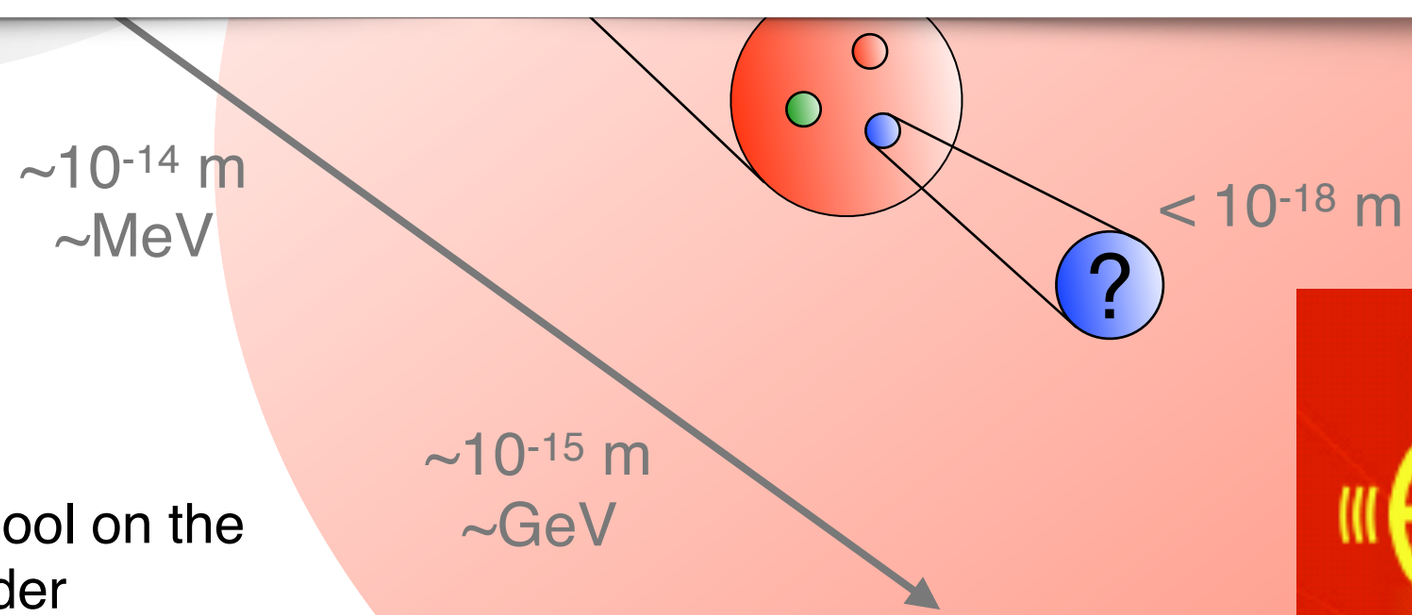
Funding support from:

EIC Physics

An Experimentalist's Perspective

Ernst Sichtermann (Lawrence Berkeley National Laboratory)



2023 CFNS-CTEQ Summer School on the Physics of the Electron-Ion Collider
Stony Brook University — June 5-16, 2023

EIC Physics: An Experimentalist's Perspective

Many thanks to the organizers for organizing this school,

you for taking part!

Lectures like these take a village… I owe a debt of gratitude to many friends and colleagues over many years — errors are of course my own.

Several useful reads:

D. Griffiths, "Introduction to Elementary Particle Physics" (or other textbooks),

G. Wolf "HERA Physics" DESY-94-22 (1994),

The EIC community's "White Paper", Eur. Phys. J. A52 (2016) 268,

The EIC community's "Yellow Report", Nucl. Phys. A 1026 (2022) 122447.

EIC Physics Experimental Perspective

Past

Possible Future

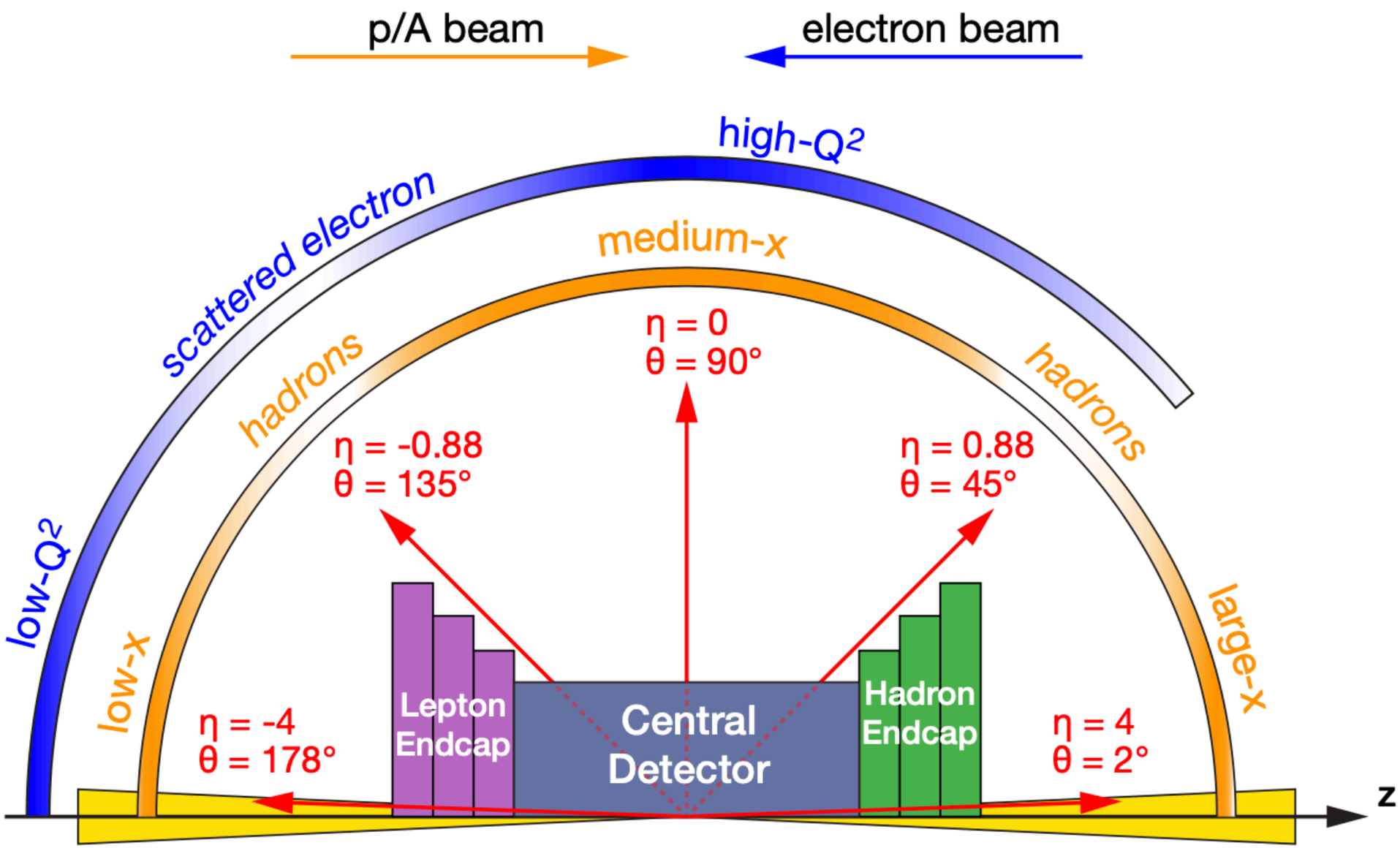
	HERA @ DESY	LHeC @ CERN	EIC in China	EIC in U.S.
$\sqrt{s_{ep}}$ [GeV]	320	200 - 1300	15 - 20	20 - 100 (140)
proton x_{min}	1×10^{-5}	5×10^{-7}	2×10^{-3}	1×10^{-4}
ion	p	p, Pb, …	p - U	p - U
polarization	-	-	p, light nuclei	p, d, ^{3}He, Li
L [$cm^{-2}s^{-1}$]	2×10^{31}	1×10^{34}	3×10^{33}	10^{33} - 10^{34}
Interaction Points	2	1	1	2
Timeline	1992 - 2007	post ALICE	Upgrade to HIAF	> 2031

High-Energy Physics

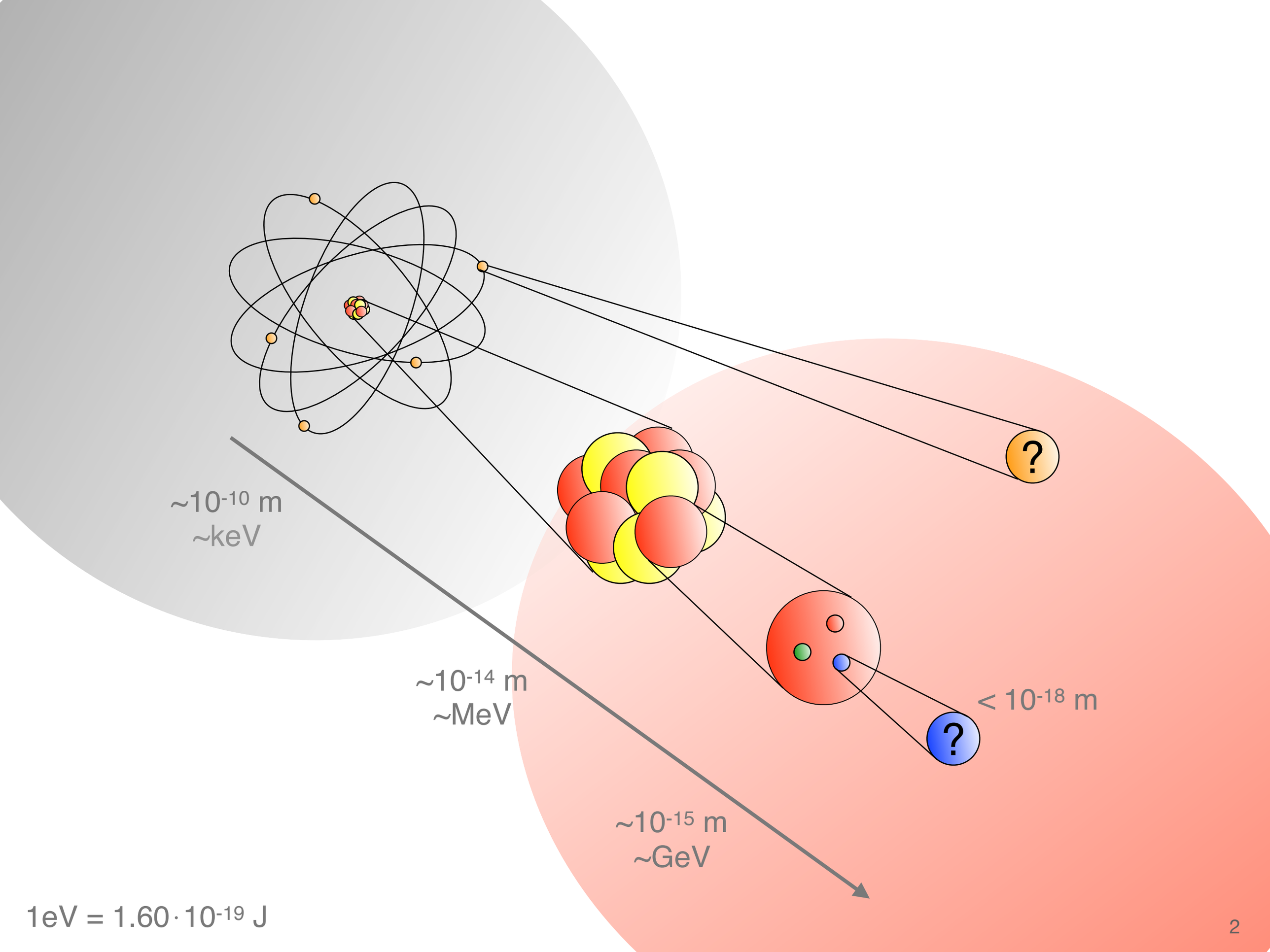
Nuclear Physics

Goal: EIC context and capabilities (today)

EIC Physics Experimental Perspective

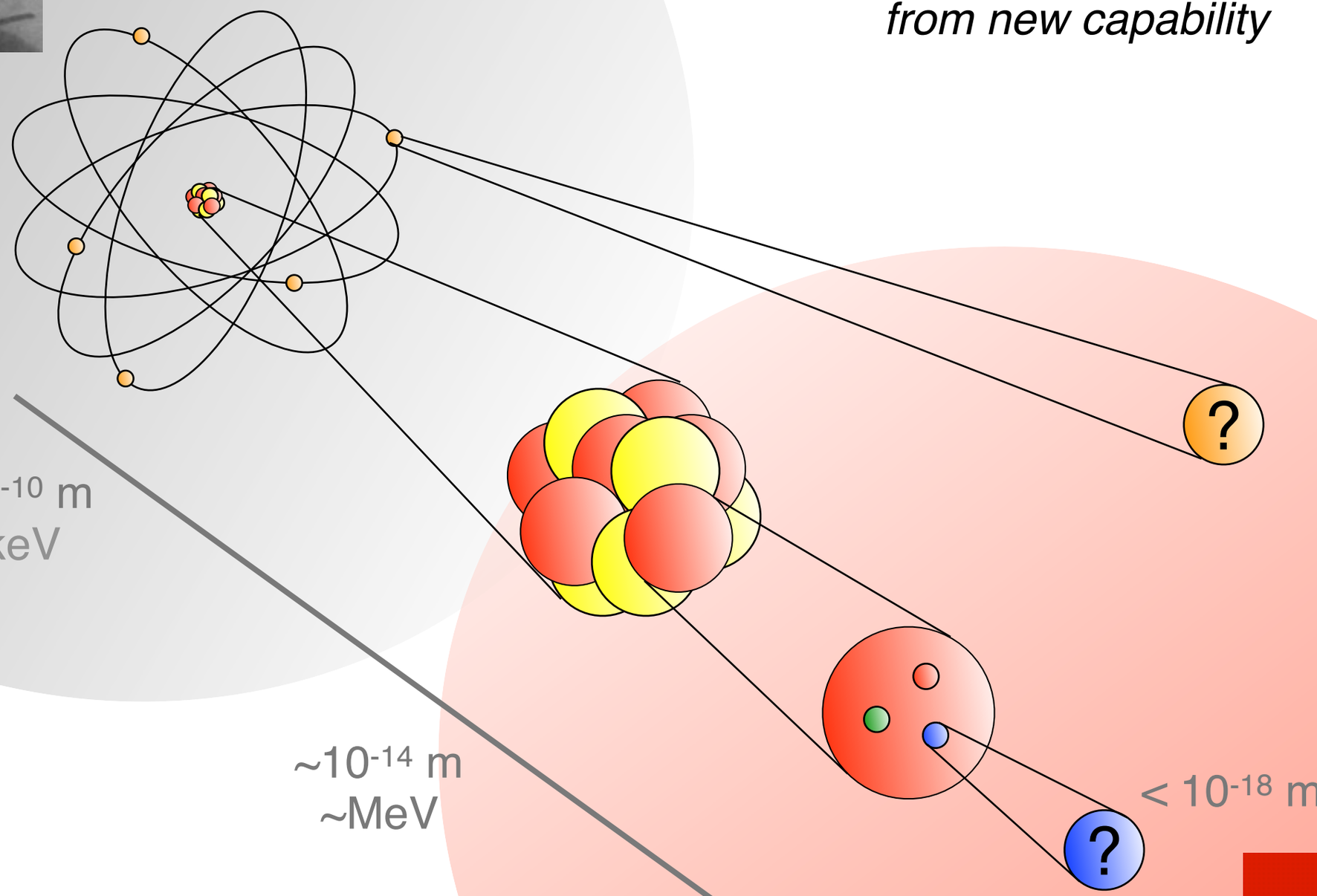


Goal: EIC experiment concepts (tomorrow)

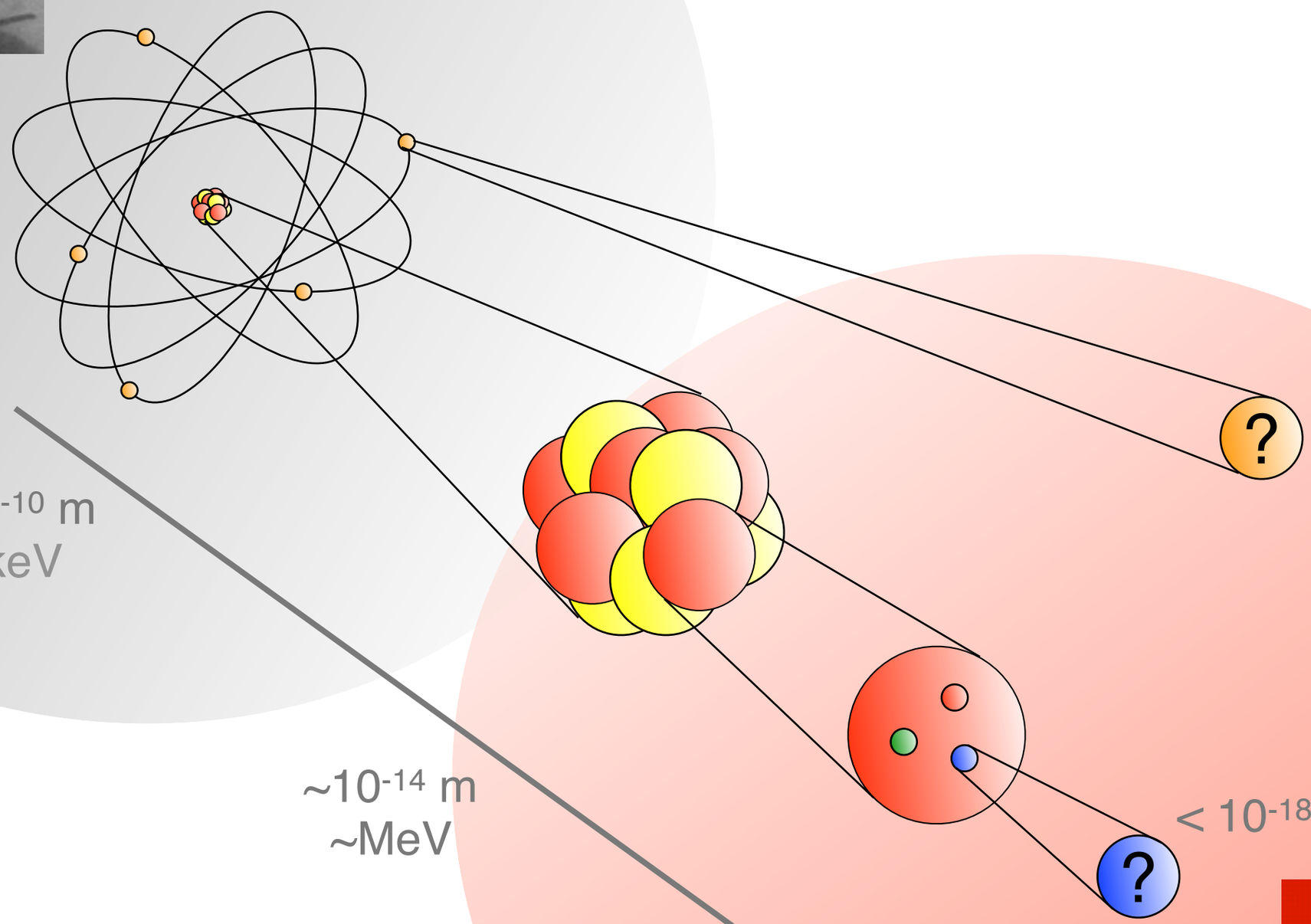


$1\text{eV} = 1.60 \cdot 10^{-19}\ \text{J}$

A history of new insight from new capability



What *is* a proton, neutron, nucleus?



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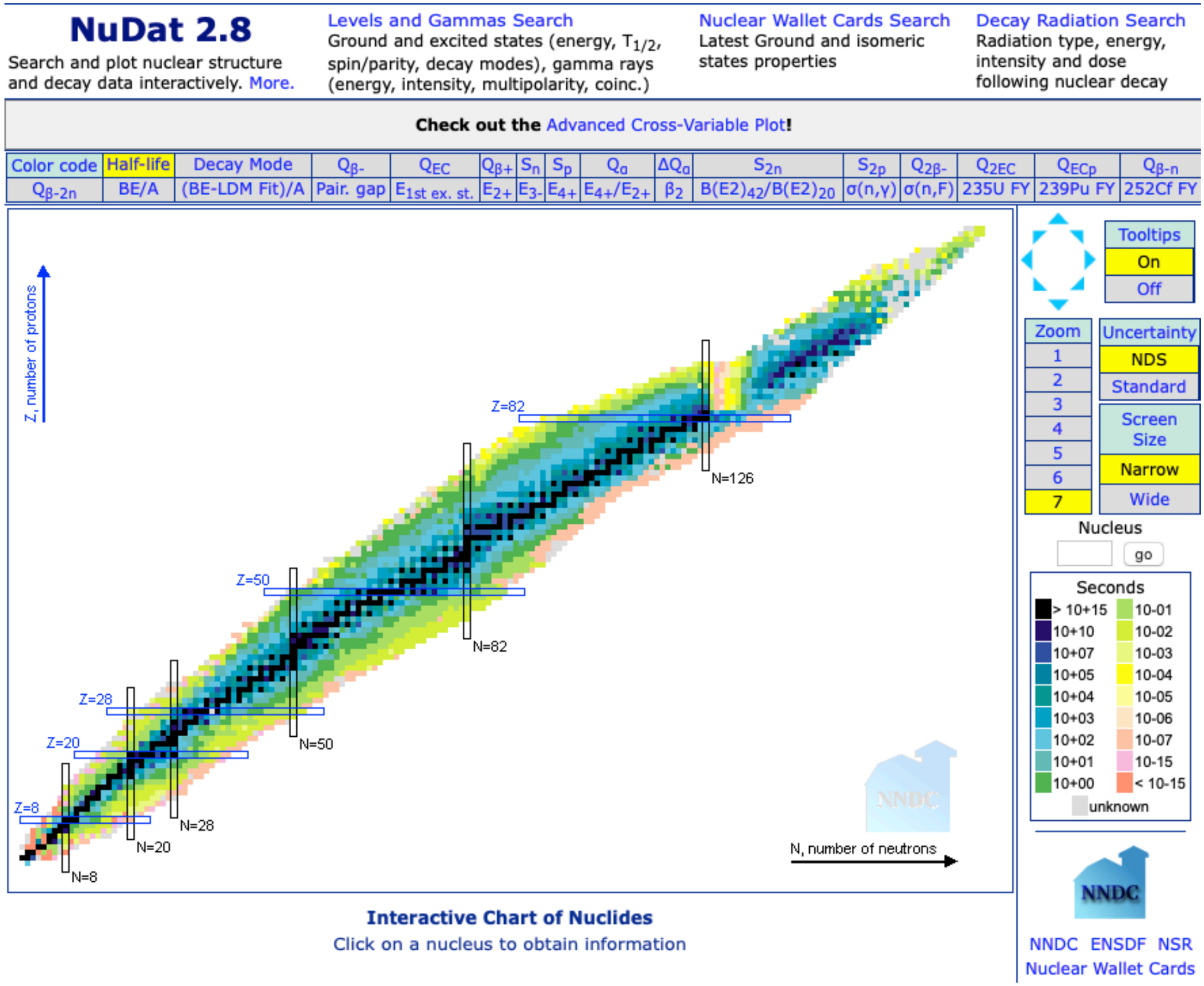

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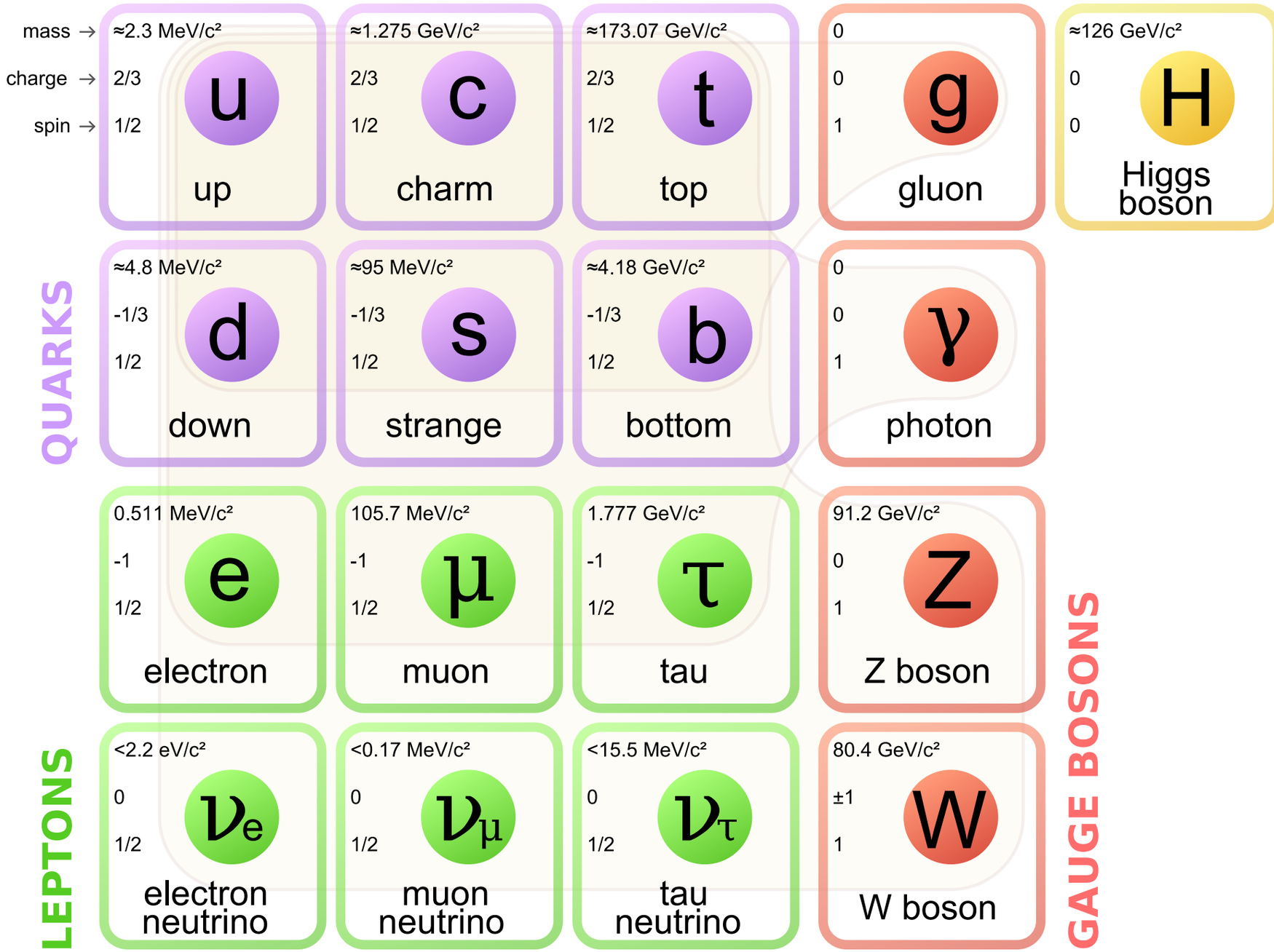


What *is* a proton, neutron, nucleus?

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

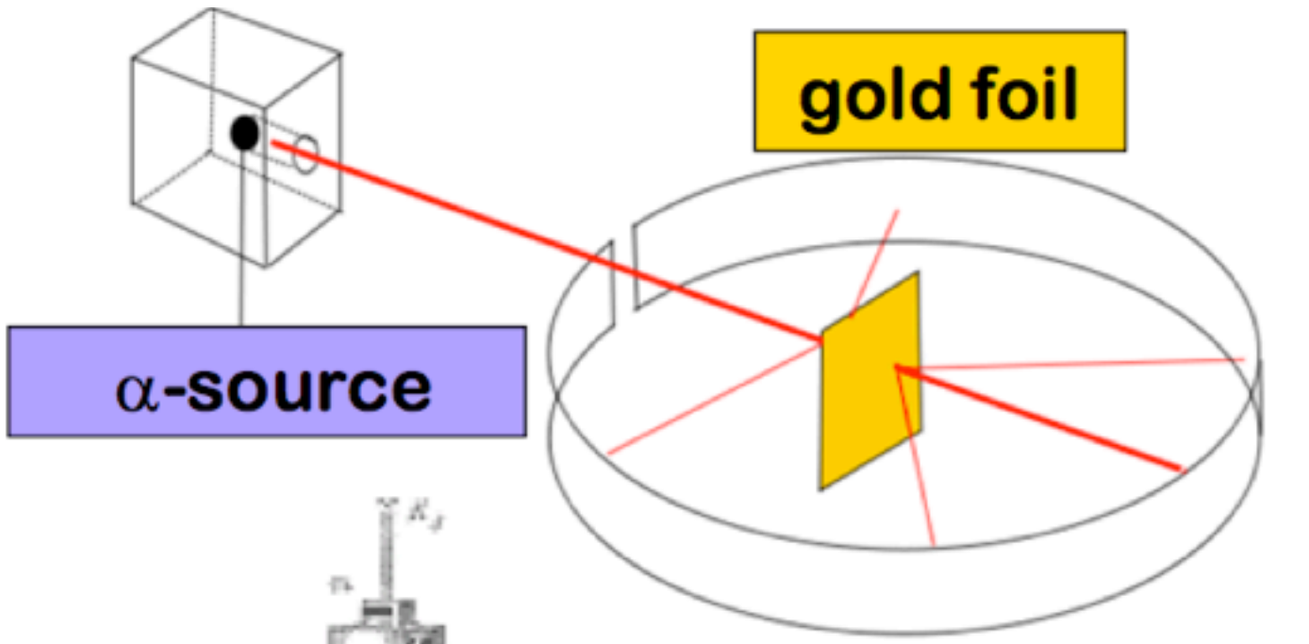
None of these are Standard Model parameters,

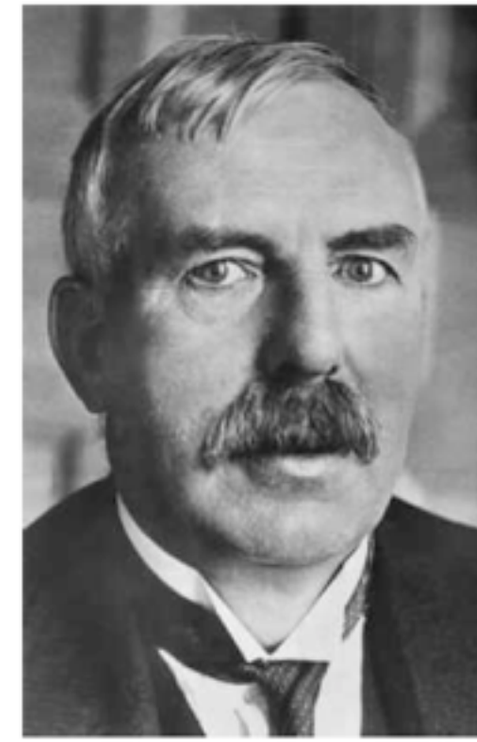
QCD theory has come quite far (although society is *far* from “QCD-engineering”),

EIC is about a combination of strengths resulting in *new* capability.

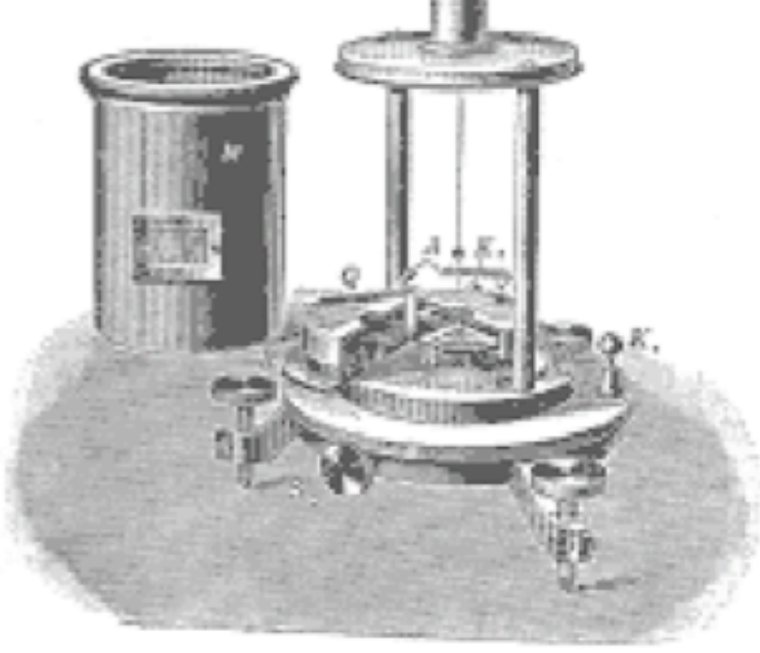
Rutherford Scattering

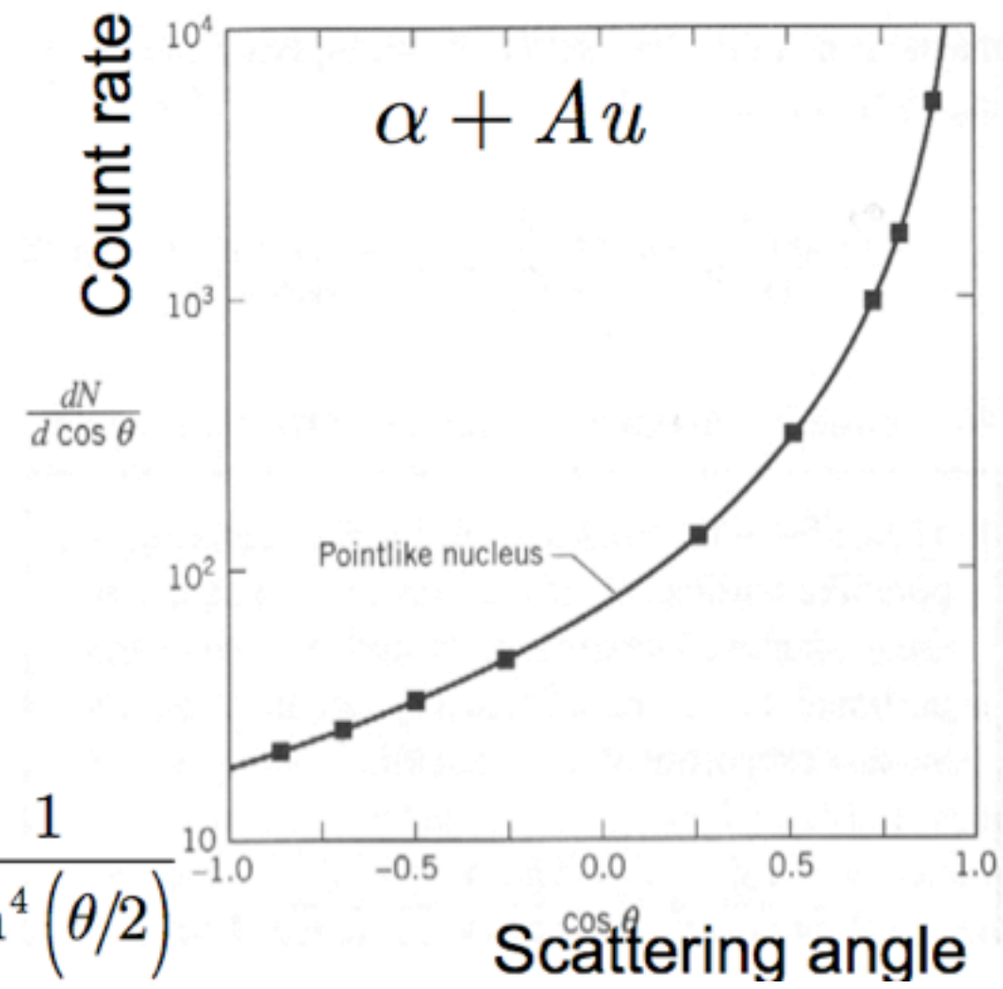
~5 MeV





Ernest Rutherford,
Nobel Prize 1908

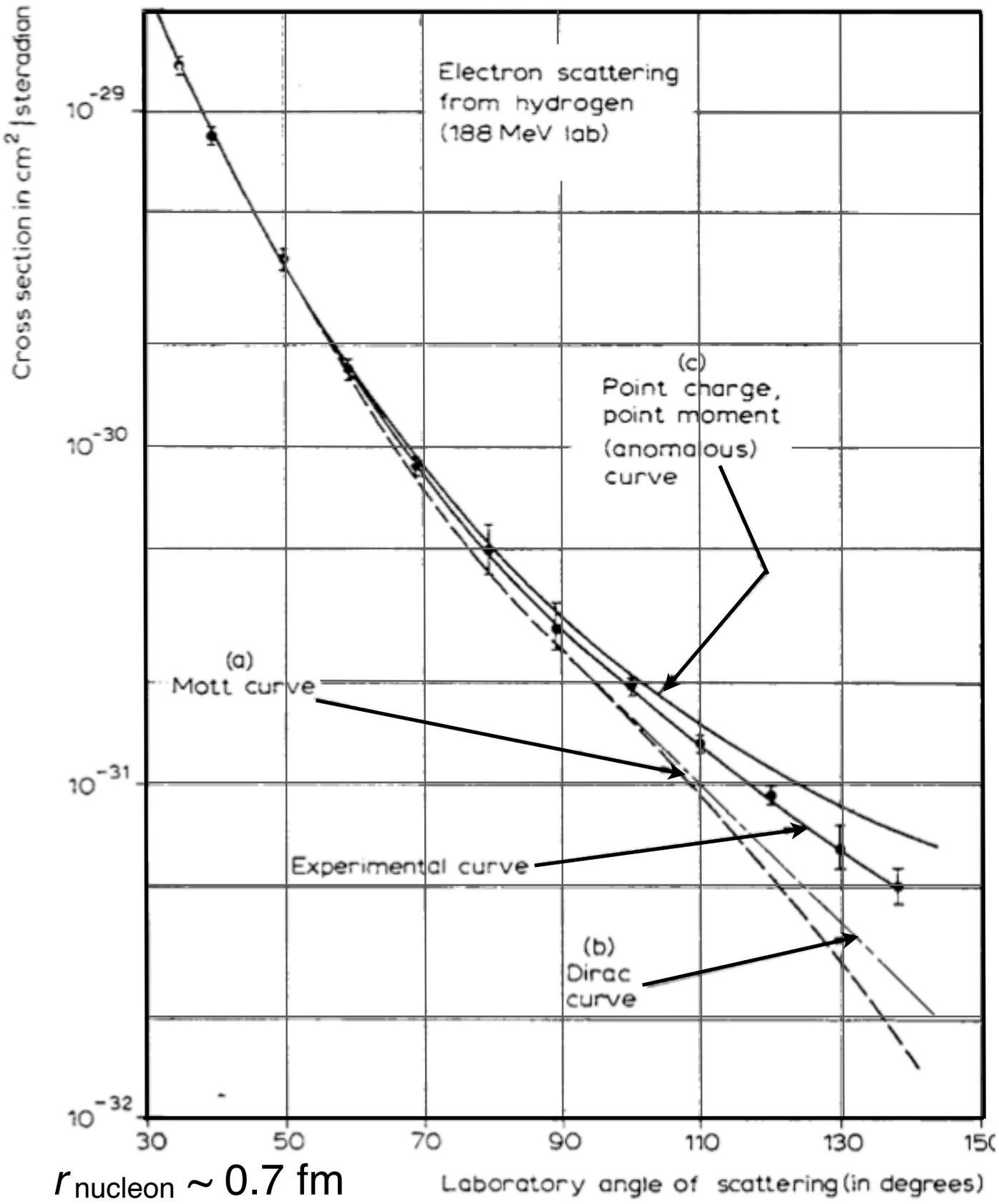




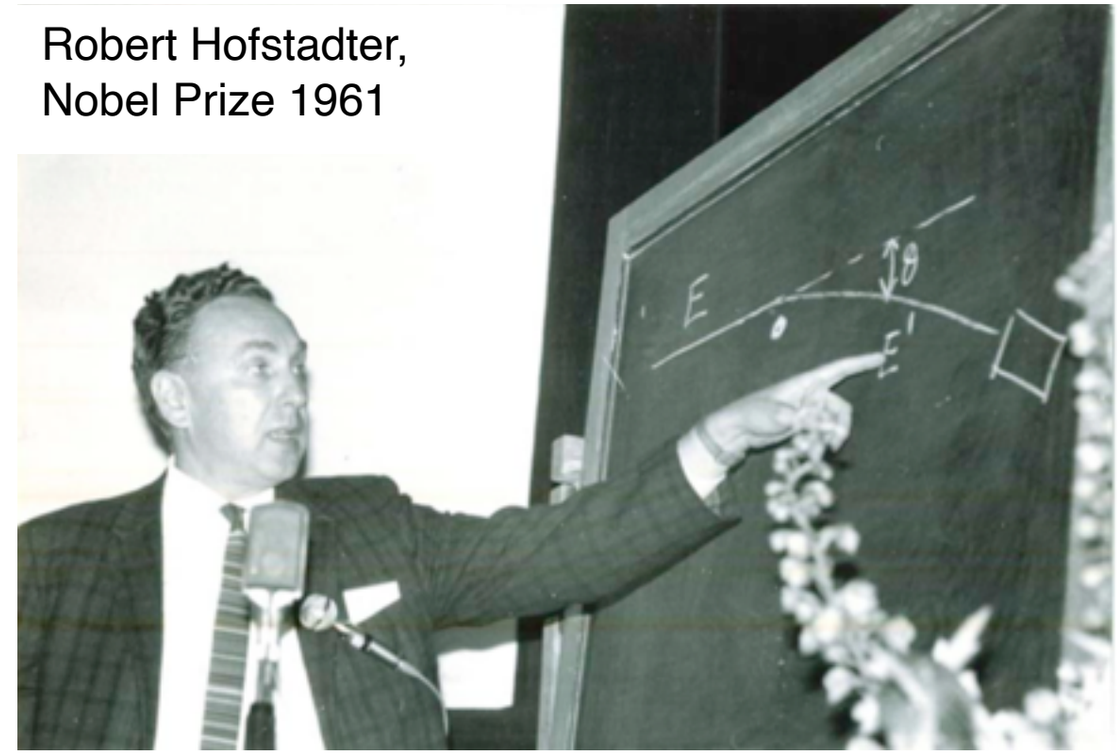
$$\frac{d\sigma}{d\Omega} = (zZ\alpha)^2 \left(\frac{\hbar c}{4E_{\text{kin}}}\right)^2 \frac{1}{\sin^4\left(\theta/2\right)}$$

Scattering off a hard sphere; $r_{\text{nucleus}} \sim (10^{-4} \,.\, r_{\text{atom}}) \sim 10^{-14}$ m

~200 MeV *Elastic* Electron Scattering



$r_{\text{nucleon}} \sim 0.7$ fm



Robert Hofstadter, Nobel Prize 1961

Scattering off a spin-1/2 Dirac particle:

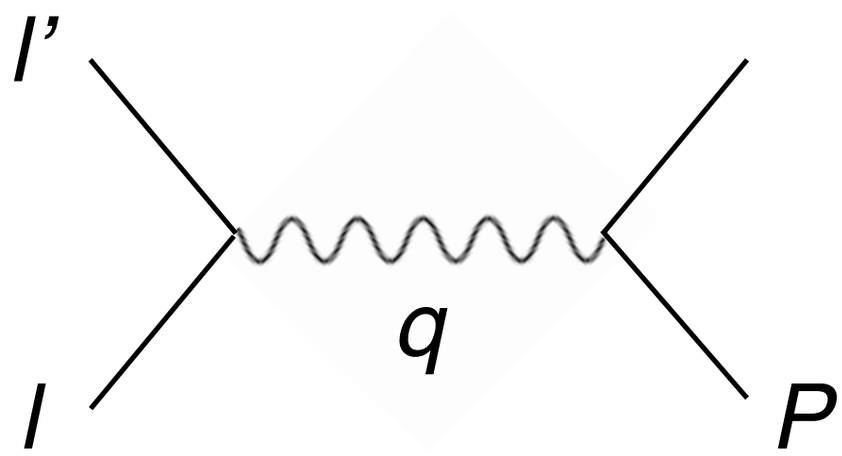
$$\frac{d\sigma}{d\Omega} = \left(\frac{\alpha}{4ME\sin^2(\theta/2)}\right)^2 \frac{E'}{E}\left[\frac{q^2}{2M}\sin^2(\theta/2) + \cos^2(\theta/2)\right]$$

The proton has an anomalous magnetic moment,

$$g_p \neq 2, \quad g_p \simeq 5.6$$

and, hence, internal (spin) structure.

Elastic Electron Scattering



$$d\sigma \propto \left\langle |\mathcal{M}|^2 \right\rangle = \frac{g_e^4}{q^4} L^{\mu\nu}_{\text{lepton}} K_{\mu\nu\,\text{nucleon}}$$

The lepton tensor is calculable:

$$L^{\mu\nu}_{\text{lepton}} = 2\left(k^\mu k'^\nu + k^\nu k'^\mu + g^{\mu\nu}(m^2 - k\cdot k')\right)$$

The nucleon tensor is not; it's general (spin-averaged, parity conserved) form is:

$$K_{\mu\nu\,\text{nucleon}} = -K_1 g_{\mu\nu} + \frac{K_2}{M^2} p_\mu p_\nu + \frac{K_4}{M^2} q_\mu q_\nu + \frac{K_5}{M^2}\left(p_\mu q_\nu + p_\nu q_\mu\right)$$

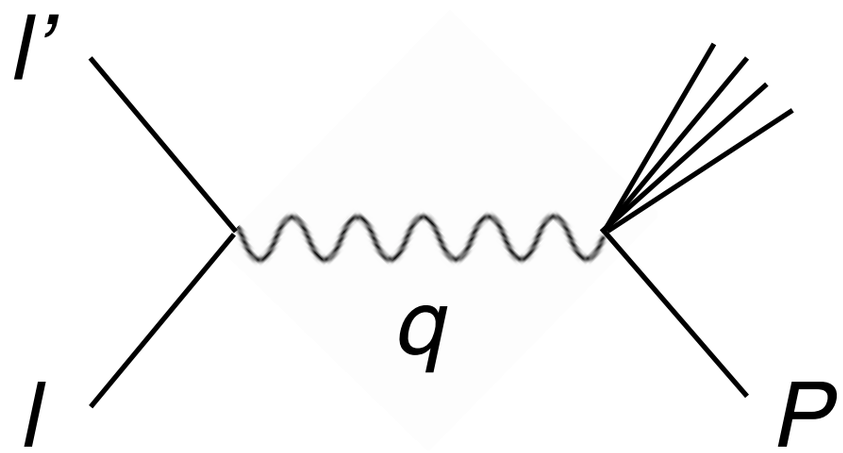
Charge conservation at the proton vertex reduces the number of structure functions:

$$q_\mu K^{\mu\nu}_{\text{nucleon}} \quad \rightarrow \quad K_4 = f(K_1, K_2), \quad K_5 = g(K_2)$$

and one obtains the Rosenbluth form, with electric and magnetic form factors:

$$\frac{d\sigma}{d\Omega} = \left(\frac{\alpha}{4ME\sin^2(\theta/2)}\right)^2 \frac{E'}{E}\left[2K_1\sin^2(\theta/2) + K_2\cos^2(\theta/2)\right], \qquad K_{1,2}(q^2)$$

Inelastic Scattering



Considerably more complex, indeed!

Simplify - consider *inclusive* inelastic scattering,

$$d\sigma \propto \left\langle |\mathcal{M}|^2 \right\rangle = \frac{g_e^4}{q^4} L^{\mu\nu}_{\text{lepton}} W_{\mu\nu\,\text{nucleon}}, \qquad W_{\mu\nu\,\text{nucleon}}(p,q)$$

Again, <u>two</u> (parity-conserving, spin-averaged) structure functions:

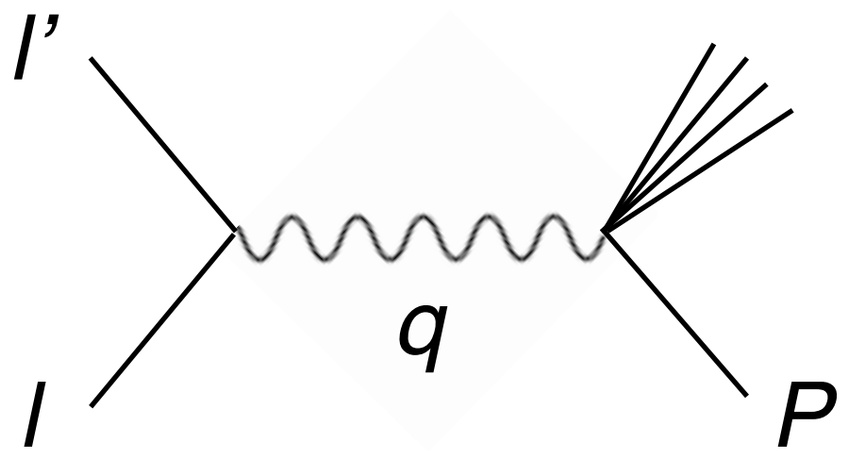
$$W_1, W_2 \;\; \text{or, alternatively expressed,} \;\; F_1, F_2$$

which may depend on <u>two</u> invariants,

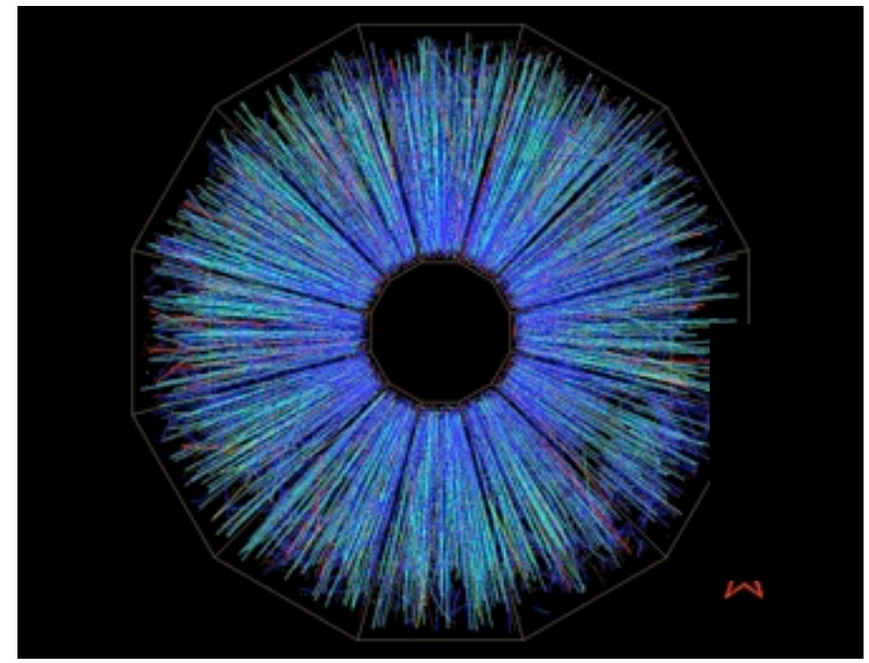
$$Q^2 = -q^2, \qquad x = -\frac{q^2}{2q.p}, \; 0 < x < 1$$

So much for the structure, the physics is in the structure functions.

Inelastic Scattering



Not convinced of additional complexity?



Simplify - consider *inclusive* inelastic scattering,

Then forget this talk, and calculate this!

$$d\sigma \propto \left\langle |\mathcal{M}|^2 \right\rangle = \frac{g_e^4}{q^4} L^{\mu\nu}_{\text{lepton}} W_{\mu\nu\,\text{nucleon}}, \qquad W_{\mu\nu\,\text{nucleon}}(p,q)$$

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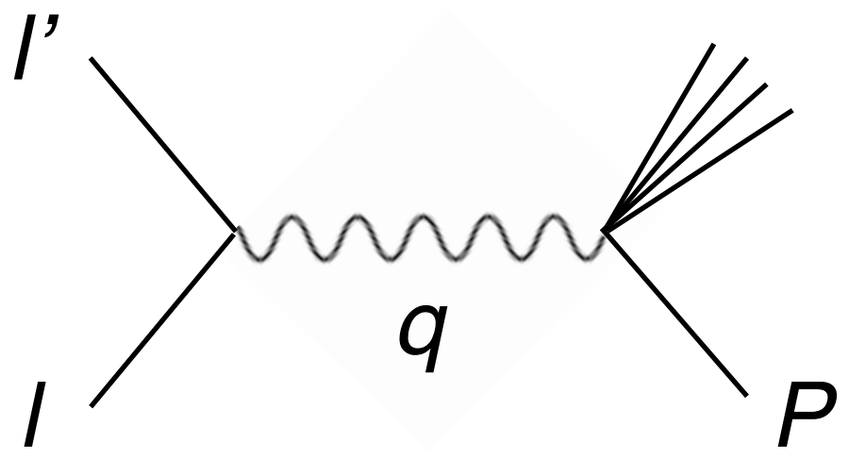

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So much for the structure, <u>the physics is in the structure functions.</u>

Elastic scattering off Dirac Protons

Compare:

$$L^{\mu\nu}_{\text{lepton}} = 2\left(k^\mu k'^\nu + k^\nu k'^\mu + g^{\mu\nu}(m^2 - k\cdot k')\right)$$

with:

$$K_{\mu\nu\,\text{nucleon}} = K_1\left(-g_{\mu\nu} + \frac{q^\mu q^\nu}{q^2}\right) + \frac{K_2}{M^2}\left(p^\mu + \frac{1}{2}q^\mu\right)\left(p^\nu + \frac{1}{2}q^\nu\right)$$

which uses the relations between $K_{1,2}$ and $K_{4,5}$

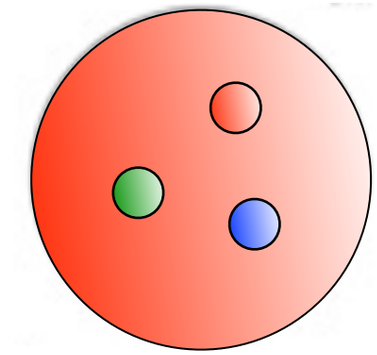
Then, e.g. by substitution of $k' = k\text{-}q$ in L:

$$K_1 = -q^2, \quad K_2 = 4M^2$$

Note, furthermore, that inelastic cross section reduces to the elastic one for:

$$W_{1,2}(q^2, x) = -\frac{K_{1,2}(q^2)}{2Mq^2}\delta(x-1)$$

Elastic scattering off Dirac Protons



Imagine *incoherent* scattering off *Dirac* Partons (quarks) *q* :

$$W_1^q = \frac{e_q^2}{2m_q}\delta(x_q - 1), \quad W_2^q = -\frac{2m_q e_q^2}{q^2}\delta(x_q - 1) \;\text{ and } x_q = -\frac{q^2}{2q\cdot p_q}$$

and, furthermore suppose that the quarks carry a fraction, *z*, of the proton momentum

$$p_q = z_q\, p, \text{ so that } x_q = \frac{x}{z_q} \quad (\text{also note } m_q = z_q M\,!)$$

which uses the relations between $K_{1,2}$ and $K_{4,5}$

Now,

$$MW_1 = \sum_q \int_0^1 \frac{e_q^2}{2M}\delta(x - z_q)\, f_q(z_q)\, dz_q = \frac{1}{2}\sum_q e_q^2 f_q(x) \equiv F_1(x)$$

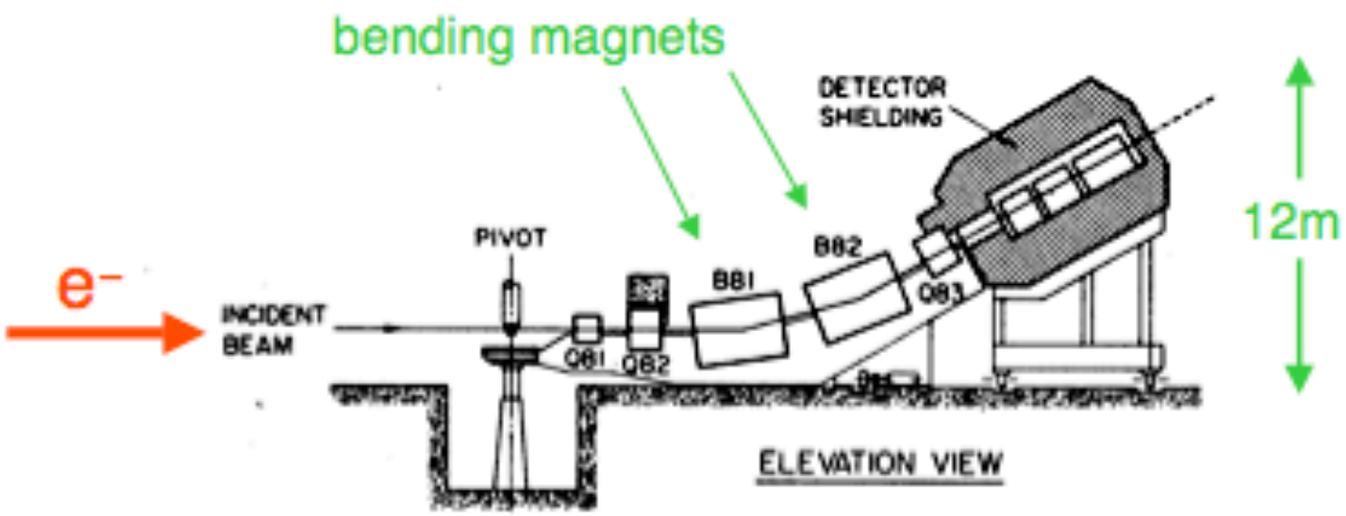
$$-\frac{q^2}{2Mx}W_2 = \int_0^1 x e_q^2 \delta(x - z_q)\, f_q(z_q)\, dz_q = x\sum_q e_q^2 f_q(x) \equiv F_2(x)$$

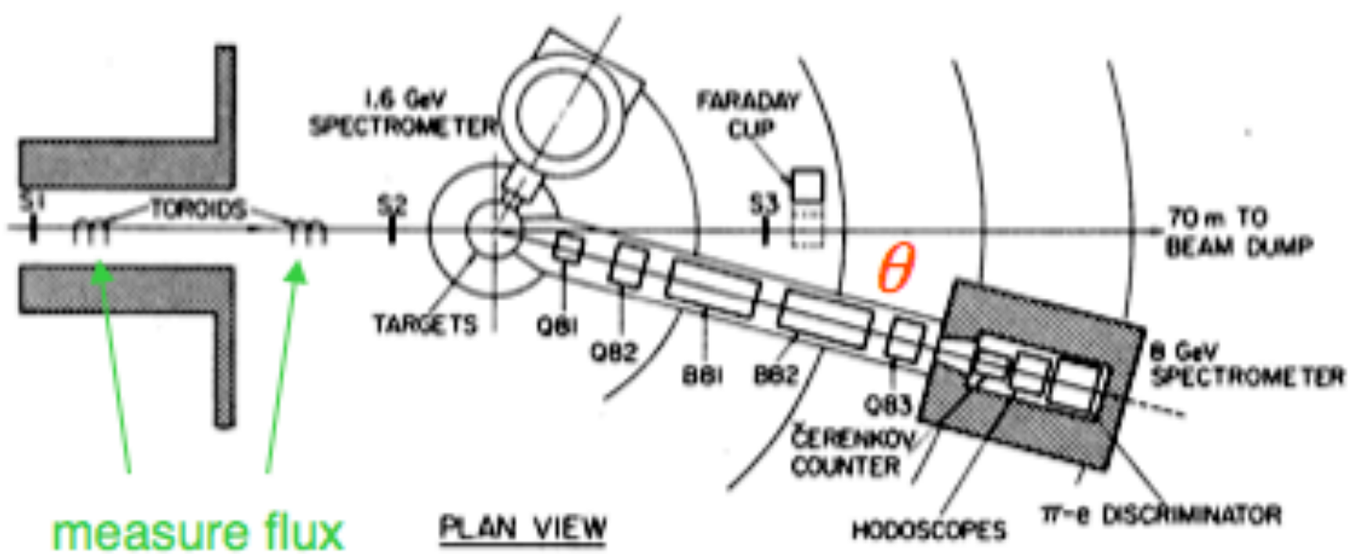
Two important *observable* consequences,

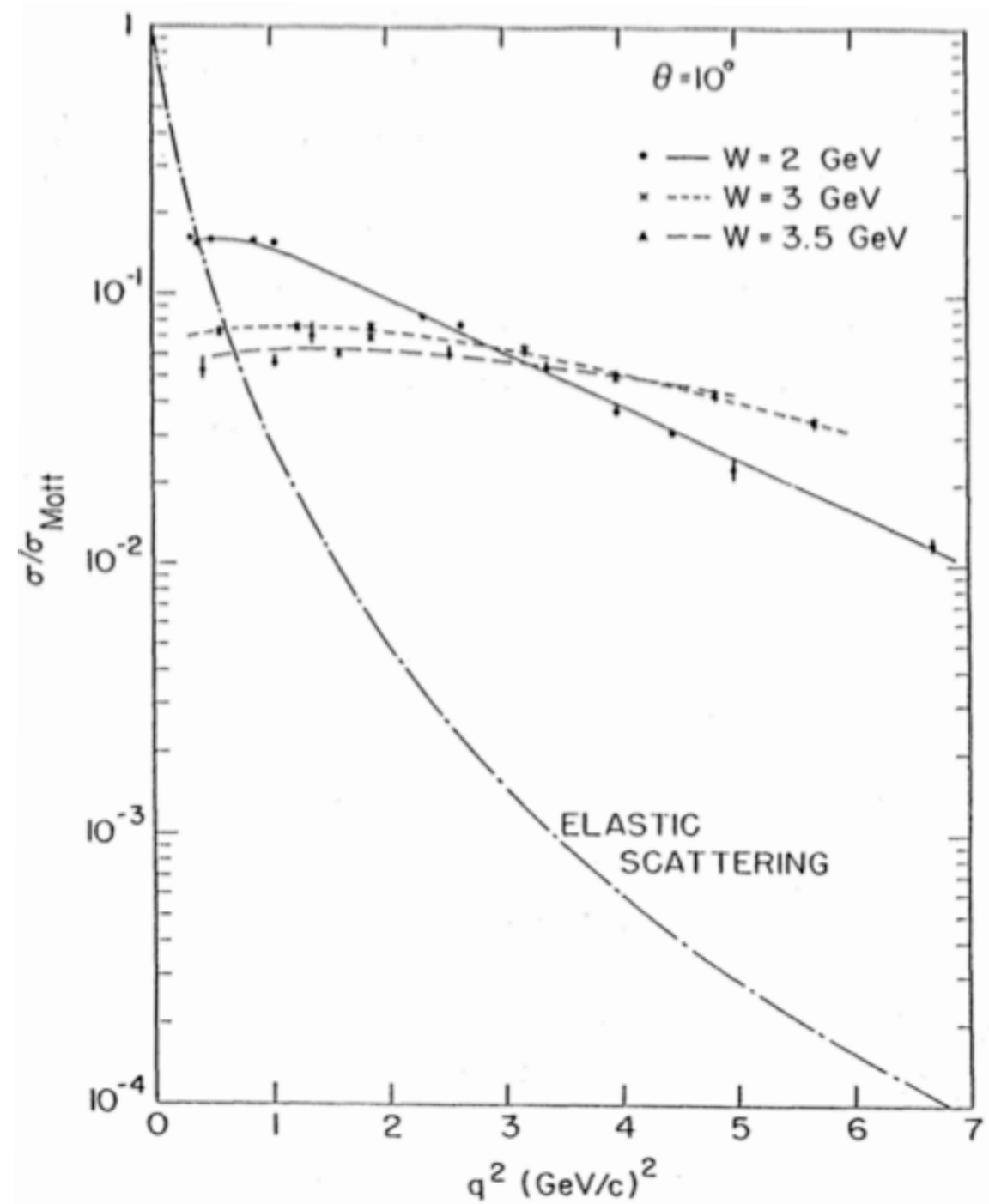
Bjorken scaling: $F_{1,2}(x), \;\text{ not } F_{1,2}(x, Q^2)$

Callan-Gross relation: $F_2 = 2xF_1(x)$

~10 GeV *Deep-Inelastic* Electron Scattering

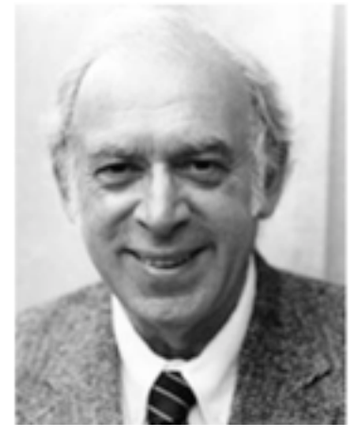






e.g. J.T.Friedman and H.W. Kendall, Ann.Rev.Nucl.Sci. 22 (1972) 203

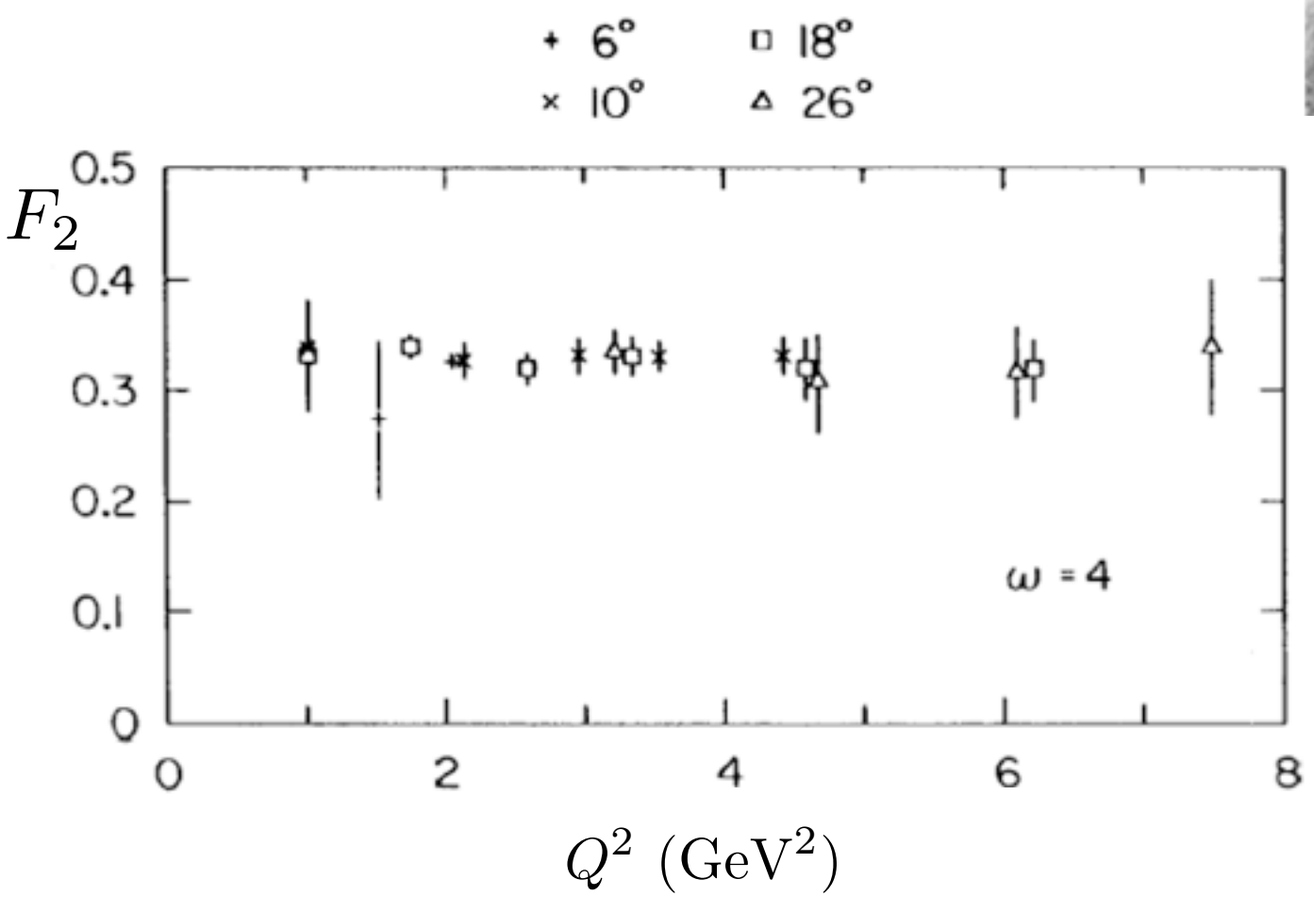
Deep-Inelastic Electron Scattering


J.T. Friedman

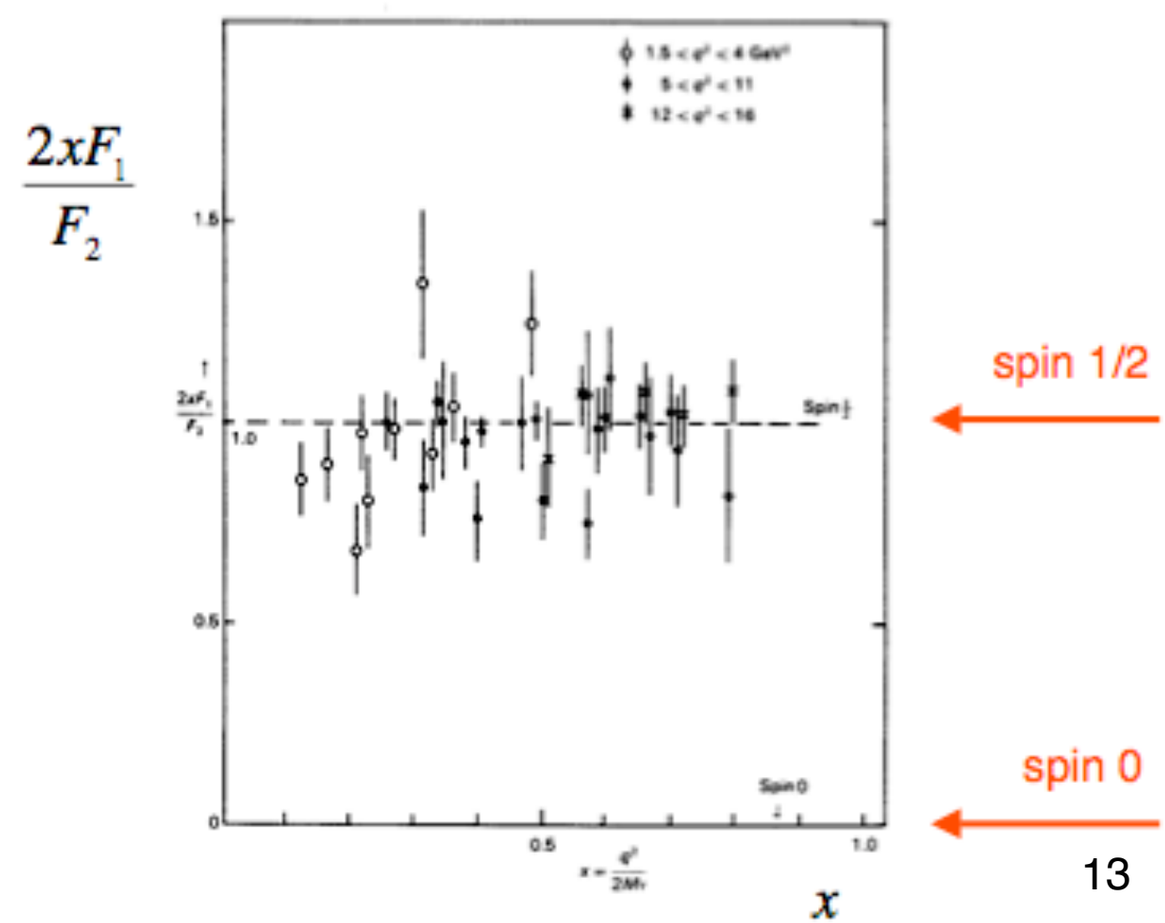

R. Taylor
Nobel Prize 1990


H.W. Kendall

Bjorken scaling:



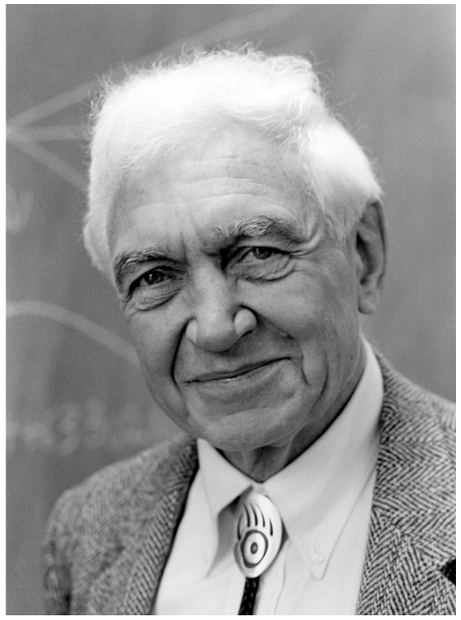
Callan-Gross relation:



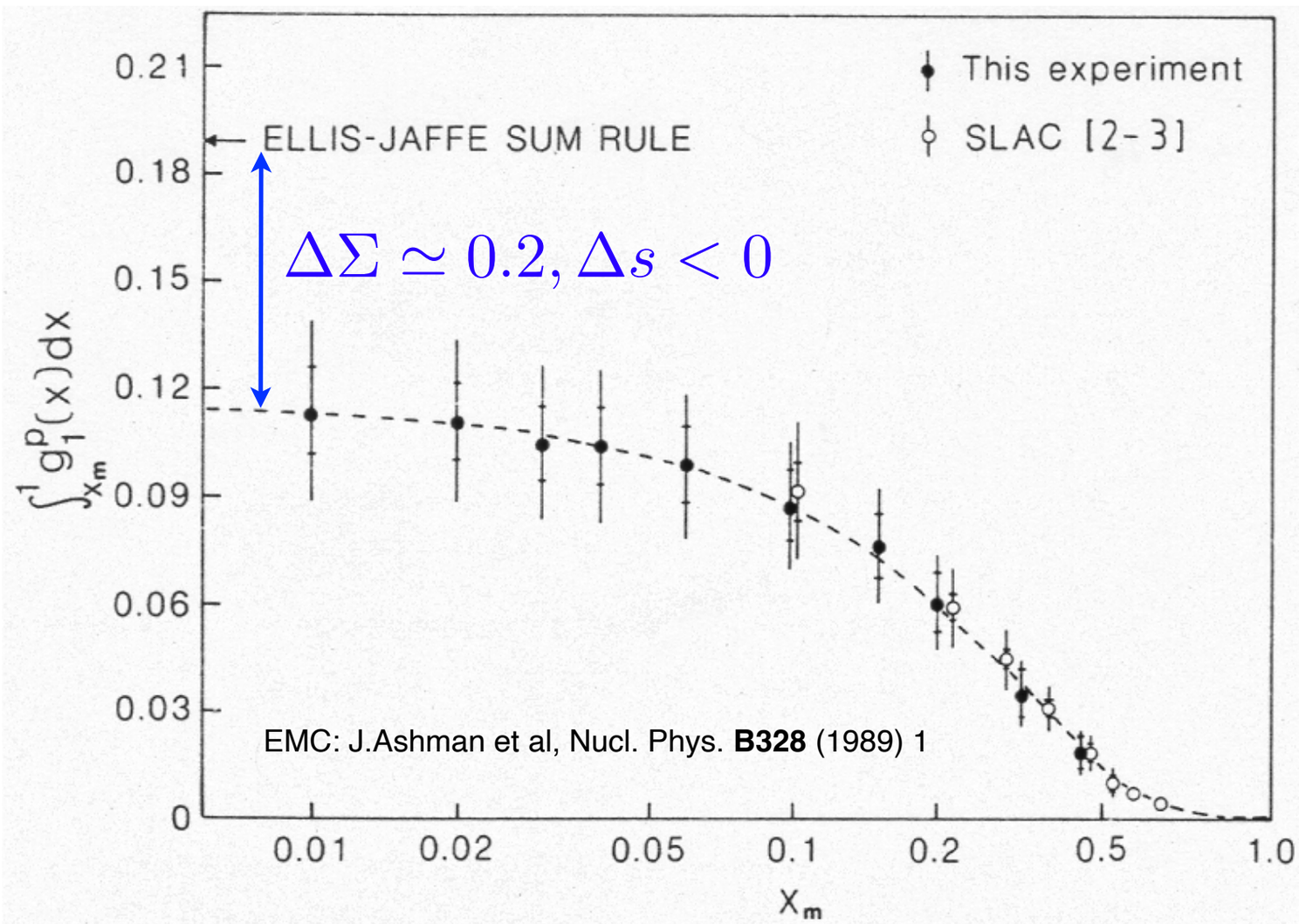
Point particles cannot be further resolved; their measurement does not depend on wavelength, hence Q^2,

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

Polarized Deep-Inelastic Scattering



V.W. Hughes (1921-2003)



“ The sum of quark and anti-quark spins contribute little to the proton spin, and strange quarks are negatively polarized. ”

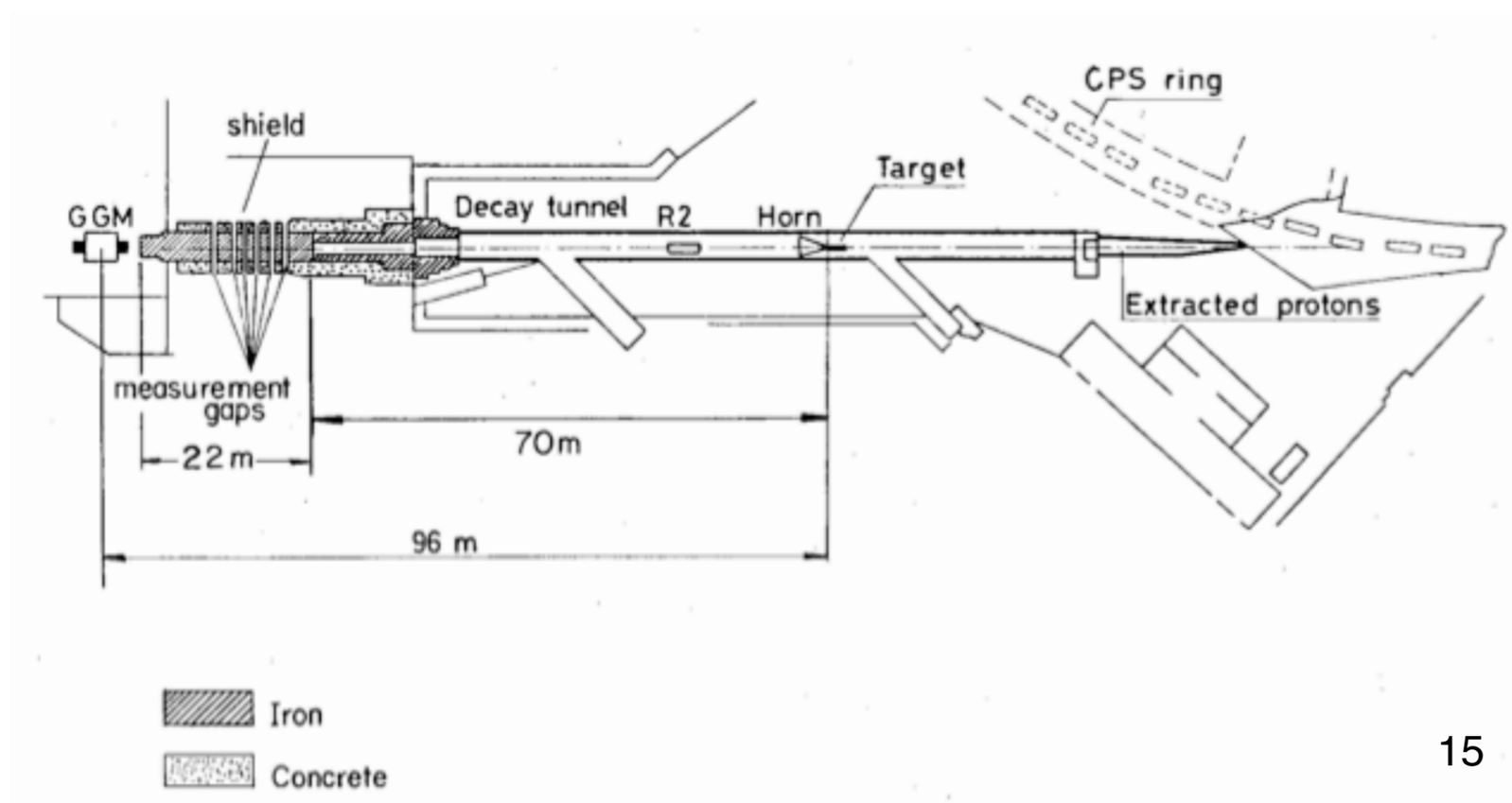
Deep-Inelastic *Neutrino* Scattering

Recognize this from CERN?

Gargamelle bubble chamber, observation of weak neutral current (1973).

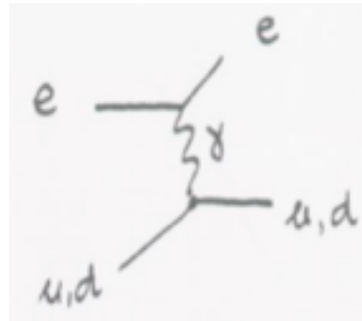
Charged-current DIS!

Nucl.Phys. **B73** (1974) 1
Nucl.Phys. **B85** (1975) 269
Nucl.Phys. **B118** (1977) 218
Phys.Lett. **B74** (1978) 134



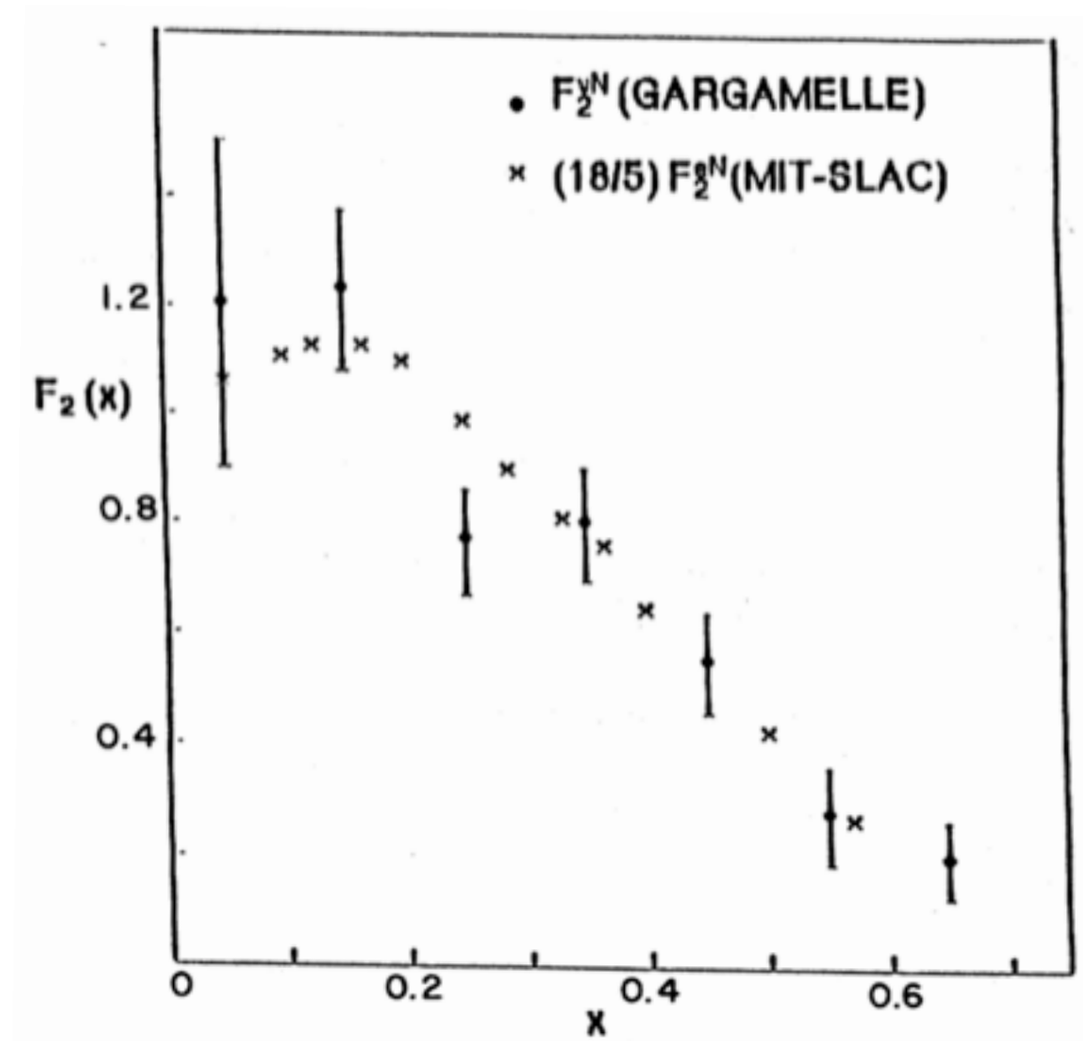
Deep-Inelastic Scattering - Fractional Electric Charges

Neutral-current (photon) DIS:

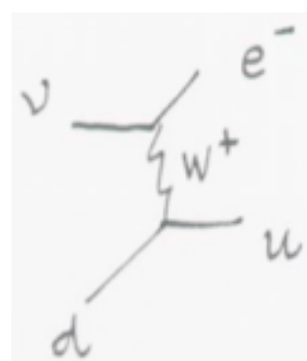


$$F_2 = x \sum e_q^2 (q + \bar{q}), \quad p : uud, \quad n : ddu$$

$$F_2^N = x \, \frac{e_u^2 + e_d^2}{2} \, (u + \bar{u} + d + \bar{d})$$



Charged-current DIS:



$$F_2^{\nu p} = 2x(d + \bar{u}), \quad F_2^{\nu n} = 2x(u + \bar{d})$$

$$F_2^{\nu N} = x(u + \bar{u} + d + \bar{d})$$

Deep-Inelastic Scattering - Fractional Electric Charges

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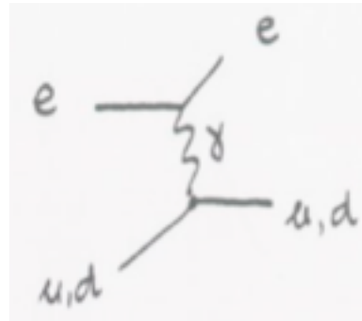

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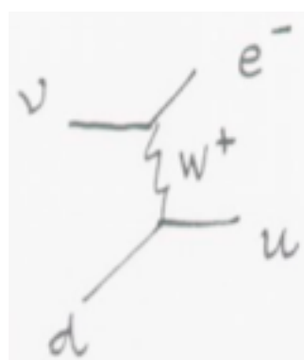
Charged-current DIS:

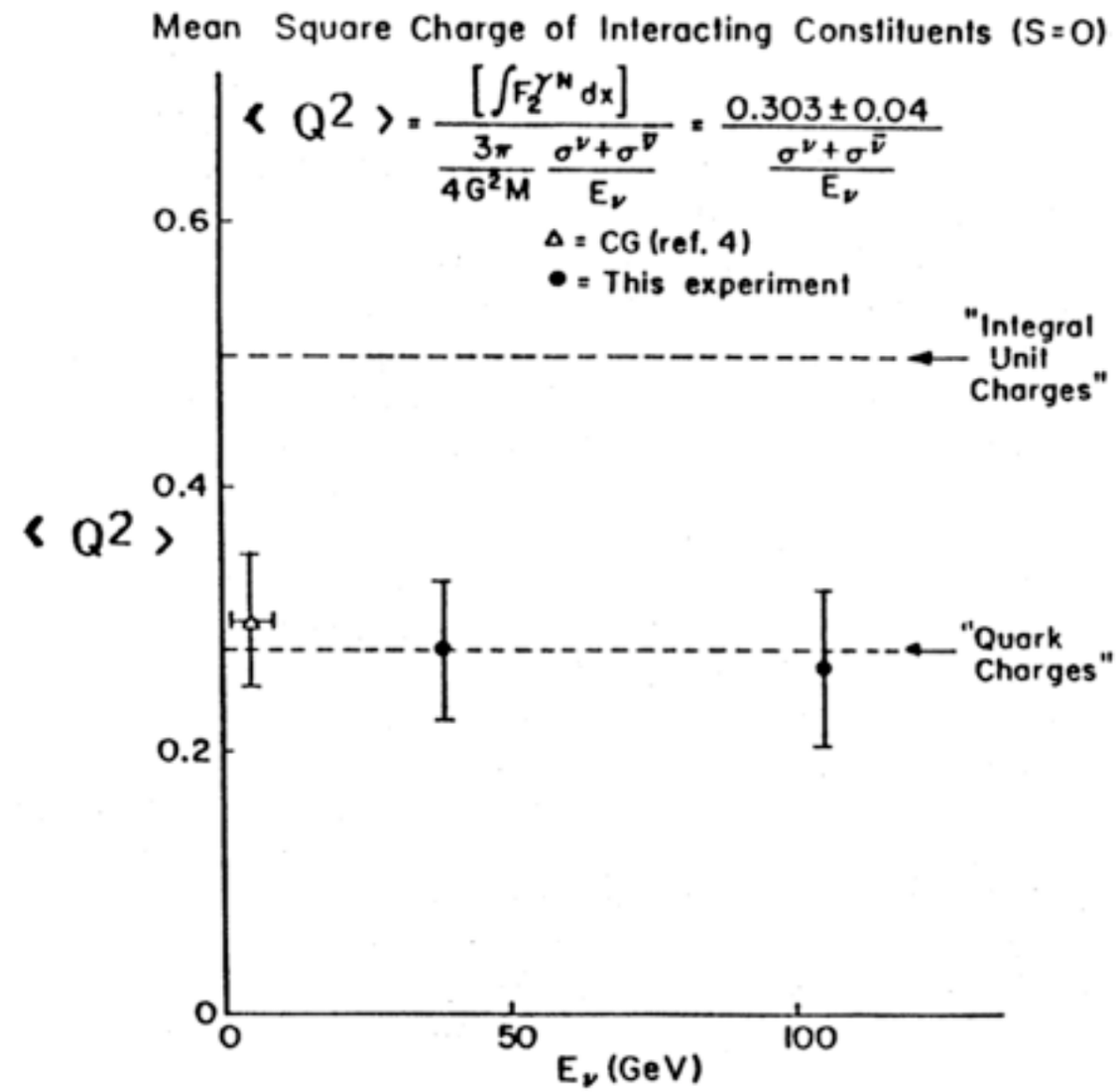


$$F_2^{\nu p} = 2x(d + \bar{u}), \quad F_2^{\nu n} = 2x(u + \bar{d})$$

$$F_2^{\nu N} = x(u + \bar{u} + d + \bar{d})$$

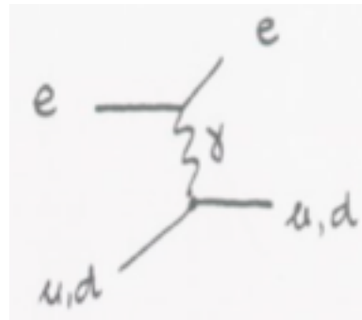
Ratio:

$$\frac{F_2^N}{F_2^{\nu N}} = \frac{1}{2}(e_u^2 + e_d^2) = \frac{5}{18} \simeq 0.28$$



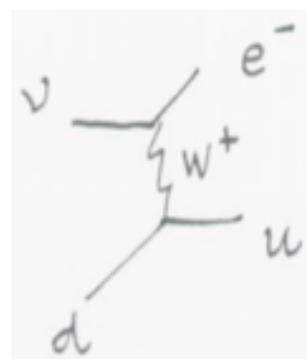
Deep-Inelastic Scattering - Momentum Conservation

Neutral-current (photon) DIS:



$$F_2^N = x\,\frac{e_u^2 + e_d^2}{2}\,(u + \bar{u} + d + \bar{d})$$

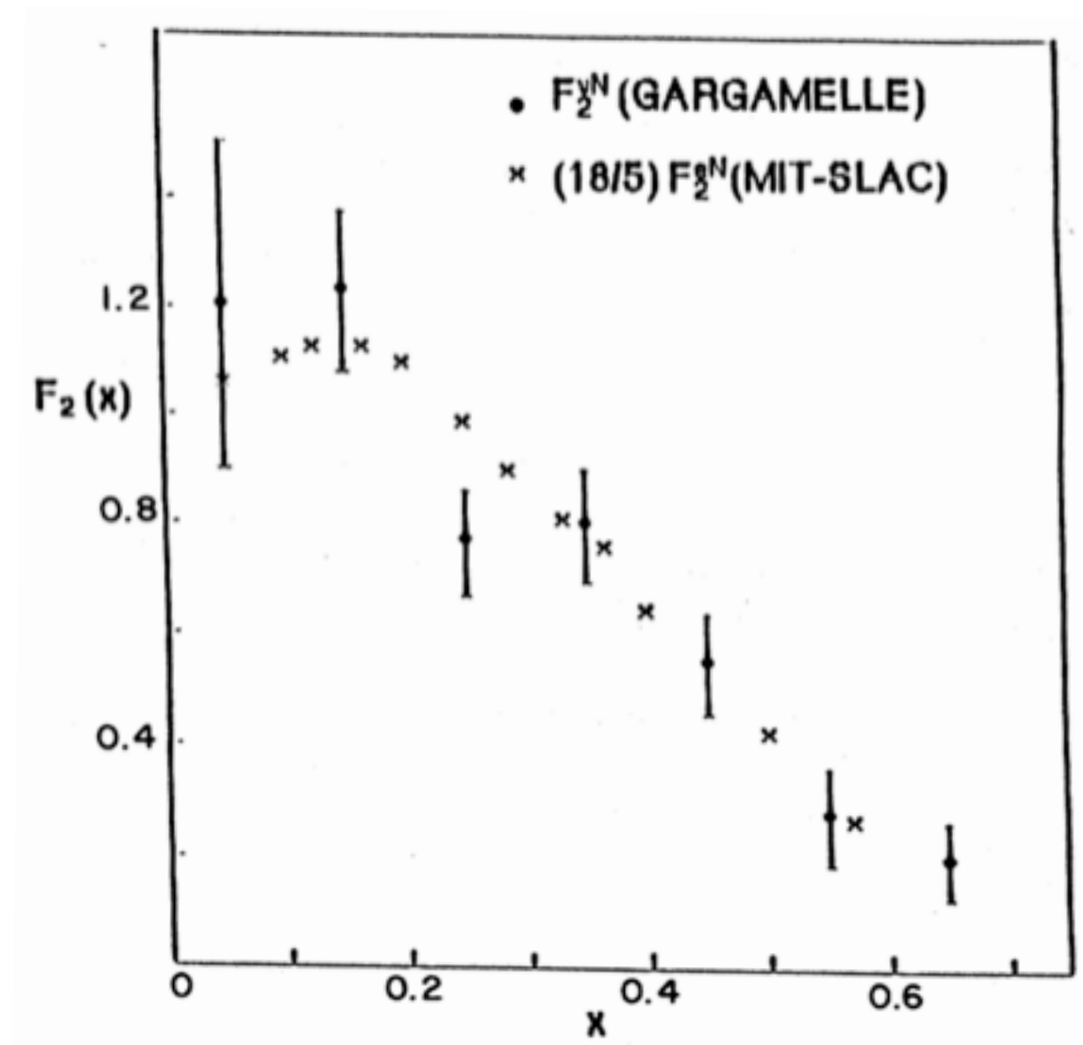
Charged-current DIS:



$$F_2^{\nu N} = x(u + \bar{u} + d + \bar{d})$$

Momentum fraction:

$$\int_0^1 F_2^N\,dx = \frac{e_u^2 + e_d^2}{2}\int_0^1 x(u + \bar{u} + d + \bar{d})$$



Gargamelle: 0.49 +/- 0.07

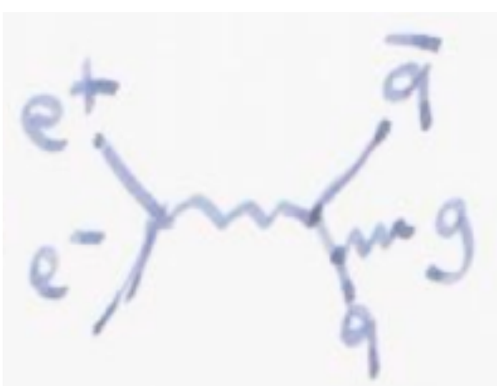
SLAC: 0.14 +/- 0.05

Quarks carry half of the nucleon momentum!

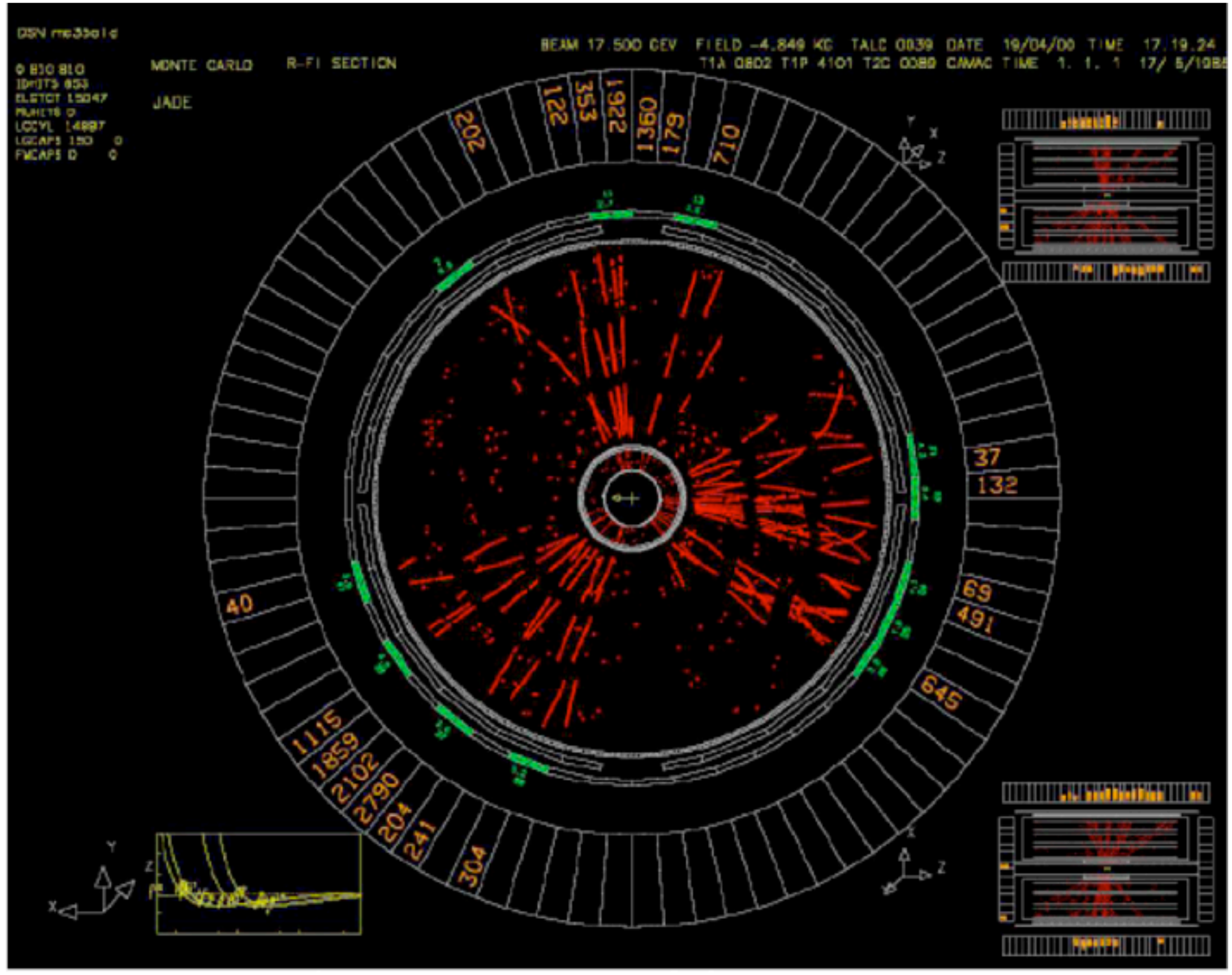
3-jet events at PETRA

Recall the intro on colour:

Observation of its higher order process,

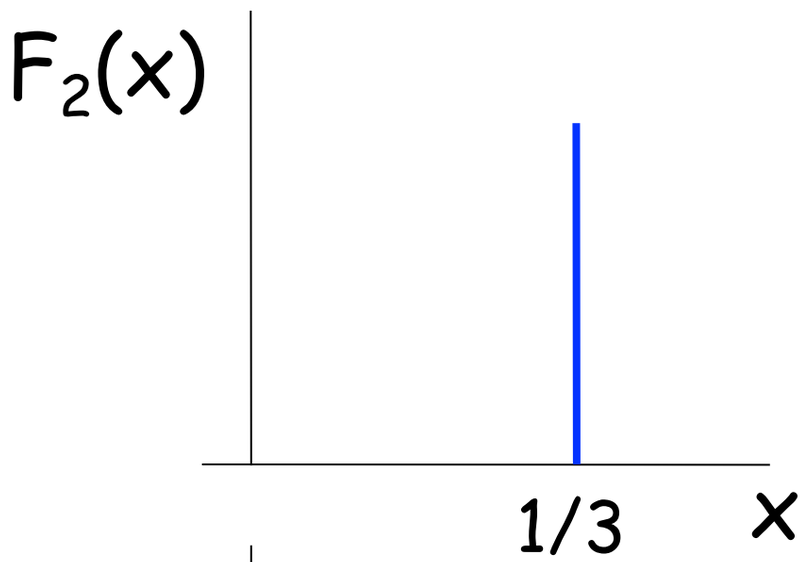


marks the discovery of the gluon.

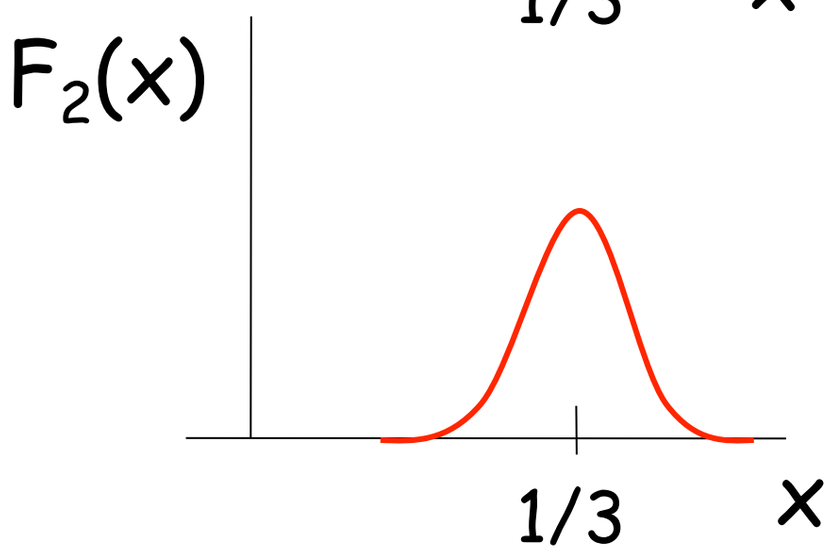


Mom. Conservation: *Gluons carry the other half of the nucleon momentum.*

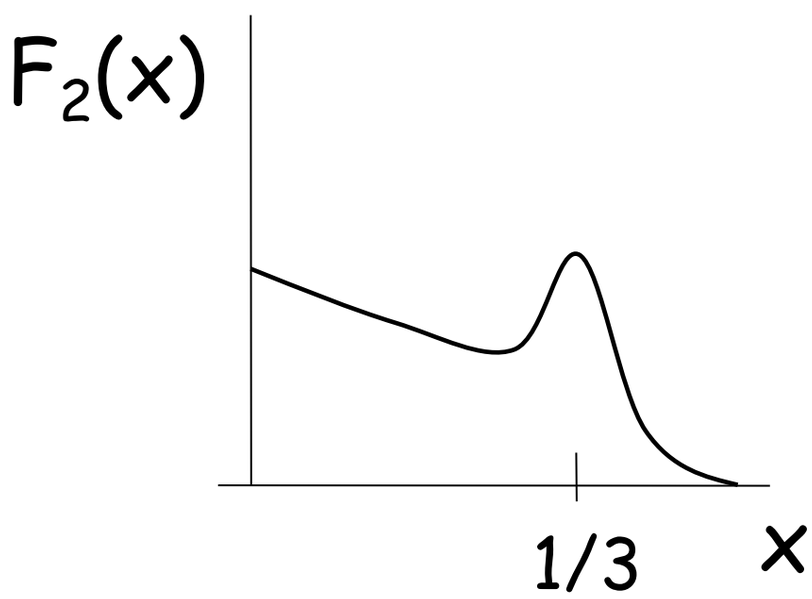
Nucleon Structure



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

Electron Ion Collider Initiatives

Past

Possible Future

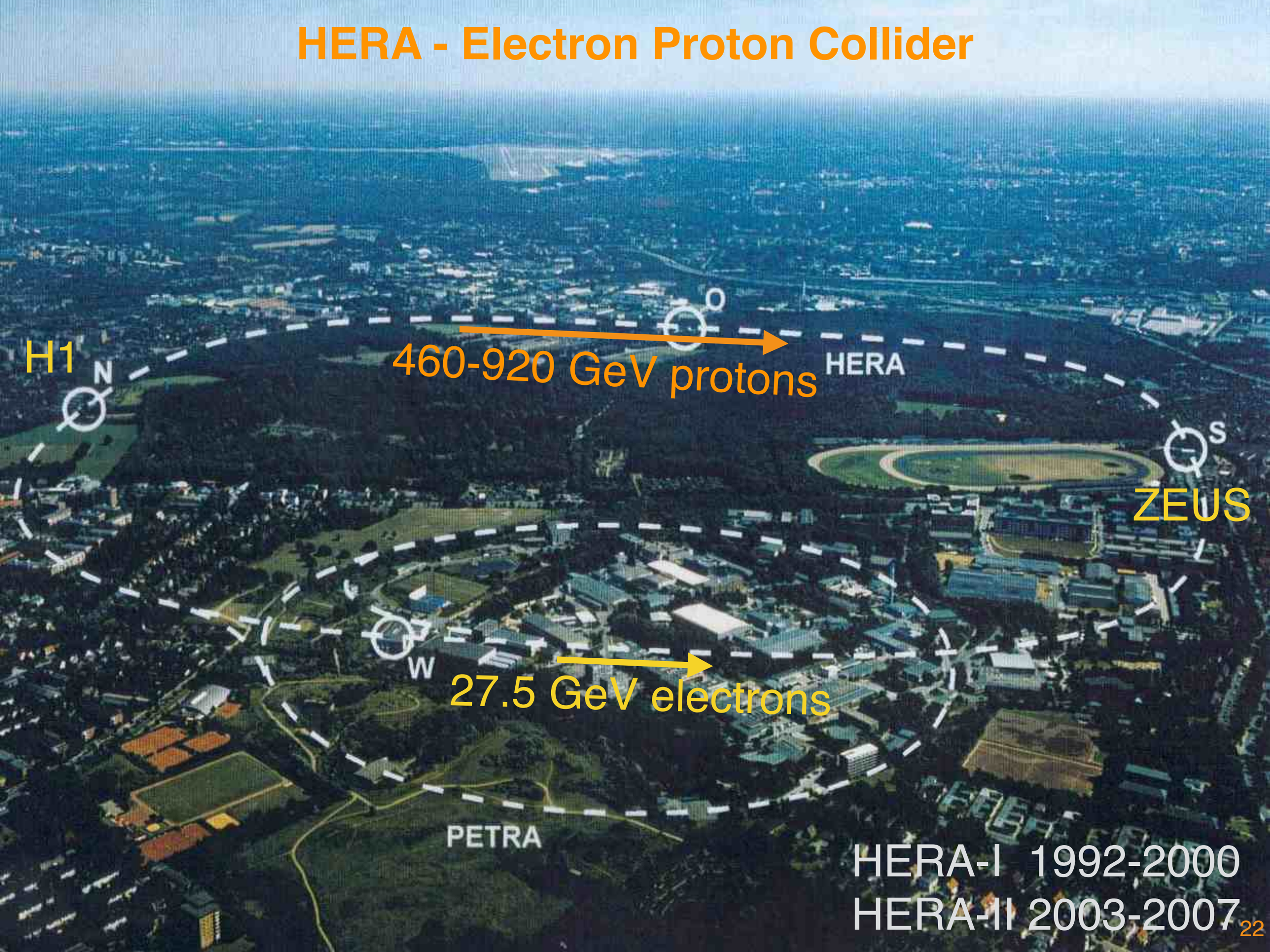
	HERA @ DESY	LHeC @ CERN	EIC in China	EIC in U.S.
$\sqrt{s_{ep}}$ [GeV]	320	200 - 1300	15 - 20	20 - 100 (140)
proton x_{min}	1×10^{-5}	5×10^{-7}	2×10^{-3}	1×10^{-4}
ion	p	p, Pb, …	p - U	p - U
polarization	-	-	p, light nuclei	p, d, ^{3}He, Li
L [$cm^{-2}s^{-1}$]	2×10^{31}	1×10^{34}	3×10^{33}	10^{33} - 10^{34}
Interaction Points	2	1	1	2
Timeline	1992 - 2007	post ALICE	Upgrade to HIAF	> 2031

High-Energy Physics

Nuclear Physics

Several initiatives not listed: HE-LHeC, PEPIC, VHEeP, FCC-eh, …

HERA - Electron Proton Collider



HERA-I 1992-2000
HERA-II 2003-2007

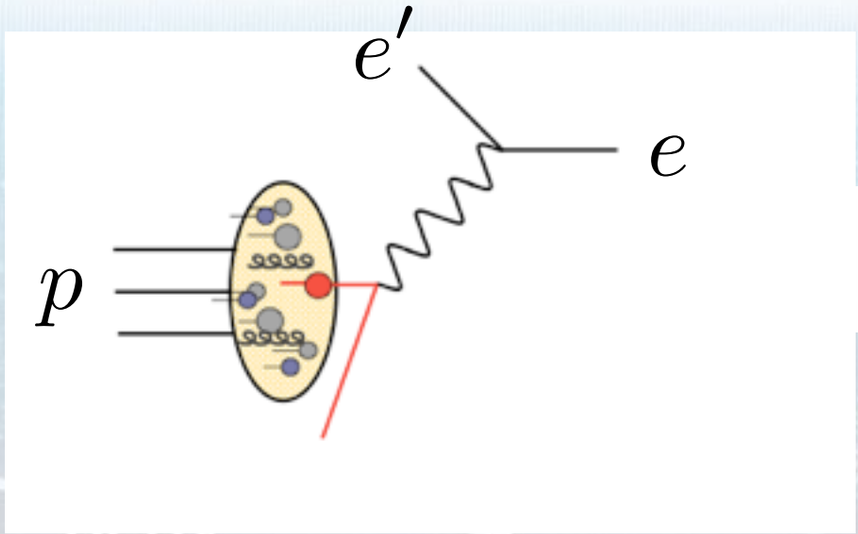
HERA - Electron Proton Collider

Observed (or known):

$$e = (0, 0, -E_e, E_e)$$

$$e' = (E'_e \sin\theta'_e, 0, E'_e \cos\theta'_e, E_e)$$

$$p = (0, 0, E_p, E_p)$$



H1

460-920 GeV protons

i.e. angles are defined *w.r.t. the hadron beam direction* (HERA-convention).

Relevant invariants:

$$s = (e + p)^2$$ Square of total c.m. energy

ZEUS

$$q = e - e' \qquad Q^2 = -(e - e')^2$$ Square of (4-)momentum transfer

$$x = \frac{Q^2}{ys}$$ Bjorken-x, ~parton mom. fraction

27.5 GeV electrons

$$y = (q.p)/(e.p)$$ Fractional energy transfer

HERA-I 1992-2000

x, Q^2 can be reconstructed from the scattered electron, the “current jet”, or hybrids.

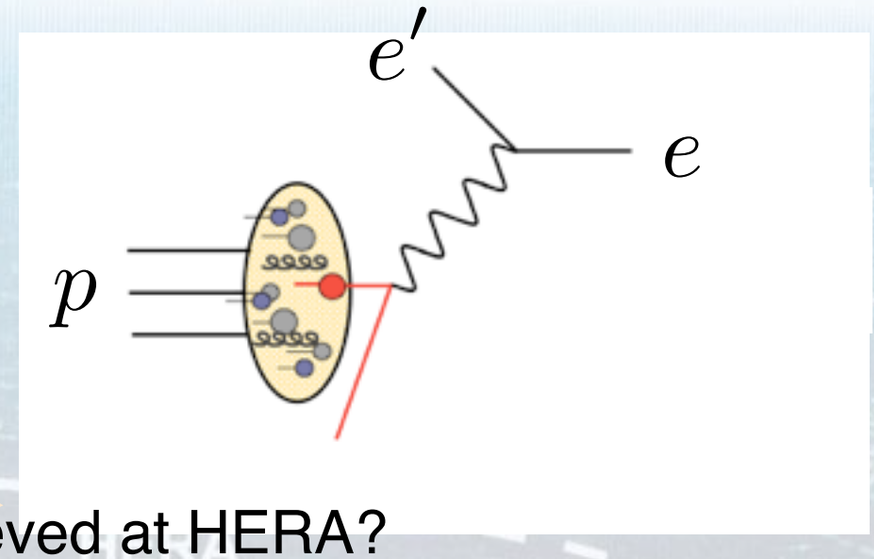
HERA-II 2003-2007

HERA - Electron Proton Collider

Relevant invariants:

$$s = (e+p)^2$$

$$x = \frac{Q^2}{ys}$$



H1 What was the maximum center-of-mass energy achieved at HERA?

920 GeV protons

What is the minimum value of Bjorken-x that could be reached for $Q^2 > 1$ GeV^2

What is the maximum value of Q^2 that could be reached for x = 0.1 ?

ZEUS

What would the electron beam energy need to be to achieve the same center-of-mass energy in a fixed-target experiment?

For discussion in the evening,

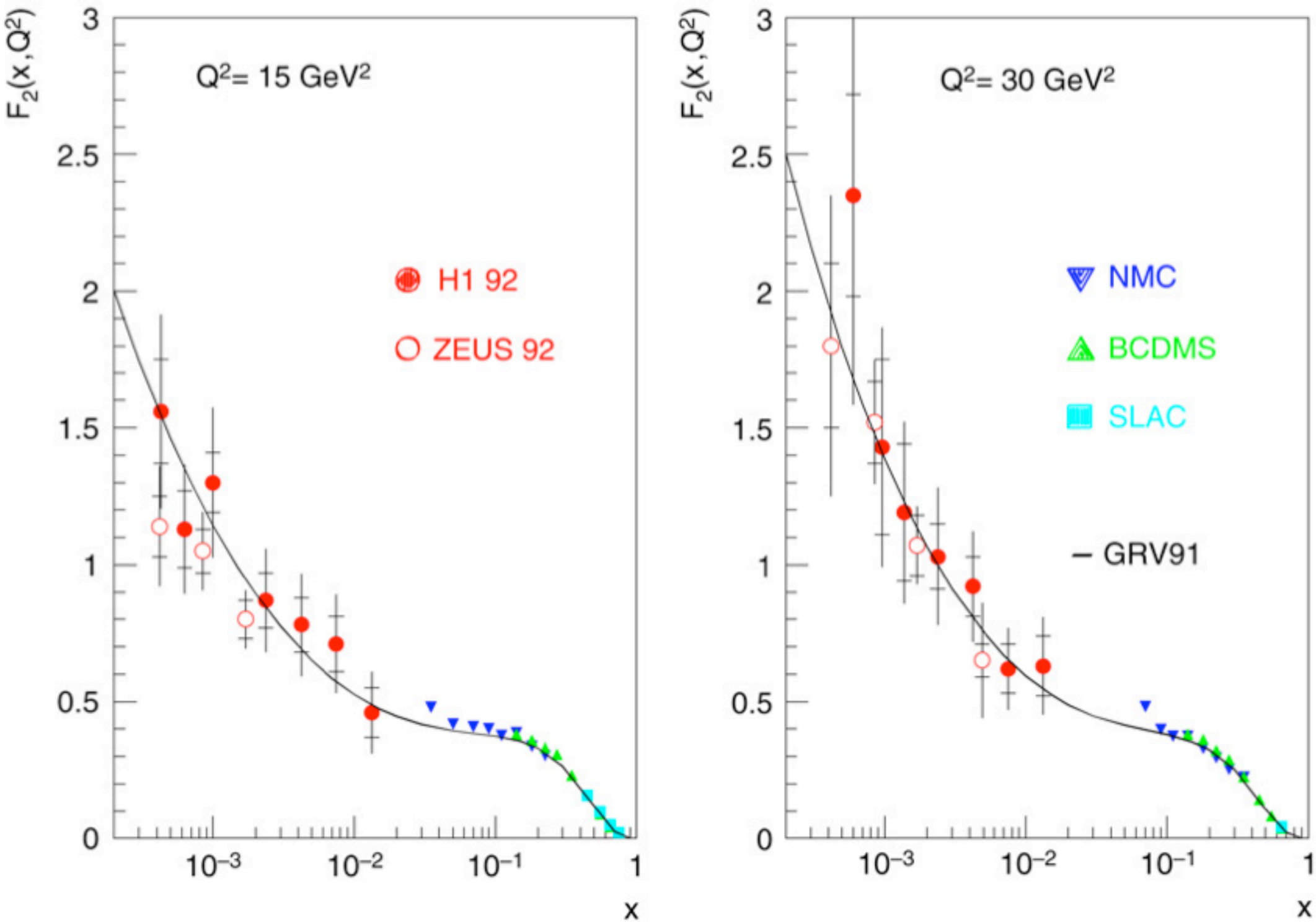
27.5 GeV electrons

What are the energy and angle of the scattered electron for $x = 10^{-3}$ and $Q^2 = 10$ GeV^2?

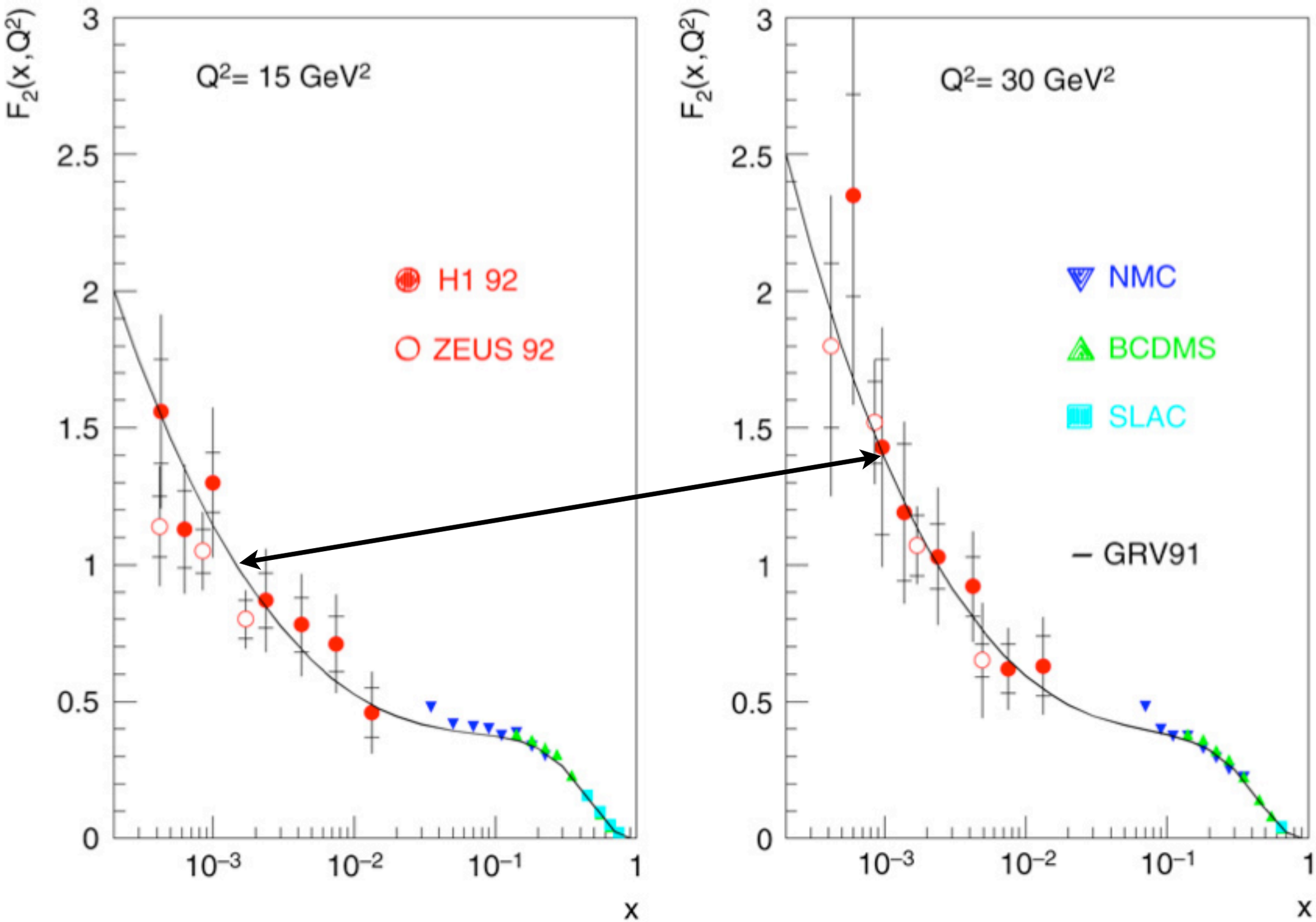
What is the angle of the struck quark ("current jet")? What would it be in a fixed-target experiment with the same center-of-mass energy?

HERA-I 1992-2000
HERA-II 2003-2007

HERA - Early Measurements



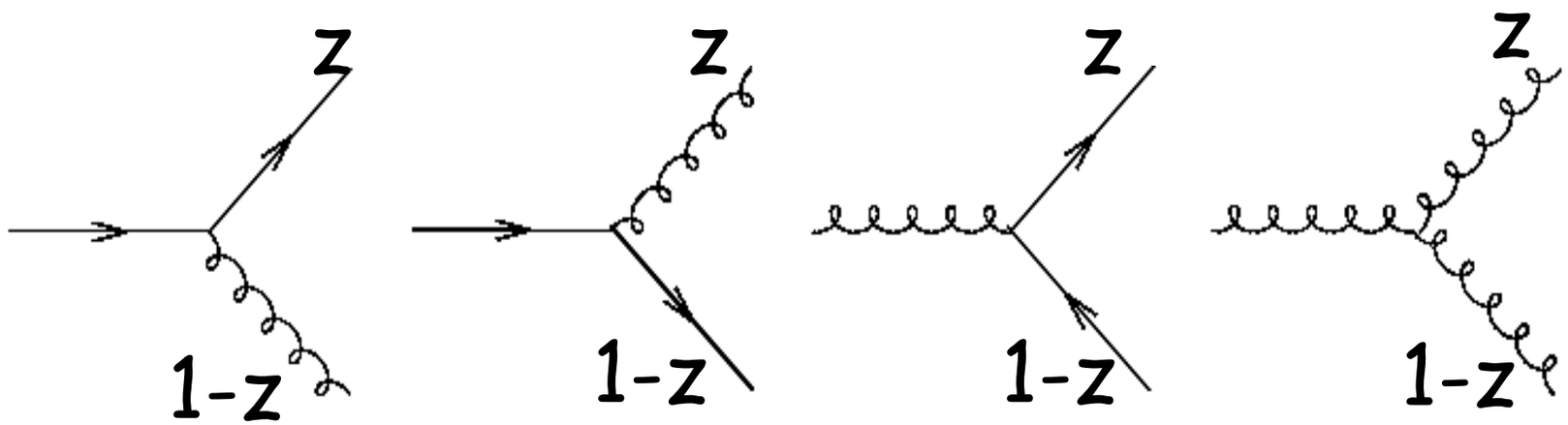
HERA - Early Measurements



Can these observations be related?

QCD Radiation

DGLAP equations are easy to “understand” intuitively, in terms of four “splitting functions”,

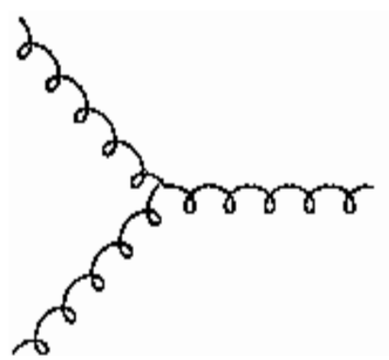


$P_{ab}(z)$: the probability that parton a will radiate a parton b with the fraction z of the original momentum carried by a.

Yu.L. Dokshitzer, Sov.Phys. JETP **46** (1977) 641,
V.N. Gribov and L.N.Lipatov, Sov. Journ. Nucl. Phys. **15** (1972) 438; ibid **15** (1972) 675
G.Altarelli and G.Parisi, Nucl.Phys. **B126** (1977) 298

QCD Radiation

DGLAP is highly successful, but not the only approach.



Gluons do not recombine,
incoherence is preserved.

Gluon-dense environments?

Similarly, process-independent quarks, survive.

How does DGLAP work?

QCD Radiation

Schematically, DGLAP equations:

convolution

$$\frac{dq_f(x,Q^2)}{d\ln Q^2} = \alpha_s\,[q_f \otimes P_{qq} + g \otimes P_{gq}]$$

strong coupling constant

That is, the change of quark distribution q with Q^2 is given by the probability that q and g radiate q.

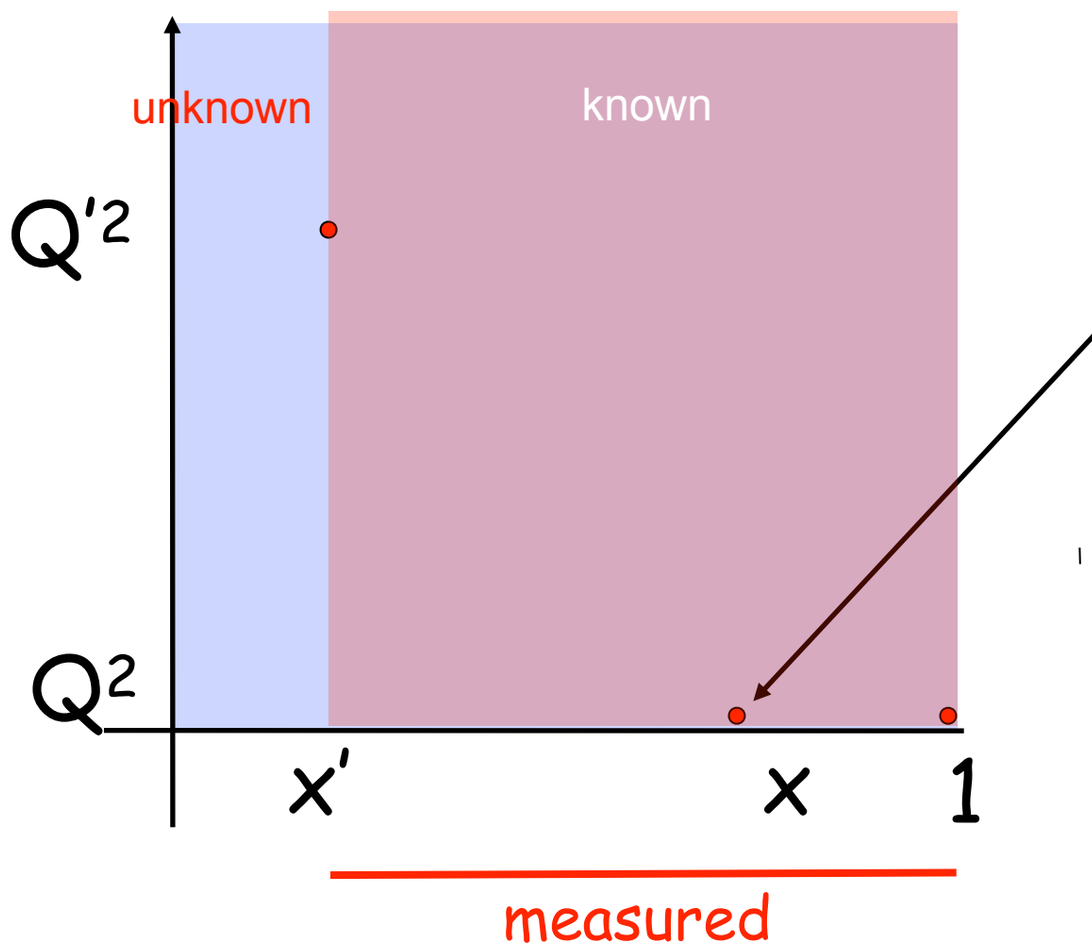
Similarly, for gluons:

$$\frac{dg(x,Q^2)}{d\ln Q^2} = \alpha_s\,[\Sigma q_f \otimes P_{qg} + g \otimes P_{gg}]$$

Side-note: the spin-dependent splitting functions are different from the spin-averaged splitting functions; for example, they generate orbital momentum.

QCD Radiation

A parton at x at Q^2 is a source of partons at $x' < x$ at $Q'^2 > Q^2$.



Any parton at $x > x'$ at Q^2 is a source.

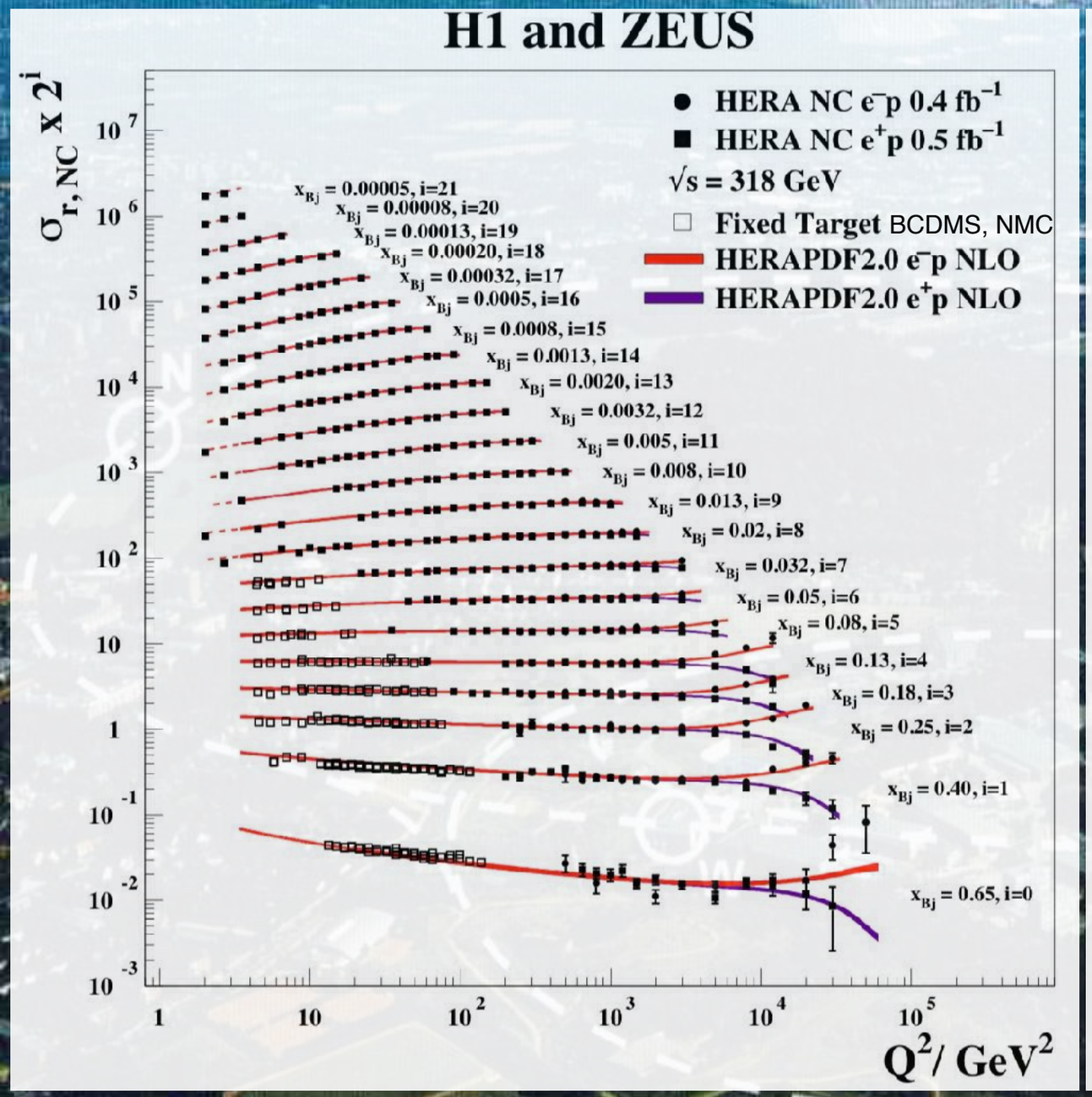
It is necessary and sufficient to know the parton densities in the range $x' \leq x \leq 1$ at a lower Q^2 to determine the parton density at x', Q'^2.

If you measure partons in range $x' \leq x \leq 1$ at some Q^2 then you know them in that range, and only that range, for all Q'^2.

Asymptotic solutions exist to the DGLAP equations that may overwhelm the intrinsic contributions.

HERA's Legacy

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

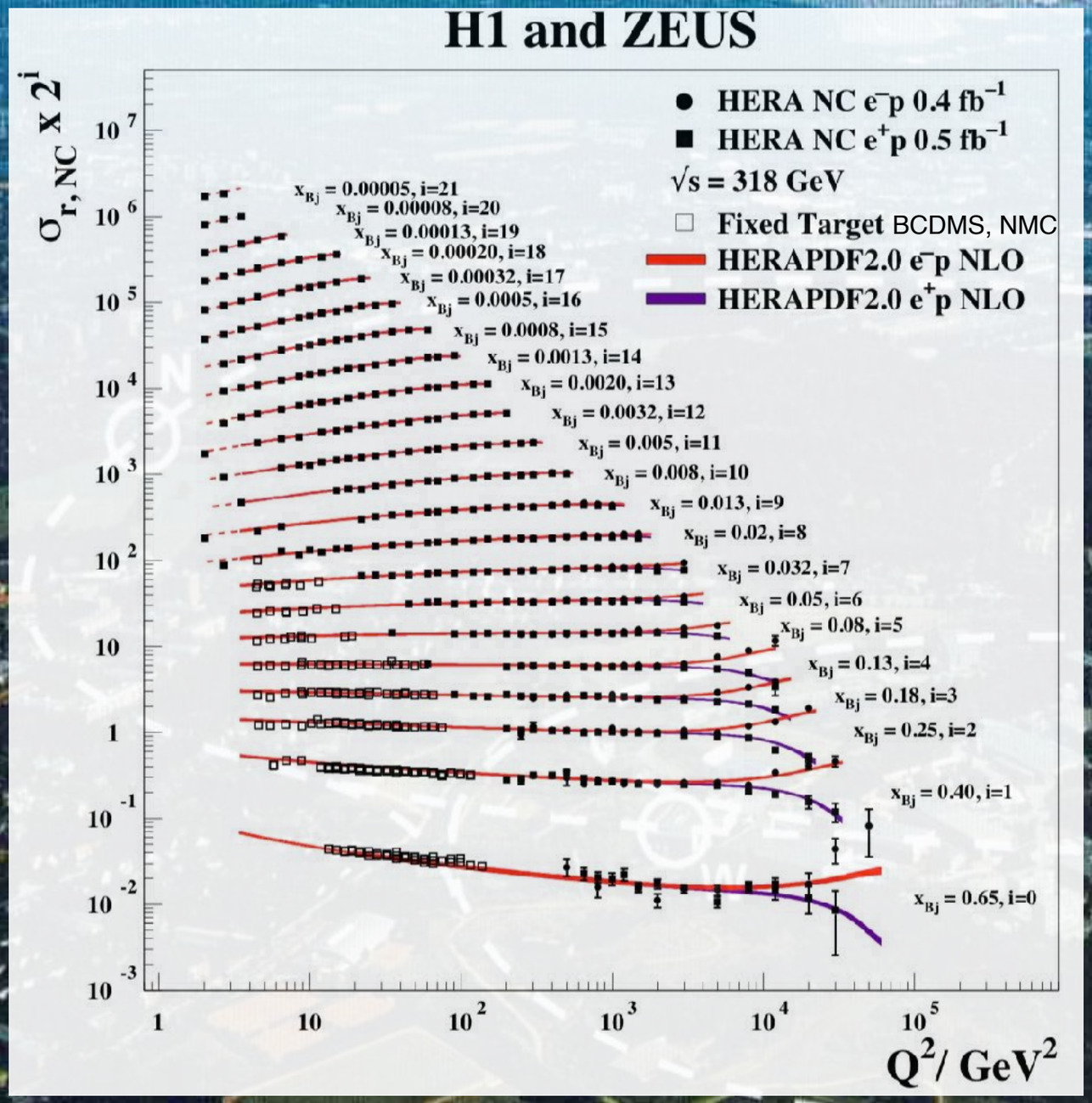


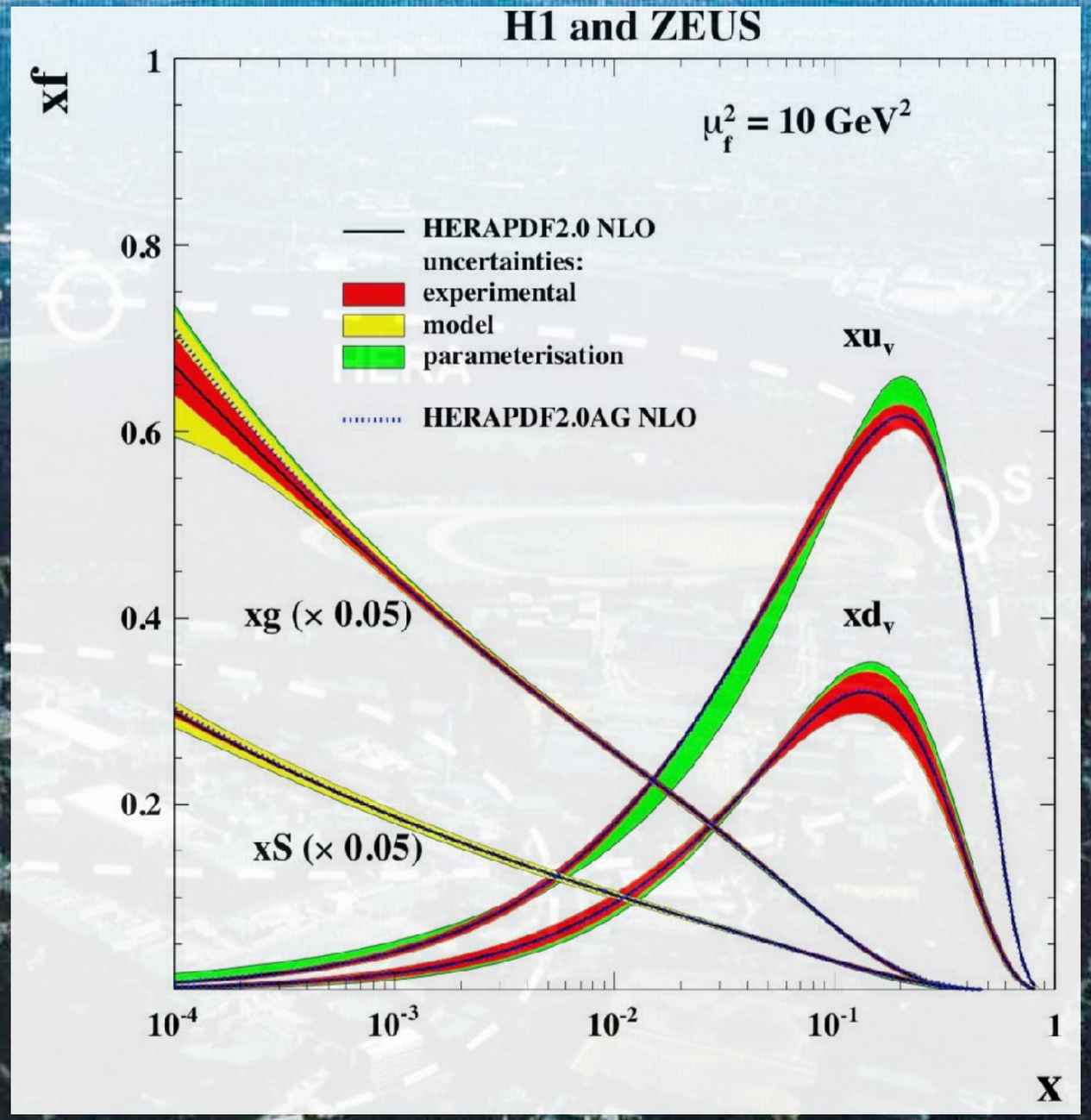
A lot in this plot:

- 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

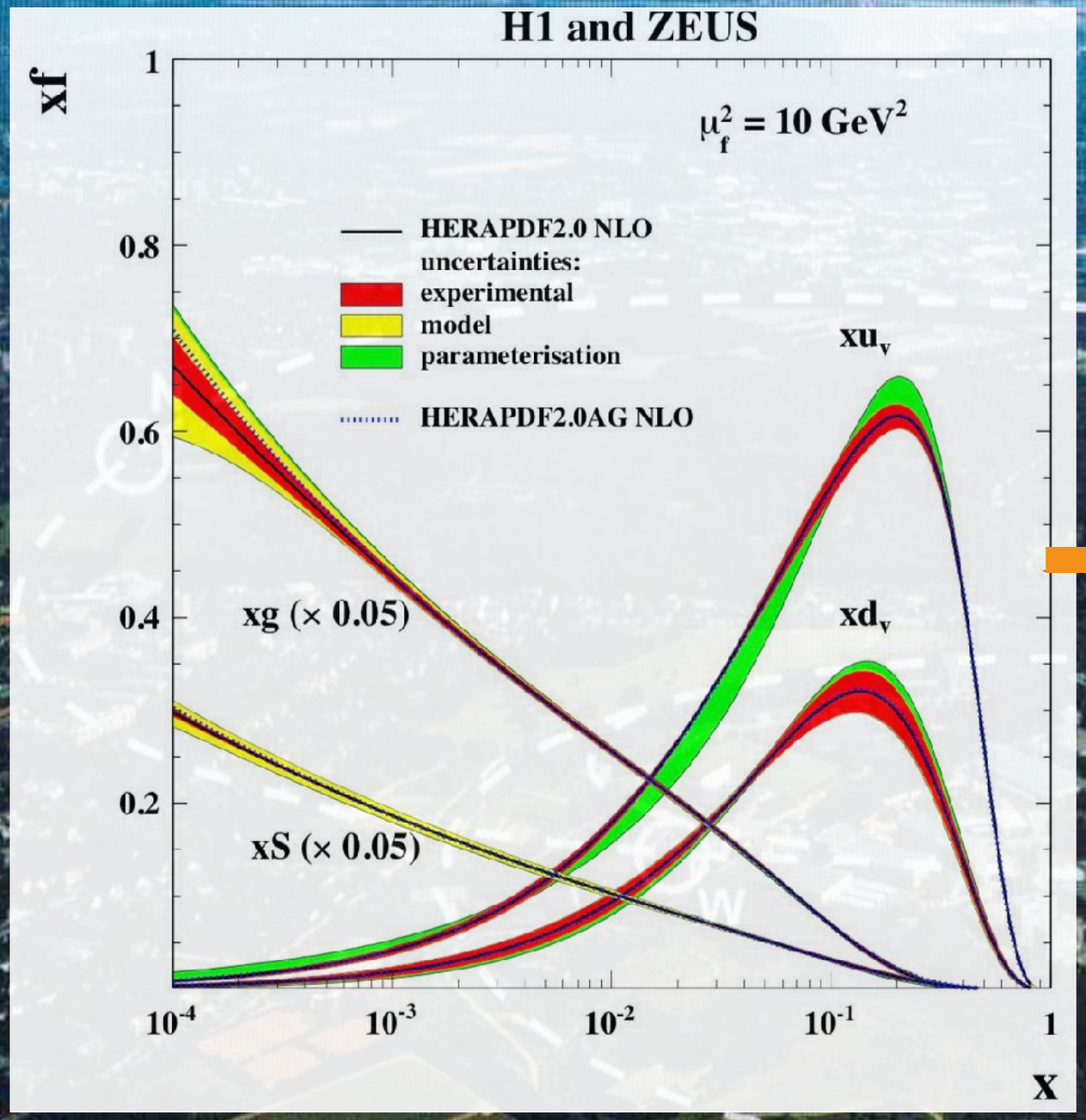
H1 and ZEUS Coll., EPJ C75 (2015) 580

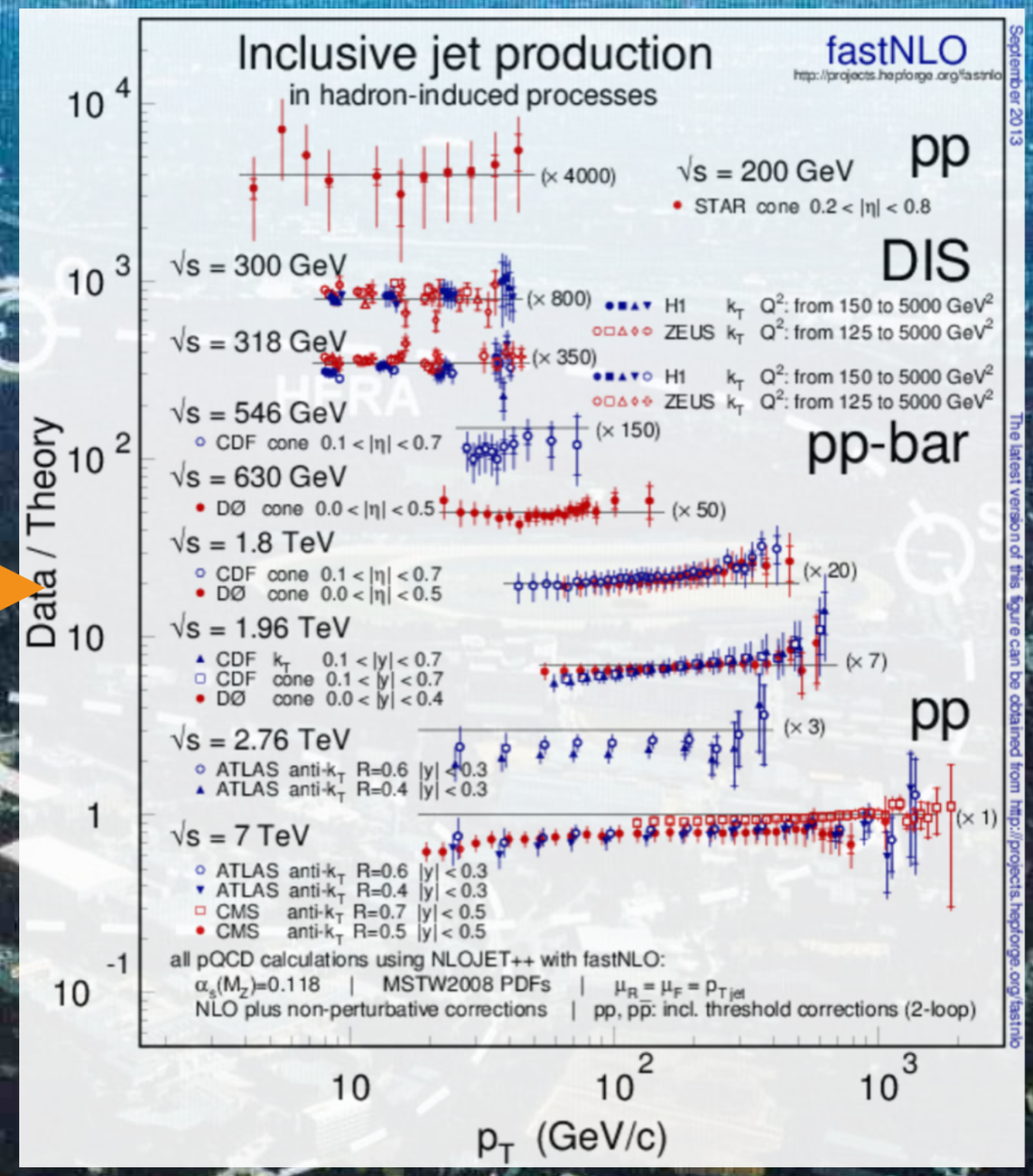




Vast body of *precision* measurements over a wide kinematic range,
Exquisite insight in high-energy proton structure and QCD dynamics.

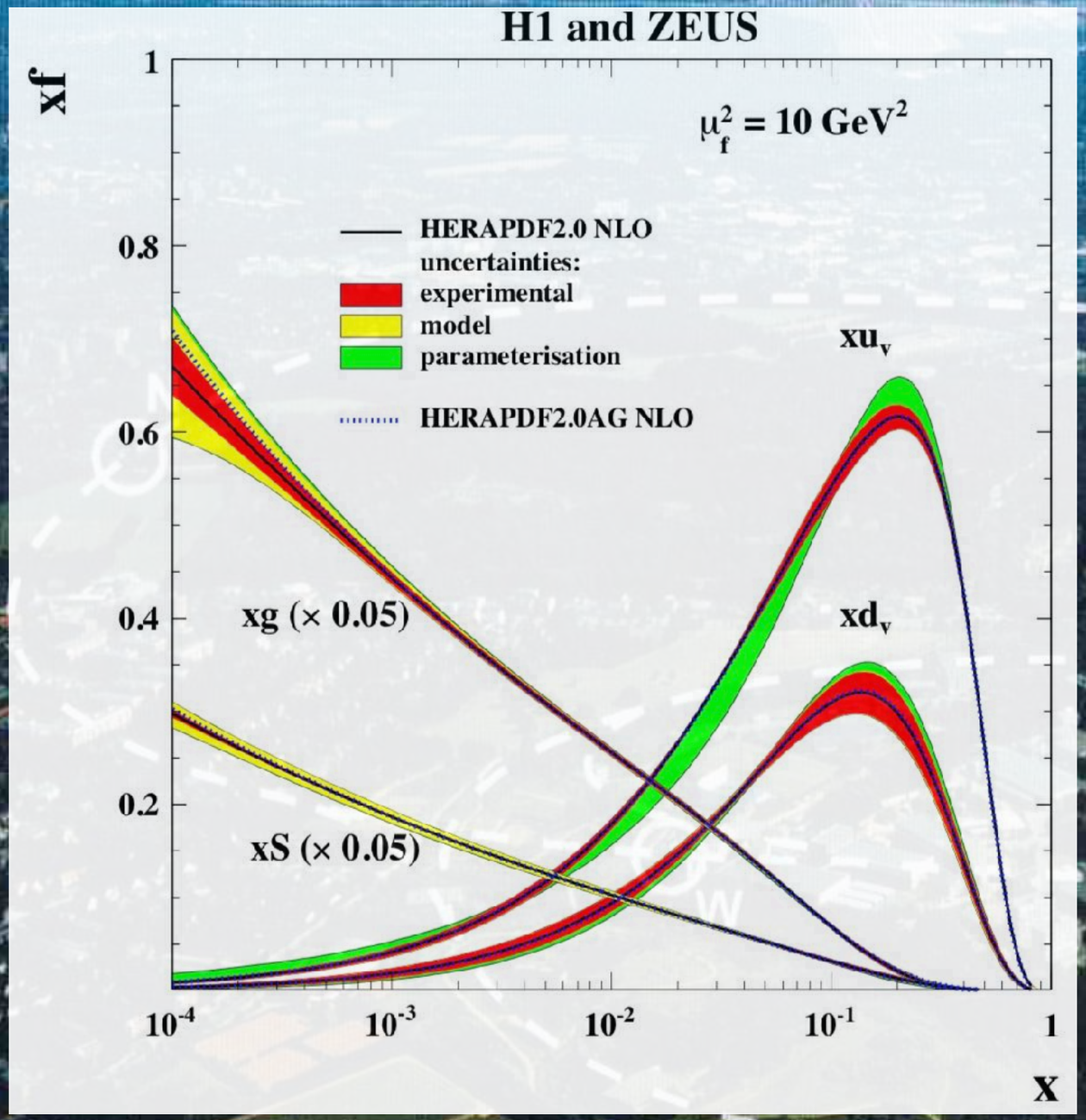
HERA's Legacy





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

HERA's Legacy



Proton structure at high-energy is:

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

Gluon content increases with decreasing *x*,

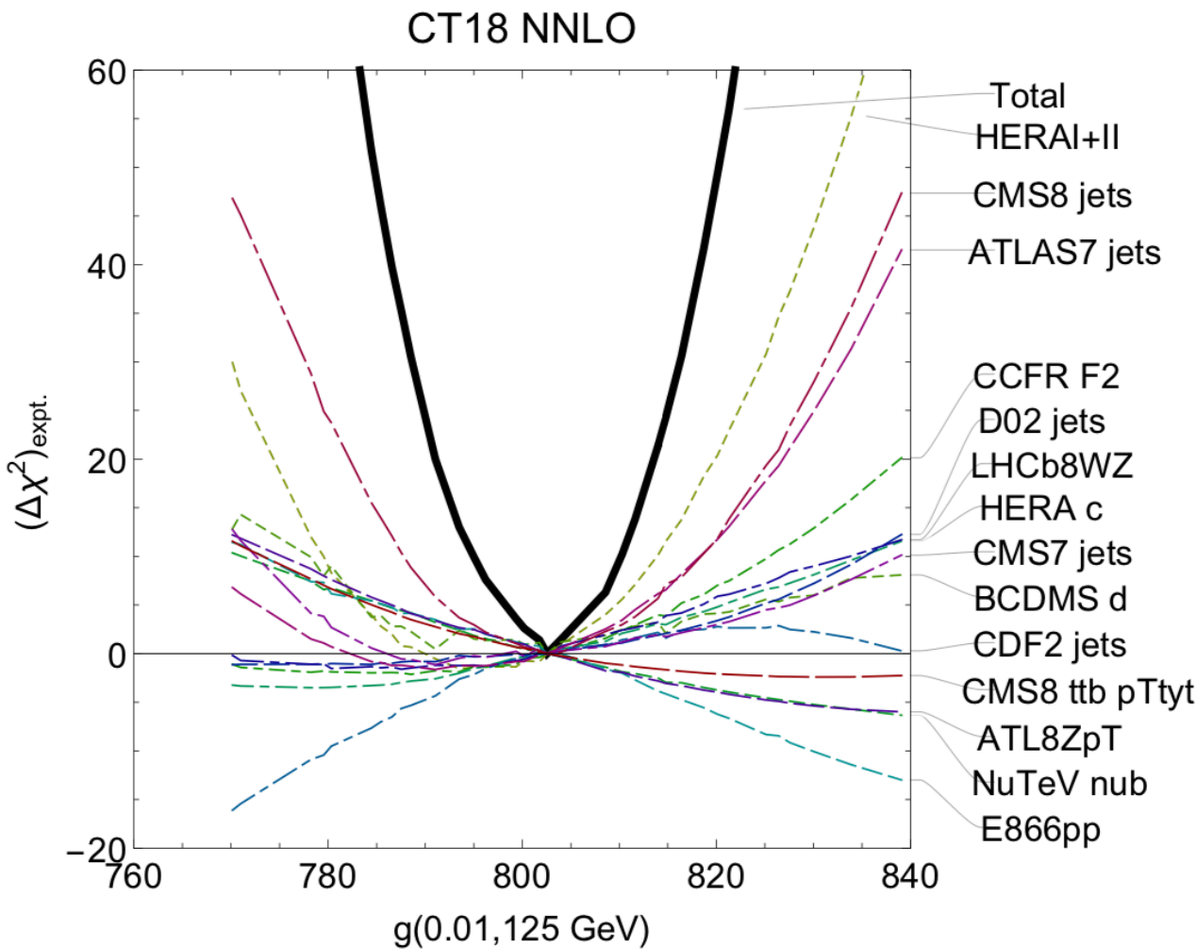
Gluons pose a number of questions; e.g. saturation

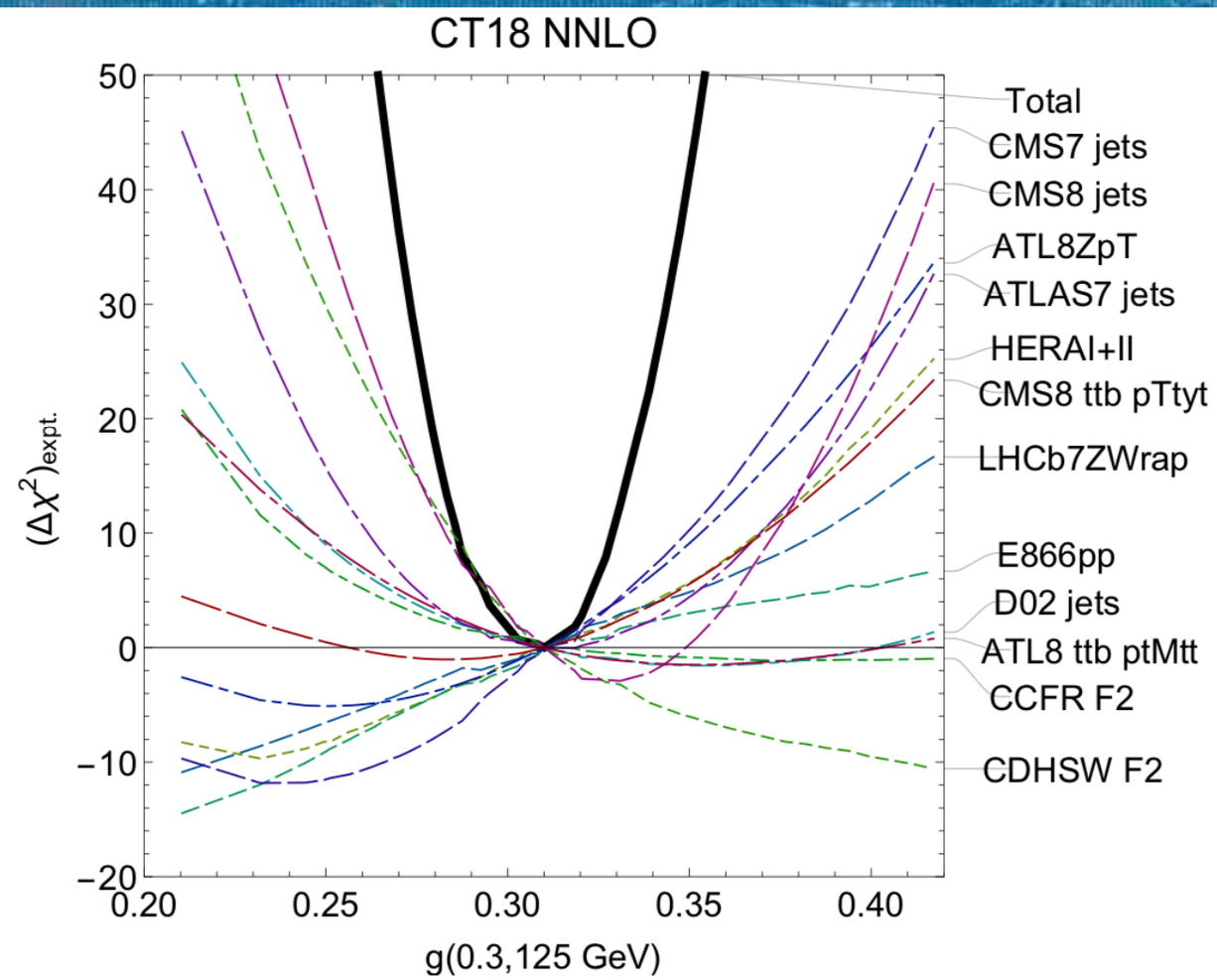
HERAPDF2.0:

14 parameters,

~1400 combined data points,

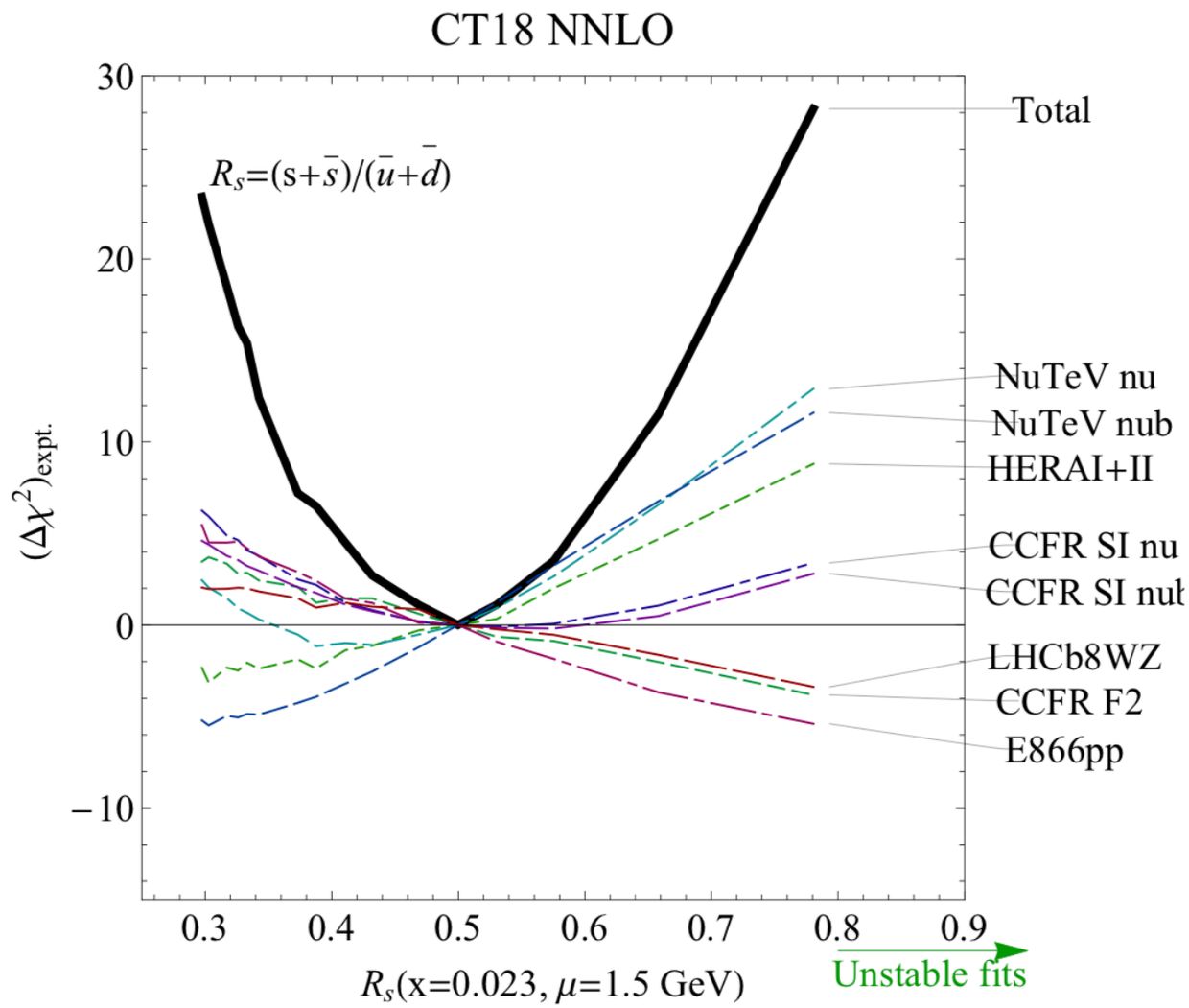
Truth in advertising….

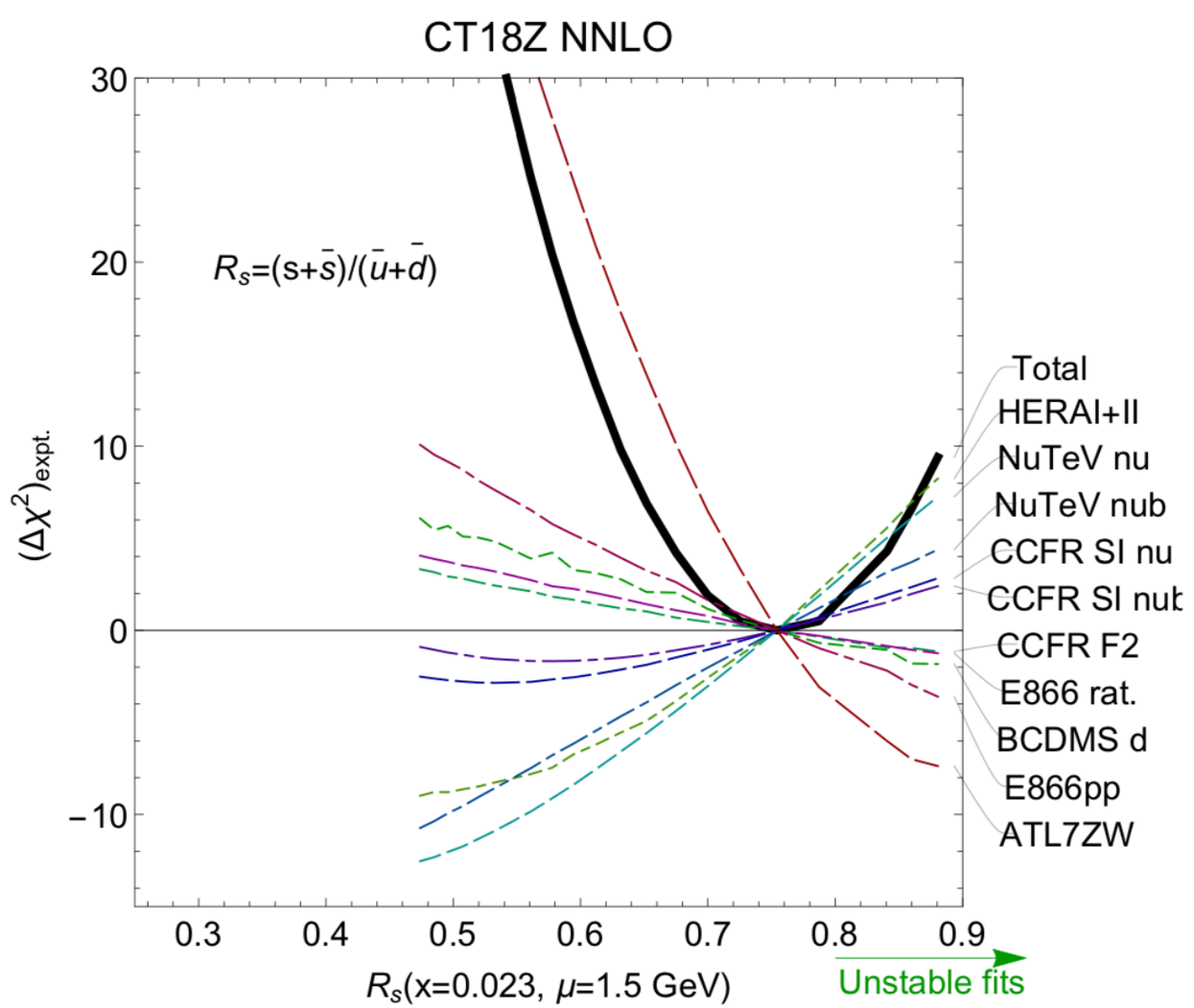




A great deal has been learned and continues to be learned from other experiments, e.g. from the LHC…. Shown here CTEQ fits, arXiv:1908.11238

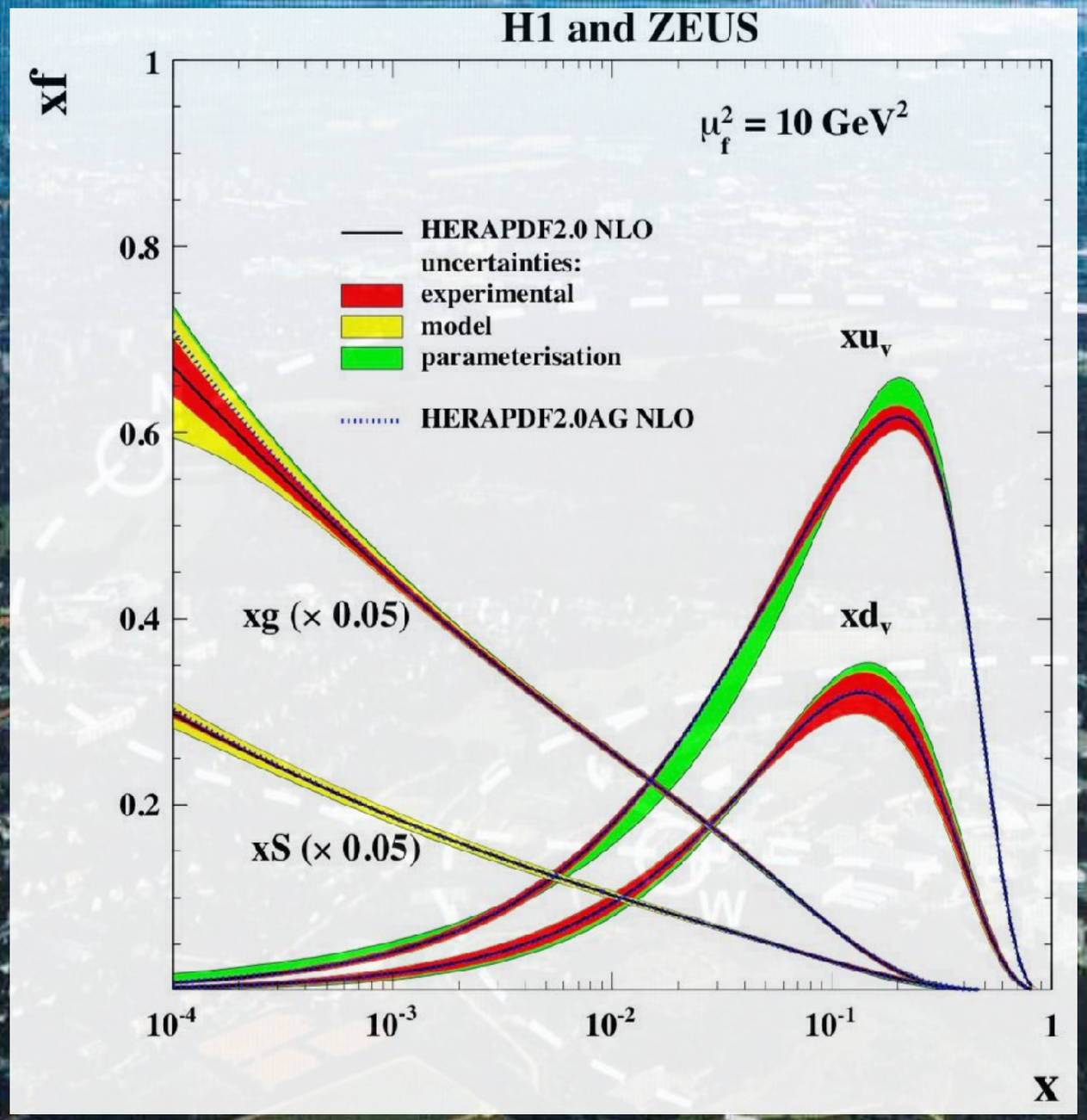
Truth in advertising….





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

HERA's Legacy



Exquisite insight in proton structure in terms of quark and gluon degrees of freedom,

… and also some quite remarkable voids;

Precision F_L - insufficient time,

Test isospin, u-d, - no deuterons,

d/u at large *x* - luminosity,

Strange quark distributions - luminosity,

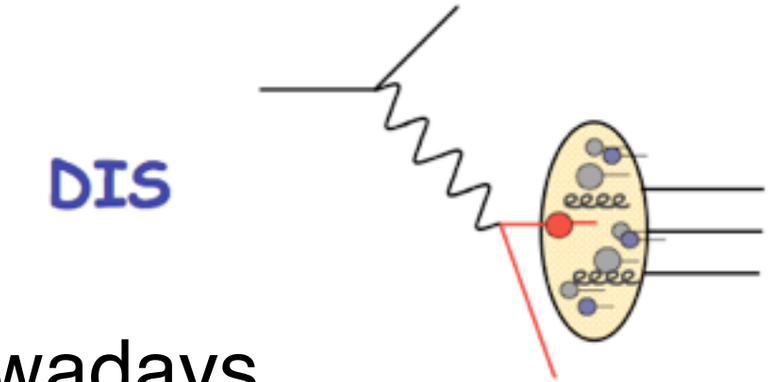
Spin puzzle - no hadron beam polarization,

Quark-gluon dynamics in nuclei - no nuclei,

Saturation - insufficient √s / no nuclei,

…

Brief recap:



- DIS is about nucleon or nuclear structure, nowadays described in terms of quarks and gluons,
- Feynman's parton model - point like partons, which behave *incoherently* - combined with QCD radiation are remarkably successful in describing DIS cross sections.
- Parton distributions $f(x)$ are *intrinsic* properties of the nucleon and (thus) process independent.
- QCD evolution allows one to relate quantitatively processes at different scales Q^2,

  This is great for RHIC, LHC, and many other areas.
- Gluons are a *very* significant part of the nucleon

Questions or comments, before we move on?

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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Renormalization group-improved Parton Model

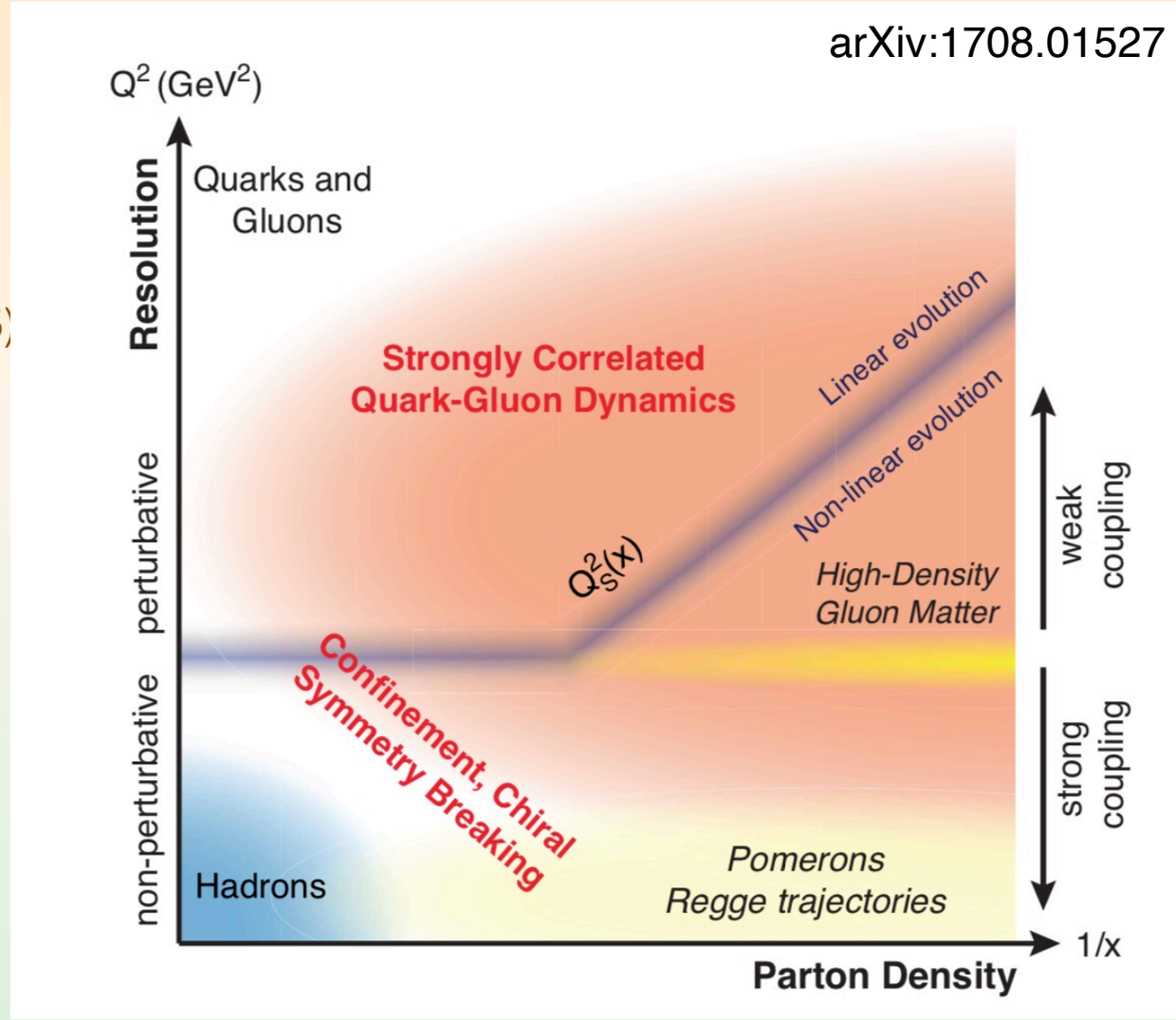
Factorization theorem(s) + one-dimensional parton distributions,
no correlations among the partons

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)

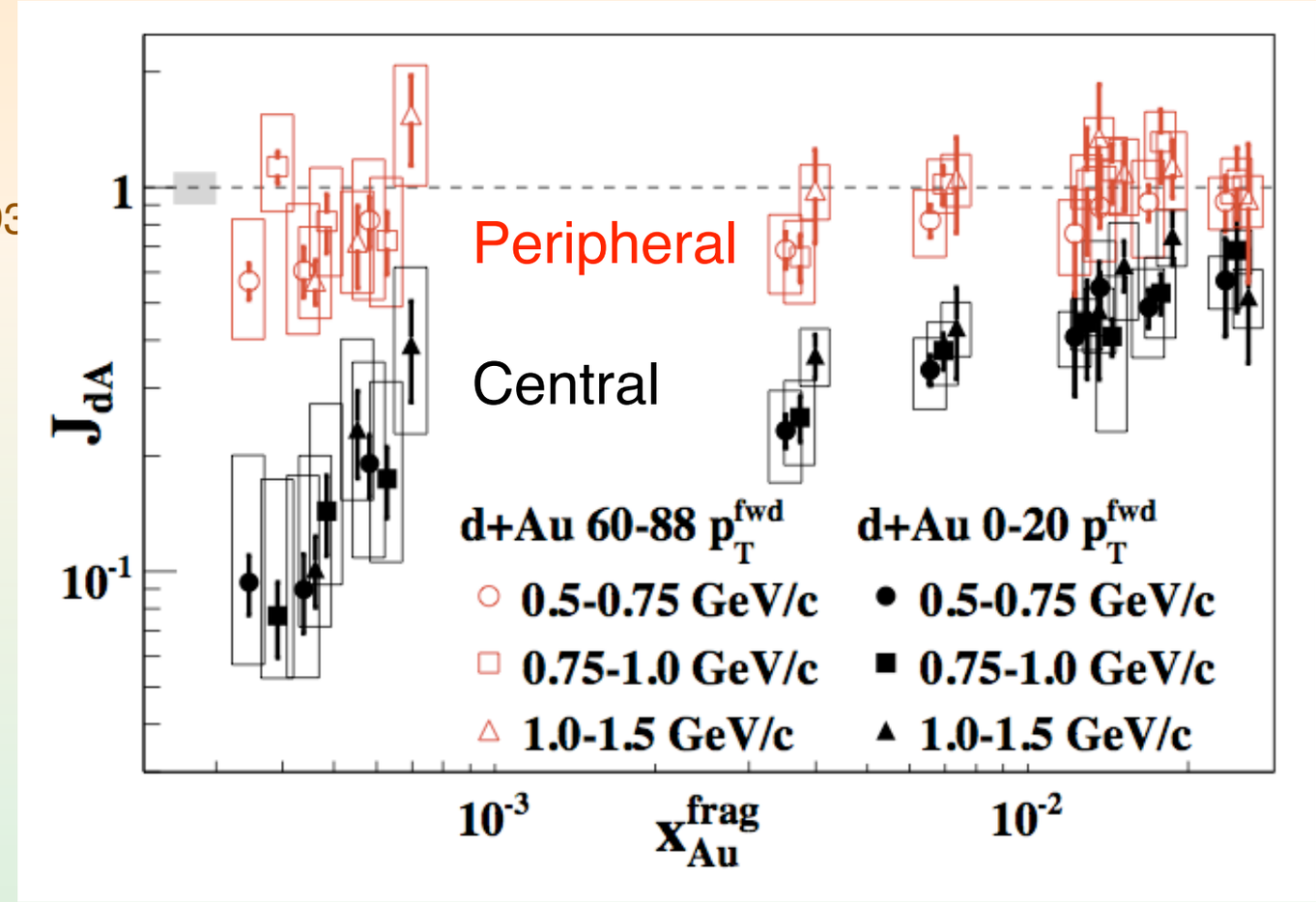


HERA - RHIC, LHC

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

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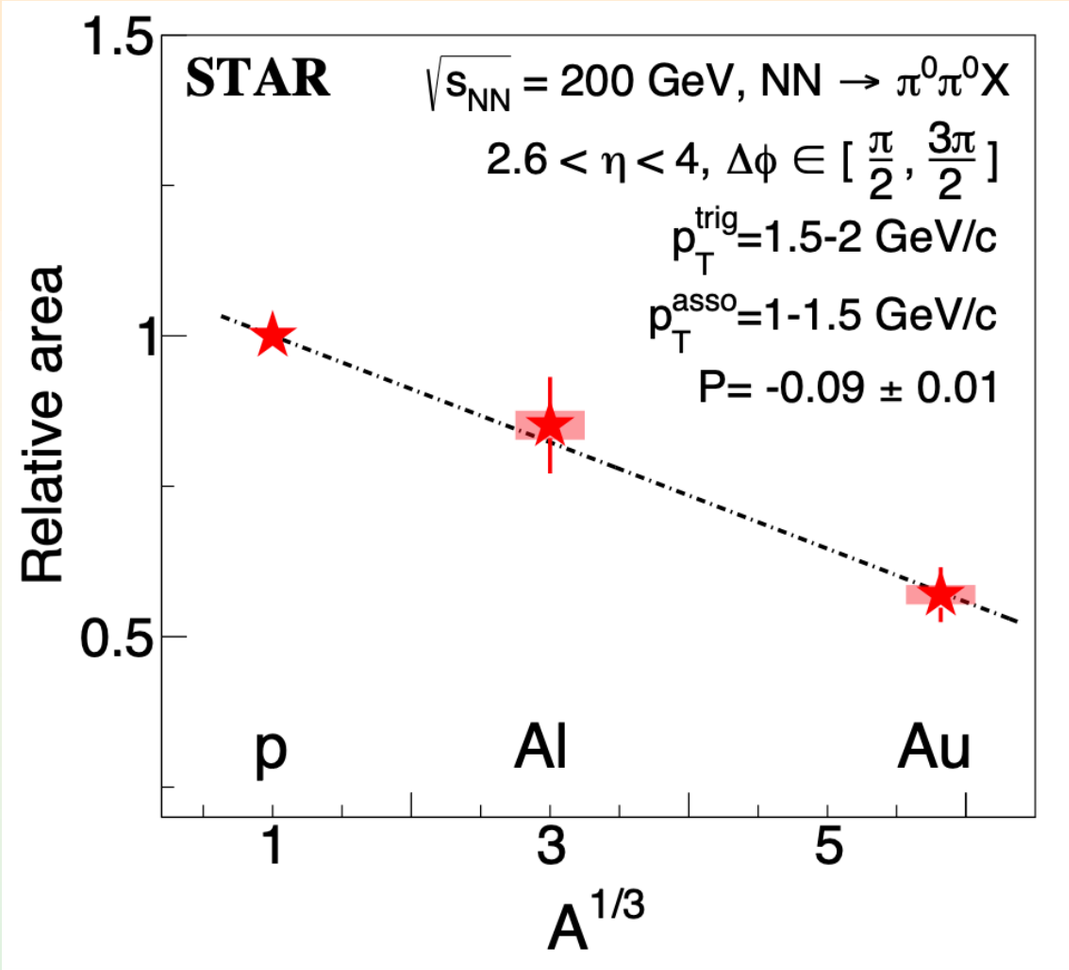

STAR, Phys.Rev.Lett. 129 (2022) 092501

HERA - RHIC, LHC

Saturation:

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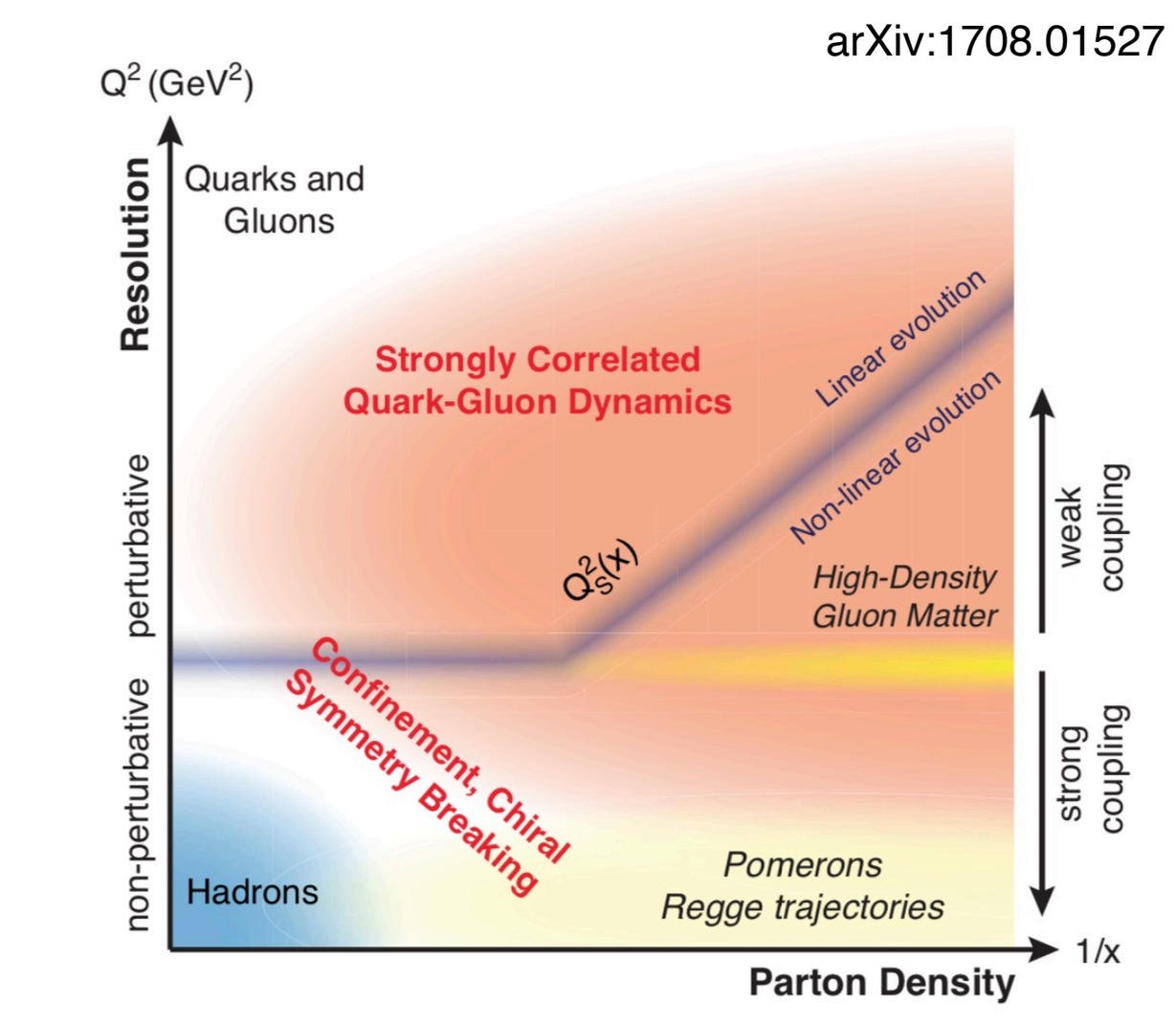
- diffractive cross-section independent of W and Q^2,
- evidence for BFKL dynamics (Ball et al., arXiv:1710.05935),
- tantalizing observations, but open questions remain.



HERA - RHIC, LHC

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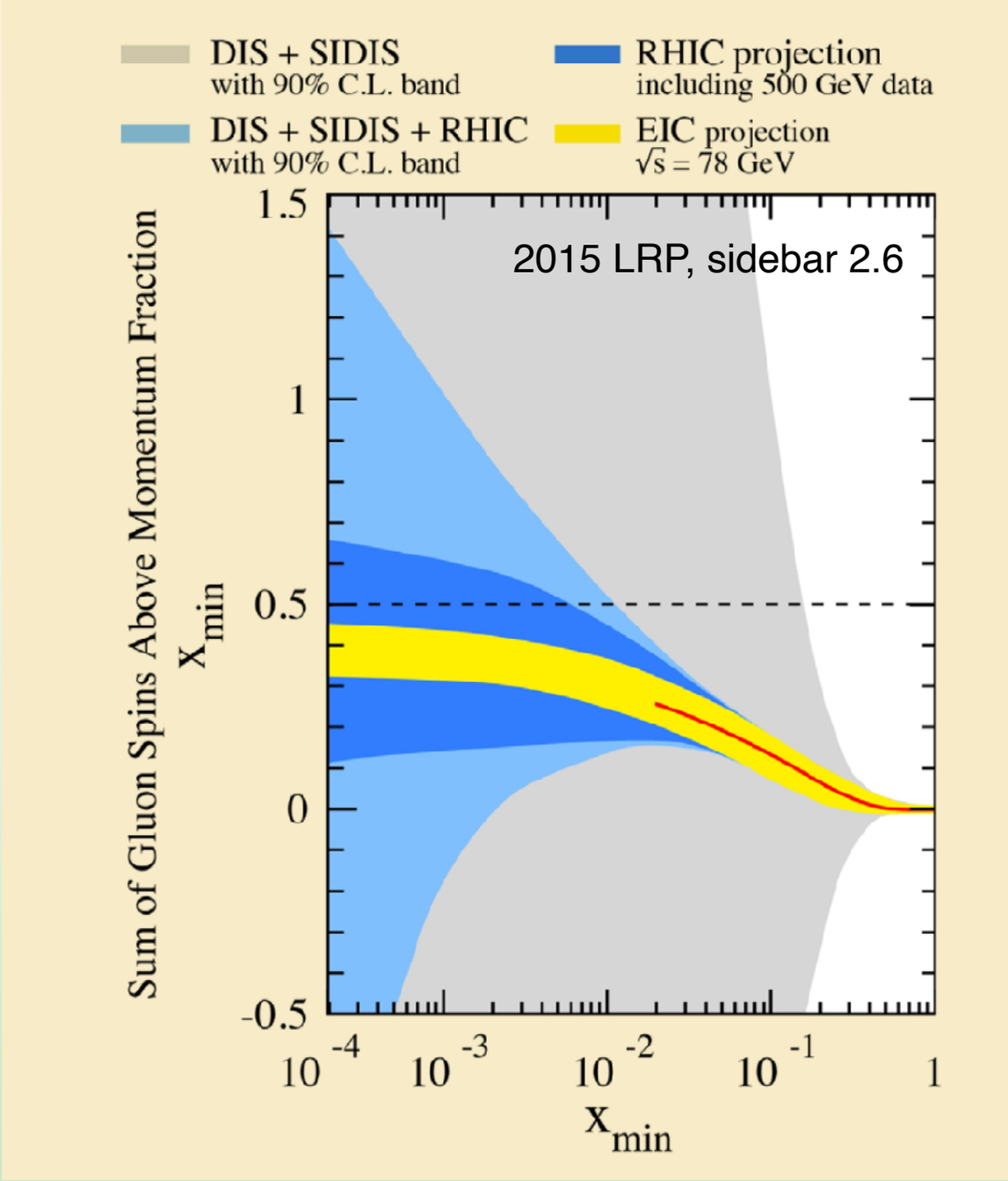
Spin puzzle:

- 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
- Lattice-QCD progress



HERA - RHIC, LHC - JLab

Saturation:

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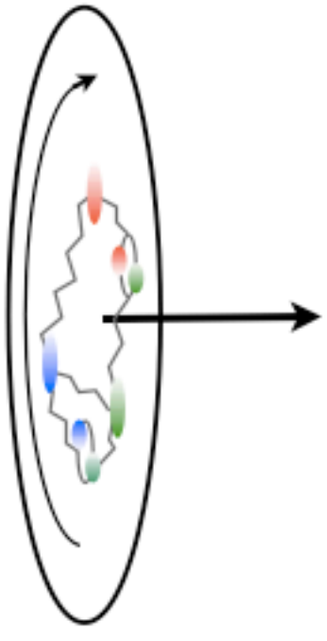
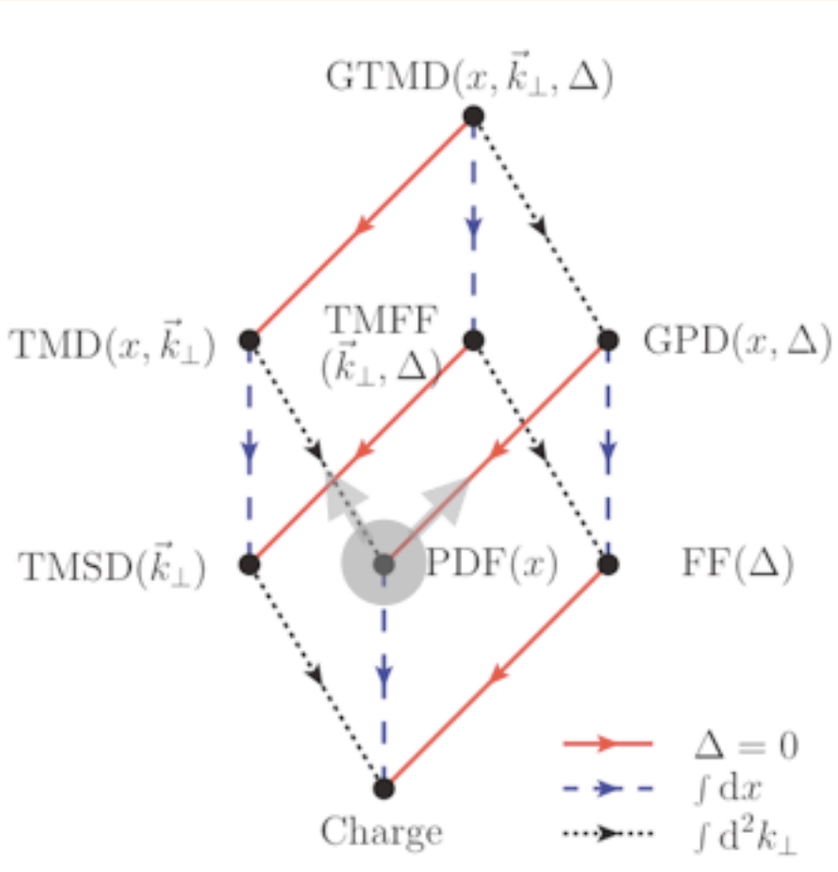




Lorce, Pasquini, Vanderhaeghen

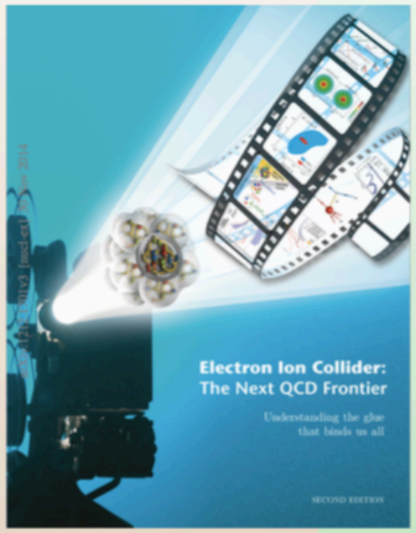
Imaging / tomography:

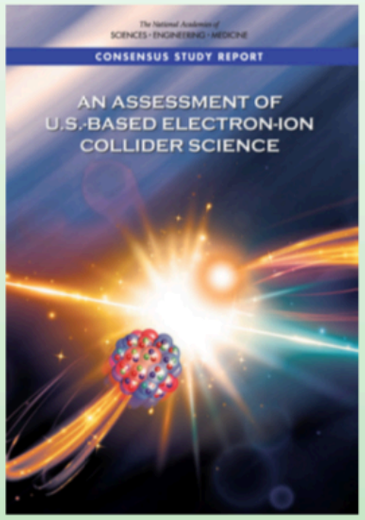
- valence quark region,

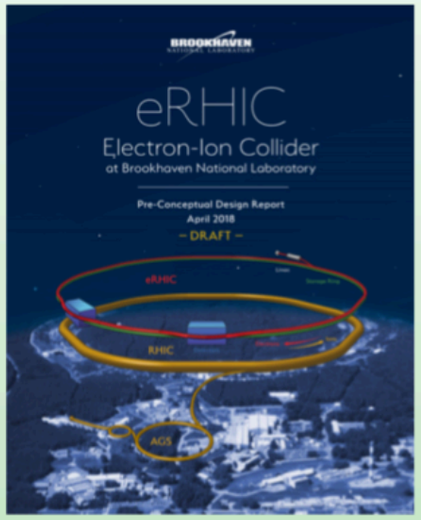
Electron Ion Collider Initiatives

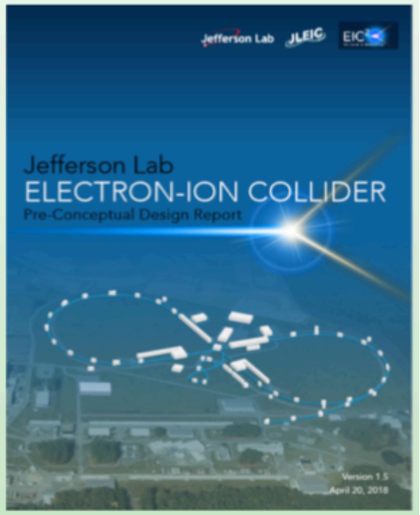
Approach: combine strengths
use existing investments (risk, cost),
pursue luminosity;100x - 1000x HERA
nuclei and *polarization*,
optimized instrumentation.

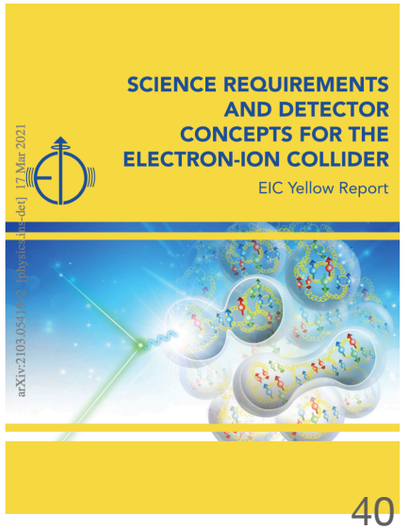
	HERA @ DESY	LHeC @ CERN	EIC in China	EIC in U.S.
$\sqrt{s_{ep}}$ [GeV]	320	200 - 1300	15 - 20	20 - 100 (140)
proton x_{min}	1×10^{-5}	5×10^{-7}	2×10^{-3}	1×10^{-4}
ion	p	p, Pb, …	p - U	p - U
polarization	-	-	p, light nuclei	p, d, ^{3}He, Li
L [$cm^{-2}s^{-1}$]	2×10^{31}	1×10^{34}	3×10^{33}	10^{33} - 10^{34}
Interaction Points	2	1	1	2
Timeline	1992 - 2007	post ALICE	Upgrade to HIAF	> 2031



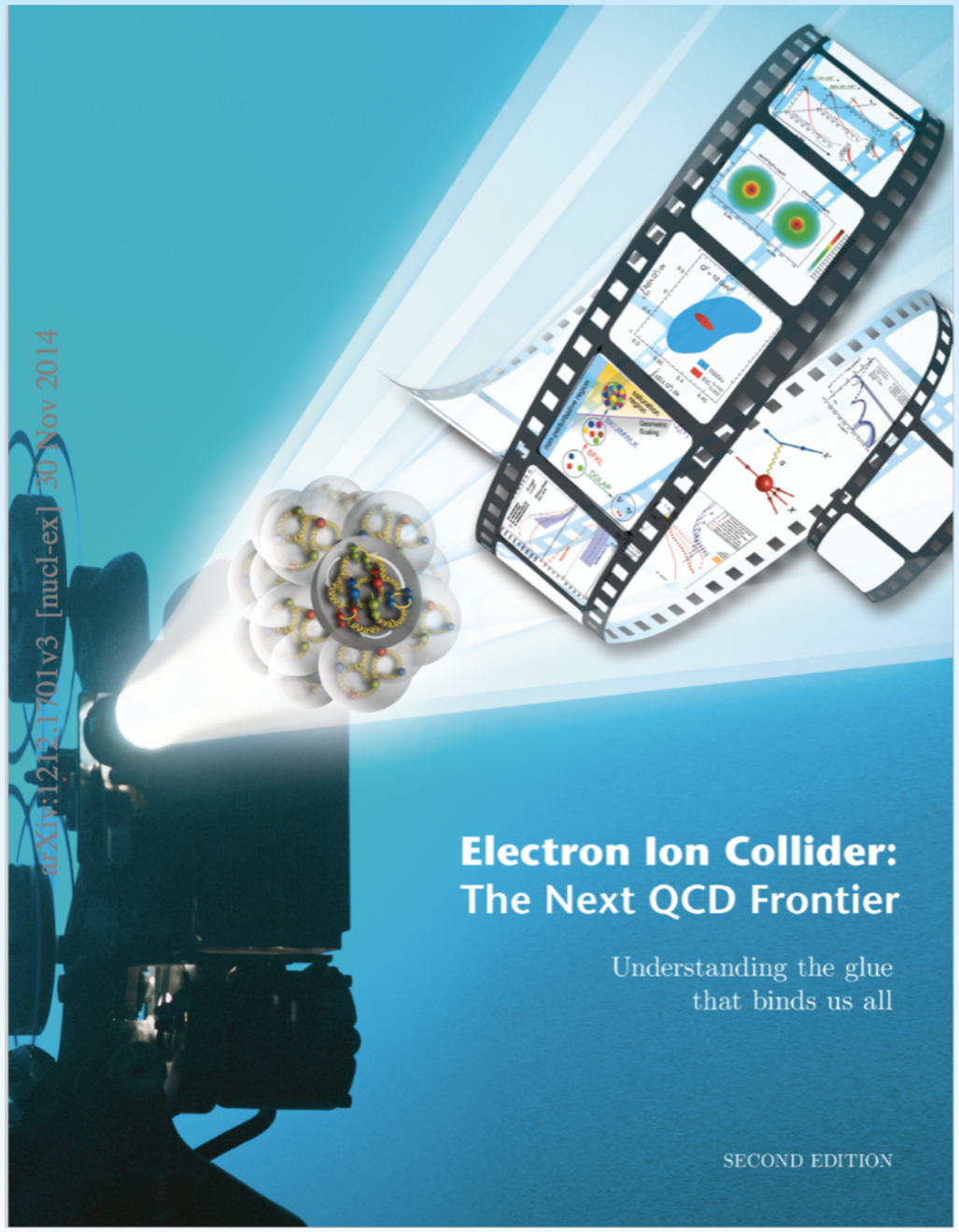








U.S. EIC Capabilities

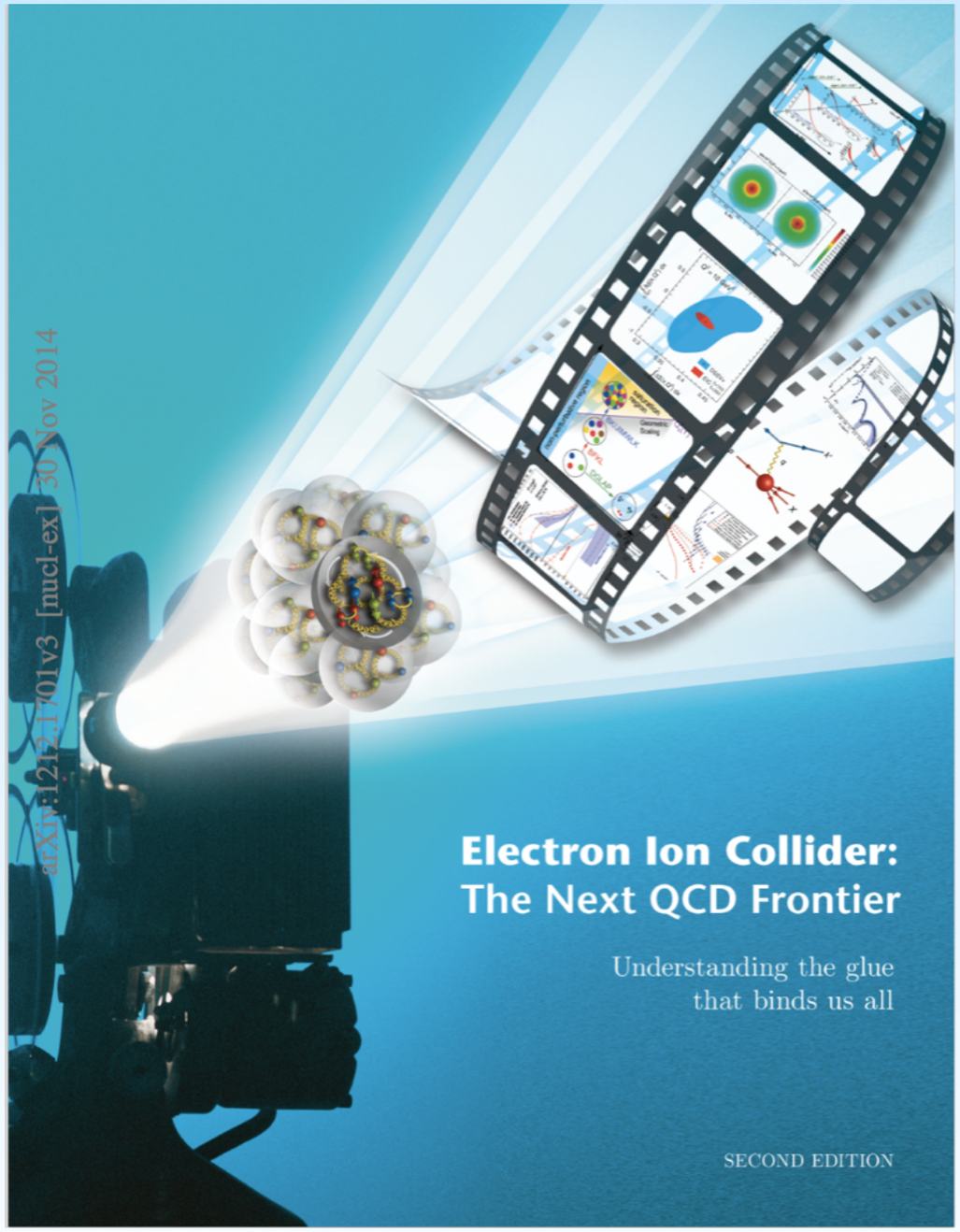


Eur. Phys. J. A52 (2016) no.9, 268

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 BNL and at JLab, re-use of existing, significant investment (BNL has since been site-selected).*

U.S. EIC Science Case

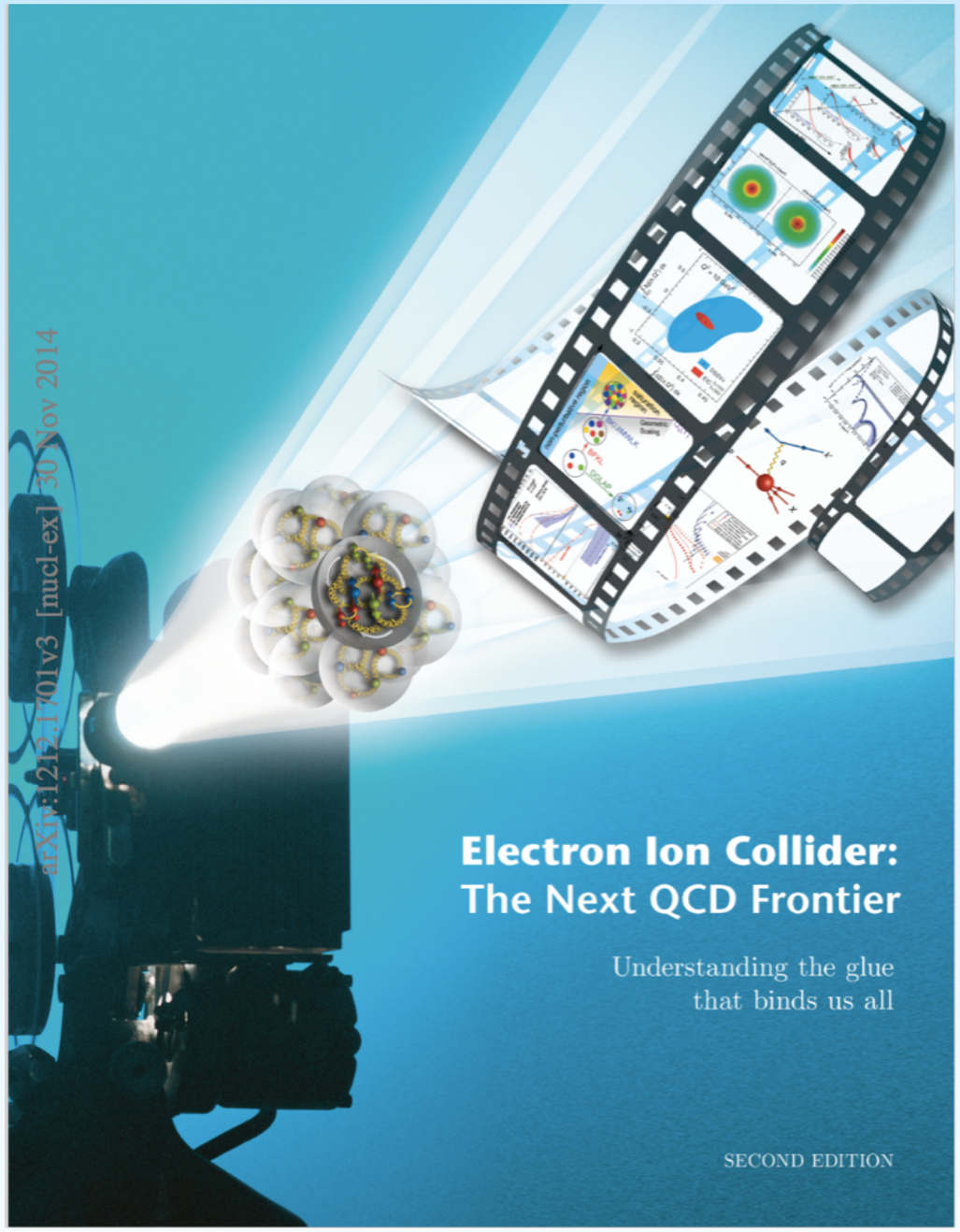


- *How are the sea quarks and gluons, and their spins, distributed in space and momentum inside the nucleus?*
- *Where does the saturation of gluon densities set in?*
- *How does the nuclear environment affect the distribution of quarks and gluons and their interactions in nuclei?*

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

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

U.S. EIC Science Case



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

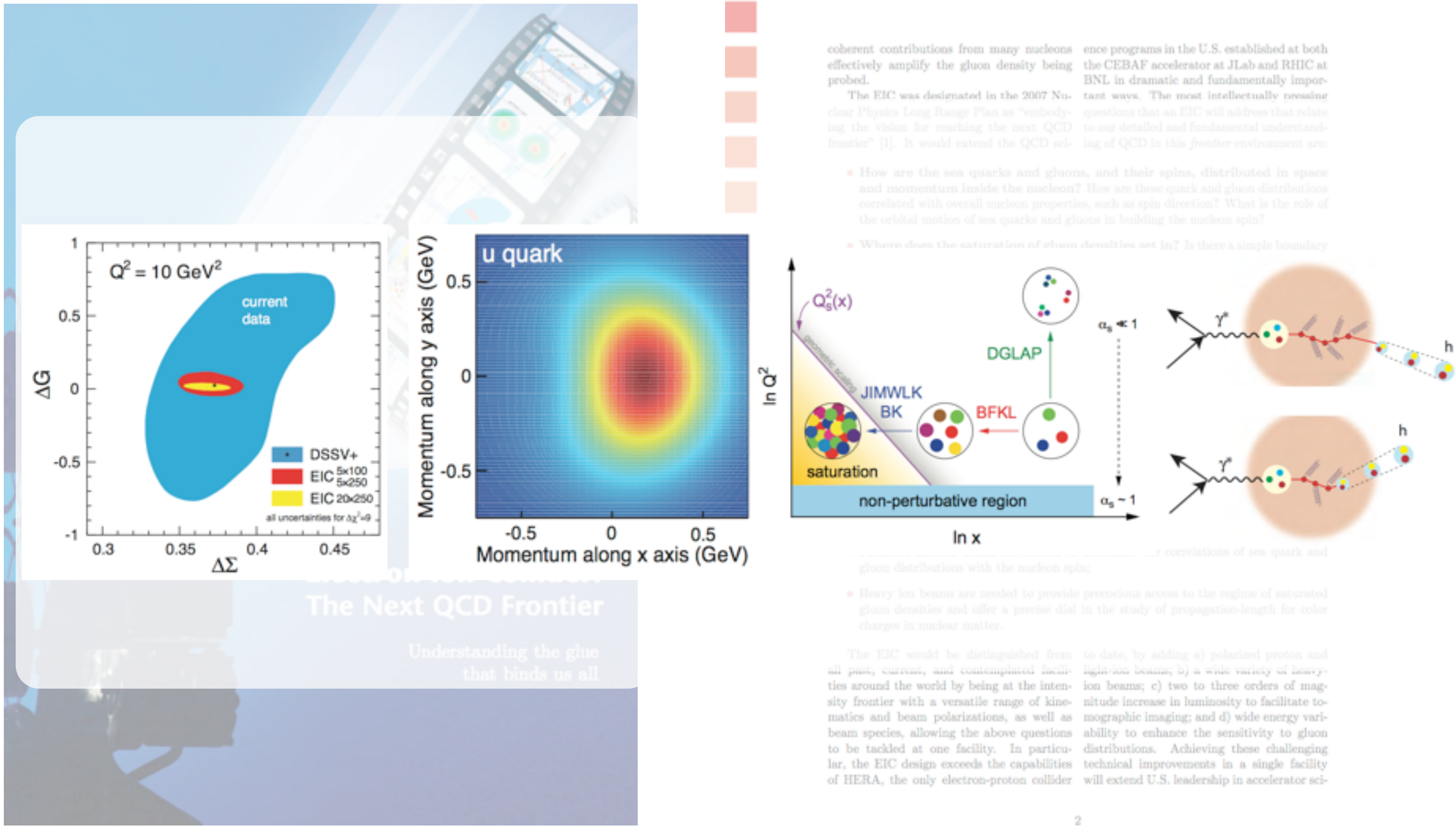
See also Rept.Prog.Phys. 82 (2019) 024301

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

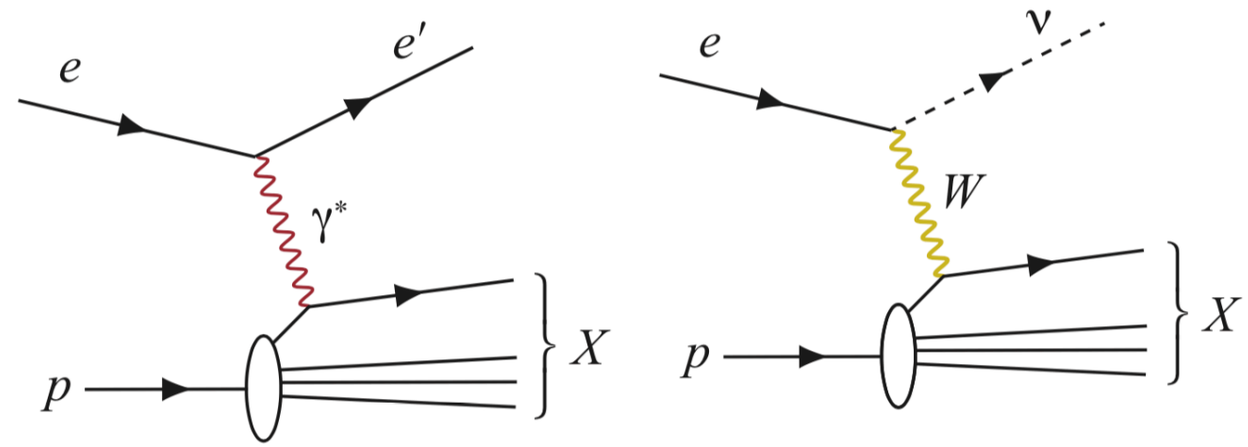
Truth in presentation: the process is never quite this A to B; instead, it is iterative.

The “Yellow Report” — Nucl. Phys. A 1026 (2022) 122447 — presents a considerable step forward, both in terms of additional measurements and quantified requirements.

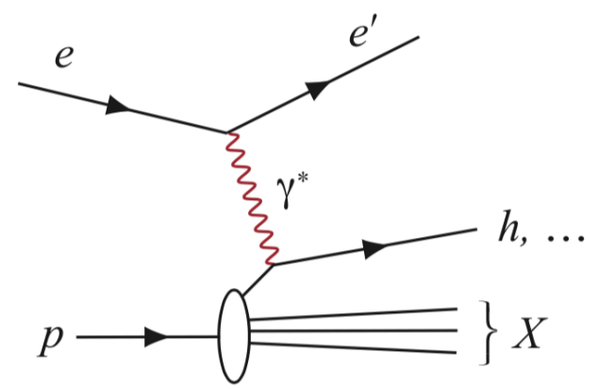
U.S.-based EIC - Nucleon Spin

U.S.-based EIC - key processes for spin physics at LO

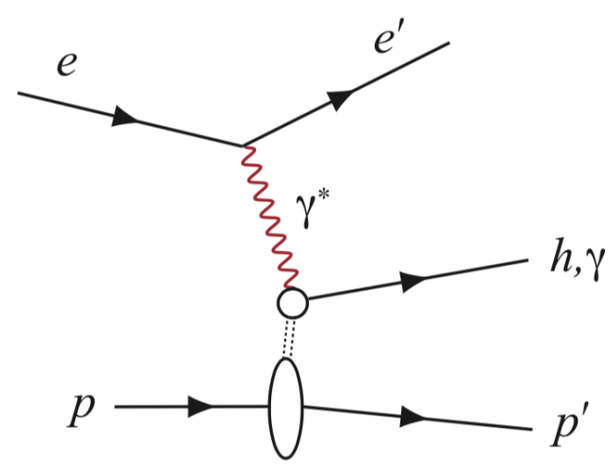
Inclusive deep-inelastic scattering



Semi-inclusive deep-inelastic scattering

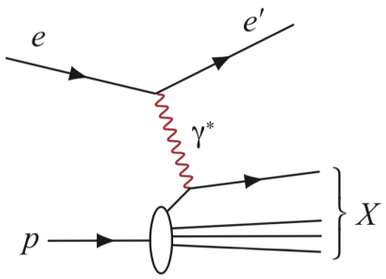


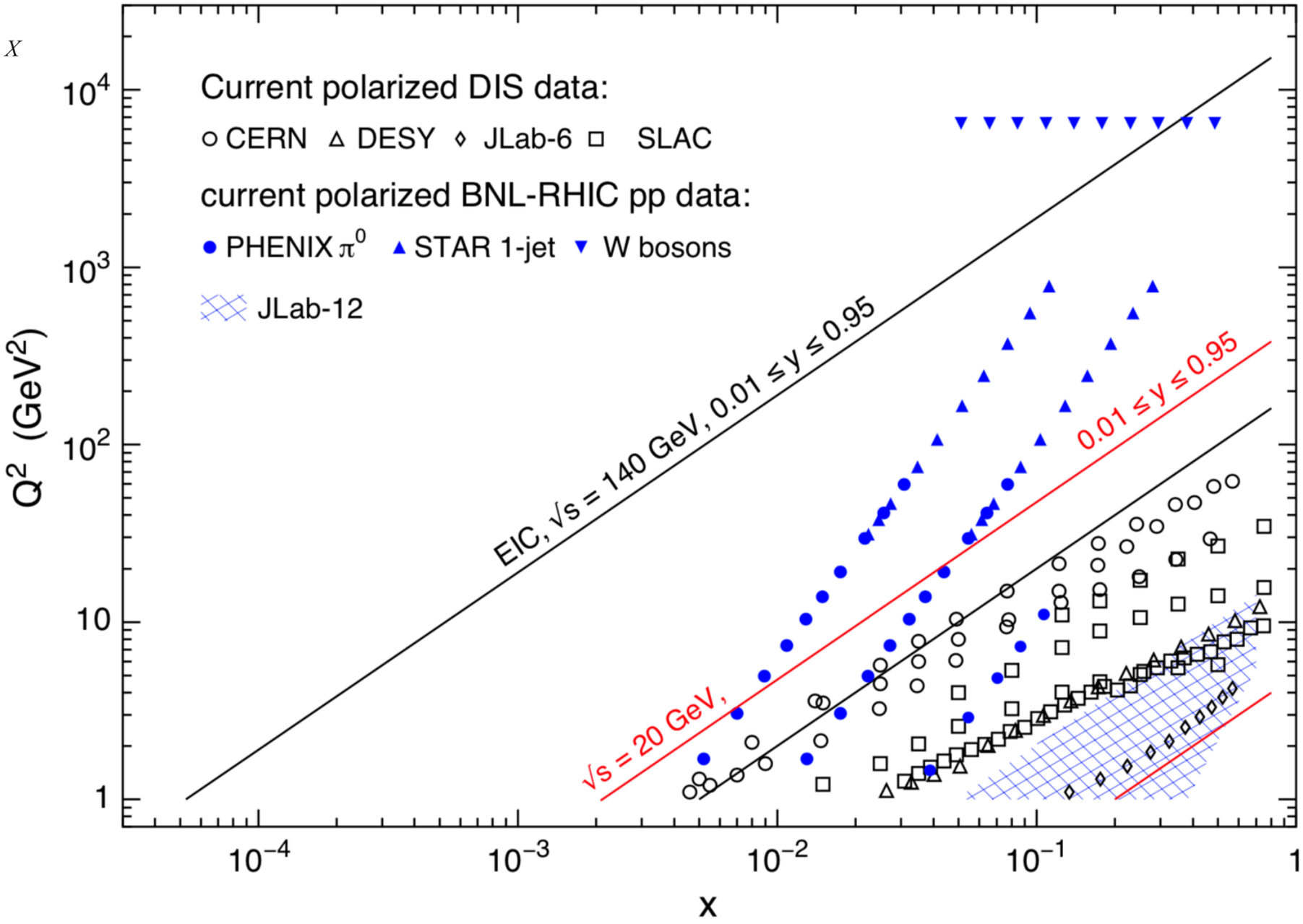
Exclusive deep-inelastic scattering



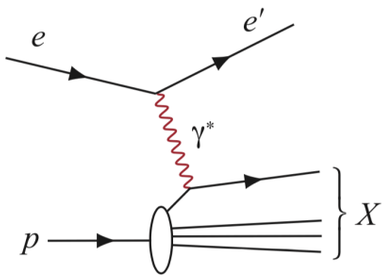
With and without polarization (!)

Polarized inclusive DIS Landscape - U.S.-based EIC





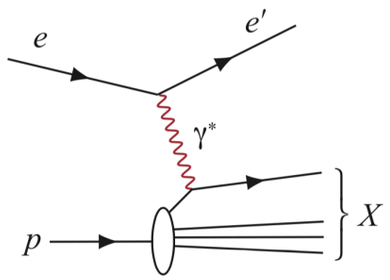
Polarized inclusive DIS Landscape - U.S.-based EIC



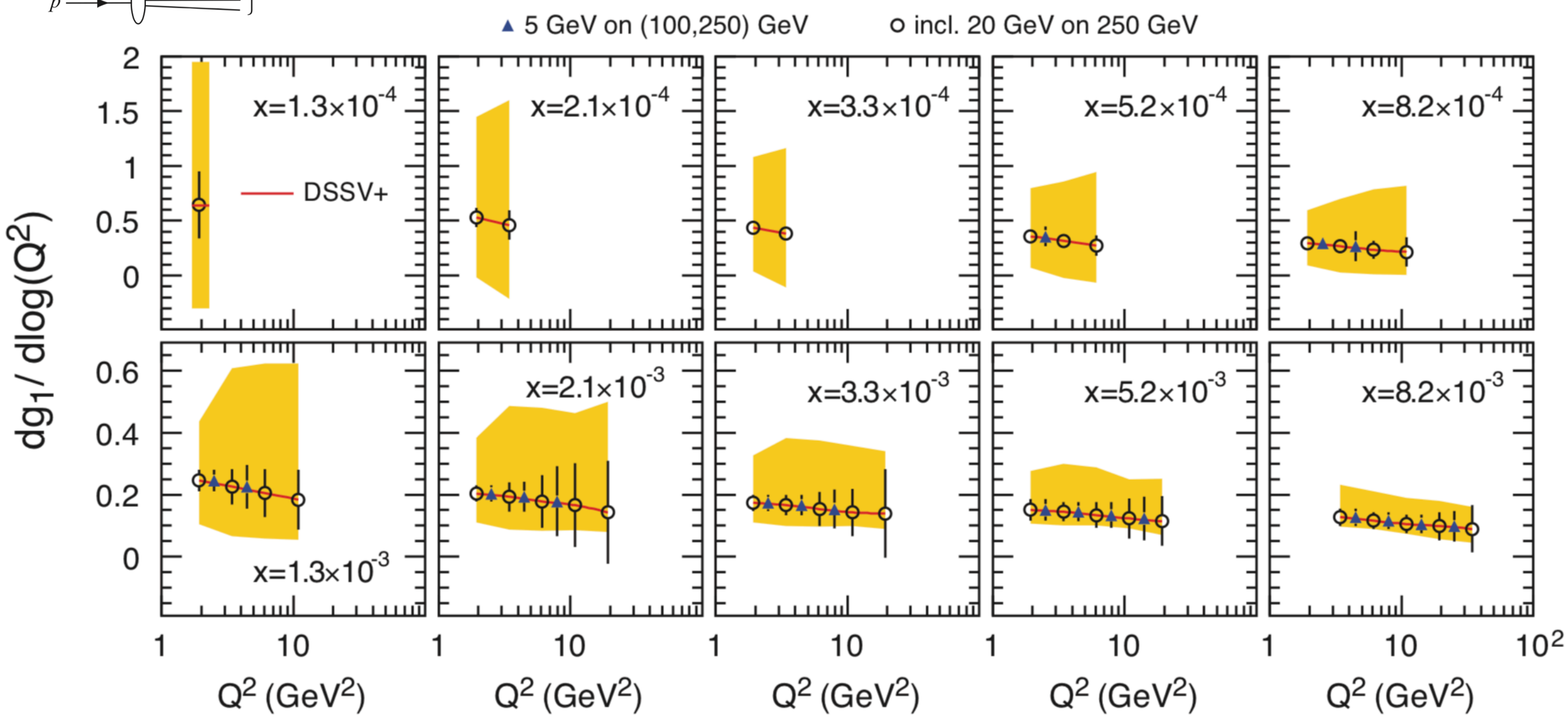
Current polarized DIS data:
○ CERN △ DESY ◇ JLab-6 □ SLAC
current polarized BNL-RHIC pp data:
● PHENIX π^0 ▲ STAR 1-jet ▼ W bosons
JLab-12
EIC, √s = 140 GeV, 0.01 ≤ y ≤ 0.95
√s = 20 GeV, 0.01 ≤ y ≤ 0.95
Q^2 (GeV^2)
x

Core questions include what is the gluon spin contribution to the proton spin?
what is the quark and anti-quark spin contribution (at low-*x*)?

U.S.-based EIC - polarized inclusive DIS



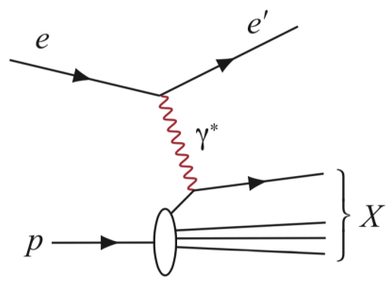
+ NLO



Core question: what is the gluon spin contribution to the proton spin?

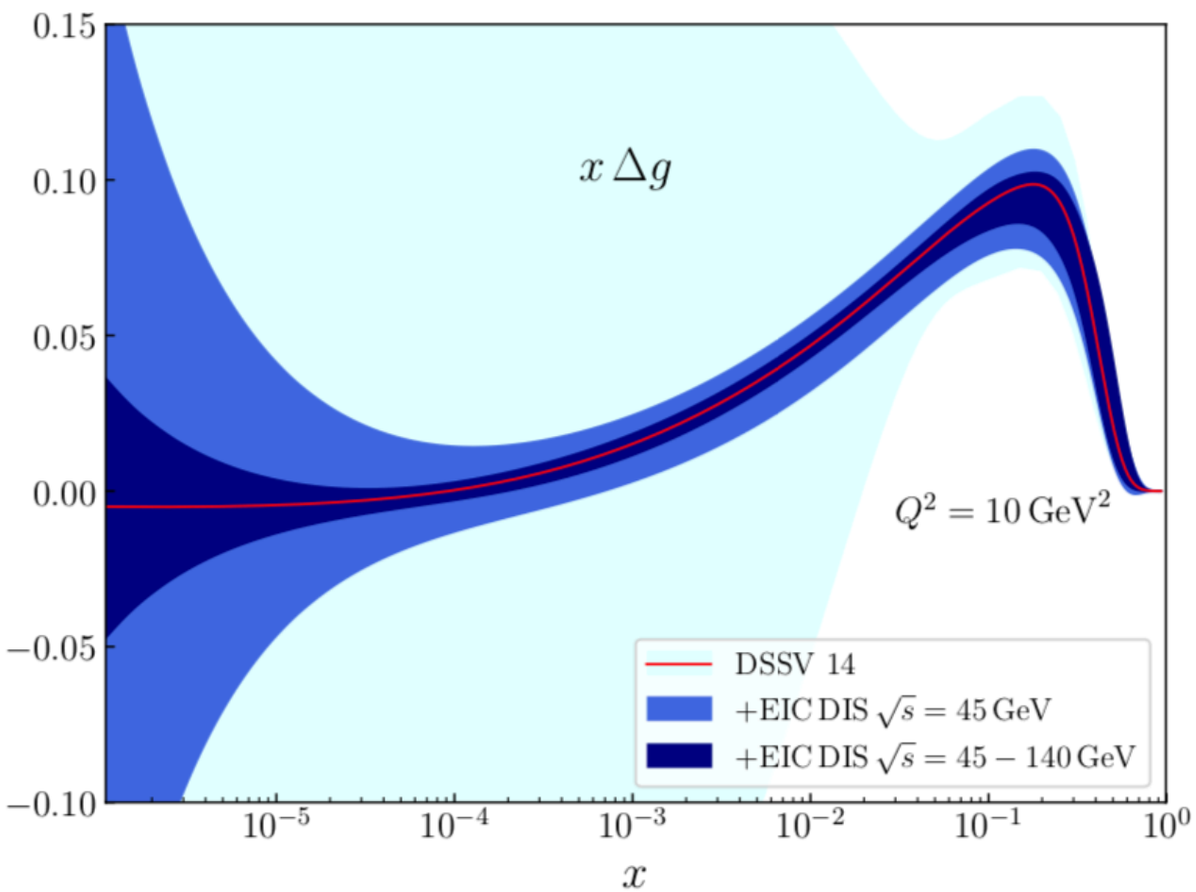
challenges include large acceptance, resolution, systematics

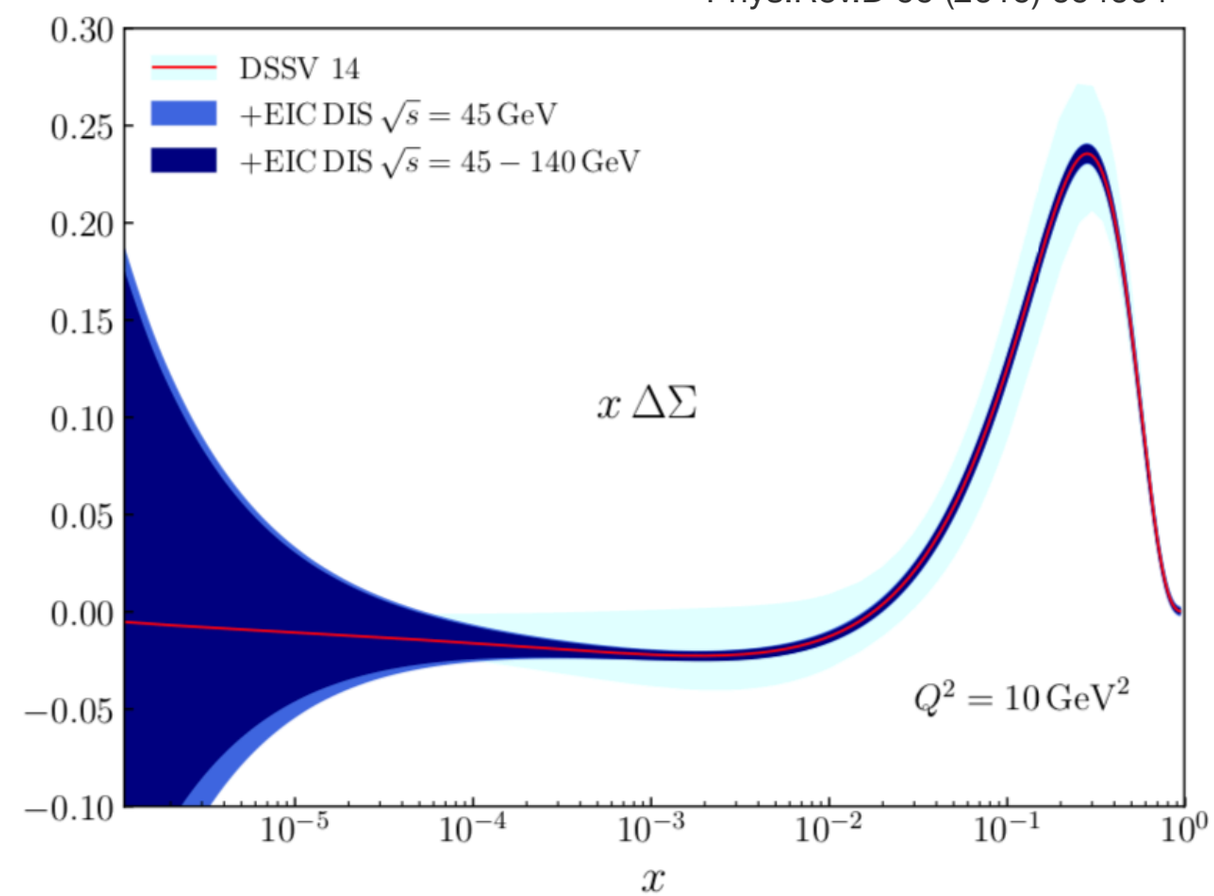
U.S.-based EIC - polarized inclusive DIS



+ NLO

Phys.Rev.D 99 (2019) 094004



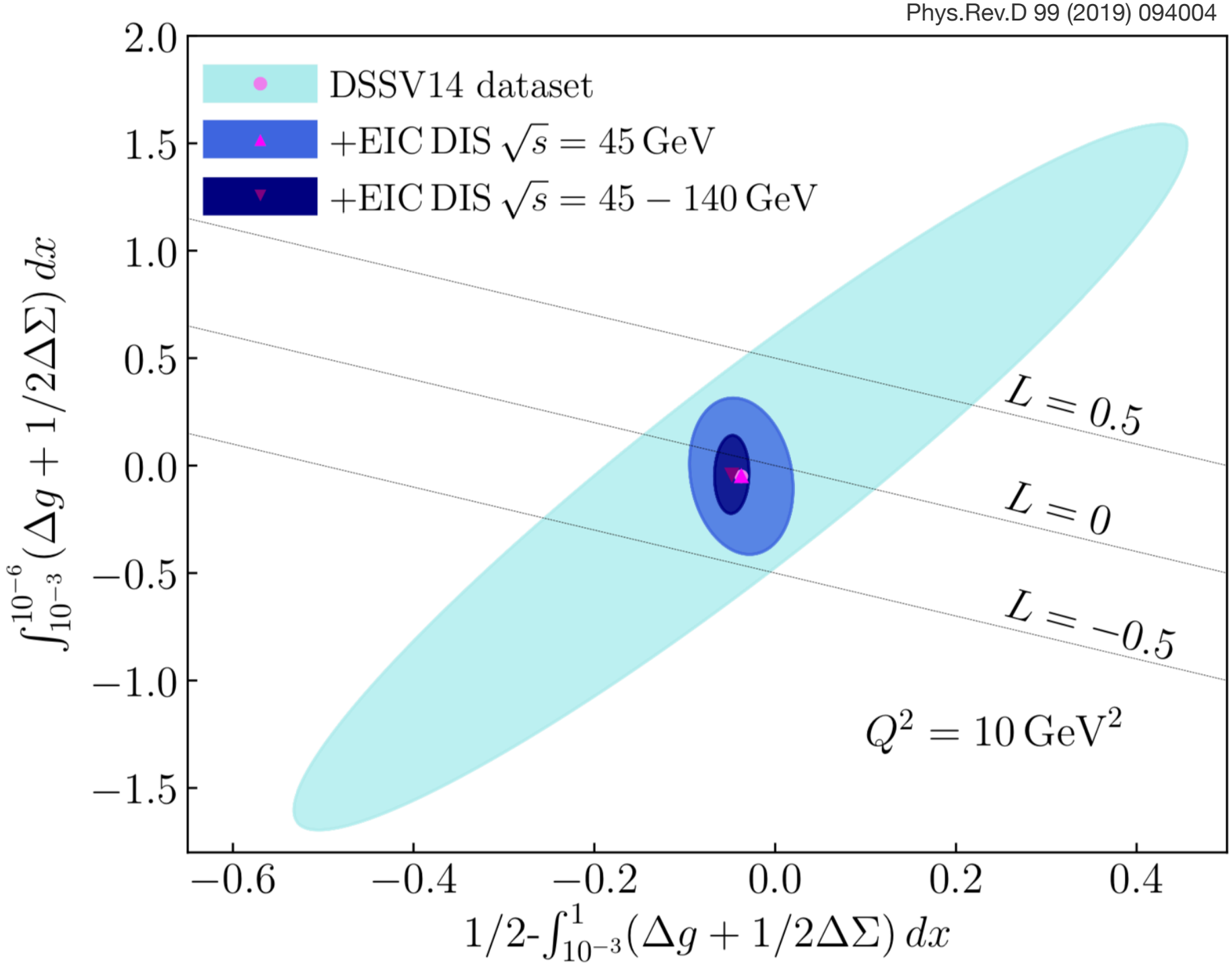


Core answers will include what is the gluon spin contribution to the proton spin?

what is the quark and anti-quark spin contribution (at low-*x*)?

U.S.-based EIC - polarized inclusive DIS

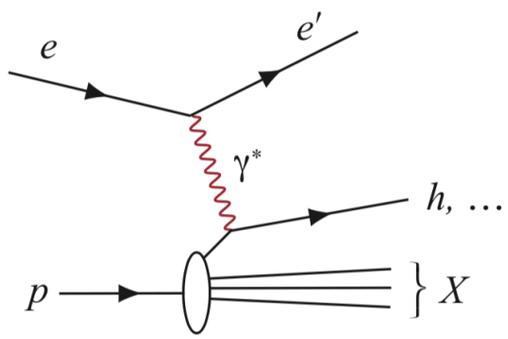
Phys.Rev.D 99 (2019) 094004



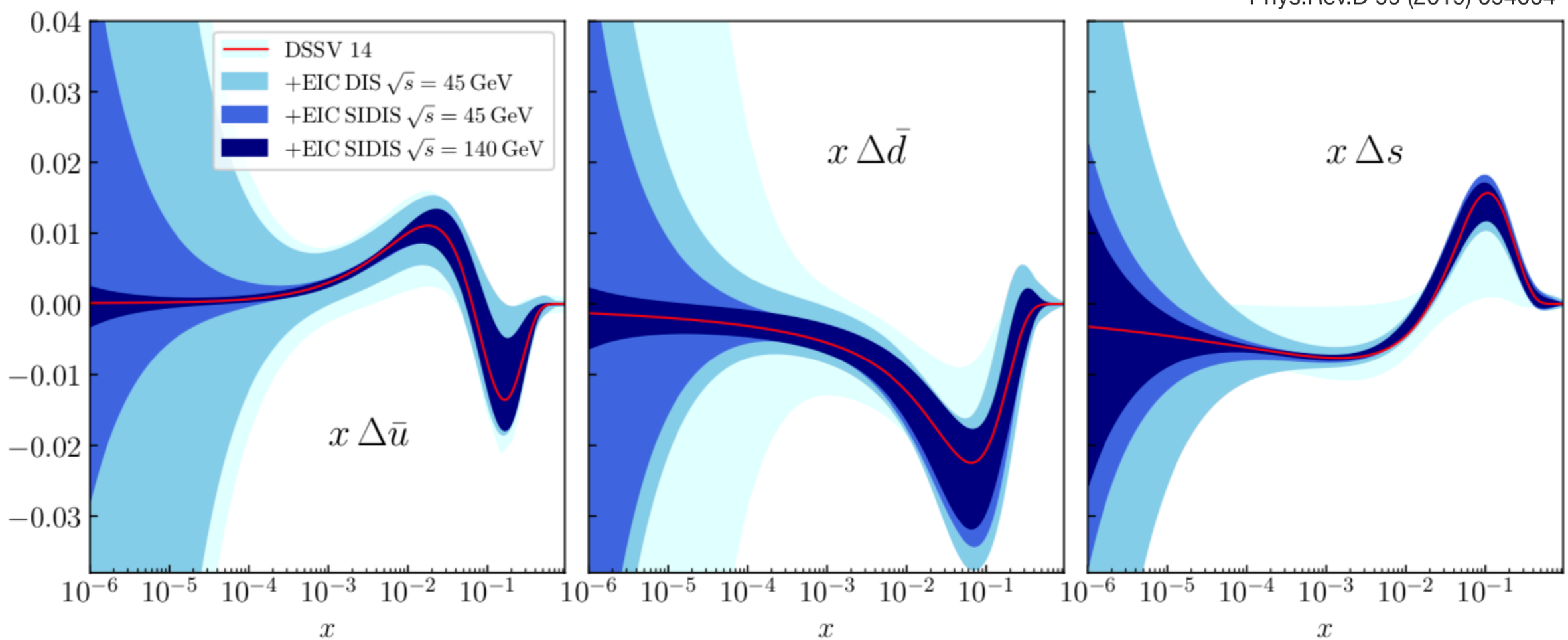
Core answers will include what is the gluon spin contribution to the proton spin?

what is the quark and anti-quark spin contribution (at low-*x*)?

U.S.-based EIC - polarized semi-inclusive DIS



Phys.Rev.D 99 (2019) 094004

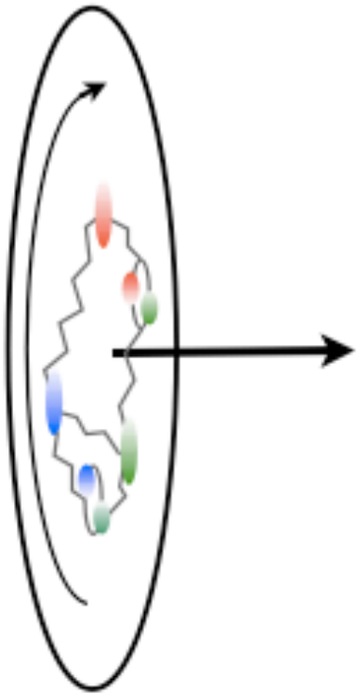


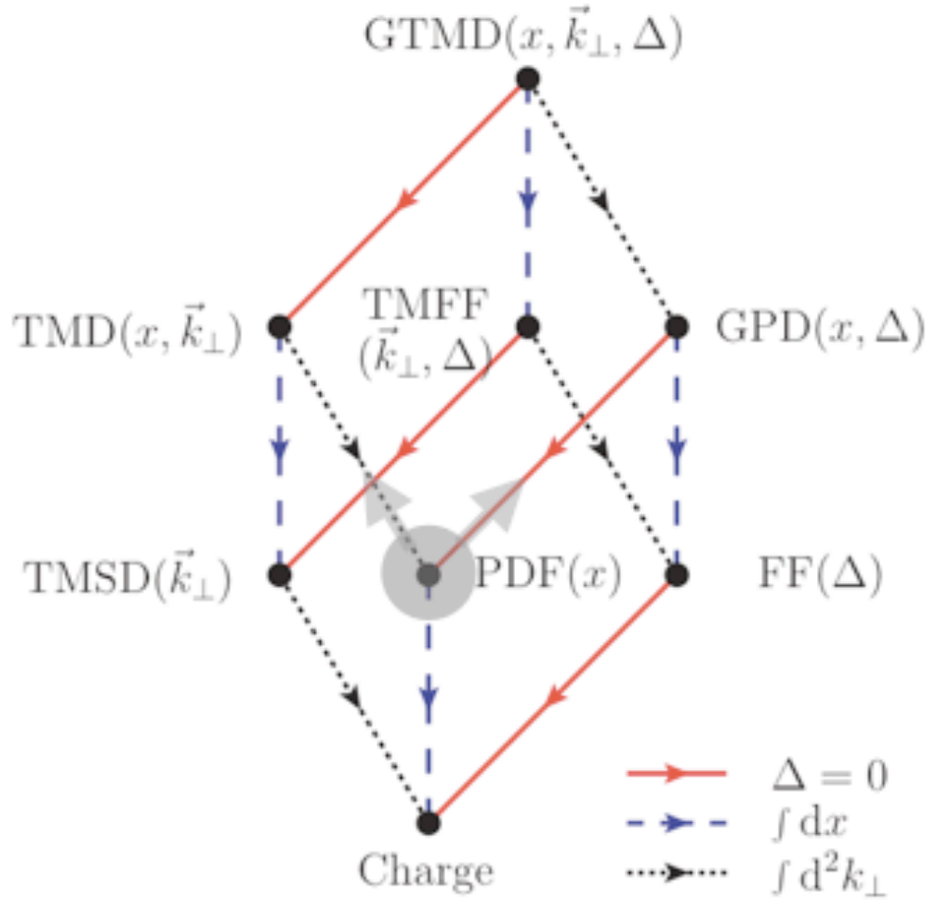
Semi-inclusive measurements will vastly advance insights in the polarized quark sea,

come with particle-identification challenges,

Charged-current measurements provide unique opportunities, e.g. g_5

U.S.-based EIC - beyond collinear parton distributions





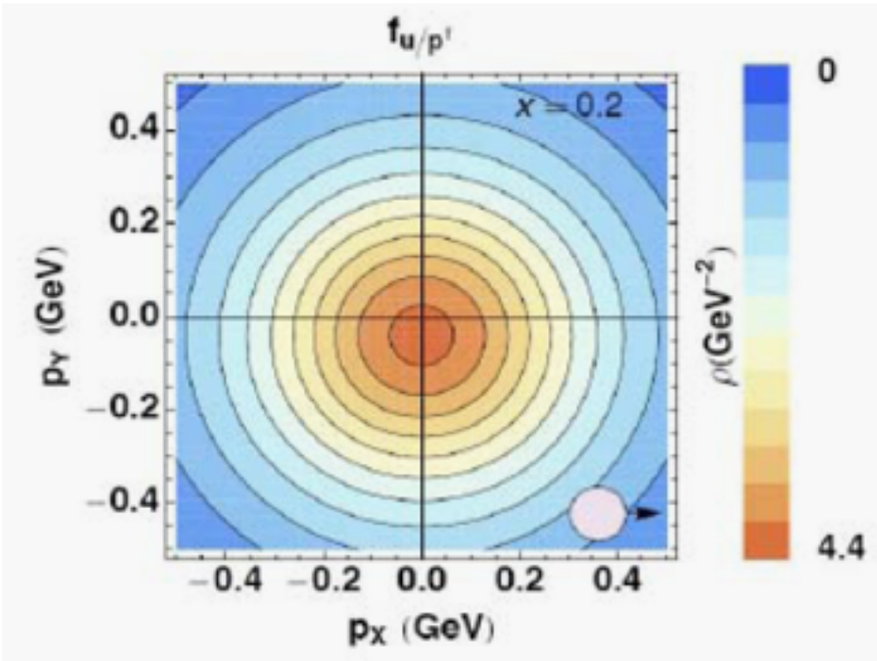
Lorce, Pasquini, Vanderhaeghen

Semi-inclusive measurements, together with exclusive measurements, are key to
probe beyond collinear parton distributions,
image the nucleon — orbital angular momenta.

U.S.-based EIC - Two Approaches to Imaging

TMDs

2+1 D picture in **momentum space**

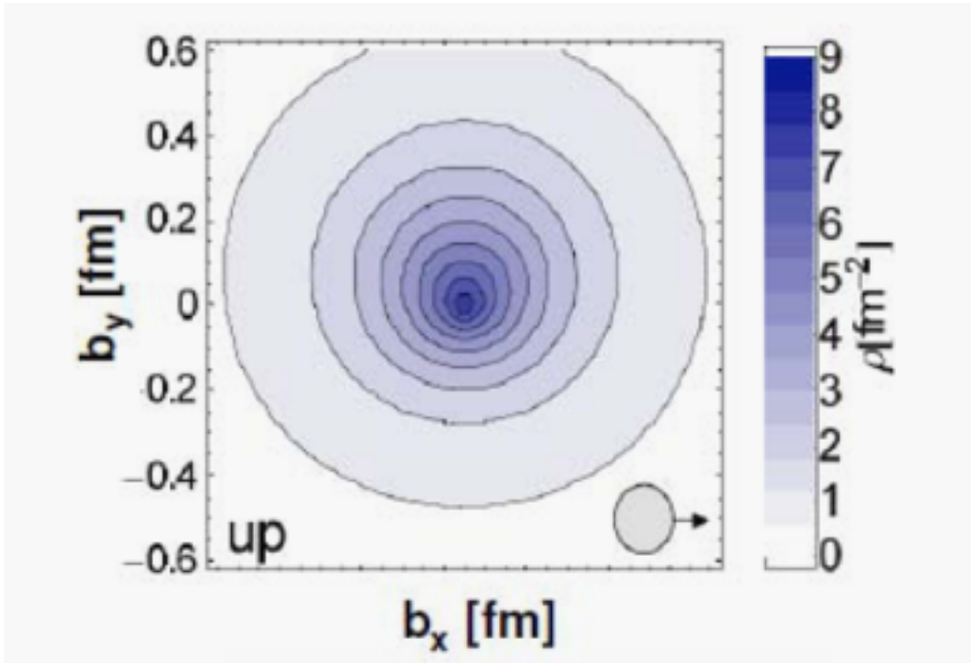


Bacchetta, Conti, Radici

- intrinsic transverse motion
- spin-orbit correlations = indicator of OAM
- non-trivial factorization
- accessible in SIDIS, DY (and at RHIC)

GPDs

2+1 D picture in **impact-parameter space**

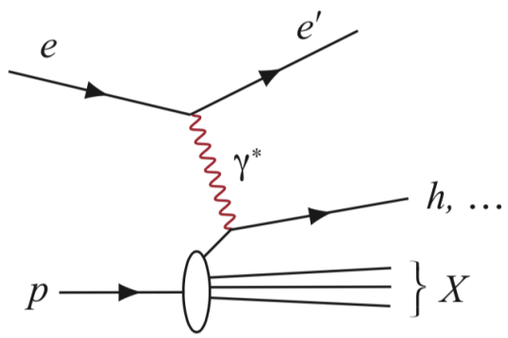


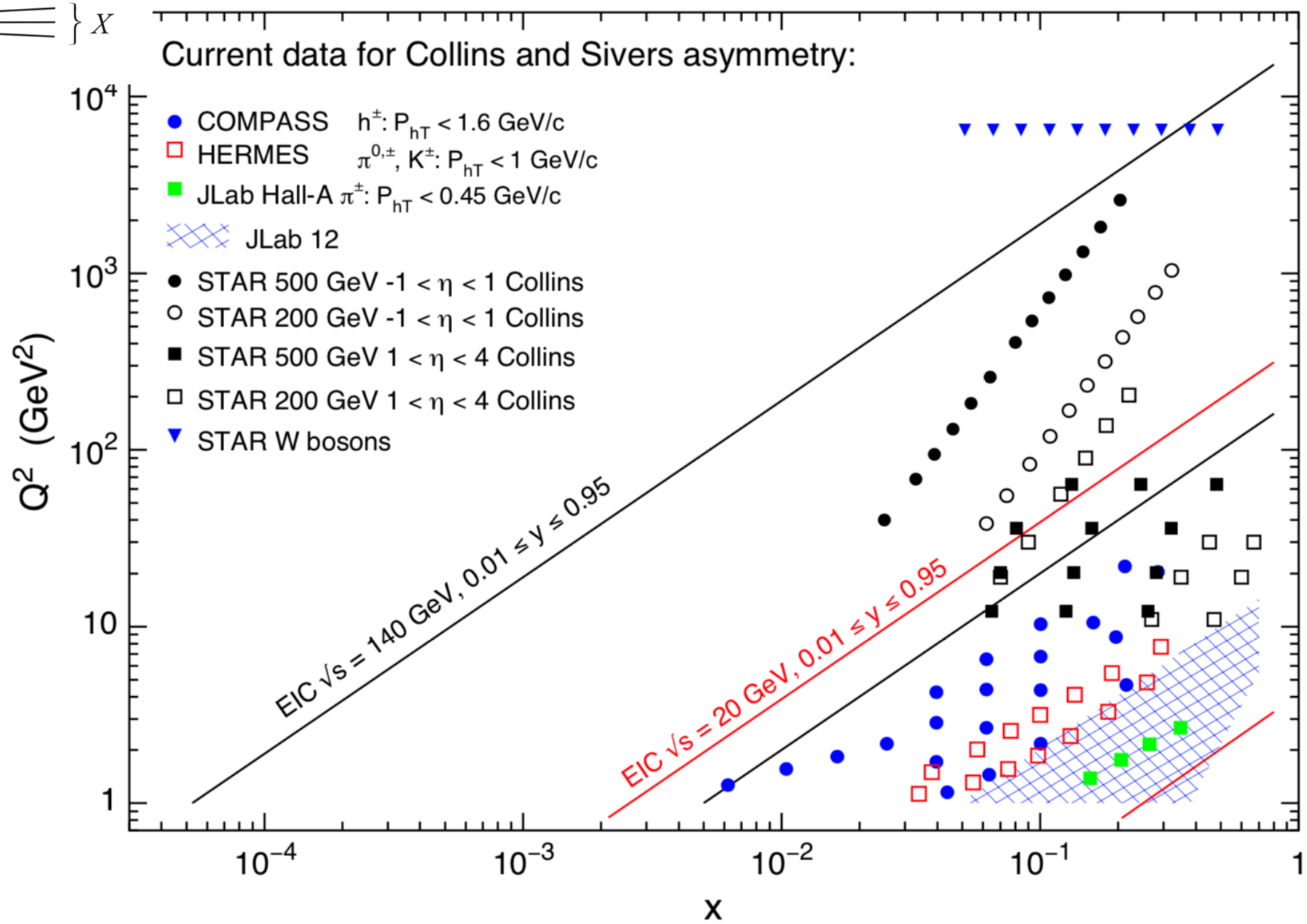
QCDSF collaboration

- collinear but long. momentum transfer
- indicator of OAM; access to Ji's total $J_{q,g}$
- existing factorization proofs
- DVCS, exclusive vector-meson production

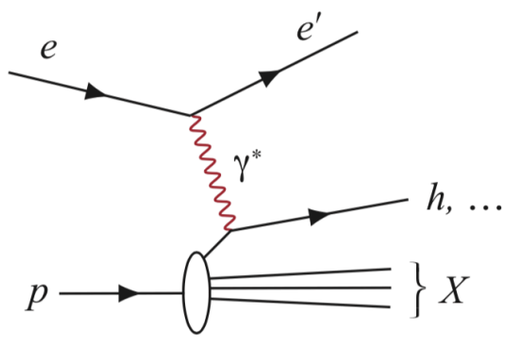
currently no direct, model-independent relation known between TMDs and GPDs

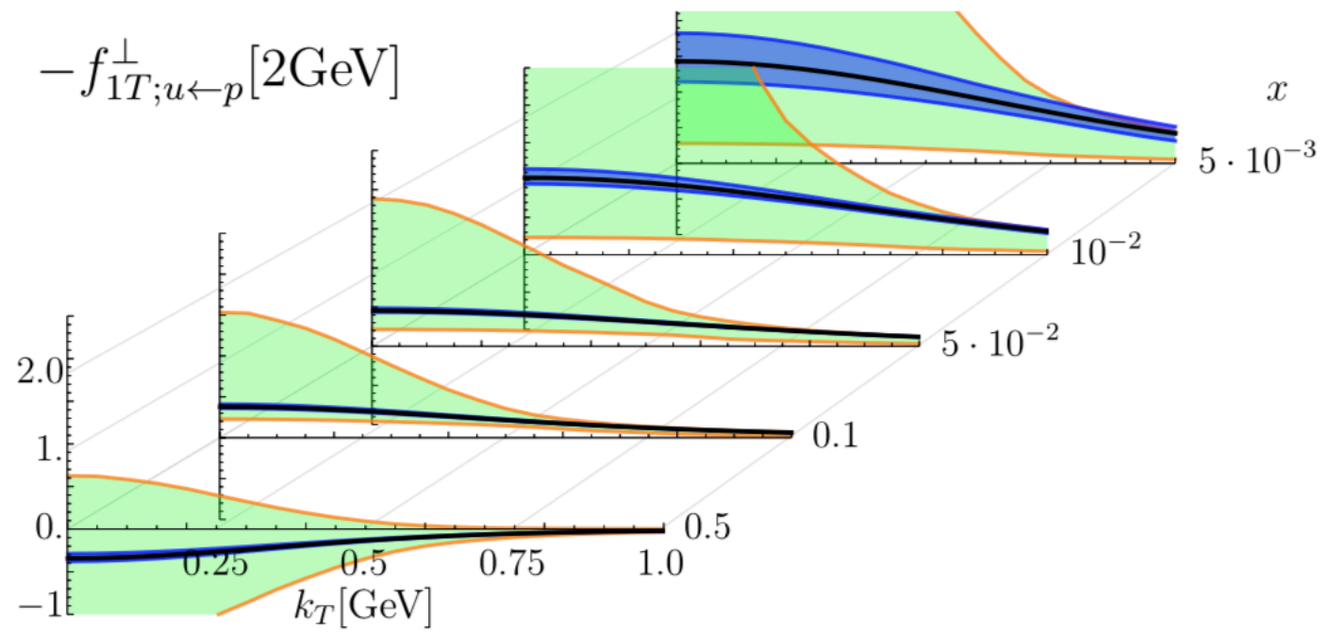
U.S.-based EIC - polarized semi-inclusive DIS

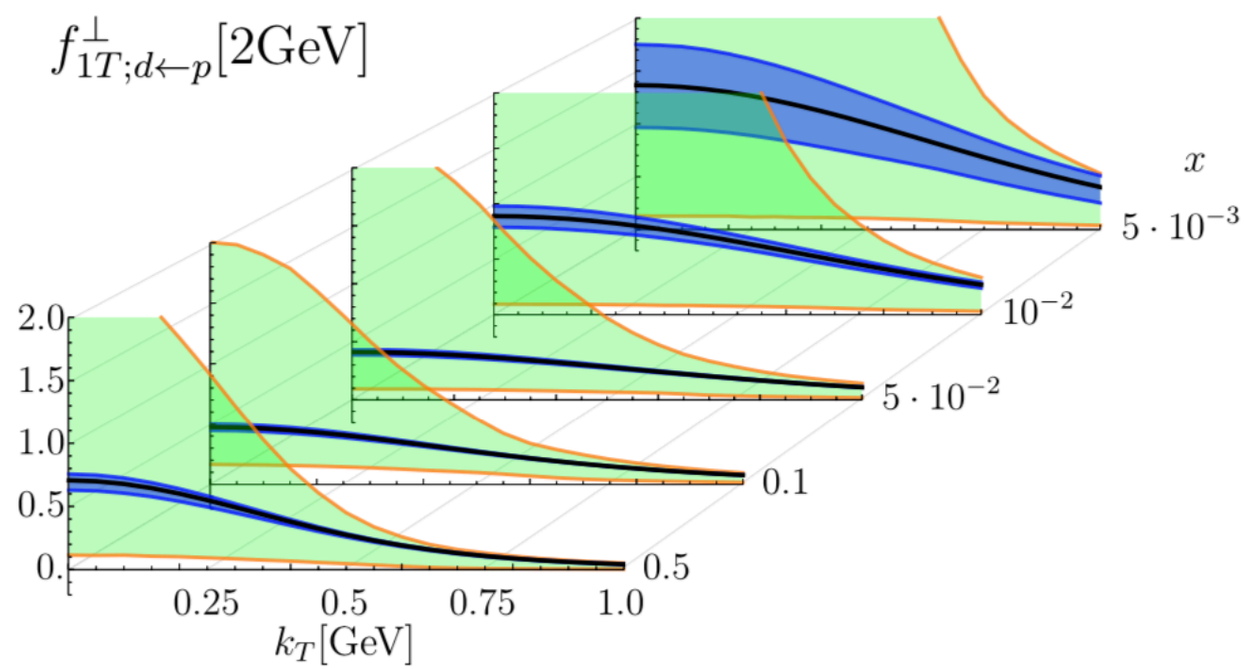




U.S.-based EIC - polarized semi-inclusive DIS

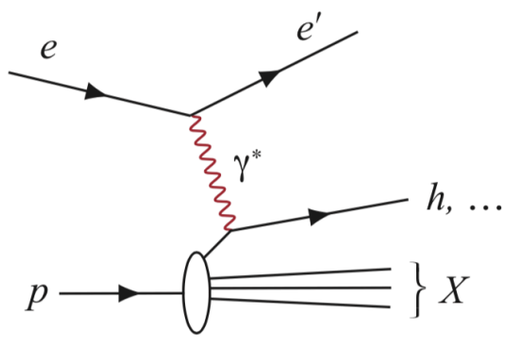


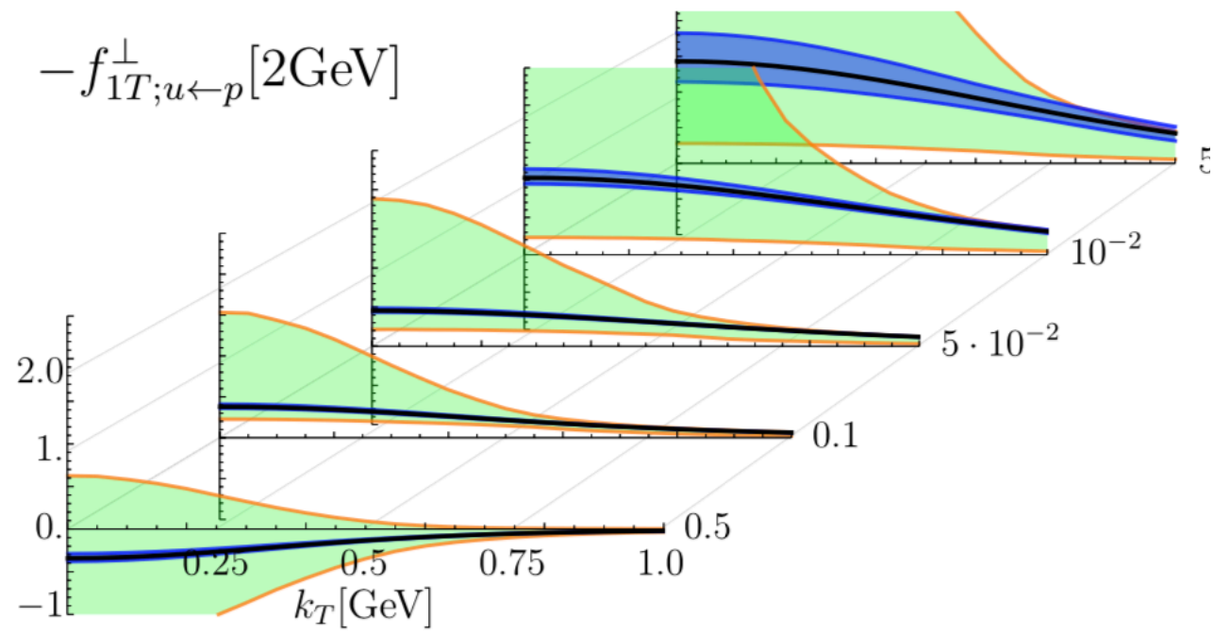


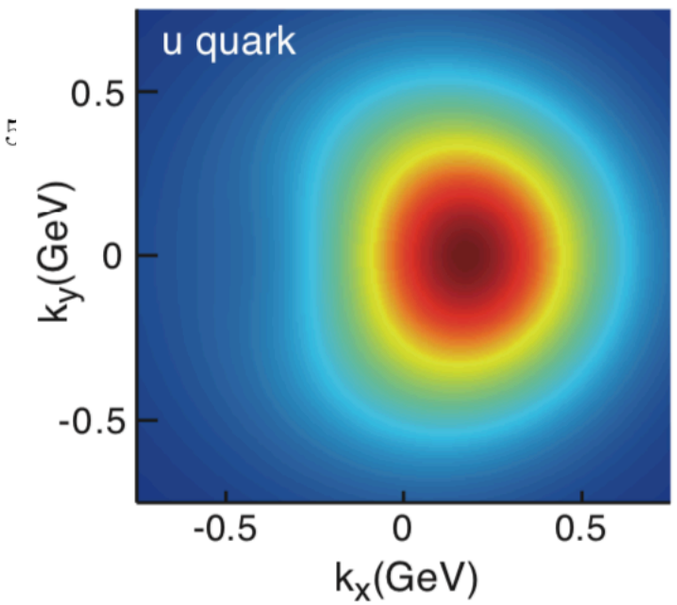


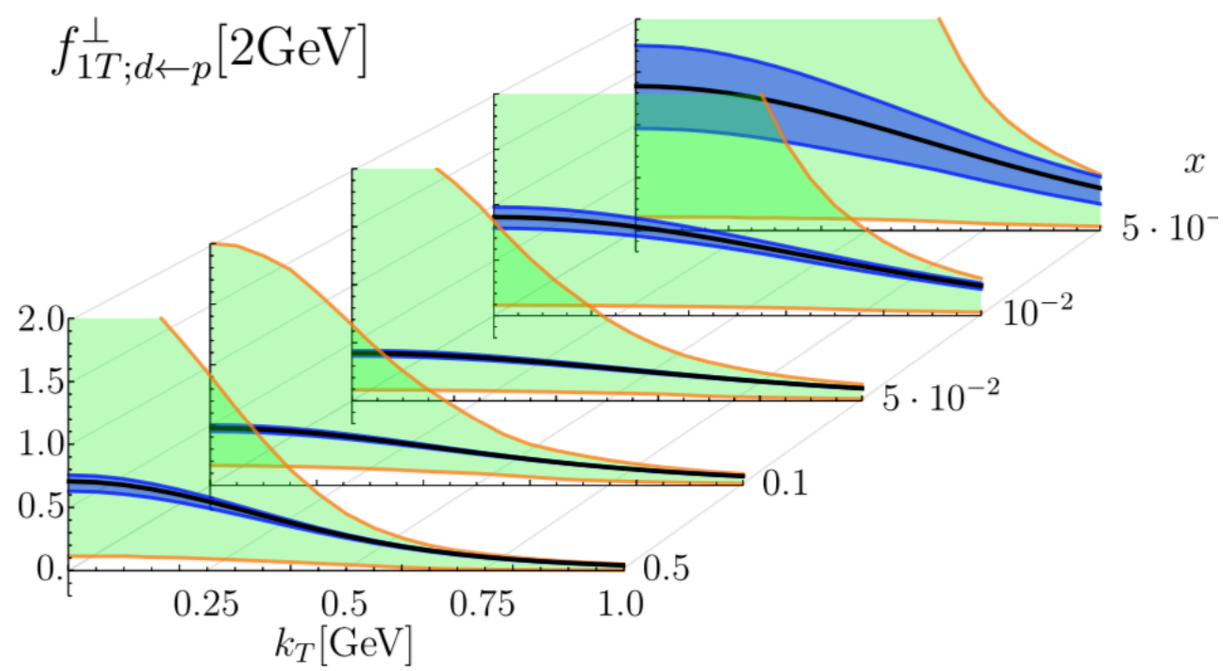
Imaging nucleon (spin) is a major EIC objective - illustrated here is the impact on the up and down Sivers' functions

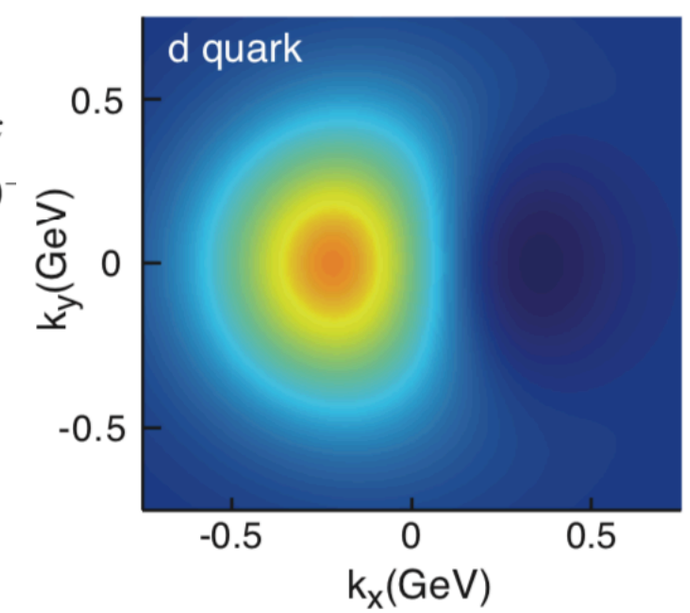
U.S.-based EIC - polarized semi-inclusive DIS





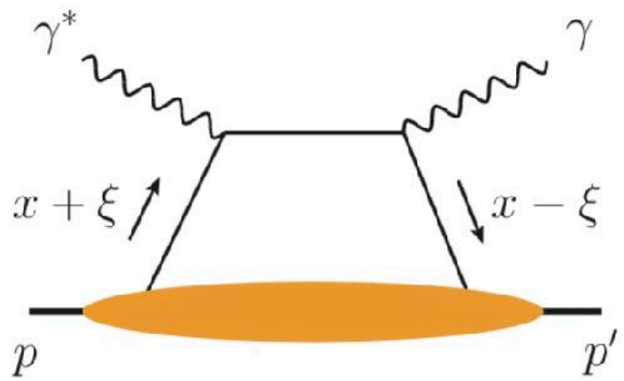


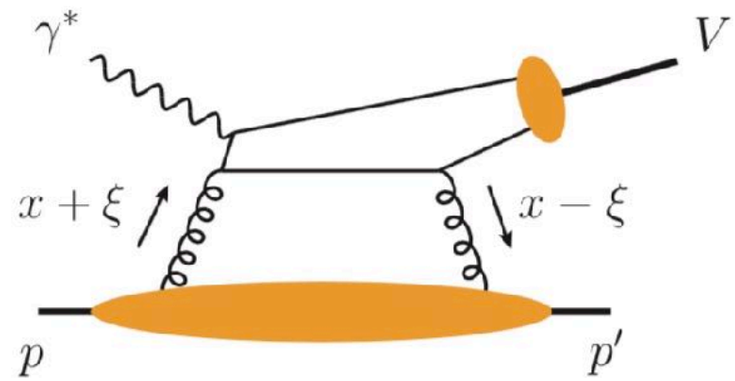


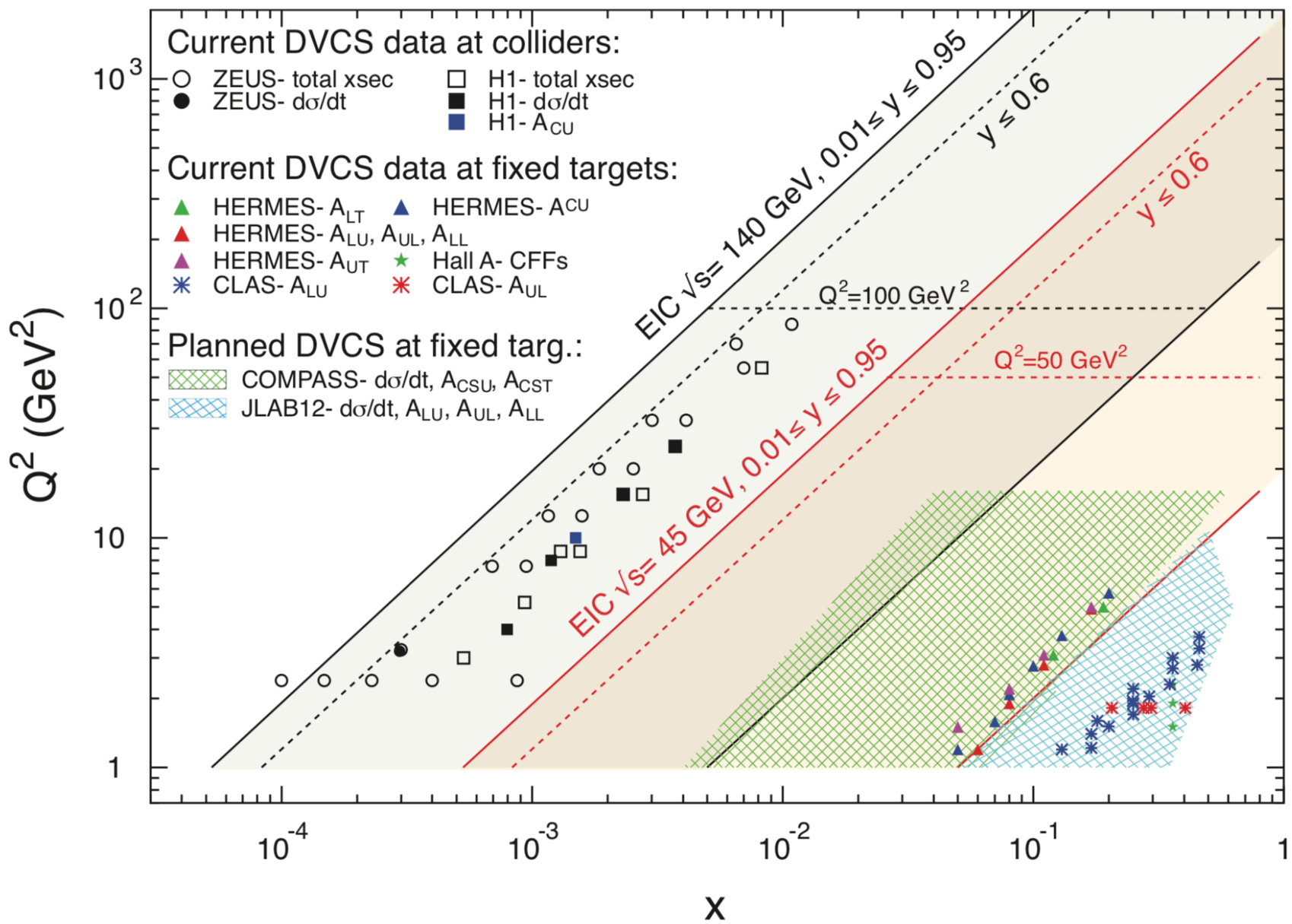


Imaging nucleon (spin) is a major EIC objective — well into the gluon dominated regime.

EIC - DVCS, DVMP, and Imaging





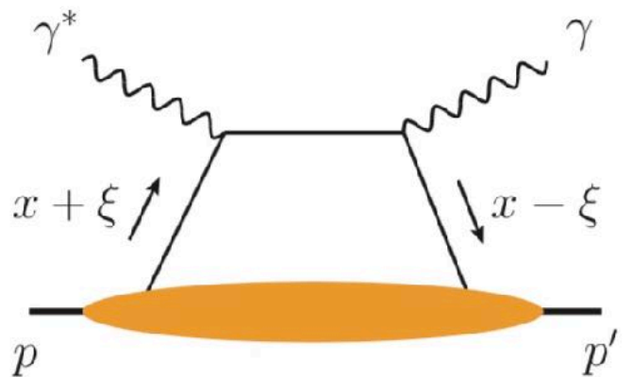


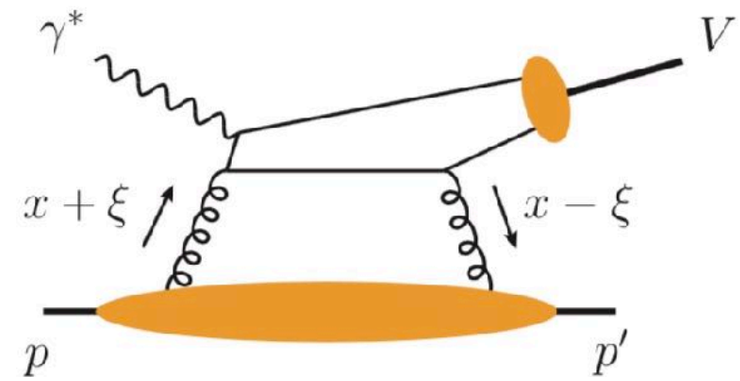
Luminosity,
Polarization,
Nuclei,
Detectors,

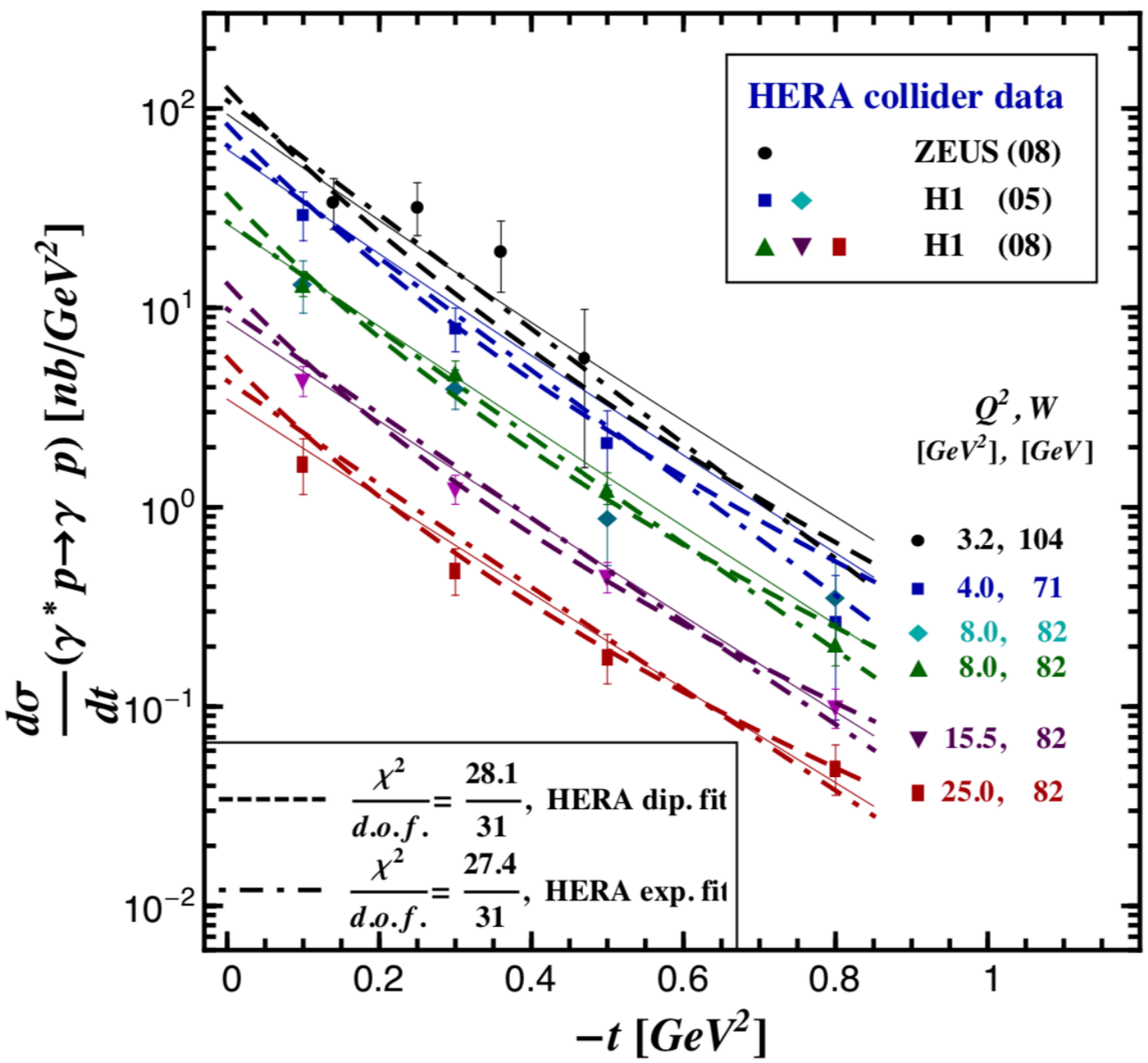
Less so about x, Q^2 range

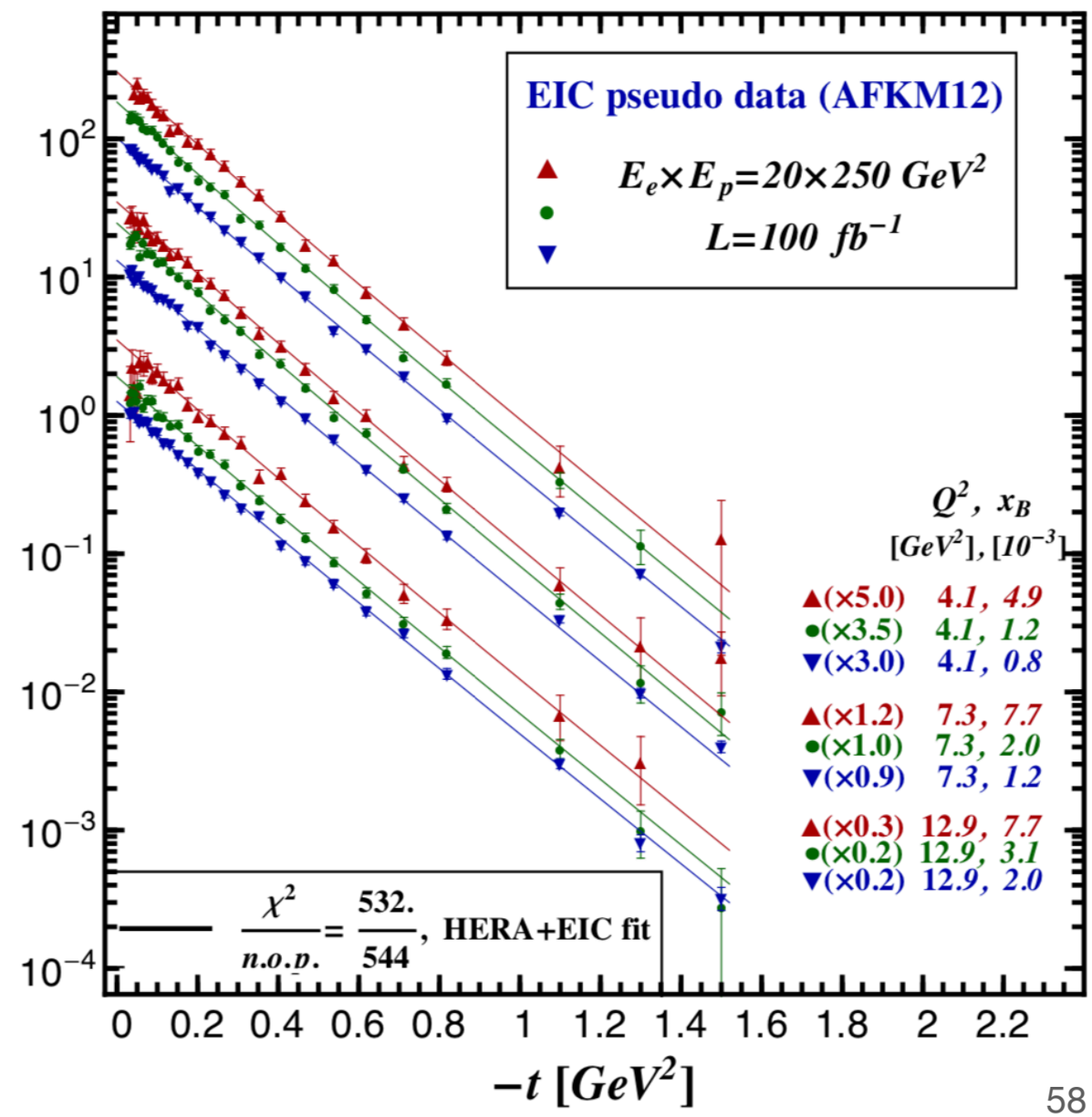
t, however, …

EIC - DVCS, DVMP, and Imaging

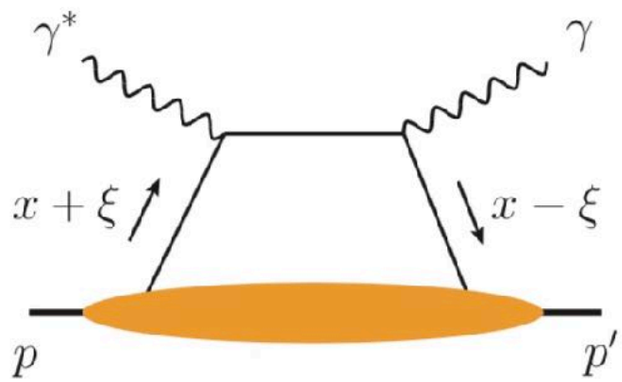


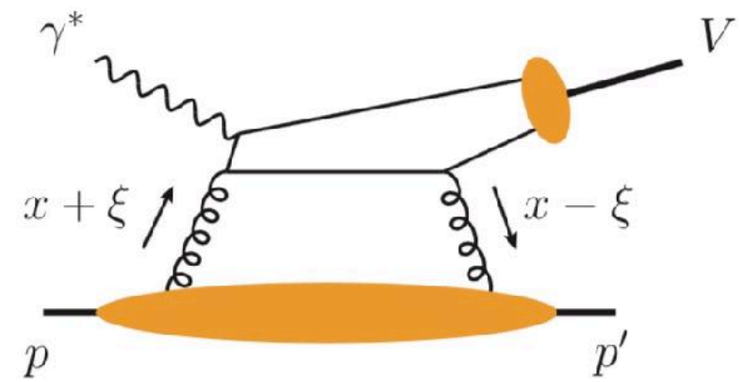


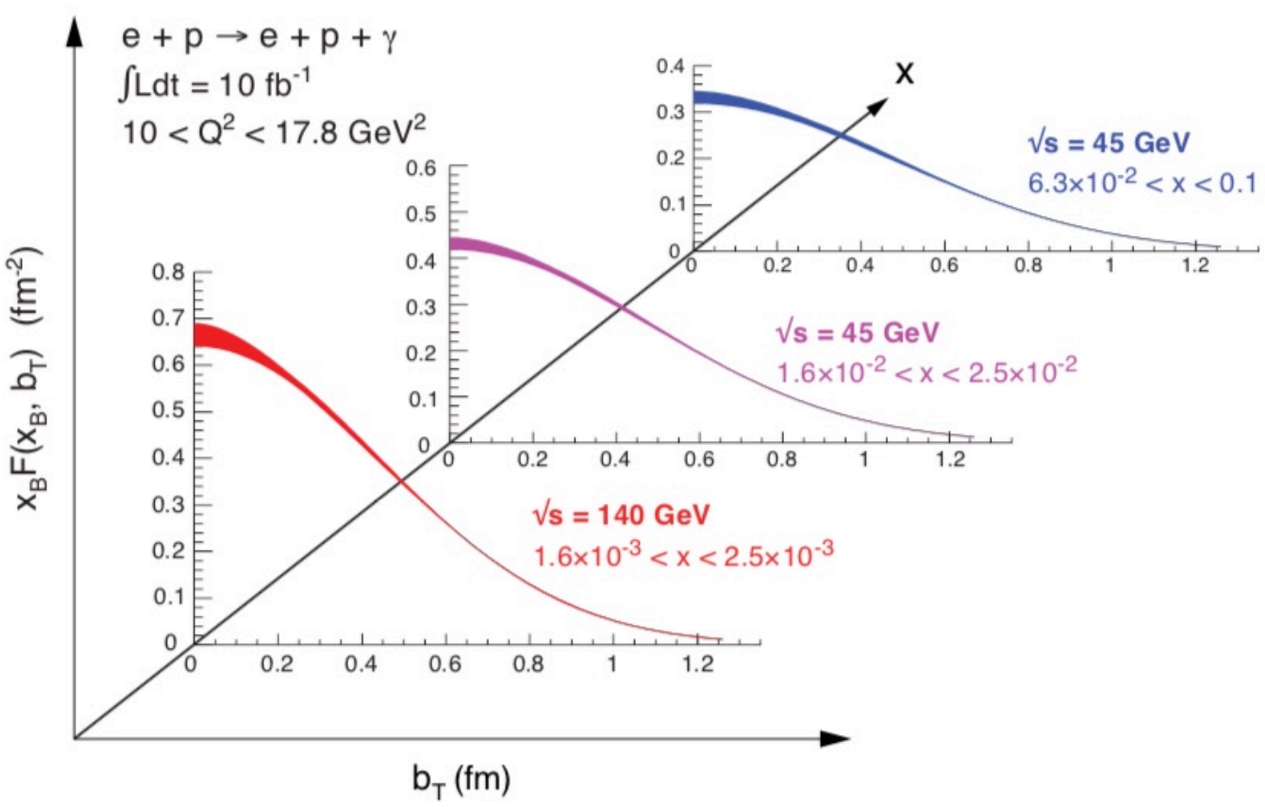


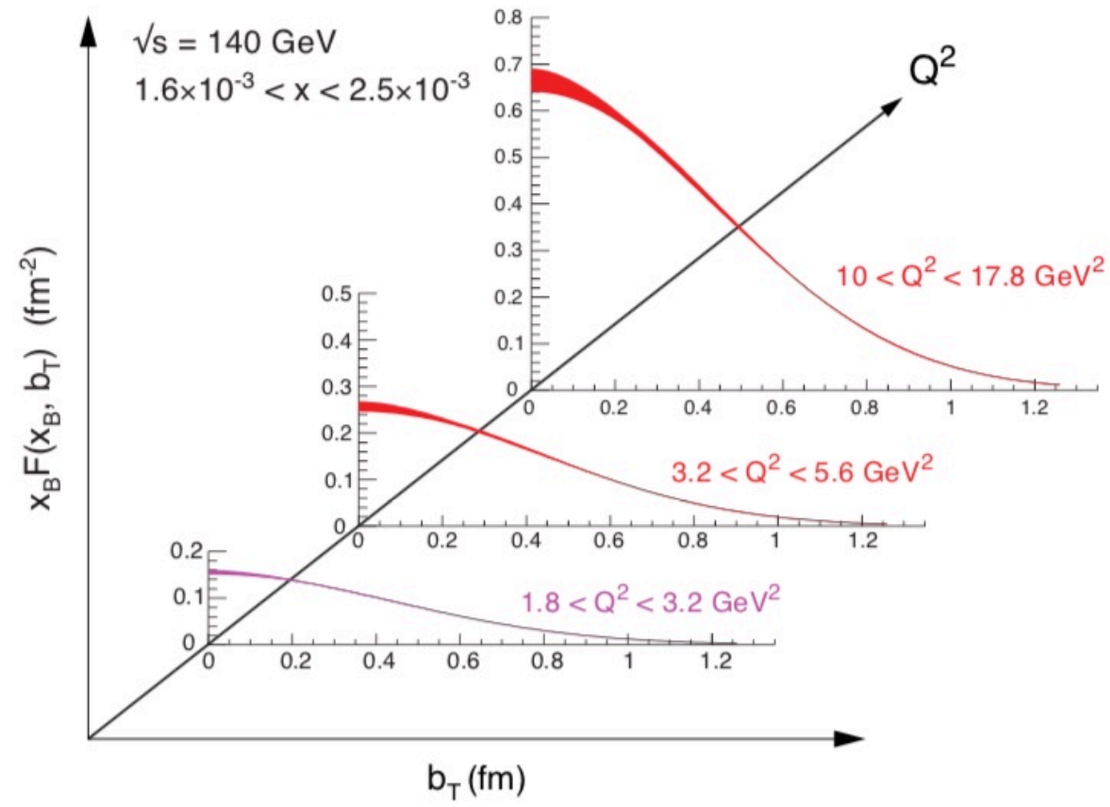


EIC - DVCS, DVMP, and Imaging







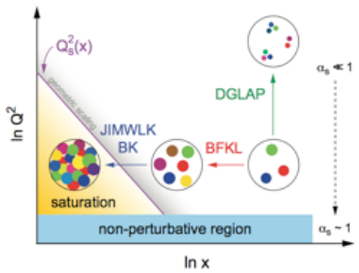


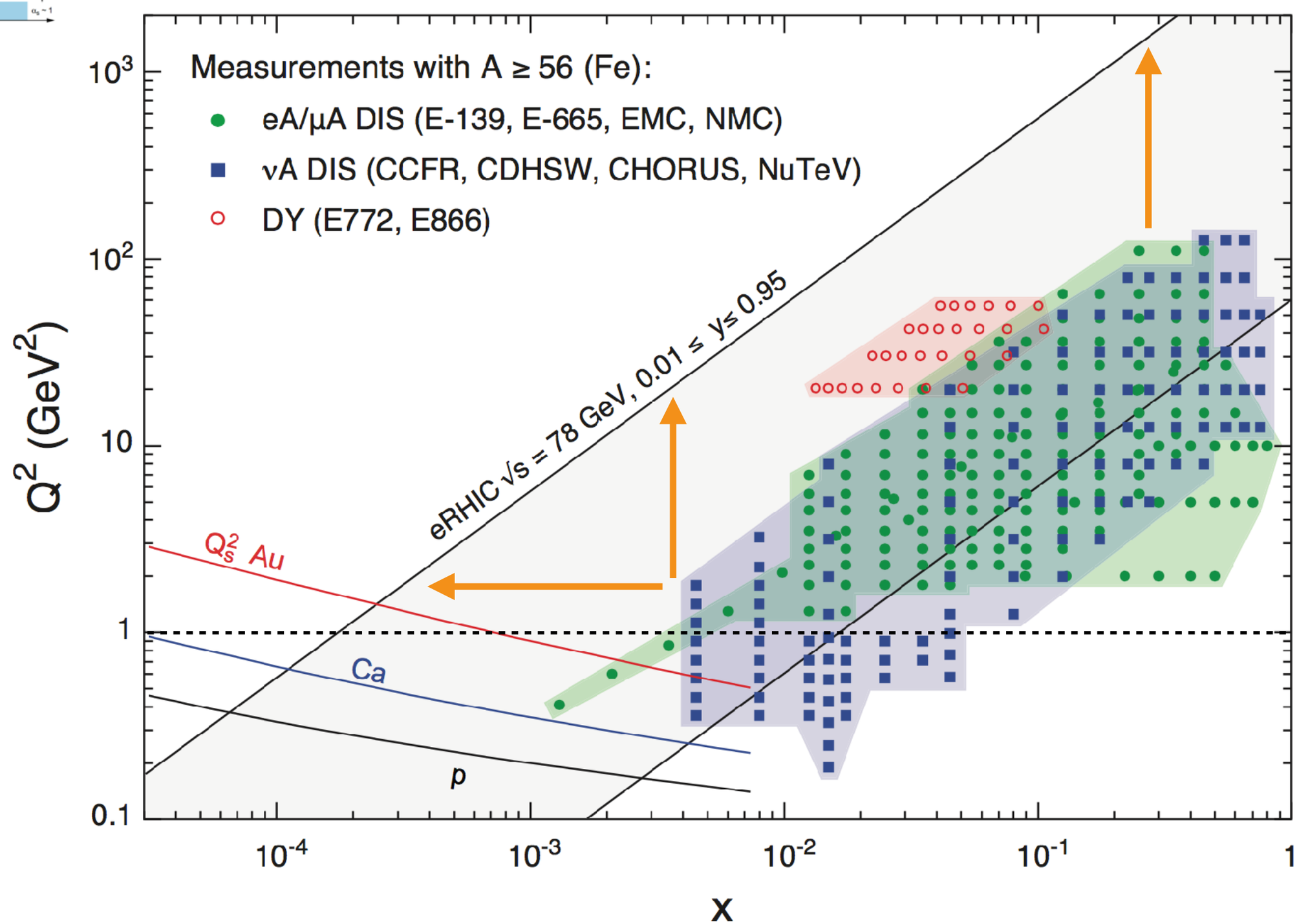
x-dependence at fixed Q^2

Q^2-dependence at fixed x

U.S.-based EIC - Nuclei

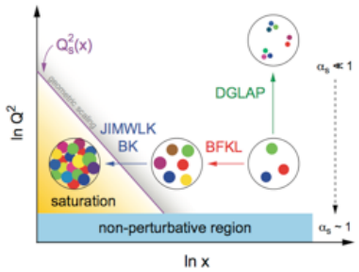
U.S.-based EIC - The Nuclear Landscape

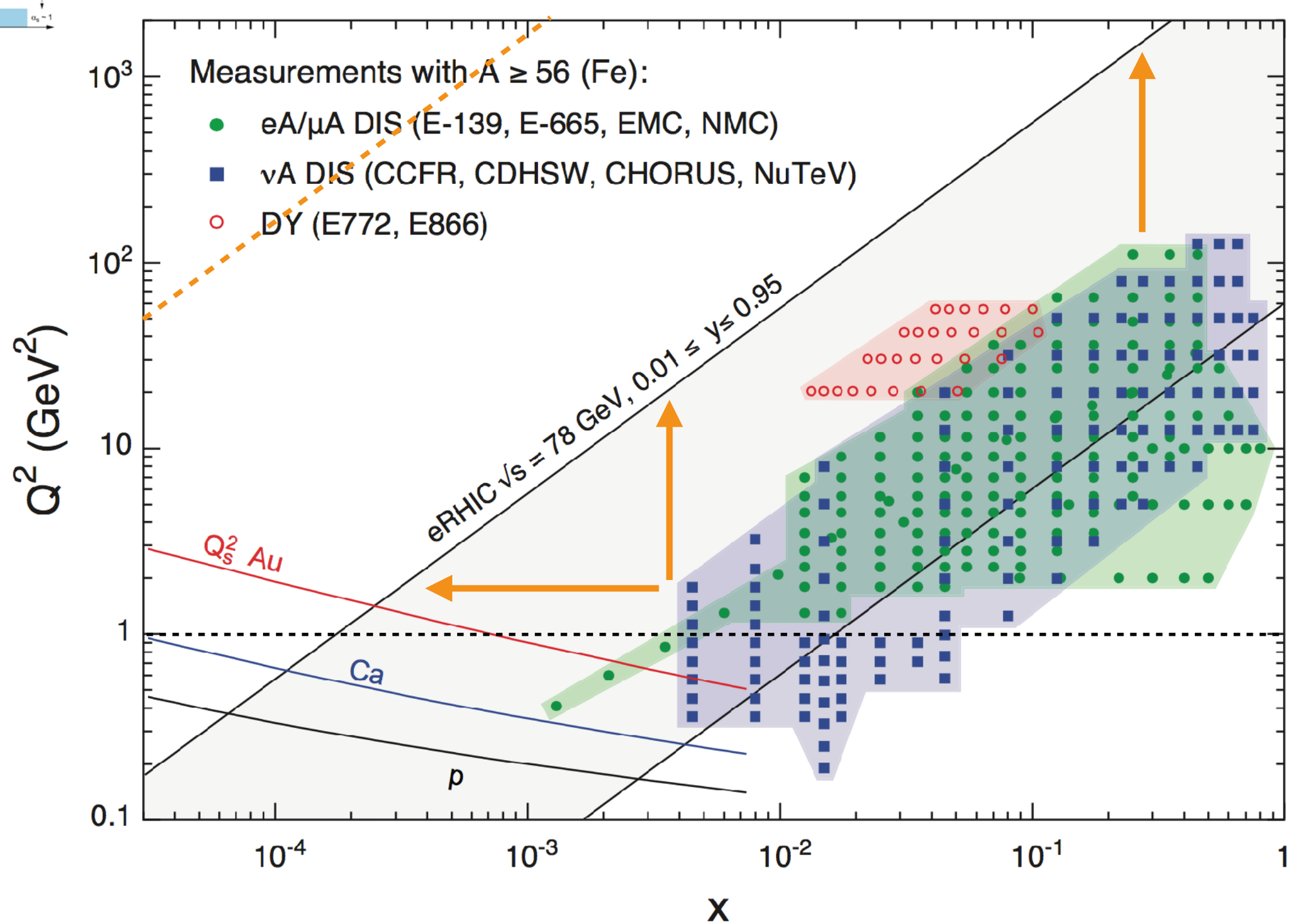




Complementarity with ongoing and future RHIC and LHC measurements,

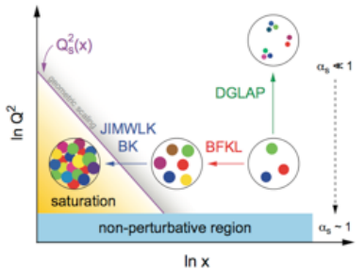
U.S.-based EIC - The Nuclear Landscape





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

U.S.-based EIC - The Nuclear Landscape



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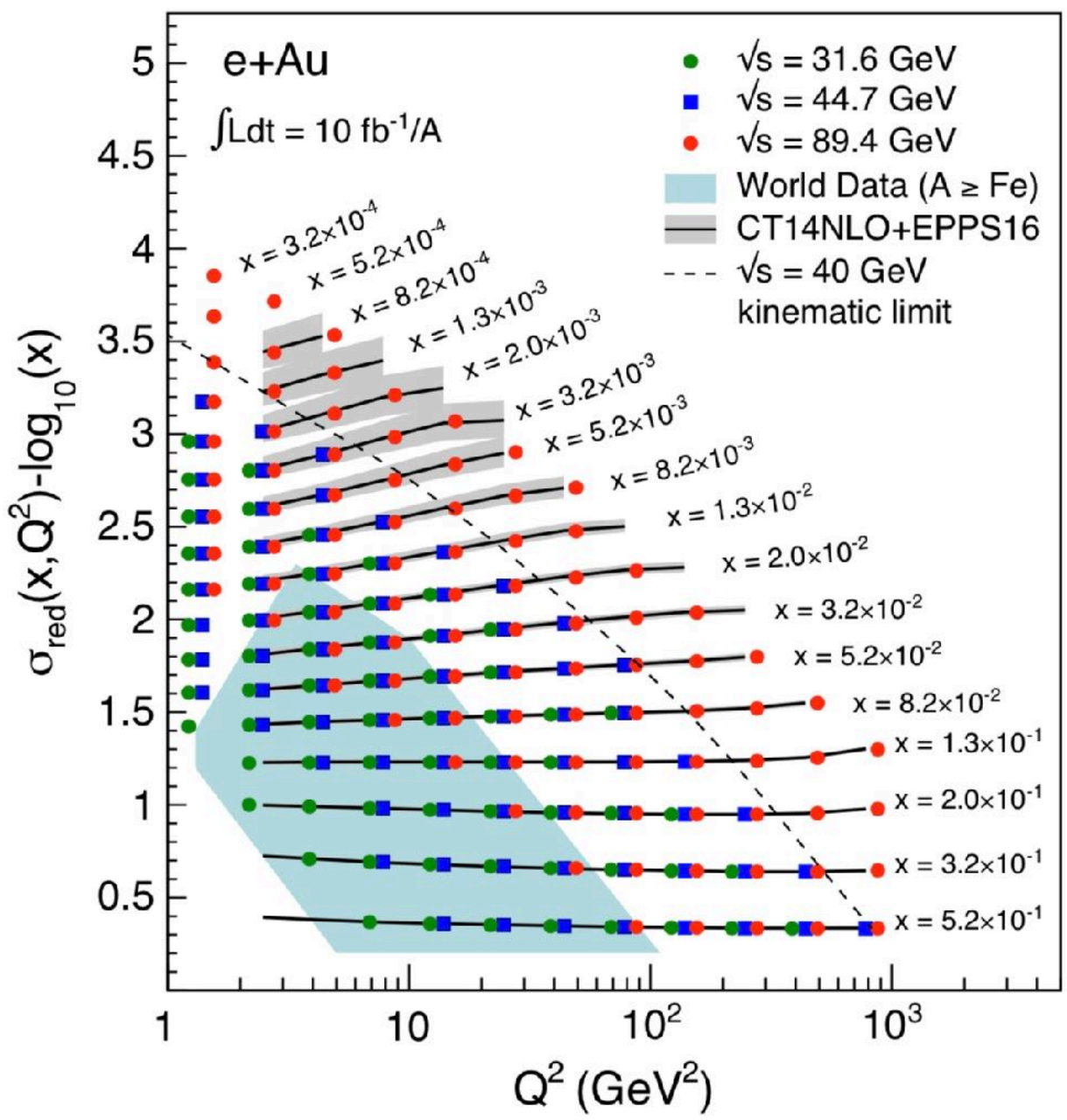
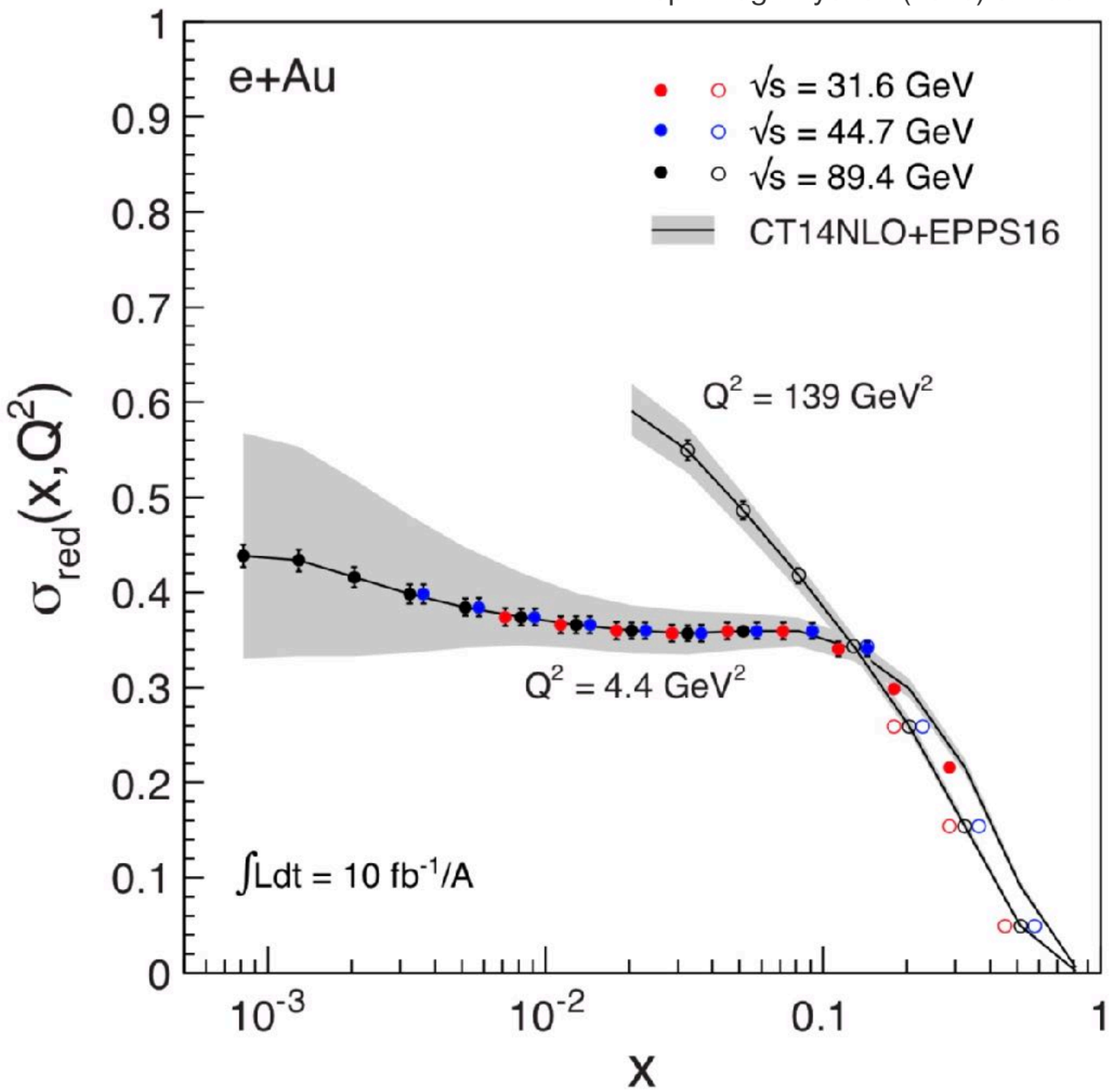
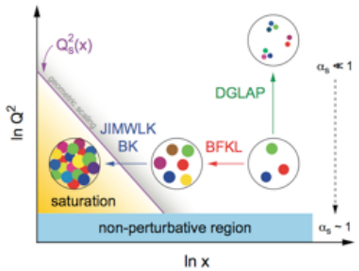




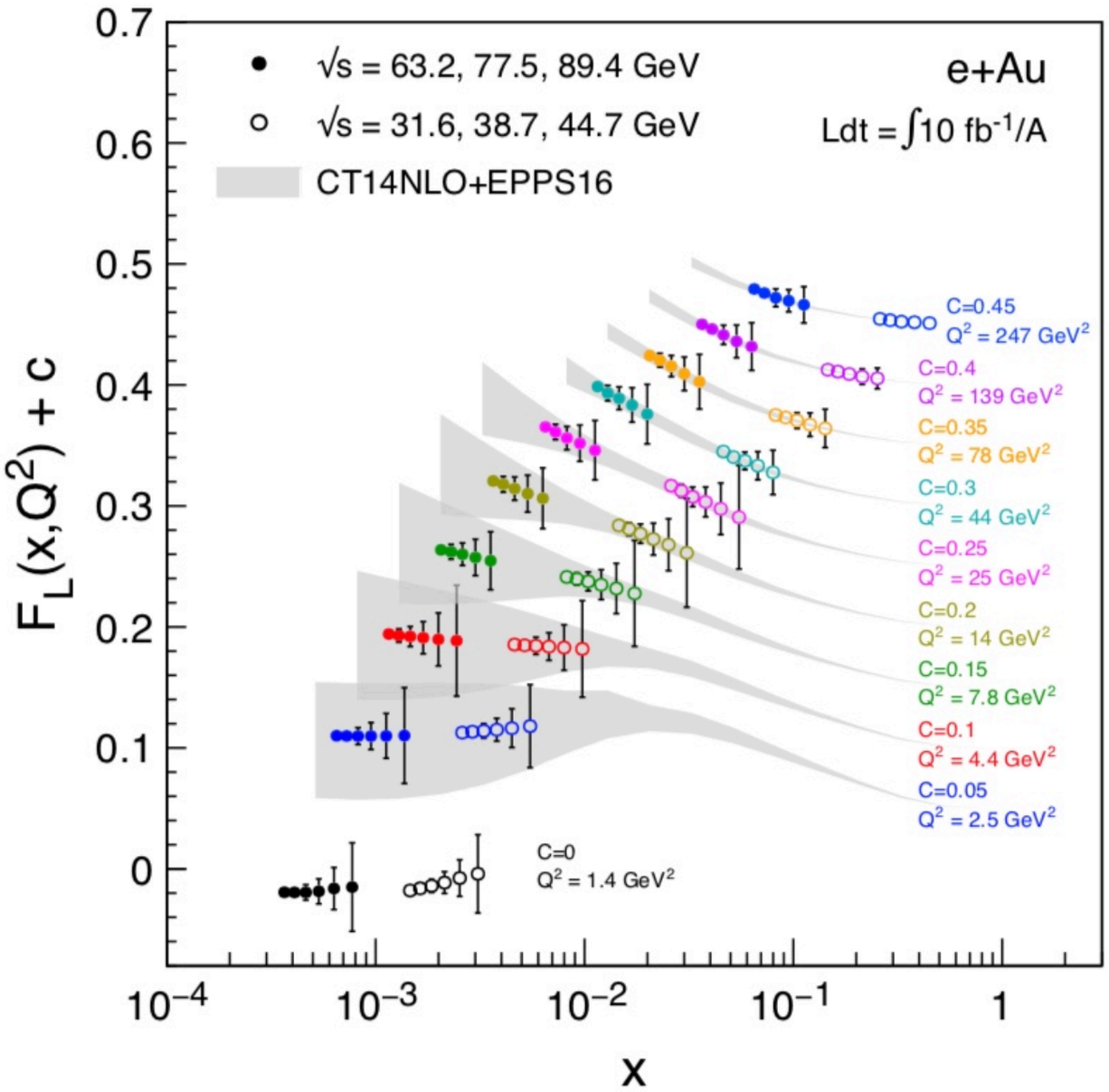
$$\sigma_{\text{reduced}} = F_2(x,Q^2) - \frac{y}{1+(1-y)^2} F_L(x,Q^2)$$

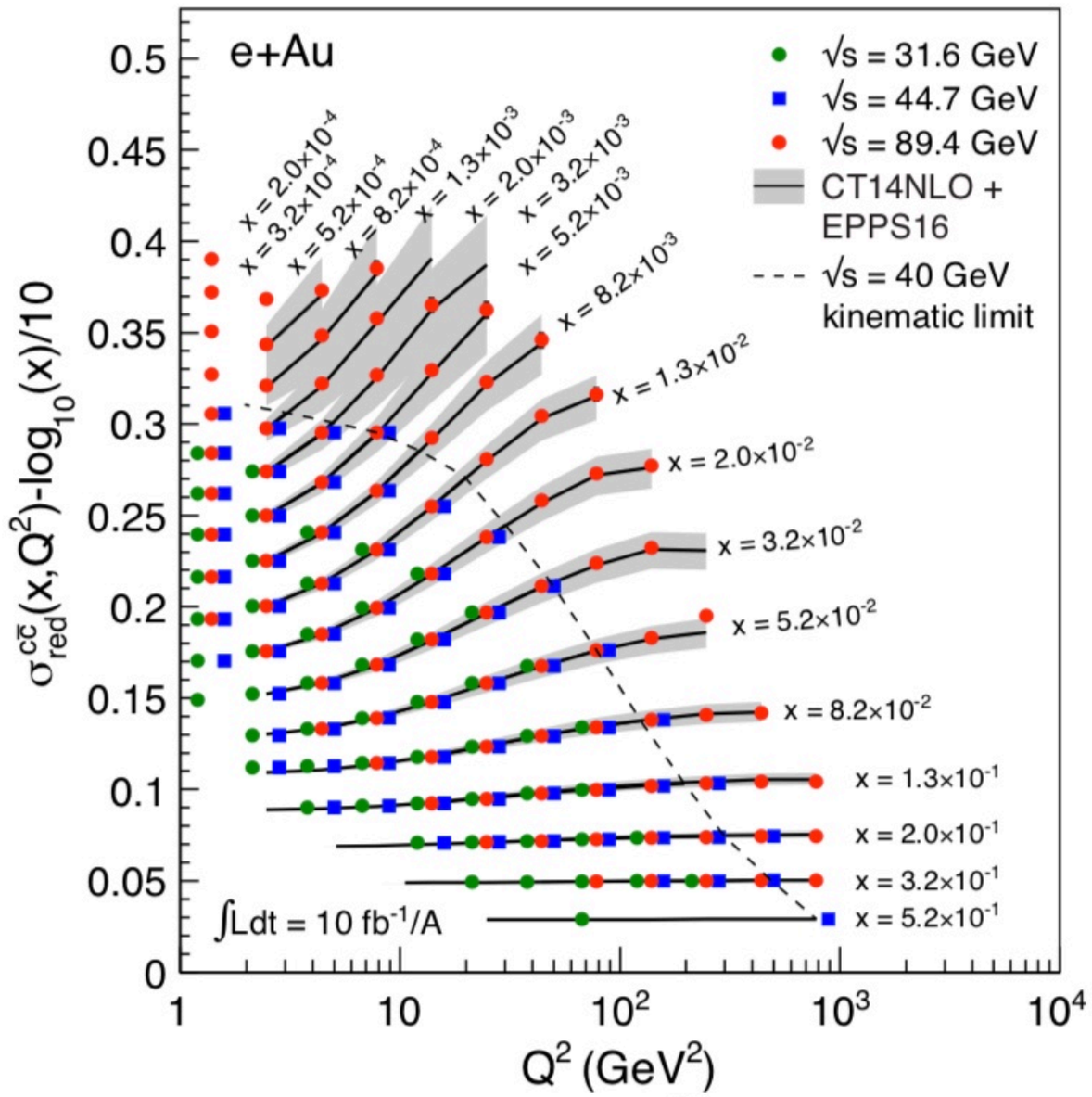
Impactful baseline inclusive measurements.

U.S.-based EIC - The Nuclear Landscape



Rept.Prog.Phys. 82 (2019) 024301

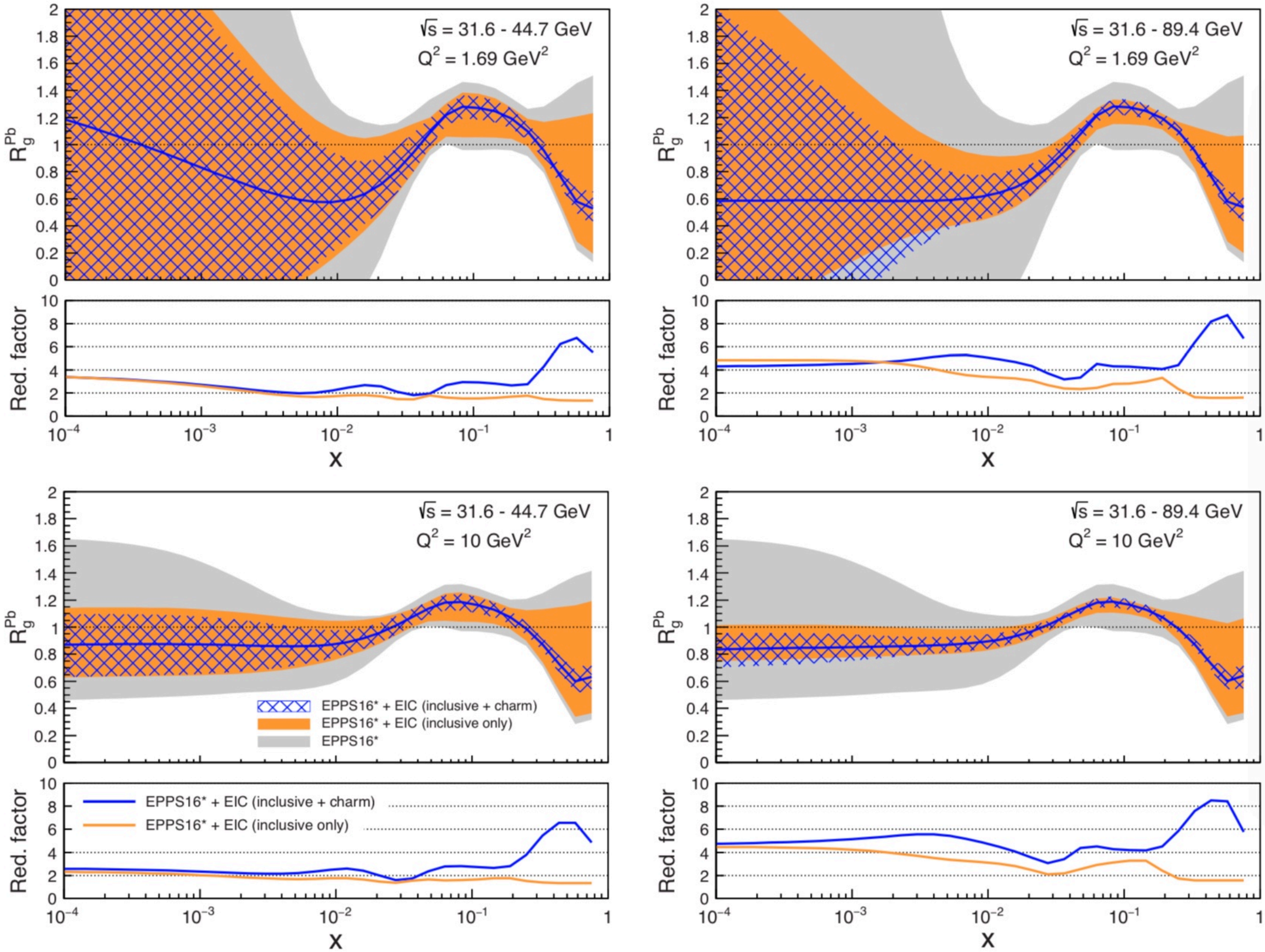




Clearly visible impact also beyond baseline inclusive measurements with "Rosenbluth separation" and semi-inclusive measurements.

Nuclear gluon will be probed sensitively with complementary channels.

U.S.-based EIC - The Nuclear Landscape



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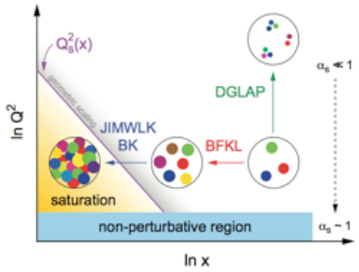
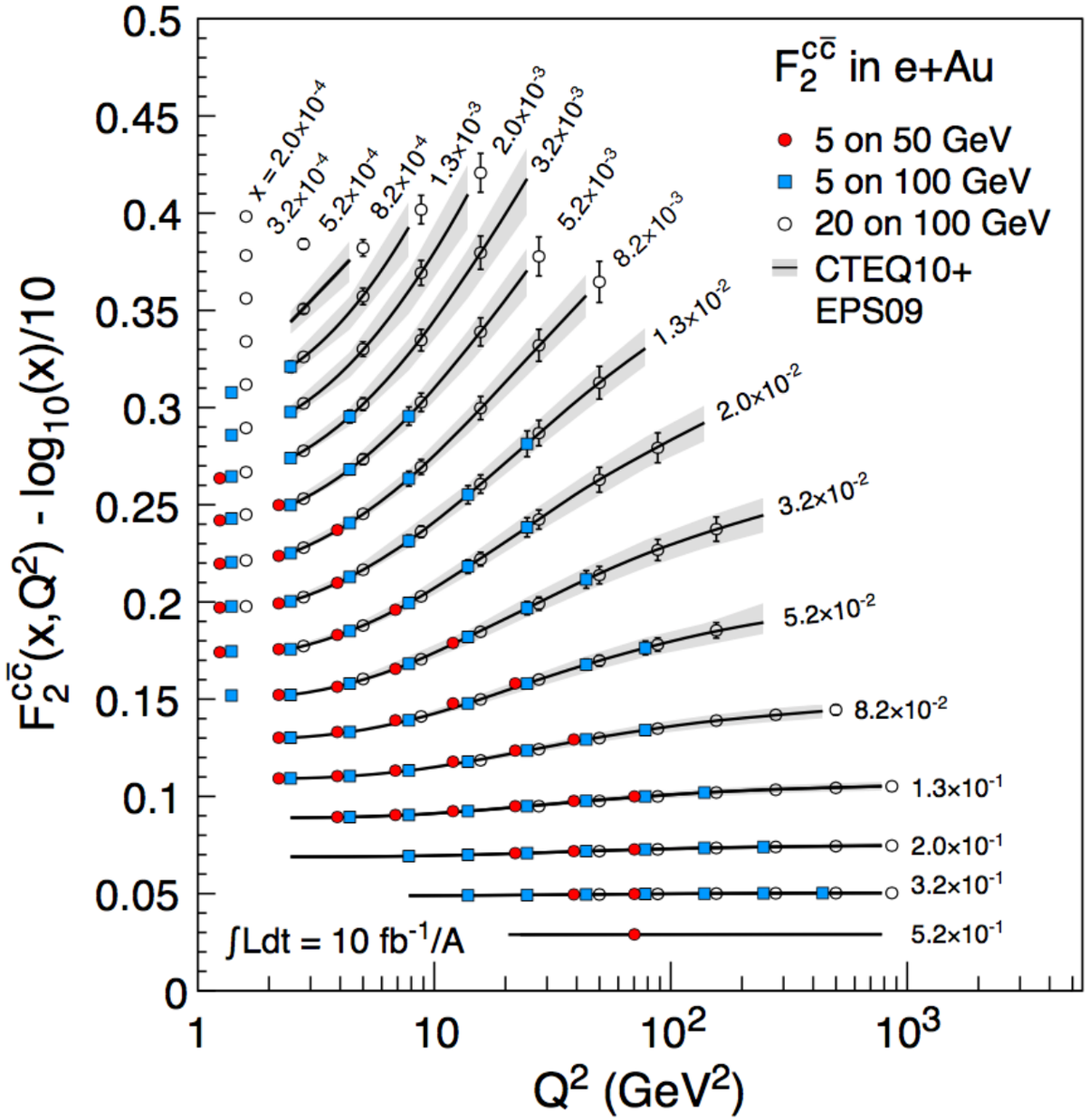
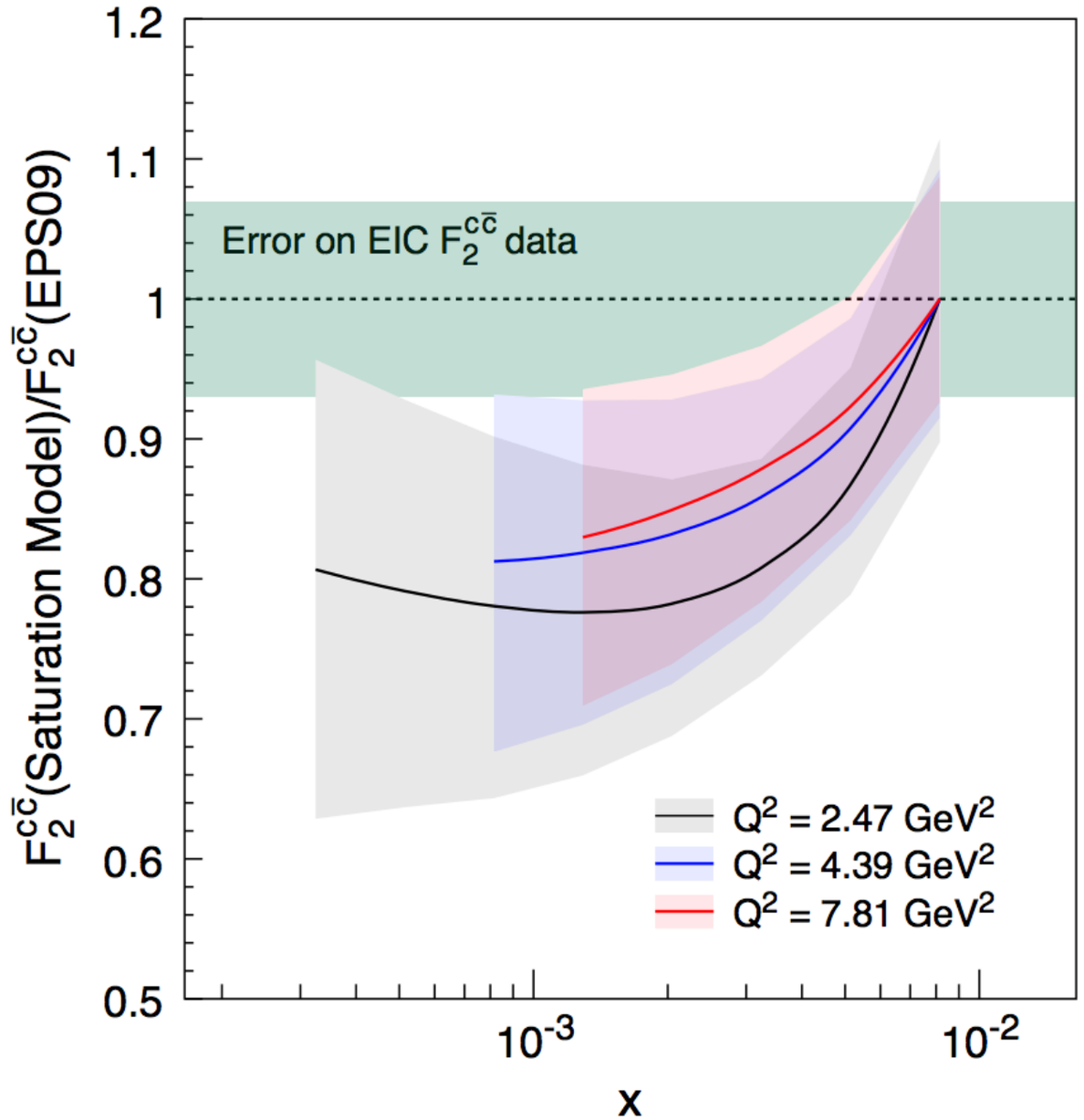


EIC - Saturation from PDFs alone?

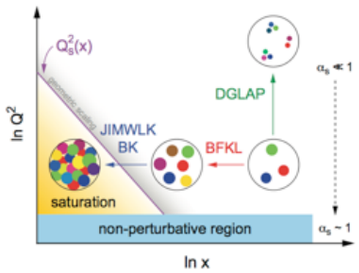


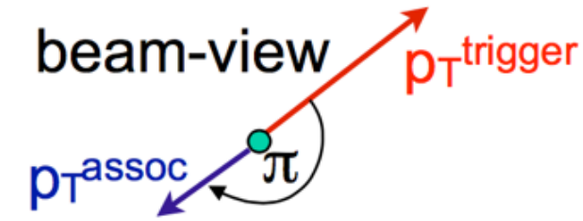


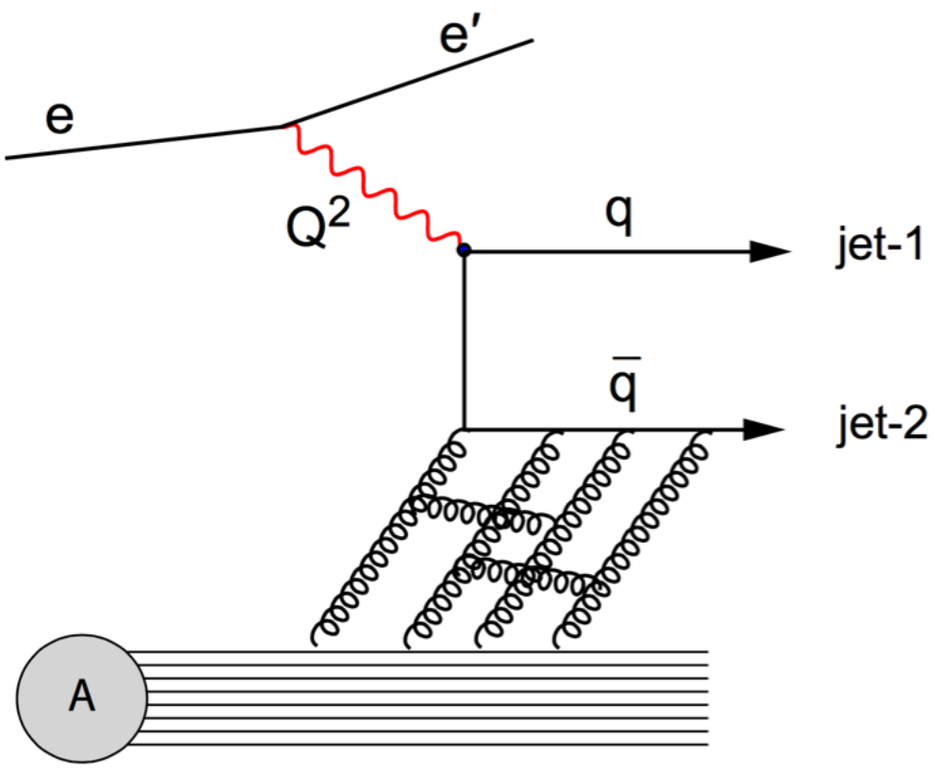
Theory will undoubtedly develop nPDFs much further;
NNLO, HT, resummations, in-medium, …

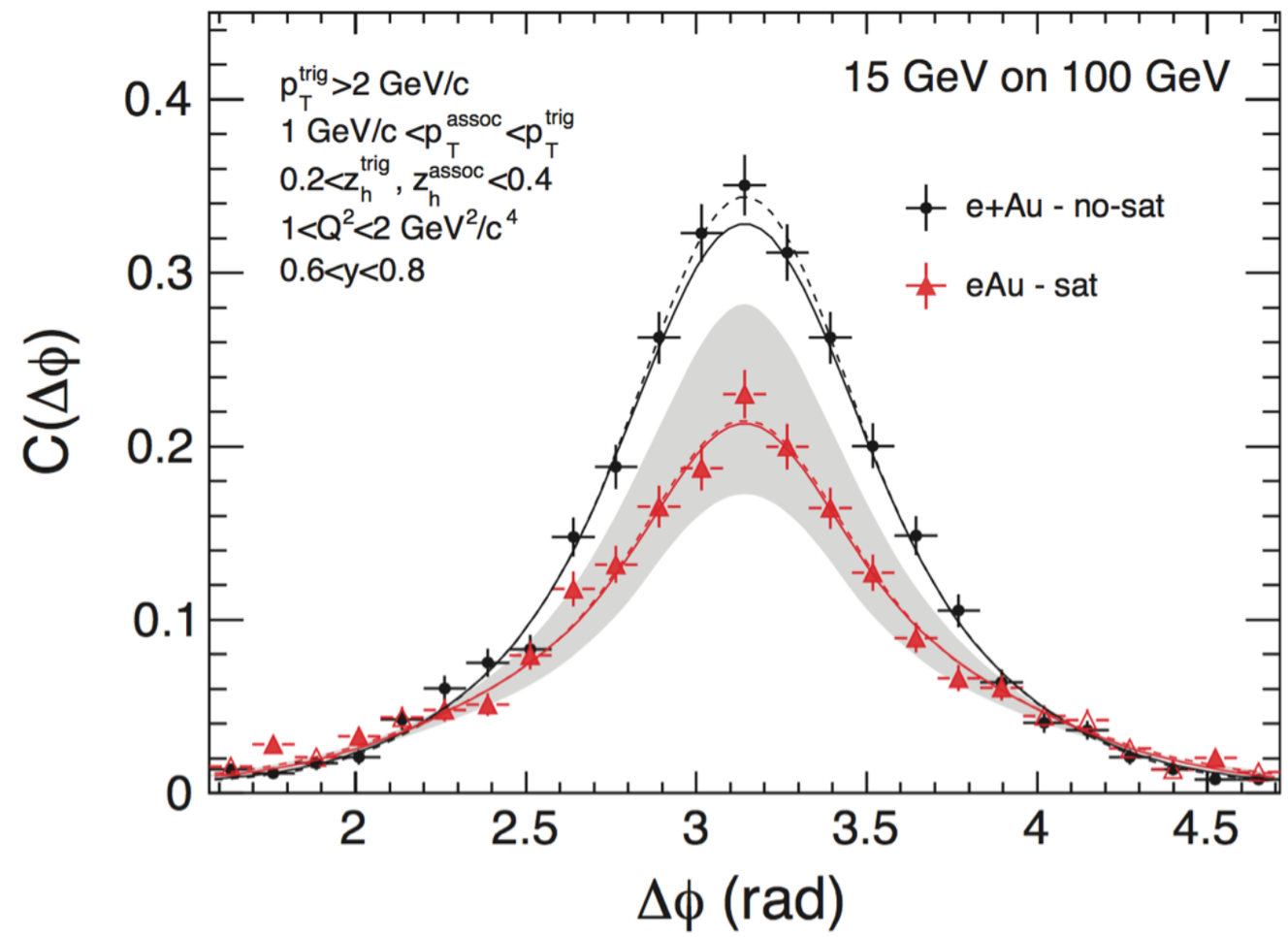
***Almost certainly no substitute* for thinking *outside* the (n)PDF…**

EIC - Dihadrons to probe Saturation









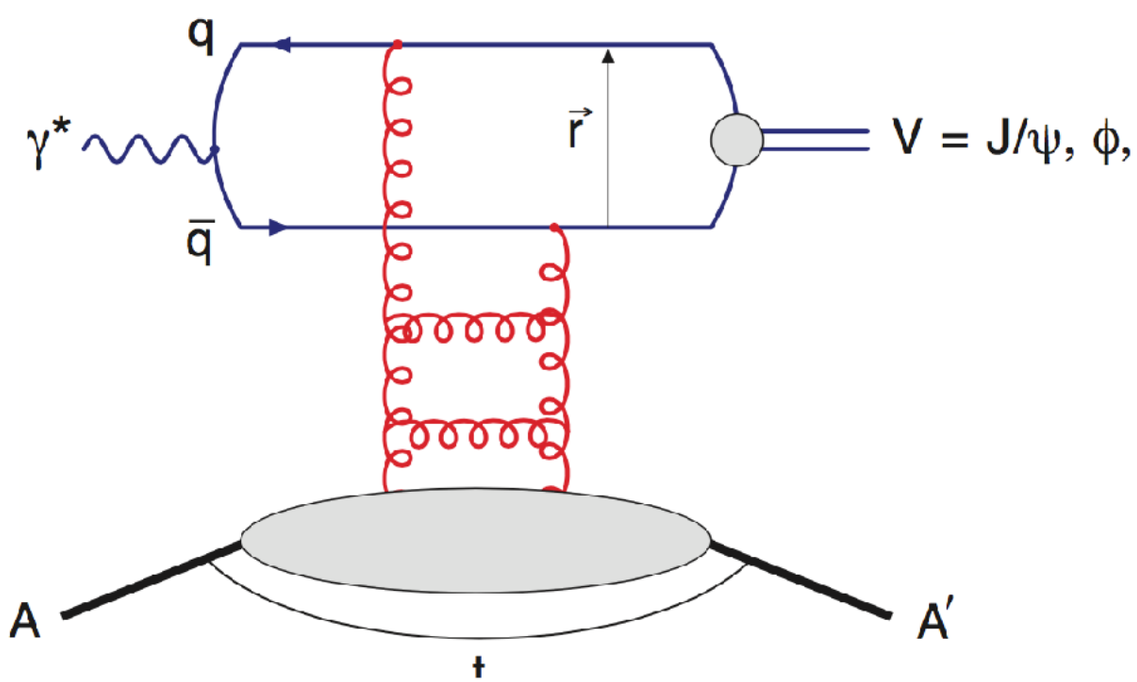
Zheng et al (2014)

Dominguez, Xiao, Yuan (2011)

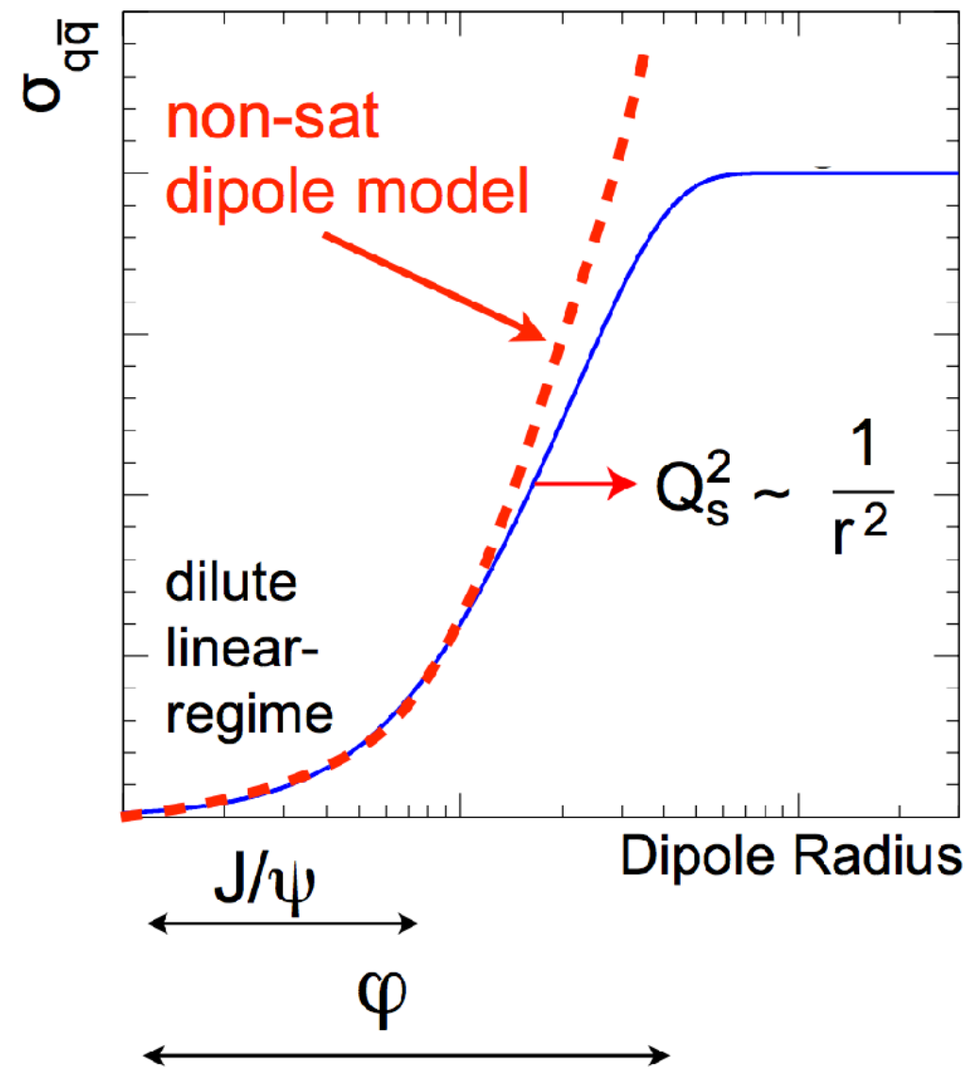
Suppression of back-to-back hadron or jet correlation directly probes the (un-)saturated gluon distributions in nuclei,

EIC - Diffractive probes of Saturation

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



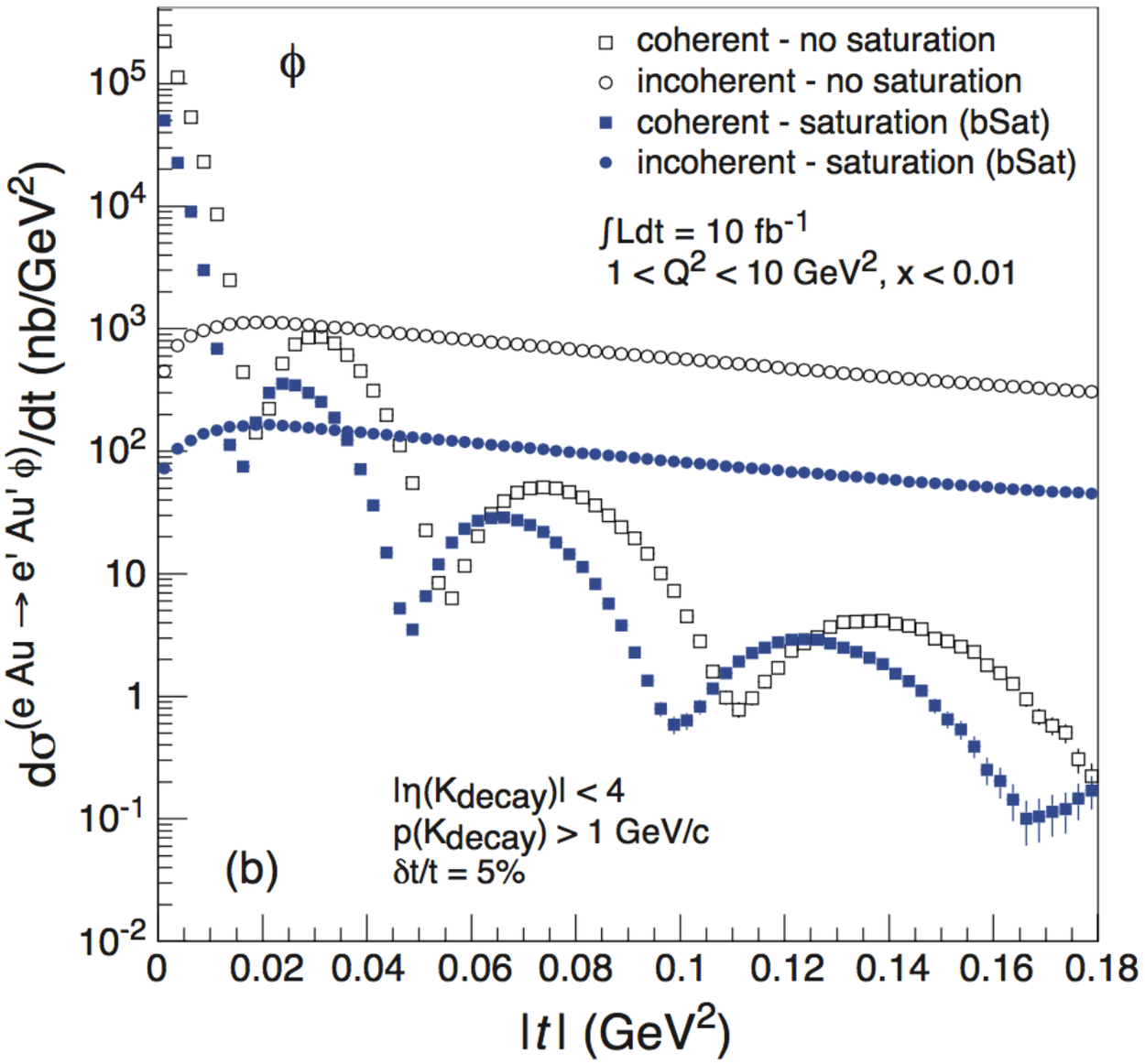
Dipole Cross-Section:

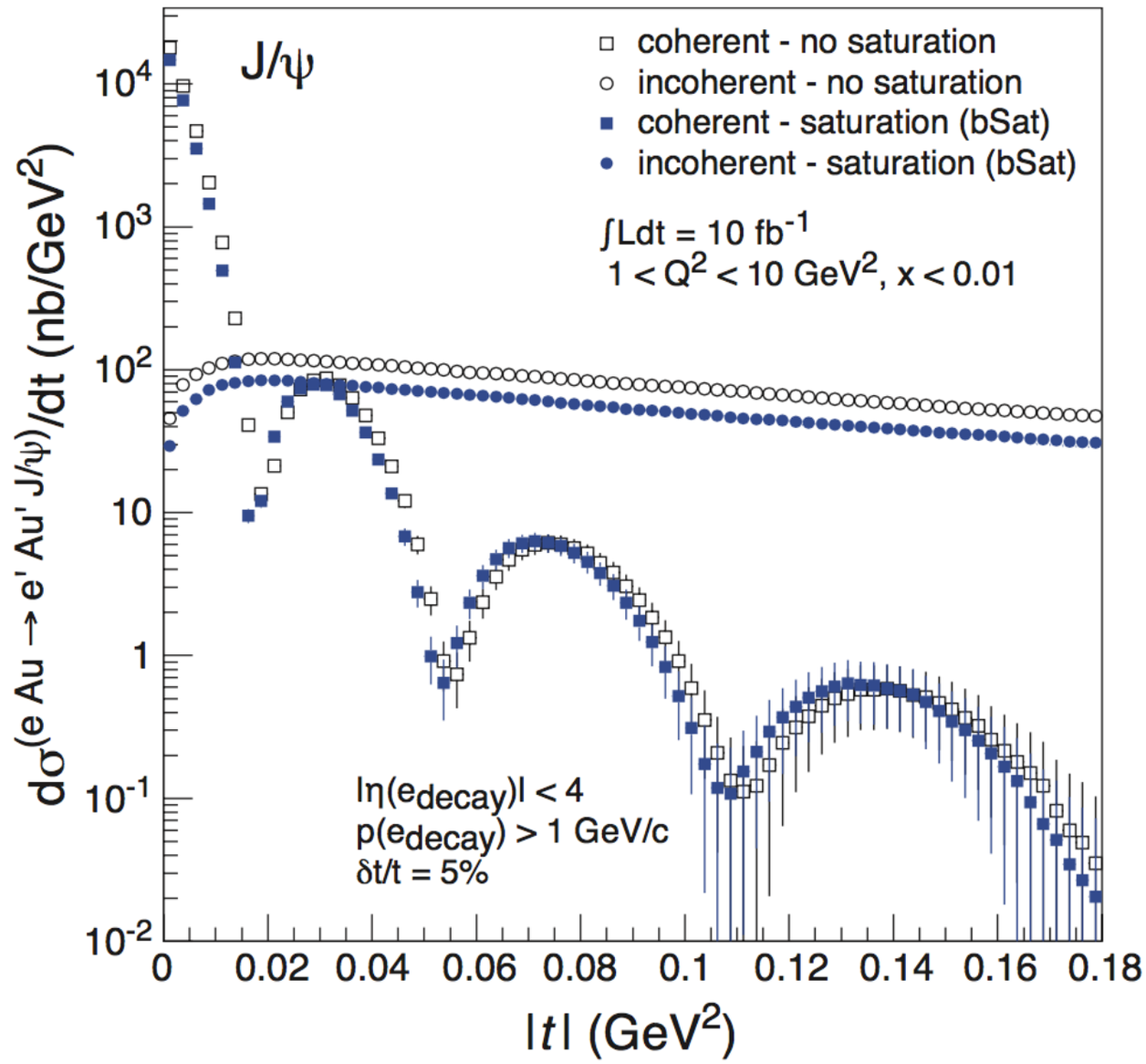


Nucleus escapes down the beampipe

(In)coherence tagged with ZDC

EIC - Diffractive probes of Saturation

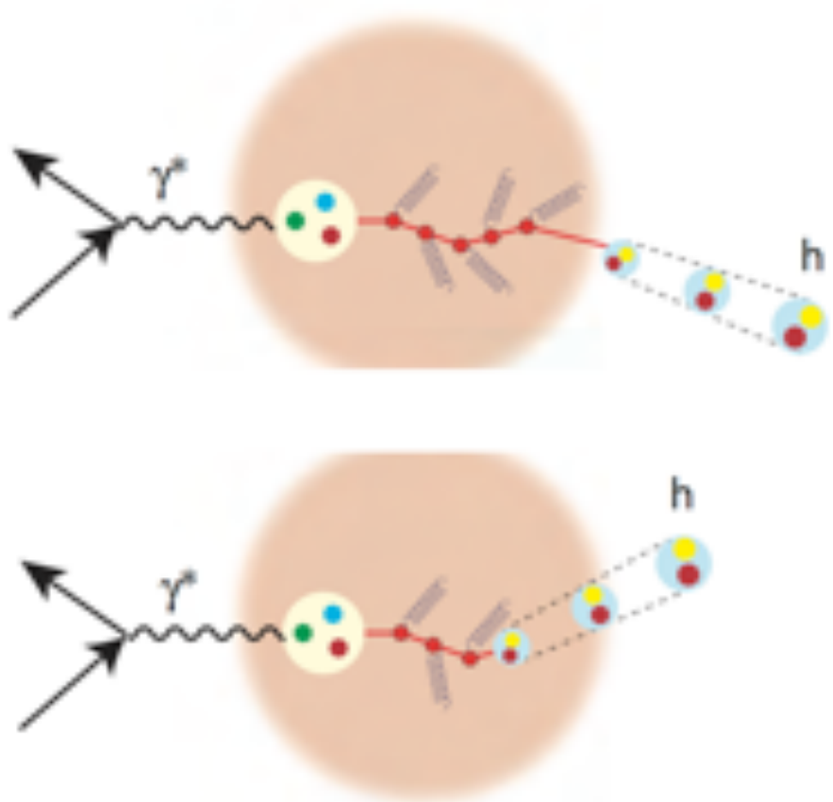


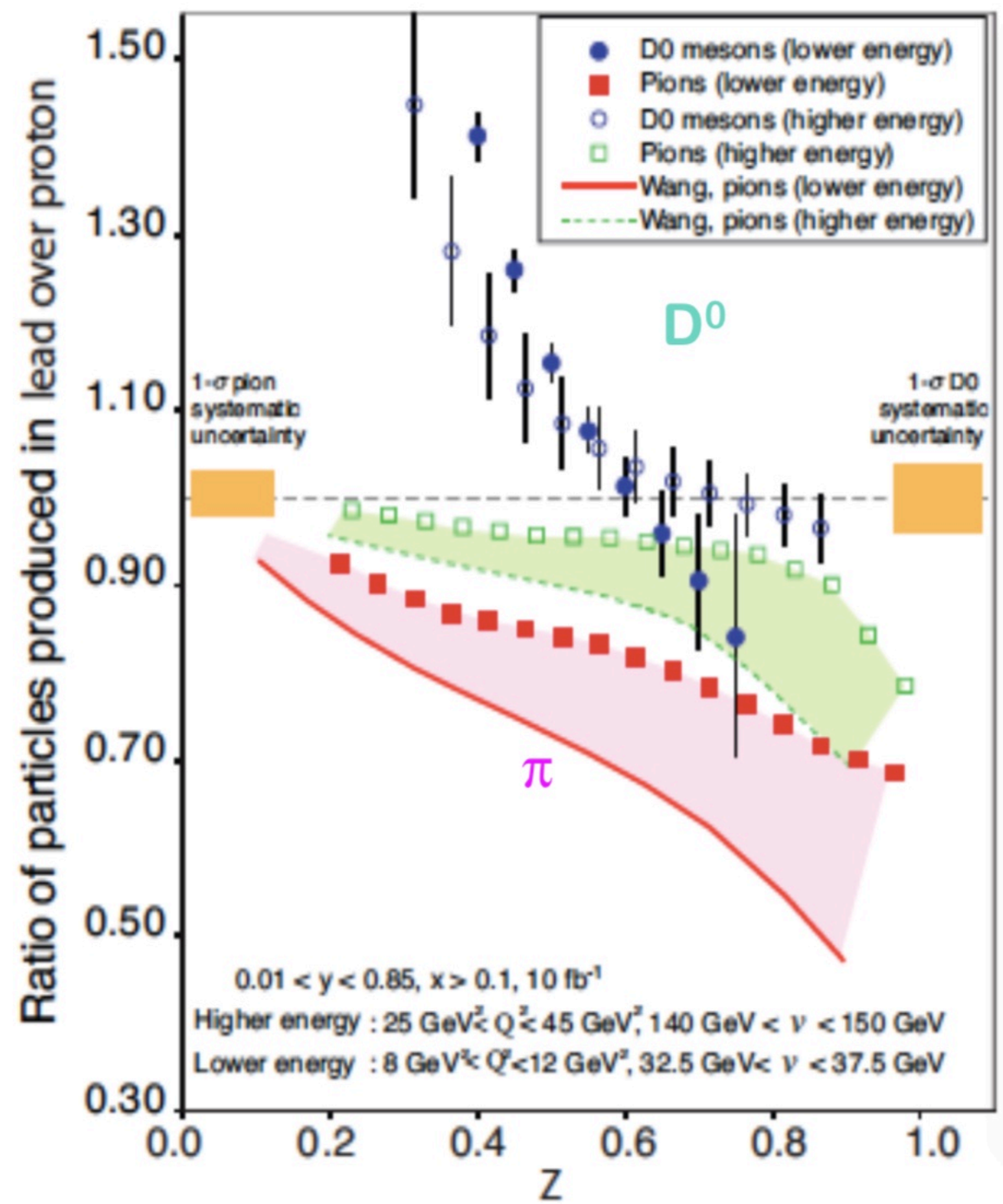


Incoherent and coherent diffraction are both key measurements to saturation,
Exclusive vector meson production is key to (all) imaging,
as is deeply virtual Compton scattering

U.S.-based EIC - Additional Opportunities (Selected)

EIC - SIDIS to study Emergence of Hadrons





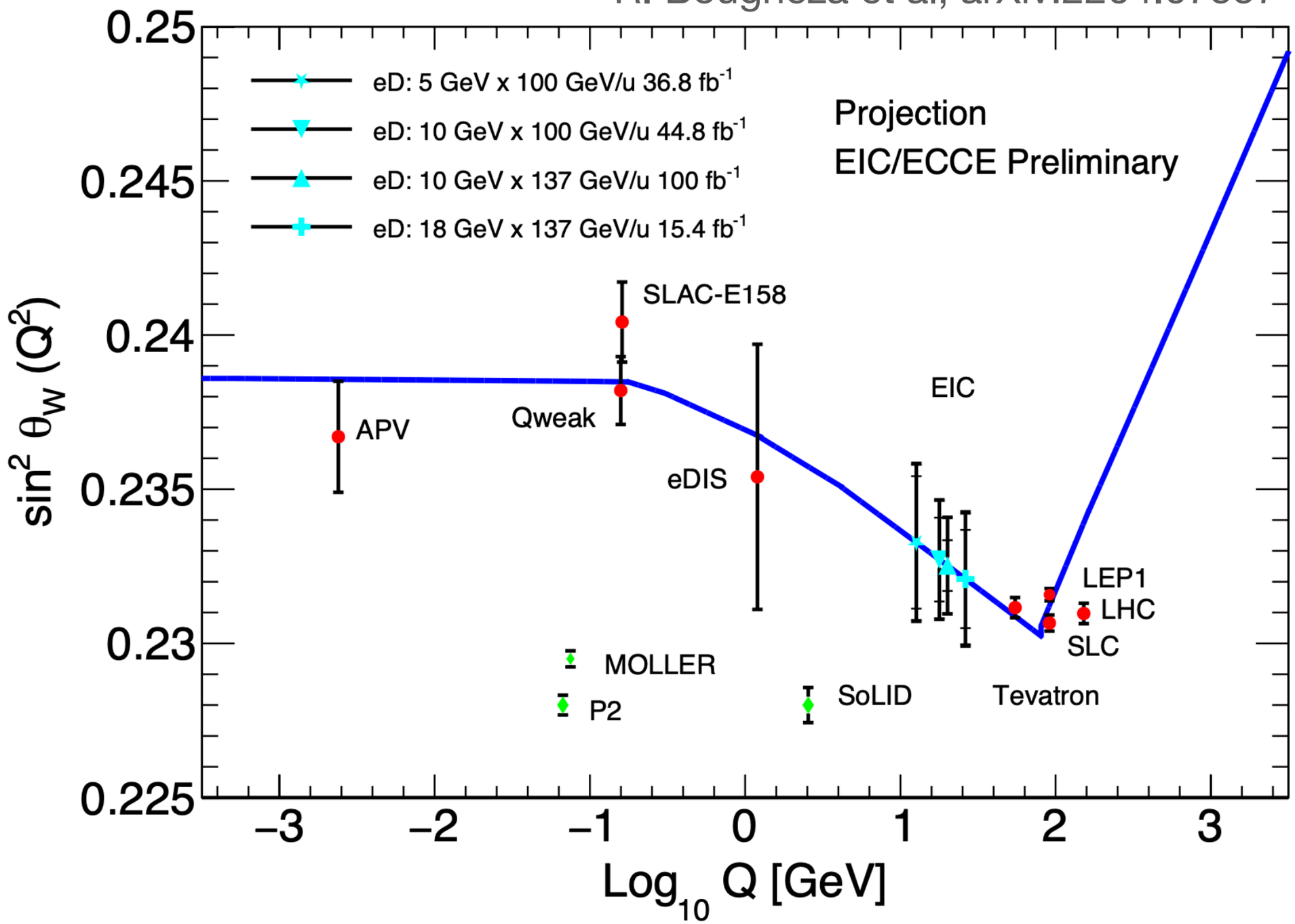
Control of $\nu = \dfrac{Q^2}{2mx}$ and

medium length

Study mass-dependence via charmed hadrons.

EIC - Electroweak Opportunities

R. Bougheza et al, arXiv:2204.07557



EIC Physics Experimental Perspective

Past

Possible Future

	HERA @ DESY	LHeC @ CERN	EIC in China	EIC in U.S.
$\sqrt{s_{ep}}$ [GeV]	320	200 - 1300	15 - 20	20 - 100 (140)
proton x_{min}	1×10^{-5}	5×10^{-7}	2×10^{-3}	1×10^{-4}
ion	p	p, Pb, …	p - U	p - U
polarization	-	-	p, light nuclei	p, d, ^{3}He, Li
L [$cm^{-2}s^{-1}$]	2×10^{31}	1×10^{34}	3×10^{33}	10^{33} - 10^{34}
Interaction Points	2	1	1	2
Timeline	1992 - 2007	post ALICE	Upgrade to HIAF	> 2031

High-Energy Physics

Nuclear Physics

Goal: EIC context and capabilities (today)

EIC Physics Experimental Perspective

Past

Possible Future

EIC will offer new capability and relies crucially on theory, accelerator, and experiment — the combined strengths of the communities,

	HERA @ DESY	LHeC @ CERN	EIC in China	EIC in U.S.
$\sqrt{s_{ep}}$ [GeV]	320	200 - 1300	15 - 20	20 - 100 (140)
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Timeline	1992 - 2007	post ALICE	Upgrade to HIAF	> 2031

EIC will address profound questions in nuclear physics

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

and offer numerous other opportunities

- *Touched on: electroweak possibilities,*
- *Not discussed here: transversity - tensor charge - EDM, lepton-flavor violation, …*
- *Not discussed here either: societal benefits*

High-Energy Physics

Nuclear Physics

Goal: EIC context and capabilities (today)