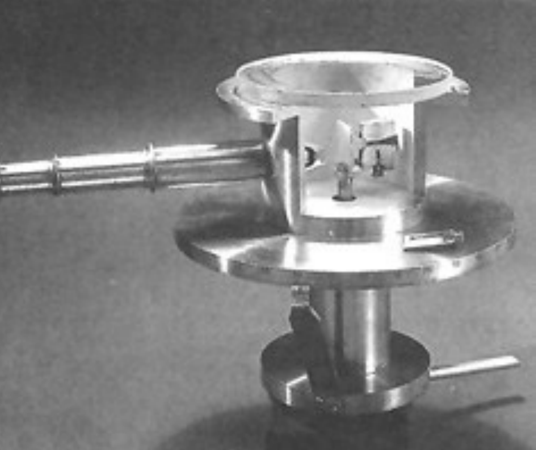
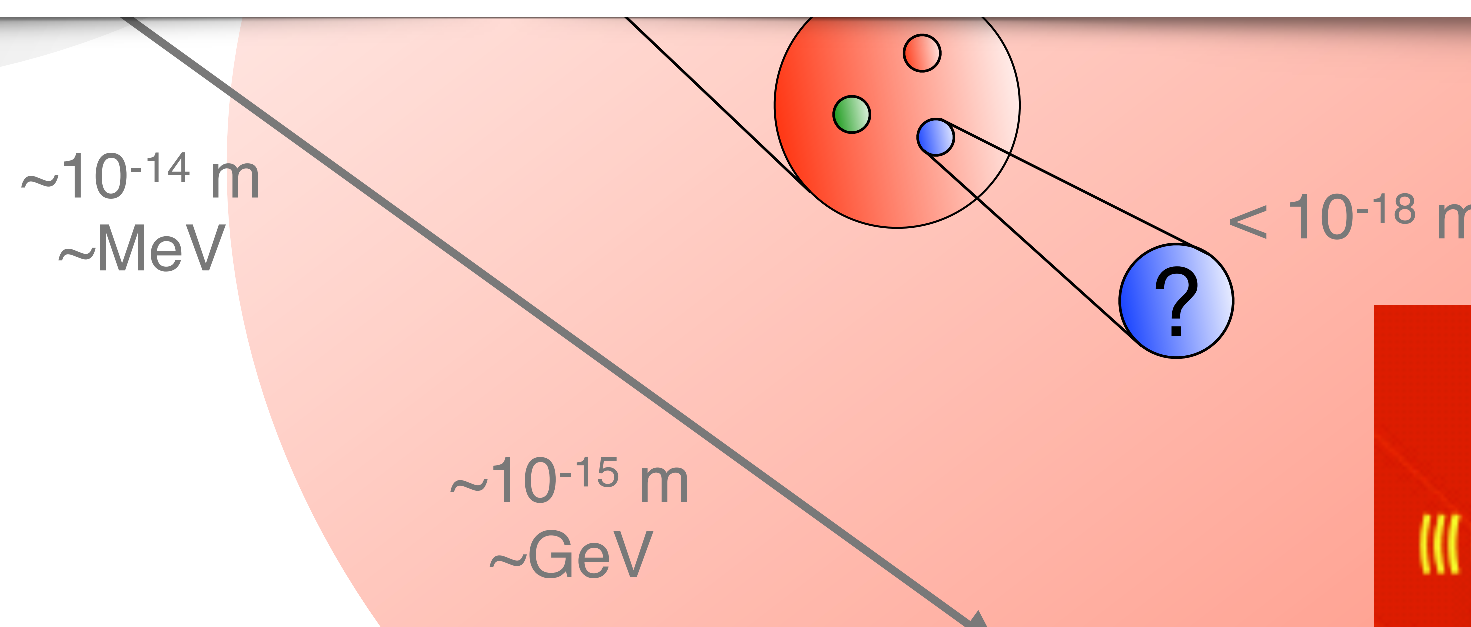


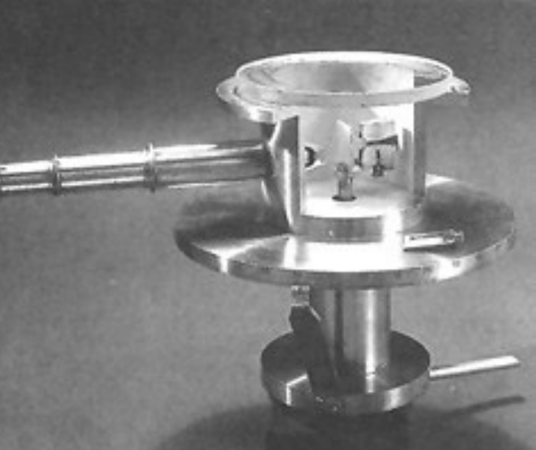
The Electron-Ion Collider

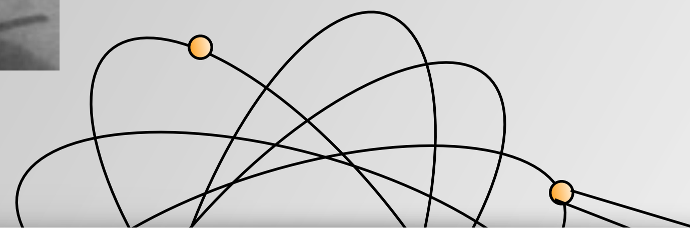
Peering deep into nucleons and nuclei

Ernst Sichtermann (Lawrence Berkeley National Laboratory)

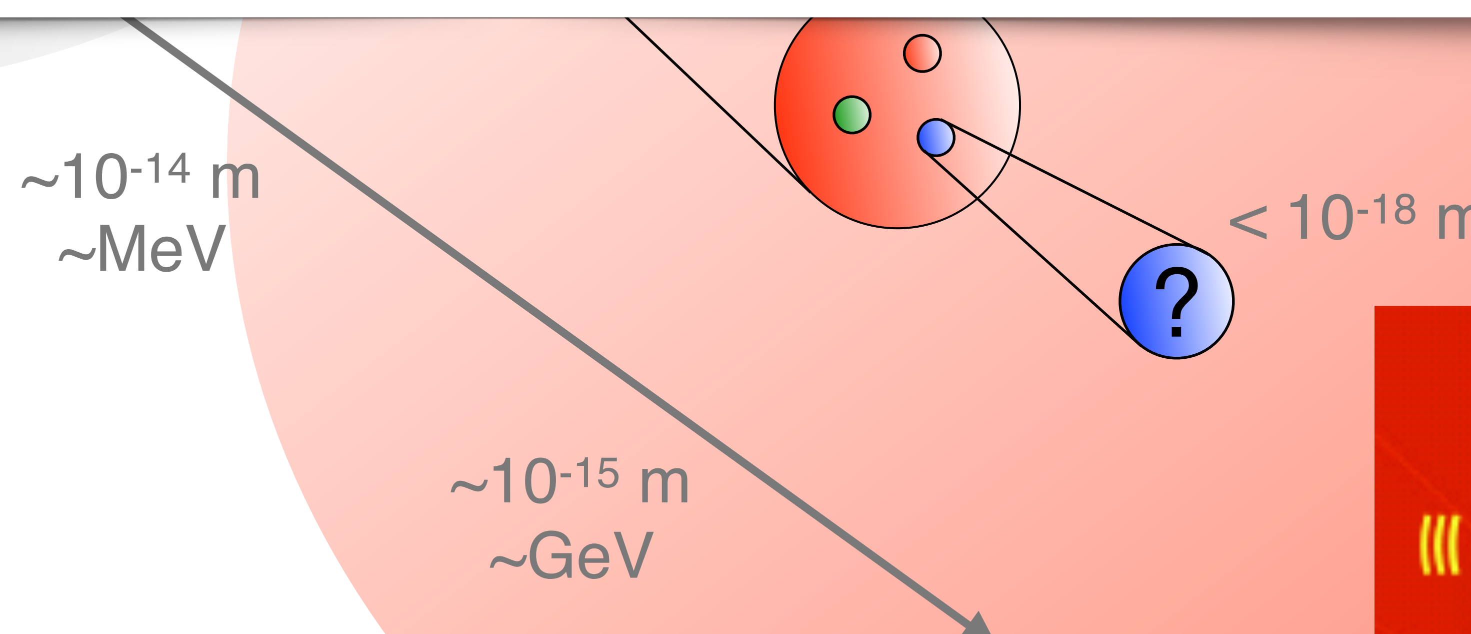


UCB PHY-290E
Sept. 7, 2022

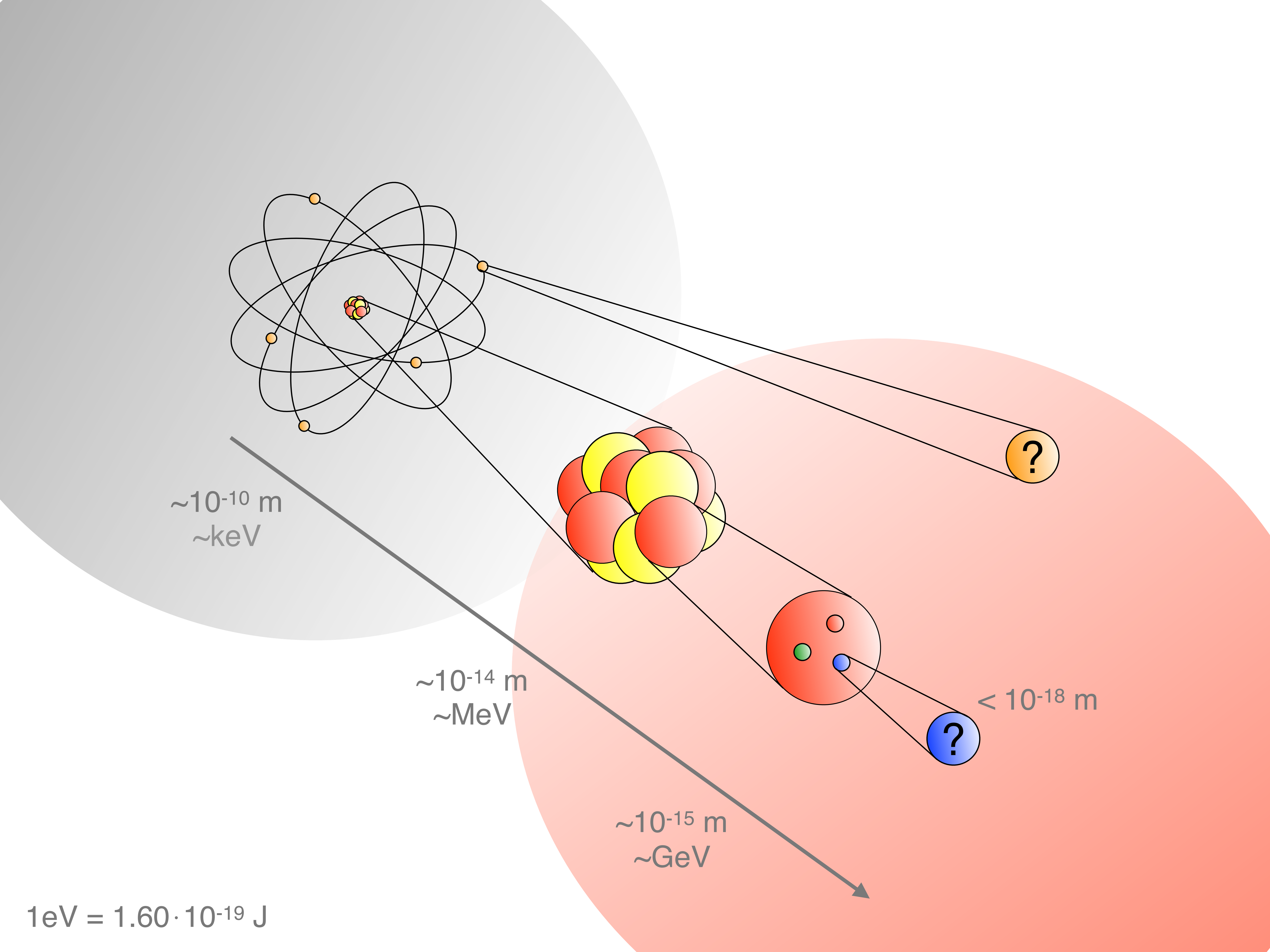




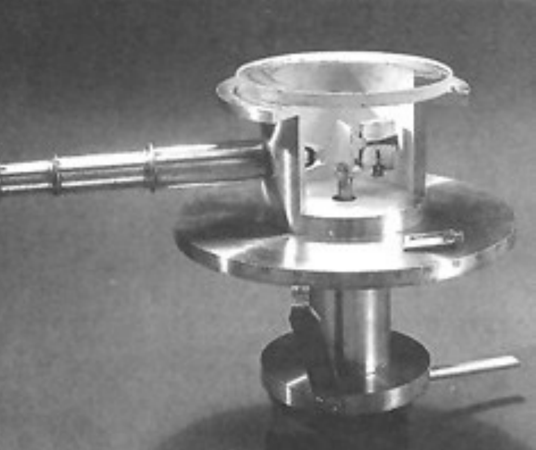
1. *Introduction and recap*
2. *HERA — Hadron Electron Ring Accelerator*
3. *EIC — Electron-Ion Collider*
4. *Discussion*



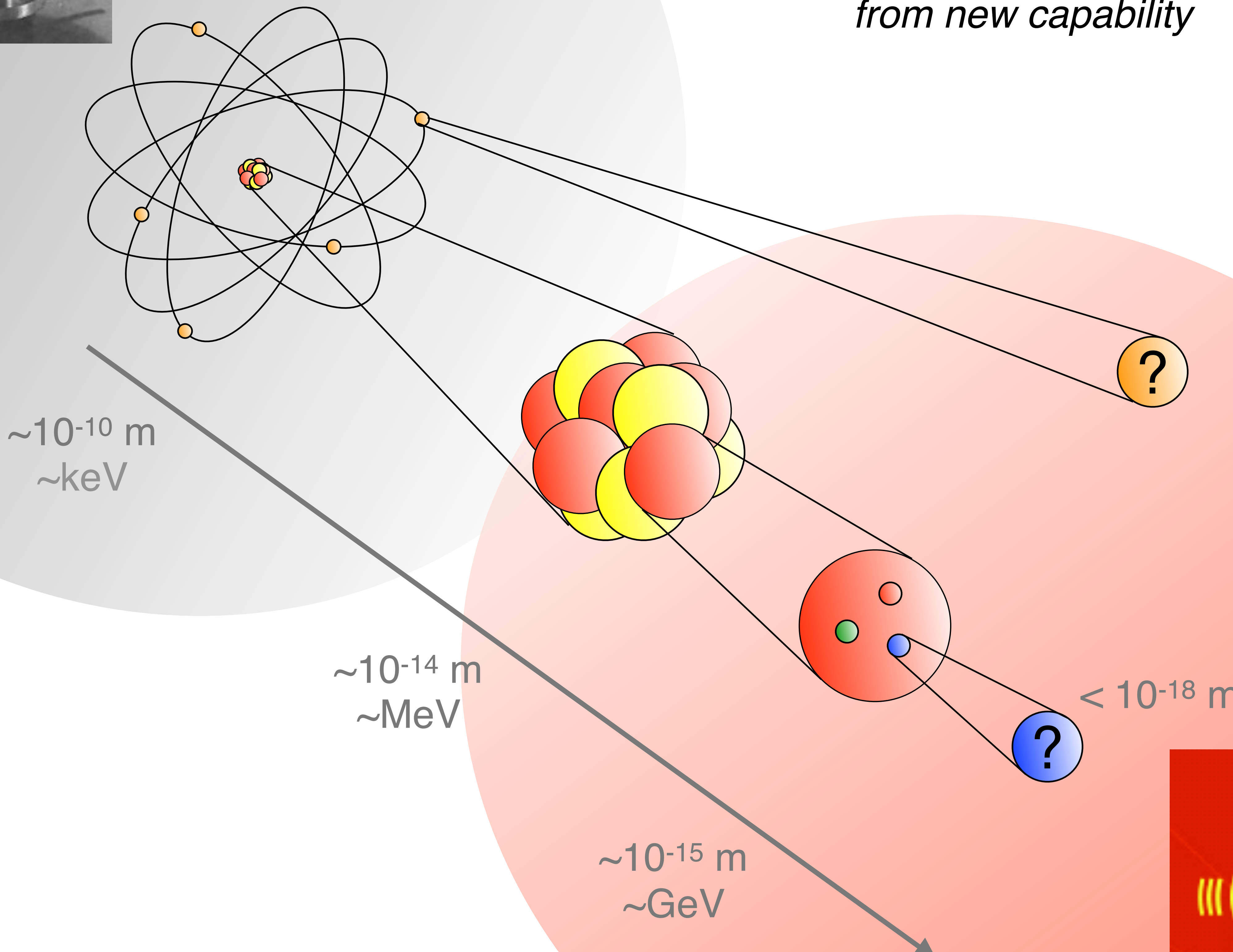
UCB PHY-290E
Sept. 7, 2022



?
~10-10 m
~keV
~10-14 m
~MeV
~10-15 m
~GeV
< 10-18 m
?
1eV = 1.60·10-19 J



A history of new insight
from new capability



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

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,

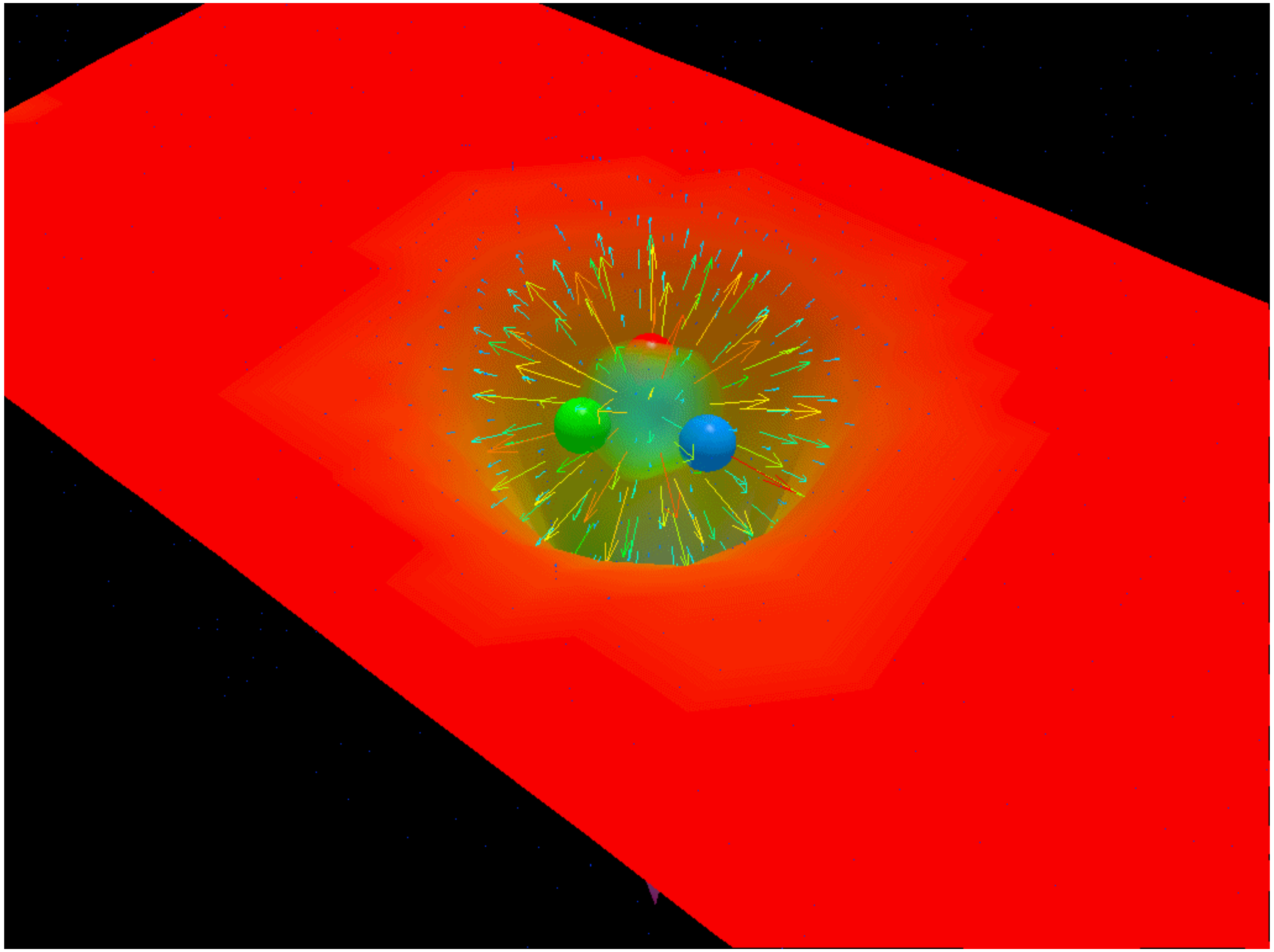
Constituent quark model — $g_p \sim 5.6$ ✓, $g_n \sim -3.8$ ✓, spectroscopy ✓

Lots of gluons in high-energy inelastic collisions,

Ab-initio (lattice) QCD calculations have started to enter the stage,

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

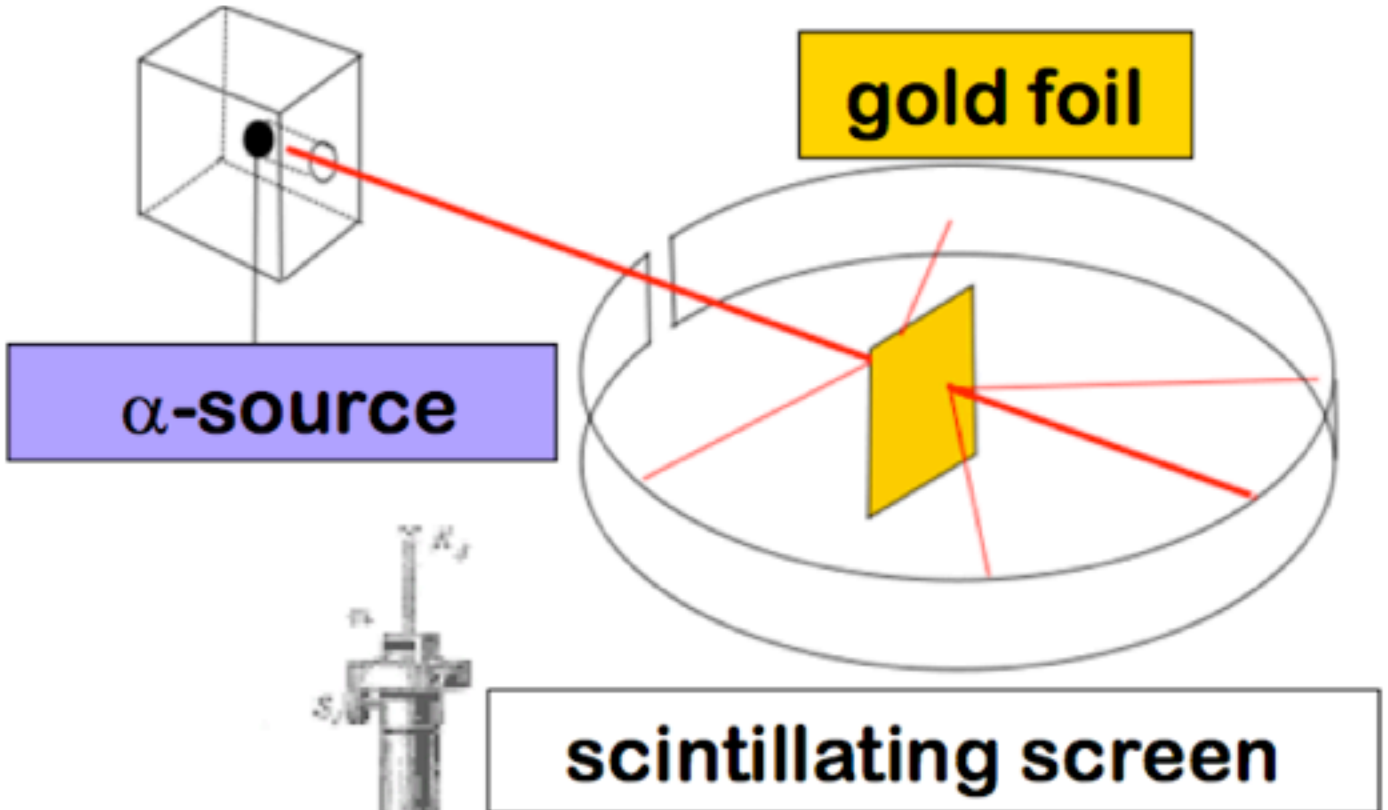
Intermezzo

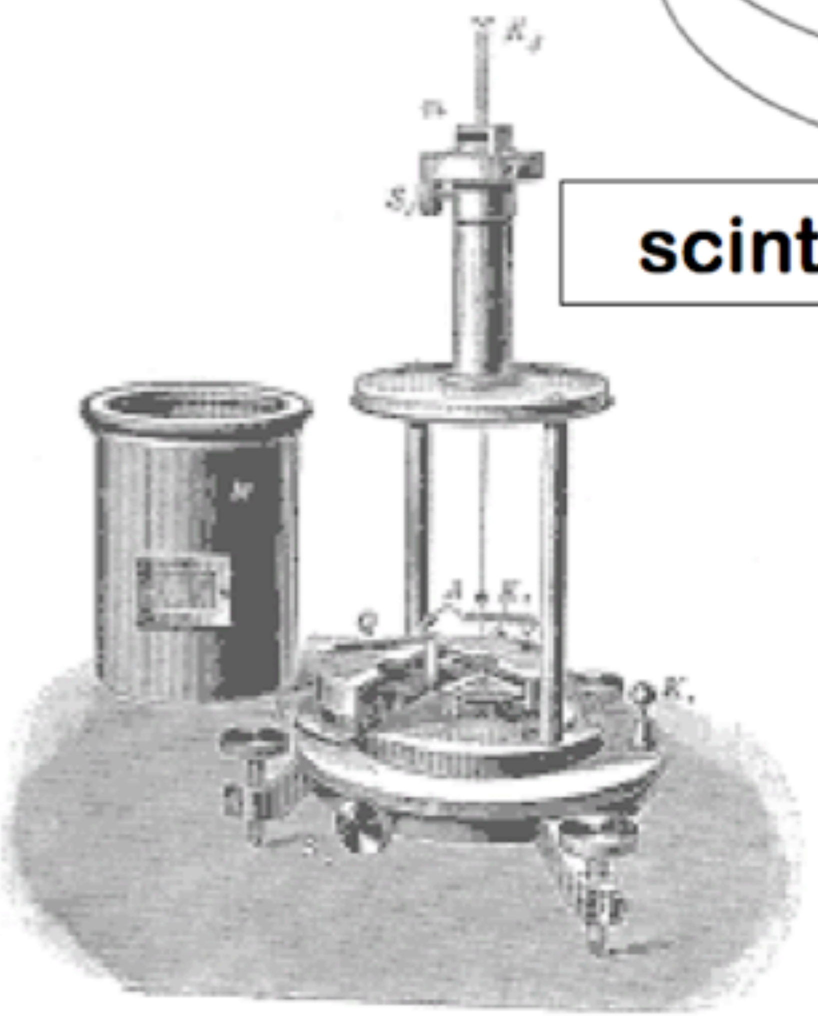


"Gluon flux-tube distribution and linear confinement in baryons",
F. Bissey, et al., Phys. Rev. D 76, 114512 (2007)

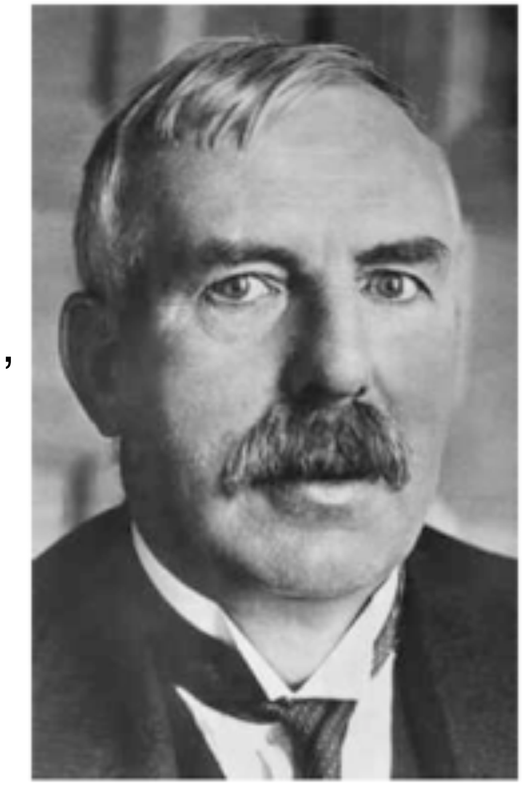
Rutherford Scattering

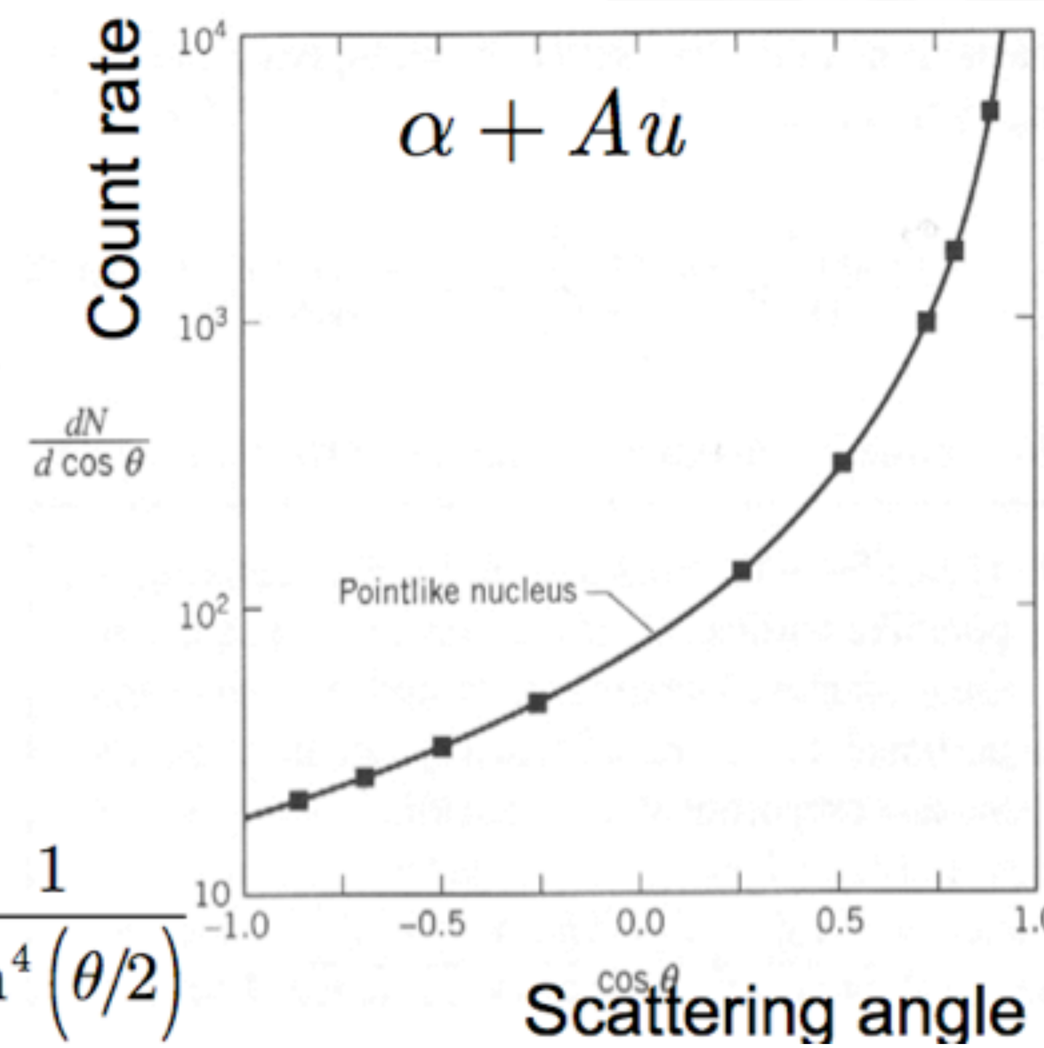
~5 MeV





Ernest Rutherford, Nobel Prize 1908



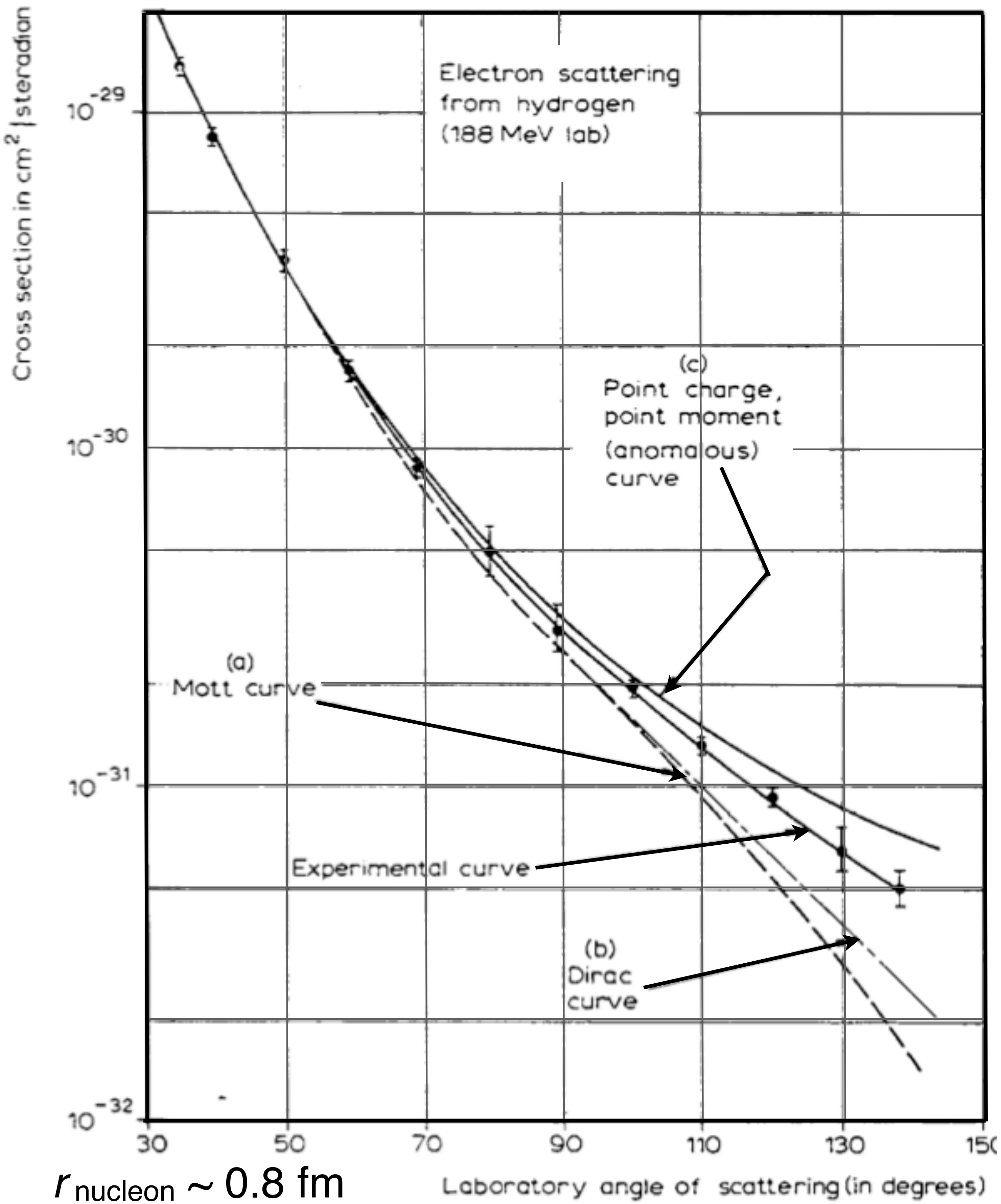


$$\frac{d\sigma}{d\Omega} = (zZ\alpha)^2 \left(\frac{\hbar c}{4E_{\text{kin}}}\right)^2 \frac{1}{\sin^4(\theta/2)}$$

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

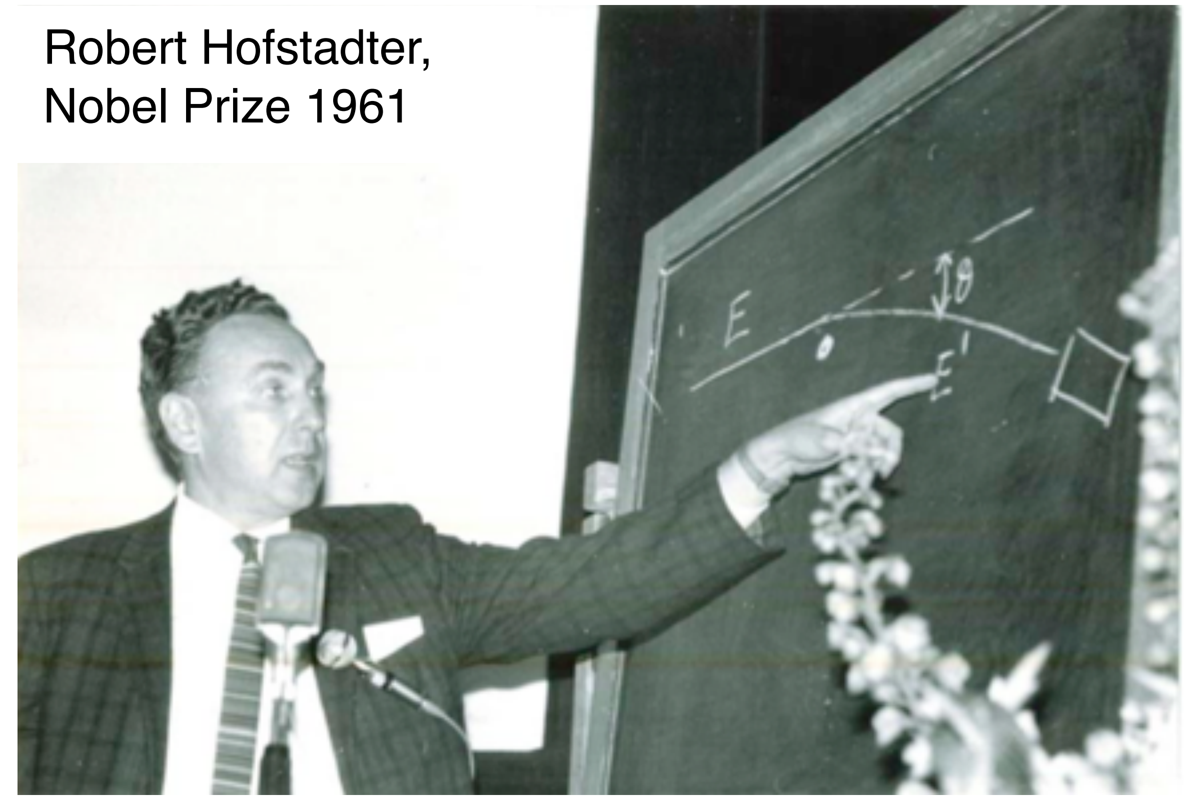
~200 MeV

Elastic Electron Scattering



$r_{\text{nucleon}} \sim 0.8$ fm

Robert Hofstadter,
Nobel Prize 1961



Scattering off a spin-1/2 Dirac particle:

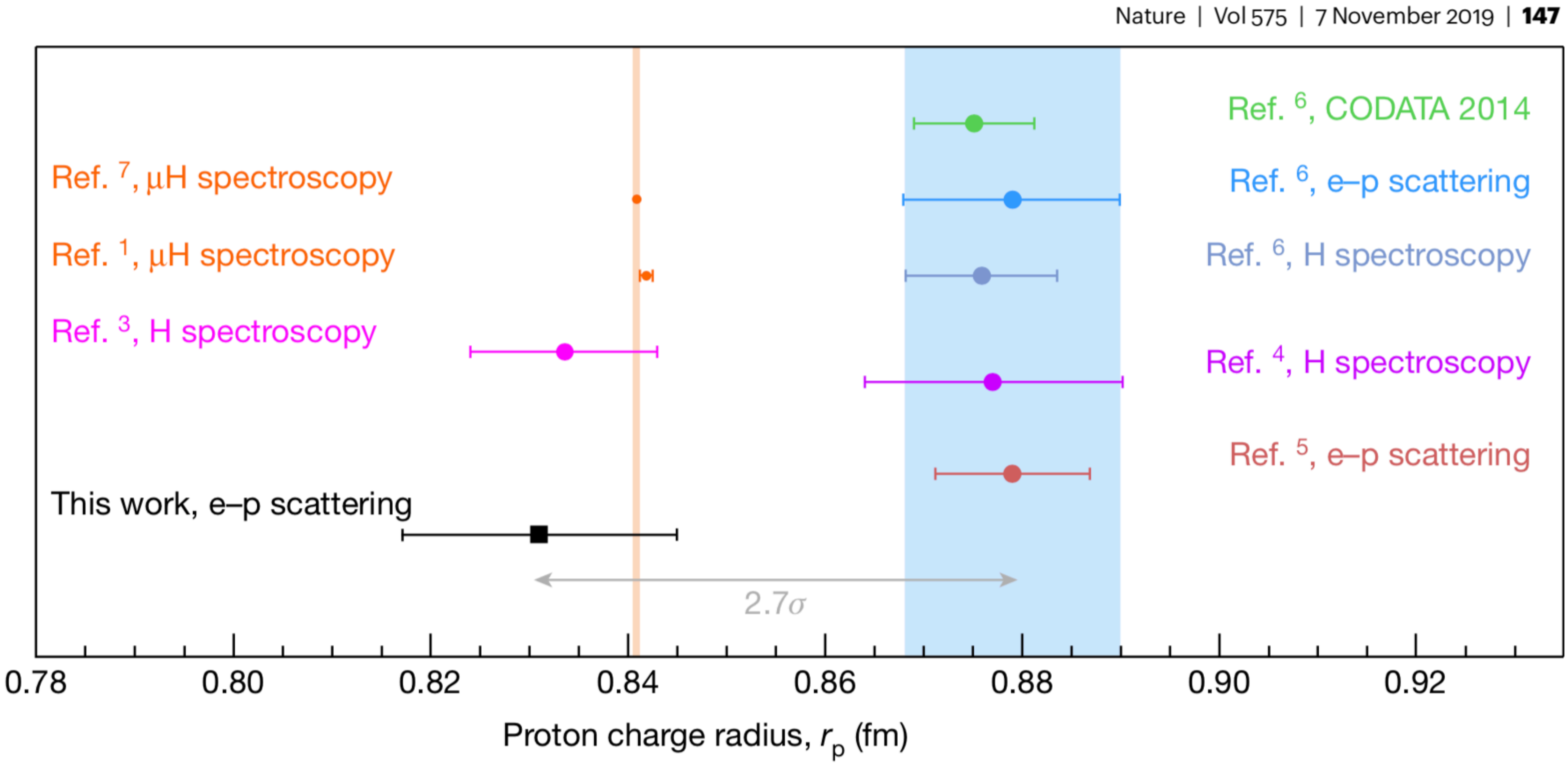
$$\frac{d\sigma}{d\Omega} = \left(\frac{\alpha}{4ME\sin^2(\theta/2)}\right)^2 \frac{E'}{E}\left[\frac{q^2}{2M}\sin^2(\theta/2) + \cos^2(\theta/2)\right]$$

The proton has an anomalous magnetic moment,

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

and, hence, internal (spin) structure.

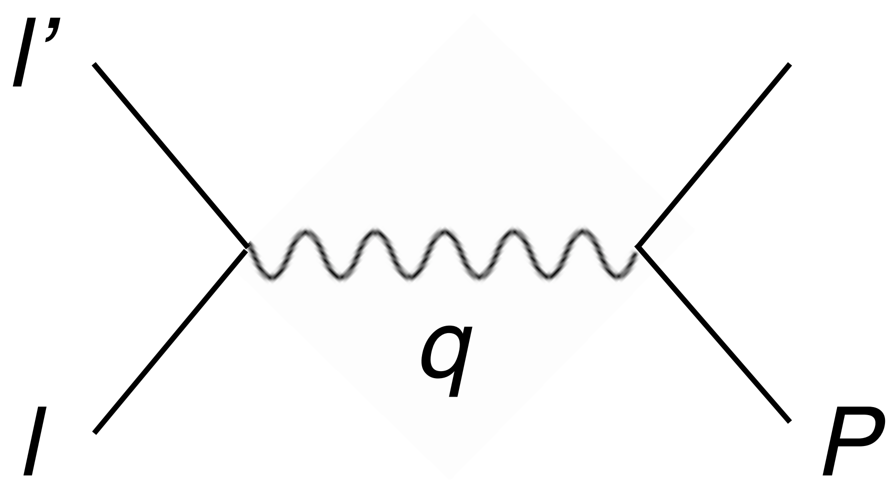
Intermezzo



Proton charge radius continues to be highly topical

Note: "This work" refers to the pRad low-Q^2 e-p scattering experiment at Jefferson Laboratory,
Look forward to μ-p scattering data from MUSE at PSI.

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:

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

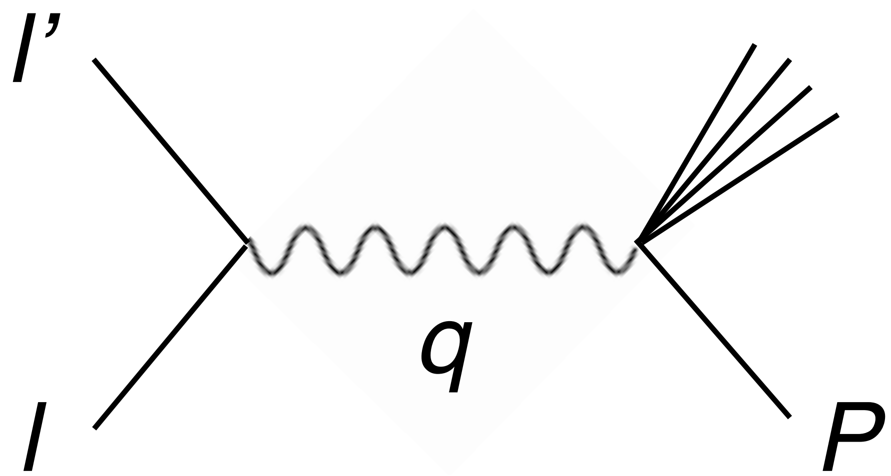
Charge conservation at the proton vertex reduces the number of structure functions:

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

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:

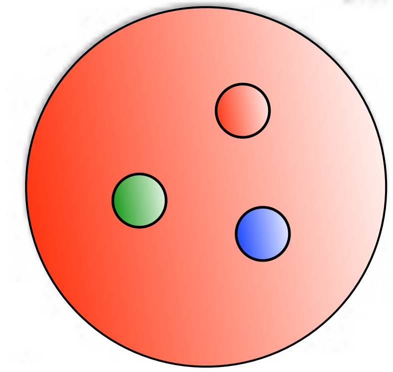
$$W_1, W_2 \;\; \text{or, alternatively expressed,} \;\; F_1, F_2$$

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.

Elastic scattering off Dirac Partons



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

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

and, furthermore[illegible]uppose that the quarks carry a fraction, *z*, of the proton momentum

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

which uses the e[illegible]ier elastic scattering example.

Now,

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

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

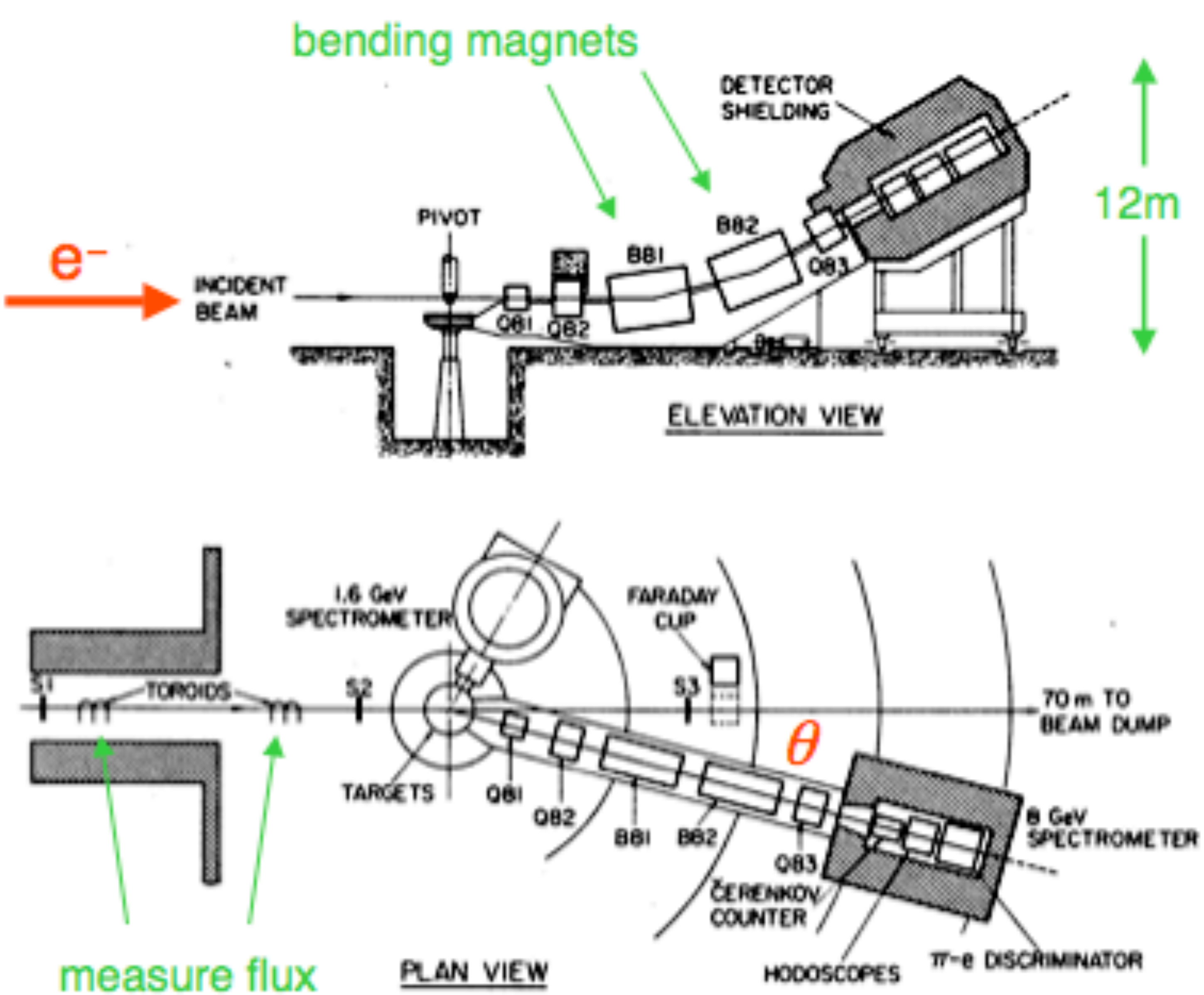
Two important *observable* consequences,

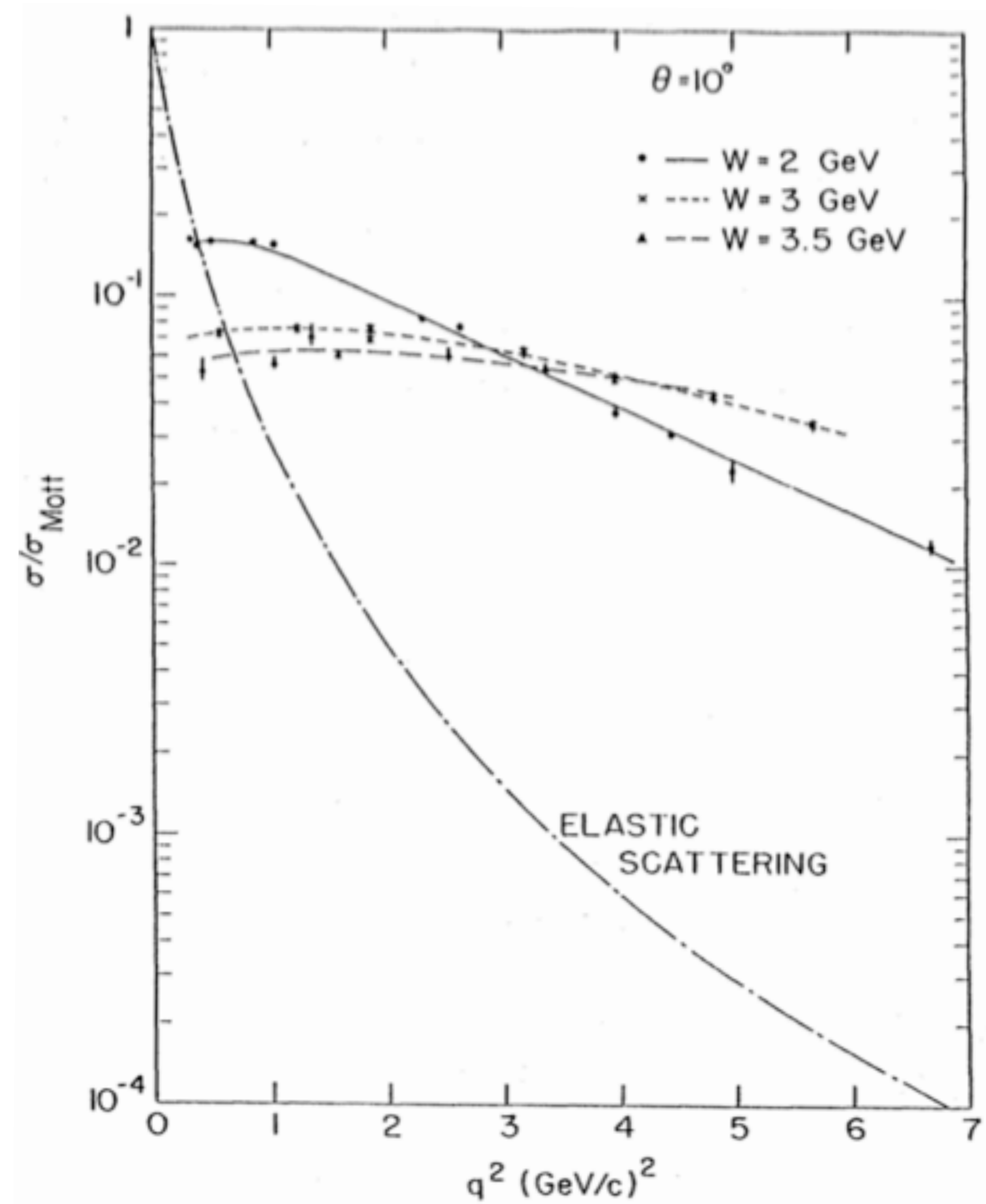
Bjorken scaling: $F_{1,2}(x), \quad \text{not } F_{1,2}(x, Q^2)$

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

~10 GeV

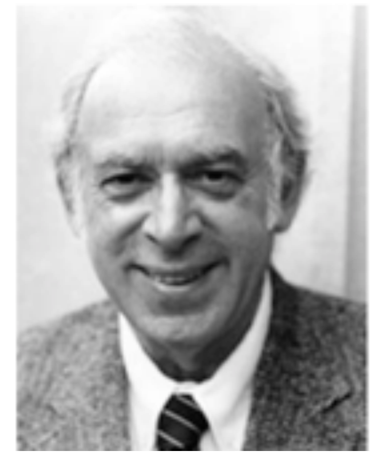
Deep-Inelastic Electron Scattering





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

Deep-Inelastic Electron Scattering

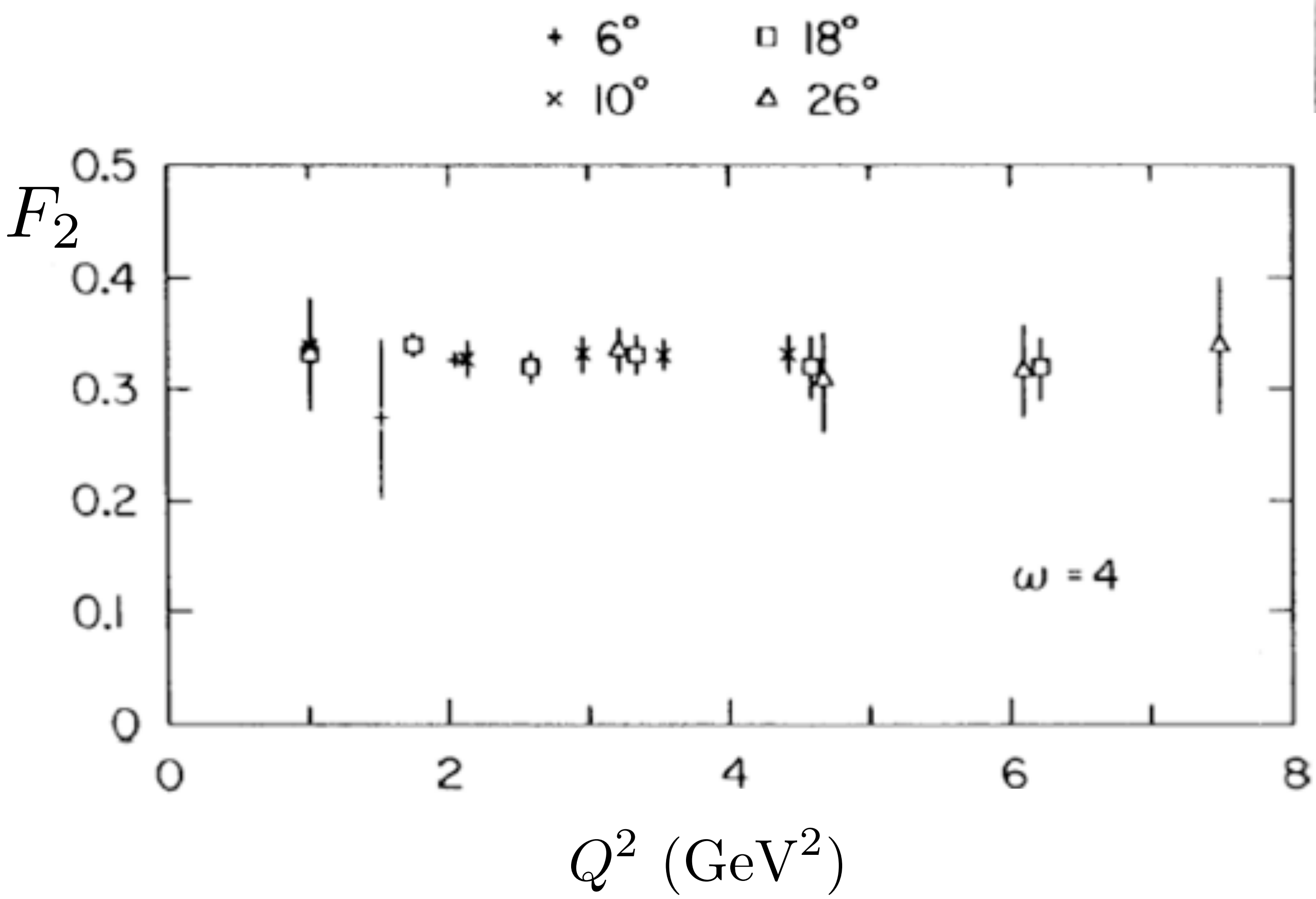


J.T. Friedman

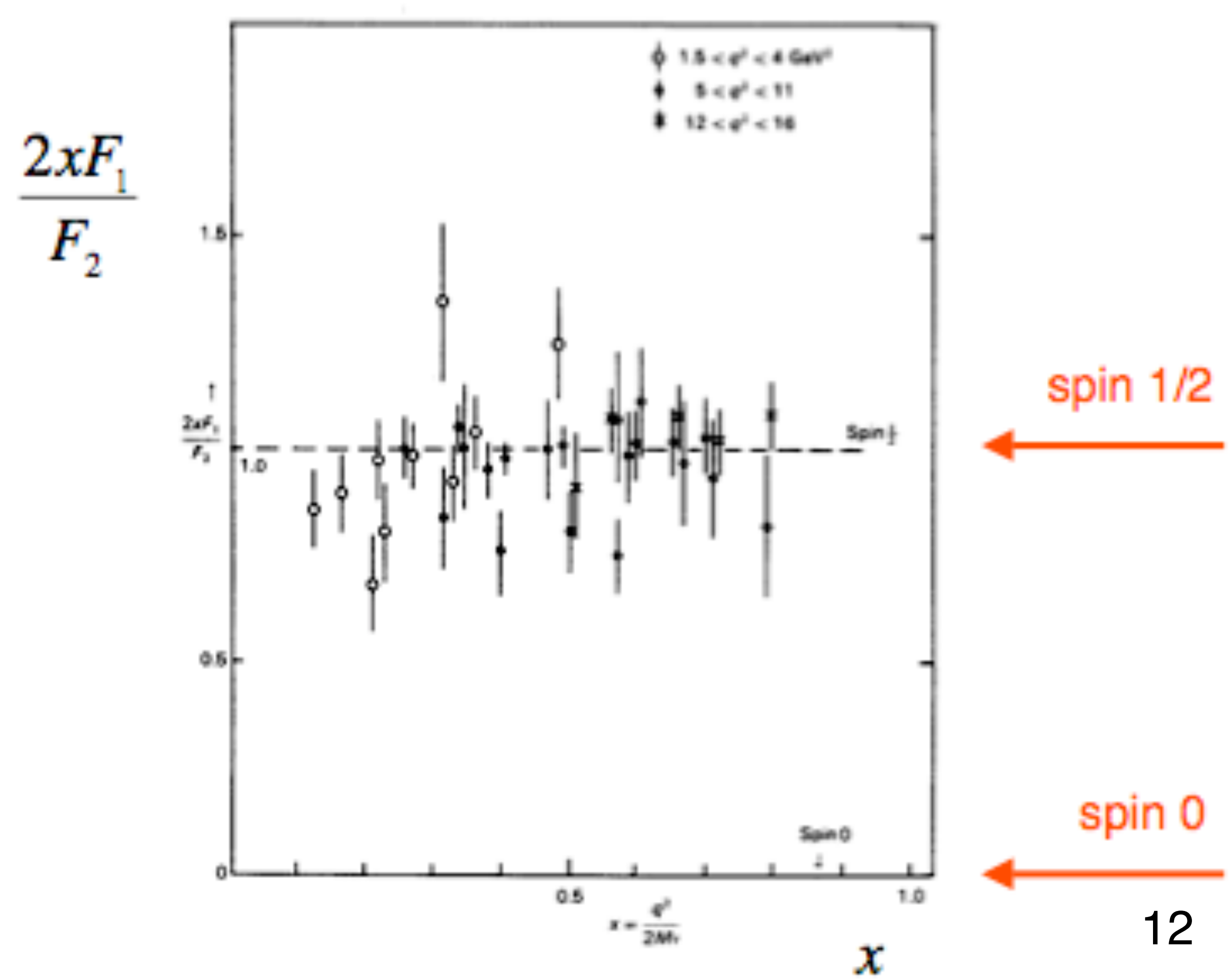
R. Taylor
Nobel Prize 1990

H.W. Kendall

Bjorken scaling:



Callan-Gross relation:



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

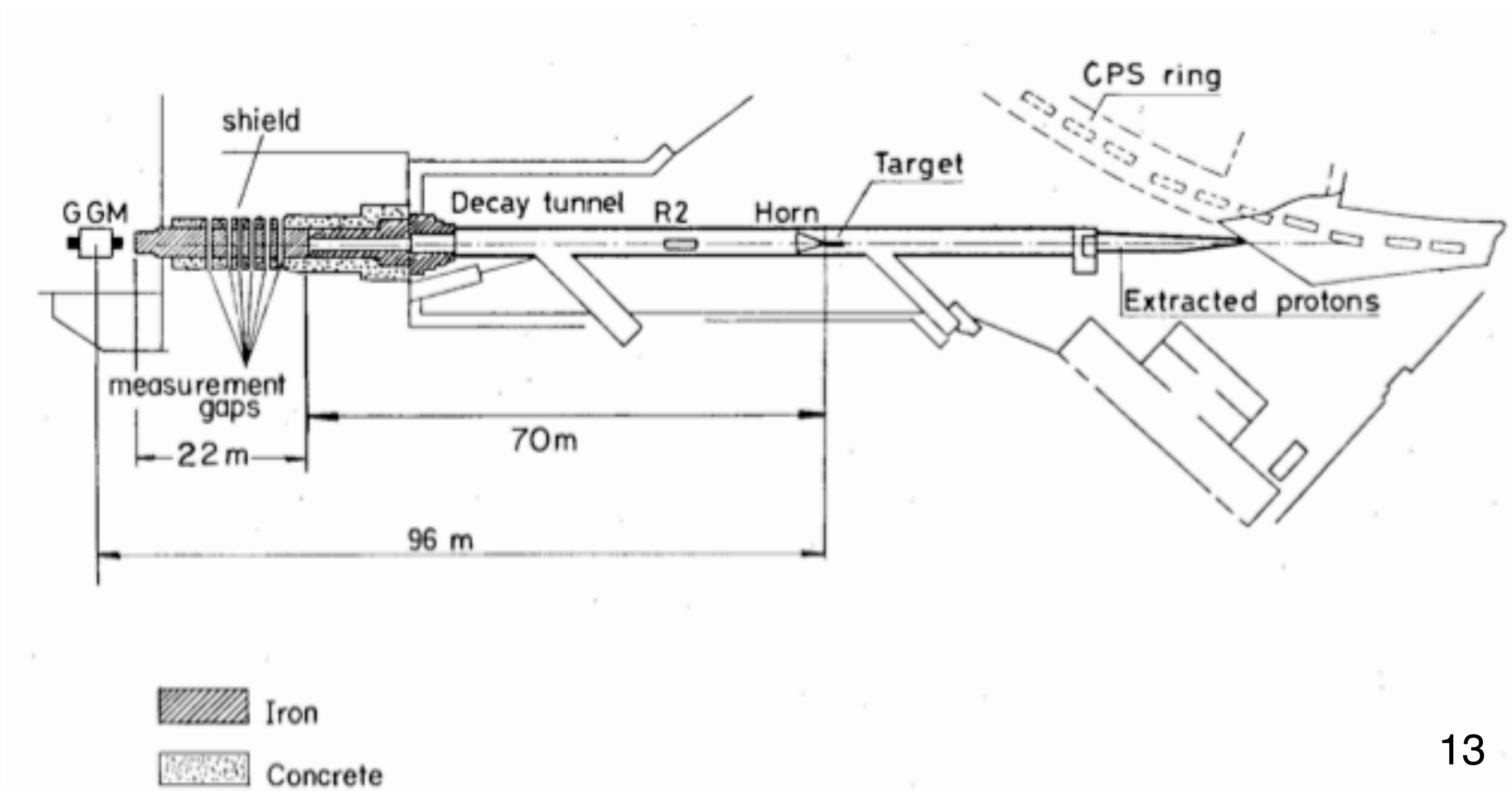
Spin-1/2 quarks cannot absorb longitudinally polarized vector bosons and, conversely, spin-0 (scalar) quarks cannot absorb transversely polarized photons.

Deep-Inelastic *Neutrino* Scattering

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

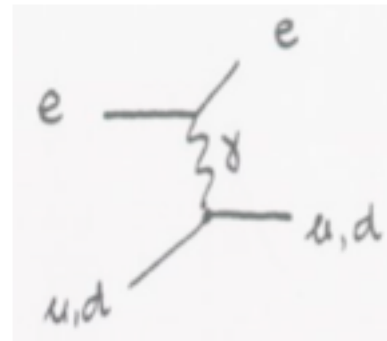
Charged-current DIS!

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



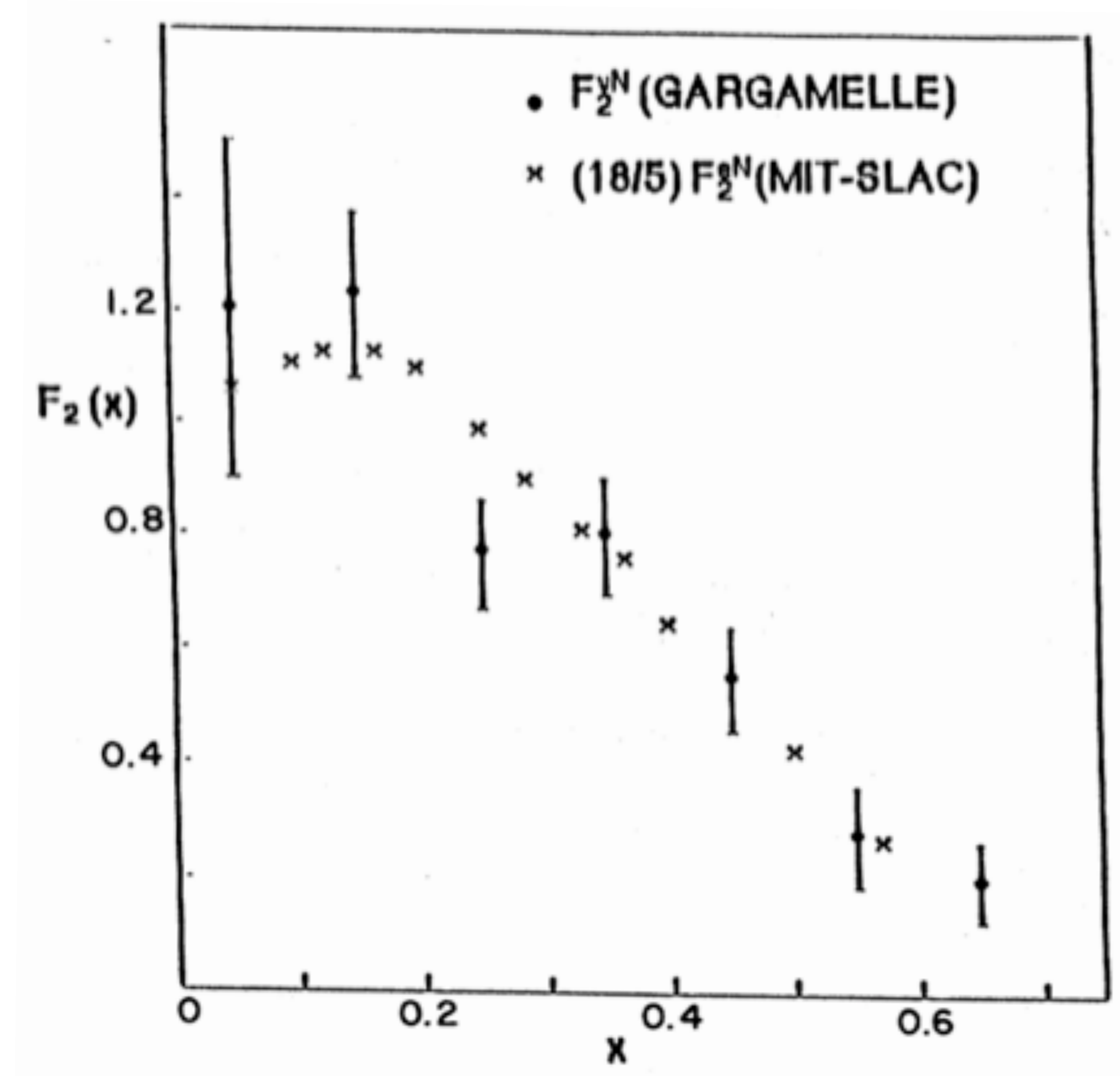
Deep-Inelastic Scattering - Fractional Electric Charges

Neutral-current (photon) DIS:

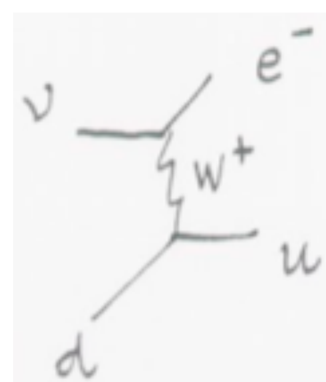


$$F_2 = x \sum e_q^2 (q + \bar{q}), \quad p : uud, \quad n : ddu$$

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



Charged-current DIS:



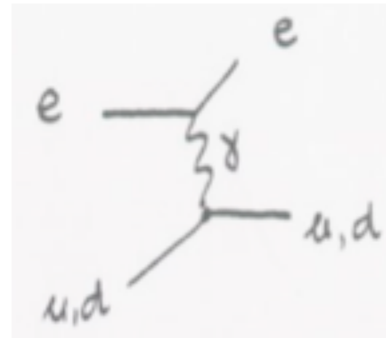
$$F_2^{\nu p} = 2x(d + \bar{u}), \quad F_2^{\nu n} = 2x(u + \bar{d})$$

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

Ratio tells us about the fractional quark charge!

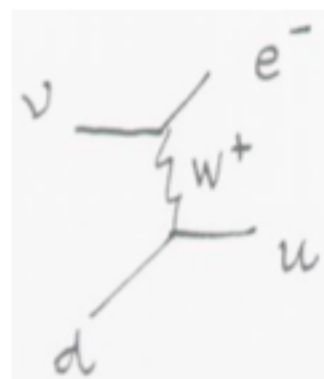
Deep-Inelastic Scattering - Momentum Conservation

Neutral-current (photon) DIS:



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

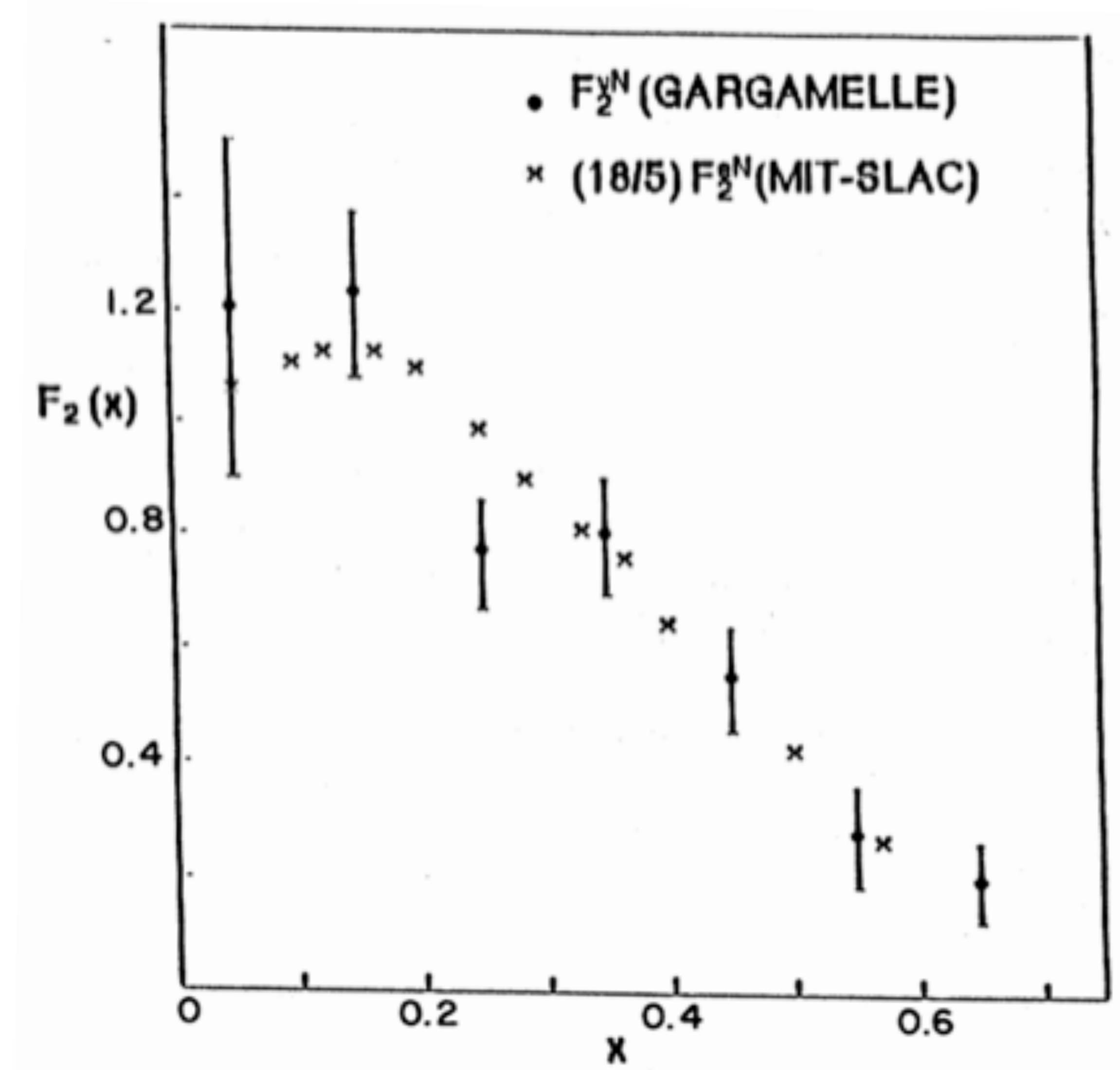
Charged-current DIS:



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

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

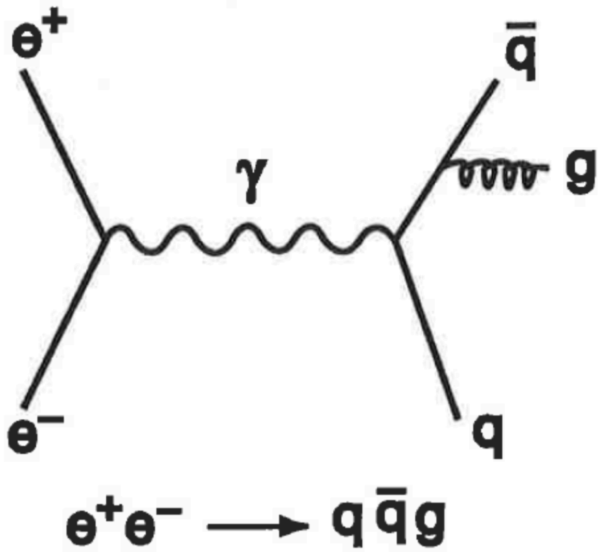
SLAC: 0.14 +/- 0.05

Quarks carry half of the nucleon momentum!

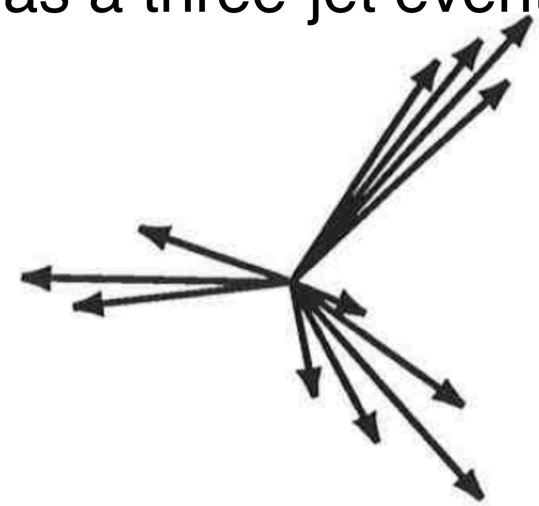
15 – 45 GeV e^+e^- *collider*

3-jet events at PETRA

Observation of the higher order process,

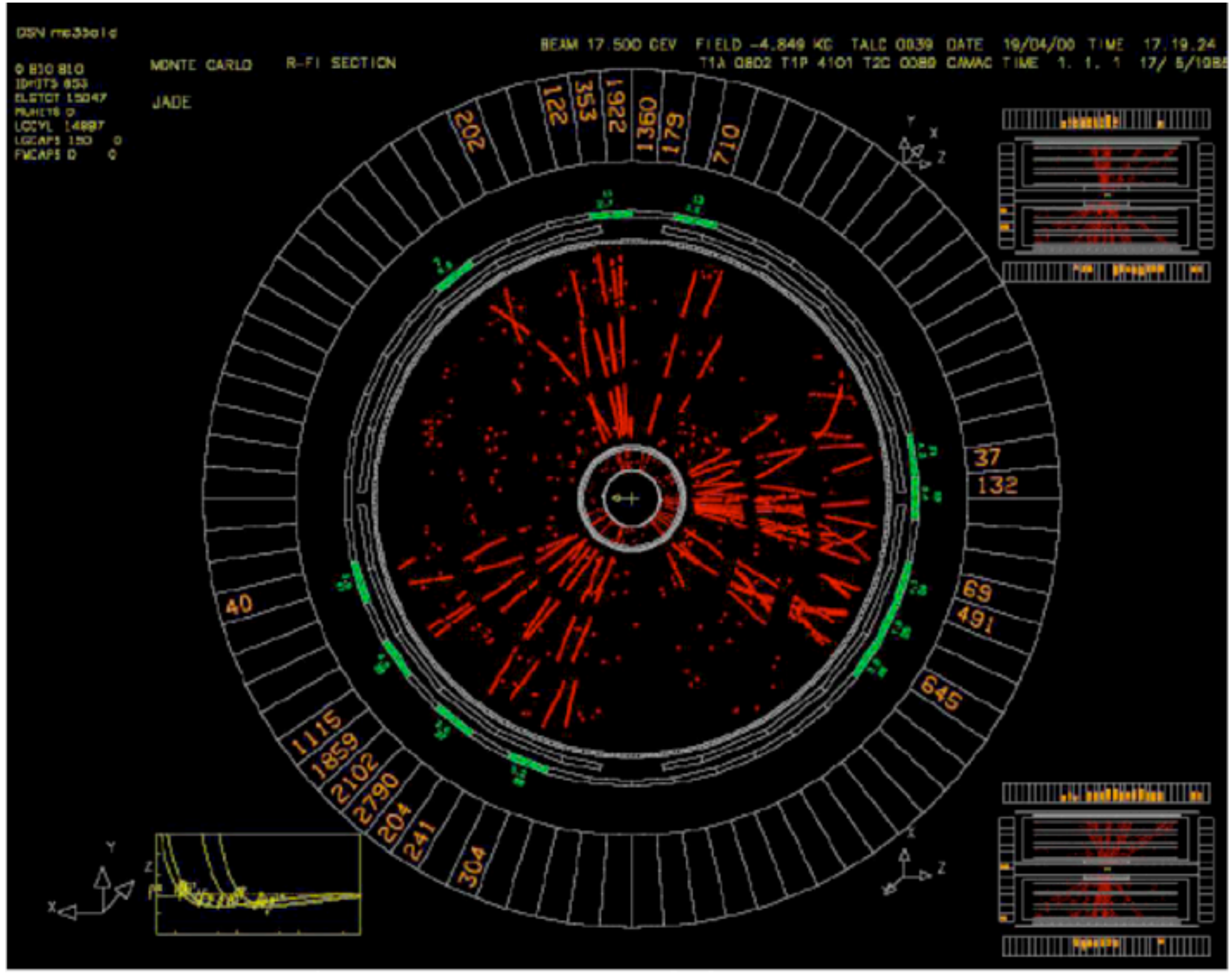


as a three-jet event,



Three-Jet Events

marks the discovery of the gluon.

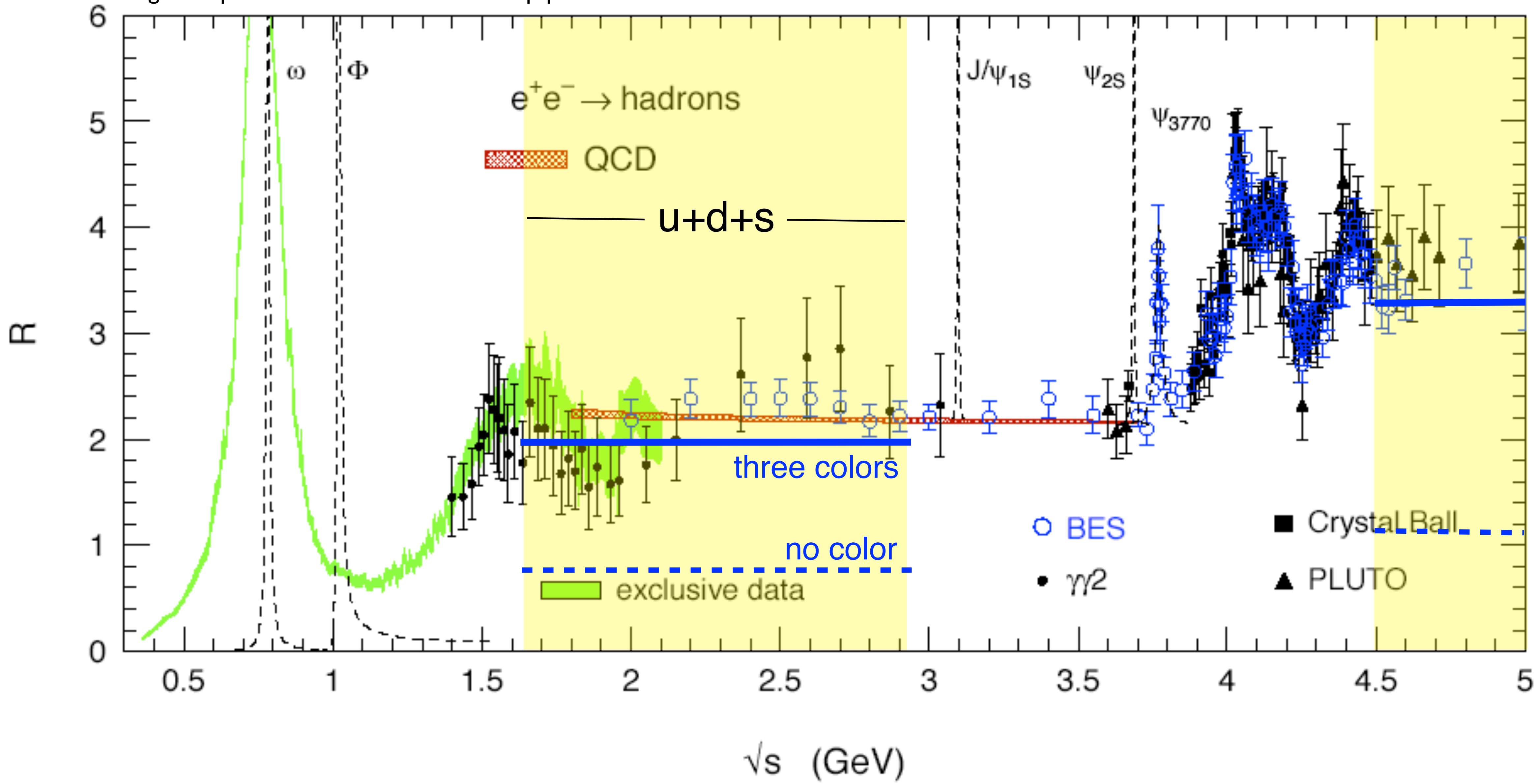


Intermezzo

Role of e^+e^- collisions goes well beyond the discovery of the gluon,

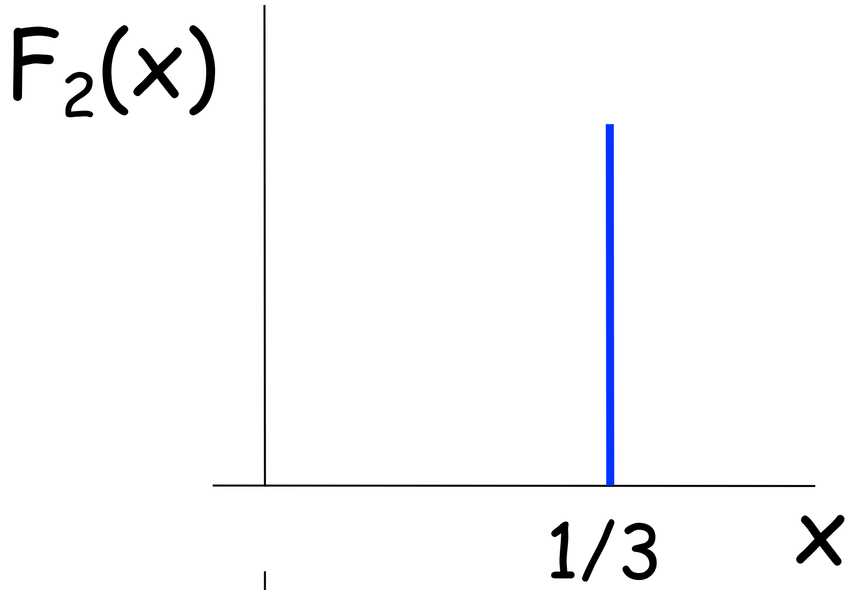
Color in QCD is a common textbook example:

Figure reproduced from Davier et al. hep-ph/0208177

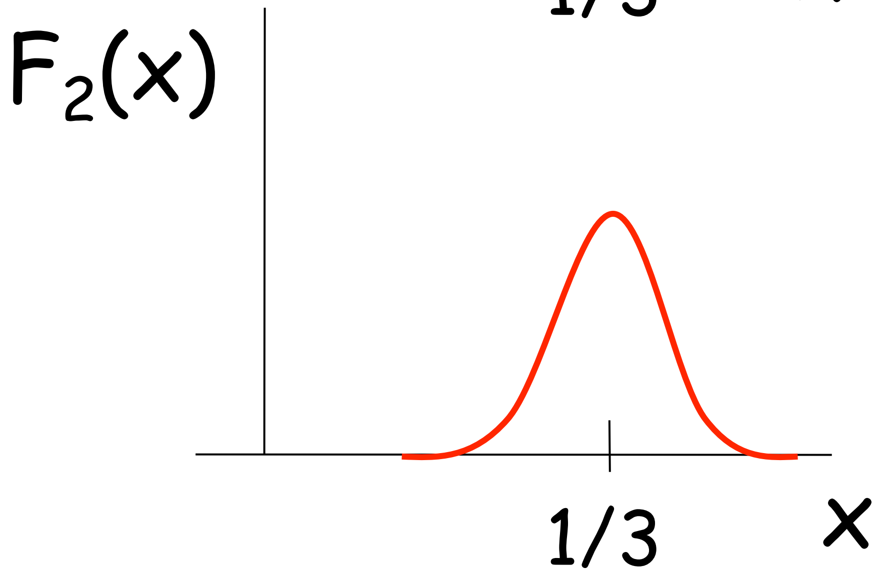


e^+e^- collisions drive insights into fragmentation functions, or colloquially how quarks (and gluons) form hadrons — see e.g. Metz and Vossen, Prog. Part. Nucl. Phys. 91 (2016) 136

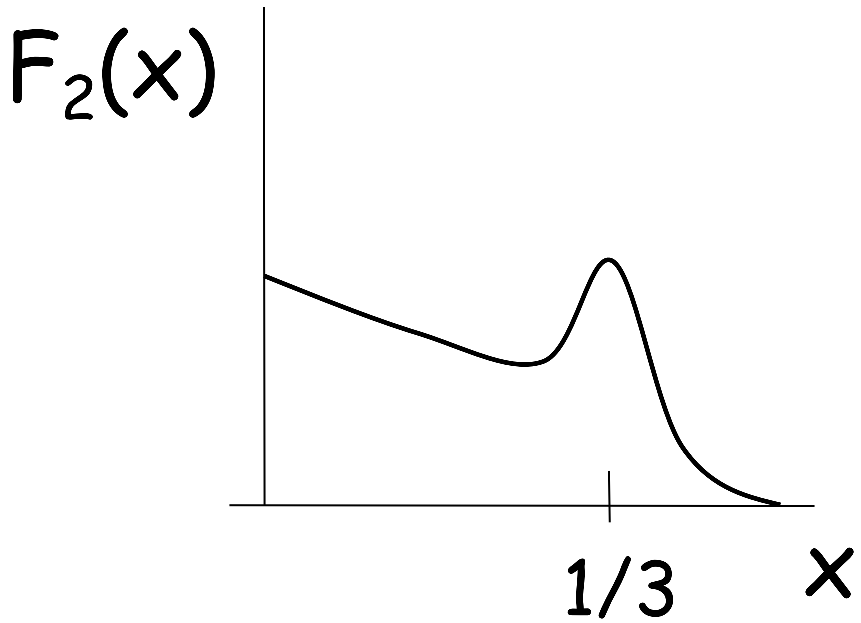
Nucleon Structure



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



Three quarks with some momentum smearing.

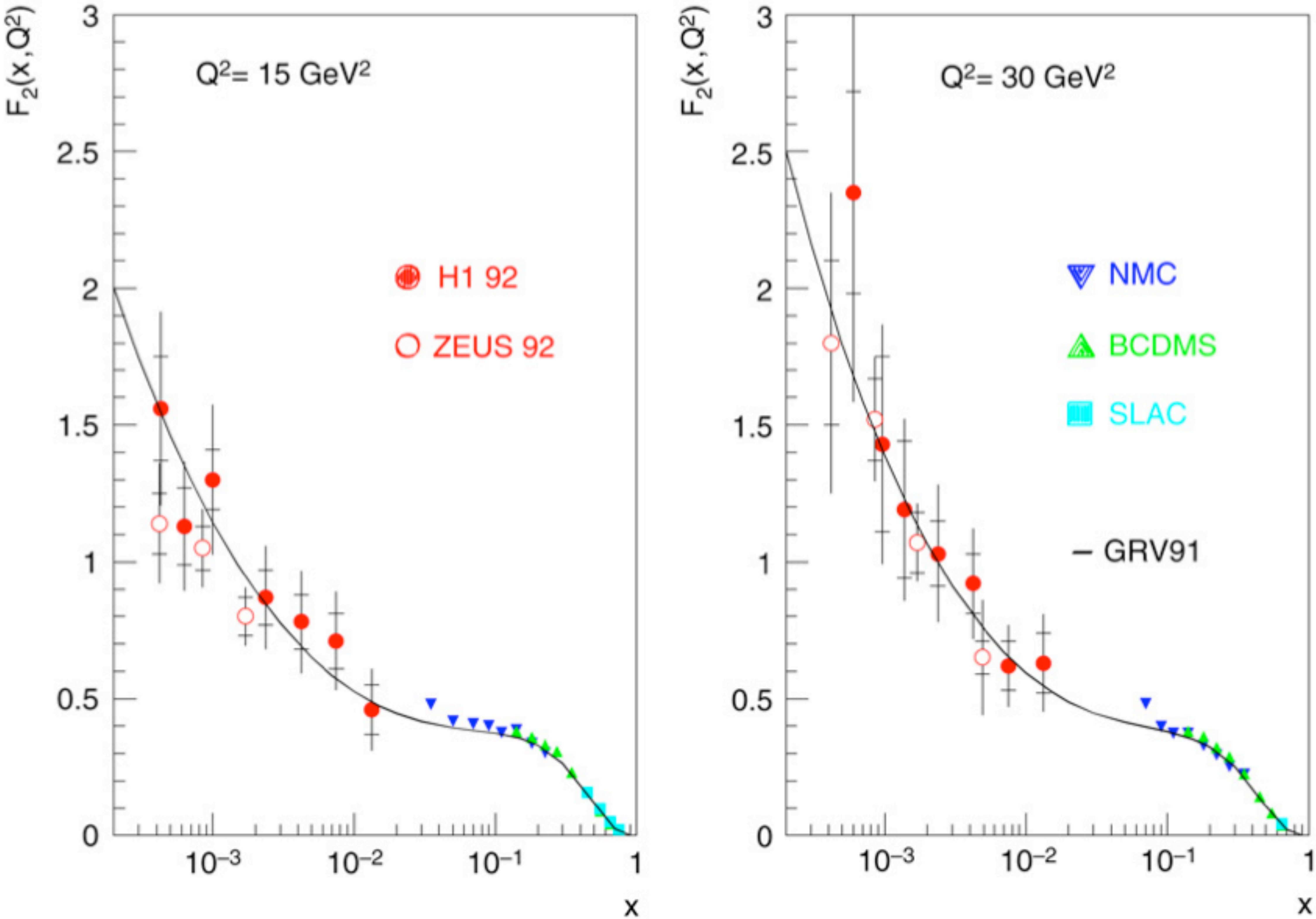


The three quarks radiate partons to lower momentum fractions *x*.

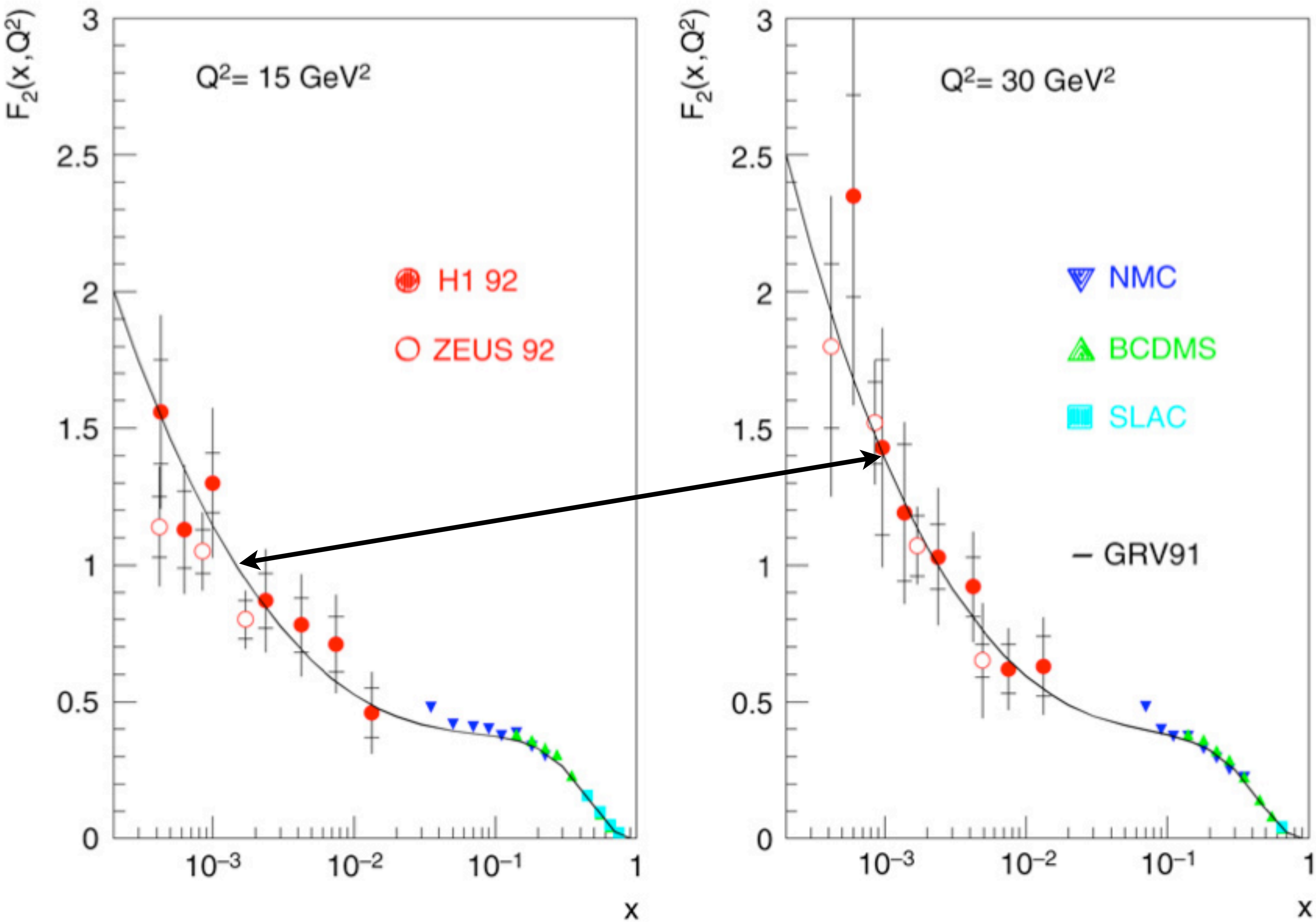
The first EIC, HERA, was a treasure trove of insight.

HERA - Electron Proton Collider

HERA - Early Measurements



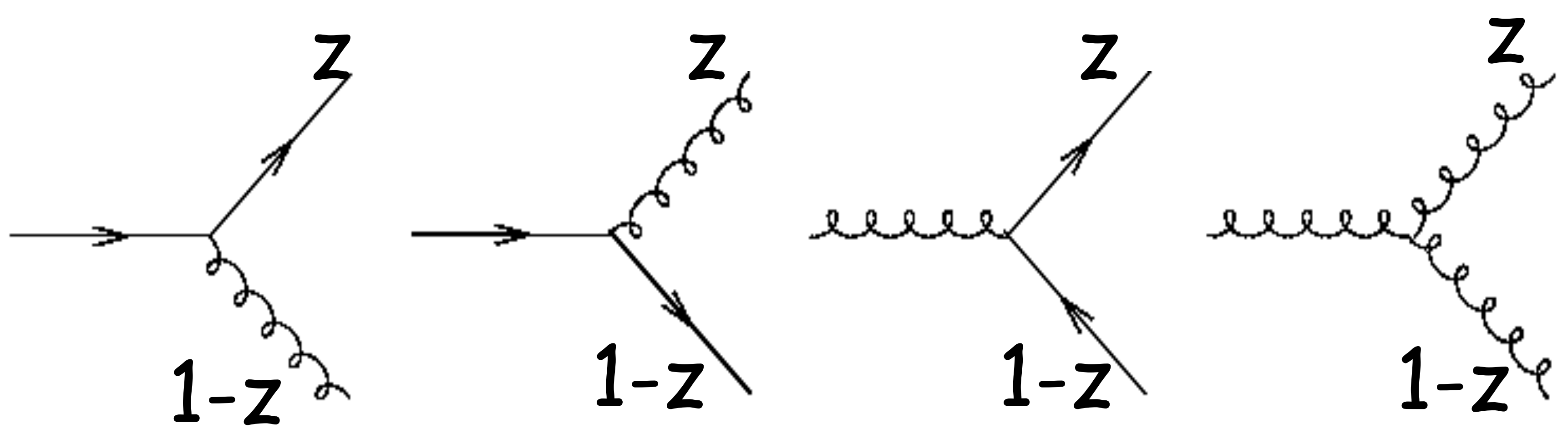
HERA - Early Measurements



(How) 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

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*.

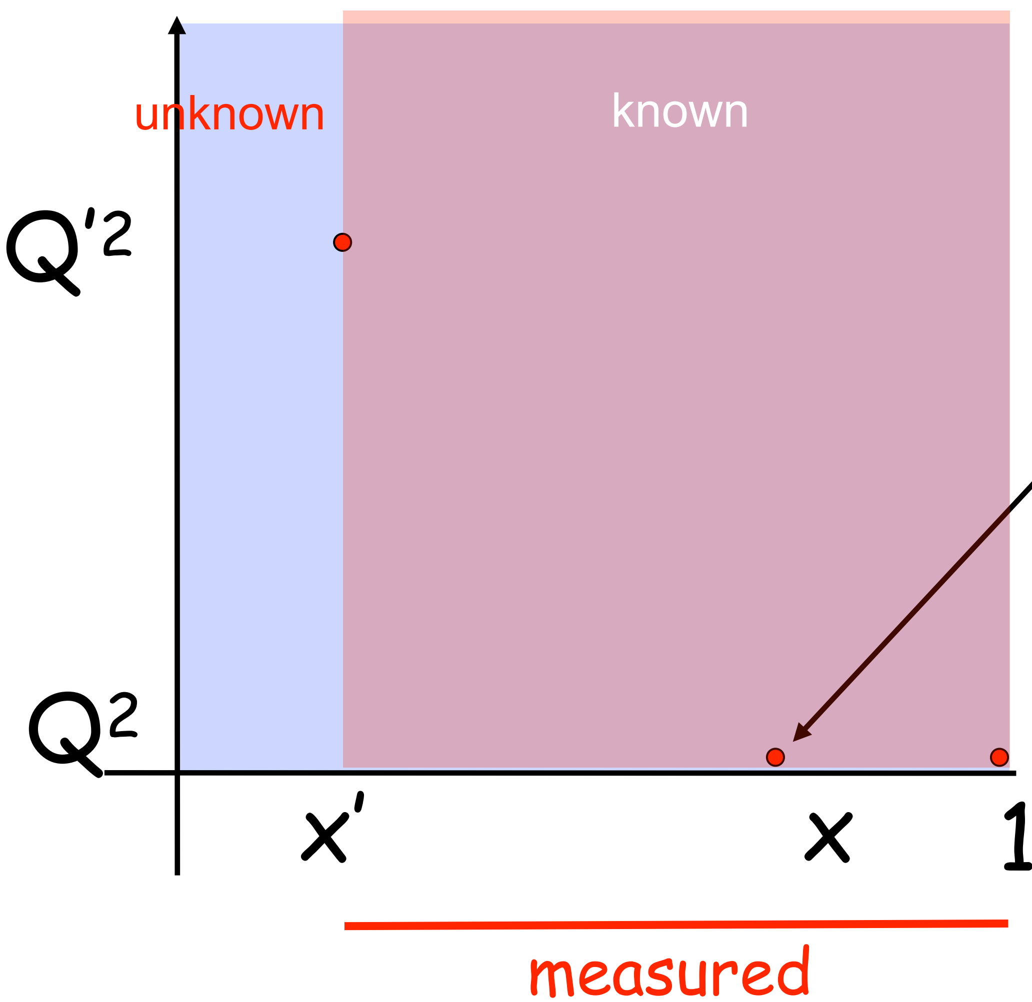
Similarly, for gluons:

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

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.

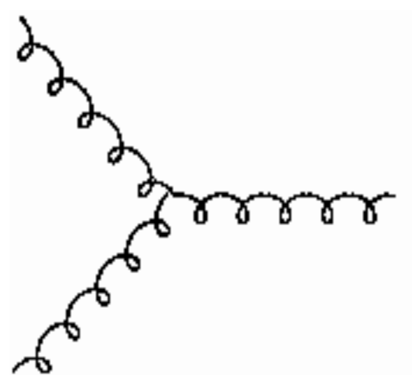
It is necessary and sufficient to know the parton densities in the range $x' \leq x \leq 1$ at a lower Q^2 to determine the parton density at x', Q'^2.

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.

QCD Radiation

DGLAP is *highly* successful, but not the only approach.



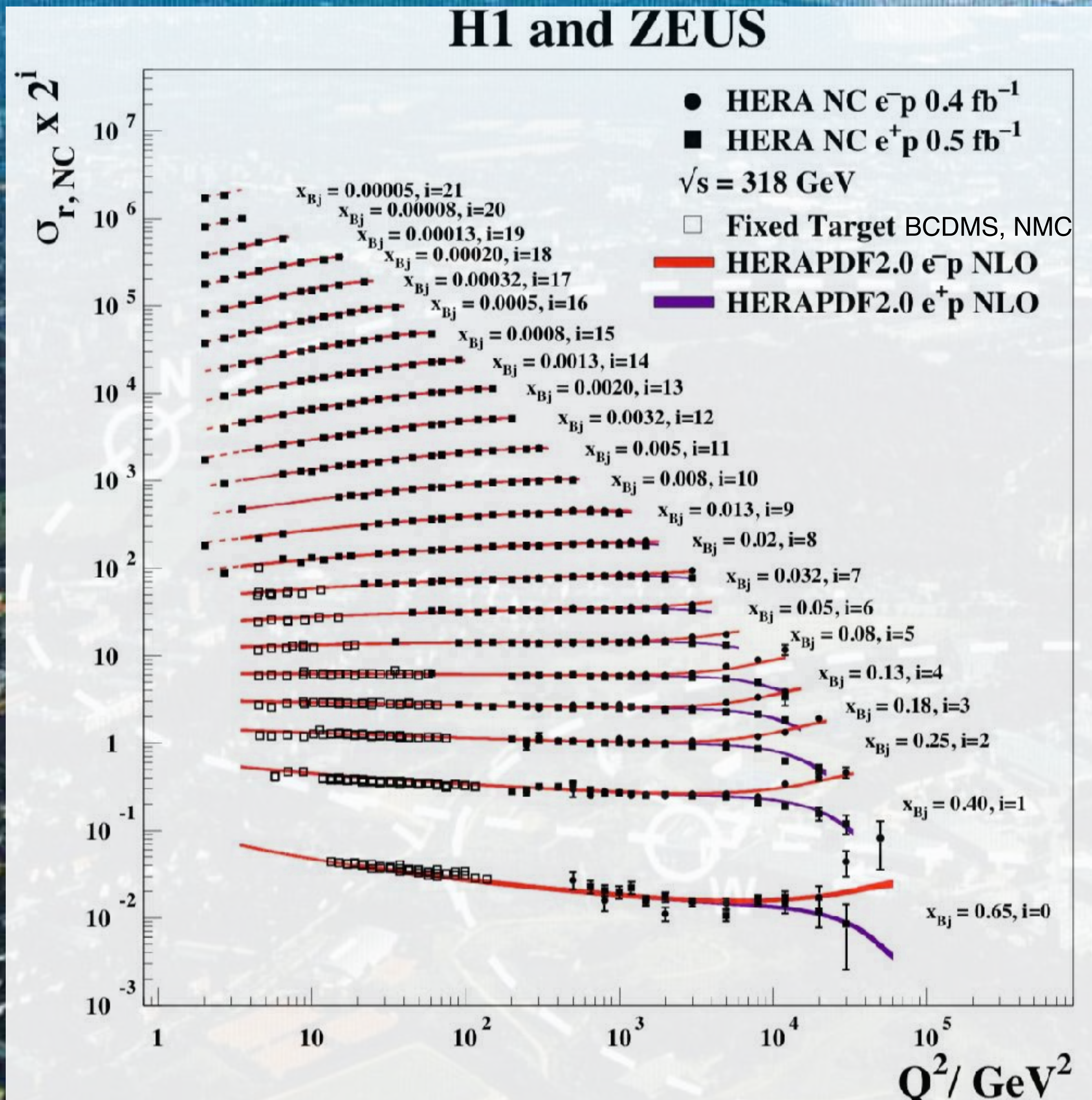
Gluons do not recombine,
incoherence is preserved.

Gluon-dense environments?

Similarly, process-independent quarks, survive.

HERA’s Legacy

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

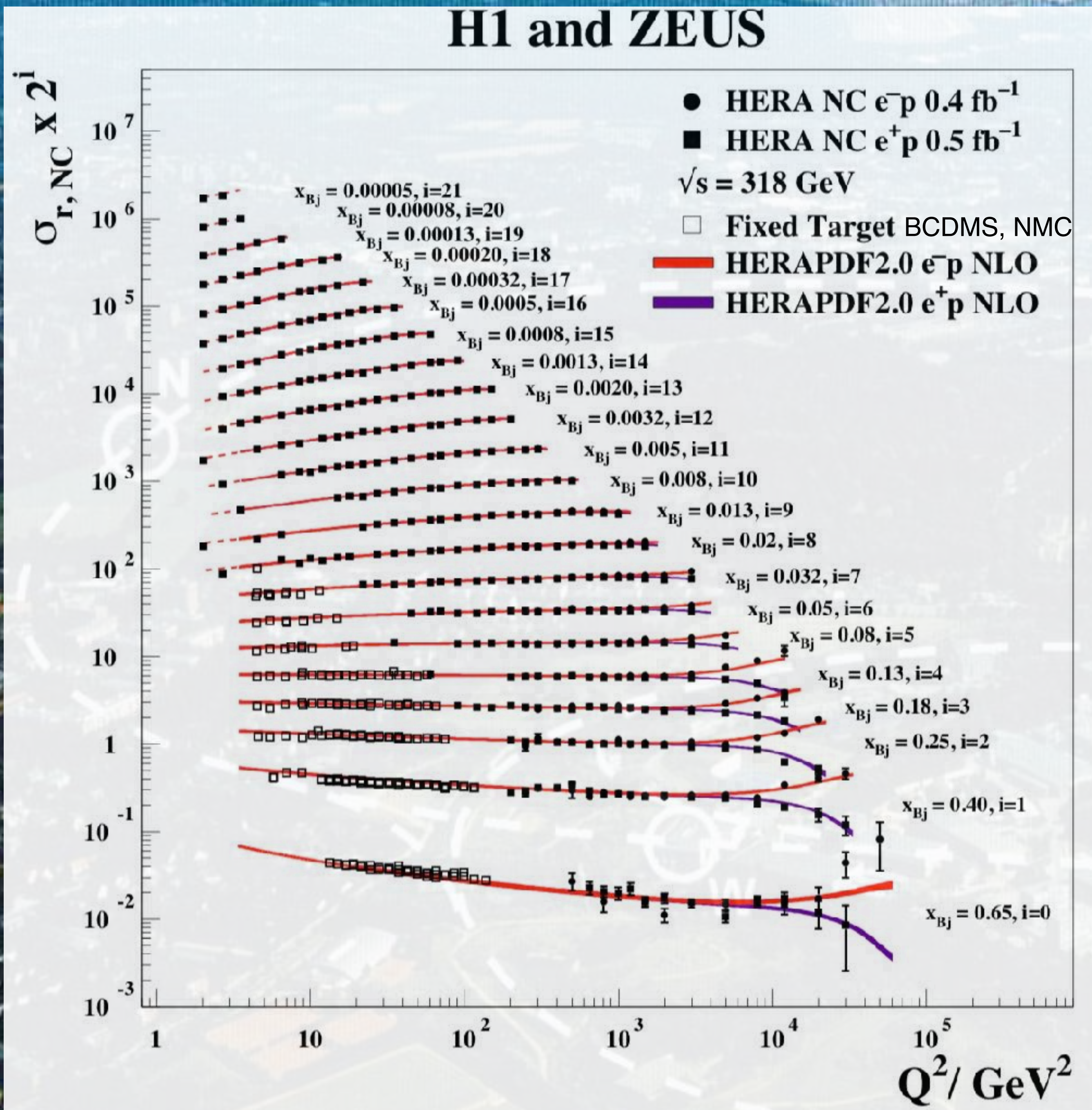


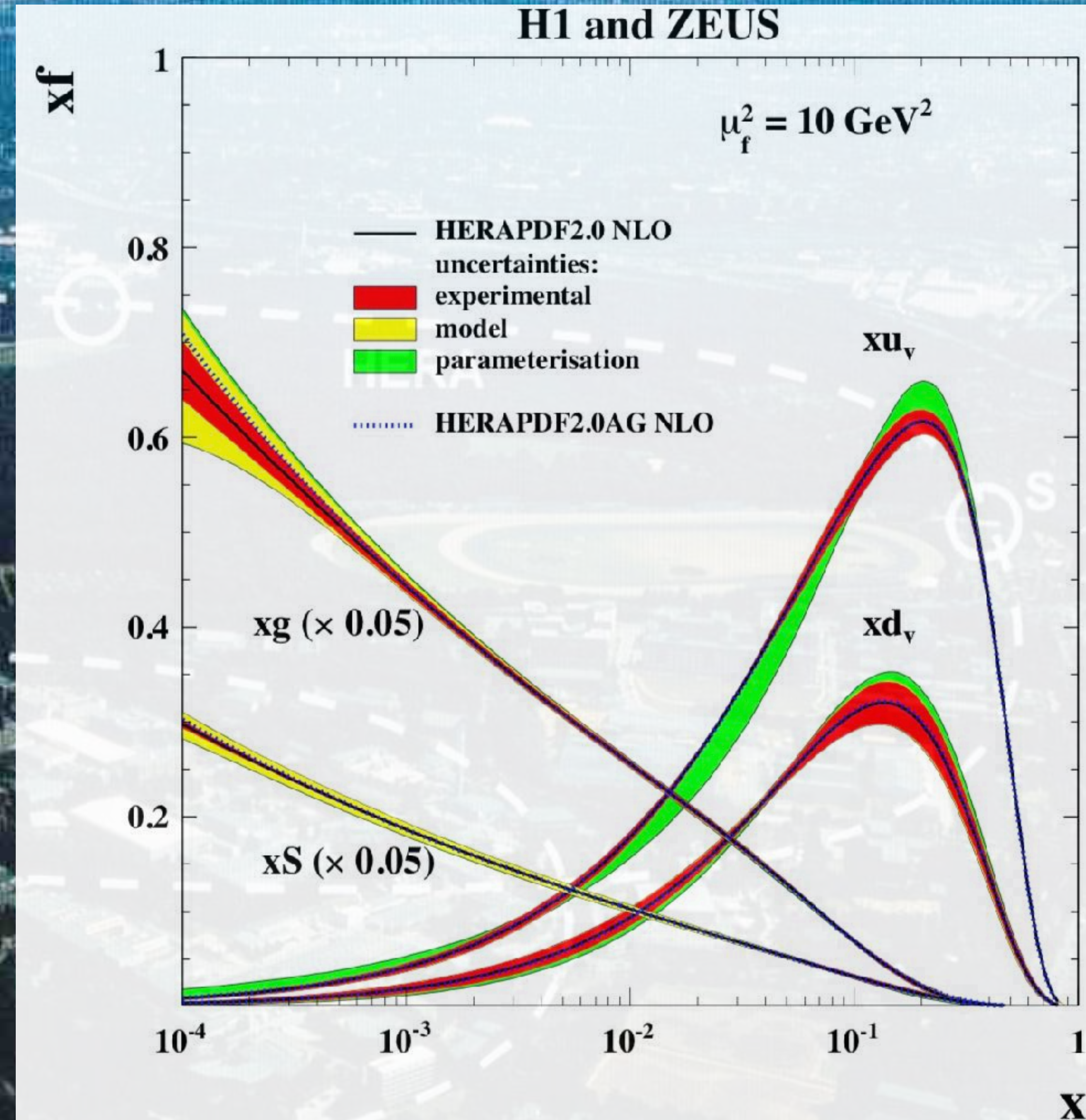
A lot in this plot:

- 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. contributions at high Q^2,
- crucial input to “PDF fits”

HERA's Legacy

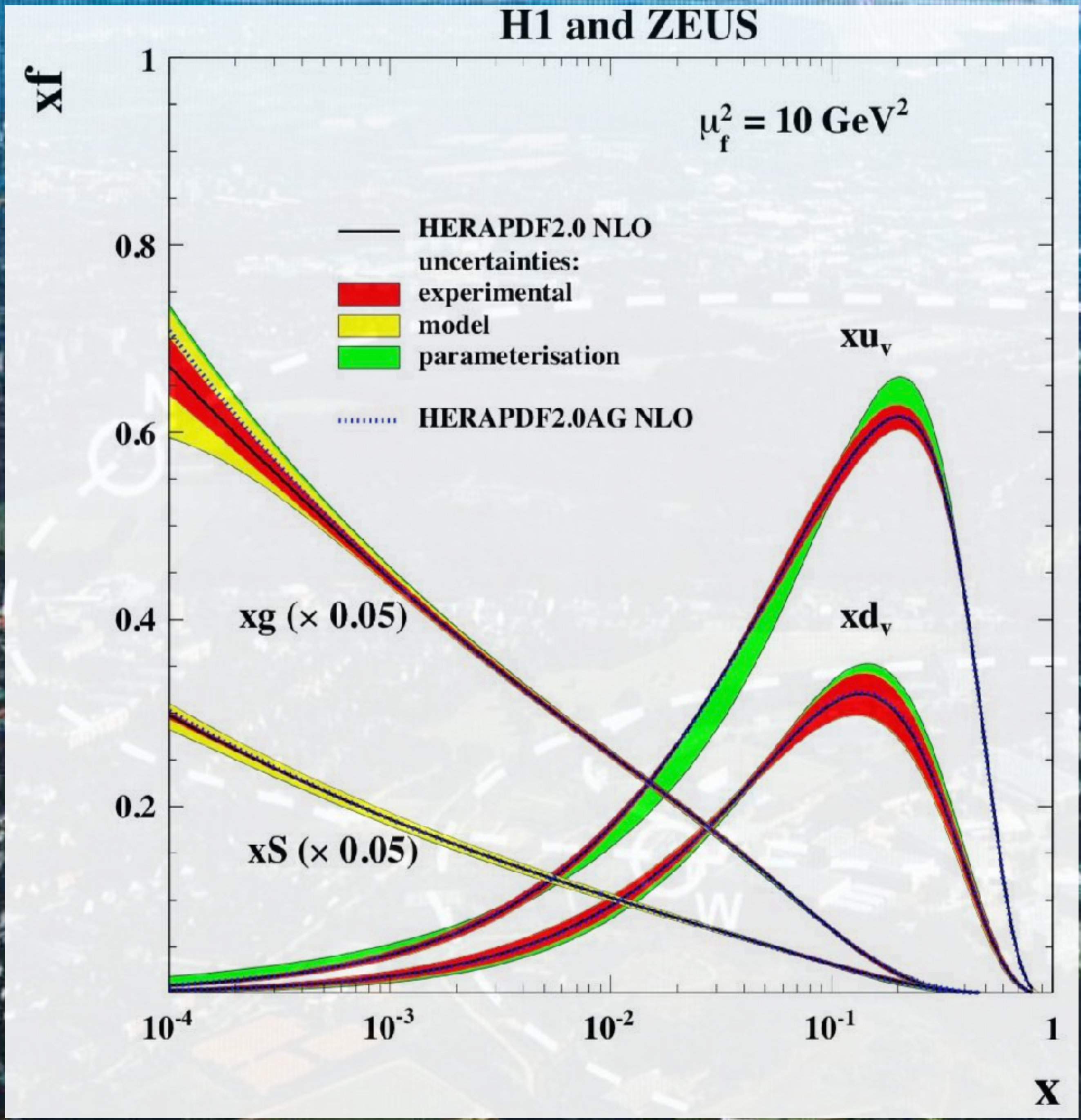
H1 and ZEUS Coll., EPJ C75 (2015) 580





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 $x < 0.1$,

HERAPDF2.0:

14 parameters,

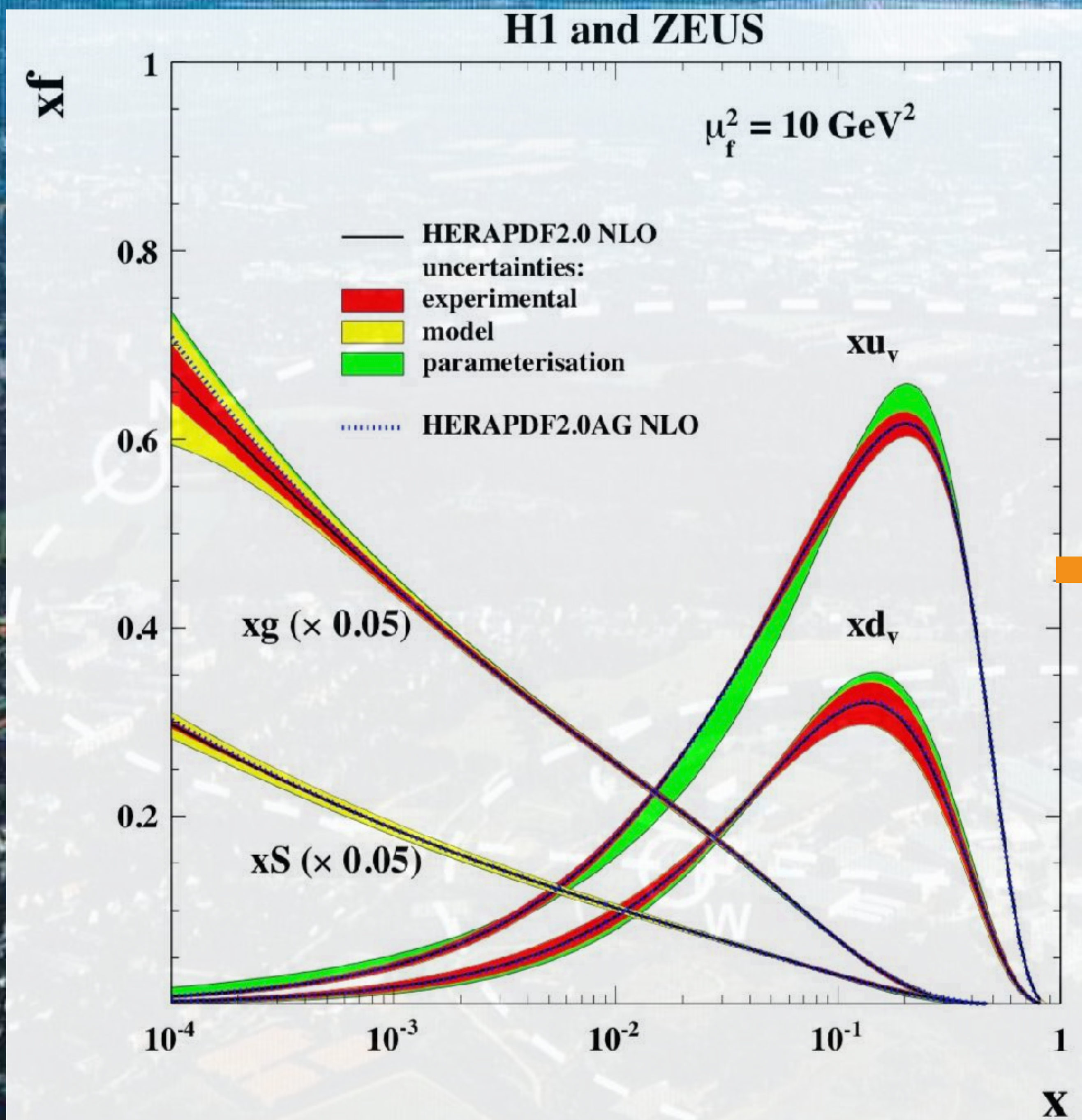
~1400 combined data points,

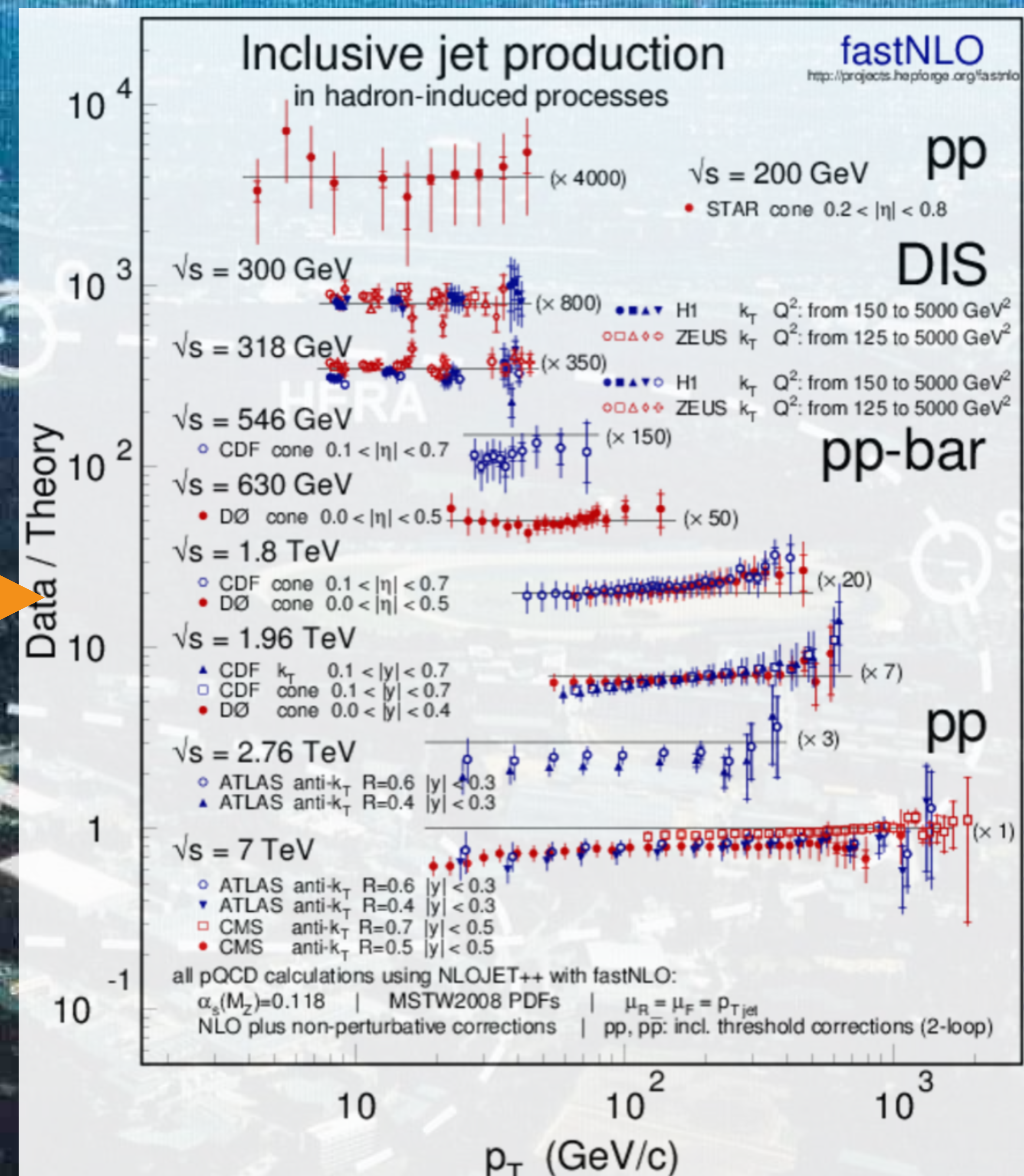
Gluon content increases with decreasing *x*,

Gluons pose a number of questions

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

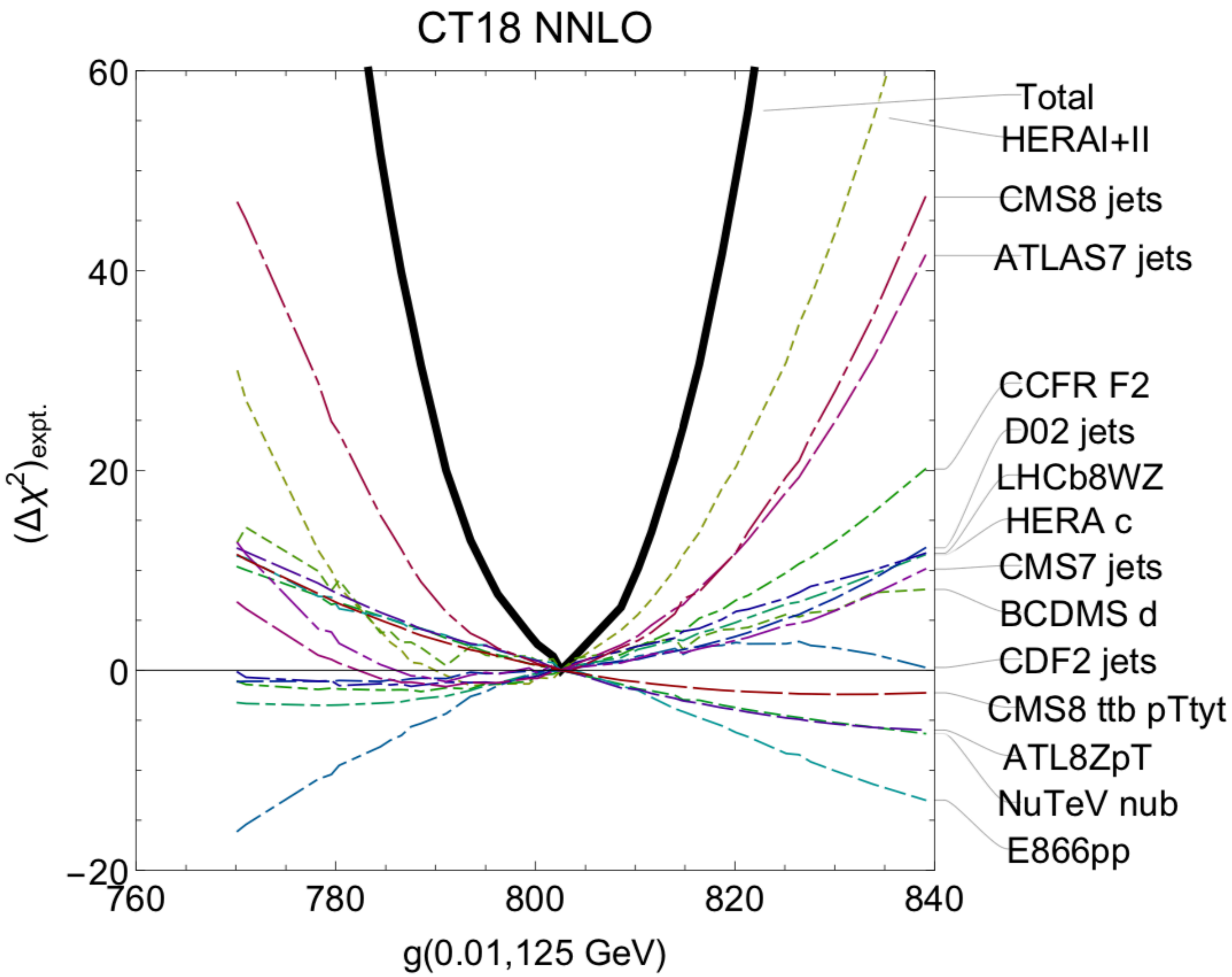
HERA's Legacy

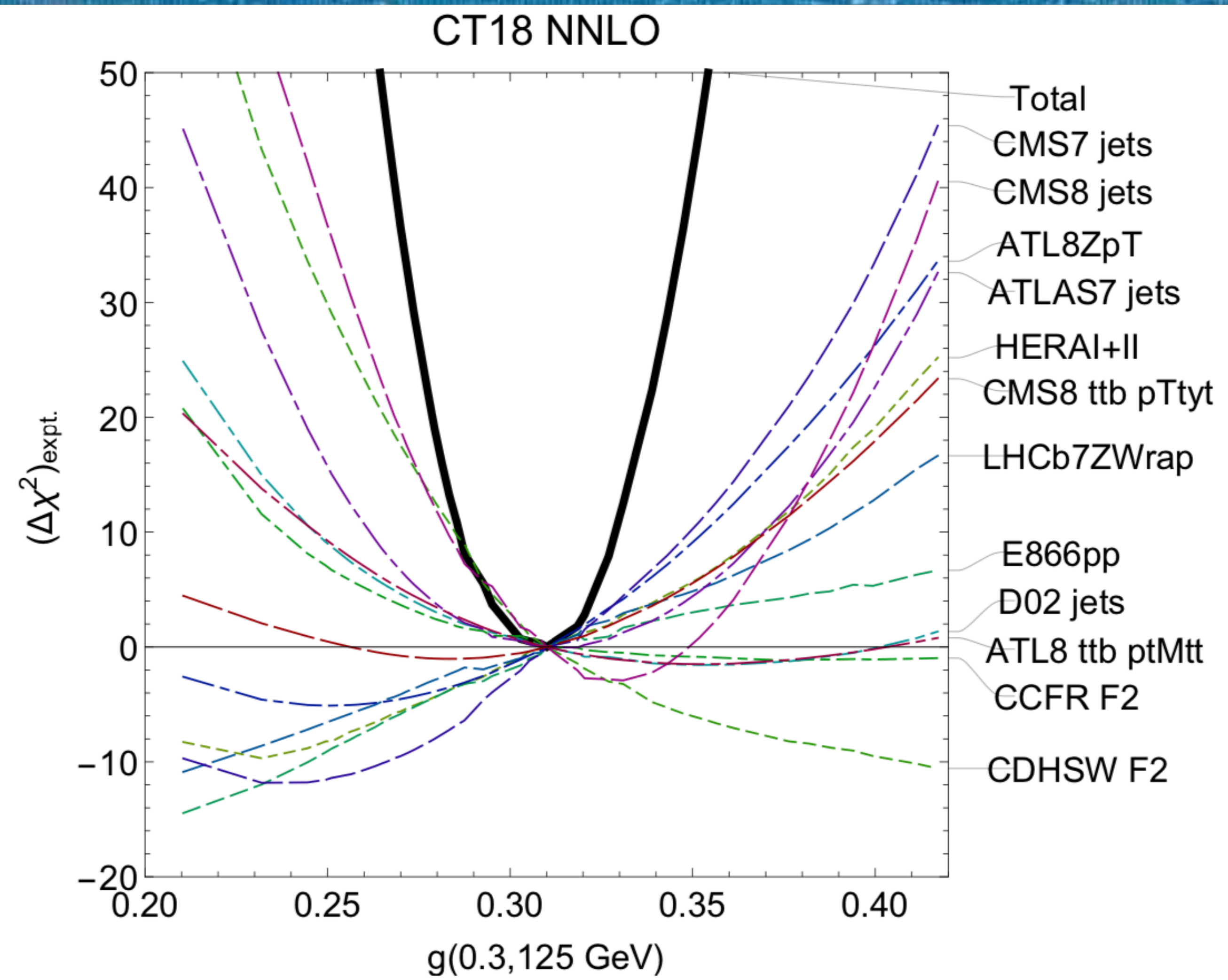




Factorization, the separation of short distance and long distance physics, combined with PDFs are 'universally invaluable' in hard scattering processes.

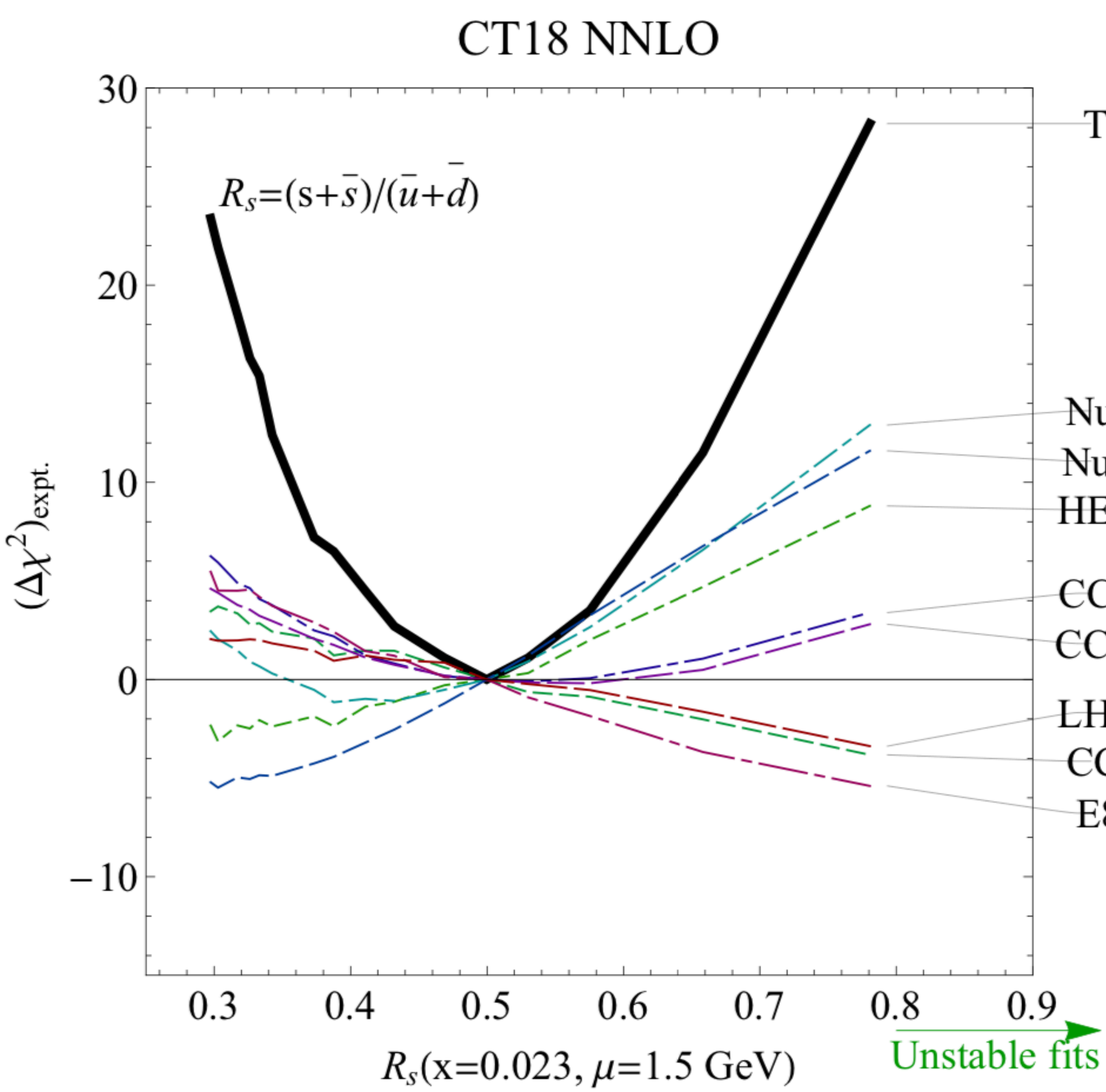
Intermezzo - Truth in advertising….

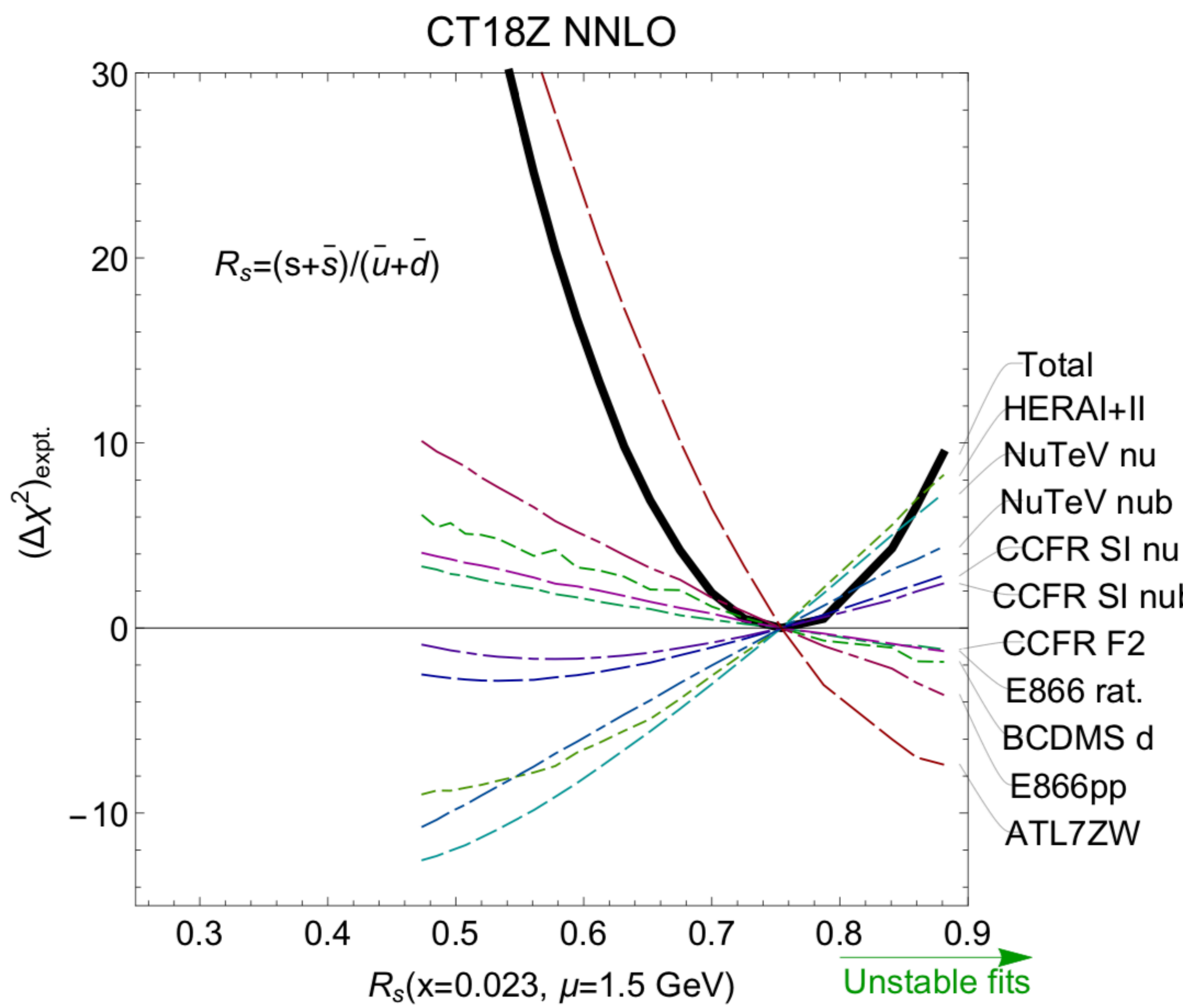




A great deal has been learned and continues to be learned from other experiments, e.g. from the LHC…. Shown here CTEQ fits, arXiv:1908.11238

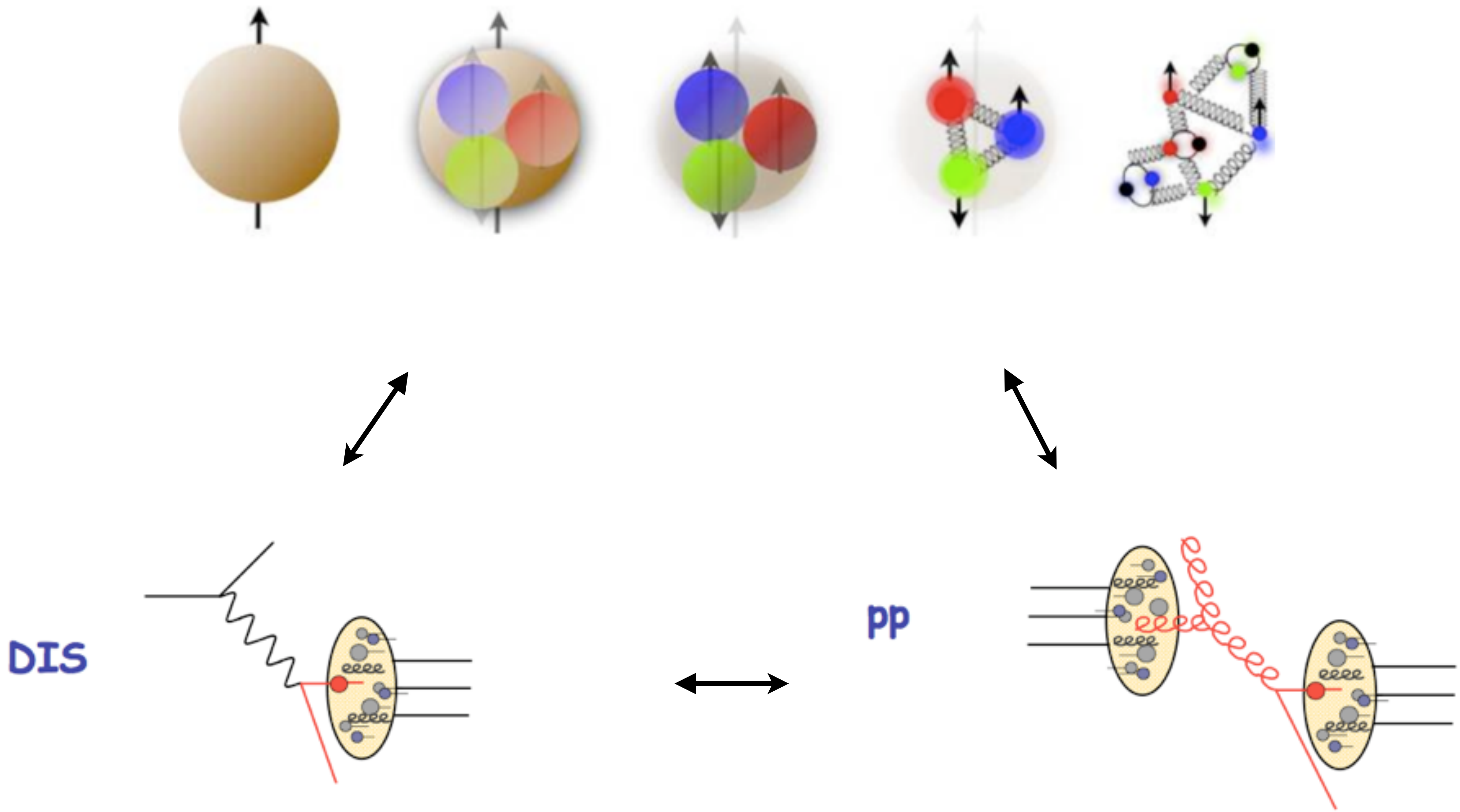
Intermezzo - Truth in advertising….





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

Intermezzo - Truth in advertising….



What *is* a proton, neutron, nucleus?

At high energy: an unseparated, broadband beam of quarks, anti-quarks, and gauge bosons (primarily gluons), and perhaps other constituents, yet unknown.

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

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

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Renormalization group-improved Parton Model

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

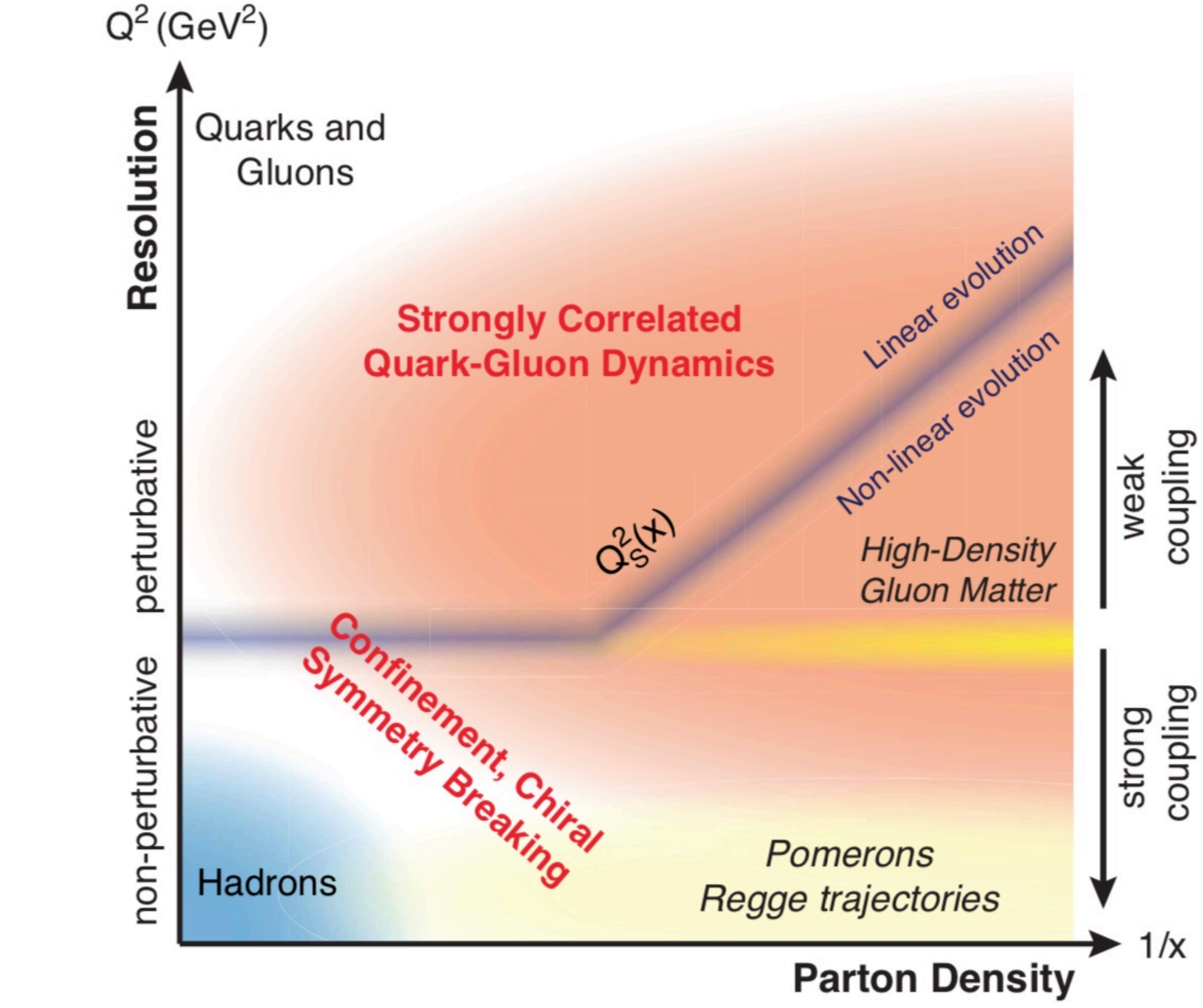
Not quite…. ***more than a few high-energy observations are actually different***
QCD is the richest part of the Standard Model Gauge Field Theory and will (have to) be developed much further, on its own and as backgrnd.

HERA - 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



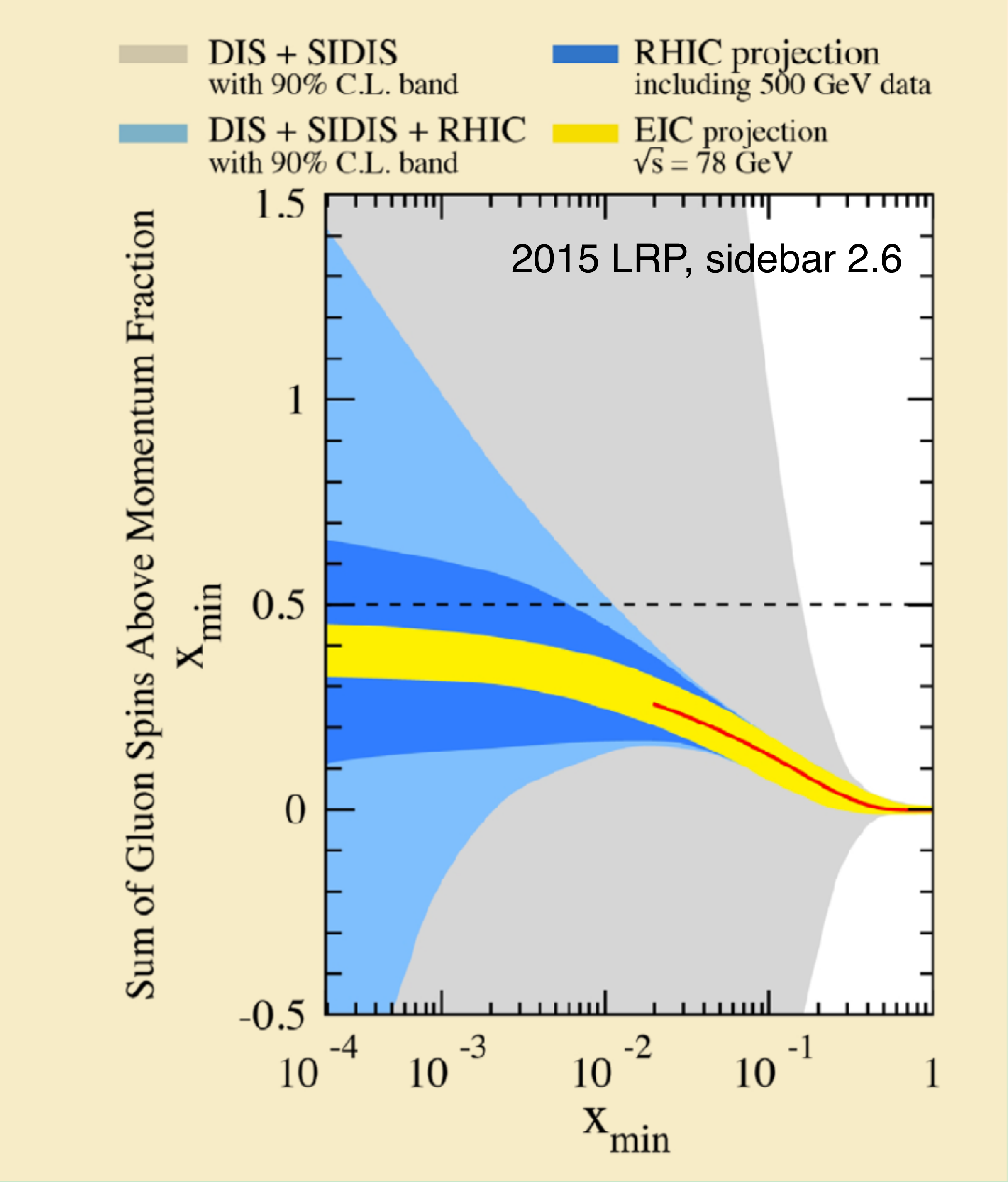
HERA - RHIC, CERN

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:

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

Spin puzzle:

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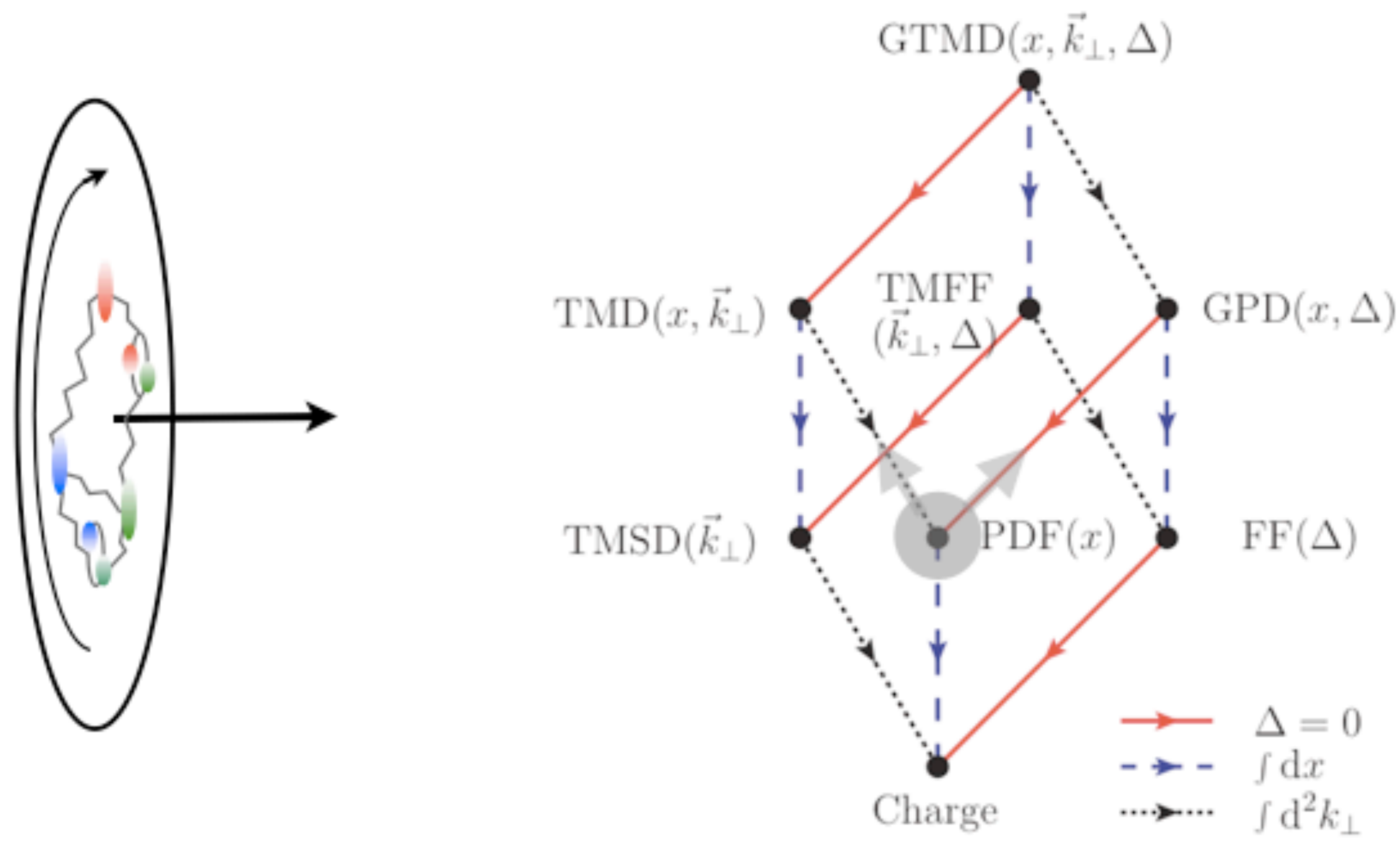
  strange (anti-)quarks?
- large forward transverse-spin phenomena
- Lattice-QCD is making impressive progress,

Imaging / tomography:

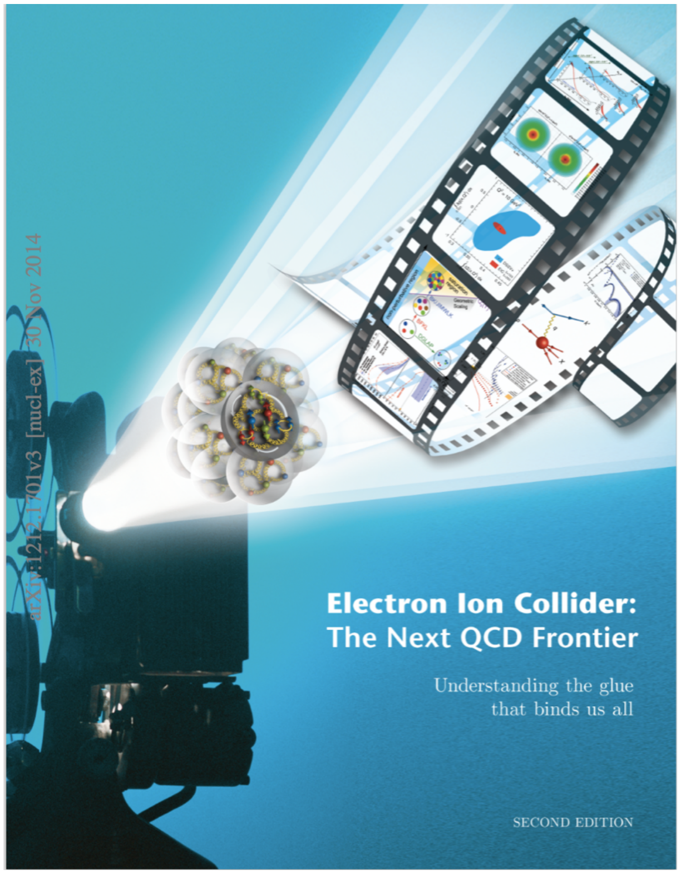
- valence quark region,



Lorce, Pasquini, Vanderhaeghen

Early 2030s Future - Electron-Ion Collider

arXiv:1212.1701, EPJ A52 (2016) 268

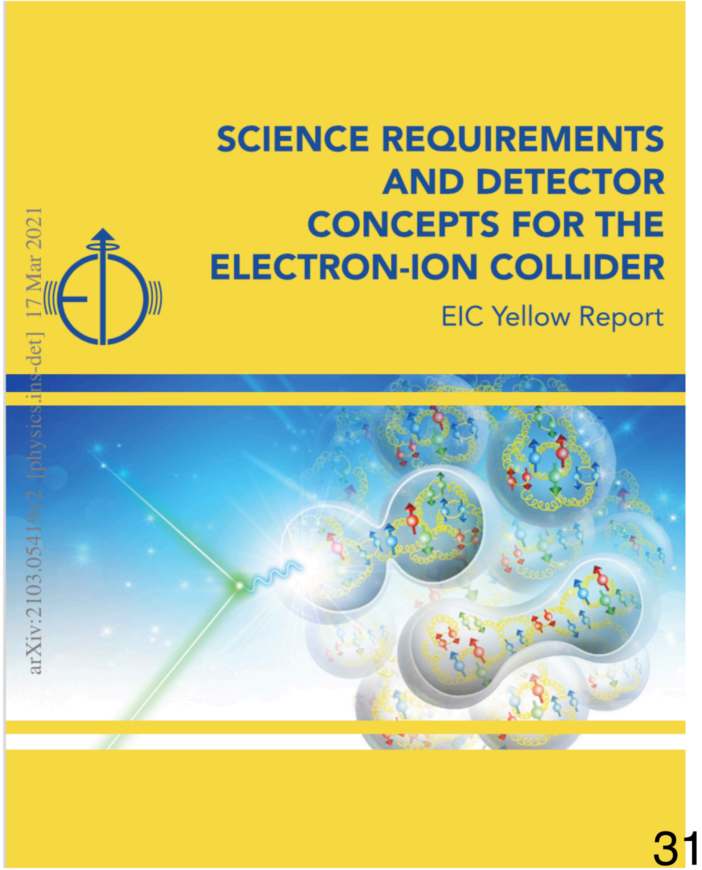


Four central nuclear physics themes:

- 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,

arXiv:2103.05419



2018 NAS Science Assessment:

“EIC is compelling, fundamental, and timely”

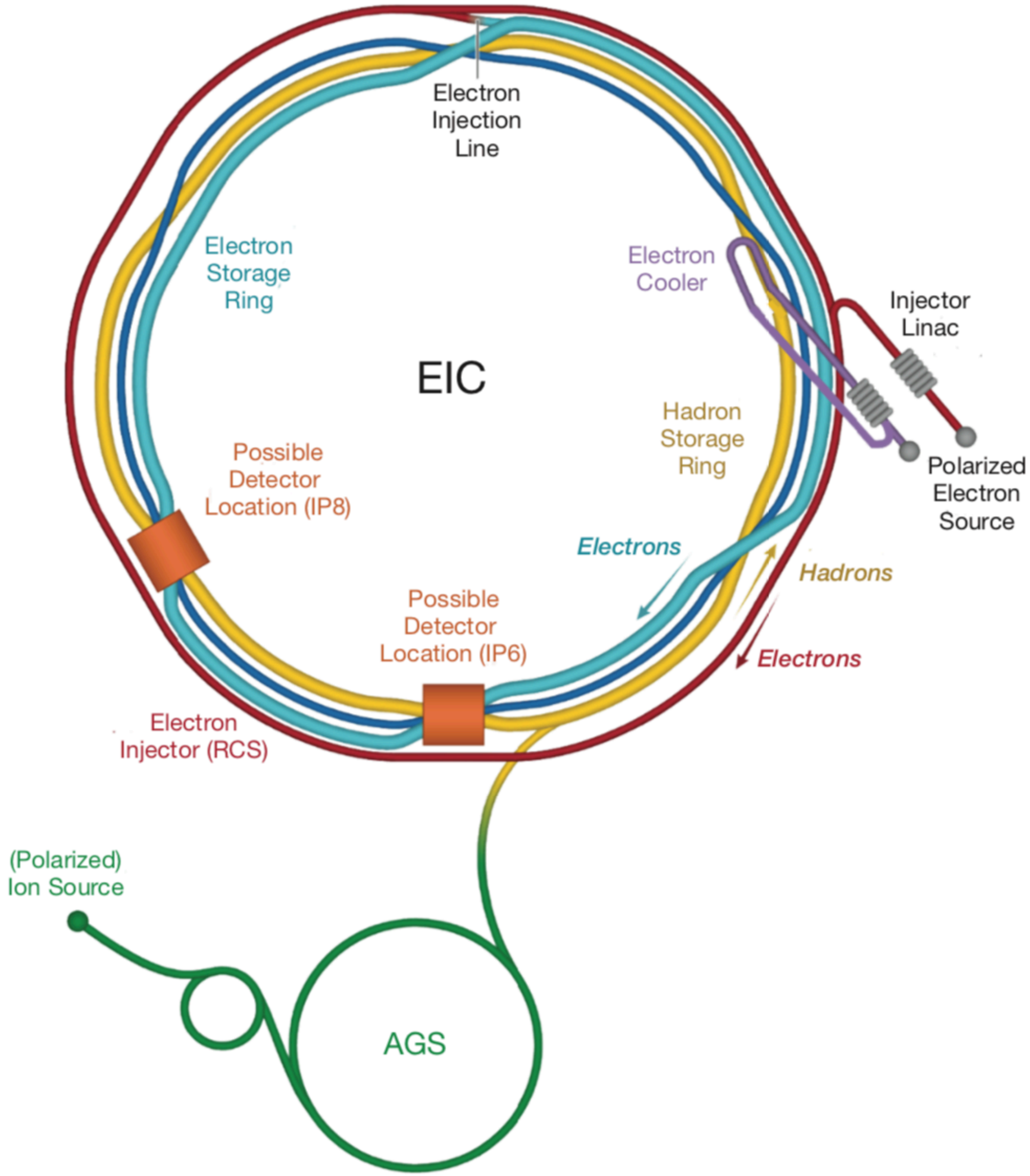
Science case: theory, experiment, *and* accelerator,

2020 site selection — BNL — and formal project start,

2021 EIC User Group has just completed a ~1 year physics and detector conceptual development study,

2022 Project detector selected following 2021 call for proposals,

Early 2030s Future - Electron-Ion Collider



World-wide unique future facility,

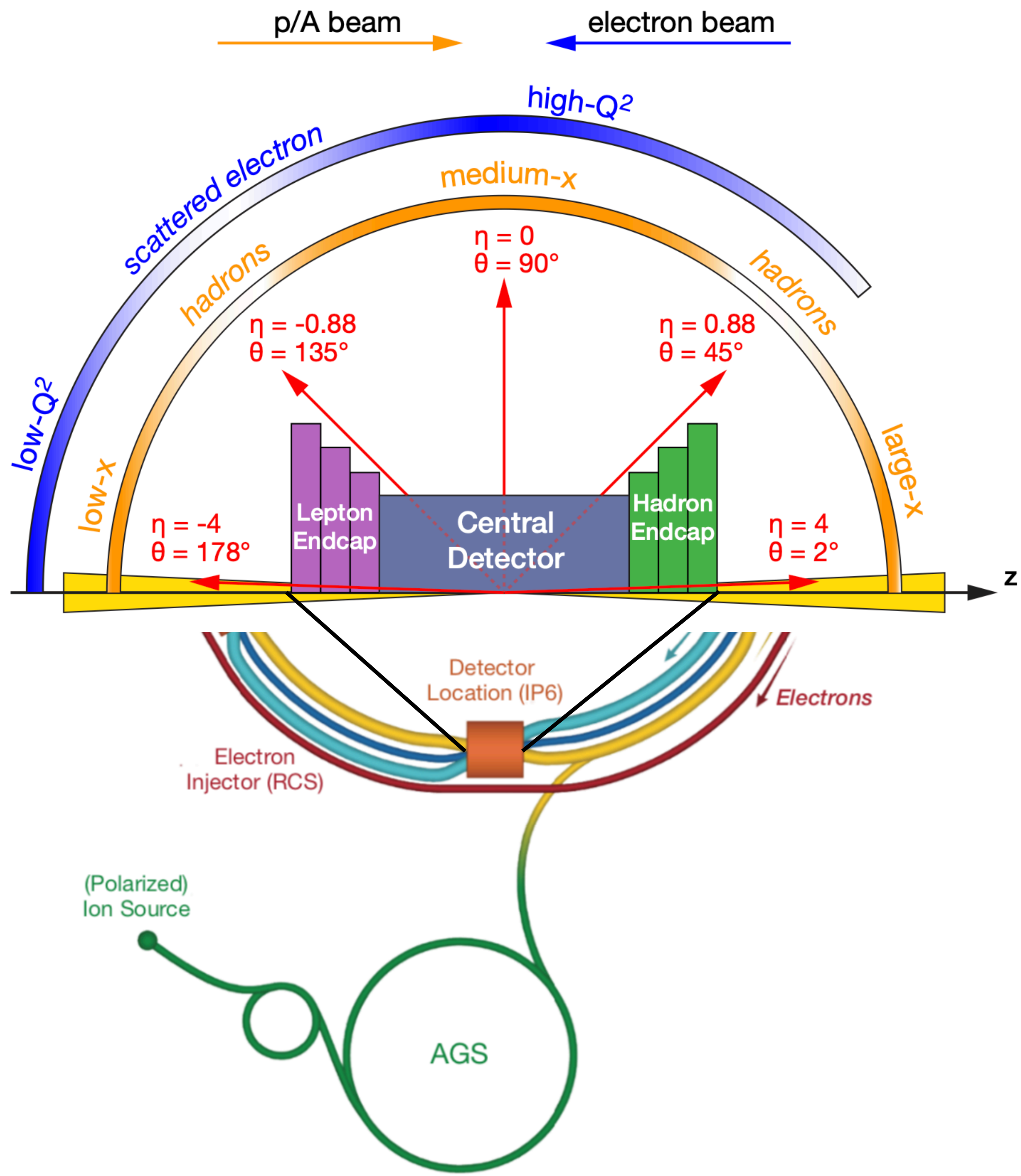
- **e**lectron (+ positron ?) **i**on **c**ollider,
- versatility: polarization, ions,

Characteristics,

- wide range of $\sqrt{s}$ ~20 to ~140 GeV,
- *high* luminosity $10^{33\text{-}34}$ $cm^{-2}s^{-1}$, i.e. 2—3 *orders* beyond HERA,
- (to be) sited at BNL,
- 2 experiment IPs,

"Combines the best of two of the current U.S.-based facilities — Jefferson Lab and RHIC"

Early 2030s Future - Electron-Ion Collider



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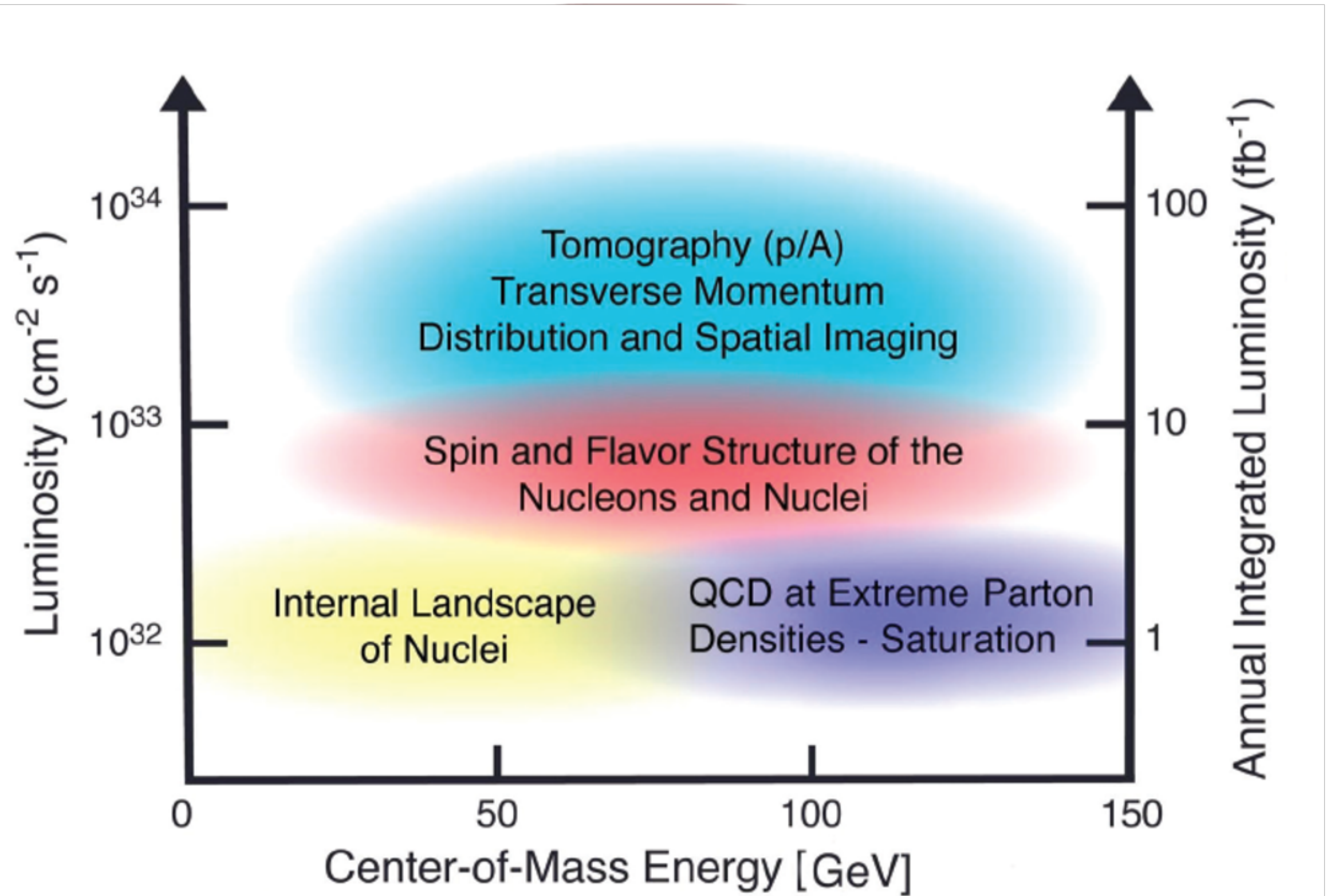

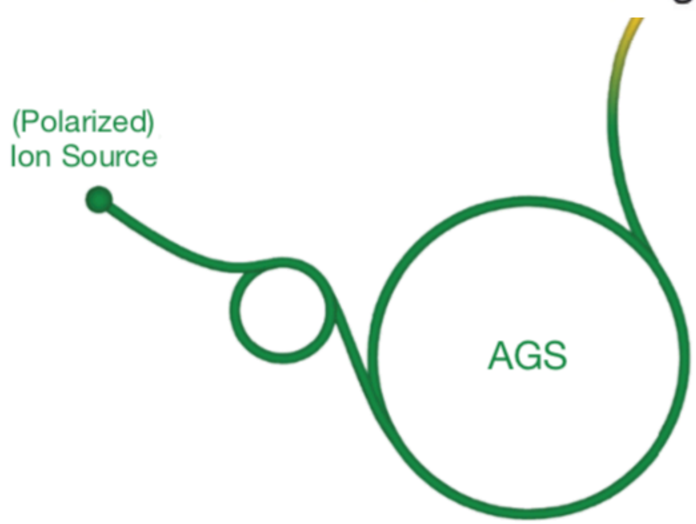

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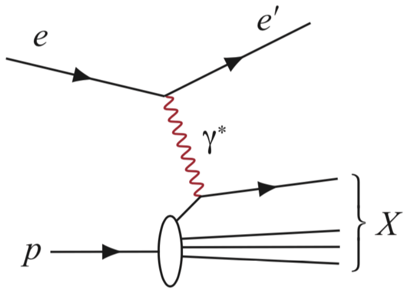
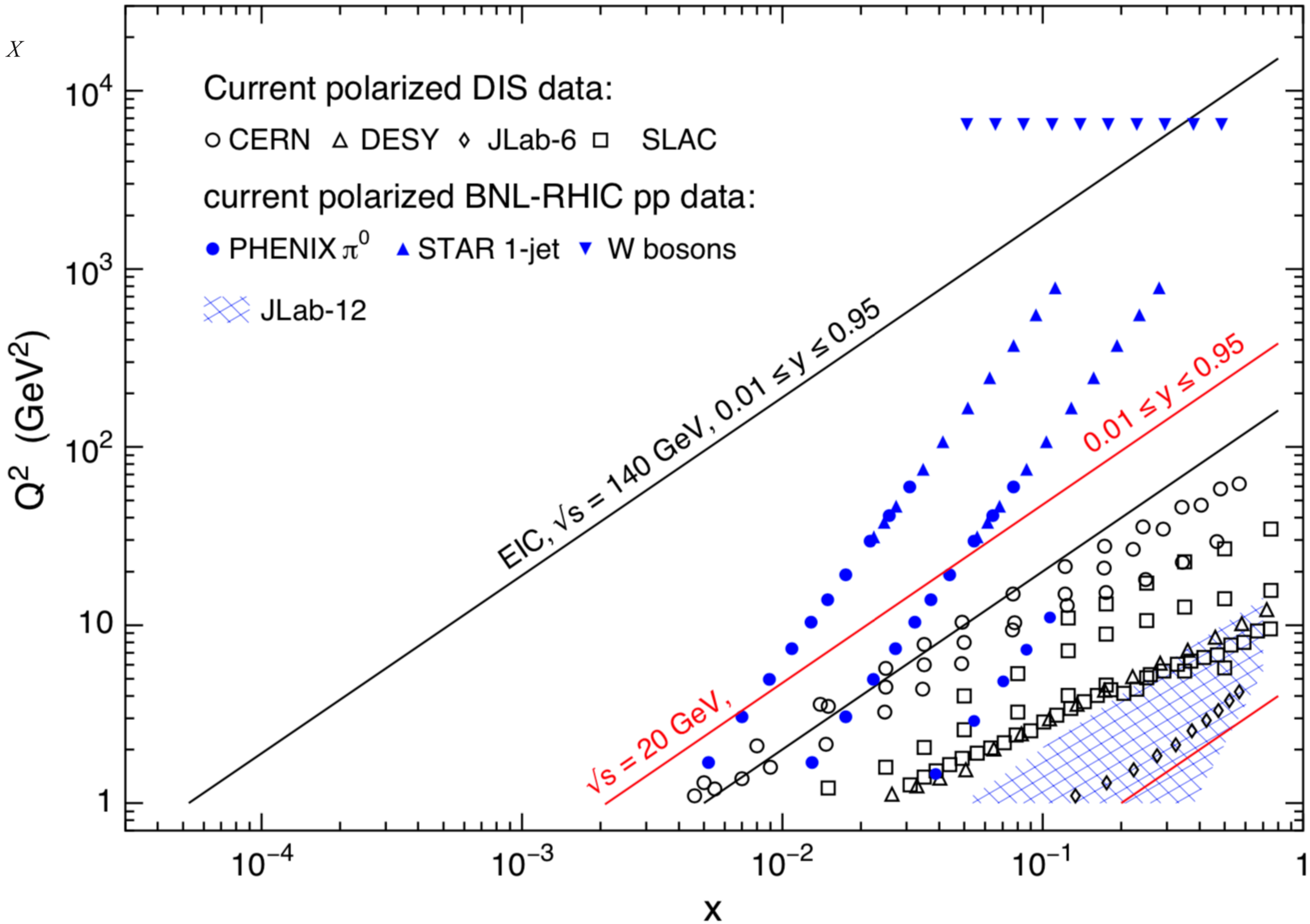
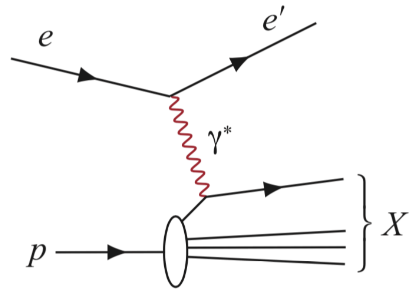
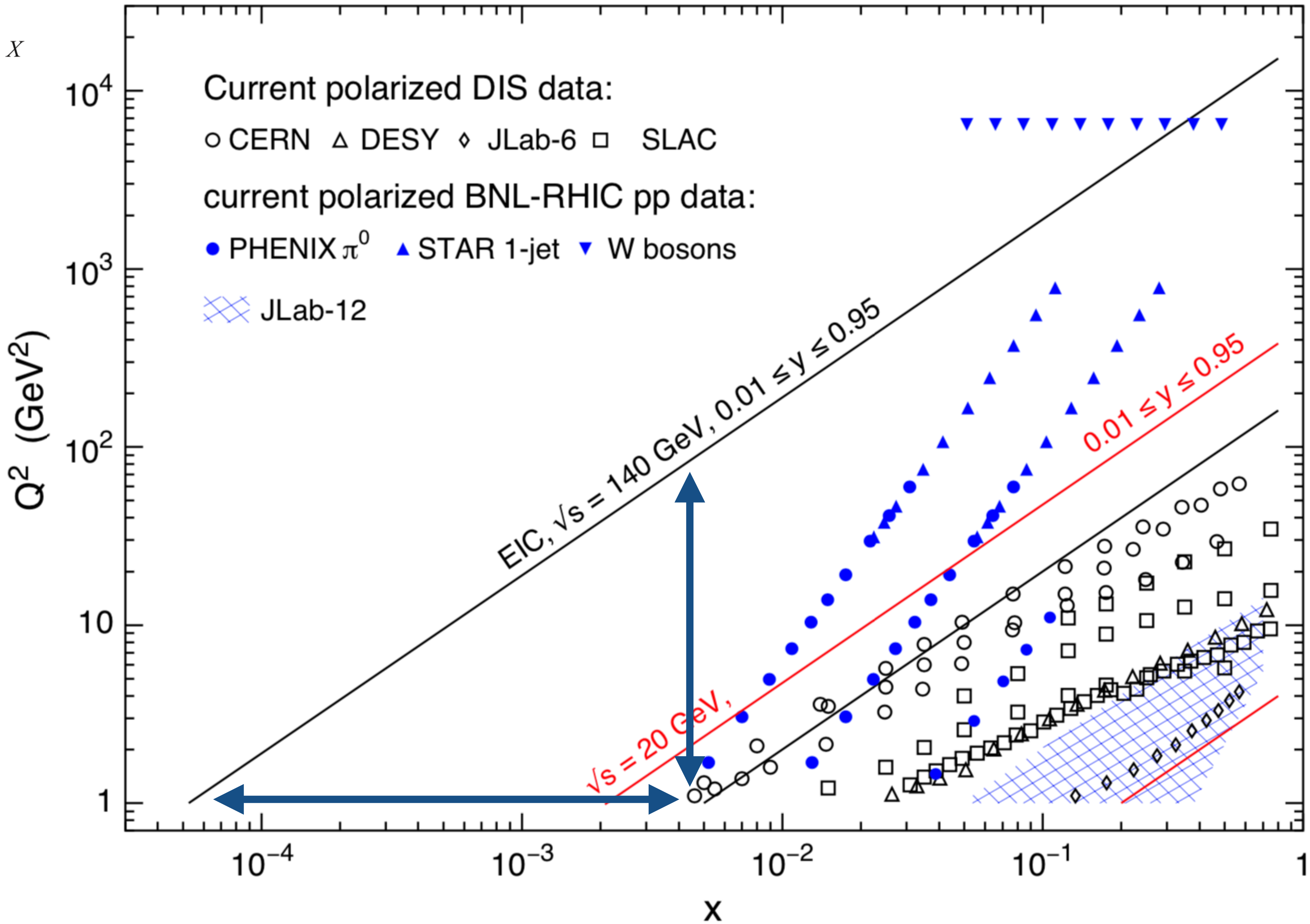
Polarized inclusive DIS Landscape - U.S.-based EIC





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

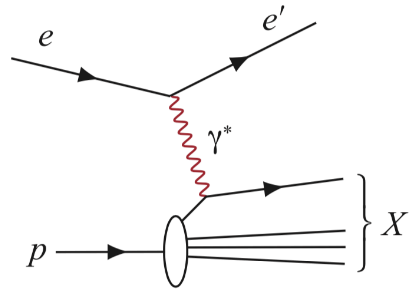




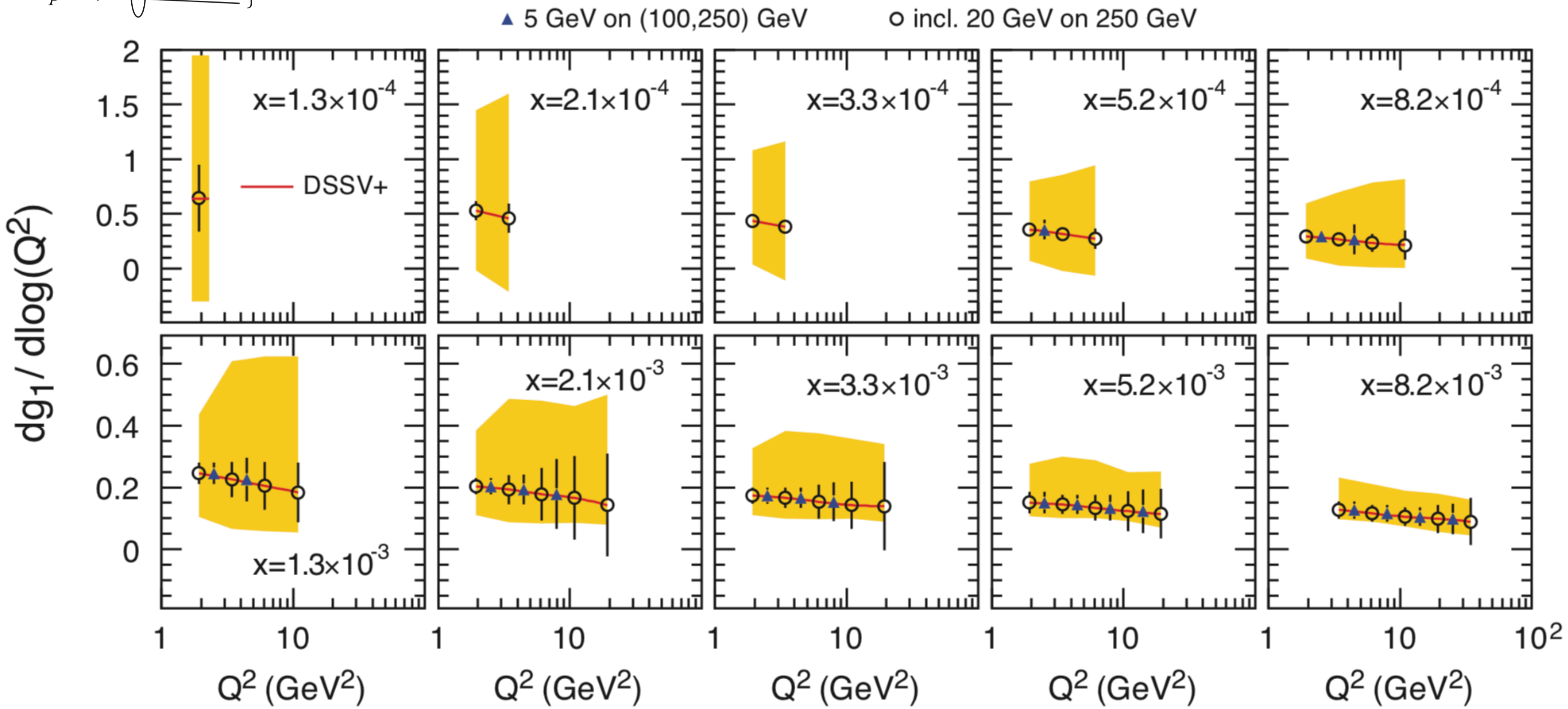
Core questions include what is the gluon spin contribution to the proton spin?

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

U.S.-based EIC - polarized inclusive DIS



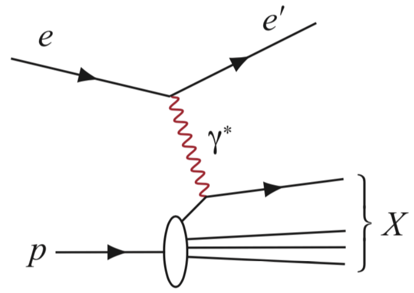
+ NLO



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



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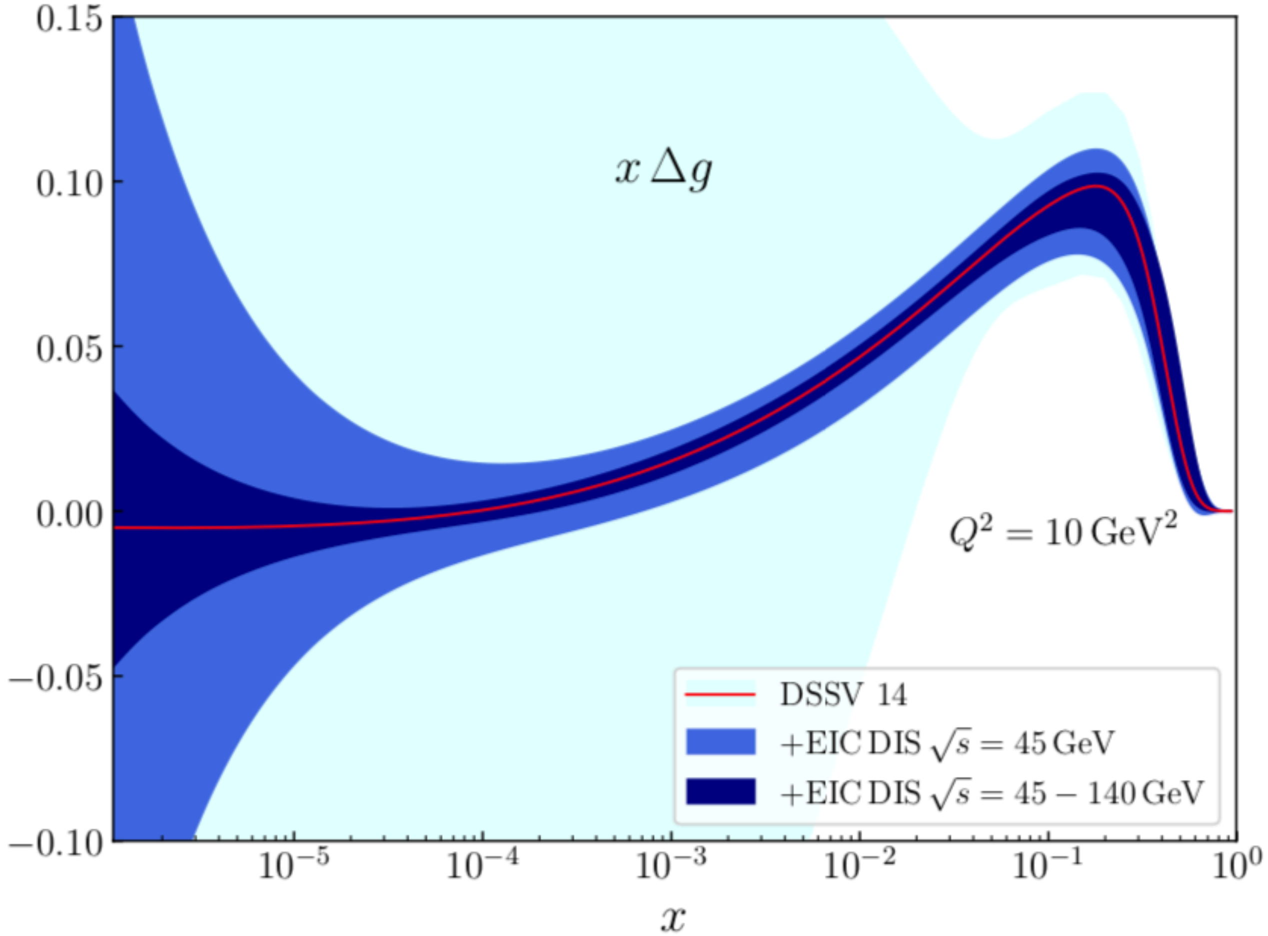

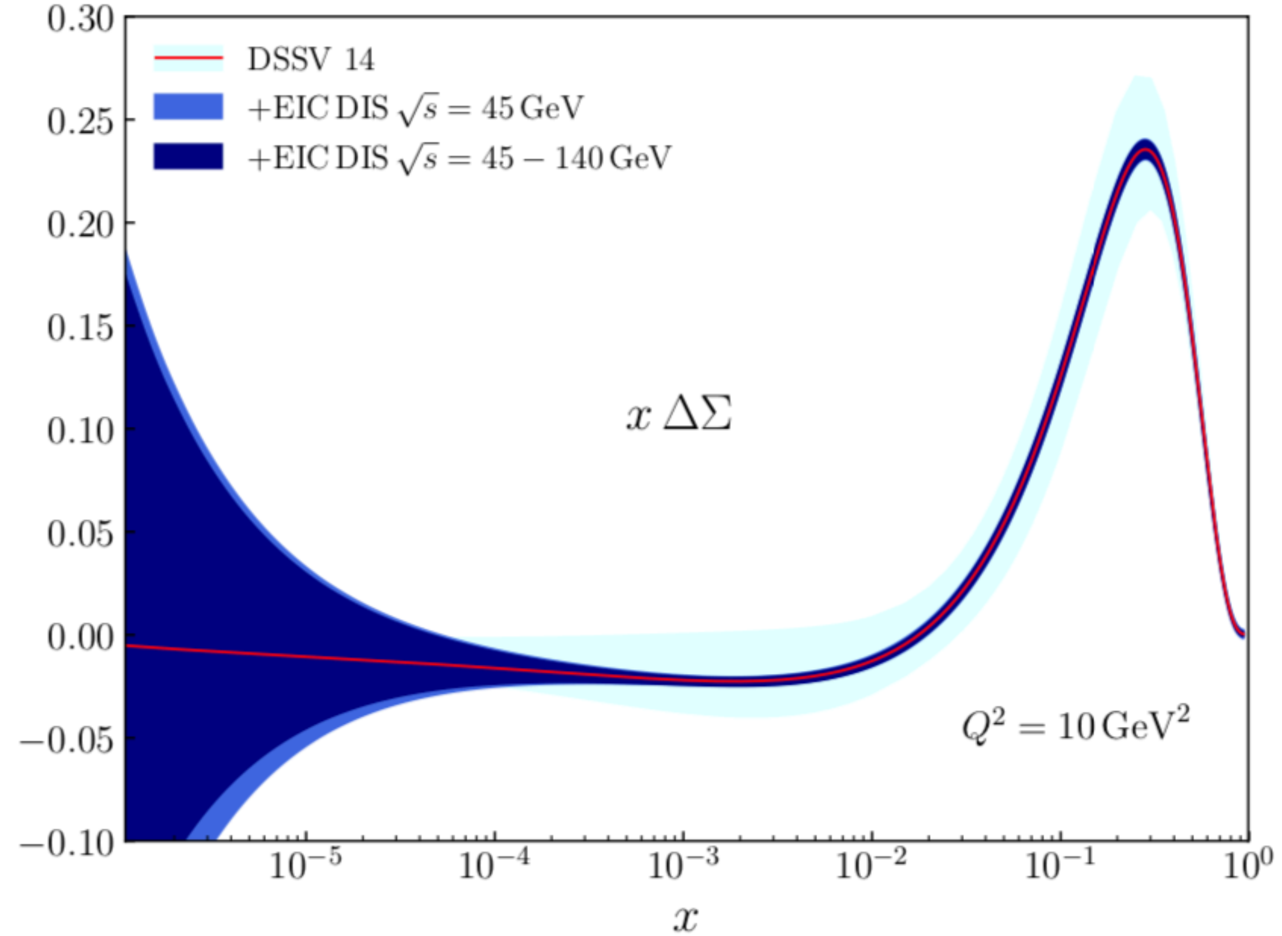

Core answers will include what is the gluon spin contribution to the proton spin?

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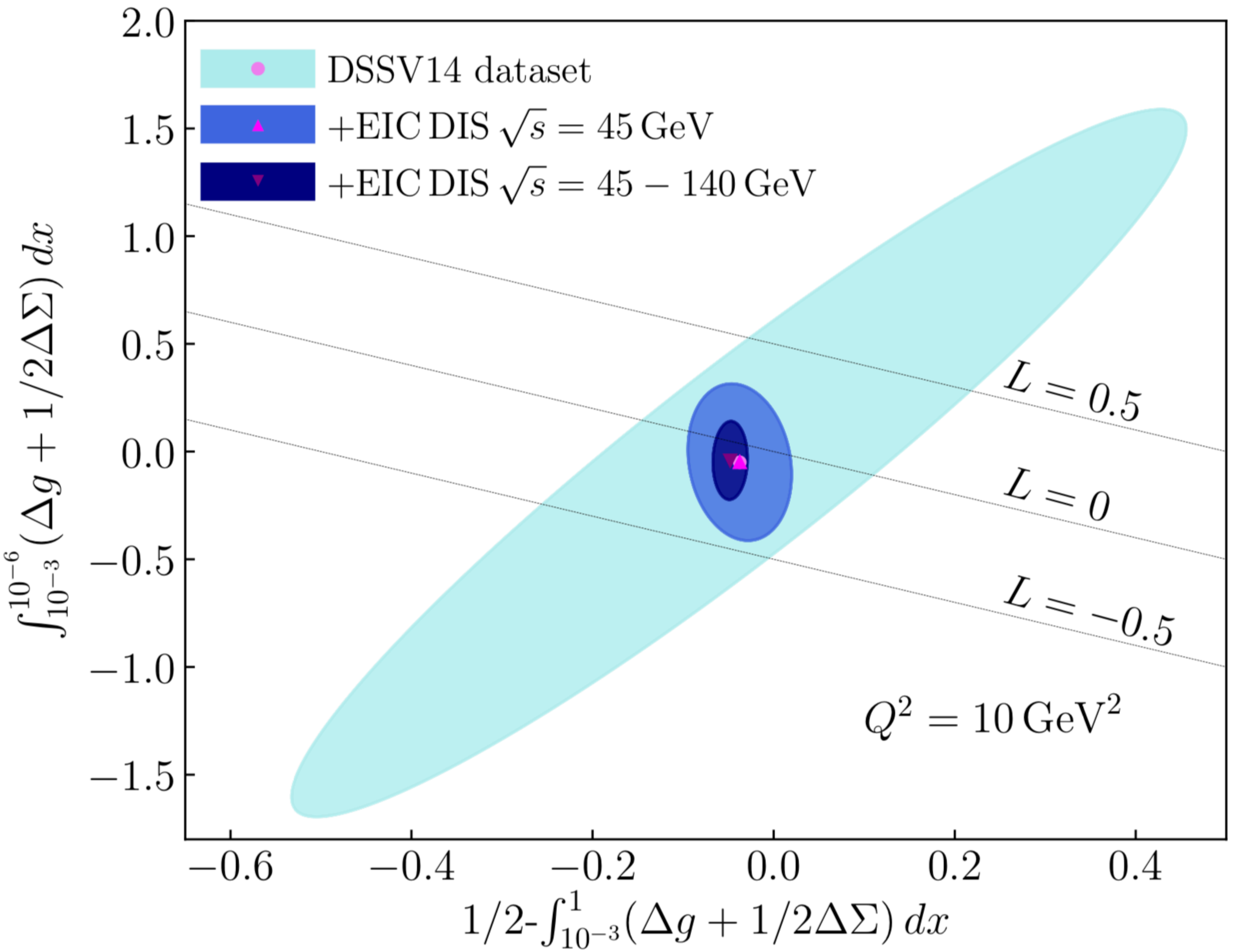
U.S.-based EIC - polarized inclusive DIS



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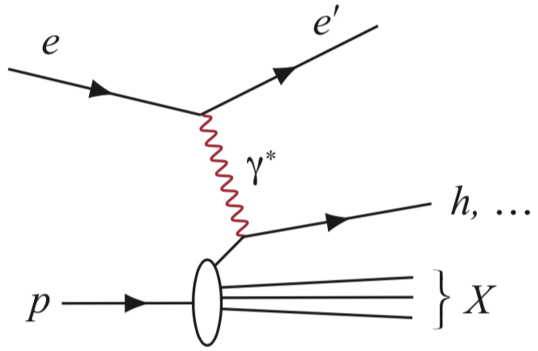
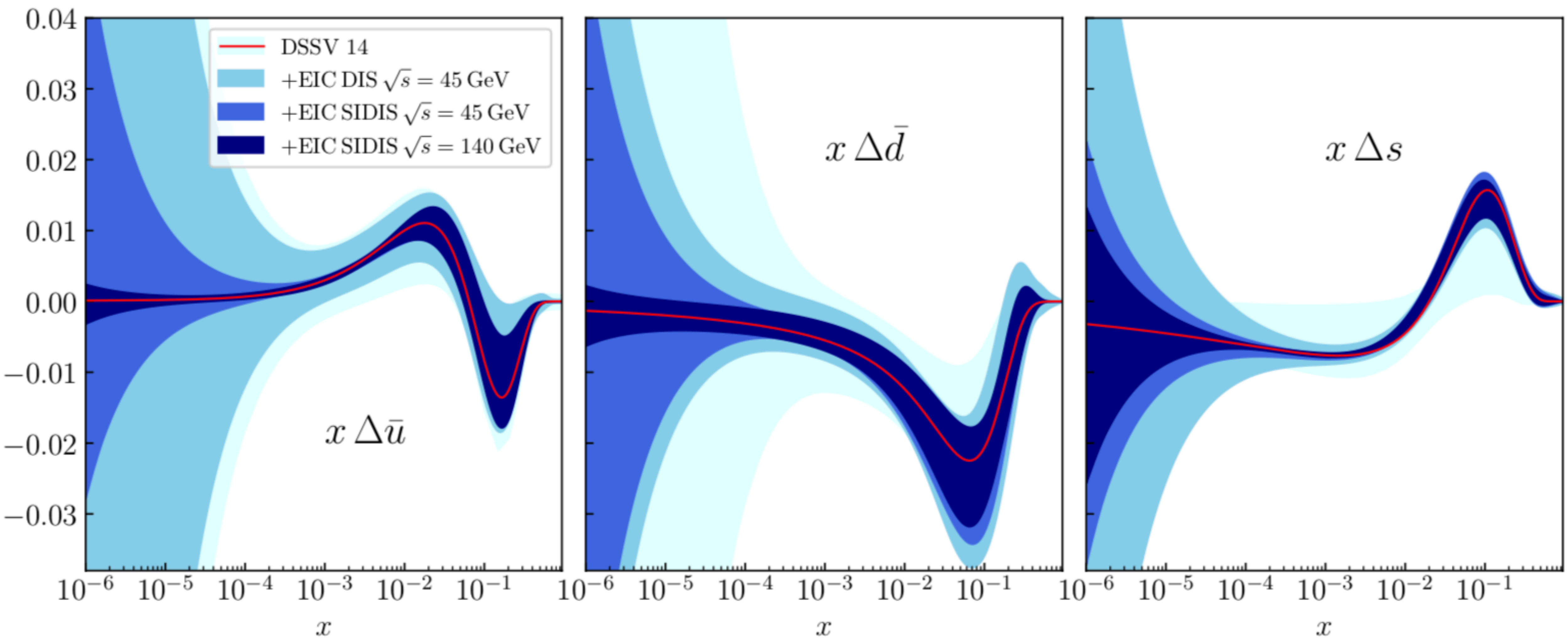
U.S.-based EIC - polarized semi-inclusive DIS



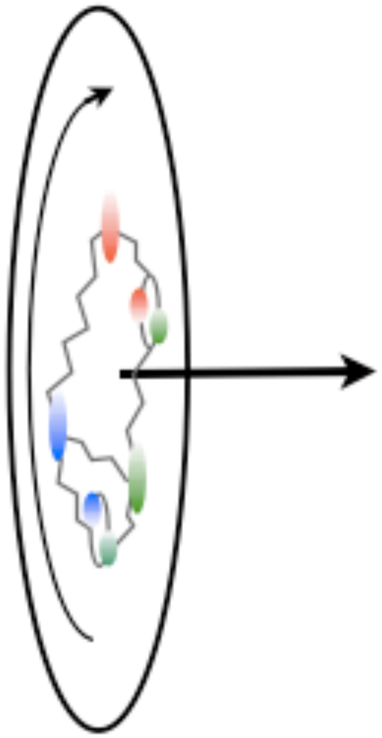


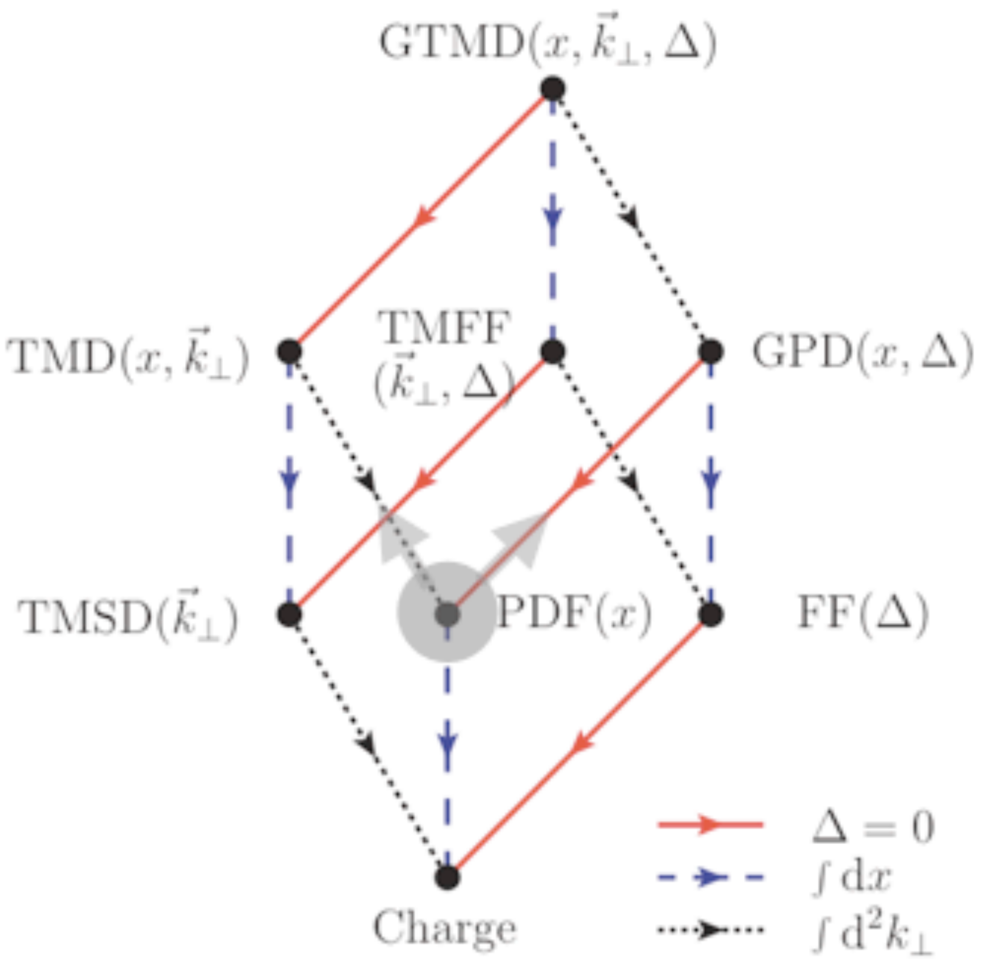
Semi-inclusive measurements will vastly advance insights in the polarized quark sea,

come with particle-identification challenges,

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

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





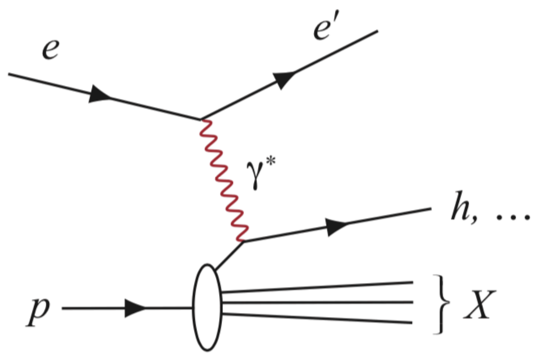
Lorce, Pasquini, Vanderhaeghen

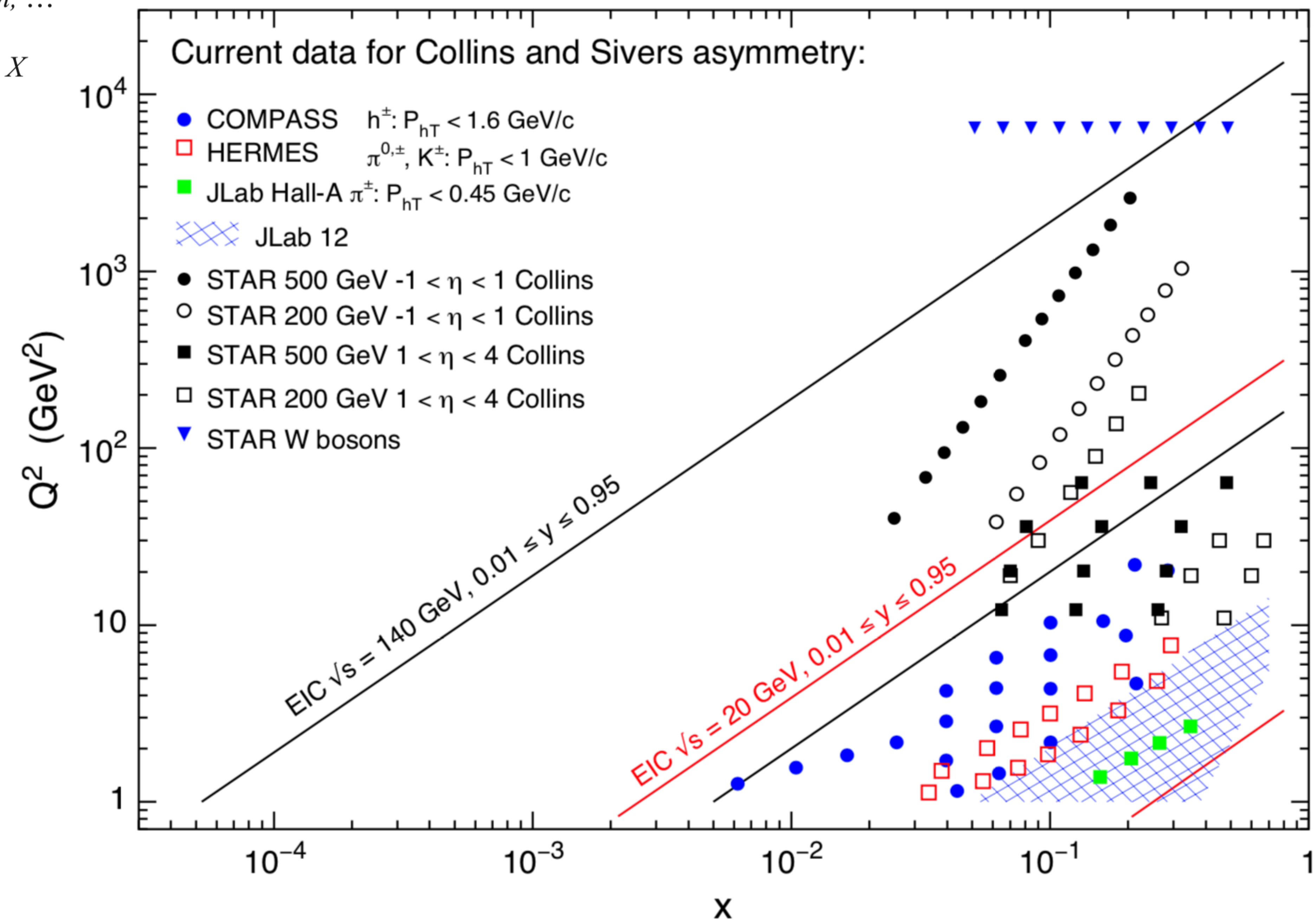
Semi-inclusive measurements, together with exclusive measurements, are key to

probe beyond collinear parton distributions,

image the nucleon — orbital angular momenta.

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



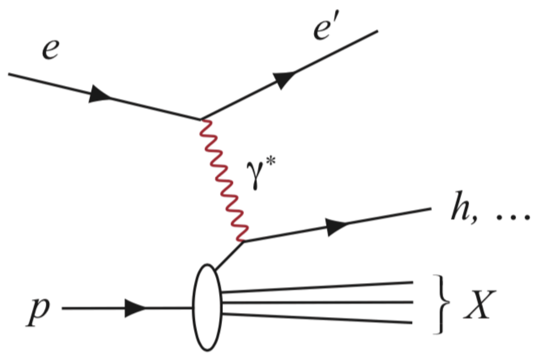


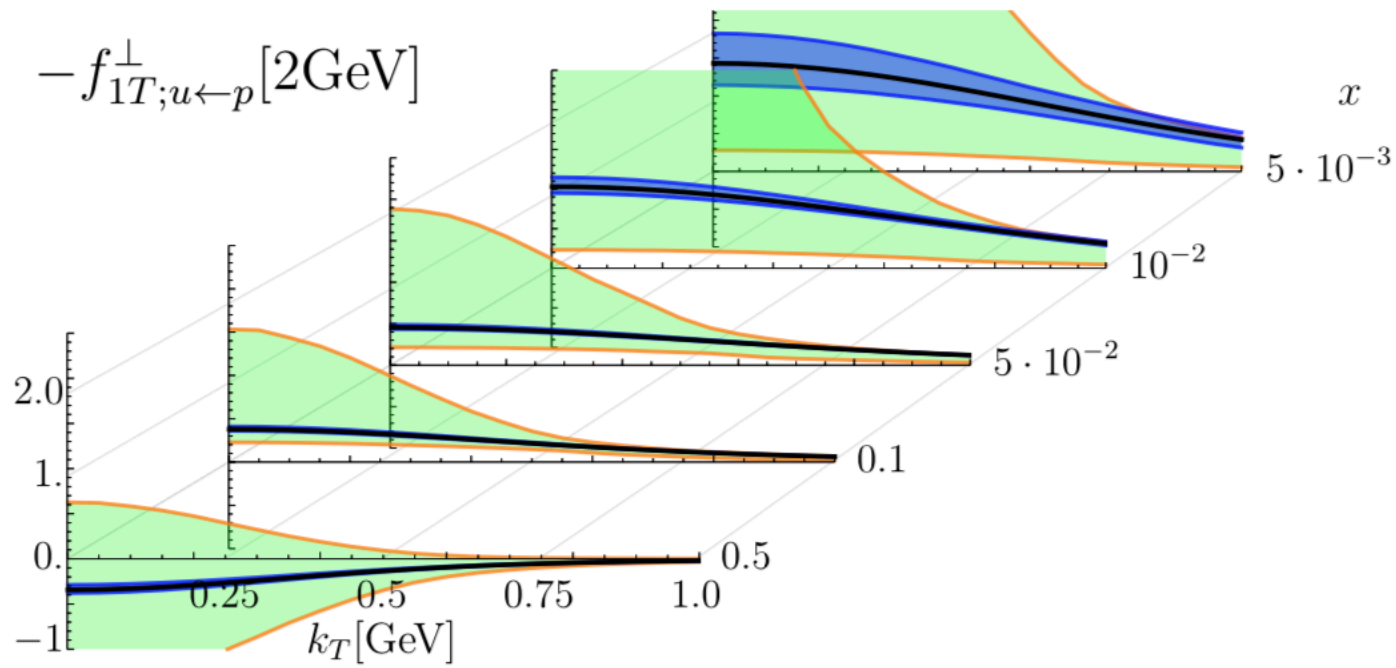
Collins asymmetry is related to the quark transversity distribution and manifested via a transverse momentum dependent fragmentation function in polarized SIDIS,

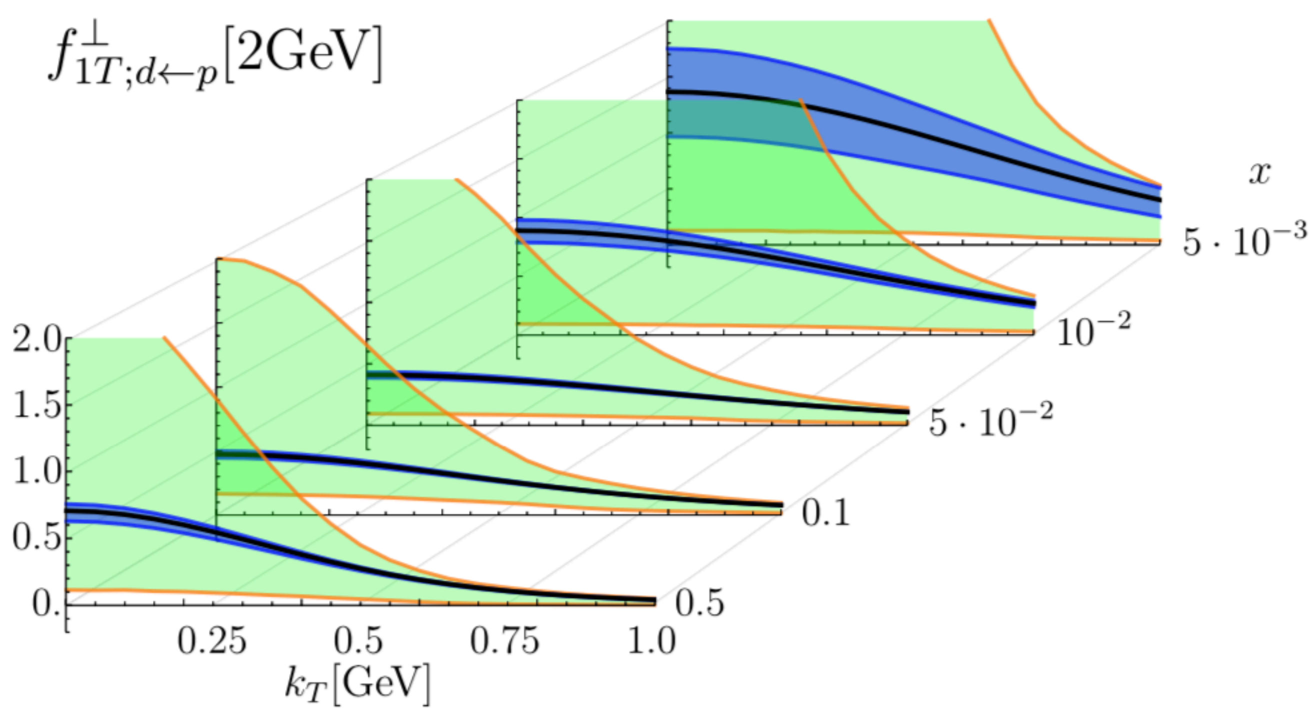
Sivers asymmetry is related to an initial state transverse-momentum correlation with spin,

They are well known examples of asymmetries involving transverse momentum dependence in the field of spin physics, but far from the only ones - many other TMDs exist

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

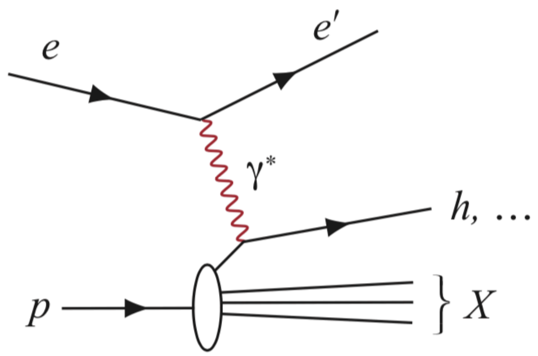


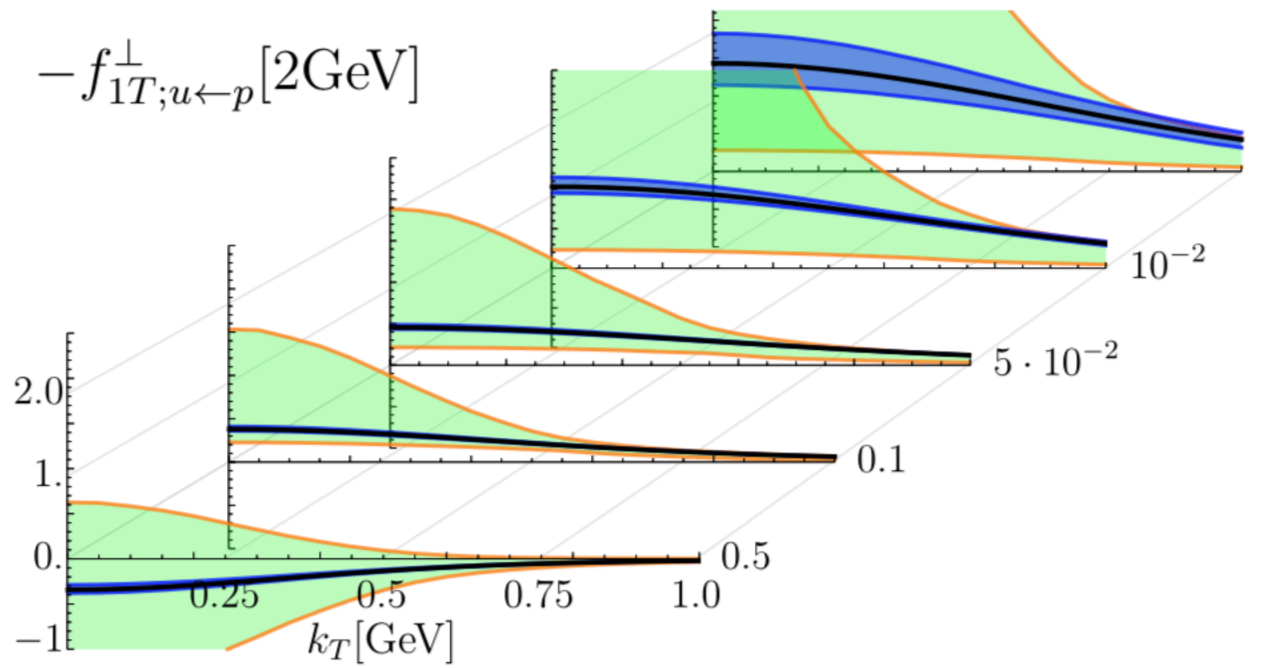


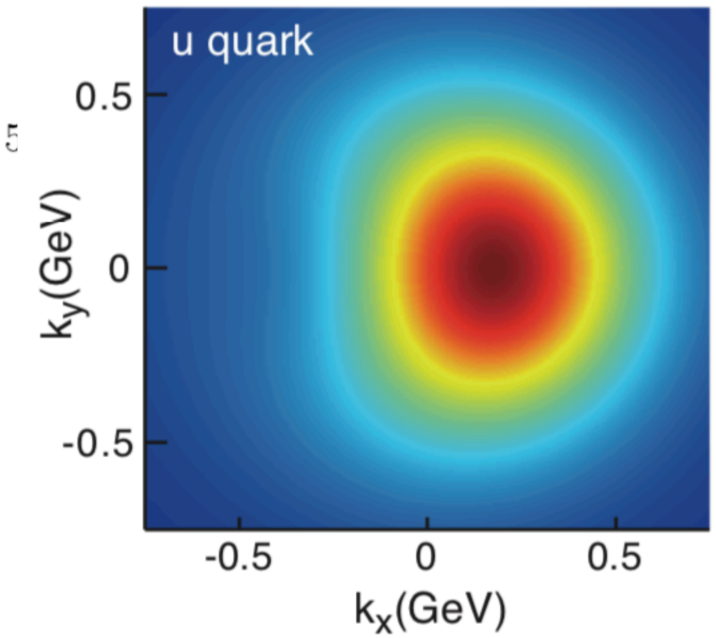


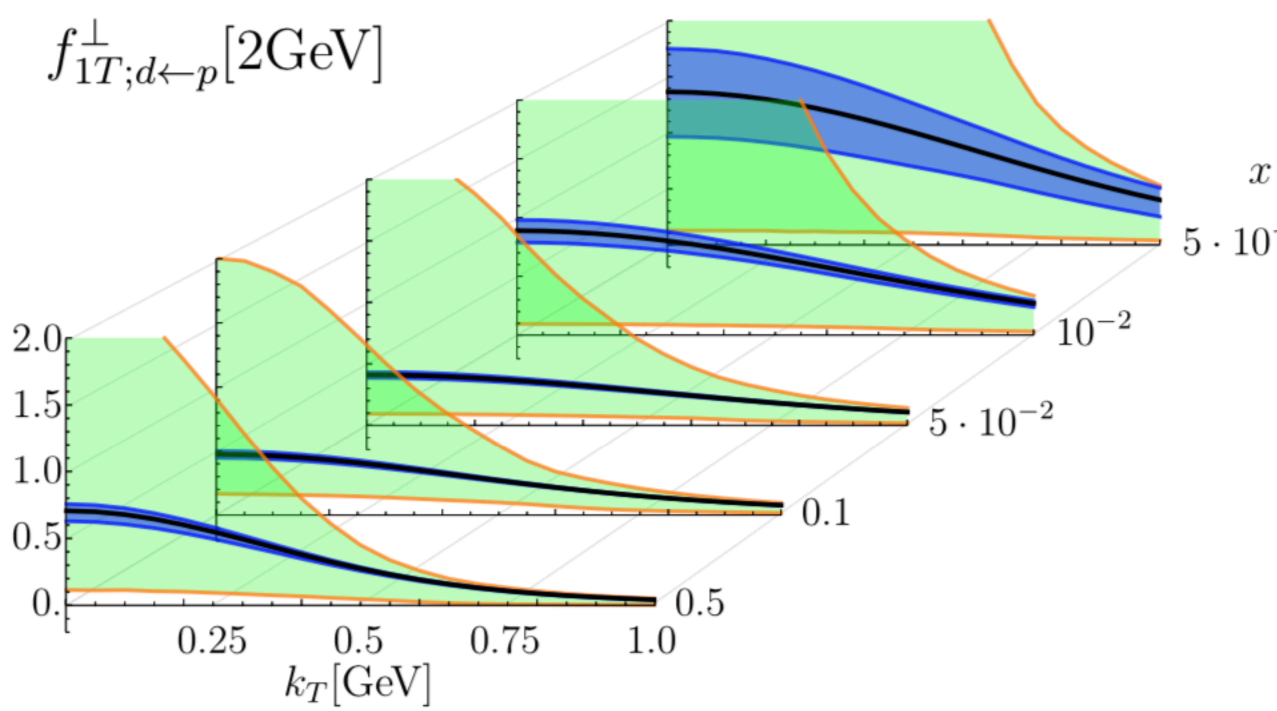
Imaging nucleon (spin) is a major EIC objective - illustrated here is the impact on the up and down Sivers' functions

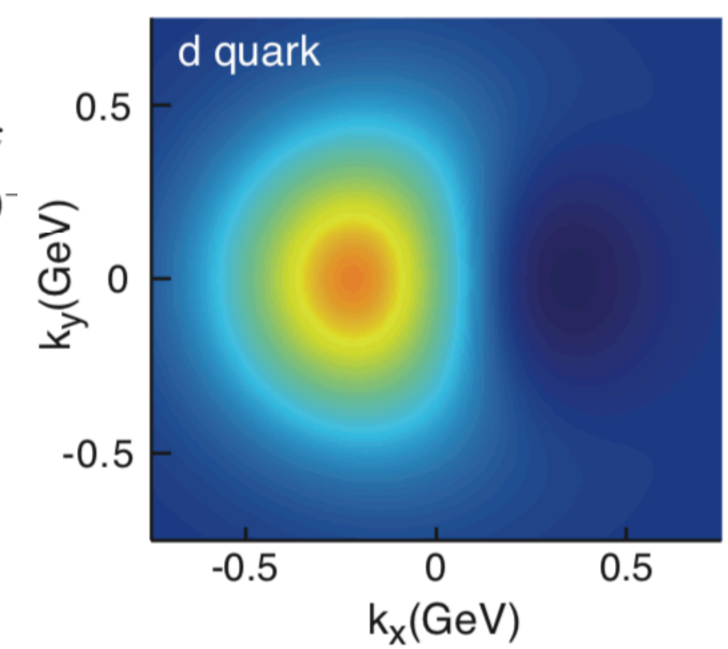
U.S.-based EIC - polarized semi-inclusive DIS





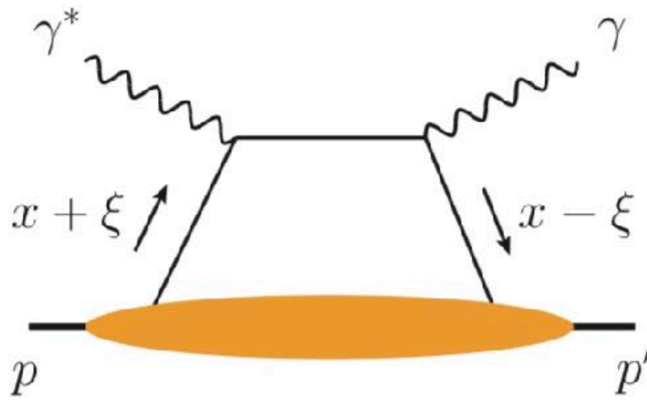


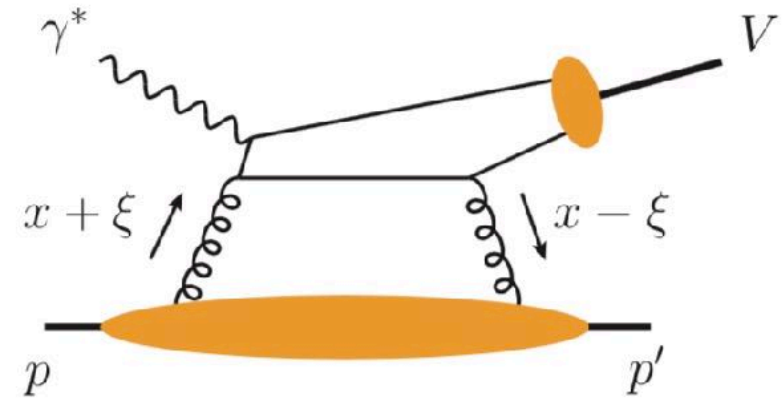


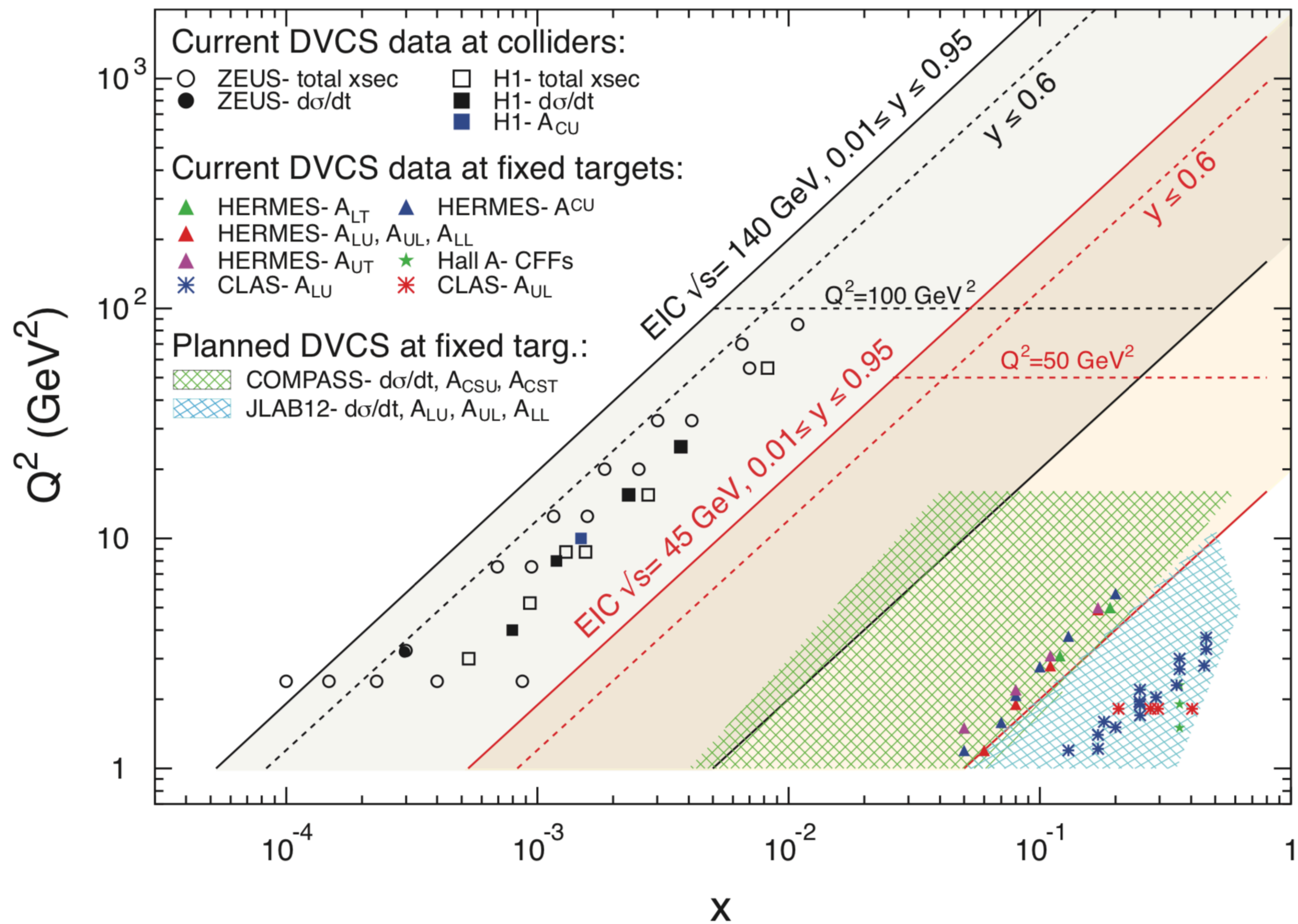


Imaging nucleon (spin) is a major EIC objective — well into the gluon dominated regime.

EIC - DVCS, DVMP, and Imaging





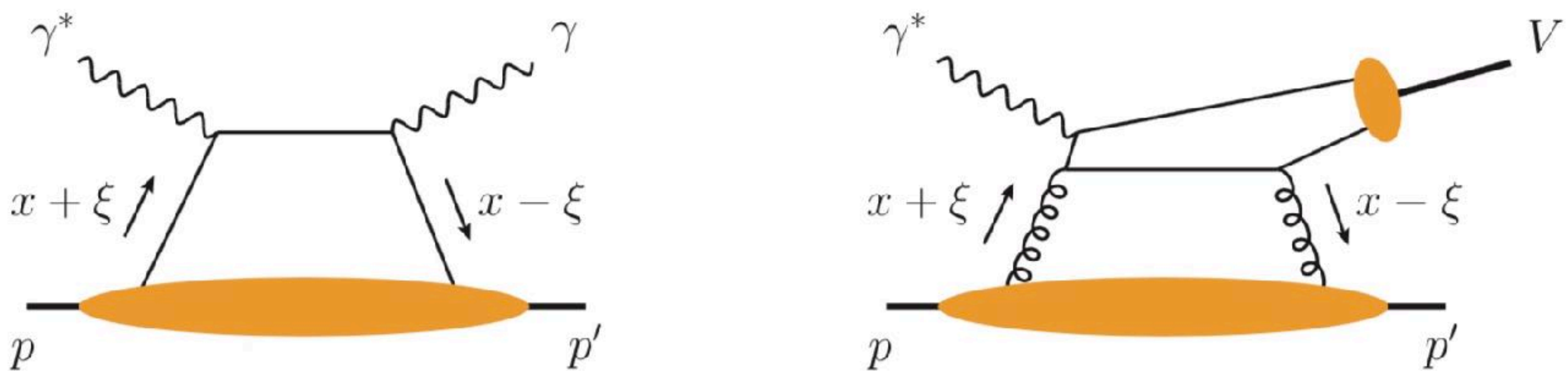


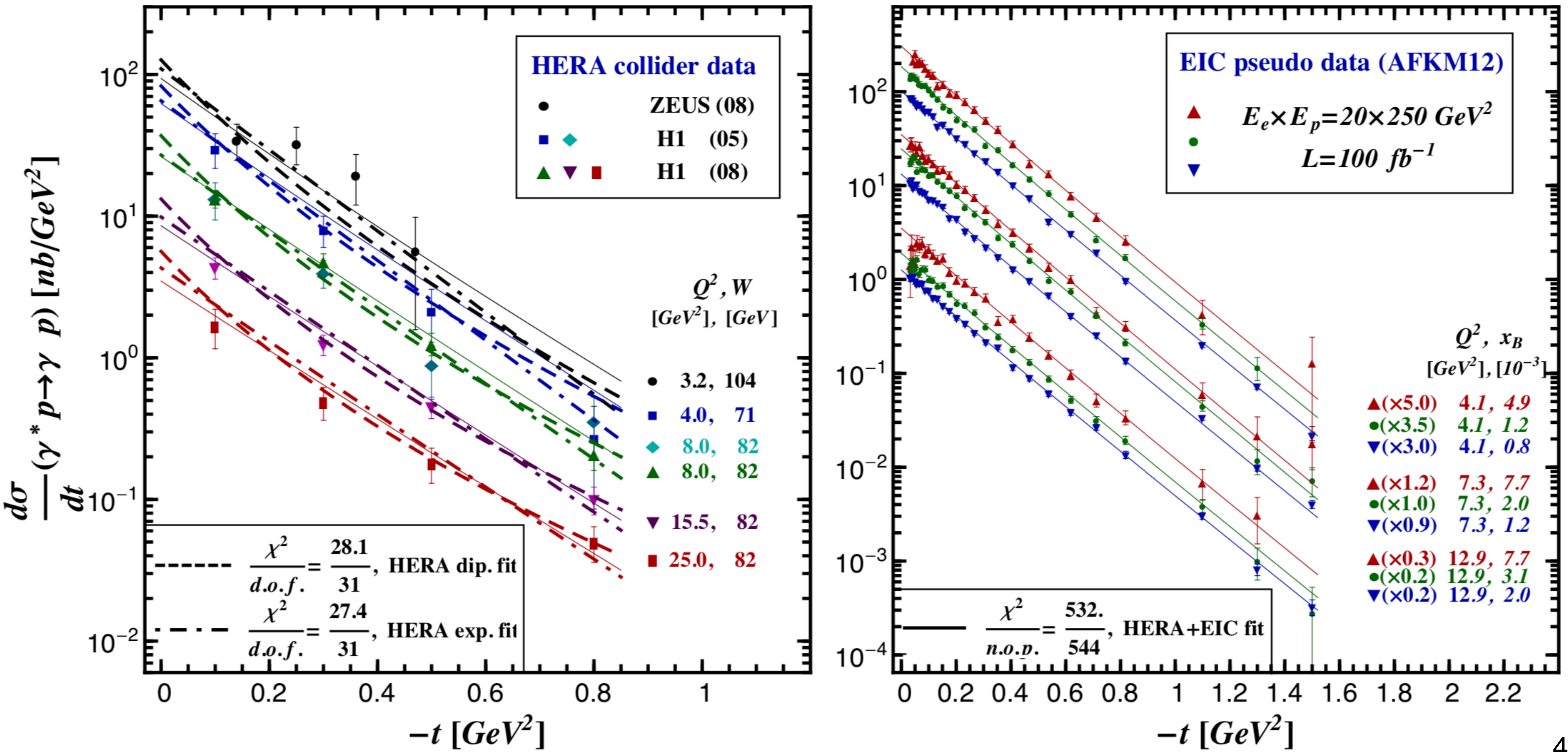
<u>Luminosity</u>, Polarization, Nuclei, Detectors,

Less so about x, Q^2 range

t, however, …

EIC - DVCS, DVMP, and Imaging





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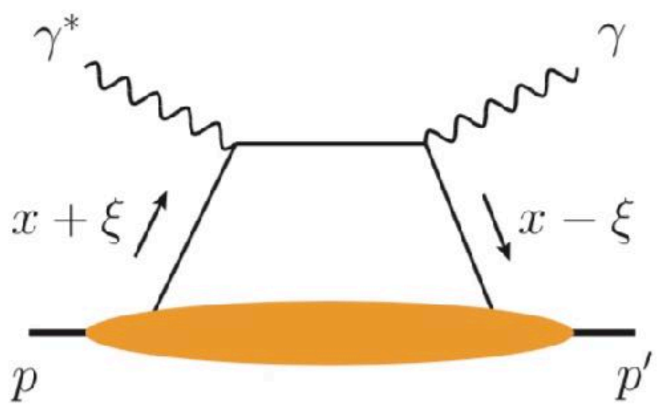
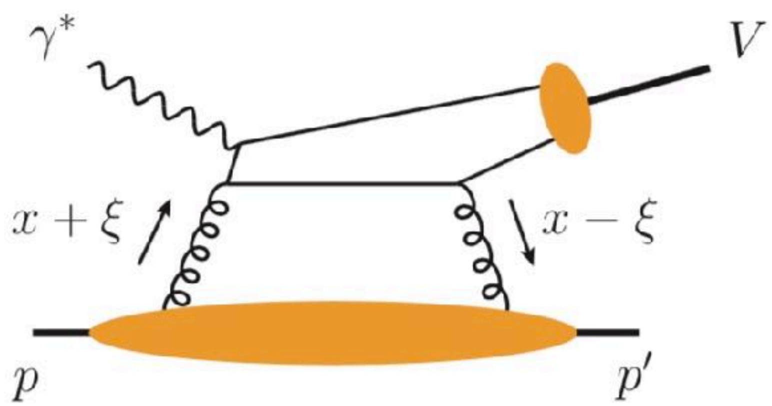
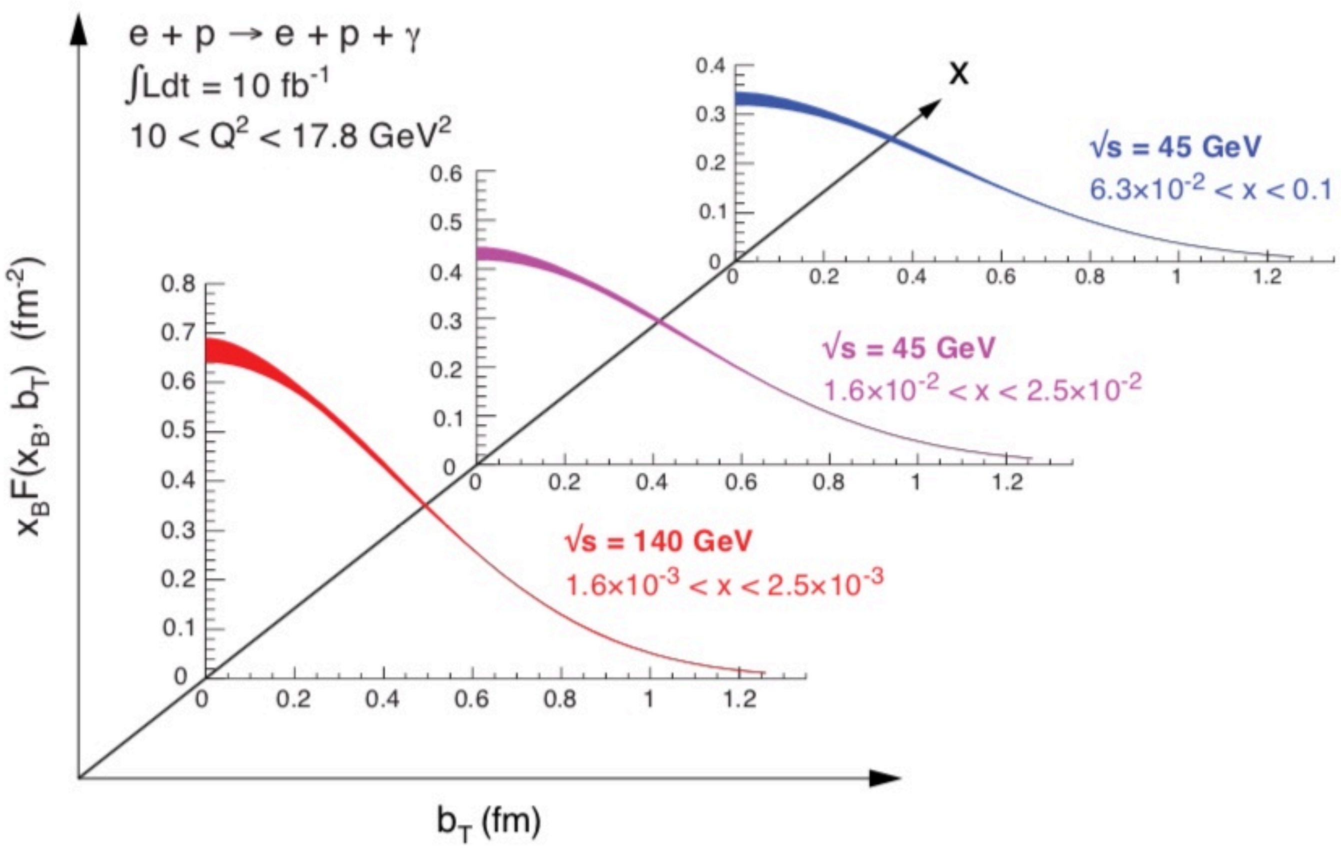
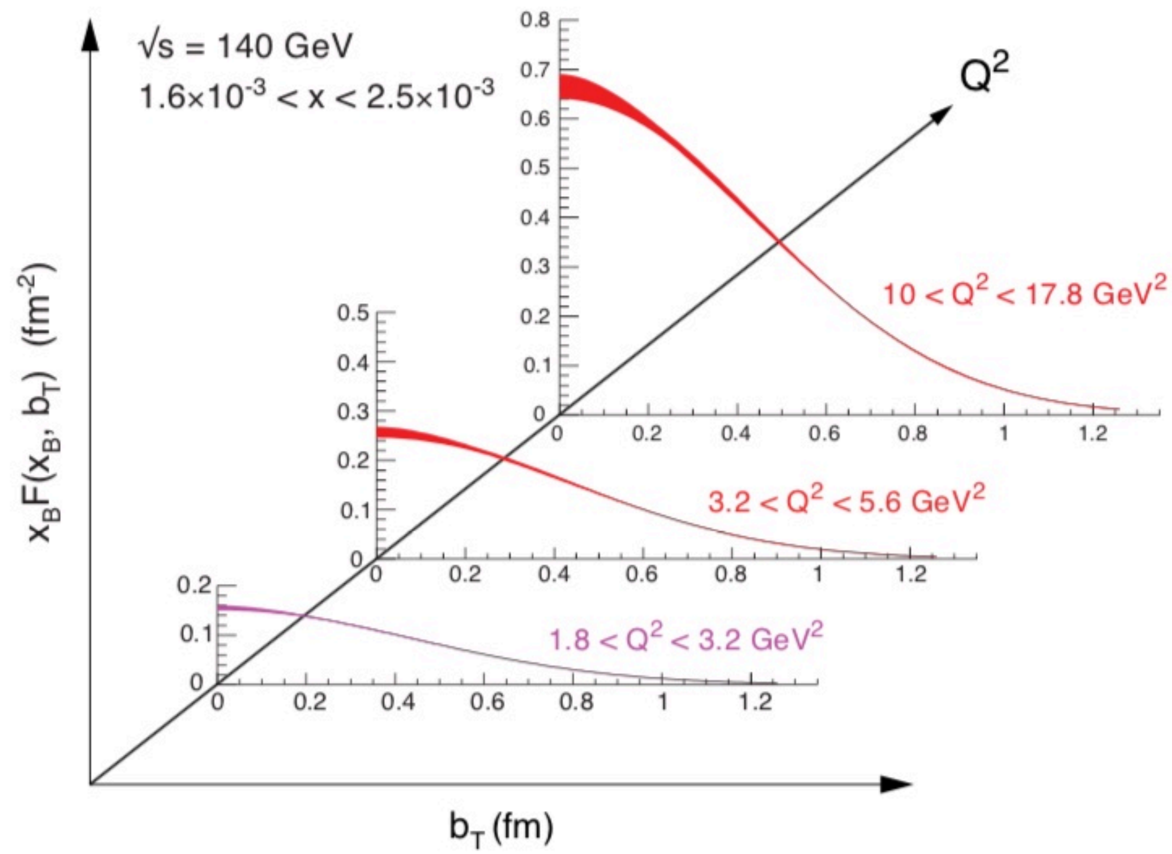




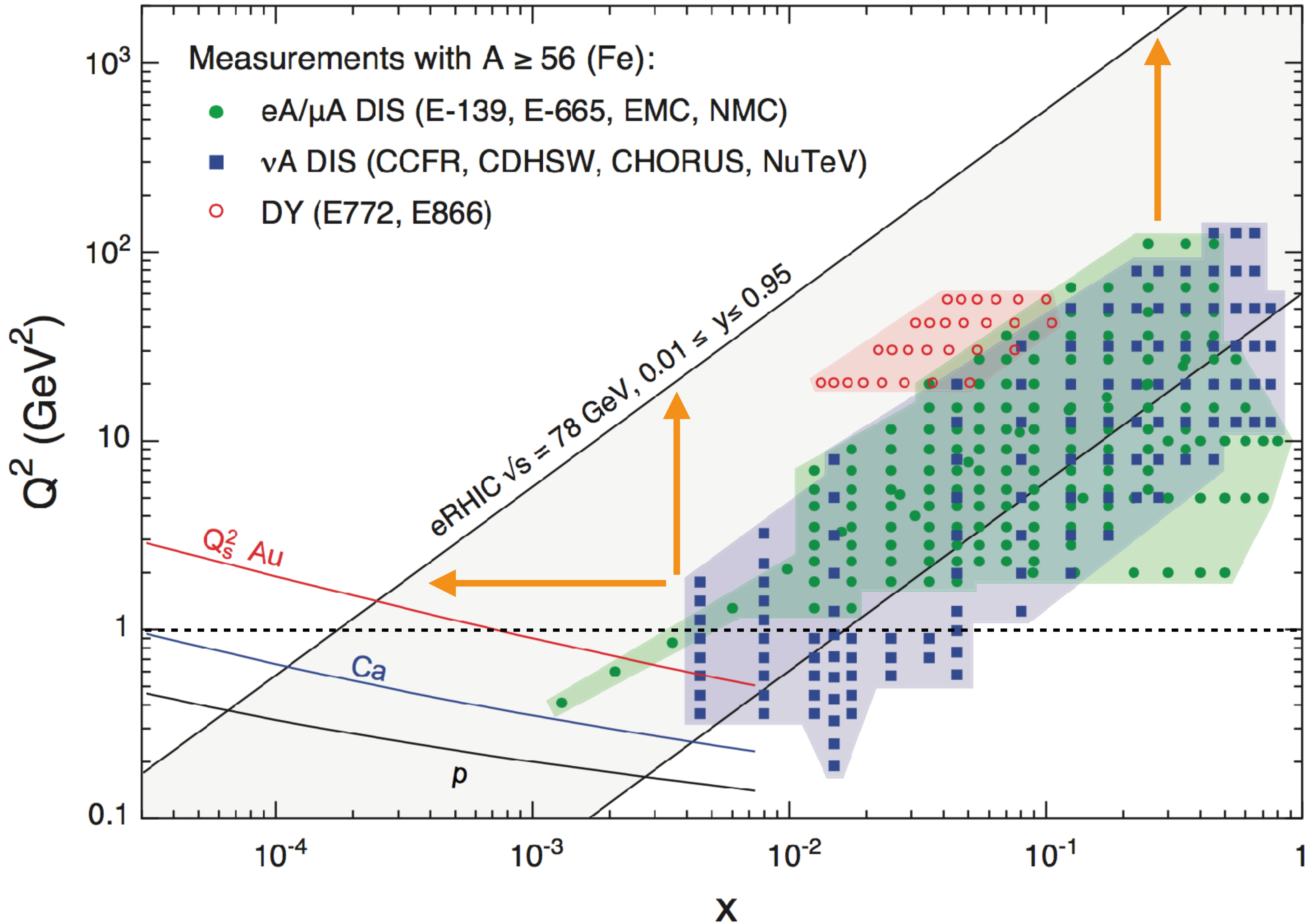


x-dependence at fixed Q^2



Q^2-dependence at fixed x

U.S.-based EIC - The Nuclear Landscape



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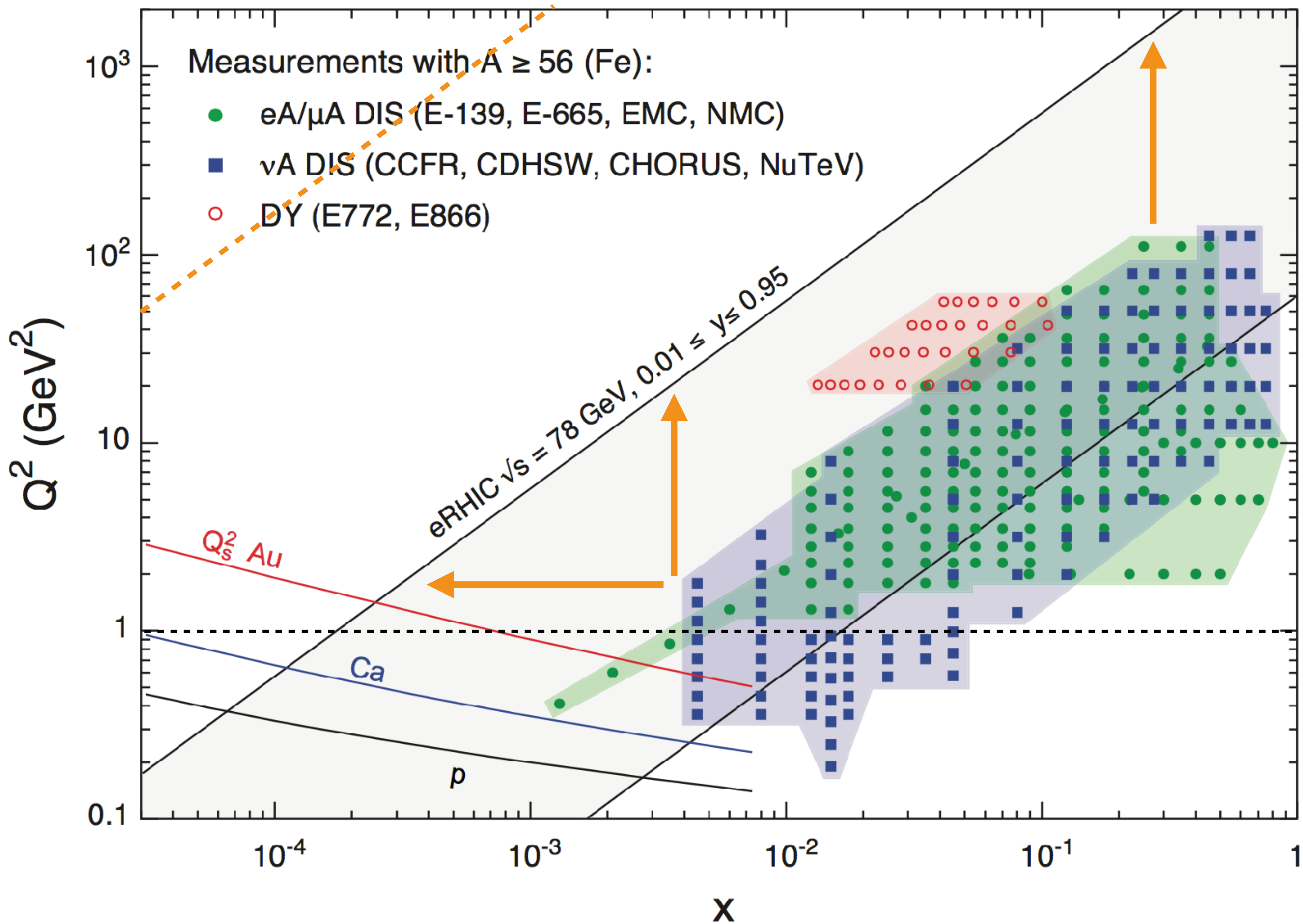
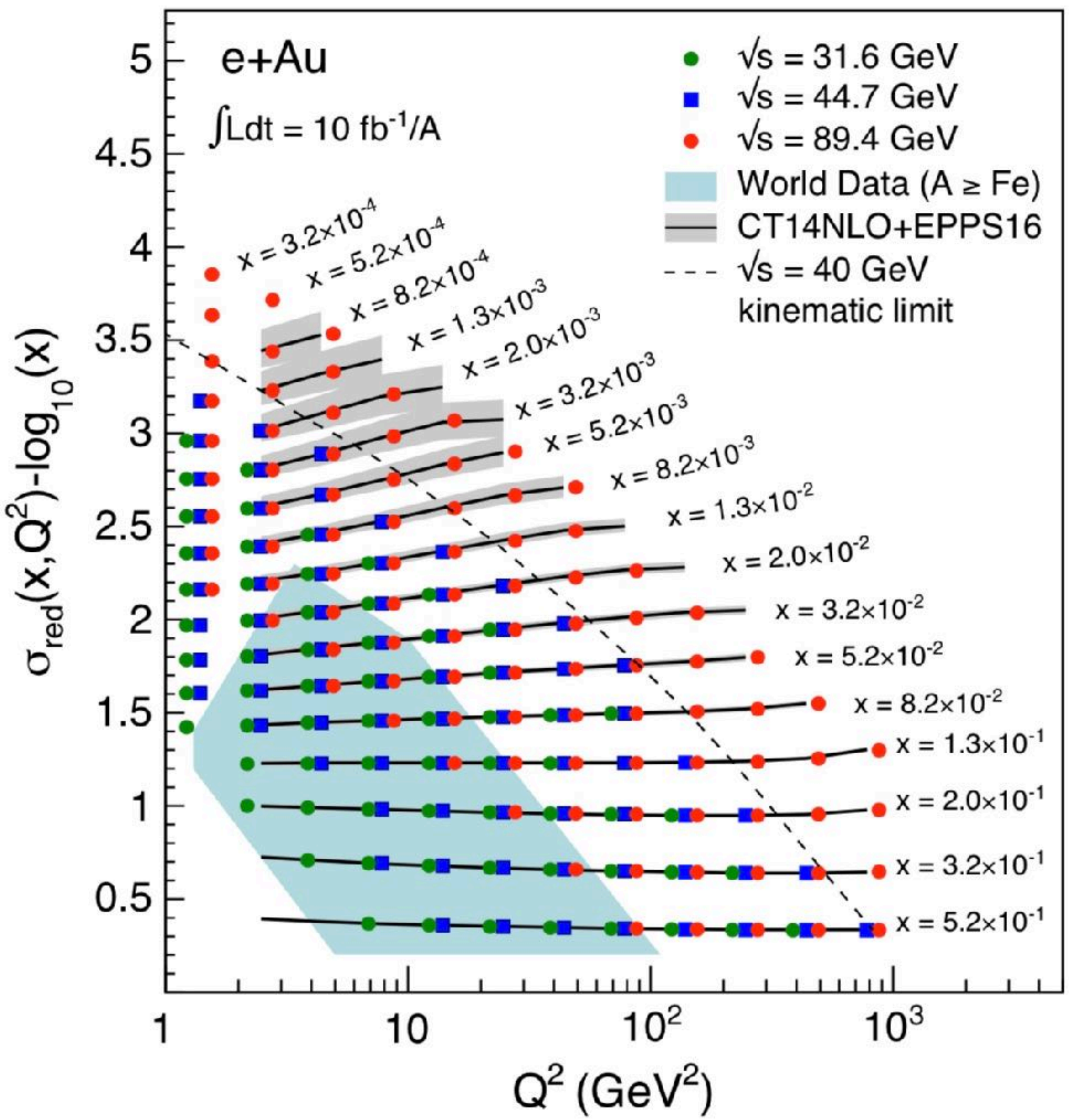
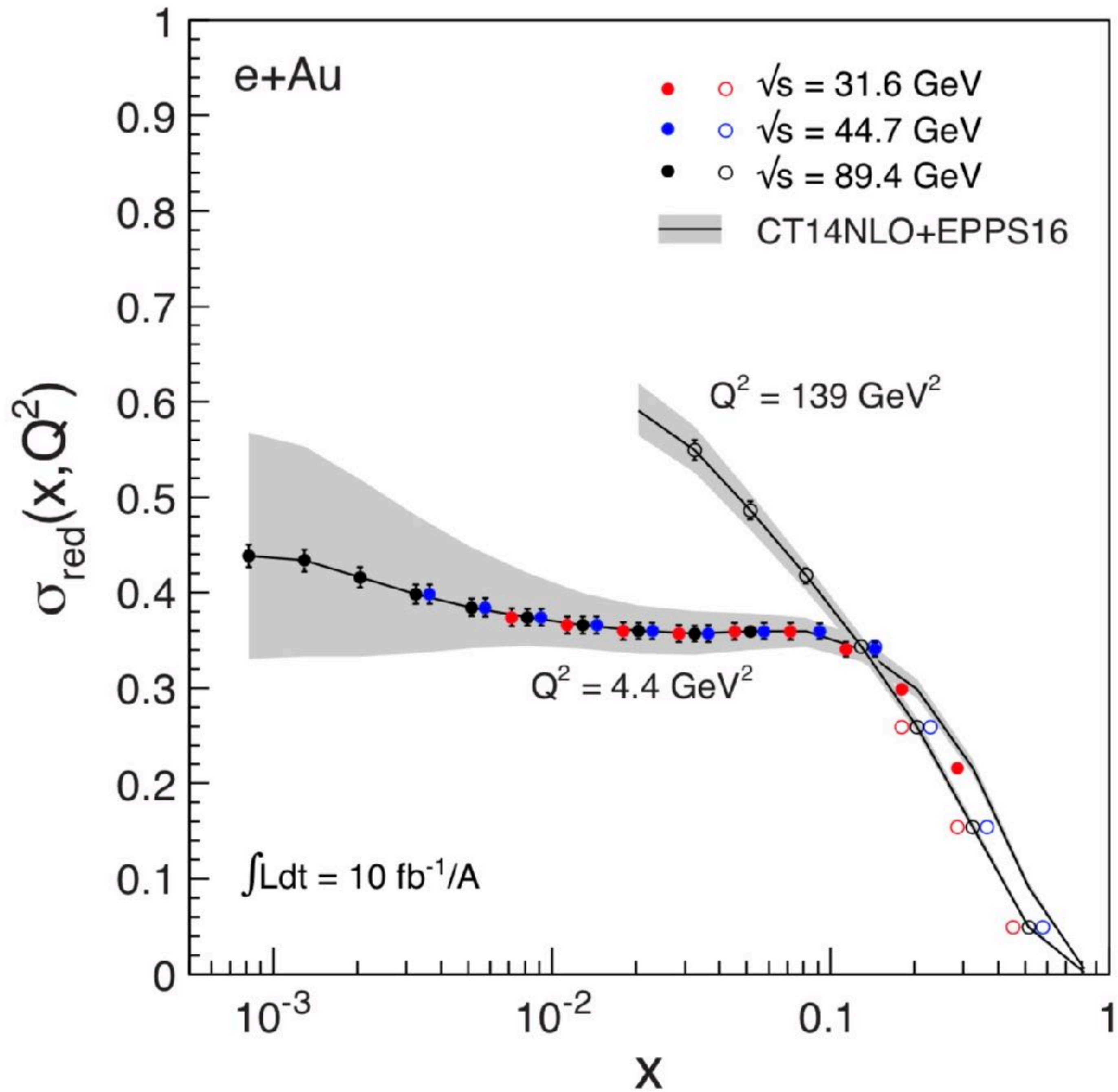


LHeC, if realized, will obviously provide unprecedented kinematic reach, complementarity in polarization, A capabilities.

Further note: high-Q^2 W,Z and dijet data from LHC not shown (but part of EPPS16)

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.

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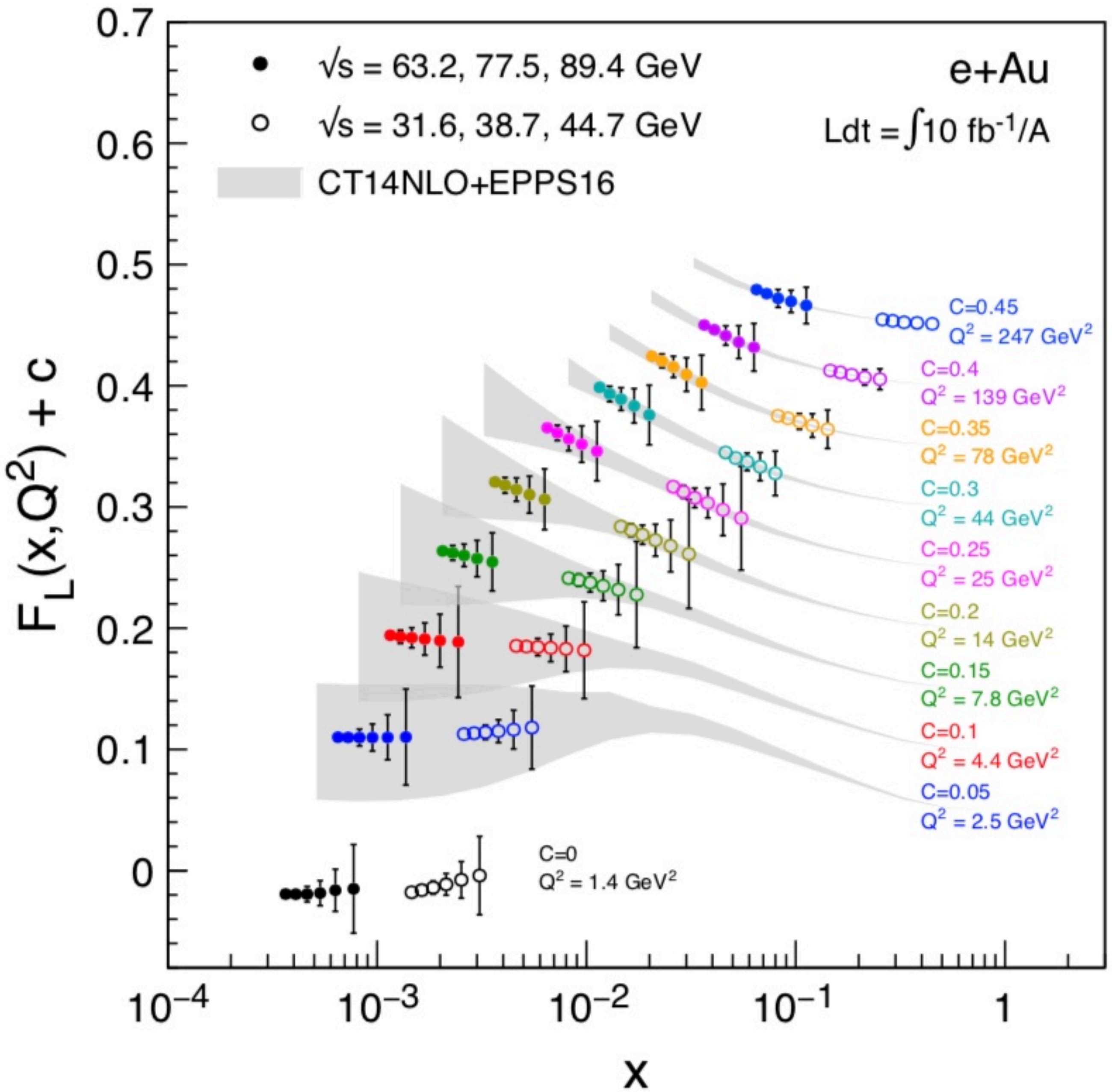
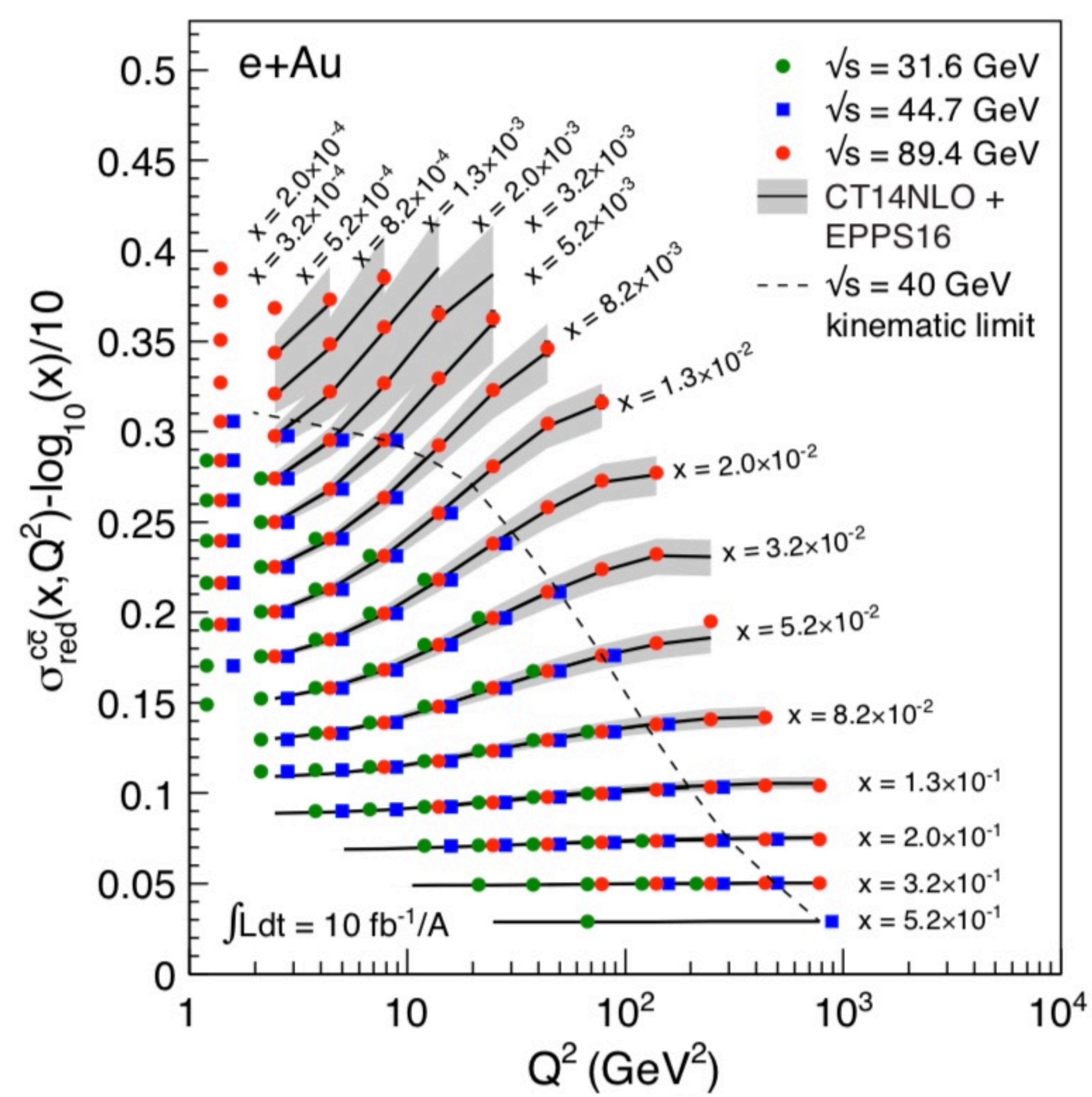
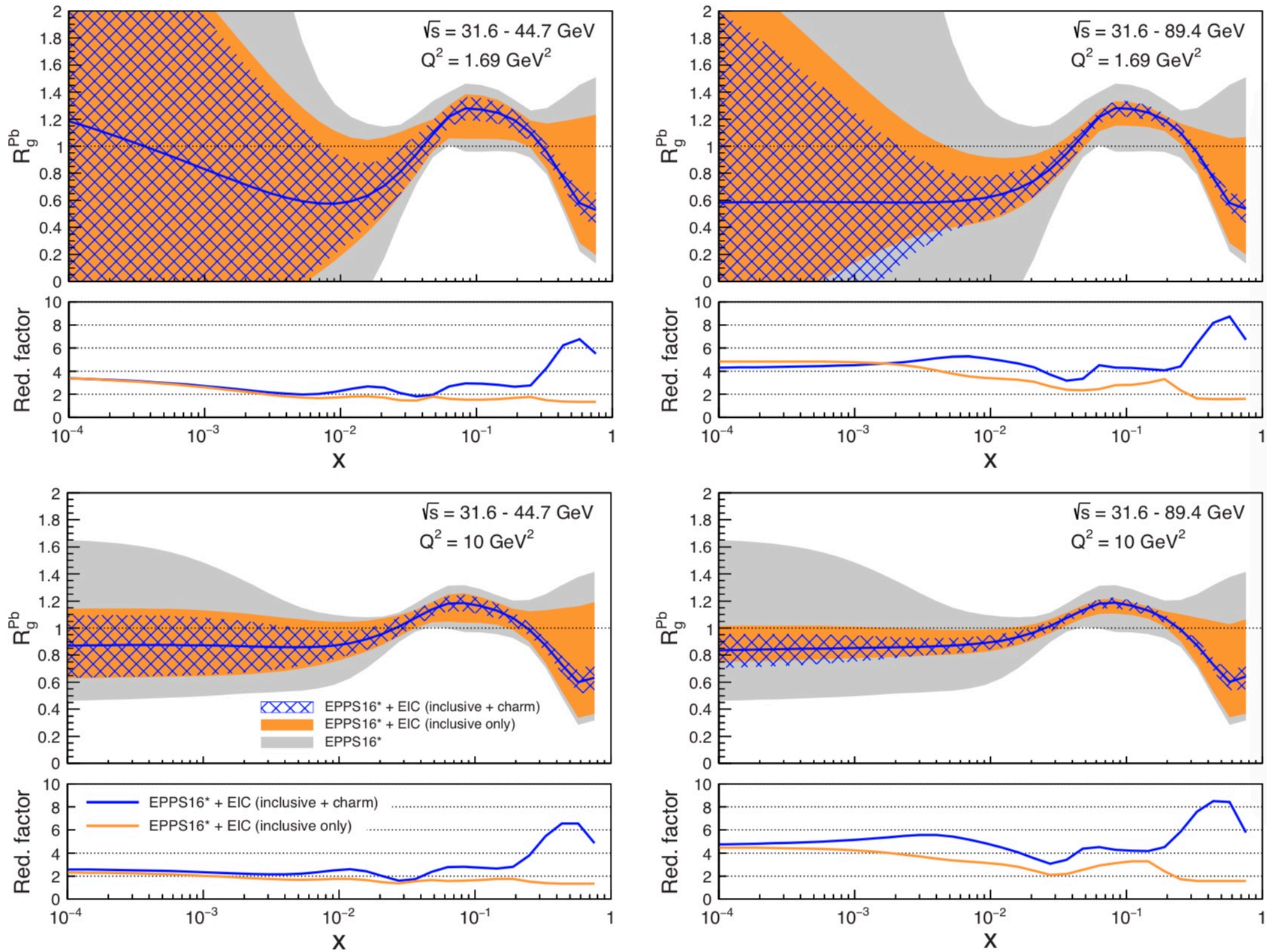




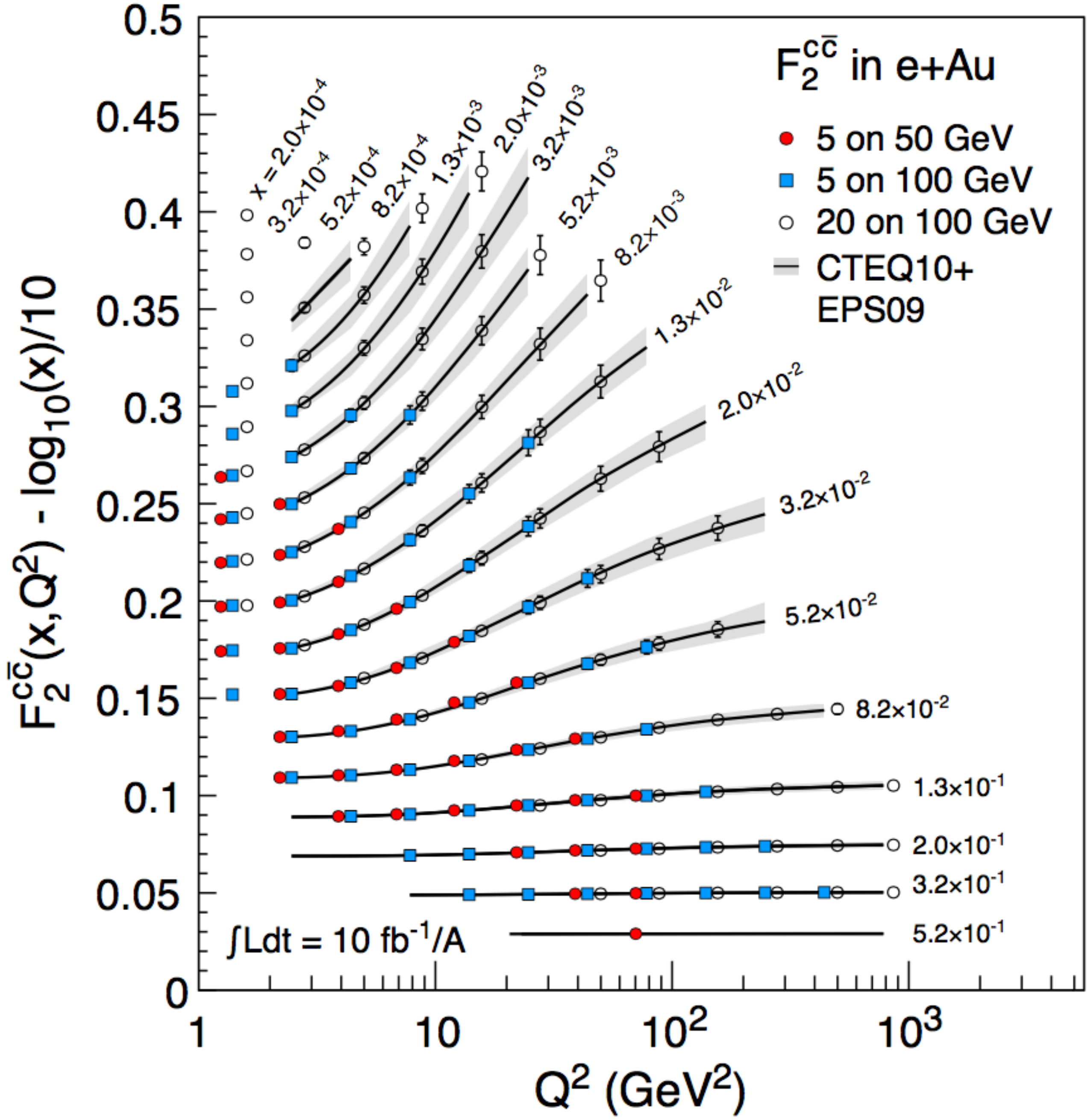
Clearly visible impact also beyond baseline inclusive measurements with "Rosenbluth separation" and semi-inclusive measurements.

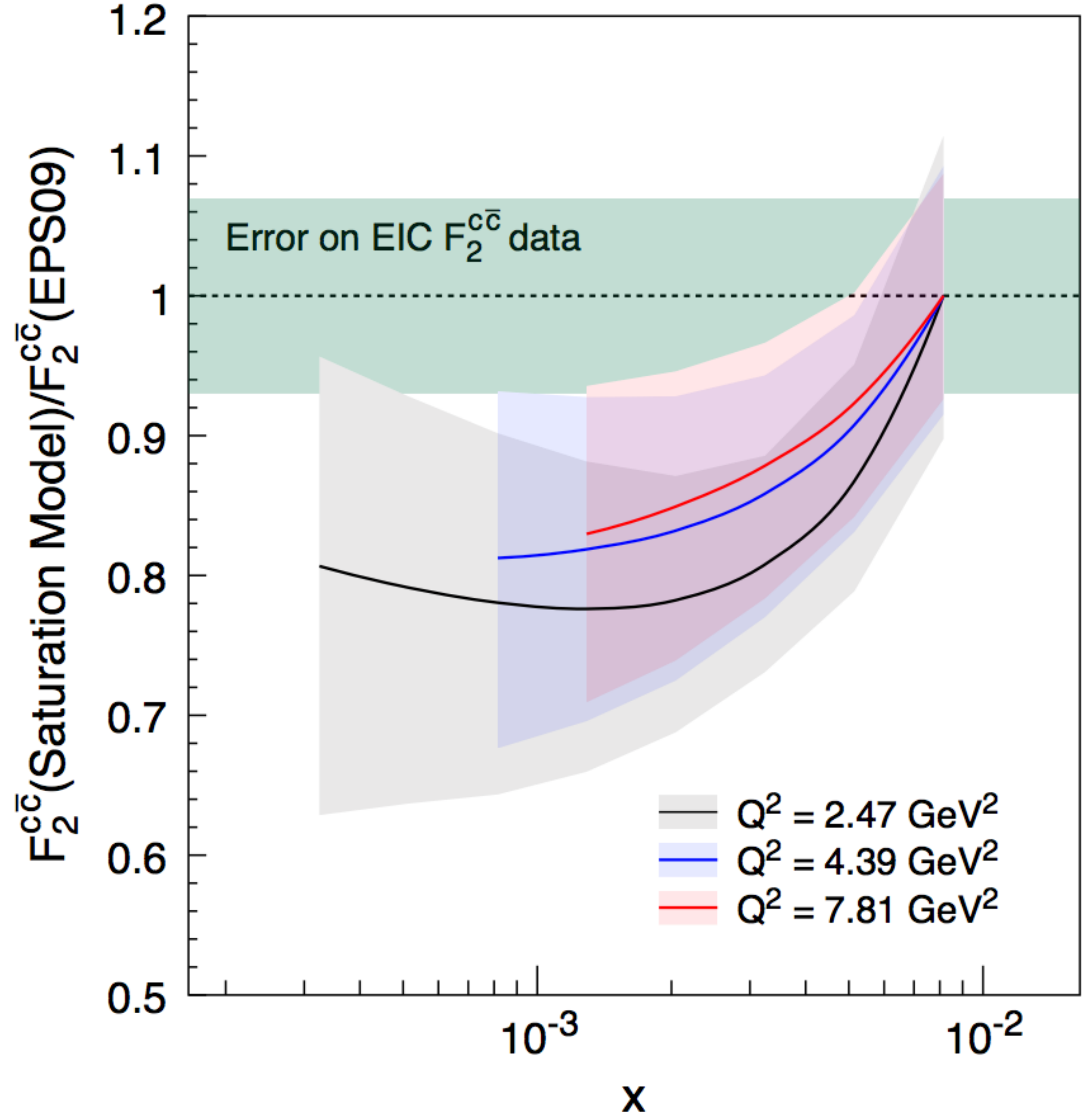
Nuclear gluon will be probed sensitively with complementary channels.

U.S.-based EIC - The Nuclear Landscape



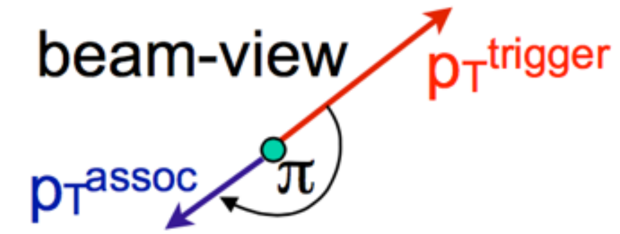
EIC - Saturation from within the PDF?

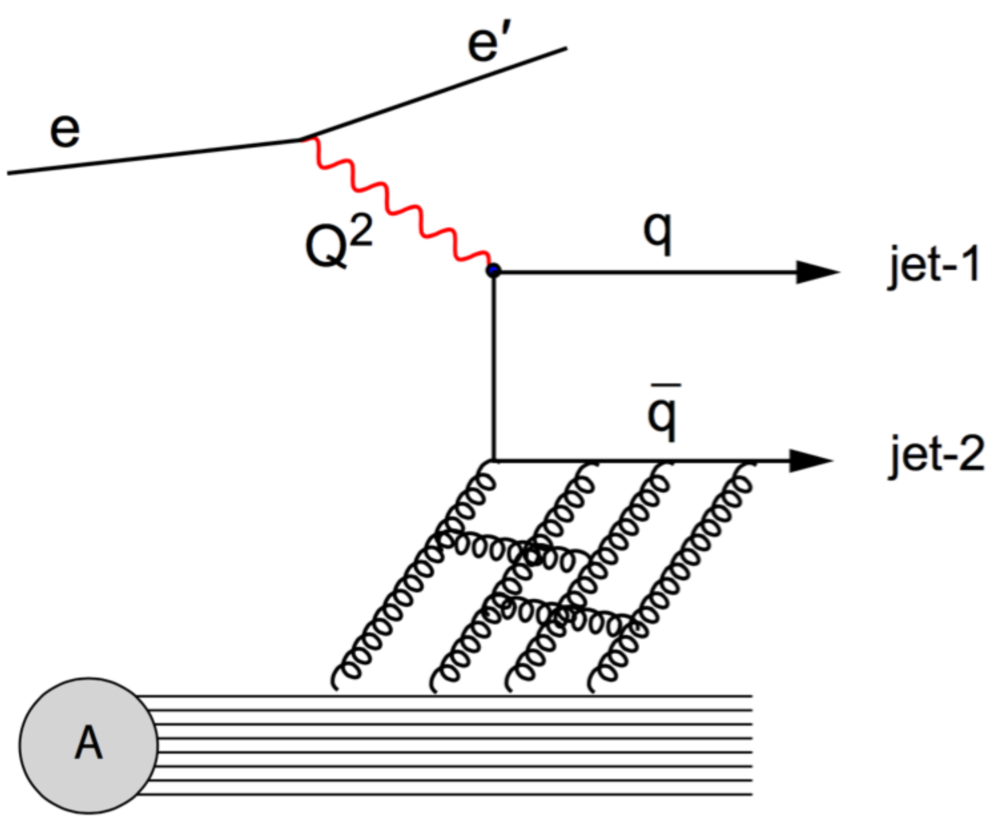




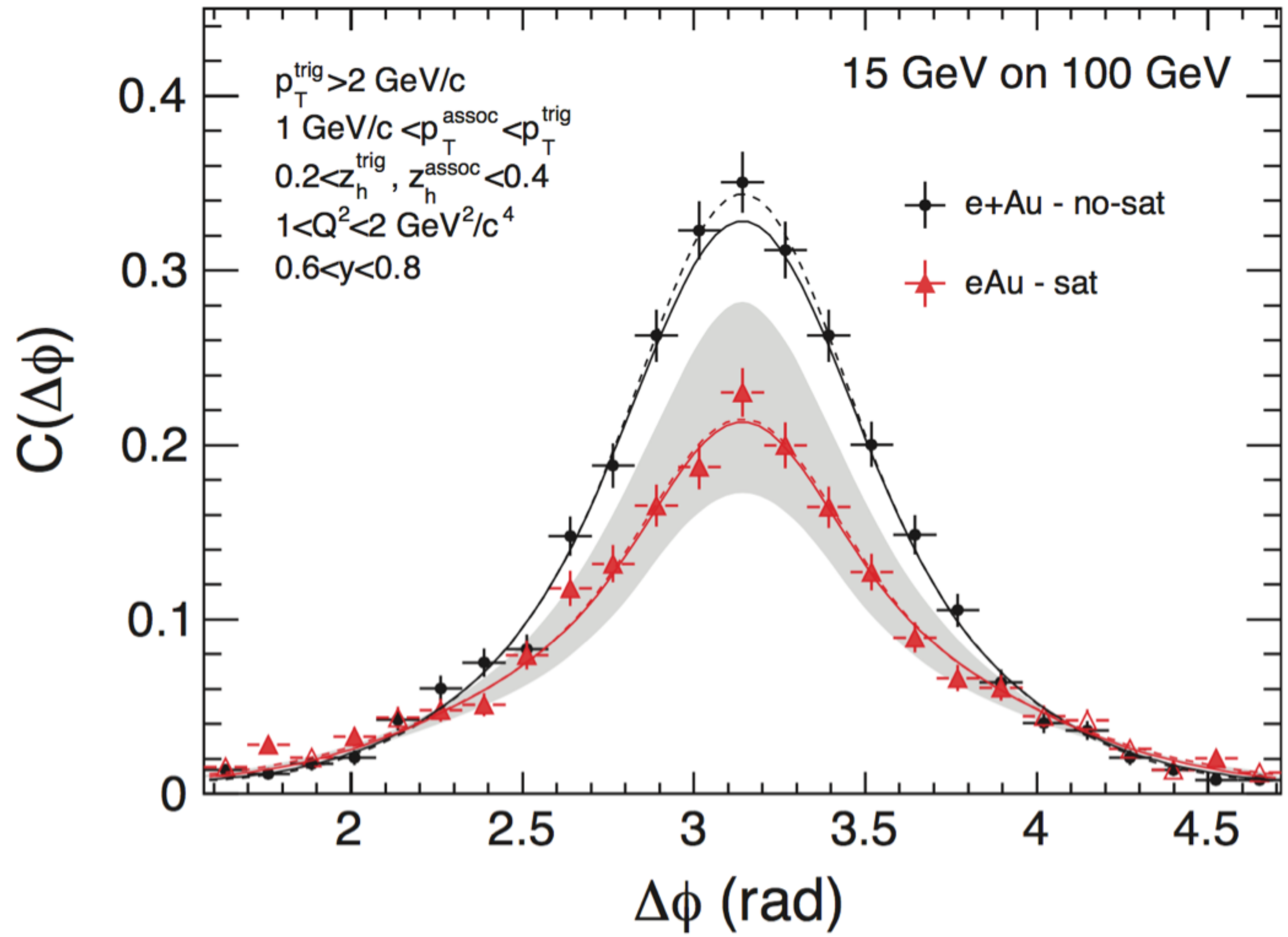
***To be seen* and *certainly no substitute* for thinking *outside* the PDF!**

EIC - Dihadrons to probe Saturation





Dominguez, Xiao, Yuan (2011)



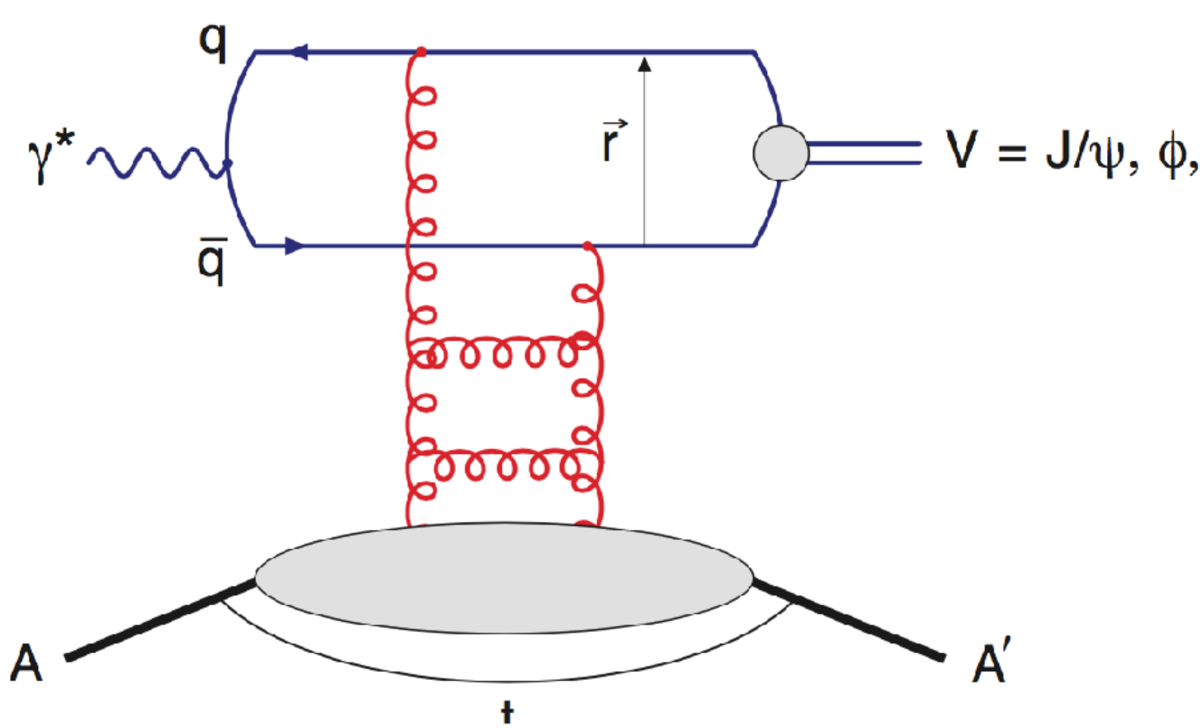
Zheng et al (2014)

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

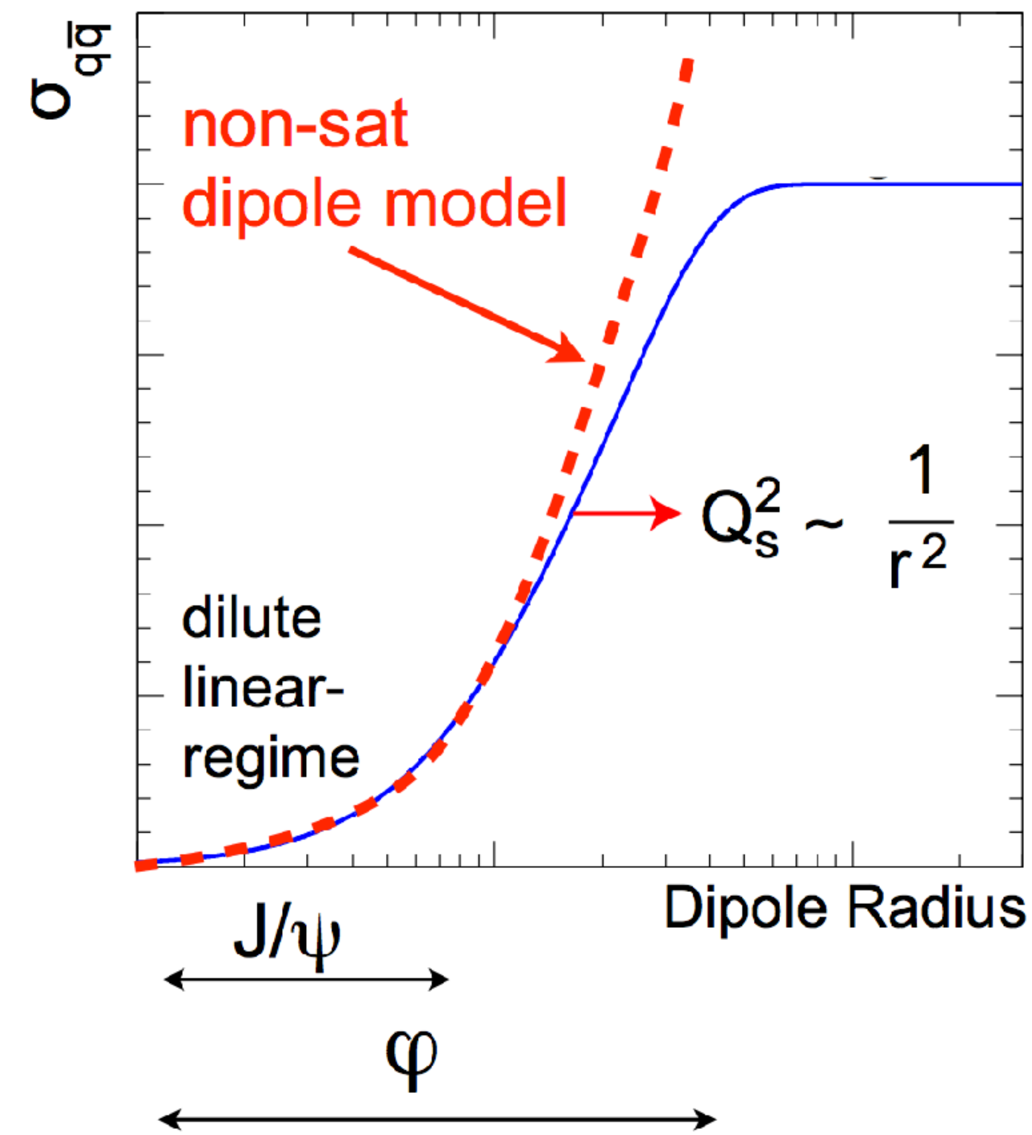
Note that diffractive cross-sections are anticipated to be other sensitive quantities,

EIC - Exclusive Vector Mesons to probe Saturation

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



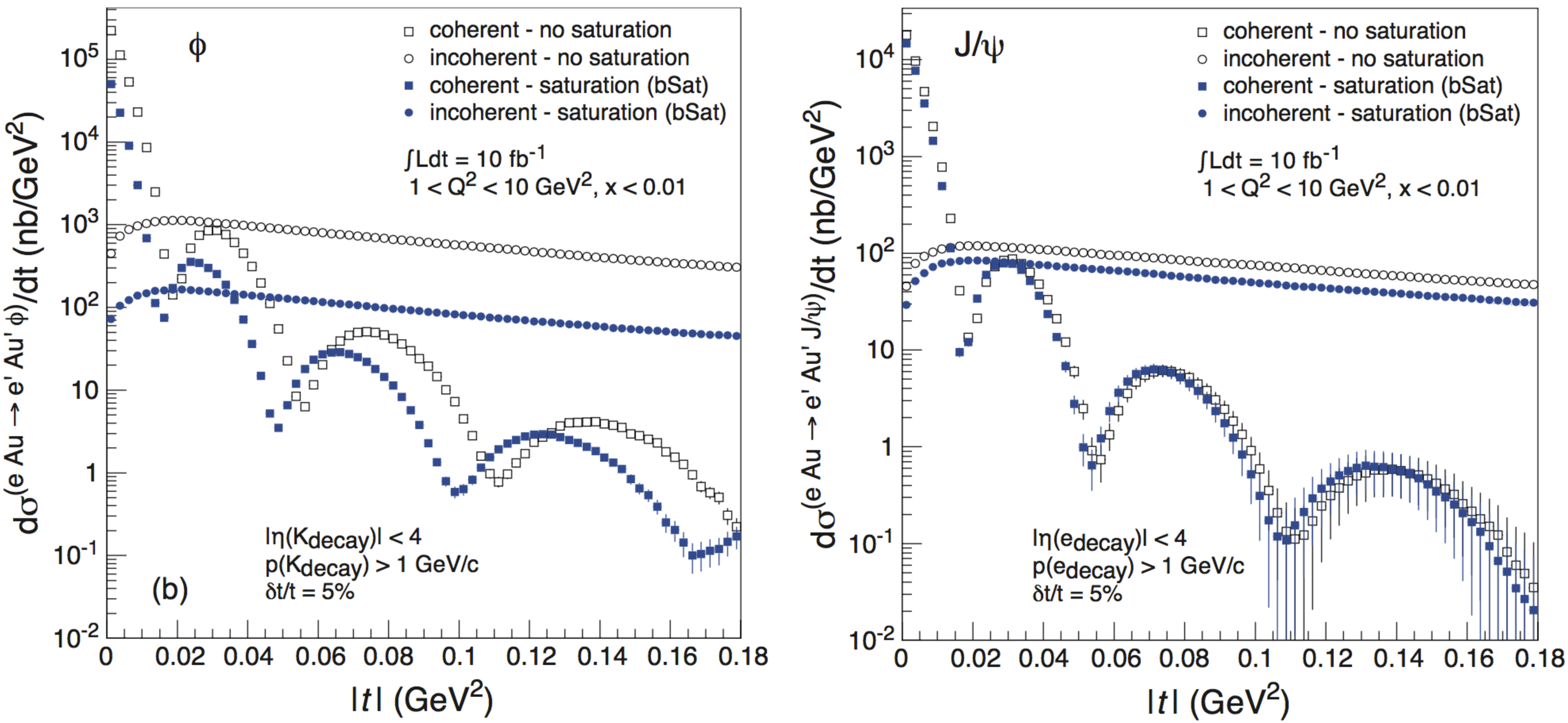
Dipole Cross-Section:



Nucleus escapes down the beampipe

(In)coherence tagged with ZDC

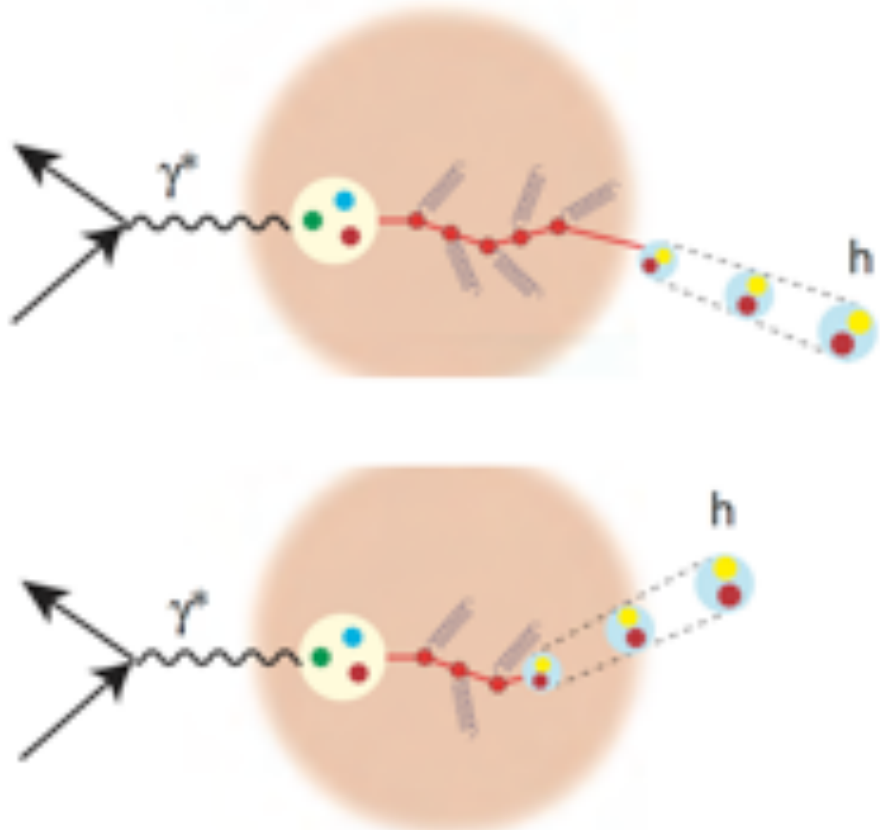
EIC - Exclusive Vector Mesons to probe Saturation



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

Experimentally among the most demanding on electron resolutions

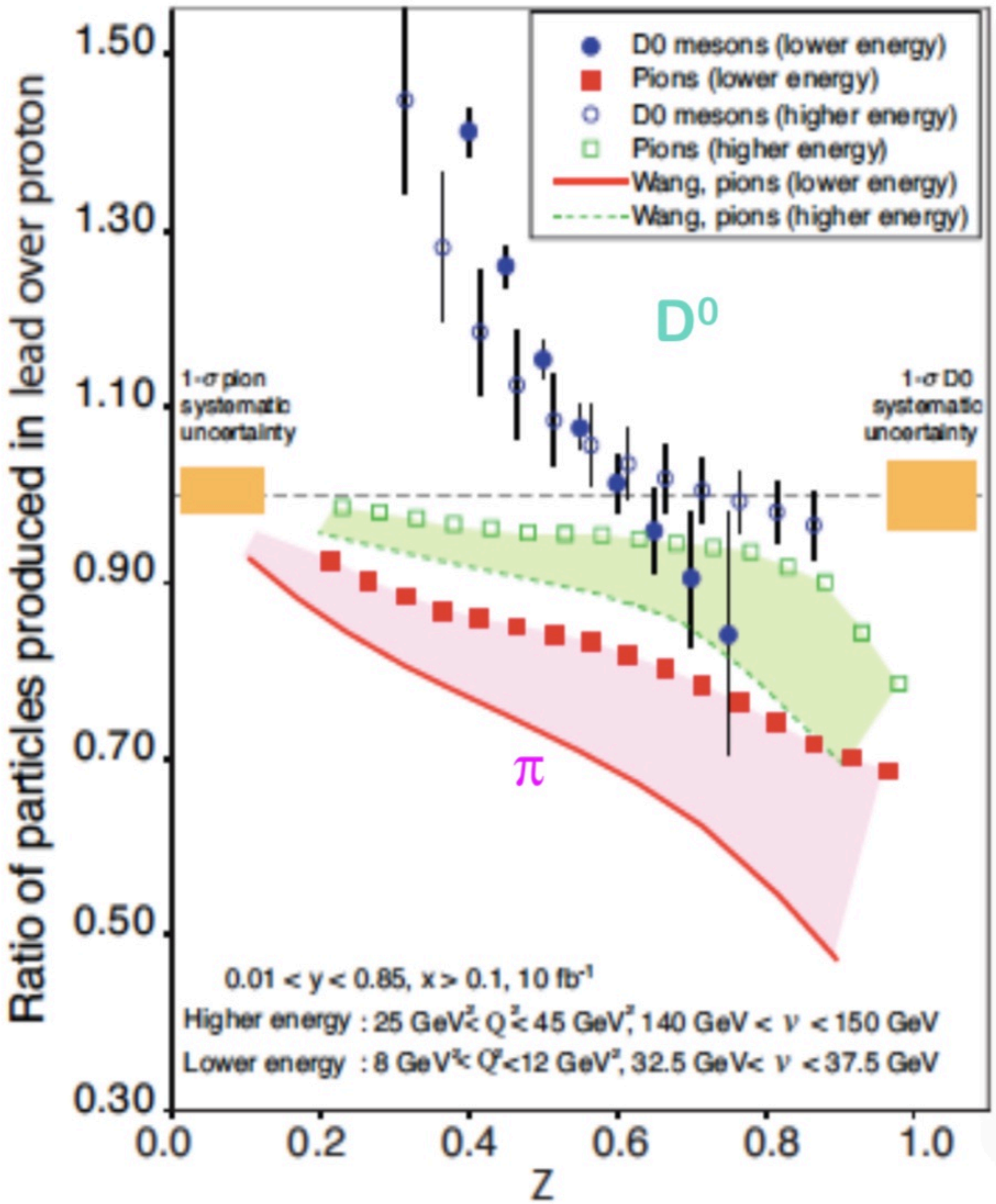
EIC - SIDIS to study Emergence of Hadrons



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

medium length

Study mass-dependence via charmed hadrons.

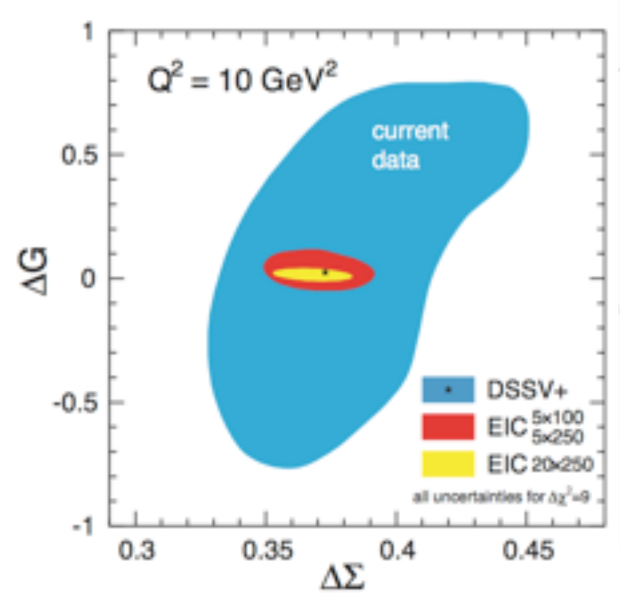


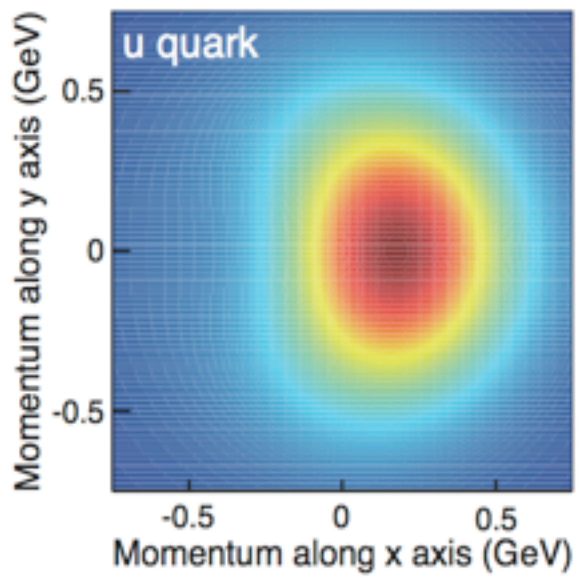
Promising developments with jet probes and their substructure — early days.

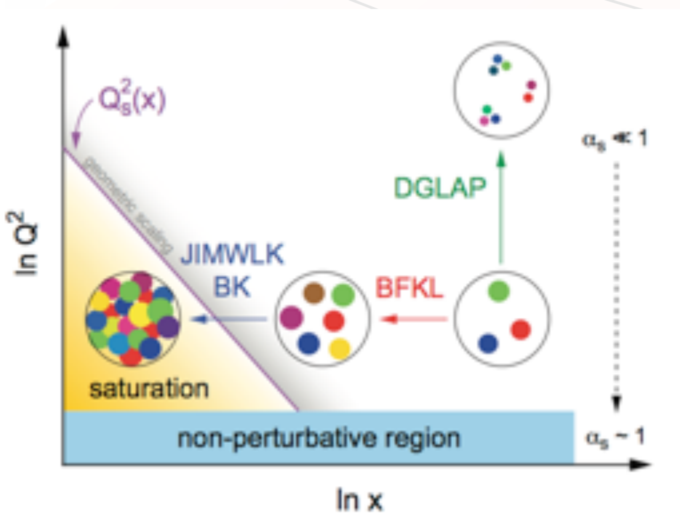
Closing Comments

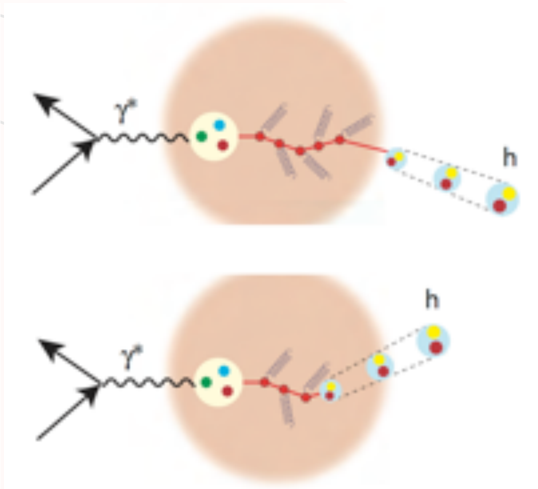
EIC will address profound questions:

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









ArXiv:1212.17010

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

Relies crucially on theory and experiment, <u>and</u> accelerator-collider capabilities.

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

Thank you!