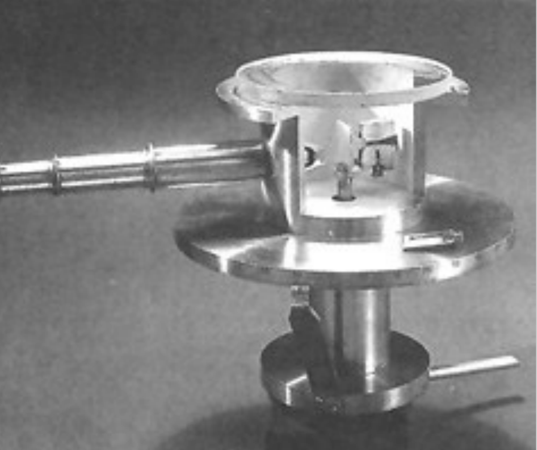
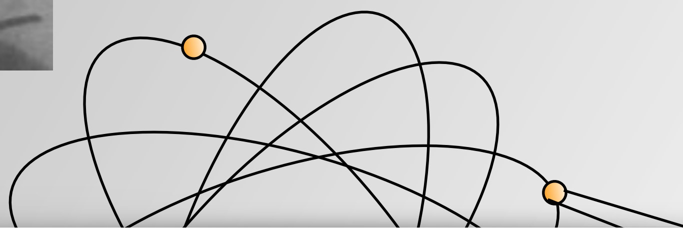
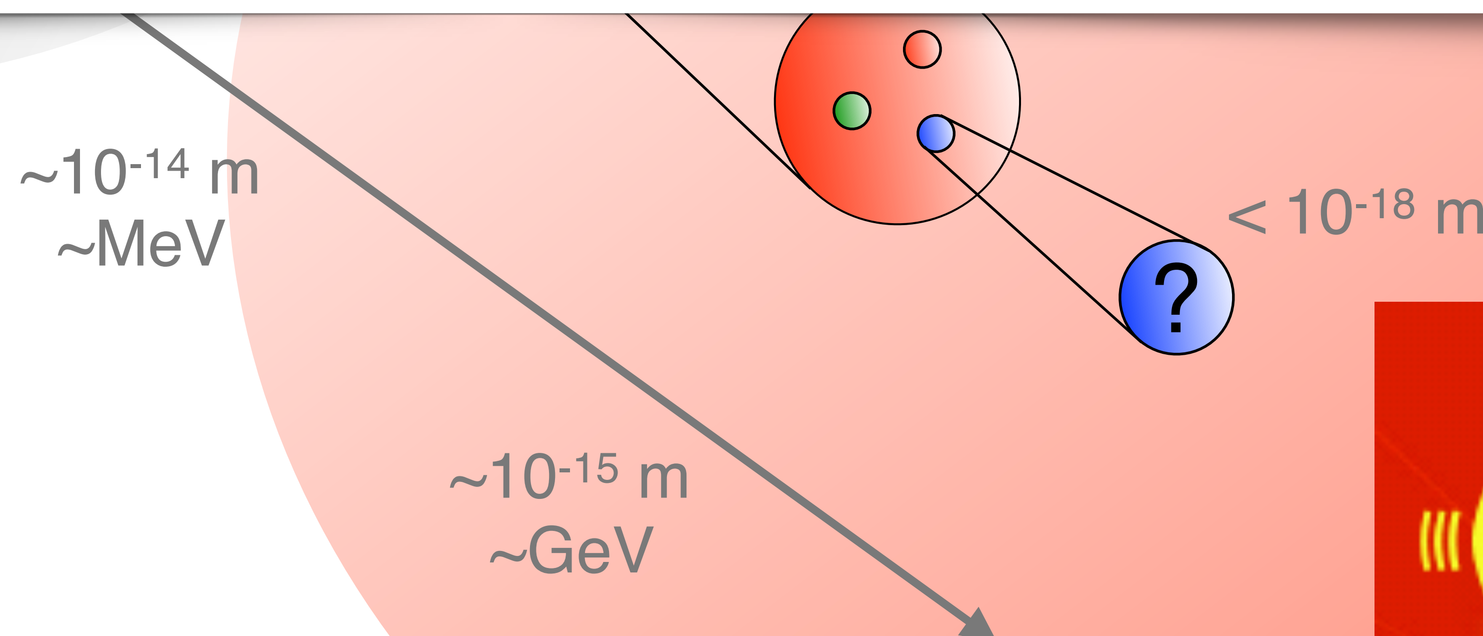




Electron-Ion Collider

Peering deeper into the protons and neutrons of atomic nuclei

Ernst Sichtermann



NSD Staff Meeting
LBNL - February 25, 2020

Department of Energy

U.S. Department of Energy Selects Brookhaven National Laboratory to Host Major New Nuclear Physics Facility

JANUARY 9, 2020

WASHINGTON, D.C. – Today, the **U.S. Department of Energy (DOE)** announced the selection of Brookhaven National Laboratory in Upton, NY, as the site for a planned major new nuclear physics research facility.

The Electron Ion Collider (EIC), to be designed and constructed over ten years at an estimated cost between \$1.6 and \$2.6 billion, will smash electrons into protons and heavier atomic nuclei in an effort to penetrate the mysteries of the "strong force" that binds the atomic nucleus together.

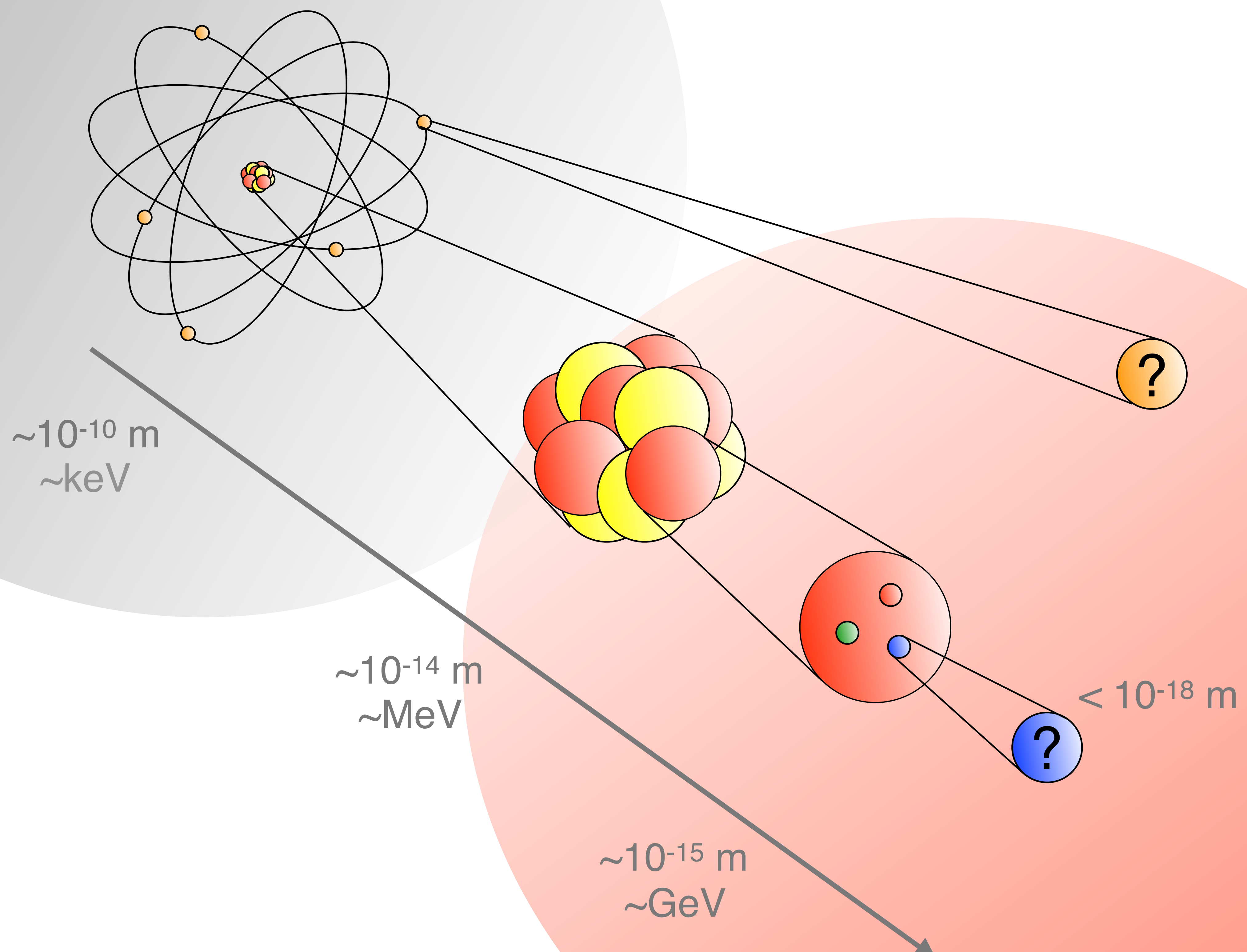
. . .

The EIC's high luminosity and highly polarized beams will push the frontiers of particle accelerator science and technology and provide unprecedented insights into the building blocks and forces that hold atomic nuclei together.

. . .

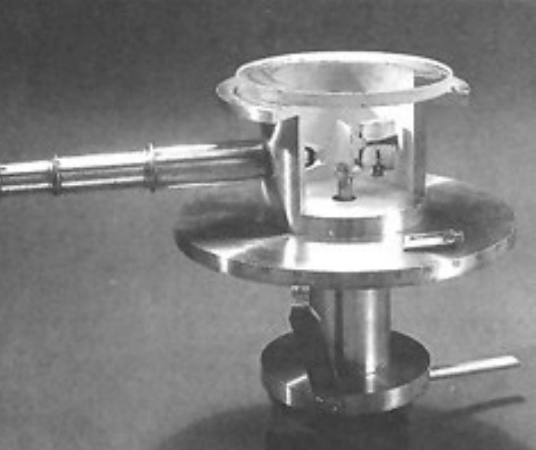
Secretary Brouillette approved Critical Decision-0, "Approve Mission Need," for the EIC on December 19, 2019.

What are we made of?

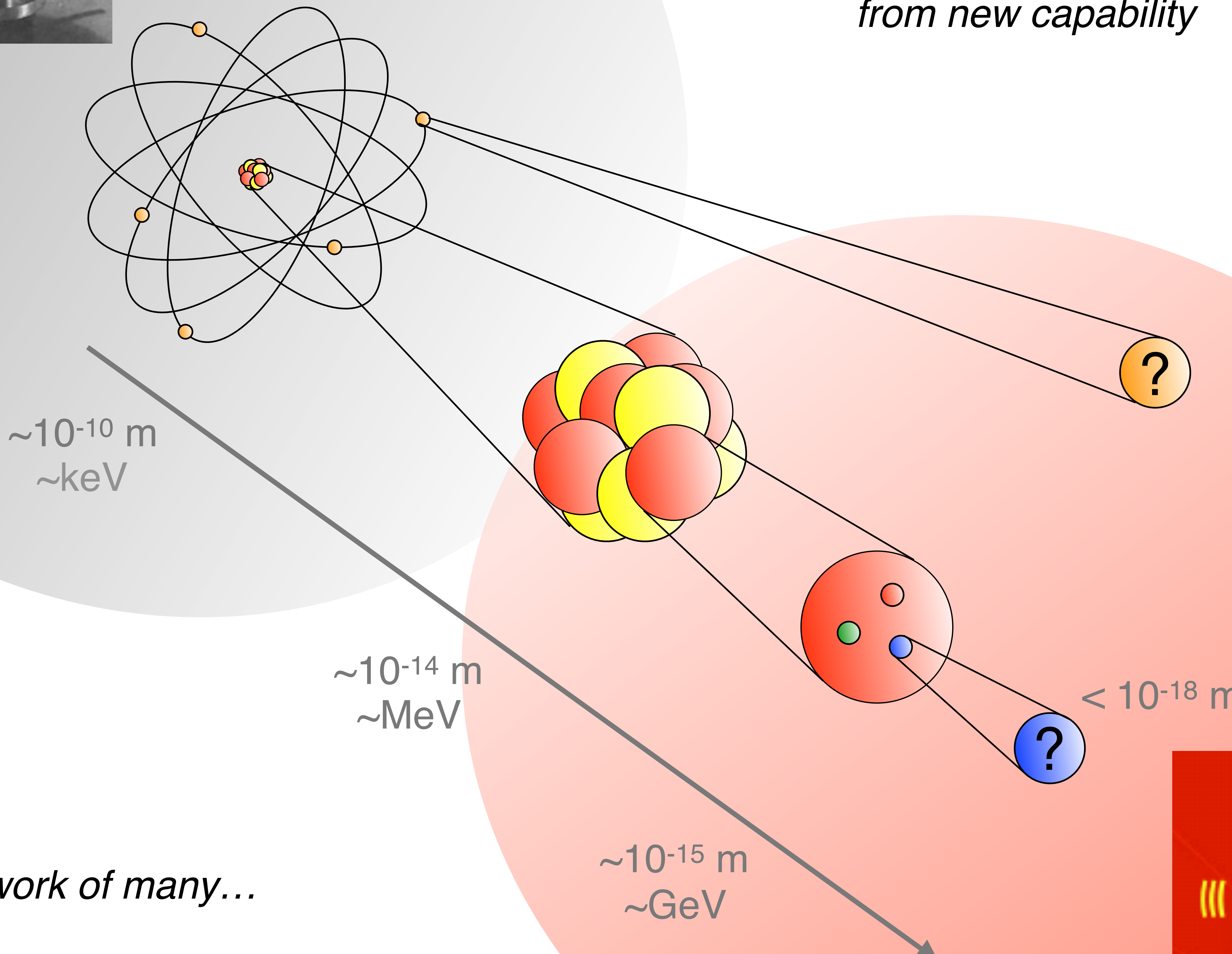


1eV = $1.60 \cdot 10^{-19}$ J

What are we made of?

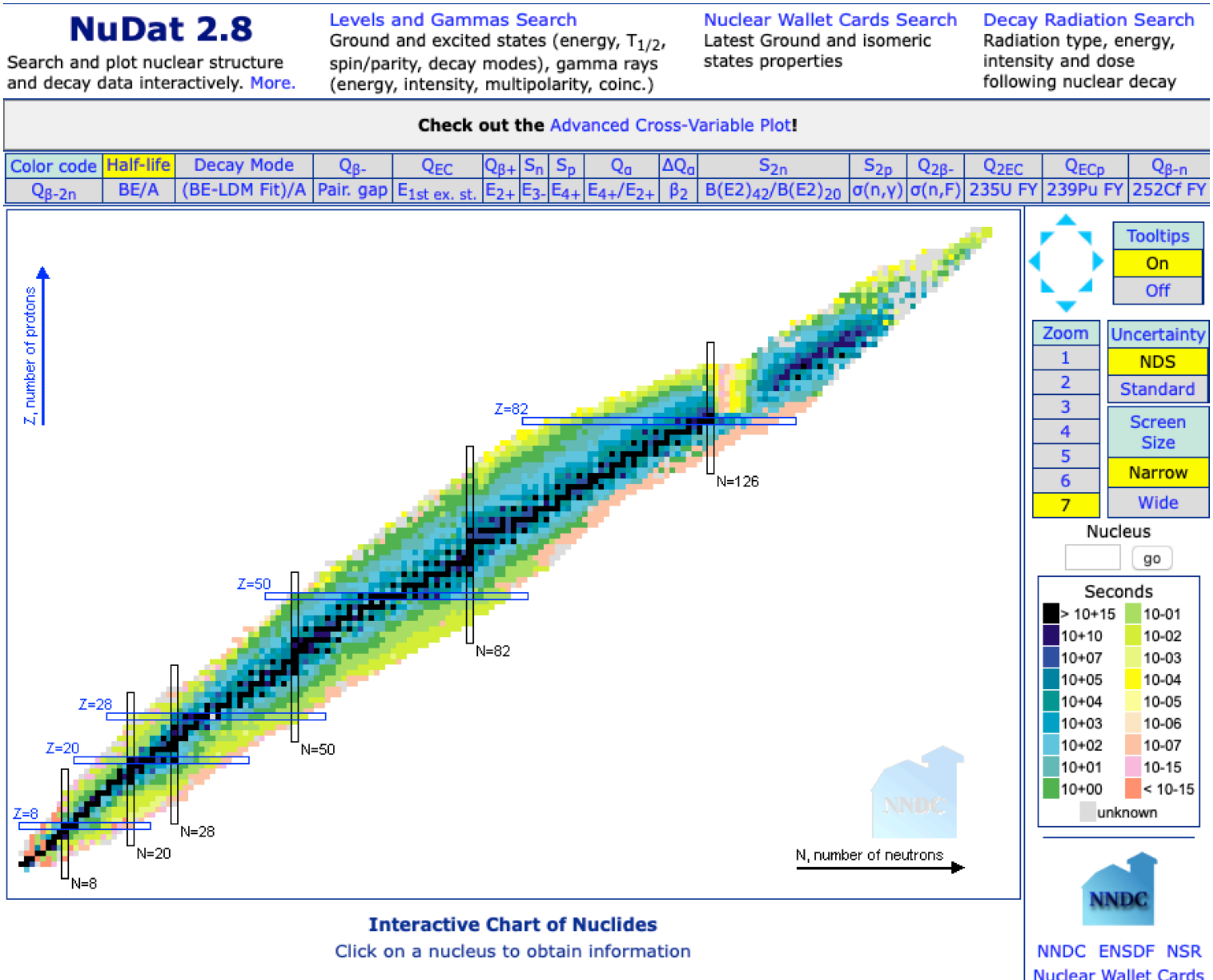


A history of new insight from new capability



The work of many…

What are we made of?



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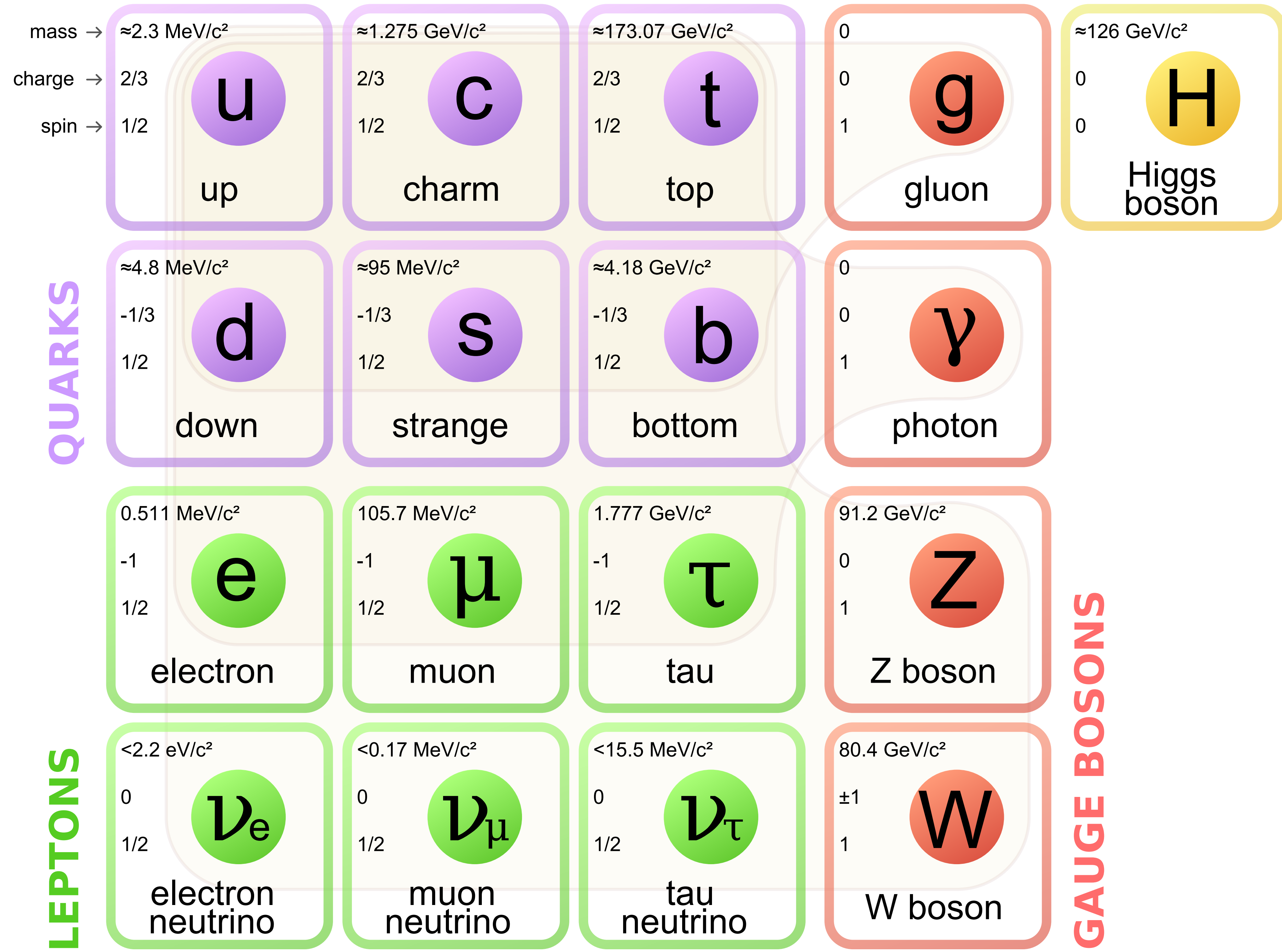


What are we made of?

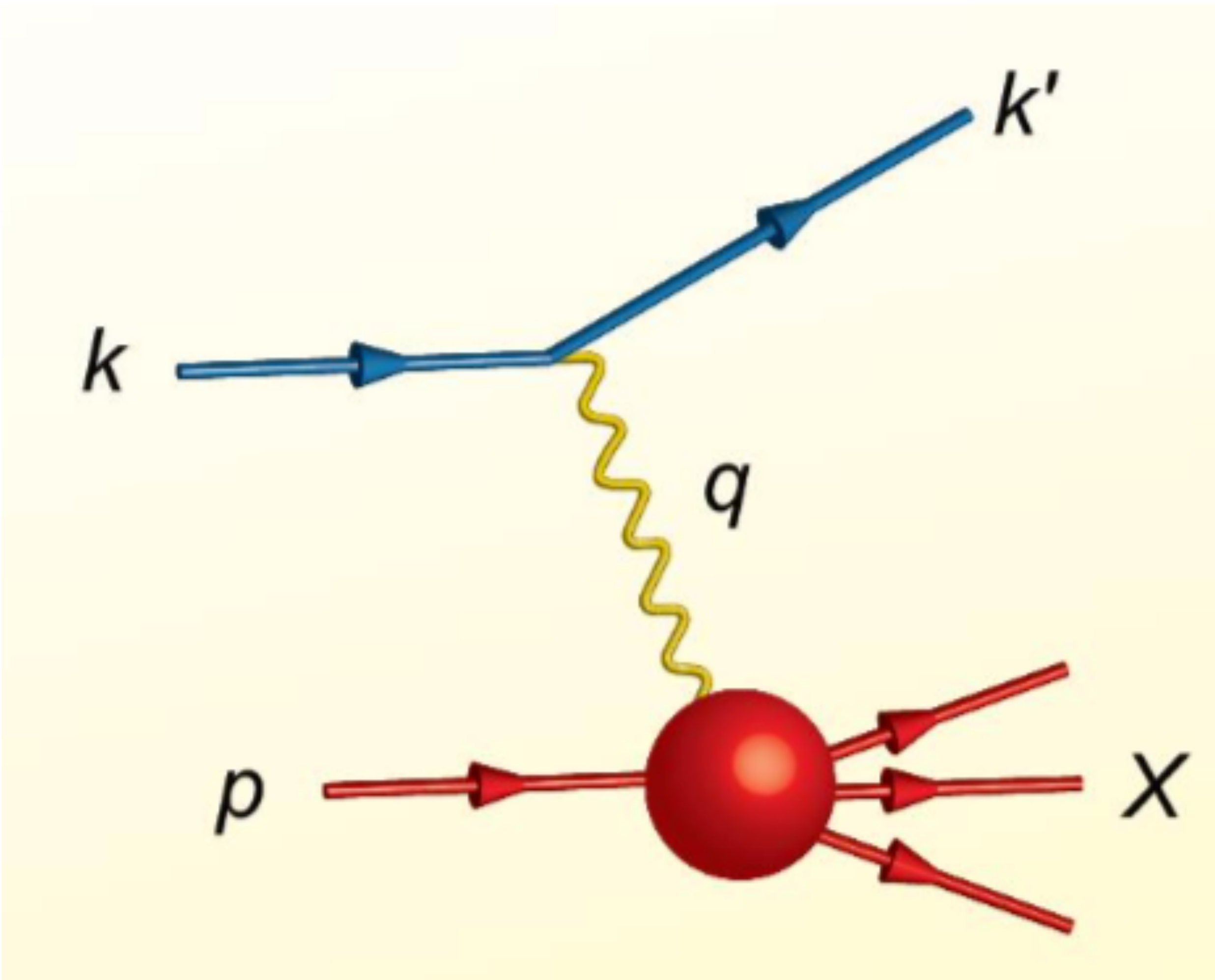
Proton — a strongly-bound object of ~0.8 fm (charge) radius,
~0.94 GeV mass
spin 1/2

None of these are Standard Model parameters,

Ab-initio (lattice) QCD calculations are starting to scratch the surface,

To provoke a little: society is still *far* from “QCD-engineering.”

High-energy (deep-inelastic) electron scattering



Lorentz invariants:

$$E_{\mathrm{cm}}^2 = (p+k)^2$$

$$Q^2 = -(k-k')^2$$

$$x = \frac{Q^2}{2\,p\cdot q}$$

In the Breit frame,

$$\gamma_{\mathrm{Breit}} = \sqrt{(1+\frac{Q^2}{4M^2})}$$

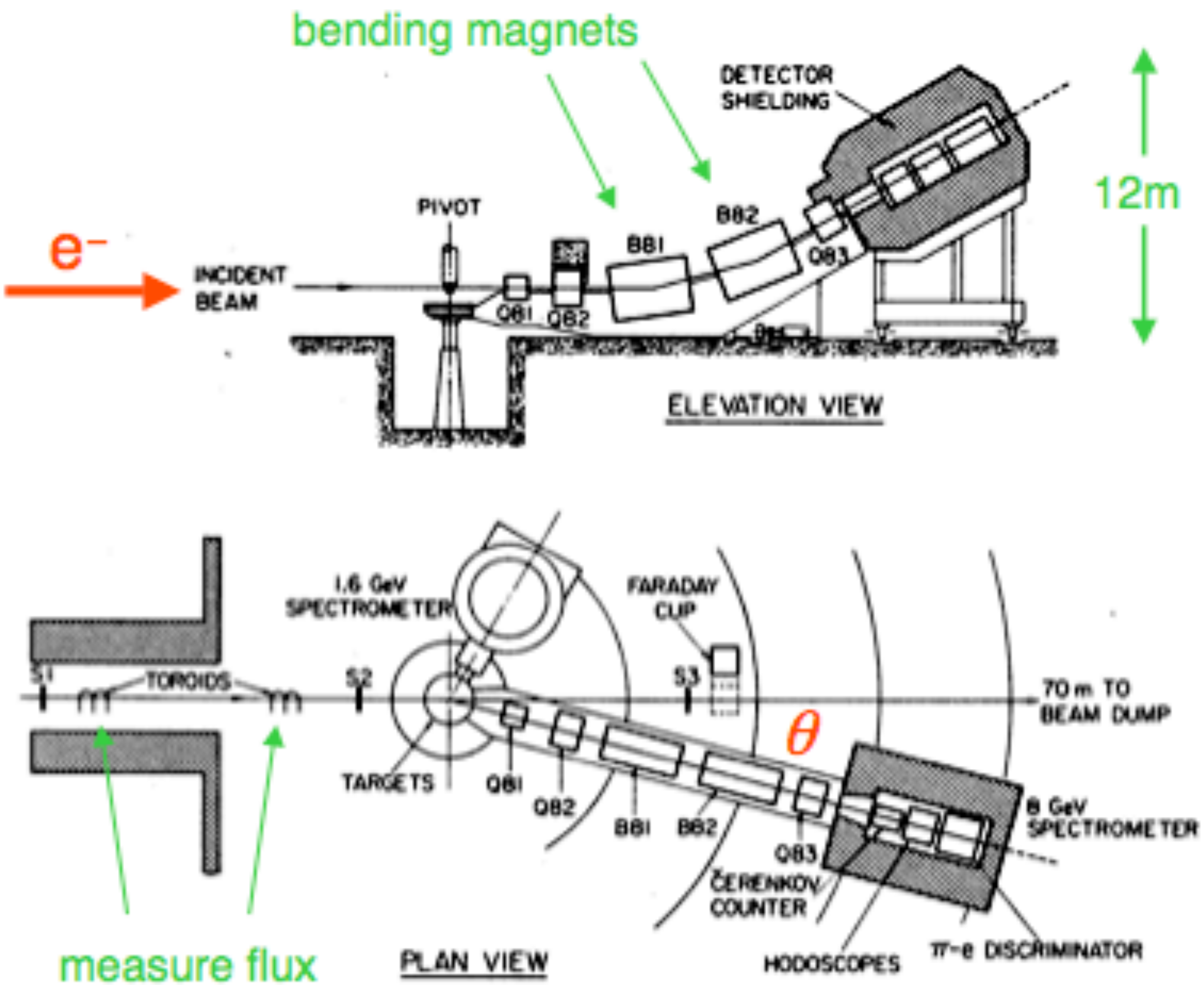
length is contracted and the motion of the proton's constituents is slowed down by time-dilation.

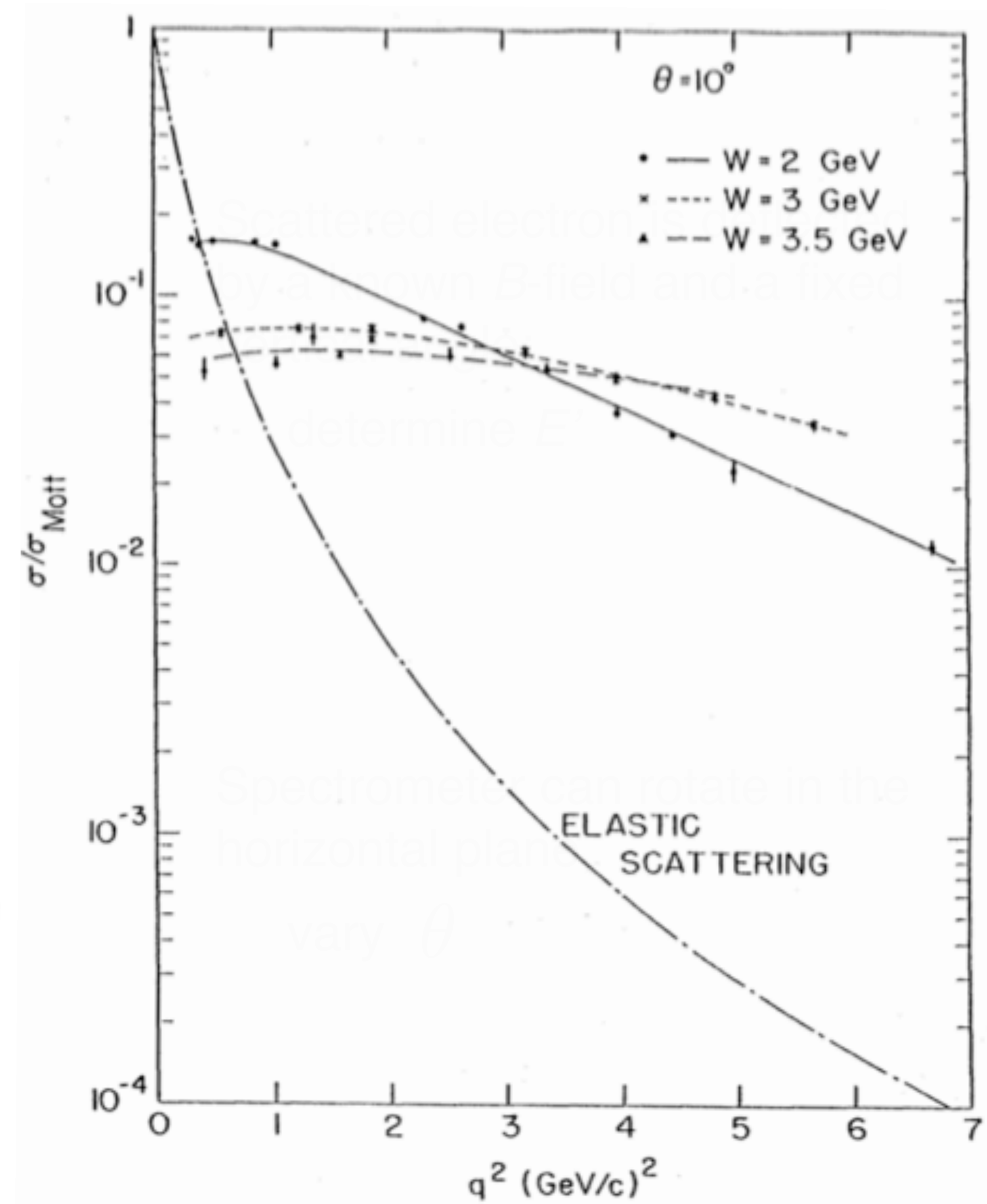
In this frame, the *instantaneous* charge distribution is seen and *x* is understood as the *longitudinal* momentum fraction;

valence quarks ~0.1 < *x* < 1

sea quarks x < ~0.1

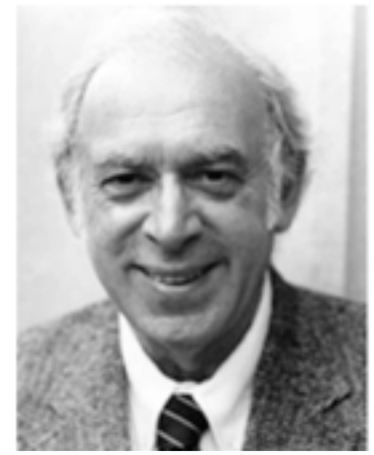
~10 GeV *Deep-Inelastic* Electron Scattering





e.g. J.T.Friedman and H.W. Kendall,
Ann.Rev.Nucl.Sci. 22 (1972) 203

~10 GeV *Deep-Inelastic* Electron Scattering

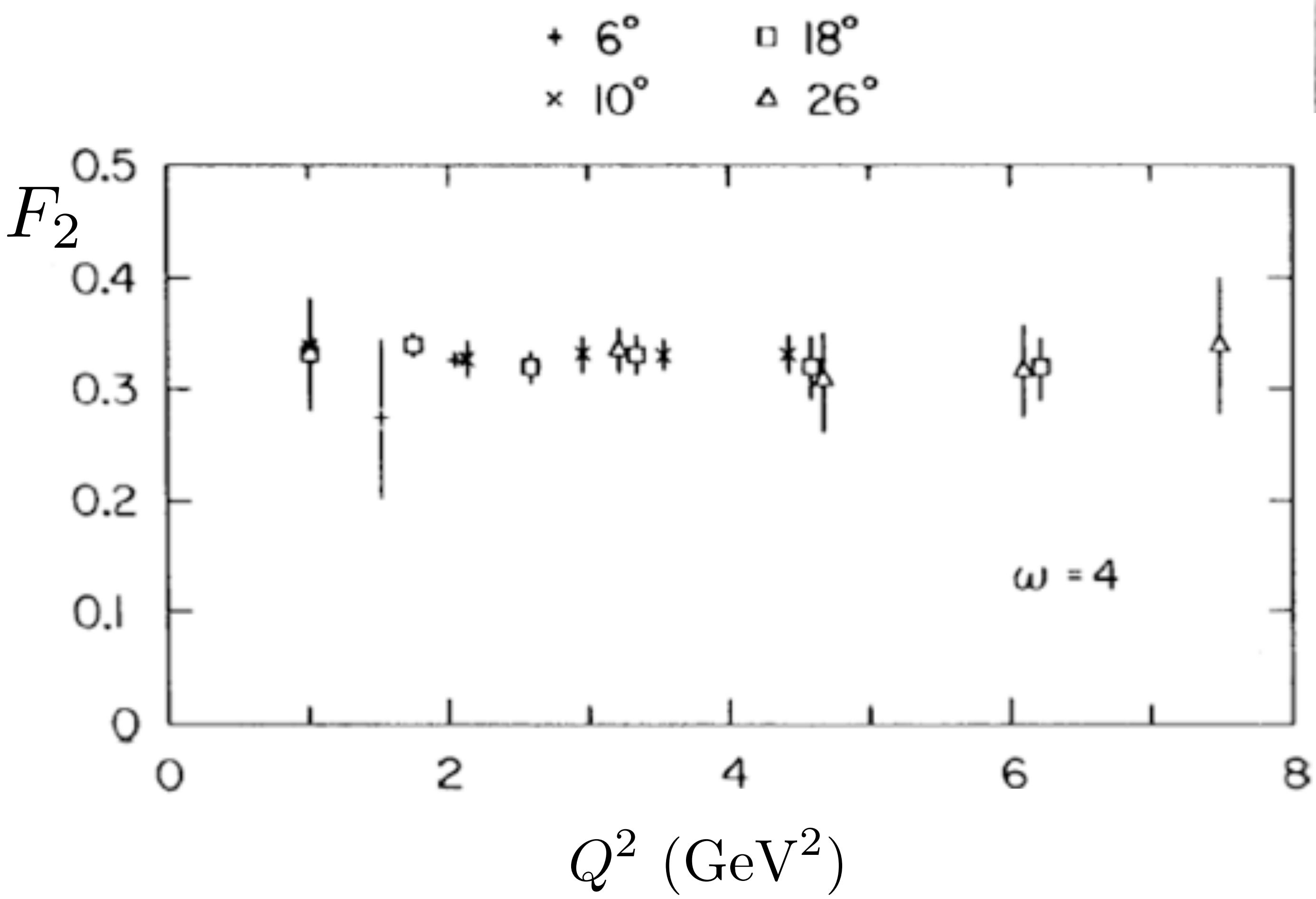


J.T. Friedman

R. Taylor
Nobel Prize 1990

H.W. Kendall

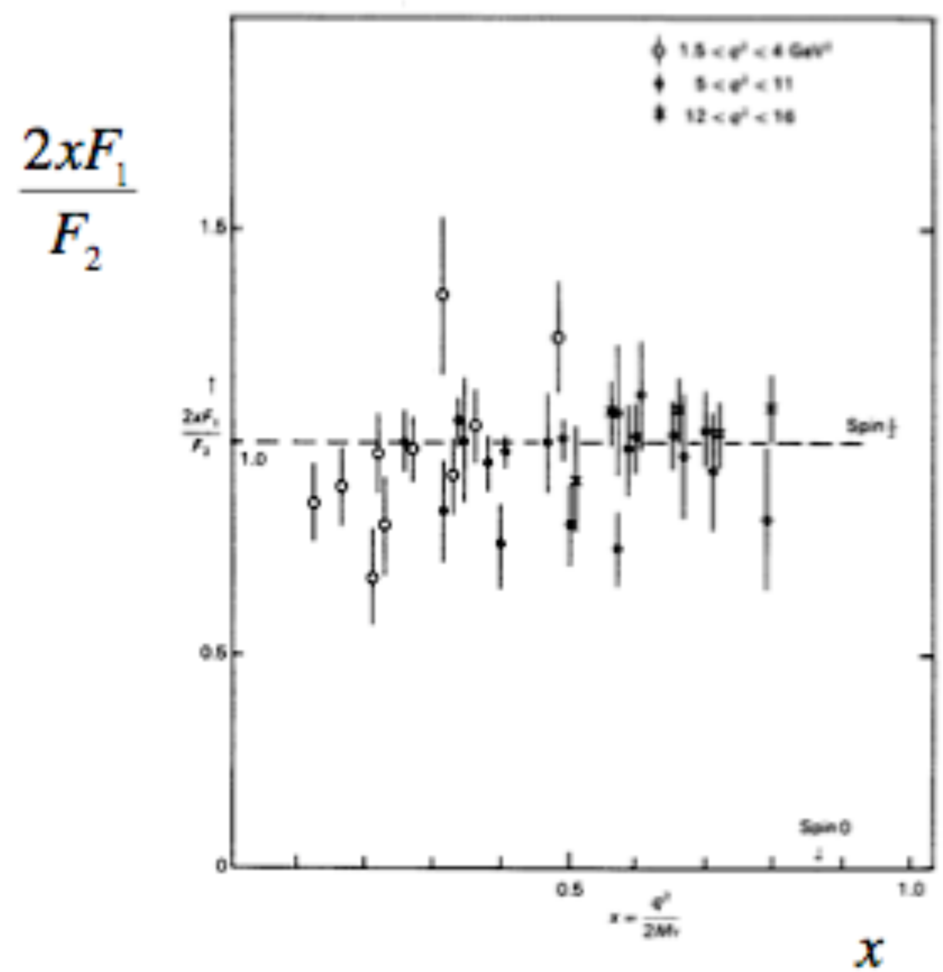
Bjorken scaling:



Point particles cannot be further resolved; their measurement does not depend on wavelength, hence Q^2,

Spin-1/2 quarks cannot absorb longitudinally polarized vector bosons and, conversely, spin-0 (scalar) quarks cannot absorb transversely polarized photons.

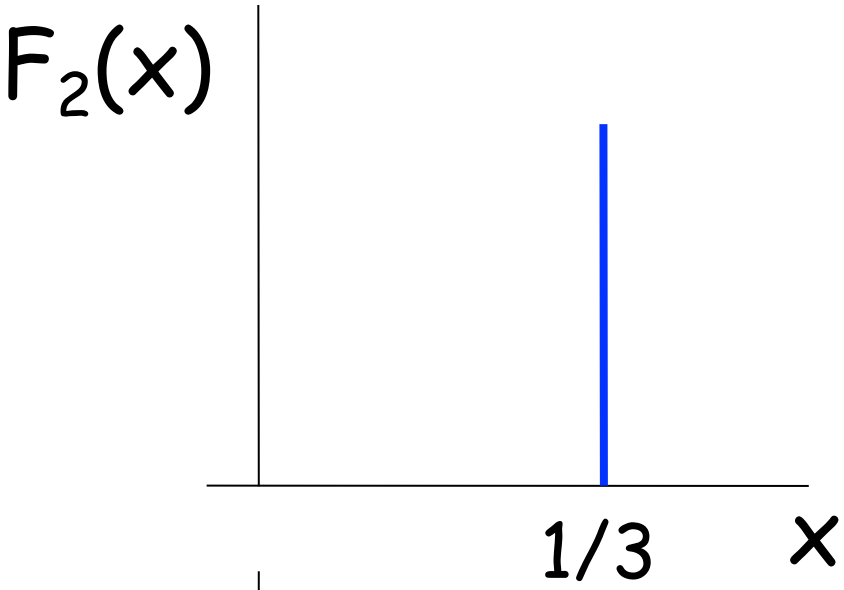
Callan-Gross relation:



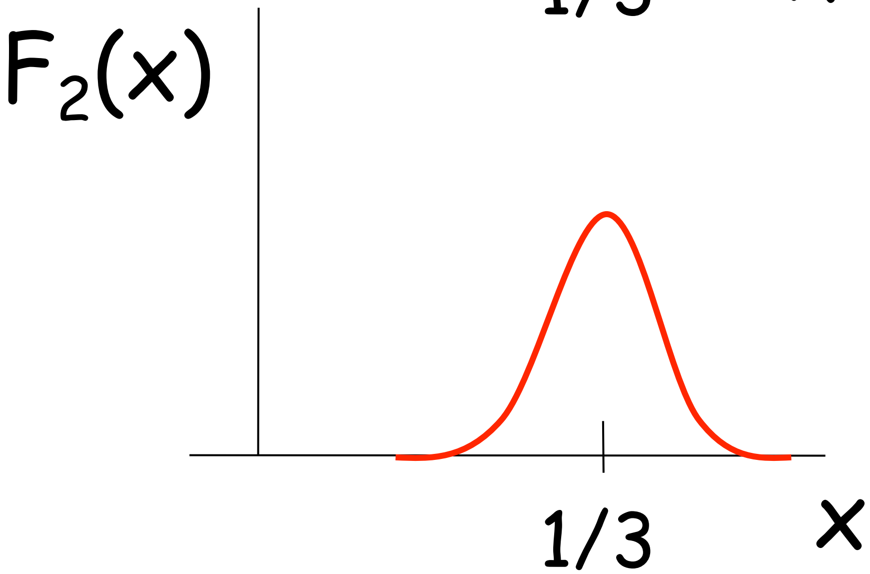
spin 1/2

spin 0

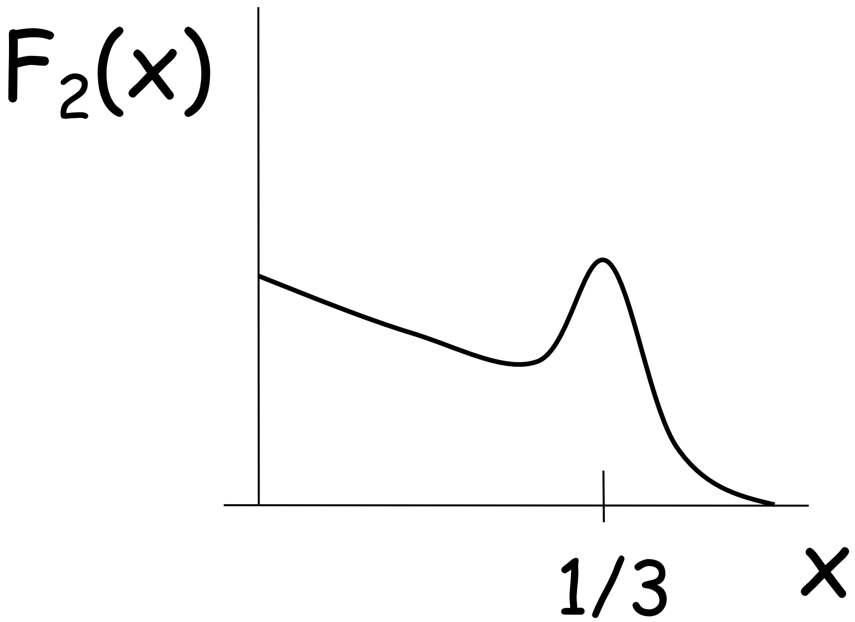
Nucleon Structure



Three quarks with 1/3 of total proton momentum each.



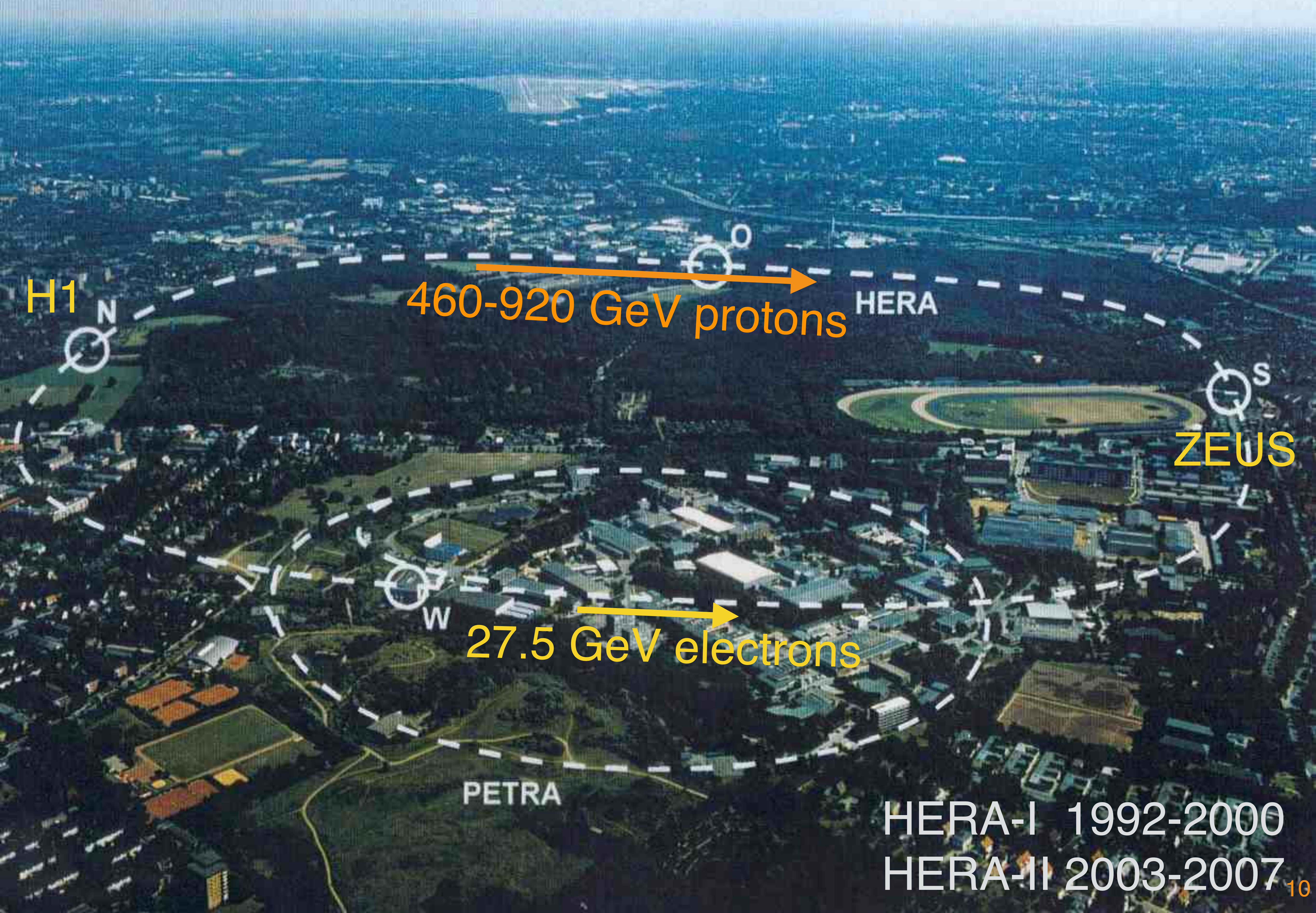
Three quarks with some momentum smearing.



The three quarks radiate partons to lower momentum fractions *x*.

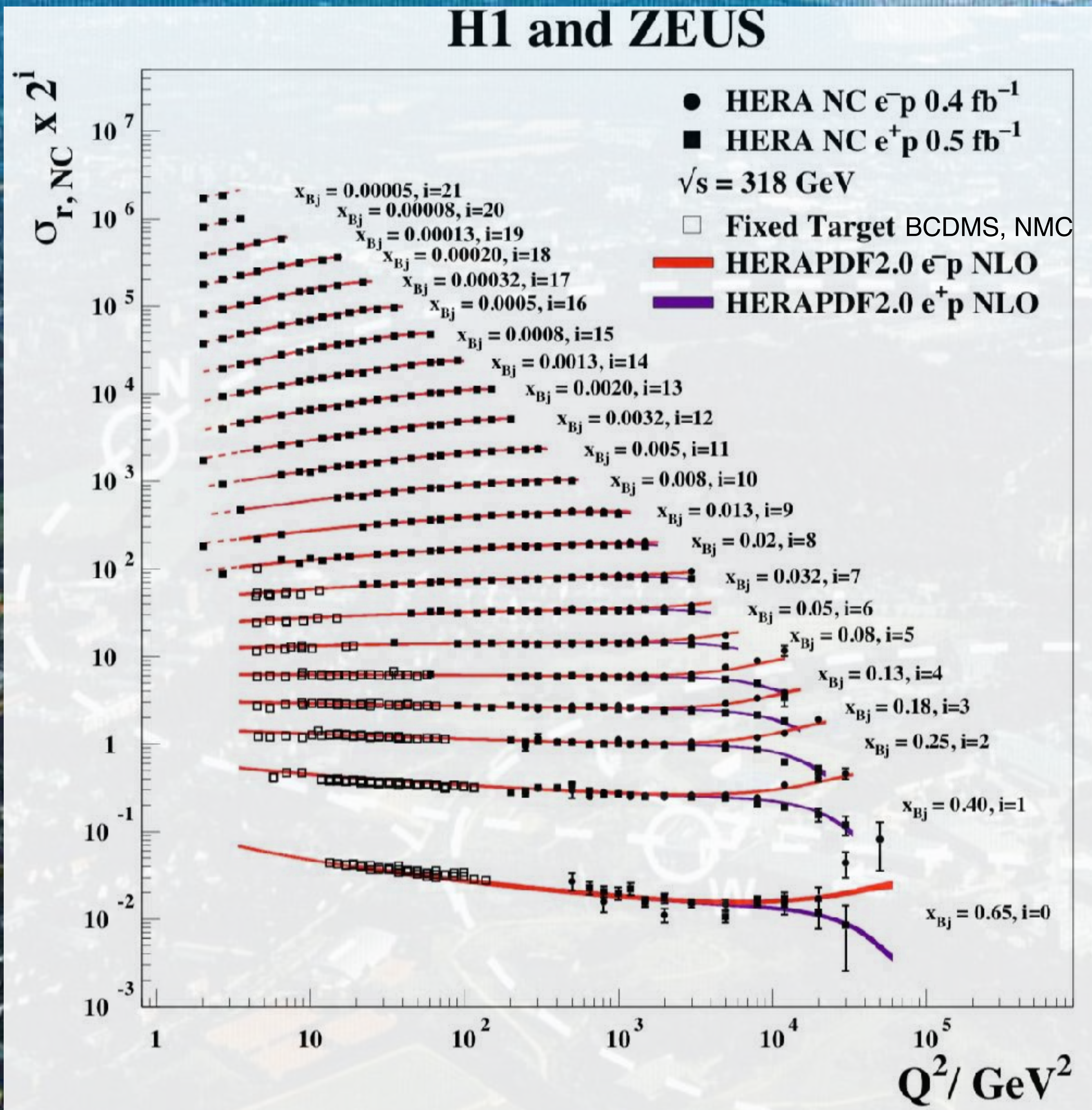
Insight really only from the first EIC, HERA

HERA - Electron Proton Collider



HERA's Legacy

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

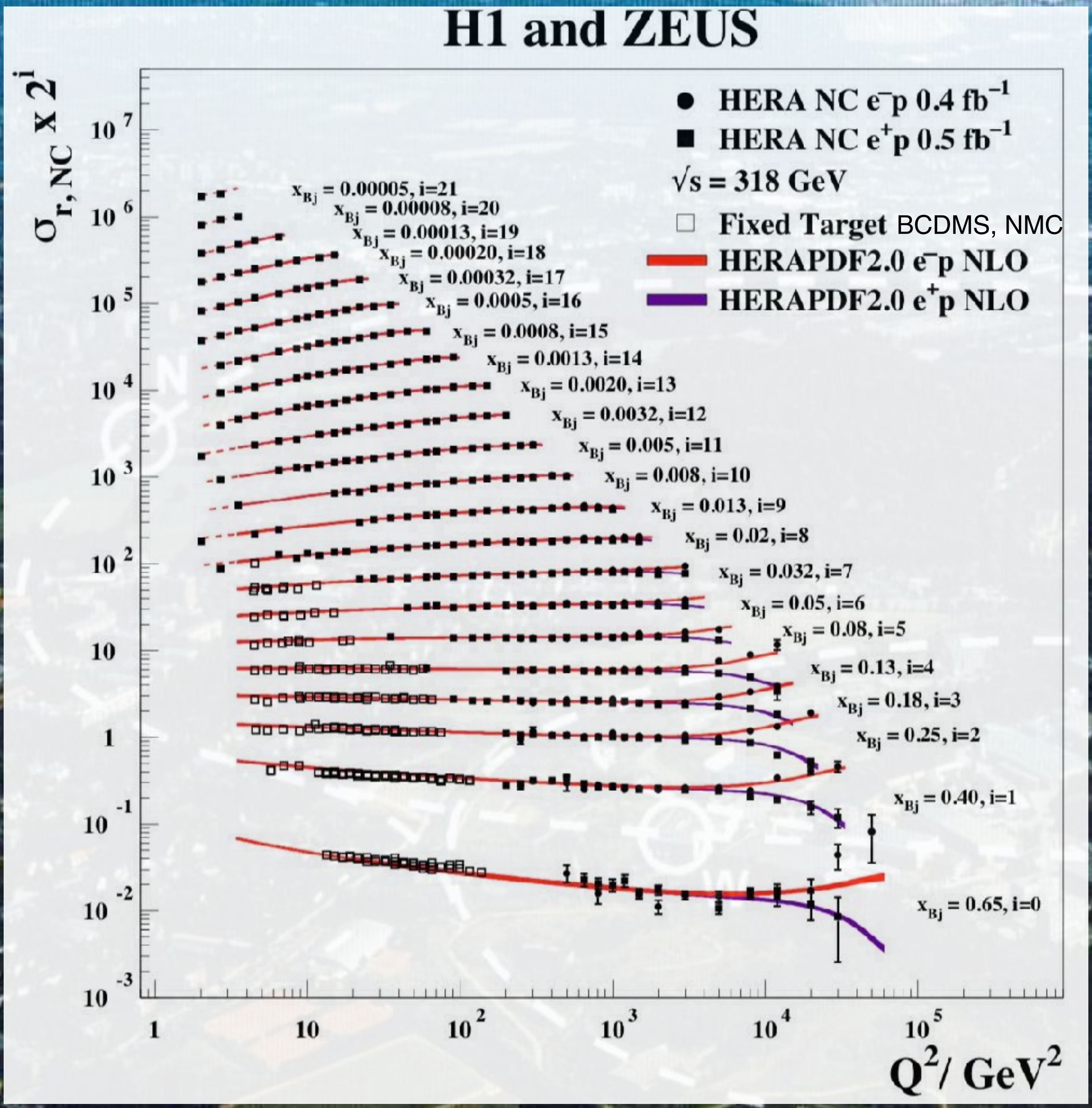


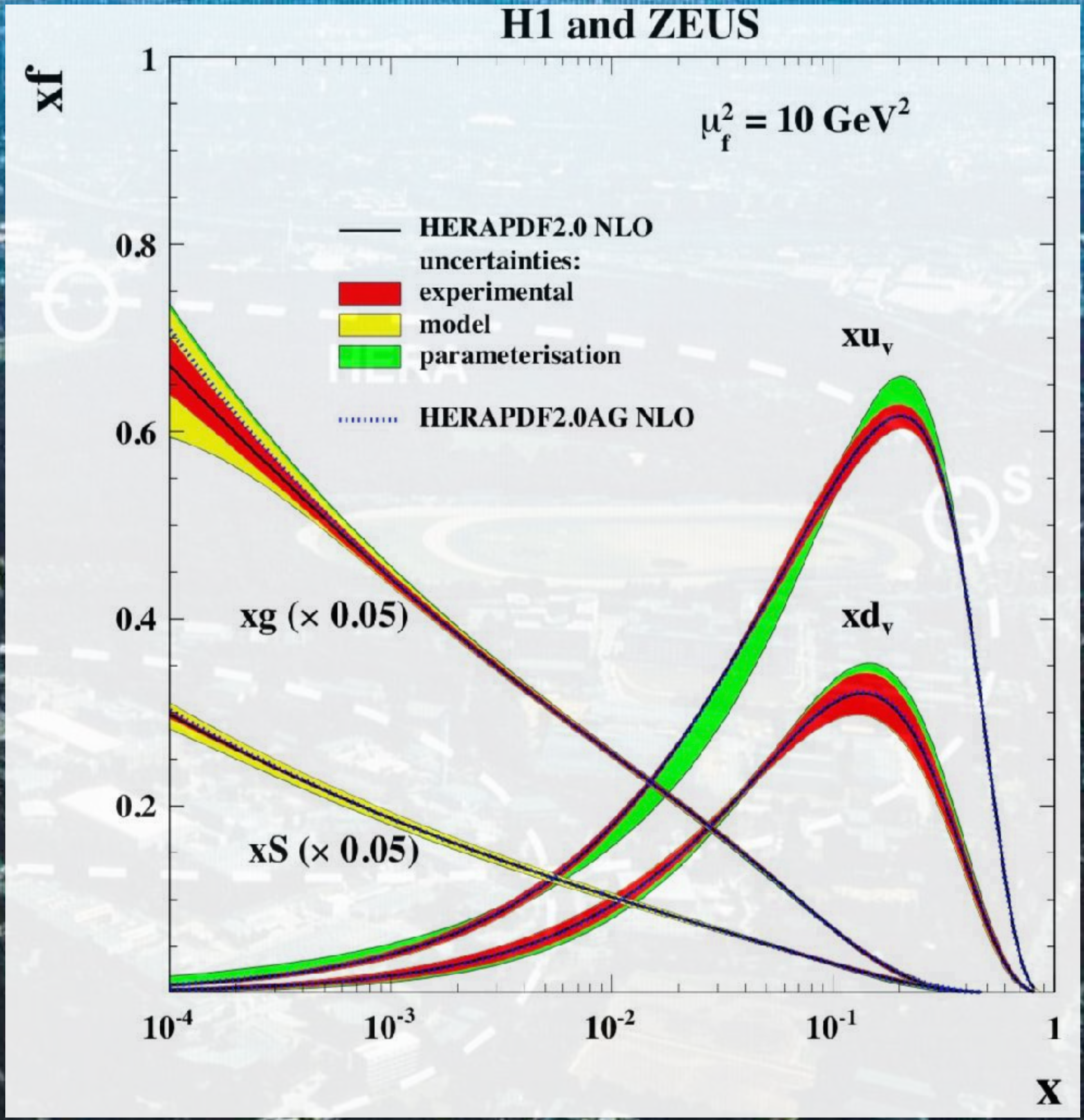
A lot in this plot:

- covers about five orders of magnitude in x and Q^2,
- consistency of fixed-target data and HERA data,
- scaling at $x \sim 0.1$ and violations elsewhere,
- strong rise of gluon density,
- E.W. interference at high Q^2,
- crucial input to “PDF fits”

HERA's Legacy

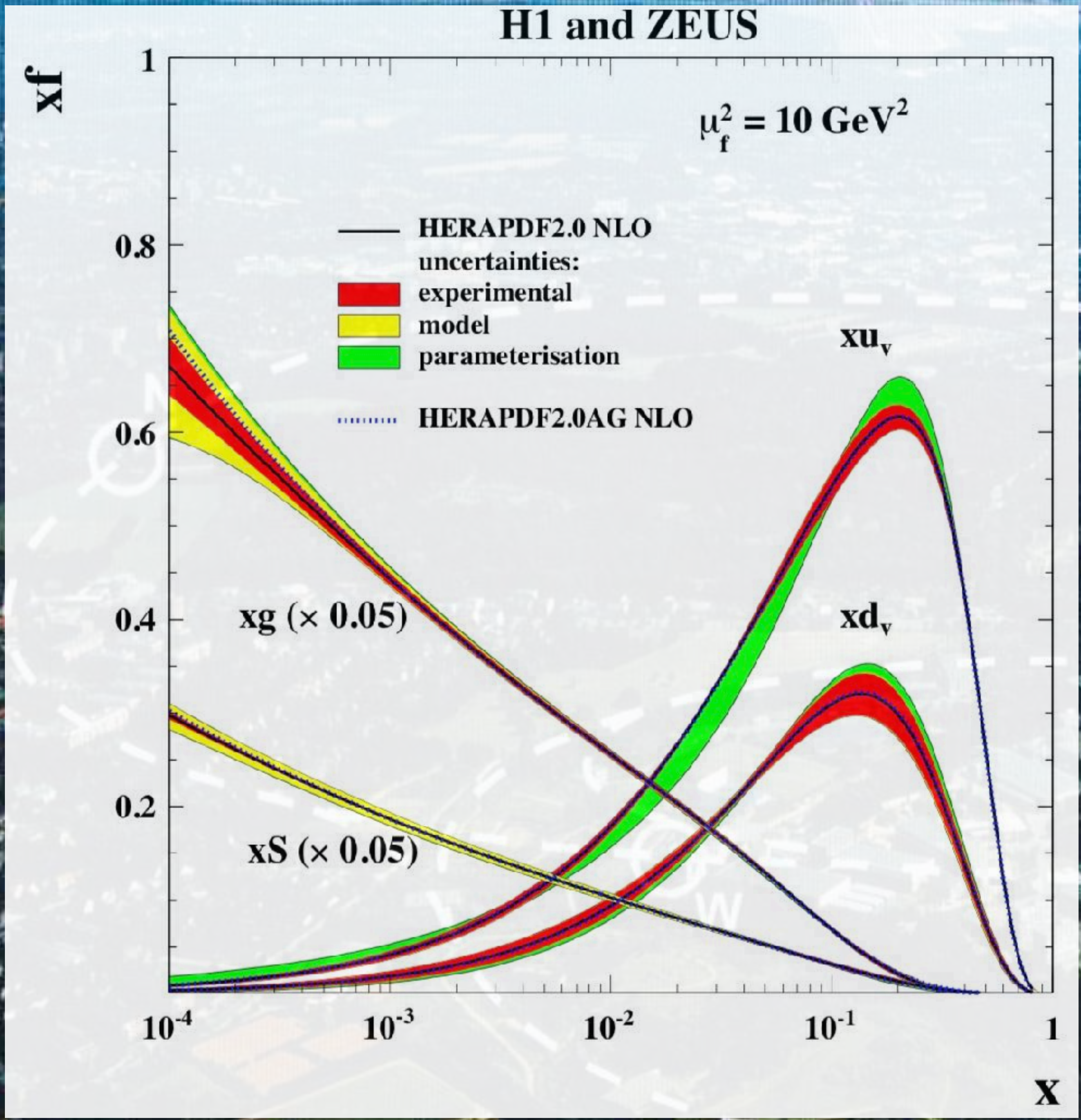
H1 and ZEUS Coll., EPJ C75 (2015) 580





Vast body of *precision* measurements over a wide kinematic range,
Exquisite insight in high-energy proton structure and QCD dynamics.

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

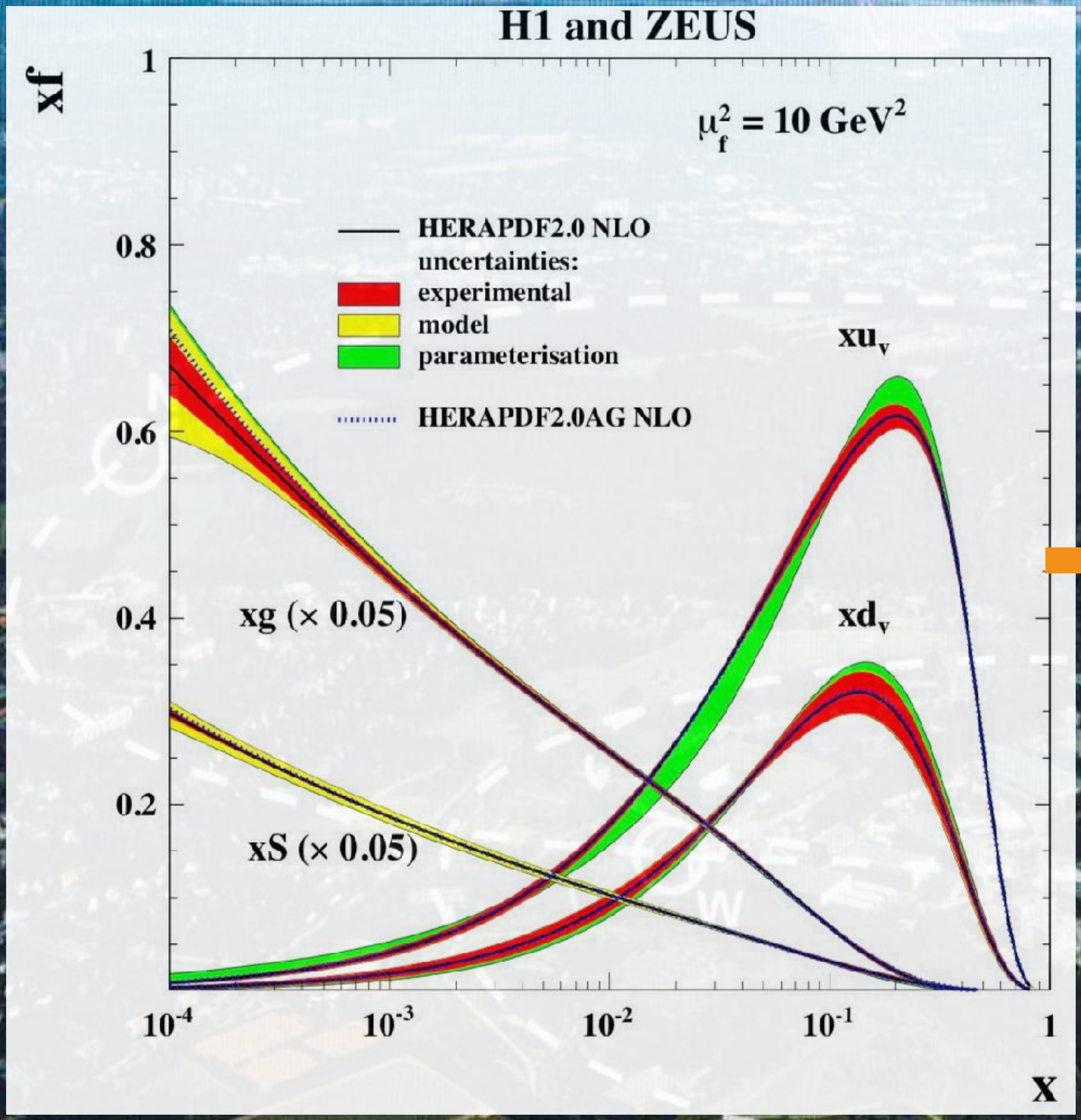
HERAPDF2.0:

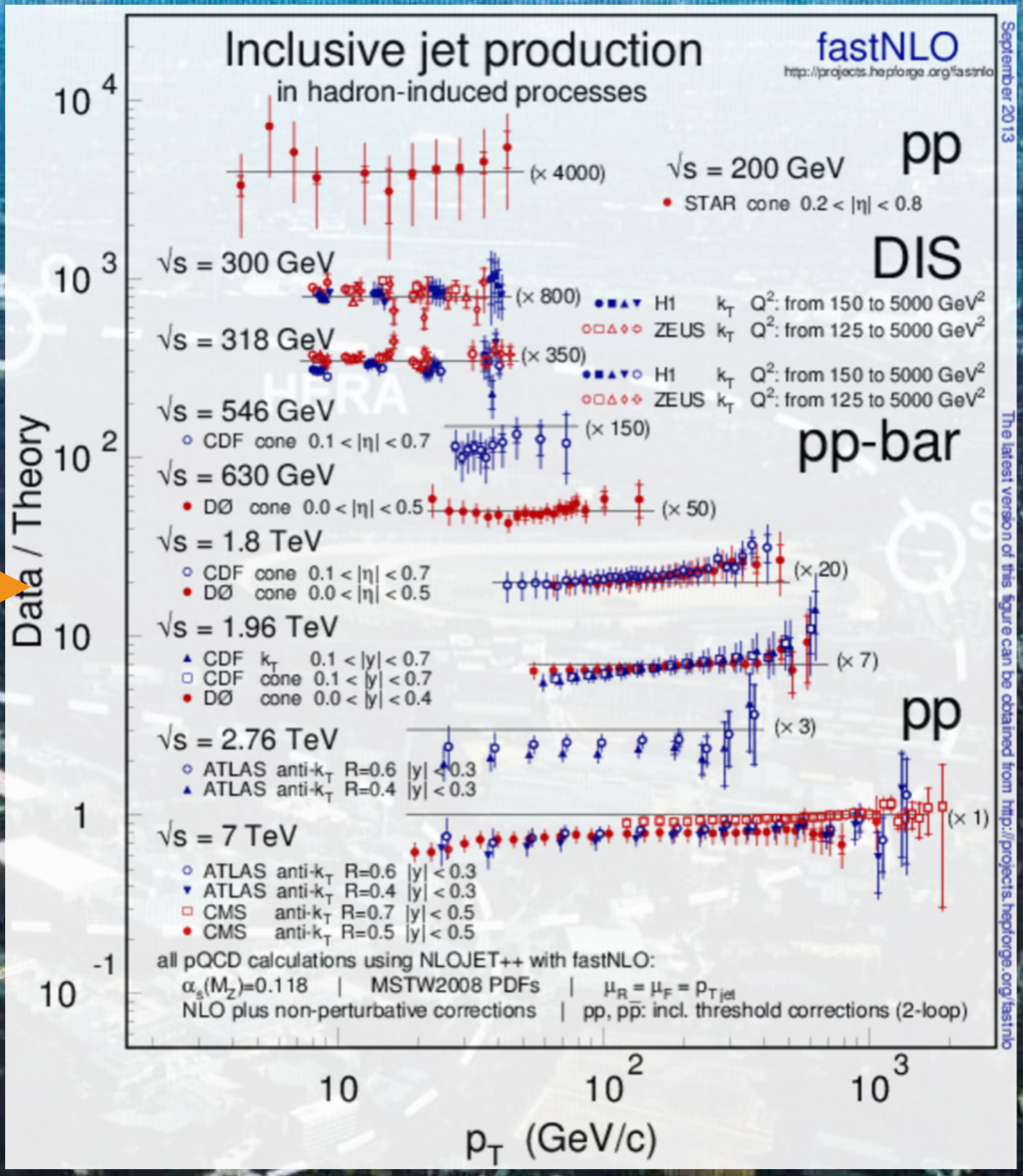
14 parameters,

~1400 combined data points,

Vast body of *precision* measurements over a wide kinematic range,
Exquisite insight in high-energy proton structure and QCD dynamics.

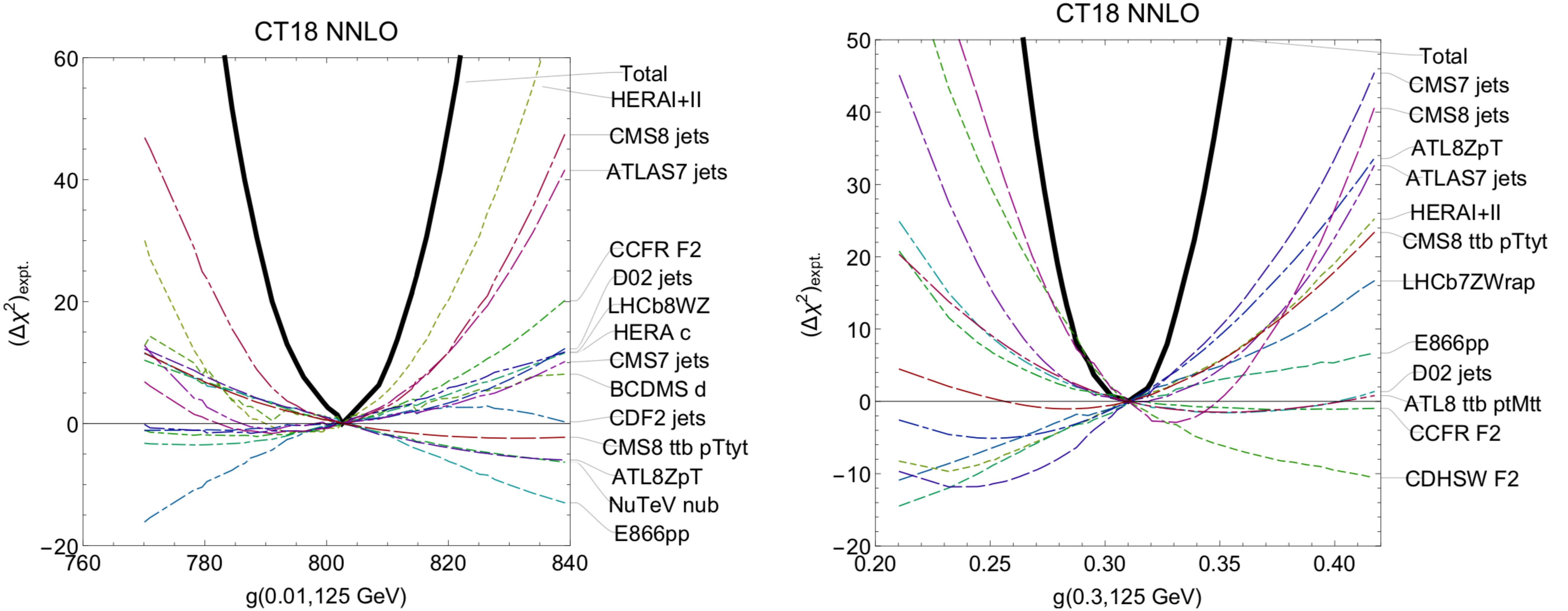
HERA's Legacy





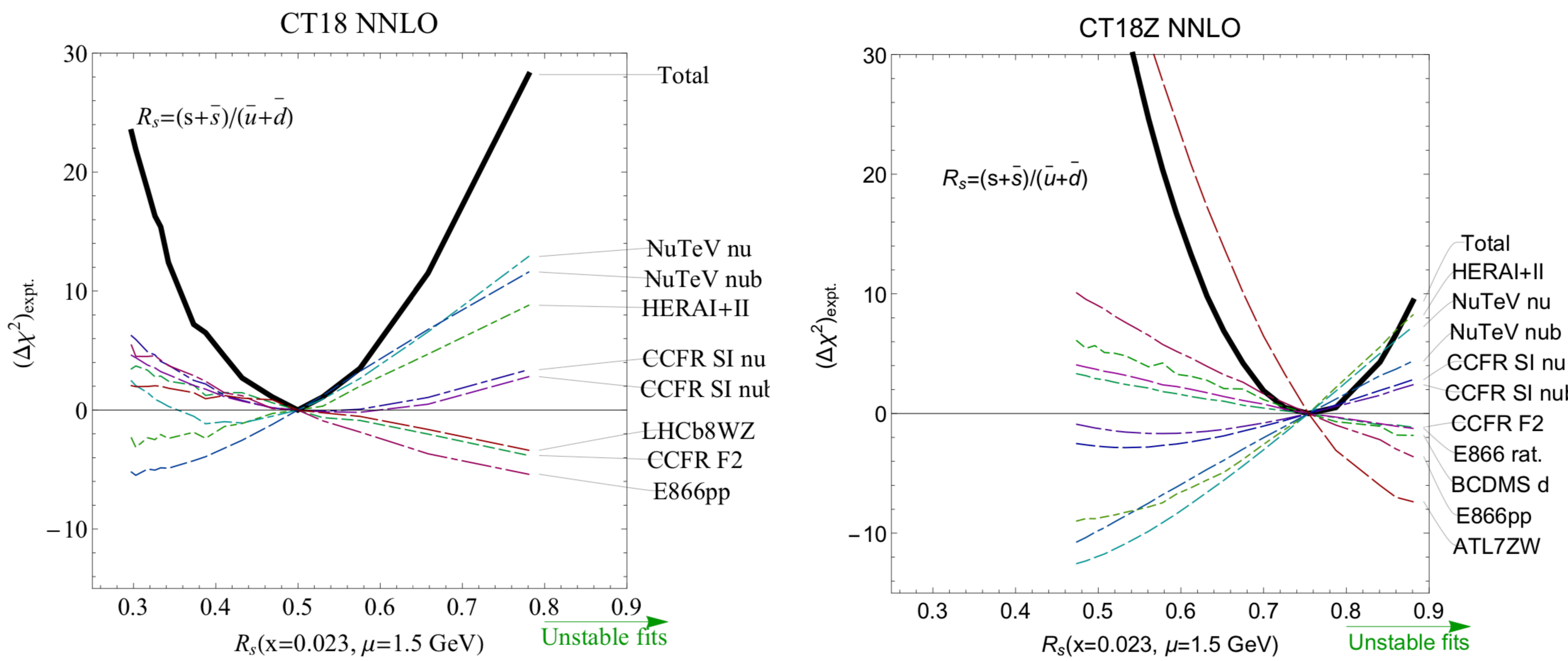
Factorization, the separation of short distance and long distance physics, combined with PDFs are 'universally invaluable' in hard scattering processes.

Truth in advertising….



A great deal has been learned and continues to be learned from other experiments, e.g. from the LHC…. Shown here CTEQ fits, arXiv:1908.11238

Truth in advertising….



CTEQ fits, arXiv:1908.11238 — How strange is the proton?
PID was missing at HERA and is an absolute *must* for EIC.

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?

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

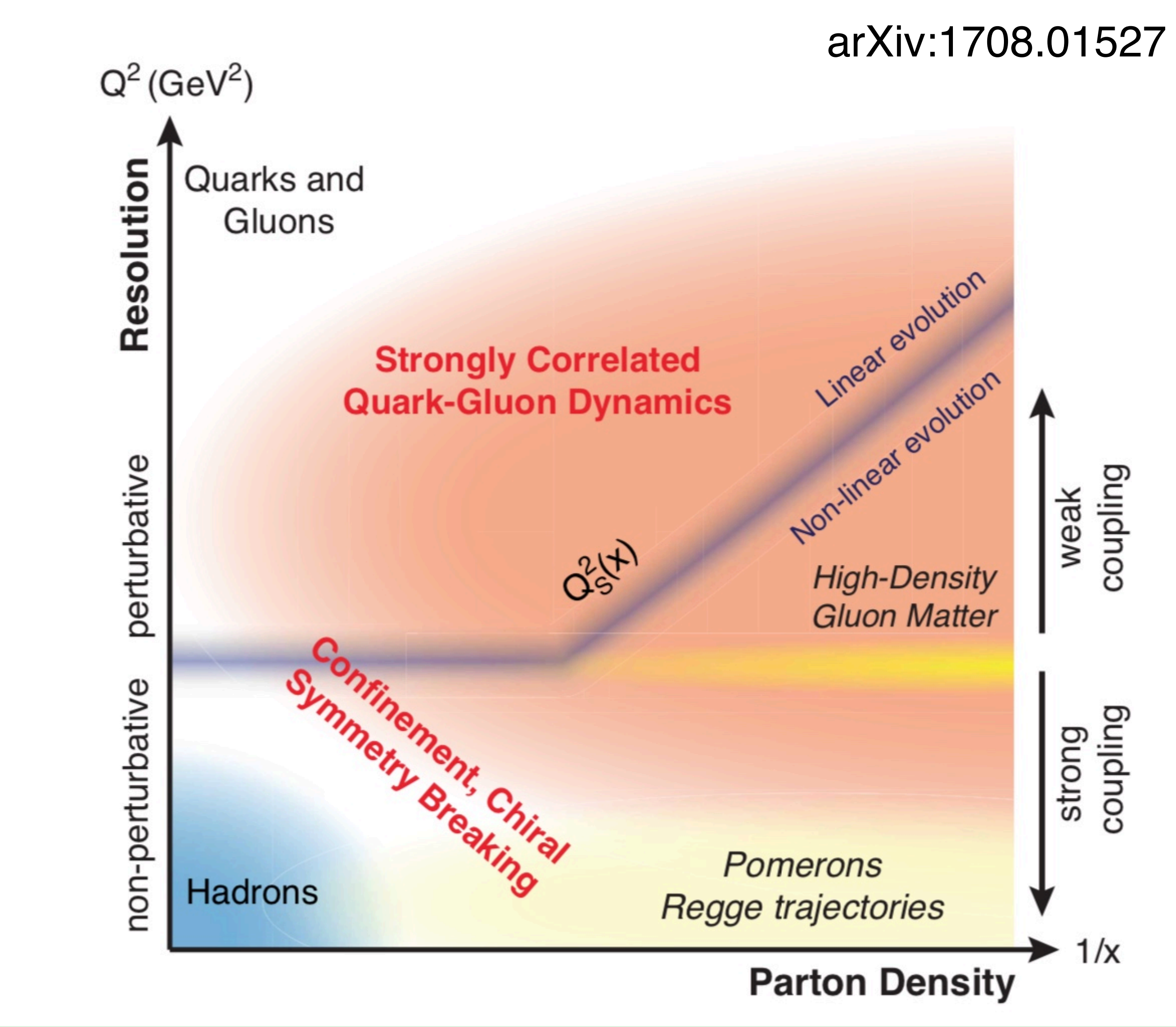
Factorization theorem(s) + one-dimensional parton distributions,
no correlations among the partons

Not quite…. ***more than a few high-energy observations are actually different***
QCD is the richest part of the Standard Model Gauge Field Theory and will (have to) be developed much further, on its own and as backgrnd.

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)

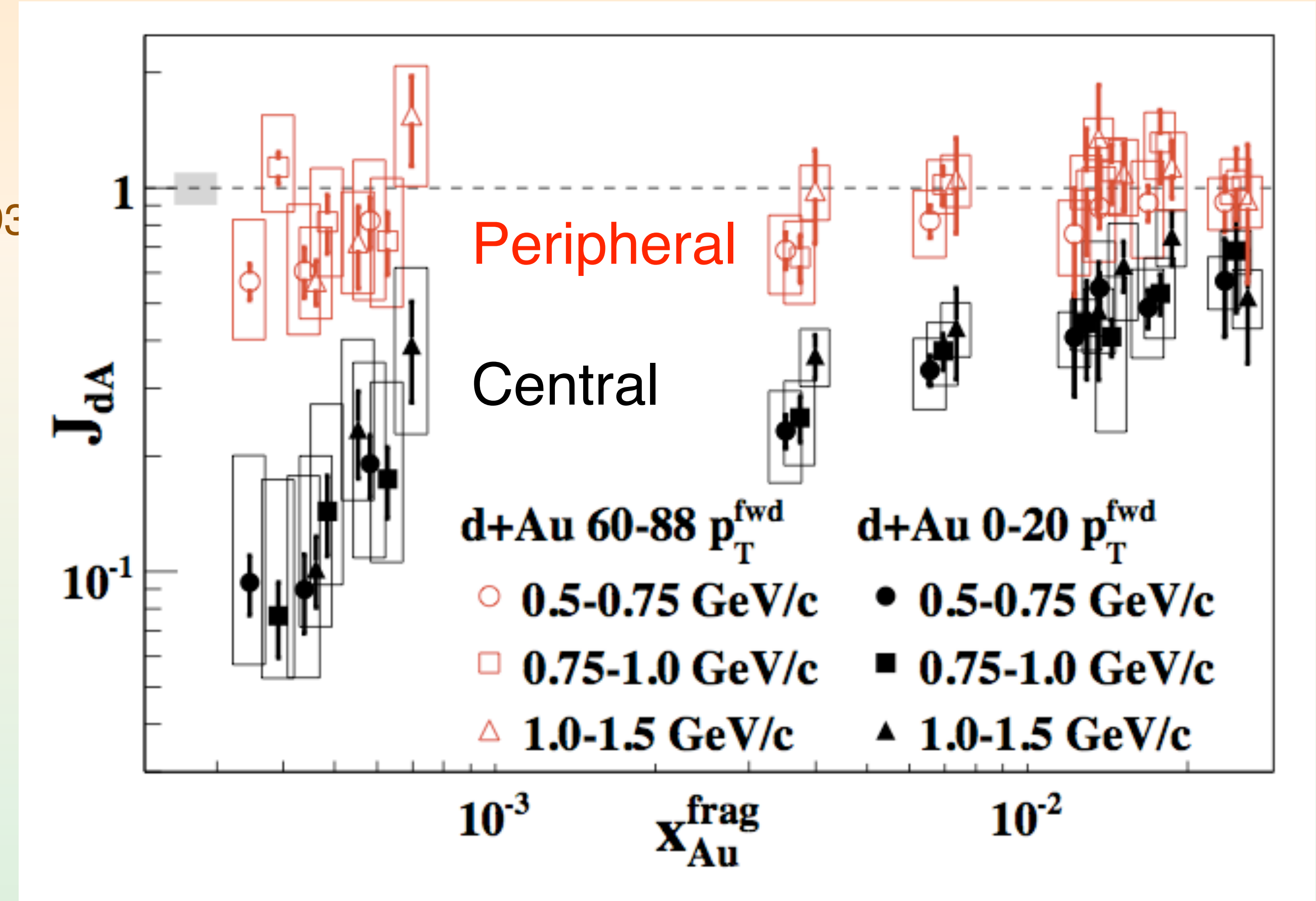


HERA - RHIC, LHC

Saturation:

- geometric scaling of the cross section,
- diffractive cross-section independent of W and Q²,
- evidence for BFKL dynamics (Ball, arXiv:1710.0593
- forward multiplicities and correlations at RHIC,

Forward-Forward Mid-forward correlation



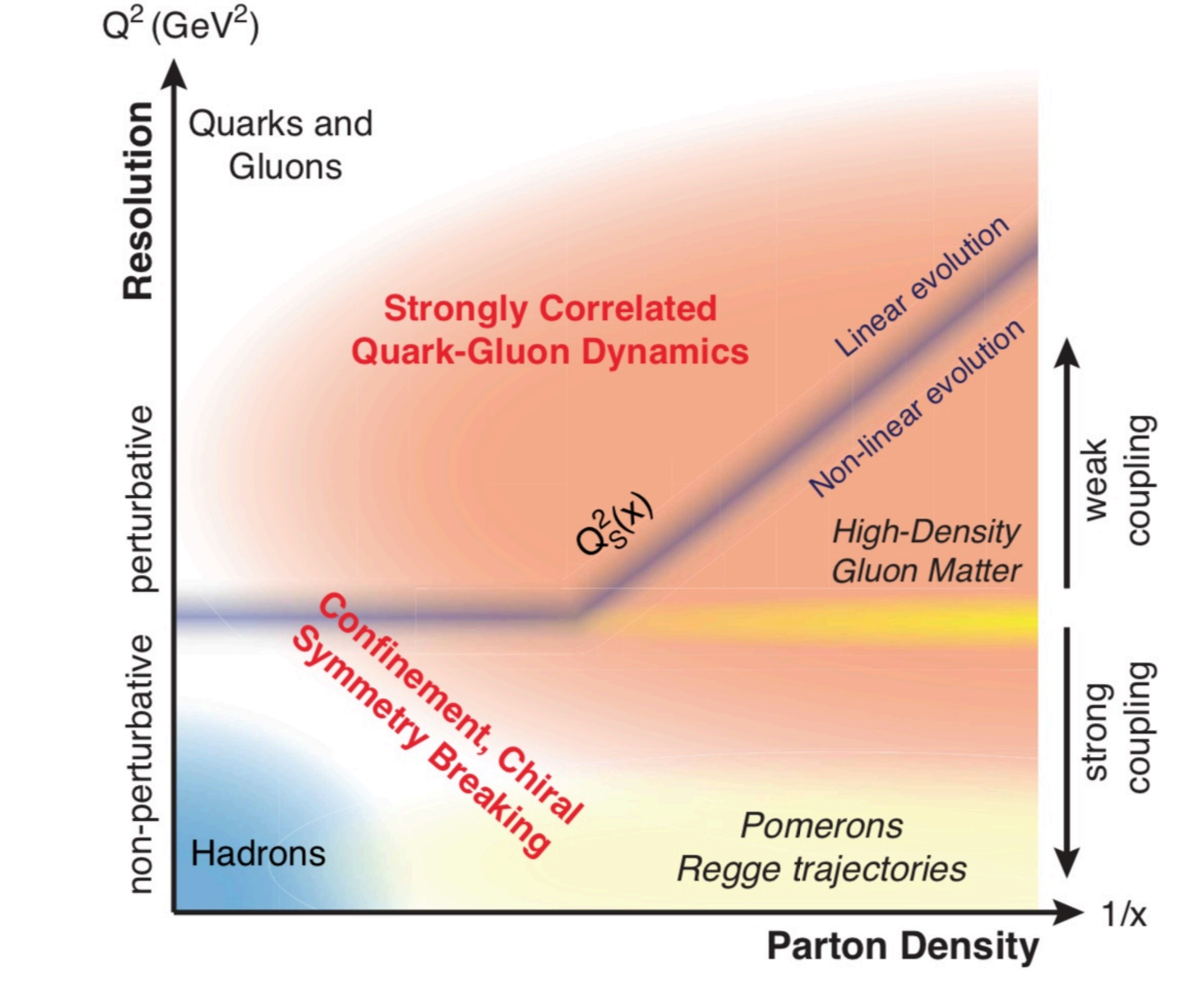
Phenix, Phys.Rev.Lett. 107 (2011) 172301

HERA - RHIC, LHC

Saturation:

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

arXiv:1708.01527



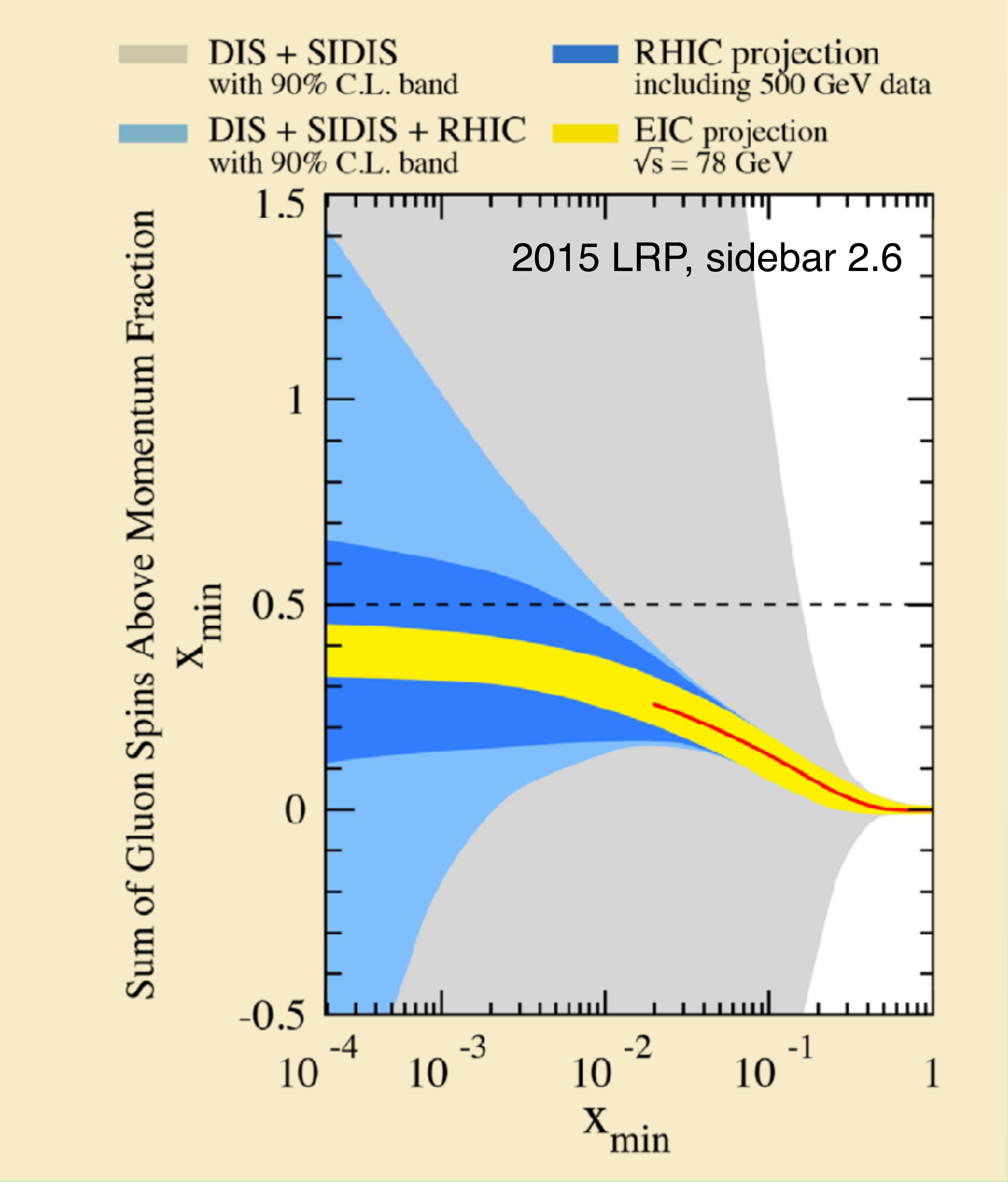
HERA - RHIC, CERN

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 is making impressive progress,



HERA - RHIC, JLab, CERN

Saturation:

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- 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:

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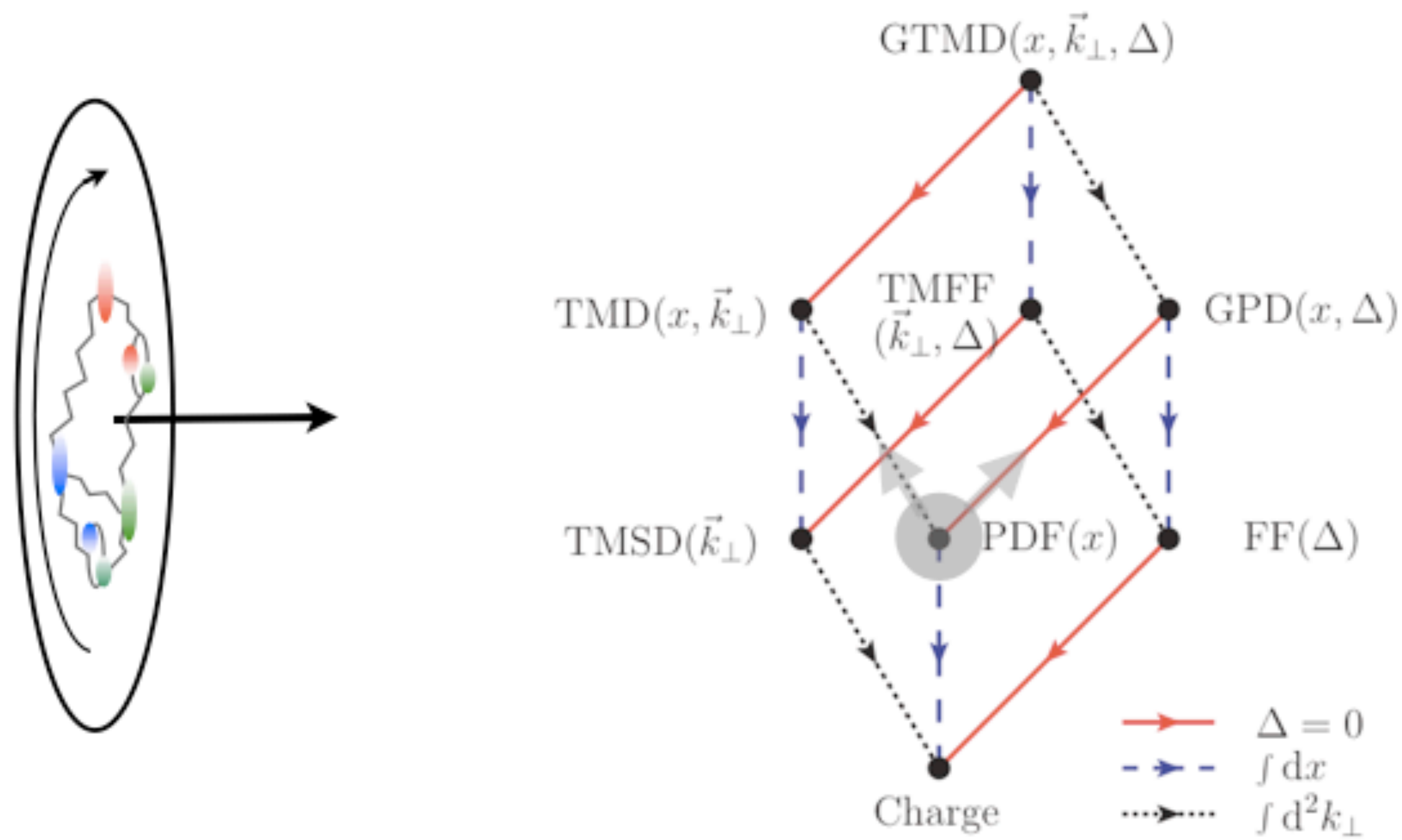
  strange (anti-)quarks?
- large forward transverse-spin phenomena
- Lattice-QCD is making impressive progress,

Imaging / tomography:

- valence quark region,



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

High-Energy Physics

Nuclear Physics

Representative though not complete, c.f. ENC, HE-LHeC, PEPIC, VHEeP, FCC-eh

Electron Ion Collider Initiatives

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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.
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proton x_{min}	1×10^{-5}	5×10^{-7}	3×10^{-3}	
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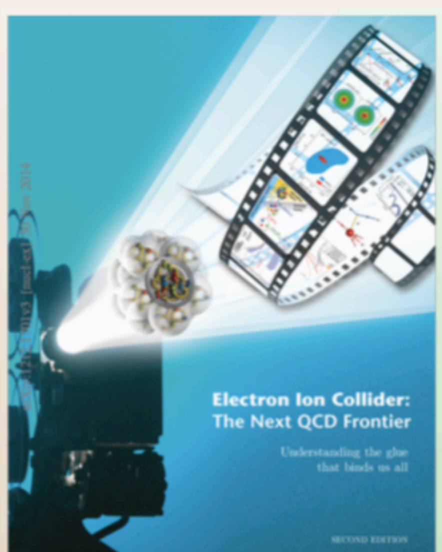
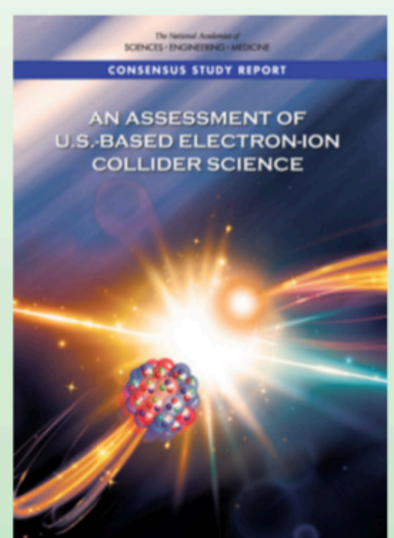
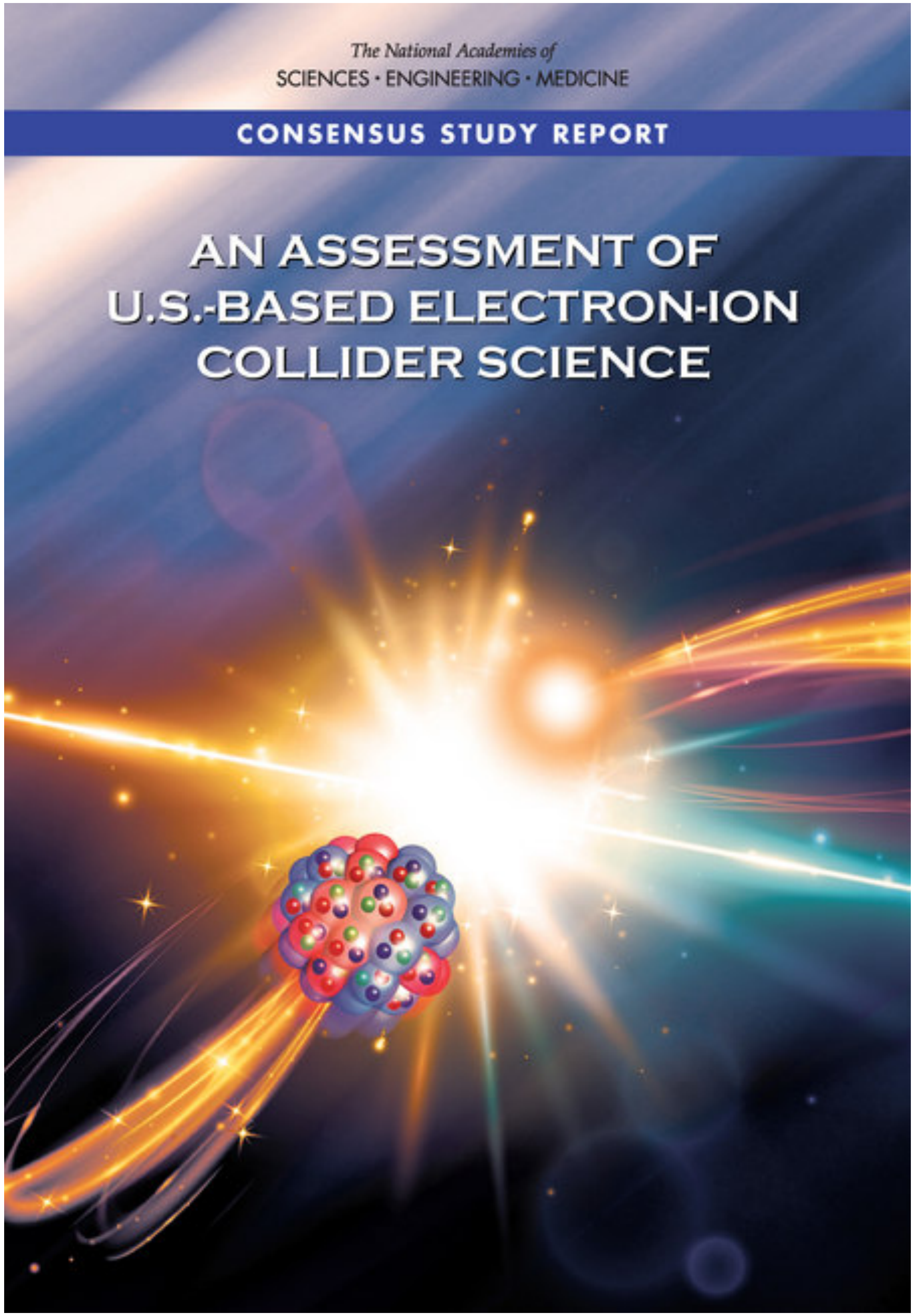




Status of U.S.-based EIC



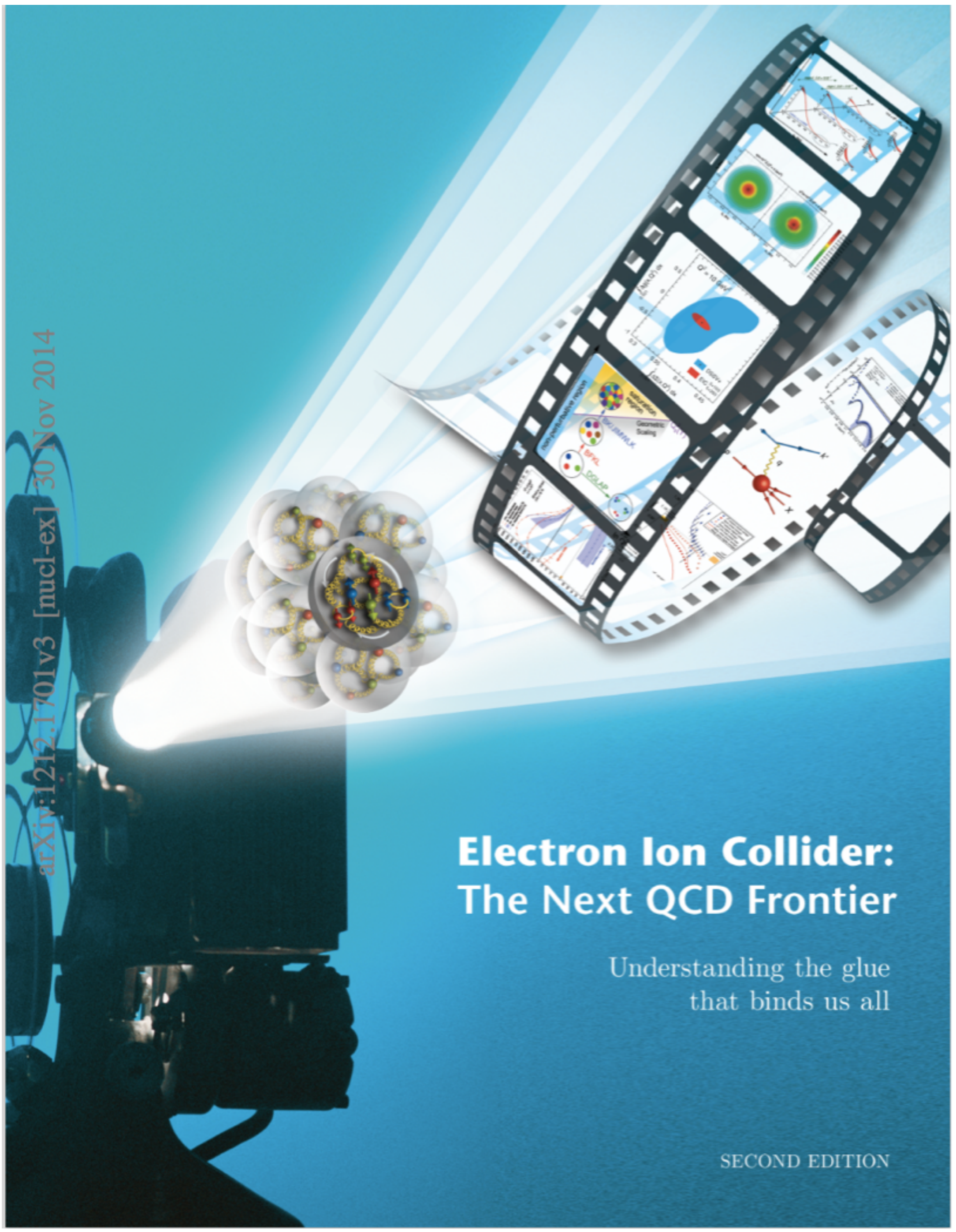
The committee *unanimously* finds that the science that can be addressed by an EIC is *compelling, fundamental, and timely.*

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.

U.S. EIC Capabilities

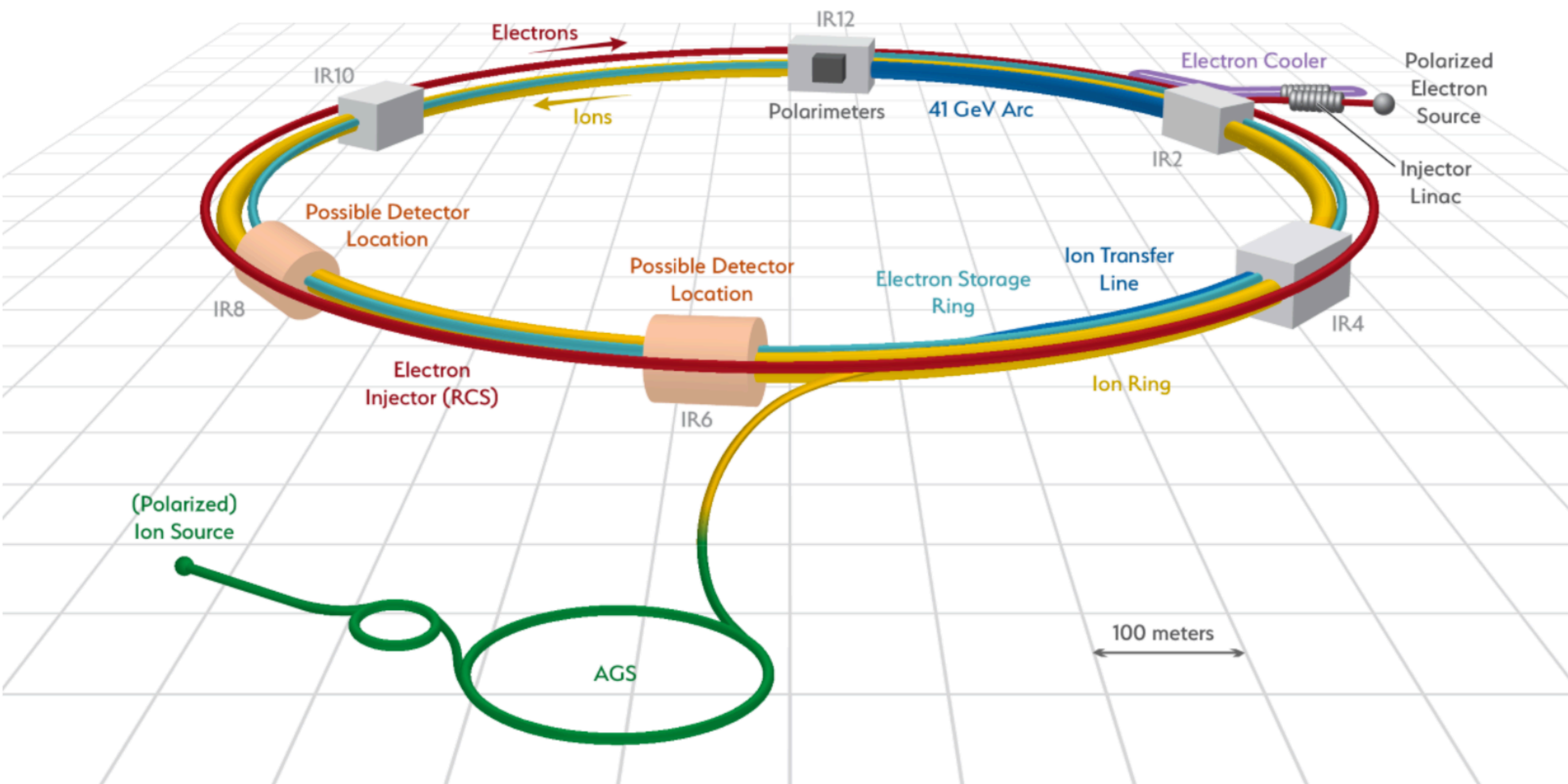


Eur. Phys. J. A52 (2016) no.9, 268 - 699 citations

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 inter-action 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, investment. RHIC now selected.*

U.S. EIC Accelerator Concept



From: An Electron-Ion Collider Study - Brookhaven National Laboratory, August 2019

U.S. EIC Challenges / Opportunities

U.S. DEPARTMENT OF ENERGY | Office of Science

Jones Panel Priority Table:

Report of the Community Review of EIC Accelerator R&D for the Office of Nuclear Physics

February 13, 2017

2017

The **key EIC machine parameters** identified in the LRP were:

- Polarized (~70%) electrons, protons, and light nuclei,
- Ion beams from deuterons to the heaviest stable nuclei,
- Variable center of mass energies ~20-100 GeV, upgradable to ~140 GeV,
- High collision luminosity ~10^{33}-10^{34} cm^{-2}sec^{-1}, and
- Possibly have more than one interaction region.

U.S. EIC Challenges / Opportunities

U.S. DEPARTMENT OF ENERGY | Office of Science

Technical Challenges for EIC

EIC will be one of the most complex collider accelerators ever to be built. It will push the envelope in many fronts including high degrees of beam polarizations, high luminosity, beam cooling, beam dynamics, crab cavities for both beams, and an interaction region with complex magnets.

Required Accelerator R&D Advances for EIC (list from the Jones panel report)

- Hadron cooling techniques
- Polarized electron sources
- Ring magnet demonstrations
- Interaction region magnet design and prototyping
- Machine-detector interfaces
- Superconducting RF technology
- Large scale cryogenics technology
- High current ERL linacs
- Crab cavity design, fabrication and testing (with beam)
- Beam and spin dynamics and benchmarking of simulation tools
- Electron cloud mitigation techniques

U.S. EIC Challenges / Opportunities

Complexity perhaps most apparent from the interaction-region concept:

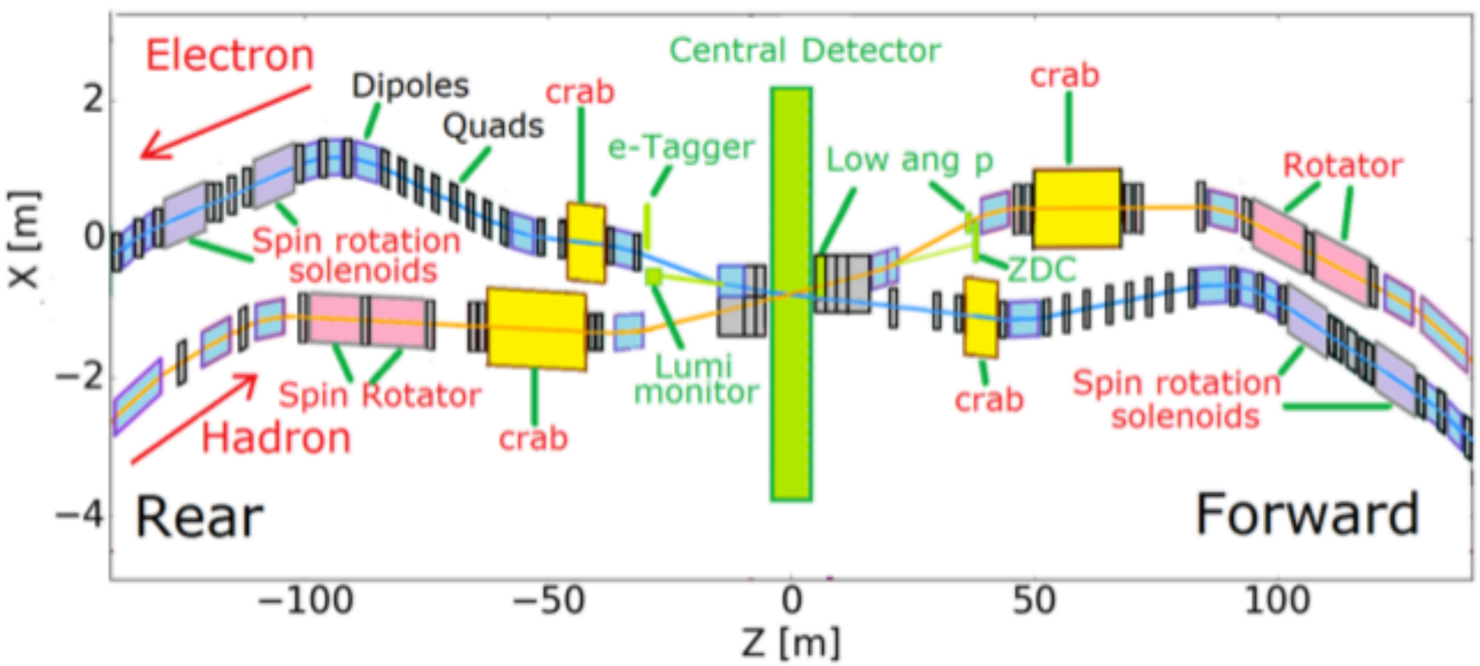


Figure 1.4: Schematic layout of the interaction region (top view, as simulated for high divergence, no cooling). Beams cross at an angle of 25 mrad. Note the length scales for the horizontal and vertical axis are very different. The IR design integrates focusing magnets for both beams, luminosity and neutron detectors, electron taggers, spectrometer magnets, near-beam detectors (Roman pots for hadrons), crab cavities, and spin rotators for both beams. The two beams are focused by quadrupole doublets. On the hadron-forward side, there are separate focusing magnets which are partially longitudinally interleaved. The first quadrupole magnet for electrons is integrated into a hadron spectrometer dipole. On the rear side, hadrons and electrons are focused by quadrupoles which are installed side-by-side in the same cryostat. The maximum β-functions in the IR for hadrons of 2000 m remain within the operating range of RHIC, while the maximum β-functions for electrons remain below 860 m.

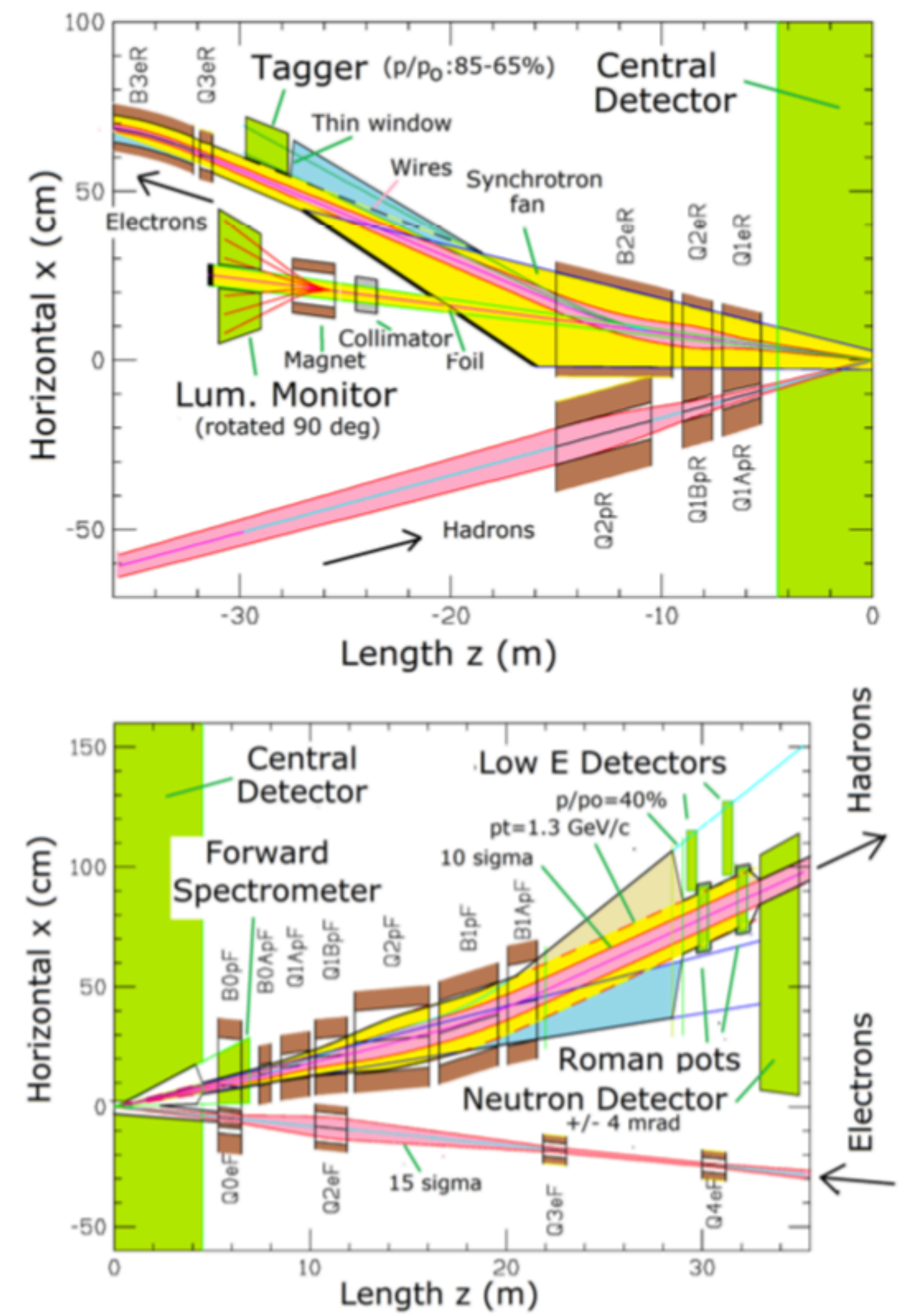
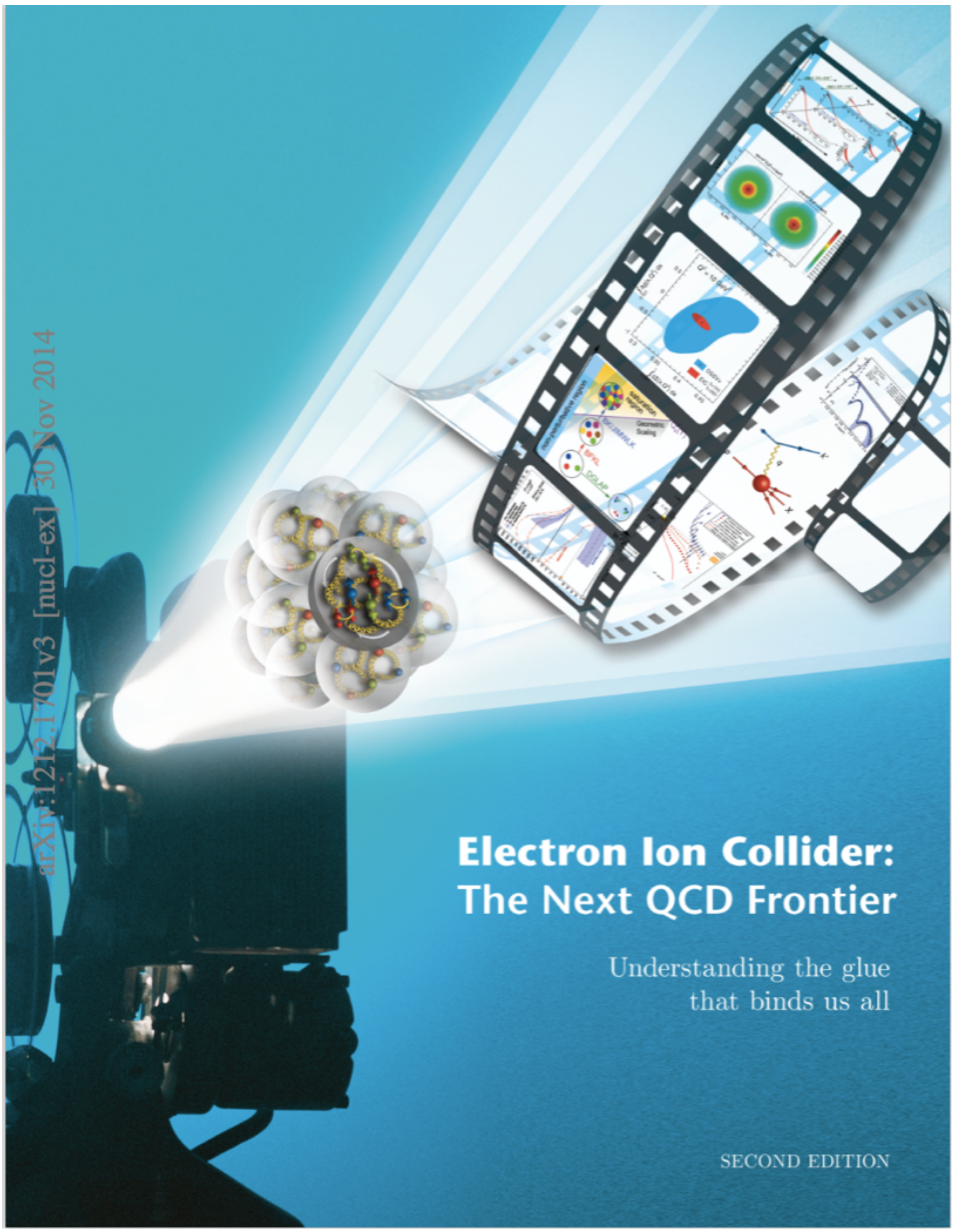


Figure 3.2: A zoom of the interaction region layout in the rear (top) and forward (bottom) directions.

Note, the central detector must have large acceptance, $-4 < \eta < 4$
low material/mass,
particle-identification over a wide kinematic range

U.S. EIC Science Case



Eur. Phys. J. A52 (2016) no.9, 268 - 699 citations

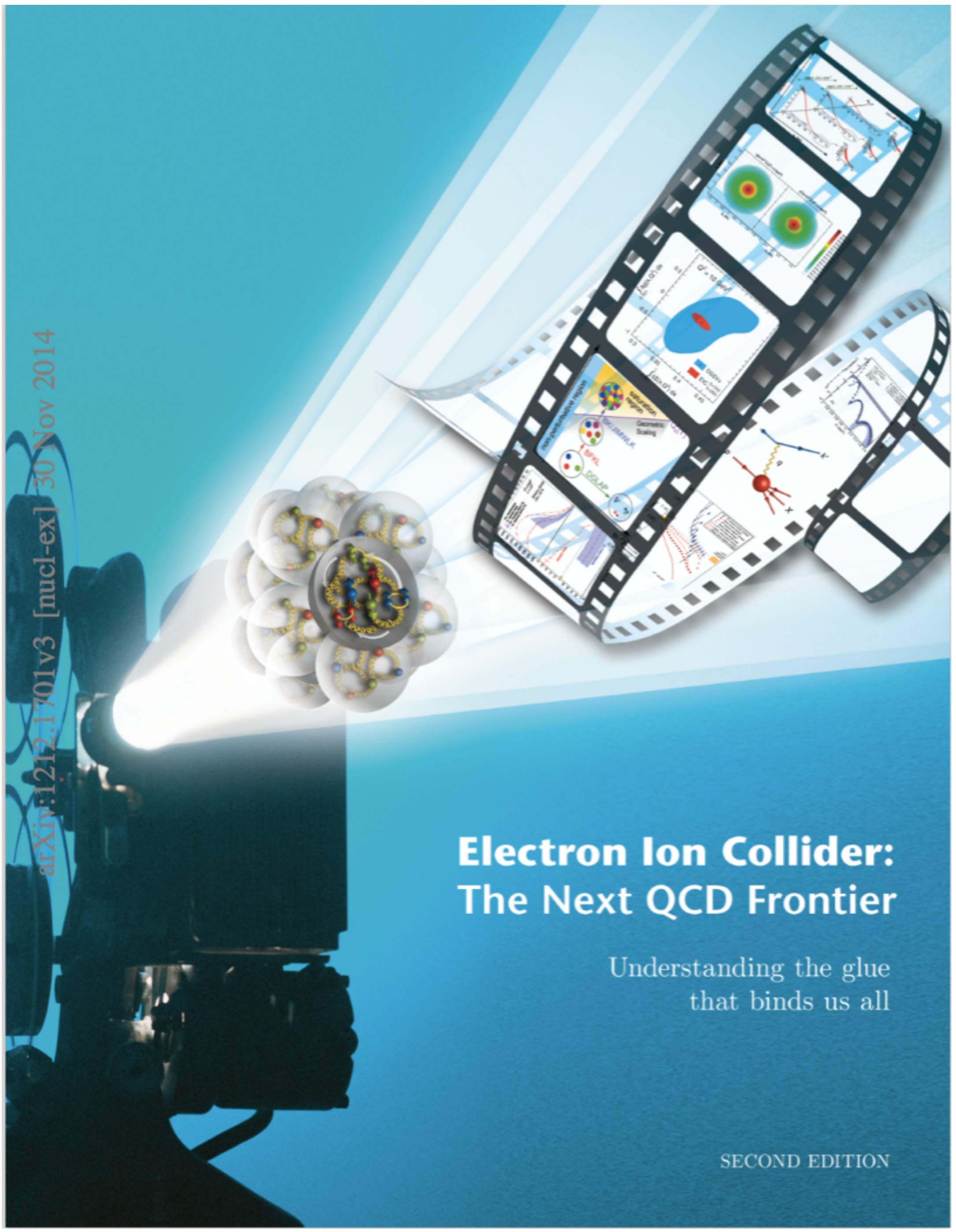
See also Rept.Prog.Phys. 82 (2019) 024301

- *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 - 699 citations

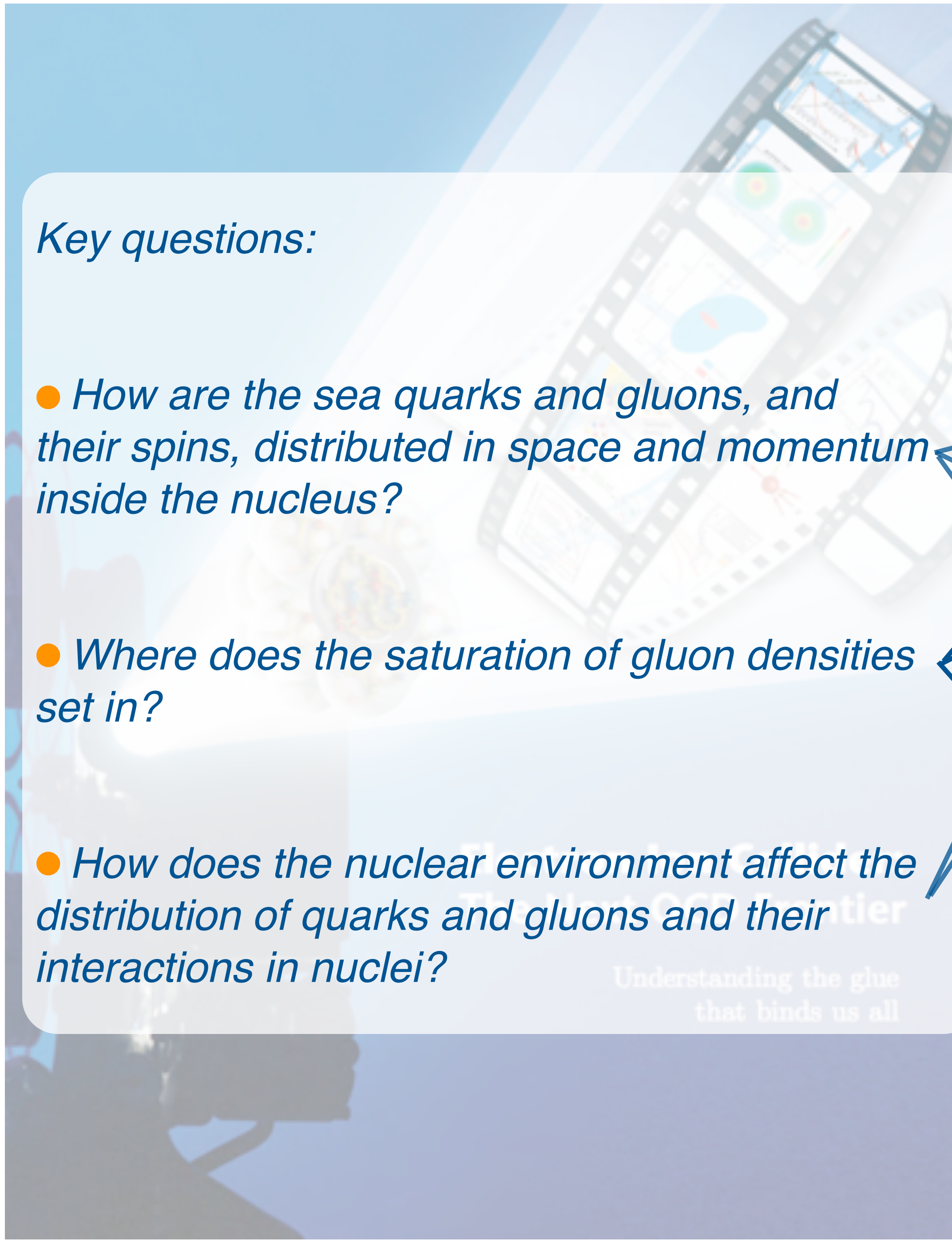
See also Rept.Prog.Phys. 82 (2019) 024301

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 - Observables



Key questions:

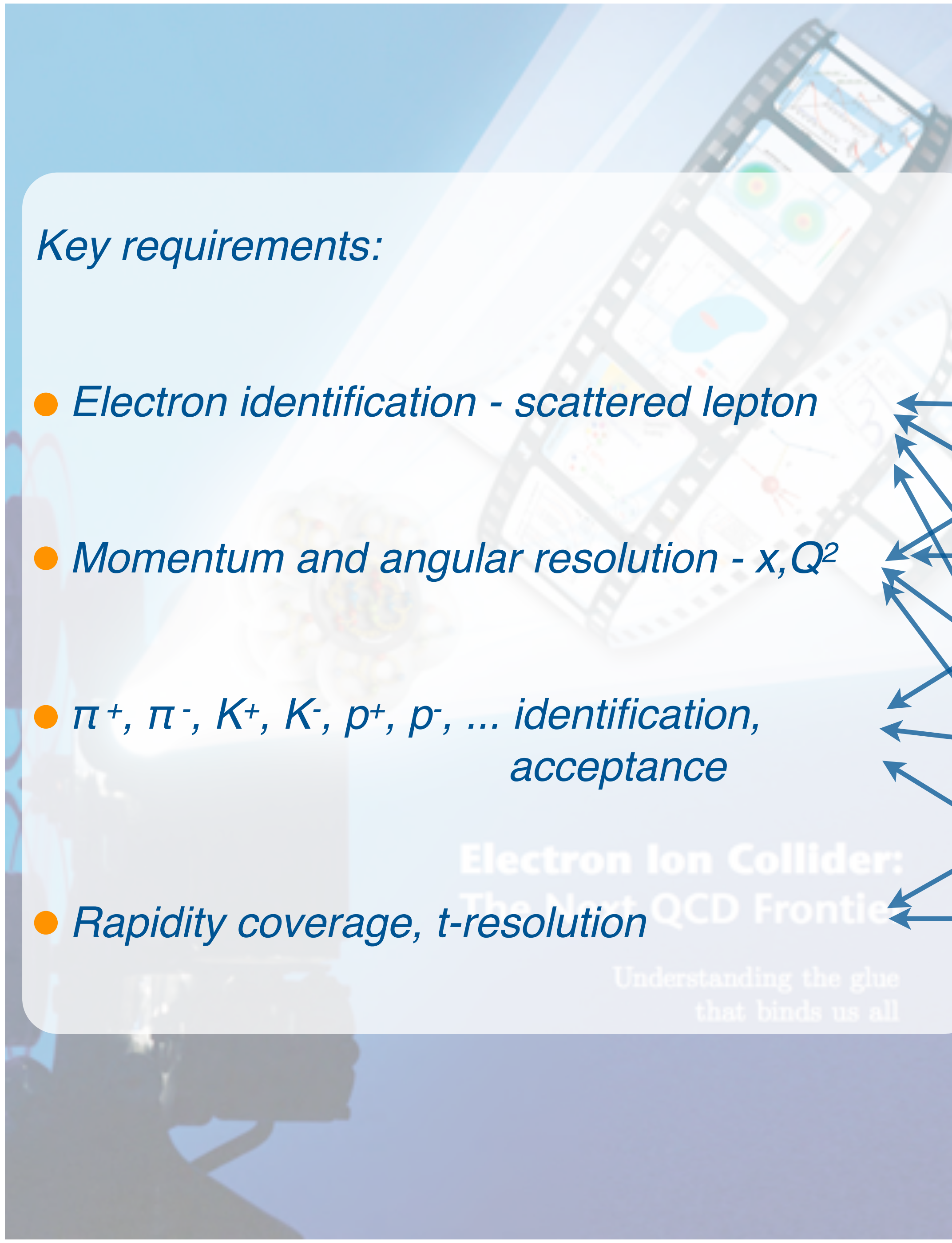
- *How are the sea quarks and gluons, and their spins, distributed in space and momentum inside the nucleus?*
- *Where does the saturation of gluon densities set in?*
- *How does the nuclear environment affect the distribution of quarks and gluons and their interactions in nuclei?*

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.*

multi-dimensional and **multi-channel**

U.S.-based EIC - Observables



Key requirements:

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

Key measurements:

- *Inclusive Deep-Inelastic Scattering,*
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U.S.-based EIC - Detector Concepts

Key requirements:

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

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,*
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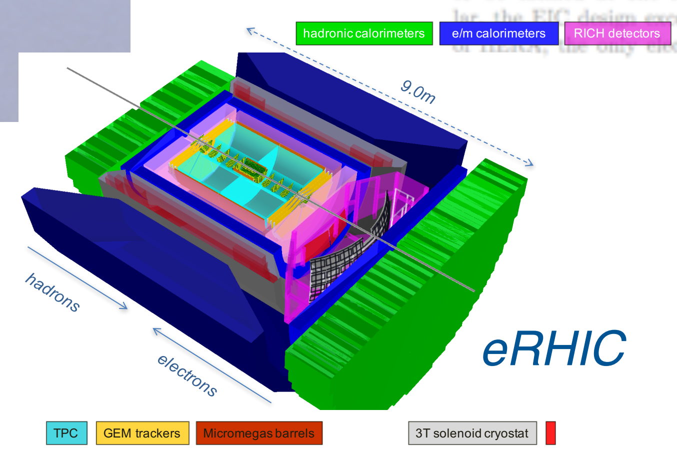
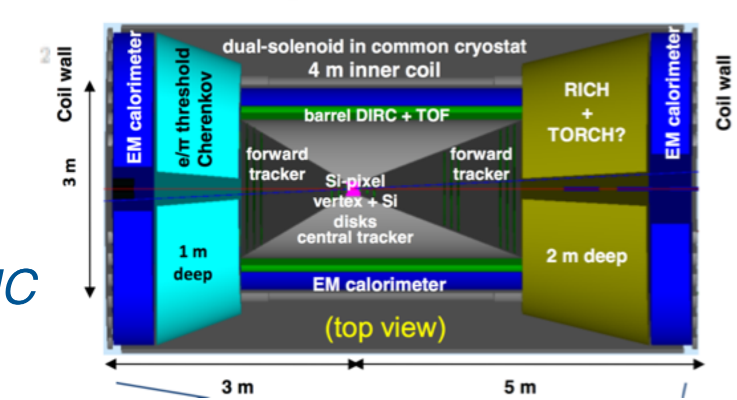
Green-field detector concepts:

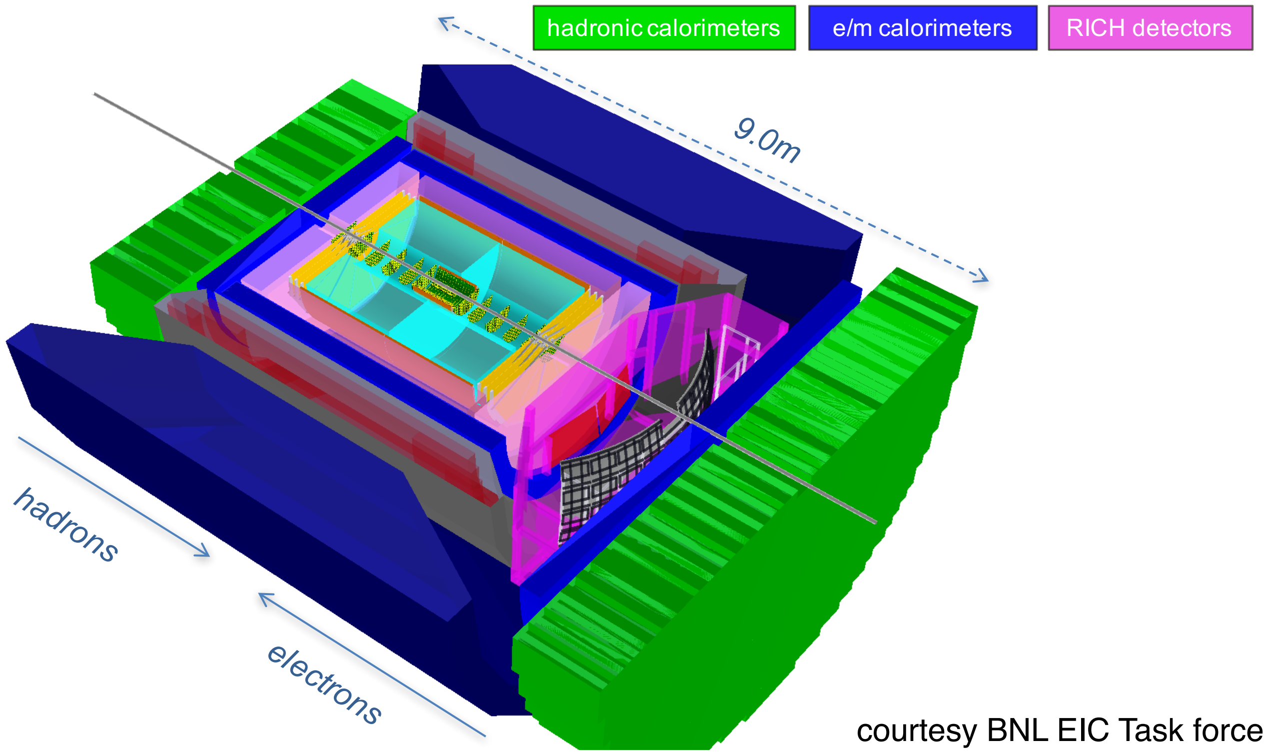


eRHIC

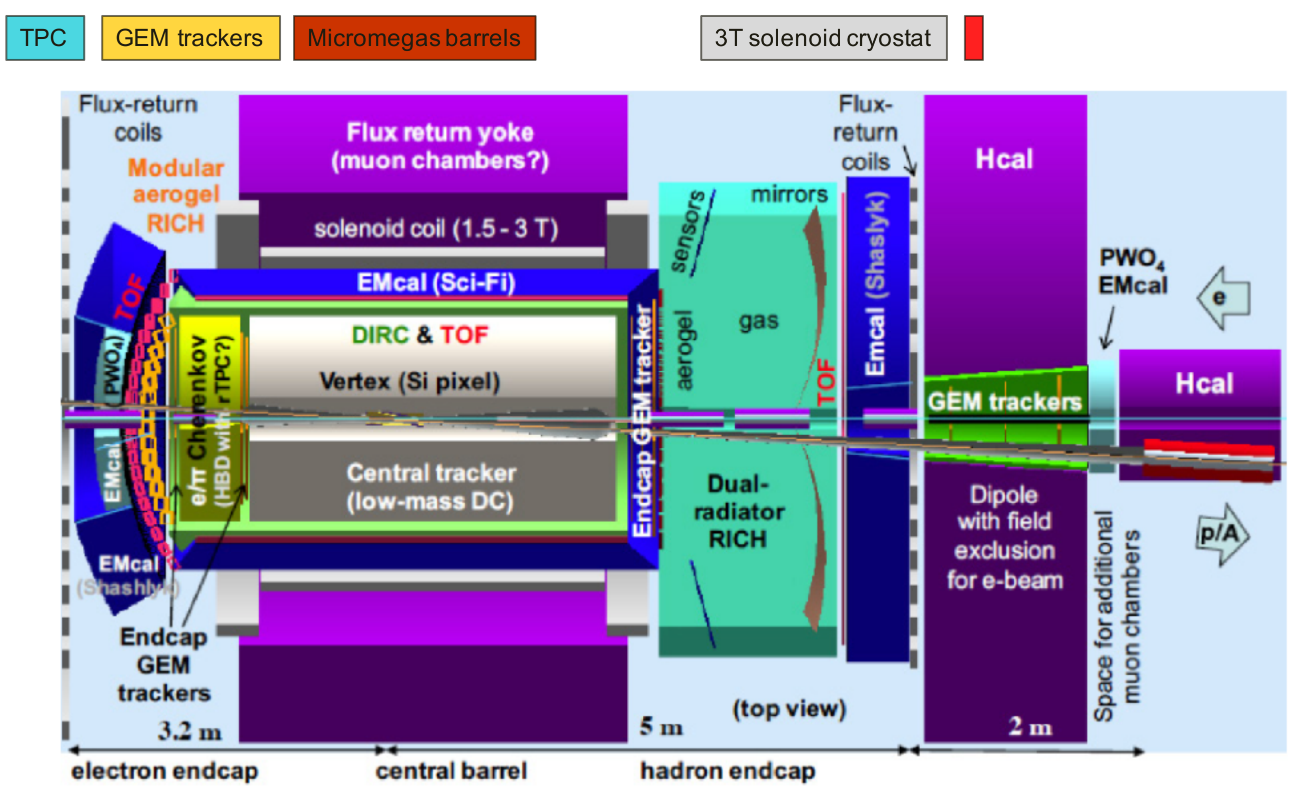
JLEIC



U.S.-based EIC - Detector Concepts



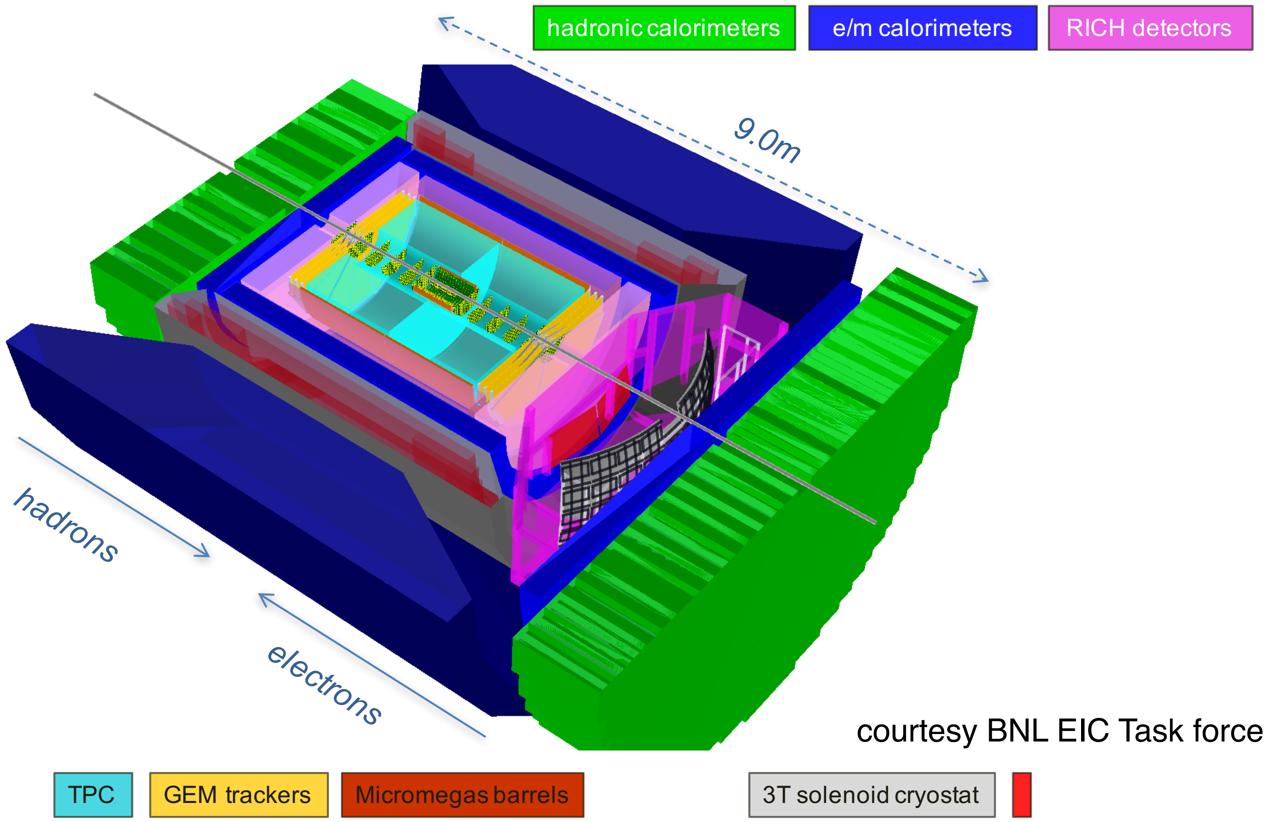
courtesy BNL EIC Task force



courtesy JLEIC Detector and Interaction Region Study Group

- *Compact design concepts,*
- *Low mass (traversed material),*
- *Channel counts (well) beyond existing and planned U.S.-based NP physics experiments, though not so compared to the LHC experiments,*
- *Active Generic Detector R&D Program, c.f. https://wiki.bnl.gov/conferences/index.php/EIC_R&D,*
  - *novel calorimetry,*
  - *micro-pattern gas detectors,*
  - *precision tracking,*
  - *computing;*
    - *simulation and analysis tools,*
    - *interfaces and integration,*
    - *planning for the future with future compatibility,*
- *The EIC User Group, eicug.org, has just started a 12-18 month effort to firm up measurement precision, detector requirements, and conceptual design(s).*

U.S.-based EIC - Detector Concepts



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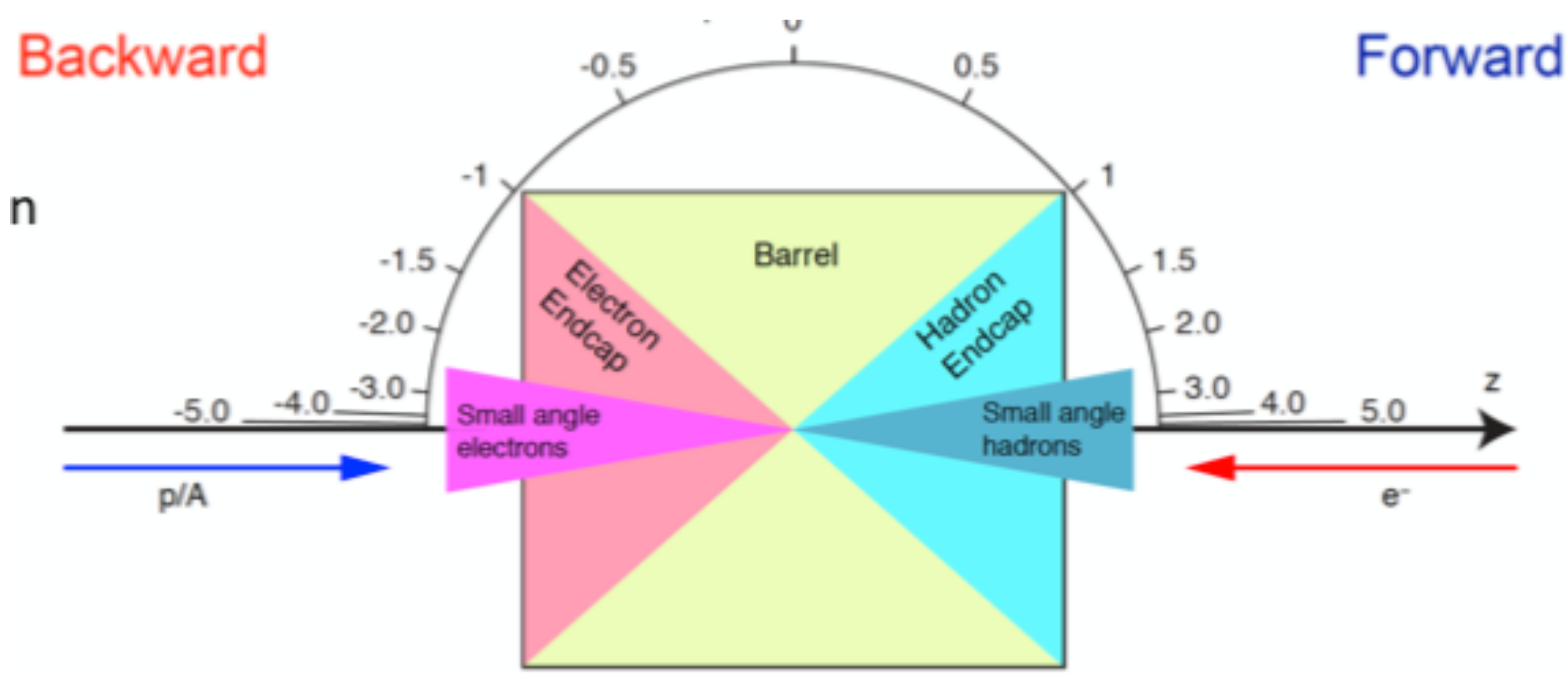
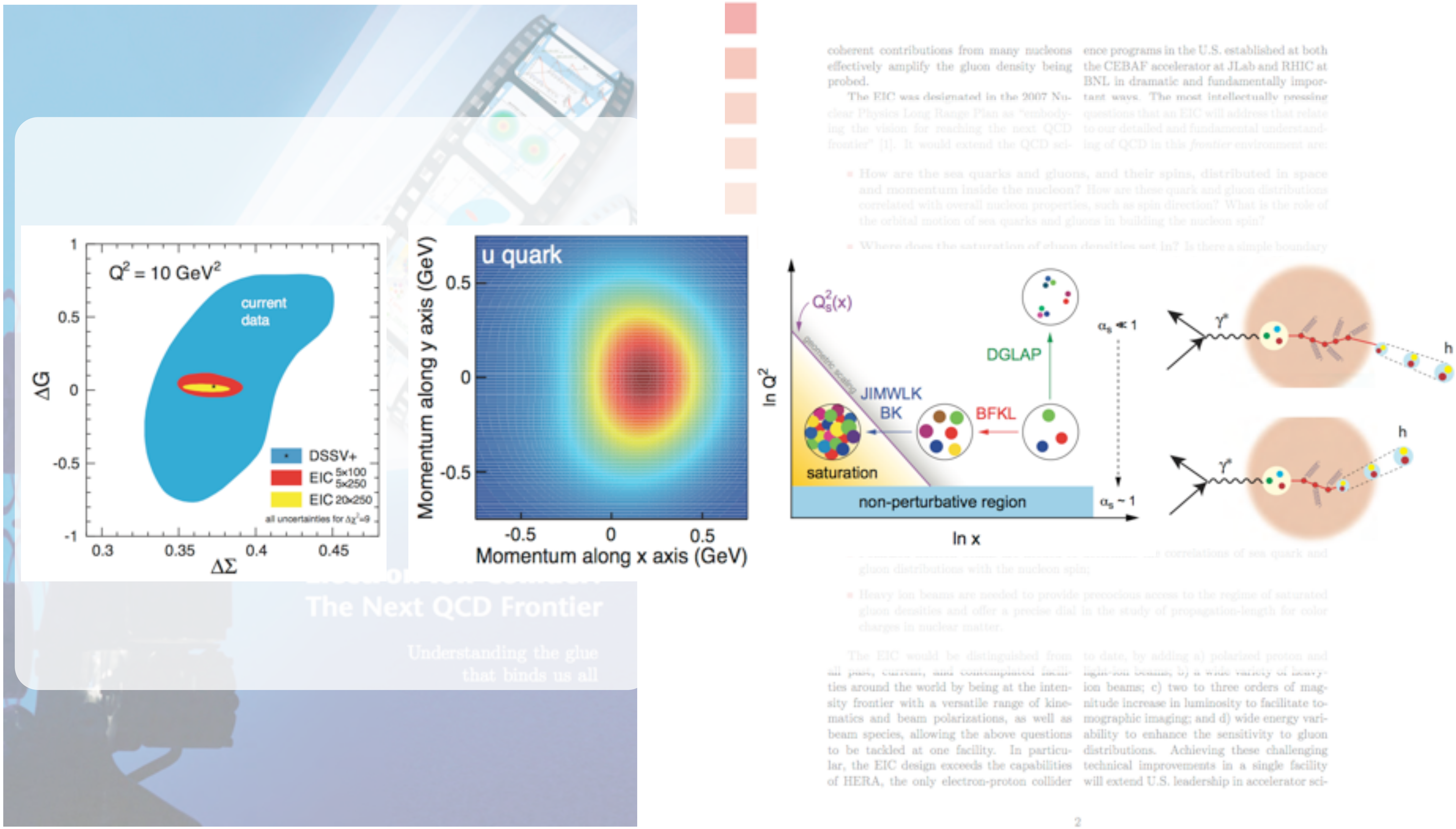


novel calorimetry,
micro-pattern gas detectors,
precision tracking,
computing;
simulation and analysis tools,
interfaces and integration,
planning for the future with future compatibility,

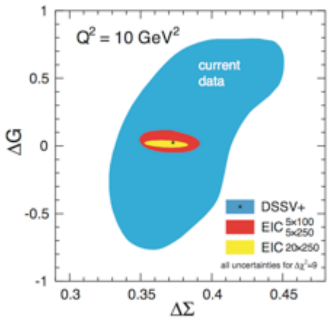
- The EIC User Group, eicug.org, has just started a 12-18 month effort to firm up measurement precision, detector requirements, and conceptual design(s).

U.S.-based EIC - Core Science

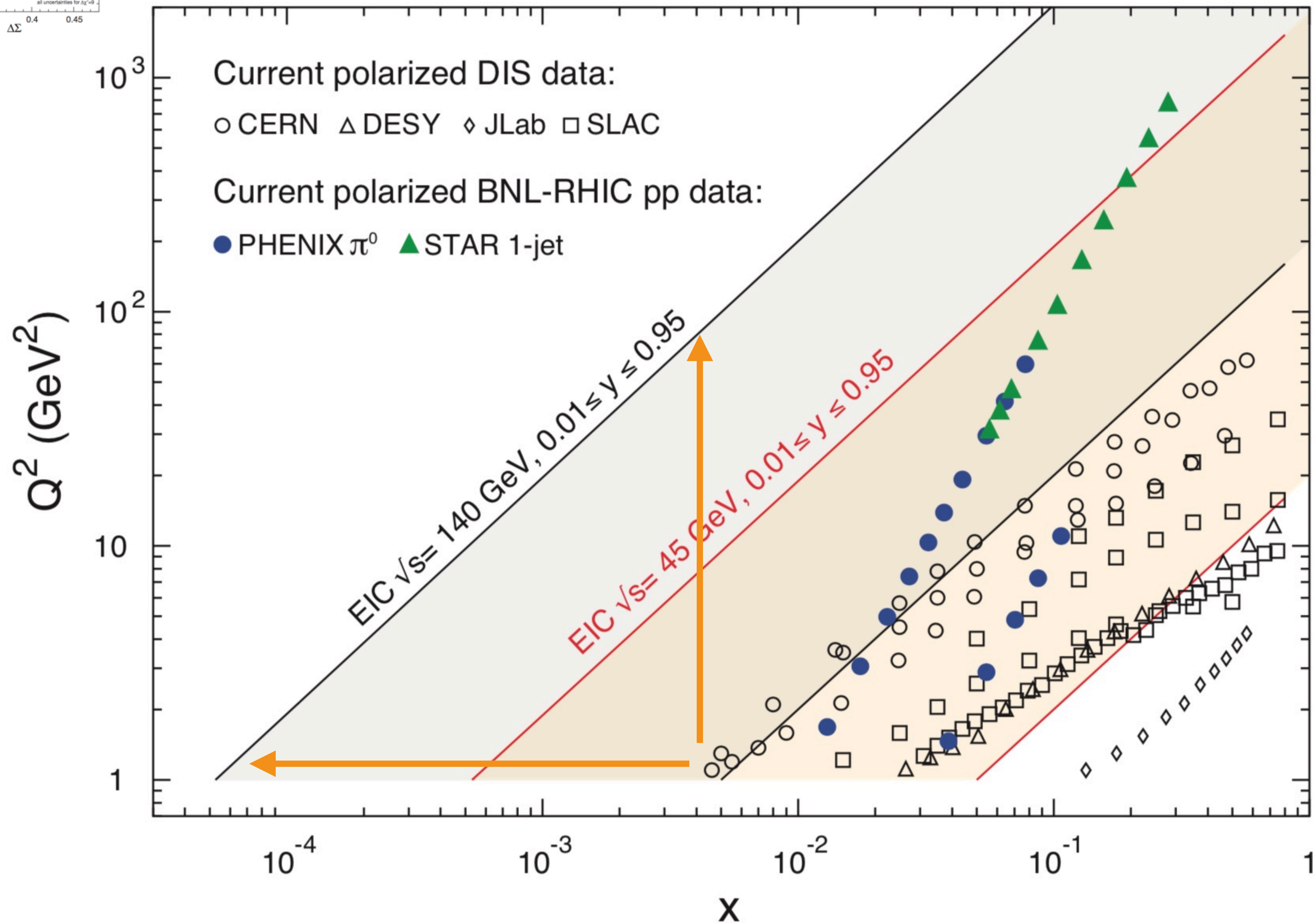


Nuclear Physics enabled by EIC **accelerator** energy, intensity, polarization, and species,
experiment capabilities,

theory

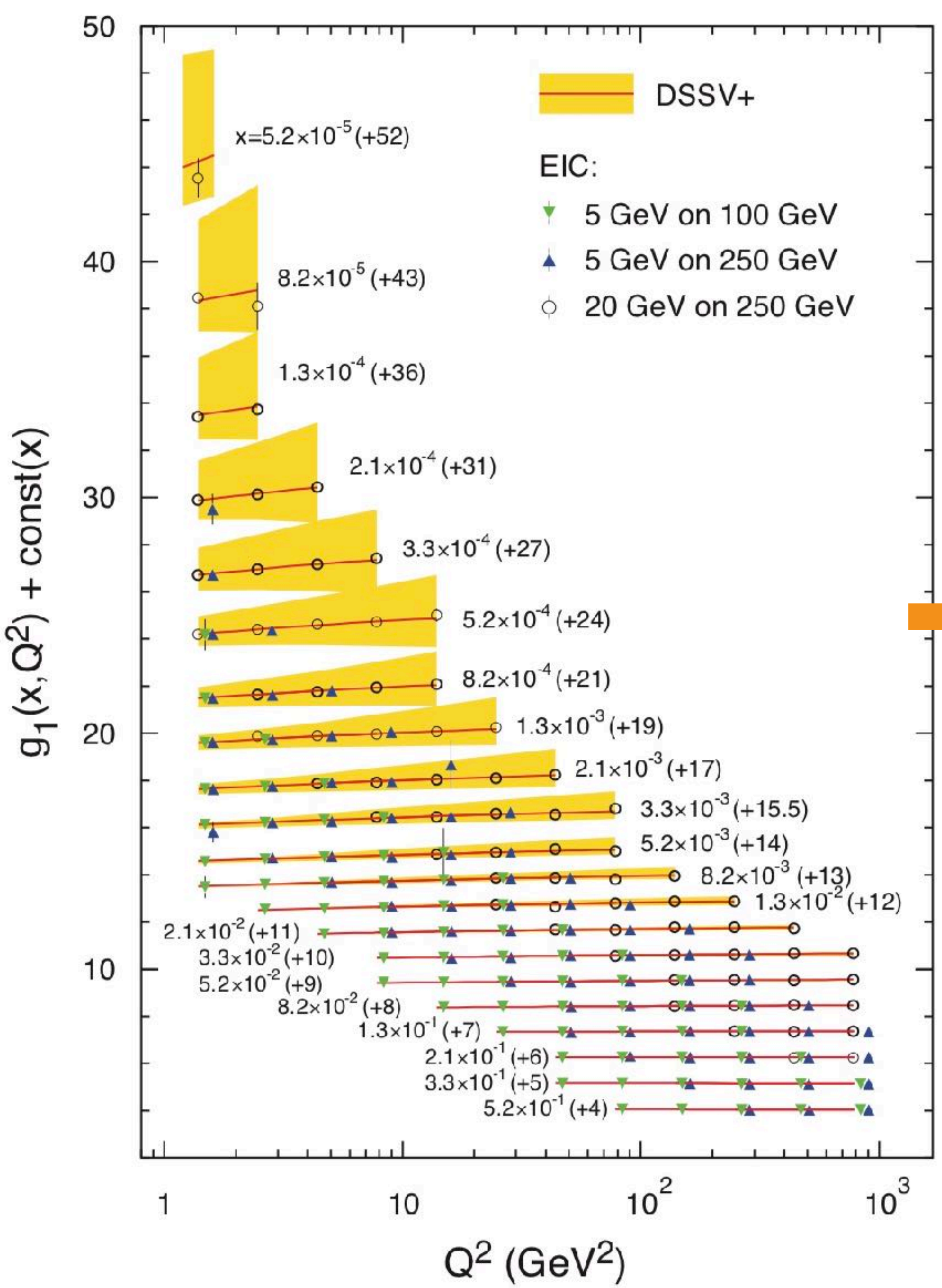


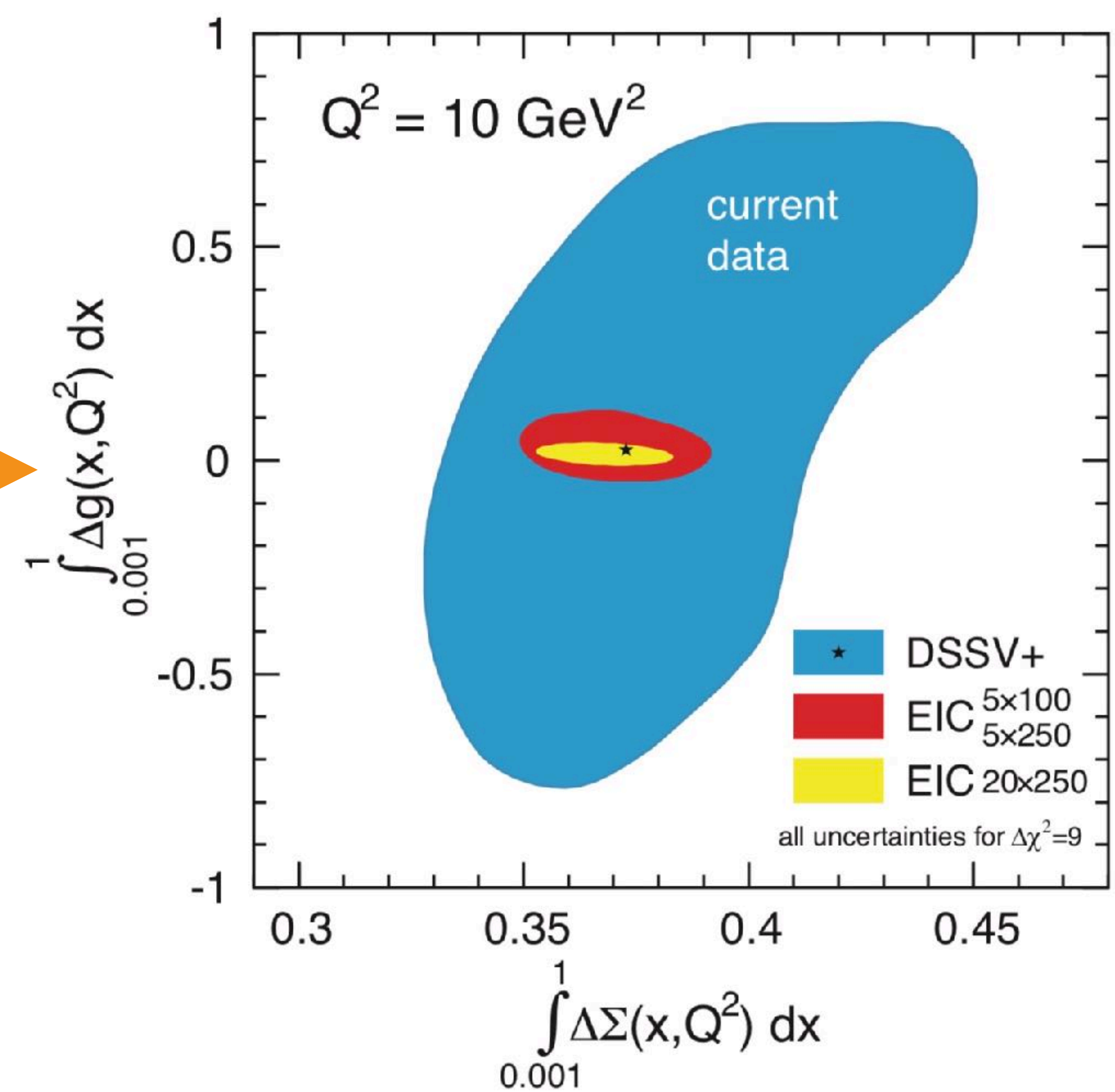
U.S.-based EIC - Proton Spin



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

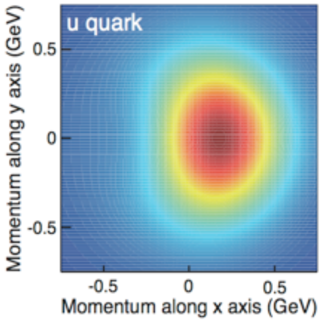
U.S.-based EIC - Proton Spin

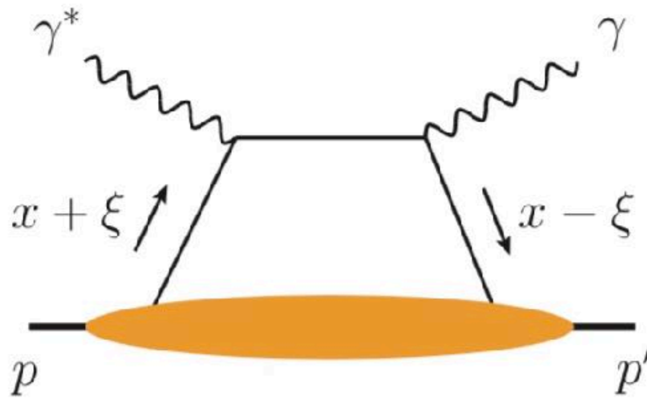


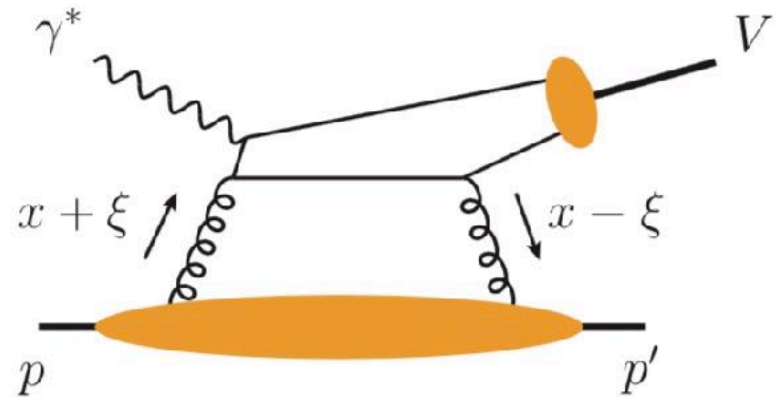


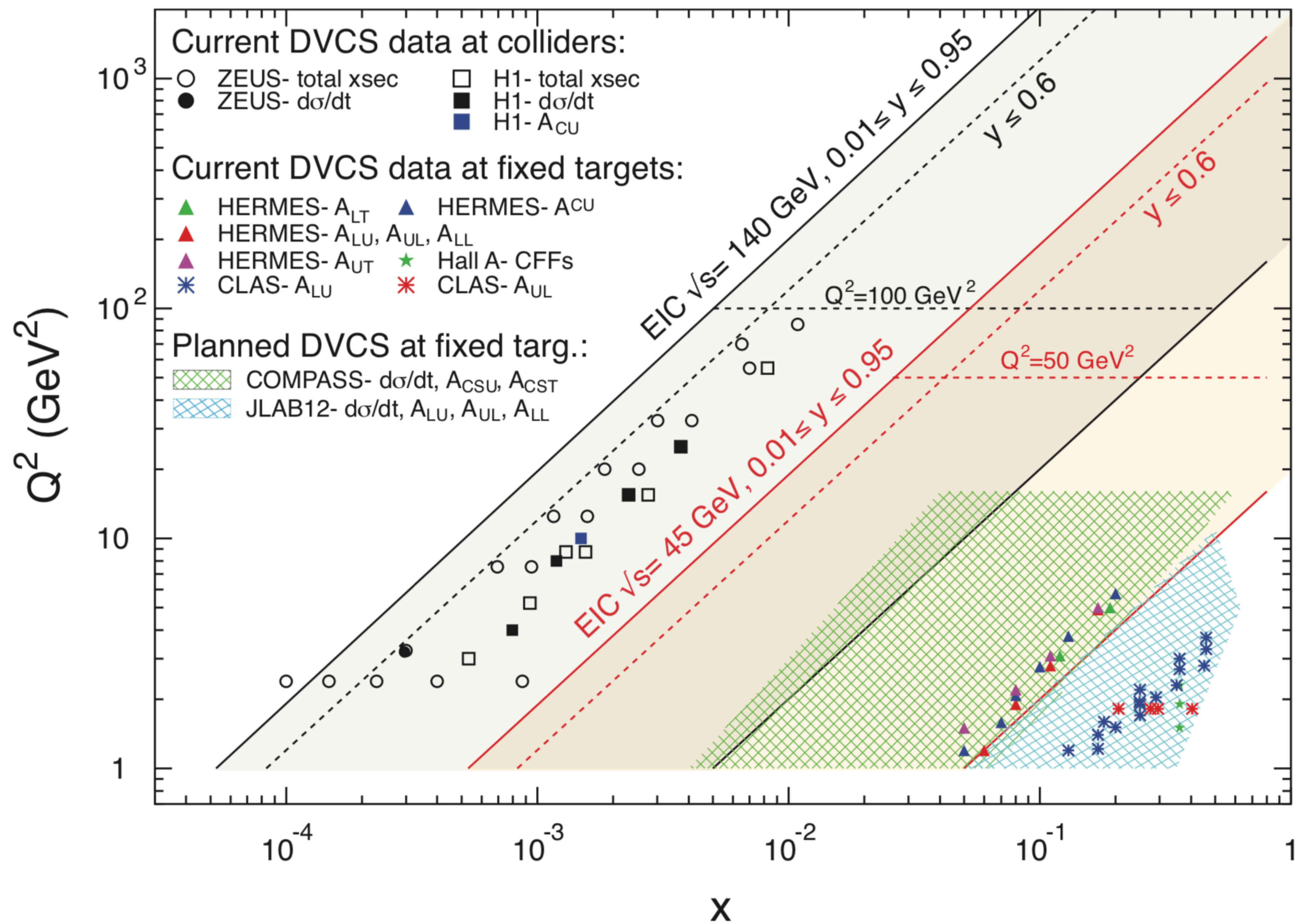
Conclusive insights in quark and gluon helicity from inclusive measurements, and orbital momentum by subtraction (!)

EIC - DVCS, DVMP, and Imaging





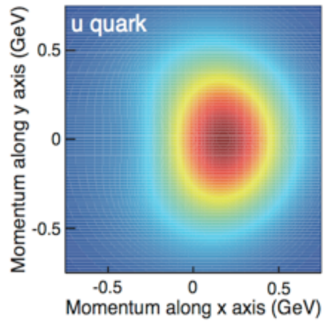




<u>Luminosity,</u>
Polarization,
Nuclei,
Detectors,

Less so about x, Q^2 range

t, however, …



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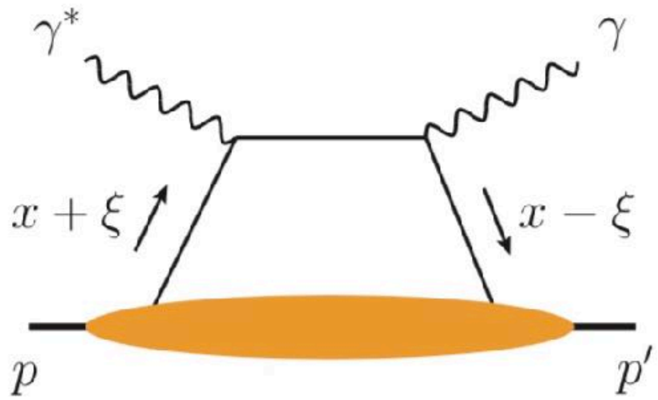
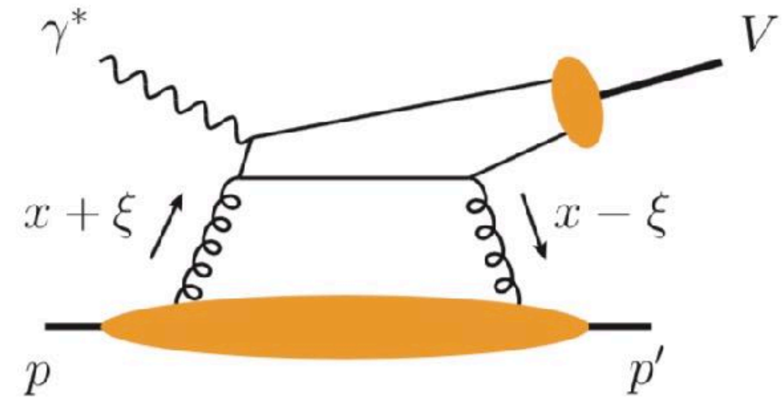
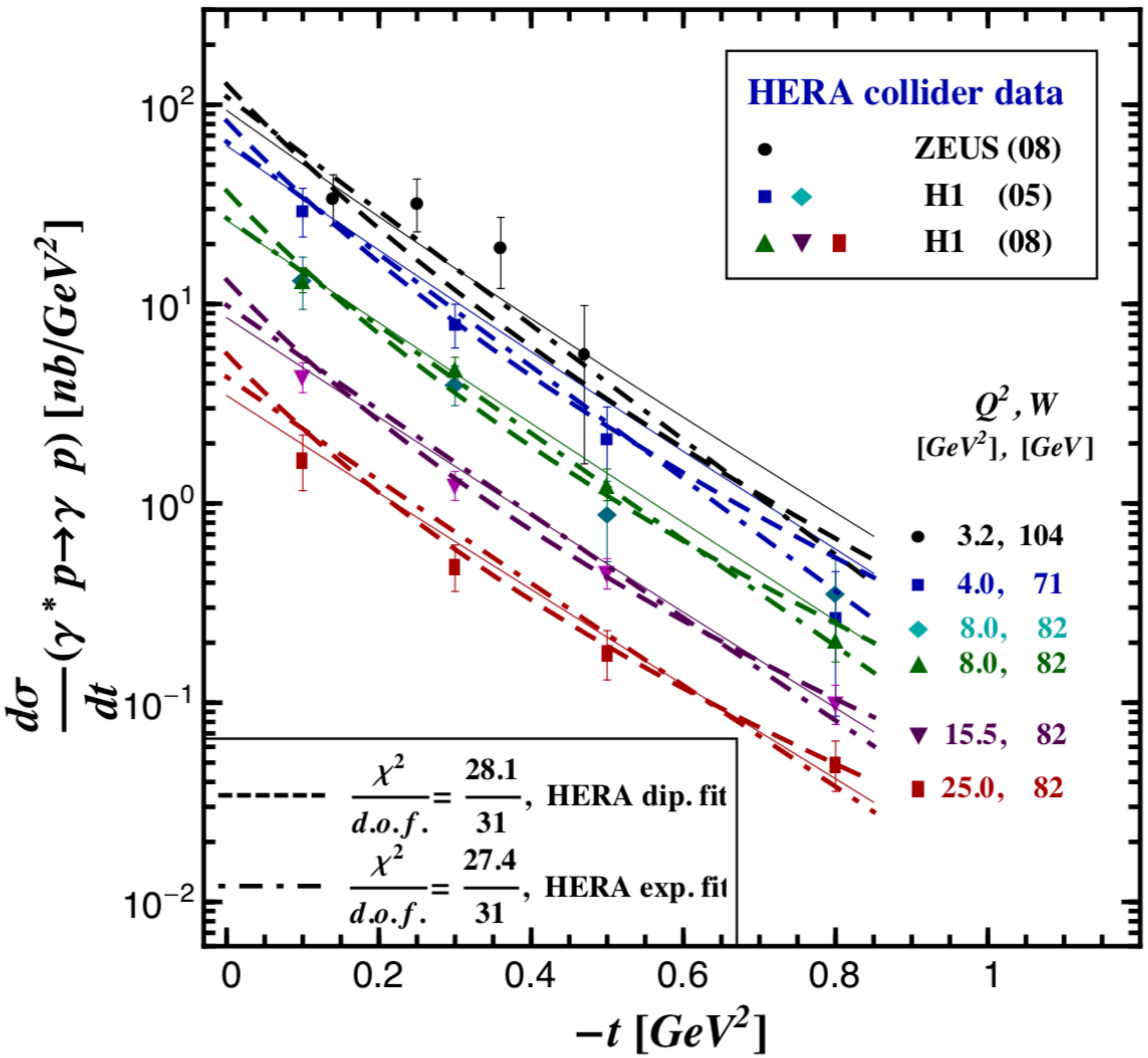
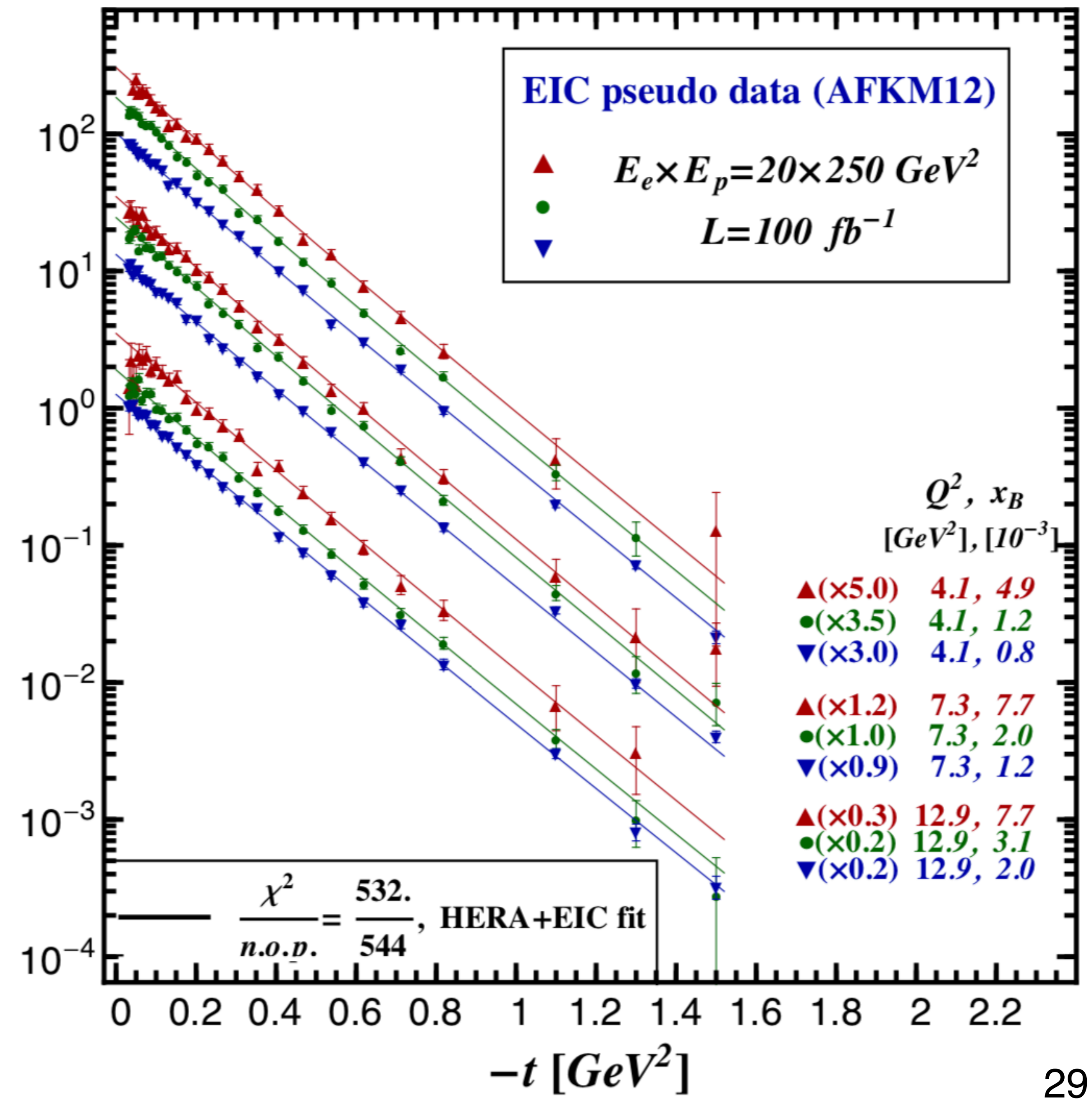
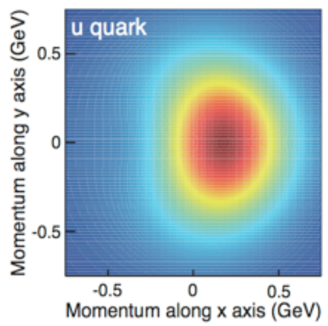


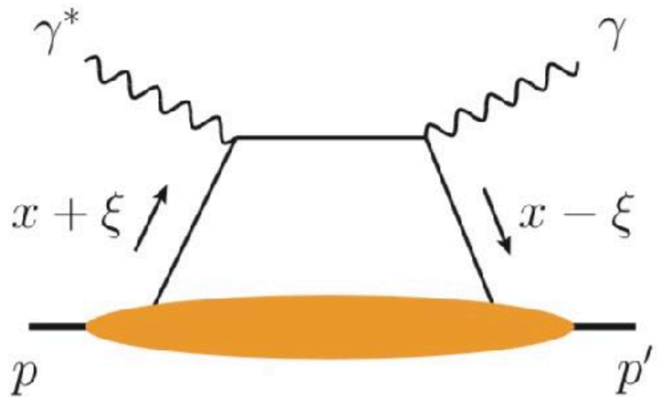


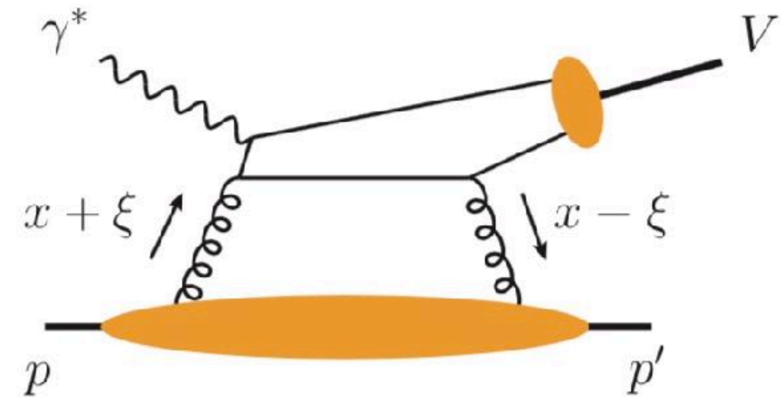


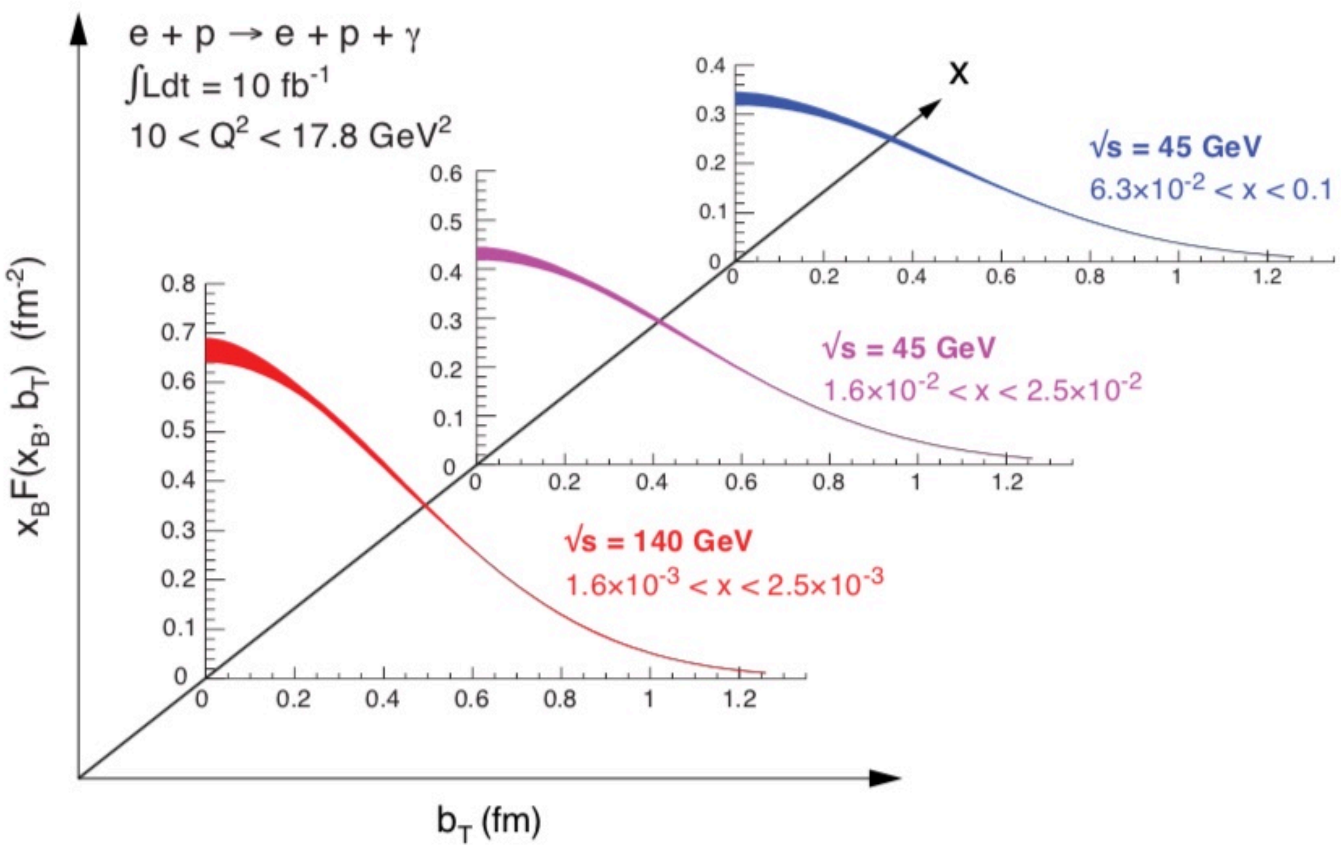


EIC - DVCS, DVMP, and Imaging

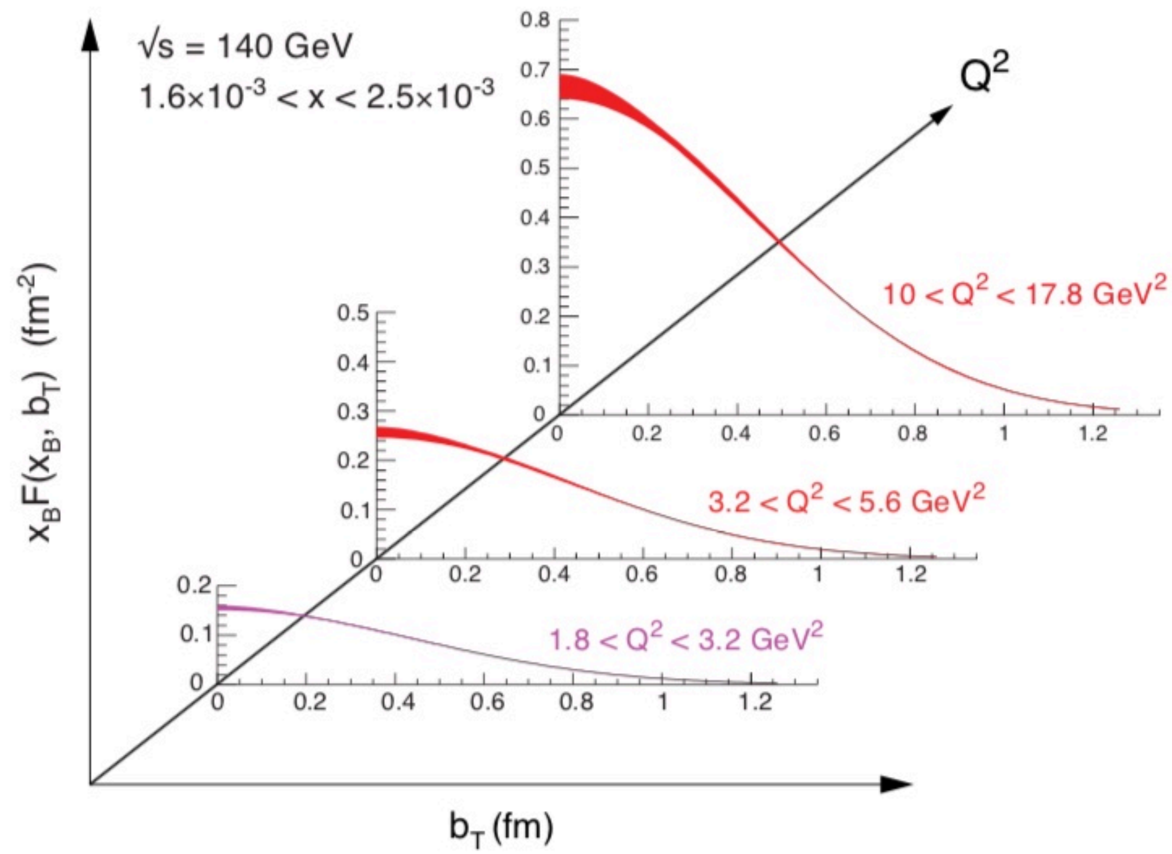




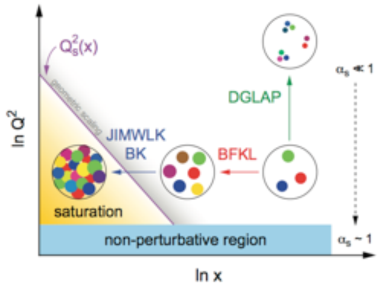




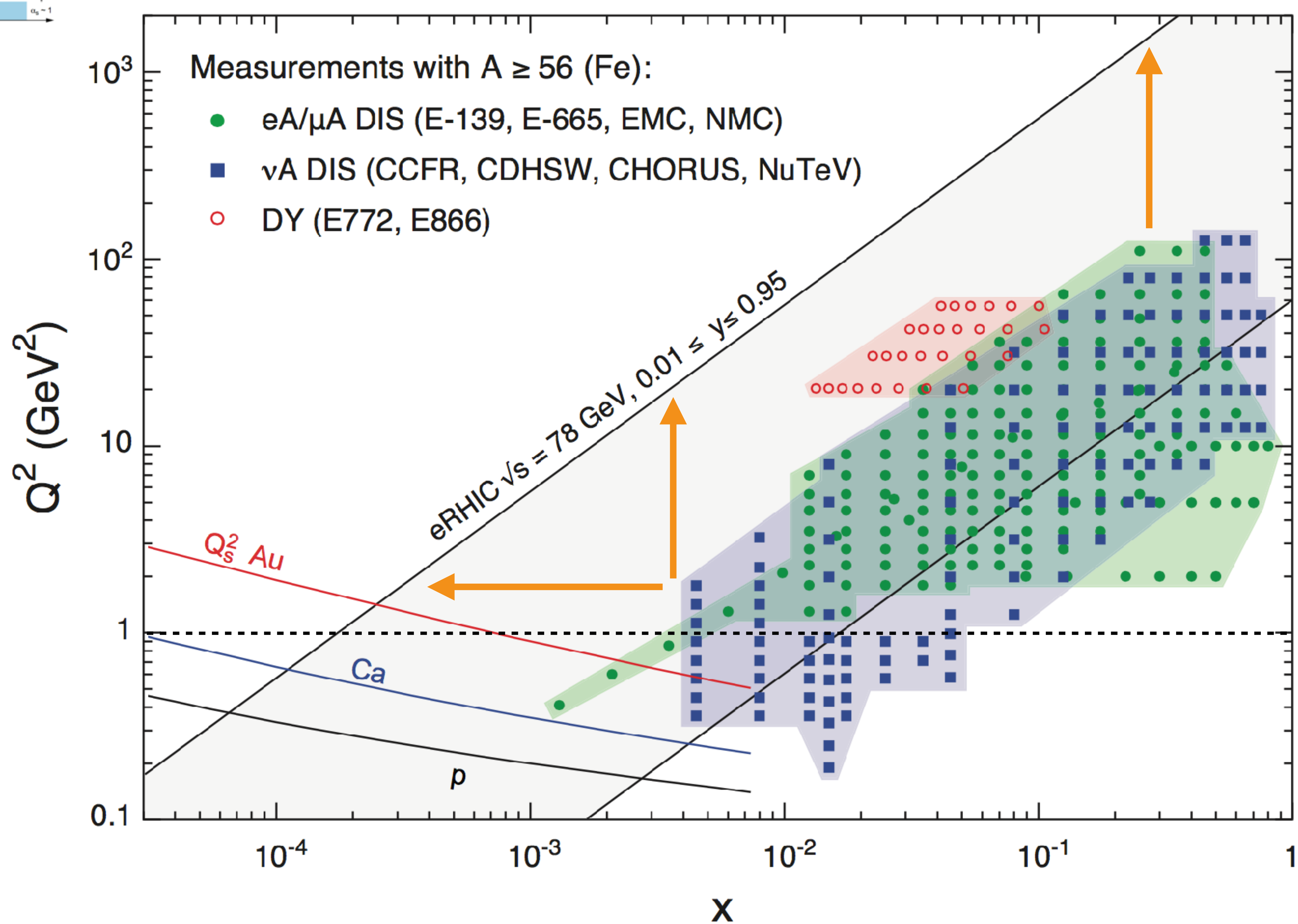
x-dependence at fixed Q^2



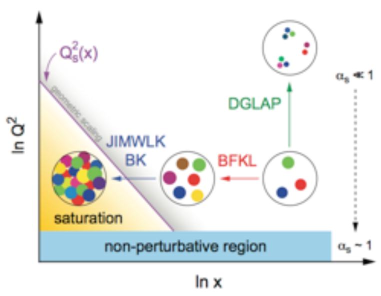
Q^2-dependence at fixed x



U.S.-based EIC - The Nuclear Landscape



Complementarity with ongoing and future RHIC and LHC measurements,



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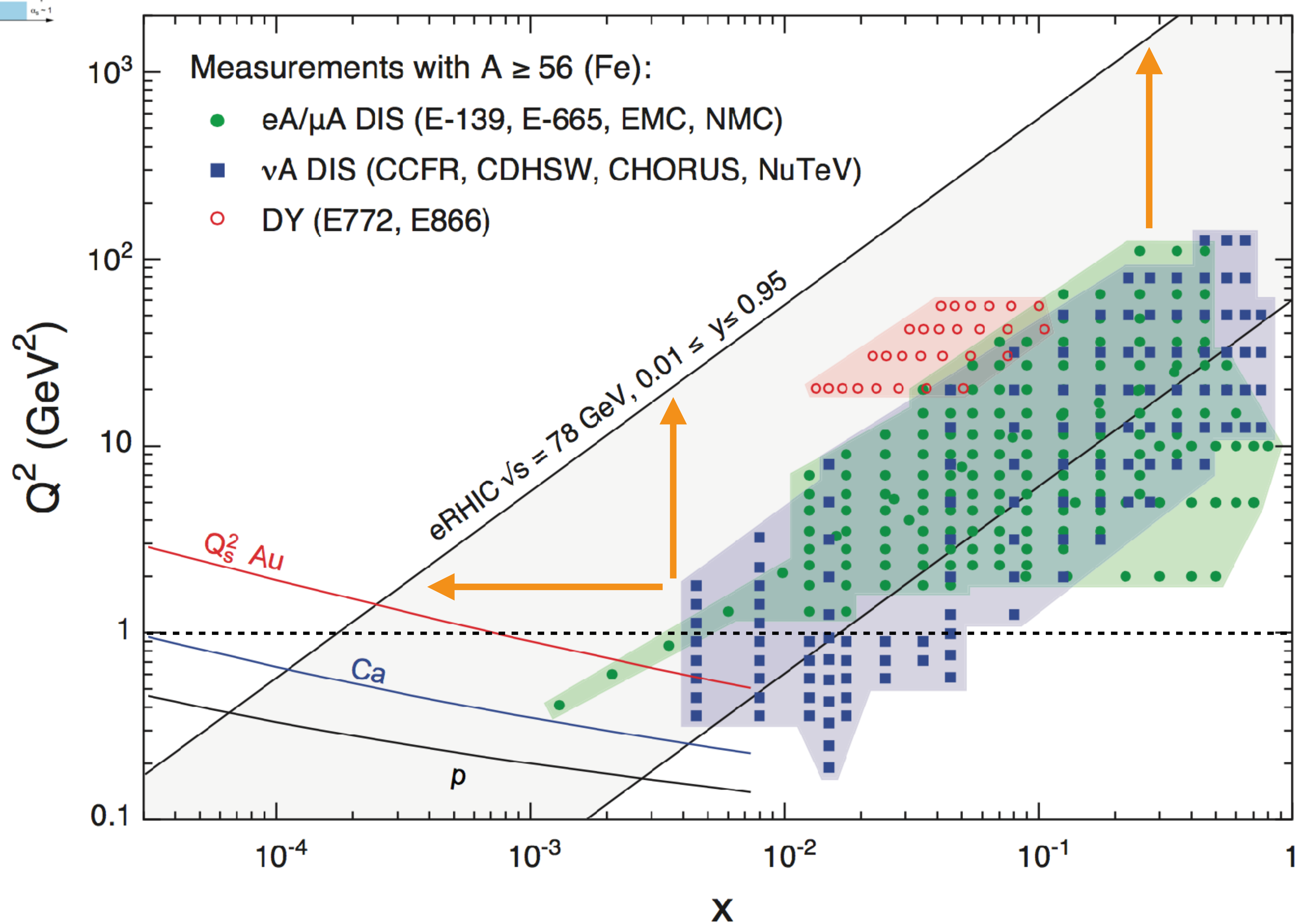
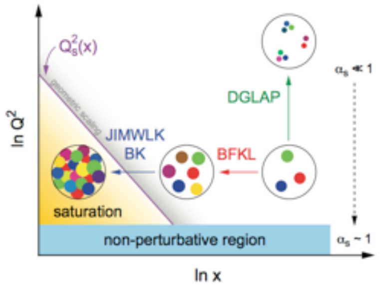
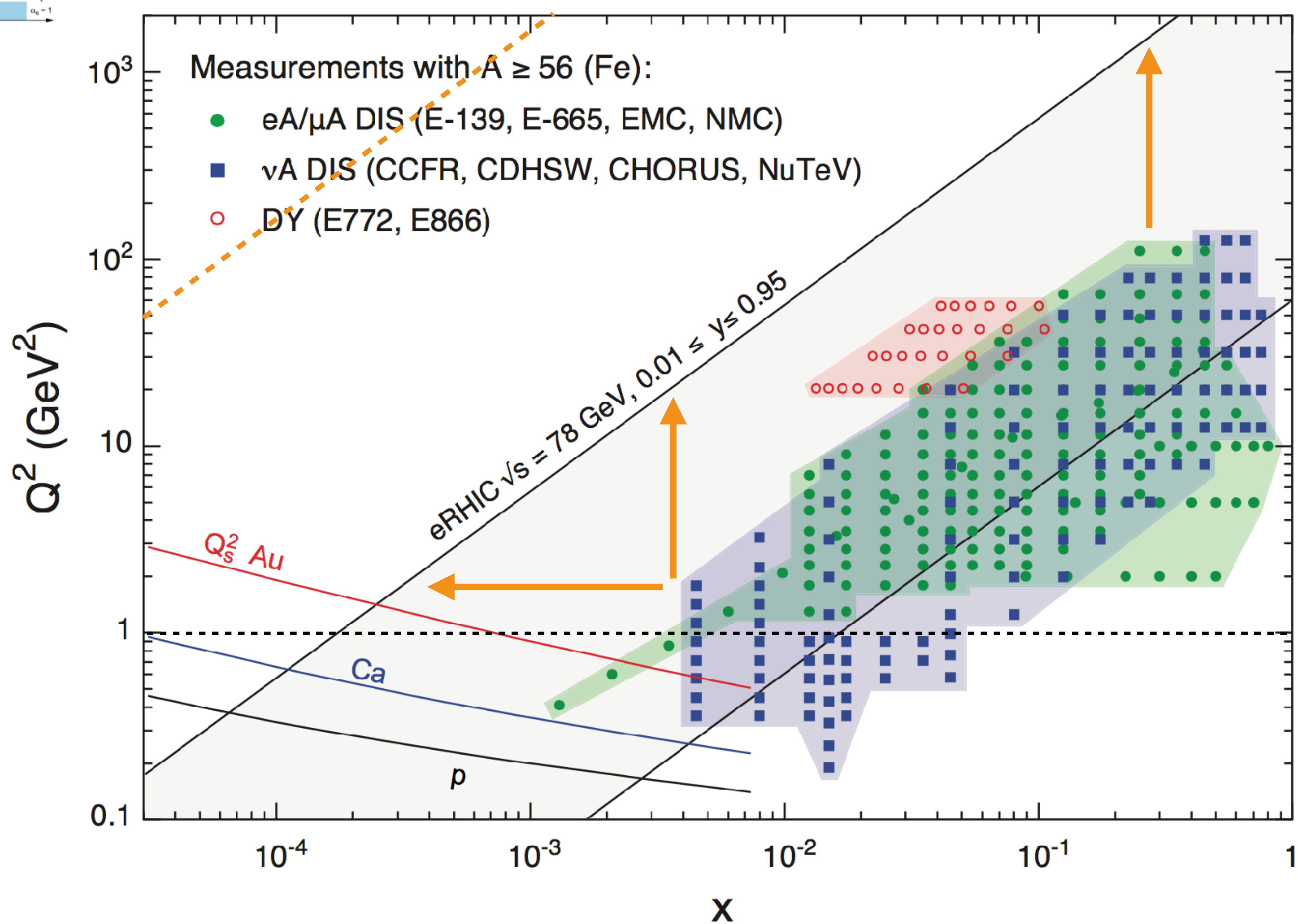


Complementarity with ongoing and future RHIC and LHC measurements, neutrino physics, cosmic ray physics, …

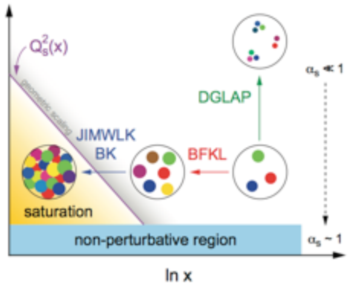


U.S.-based EIC - The Nuclear Landscape

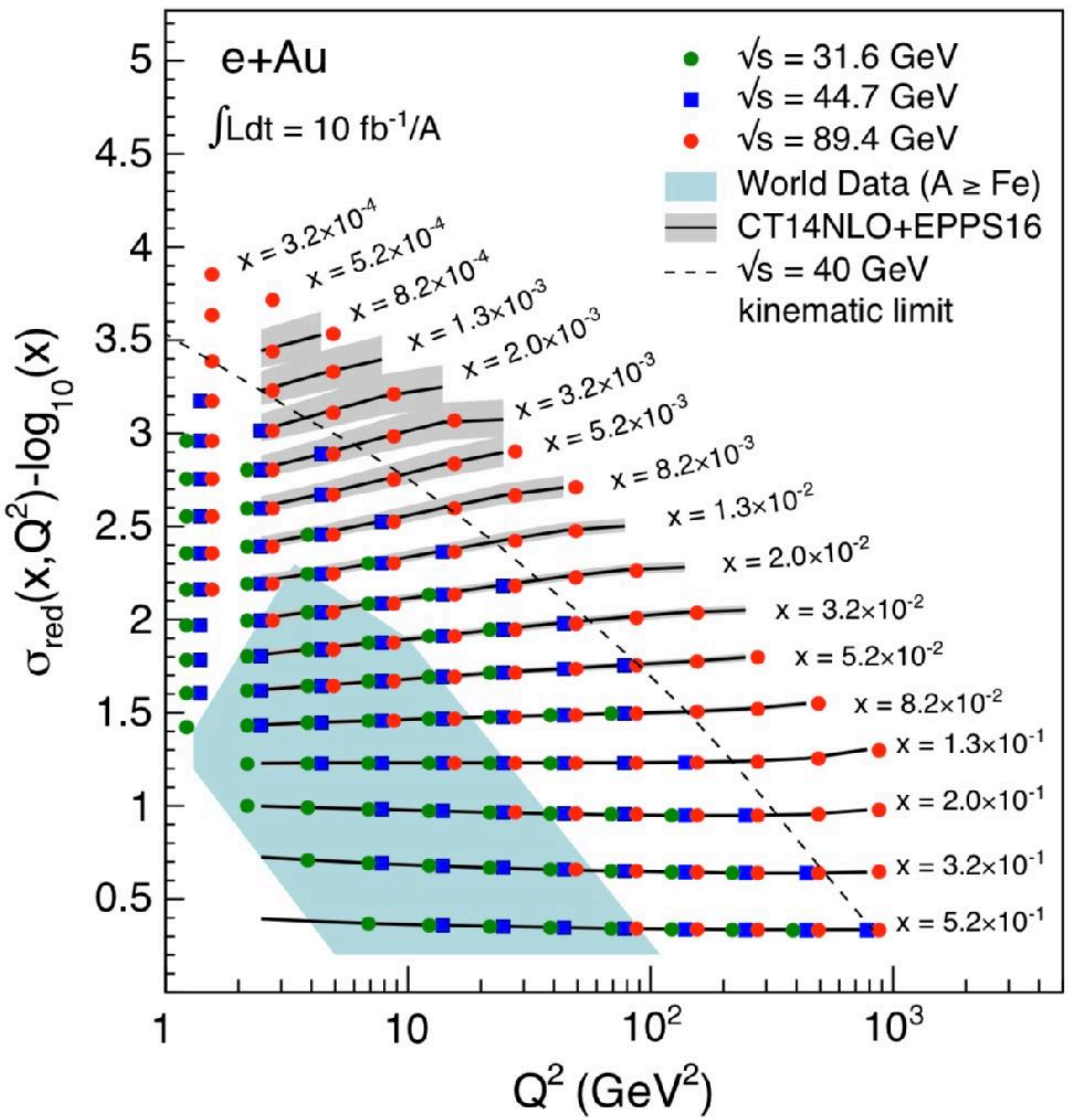


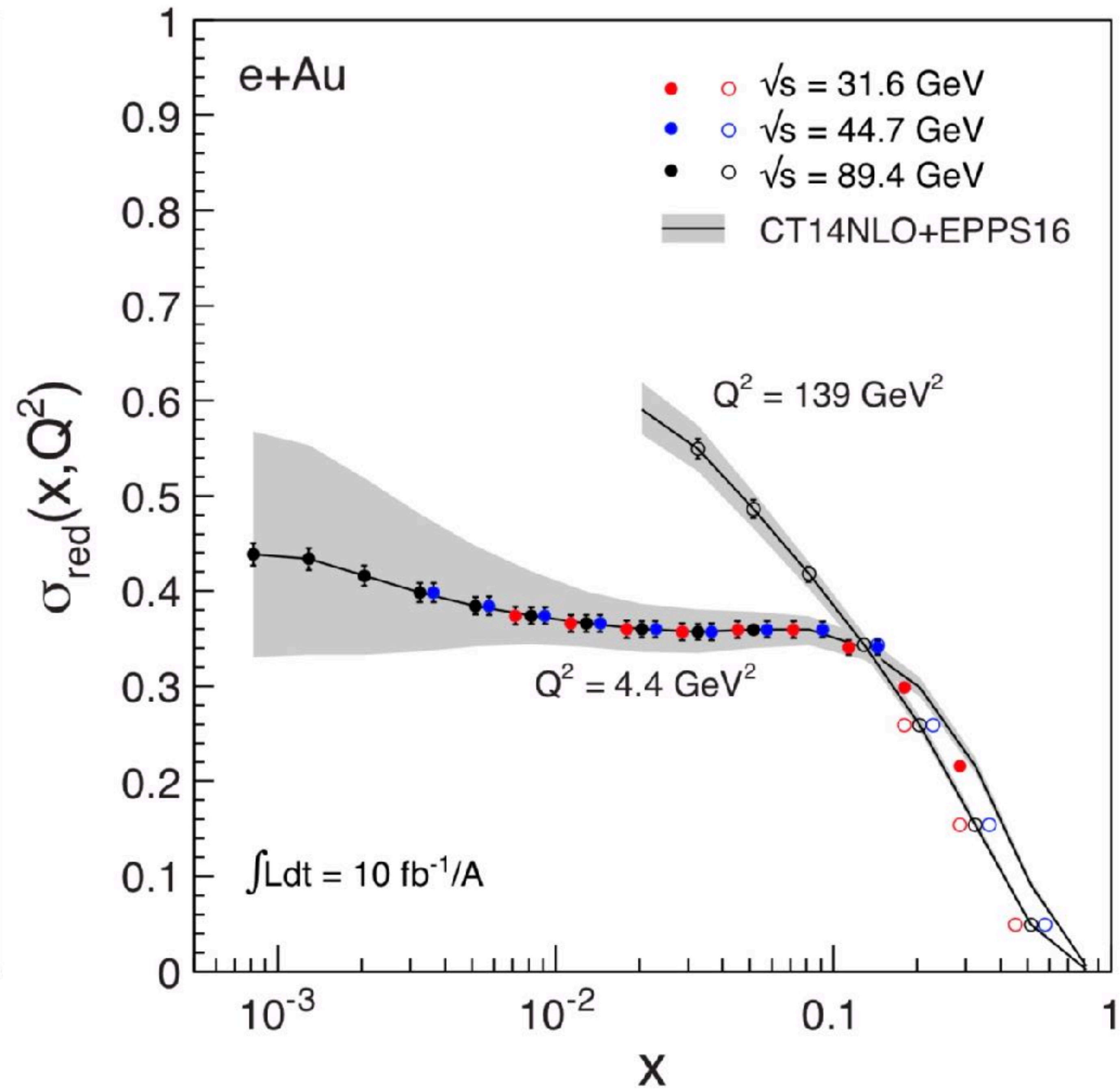
Complementarity with ongoing and future RHIC and LHC measurements, neutrino physics, cosmic ray physics, …

LHeC, if it will be realized, will further extend the kinematic coverage.



U.S.-based EIC - The Nuclear Landscape

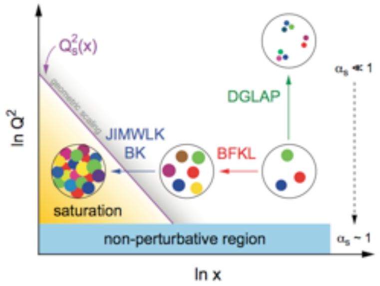


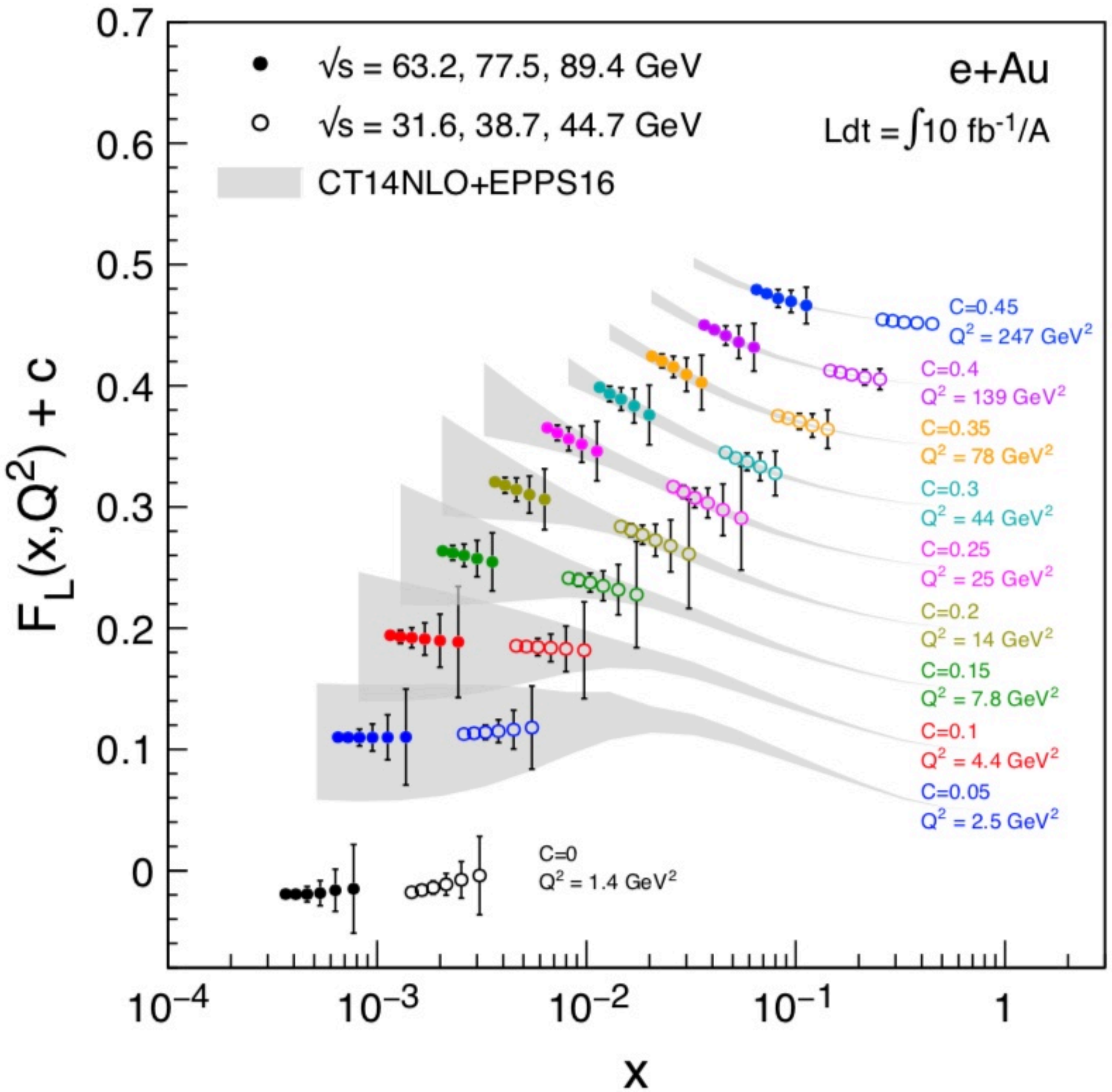


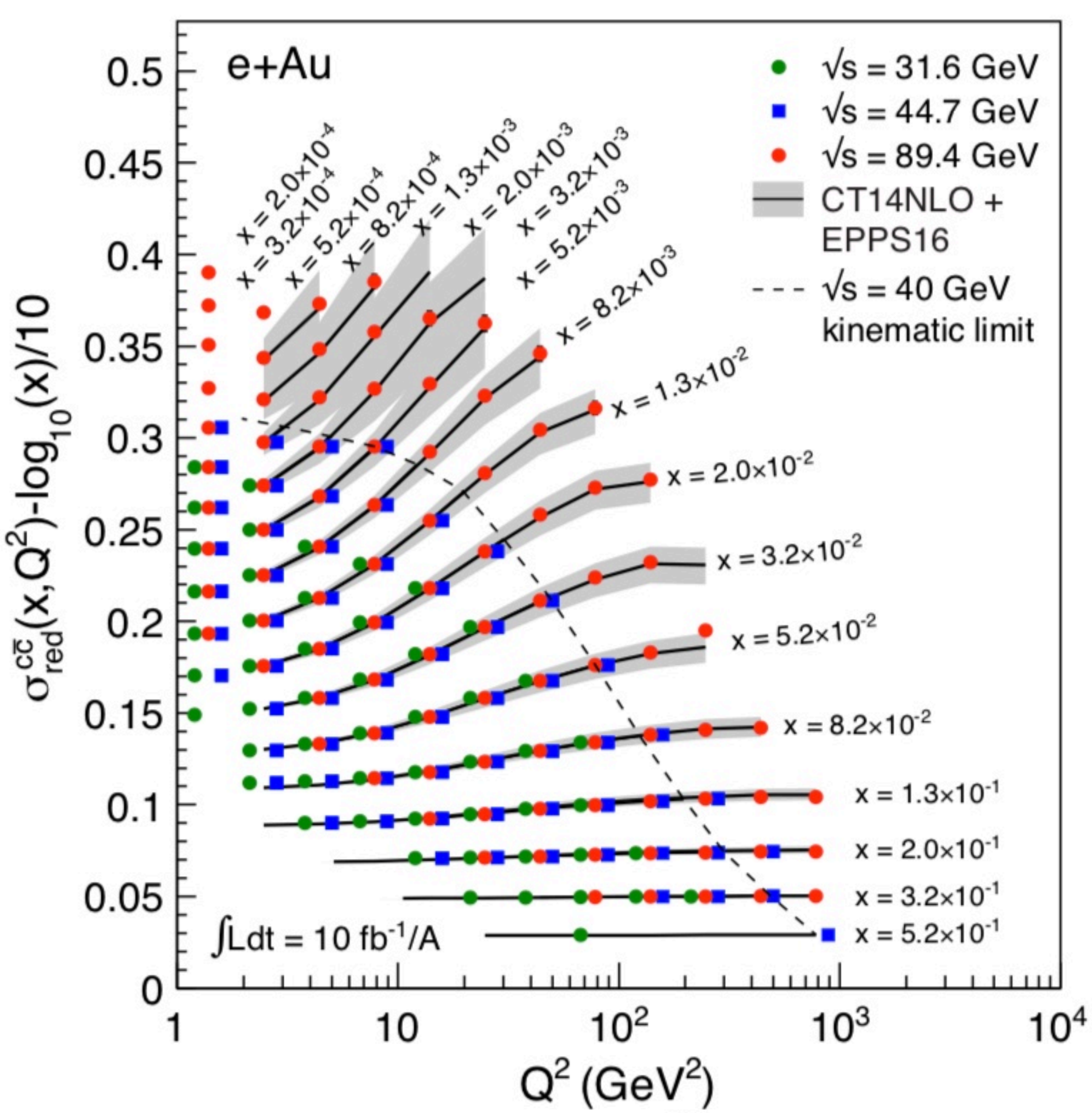
$$\sigma_{\text{reduced}} = F_2(x, Q^2) - \frac{y}{1 + (1-y)^2} F_L(x, Q^2)$$

Impactful baseline inclusive measurements.

U.S.-based EIC - The Nuclear Landscape

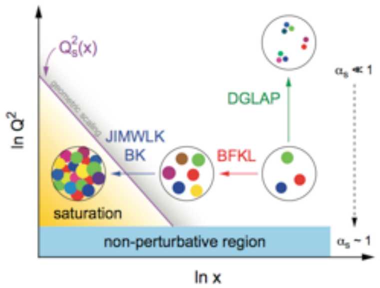




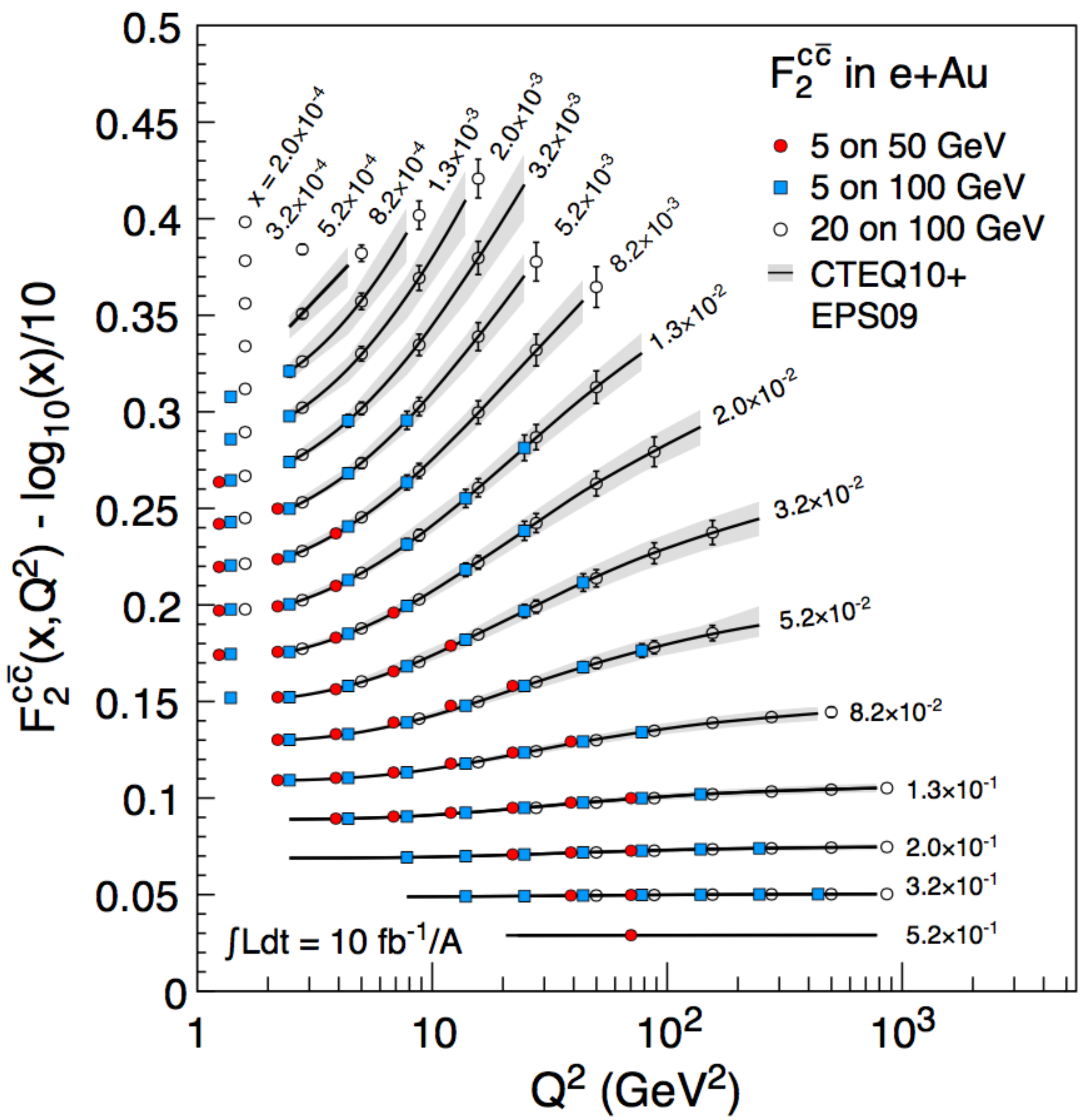


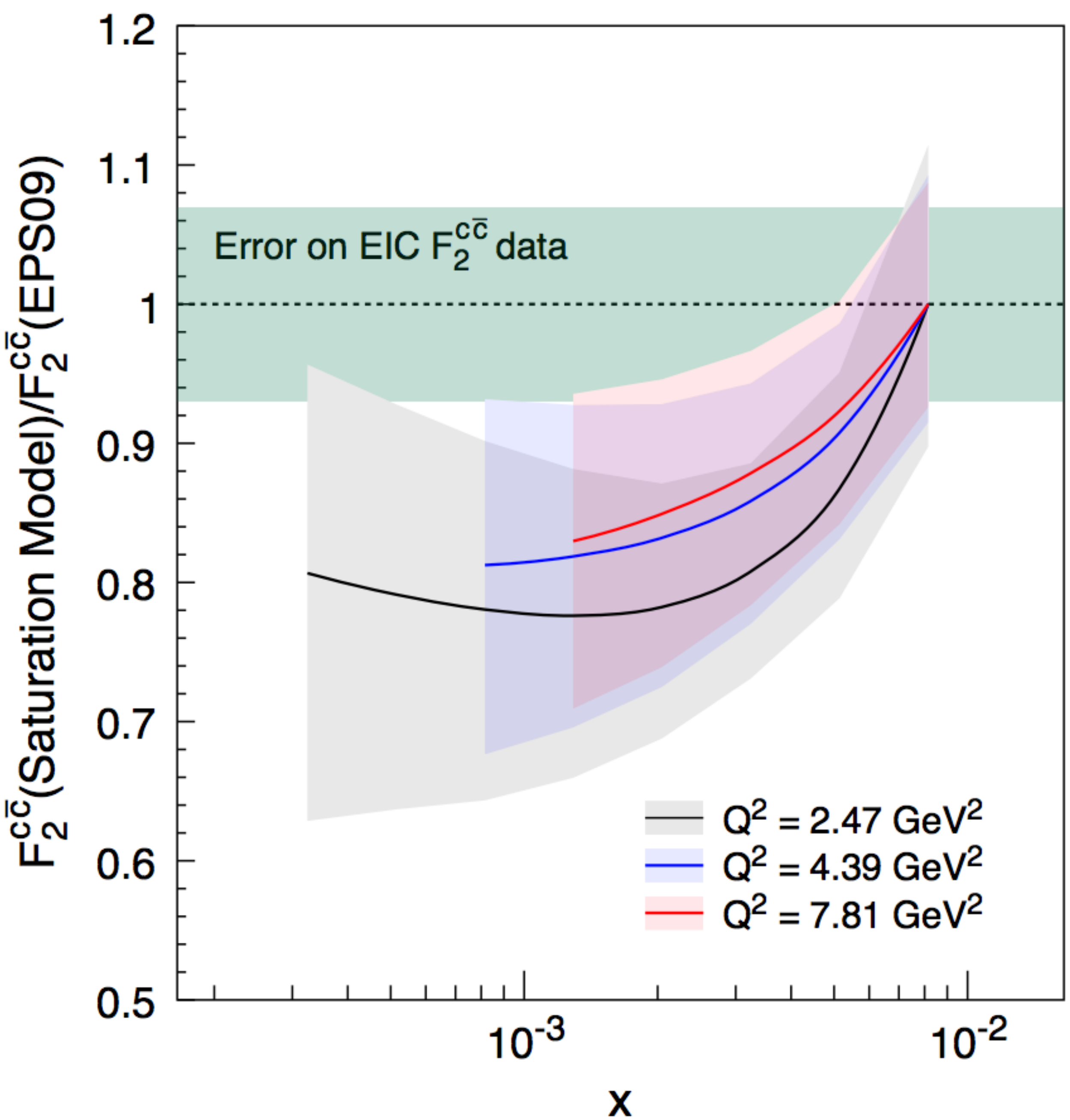
Clearly visible impact also beyond baseline inclusive measurements with "Rosenbluth separation" and semi-inclusive measurements.

Nuclear gluon will be probed sensitively with complementary channels.



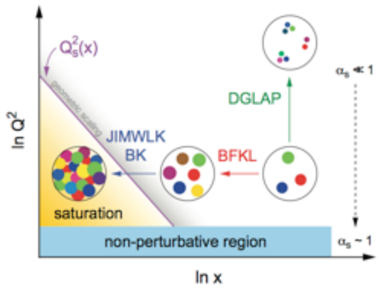
EIC - Saturation from within the PDF?

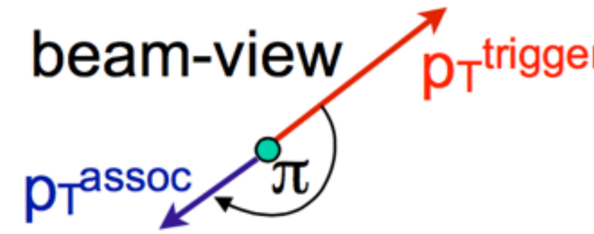


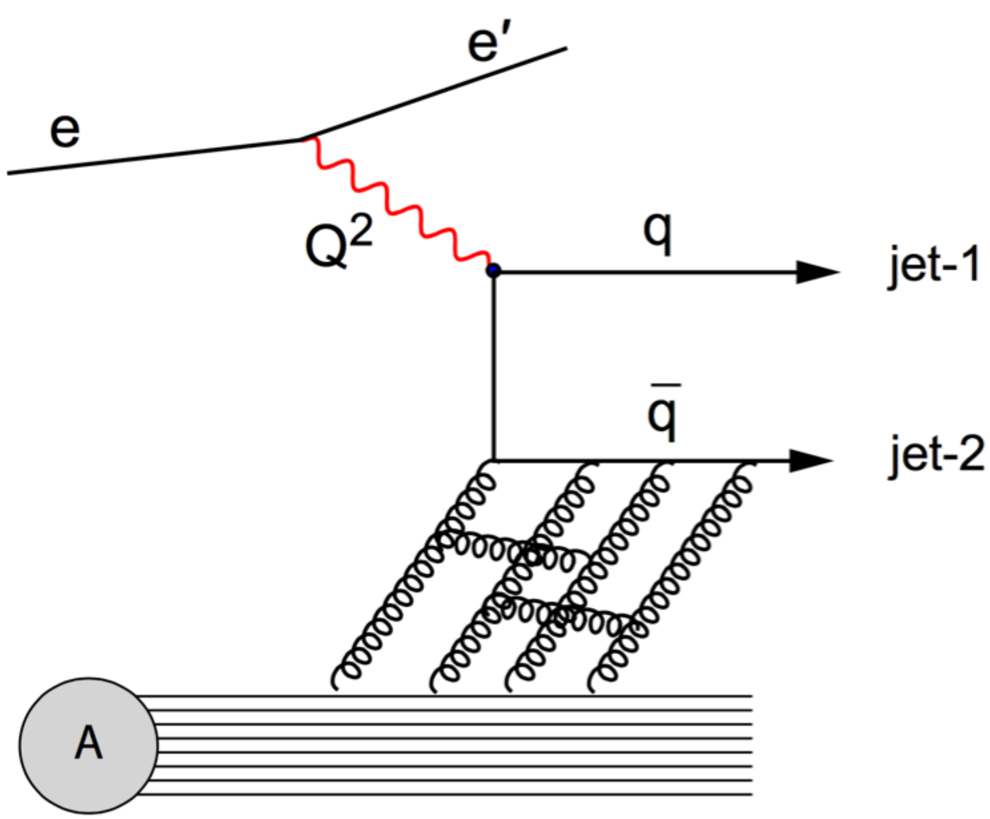


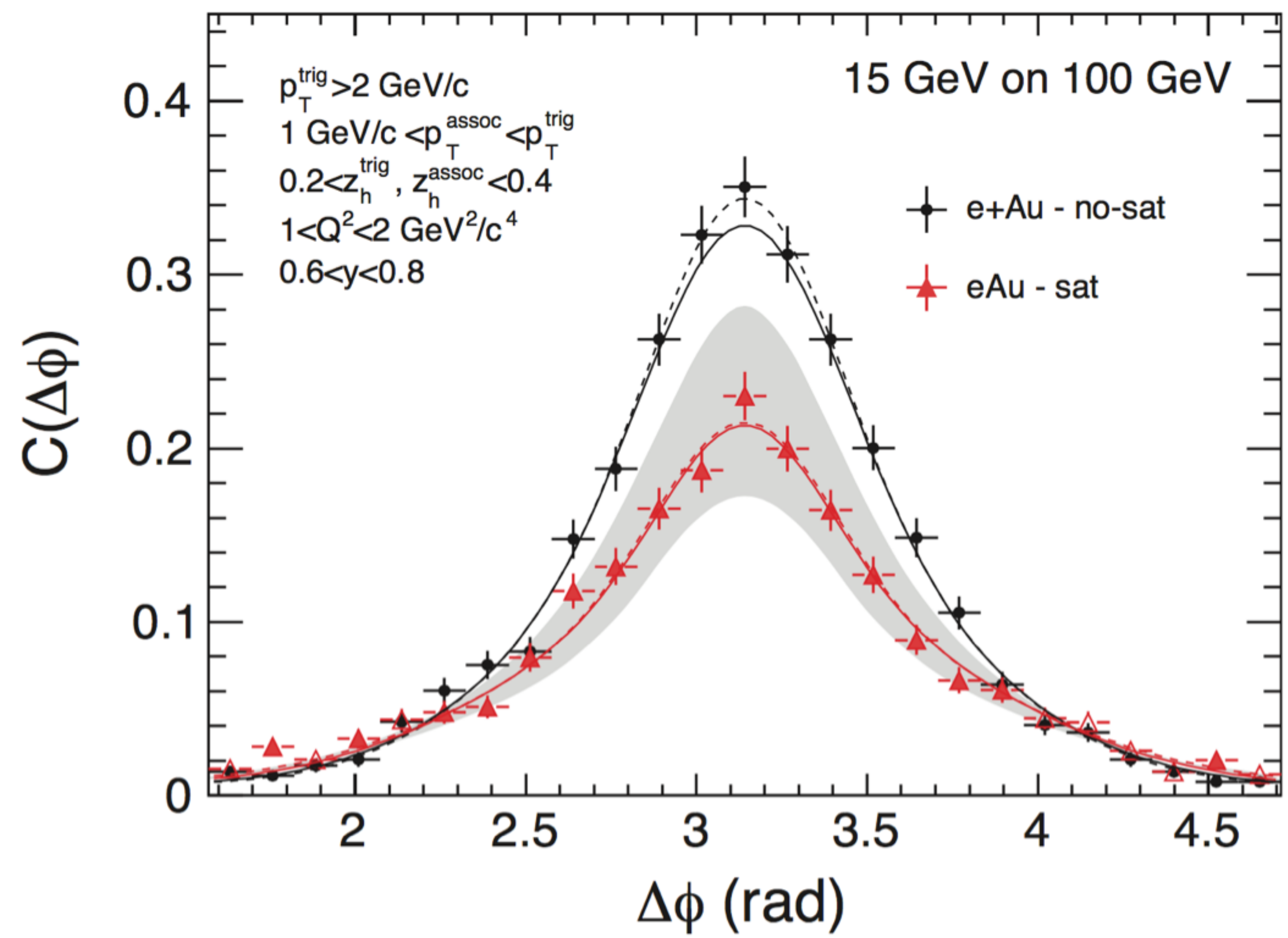
Improbable **and** ***certainly no substitute*** **for thinking** ***outside*** **the PDF!**

EIC - Dihadrons to probe Saturation









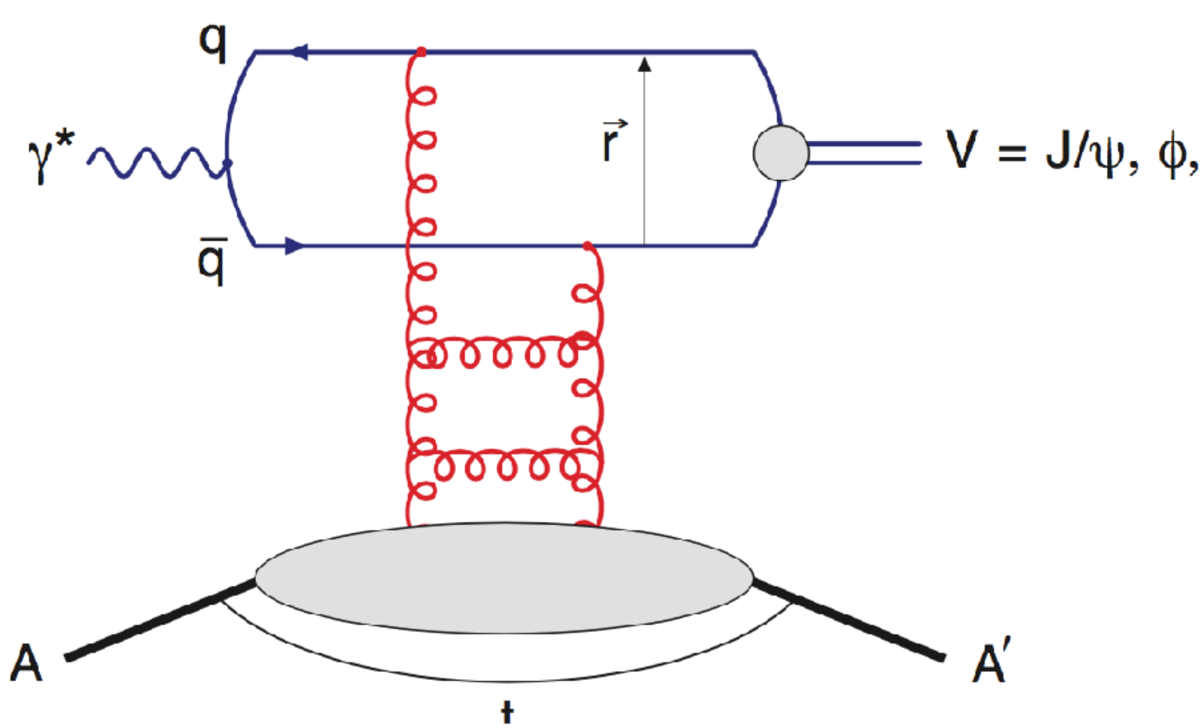
Zheng et al (2014)

Dominguez, Xiao, Yuan (2011)

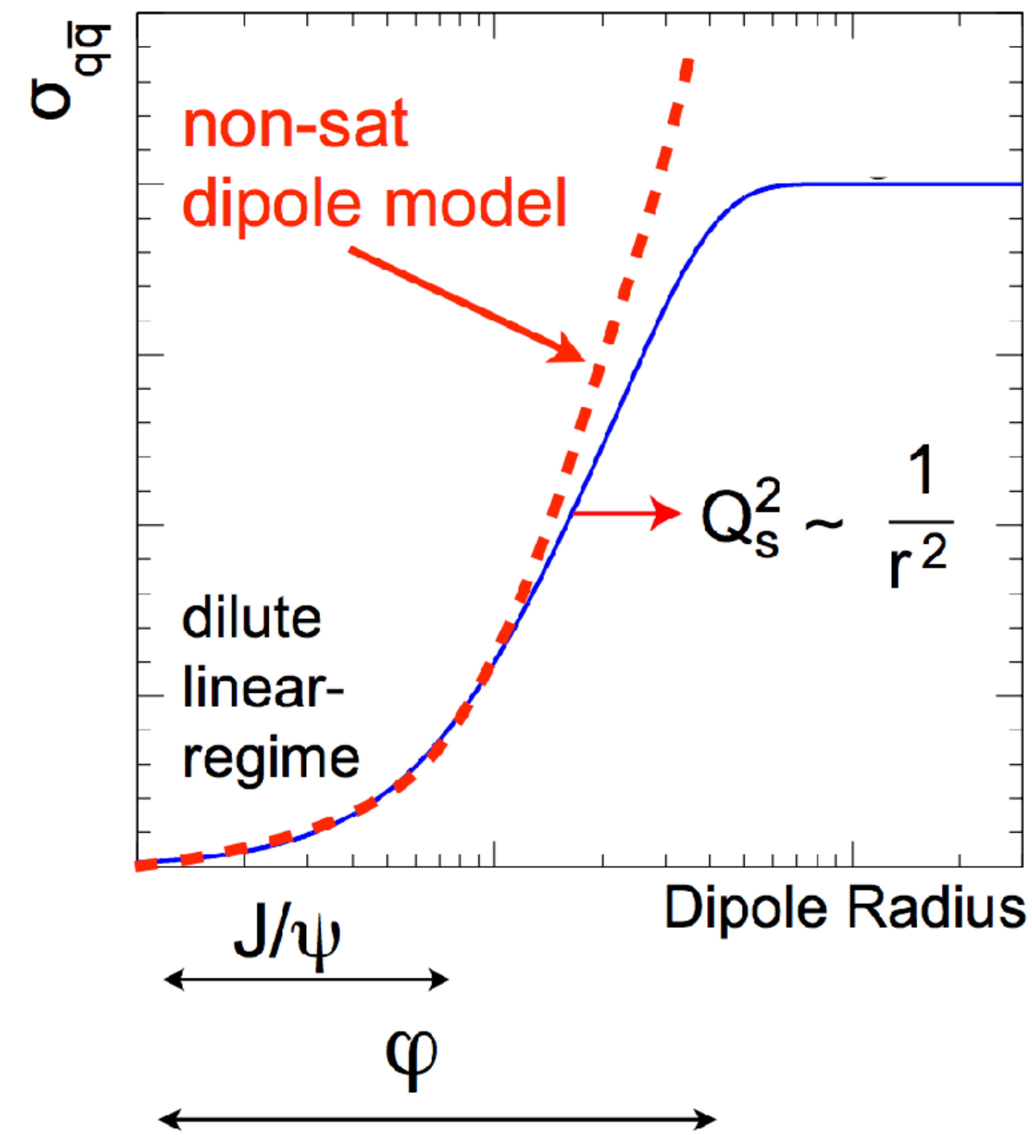
Suppression of back-to-back hadron or jet correlation directly probes the (un-)saturated gluon distributions in nuclei,

EIC - Exclusive Vector Mesons to probe Saturation

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



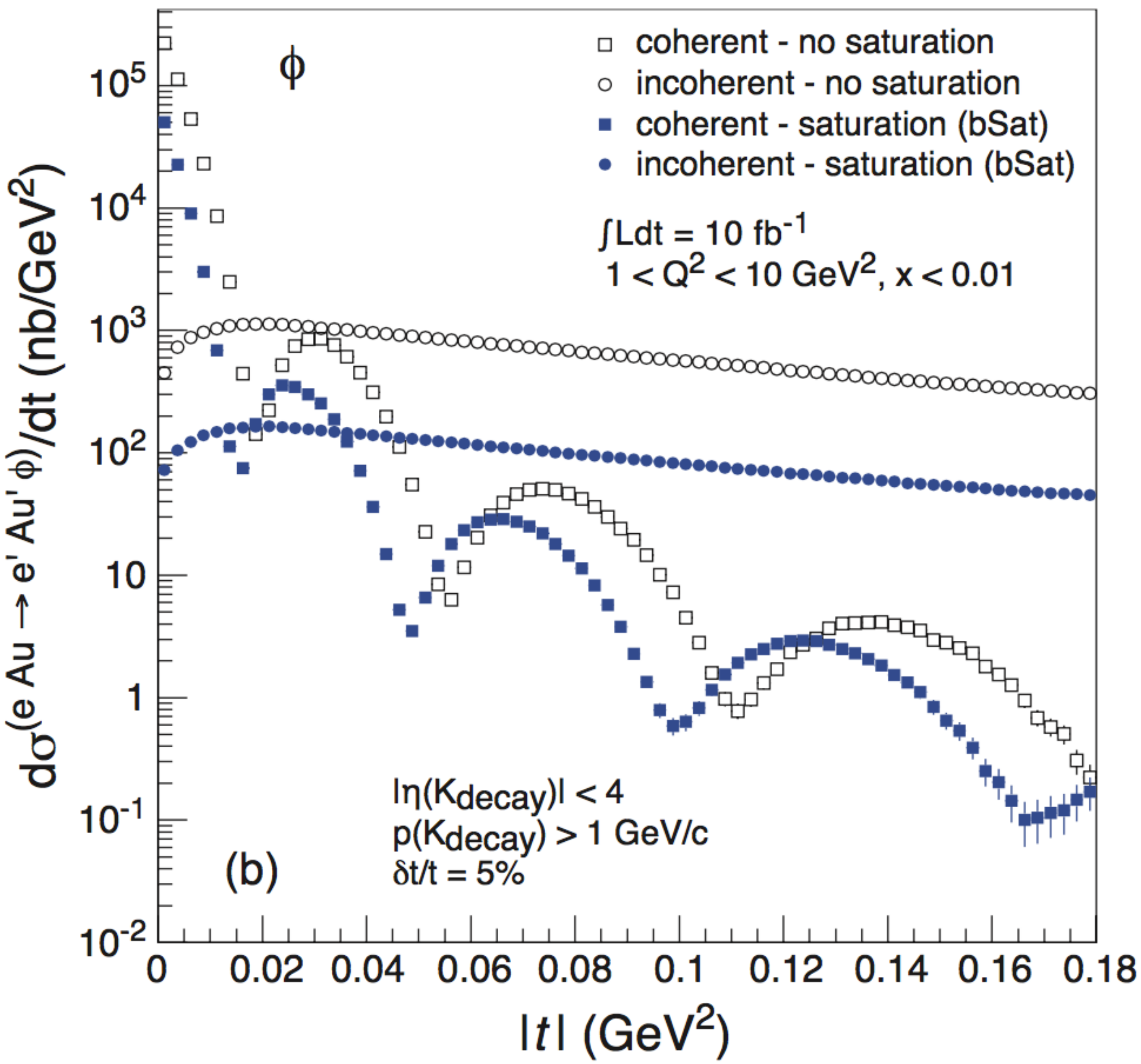
Dipole Cross-Section:

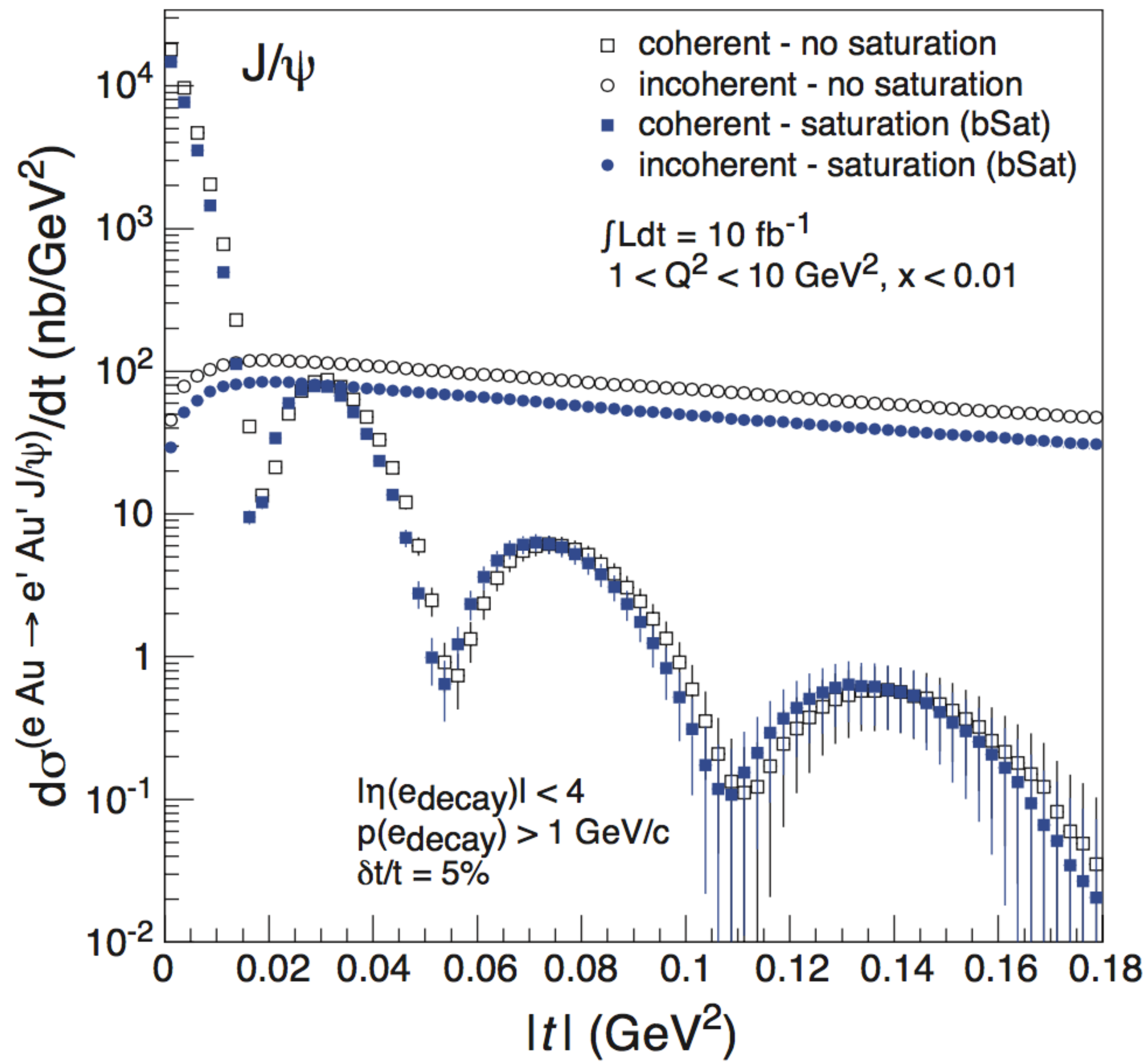


Nucleus escapes down the beampipe

(In)coherence tagged with ZDC

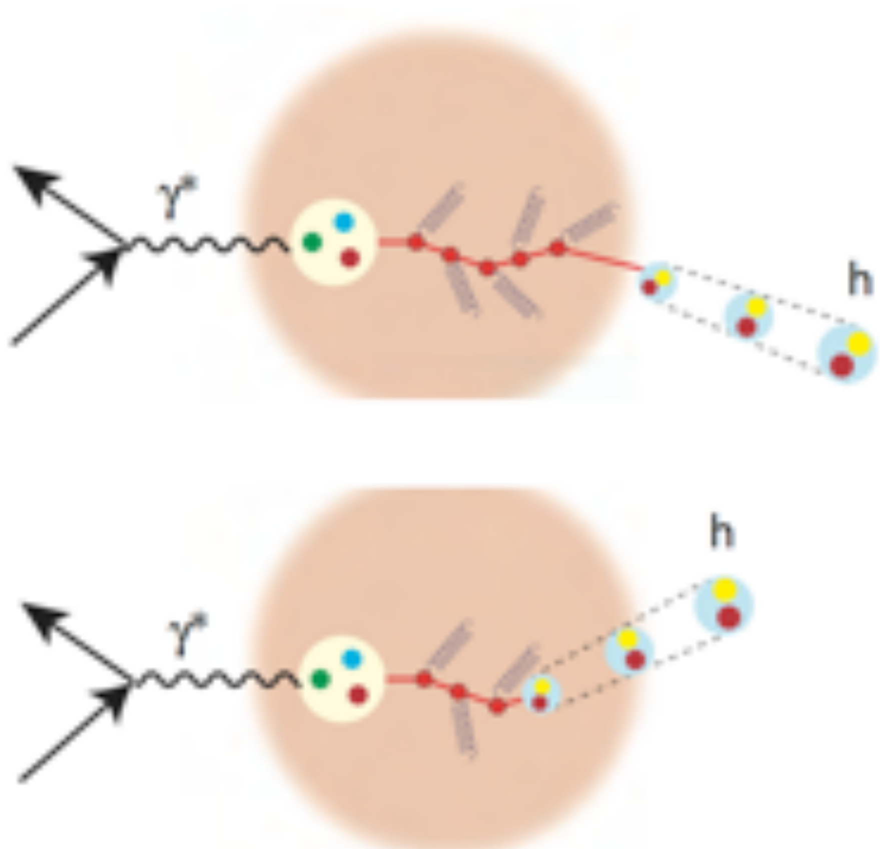
EIC - Exclusive Vector Mesons to probe Saturation





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

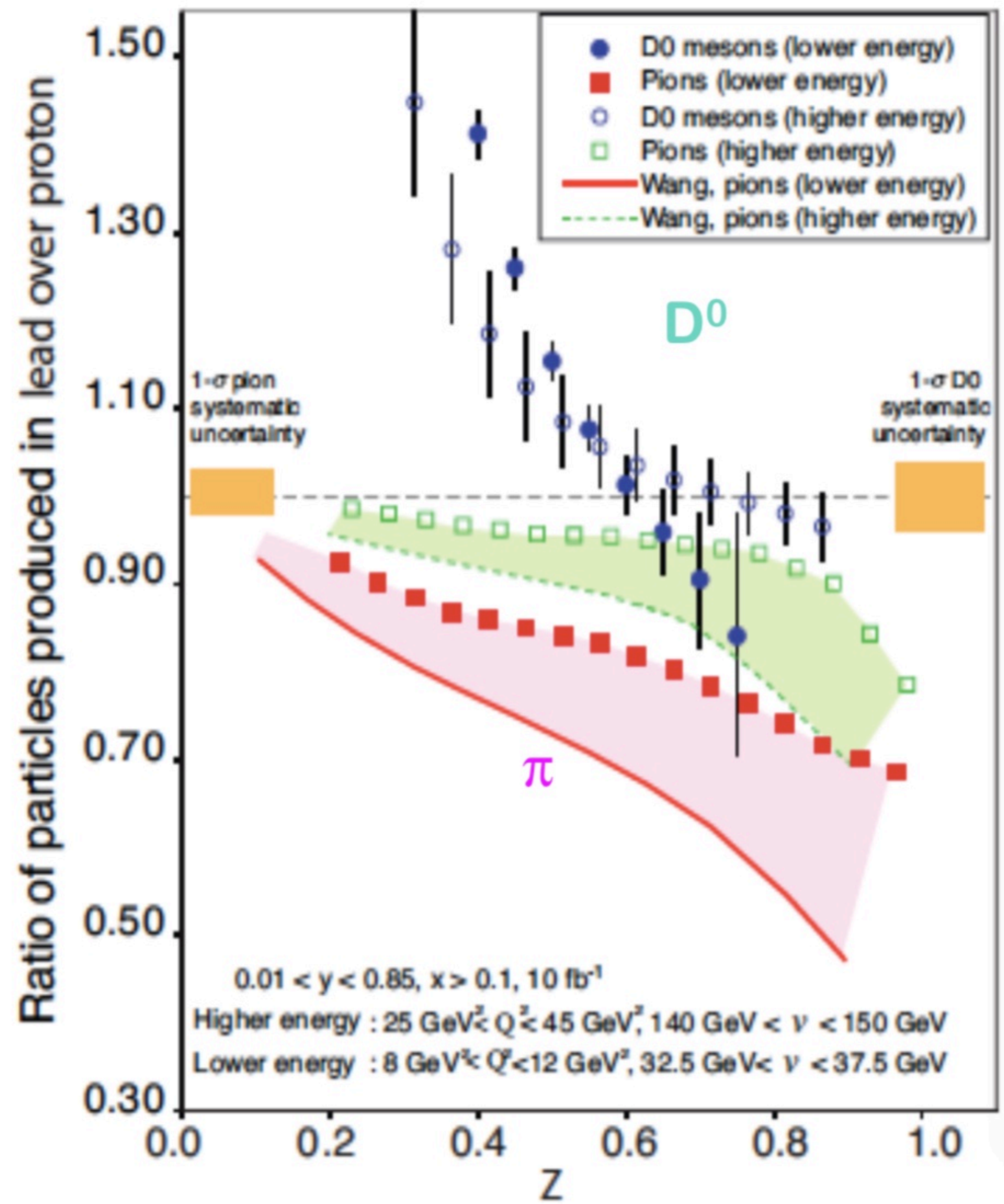
EIC - SIDIS to study Emergence of Hadrons



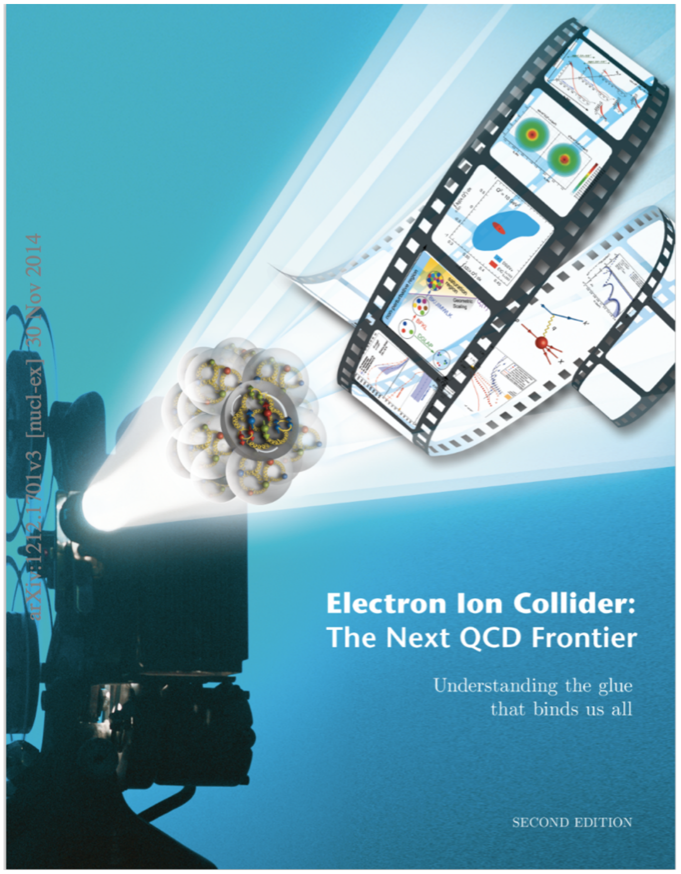
Control of $\nu = \dfrac{Q^2}{2mx}$ and

medium length

Study mass-dependence via charmed hadrons.



Perhaps the least-well articulated case thus far; opportunities abound



Four central nuclear physics themes:

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

U.S.-based Electron-Ion Collider is strongly endorsed in the 2015 Long Range Plan for Nuclear Physics,

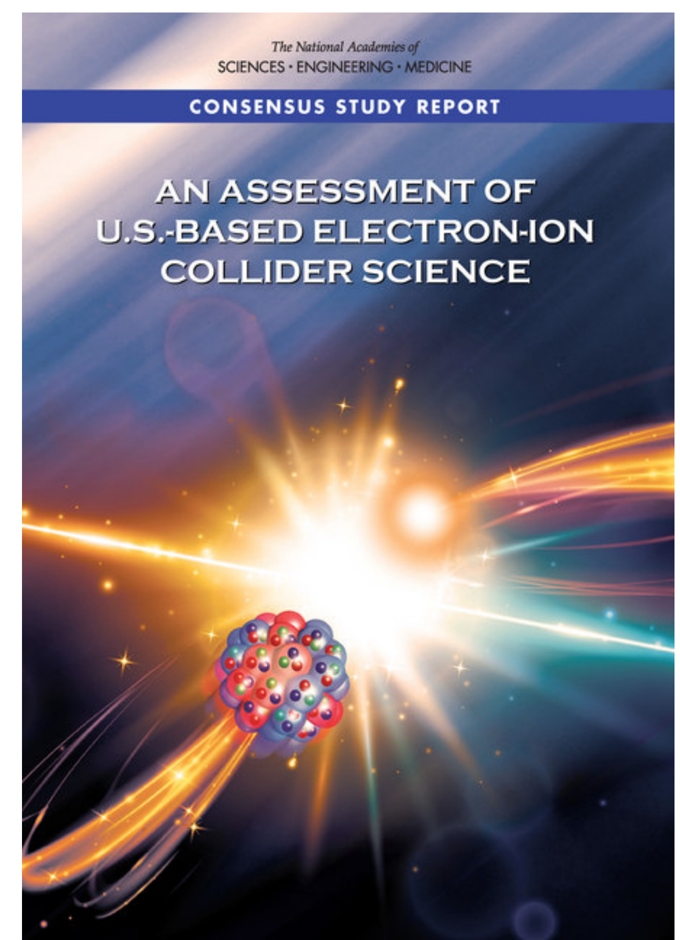
2018 NAS Science Assessment:

"EIC is compelling, fundamental, and timely"

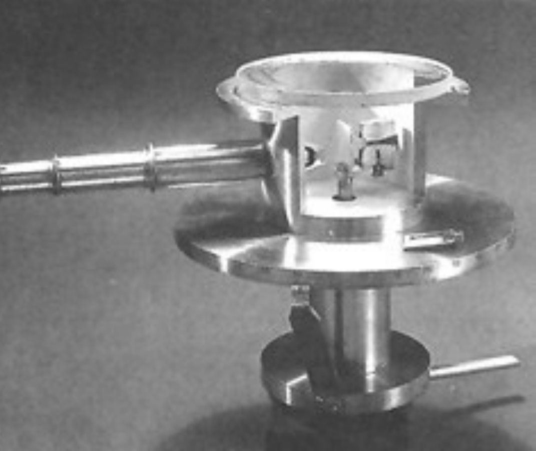
Science case: theory, experiment, *and* accelerator,

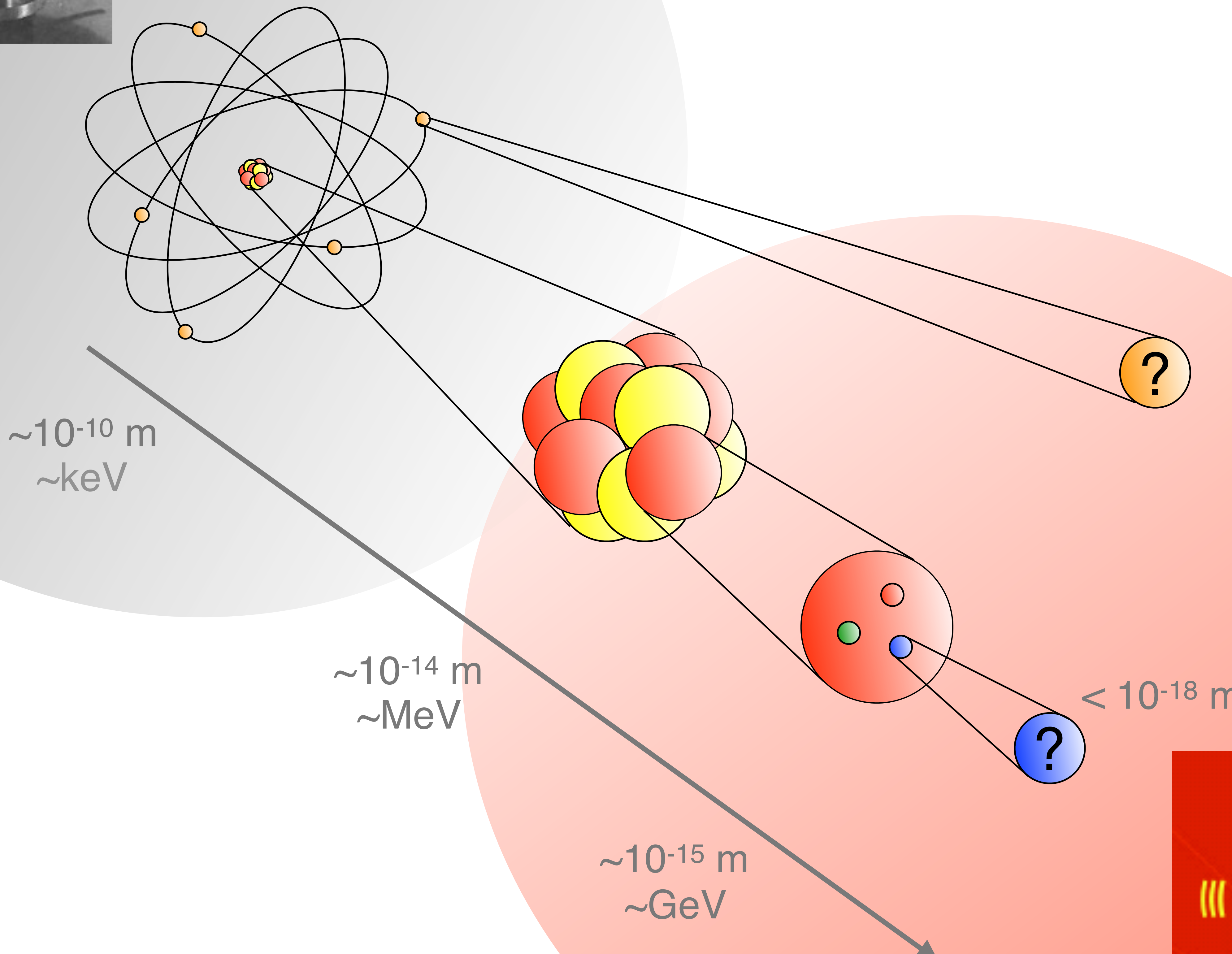
U.S. Department of Energy and host-laboratory are working together towards realizing the *project*,

The EIC User Group, eicug.org, welcomes new collaborators;
Start-up phase of a 12-18 month (new) physics and detector conceptual development study, a precursor to collaborations.



Thank you!





eicug.org