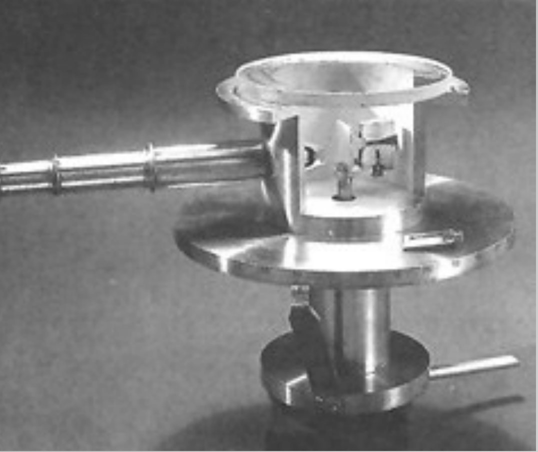
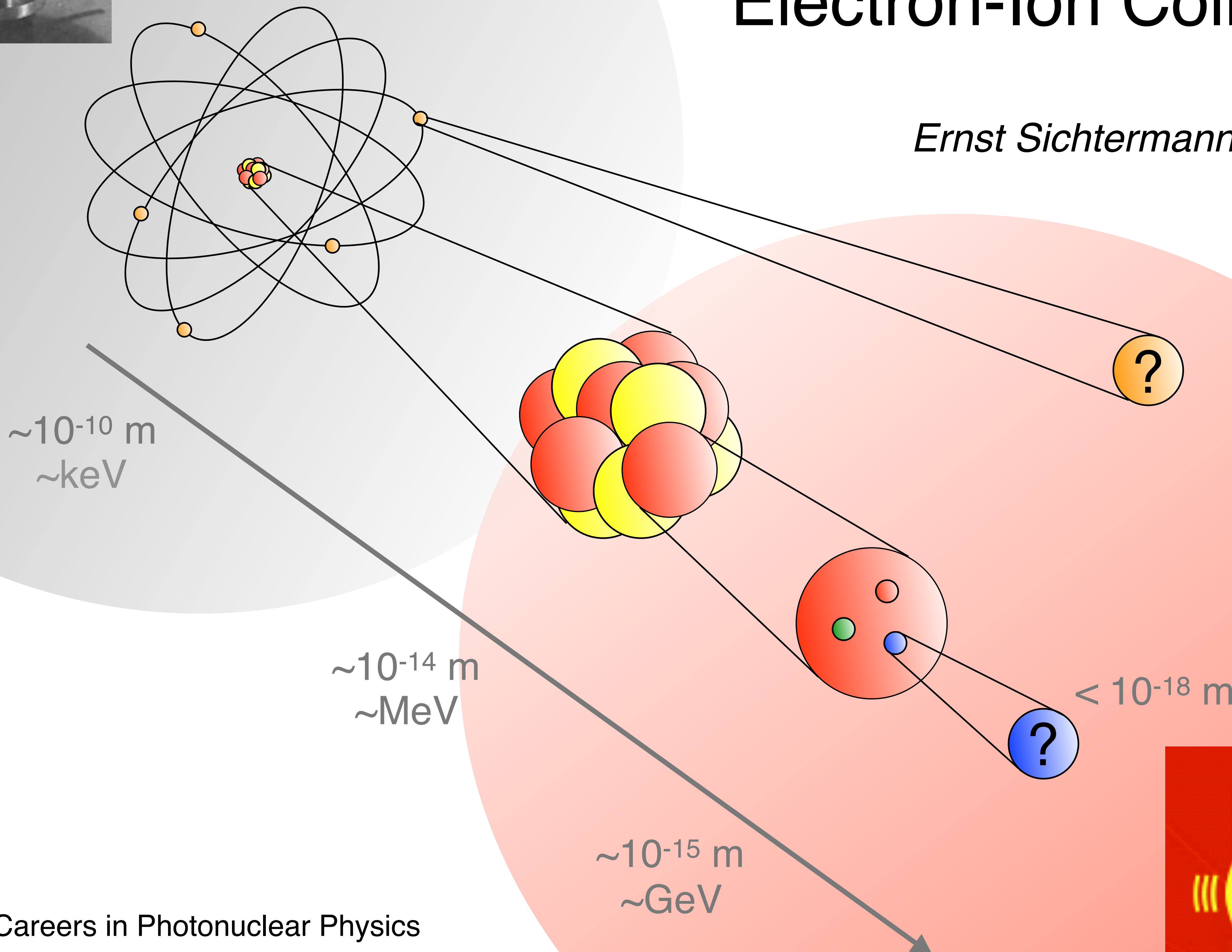
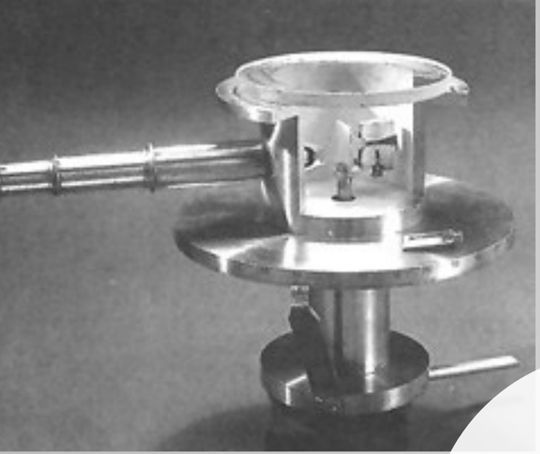


Electron-Ion Collider

Ernst Sichtermann



Frontiers and Careers in Photonuclear Physics
EINN2019
Paphos, Cyprus - October 28, 2019



Many Thanks to the Organizers,

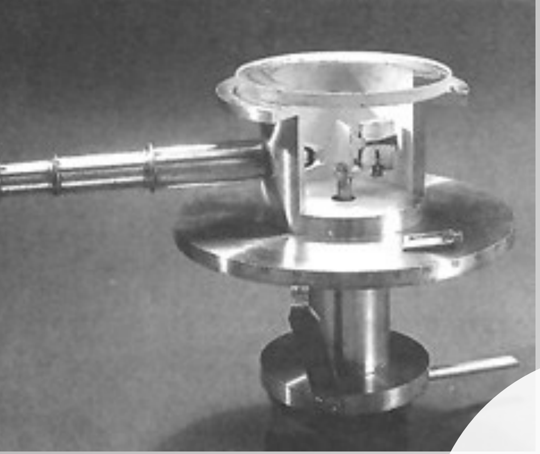
in particular Lena Heijkenskjöld
Afroditi Papadopoulou

~10^{-10} m
~keV

~10^{-14} m
~MeV

~10^{-15} m
~GeV

< 10^{-18} m



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<u>You</u> for taking part in this <u>discussion</u>

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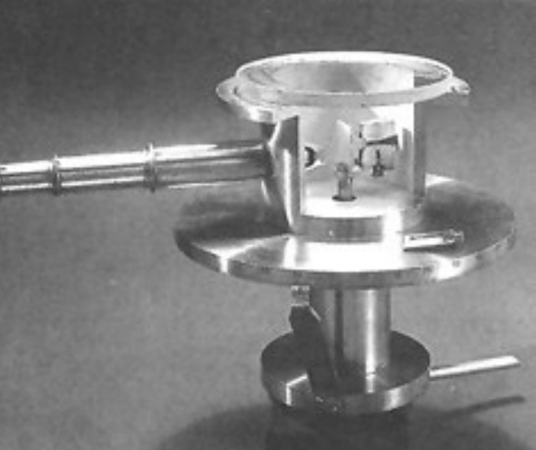

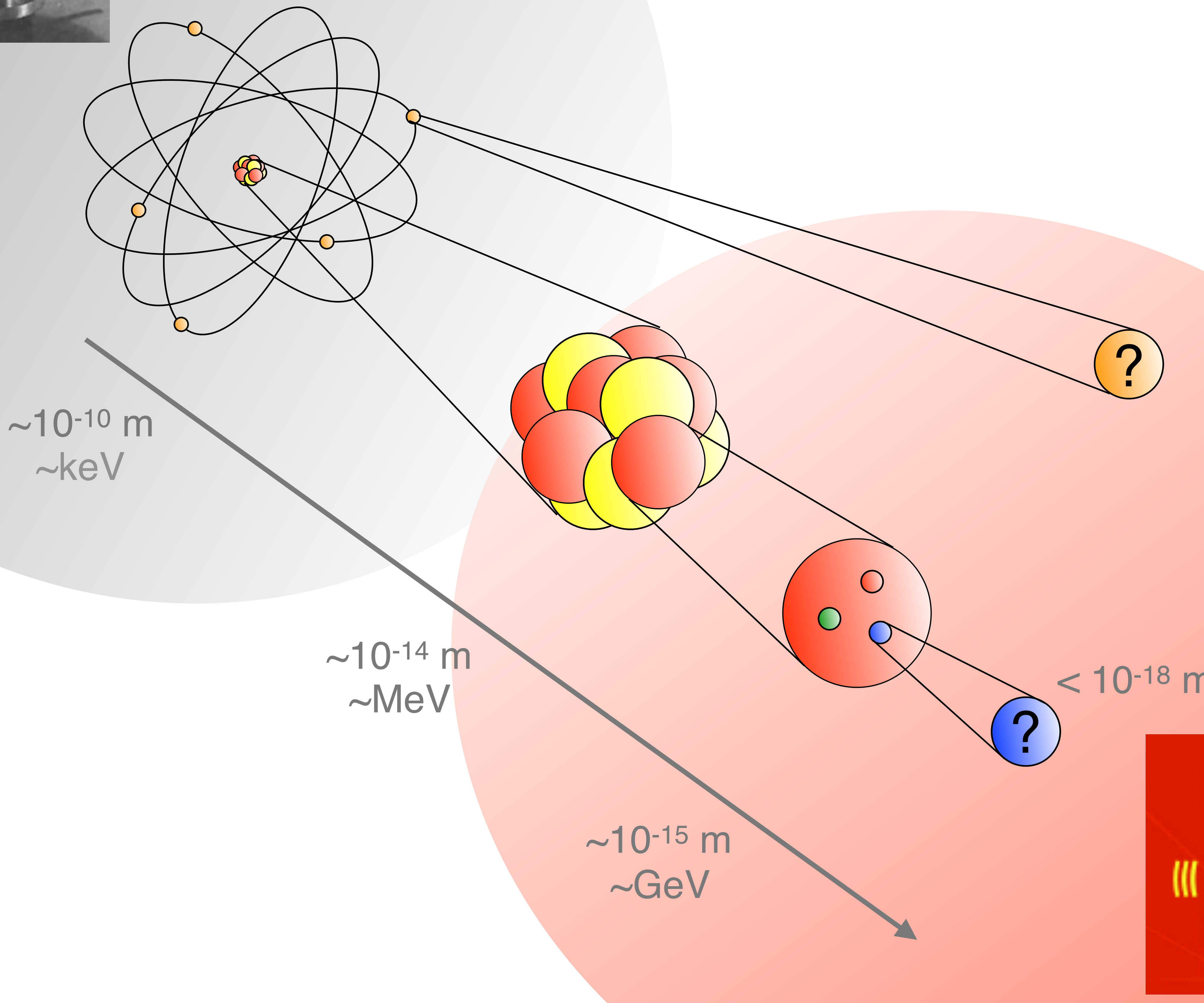

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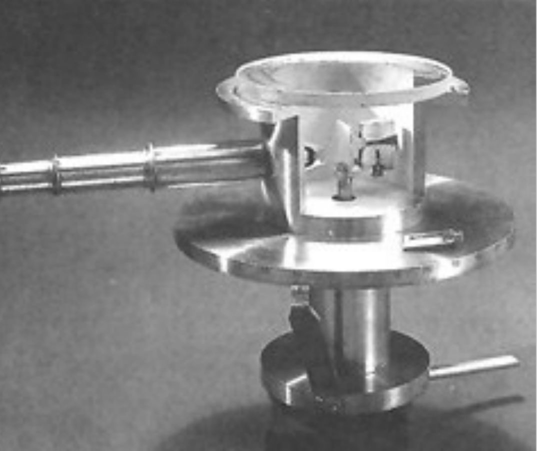
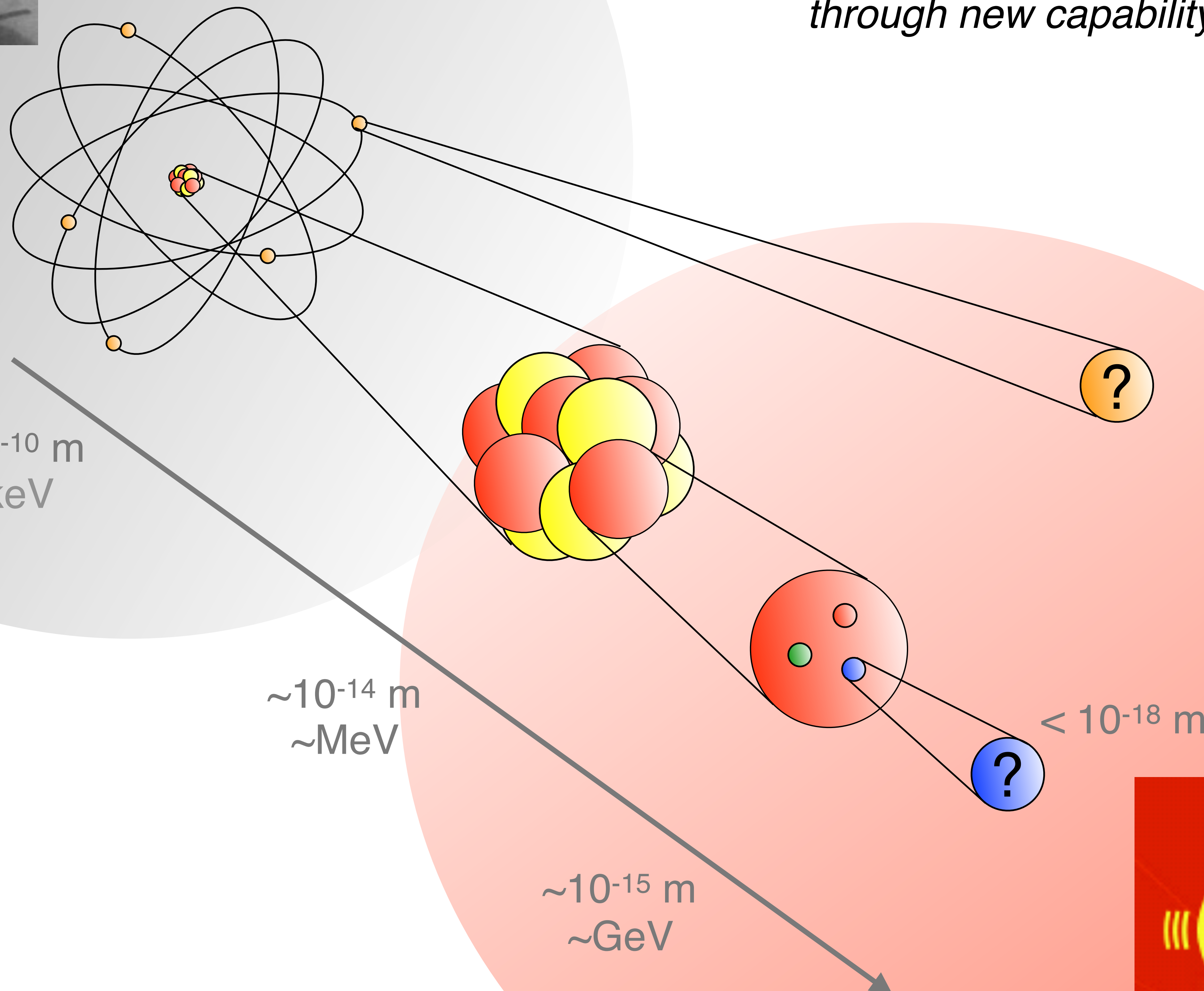
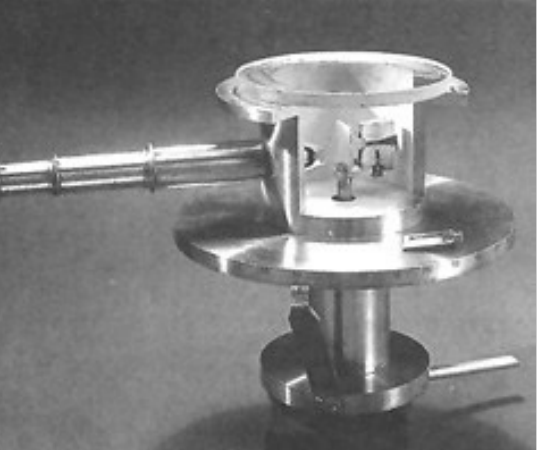
?
?

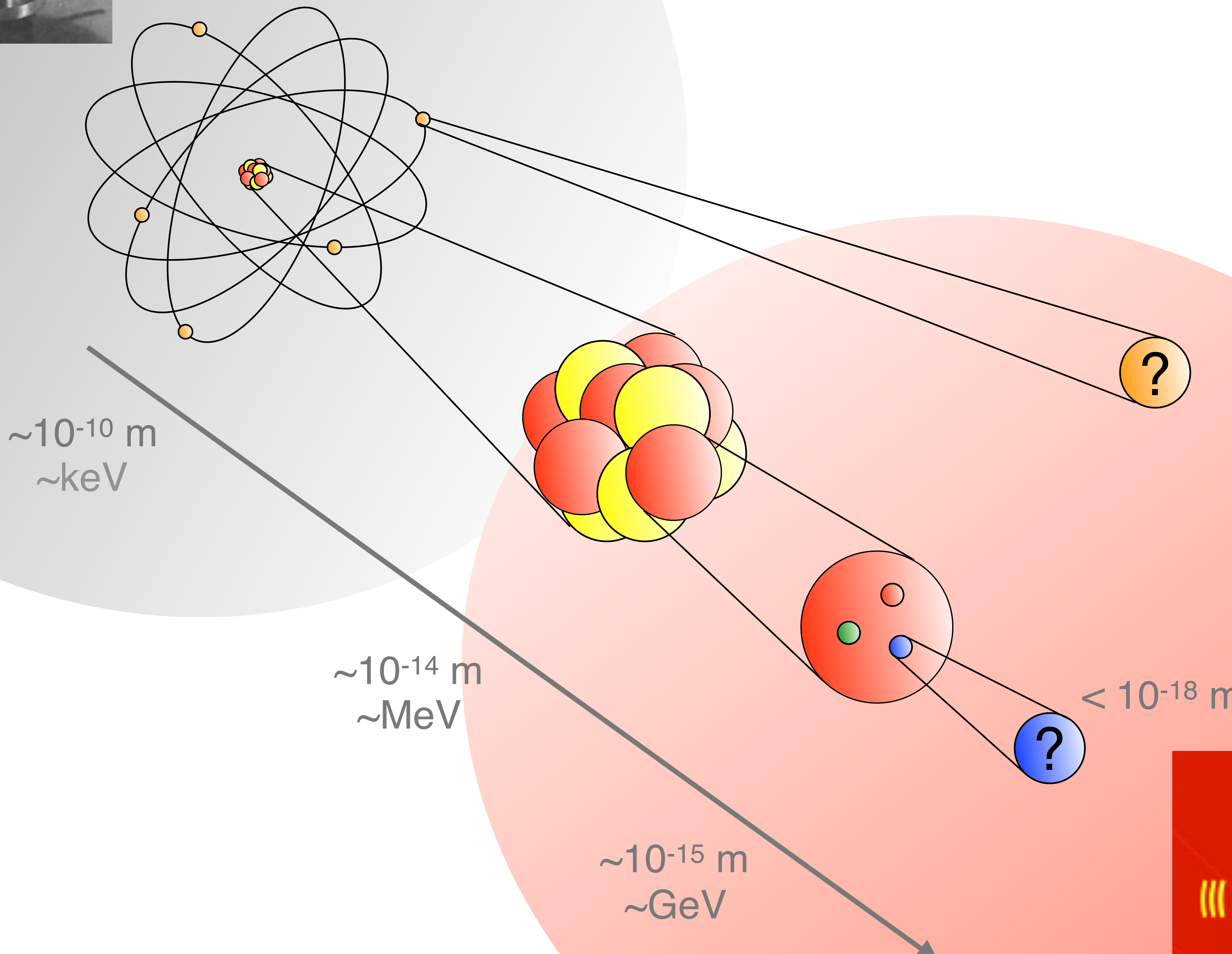


A history of new insight through new capability





What *is* a proton, neutron, nucleus?



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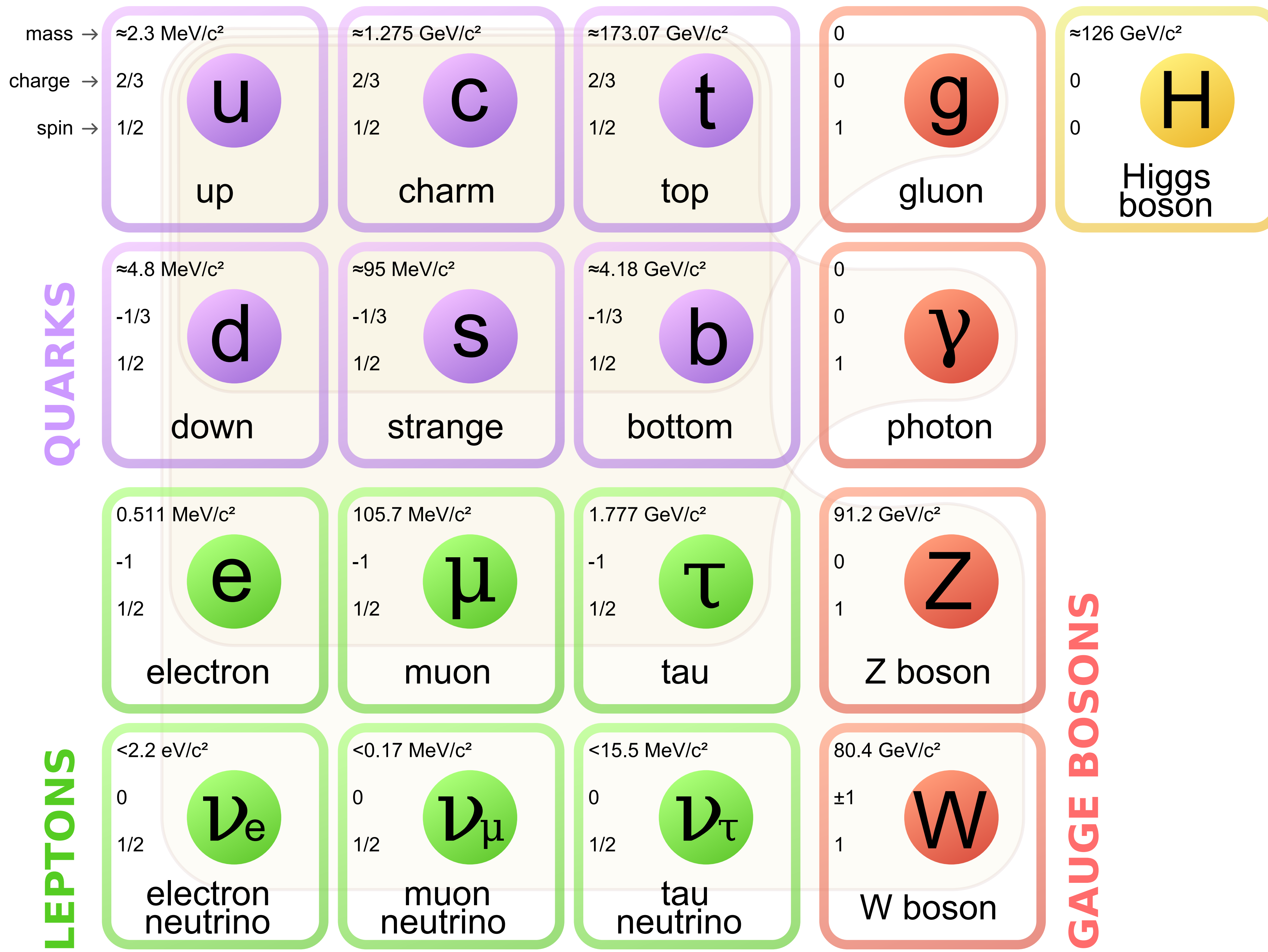
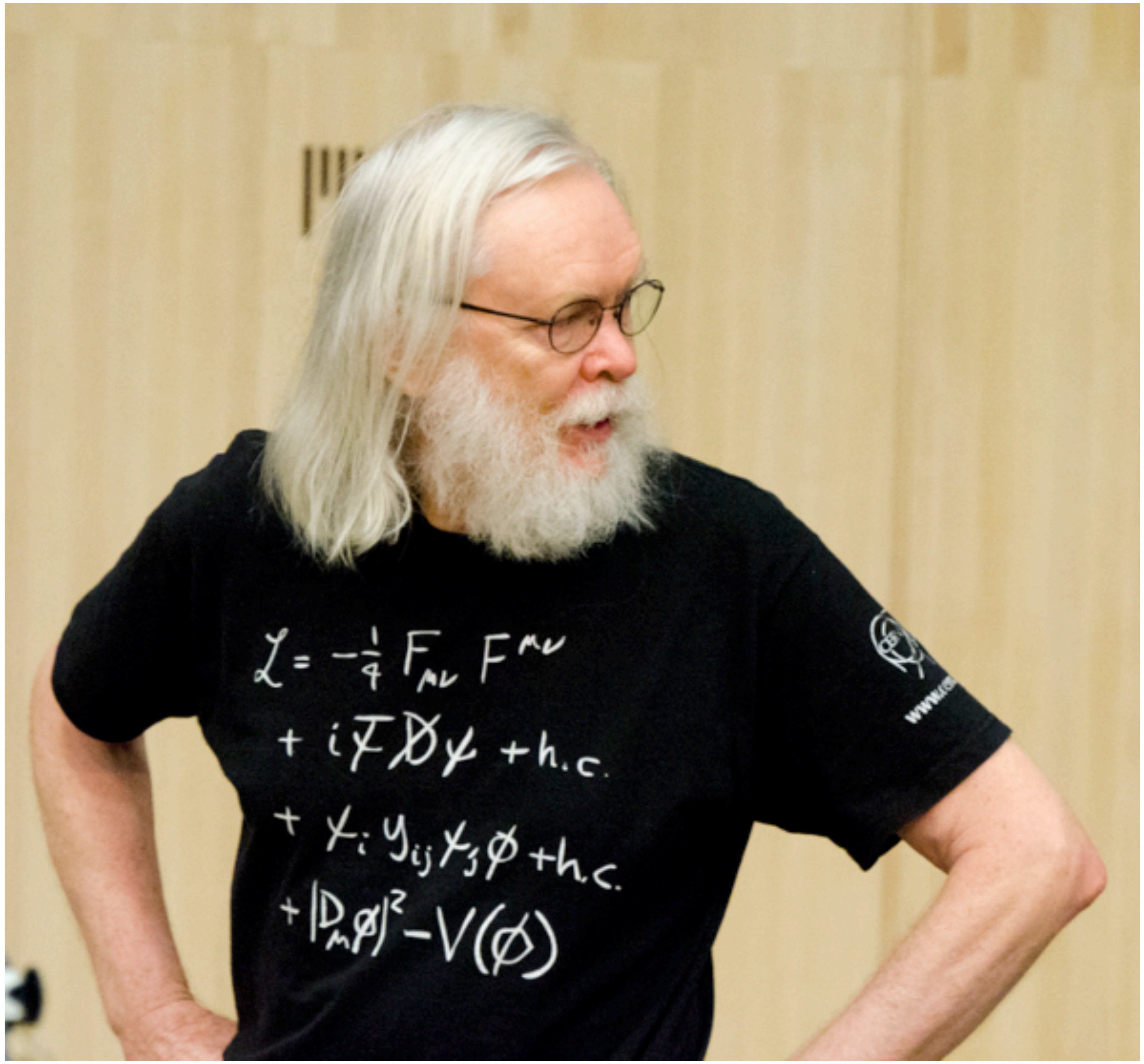


The proton is just 2 up quarks and 1 down quark, …

What *is* a proton, neutron, nucleus?



QCD - *been there, done that, got the T-shirt ?!*

What *is* a proton, neutron, nucleus?

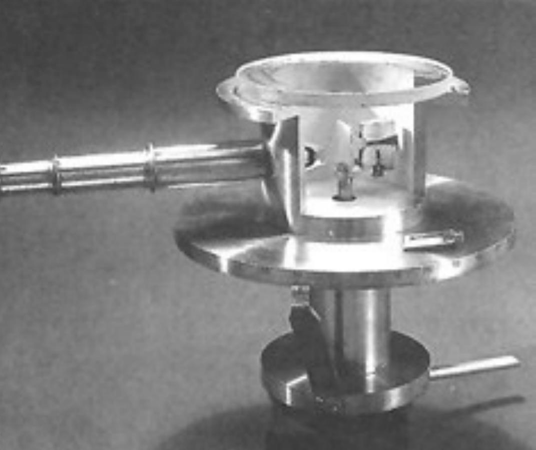
A strongly-bound object of ~0.8fm radius,
~0.94 GeV mass
spin 1/2

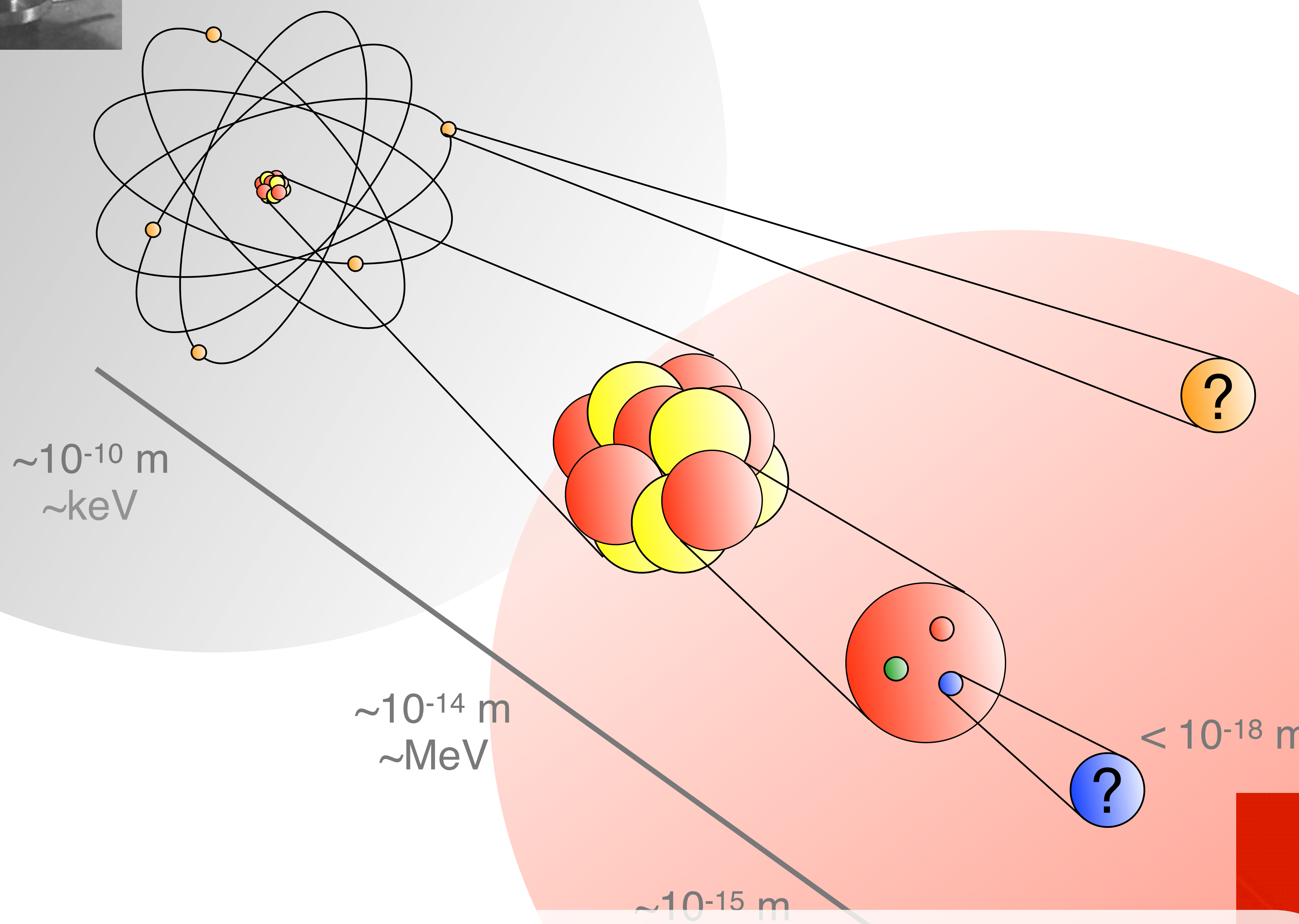
None of these are Standard Model parameters,

Ab-initio calculations are starting to scratch the surface,

To provoke a little: we are still *far* from “QCD-engineering,”
“QED-engineering” brought us the transistor.

What *is* a proton, neutron, nucleus?

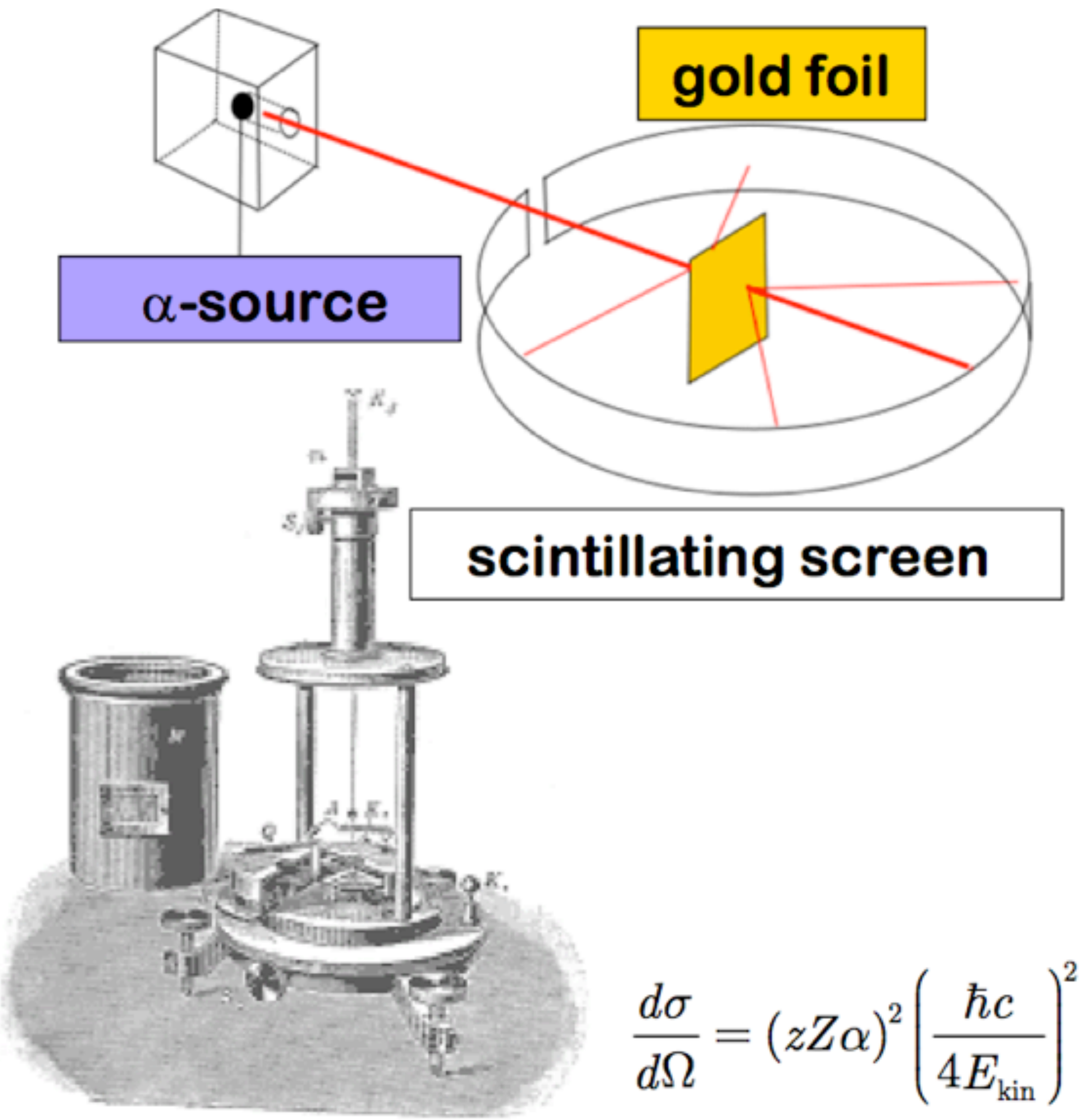




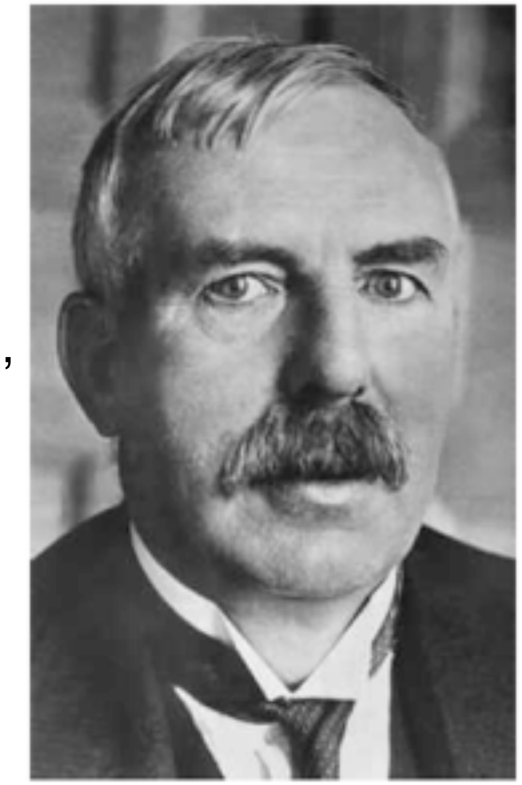
Strongly bound objects with rich structure and dynamics;
partially understood thanks to *decades* of
interplay between theory and *experiment*

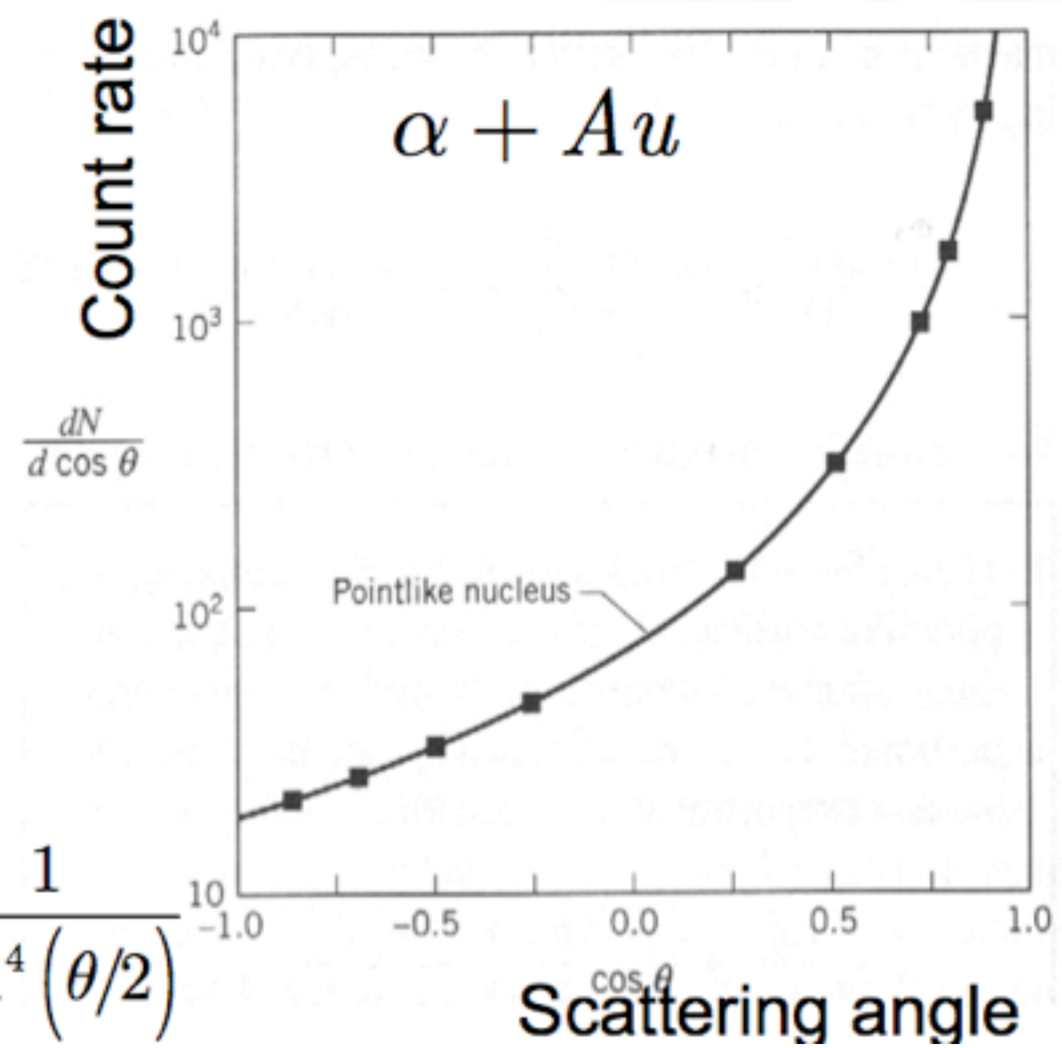
Rutherford Scattering

~5 MeV



Ernest Rutherford,
Nobel Prize 1908



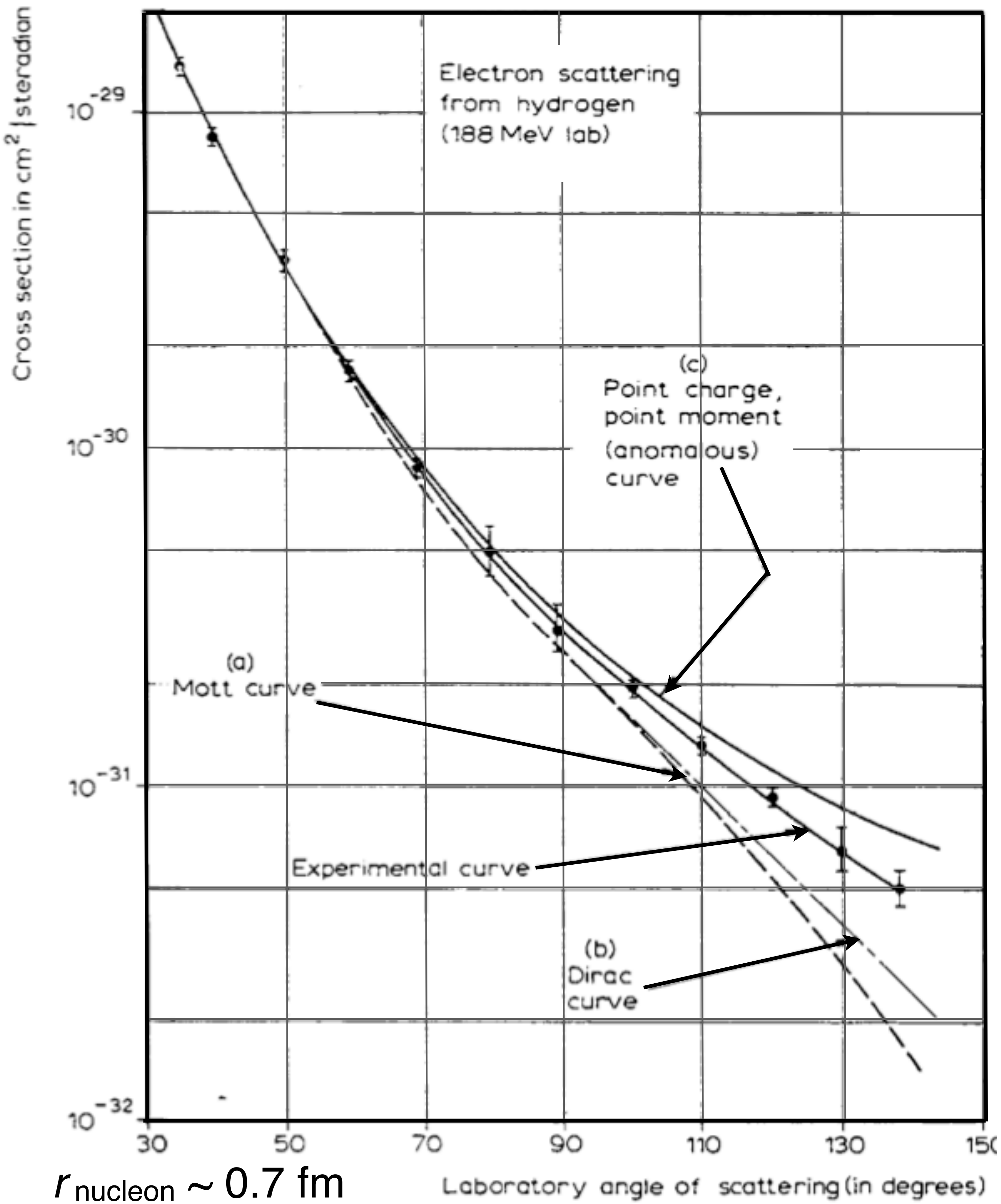


$$\frac{d\sigma}{d\Omega} = (zZ\alpha)^2 \left(\frac{\hbar c}{4E_{\text{kin}}}\right)^2 \frac{1}{\sin^4(\theta/2)}$$

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

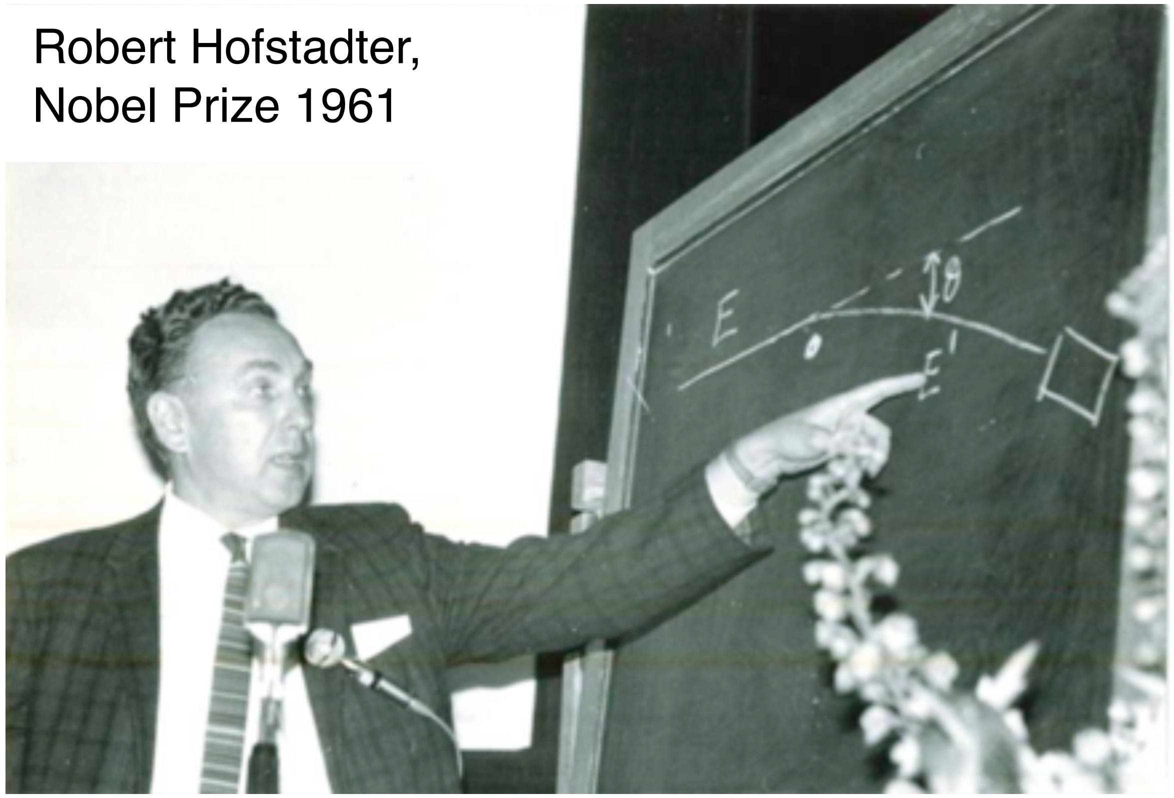
~200 MeV

Elastic Electron Scattering



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

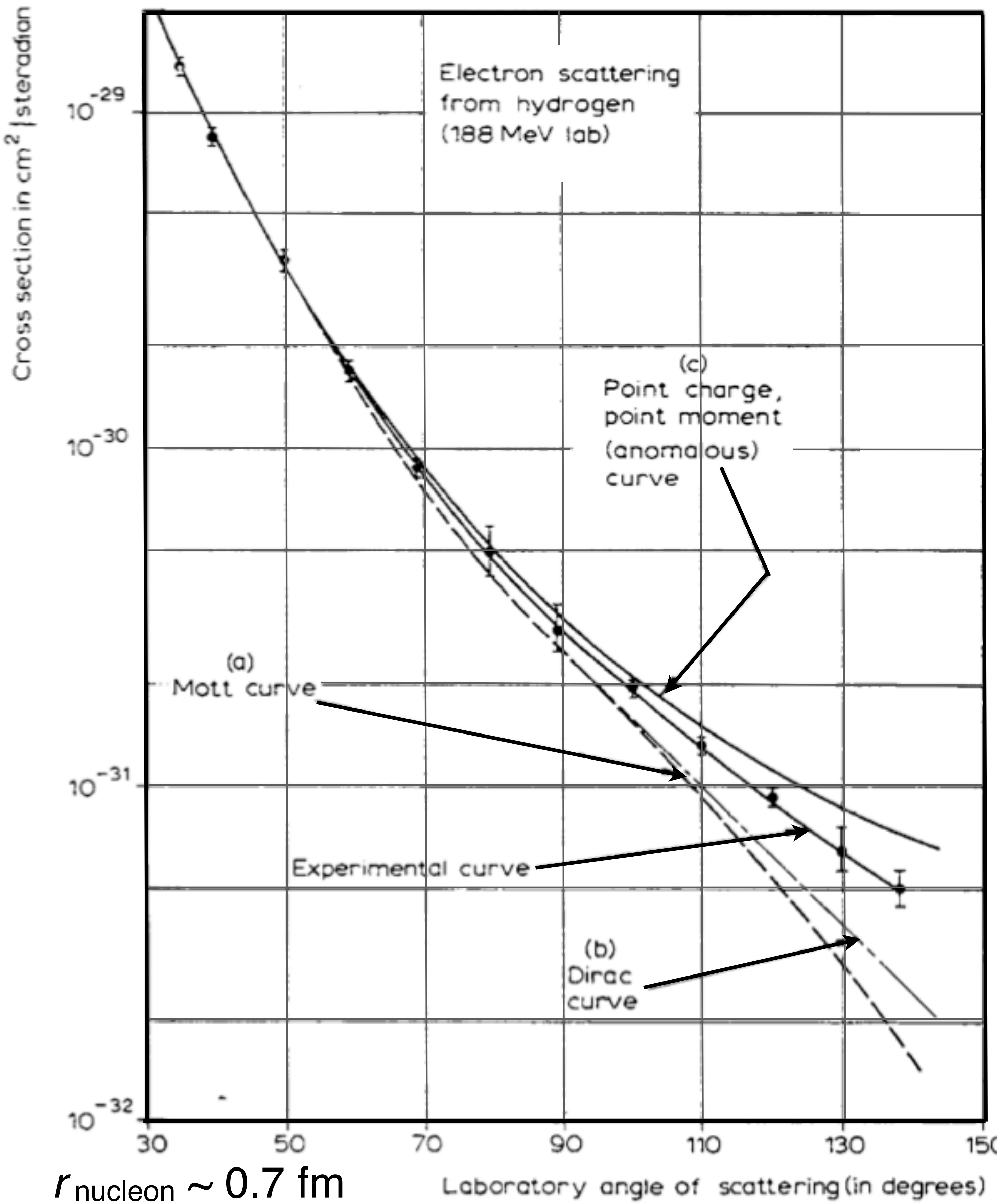
$$g_p \neq 2, \quad g_p \simeq 5.6$$

and, hence, internal (spin) structure.

Proton "radius" remains topical - see e.g. Nilanga Liyanage's talk on Wednesday

Elastic Electron Scattering

~200 MeV



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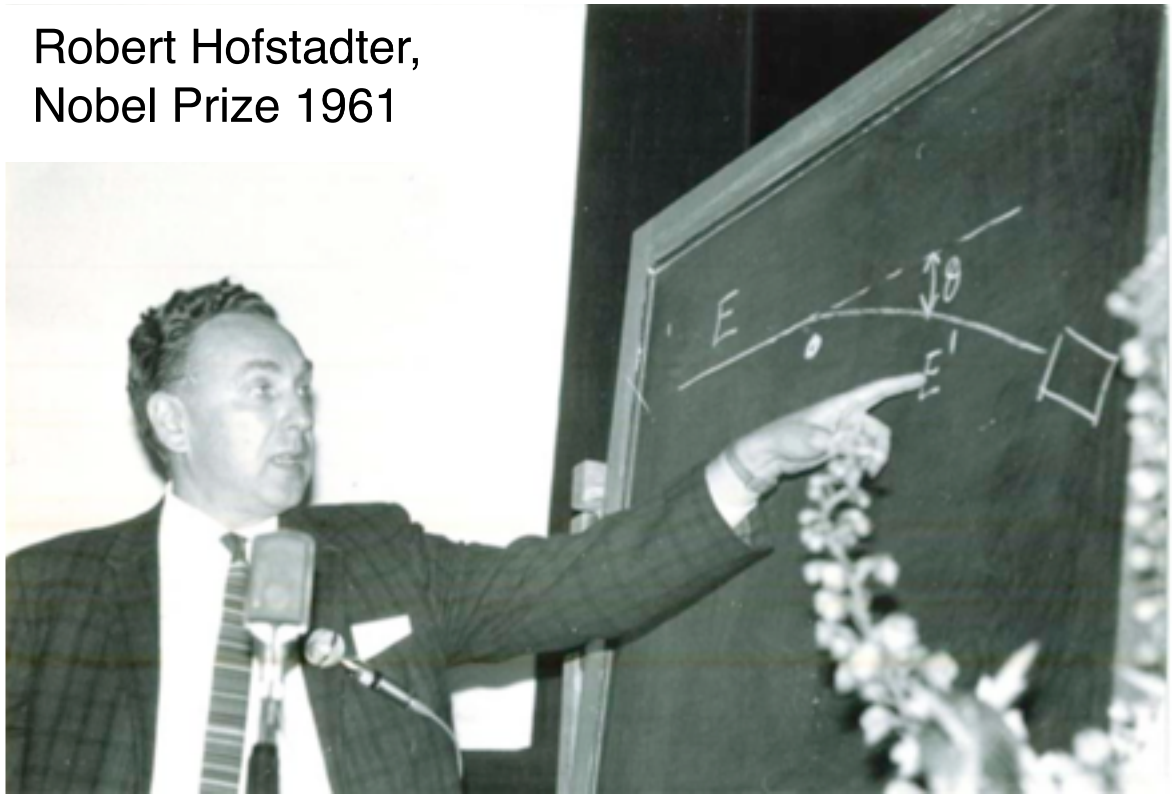

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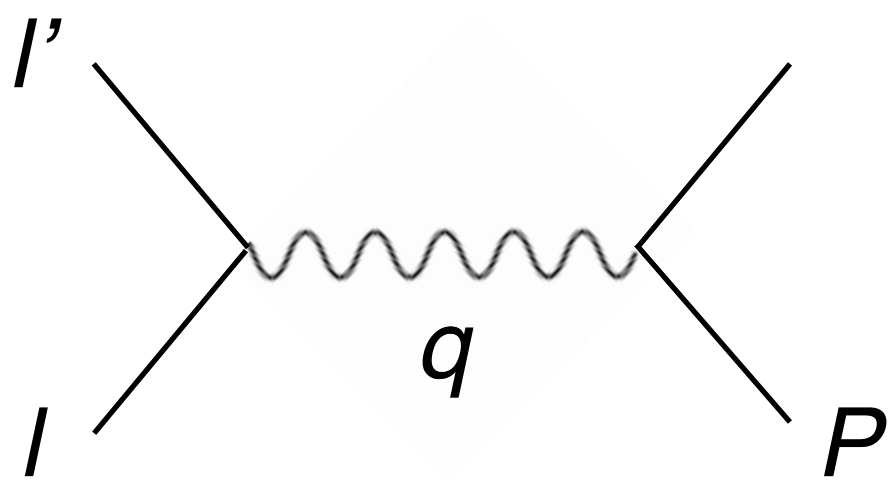


$$d\sigma \propto \left\langle |\mathcal{M}|^2 \right\rangle = \frac{g_e^4}{q^4} L^{\mu\nu}_{\text{lepton}} K_{\mu\nu\,\text{nucleon}}$$

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:

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

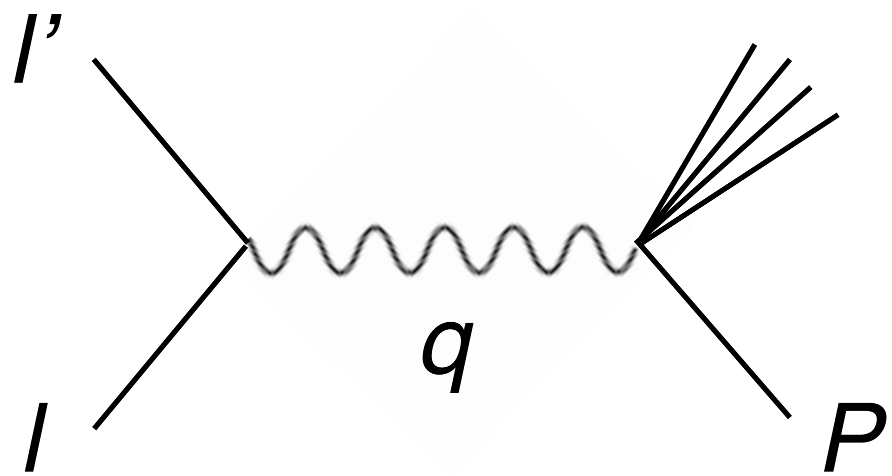
Charge conservation at the proton vertex reduces the number of structure functions:

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

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,

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

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

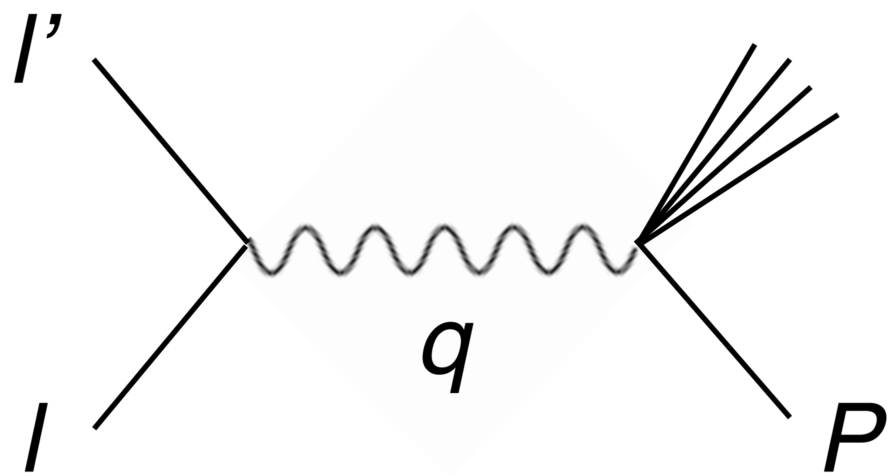
$$W_1, W_2 \;\; \text{or, alternatively expressed,} \;\; F_1, F_2$$

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

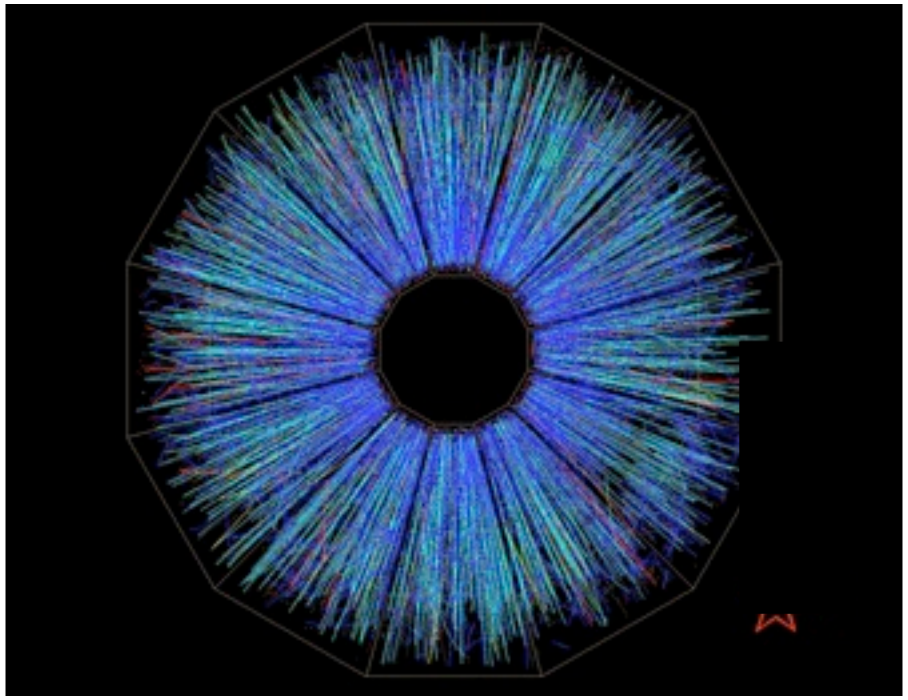
$$Q^2 = -q^2, \qquad x = -\frac{q^2}{2q.p}, \;\; 0 < x < 1$$

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

Inelastic Scattering



Not convinced of additional complexity?



Then forget this talk, and calculate this!

Simplify - consider *inclusive* inelastic scattering,

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

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

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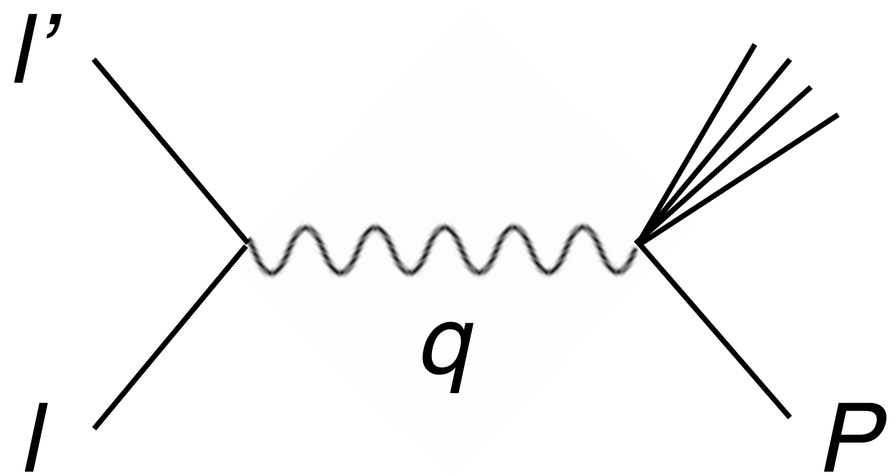
Inelastic Scattering



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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, <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 $K_{4,5}$

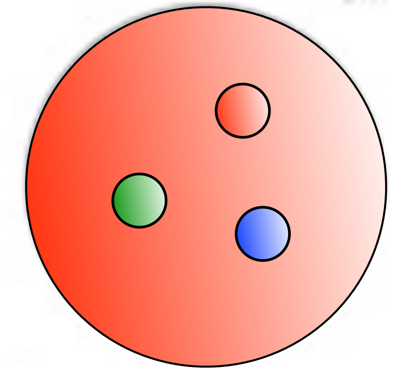
Then, e.g. by substitution of $k' = k - q$ in L:

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

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 Partons



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,

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

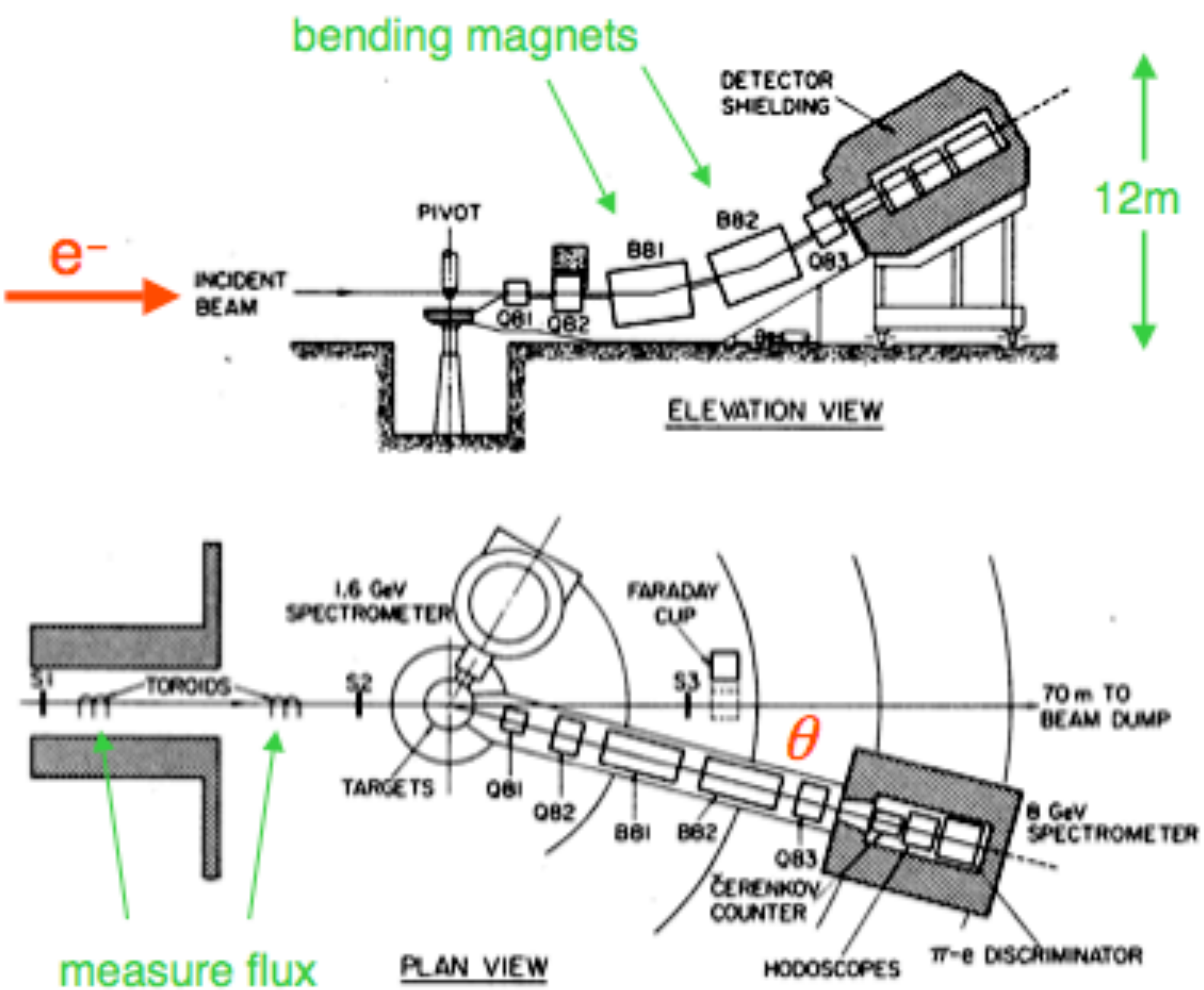
$$-\frac{q^2}{2Mx}W_2 = \sum_q \int_0^1 x e_q^2 \delta(x - z_q)\, f_q(z_q)\, dz_q = x\sum_q e_q^2 f_q(x) \equiv F_2(x)$$

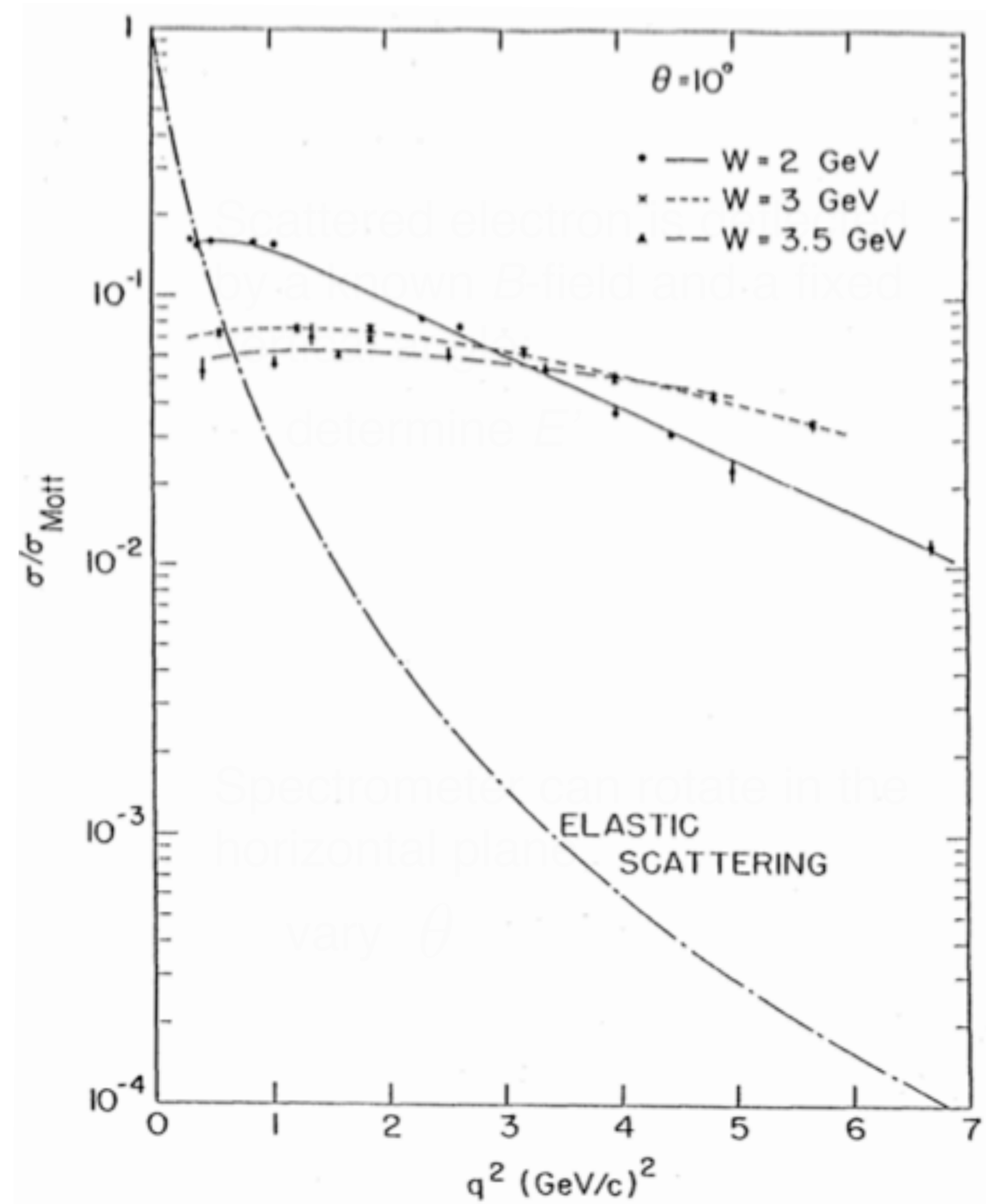
Two important *observable* consequences,

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

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

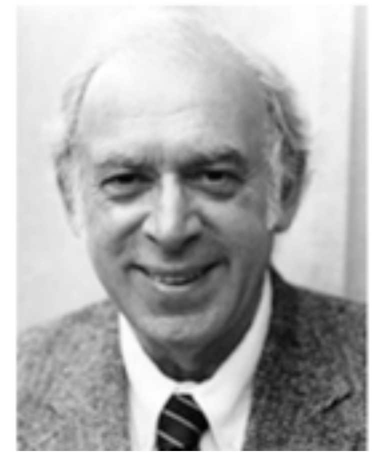
~10 GeV *Deep-Inelastic* Electron Scattering





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

Deep-Inelastic Electron Scattering

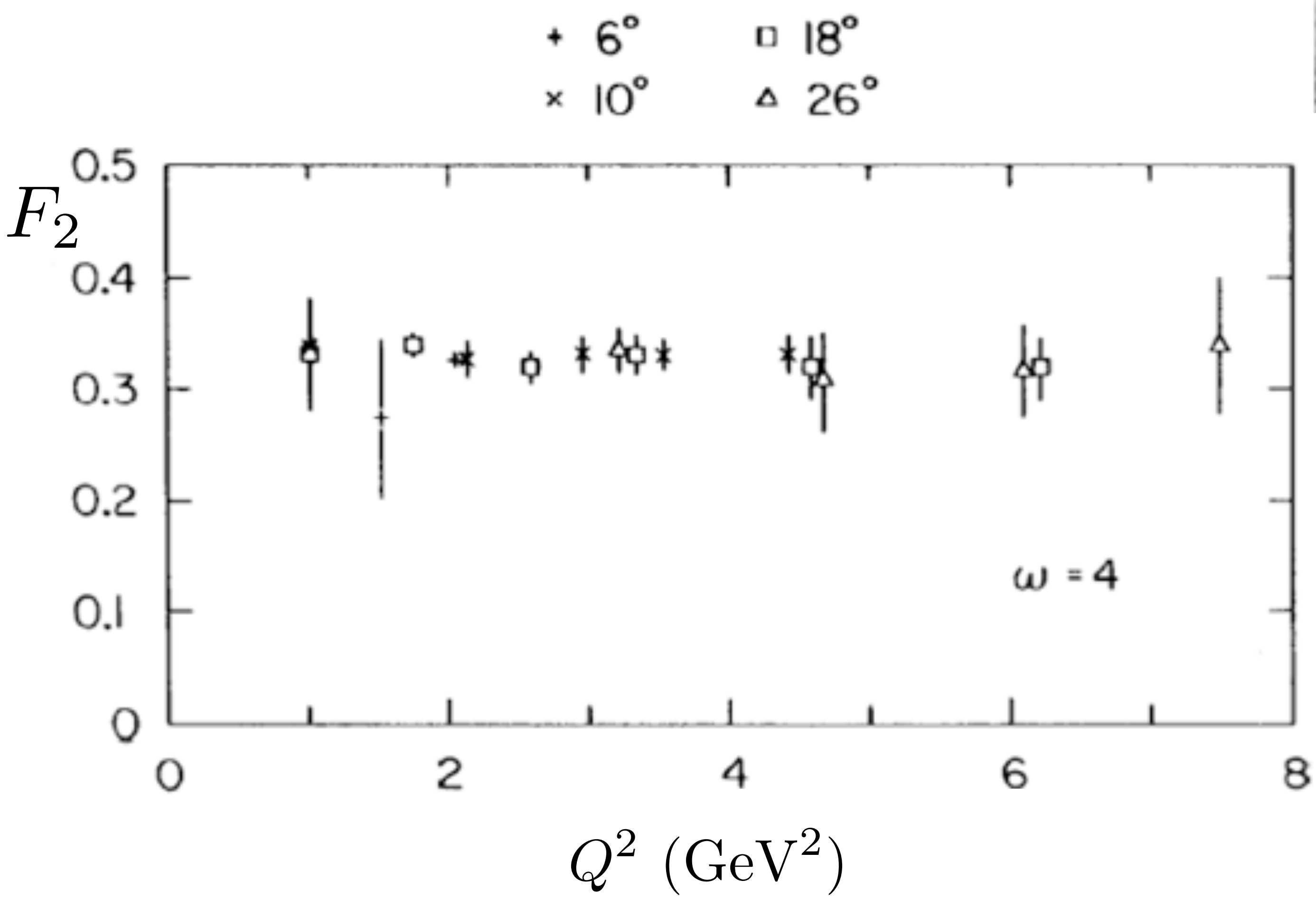


J.T. Friedman

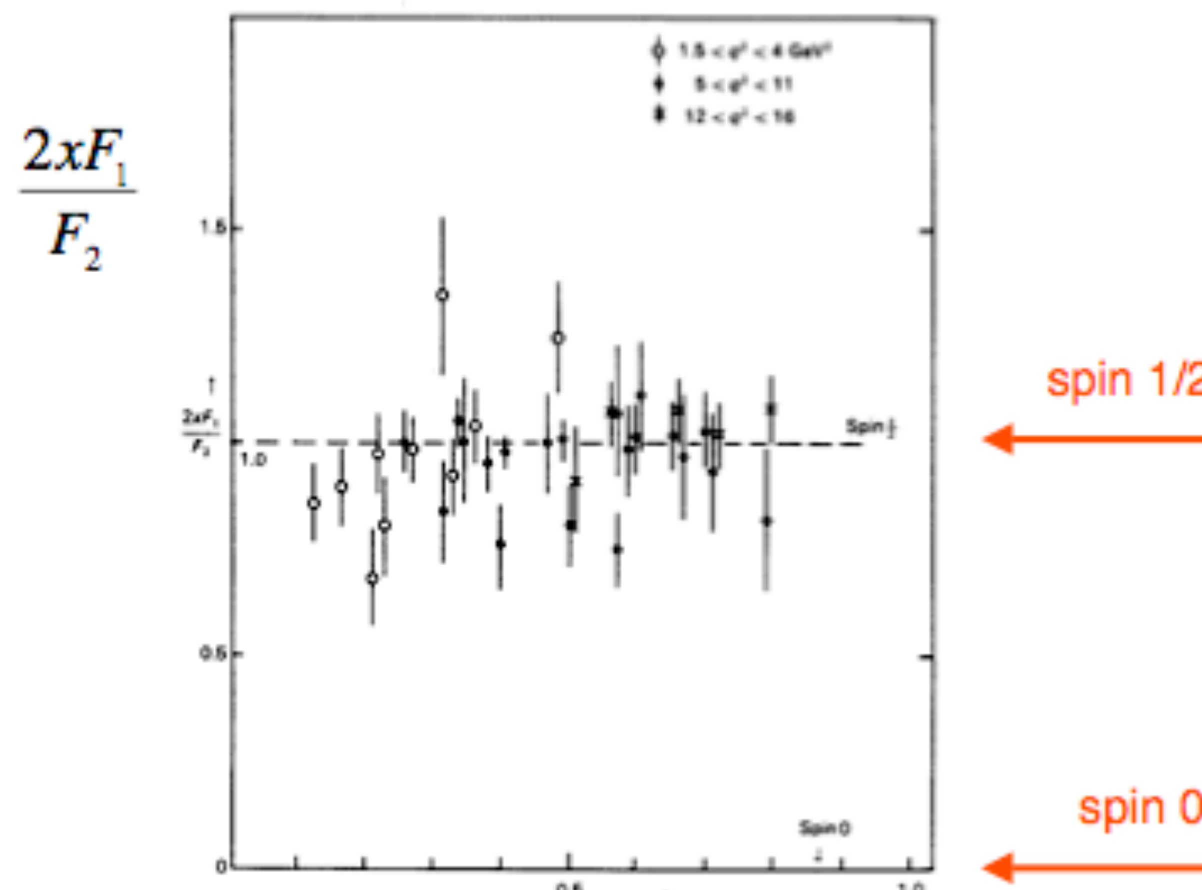
R. Taylor
Nobel Prize 1990

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.

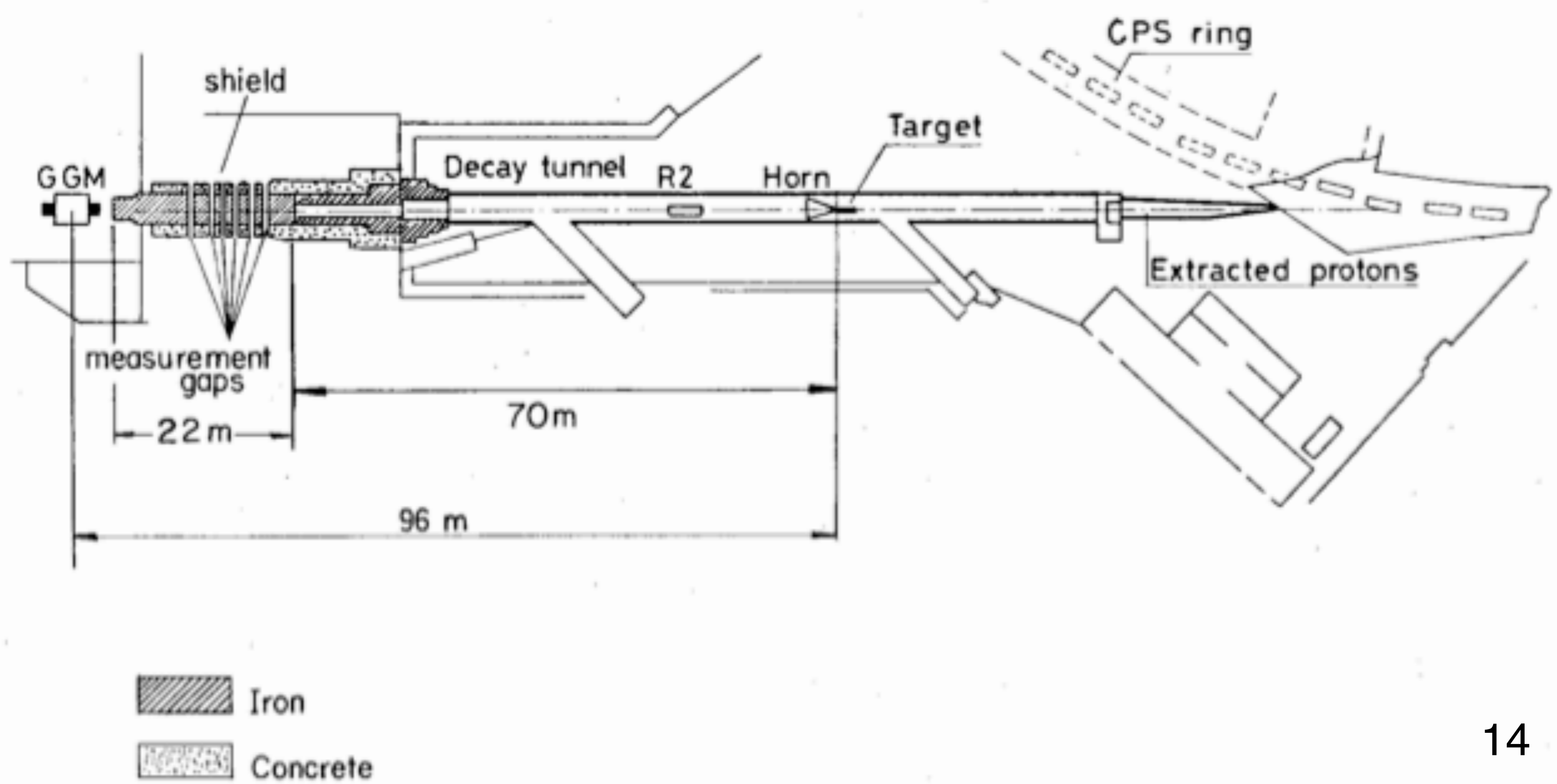
Deep-Inelastic *Neutrino* Scattering

Recognize this from CERN?

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

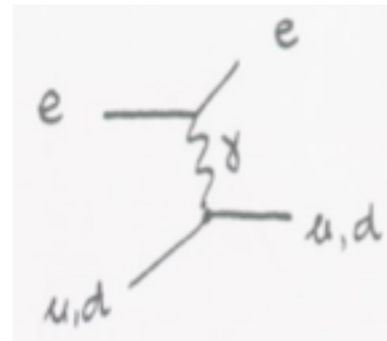
Charged-current DIS!

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

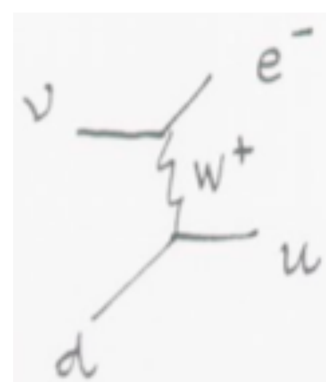
Neutral-current (photon) DIS:



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

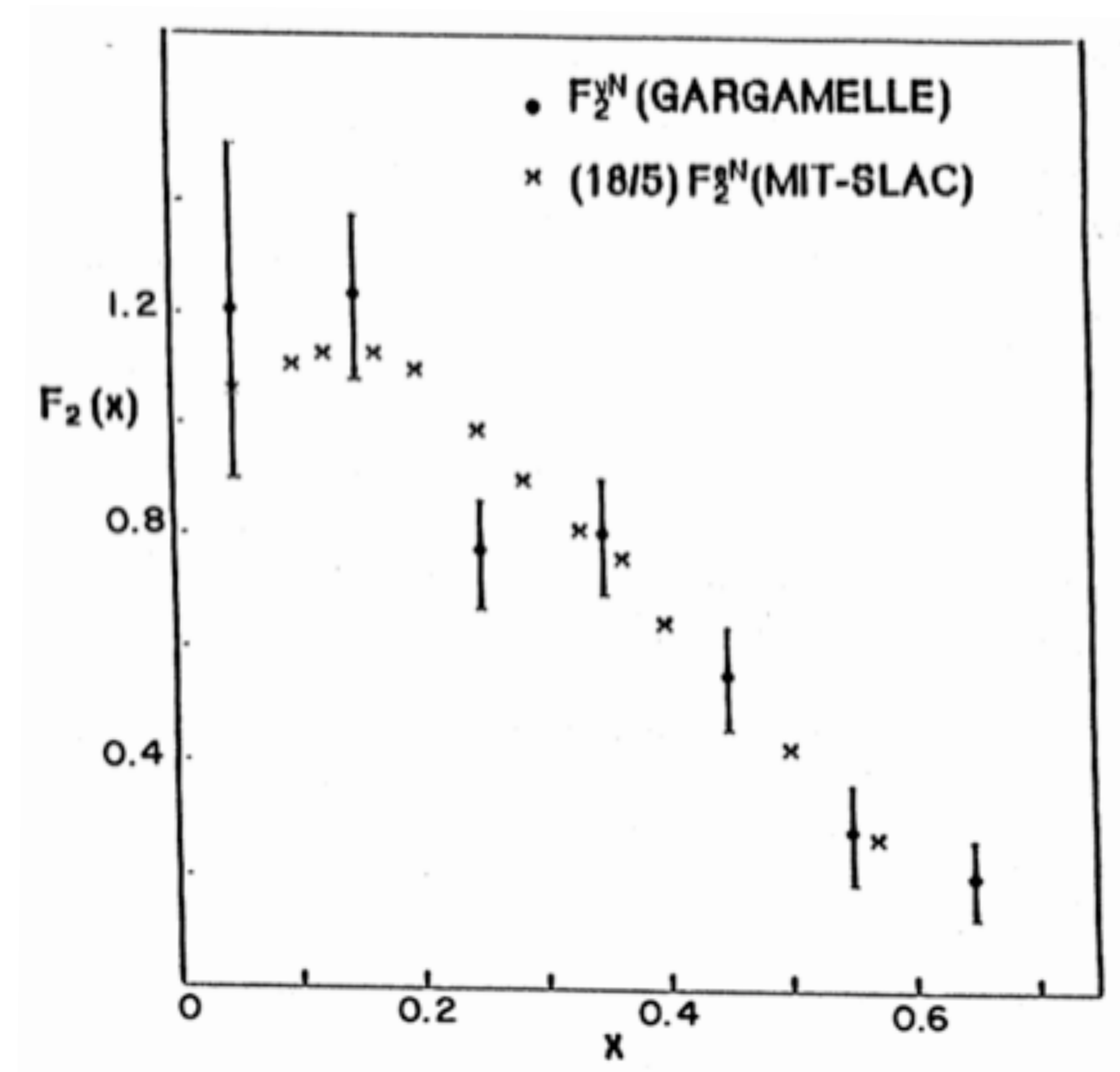
$$F_2^N = x \, \frac{e_u^2 + e_d^2}{2} \, (u + \bar{u} + d + \bar{d})$$

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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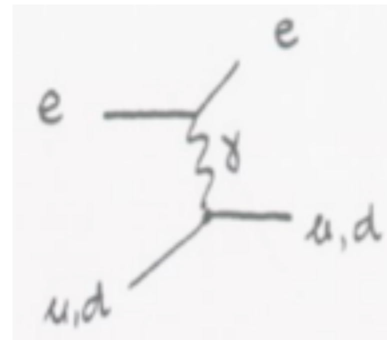

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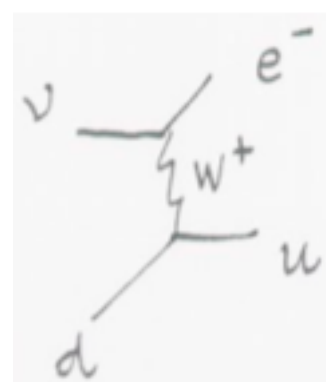
Charged-current DIS:



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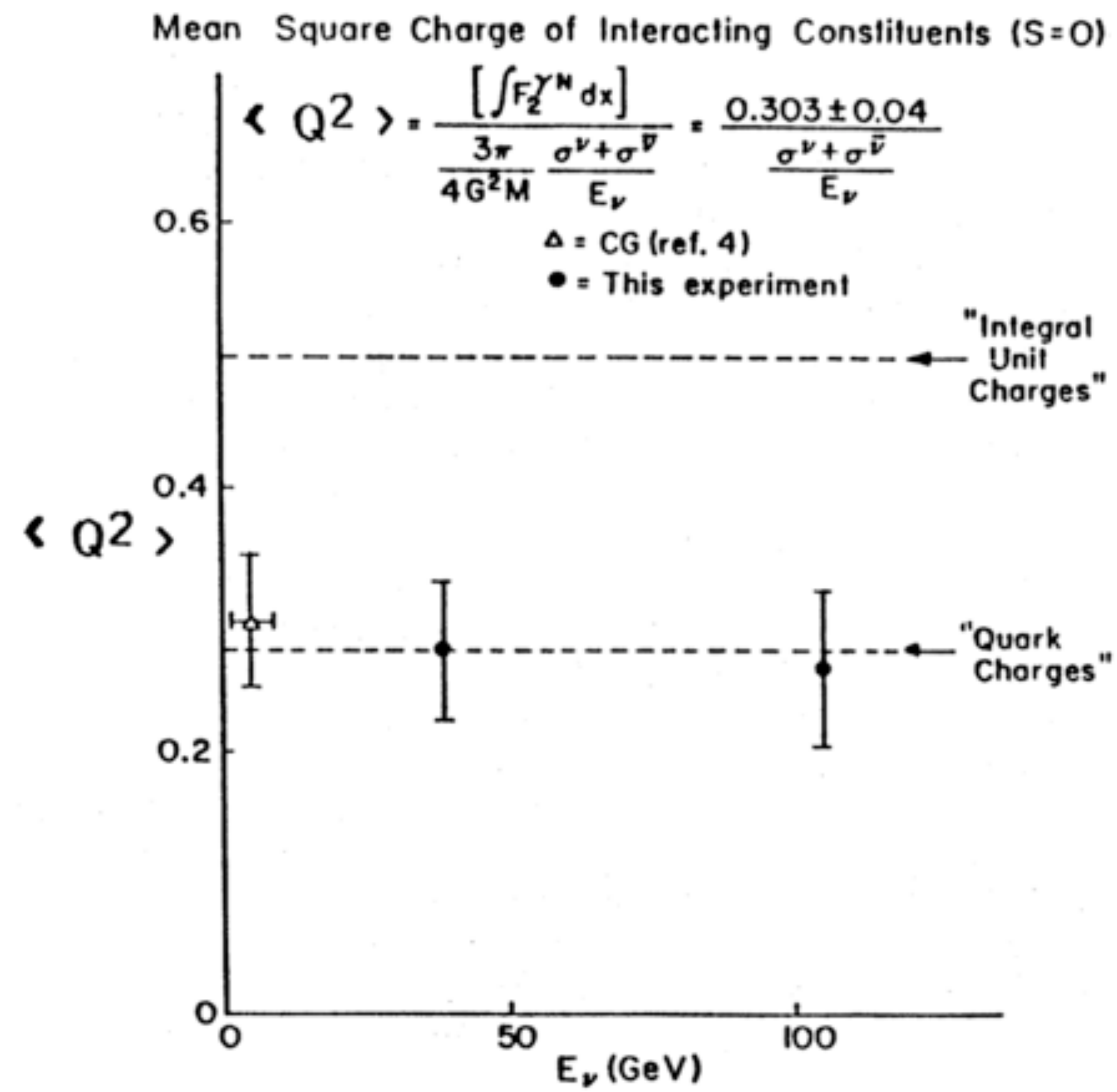


Ratio:

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

Deep-Inelastic Scattering - Valence and Sea Quarks

Charged-current DIS:

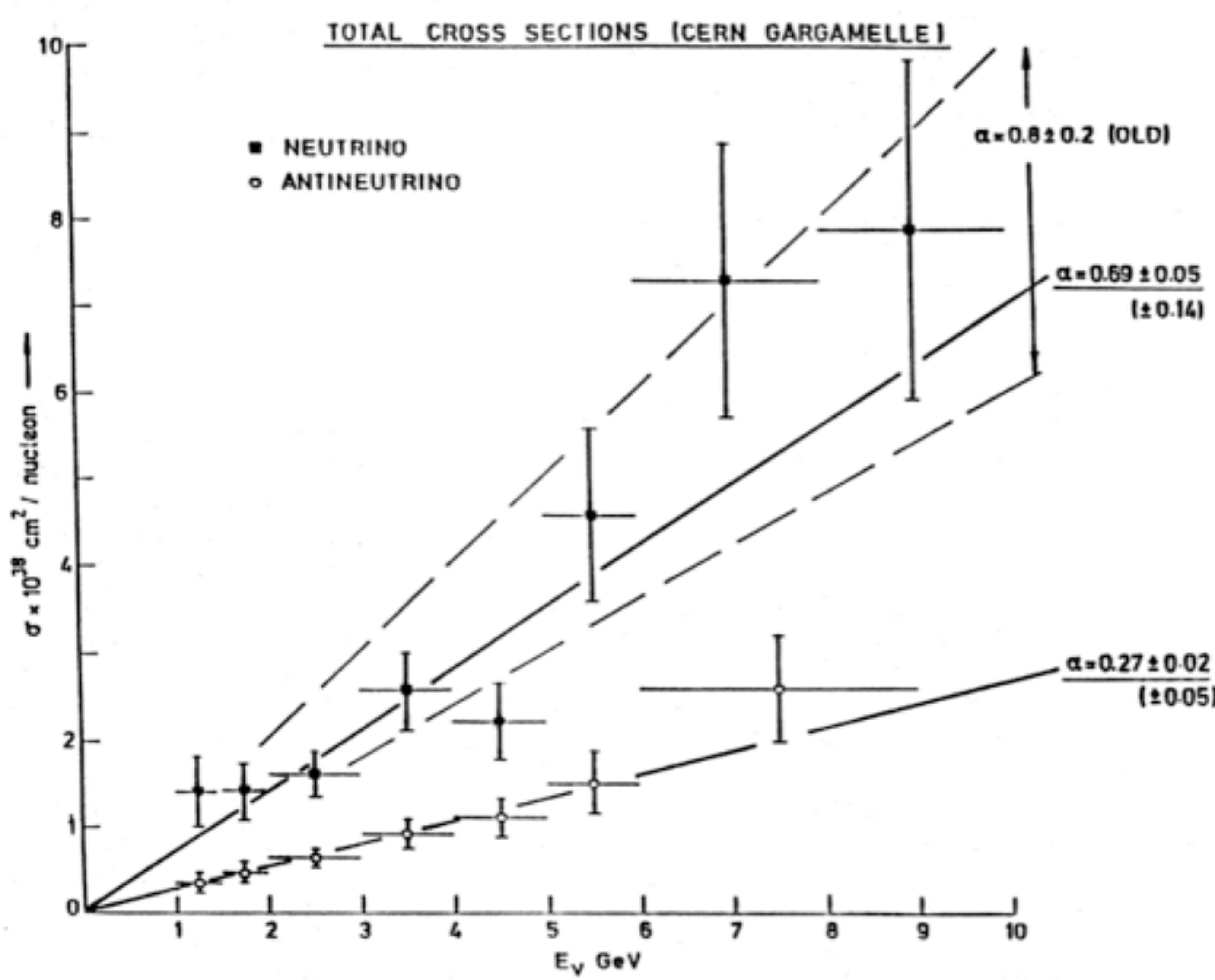
$$F_2^\nu = 2x\sum(q+\bar{q})$$

$$xF_3^{\nu N} = 2x\sum(q-\bar{q})$$

$$\int_0^1 xF_3^{\nu\mathrm{N}}\,\frac{dx}{x} = \int_0^1 (u_v+d_v)dx$$

Gross Llewellyn-Smith: 3

Gargamelle: 3.2 +/- 0.6



$$\frac{d^2\sigma^{\bar{\nu}N}}{dxdy} \propto \left[\bar{u}+\bar{d}+(u+d)(1-y)^2\right]$$

$$\frac{d^2\sigma^{\nu N}}{dxdy} \propto \left[u+d+(\bar{u}+\bar{d})(1-y)^2\right]$$

Deep-Inelastic Scattering - Valence and Sea Quarks

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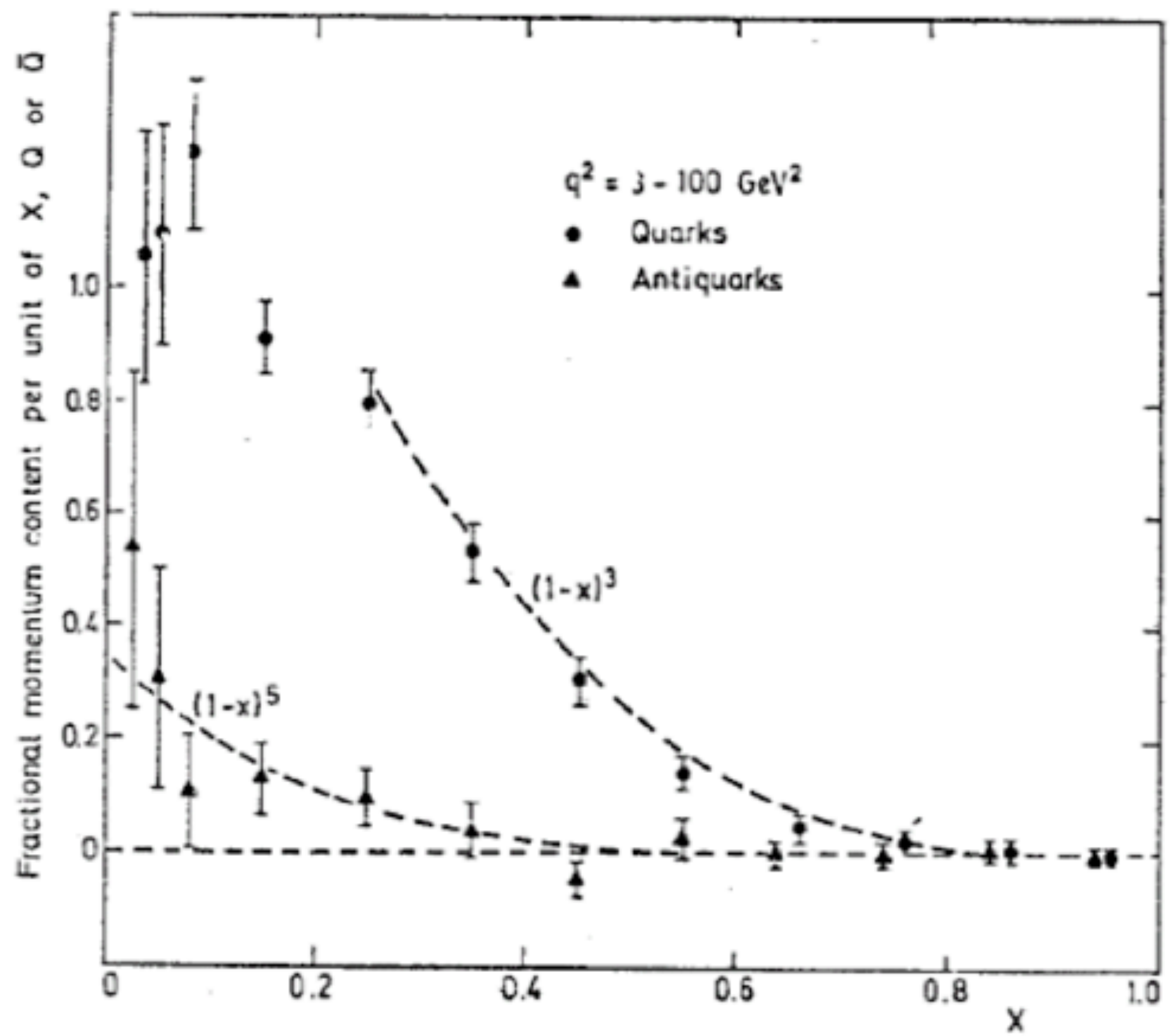
Gargamelle: 3.2 +/- 0.6

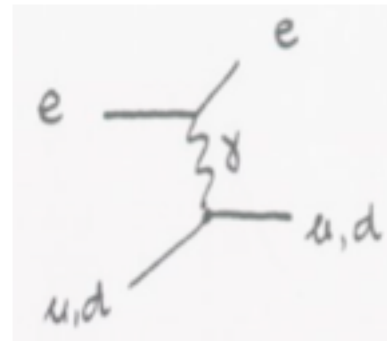


$$\frac{d^2\sigma^{\bar{\nu}N}}{dxdy} \propto \left[\bar{u}+\bar{d}+(u+d)(1-y)^2\right]$$

$$\frac{d^2\sigma^{\nu N}}{dxdy} \propto \left[u+d+(\bar{u}+\bar{d})(1-y)^2\right]$$

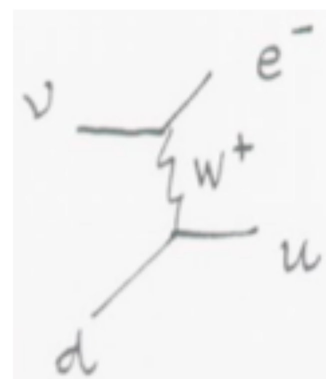
Deep-Inelastic Scattering - Momentum Conservation

Neutral-current (photon) DIS:



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

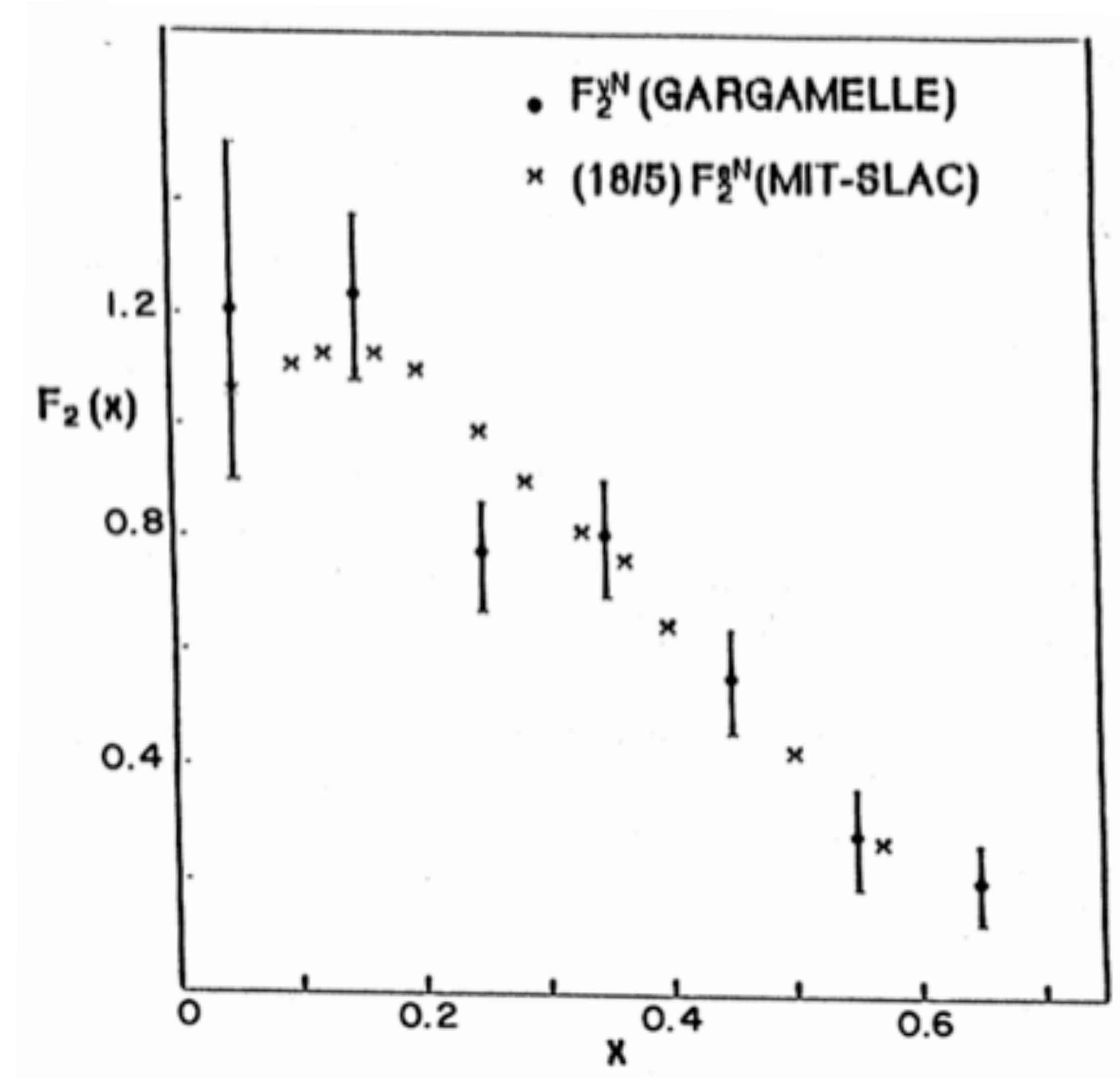
Charged-current DIS:



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

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

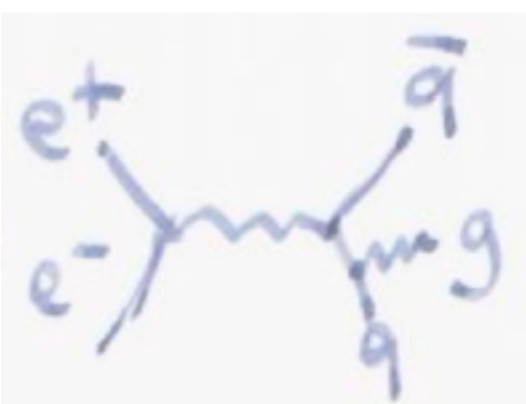
SLAC: 0.14 +/- 0.05

Quarks carry half of the nucleon momentum!

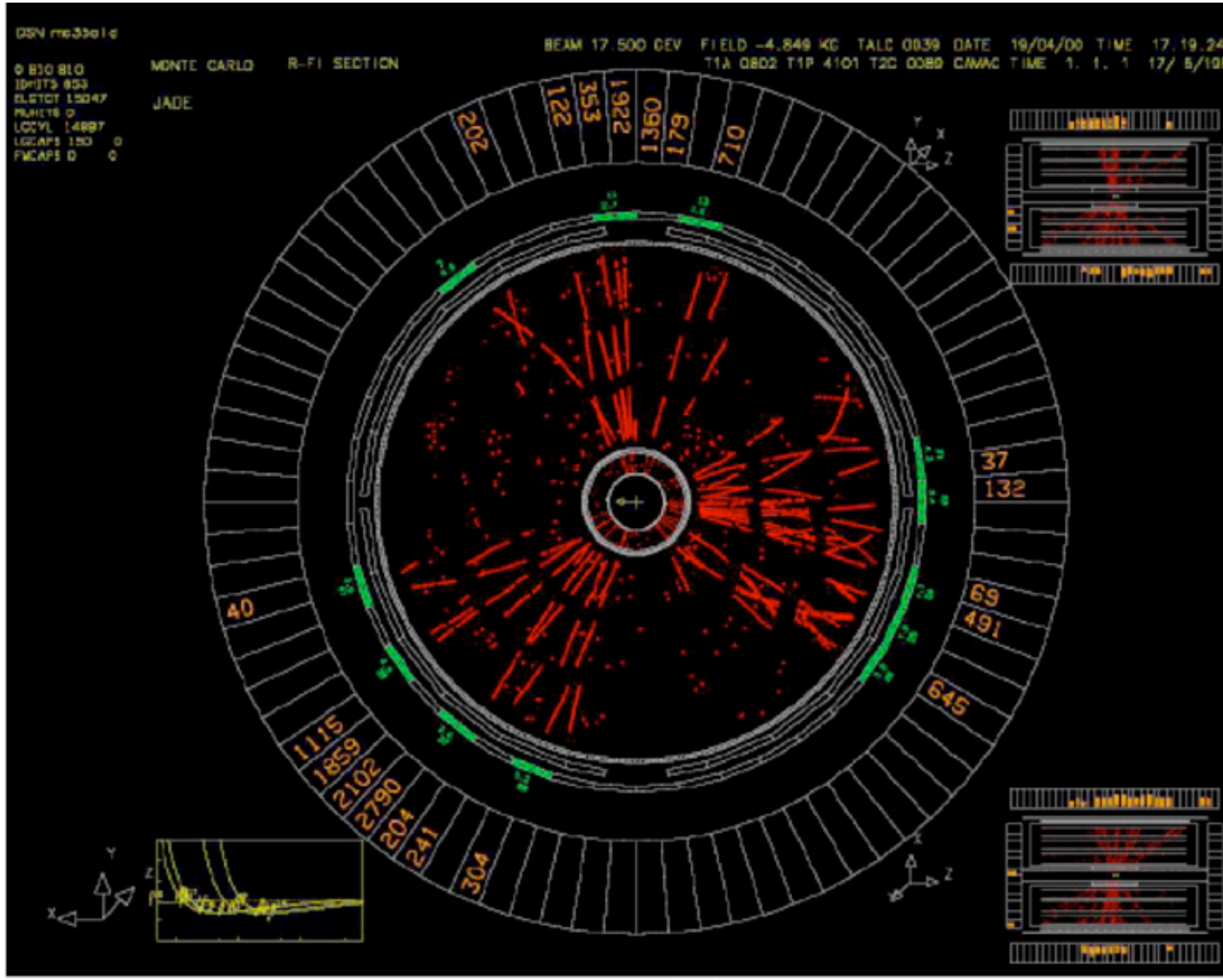
3-jet events at PETRA

Recall the intro on colour:

Observation of its higher order process,

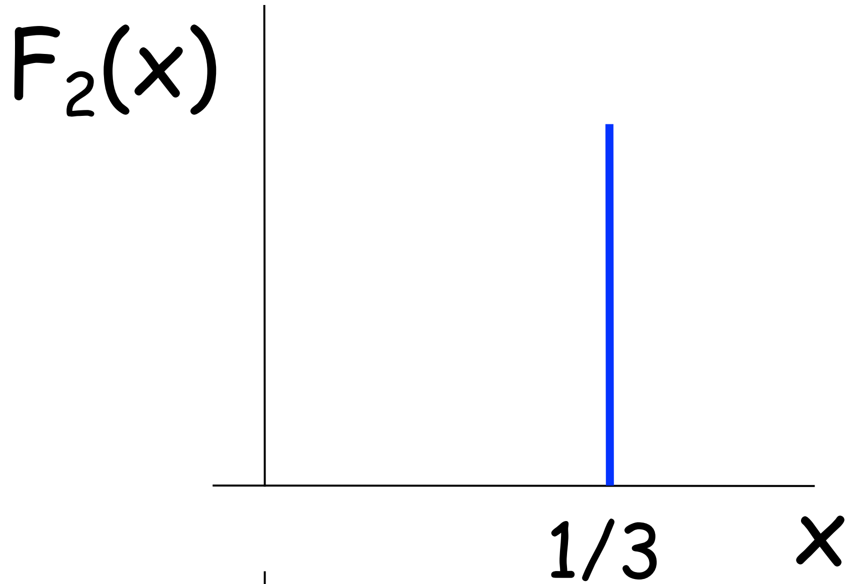


marks the discovery of the gluon.

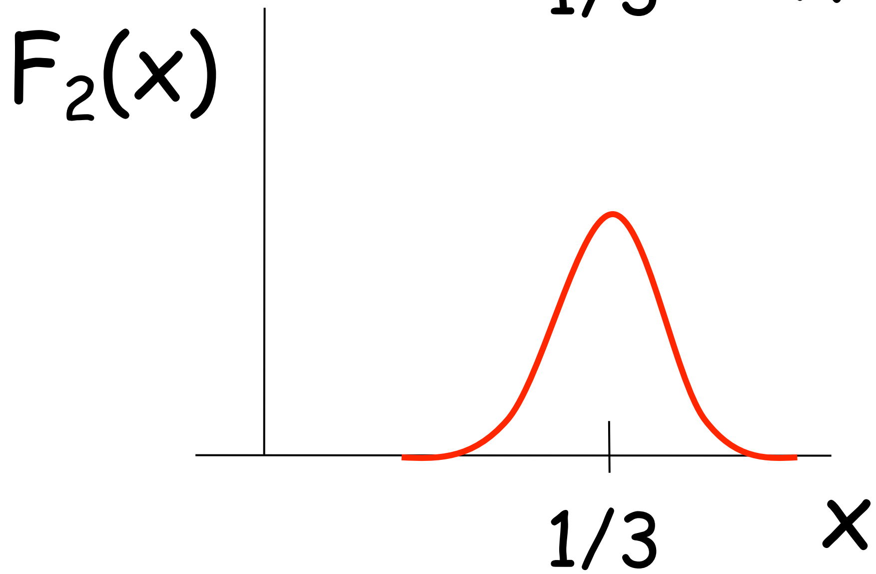


Mom. Conservation: *Gluons carry the other half of the nucleon momentum.*

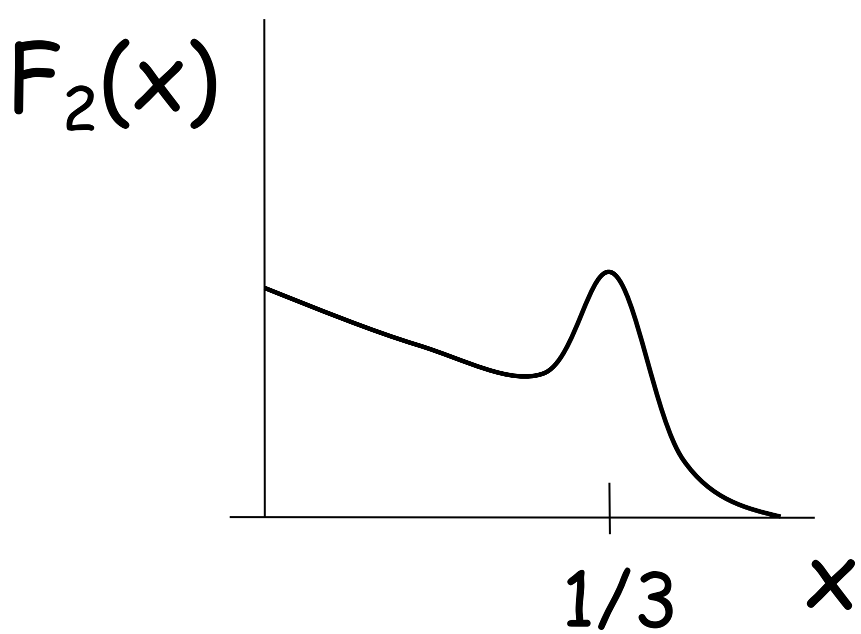
Nucleon Structure



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



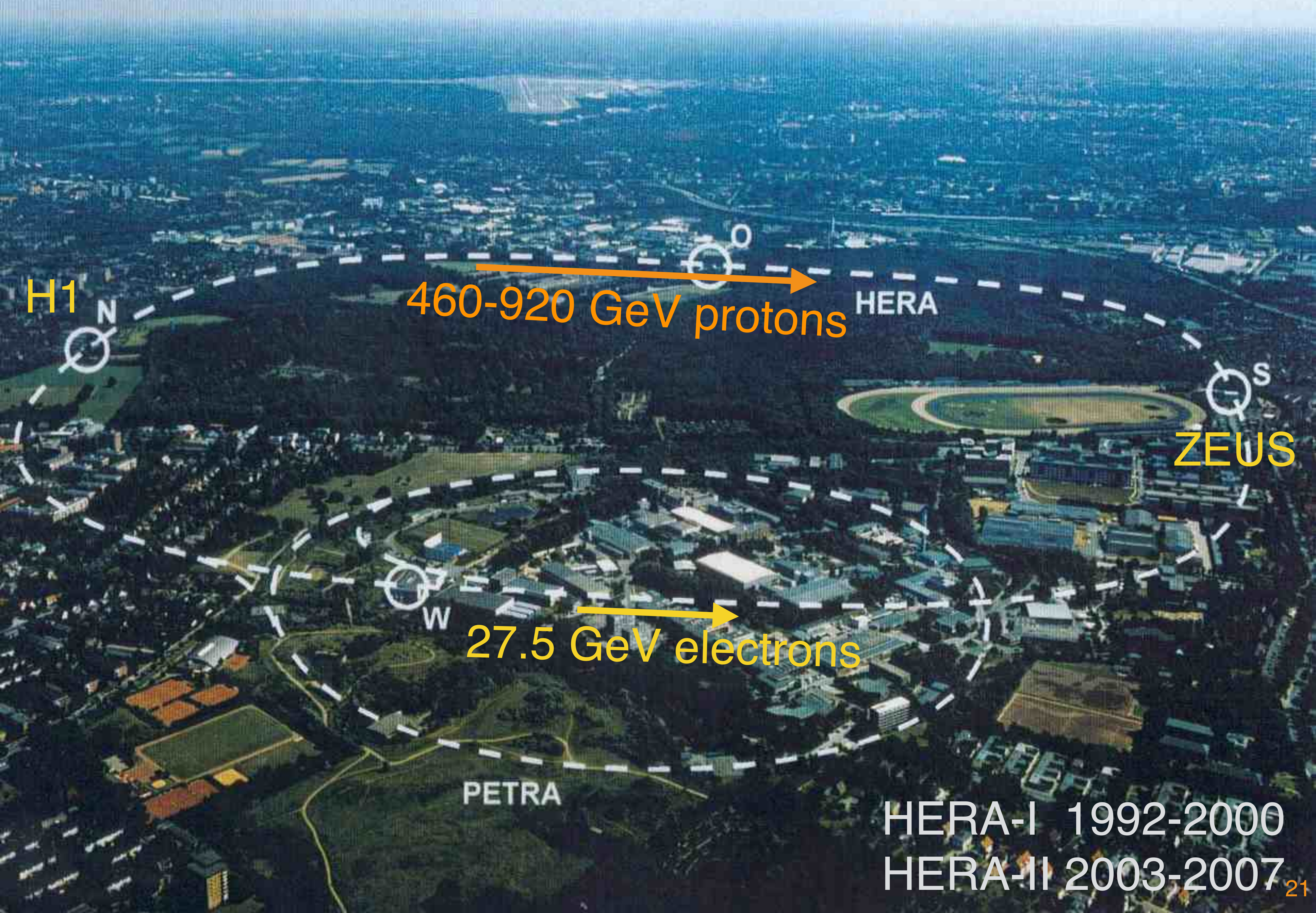
Three quarks with some momentum smearing.



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

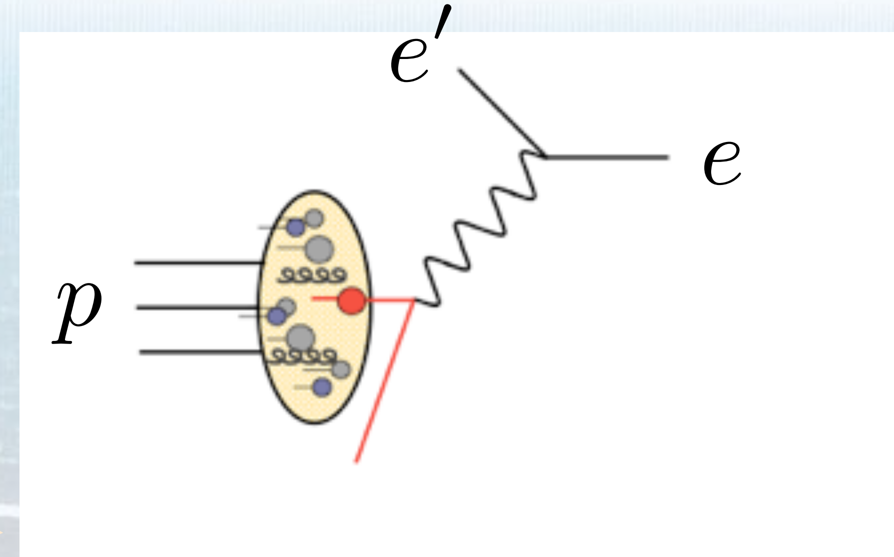
Insight really only from the first EIC, HERA

HERA - Electron Proton Collider



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:

ZEUS

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

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

27.5 GeV electrons

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

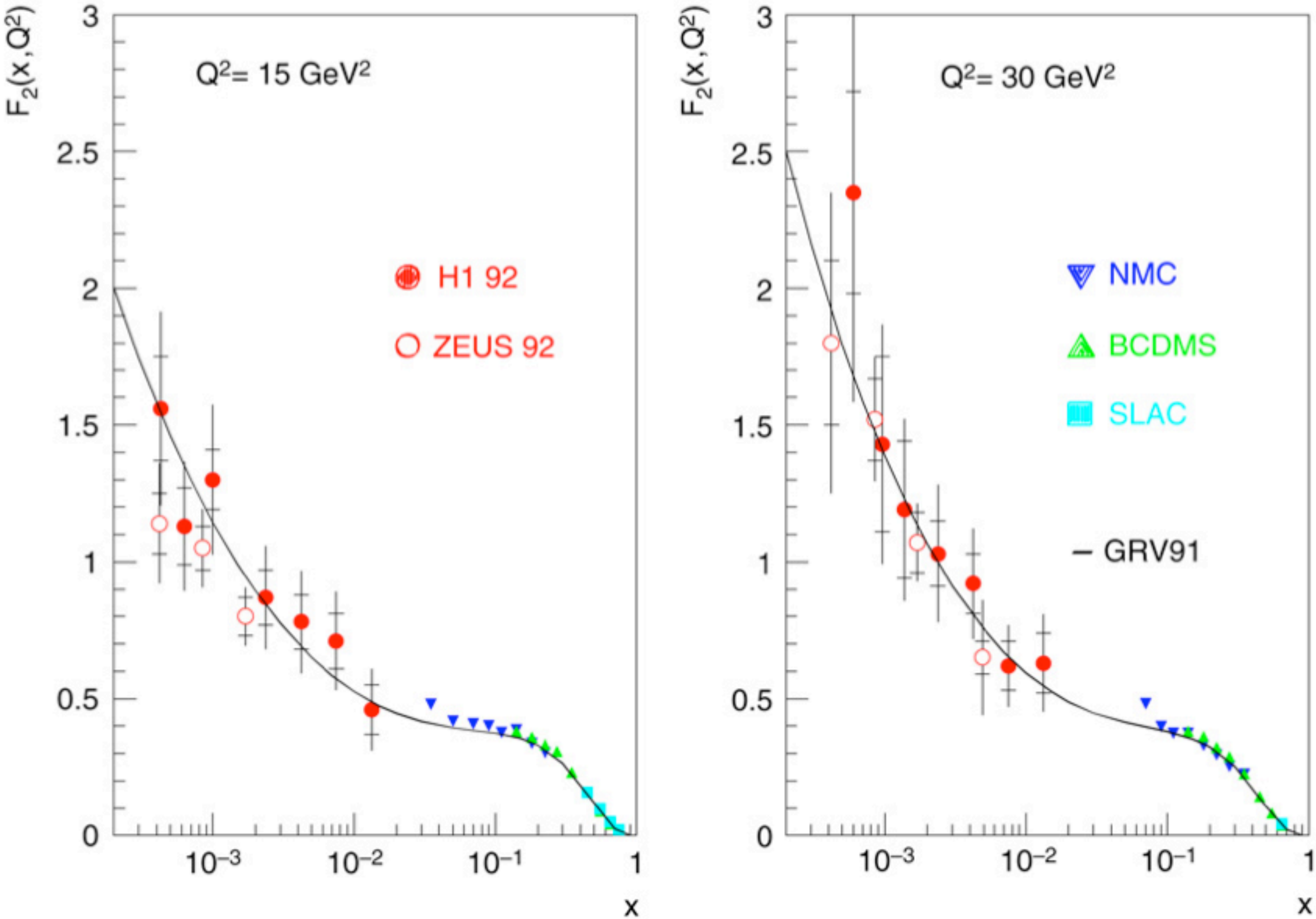
$$y = (q.p)/(e.p)$$ Fractional energy transfer

HERA-I 1992-2000

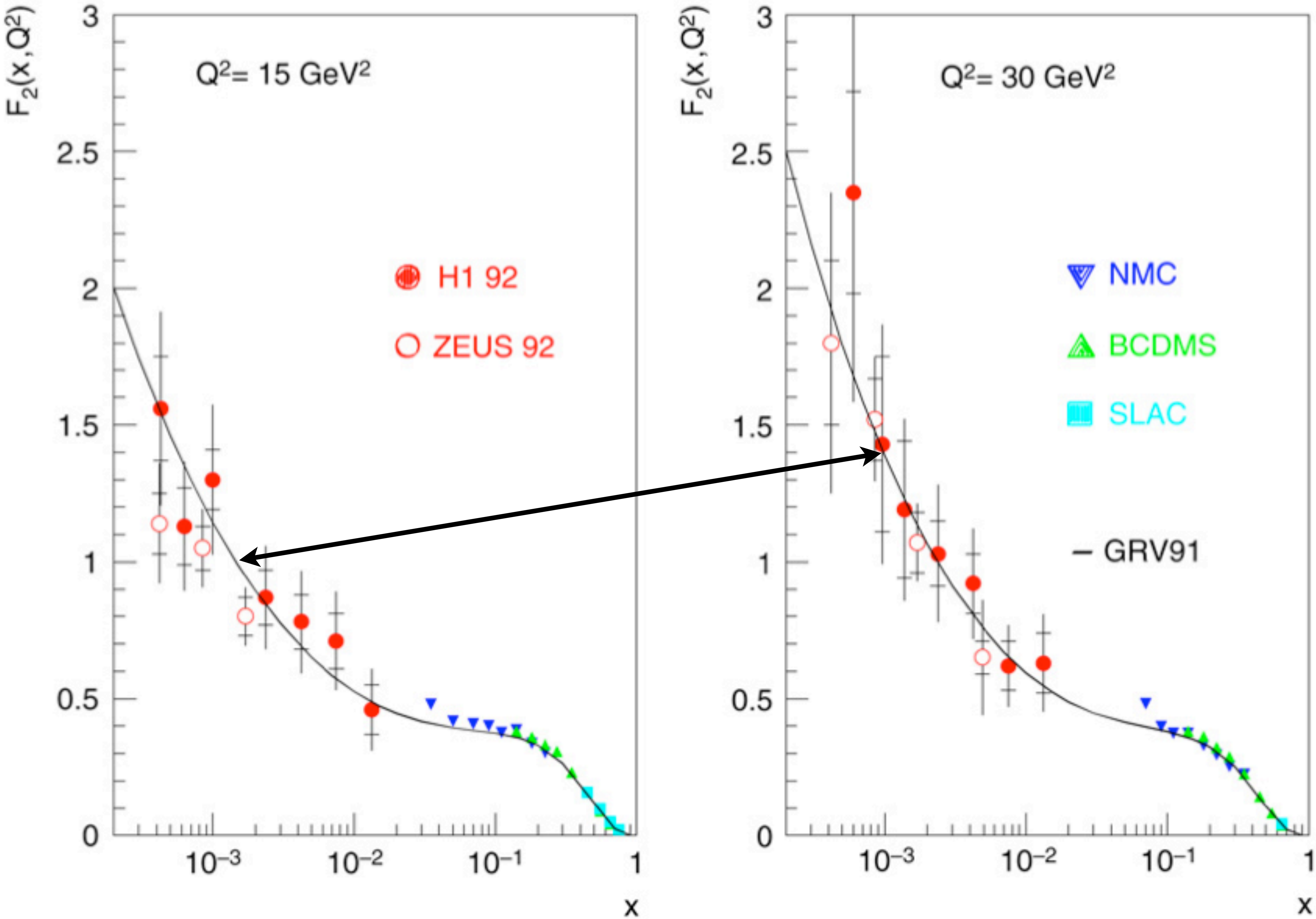
x, Q ^{2} can be reconstructed from the scattered electron, the “current jet”, or hybrids.

HERA-II 2003-2007

HERA - Early Measurements



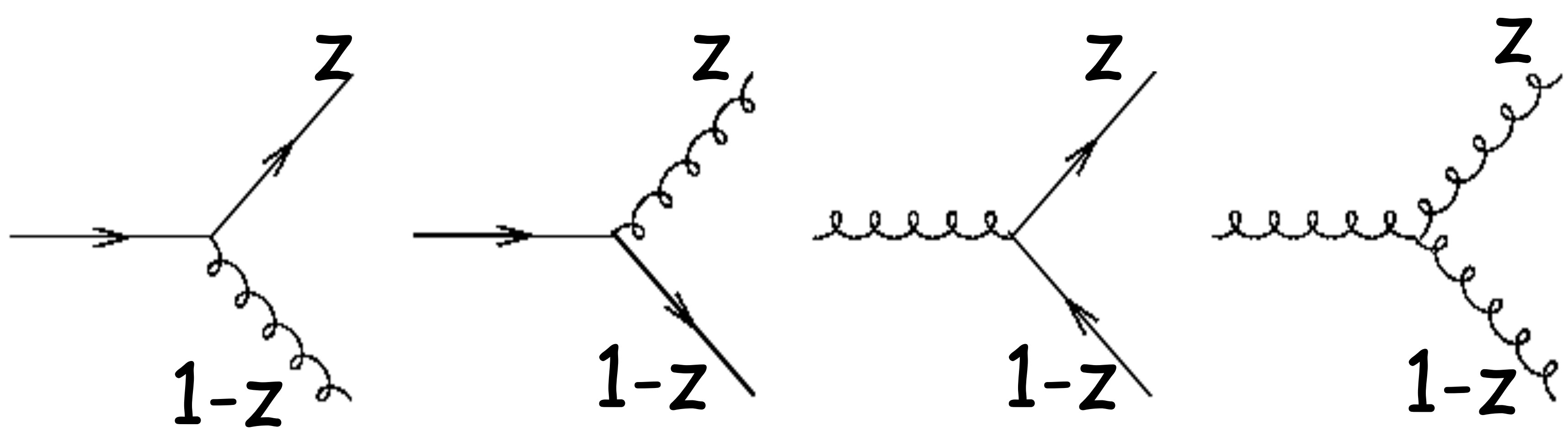
HERA - Early Measurements



Can these observations be related?

QCD Radiation

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

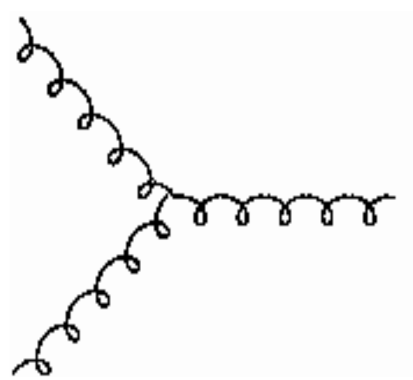


$P_{ab}(z)$: the probability that parton a will radiate a parton b with the fraction z of the original momentum carried by a.

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:

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

convolution

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

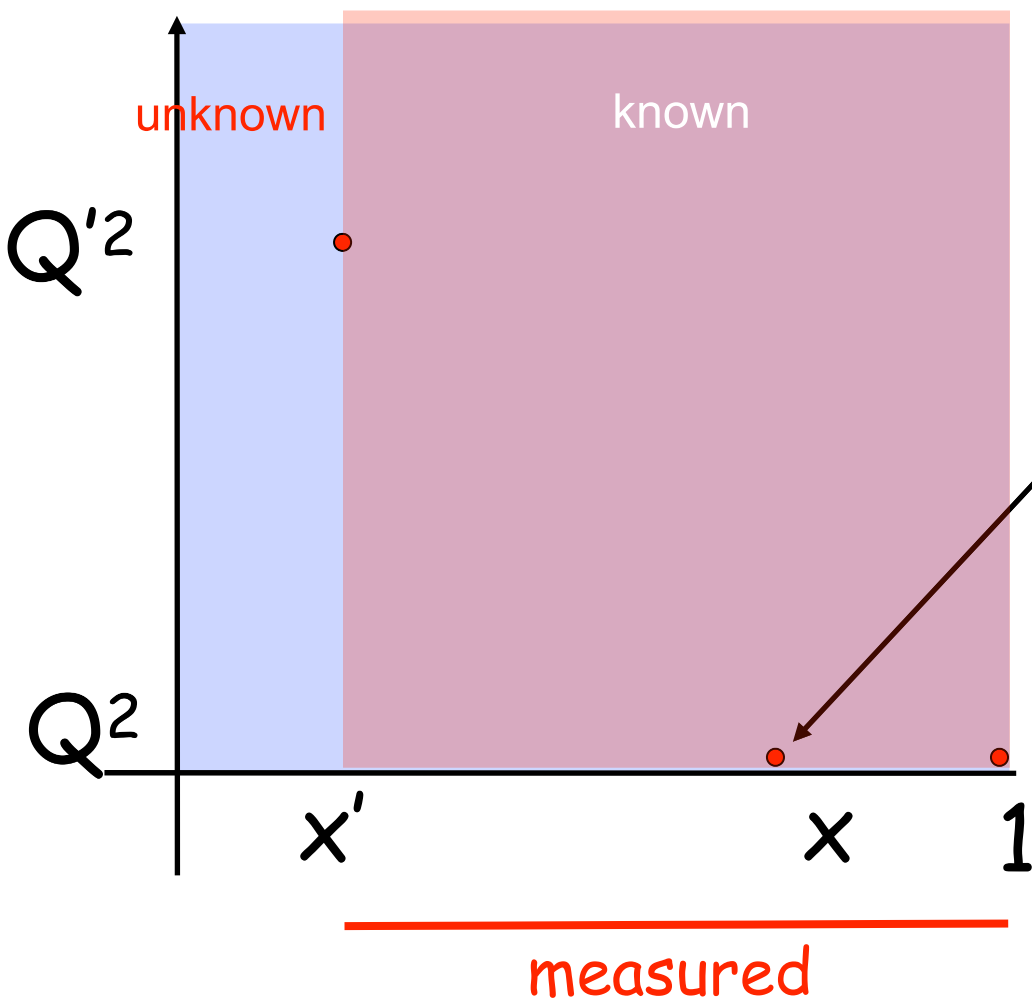
Similarly, for gluons:

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

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.

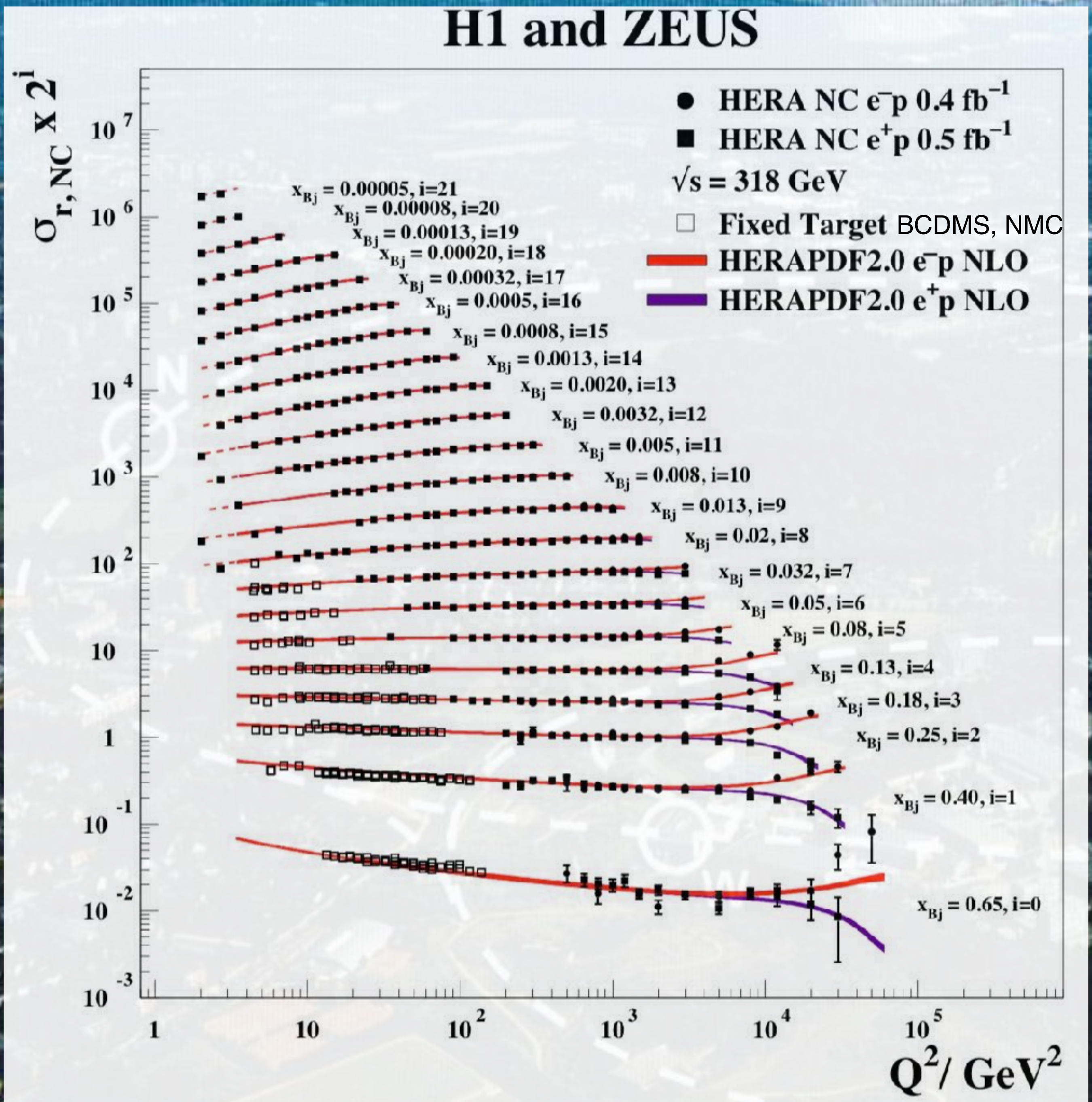
It is necessary and sufficient to know the parton densities in the range $x' \leq x \leq 1$ at a lower Q^2 to determine the parton density at x', Q'^2.

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

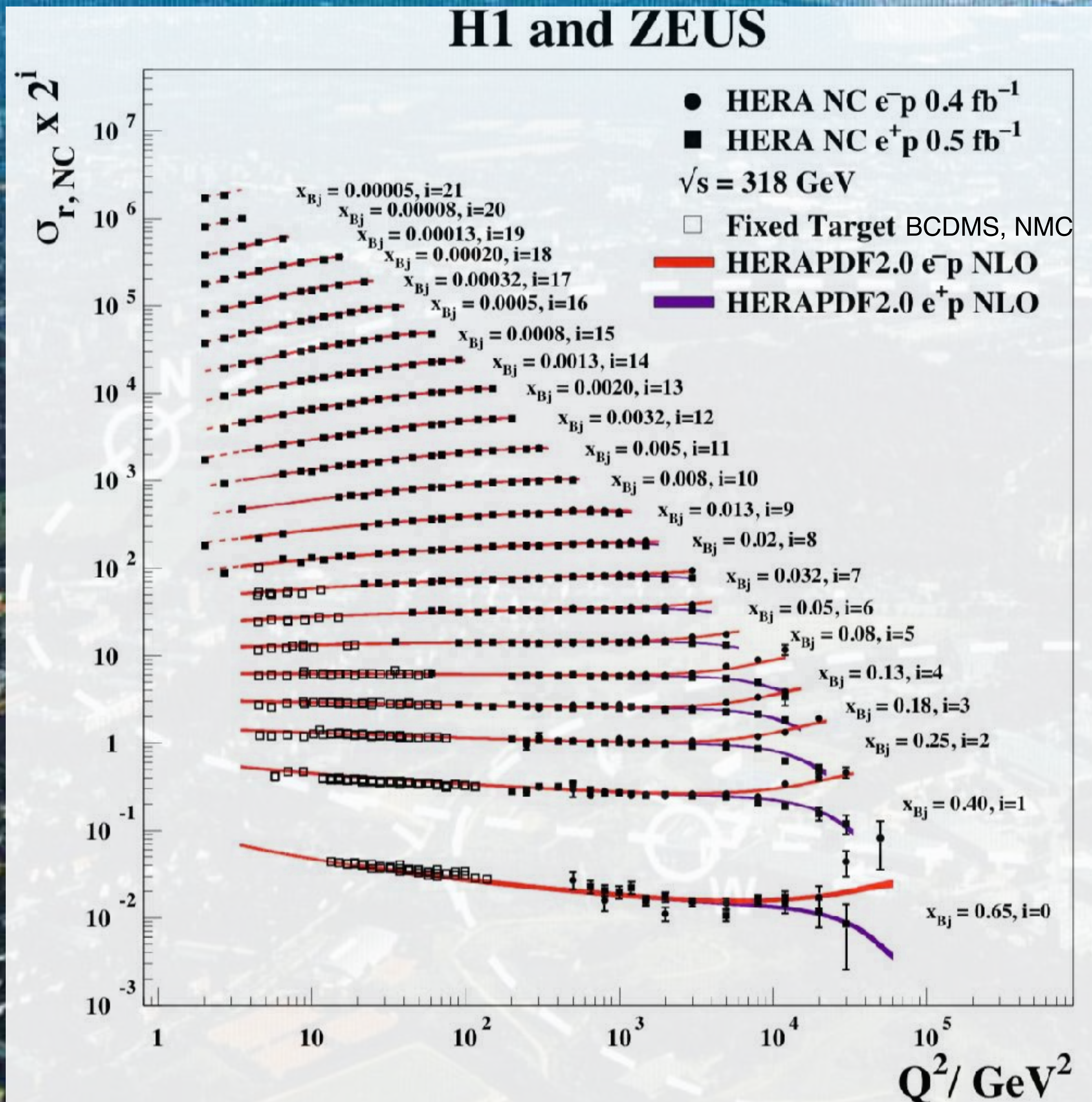


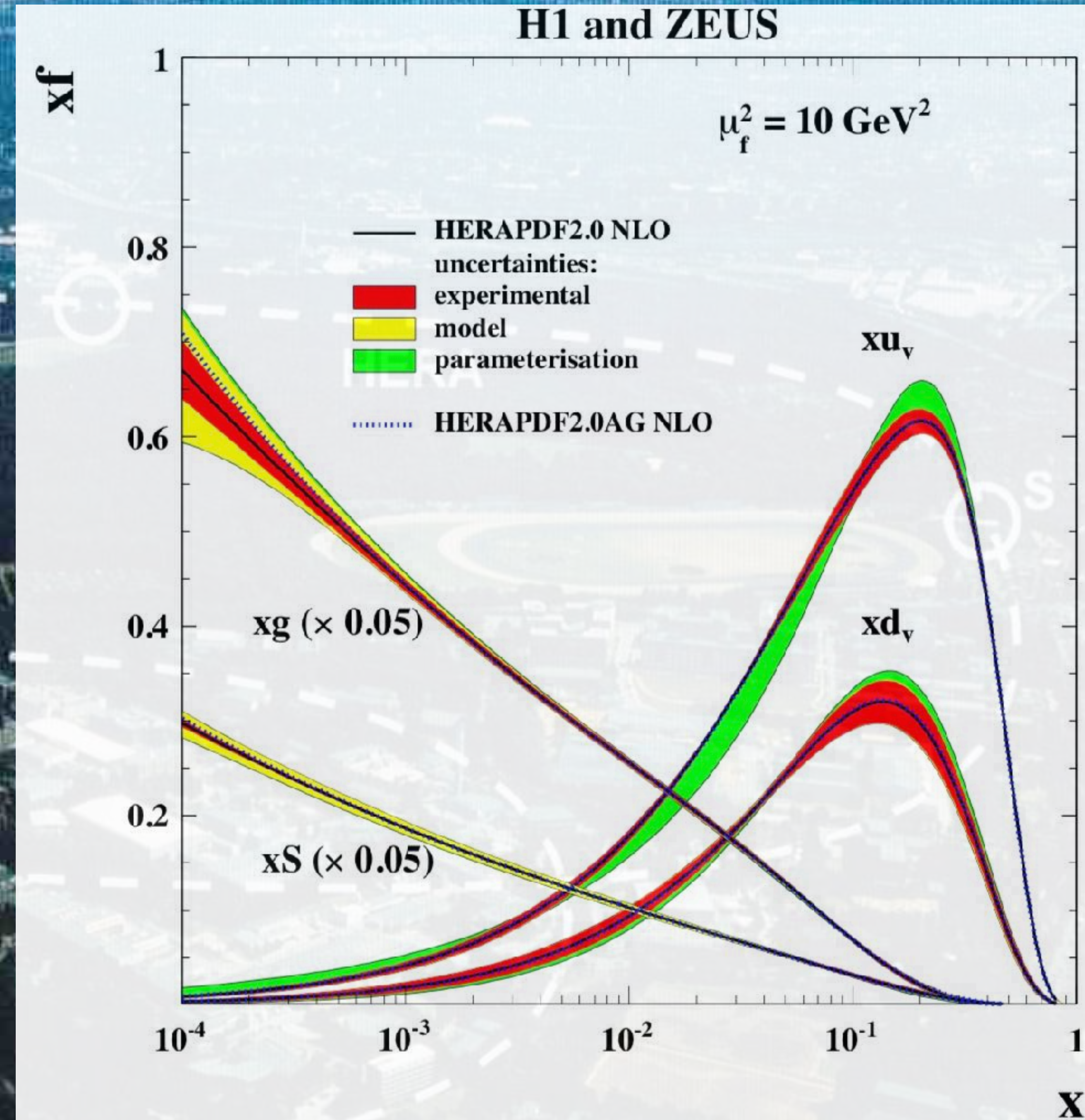
A lot in this plot:

- 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

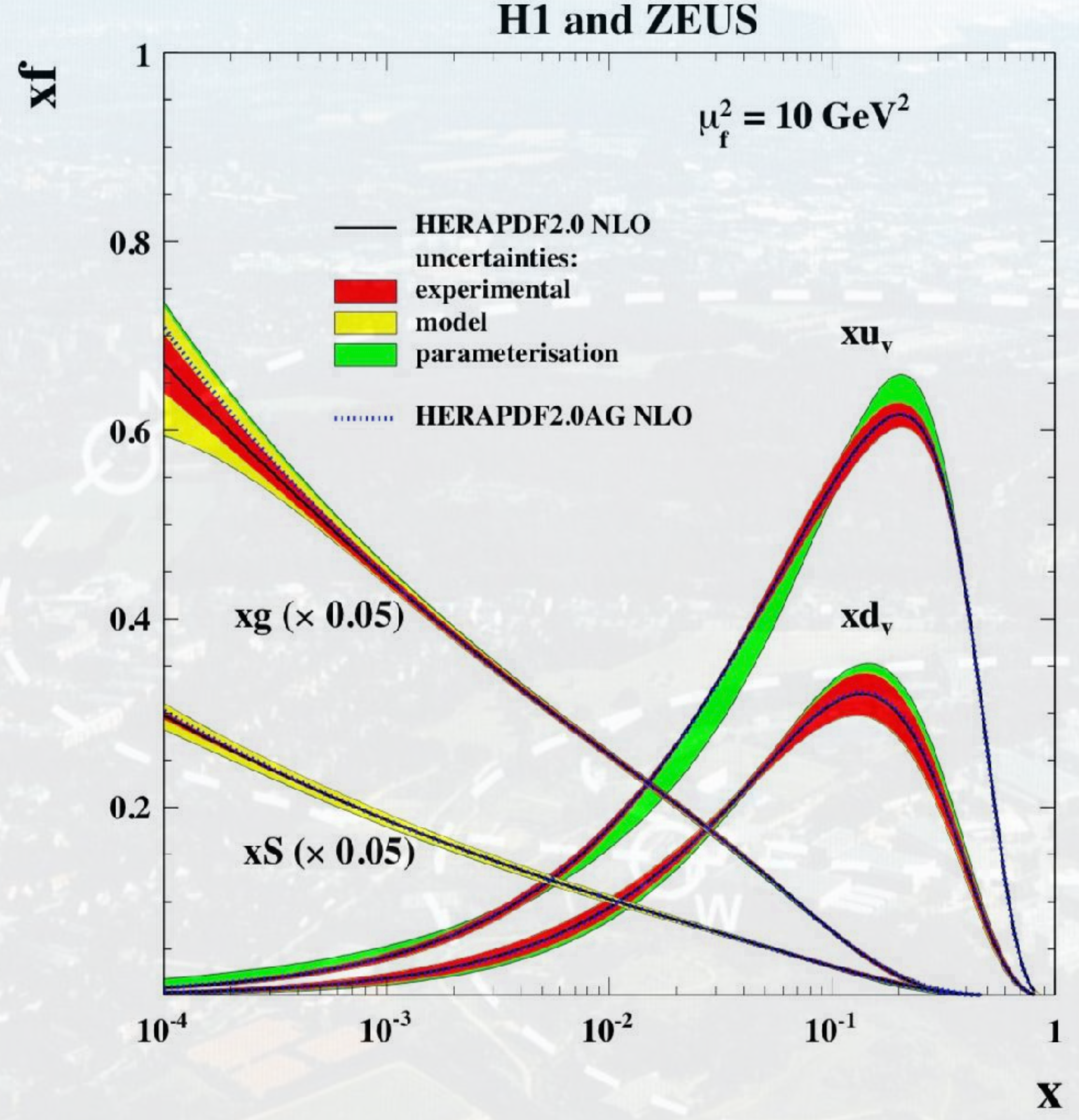
H1 and ZEUS Coll., EPJ C75 (2015) 580





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

HERA's Legacy



Proton structure at high-energy is:

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

Gluon content increases with decreasing *x*,

Gluons pose a number of questions

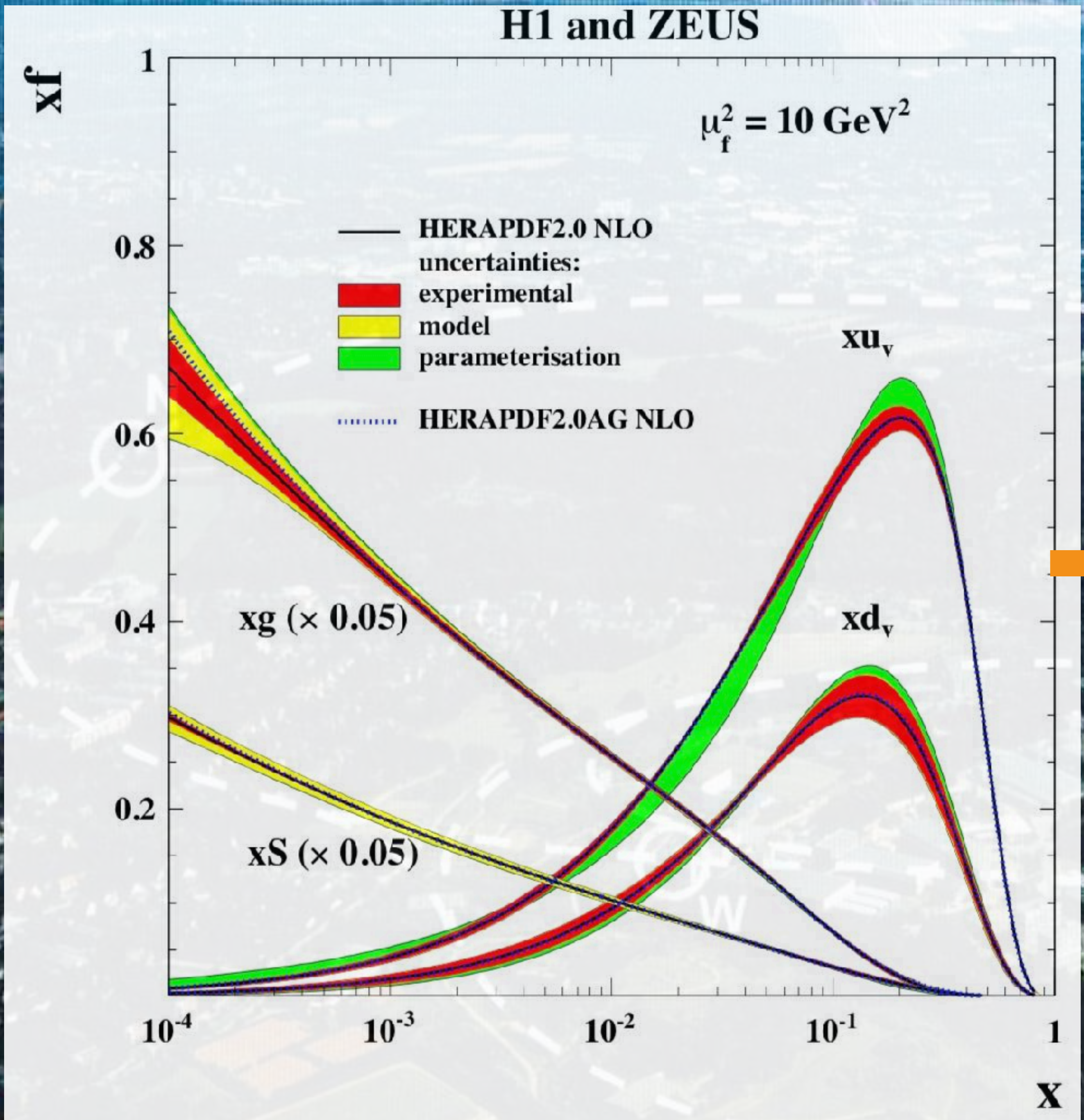
HERAPDF2.0:

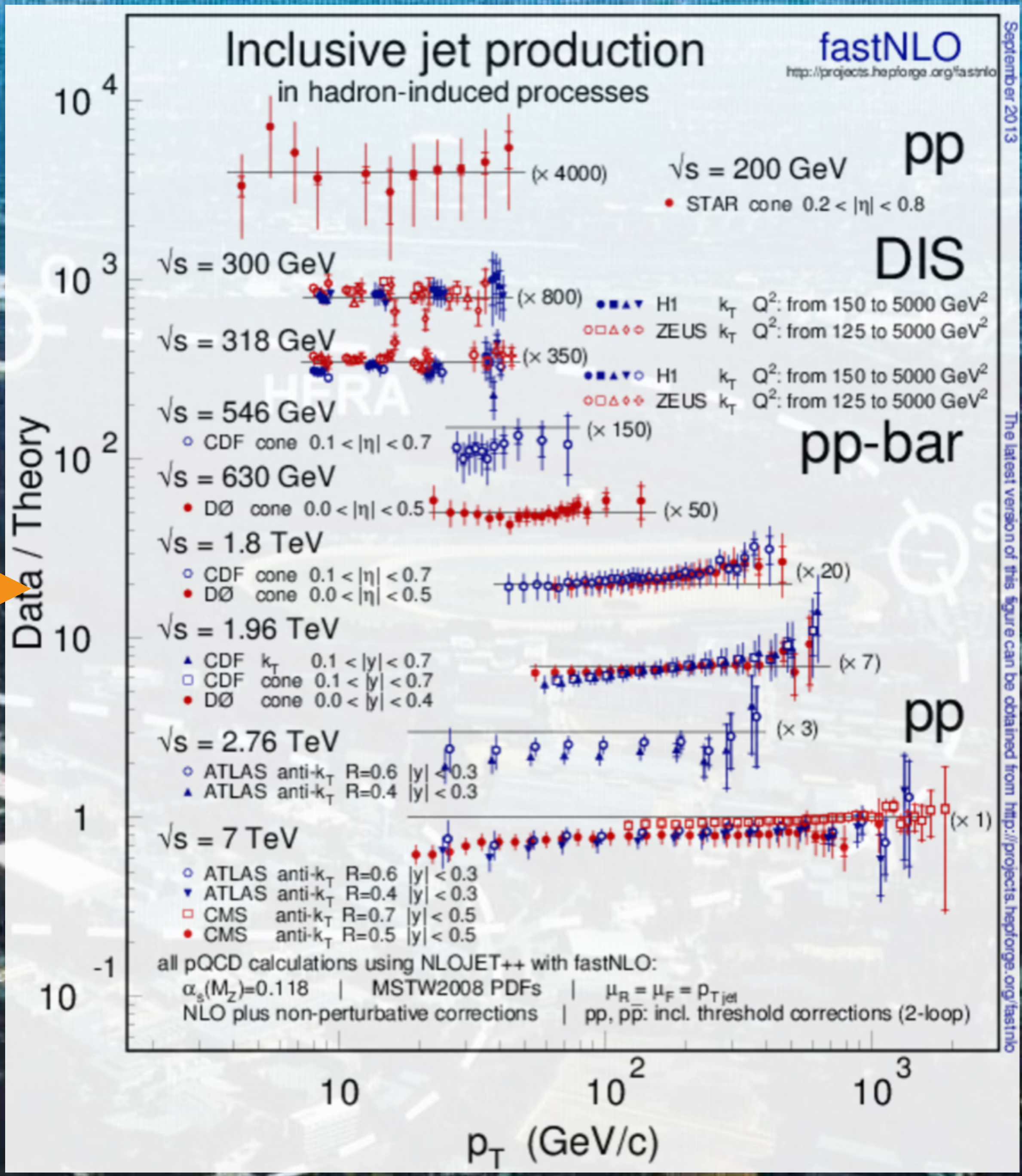
14 parameters,

~1400 combined data points,

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

HERA’s Legacy





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

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.

What *is* a proton, neutron, nucleus?

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

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

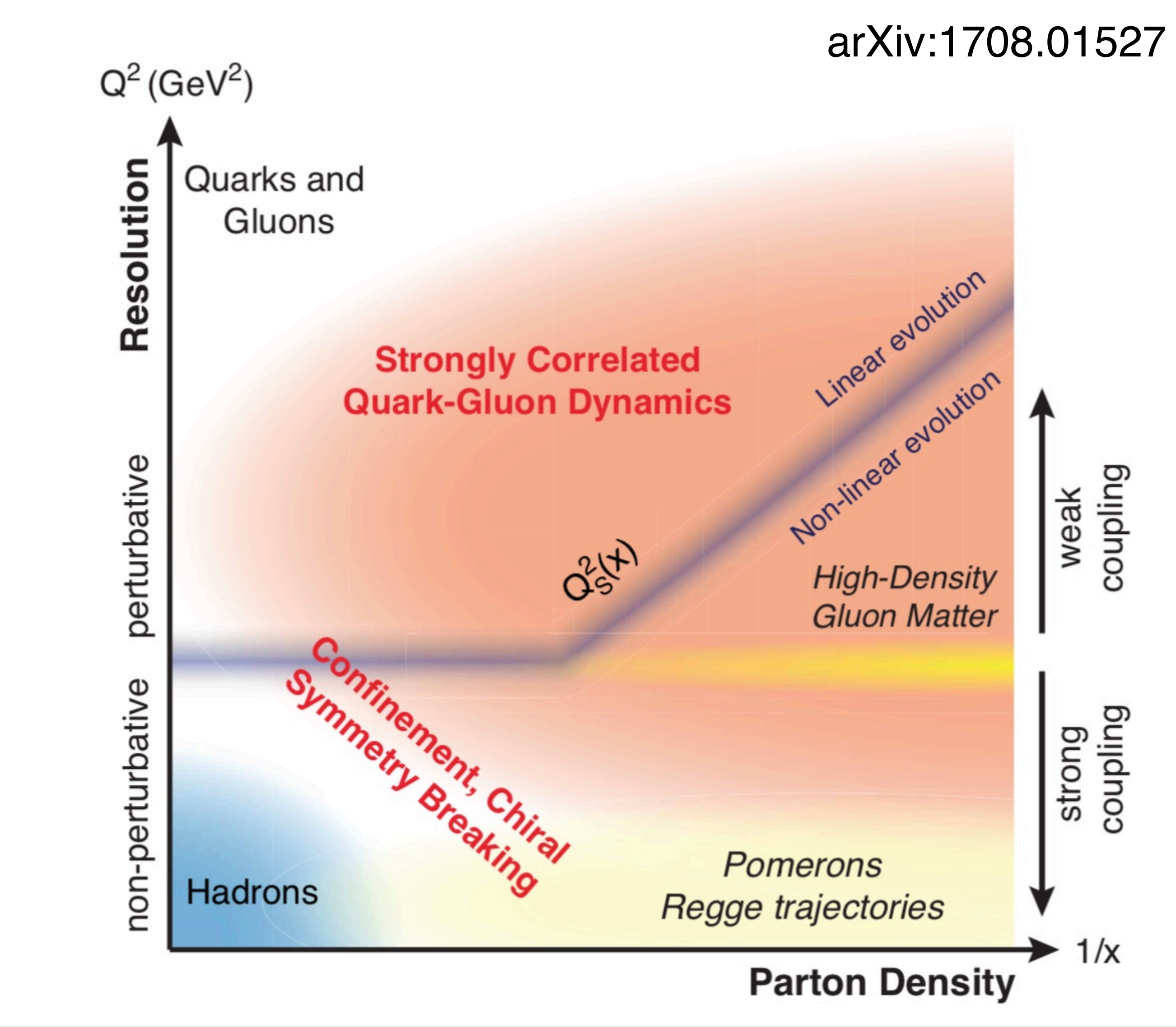
Factorization theorem(s) + one-dimensional parton distributions,
no correlations among the partons

Not quite…. ***more than a few high-energy observations are actually different***
Imperative to separate intrinsic structure from interaction dynamics,
push the envelope beyond the theoretically established,
obtain meaningful accuracy.

HERA

Saturation:

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

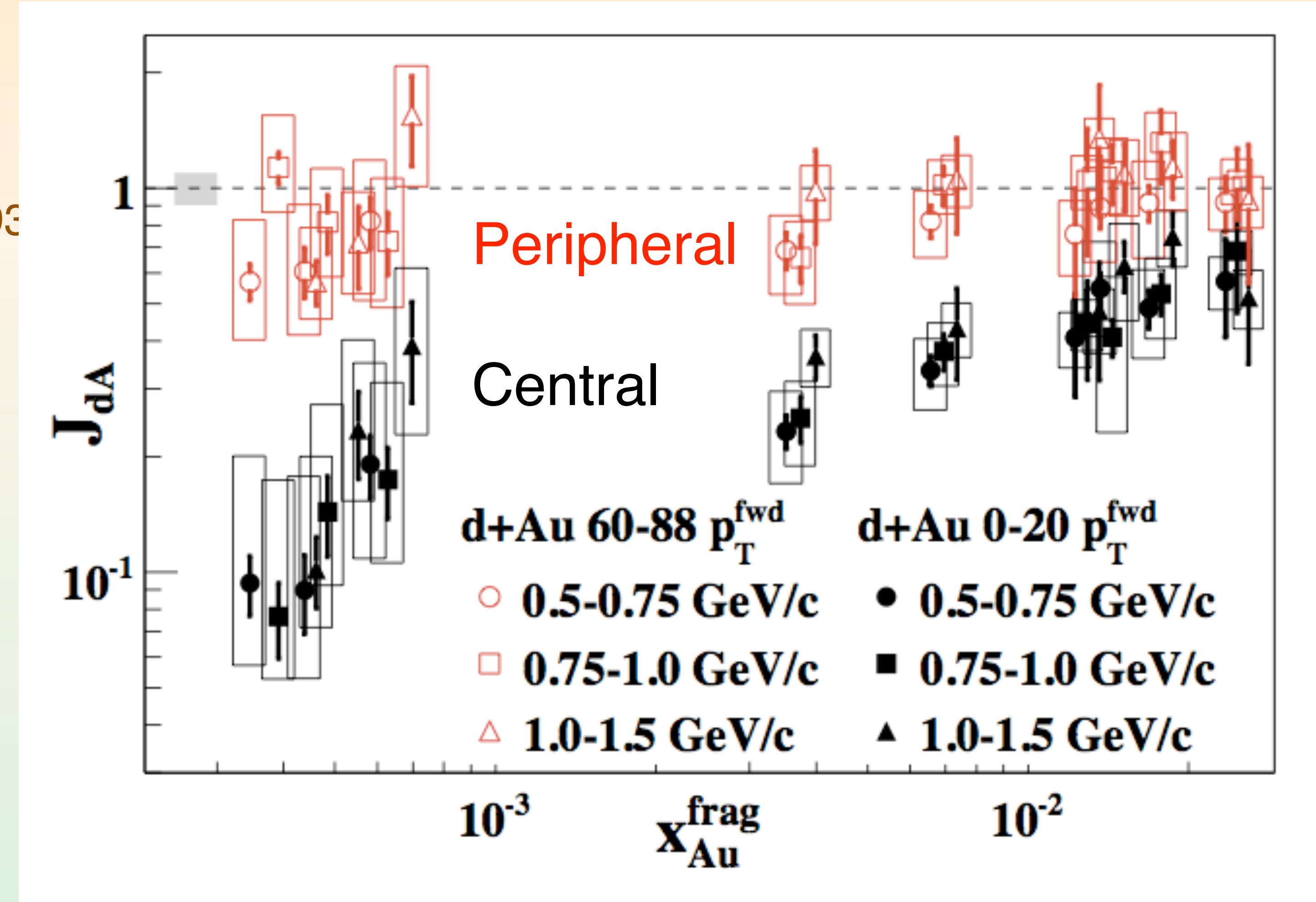


HERA - RHIC

Saturation:

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

Forward-Forward Mid-forward correlation



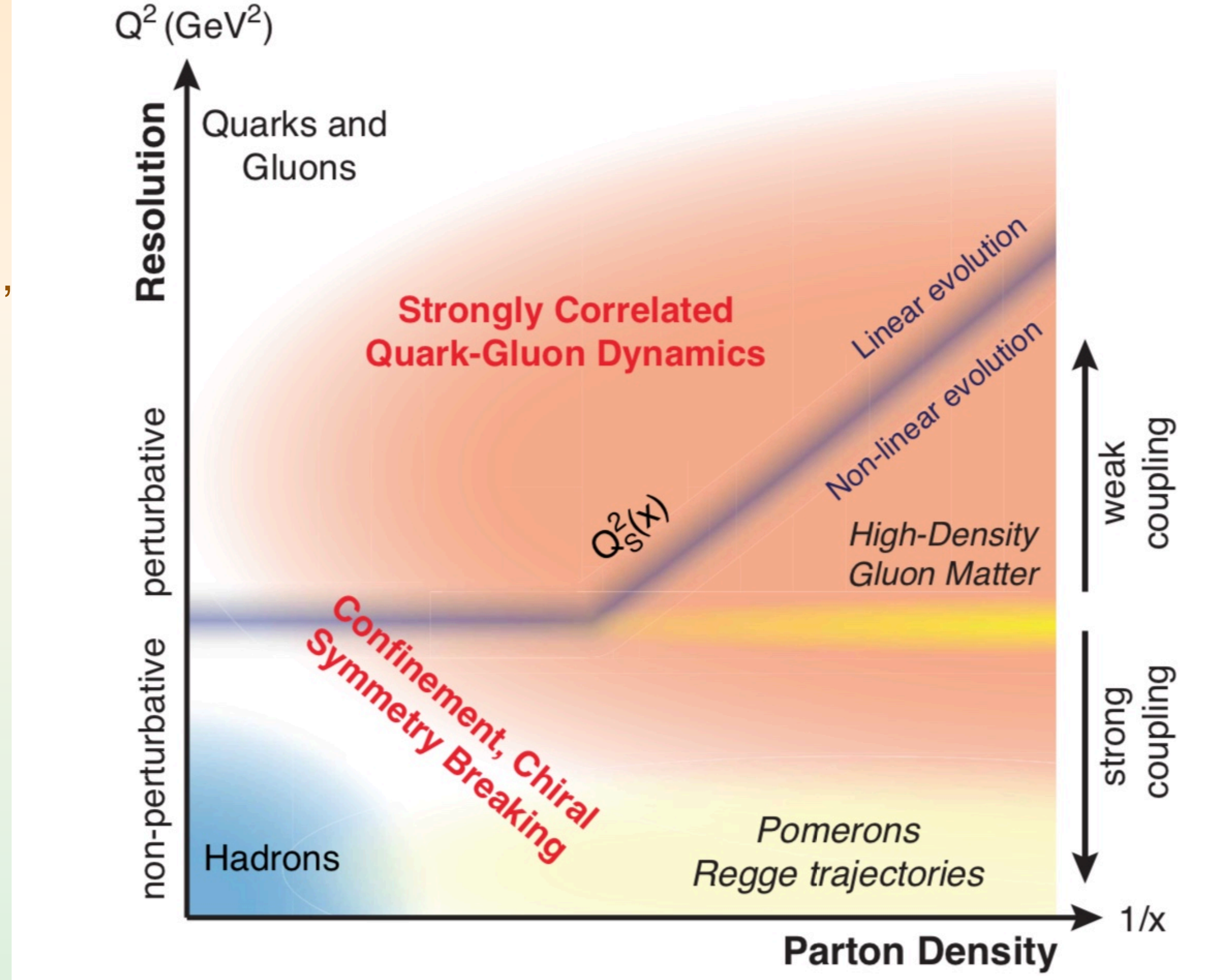
Phenix, Phys.Rev.Lett. 107 (2011) 172301

HERA - RHIC, LHC

Saturation:

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

arXiv:1708.01527



HERA - RHIC, CERN

Saturation:

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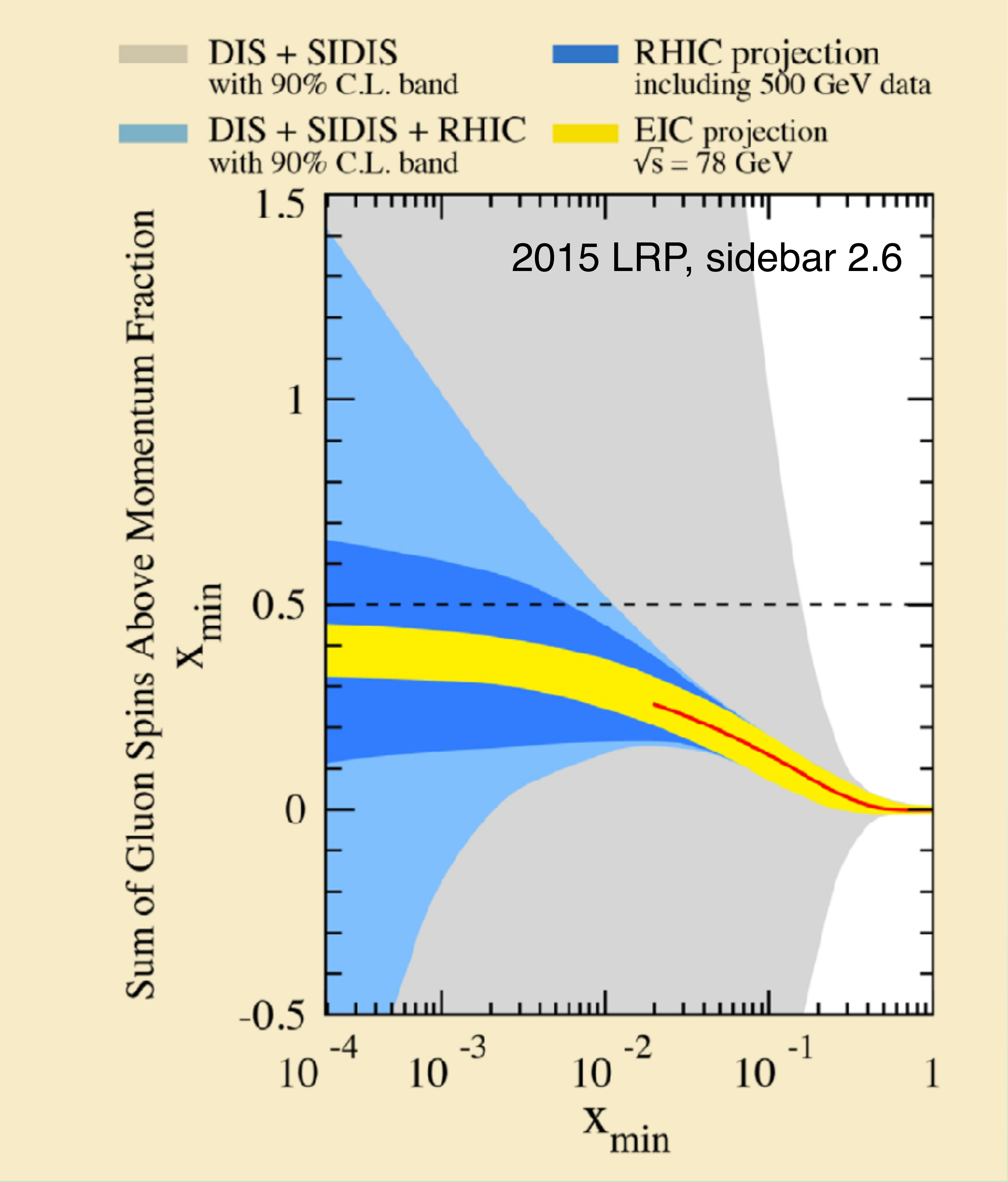

Spin puzzle:

- 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 is making impressive progress,

See e.g. Renee Fatemi's talk on RHIC-spin tomorrow,
Numerous talks on PDFs in WS1 tomorrow,
Numerous talks on Lattice QCD.

HERA - RHIC, JLab, CERN

Saturation:

- geometric scaling of the cross section,
- diffractive cross-section independent of W and Q^2,
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- large forward transverse-spin phenomena
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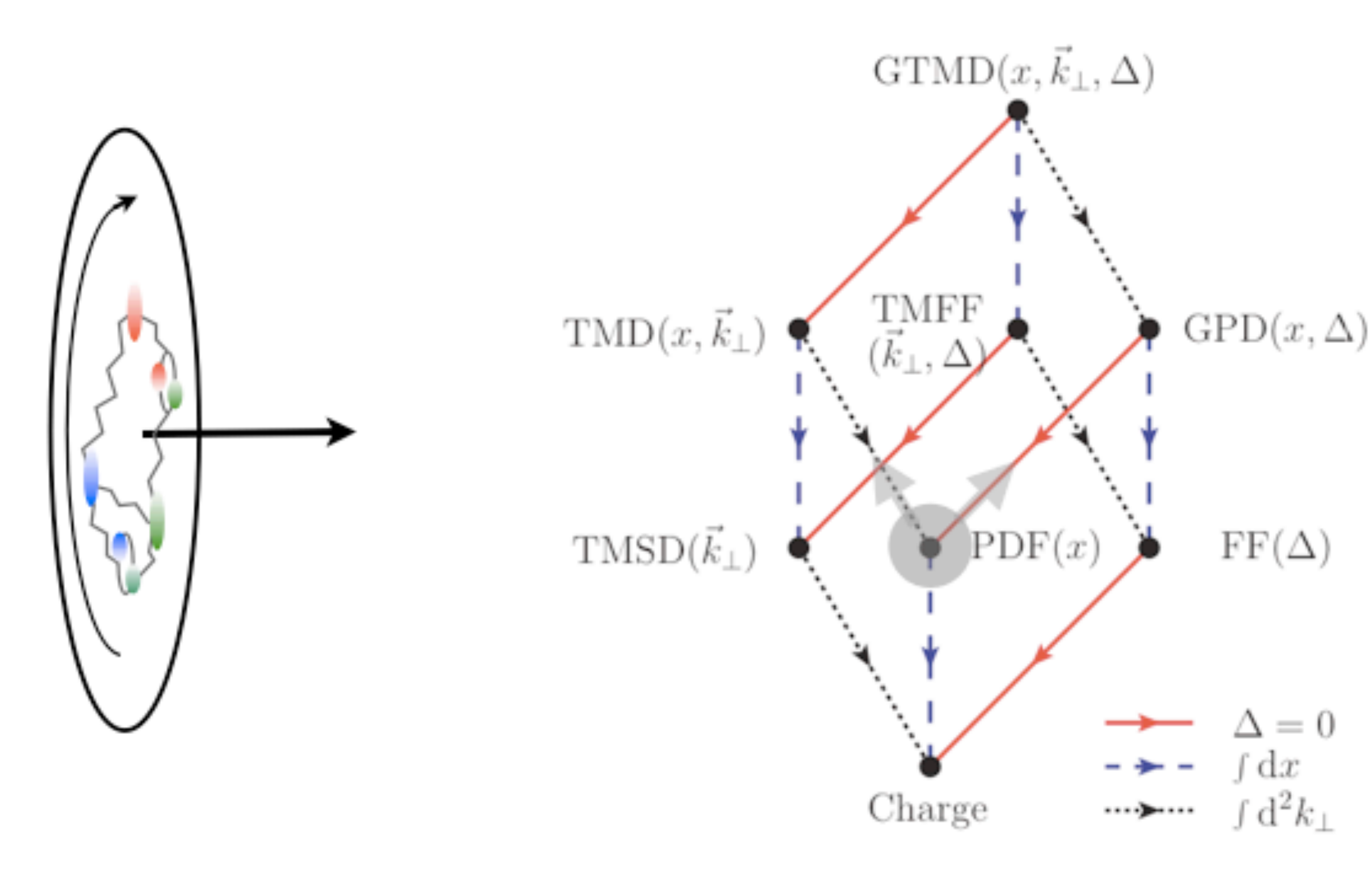
Imaging / tomography:

- valence quark region,



See e.g. Alexei Prokudin's talk on Friday

Lorce, Pasquini, Vanderhaeghen

Electron Ion Collider Initiatives

Past

Possible Future

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

High-Energy Physics

Nuclear Physics

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

Electron Ion Collider Initiatives

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High-Energy Physics

Nuclear Physics

World Wide Interest

Electron Ion Collider Initiatives

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

	HERA @ DESY	LHeC @ CERN	EIC in China	EIC in U.S.
$\sqrt{s_{ep}}$ [GeV]	320	200 - 1300	17	20 - 100 (140)
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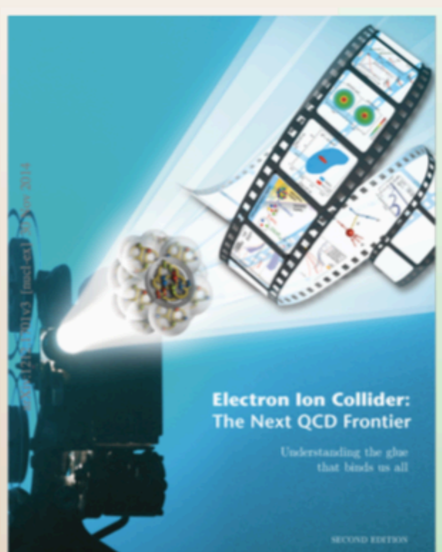
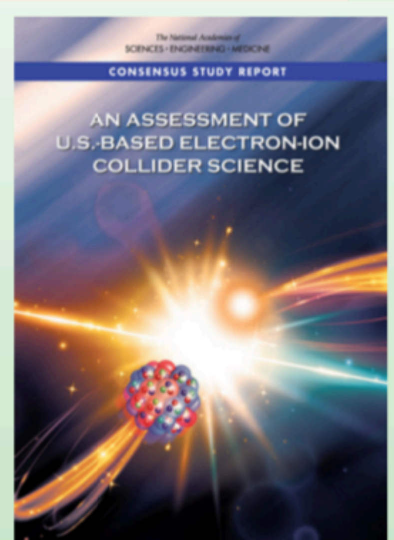
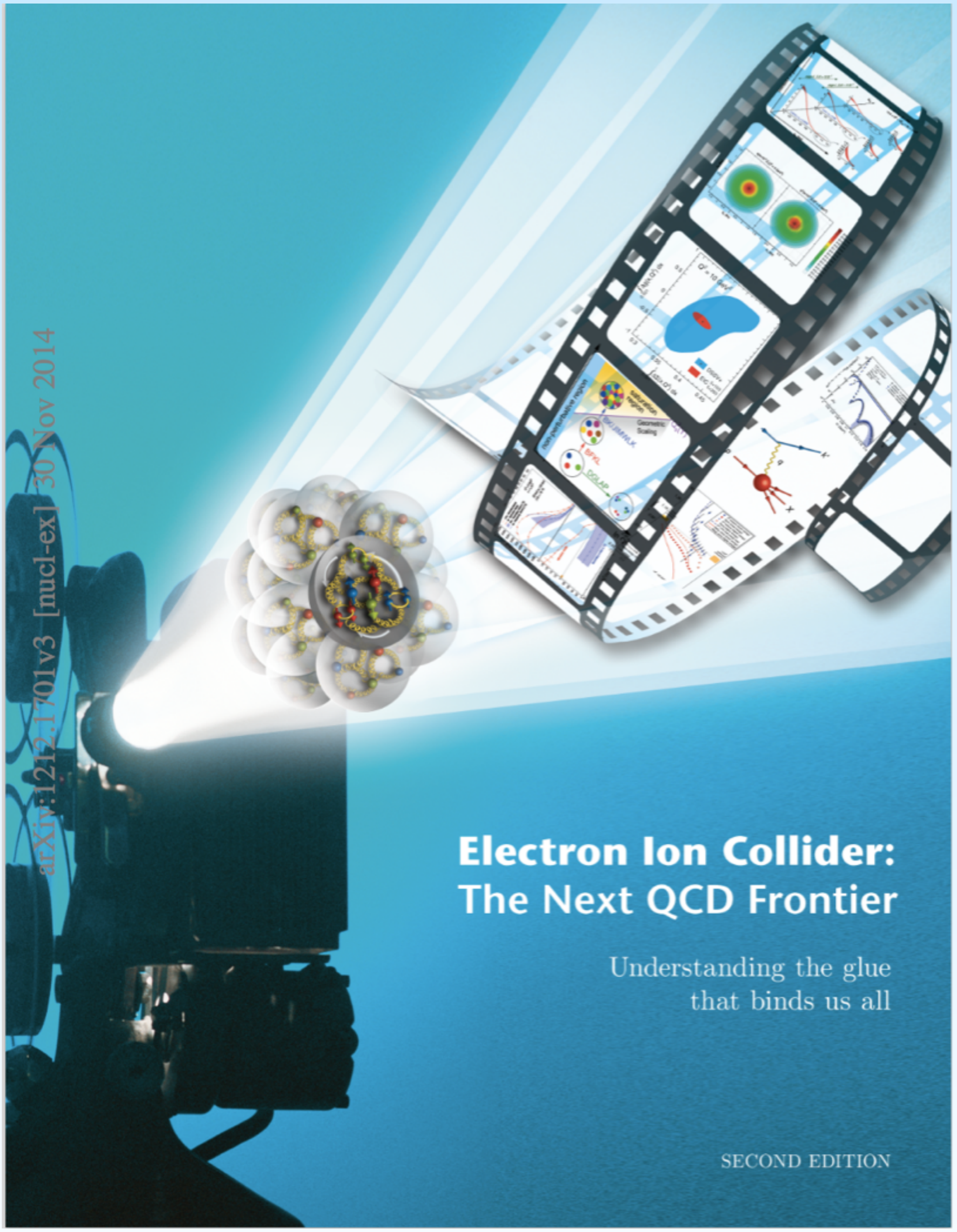




U.S. EIC Capabilities



Eur. Phys. J. A52 (2016) no.9, 268 - 644 citations

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

- *A collider to provide kinematic reach well into the gluon dominated regime,*
- *Electron beams provide the unmatched precision of the electromagnetic inter-action as a probe,*
- *Polarized nucleon beams to determine the correlations of sea quark and gluon distributions with the nucleon spin,*
- *Heavy Ion beams to access the gluon-saturated regime and as a precise dial to study propagation of color charges in nuclear matter.*
- *Facility concepts at RHIC and at Jefferson Laboratory, re-use of existing, significant investment.*

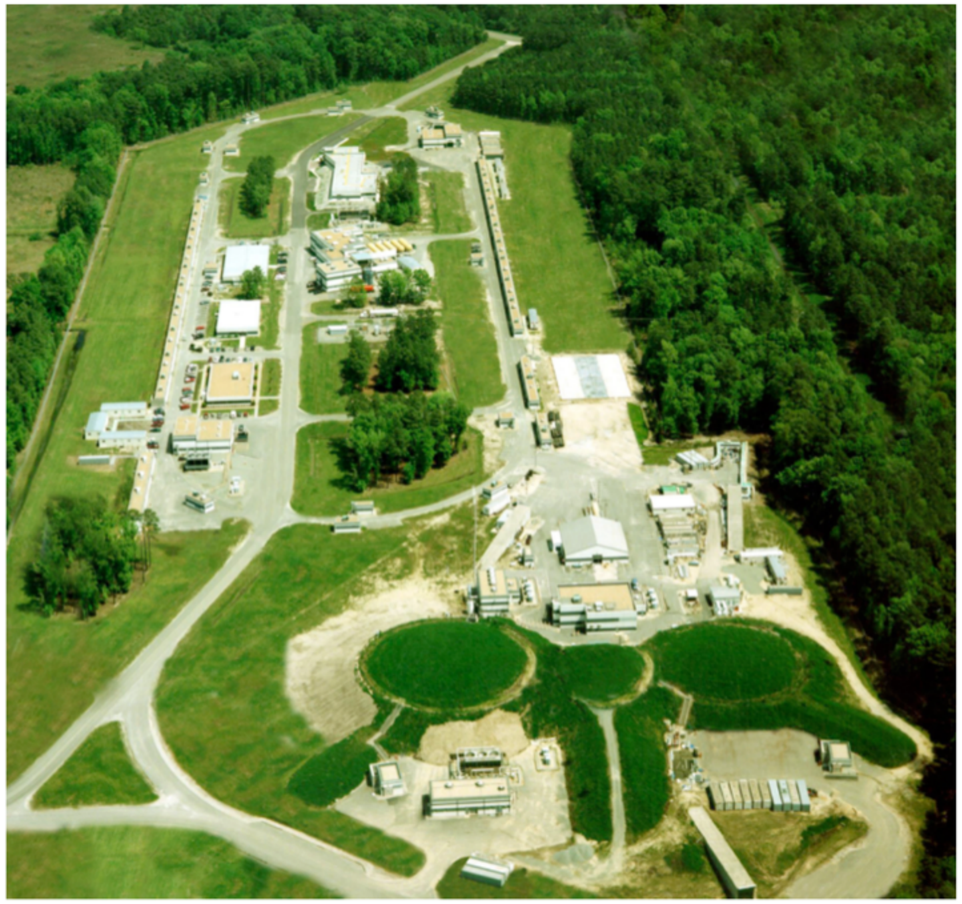
U.S.-based EIC - Two Facility Concepts

eRHIC:

- re-use existing RHIC hadron beam,

JLEIC:

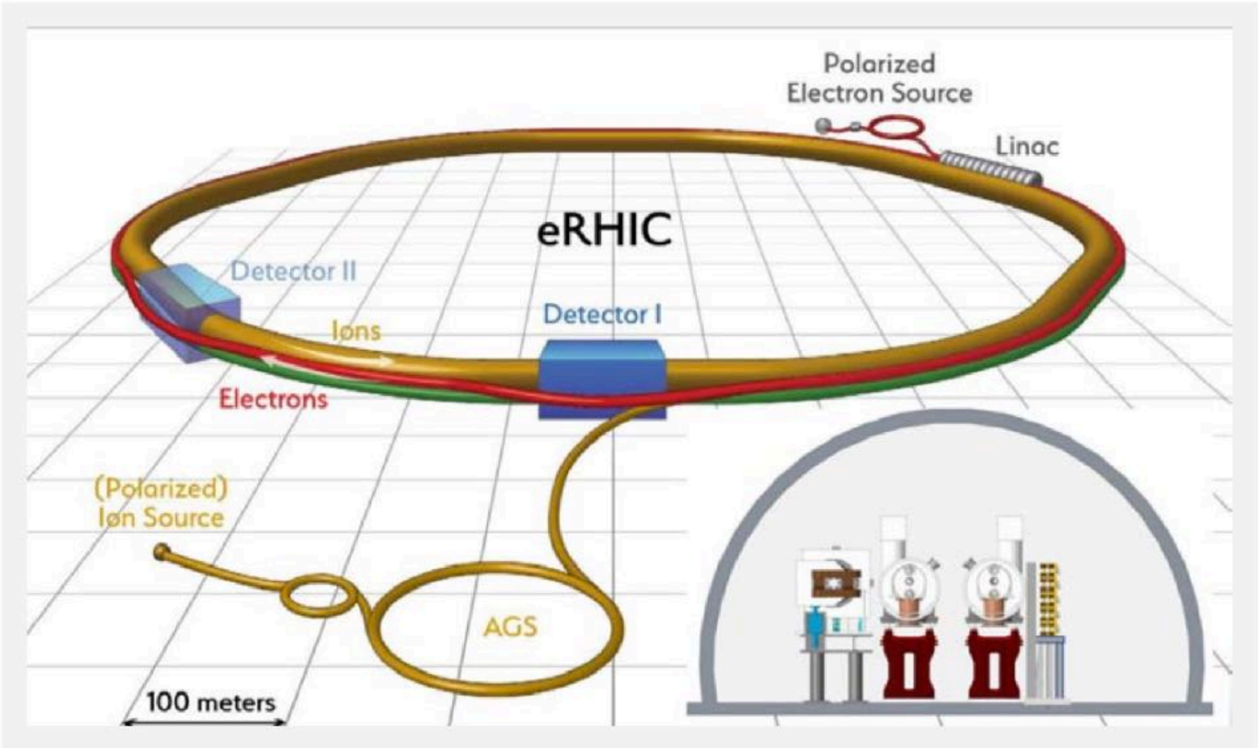
- re-use existing CEBAF 12 GeV electron beam,



U.S.-based EIC - Two Facility Concepts

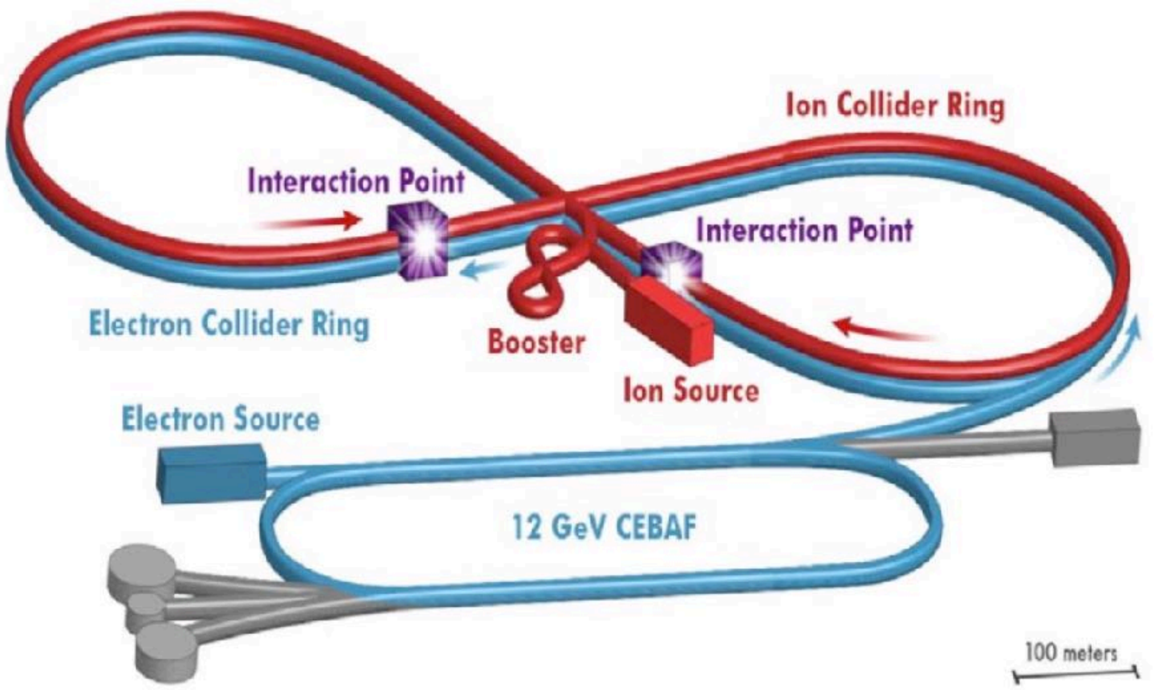
eRHIC (as presented in the W.P.):

- re-use RHIC hadron beam,
- new electron storage ring,
- 5 - 18 GeV e energy,
- Heavy Ions up to 100 GeV/u
- $\sqrt{s}$ up to 93 GeV
- L ~ 0.4×10^{34} cm^{-2}s^{-1}/A base design,
  1.0×10^{34} cm^{-2}s^{-1}/A w. strong cooling



JLEIC (as presented in W.P.):

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



Science cases by themselves!

U.S.-based EIC - Two Facility Concepts

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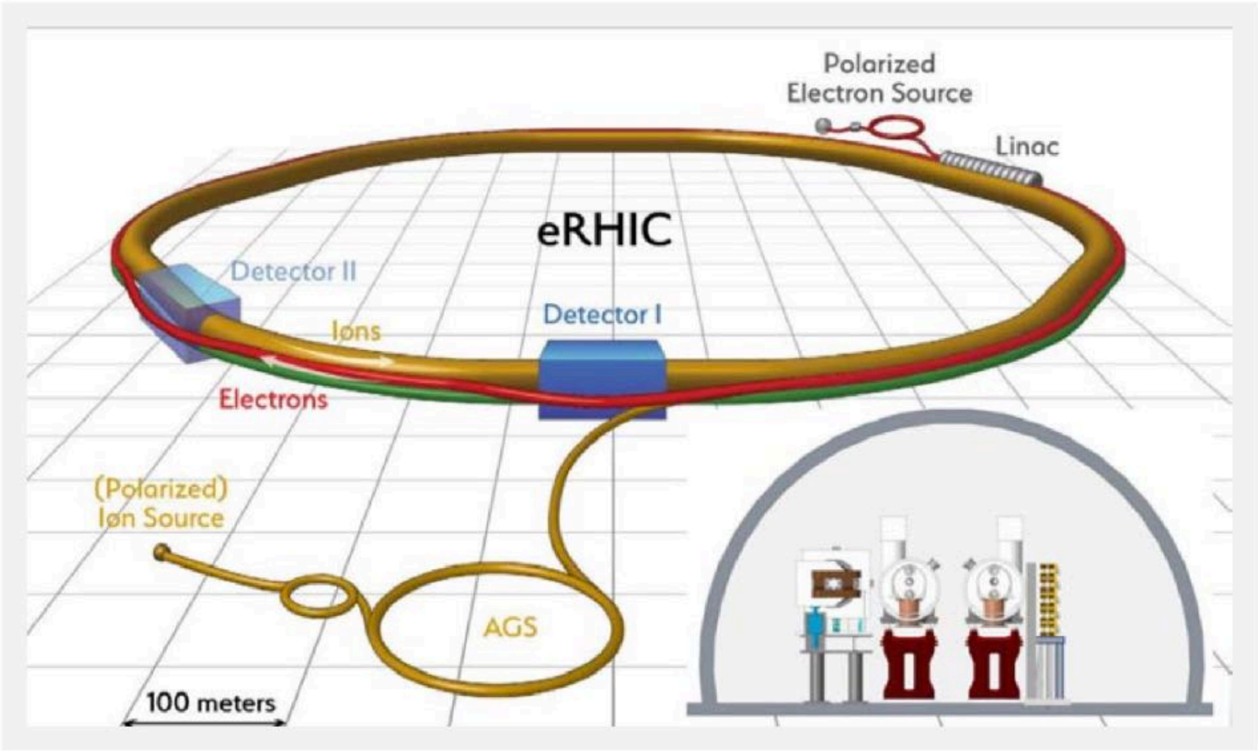

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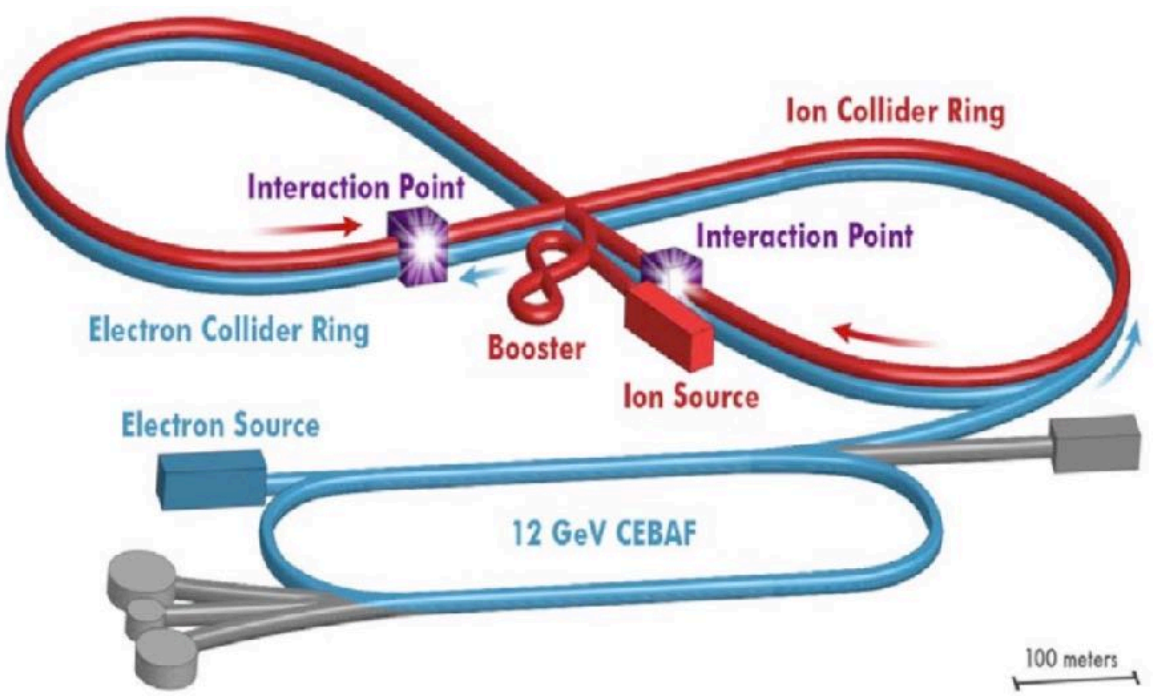
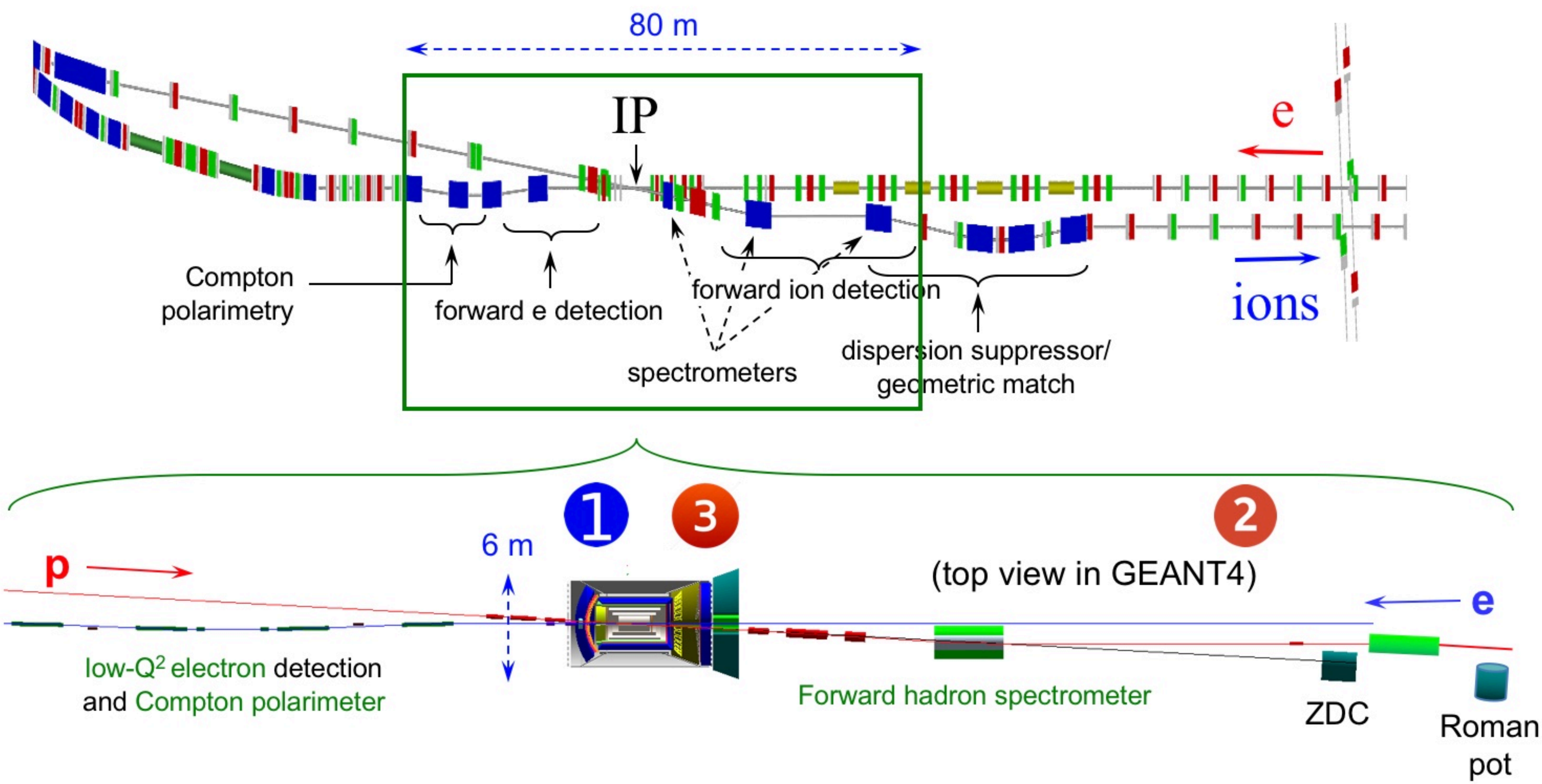


See Valily Morozov's talk on EIC Accelerator Design Status in WS2 tomorrow

U.S.-based EIC - Two Facility Concepts

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

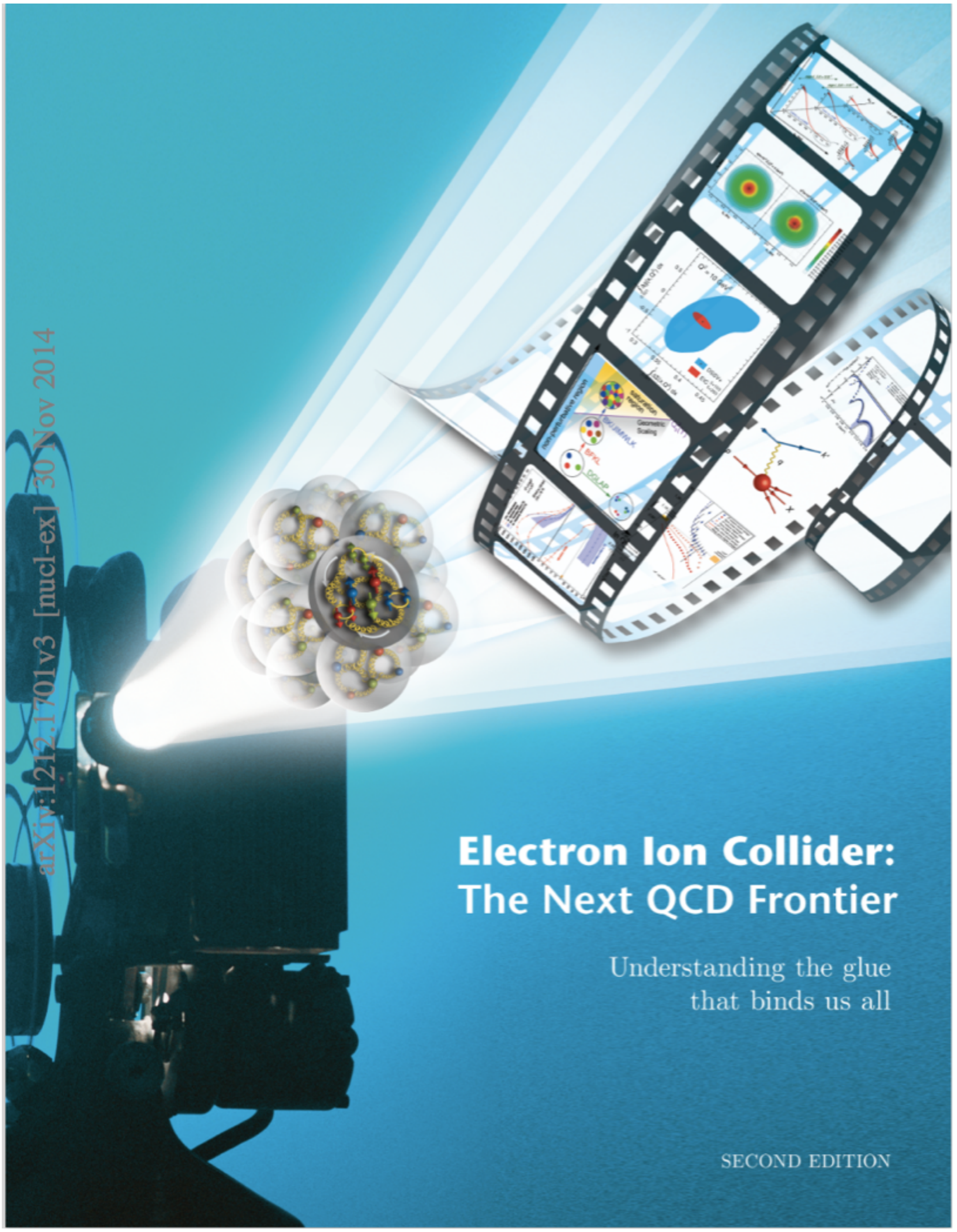


courtesy V. Morozov (JLab)

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

U.S. EIC Science Case

See Abhay Deshpande's talk "EIC Science Overview" in WS2 tomorrow

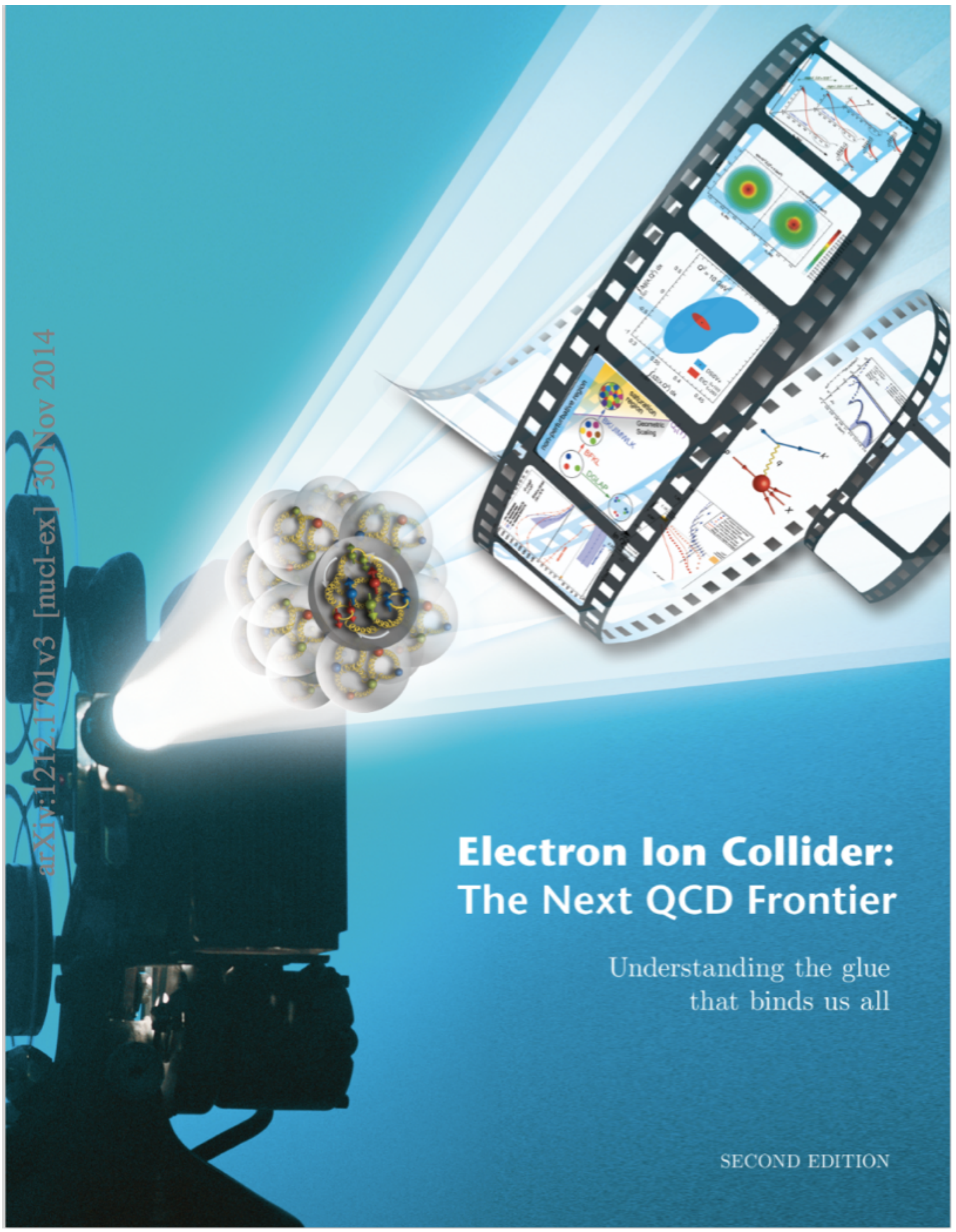


Eur. Phys. J. A52 (2016) no.9, 268 - 441 citations

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

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

U.S. EIC Science Case



Eur. Phys. J. A52 (2016) no.9, 268 - 644 citations

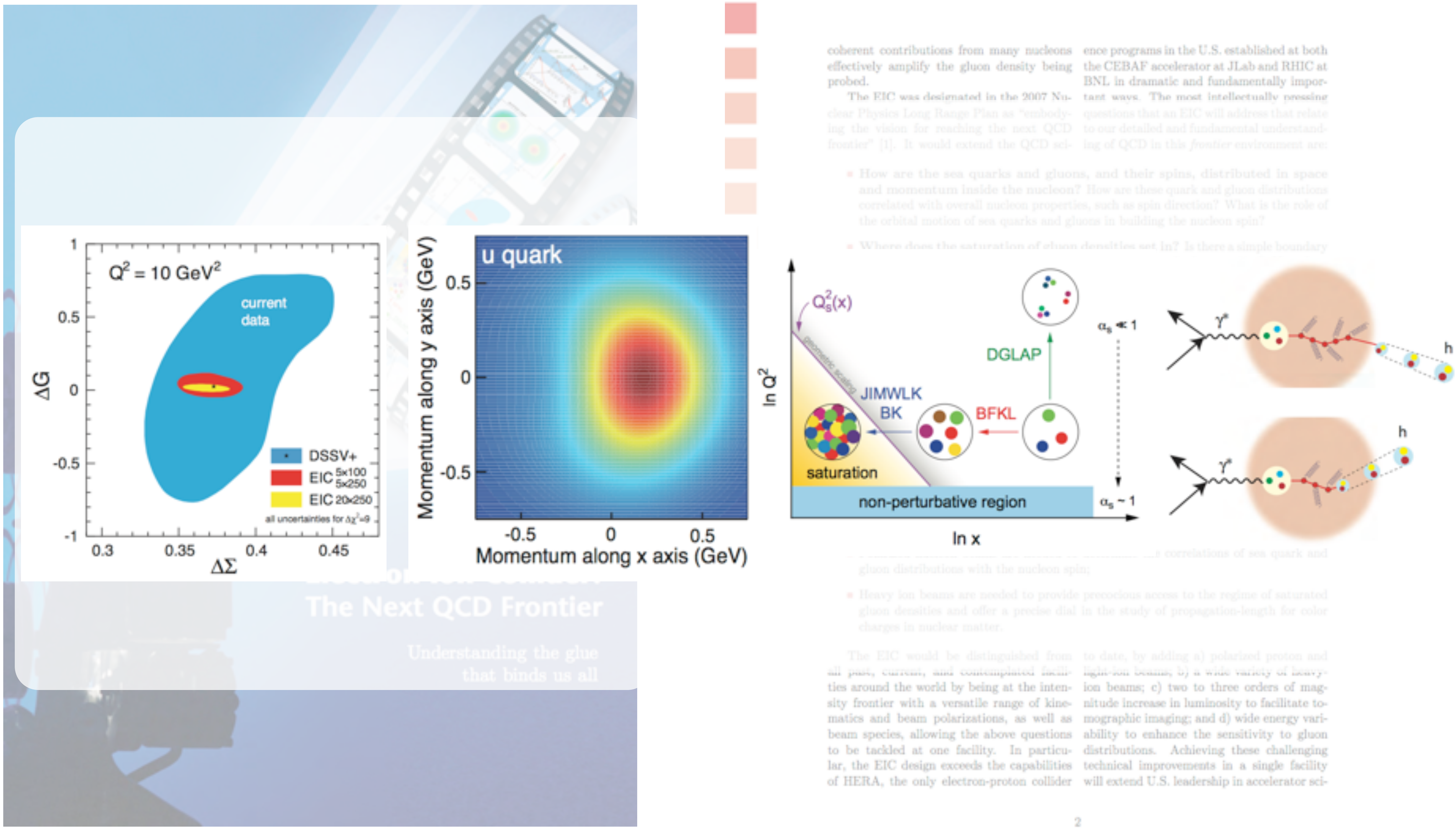
See also Rept.Prog.Phys. 82 (2019) 024301

Organized around four themes:

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

Identified measurements and impact.

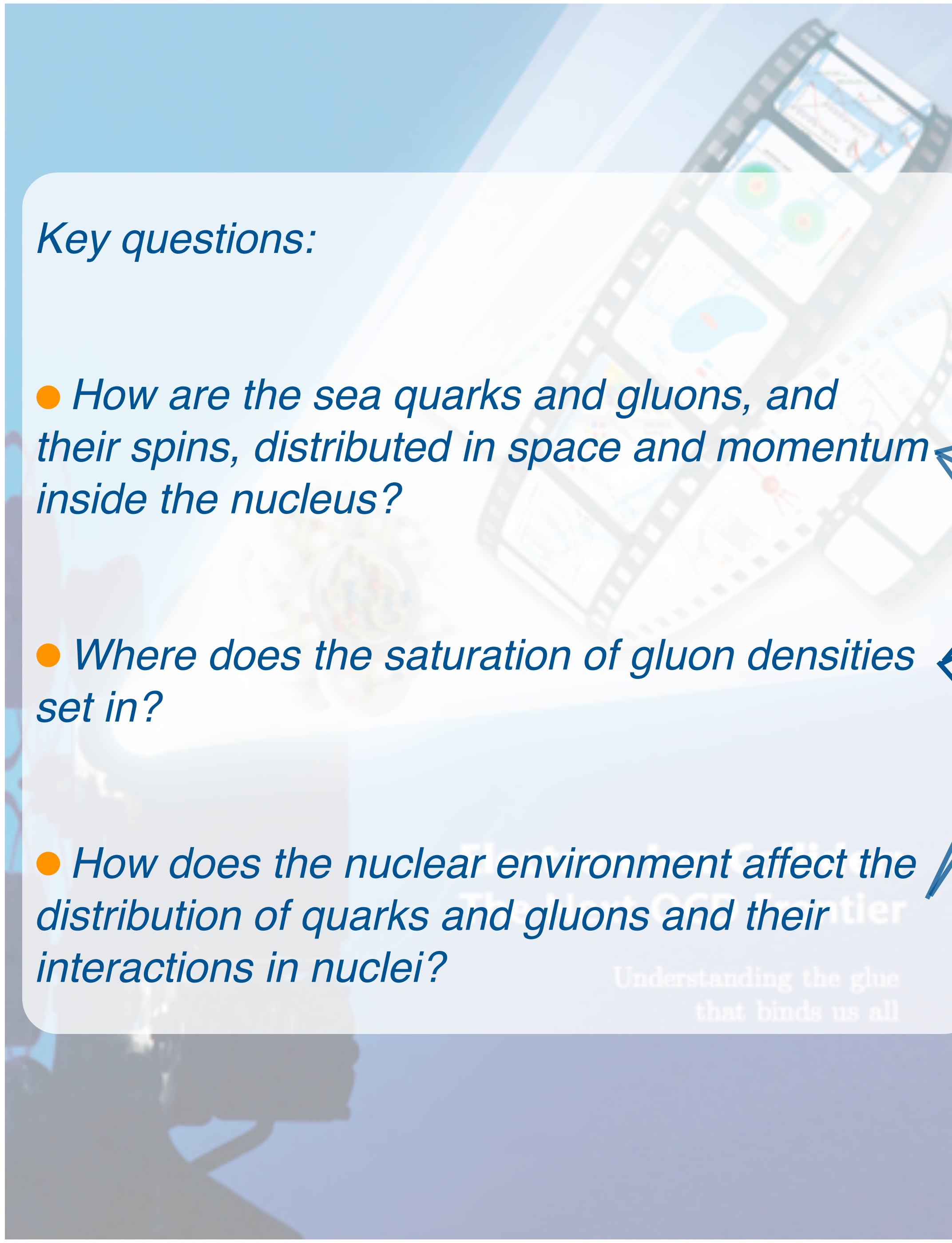
U.S.-based EIC - Core Science



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

theory

U.S.-based EIC - Observables



Key questions:

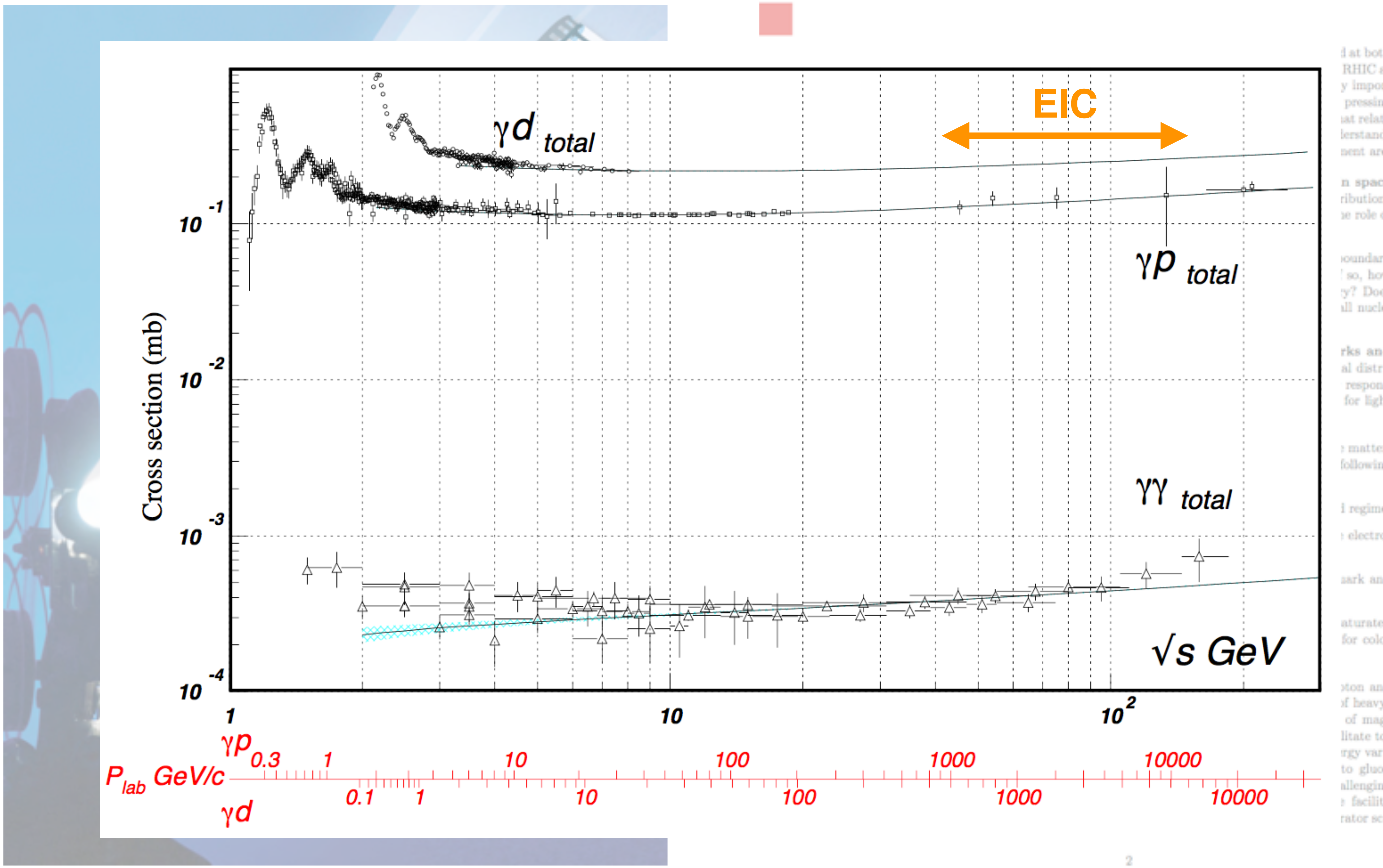
- *How are the sea quarks and gluons, and their spins, distributed in space and momentum inside the nucleus?*
- *Where does the saturation of gluon densities set in?*
- *How does the nuclear environment affect the distribution of quarks and gluons and their interactions in nuclei?*

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**

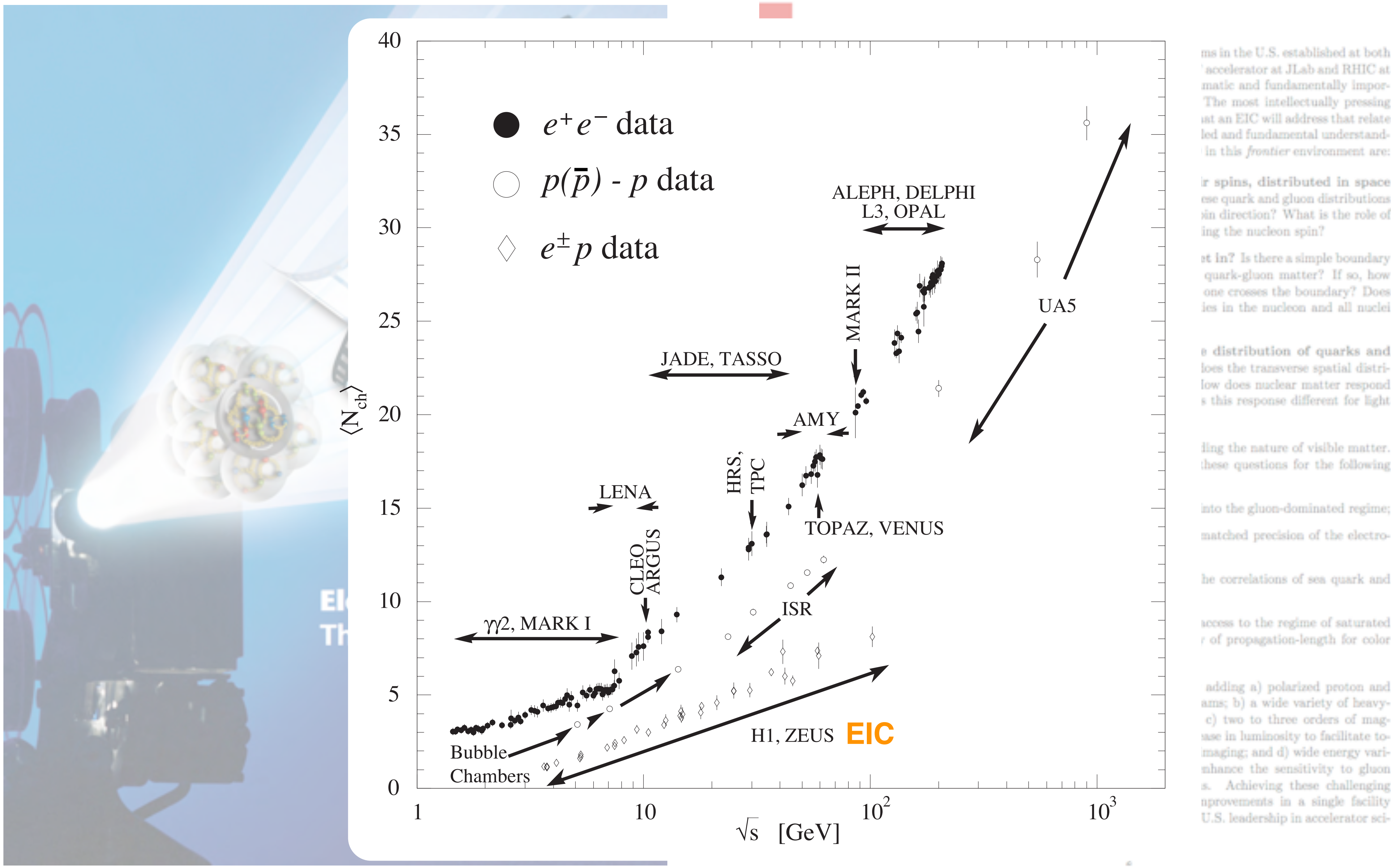
U.S.-based EIC - Observables



Photoproduction is the dominant cross-section; well known,

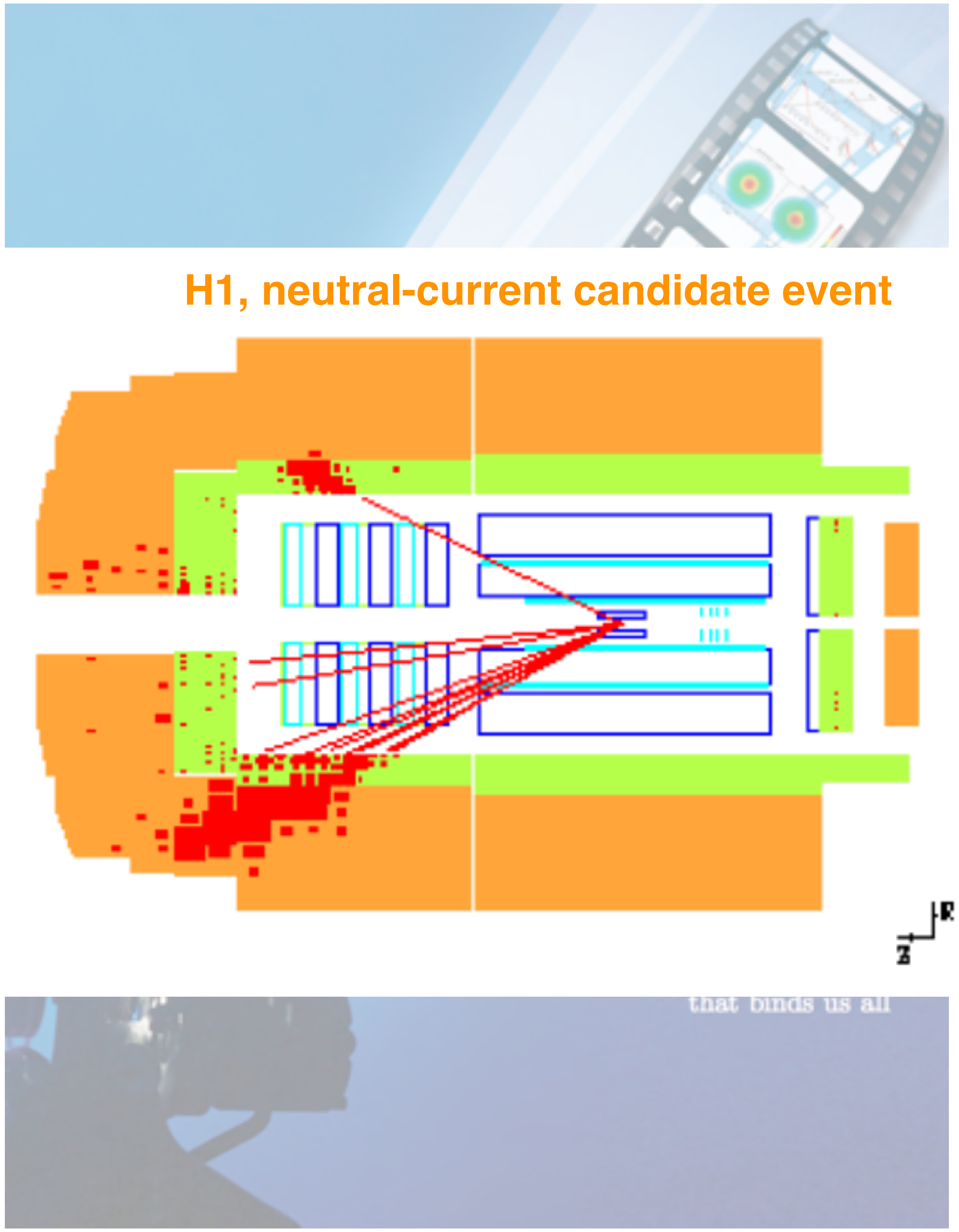
2 orders below RHIC, LHC

U.S.-based EIC - Observables

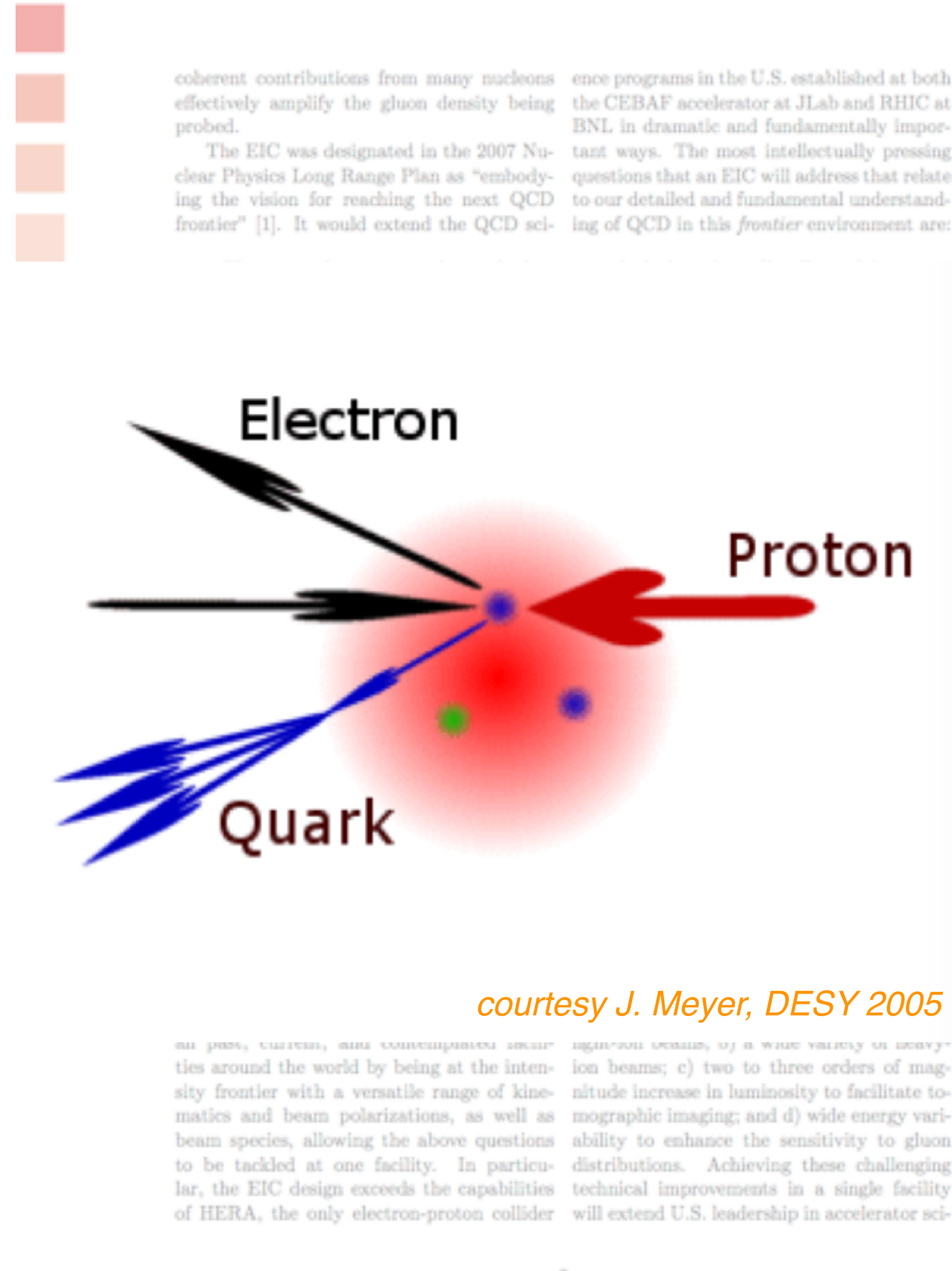


Likewise, particle multiplicities are well below those at the hadron colliders,

U.S.-based EIC - Observables



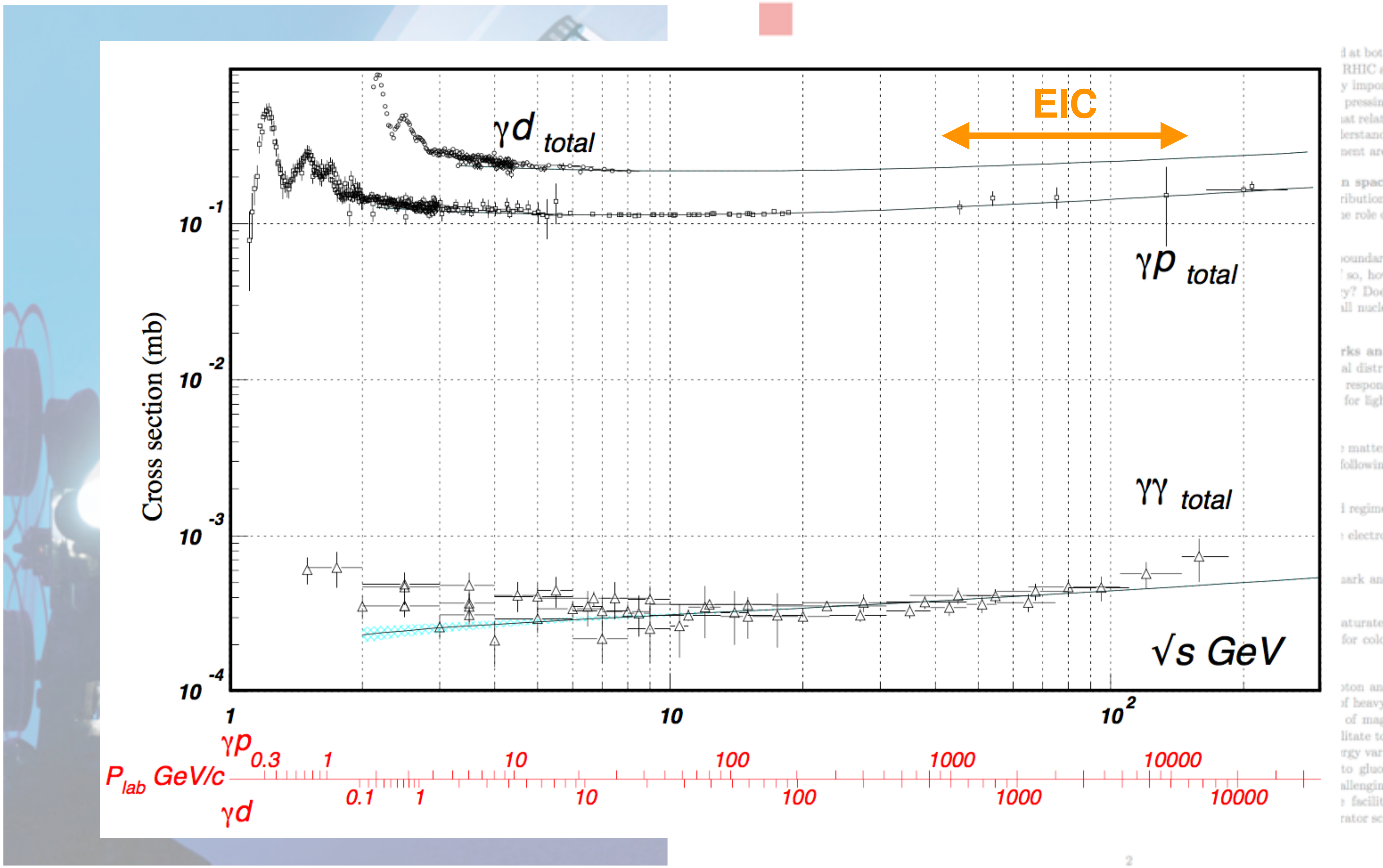
H1, neutral-current candidate event



courtesy J. Meyer, DESY 2005

Likewise, particle multiplicities are well below those at the hadron colliders, event topologies are well known from HERA

U.S.-based EIC - Observables



L ~ $10^{33(34)}$ $cm^{-2}s^{-1}$ implies a ~50 (500) kHz collision-event rate,

<< EIC bunch cross crossing rate

~ similar to μs integration times

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.*

U.S.-based EIC - Detector Concepts

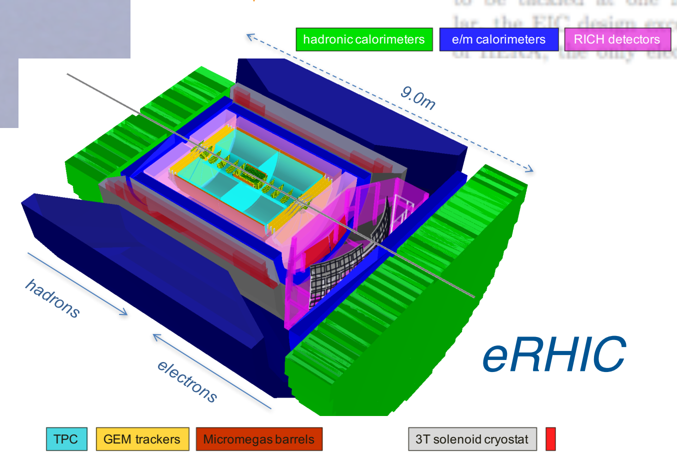
Key requirements:

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

Key measurements:

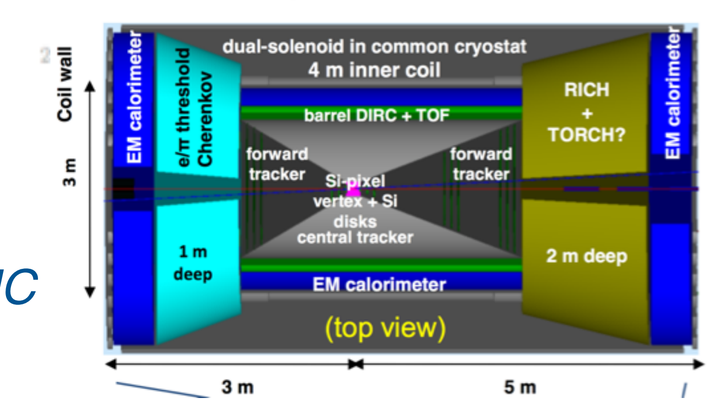
- *Inclusive Deep-Inelastic Scattering,*
- *Semi-inclusive deep-inelastic scattering with one or two of the particles in the final state,*
- *Exclusive deep-inelastic scattering,*
- *Diffraction.*

Green-field detector concepts:



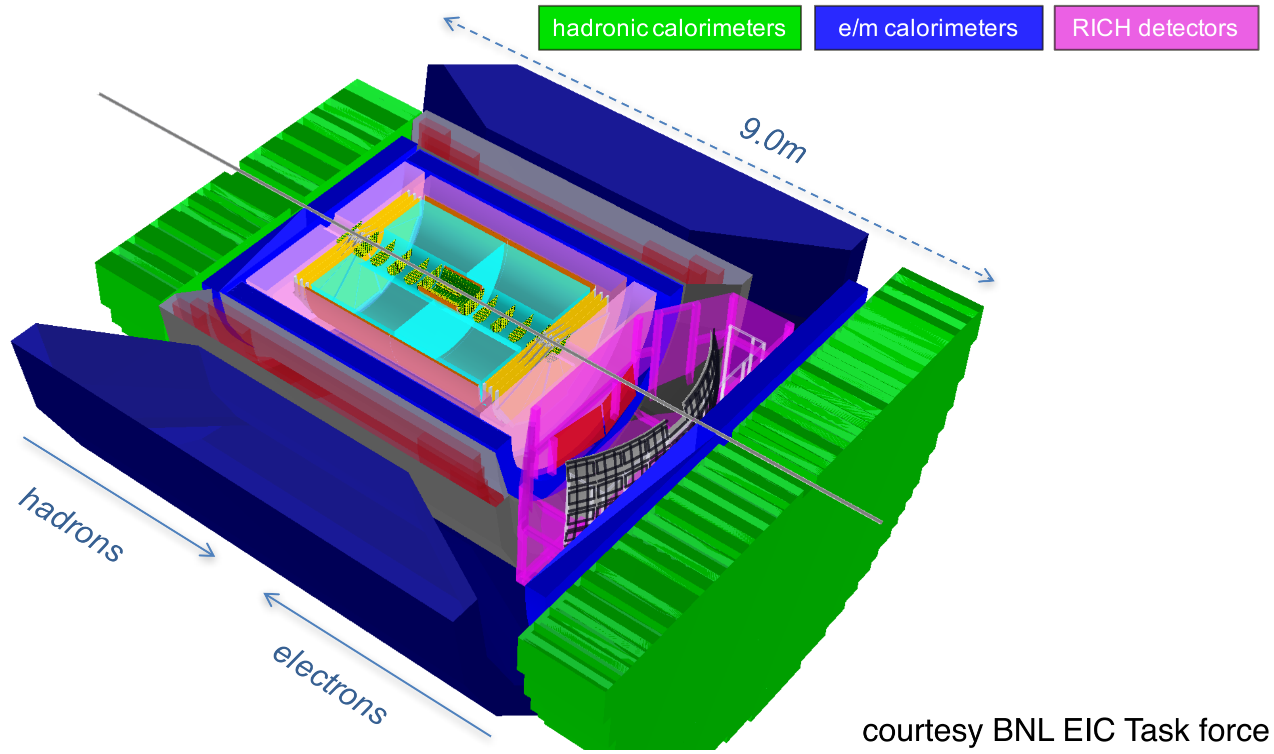
eRHIC

JLEIC

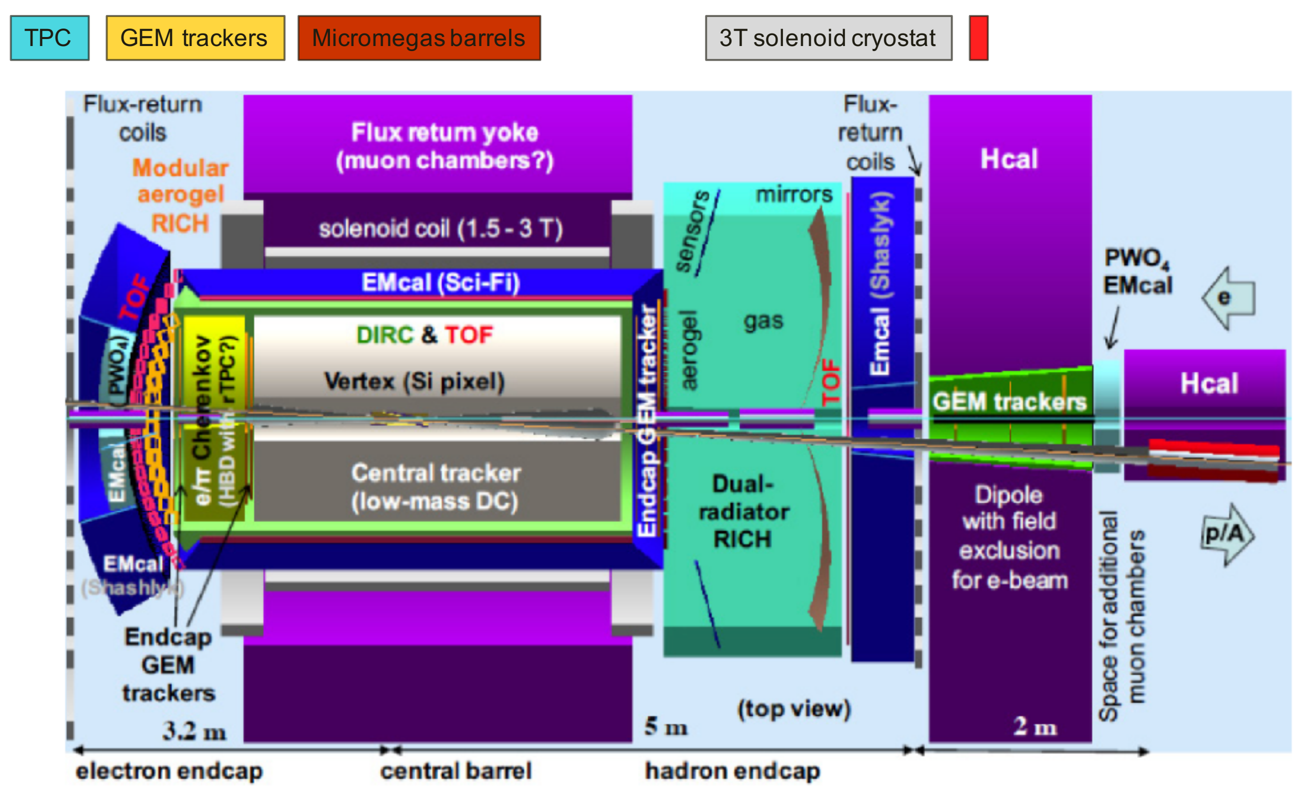


U.S.-based EIC - Detector Concepts

See Alexander Kiselev's talk EIC Detectors in WS2 tomorrow



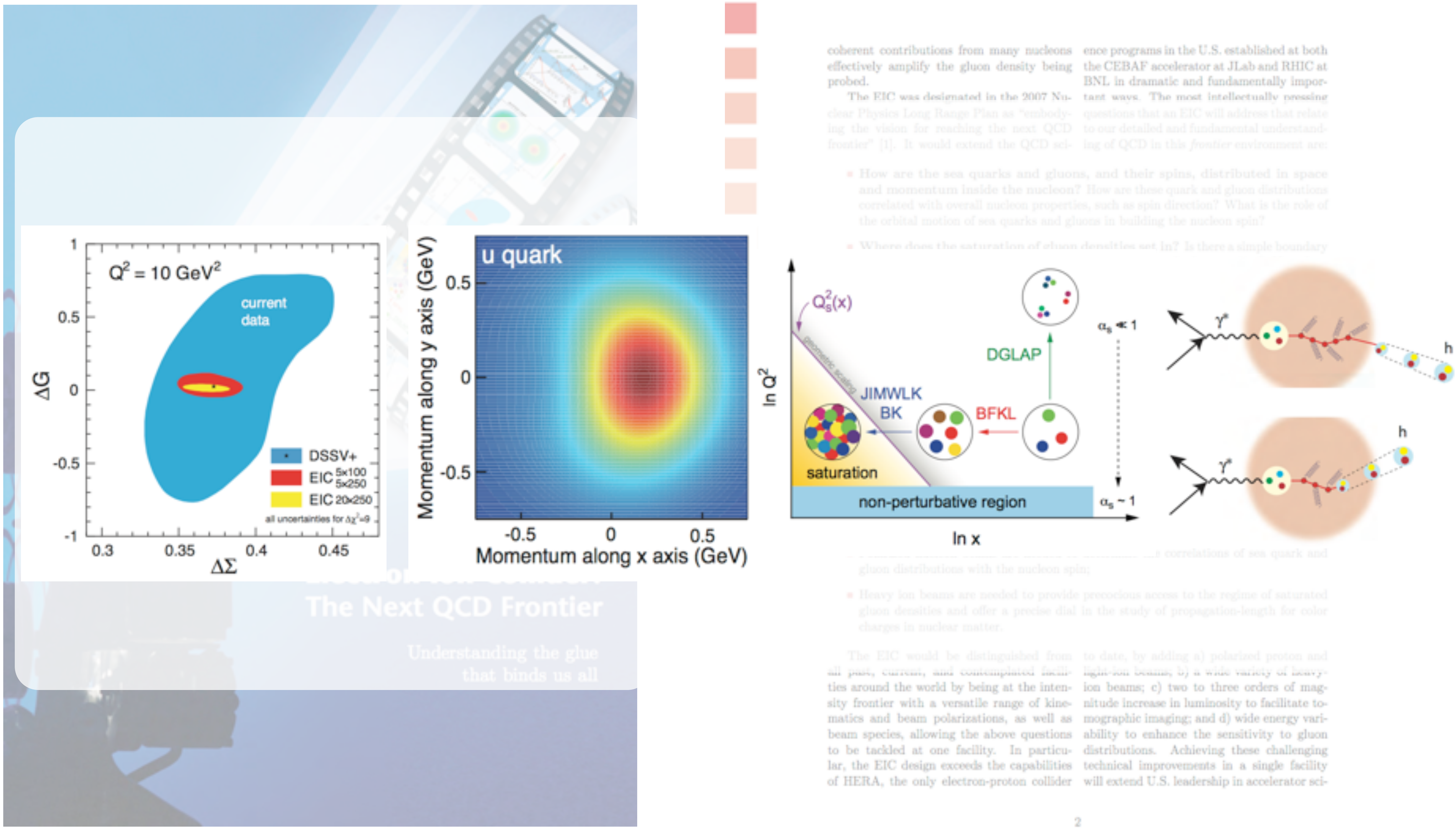
courtesy BNL EIC Task force



courtesy JLEIC Detector and Interaction Region Study Group

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

U.S.-based EIC - Core Science



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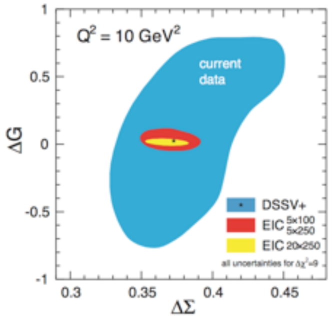
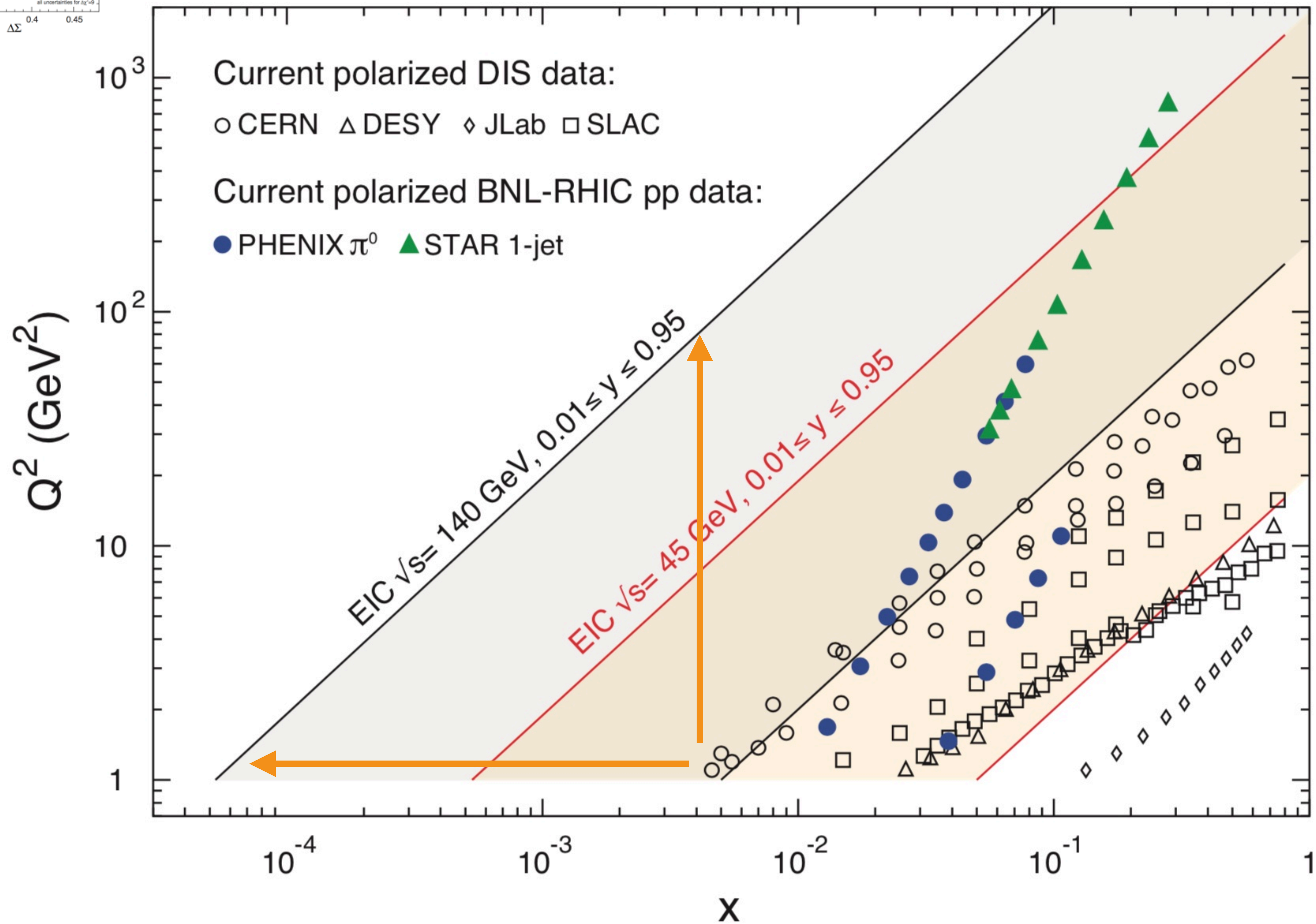
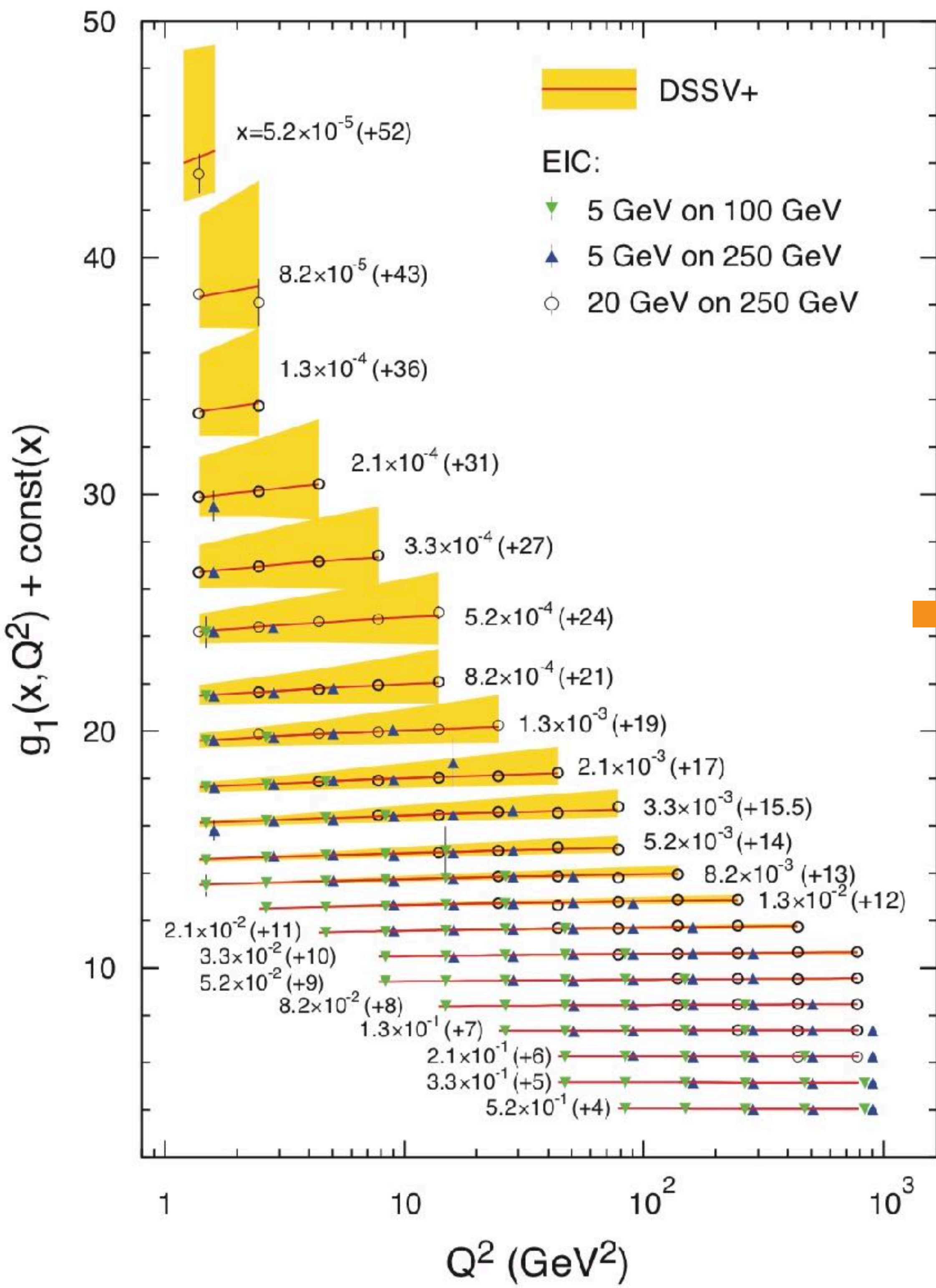


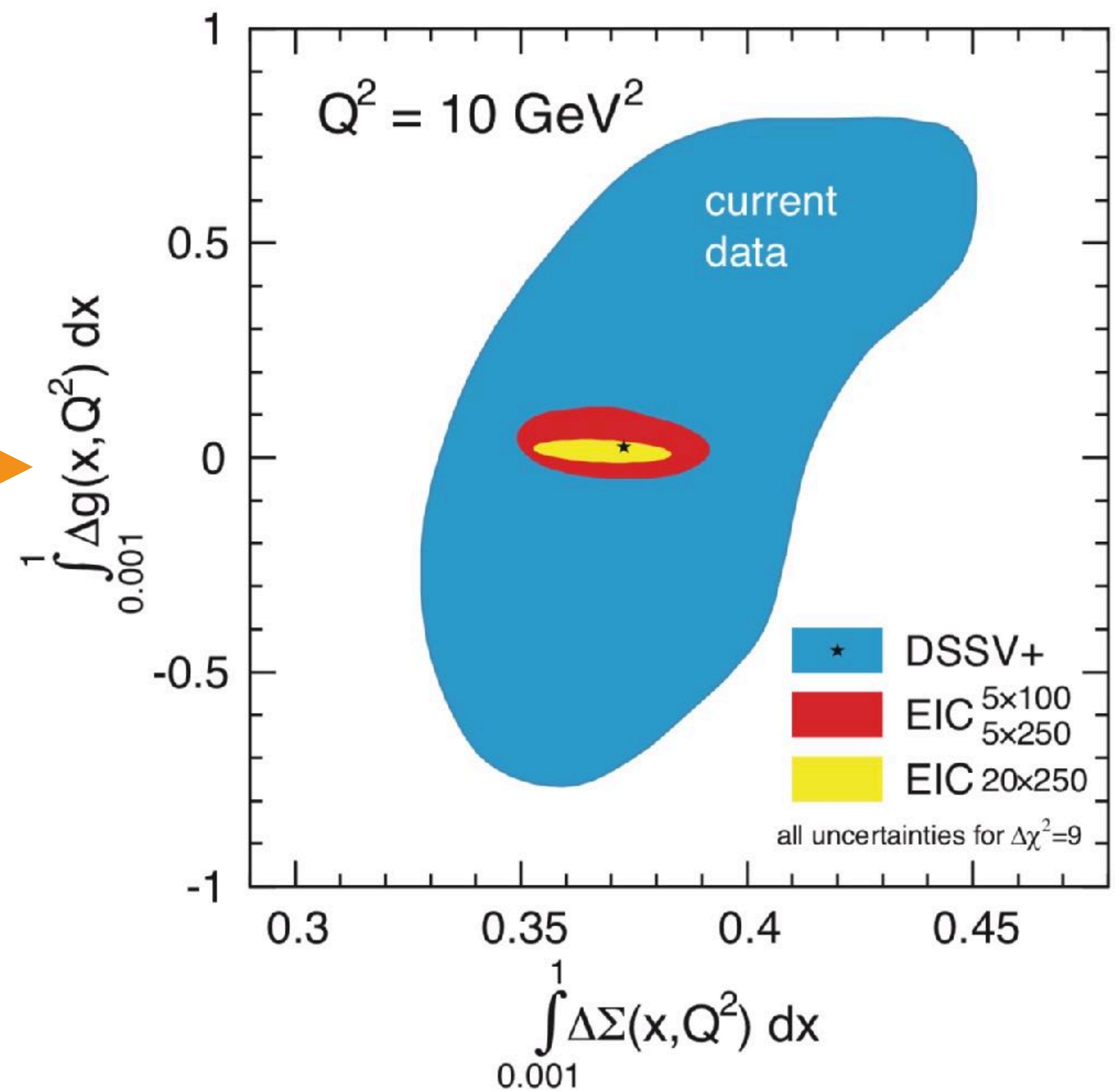
U.S.-based EIC - Proton Spin



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

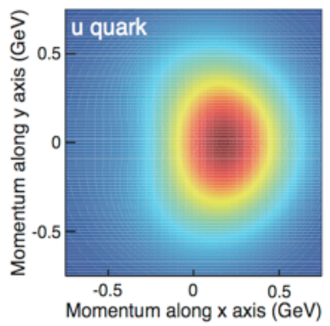
U.S.-based EIC - Proton Spin

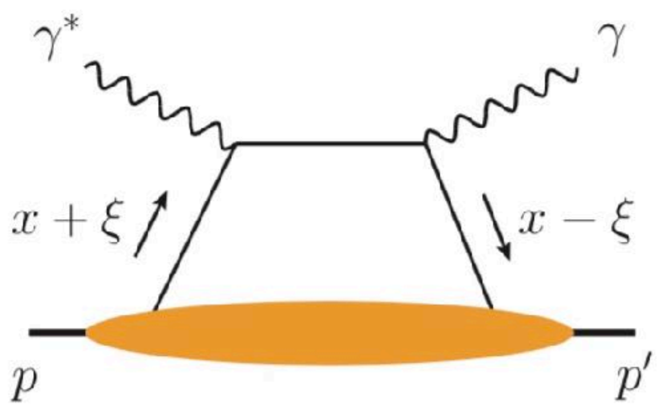


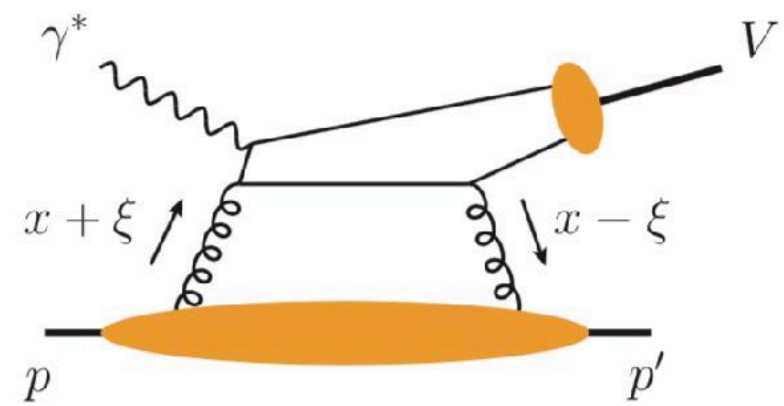


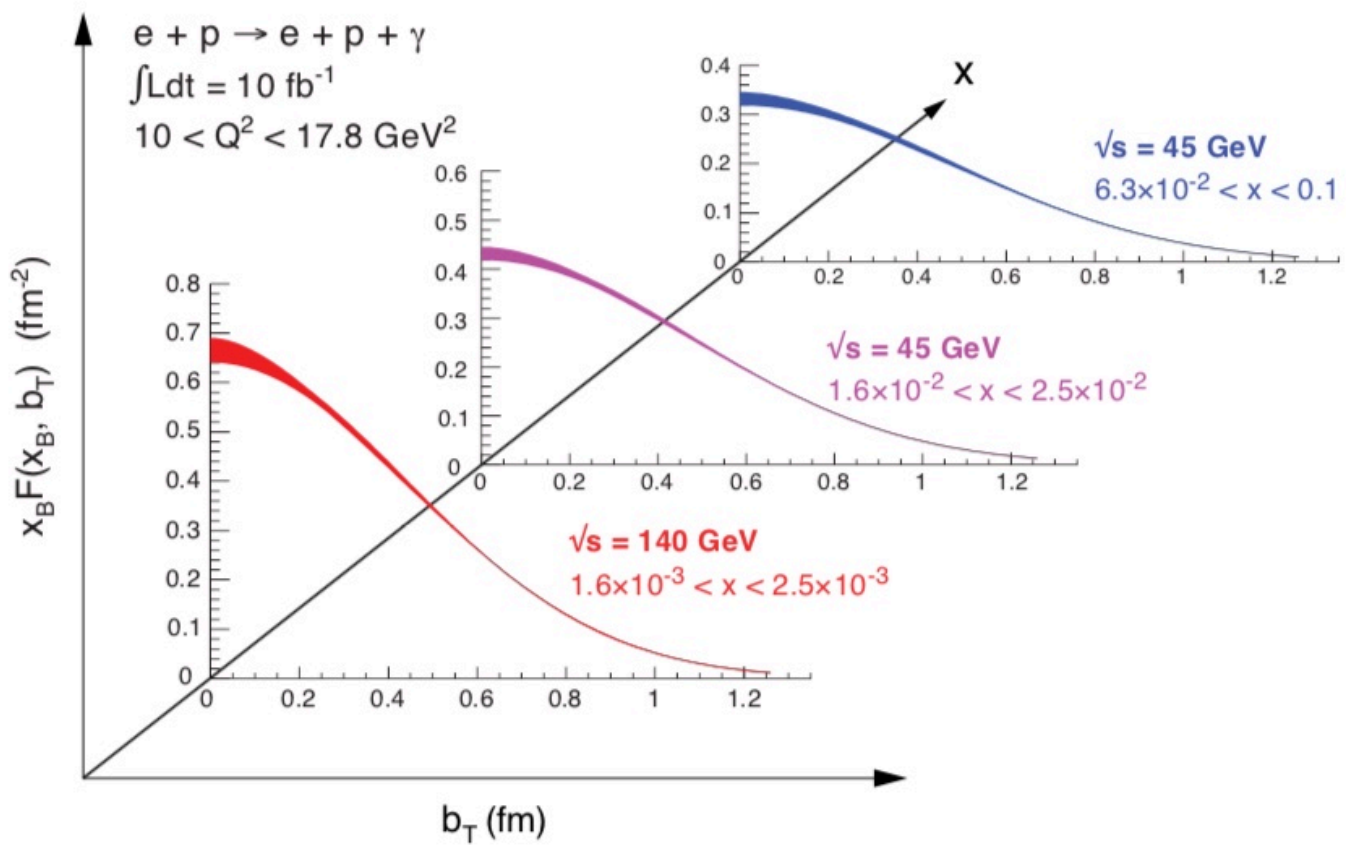
Conclusive insights in quark and gluon helicity from inclusive measurements, and orbital momentum by subtraction (!)

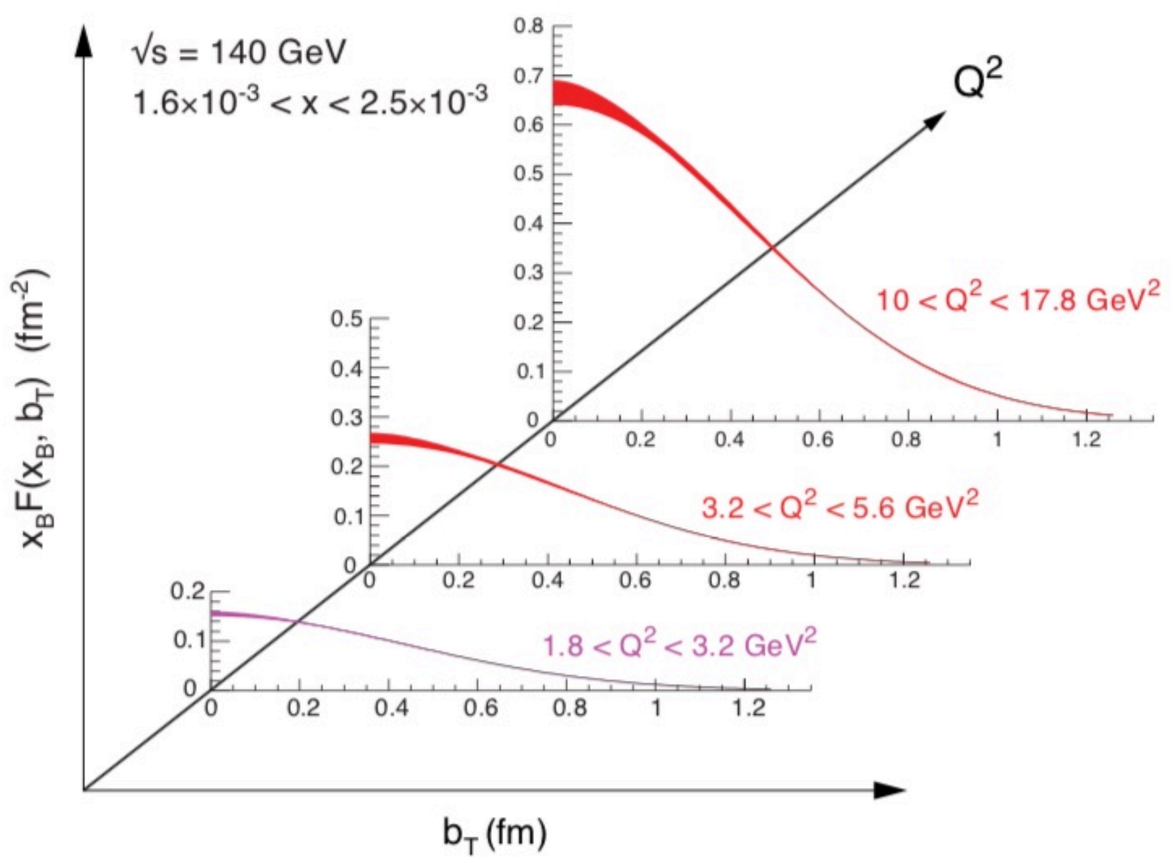
EIC - DVCS, DVMP, and Imaging





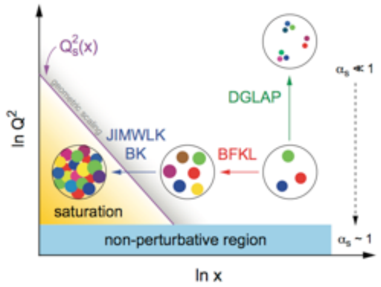




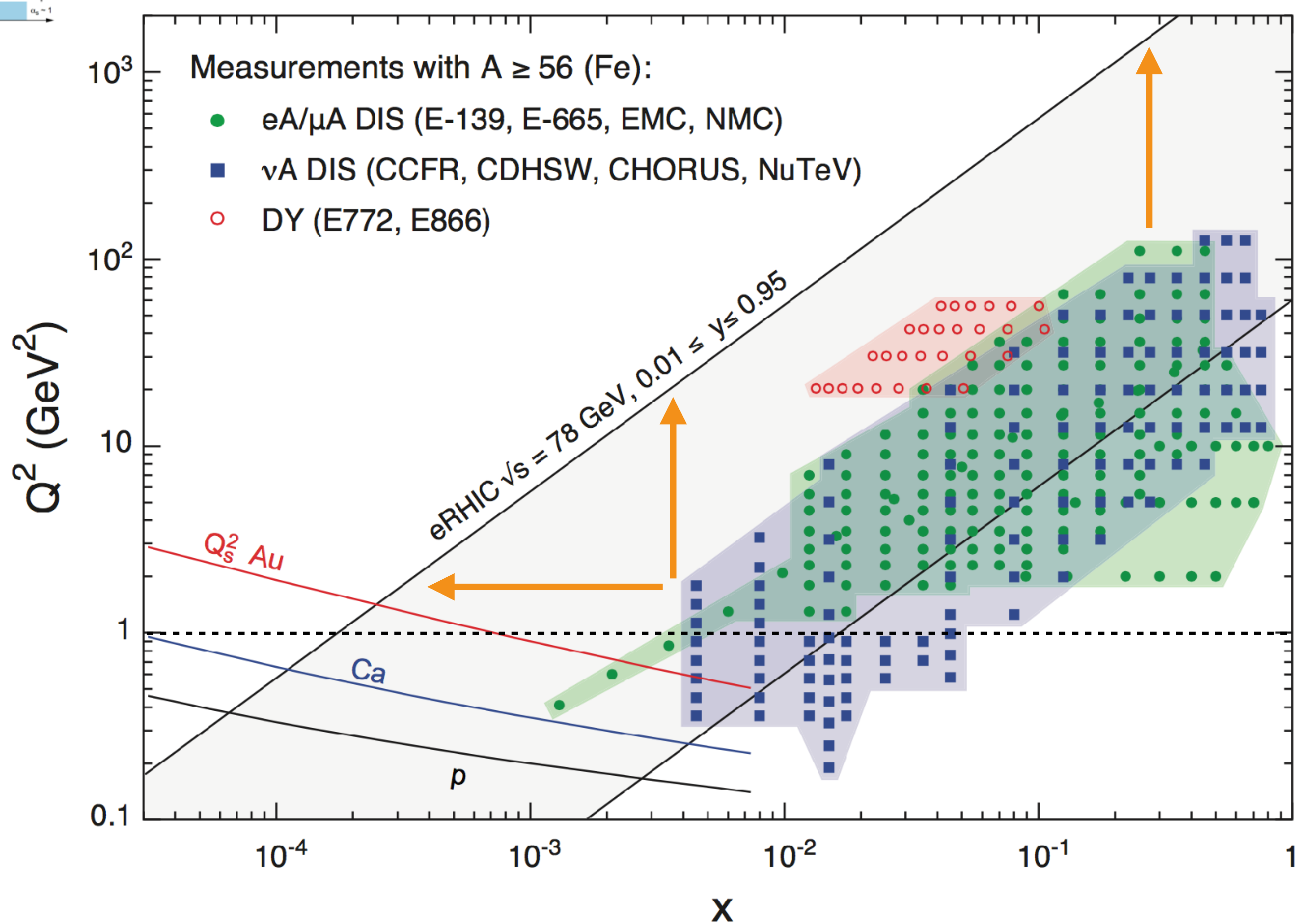


x-dependence at fixed Q^2

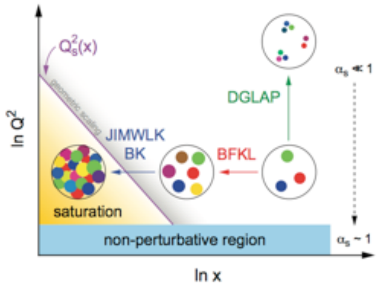
Q^2-dependence at fixed x



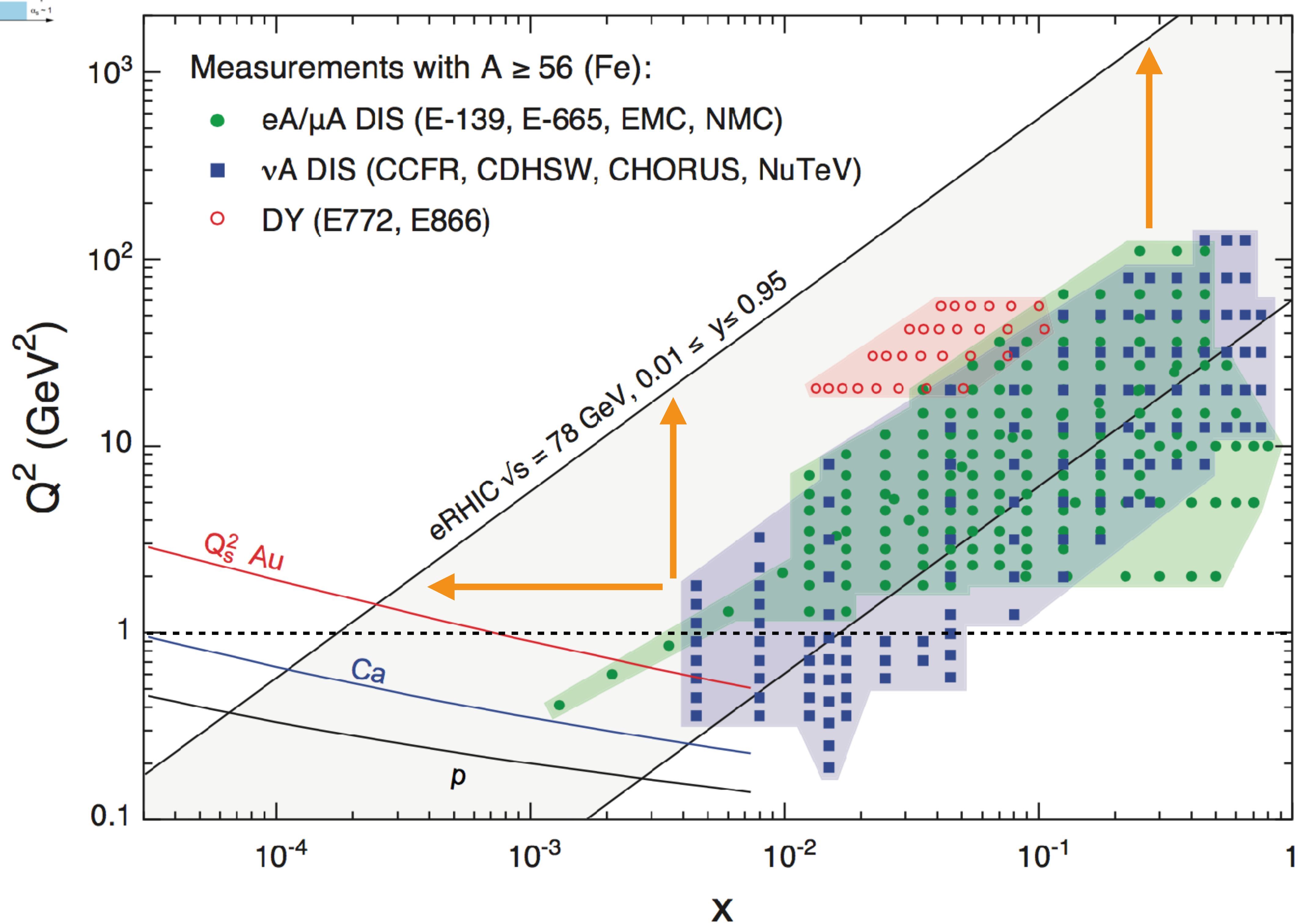
U.S.-based EIC - The Nuclear Landscape



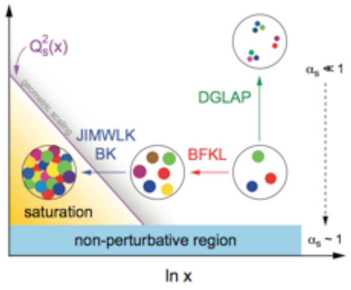
Complementarity with ongoing and future RHIC and LHC measurements,



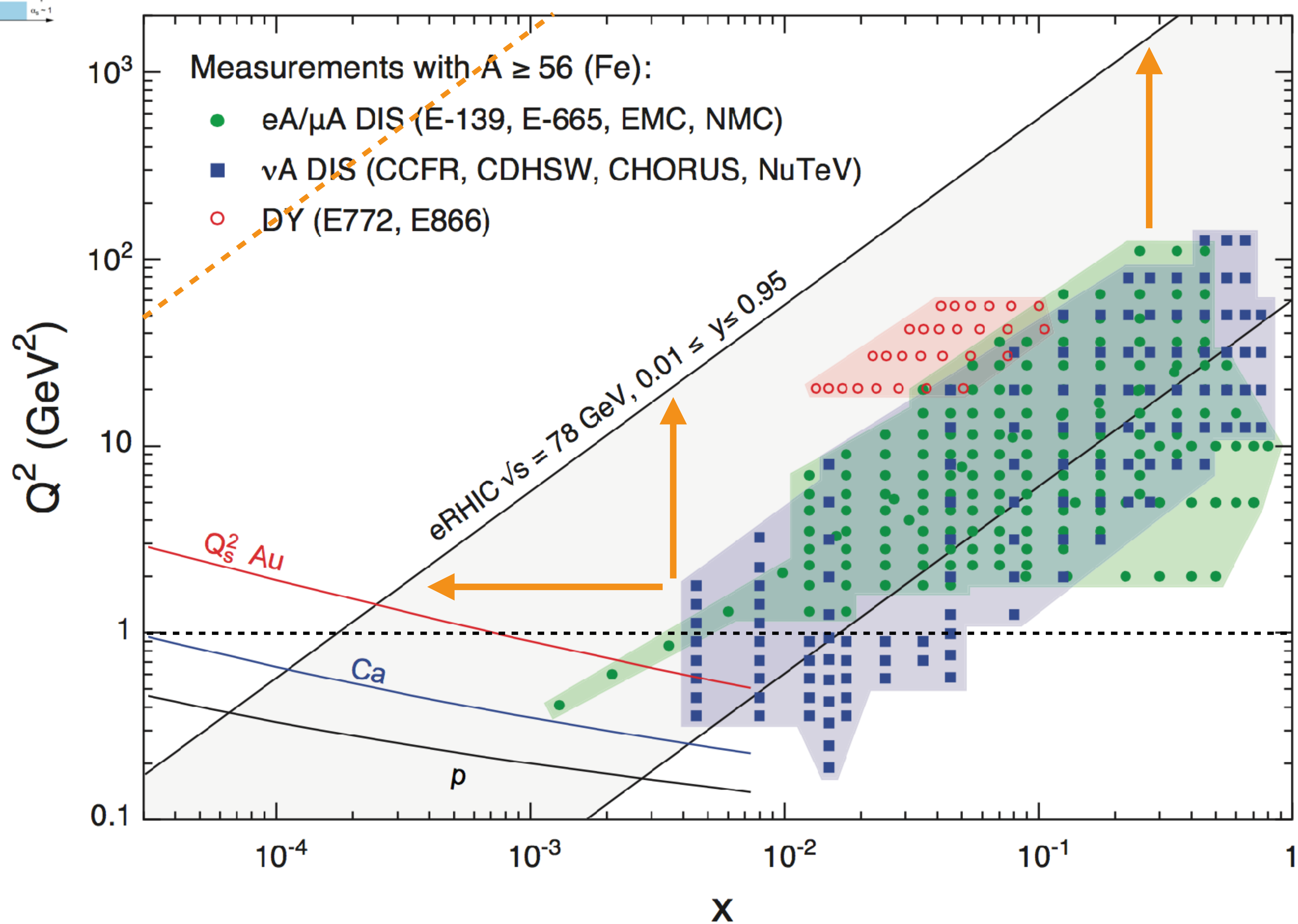
U.S.-based EIC - The Nuclear Landscape



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



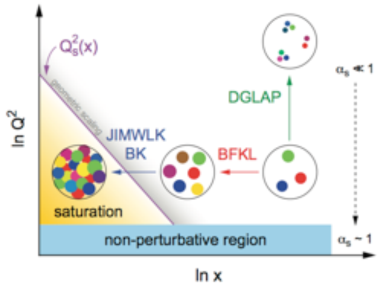
U.S.-based EIC - The Nuclear Landscape

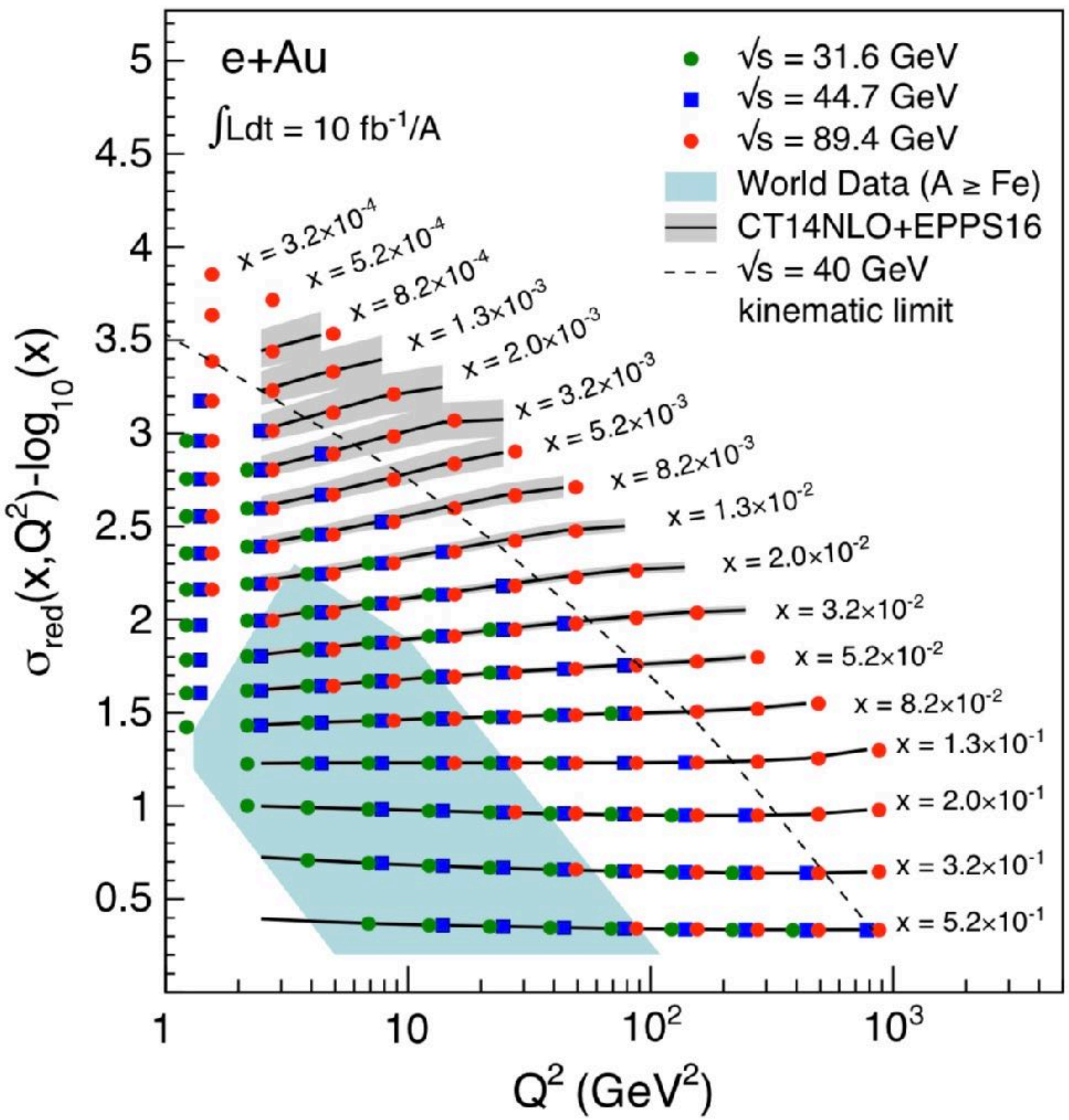


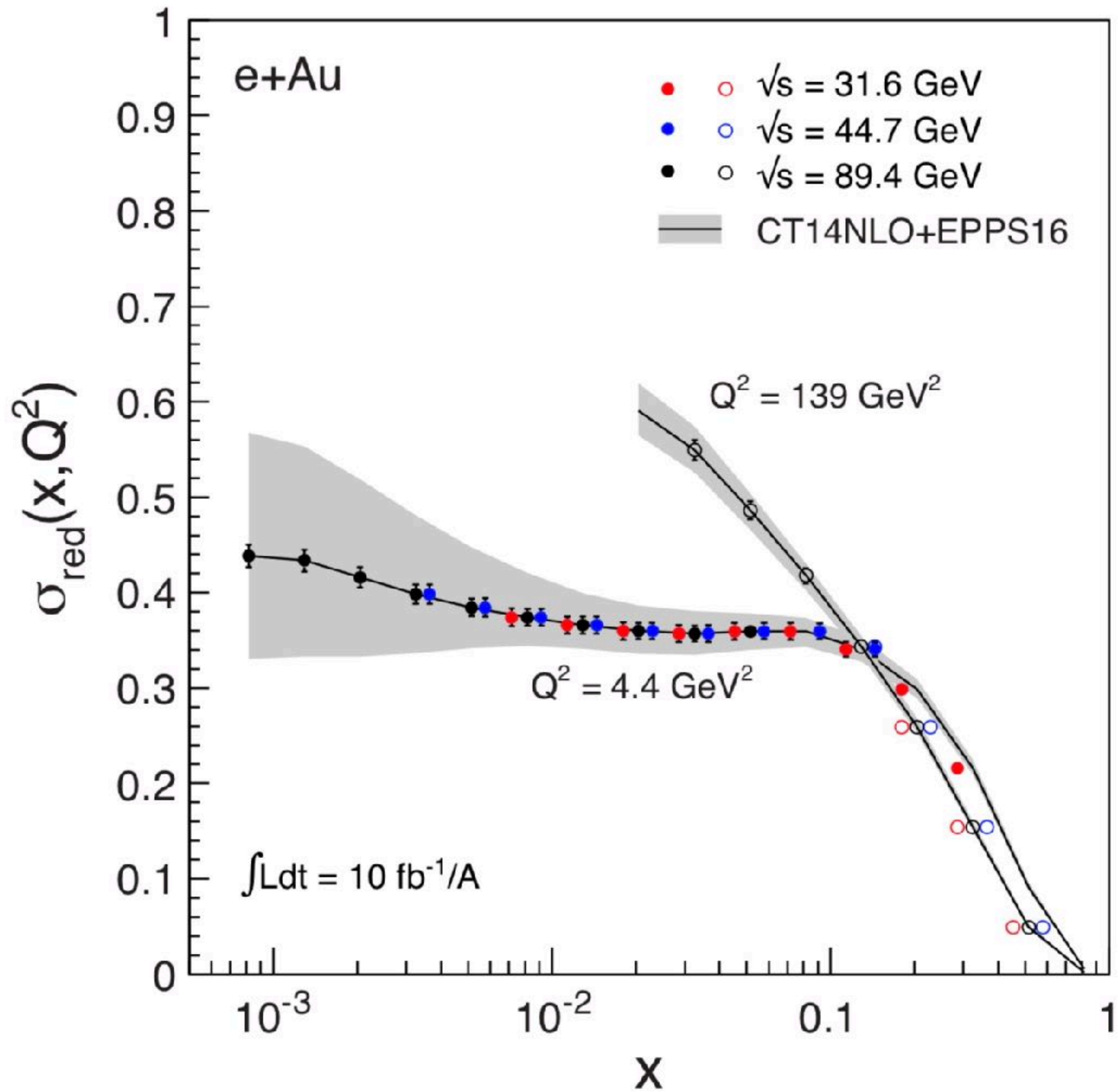
Complementarity with ongoing and future RHIC and LHC measurements, neutrino physics, cosmic ray physics, …

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

U.S.-based EIC - The Nuclear Landscape

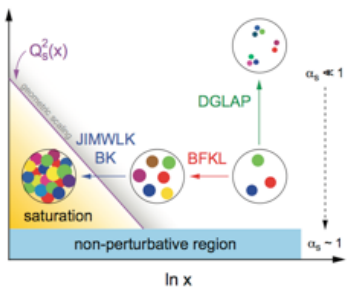




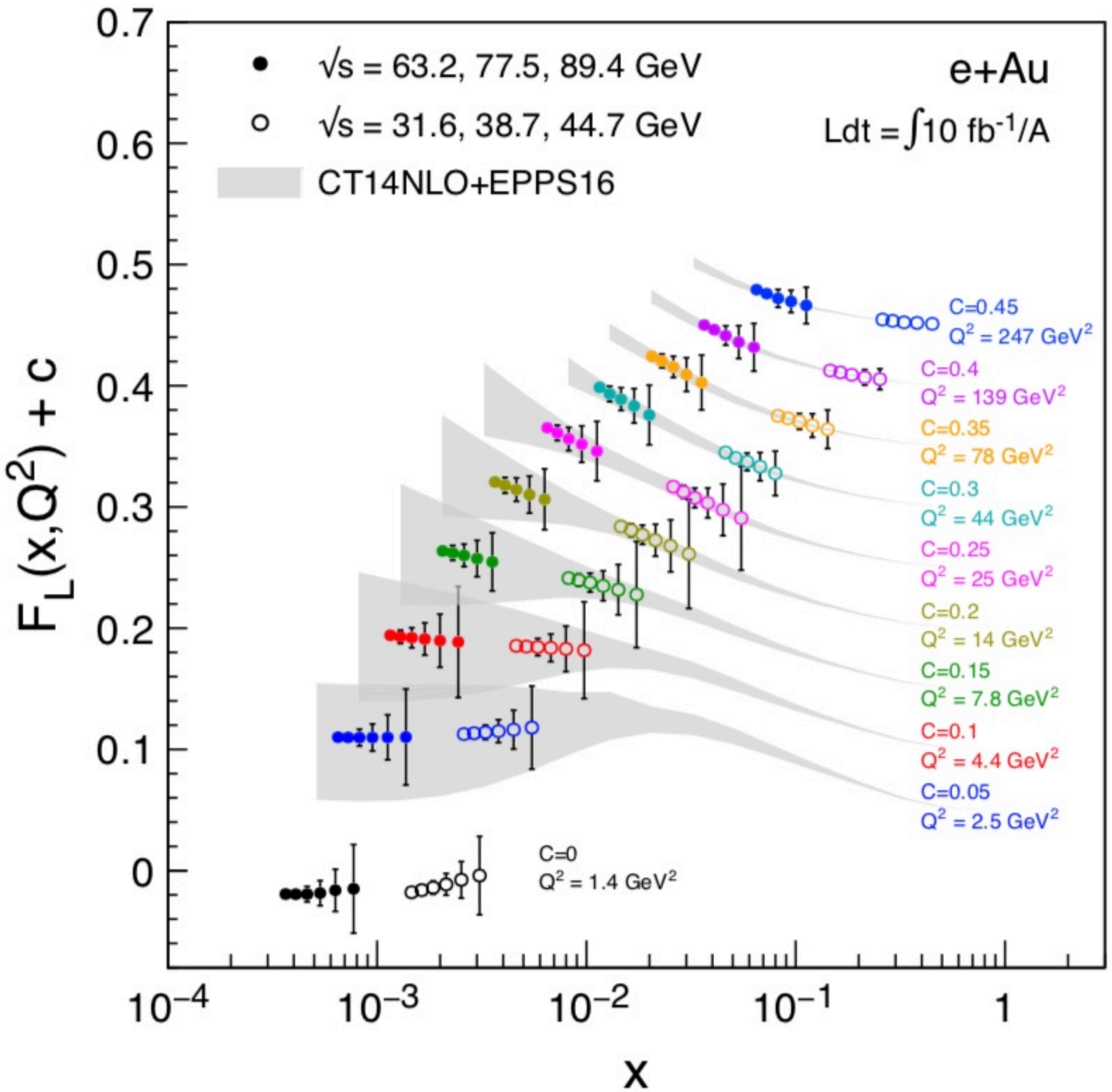


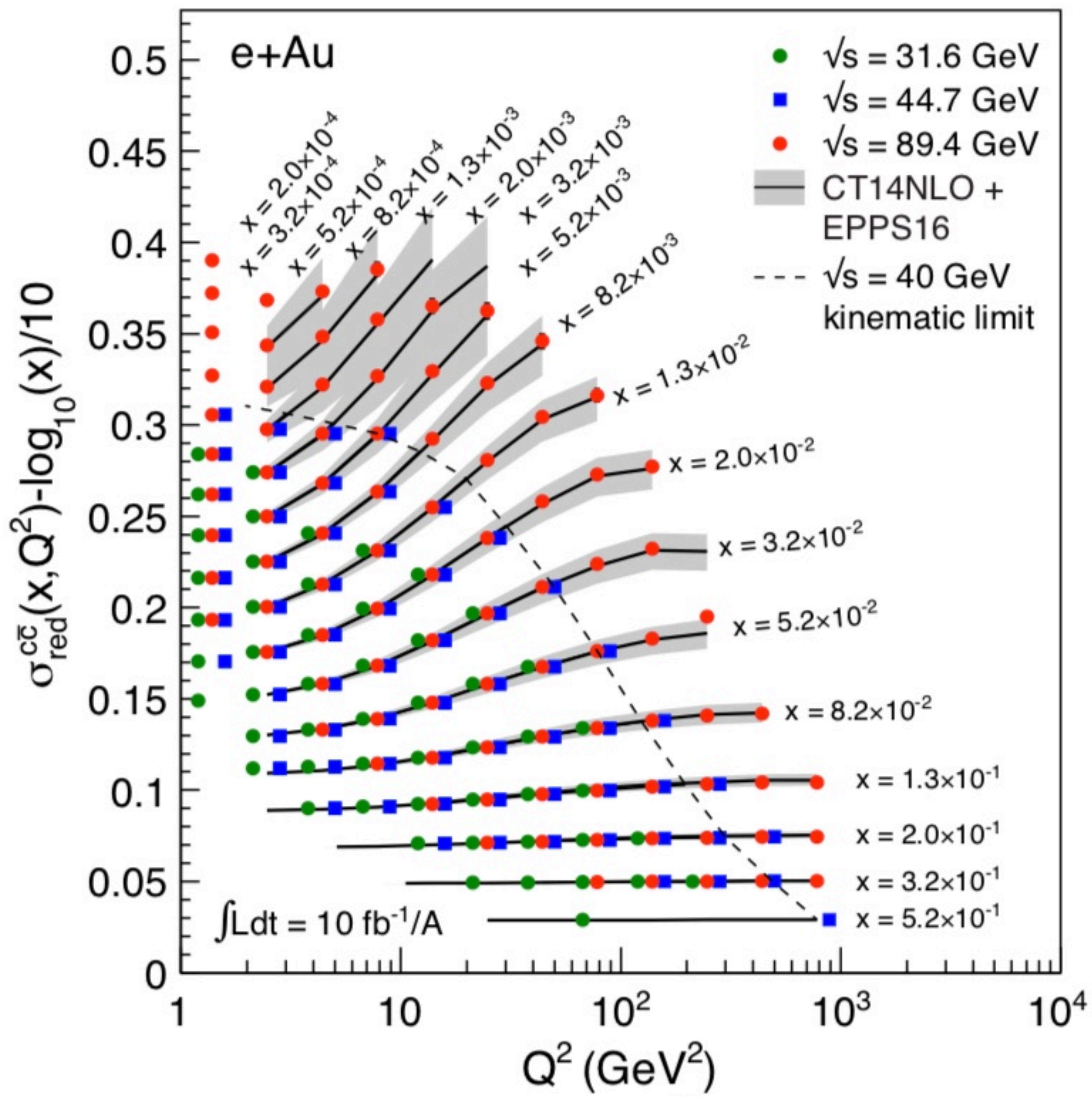
$$\sigma_{\text{reduced}} = F_2(x, Q^2) - \frac{y}{1 + (1 - y)^2} F_L(x, Q^2)$$

Impactful baseline inclusive measurements.



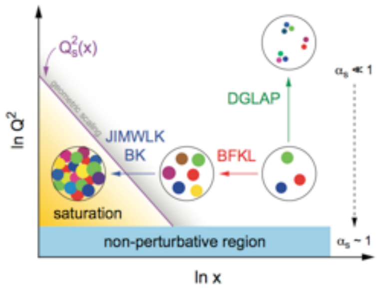
U.S.-based EIC - The Nuclear Landscape



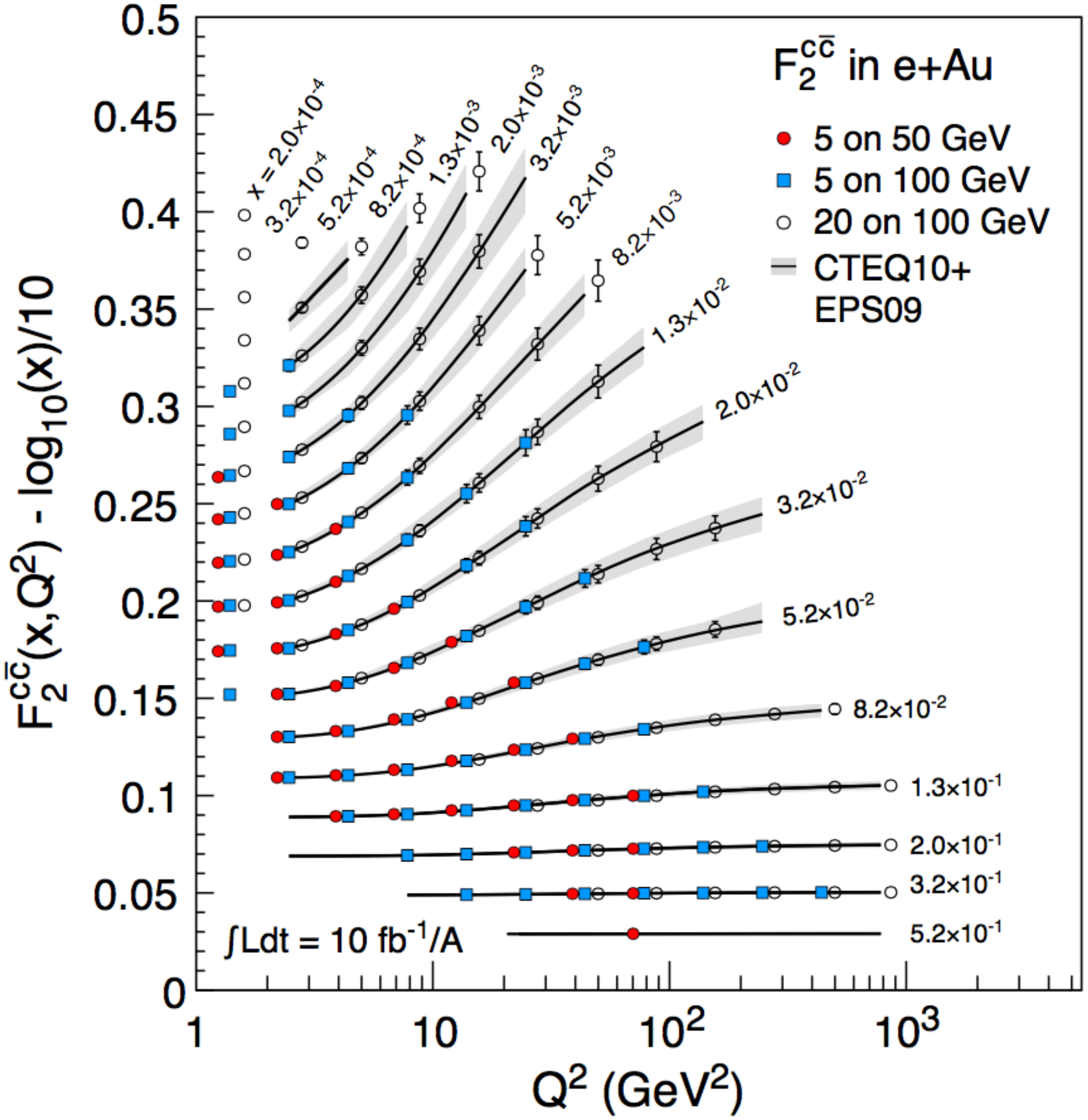


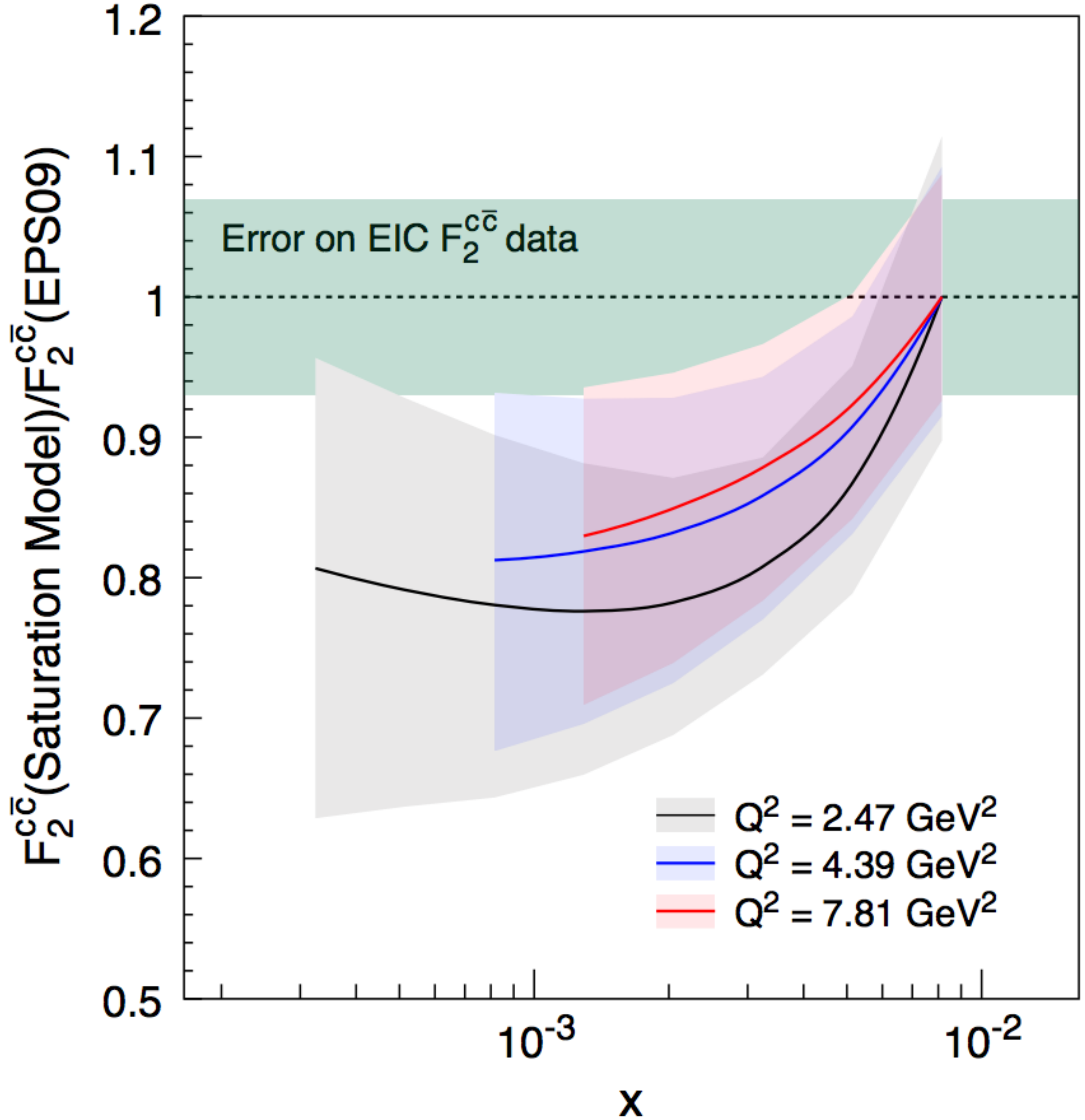
Clearly visible impact also beyond baseline inclusive measurements with “Rosenbluth separation” and semi-inclusive measurements.

Nuclear gluon will be probed sensitively with complementary channels.

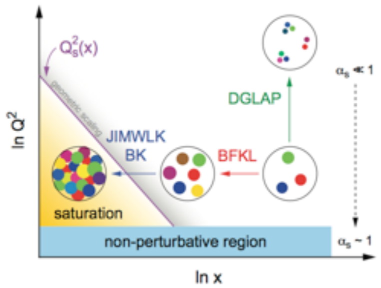


EIC - Saturation from within the PDF?

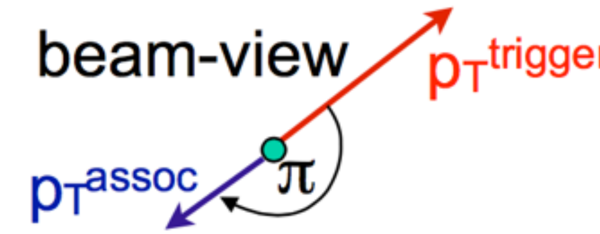


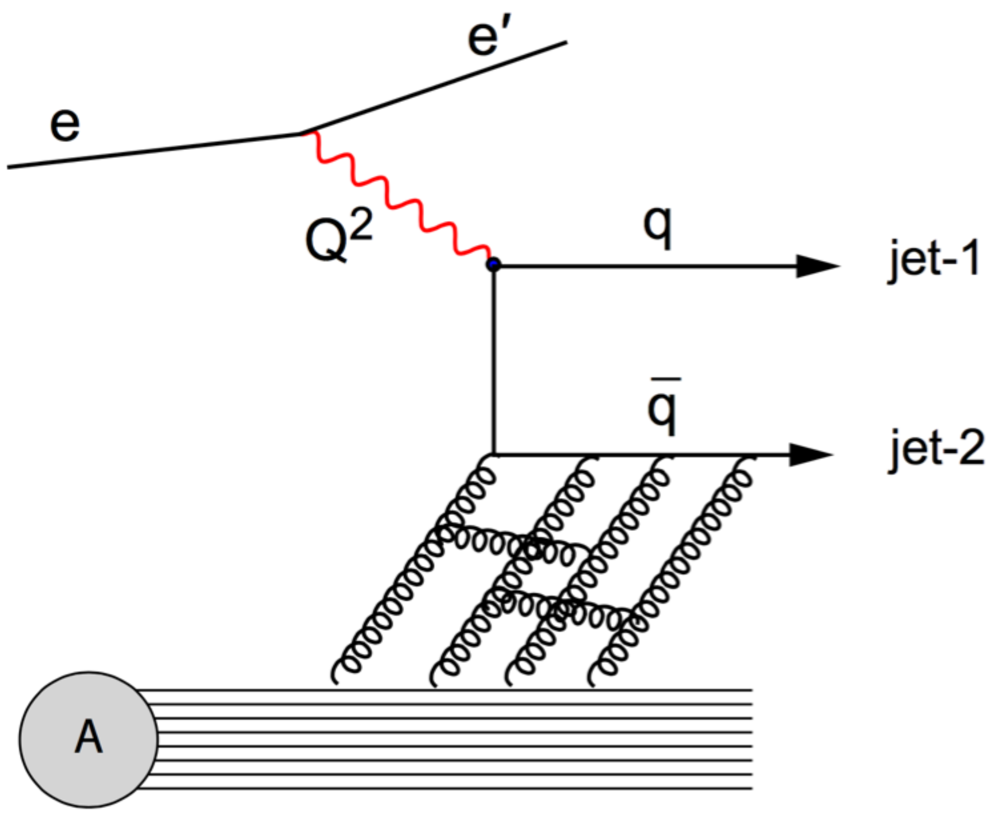


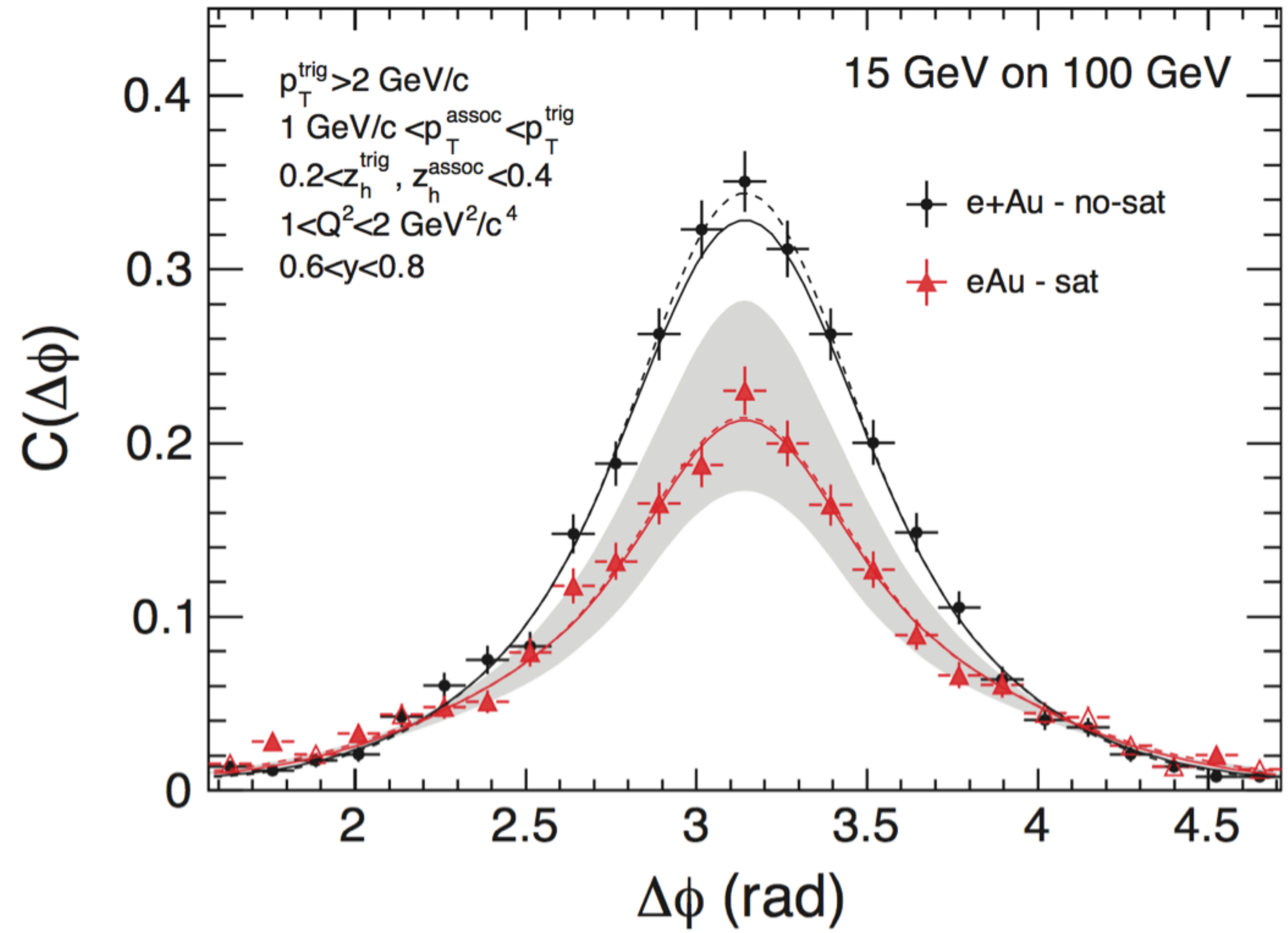
***Improbable* and *certainly no substitute* for thinking *outside* the PDF!**



EIC - Dihadrons to probe Saturation







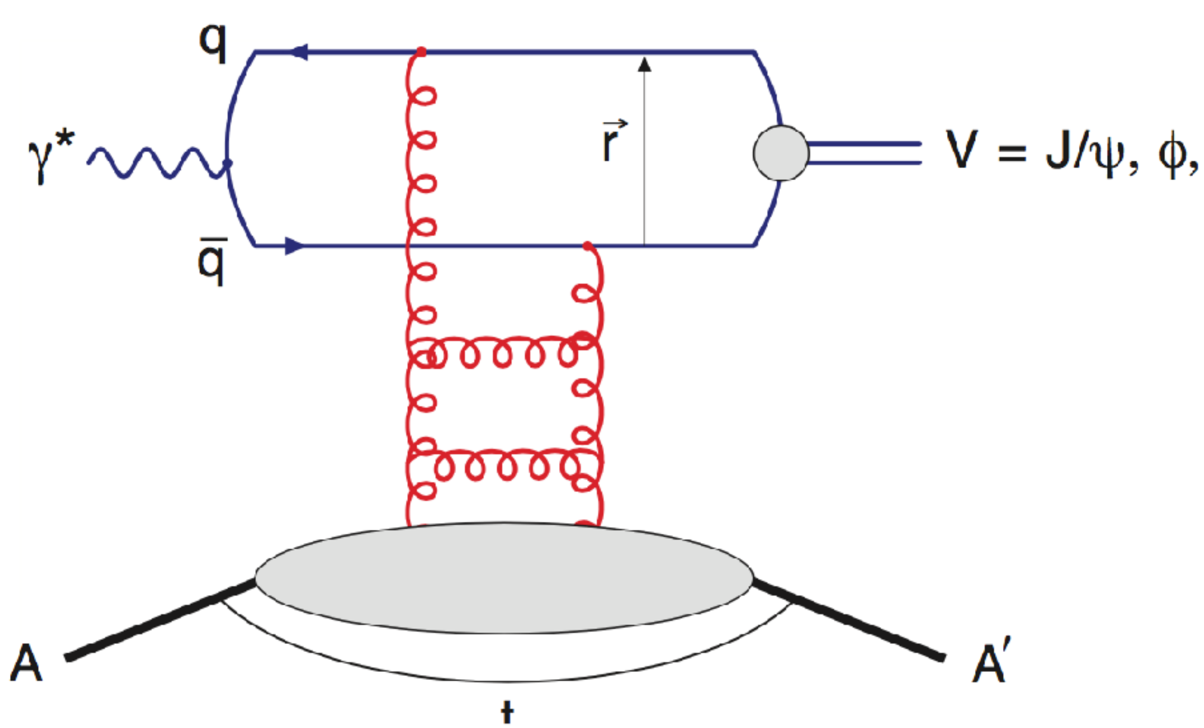
Zheng et al (2014)

Dominguez, Xiao, Yuan (2011)

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

EIC - Exclusive Vector Mesons to probe Saturation

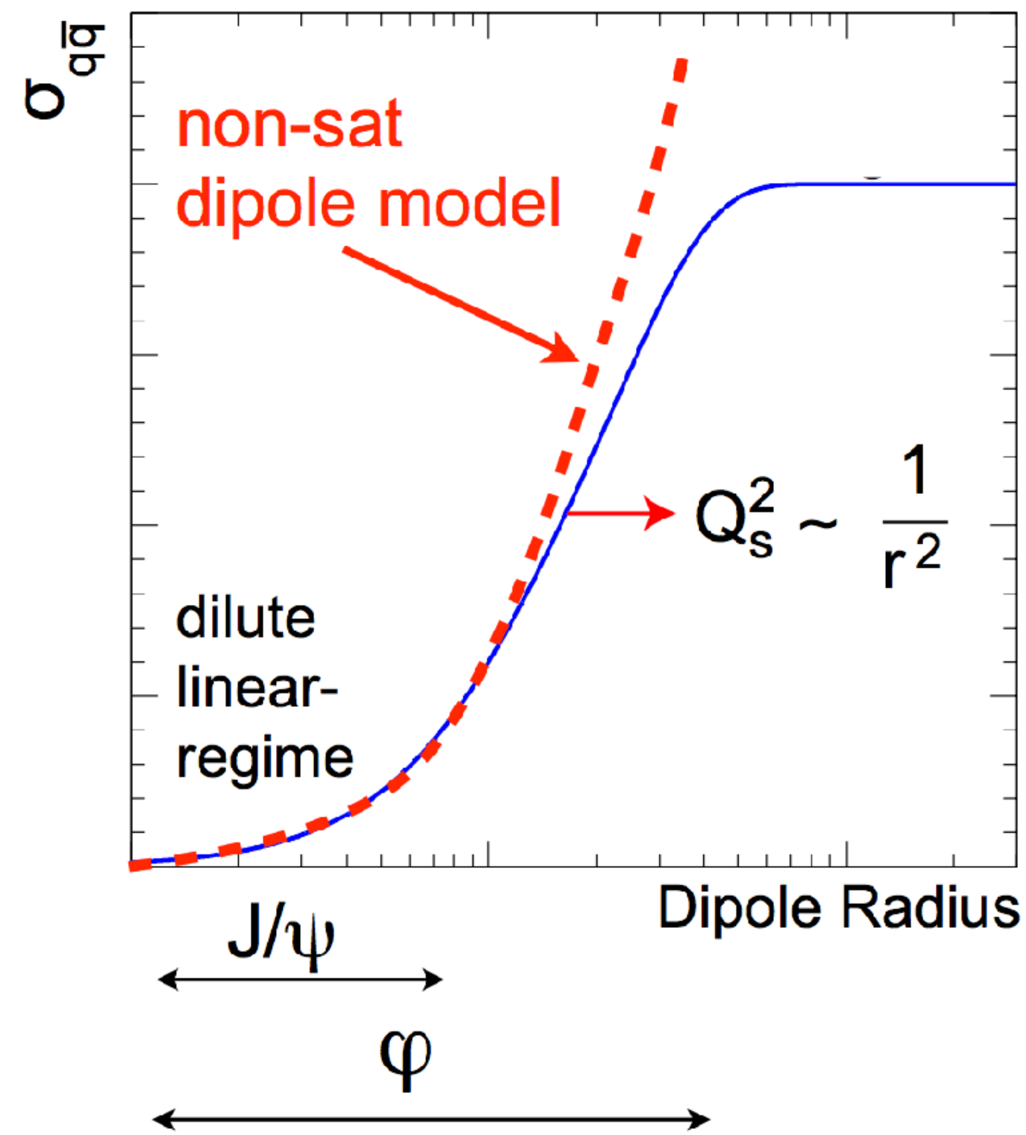
$$t = (\boldsymbol{p}_A - \boldsymbol{p}_{A'})^2 = (\boldsymbol{p}_{\mathrm{VM}} + \boldsymbol{p}_{e'} - \boldsymbol{p}_e)^2$$



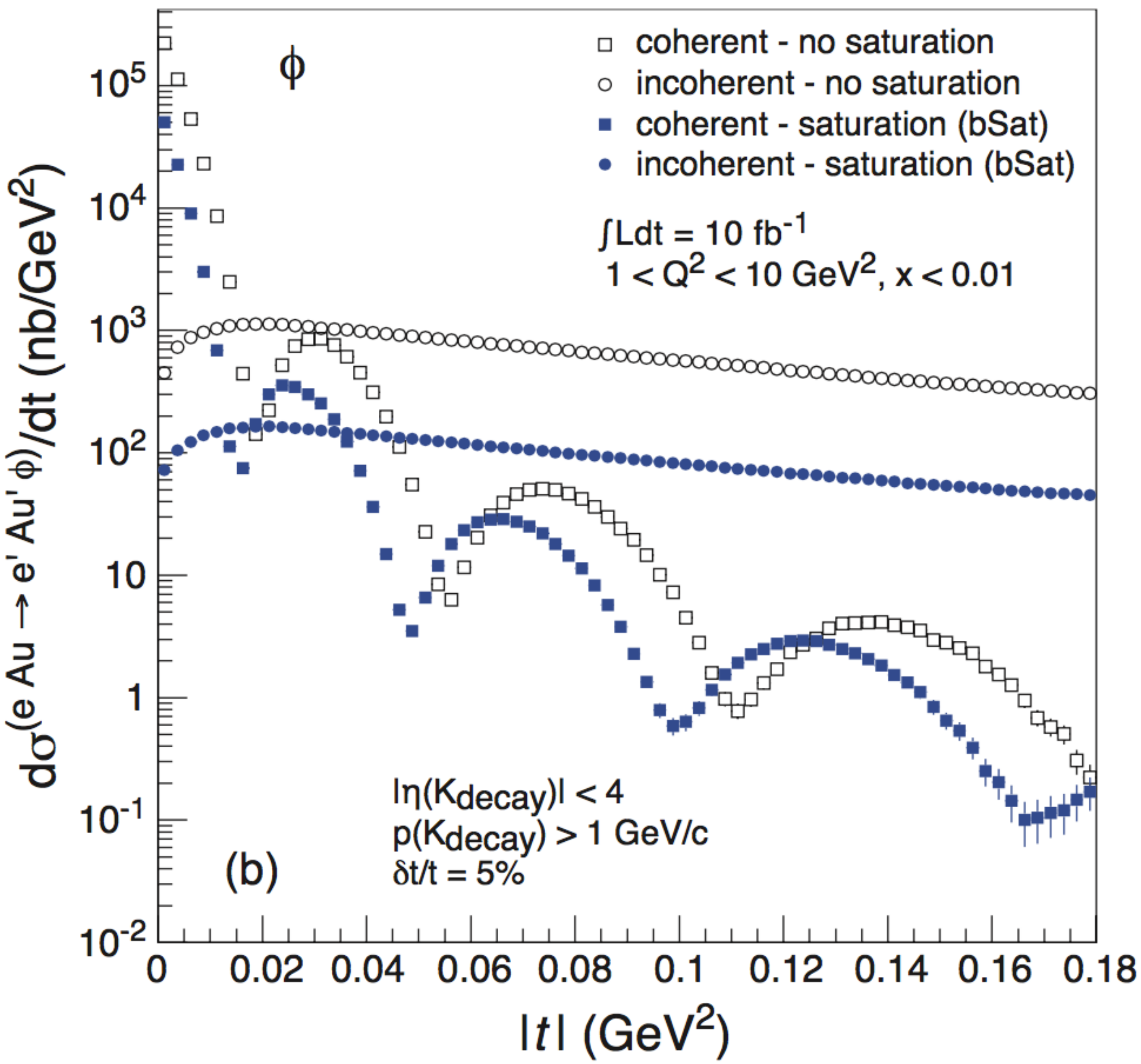
Nucleus escapes down the beampipe

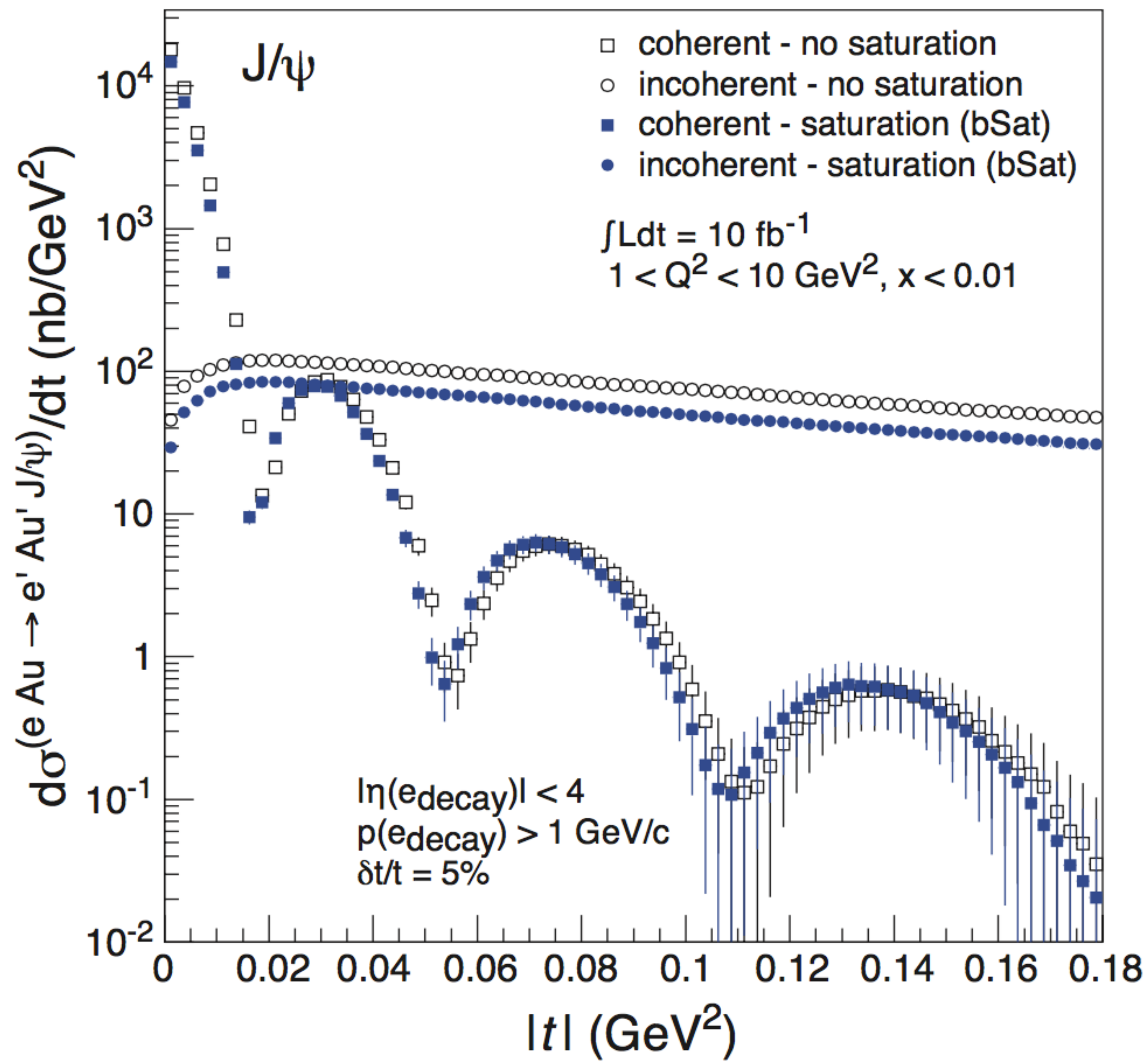
(In)coherence tagged with ZDC

Dipole Cross-Section:



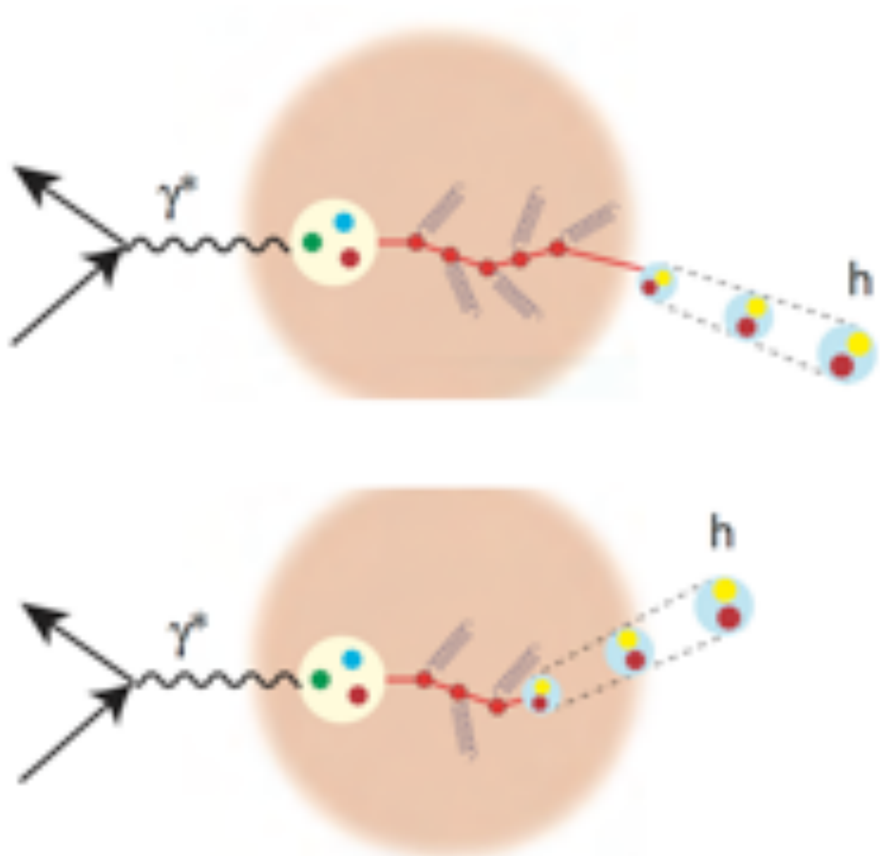
EIC - Exclusive Vector Mesons to probe Saturation





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

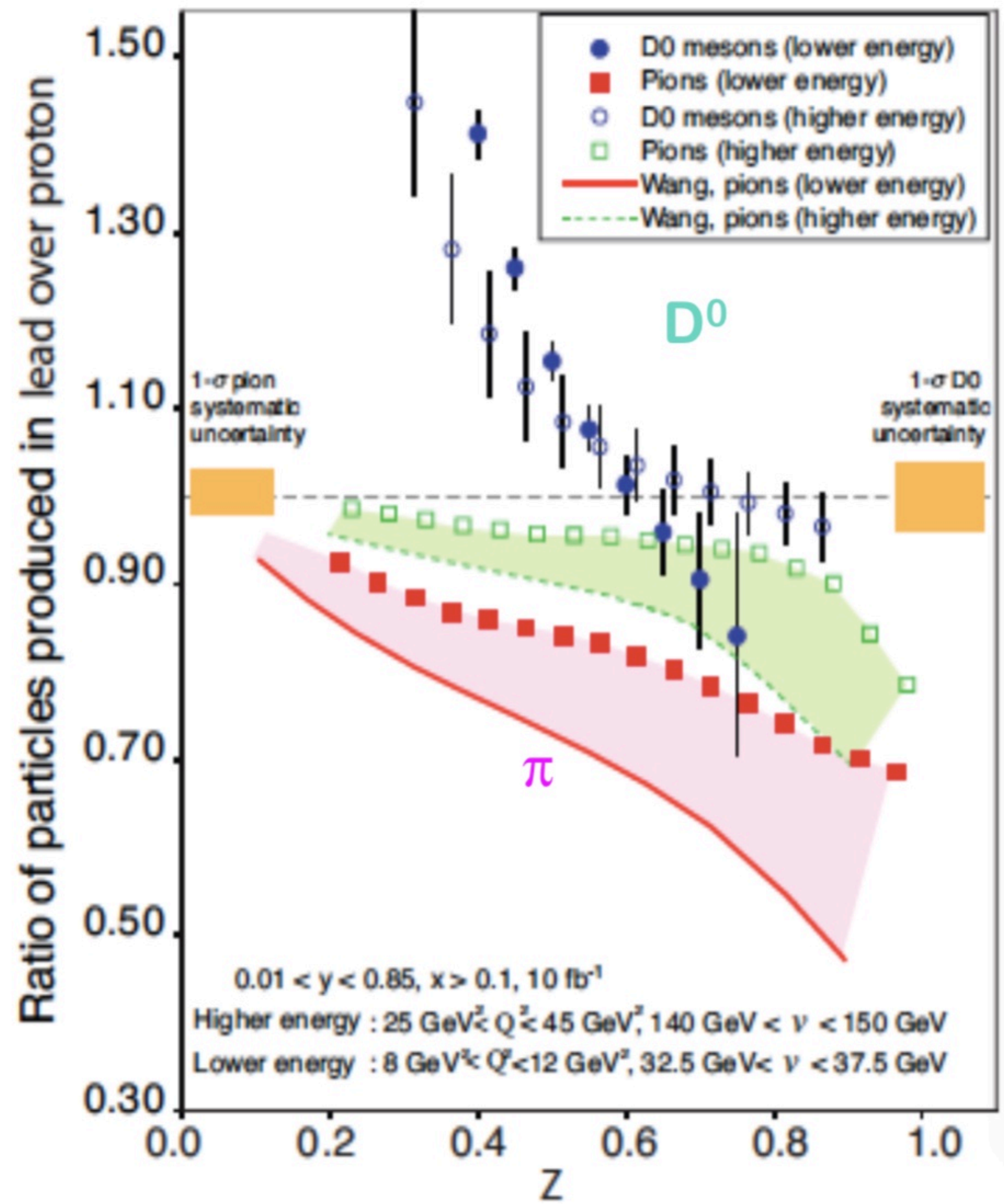
EIC - SIDIS to study Emergence of Hadrons



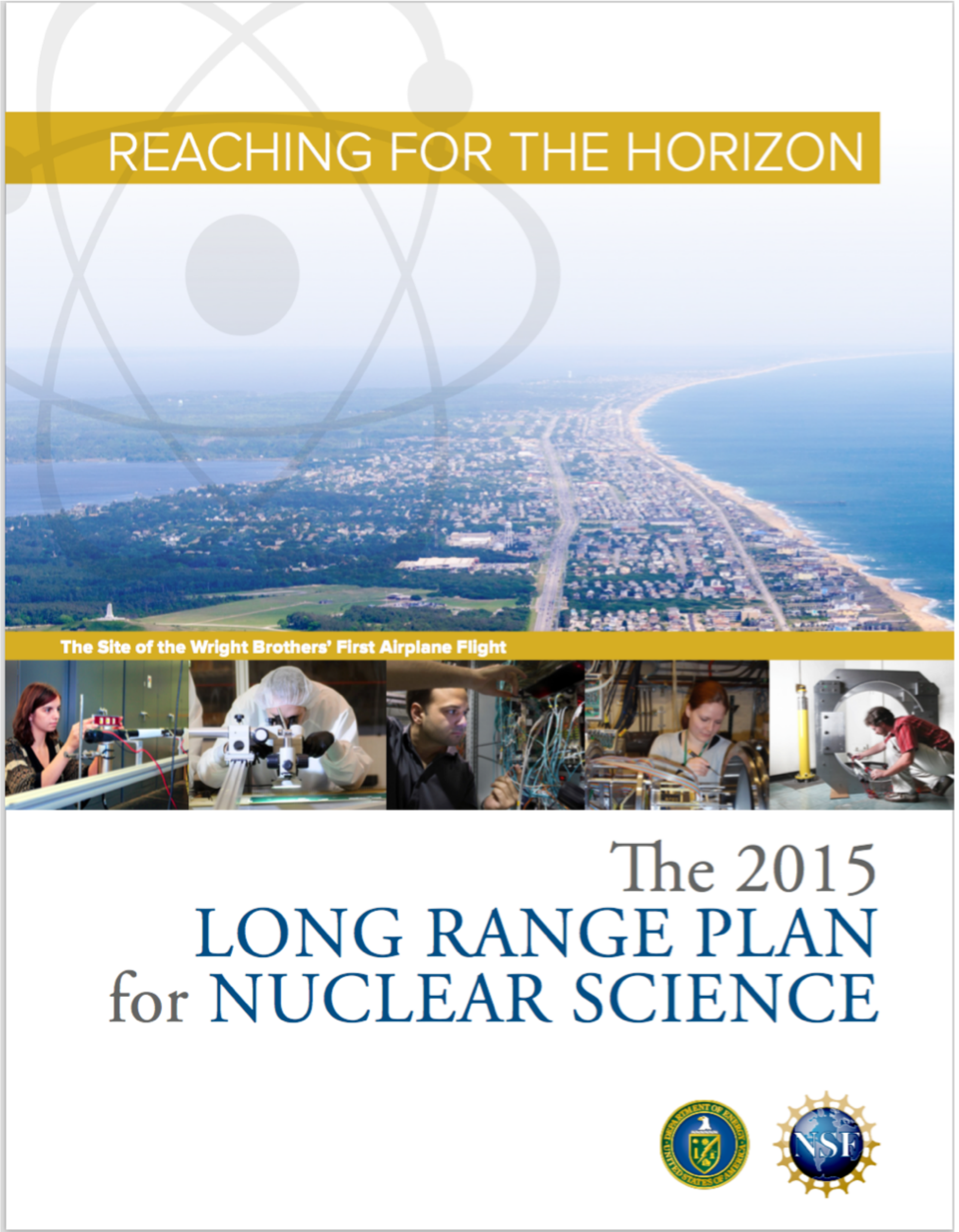
Control of $\nu = \dfrac{Q^2}{2mx}$ and

medium length

Study mass-dependence via charmed hadrons.



Status of U.S.-based EIC



RECOMMENDATION I

The progress achieved under the guidance of the 2007 Long Range Plan has reinforced U.S. world leadership in nuclear science. The highest priority in this 2015 Plan is to capitalize on the investments made.

RECOMMENDATION II

We recommend the timely development and deployment of a U.S.-led ton-scale neutrinoless double beta decay experiment.

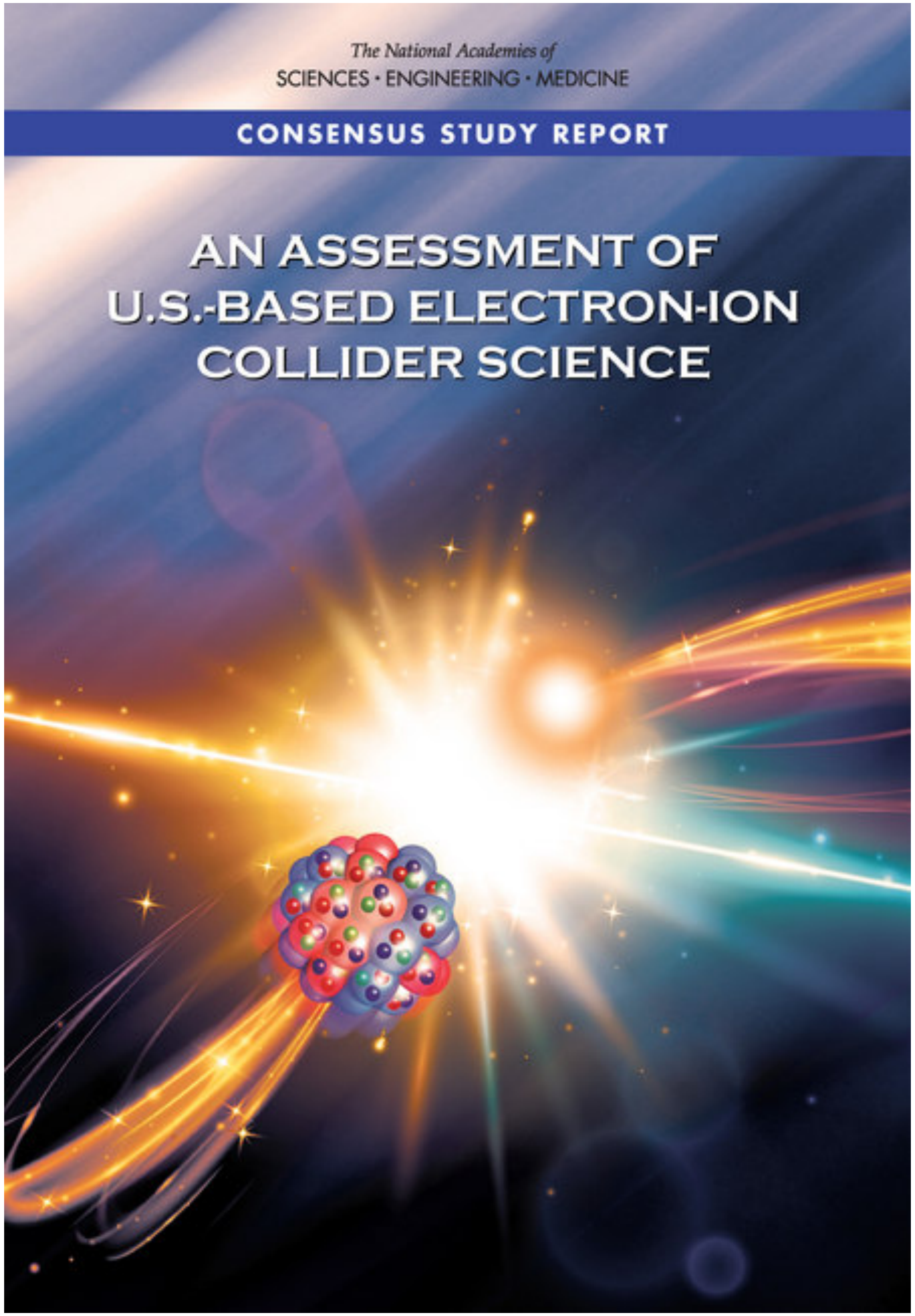
RECOMMENDATION III

We recommend a high-energy high-luminosity polarized EIC as the highest priority for new facility construction following the completion of FRIB. [Q3 FY22]

RECOMMENDATION IV

We recommend increasing investment in small-scale and mid-scale projects and initiatives that enable forefront research at universities and laboratories.

Status of U.S.-based EIC



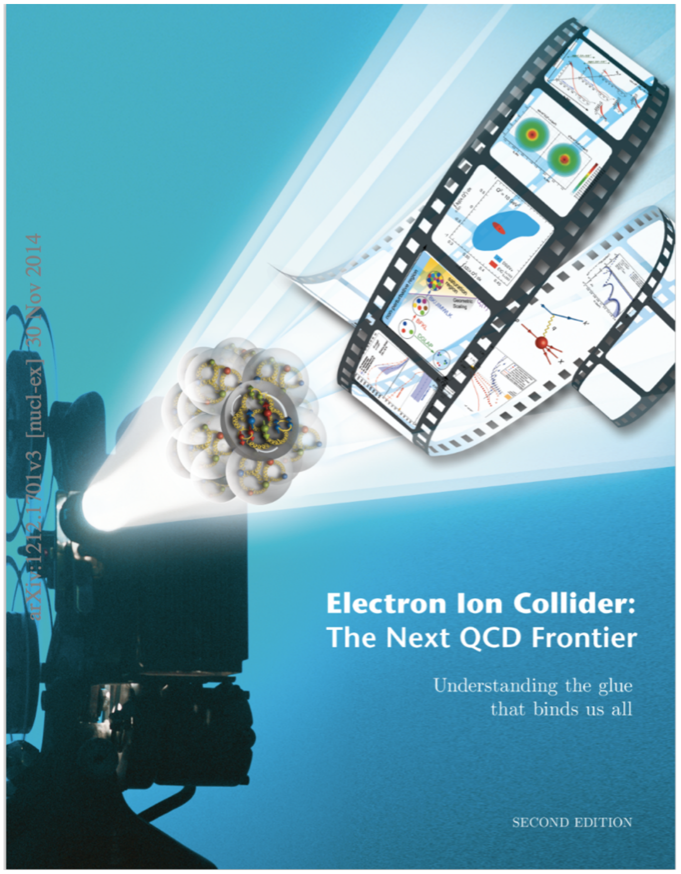
The committee *unanimously* finds that the science that can be addressed by an EIC is *compelling, fundamental, and timely.*

The *unanimous* conclusion of the Committee is that an EIC, as envisioned in this report, would be a *unique facility in the world that would boost the U.S. STEM workforce and help maintain U.S. scientific leadership in nuclear physics.*

The project is strongly supported by the nuclear physics community.

The technological benefits of meeting the accelerator challenges are enormous, both for basic science and for applied areas that use accelerators, including material science and medicine.

U.S.-based EIC - Closing Comments



Four central nuclear physics themes:

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

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

2018 NAS Science Assessment:

"EIC is compelling, fundamental, and timely"

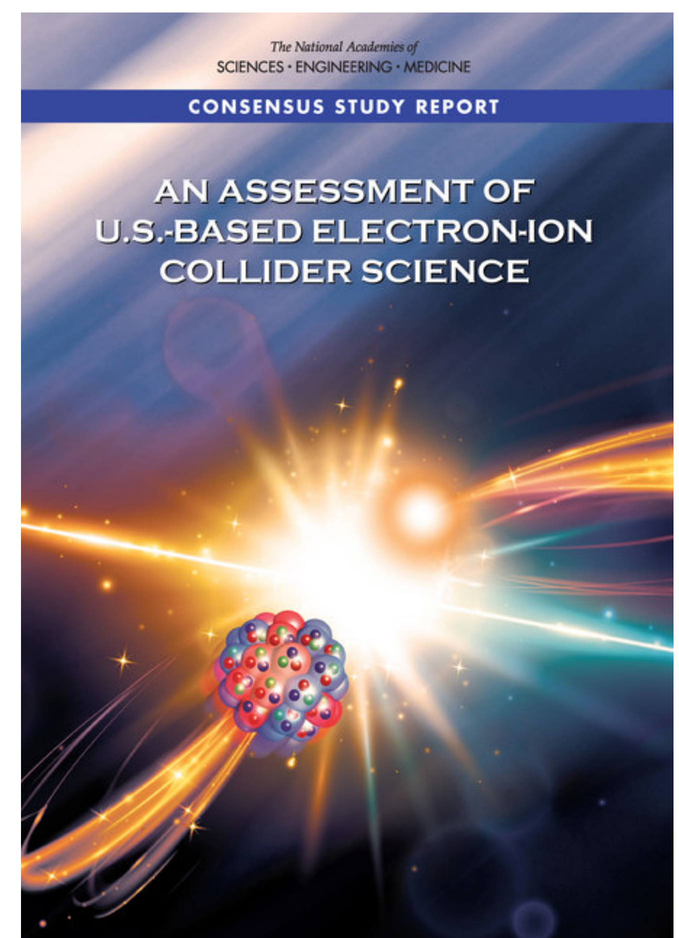
Science case: theory, experiment, *and* accelerator,

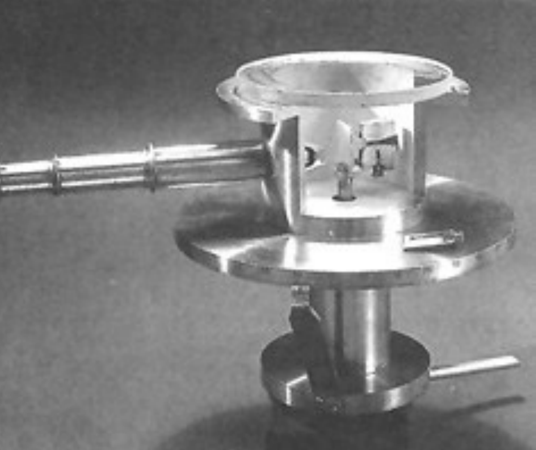
U.S. Department of Energy and both candidate host-laboratories are working together towards realizing the *project*,

Cost review complete, site selection ongoing,

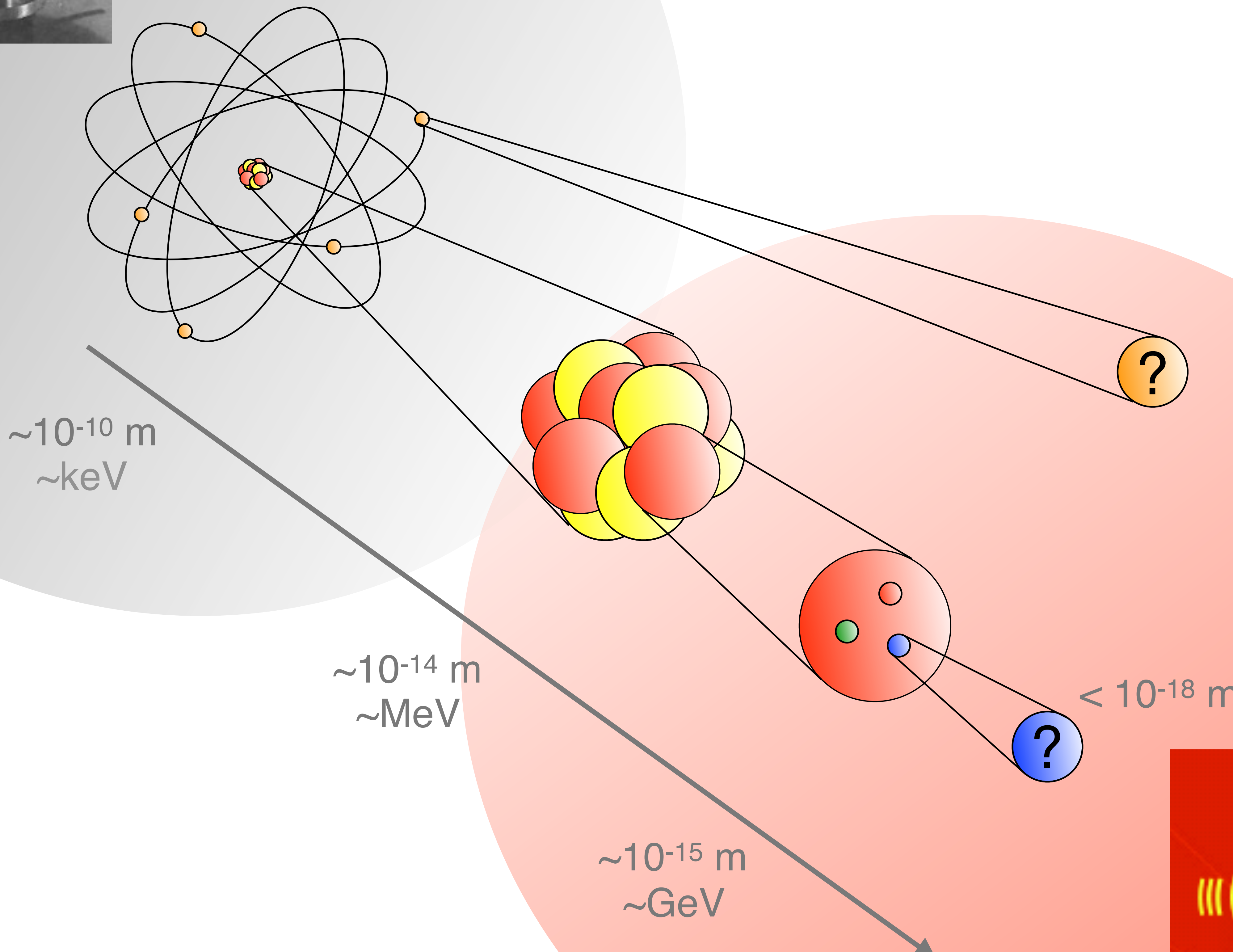
NP budget has an overall positive (recent) past and outlook,

The EIC User Group, eicug.org, welcomes new collaborators;
About to embark on a 12-18 month physics and detector conceptual development study.





Thank You



eicug.org