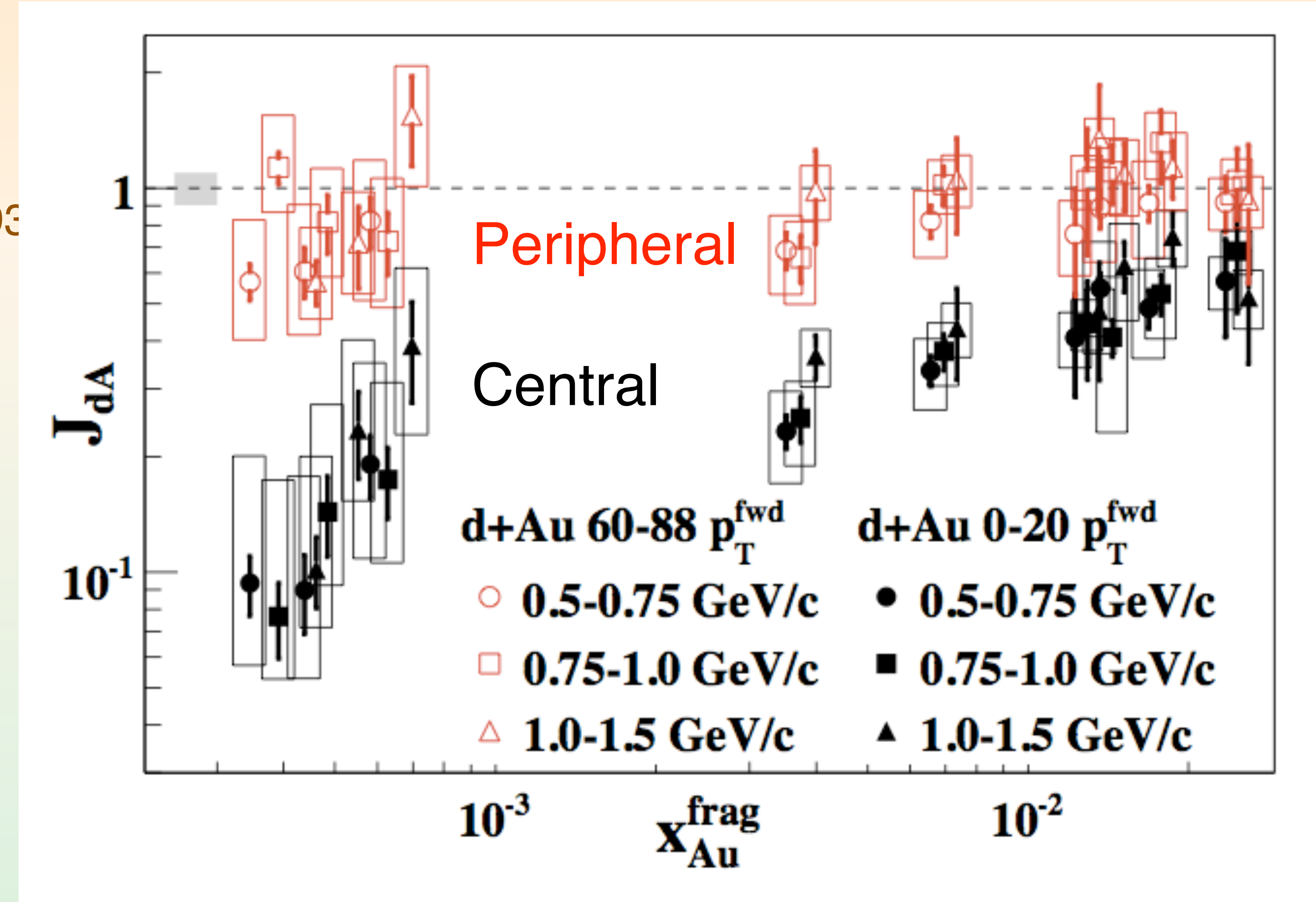


HERA - RHIC

Saturation:

- geometric scaling of the cross section,
- diffractive cross-section independent of W and Q^2,
- evidence for BFKL dynamics (Ball, arXiv:1710.0593
- forward multiplicities and correlations at RHIC,

Forward-Forward Mid-forward correlation



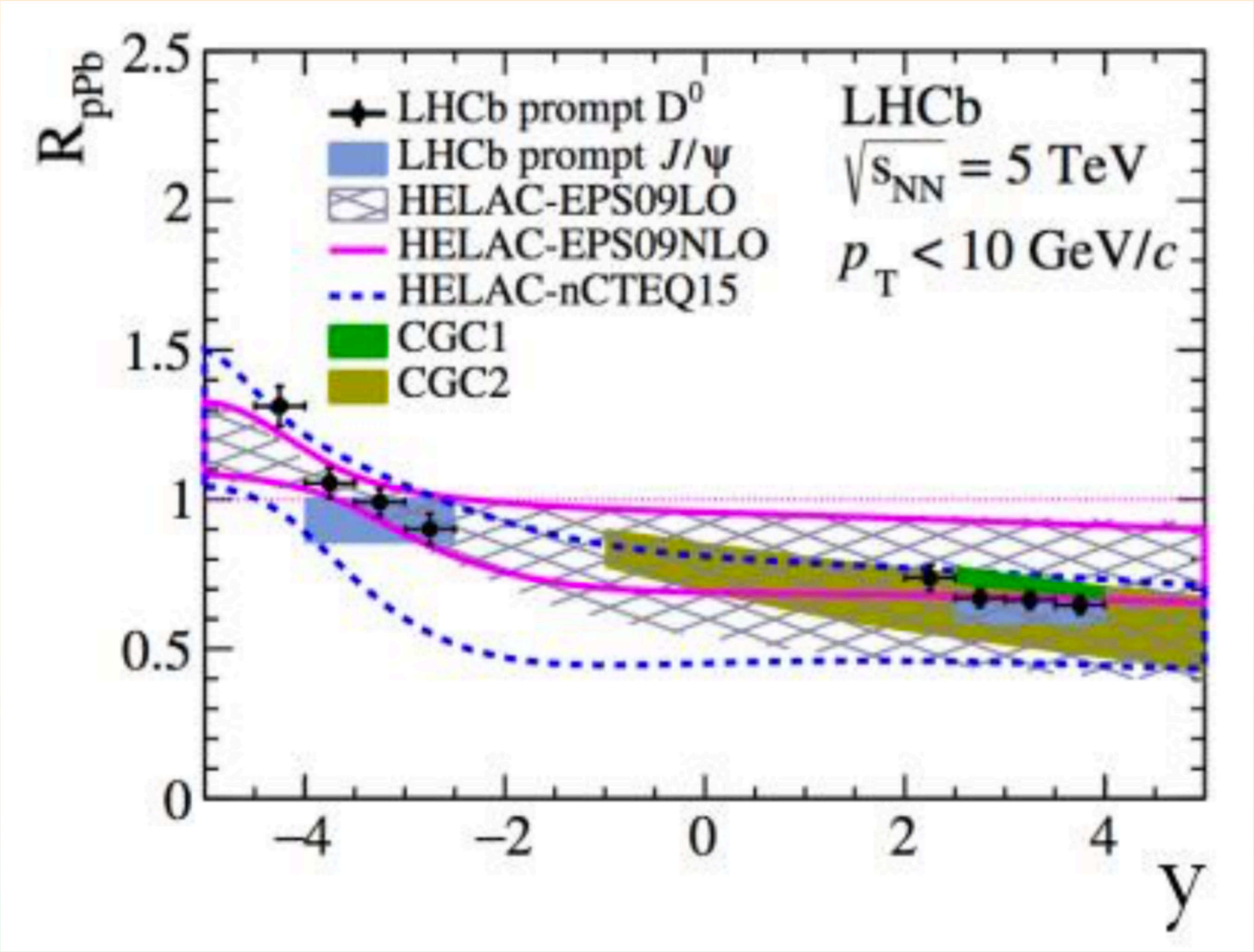
Phenix, Phys.Rev.Lett. 107 (2011) 172301

HERA - RHIC, LHC

Saturation:

- geometric scaling of the cross section,
- diffractive cross-section independent of W and Q^2,
- evidence for BFKL dynamics (Ball, arXiv:1710.05935),
- forward multiplicities and correlations at RHIC,

- inticrate interpretation(s), c.f. T. Atoniuk
- beautiful (new) data from LHCb, c.f. B. Schmidt
  ATLAS, c.f. D. Perepelitsa
  and others

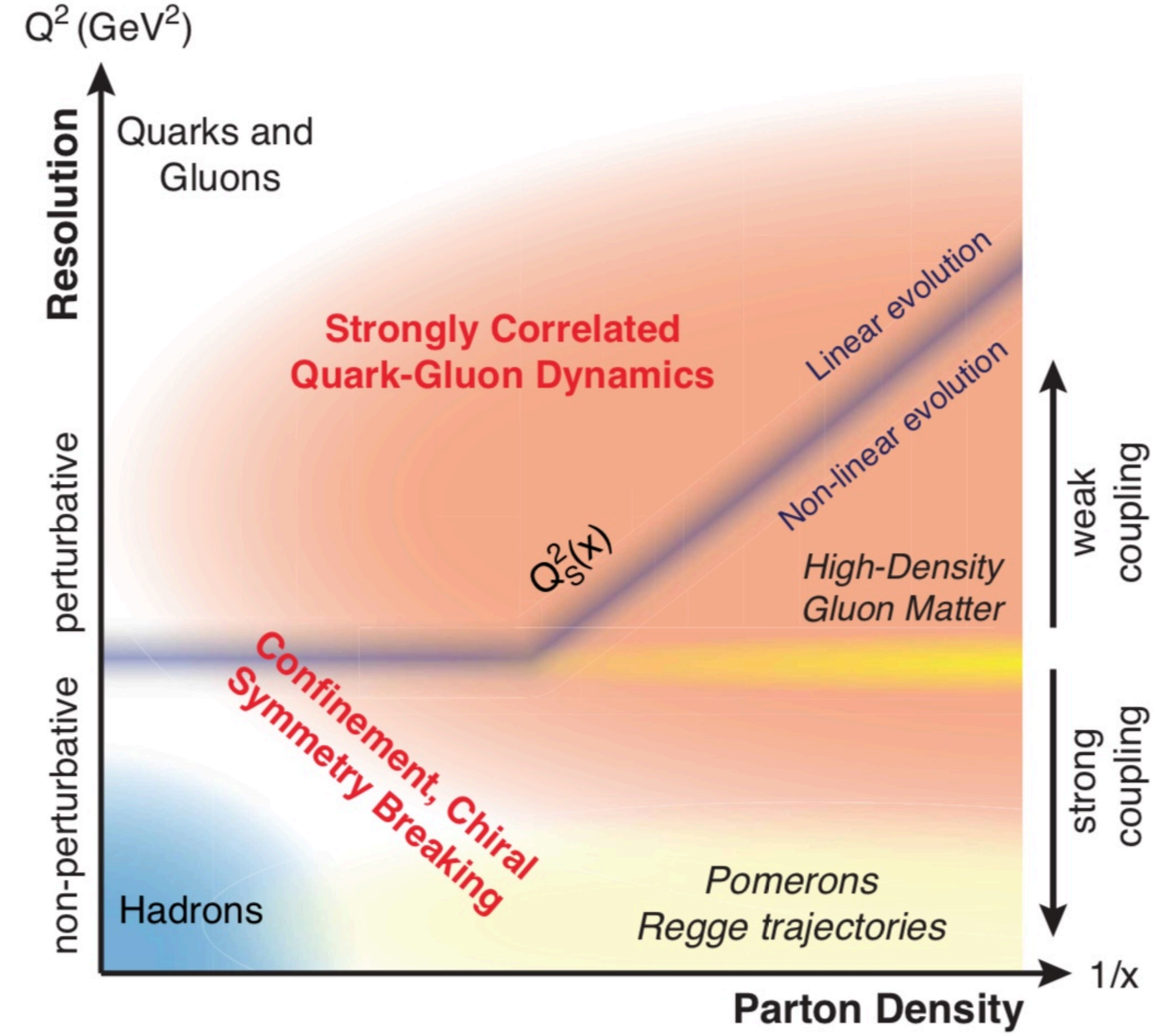


HERA - RHIC, LHC

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),
- tantalizing observations, but open questions remain.

arXiv:1708.01527



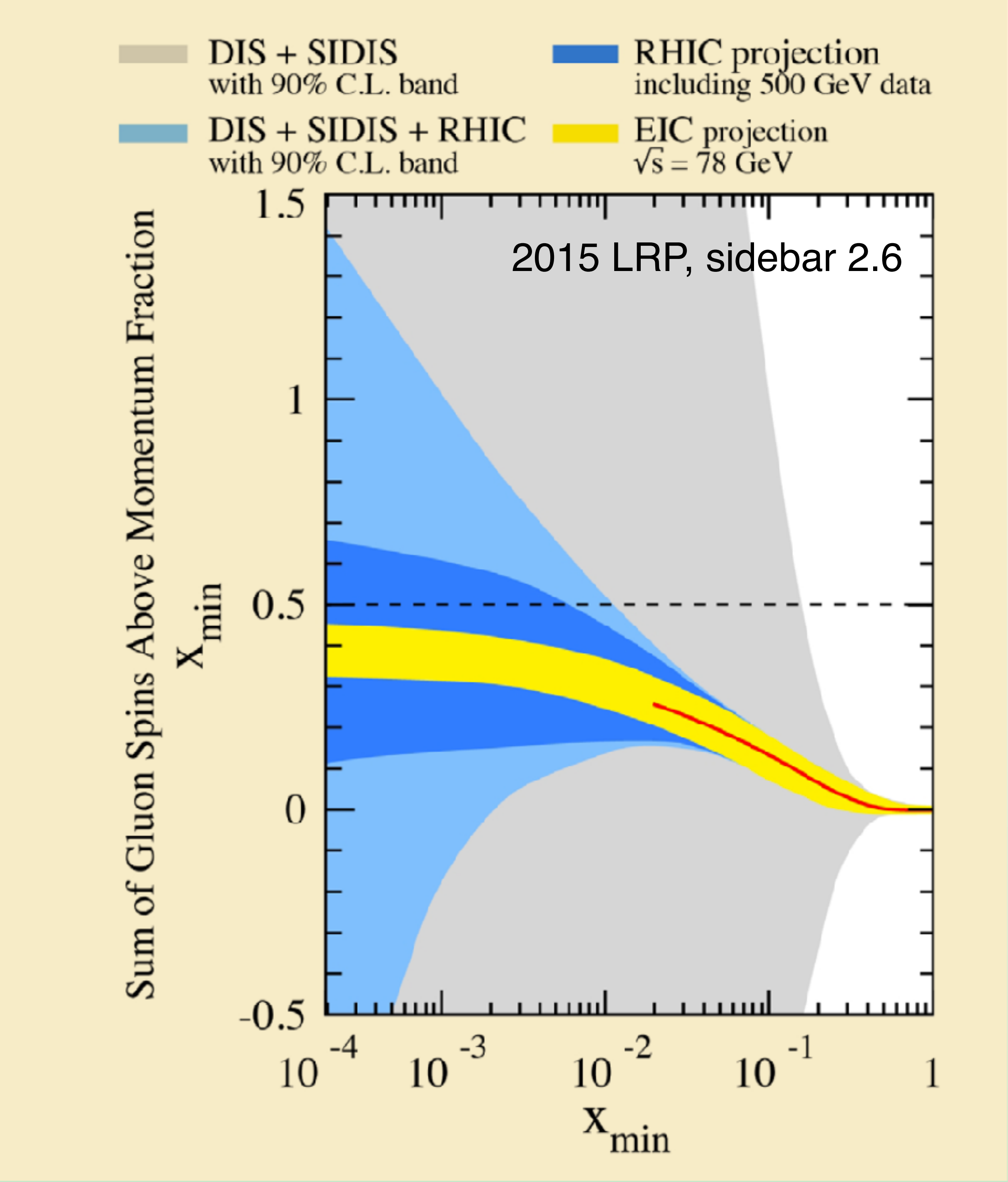
HERA - RHIC

Saturation:

- geometric scaling of the cross section,
- diffractive cross-section independent of W and Q^2,
- evidence for BFKL dynamics (Ball, arXiv:1710.05935),
- tantalizing observations, but open questions remain.

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
- Lattice-QCD progress, c.f. P. Shanahan’s talk



HERA - RHIC, JLab

Saturation:

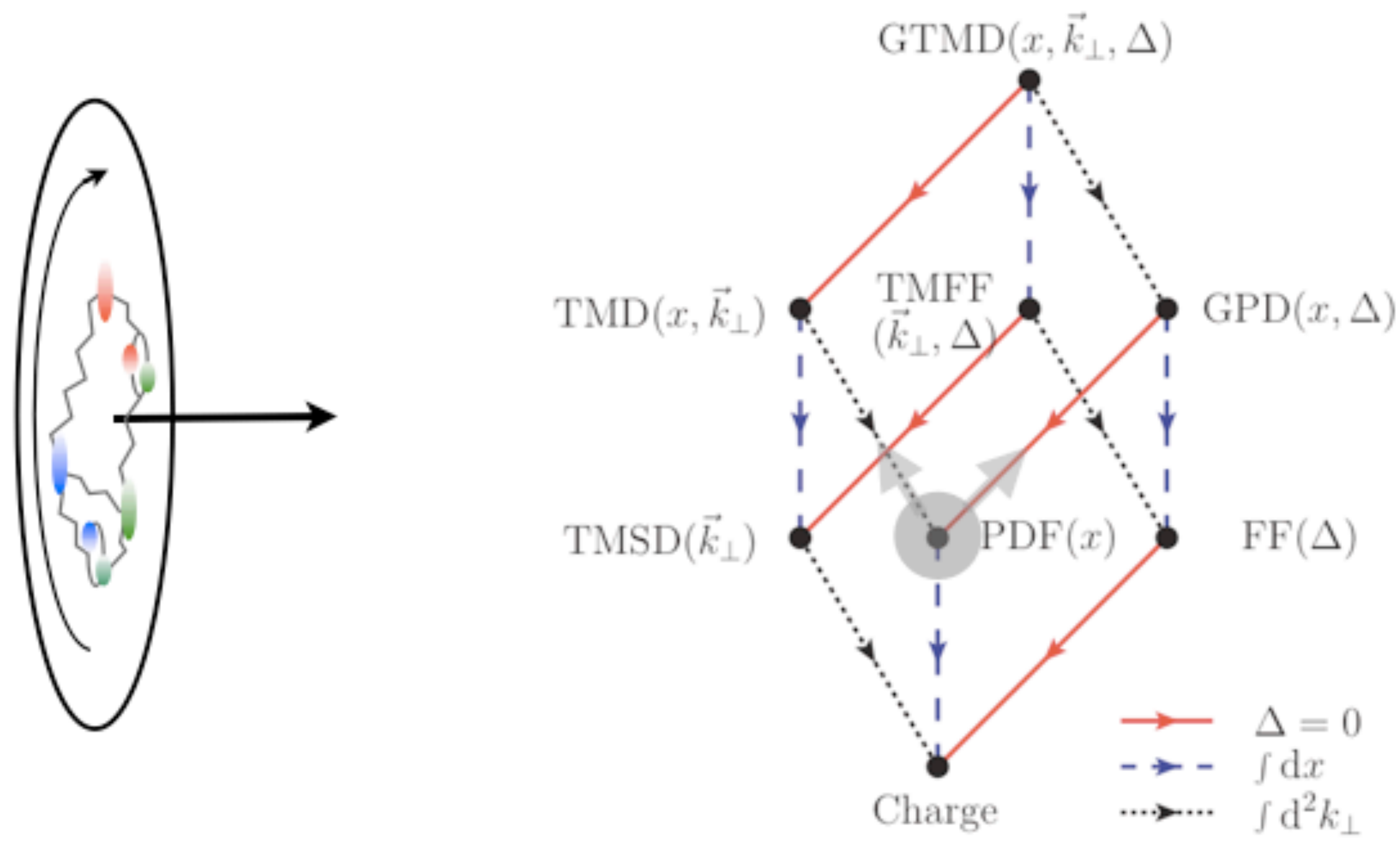
- geometric scaling of the cross section,
- diffractive cross-section independent of W and Q^2,
- evidence for BFKL dynamics (Ball, arXiv:1710.05935),
- forward multiplicities and correlations at RHIC,

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
- Lattice-QCD progress, c.f. P. Shanahan's talk

Imaging / tomography:

- valence quark region,



Lorce, Pasquini, Vanderhaeghen

HERA - RHIC, JLab

Saturation:

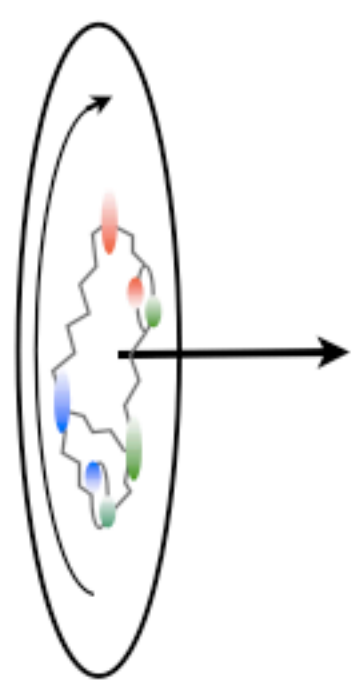
- geometric scaling of the cross section,
- diffractive cross-section independent of W and Q^2,
- evidence for BFKL dynamics (Ball, arXiv:1710.05935),
- forward multiplicities and correlations at RHIC,

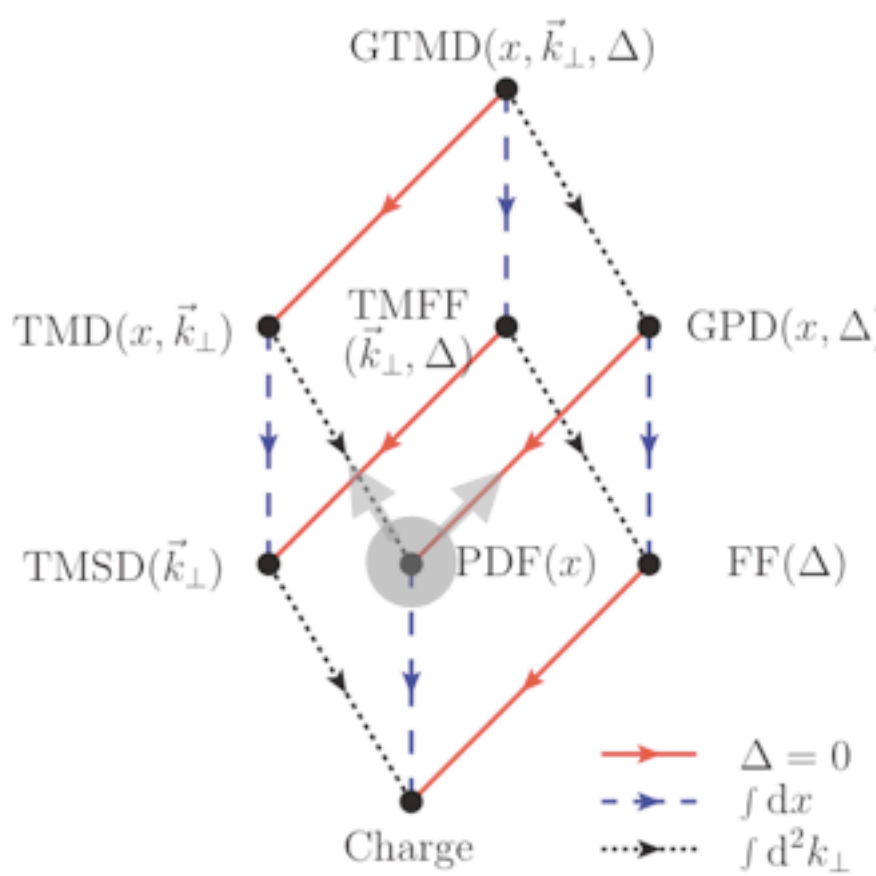
Spin puzzle:

- 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
- Lattice-QCD progress, c.f. P. Shanahan's talk

Imaging / tomography:

- valence quark region,
  C. Keppel discussed JLab 12 GeV status,
  IS synergies evident e.g. from talks by R. Boussarie
  A. Dumitru





Lorce, Pasquini, Vanderhaeghen

Electron Ion Collider Initiatives

Past

Possible Future

	HERA @ DESY	LHeC @ CERN	EIC in China	EIC in U.S.
$\sqrt{s_{ep}}$ [GeV]	320	200 - 1300	17	20 - 100 (140)
proton x_{min}	1×10^{-5}	5×10^{-7}	3×10^{-3}	
ion	p	p, Pb, …	p - Pb	p - U
polarization	-	-	p, light nuclei	p, d, ^{3}He, Li
L [$cm^{-2}s^{-1}$]	2×10^{31}	1×10^{34}	5×10^{33}	10^{33} - 10^{34}
Interaction Points	2	1	1	2
Timeline	1992 - 2007	post ALICE	> 2028	> 2028

N. Armesto (next speaker)

High-Energy Physics

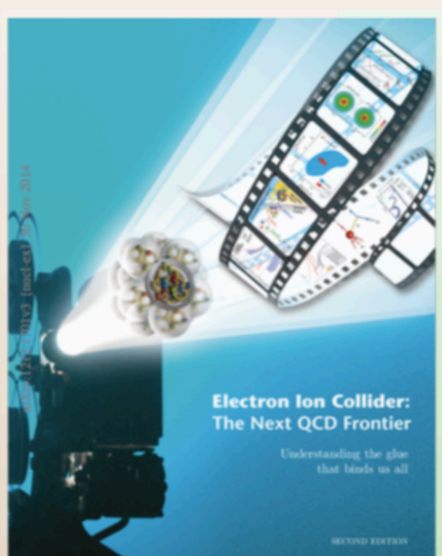
Nuclear Physics

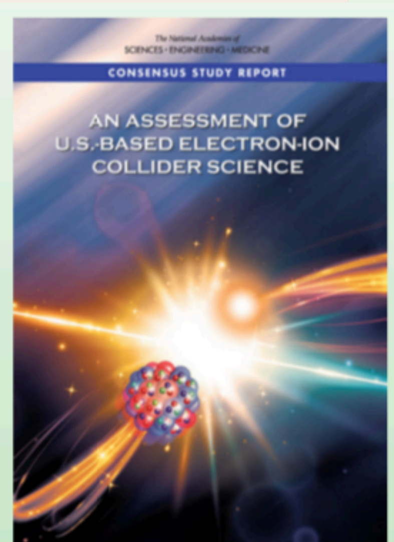
World Wide Interest

Electron Ion Collider Initiatives

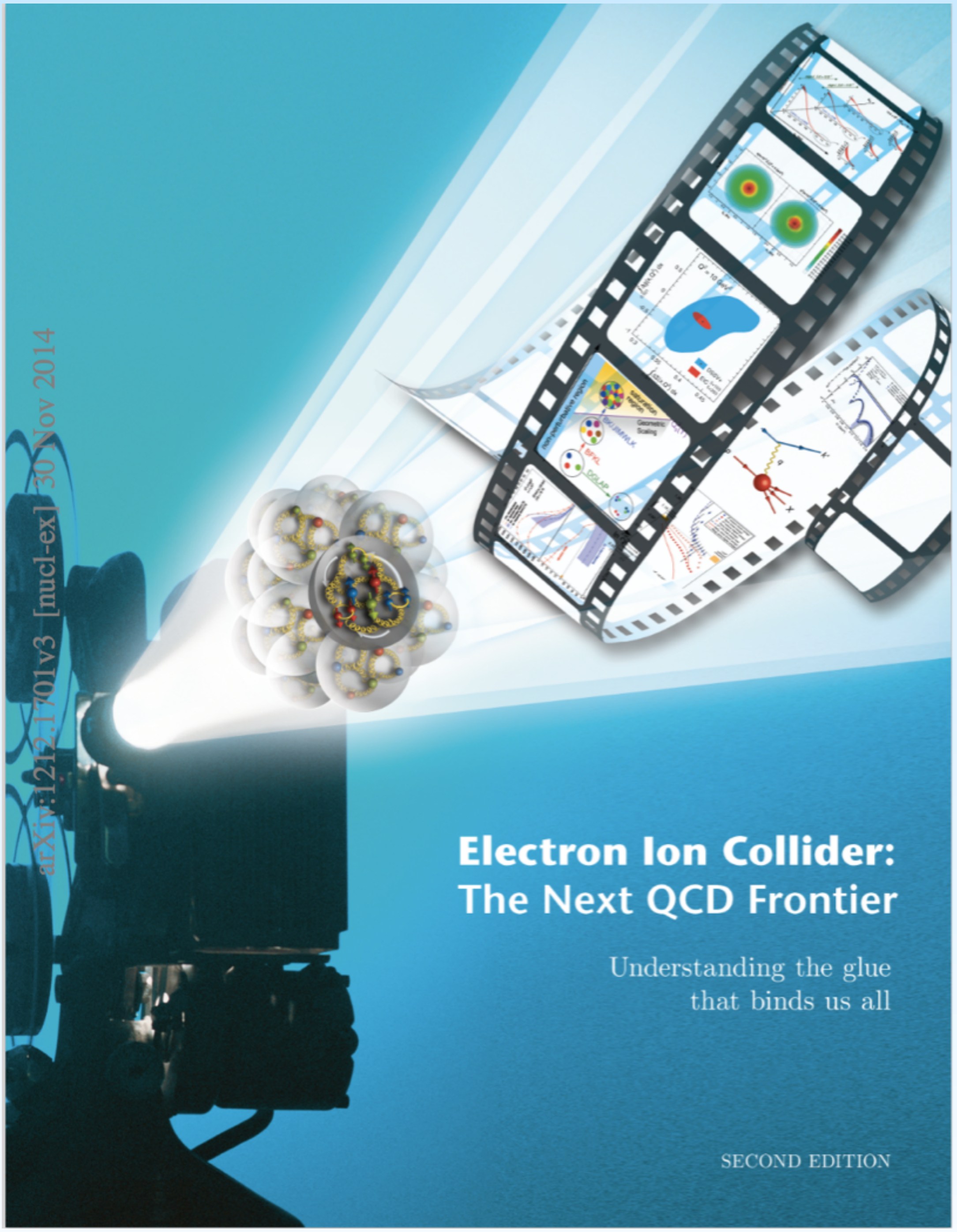
Approach: combine strengths
use existing investments (risk, cost),
pursue luminosity;100x - 1000x HERA
nuclei and *polarization*,
optimized instrumentation.

	HERA @ DESY	LHeC @ CERN	EIC in China	EIC in U.S.
$\sqrt{s_{ep}}$ [GeV]	320	200 - 1300	17	20 - 100 (140)
proton x_{min}	1×10^{-5}	5×10^{-7}	3×10^{-3}	
ion	p	p, Pb, …	p - Pb	p - U
polarization	-	-	p, light nuclei	p, d, ^{3}He, Li
L [$cm^{-2}s^{-1}$]	2×10^{31}	1×10^{34}	5×10^{33}	10^{33} - 10^{34}
Interaction Points	2	1	1	2
Timeline	1992 - 2007	post ALICE	> 2028	> 2028





U.S. EIC Science Case

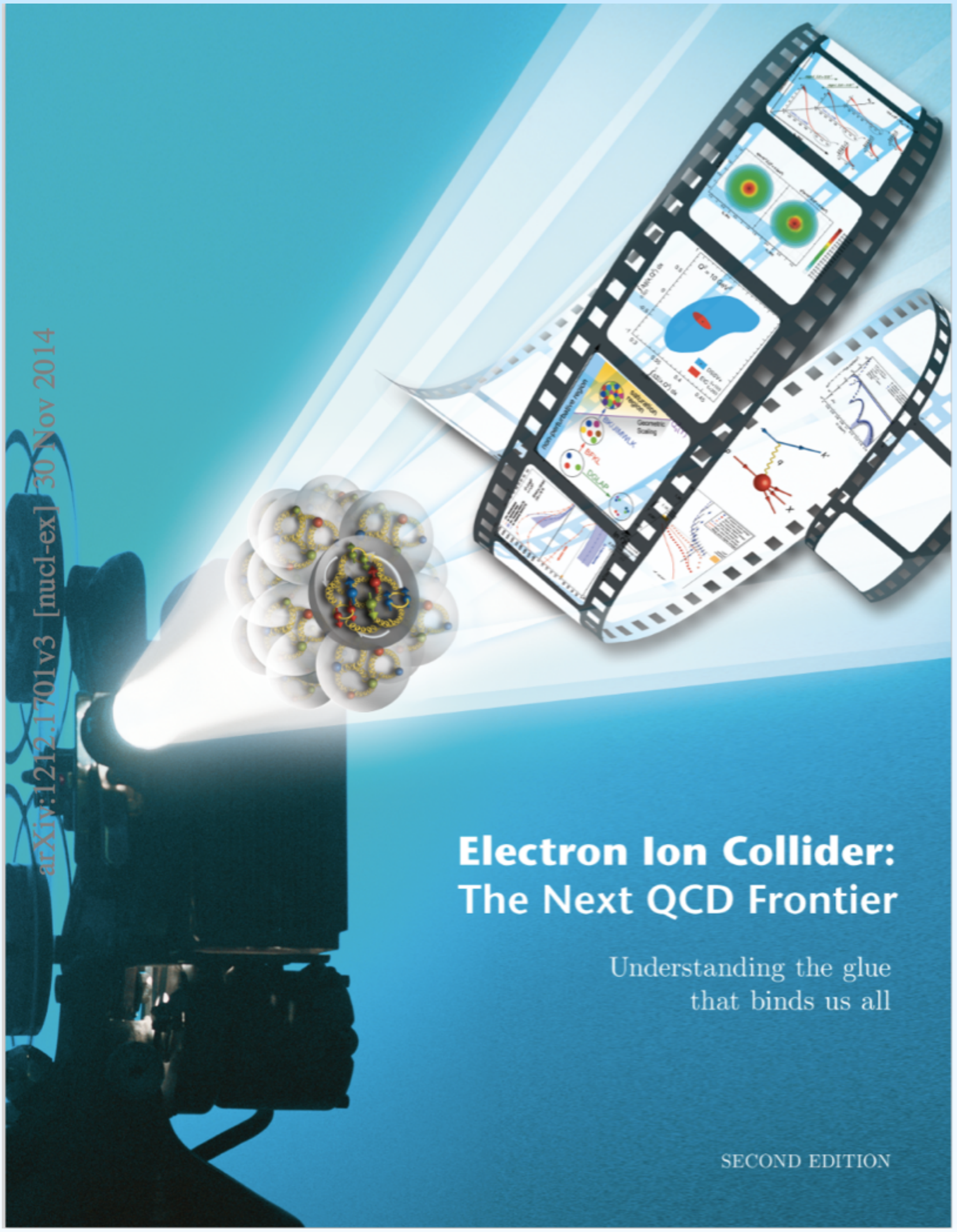


Eur. Phys. J. A52 (2016) no.9, 268 - 500+ citations

See also Rept.Prog.Phys. 82 (2019) 024301

- *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. EIC Capabilities



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

See also Rept.Prog.Phys. 82 (2019) 024301

- *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 at RHIC and at Jefferson Laboratory, re-use of existing, significant investment.*

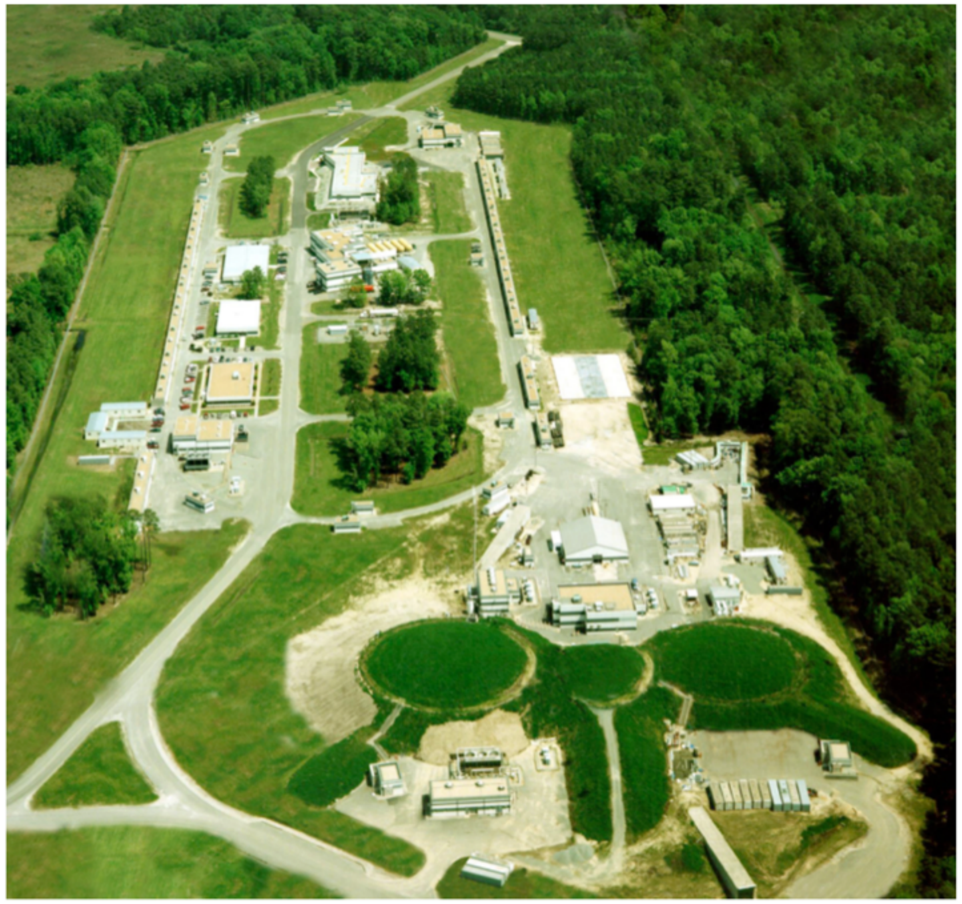
U.S.-based EIC - Two Facility Concepts

eRHIC:

- re-use existing RHIC hadron beam,

JLEIC:

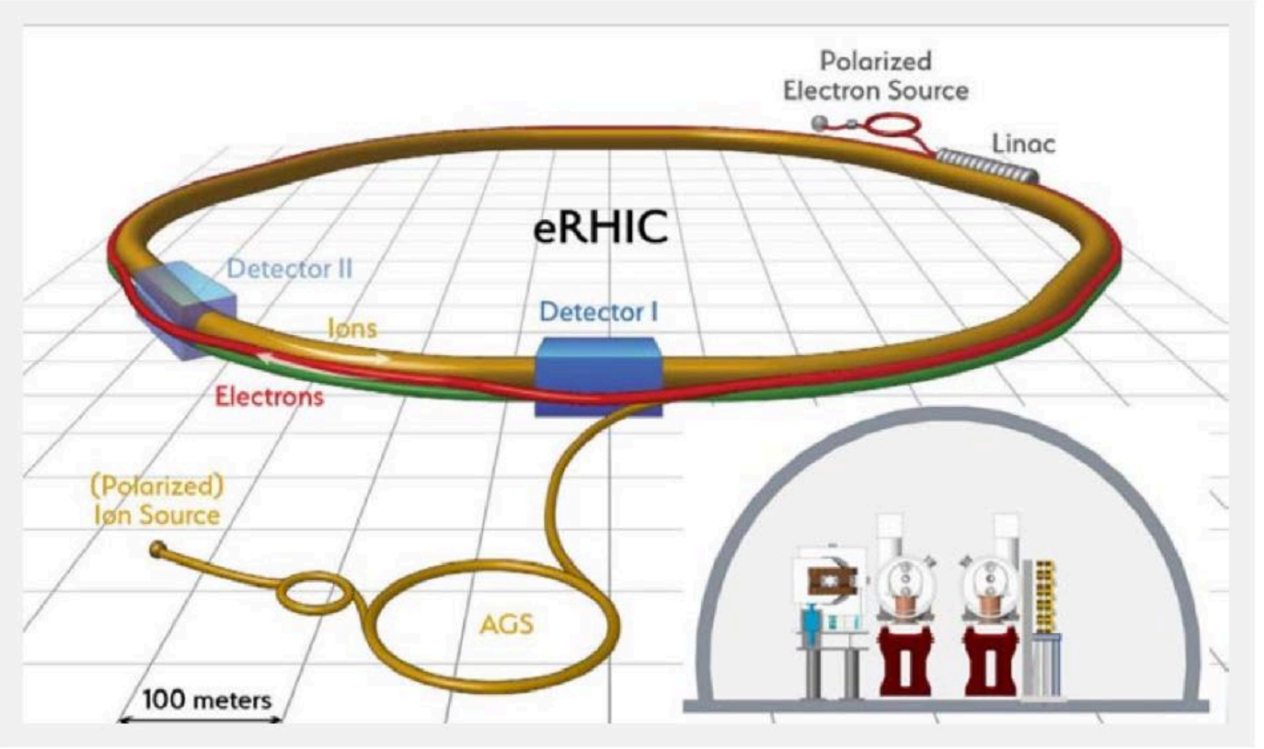
- re-use existing CEBAF 12 GeV
  electron beam,



U.S.-based EIC - Two Facility Concepts

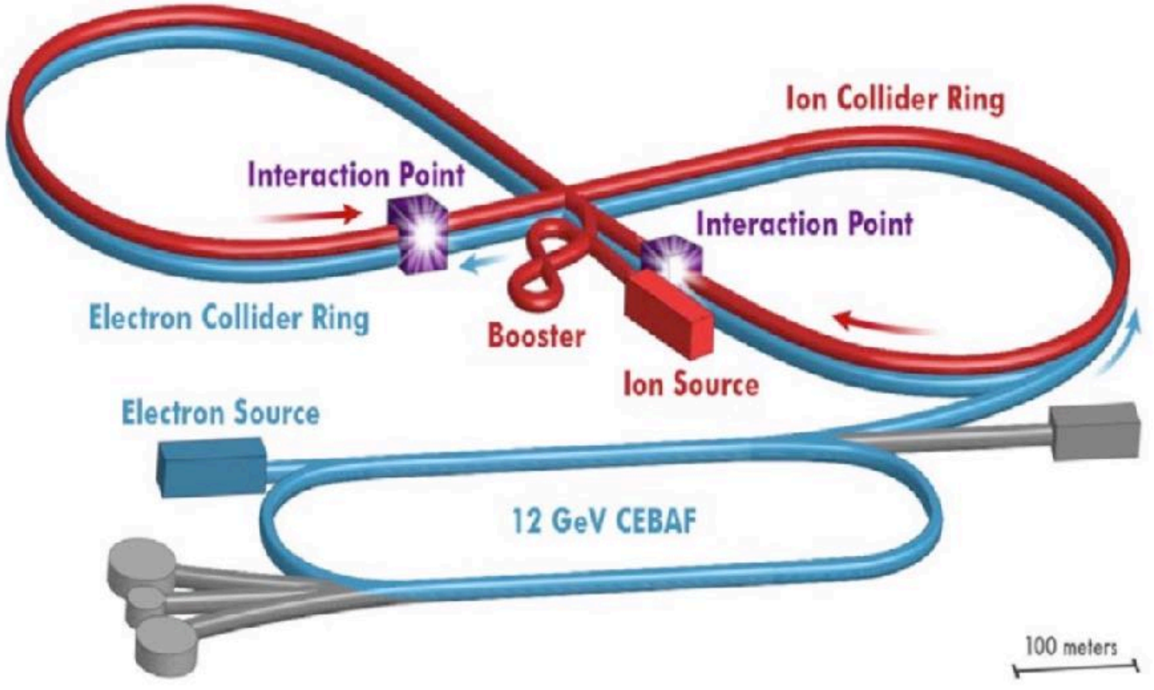
eRHIC (as presented in the W.P.):

- re-use 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 ~ 0.4×10^{34} $cm^{-2}s^{-1}$/A base design,
  1.0×10^{34} $cm^{-2}s^{-1}$/A w. strong cooling



JLEIC (as presented in W.P.):

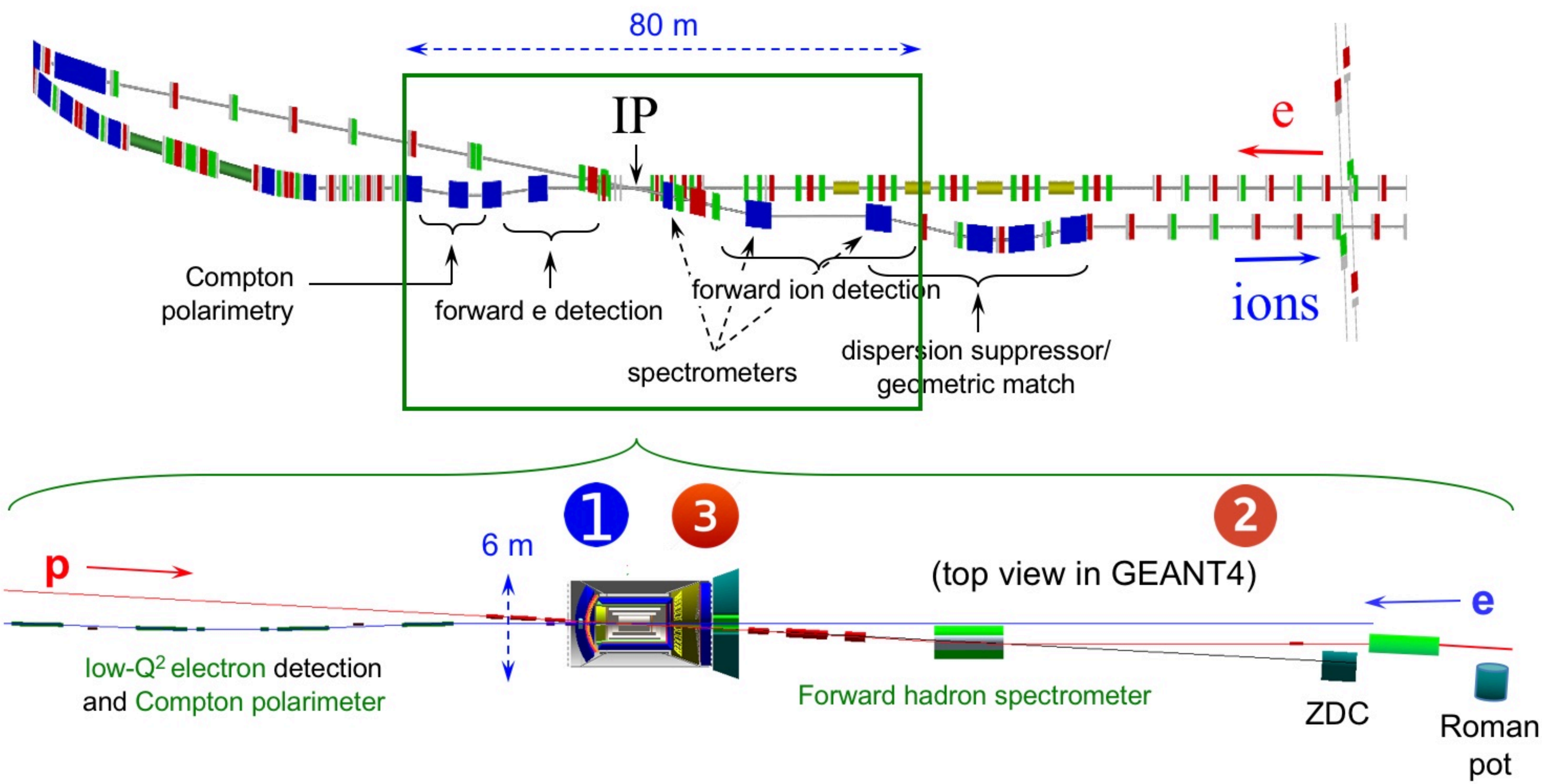
- re-use CEBAF 12 GeV electron beam facility,
- new hadron injector,
- new figure-8 collider configuration,
- 3-10 GeV electron energy,
- 12-40 GeV/u Heavy Ion energy, upgradable (ion arc dipole)
- L ~10^{34} $cm^{-2}s^{-1}$/A



Science cases by themselves!

U.S.-based EIC - Two Facility Concepts

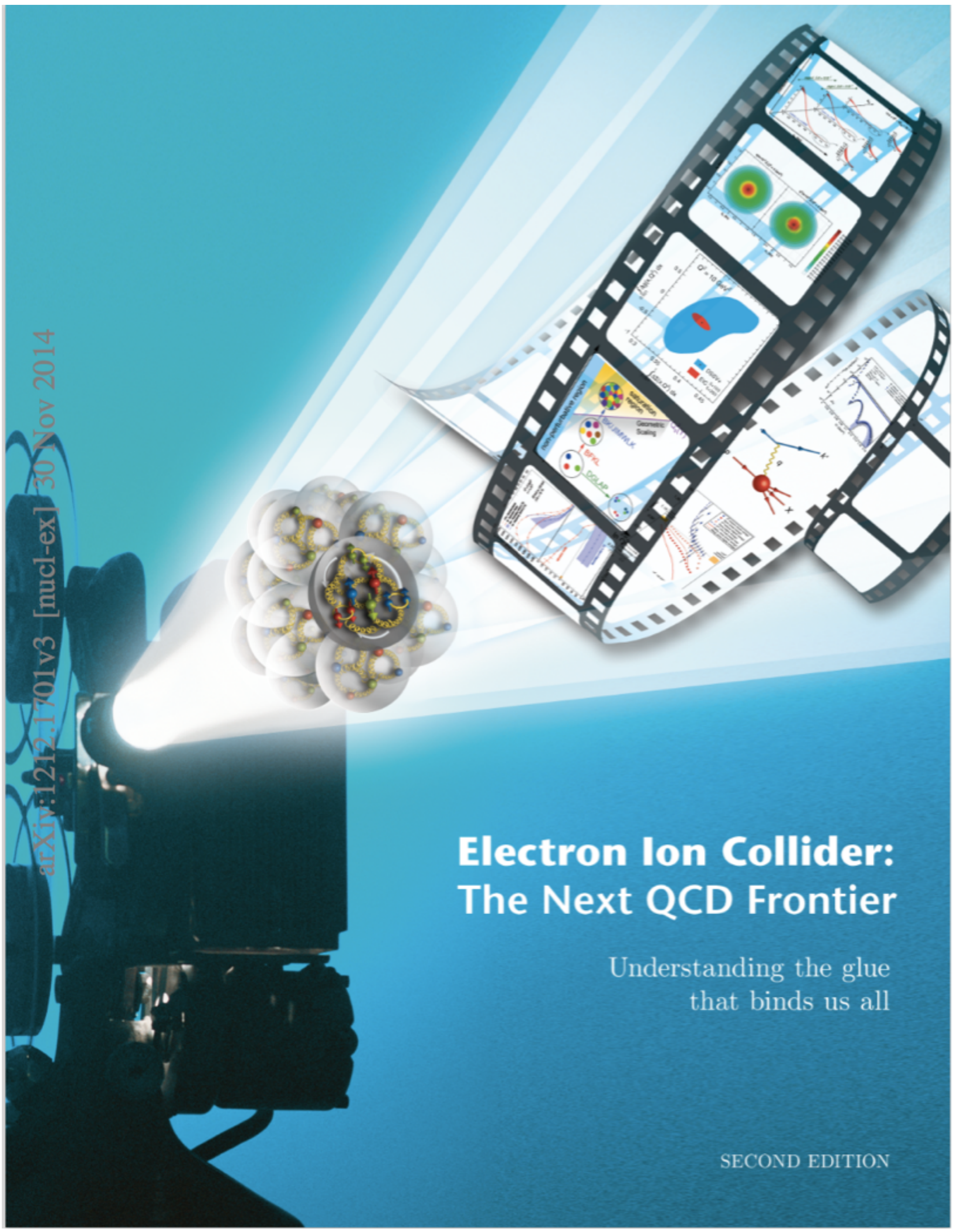
Science cases by themselves requiring, for example, tight integration with detectors



courtesy V. Morozov (JLab)

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

U.S. EIC Science Case

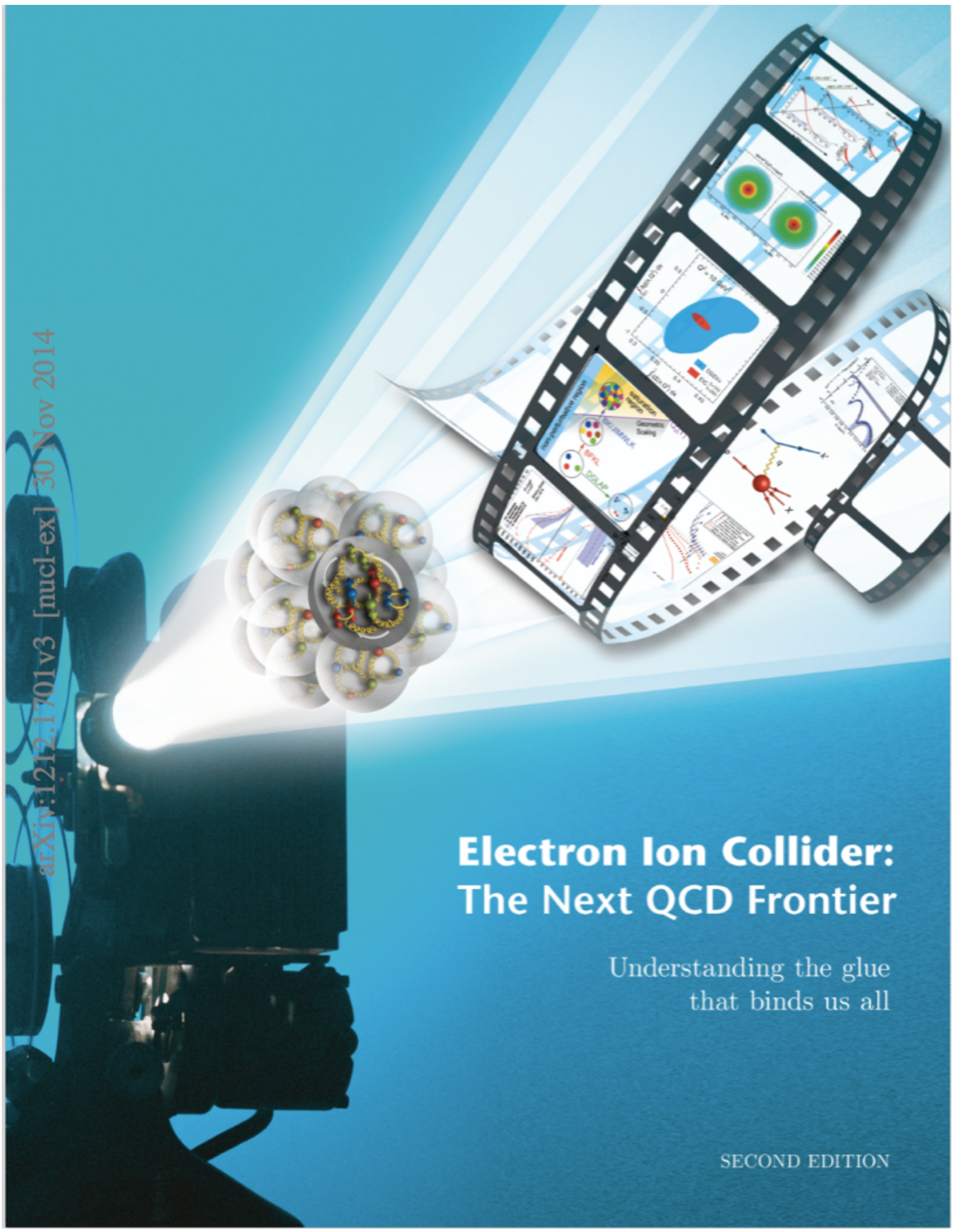


Eur. Phys. J. A52 (2016) no.9, 268 - 441 citations

See also Rept.Prog.Phys. 82 (2019) 024301

- *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. EIC Science Case



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

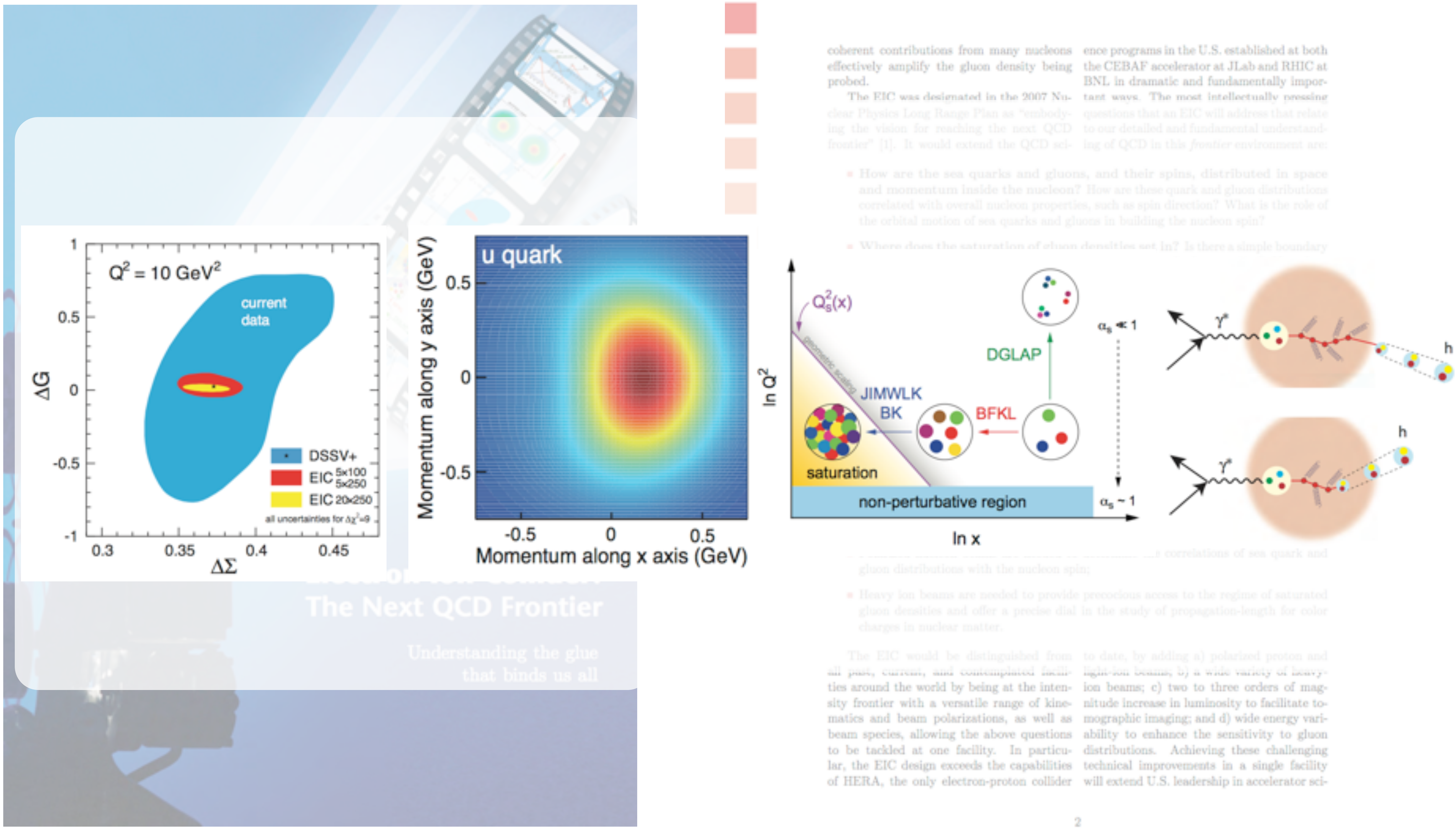
See also Rept.Prog.Phys. 82 (2019) 024301

Organized around four themes:

- *Proton spin,*
  quark and gluon helicity distributions,
  orbital motion
- *Imaging of nucleons and nuclei*
  TMDs, GPDs, Wigner functions
- *Saturation*
  Non-linear evolution,
  Color-glass condensate,
- *Hadronization and fragmentation,*
  in-medium propagation,attenuation

Identified measurements and impact.

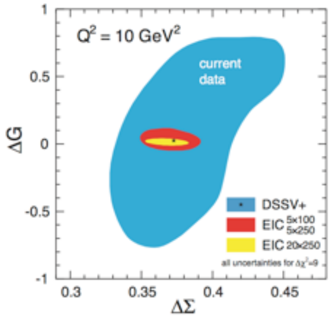
U.S.-based EIC - Core Science



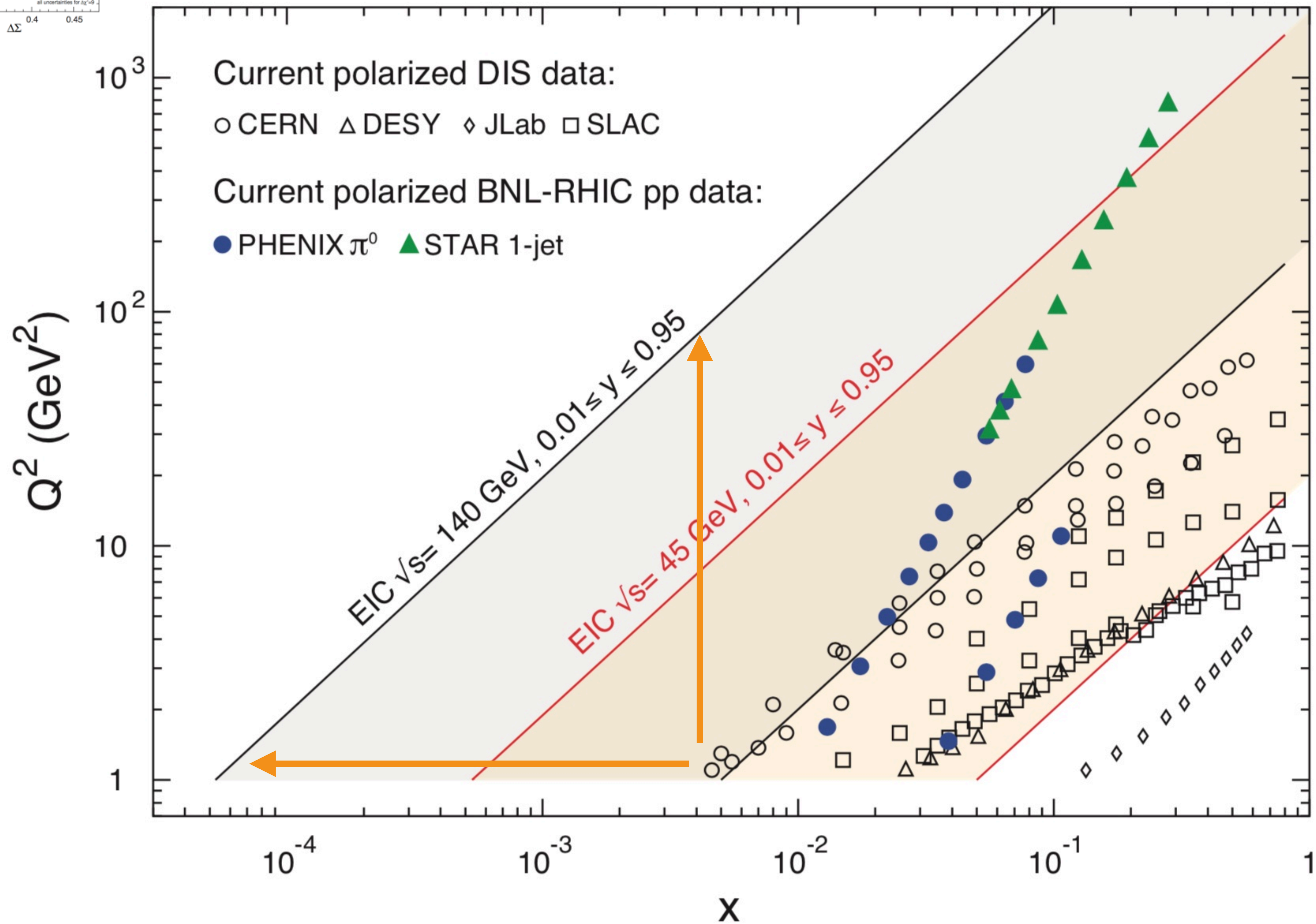
Nuclear Physics enabled by EIC **accelerator** energy, intensity, polarization, and species,

experiment capabilities,

theory

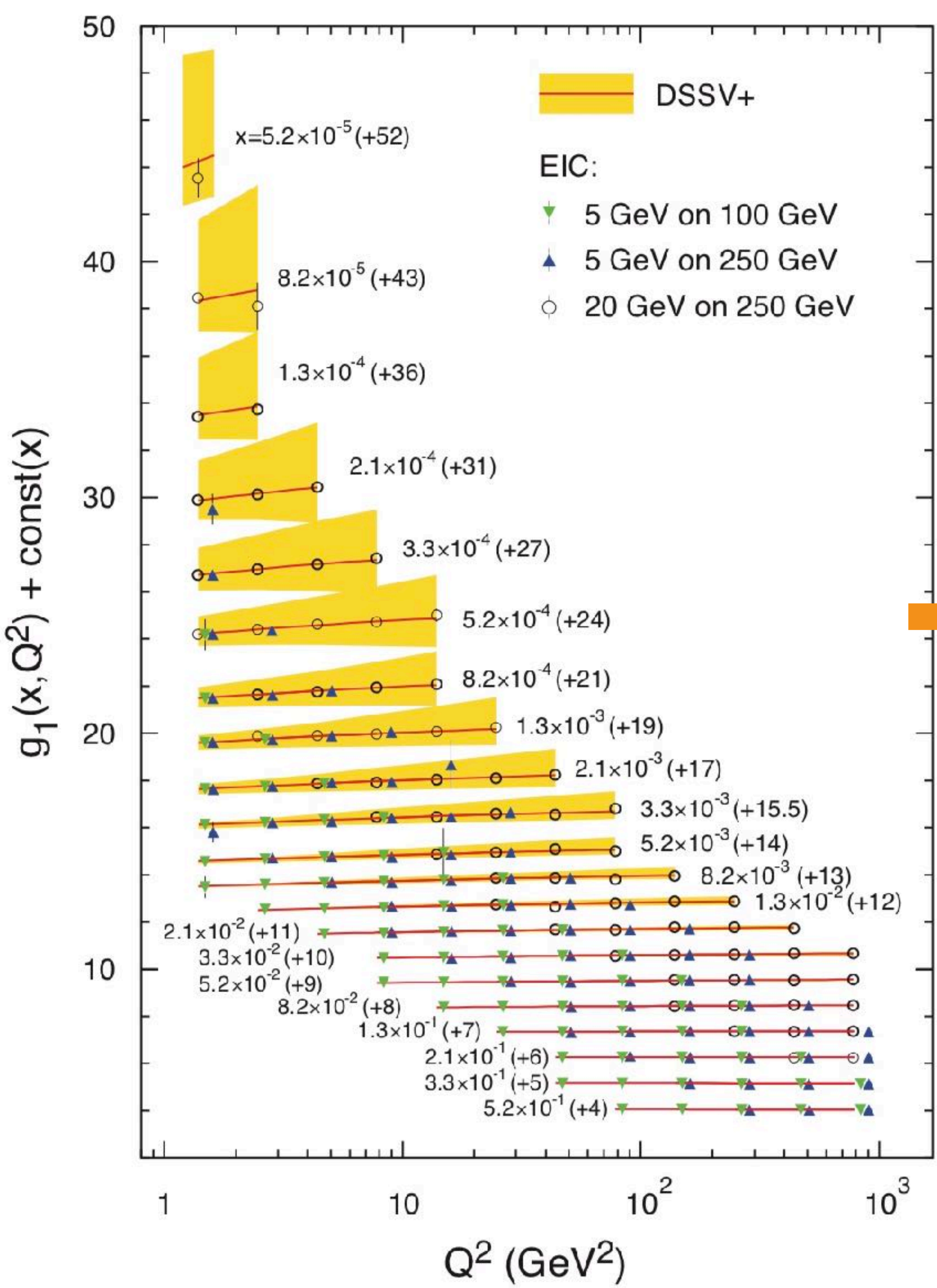


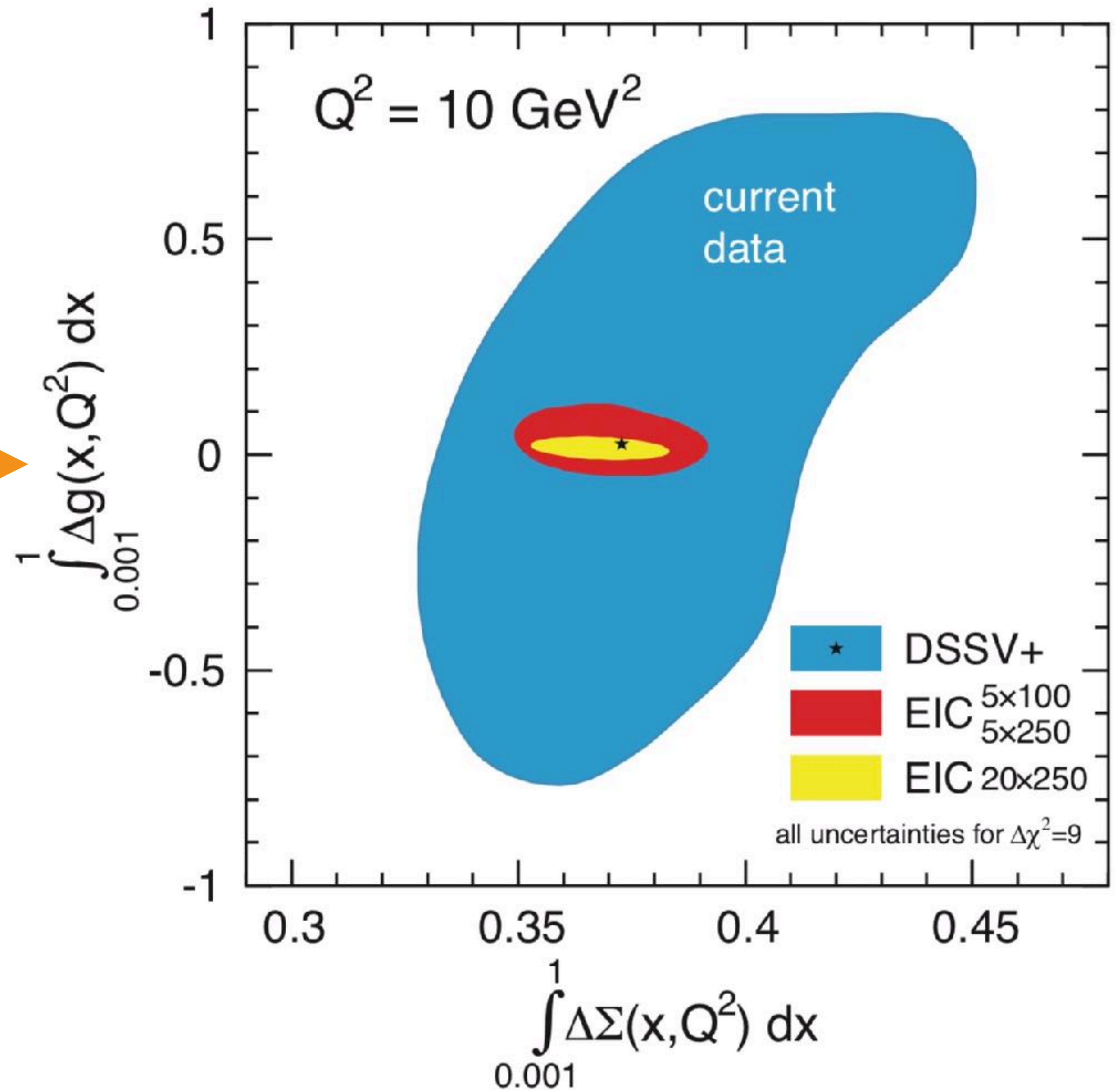
U.S.-based EIC - Proton Spin



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

U.S.-based EIC - Proton Spin

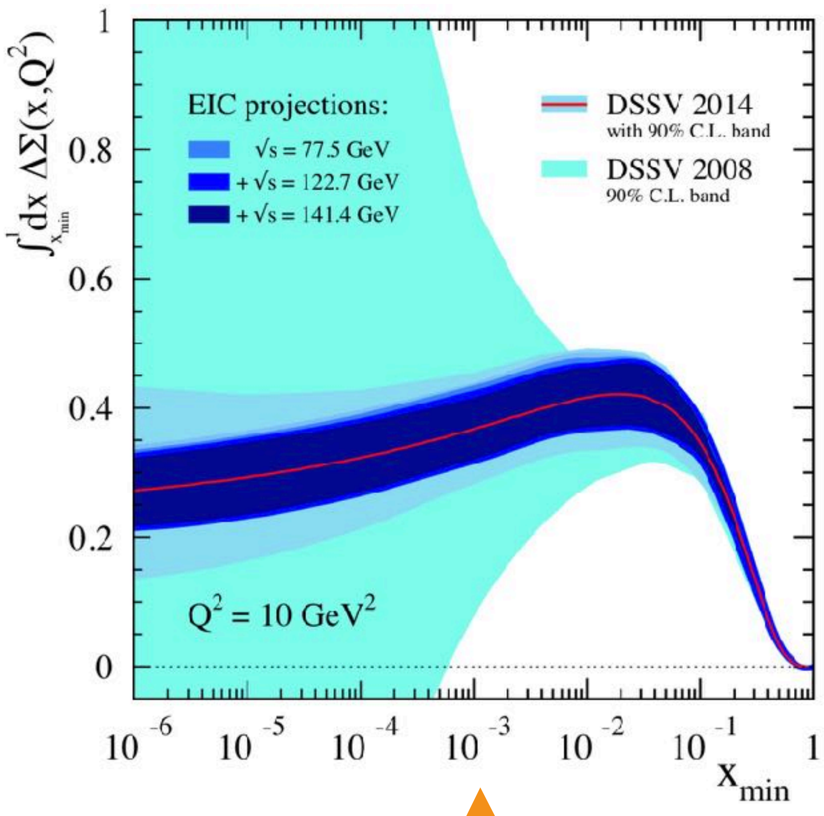




Conclusive insights in quark and gluon helicity from inclusive measurements, and orbital momentum by subtraction (!)

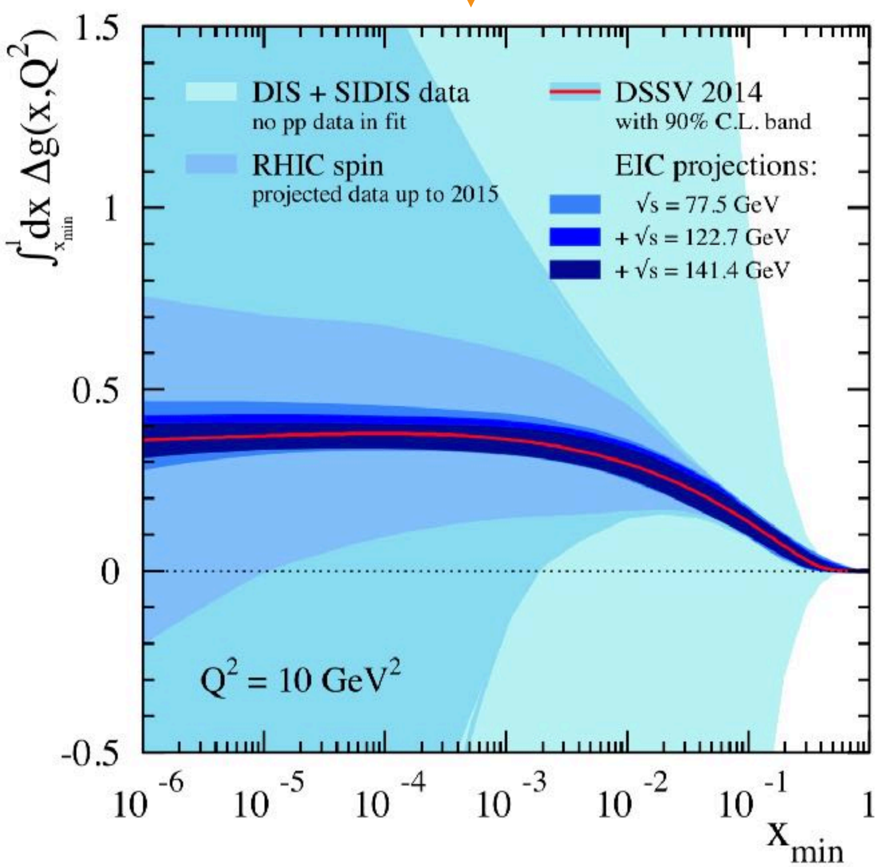
U.S.-based EIC - Proton Spin

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

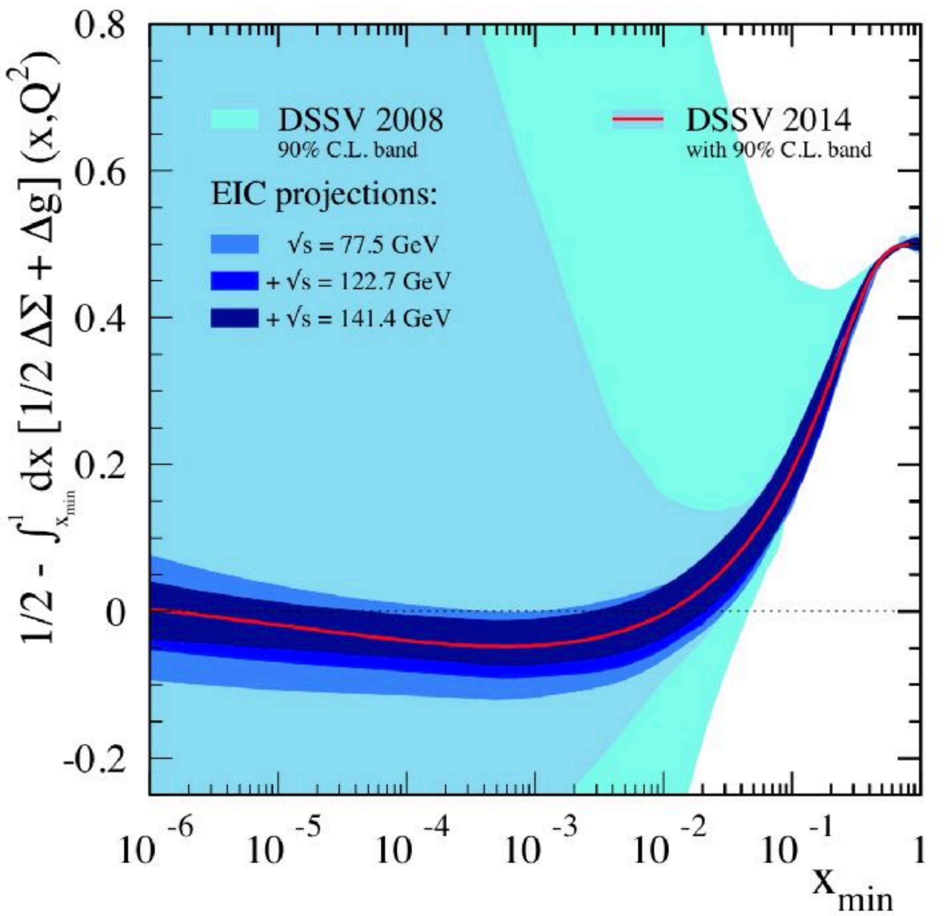


(anti-)quark helicity

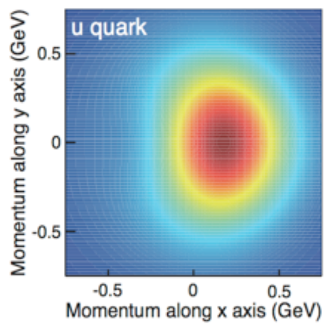
gluon helicity



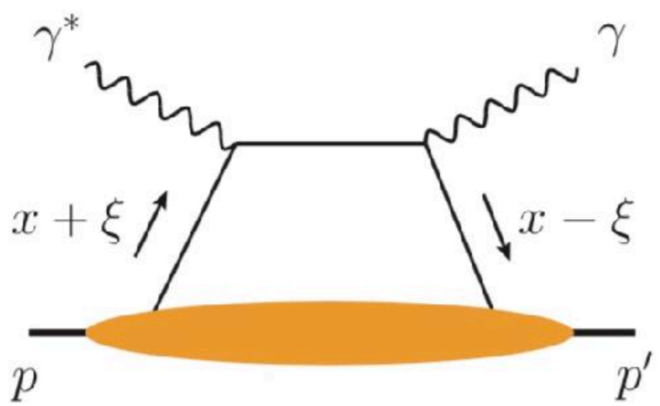
orbital momenta

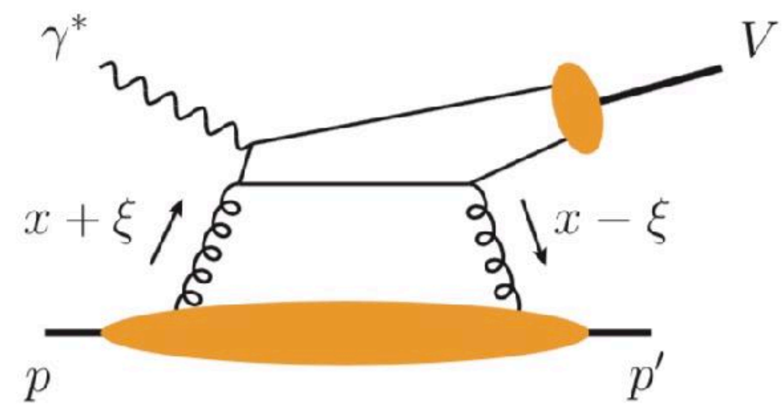


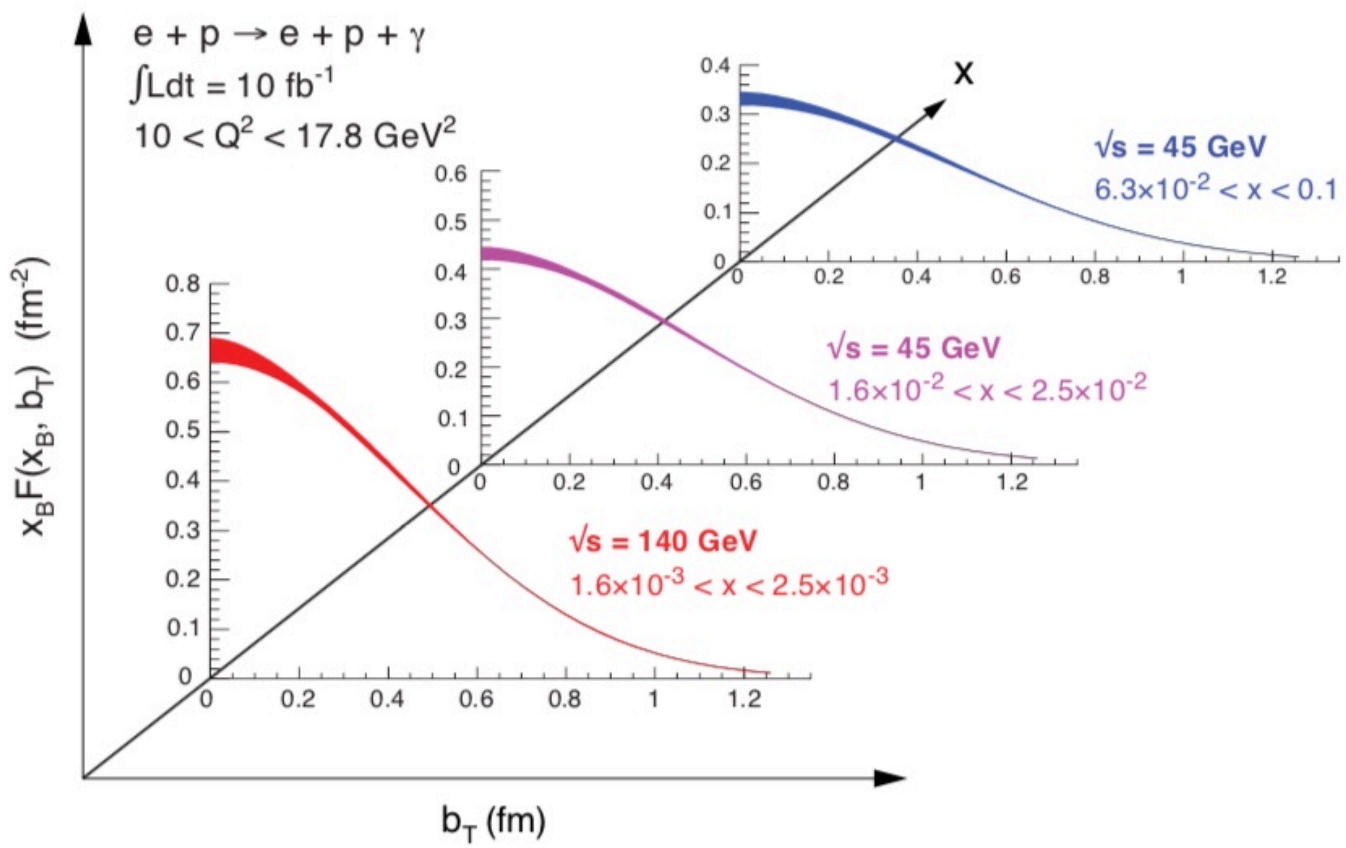
Clearly requires EIC



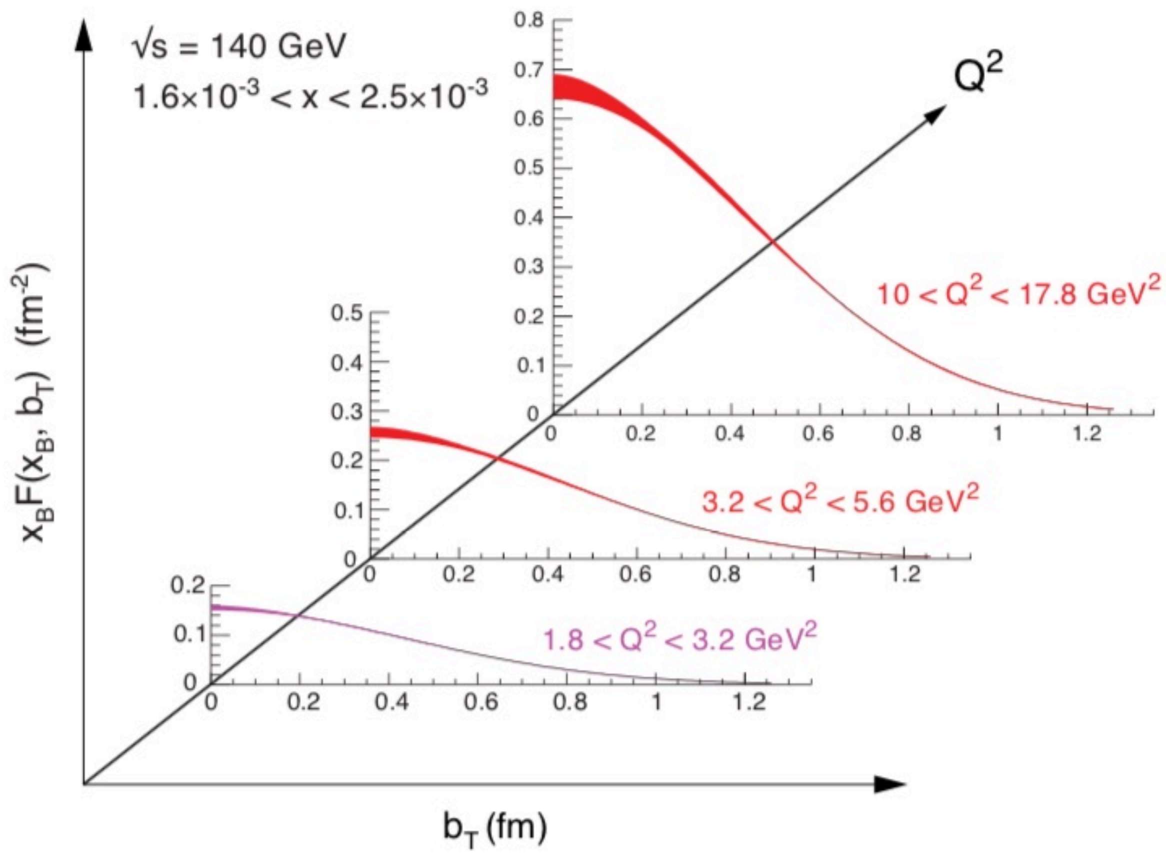
EIC - DVCS, DVMP, and Imaging



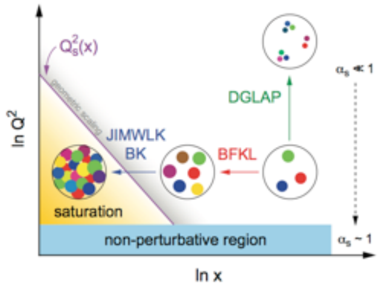




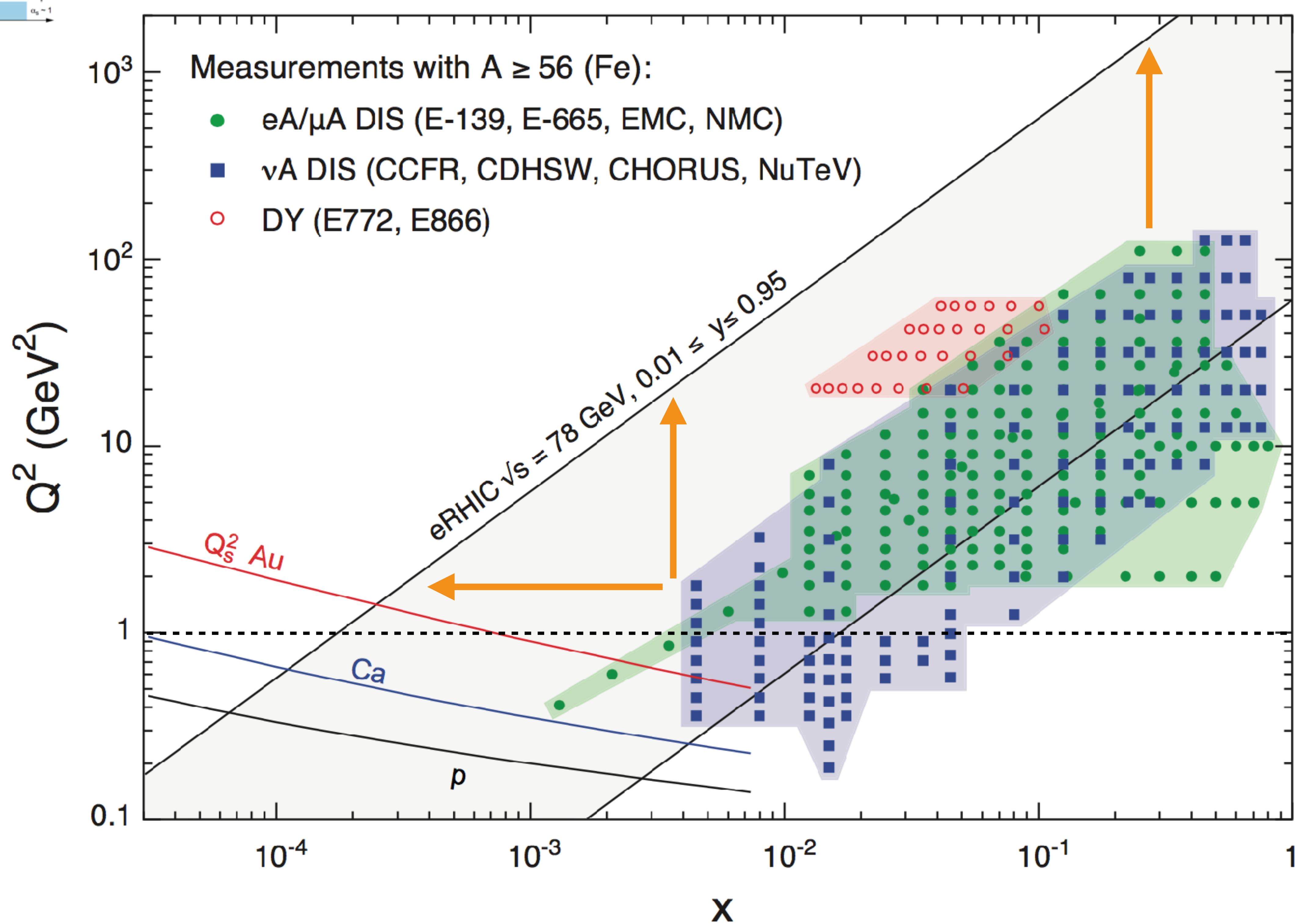
x-dependence at fixed Q2



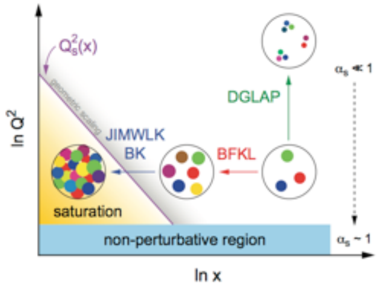
Q2-dependence at fixed x



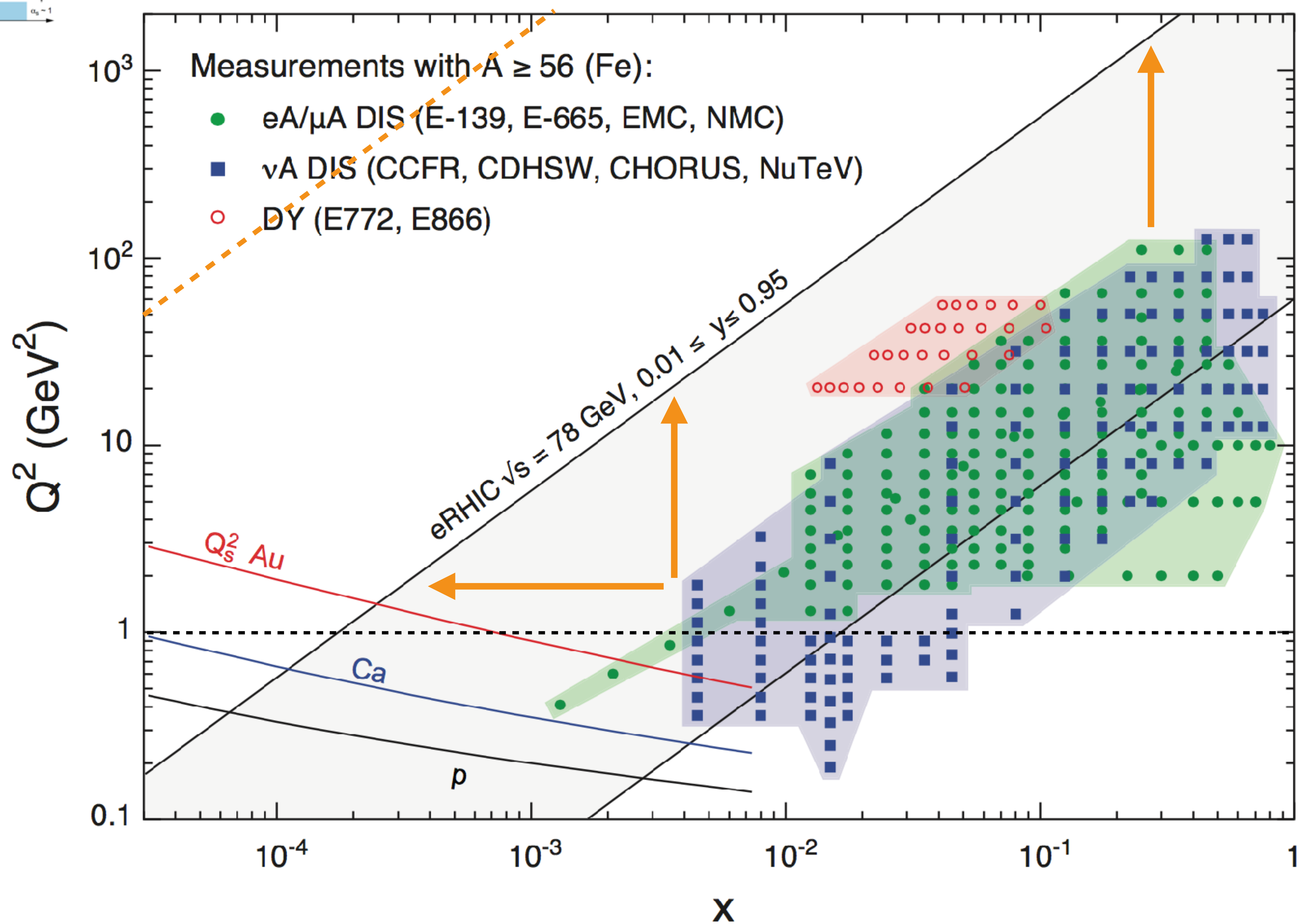
U.S.-based EIC - The Nuclear Landscape



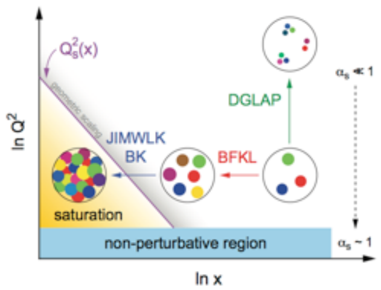
Complementarity with ongoing and future RHIC and LHC measurements,
c.f. D. Caffarri, J. Jia, B. Schmidt, J. Wang, … A. Bylinkin,
D. Perepelitsa, …, D. Brandenburg, P. Di Nezza, J. Lajoie, …



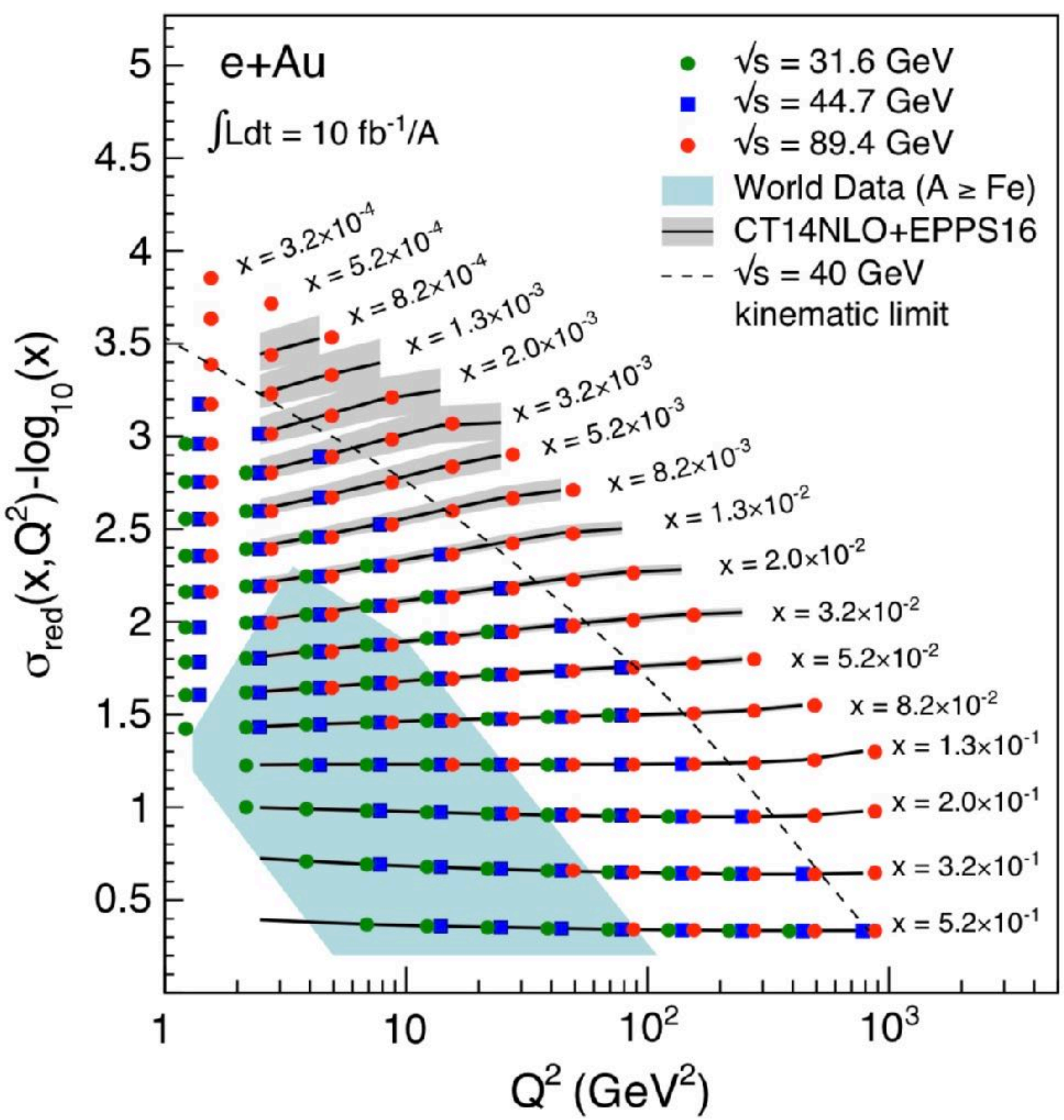
U.S.-based EIC - The Nuclear Landscape

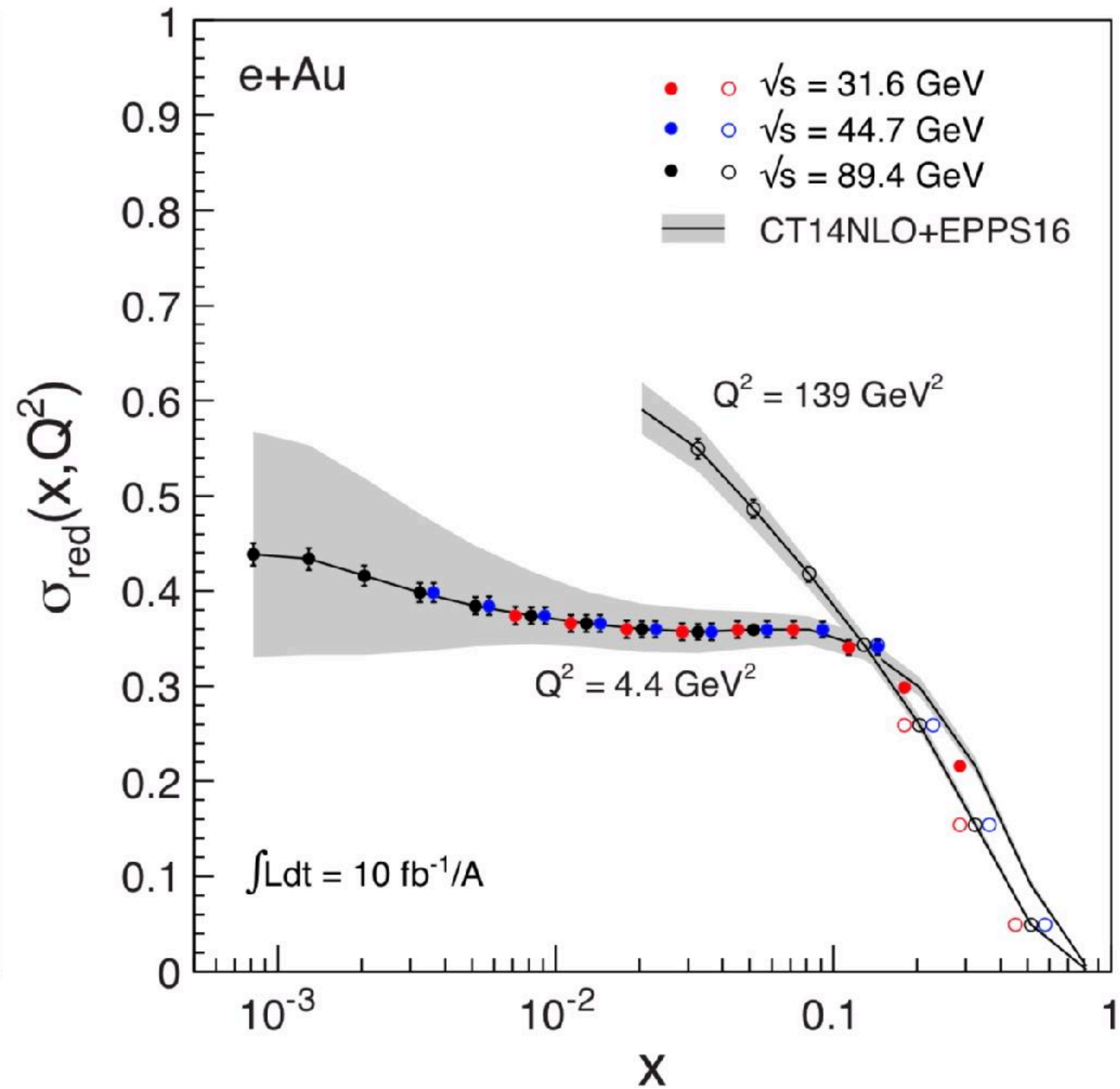


LHeC, if realized, will obviously provide unprecedented kinematic reach, complementarity in polarization, A capabilities - c.f. N. Armesto



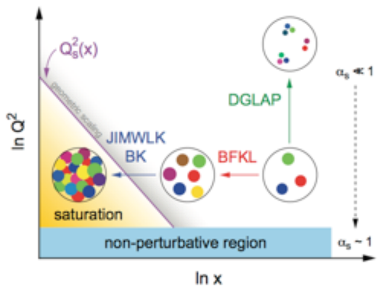
U.S.-based EIC - The Nuclear Landscape



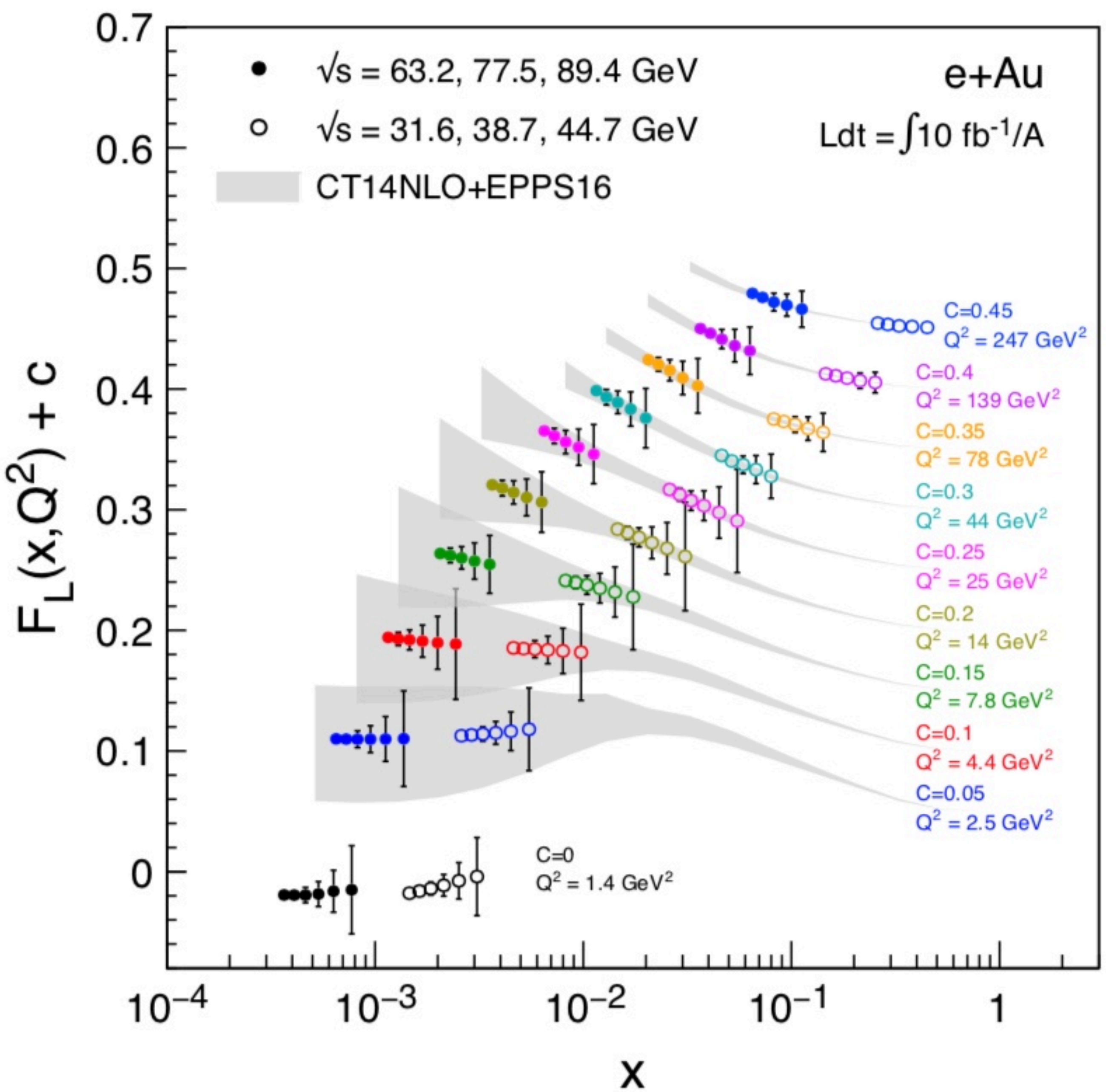


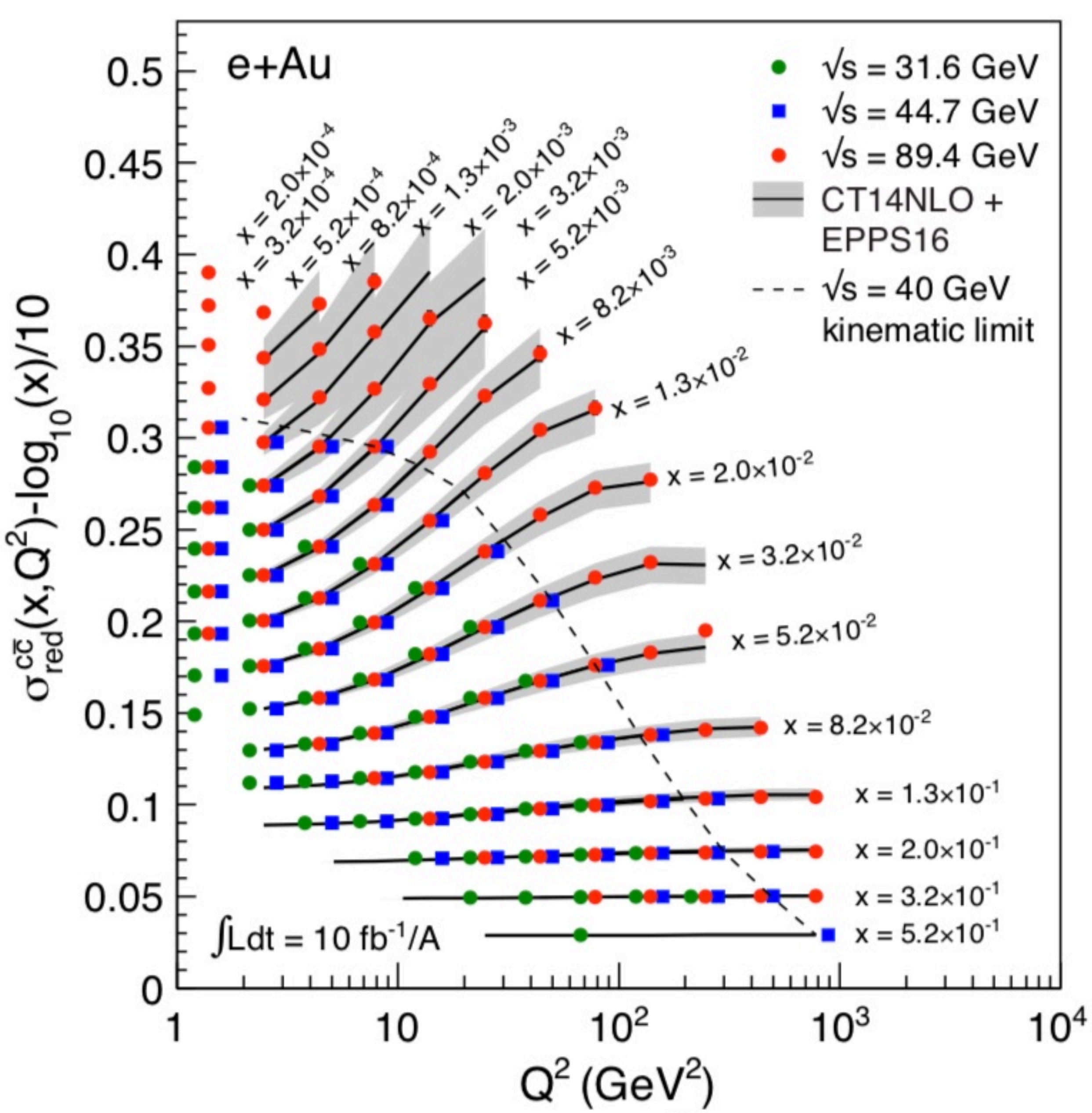
$$\sigma_{\text{reduced}} = F_2(x,Q^2) - \frac{y}{1+(1-y)^2} F_L(x,Q^2)$$

Impactful baseline inclusive measurements.



U.S.-based EIC - The Nuclear Landscape

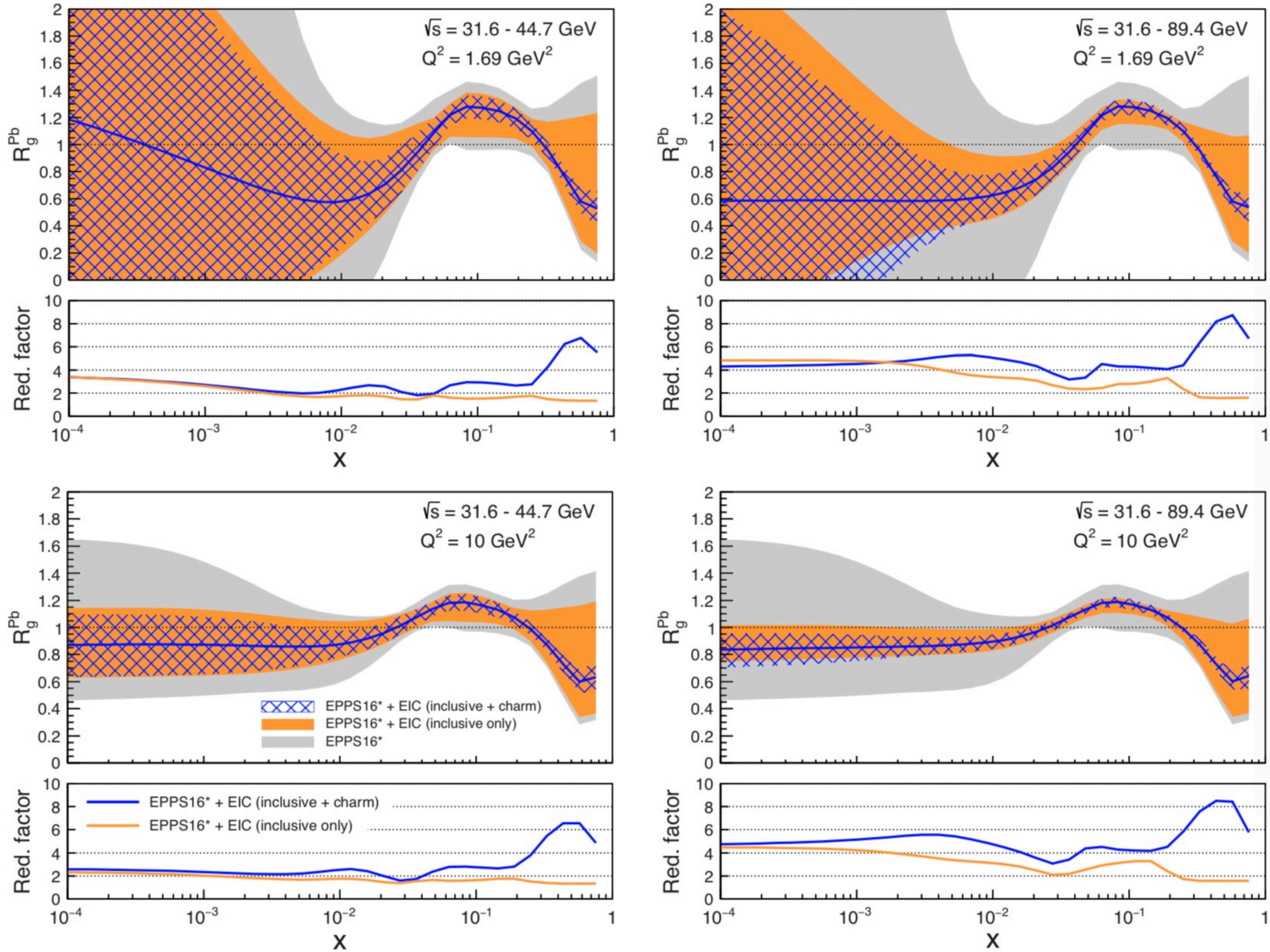




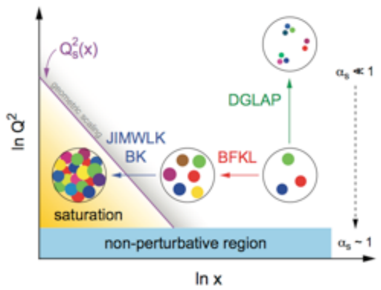
Clearly visible impact also beyond baseline inclusive measurements with “Rosenbluth separation” and semi-inclusive measurements.

Nuclear gluon will be probed sensitively with complementary channels.

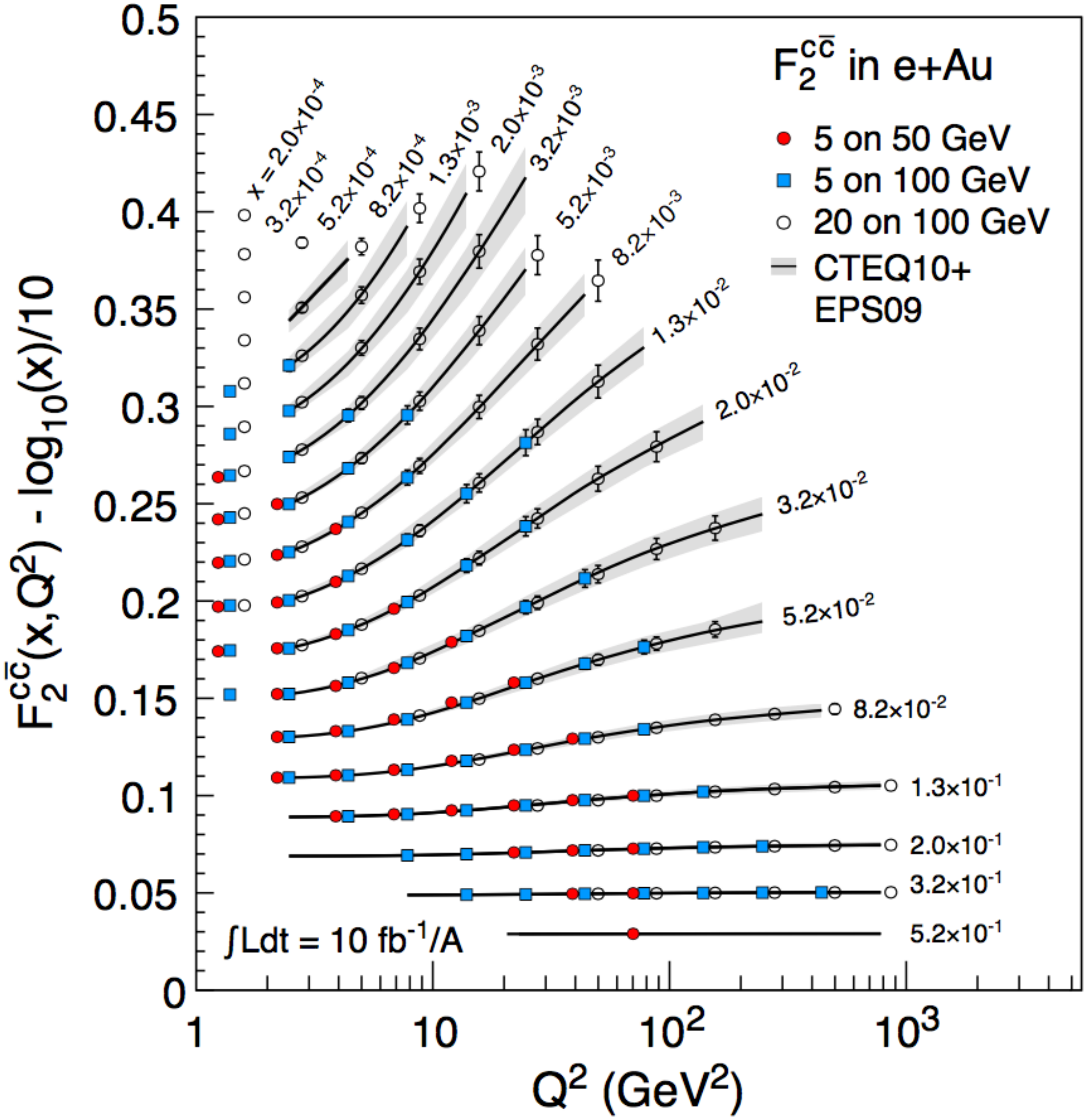
U.S.-based EIC - The Nuclear Landscape

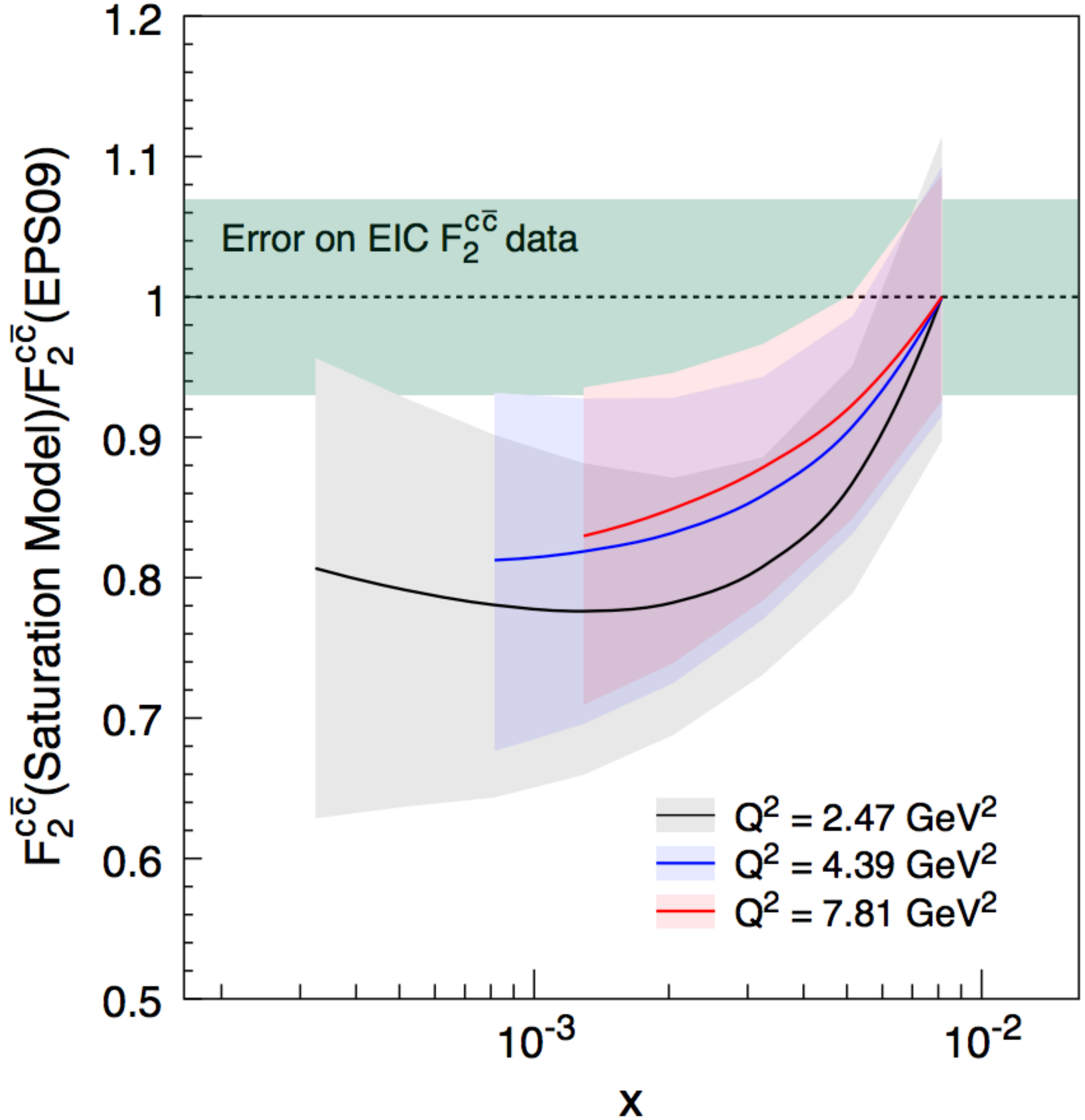


See P. Zurita's talk, but see also I.Vitev's (medium-modified splitting)



EIC - Saturation from PDFs alone?



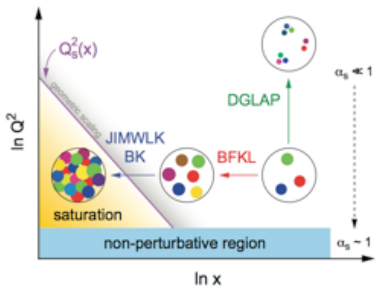


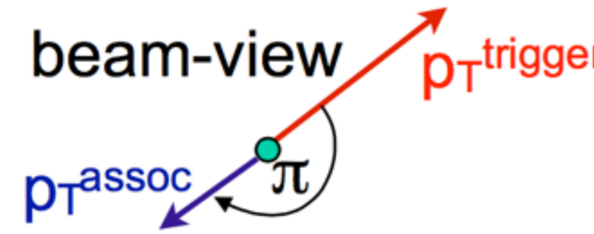
Theory will undoubtedly develop nPDFs much further;

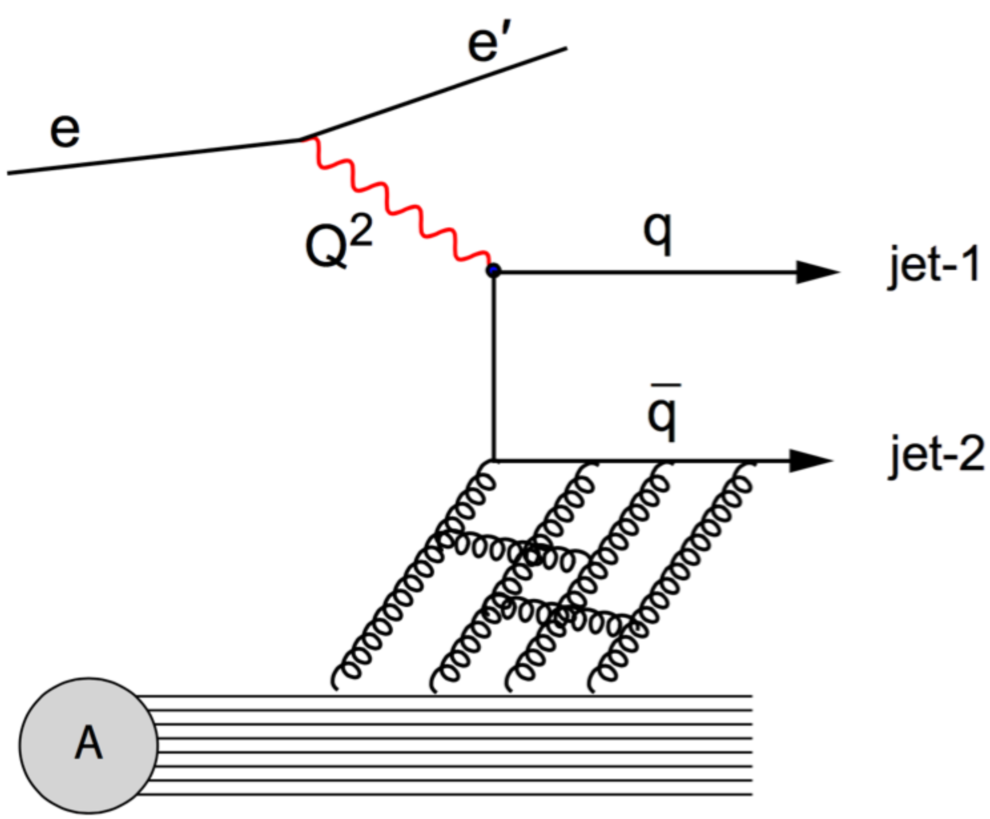
NNLO, HT, resummations, in-medium, …

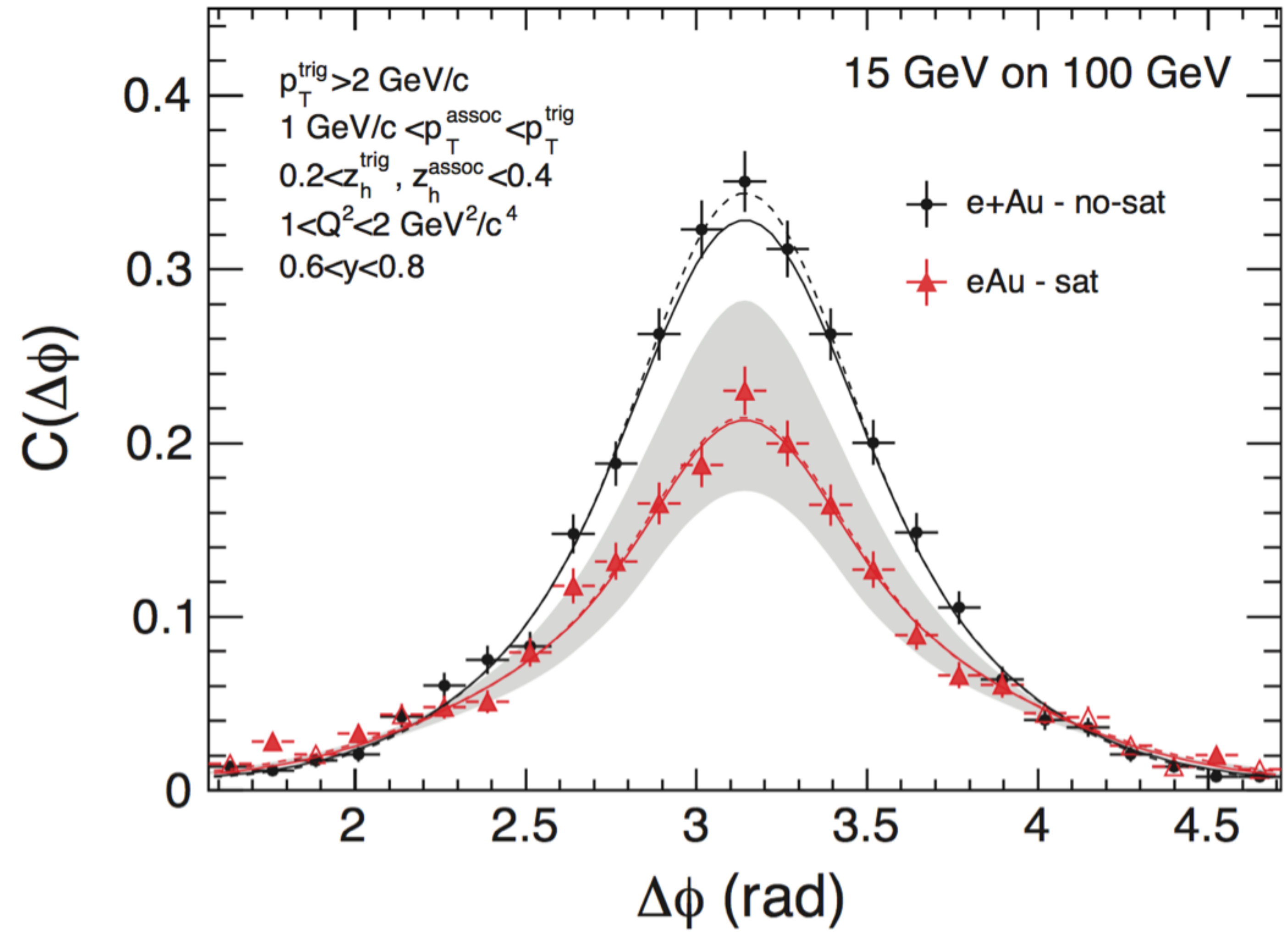
***Almost certainly no substitute* for thinking *outside* the (n)PDF…**

EIC - Dihadrons to probe Saturation









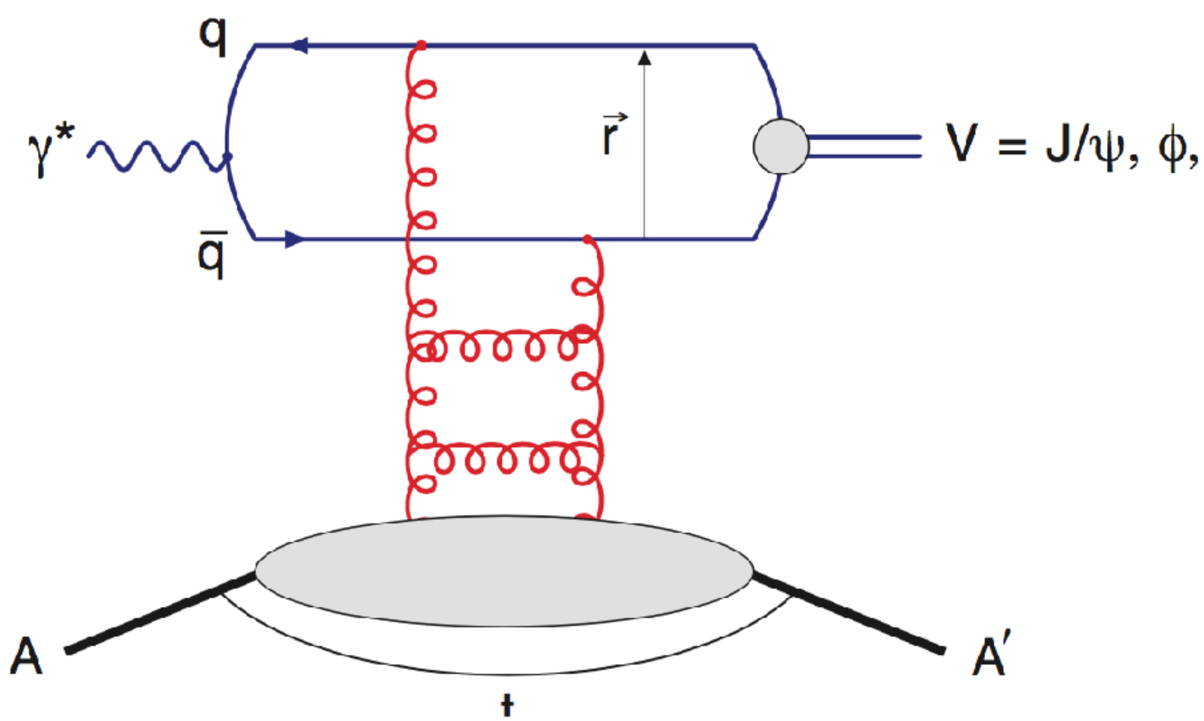
Zheng et al (2014)

Dominguez, Xiao, Yuan (2011)

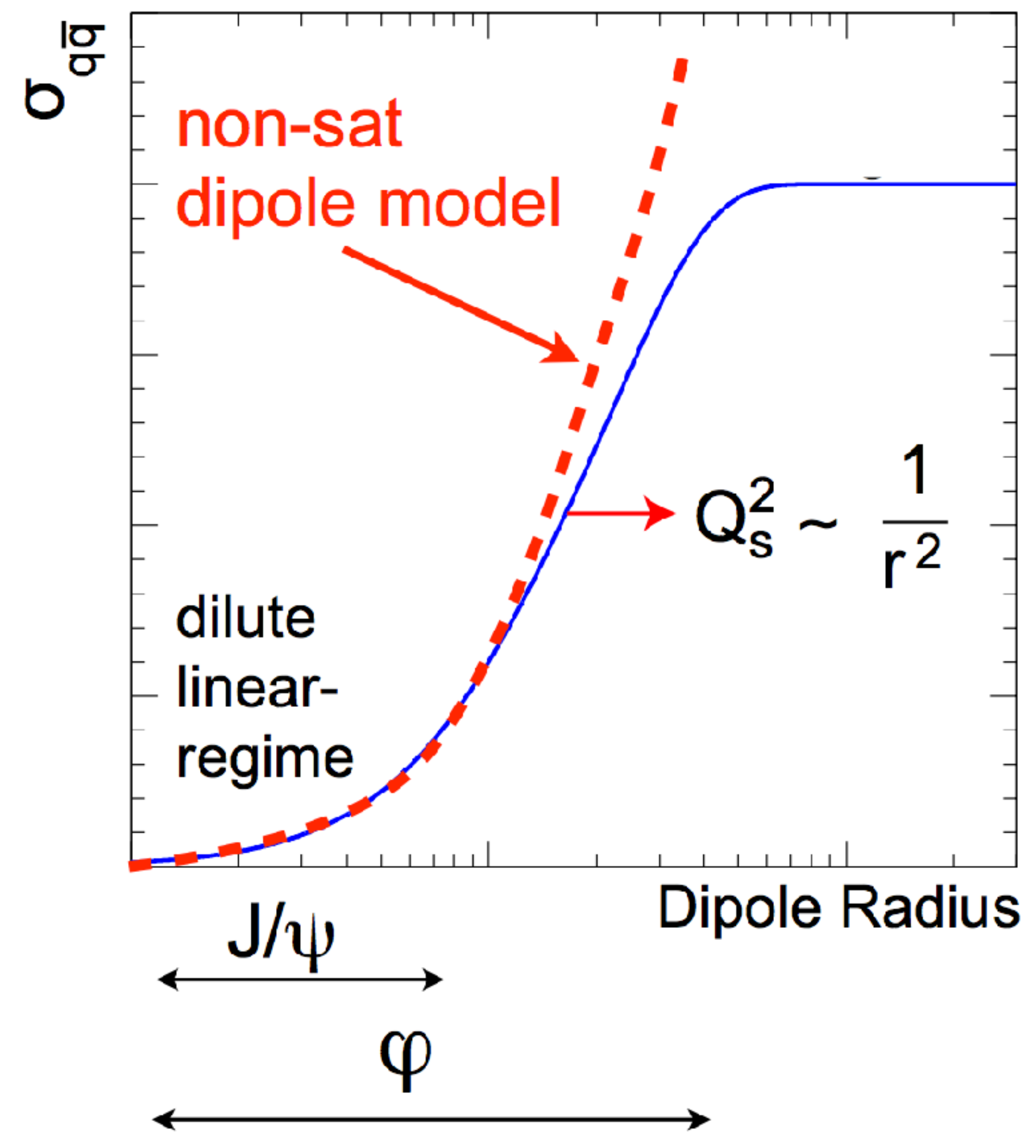
Suppression of back-to-back hadron or jet correlation directly probes the (un-)saturated gluon distributions in nuclei,

EIC - Diffractive probes of Saturation

$$t = (p_A - p_{A'})^2 = (p_{VM} + p_{e'} - p_e)^2$$



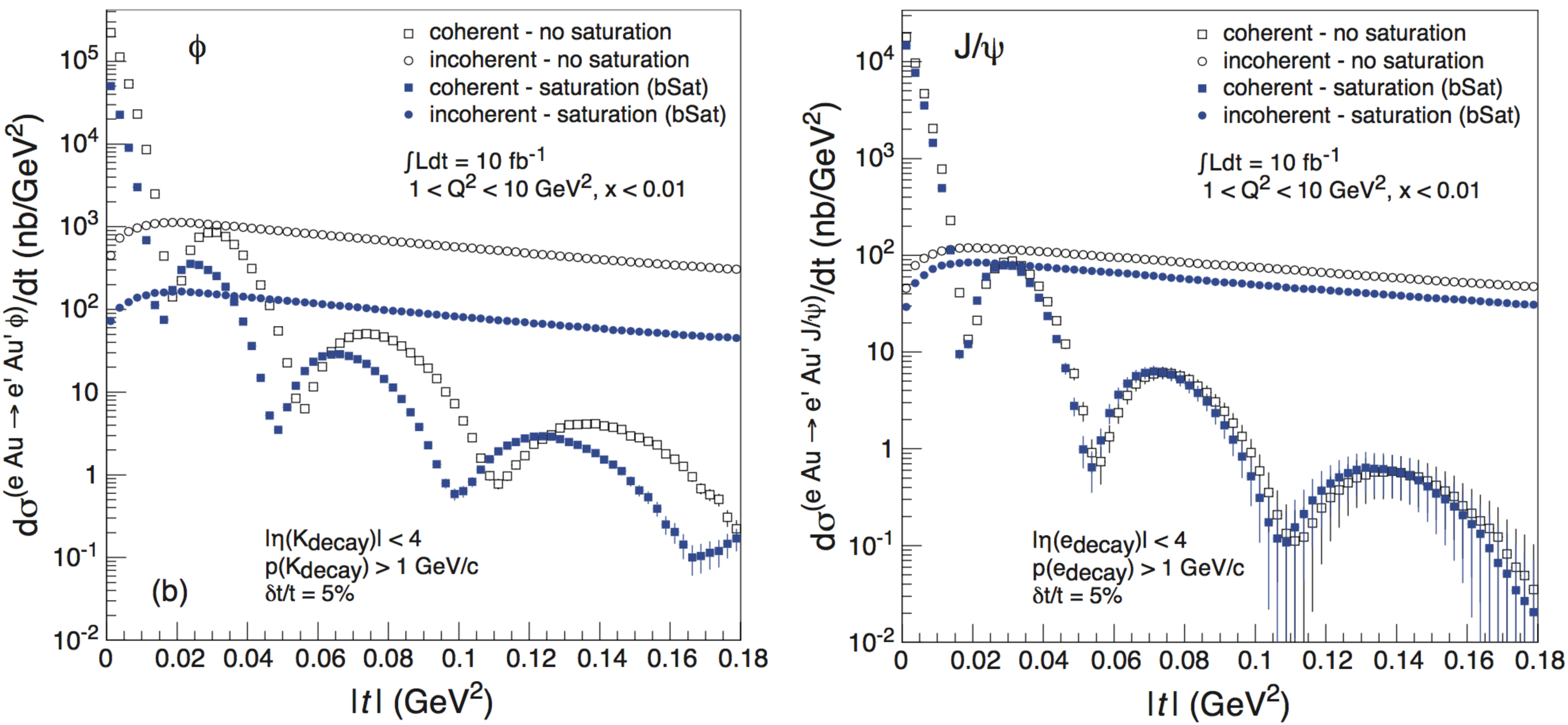
Dipole Cross-Section:



Nucleus escapes down the beampipe

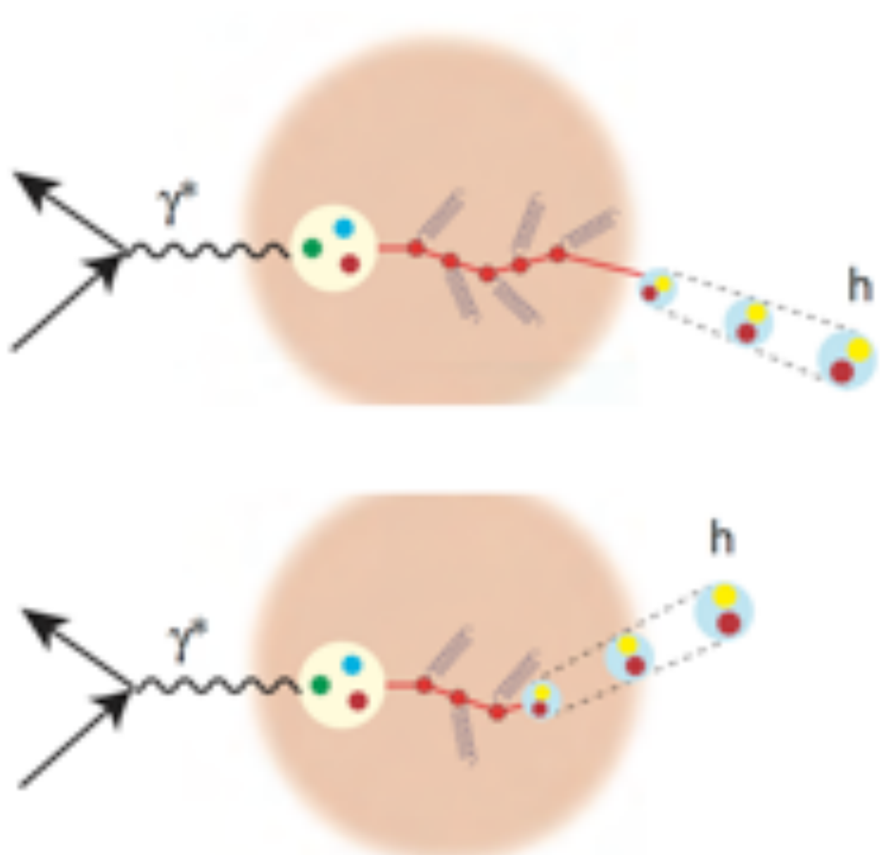
(In)coherence tagged with ZDC

EIC - Diffractive probes of Saturation



Incoherent and coherent diffraction are both key measurements to saturation,
Exclusive vector meson production is key to (all) imaging,
as is deeply virtual Compton scattering

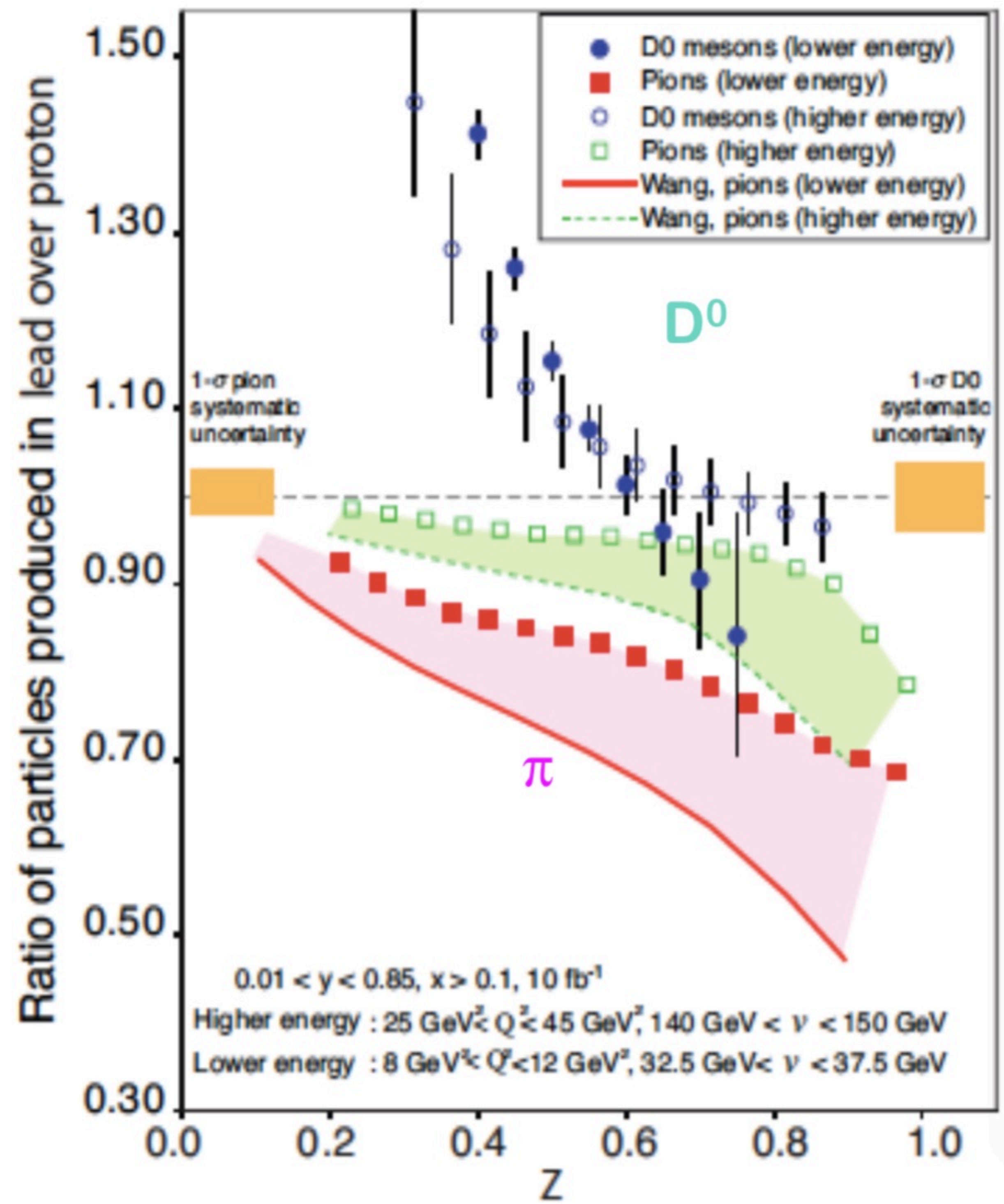
EIC - SIDIS to study Emergence of Hadrons



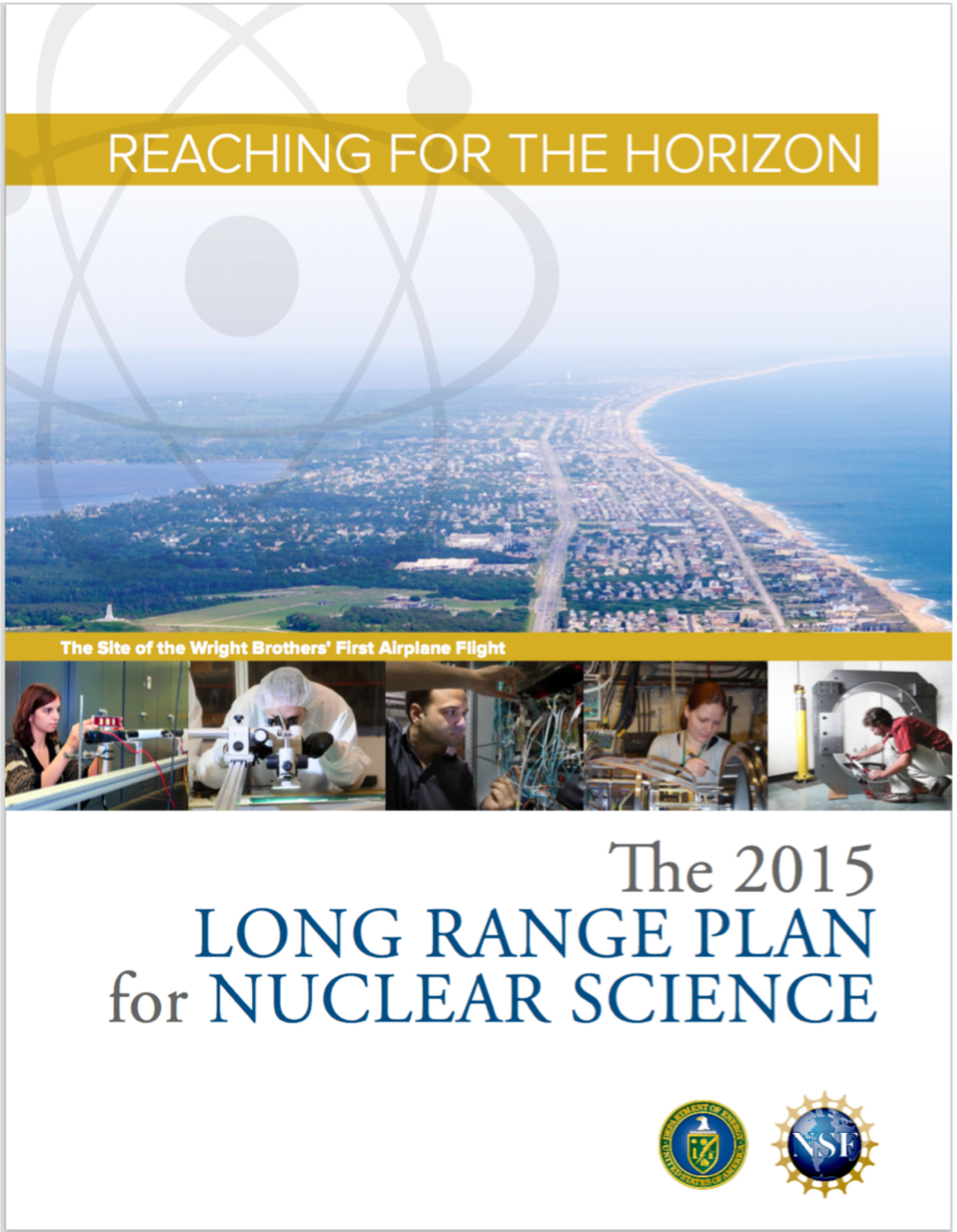
Control of $\nu = \dfrac{Q^2}{2mx}$ and

medium length

Study mass-dependence via charmed hadrons.



Status of U.S.-based EIC



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.

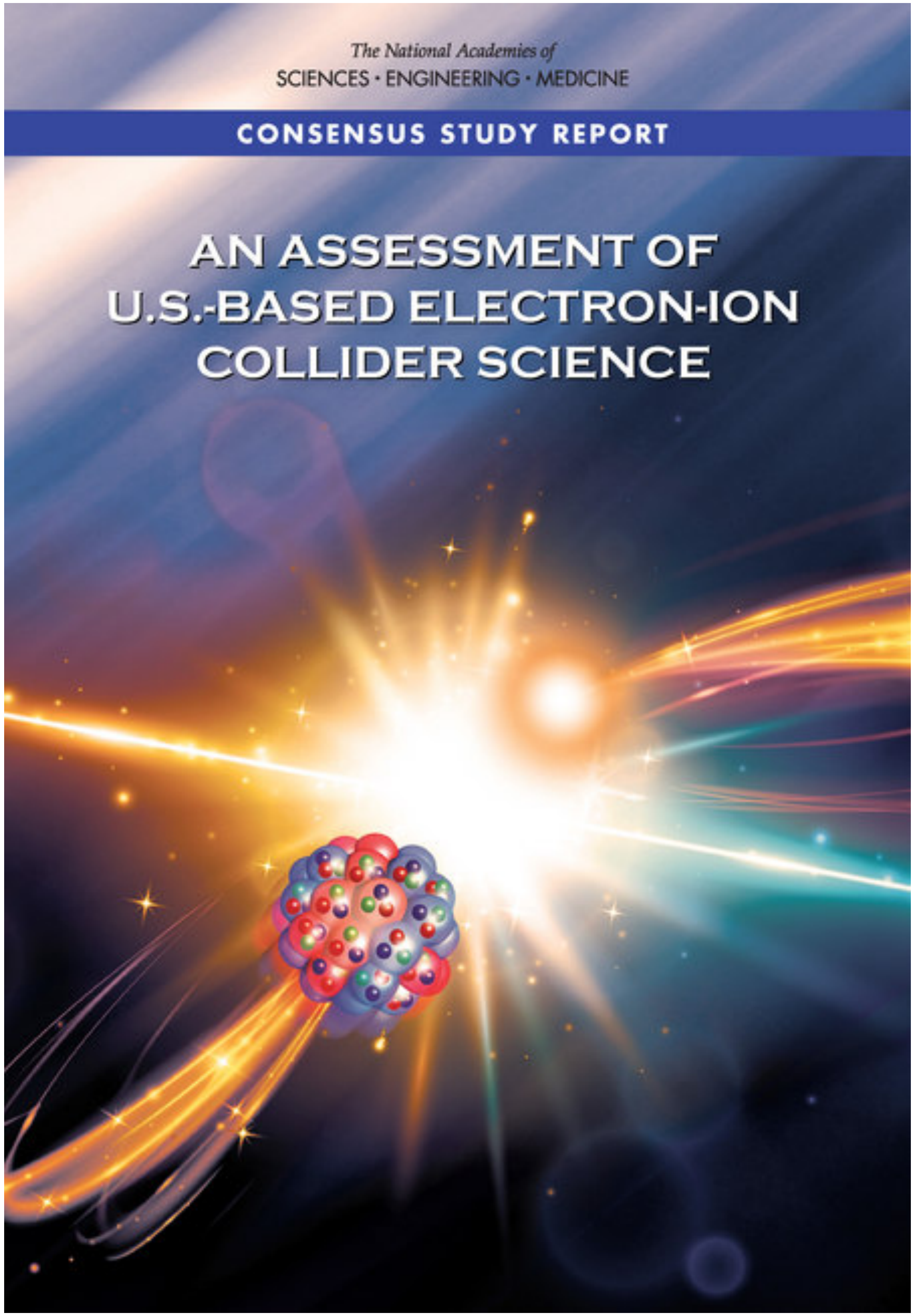
RECOMMENDATION III

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.

Status of U.S.-based EIC



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.

Status of U.S.-based EIC

U.S.-based Electron-Ion Collider is strongly endorsed in the 2015 LRP for Nuclear Physics and, *independently*, the 2018 NAS Science Assessment study.

Both candidate host-laboratories have prepared pre-conceptual facility designs for the U.S. Department of Energy,

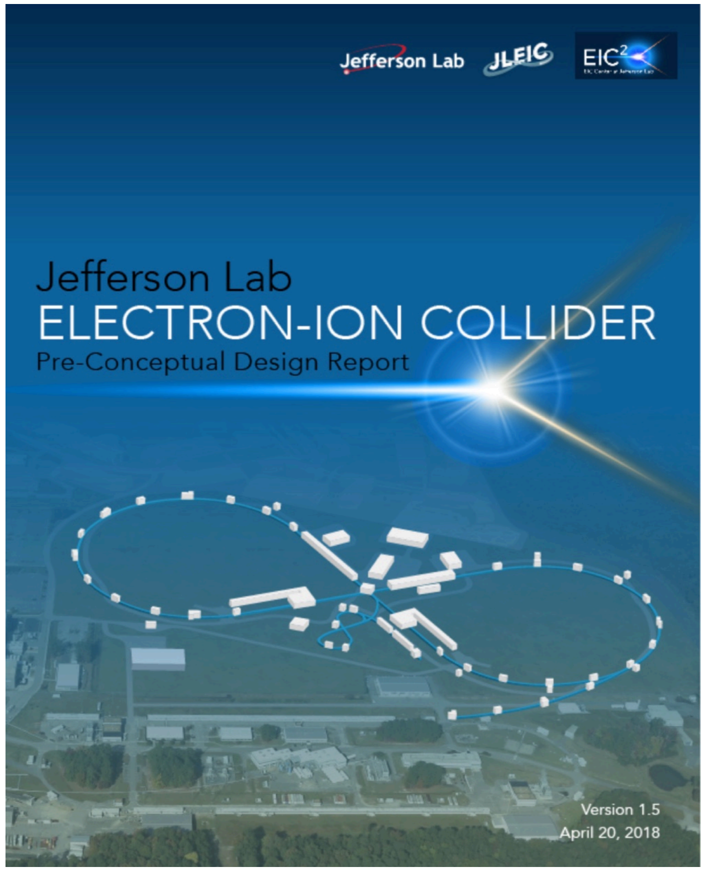
U.S. investment in accelerator-collider R&D for EIC is ramping up; many of the funded proposals are *collaborative,*

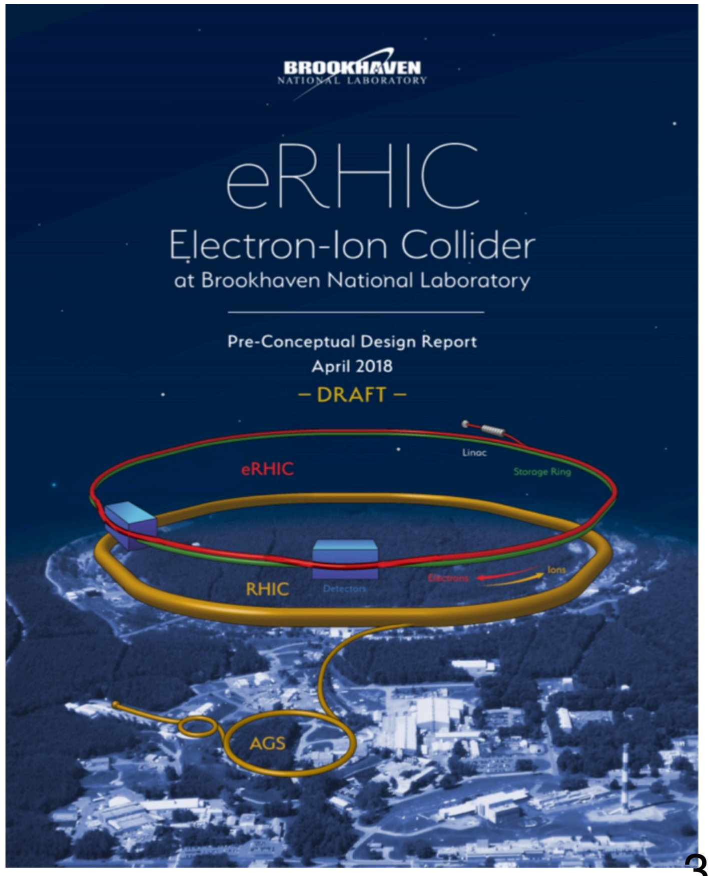
Generic Detector R&D Program continues; open, with (very) limited funds,

Recent program 18-3 by the Institute for Nuclear Theory at the University of Washington to refine the science case,

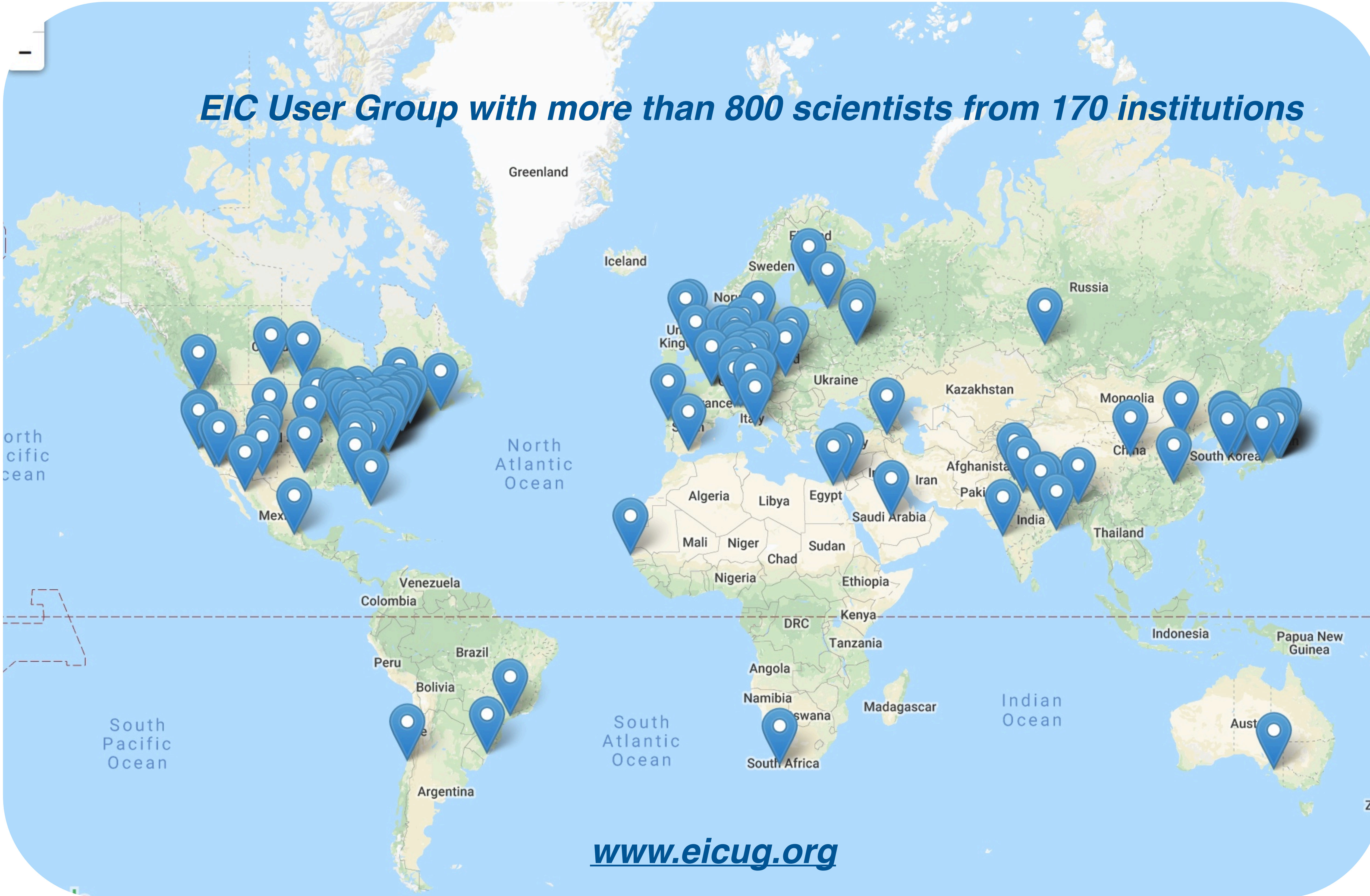
EIC User Group continues to grow and is increasingly active in many areas; theory, experiment, outreach, advocacy…

Looking forward to “Mission Need” or project start this FY.





Status of U.S.-based EIC




EICUG
Electron-Ion Collider User Group Meeting
2019 JULY 22-26
PARIS
École Nationale Supérieure de Chimie
The world's most powerful microscope for studying the "glue" that binds the building blocks of visible matter
International Advisory Committee
Daniël BOER: Groningen
Silvia DALLA TORRE: INFN/Trieste
Abhay DESHPANDE: BNL/Stony Brook
Rolf ENT: JLAB
Yuji GOTO: RIKEN
Tanja HORN: CUA
Charles HYDE: ODU
Richard MILNER: MIT
Carlos MUÑOZ CAMACHO: CNRS/IN2P3
Marco RADICI: INFN/Pavia
Franck SABATIÉ: CEA-Saclay
Andrei SERYI: JLAB
Ernst SICHTERMANN: LBNL
Bernd SURROW: Temple
Thomas ULLRICH: BNL
Ferdinand WILLEKE: BNL
Rikutaro YOSHIDA: JLAB
3D STRUCTURE OF PROTON AND NUCLEI
GLUON SATURATION AND THE COLOR GLASS CONDENSATE
SOLVING THE MYSTERY OF THE PROTON SPIN
QUARK AND GLUON CONFINEMENT
Local Organizing Committee
Francesco BOSSU: CEA-Saclay
Valérie FROIS: CNRS/IN2P3, Secretary
Carlos MUÑOZ CAMACHO: CNRS/IN2P3
Franck SABATIÉ: CEA-Saclay
https://indico.in2p3.fr/event/EICUG2019
cea
Irfu
cnrs
UNIVERSITÉ PARIS SUD
Scan me

Physics **O**pportunities at an **E**lec**T**ron-**I**on **C**ollider IX

Structure of hadrons
QCD at high parton densities
Hadronization and jet properties
Complementarity and connections with topics in Nuclear and High-Energy Physics
Future DIS facilities and developments

Photo courtesy Brocken Inaglory

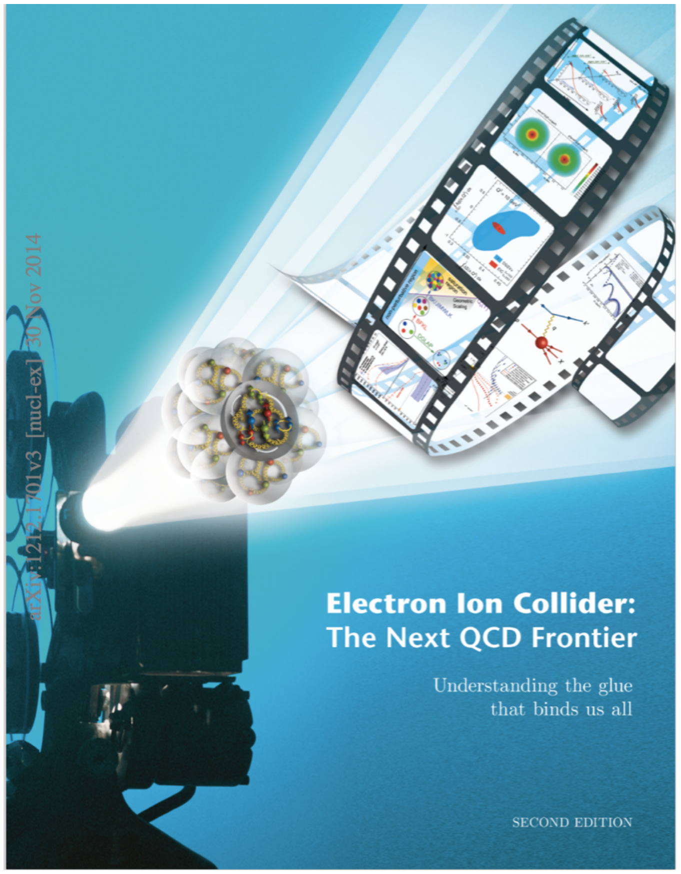
When: September 16-21, 2019, Satellite Meetings Mon-Wed, Workshop Thu-Sat.

Where: Lawrence Berkeley National Laboratory - Berkeley, California, USA
main nearby airport: San Francisco International Airport (SFO)

Contacts: Feng Yuan and Ernst Sichtermann, LOC, IAC

poetic9.lbl.gov

U.S.-based EIC - Closing Comments



Four central themes:

- nucleon spin,
- imaging in nucleon and nuclei,
- gluon-dense matter / saturation,
- hadronization and fragmentation

Synergies with (initial stages of) Heavy-Ion Collisions:

- initial state; nPDFs *and* imaging
- saturation phenomena
- photo-production on nuclei vis-a-vis p+A
- hadronization of probes and their propagation

U.S.-based Electron-Ion Collider is strongly endorsed in the 2015 LRP for Nuclear Physics and, *independently*, the 2018 NAS Science Assessment study,

Science case: theory, experiment, *and* accelerator,

U.S. Department of Energy and both candidate host-laboratories are working together towards realizing the project,

EIC User Group seeks and welcomes collaboration,

Thank you for your attention!