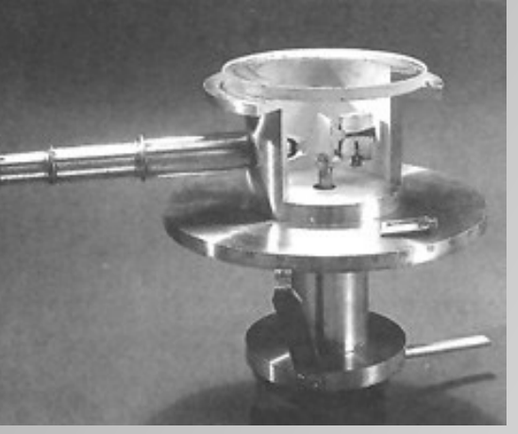
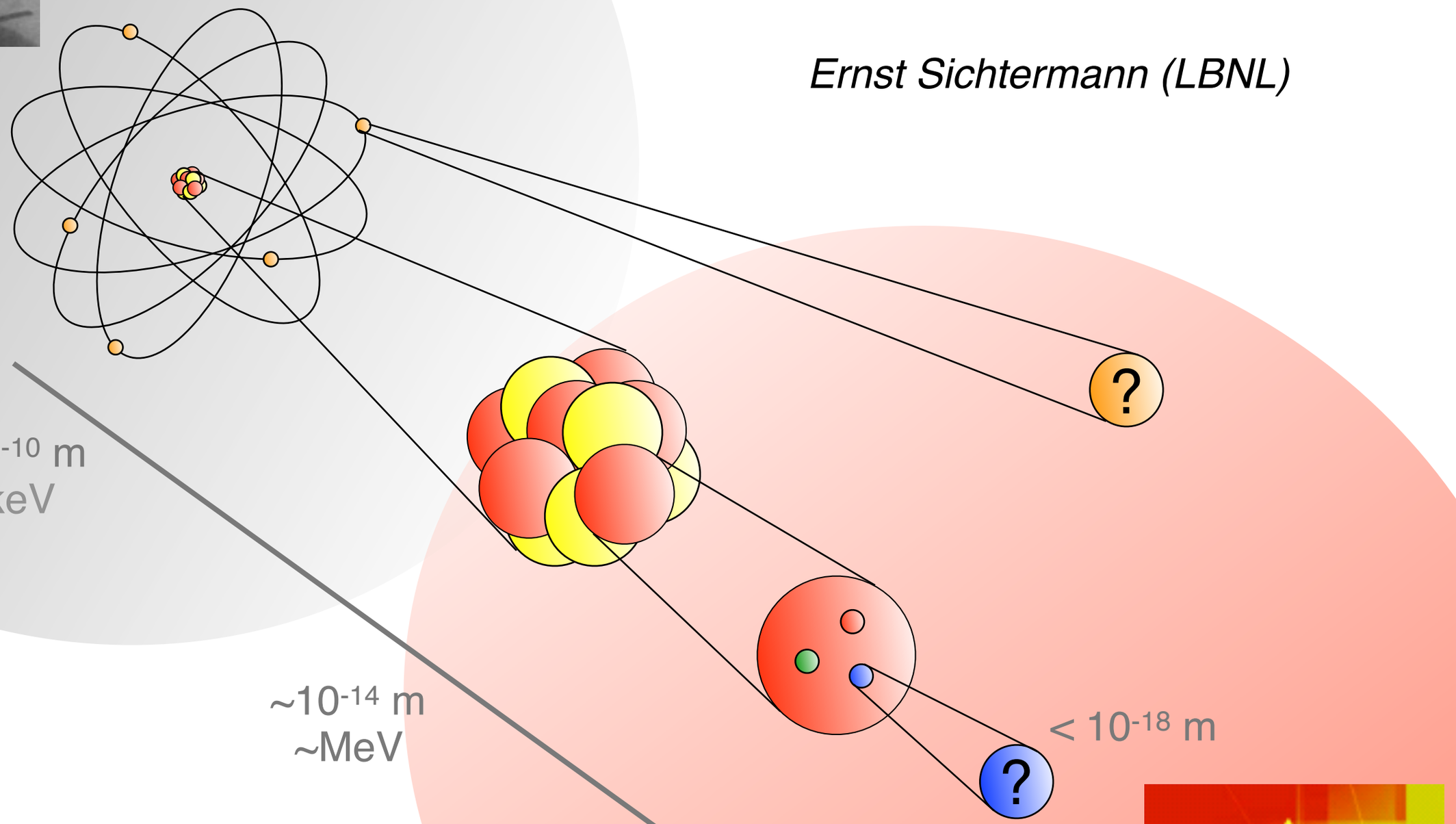


Physics with an Electron-Ion Collider

Ernst Sichtermann (LBNL)



CIPANP- May 31, 2018
Palm Springs, CA

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.

Electron Ion Collider Initiatives

Past

Possible Future

	HERA @ DESY	LHeC @ CERN	HIAF @ CAS	ENC @ GSI	JLEIC @ JLab	eRHIC @ BNL
√s [GeV]	320	800 - 1300	12 - 65	14	20 - 140	78 - 145
proton x_{min}	1×10^{-5}	5×10^{-7}	7×10^{-3} - 3×10^{-4}	5×10^{-3}	1×10^{-4}	5×10^{-5}
ion	p	p to Pb	p to U	p to ~^{40}Ca	p to Pb	p to U
polarization	-	-	p, d, ^{3}He	p, d	p, d, ^{3}He (^{6}Li)	p, ^{3}He
L [$cm^{-2}s^{-1}$]	2×10^{31}	10^{34}	$10^{32\text{-}33}$ - 10^{35}	10^{32}	$10^{33\text{-}34}$	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

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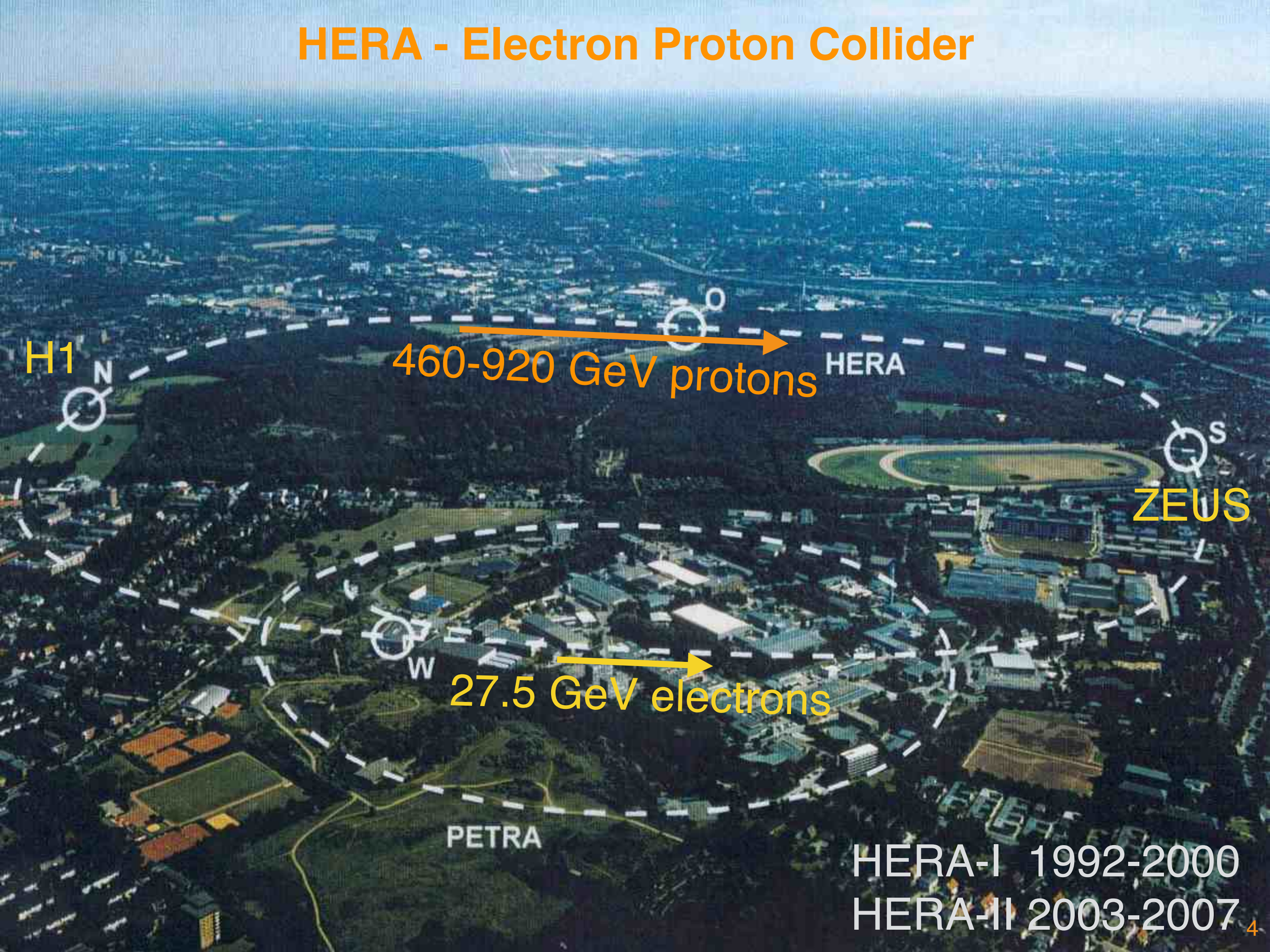
High-Energy Physics

Nuclear Physics

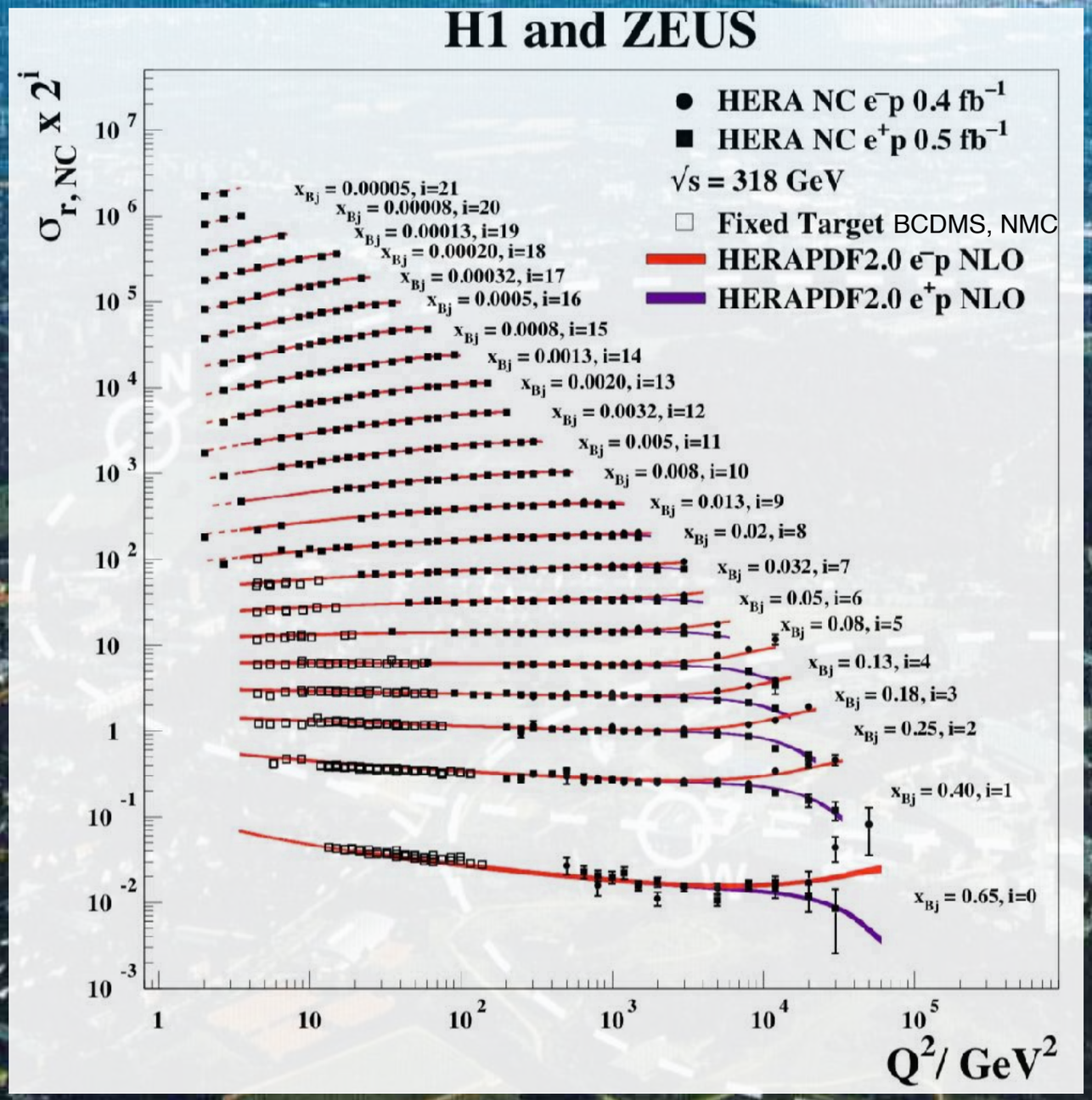
World Wide Interest

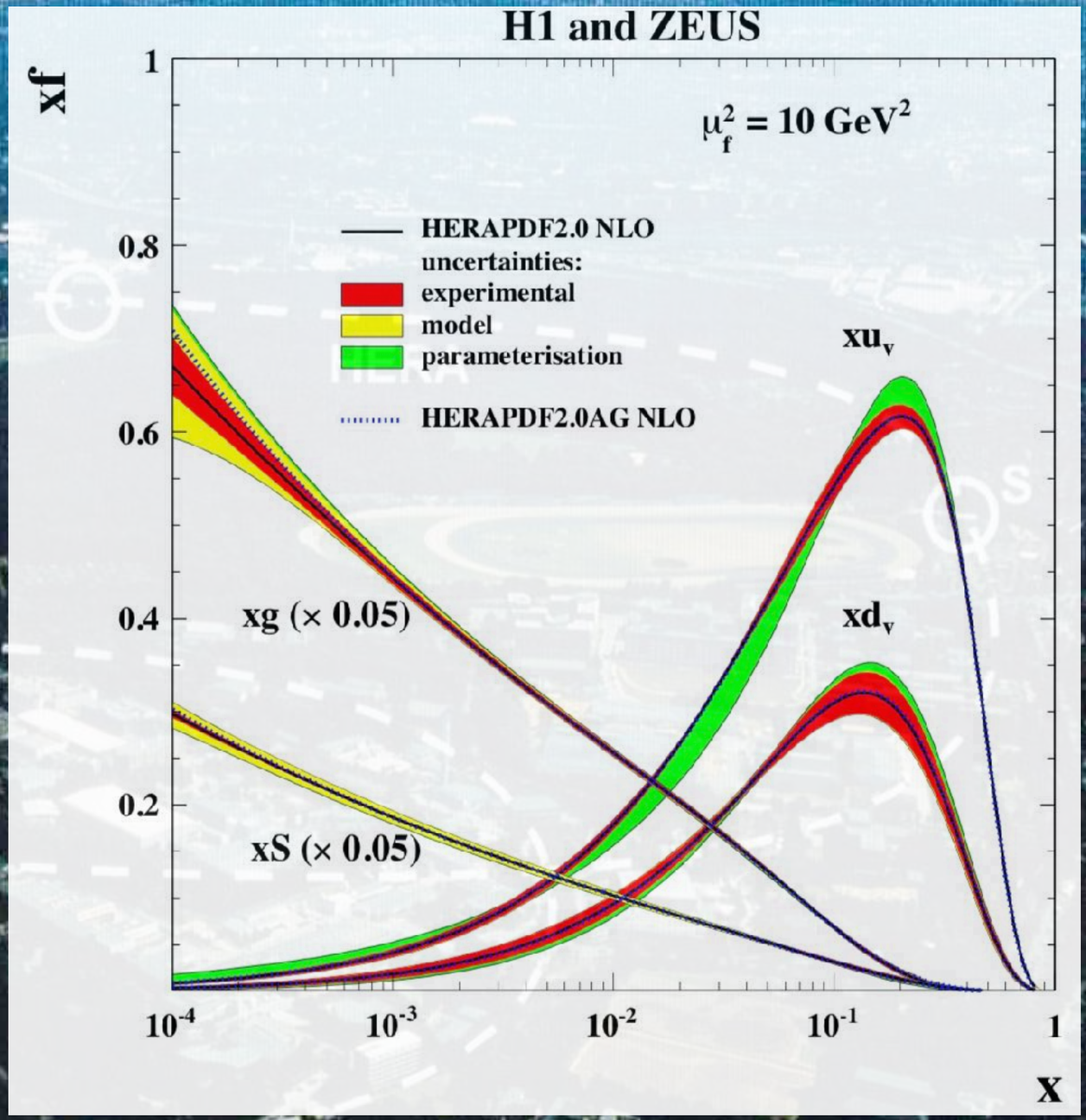
HERA - Electron Proton Collider



HERA's Legacy

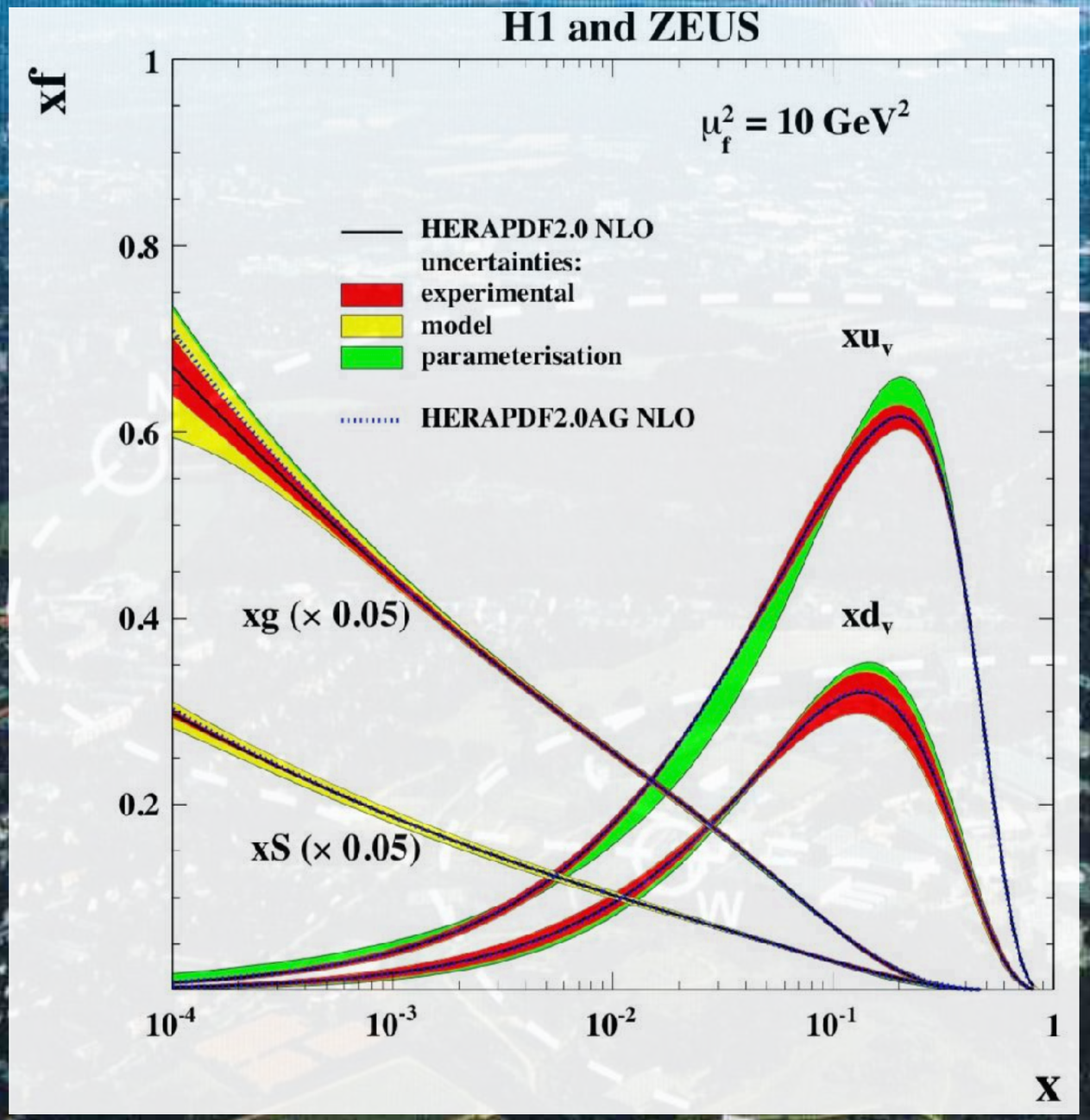
H1 and ZEUS Coll., EPJ C75 (2015) 580





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

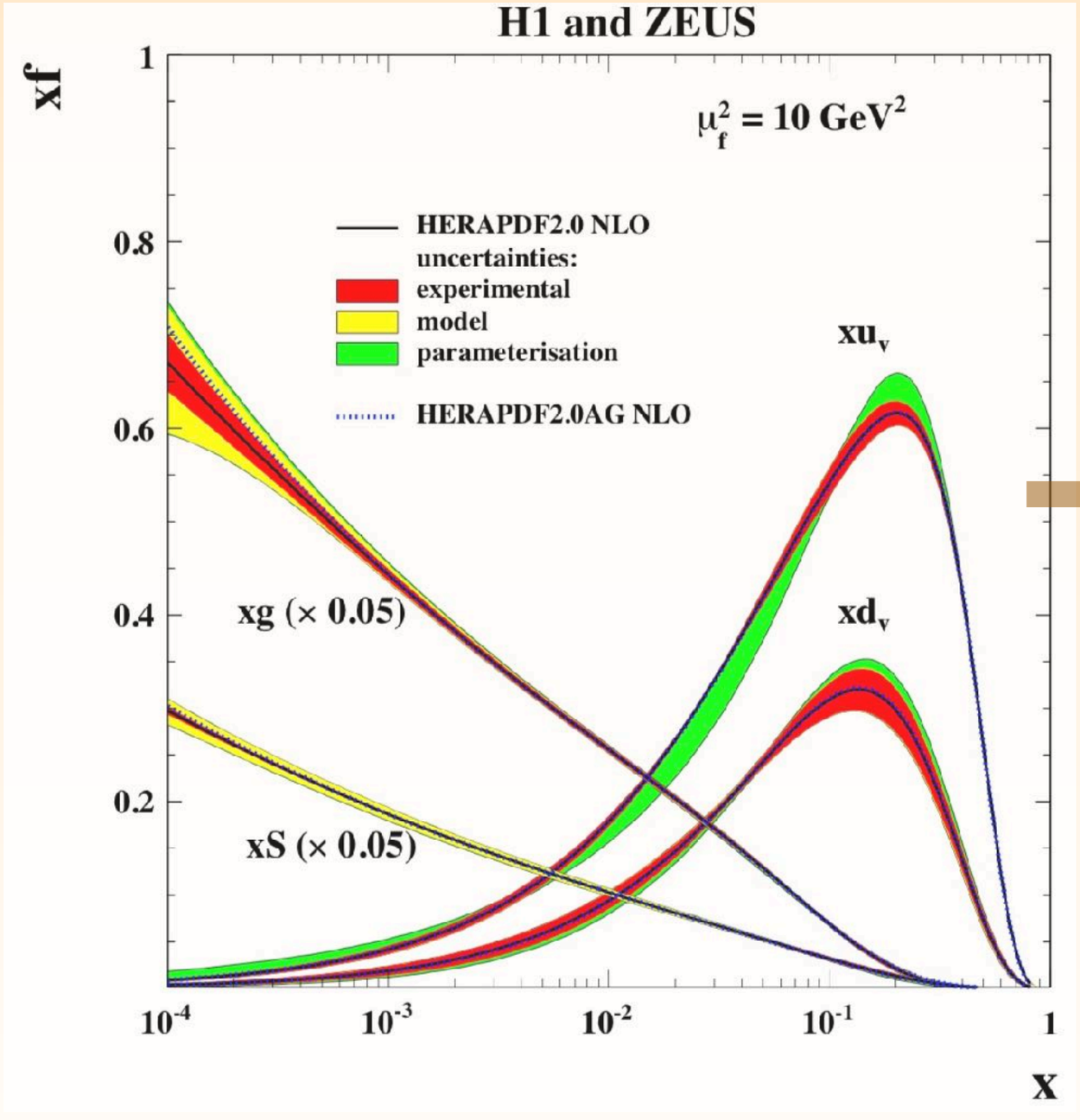
HERAPDF2.0:

14 parameters,

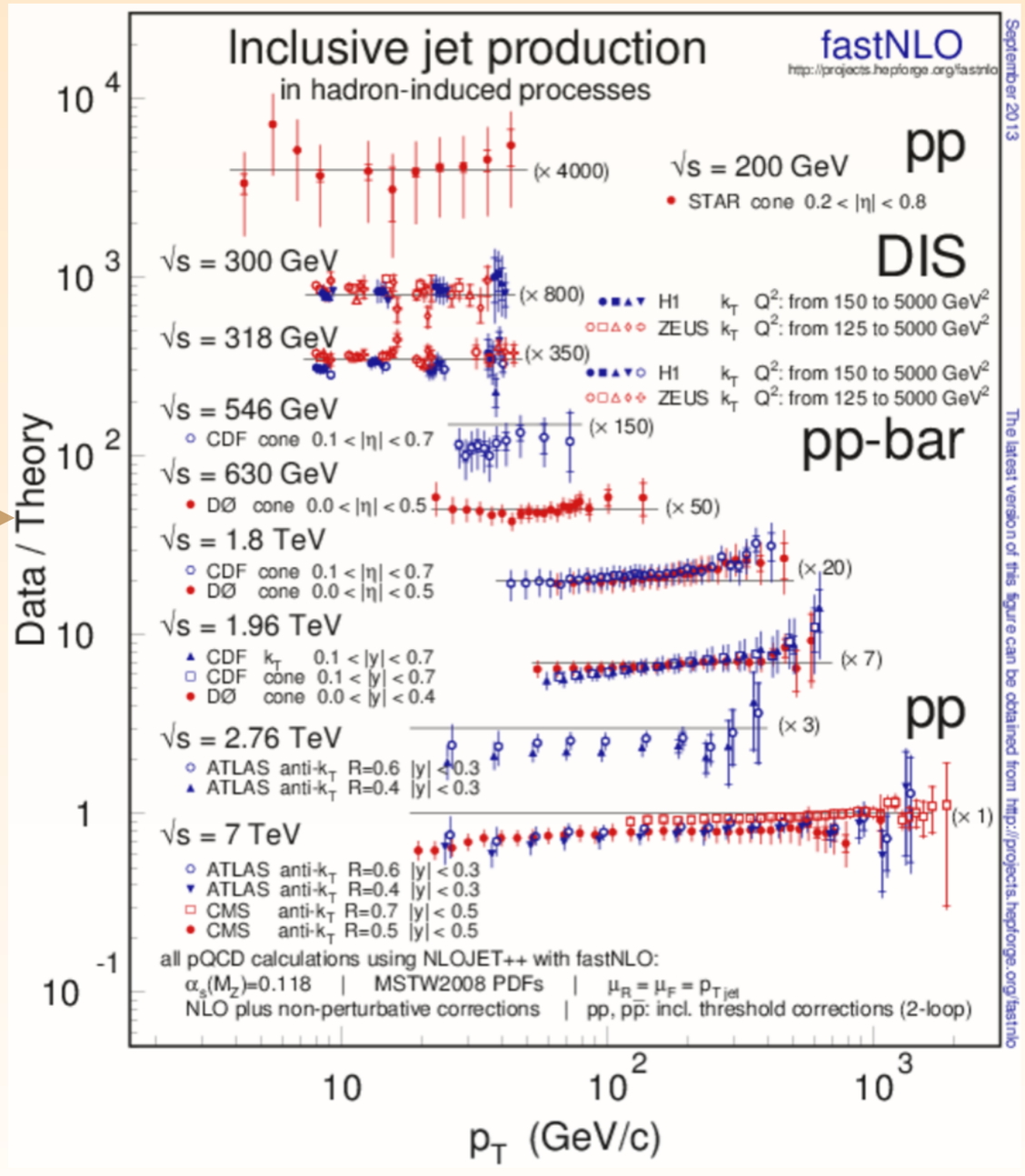
~1400 combined data points,

HERA's Legacy

The proton in terms of gluons and quarks



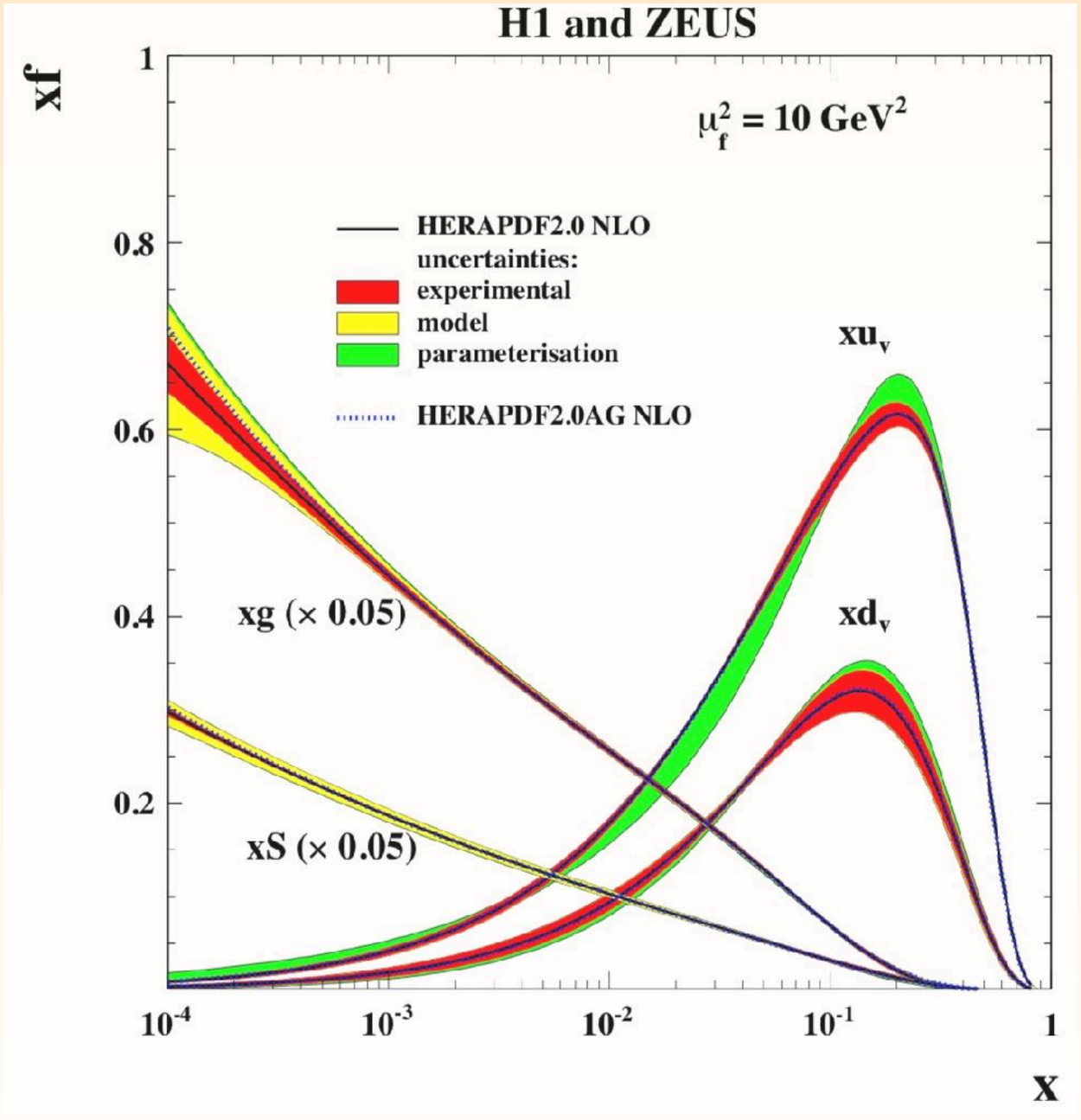
pQCD at work...



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 √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

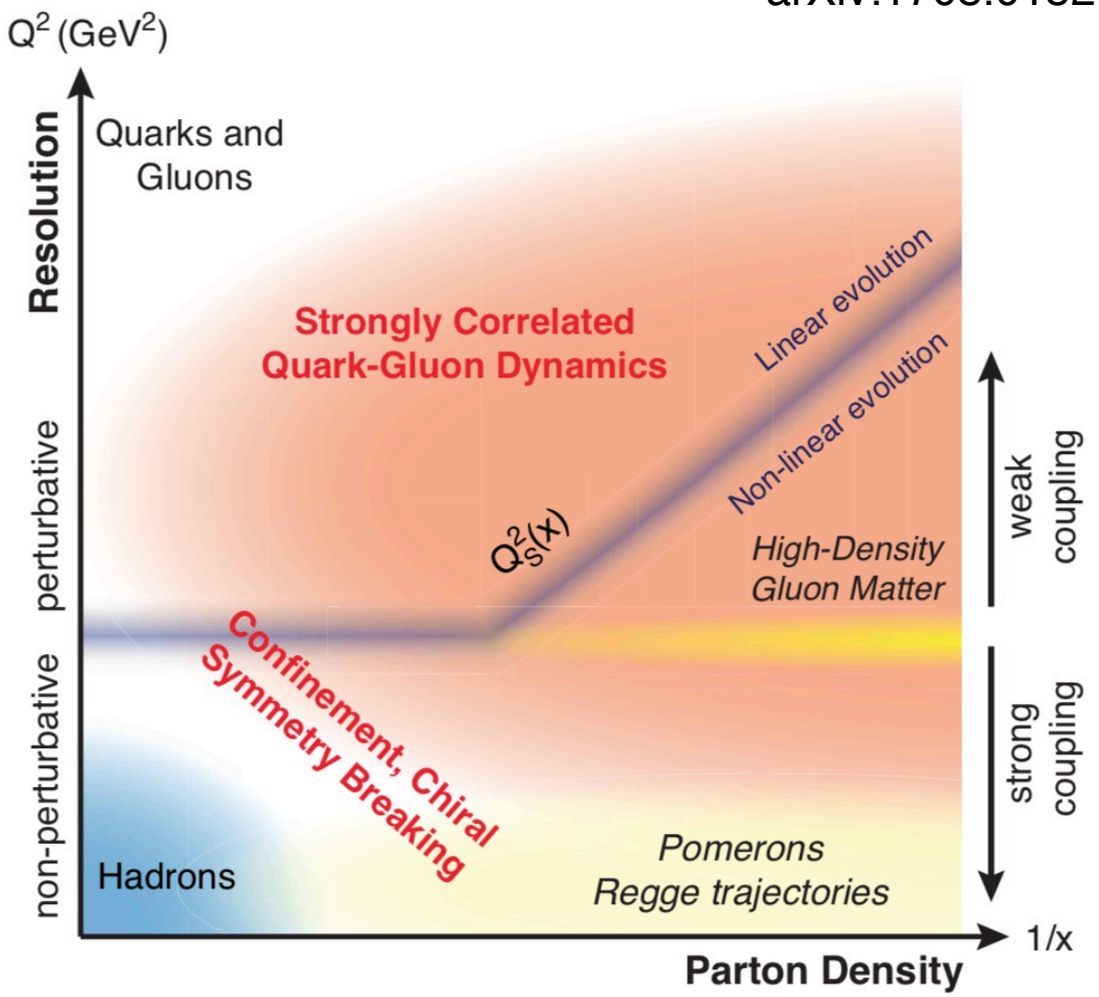
Really? ***More than a few of our high-energy observations are actually different***
Essential to separate intrinsic structure from interaction dynamics,
push the envelope beyond the theoretically established,
obtain meaningful accuracy.

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)

arXiv:1708.01527



HERA - RHIC

Saturation:

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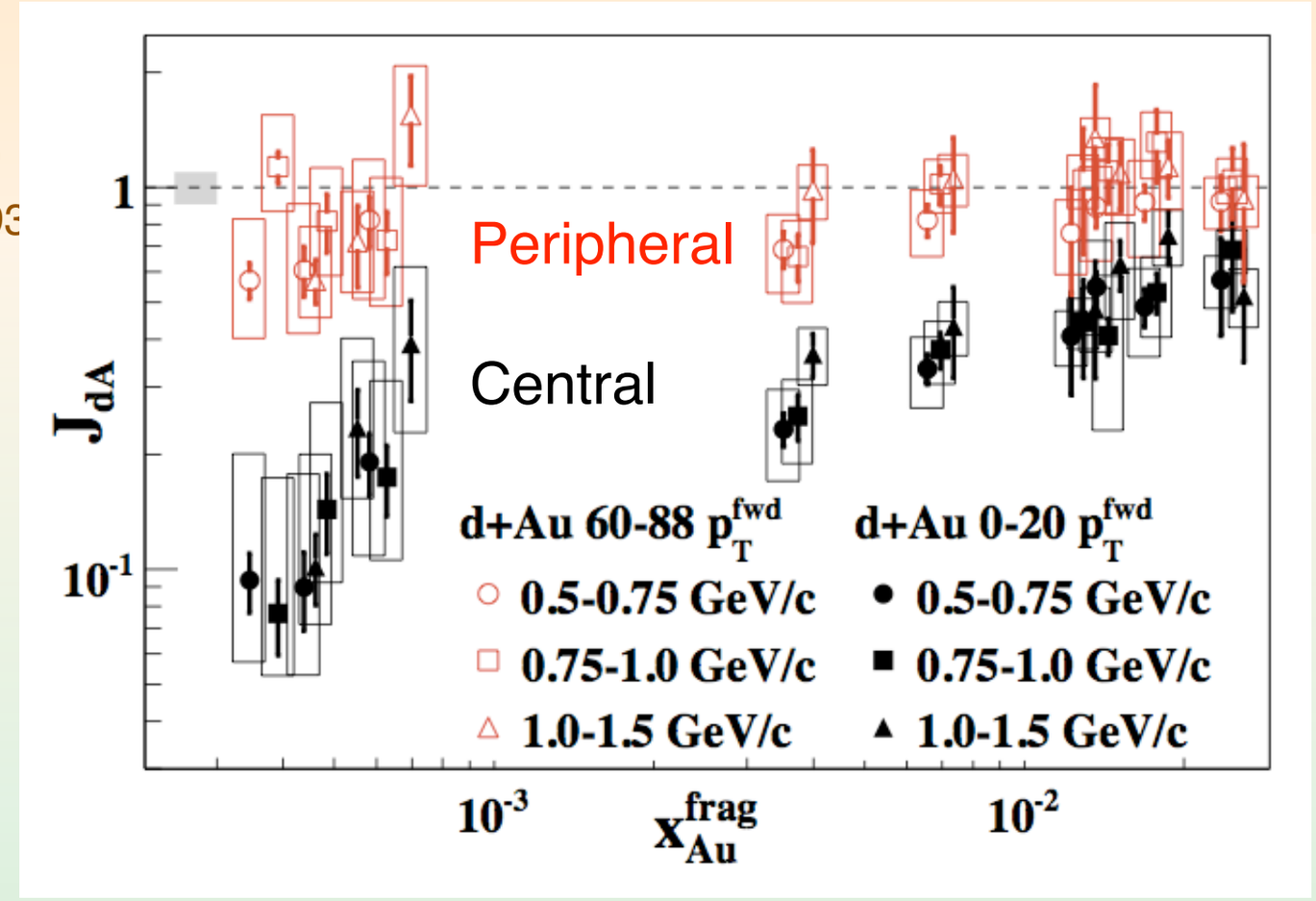
- forward multiplicities and correlations at RHIC,

Forward-Forward Mid-forward correlation



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

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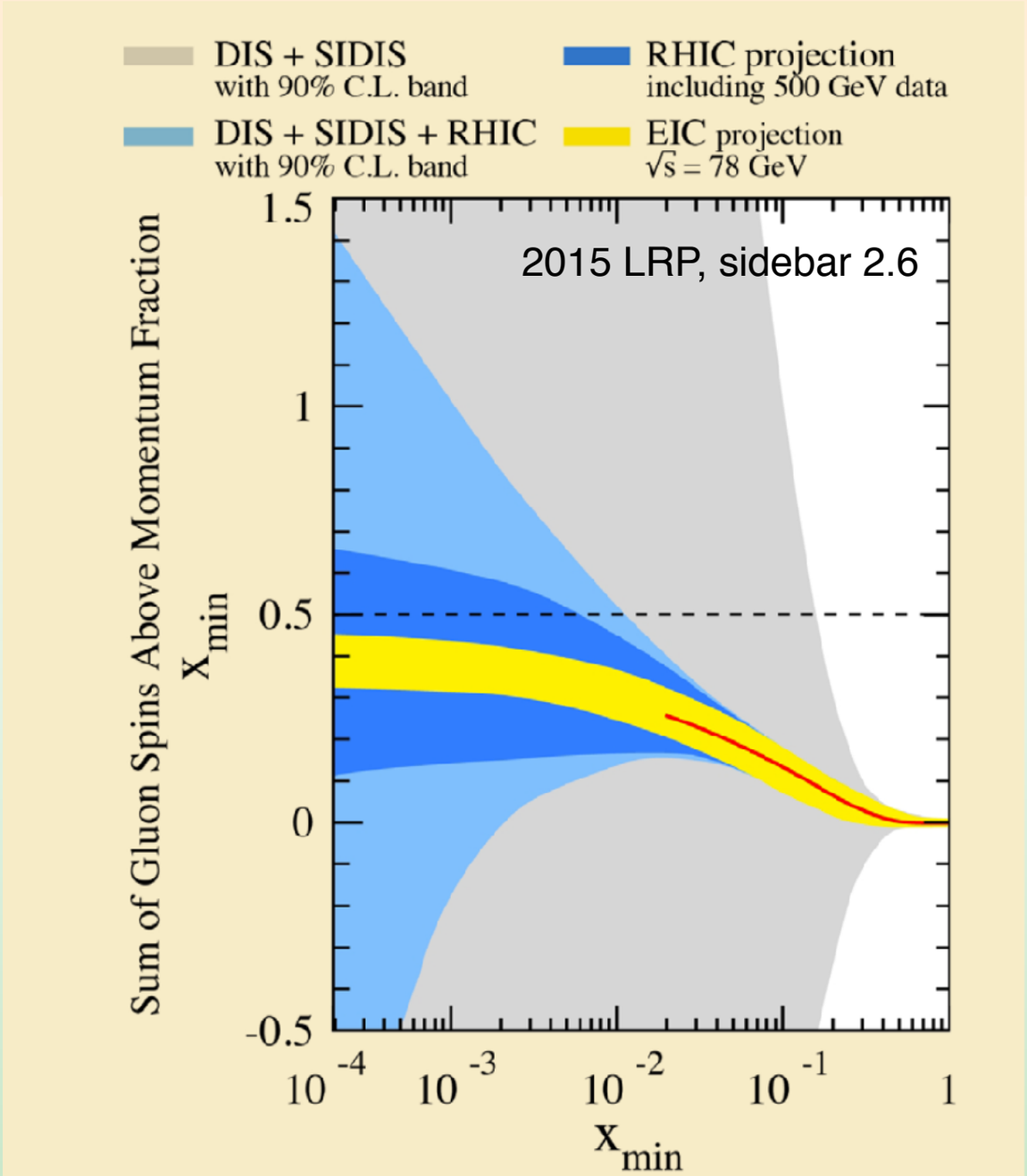
Spin puzzle:

- 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

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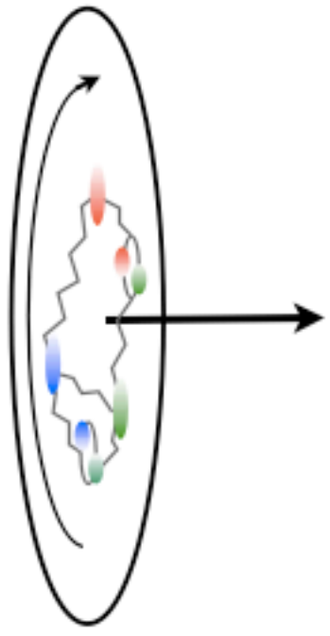

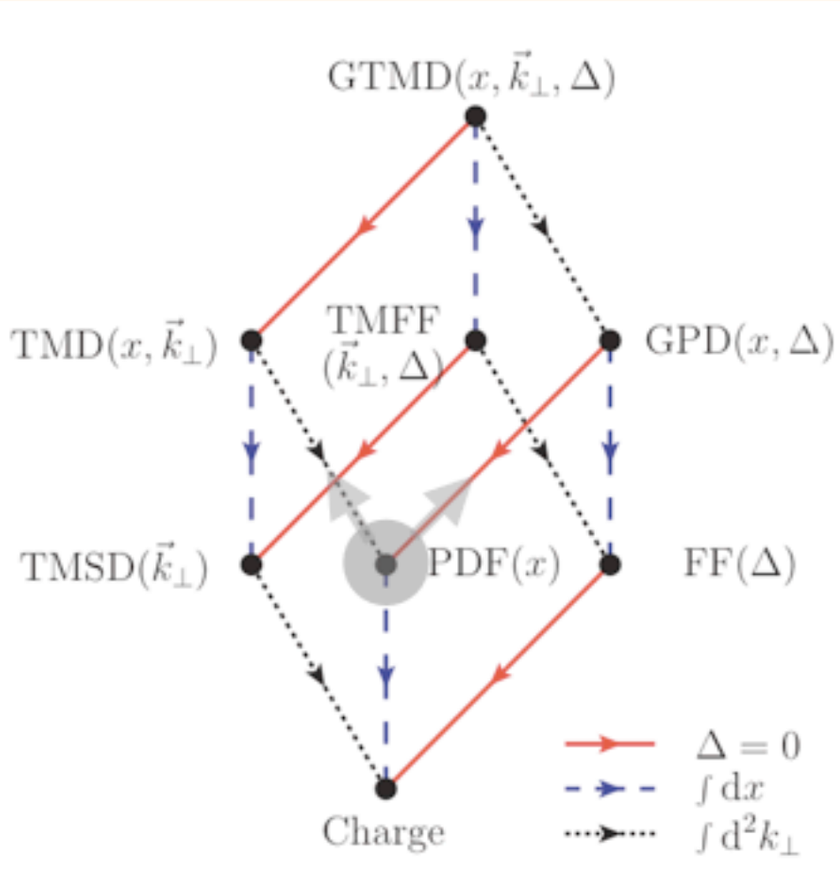

Lorce, Pasquini, Vanderhaeghen

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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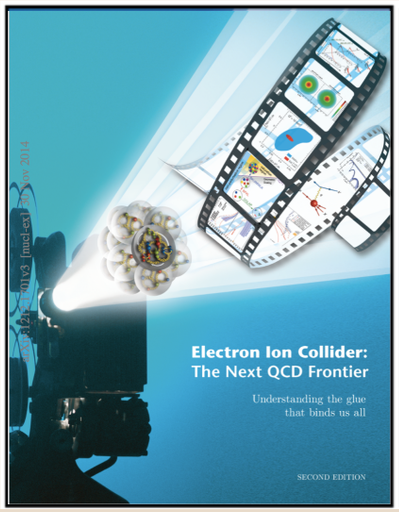
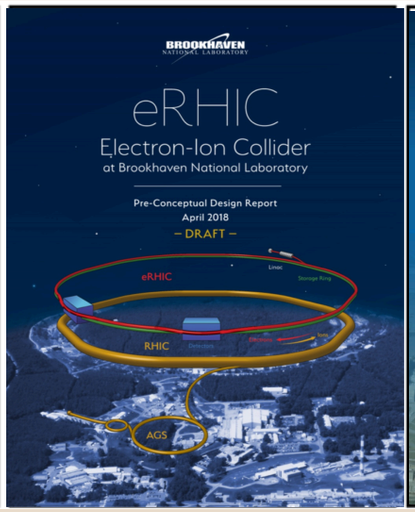
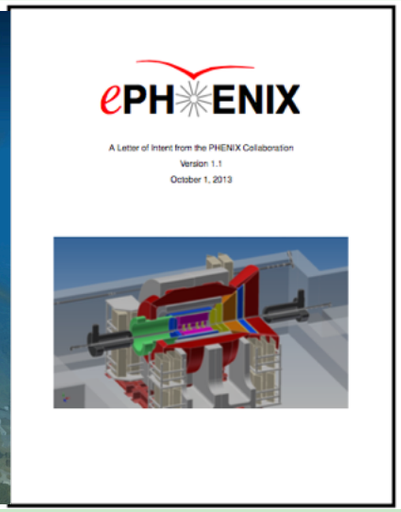
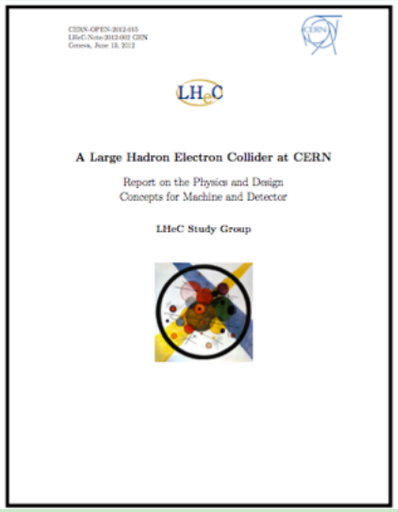
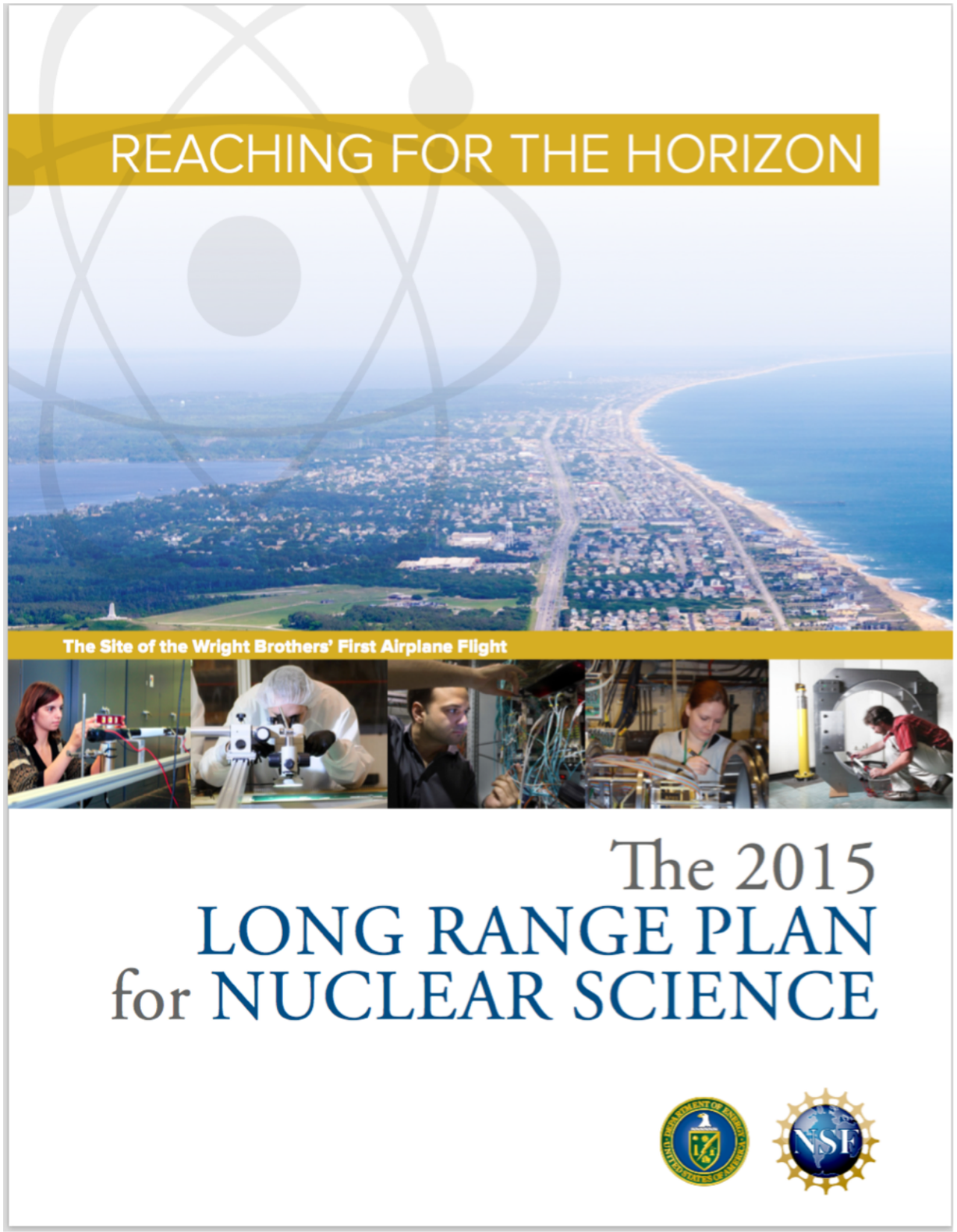








U.S.-based EIC - Context



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.

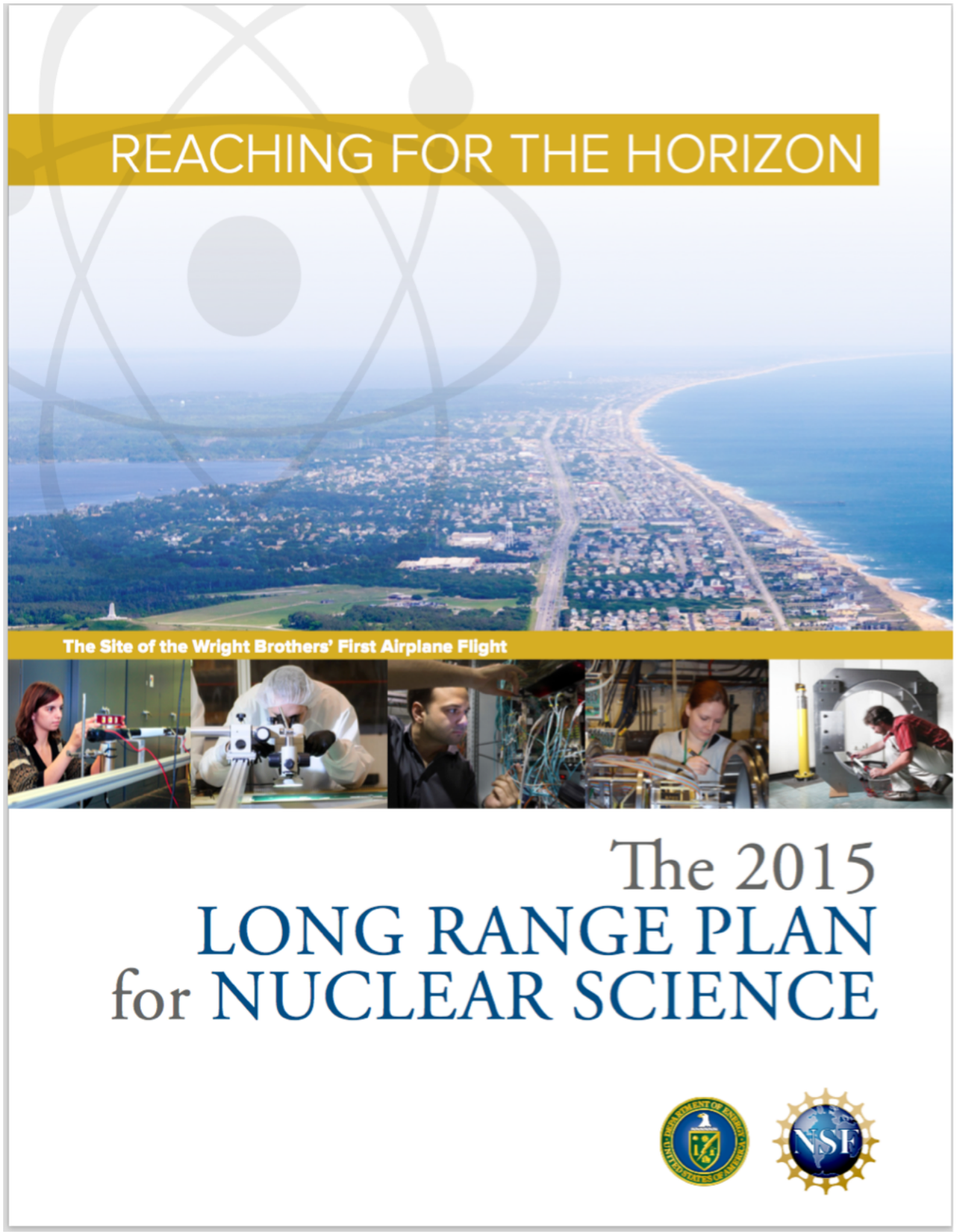
RECOMMENDATION III

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.

U.S.-based EIC - Context



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Independent NAS science assessment being finalized.

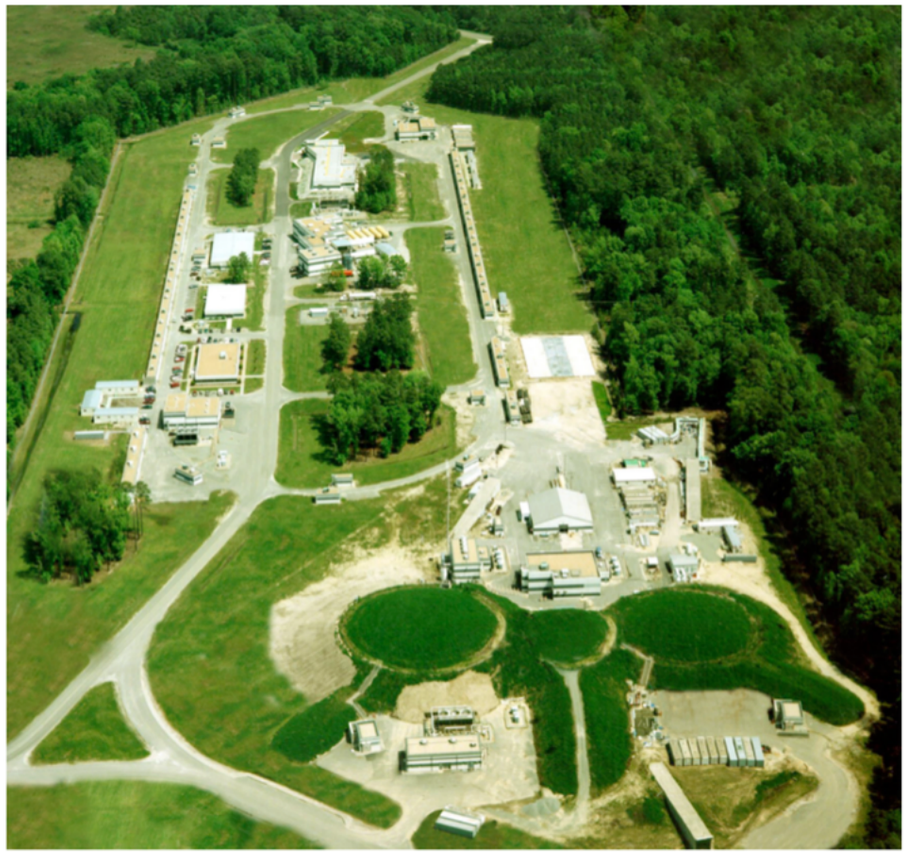
U.S.-based EIC - Two Facility Concepts

eRHIC:

- upgrade to existing RHIC hadron beam,

JLEIC:

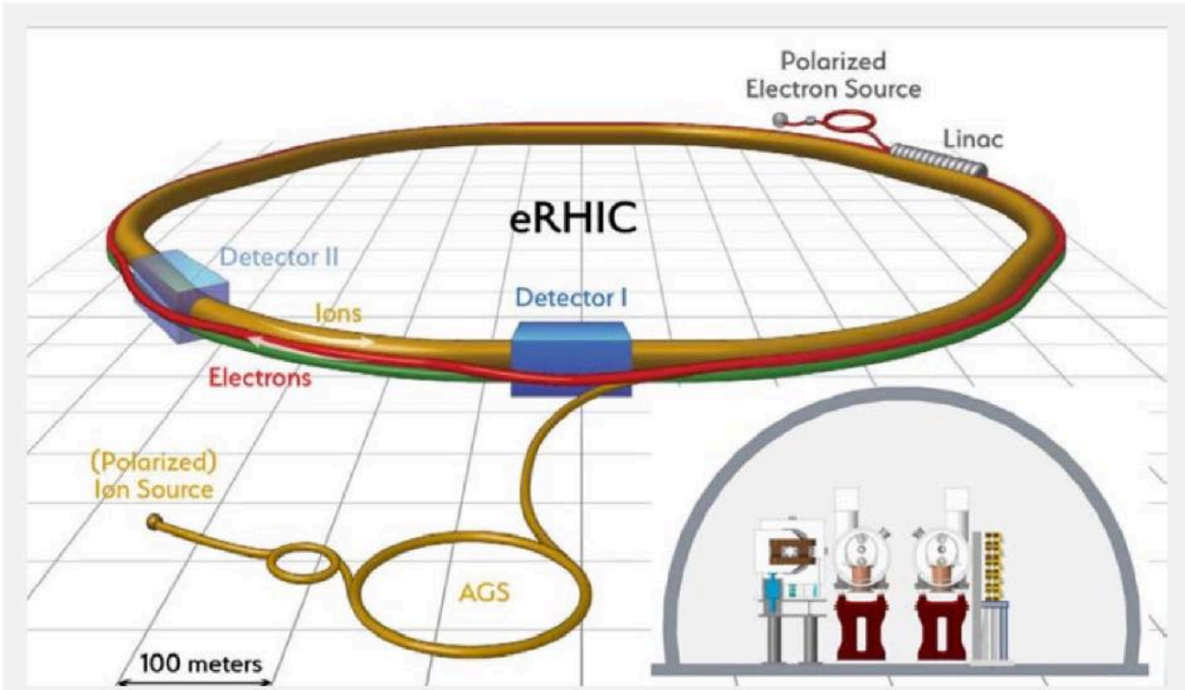
- upgrade to existing CEBAF 12 GeV electron beam,



U.S.-based EIC - Two Facility Concepts

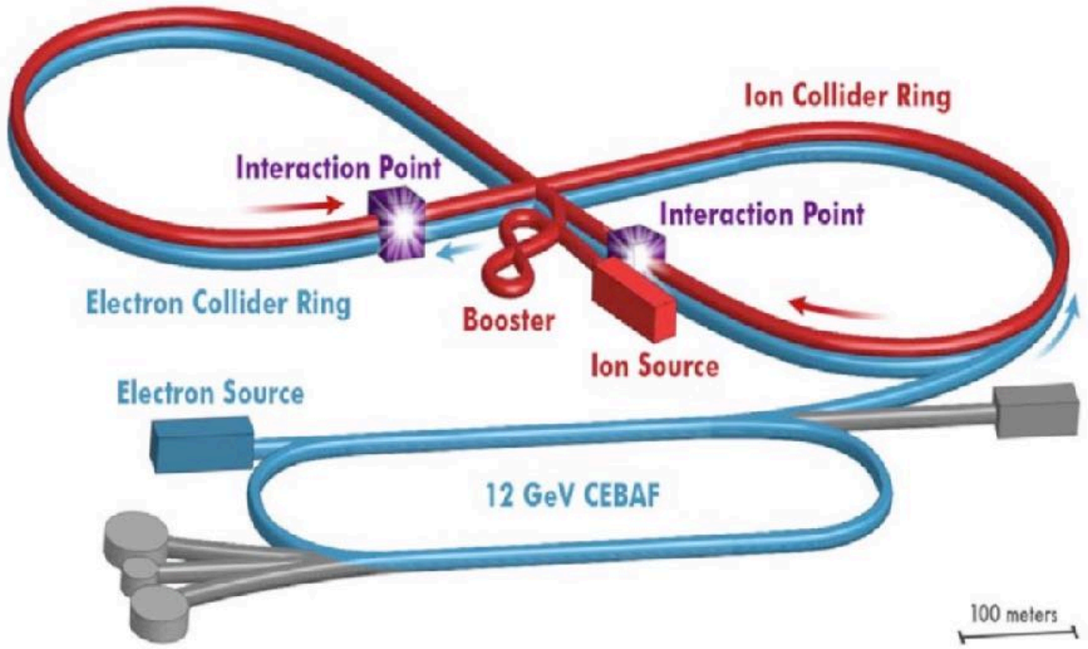
eRHIC:

- upgrade to RHIC hadron beam,
- new electron storage ring,
- 5 - 18 GeV e energy,
- Heavy Ions up to 100 GeV/u
- √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:

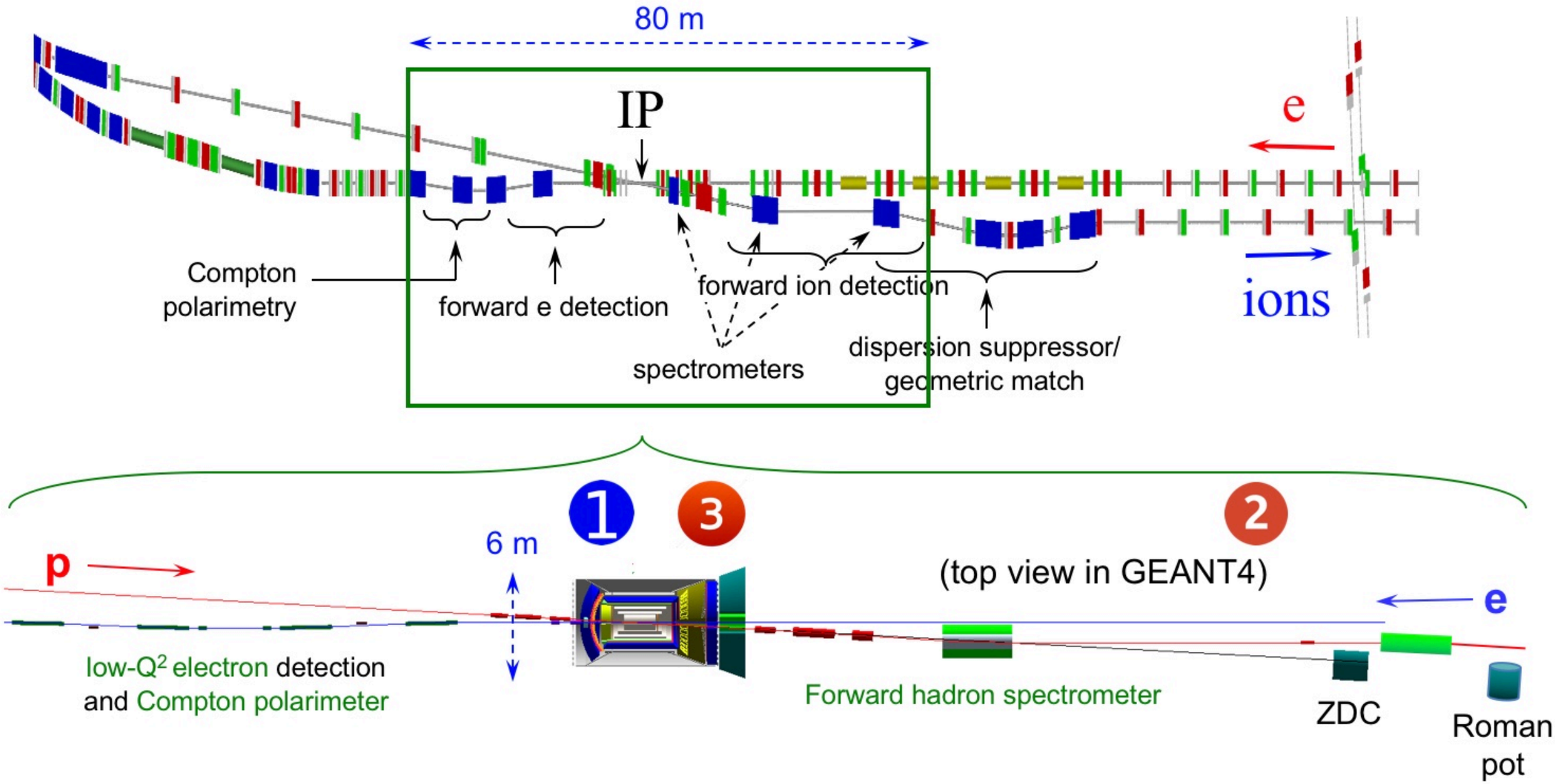
- upgrade to CEBAF 12 GeV electron beam facility,
- new hadron injector,
- new figure-8 collider configuration,
- 3-10 GeV electron energy,
- 12-40 GeV/u Heavy Ion energy, upgradable (ion arc dipole)
- L ~10^{34} $cm^{-2}s^{-1}$/A



Science cases by themselves!

U.S.-based EIC - Two Facility Concepts

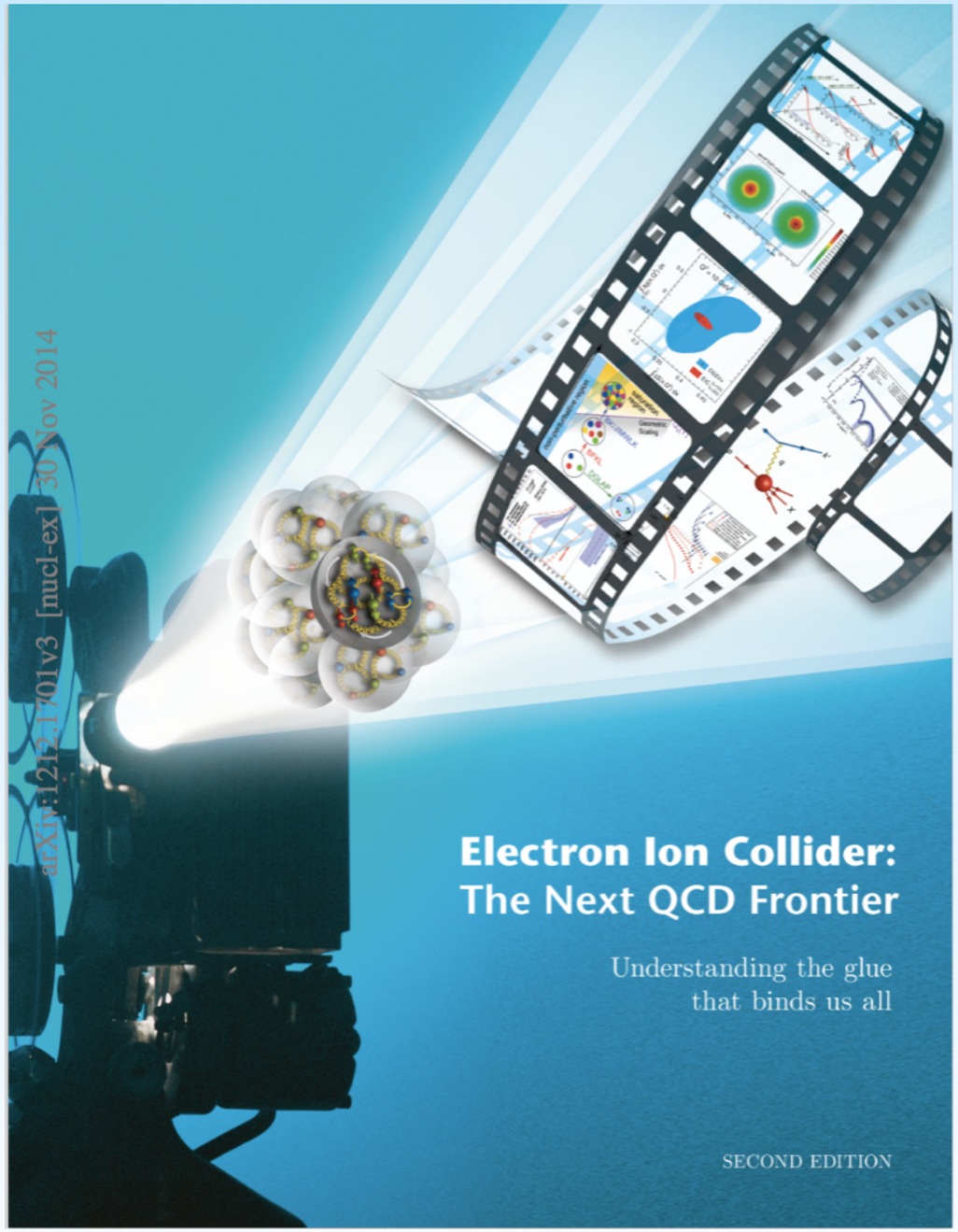
Science cases by themselves requiring, for example, tight integration with detectors



courtesy V. Morozov (JLab)

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

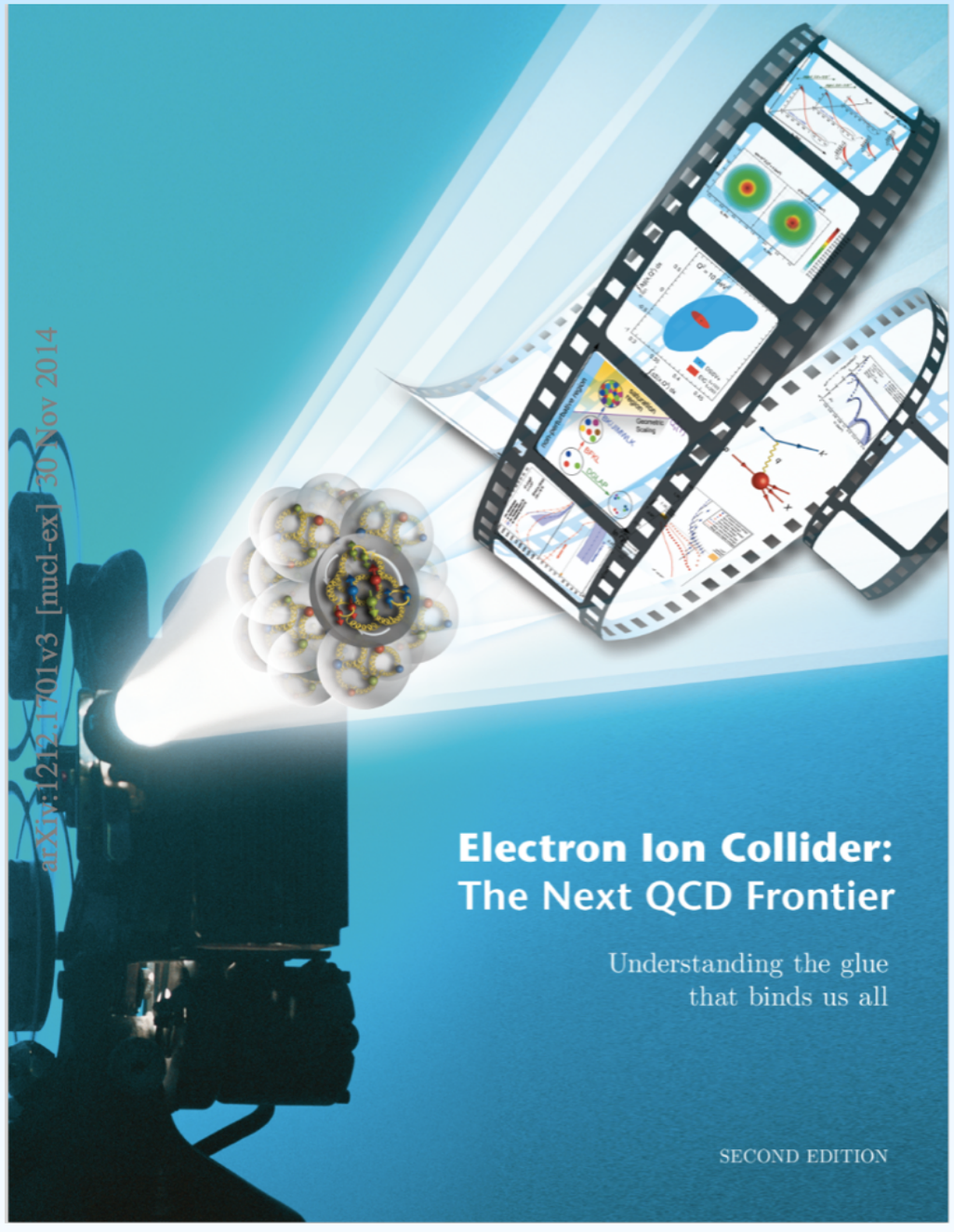
U.S. EIC Capabilities



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



- *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?*

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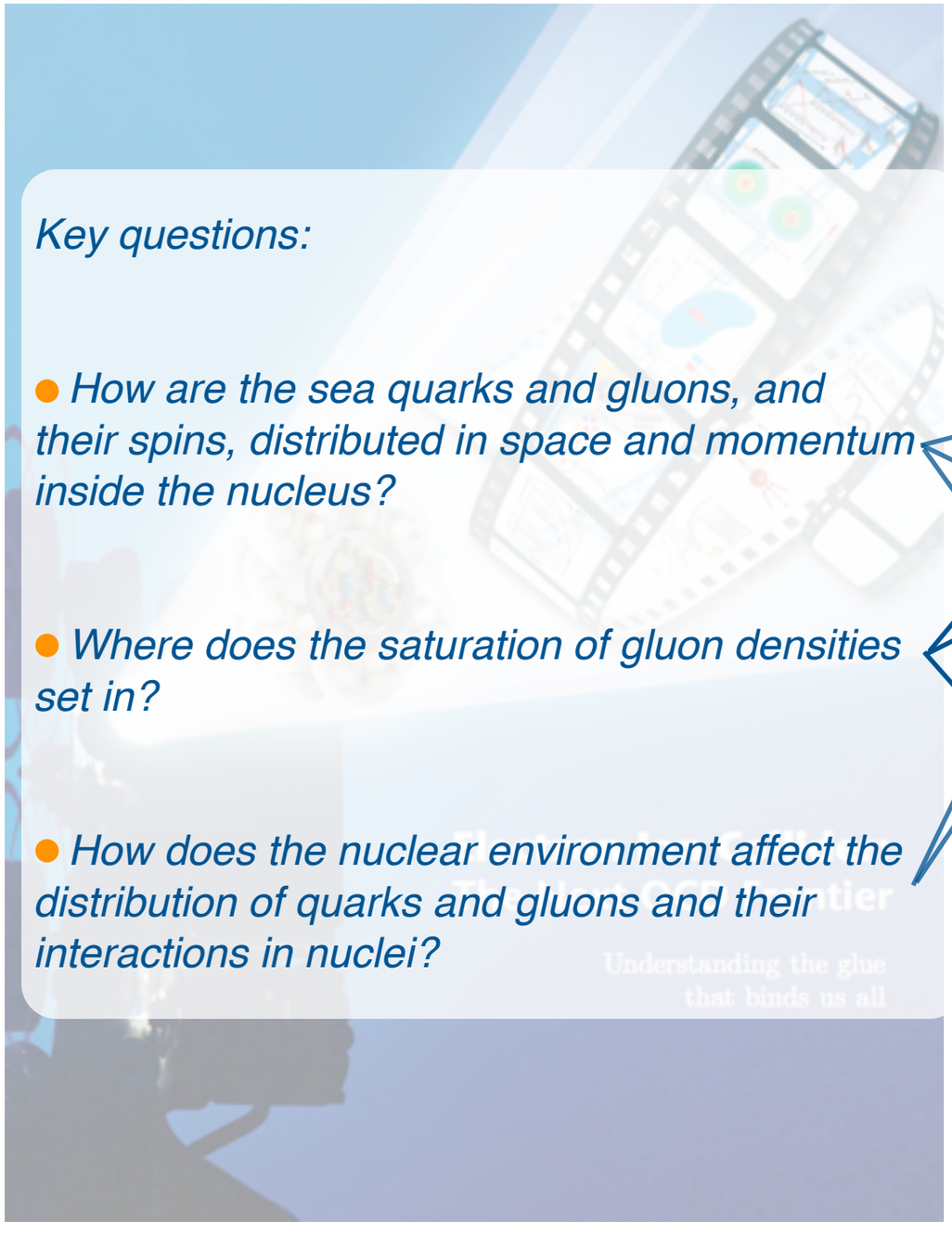
See also arXiv:1708.01527

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.*

U.S.-based EIC - Observables

Key requirements:

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

Key measurements:

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U.S.-based EIC - Detector Concepts

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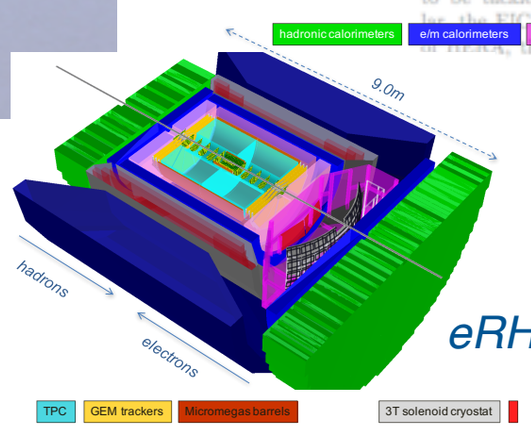
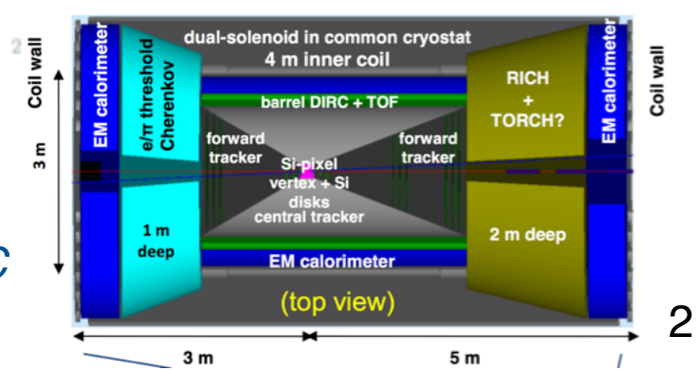
Green-field detector concepts:

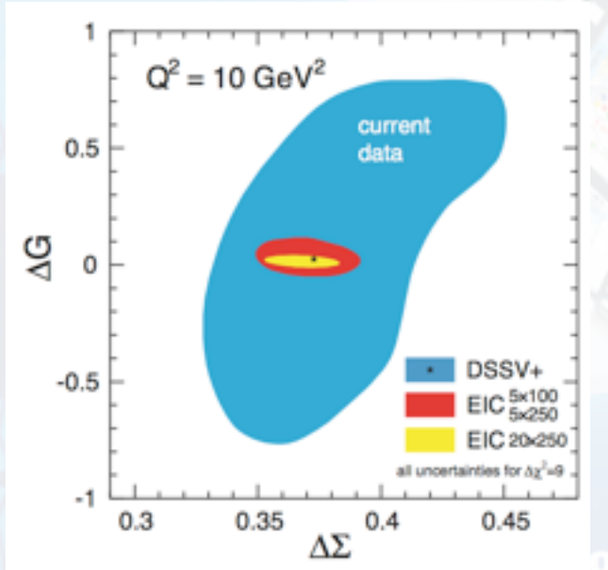


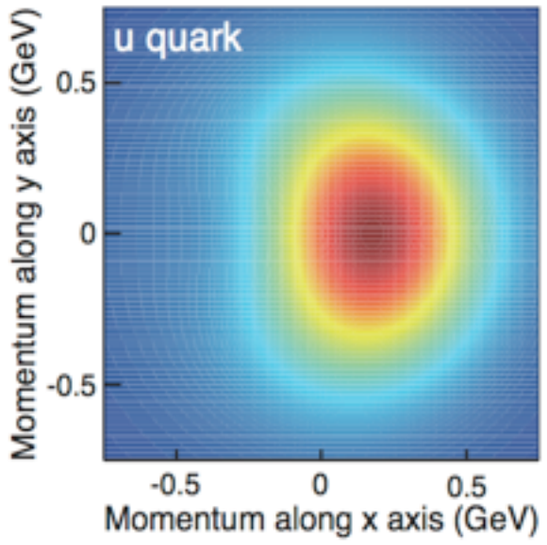
eRHIC

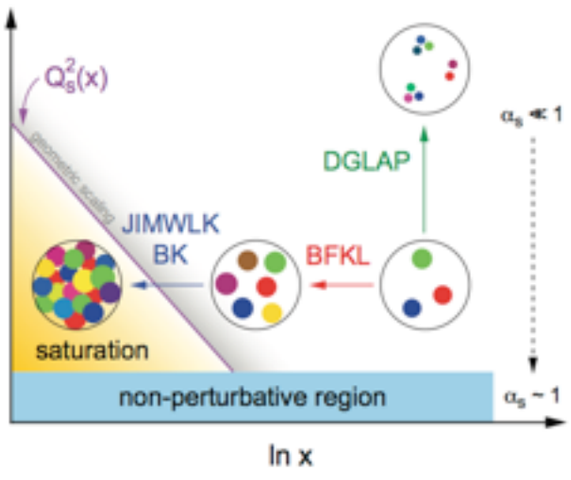
JLEIC

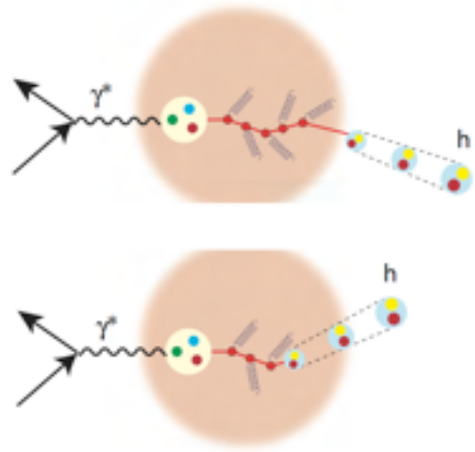


U.S.-based EIC - Core Science





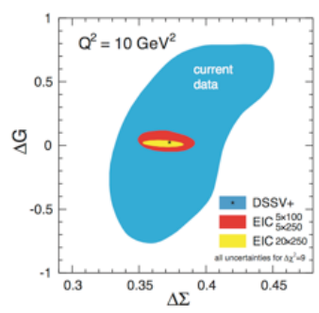




Nuclear Physics enabled by EIC **beam** energy, intensity, polarization, and species, **detector** capabilities,

Theory

U.S.-based EIC - Proton Spin



Current polarized DIS data:

○ CERN △ DESY ◊ JLab □ SLAC

Current polarized BNL-RHIC pp data:

● PHENIX π^0 ▲ STAR 1-jet

EIC √s= 140 GeV, 0.01≤ y ≤ 0.95

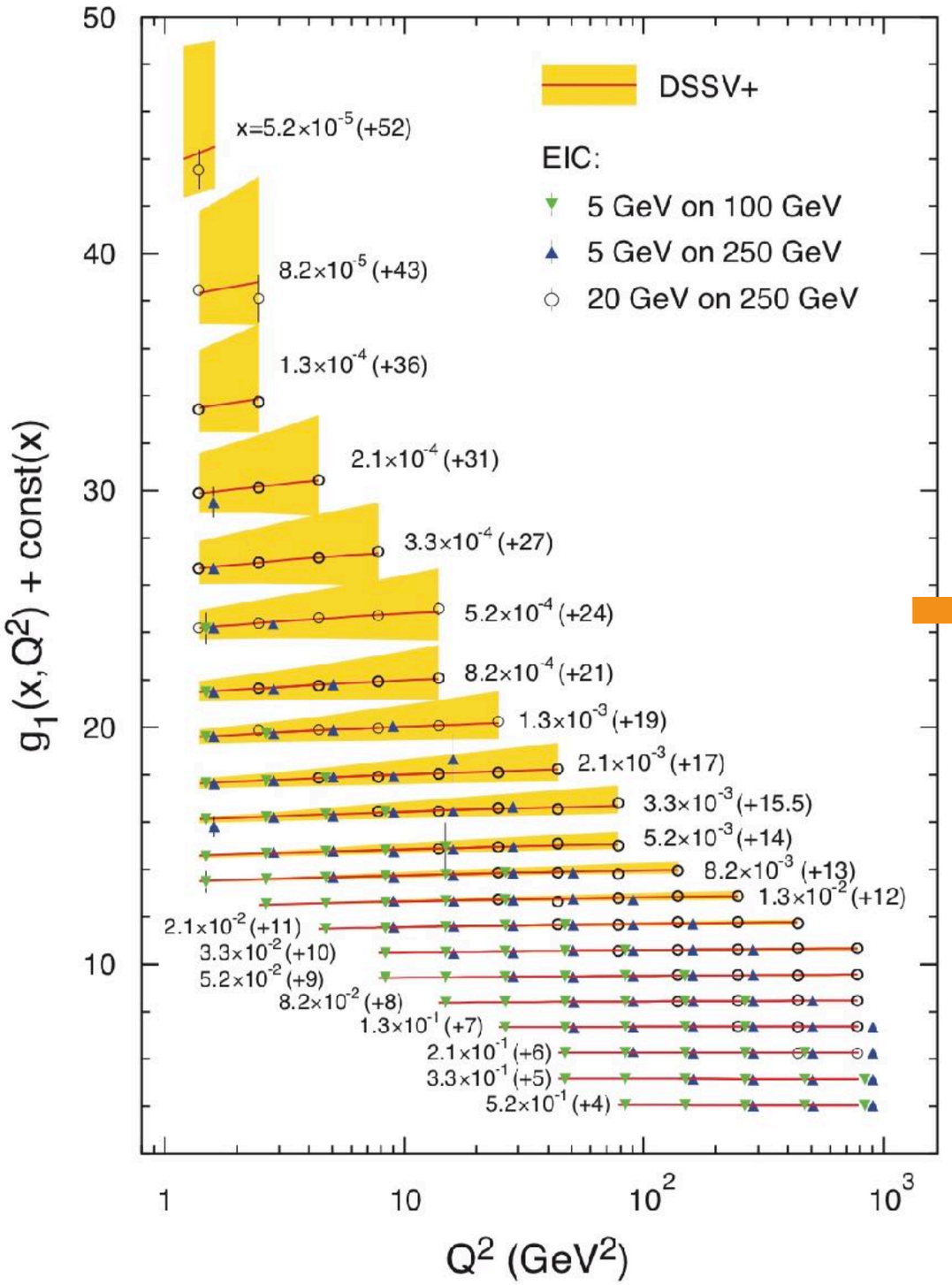
EIC √s= 45 GeV, 0.01≤ y ≤ 0.95

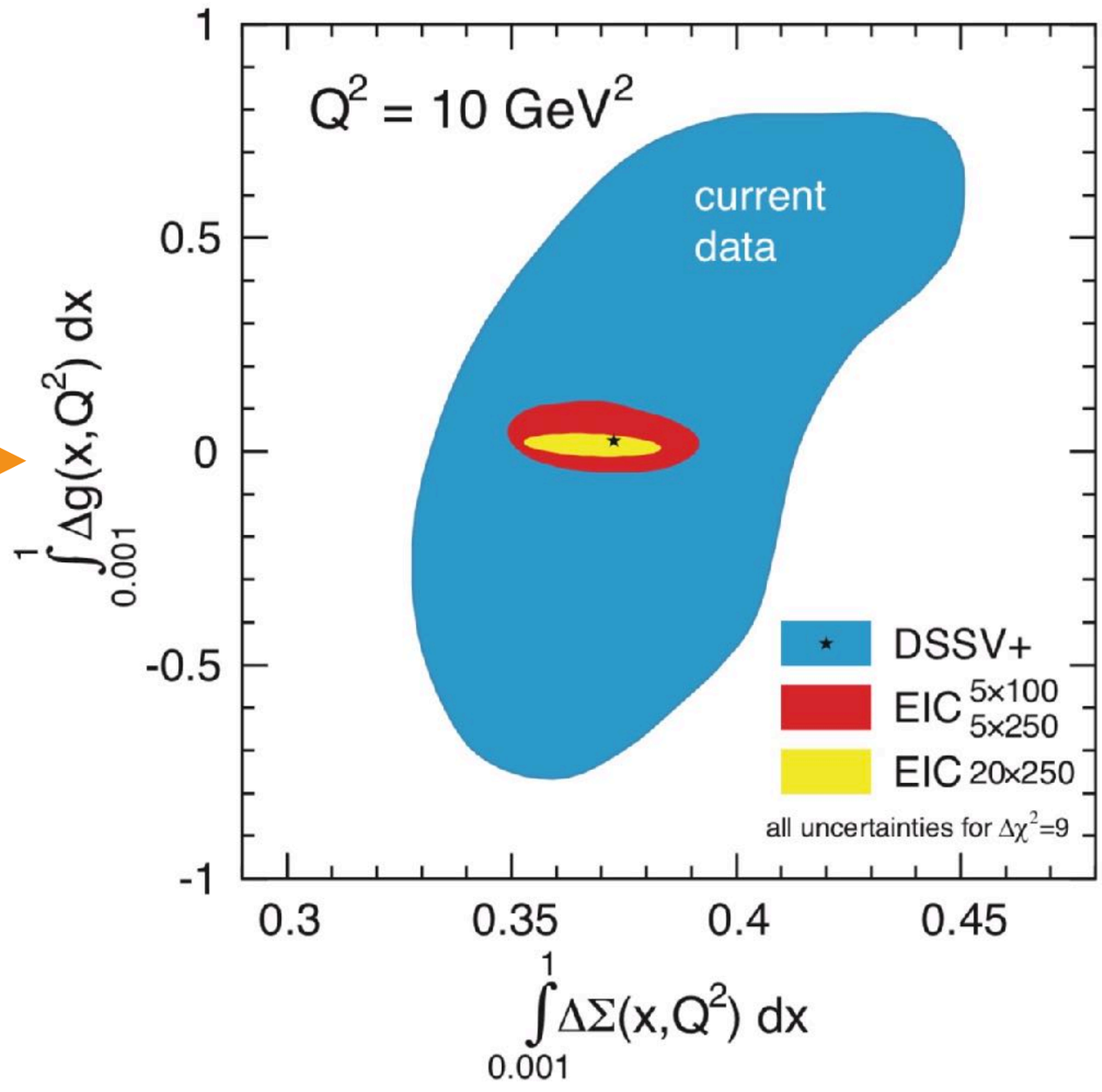
Q^2 (GeV^2)

x

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

U.S.-based EIC - Proton Spin

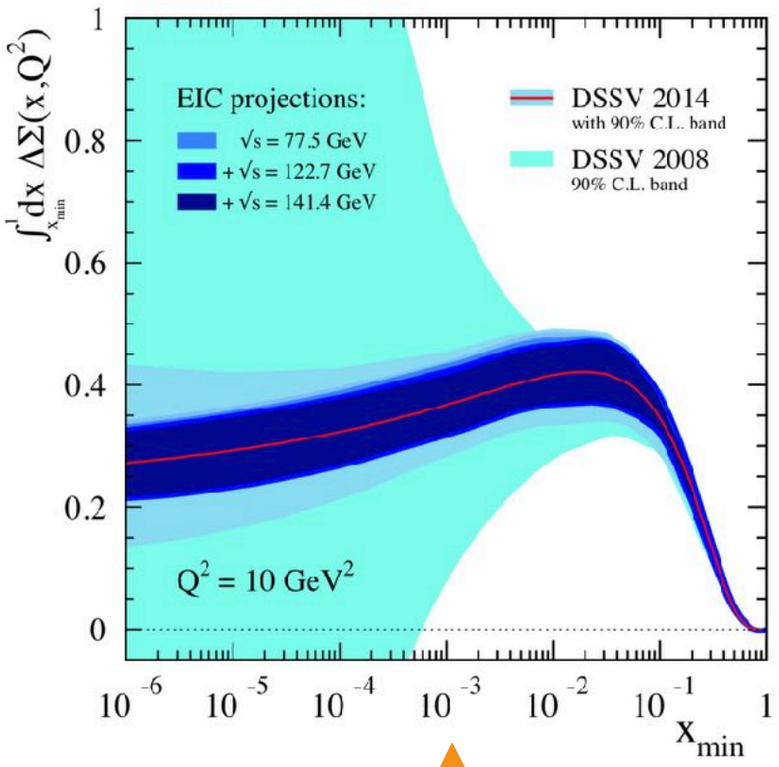




Conclusive insights in quark and gluon helicity from inclusive measurements, and orbital momentum by subtraction (!)

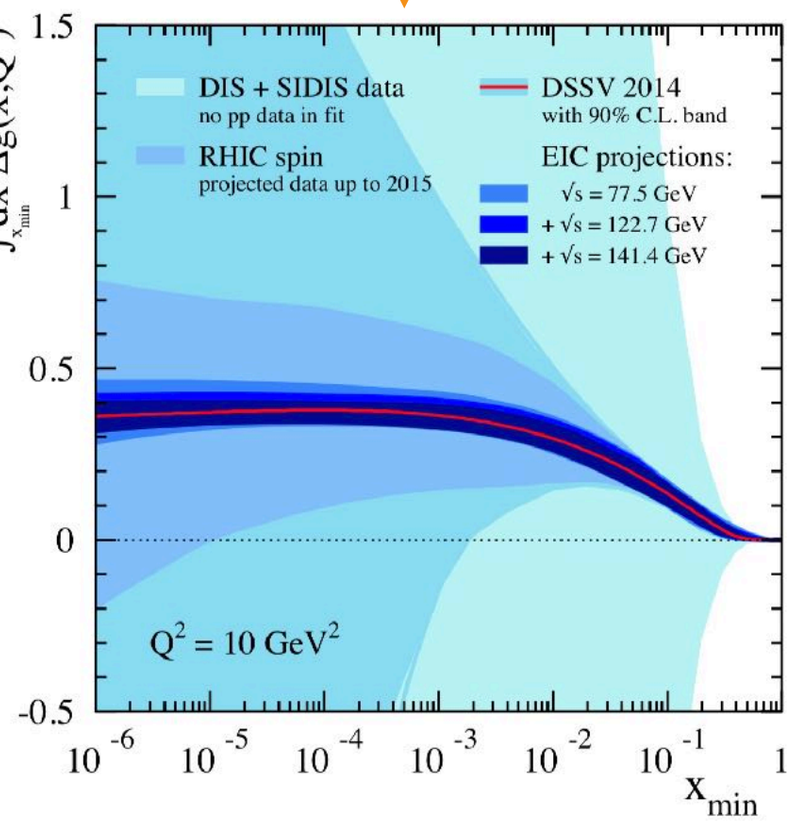
U.S.-based EIC - Proton Spin

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

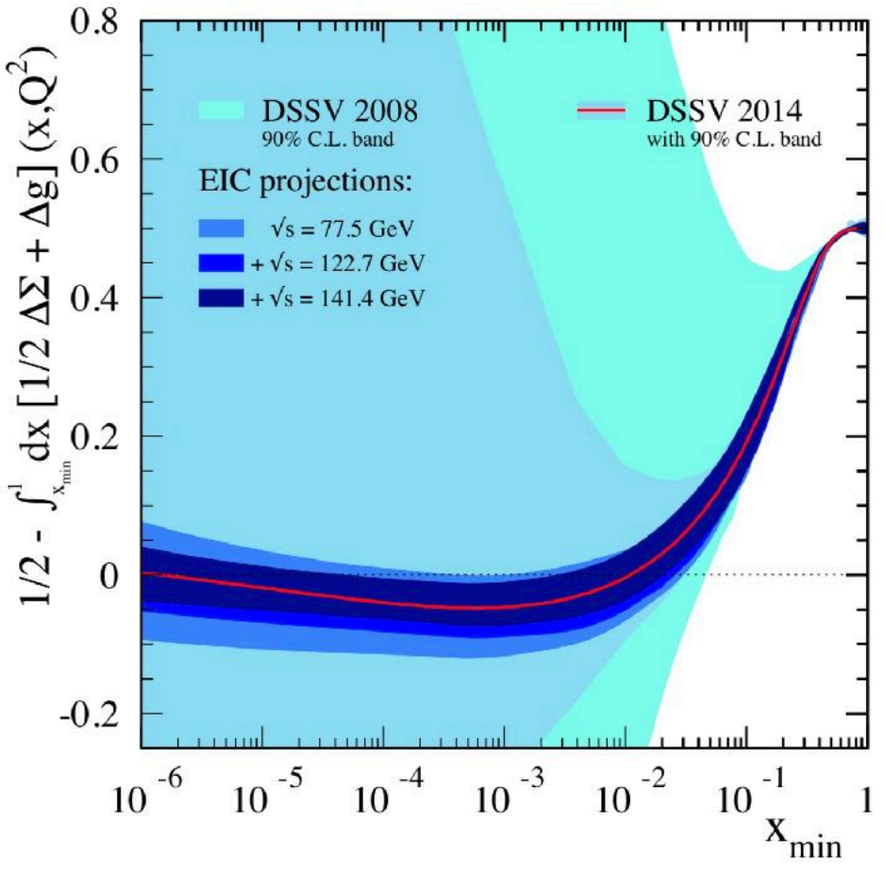


(anti-)quark helicity

gluon helicity

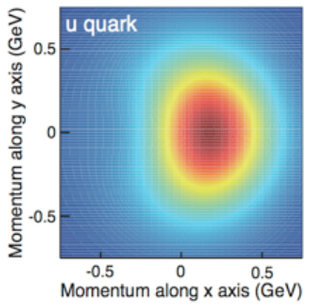


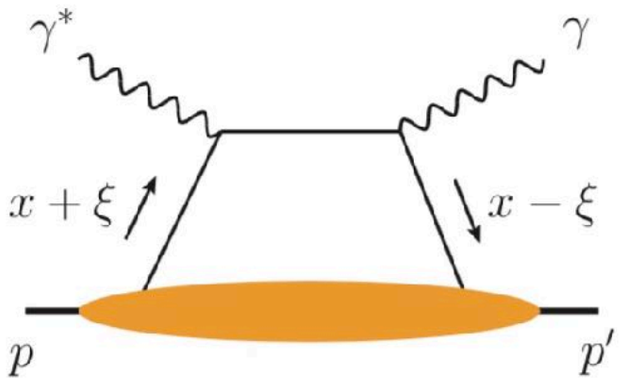
orbital momenta

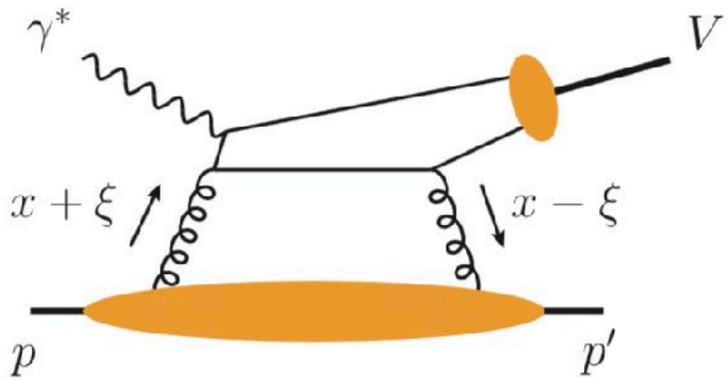


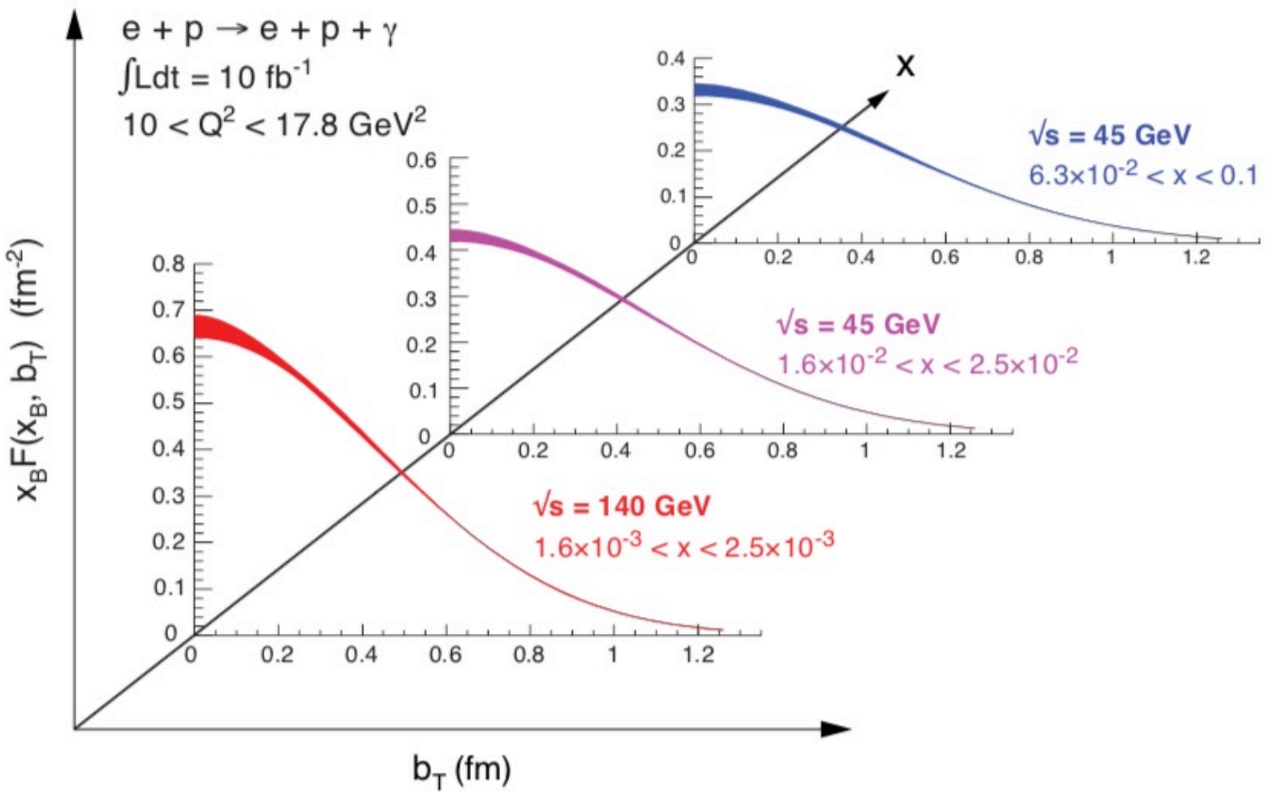
Clearly requires EIC

EIC - DVCS, DVMP, and Imaging

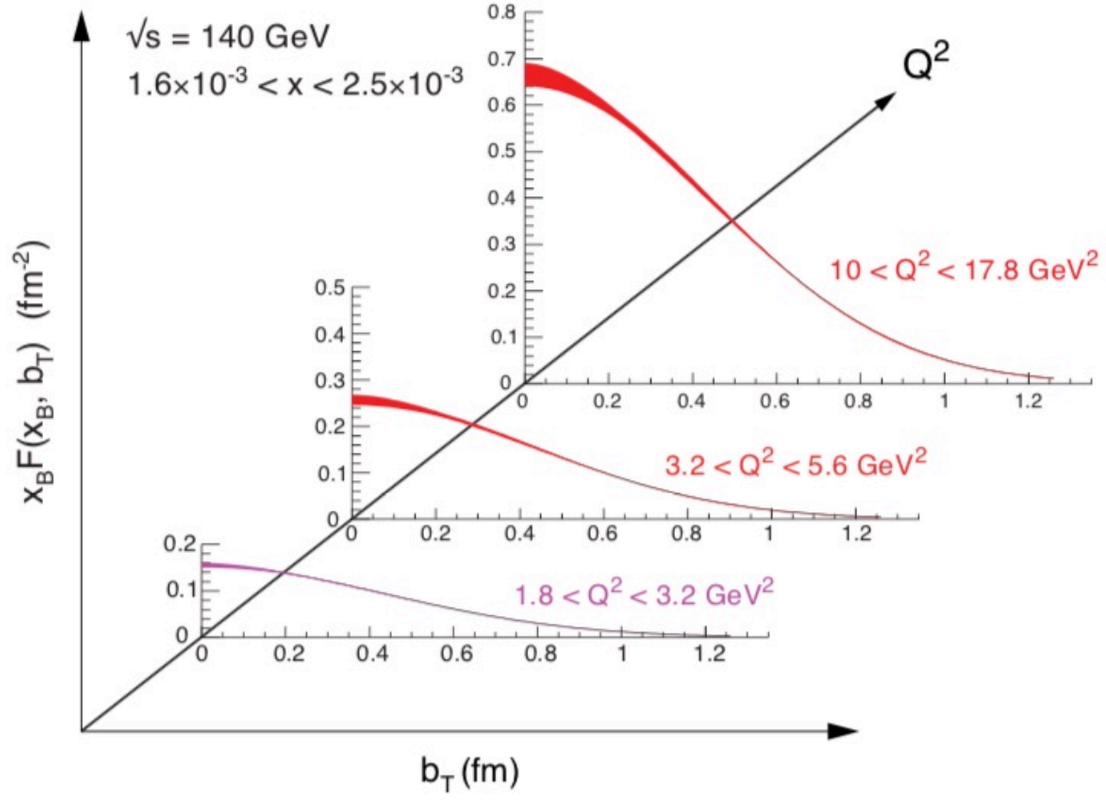






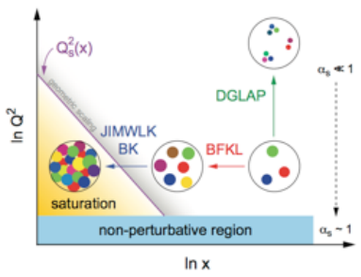


x-dependence at fixed Q^2



Q^2-dependence at fixed x

U.S.-based EIC - The Nuclear Landscape



Measurements with A ≥ 56 (Fe):

- eA/μA DIS (E-139, E-665, EMC, NMC)
- νA DIS (CCFR, CDHSW, CHORUS, NuTeV)
- DY (E772, E866)

eRHIC √s = 78 GeV, 0.01 ≤ y≤ 0.95

Q_s^2 Au

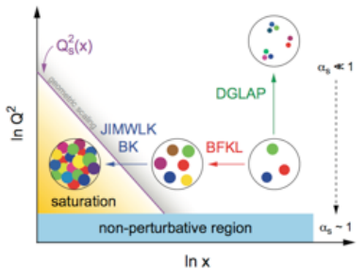
Ca

p

Q^2 (GeV^2)

x

U.S.-based EIC - The Nuclear Landscape



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Q_s^2 Au

Ca

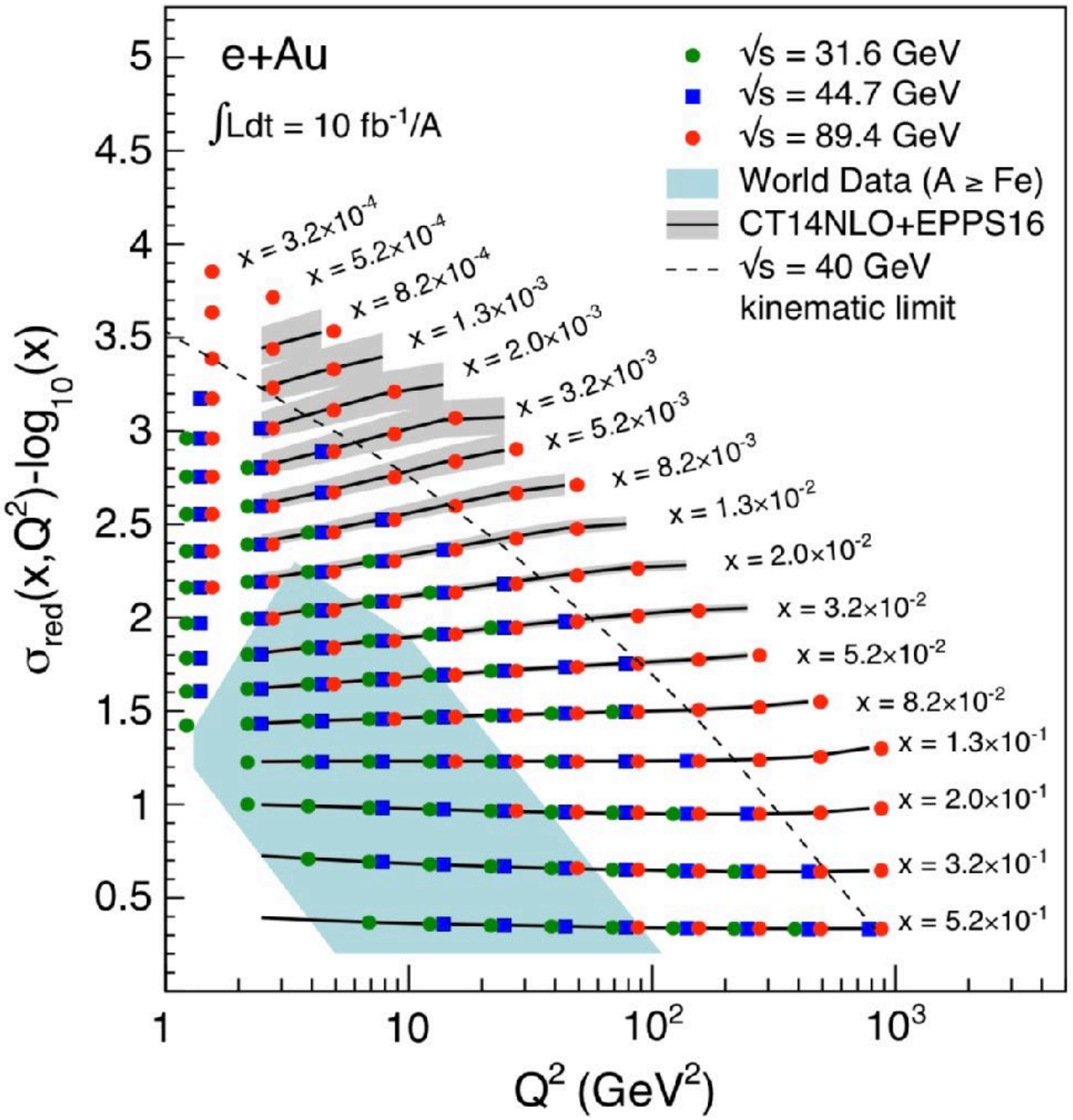
p

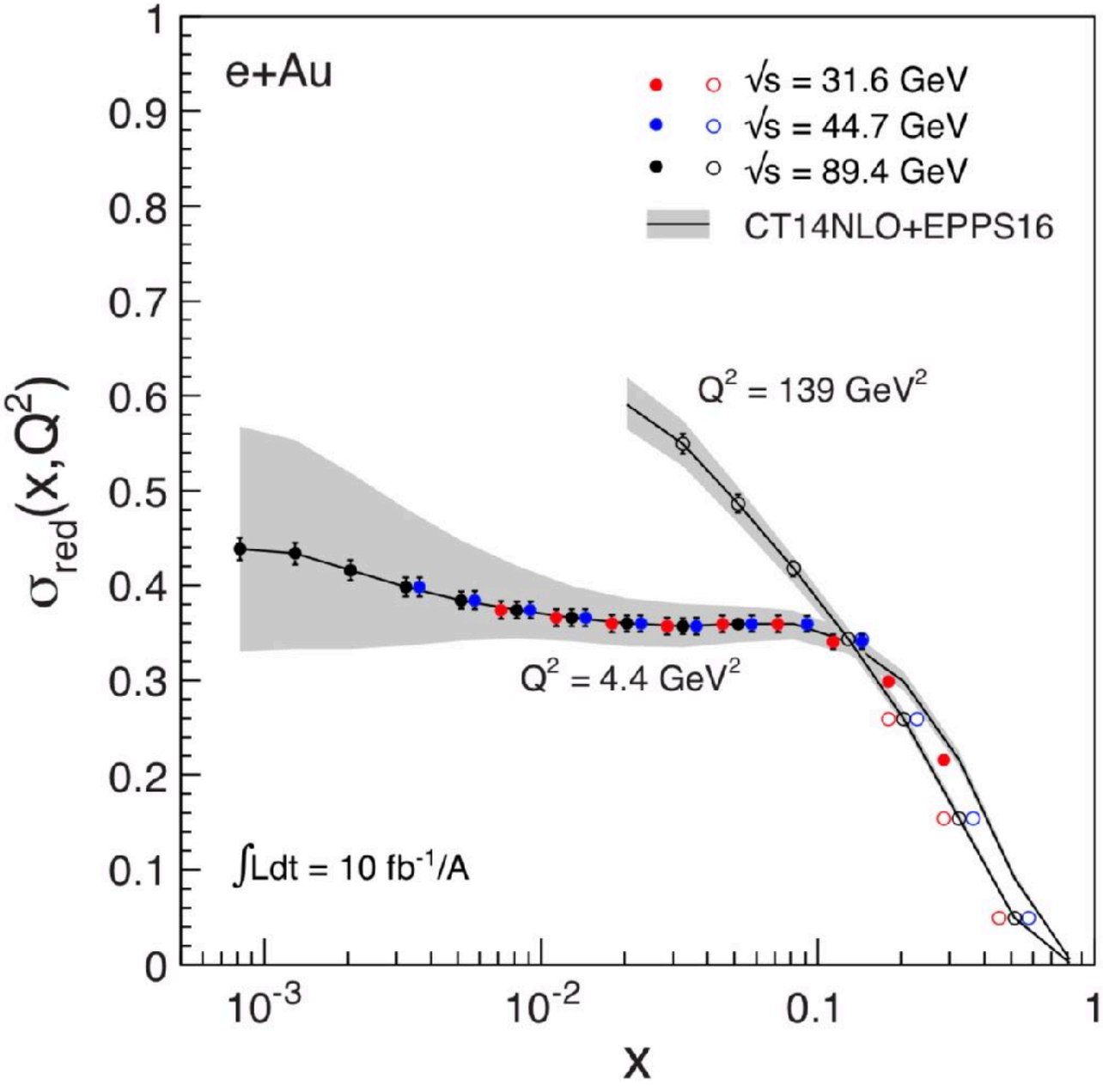
Q^2 (GeV^2)

x

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

U.S.-based EIC - The Nuclear Landscape

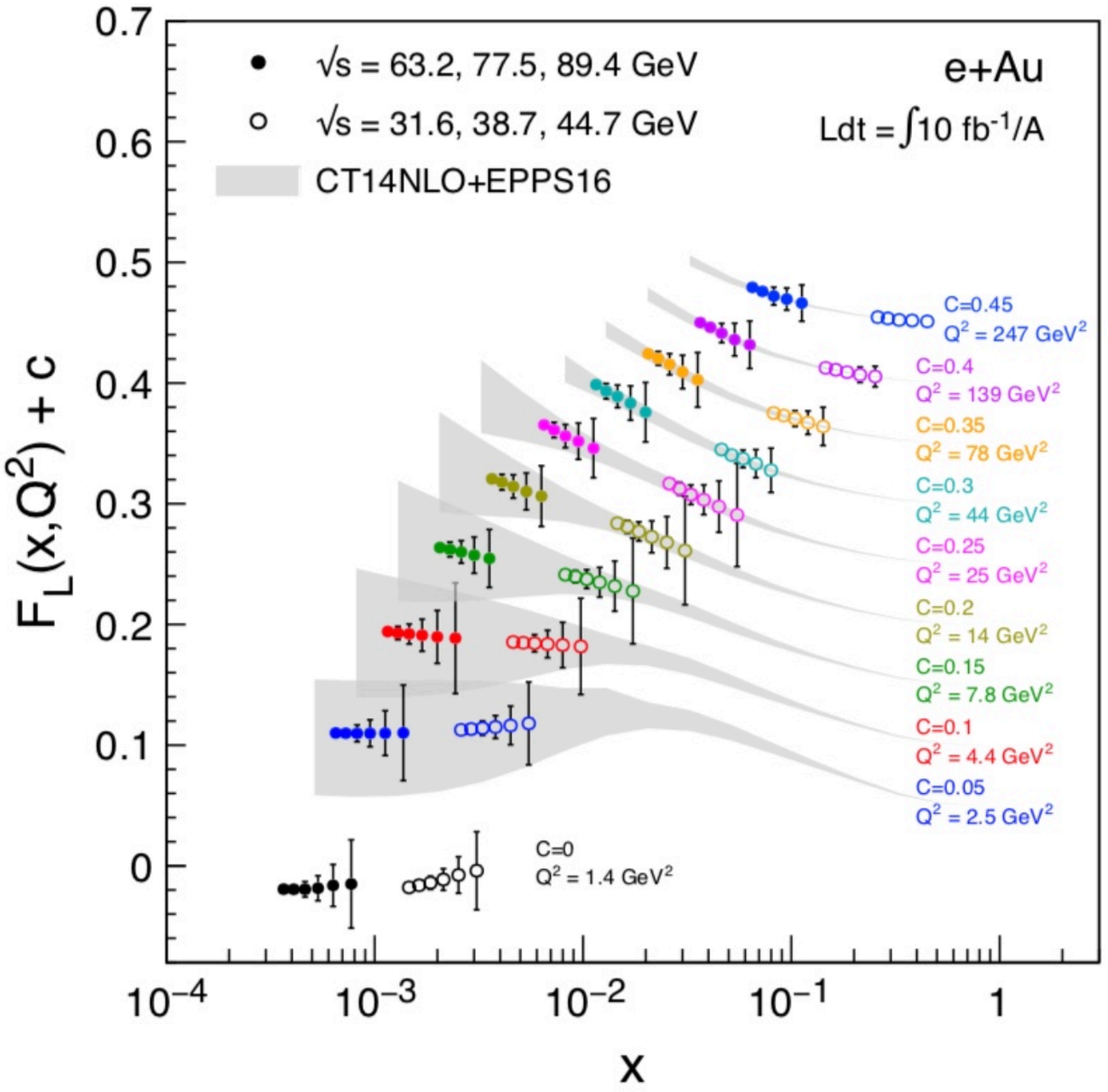


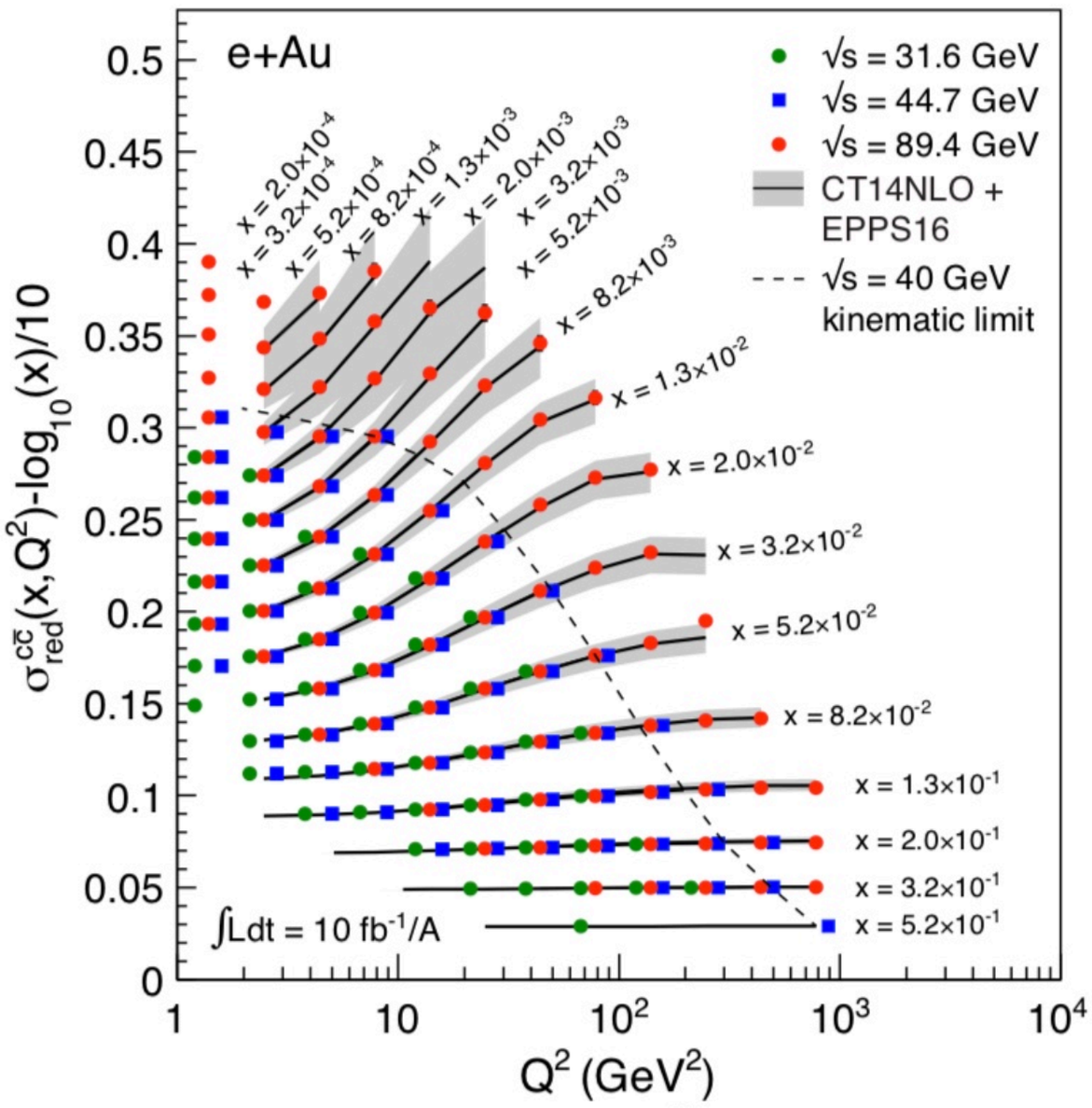


$$\sigma_{\text{reduced}} = F_2(x,Q^2) - \frac{y}{1+(1-y)^2} F_L(x,Q^2)$$

Impactful baseline inclusive measurements.

U.S.-based EIC - The Nuclear Landscape

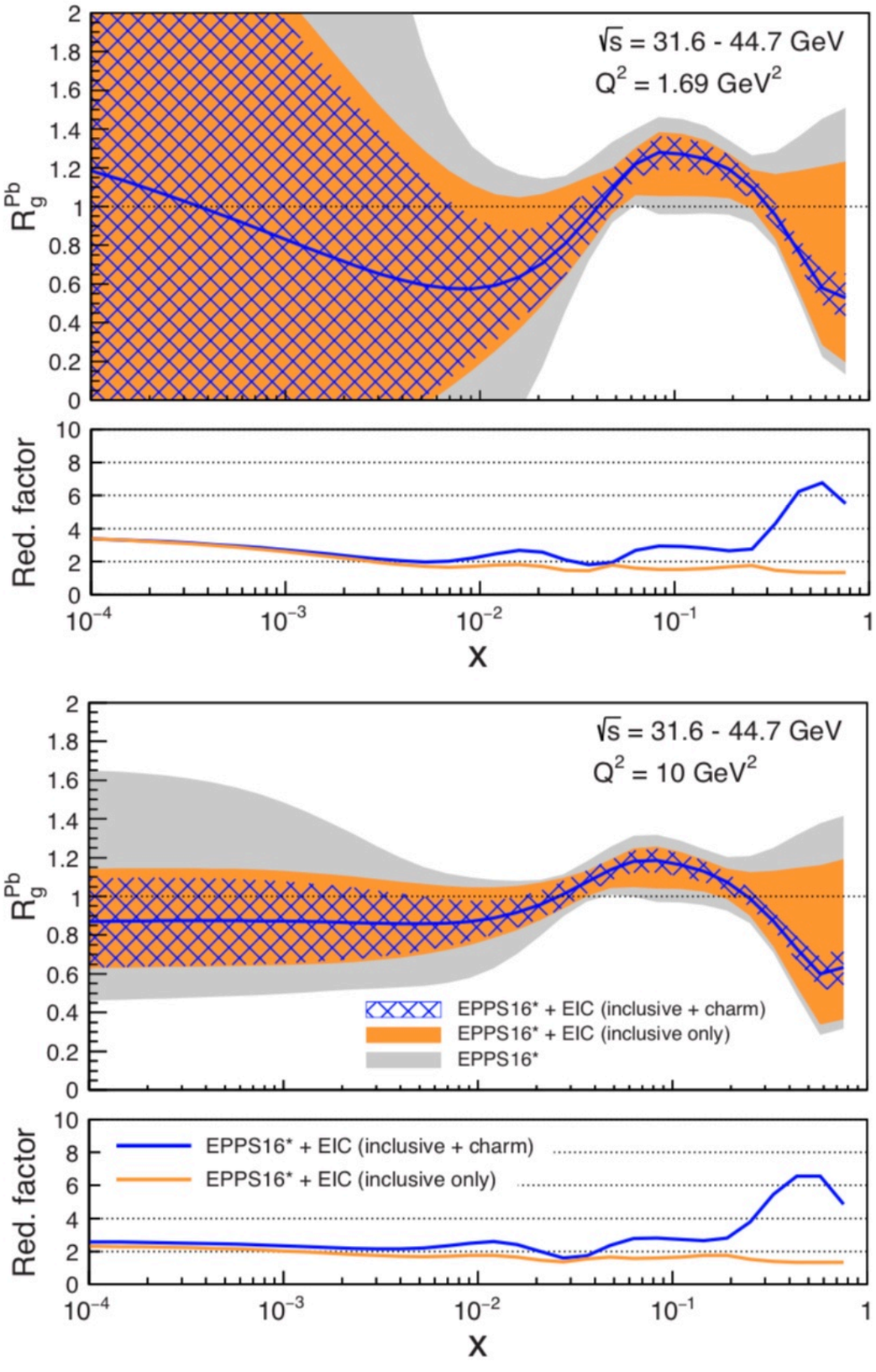




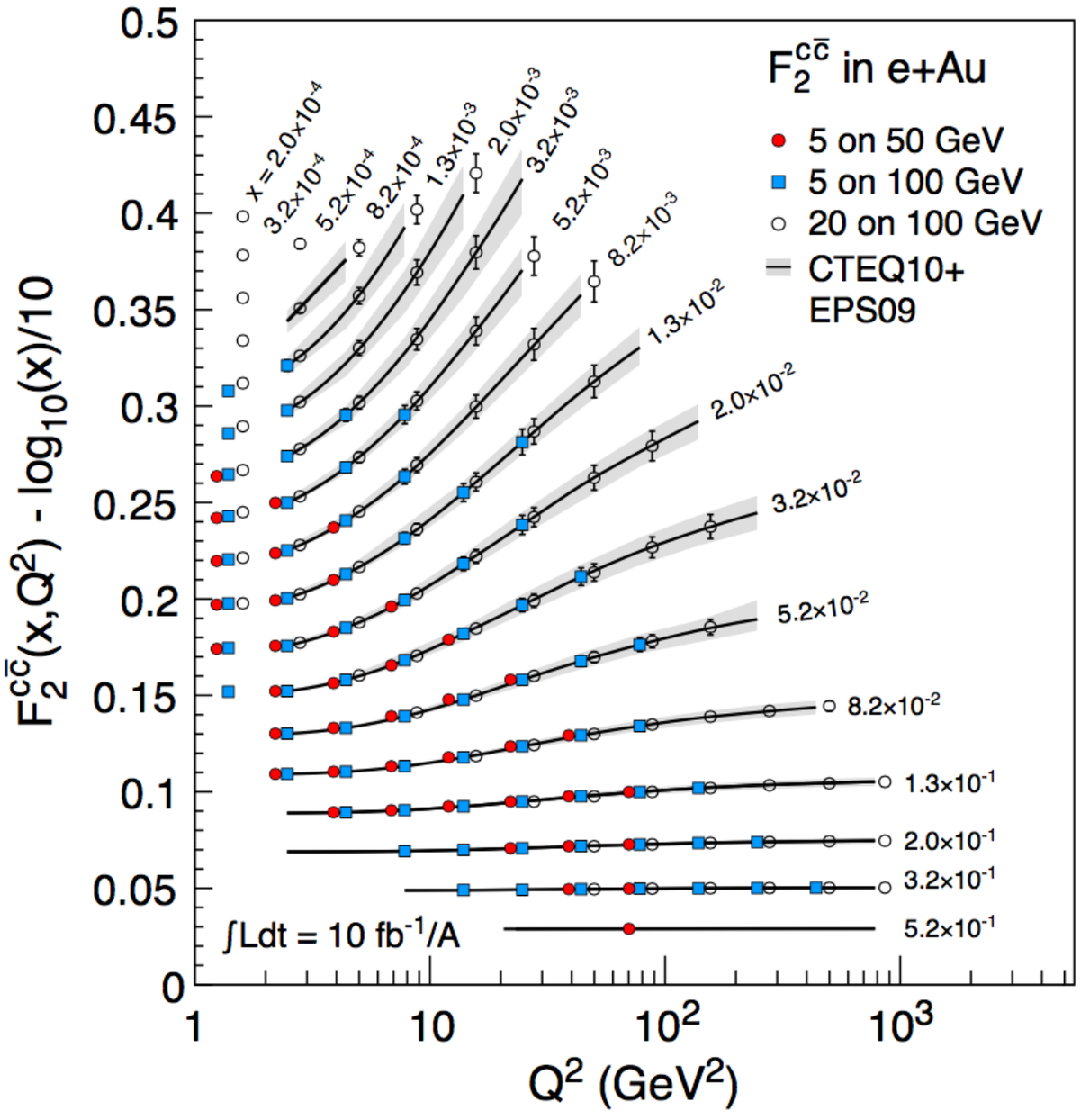
Clearly visible impact also beyond baseline inclusive measurements with "Rosenbluth separation" and semi-inclusive measurements.

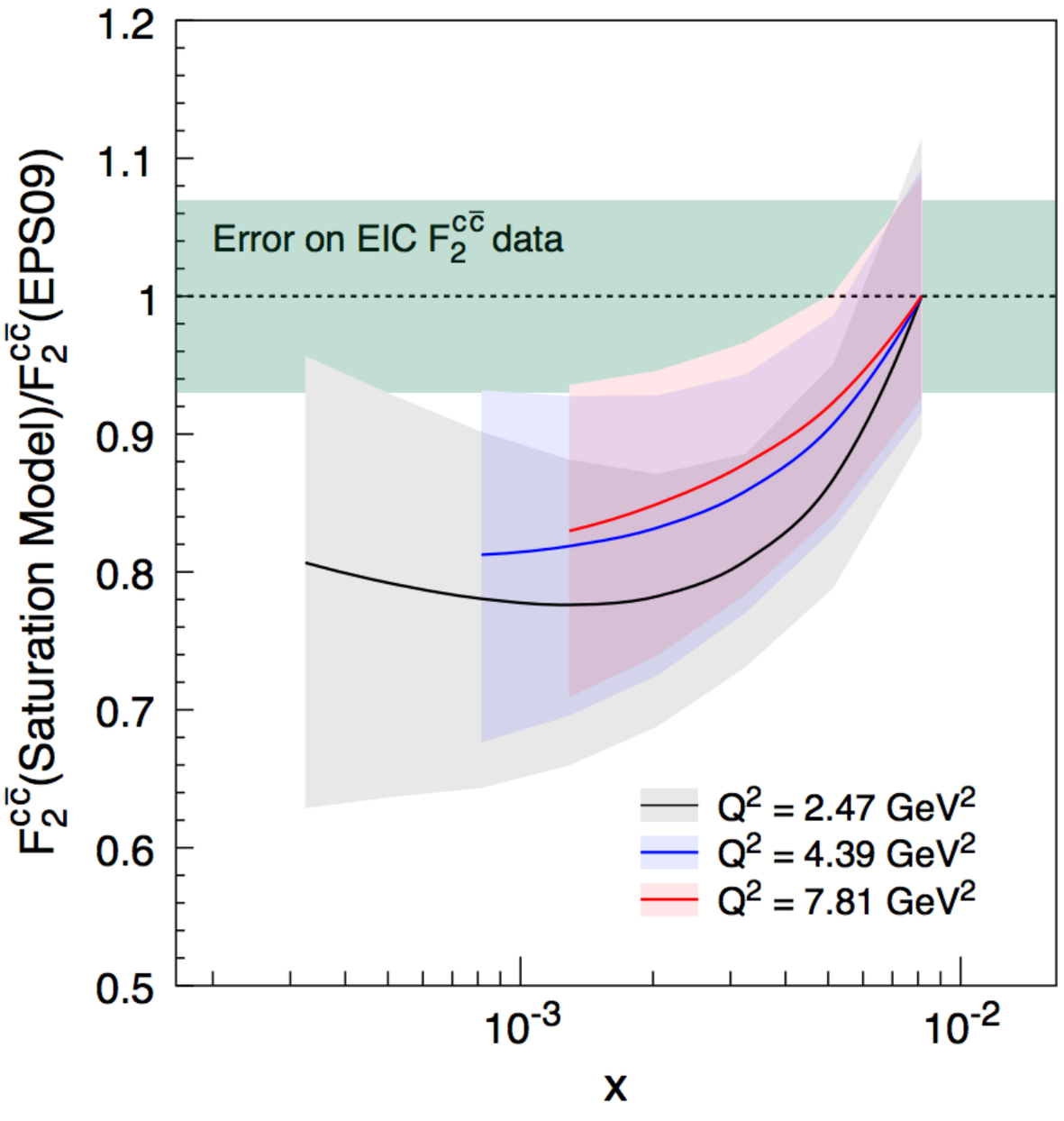
Nuclear gluon will be probed sensitively with complementary channels.

U.S.-based EIC - The Nuclear Landscape



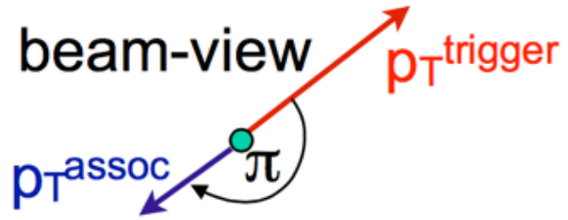
EIC - Saturation from within the PDF?

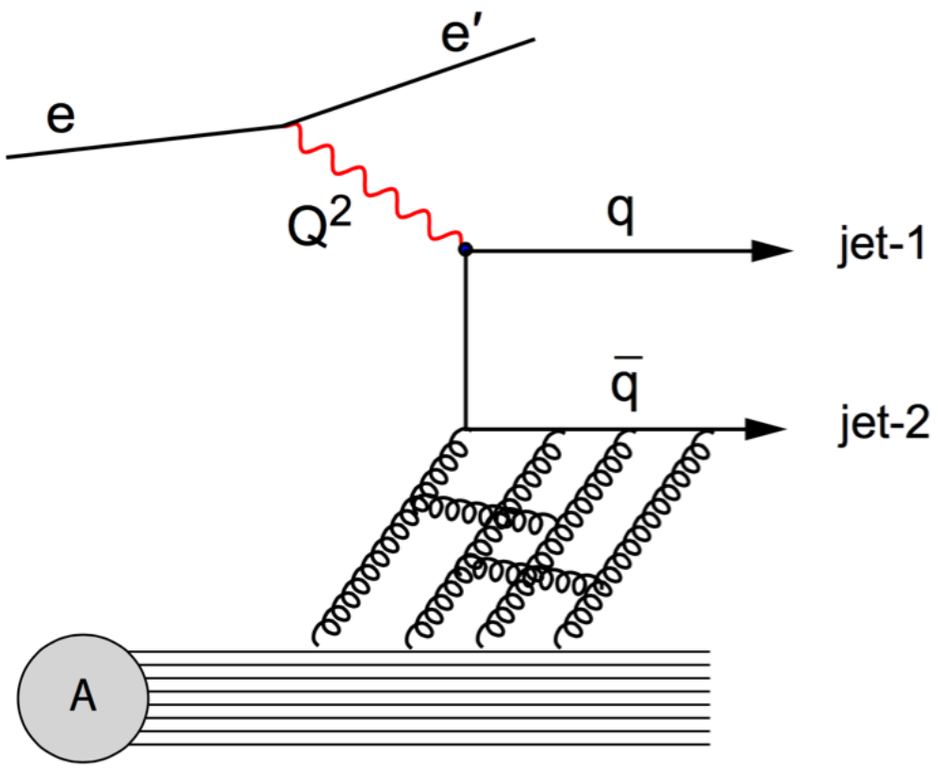




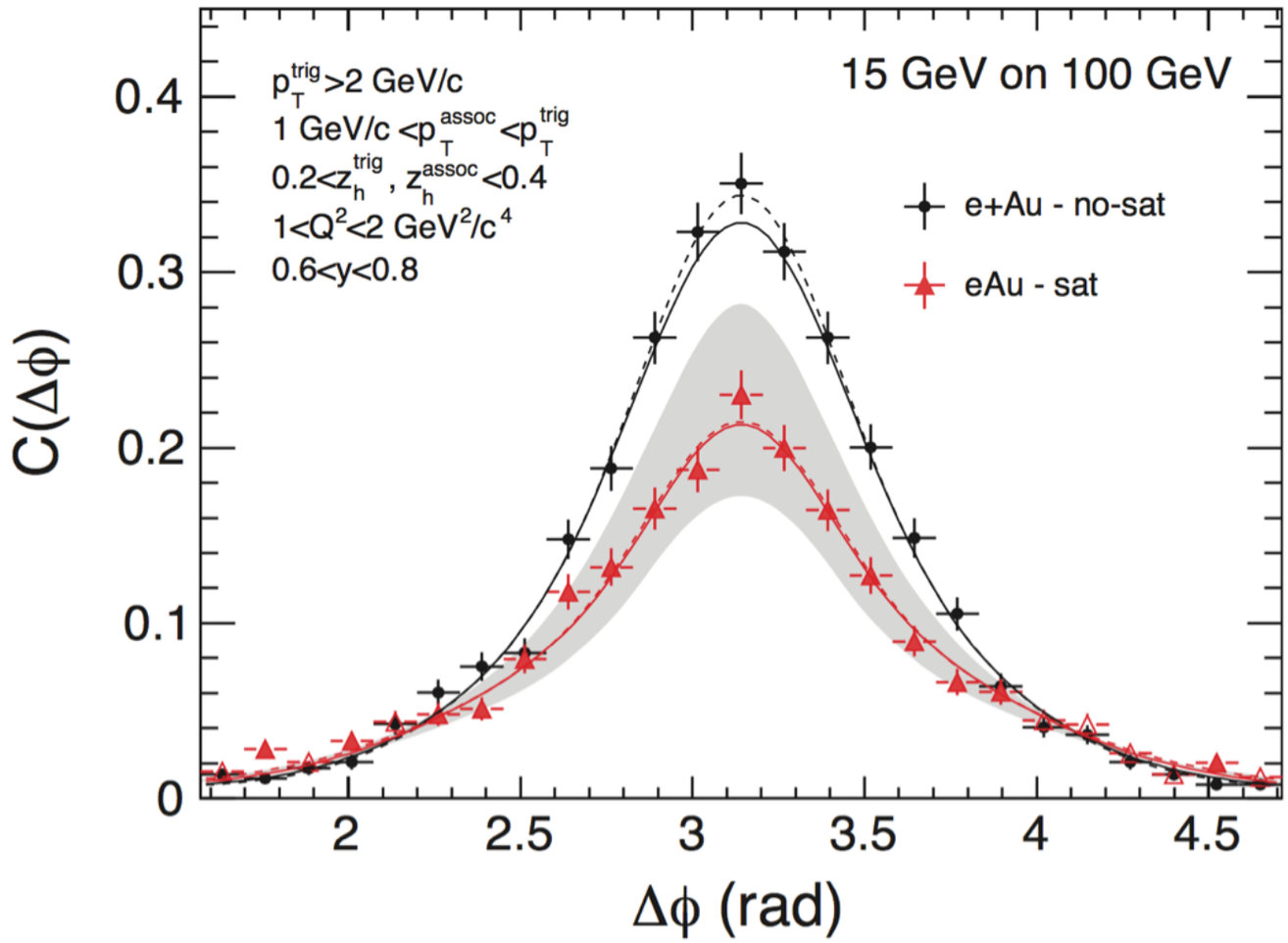
Improbable **and** ***certainly no substitute*** **for thinking** ***outside*** **the PDF!**

EIC - Dihadrons to probe Saturation





Dominguez, Xiao, Yuan (2011)

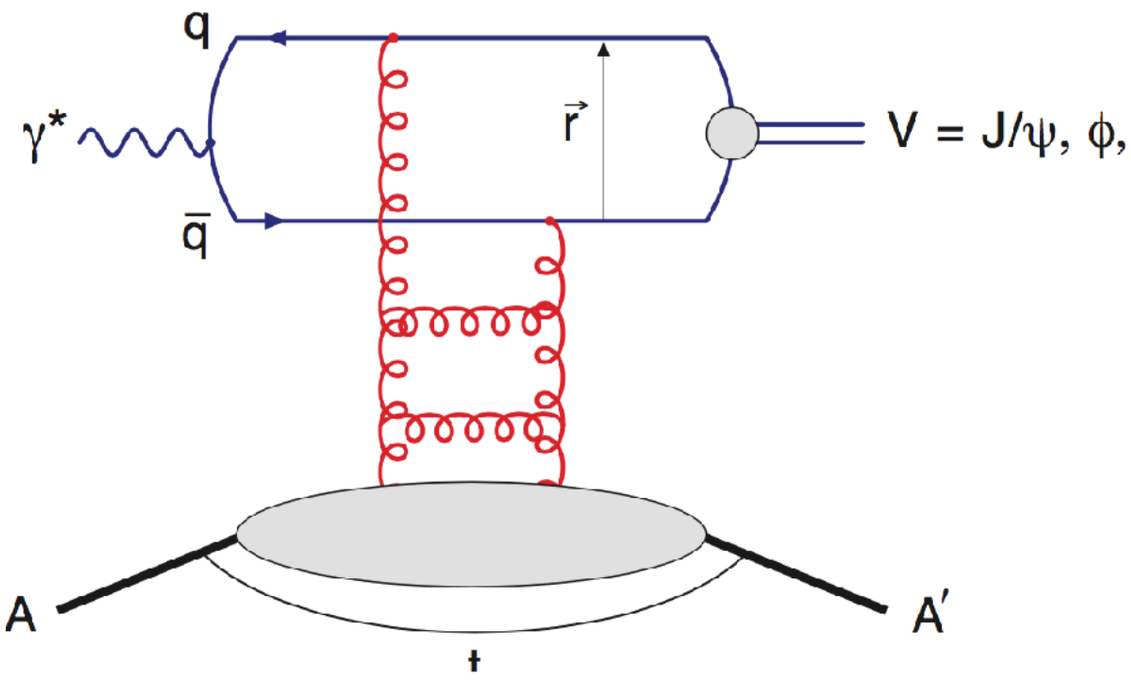


Zheng et al (2014)

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

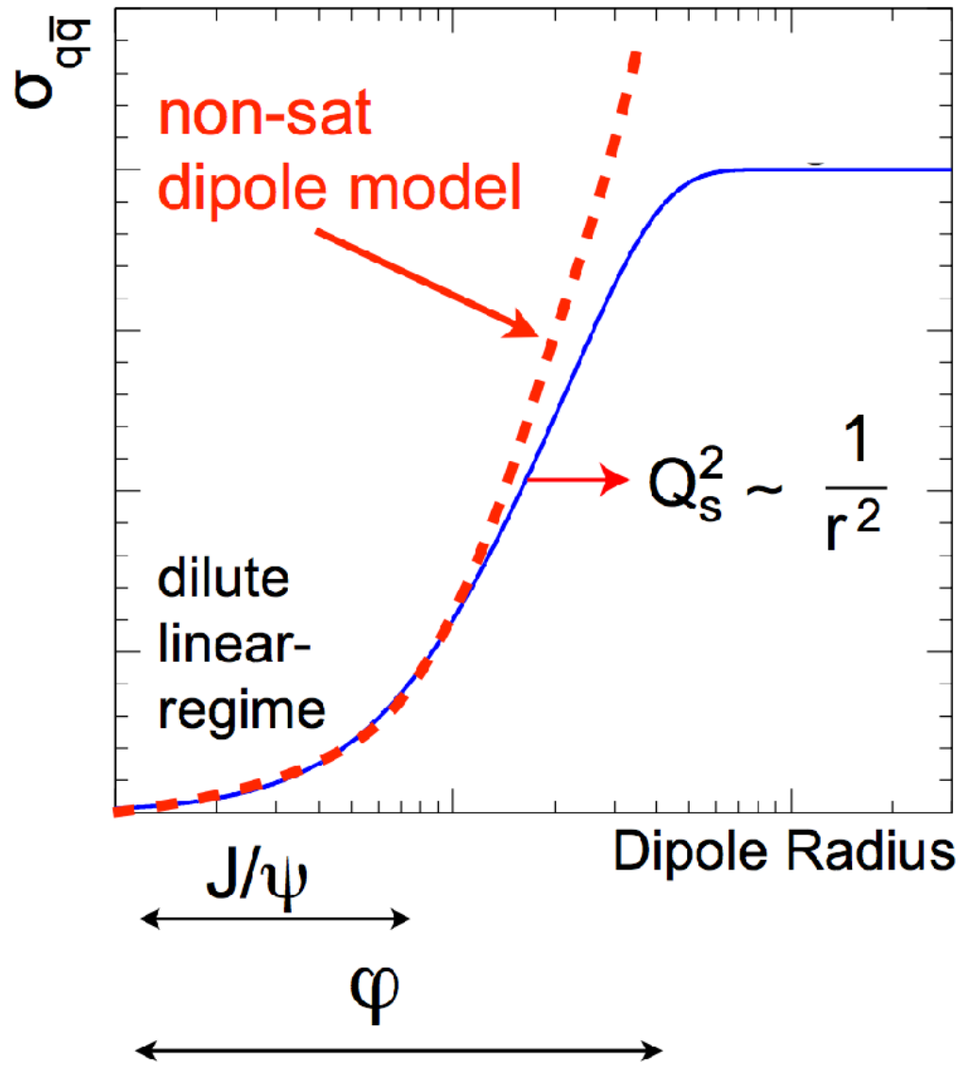
$$t = (p_A - p_{A'})^2 = (p_{\mathrm{VM}} + p_{e'} - p_e)^2$$



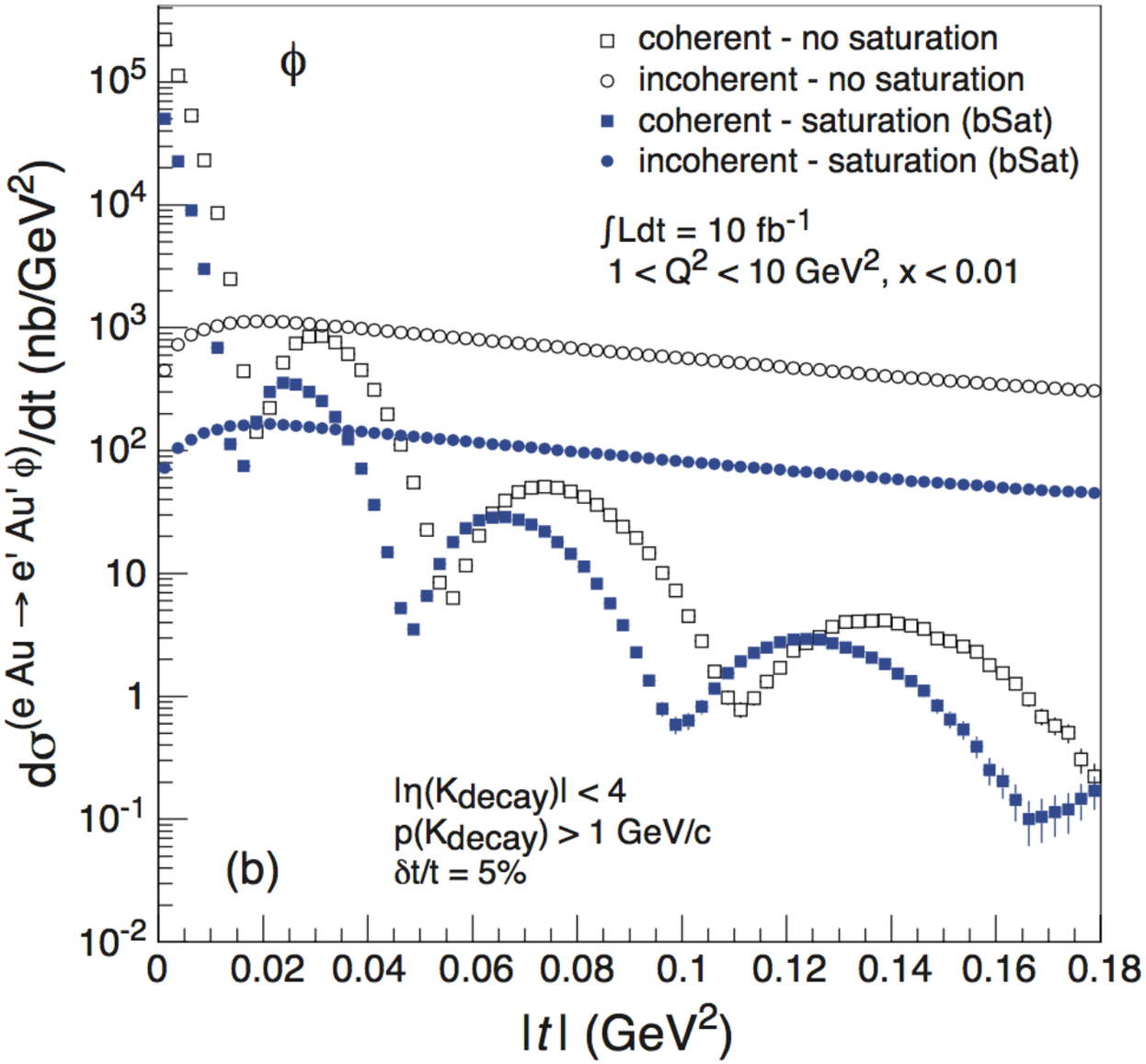
Nucleus escapes down the beampipe

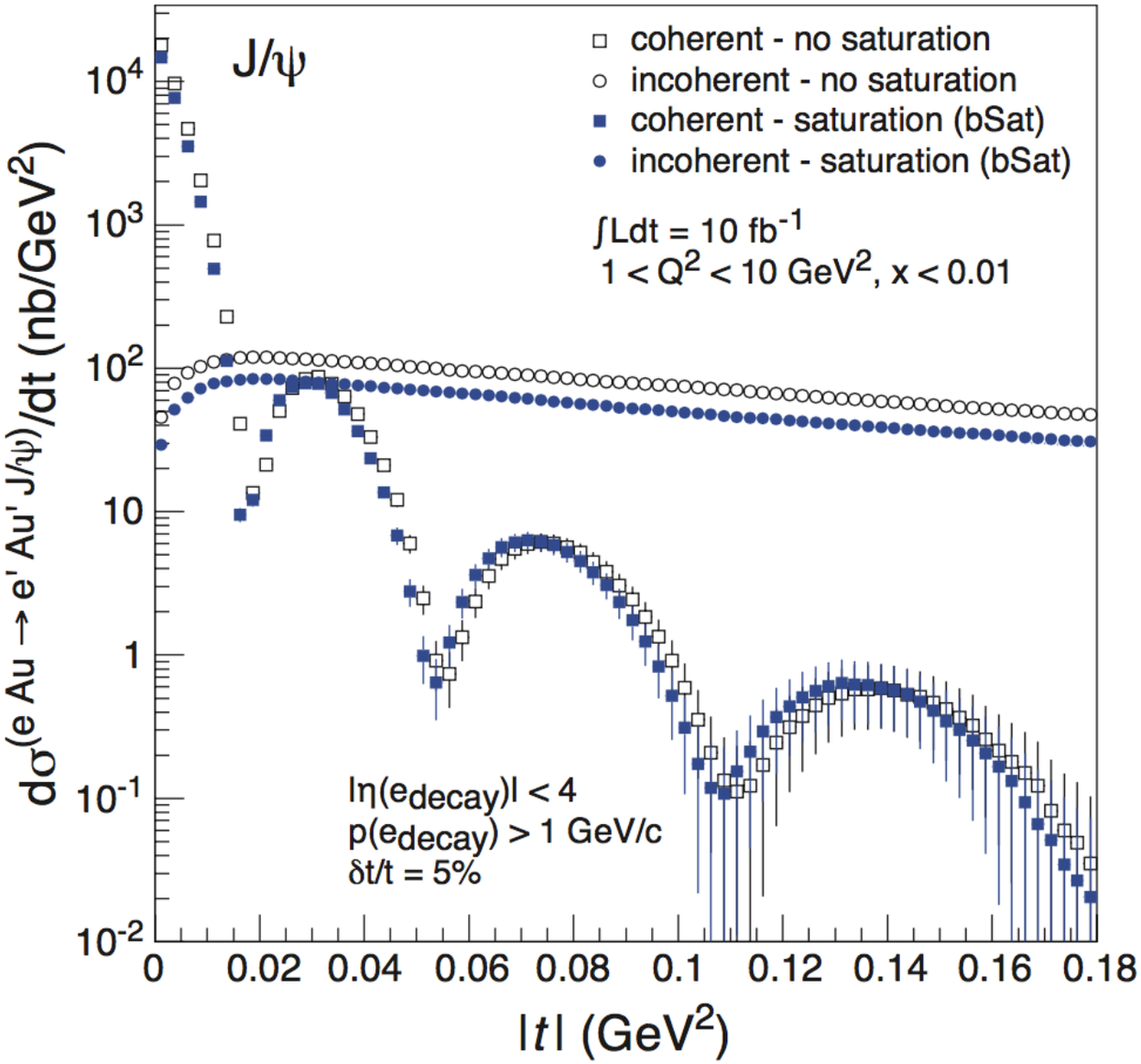
(In)coherence tagged with ZDC

Dipole Cross-Section:



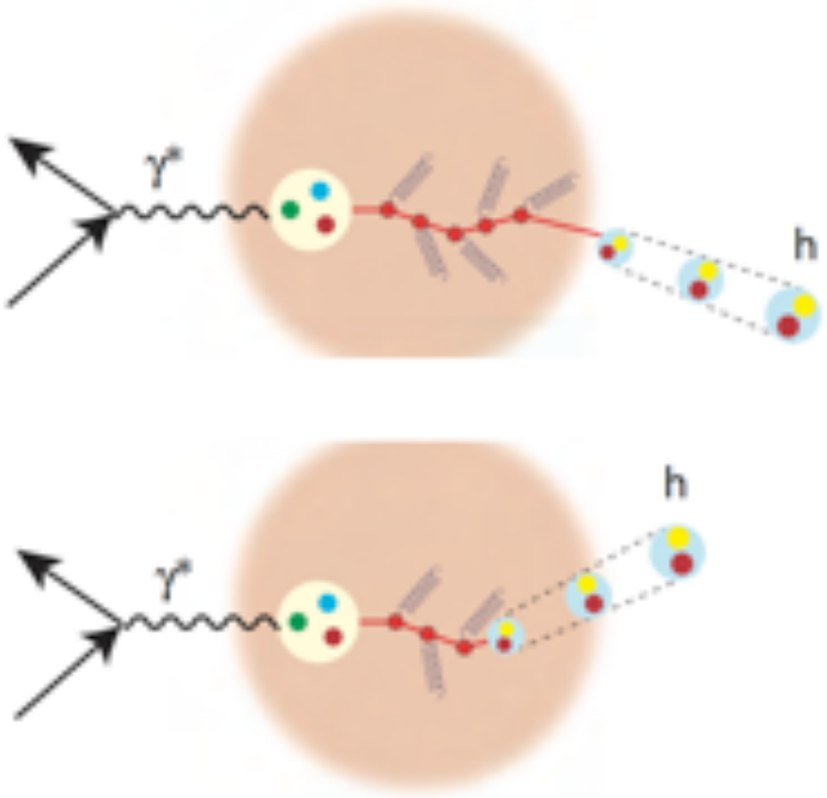
EIC - Exclusive Vector Mesons to probe Saturation





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

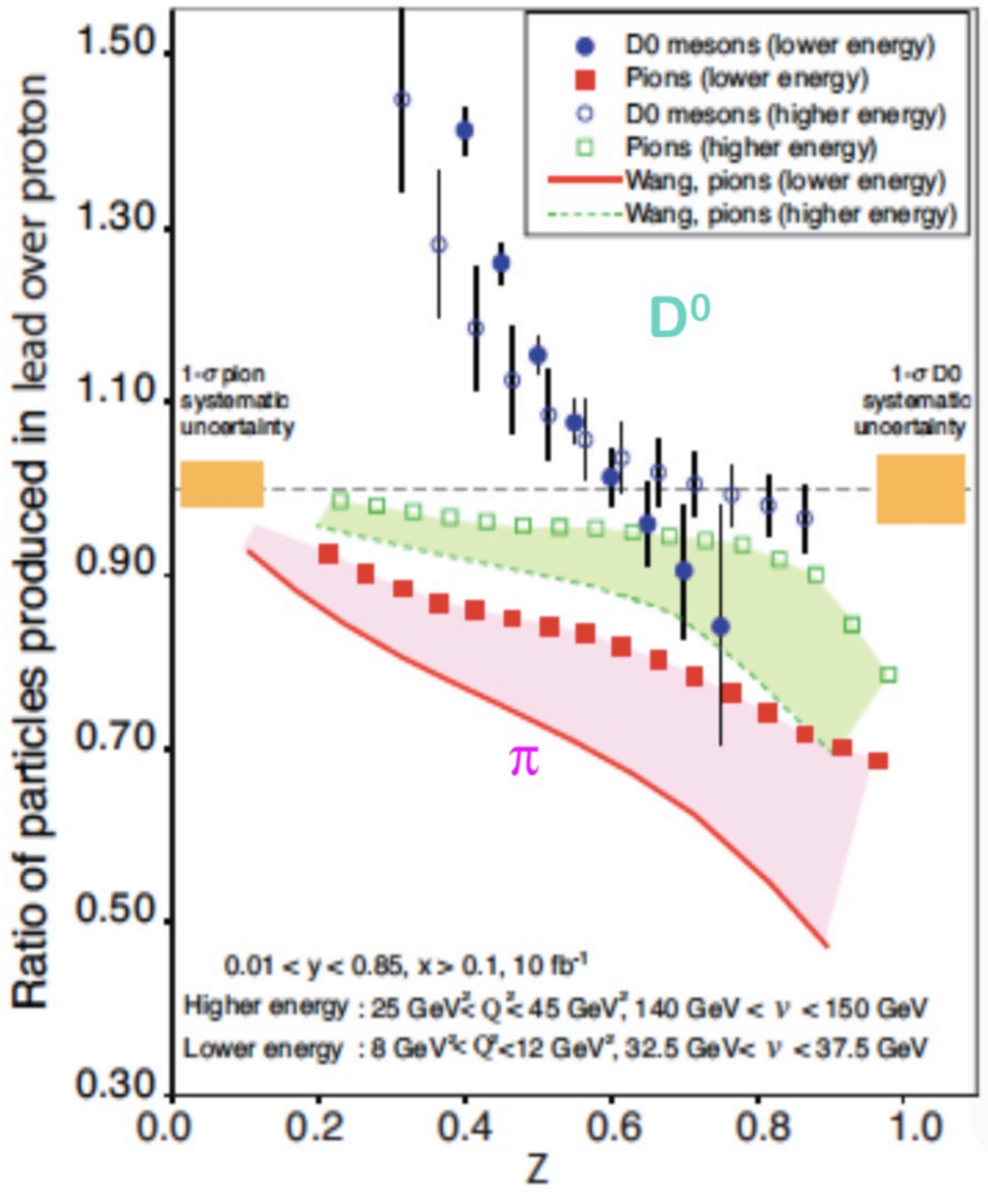
EIC - SIDIS to study Emergence of Hadrons



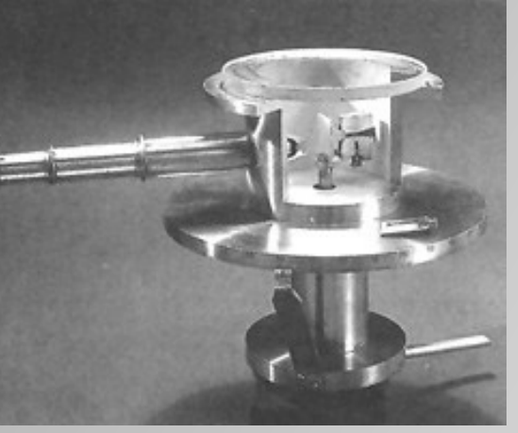
Control of $\nu = \dfrac{Q^2}{2mx}$ and

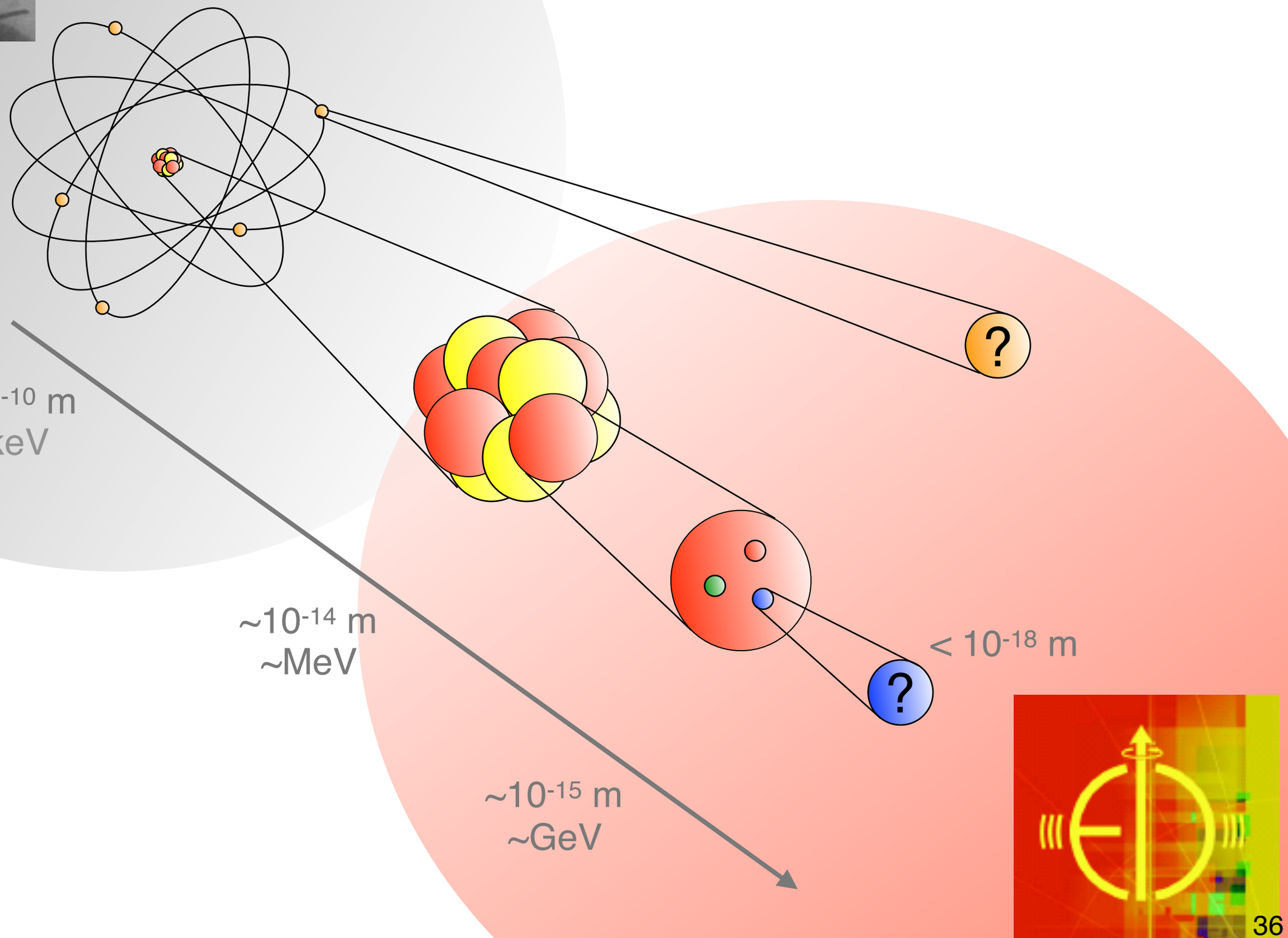
medium length

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?*
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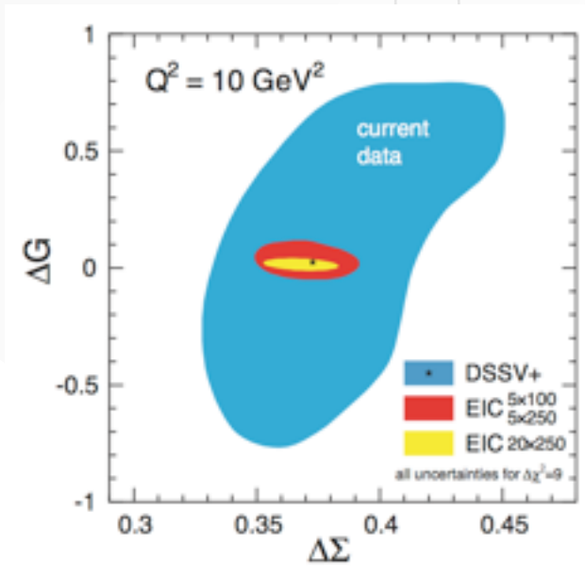

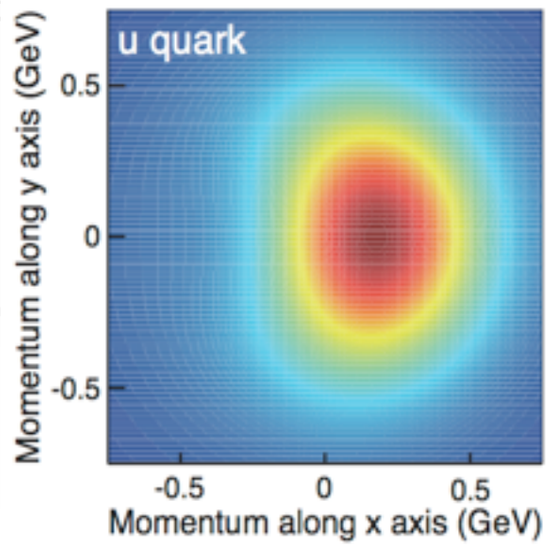

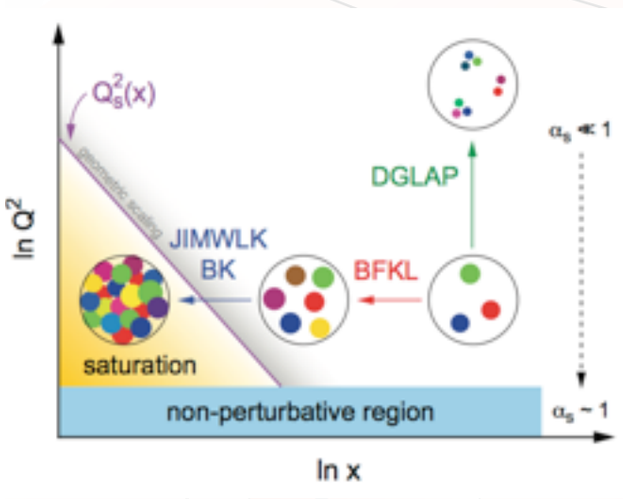

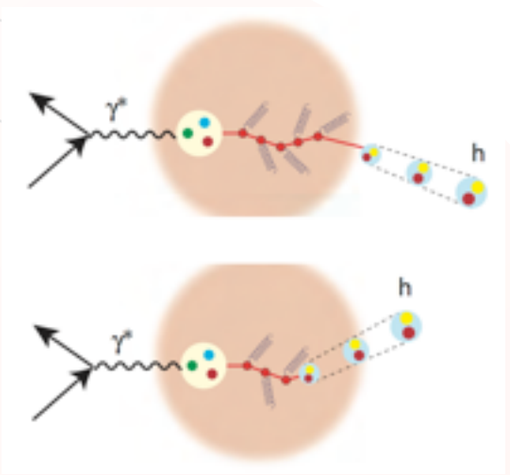

ArXiv:1212.17010

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

Relies crucially on theory and experiment,
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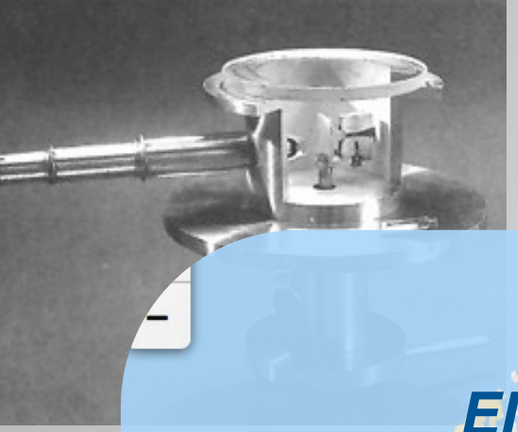
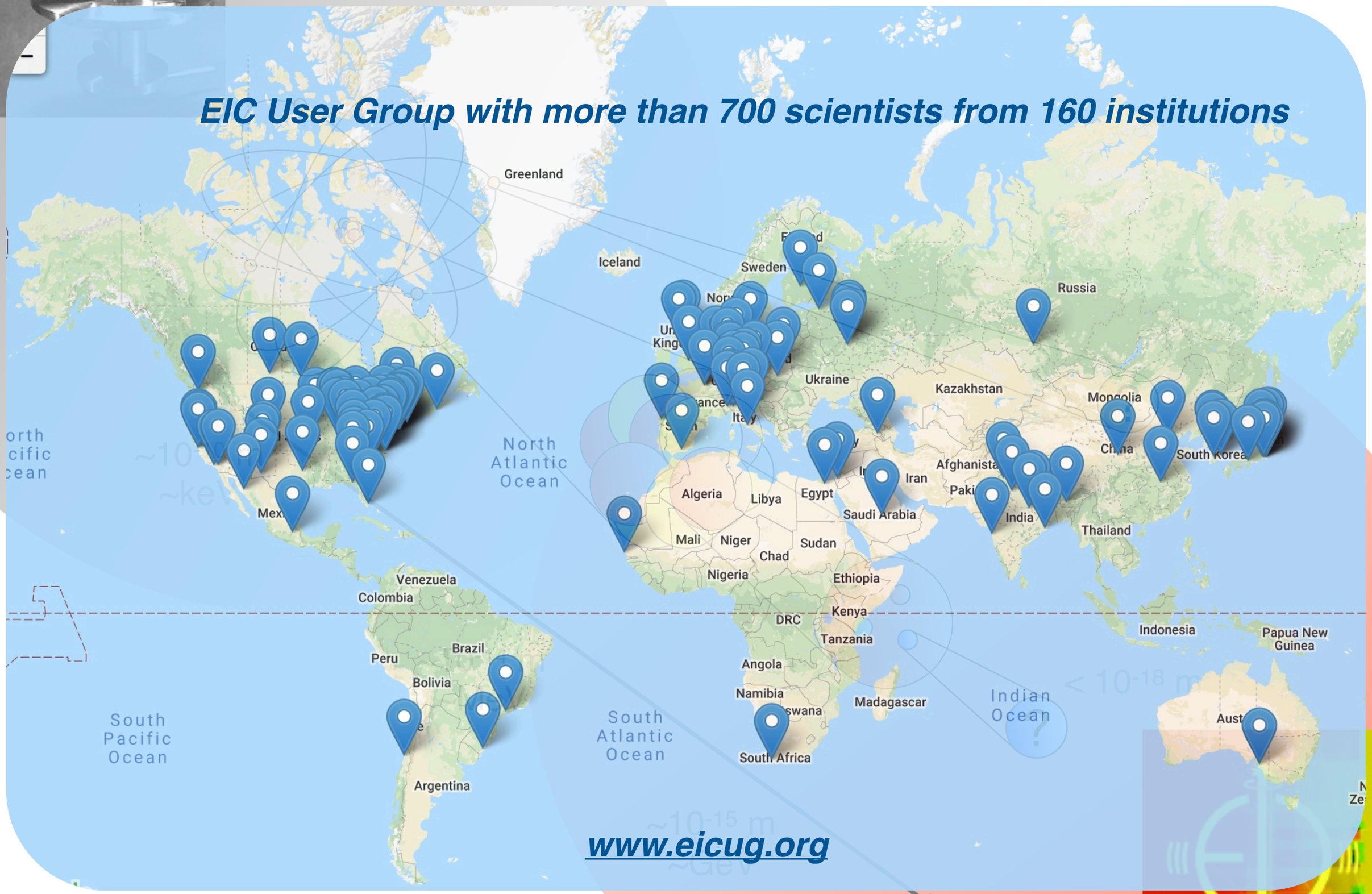
There is precedent for surprises in nature, provided you look.



EIC User Group with more than 700 scientists from 160 institutions



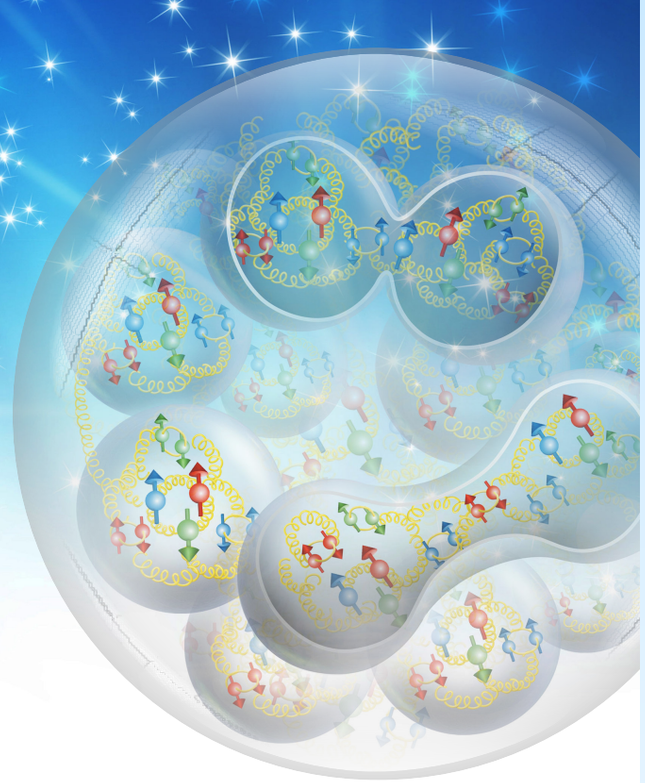
www.eicug.org

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 Plane 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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Jefferson Lab CUA BROOKHAVEN NATIONAL LABORATORY

Closing Comments

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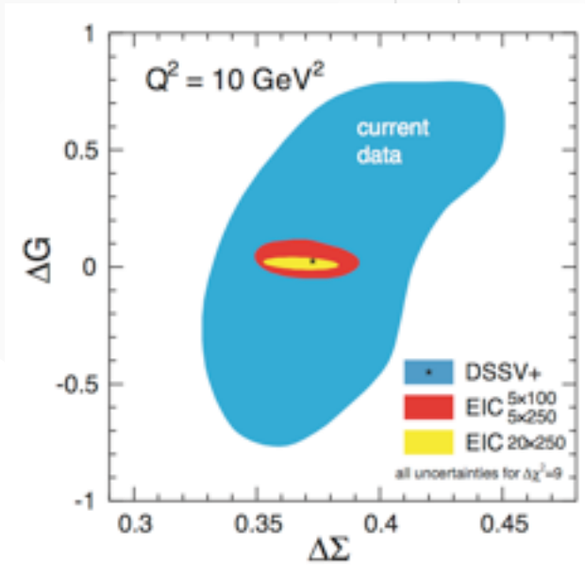

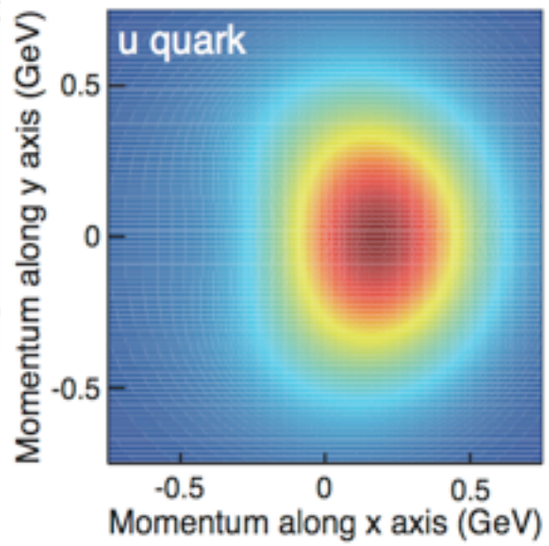

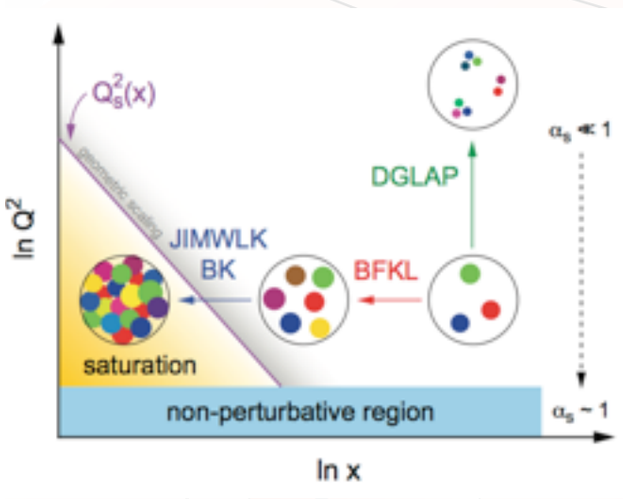

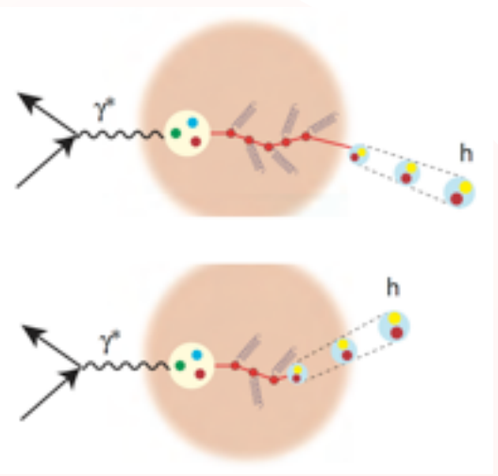

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