Physics of the nucleon form factors

- The long history of how the study of elastic nucleon form factors have contributed to discovery, both directly and indirectly.
- Increasingly precise measurements at Jlab of form factors at high Q^2 have dramatically influenced our view of the structure of the nucleon.
- The "Super Bigbite Spectrometer" (SBS) program (ongoing!) that is greatly expanding the frontier of high-Q^2 high-precision form factor measurements.

Gordon D. Cates
SBS Collaboration Meeting
September 12, 2024

Super Bigbite

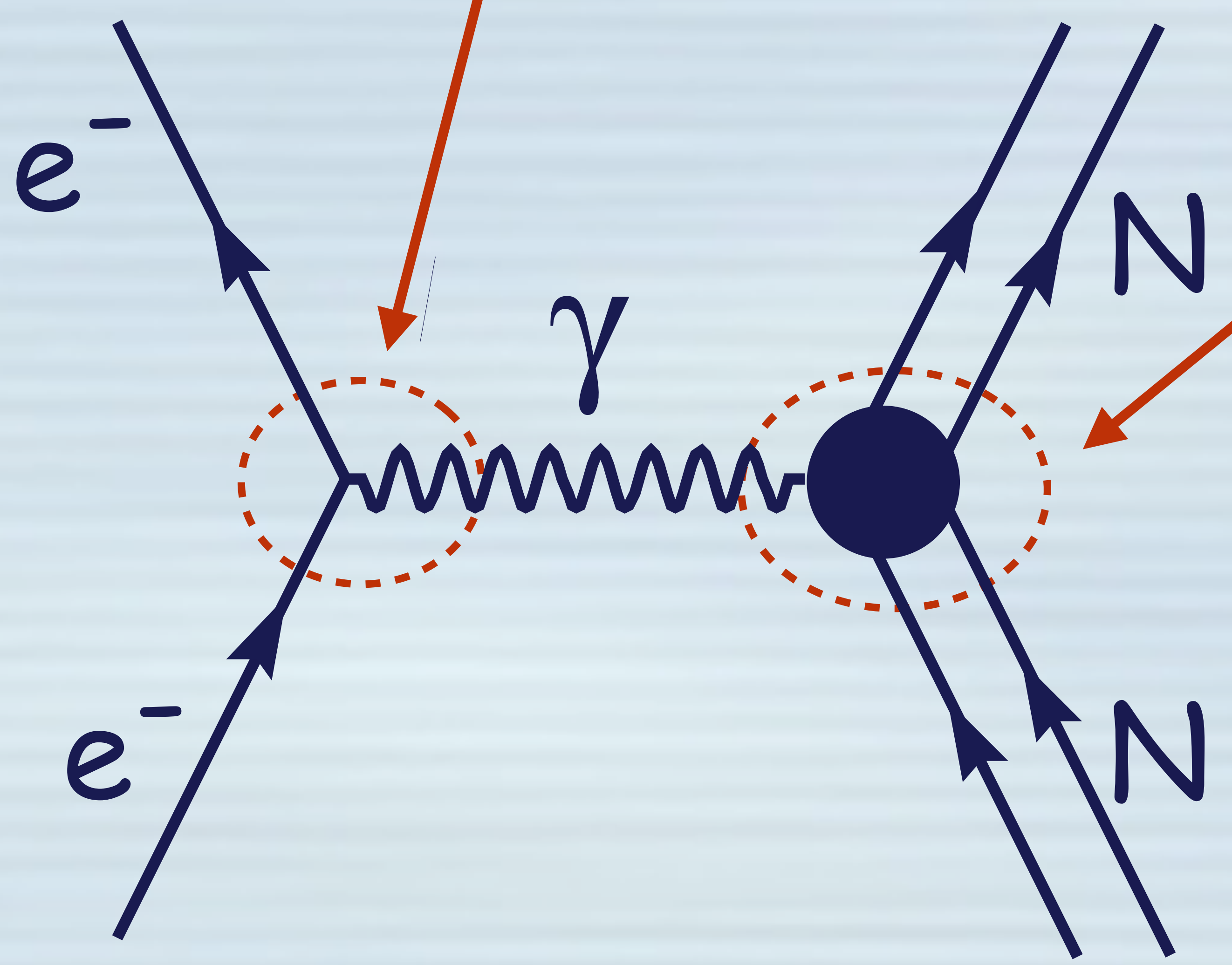
University of Virginia

Jefferson Lab
EXPLORING THE NATURE OF MATTER

Electromagnetic scattering and "the purity of the probe"

The (single photon) scattering amplitude for elastic scattering:

$$M^{\mathrm{EM}} = -\frac{4\pi\alpha}{Q^2} \; \underbrace{\bar{e}(k')\gamma^\mu e(k)}_{\text{leptonic current}} \; \underbrace{\overline{N}(P')\left[\gamma_\mu F_1^N(Q^2) + \frac{i\sigma_{\mu\nu}q^\nu}{2M}F_2^N(Q^2)\right]N(P)}_{\text{hadronic current}}$$



Because the leptonic vertex is so well understood, elastic scattering provides a clean measure of the hadronic current in which F_1^N and F_2^N encode the structure of the hadron.

The elastic form factors are fundamental properties of the nucleon that encode a surprising variety of information about nucleon structure

The Sachs form factors, linear combinations of F_1 and F_2:

$$G_E^N(Q^2) = F_1^N(Q^2) - \tau F_2^N(Q^2)$$

The electric form factor encodes information about the distribution of charge

$$G_M^N(Q^2) = F_1^N(Q^2) - F_2^N(Q^2)$$

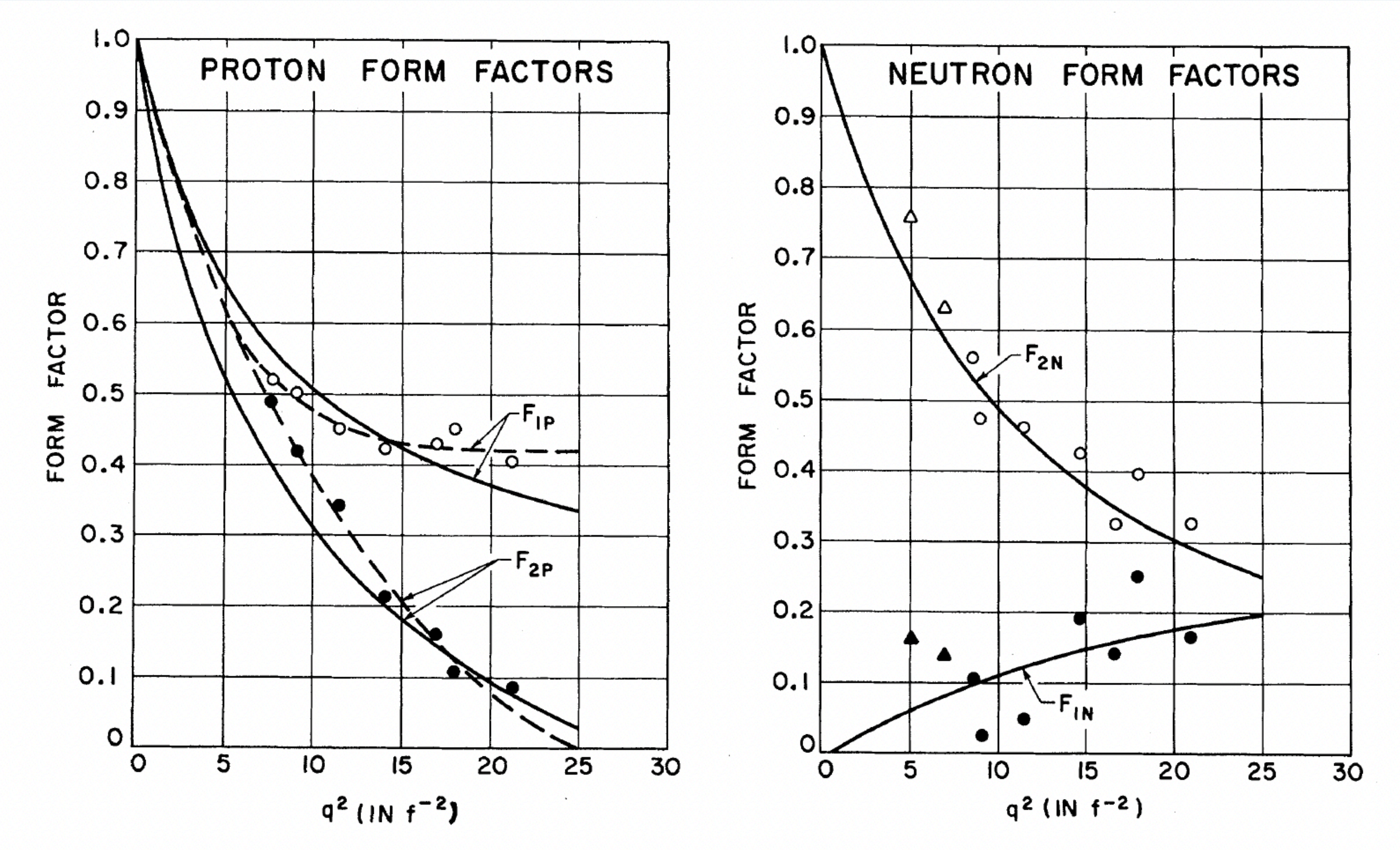
The magnetic form factor encodes information about the distribution of magnetization

Here $\tau = Q^2/4M^2$

Among other things, the slope of G_E^p as $Q^2 \rightarrow 0$ is proportional to the proton's RMS charge radius.

Hofstadter directly measured of the size of the proton and neutron

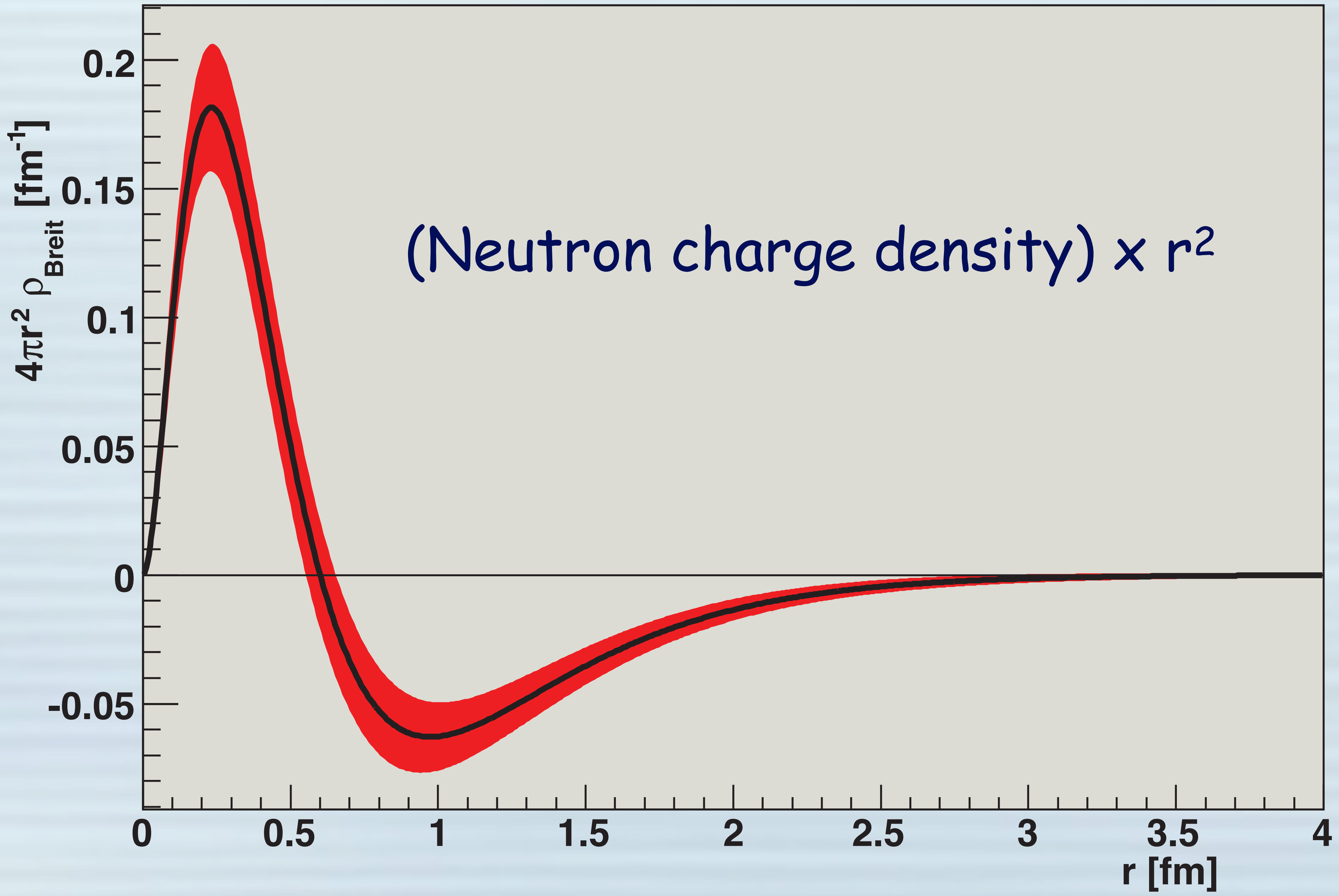
1961



"for his pioneering studies of electron scattering in atomic nuclei and for his thereby achieved discoveries concerning the structure of the nucleons"

Historically, G_E^n was viewed as confirming the (lab frame) picture of the neutron as a proton surrounded by a π^- cloud

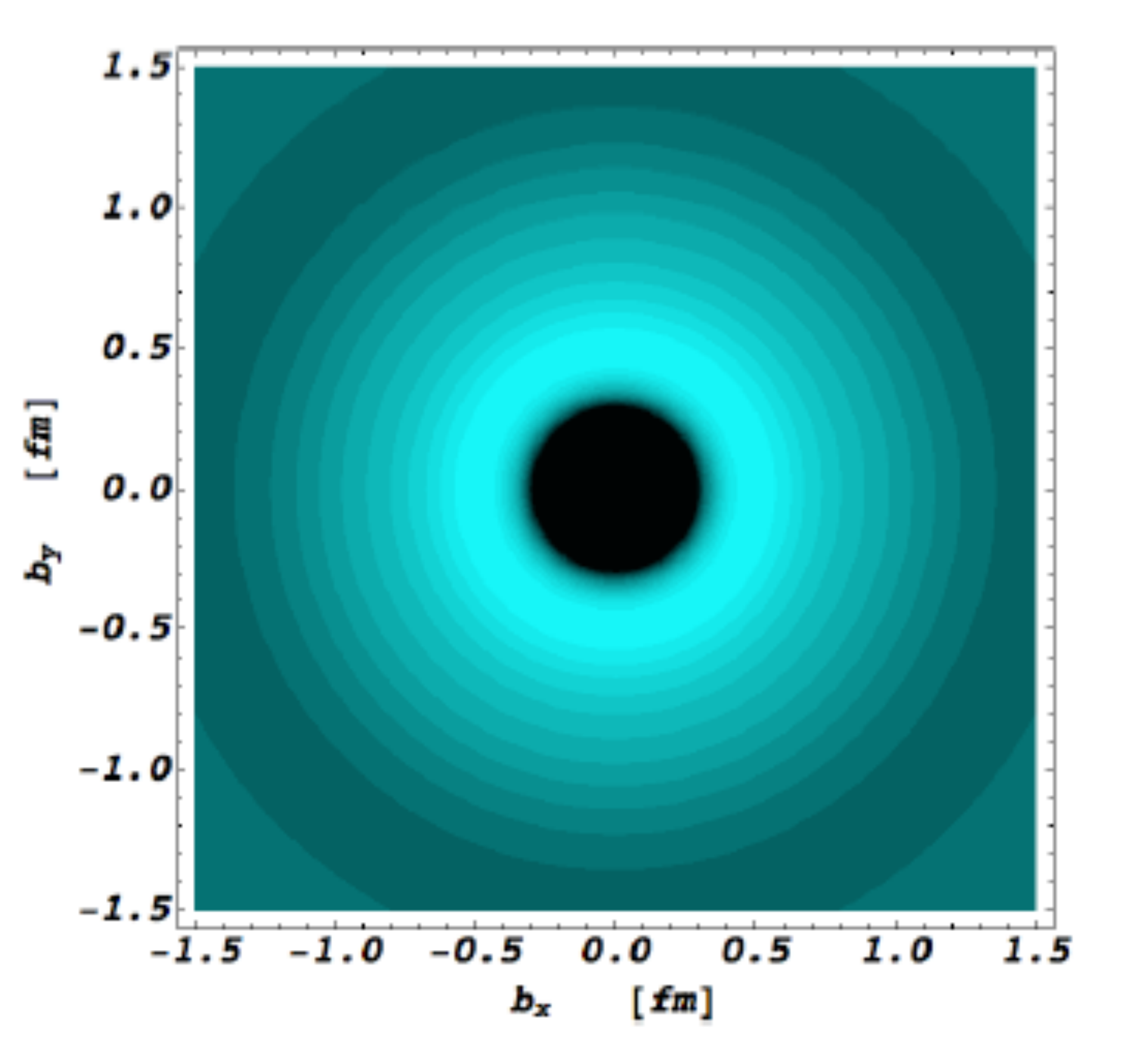
In a non-relativistic picture, essentially take the Fourier transform of G_E^n to obtain the charge distribution.



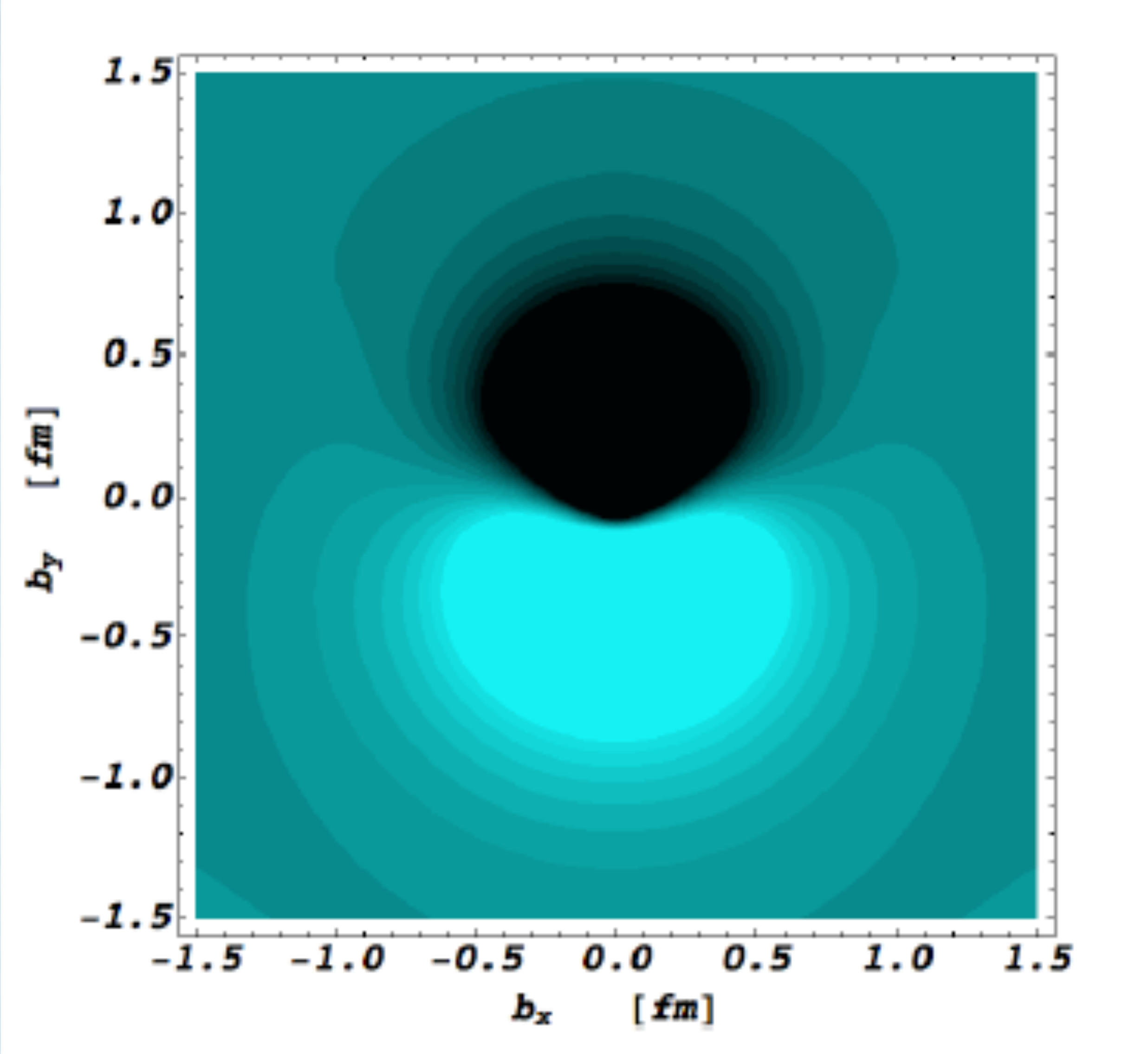
From the 2007 Long Range Plan

From the text of the Long Range Plan: "These results clearly identify the neutron's positively charged interior and negatively charged halo…" [from the pion cloud].

A relativistic "snapshot" of the neutron
(light-front density distribution)



Longitudinally
polarized neutron



Transversely
polarized neutron

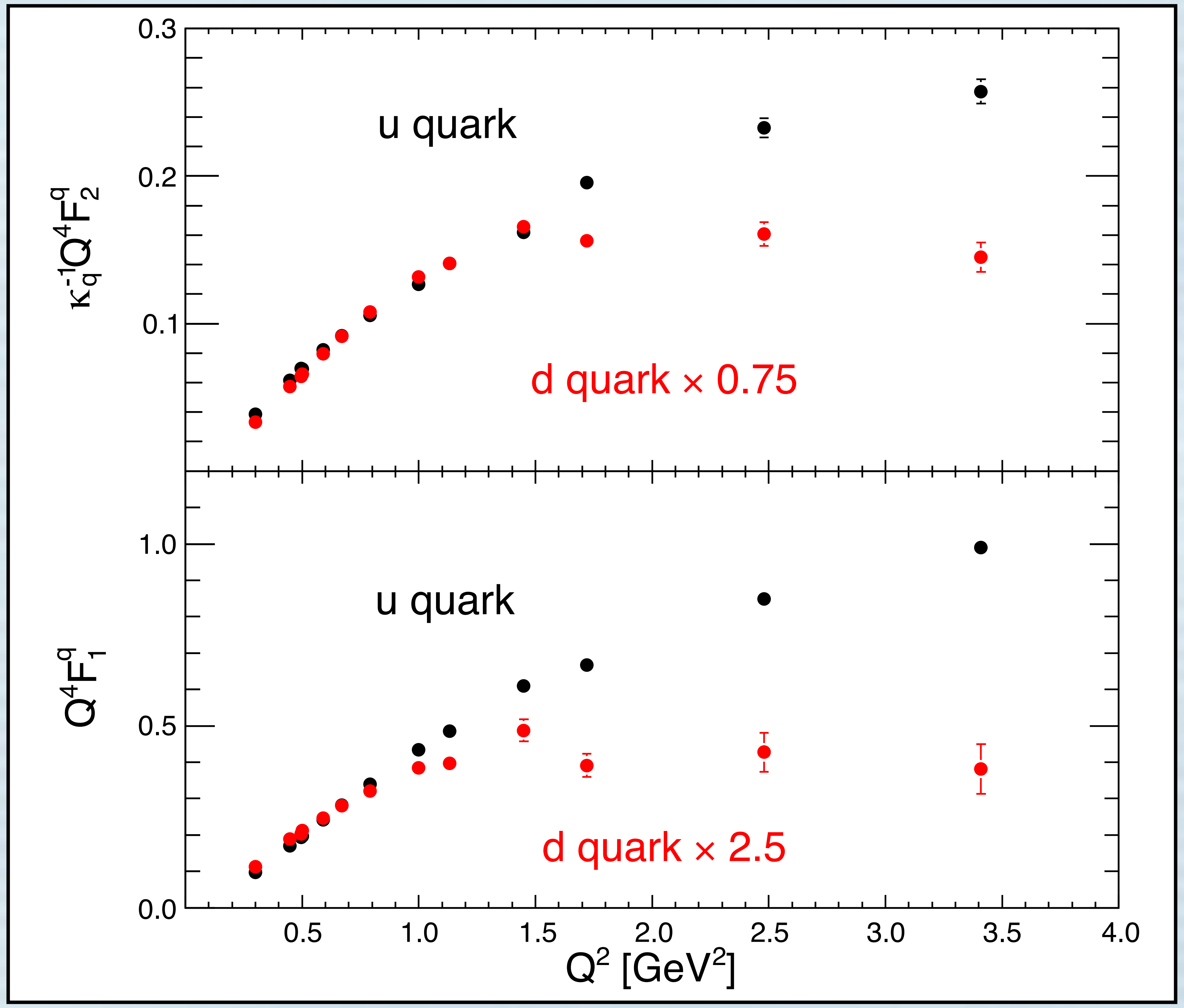
Carlson and Vanderhaeghen, PRL v.100, pg.032004 (2008)

- Here we are seeing what we can think of as a charge density when viewed from a light front moving toward the neutron.
- Notice that the transversely polarized neutron appears to have an electric dipole moment - this is due to the magnetic dipole moment when viewed from a boosted reference frame

Flavor decomposition of the elastic nucleon electromagnetic form factors

Flavor decomposition of the elastic nucleon electromagnetic form factors

With the SBS GEn-I experiment, it became possible to extract the u- and d- contributions to both the Dirac and Pauli form factors. It was discovered that the Q^2 behavior of the u- and d-quark contributions are quite different from one another.



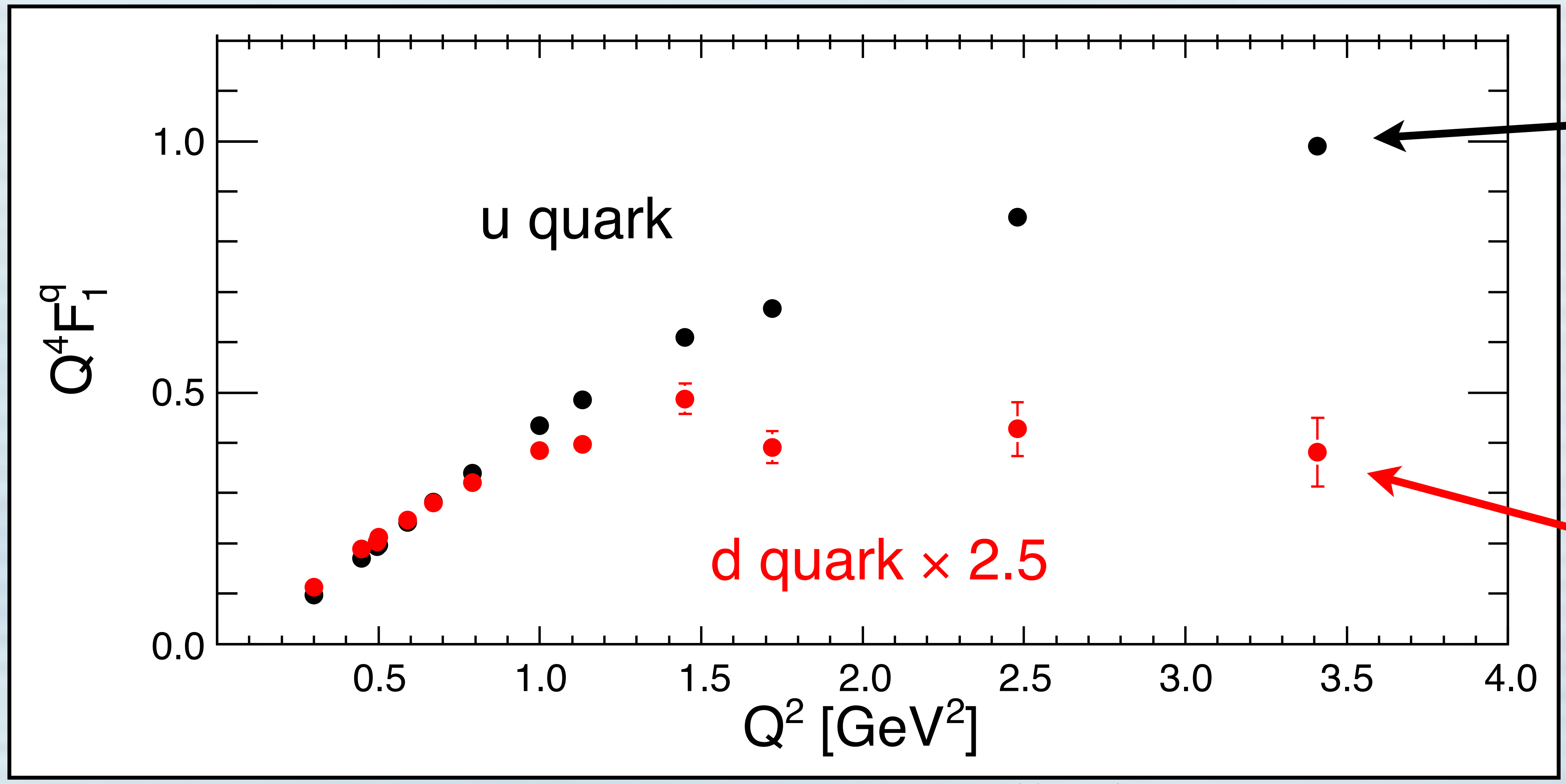
$$F^u_{1(2)} = 2F^p_{1(2)} + F^n_{1(2)} \quad \text{and} \quad F^d_{1(2)} = 2F^n_{1(2)} + F^p_{1(2)}$$

Cates, de Jager, Riordan and Wojtsekhowski, PRL vol. 106, pg 252003 (2011)

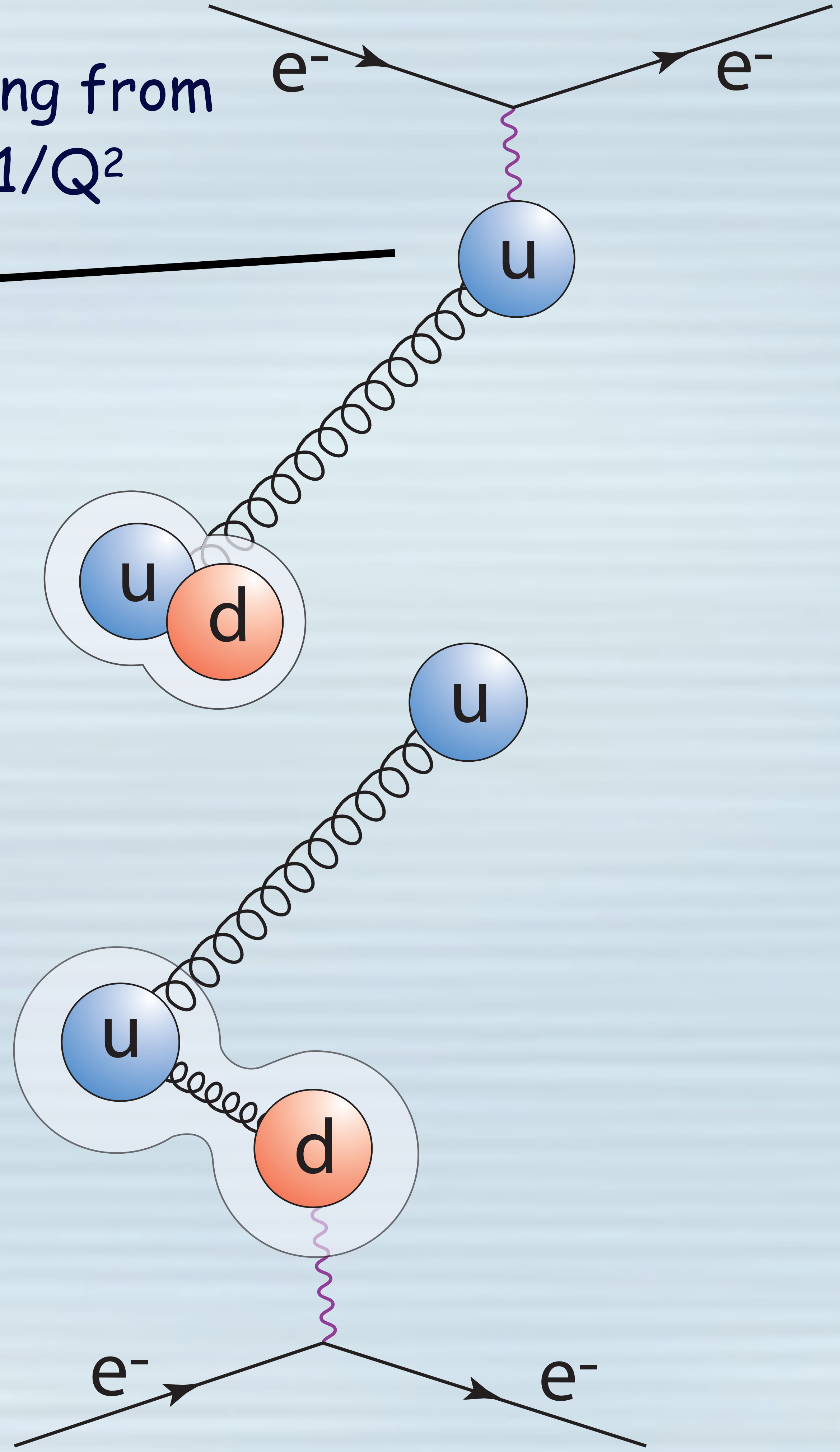
Many of the theoretical models that reproduce the above trends indicate the importance of <u>diquark correlations</u>.

I have often shown this cartoon illustrating an explanation based on a verbal suggestion from Jerry Miller based on quark counting rules

u-quark scattering amplitude is dominated by scattering from the lone "outside" quark. Two constituents implies $1/Q^2$



Cates, de Jager, Riordan and Wojtsekhowski,
PRL vol. 106, pg 252003 (2011)

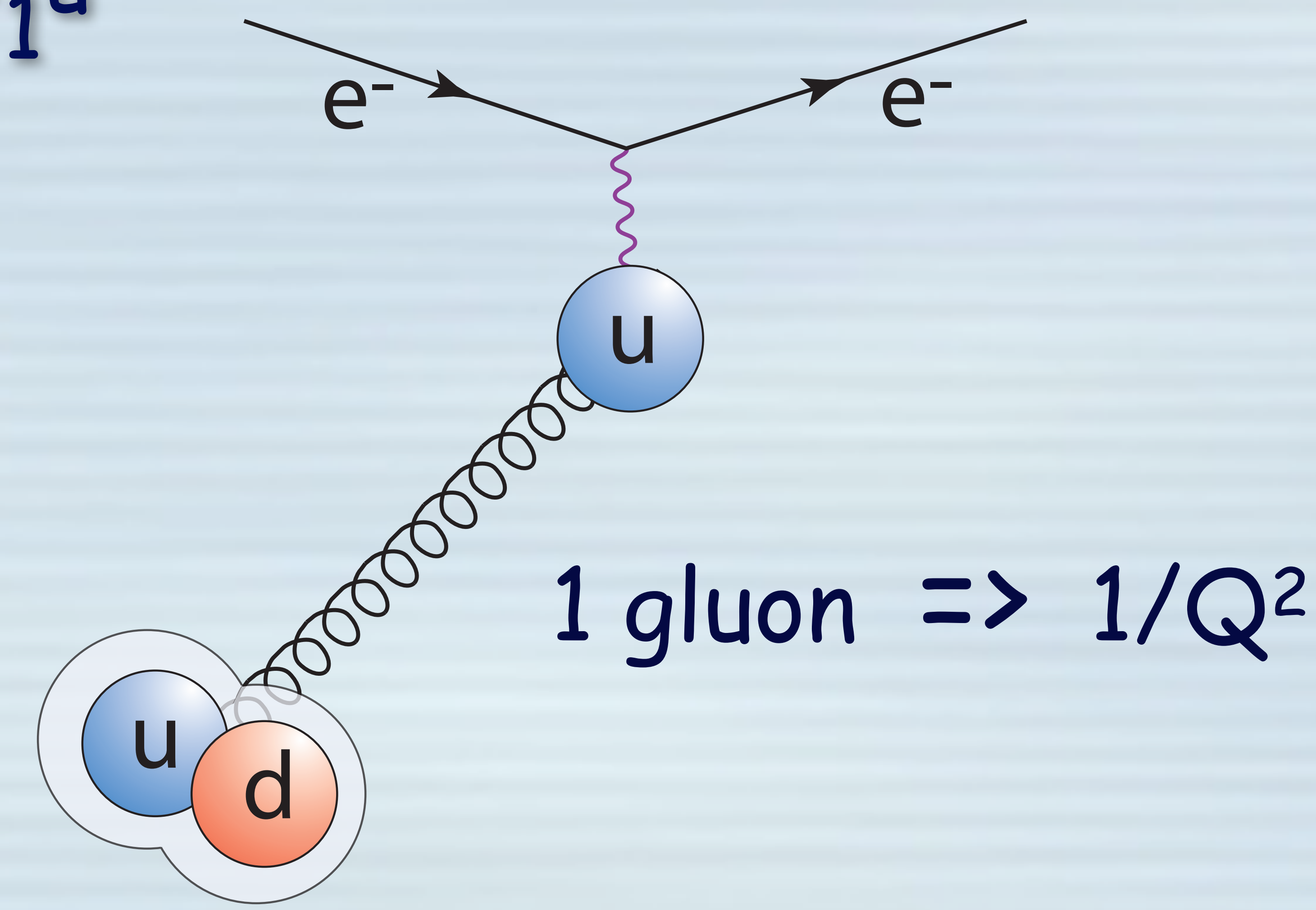


d-quark scattering amplitude is necessarily probing inside the diquark. Two gluons need to be exchanged (or the diquark would fall apart), so scaling goes like $1/Q^4$

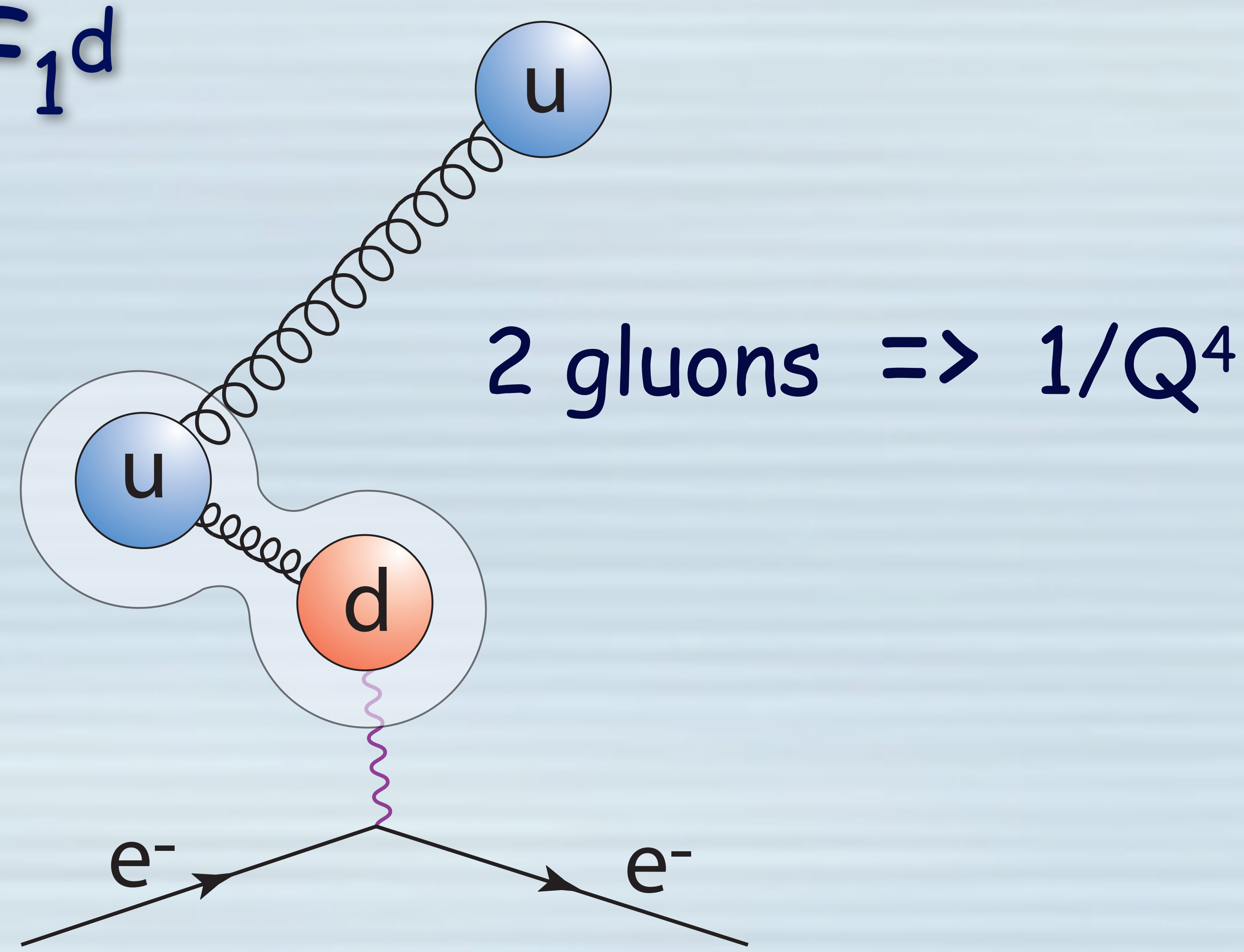
But other than lattice QCD, and perhaps scaling at high Q^2, it is not possible to perform a true ab initio calculation of F_1^u and F_1^d

So … to what extent can we take at least this cartoon seriously?

F_1^u



F_1^d



Two examples of calculations using dressed quark cores in which the mass is dynamically generated and the nucleon amplitude is obtained by solving the Faddeev equation

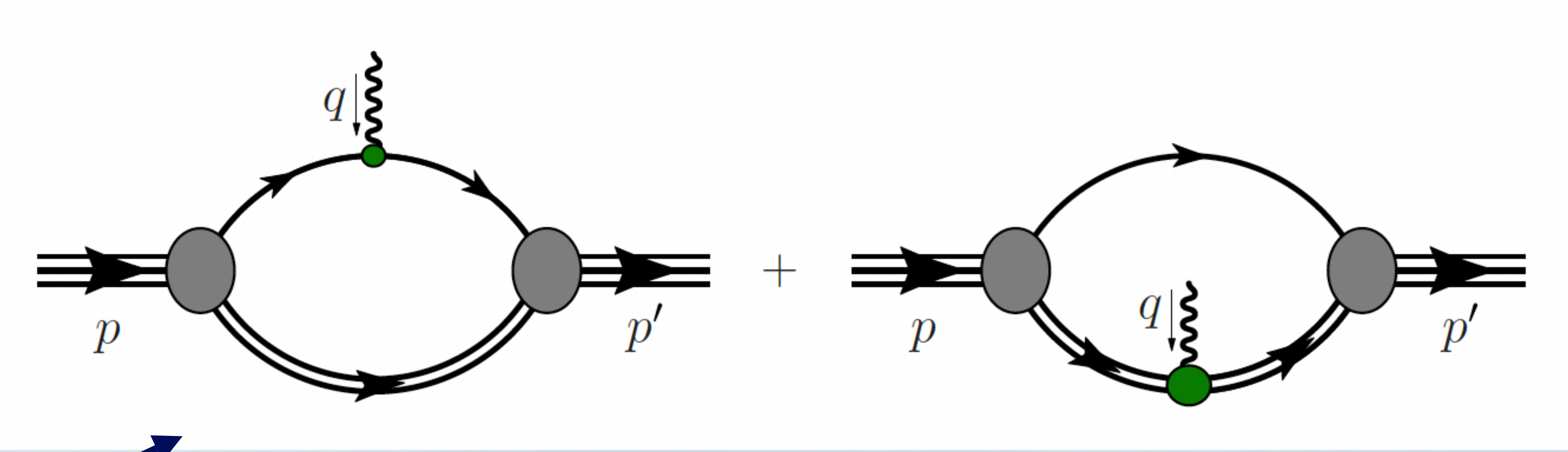
Role of diquark correlations and the pion cloud in nucleon elastic form factors
(using the Nambu-Jona-Lasinio Model and solving the Faddeev equation)

PHYSICAL REVIEW C **90**, 045202 (2014)

Ian C. Cloët,[1] Wolfgang Bentz,[2] and Anthony W. Thomas[3]

"The NJL models … is now interpreted as a QCD-motivated chiral effective quark theory characterized by a 4-fermion contact interaction between the quarks" (i.e. no gluons)

Both the quark and diquark propagators are "dressed" with mass dynamically generated by solving the Bethe-Salpeter equation (BSE), a similar approach to the DSE approach.



The electromagnetic current in the NJL model. The diquark diagram is actually four diagrams in that the photon can interact with either a scalar or axial-vector diquark, or cause a transition between the two. The photon interacts with a quark within the diquark, thereby resolving the structure of the diquark.

The role of diquark and the pion cloud in nucleon elastic form factors
(using the Nambu-Jona-Lasinio Model)

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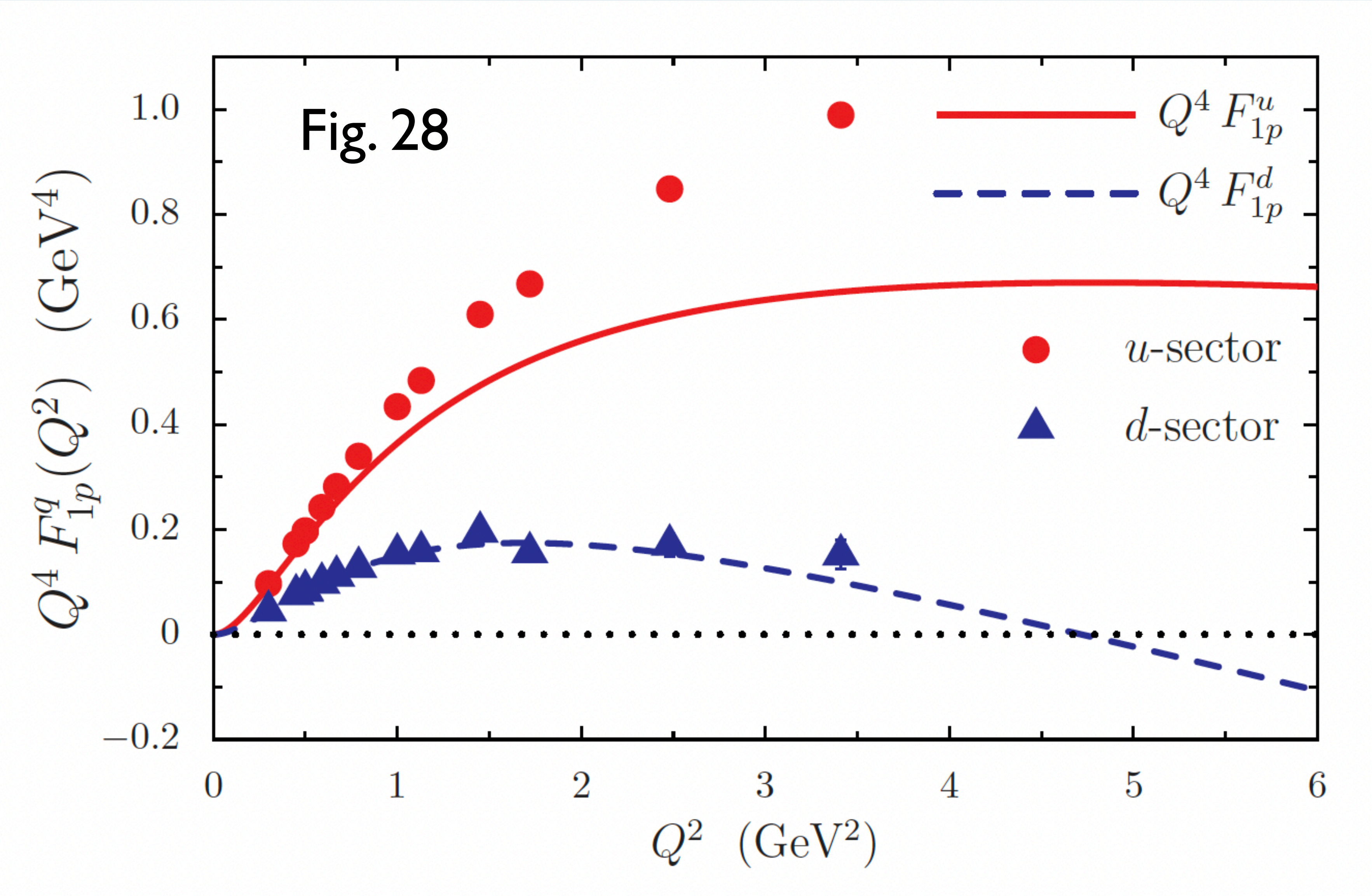
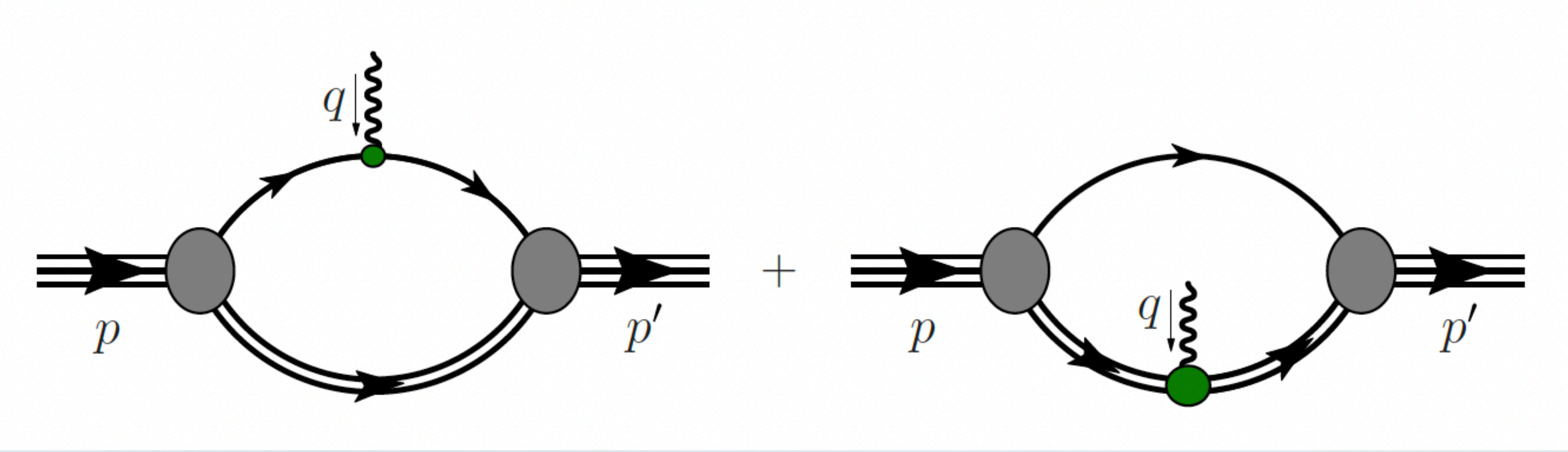




For the scalar diquark (ud) diagram, the only d quark is in the diquark itself.

"The empirical results illustrated in Fig. 28 are straightforward to understand within our framework. The dominant contributions to the quark-sector Dirac form factors come from the two Feynman diagrams which involve only *a quark and a scalar diquark* [emphasis added]….. The ….. current d quarks that contribute to F_{1p}^d must primarily come from the dressed-down quark, and these contributions are suppressed by order $1/Q^2$ relative to the current u quarks from the quark diagram that contributes to F_{1p}^u. Thus, the dominance of scalar diquark correlations in the nucleon clearly provides a very natural explanation of the data in Fig. 28."

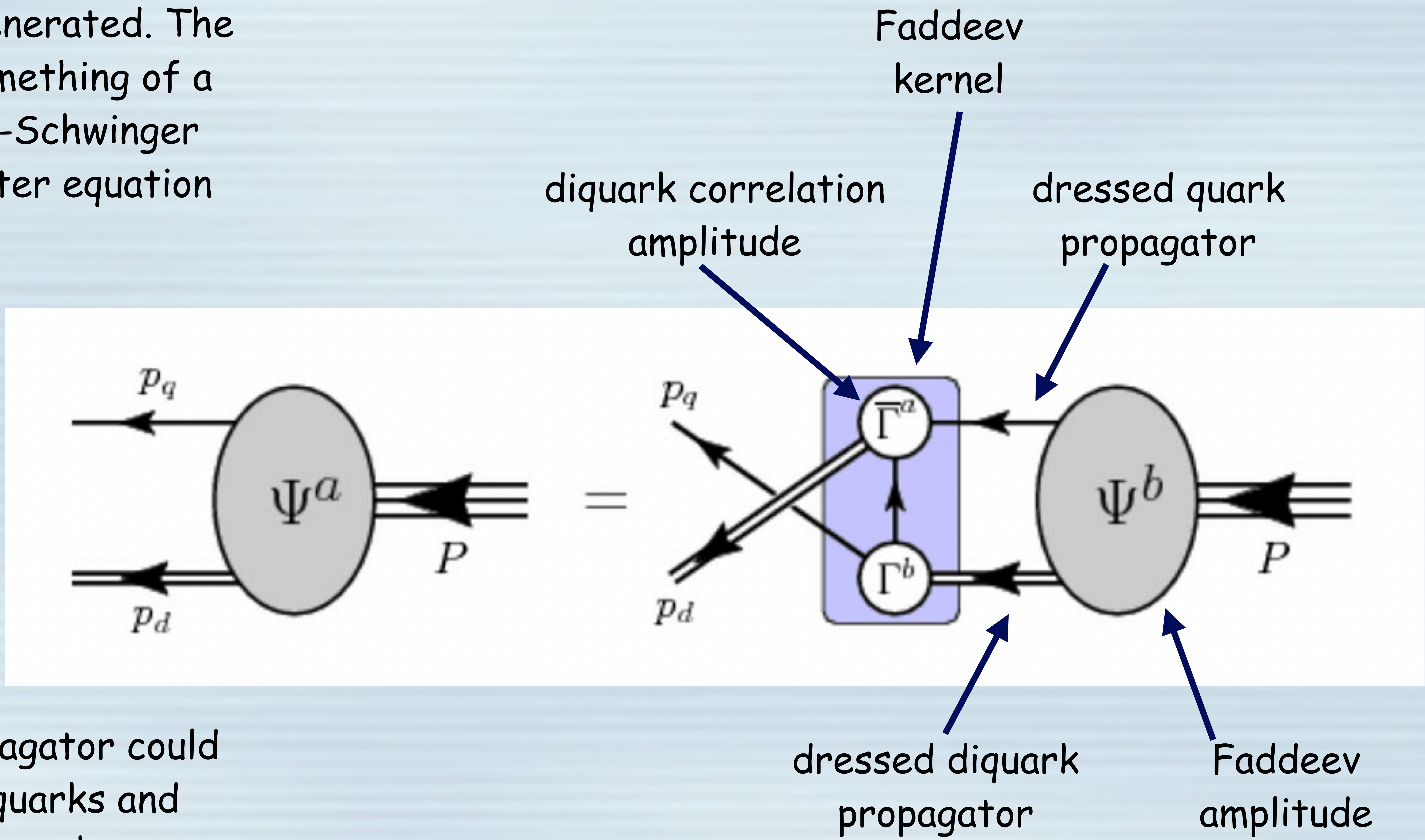
Another calculation …

Nucleon elastic form factors at accessible large spacelike momenta

PHYSICAL REVIEW D **102,** 014043 (2020)

Zhu-Fang Cui,[1,2,*] Chen Chen,[3,†] Daniele Binosi,[4,‡] Feliciano De Soto,[5,§] Craig D. Roberts,[1,2,‖] José Rodríguez-Quintero,[6,¶] Sebastian M. Schmidt,[7,8,**] and Jorge Segovia[9,2,††]

The calculation uses a dressed quark core in which the mass is dynamically generated. The procedure employed here is something of a hybrid of using either a Dyson-Schwinger equation (DSE) or Bethe-Salpeter equation (BSE) approach.



Note, the dressed diquark propagator could represent isoscalar-scalar diquarks and isovector-pseudovector diquarks.

Nucleon elastic form factors at accessible large space like momenta

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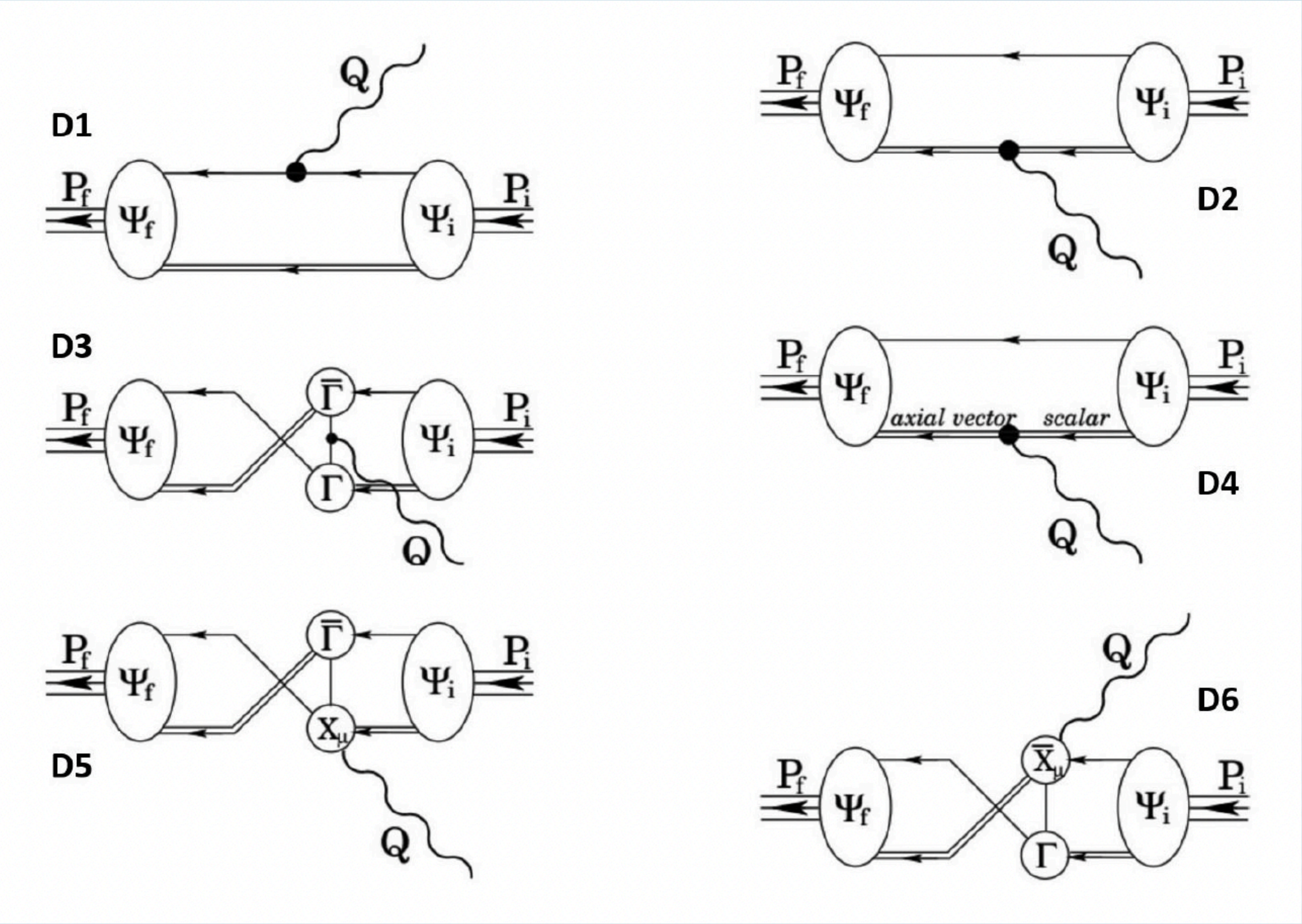
Illustrated are different ways in which a photon can interact with the system. Note, the photon vertex can interact with either a quark propagator, a diquark propagator or even with with the diquark amplitude itself.



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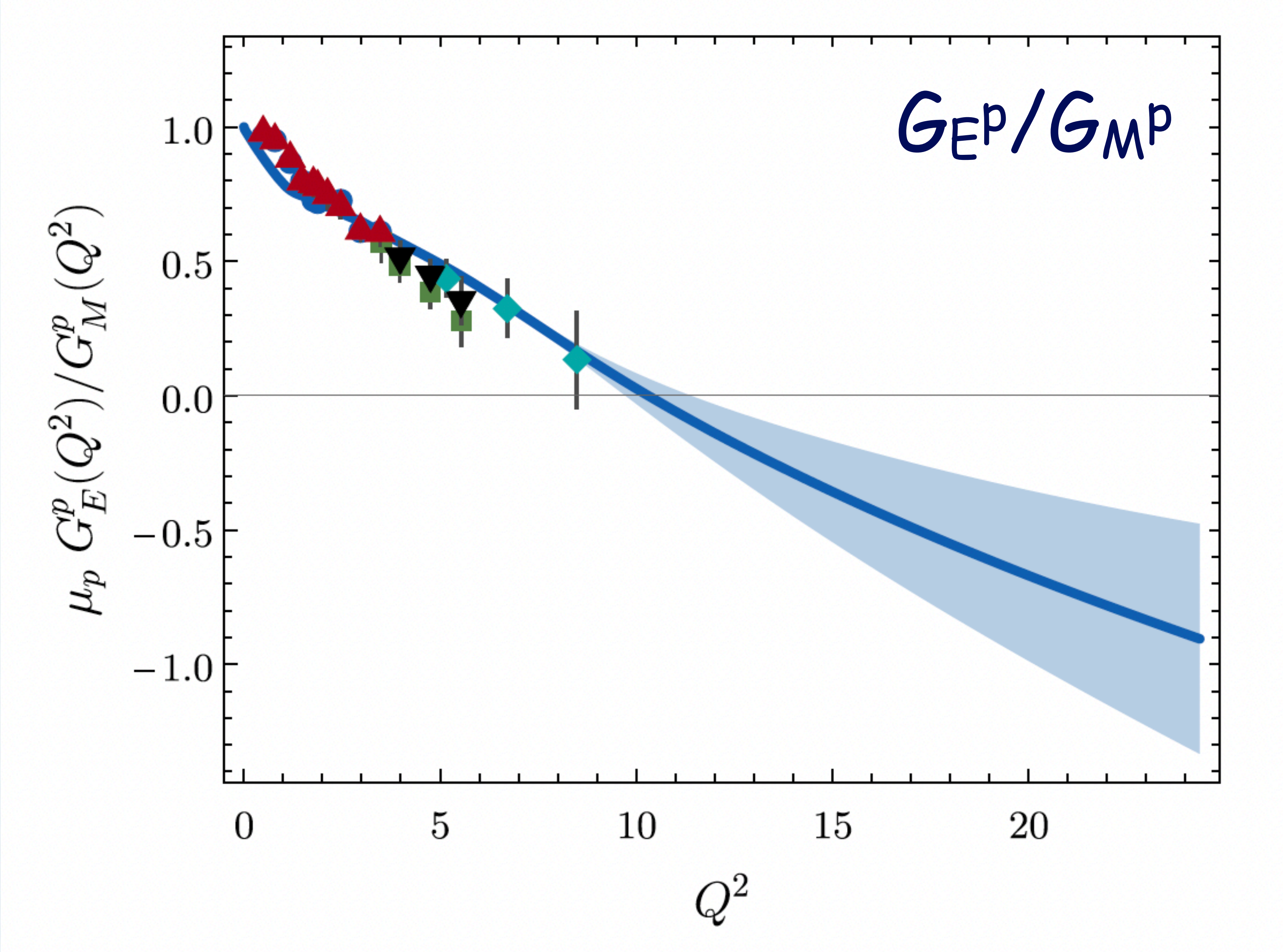
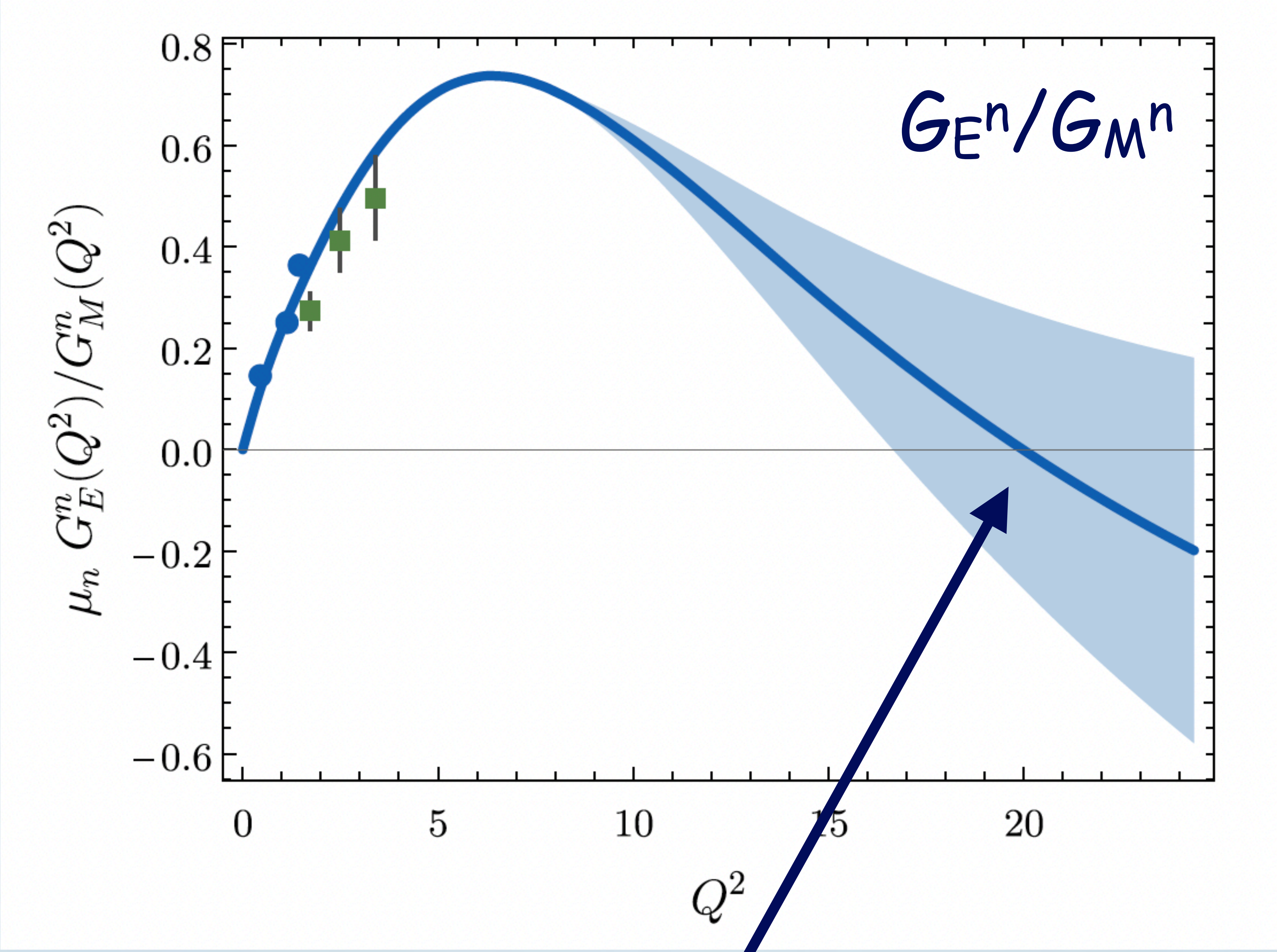


A clear conclusion … is that pseudovector diquark correlations have little influence on the momentum dependence of $R_{EM}(Q^2)$ [G_E^p/G_M^p].

… the evolution of $R_{EM}(Q^2)$ with Q^2 is primarily determined by the proton's scalar diquark component.



Unfortunately, the zero crossing of G_E^n/G_M^n does not occur until around 20 GeV^2, abut 10 GeV^2 higher than earlier predictions around the time that GEn-II was proposed.

Nucleon elastic form factors at accessible large space like momenta

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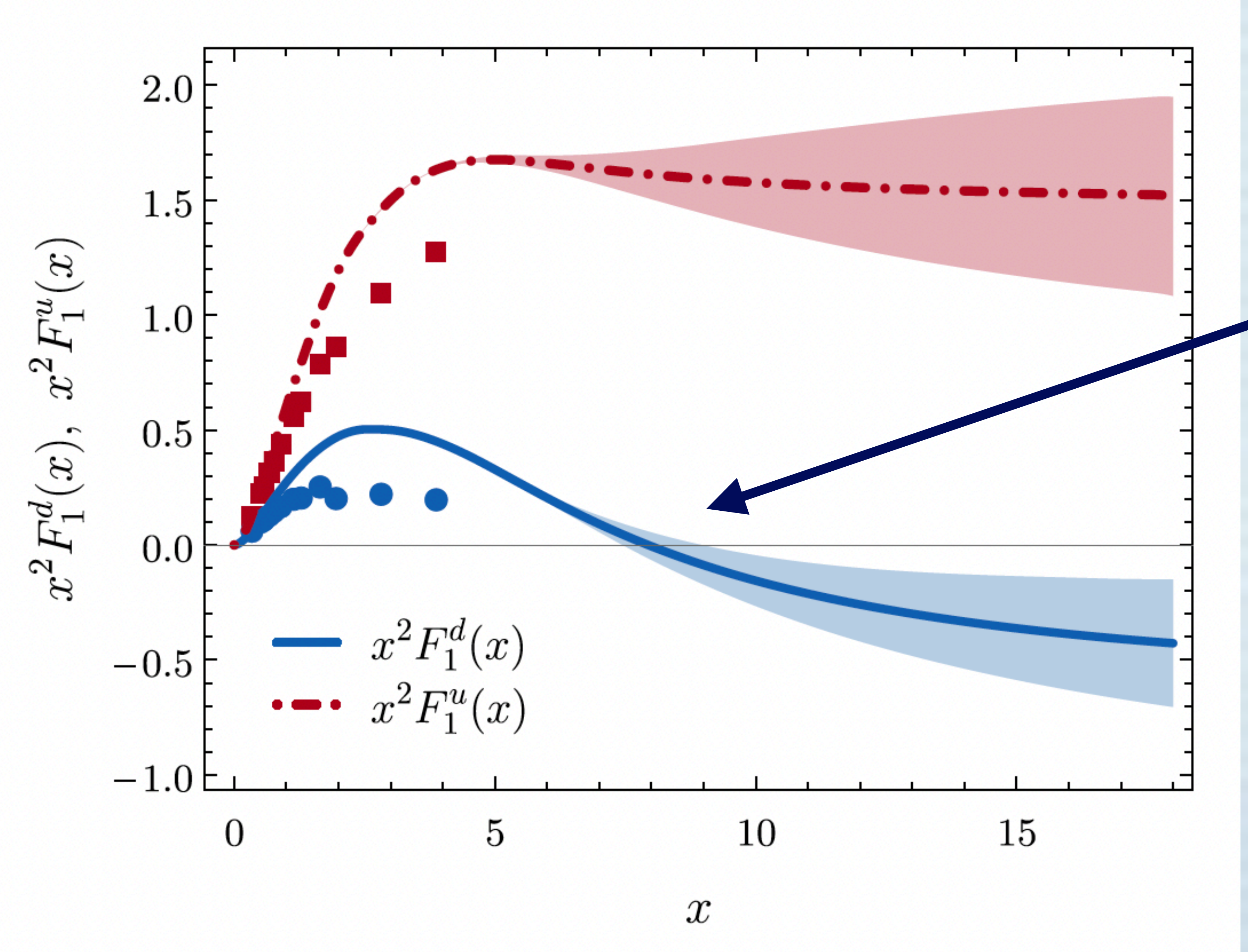


Note, while the zero crossing of G_E^n/G_M^n may not be accessible to GEn-II, the zero crossing of F_1^d is !!!

Quote from earlier paper referred to within PRD **102**, 014043 (2020):

"Any interaction with the *d*-quark attracts a $1/Q^2$ suppression because it is always locked into a correlation described by a meson-like form factor"

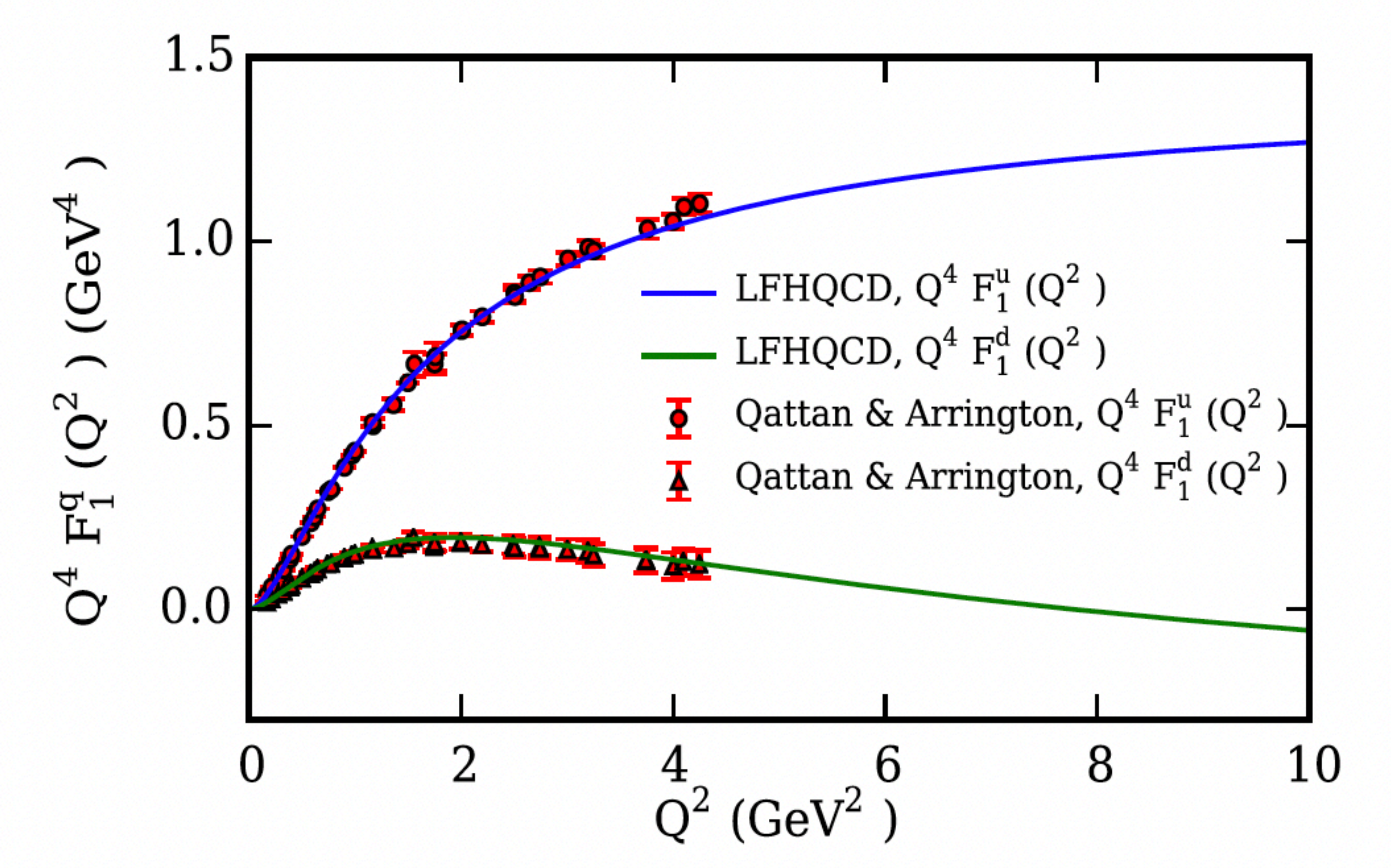
I also note that authors comment that some of the lack of agreement with the data is due to the lack including pions in this calculation.

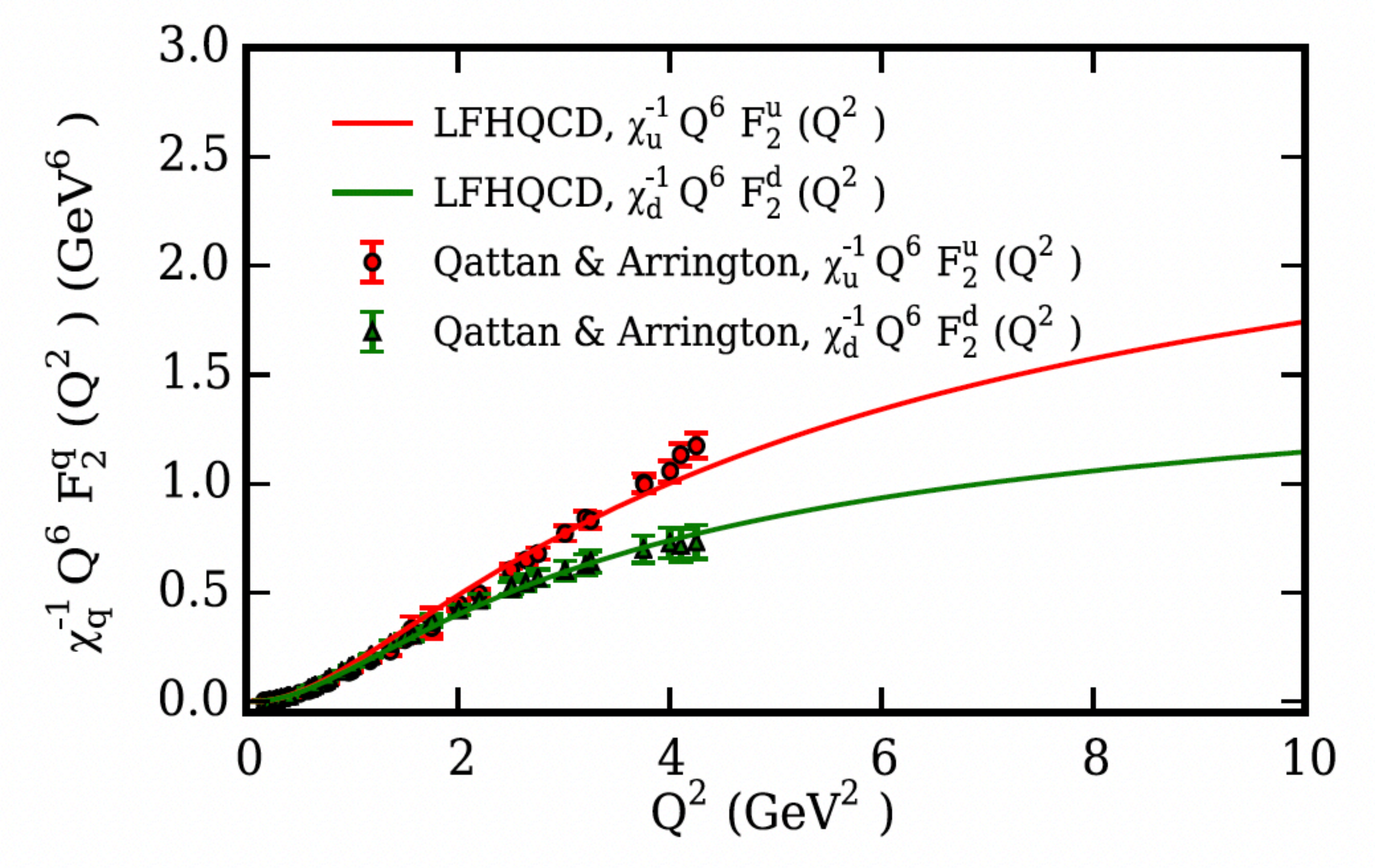
Lightfront holographic QCD

Analysis of nucleon electromagnetic form factors from light-front holographic QCD: The space like region

PHYSICAL REVIEW D **95,** 014011 (2017)

Raza Sabbir Sufian,[1] Guy F. de Téramond,[2] Stanley J. Brodsky,[3] Alexandre Deur,[4] and Hans Günter Dosch[5]





For a multiquark bound state, the LF invariant impact variable ζ applies to a system composed of an active quark plus a spectator "cluster." For example, for a three-quark nucleon state, the three-body problem is reduced to an effective two-body problem where two of the constituents form a diquark cluster [34].

The LFHQCD prediction of a faster increase of the up-quark contribution to $Q^4F_1^u$ for $Q^2 > 1$ GeV^2 compared to $Q^4F_1^d$ is consistent with the flavor decomposition performed in Ref. [101].

The importance of elastic form factors to determining GPD's

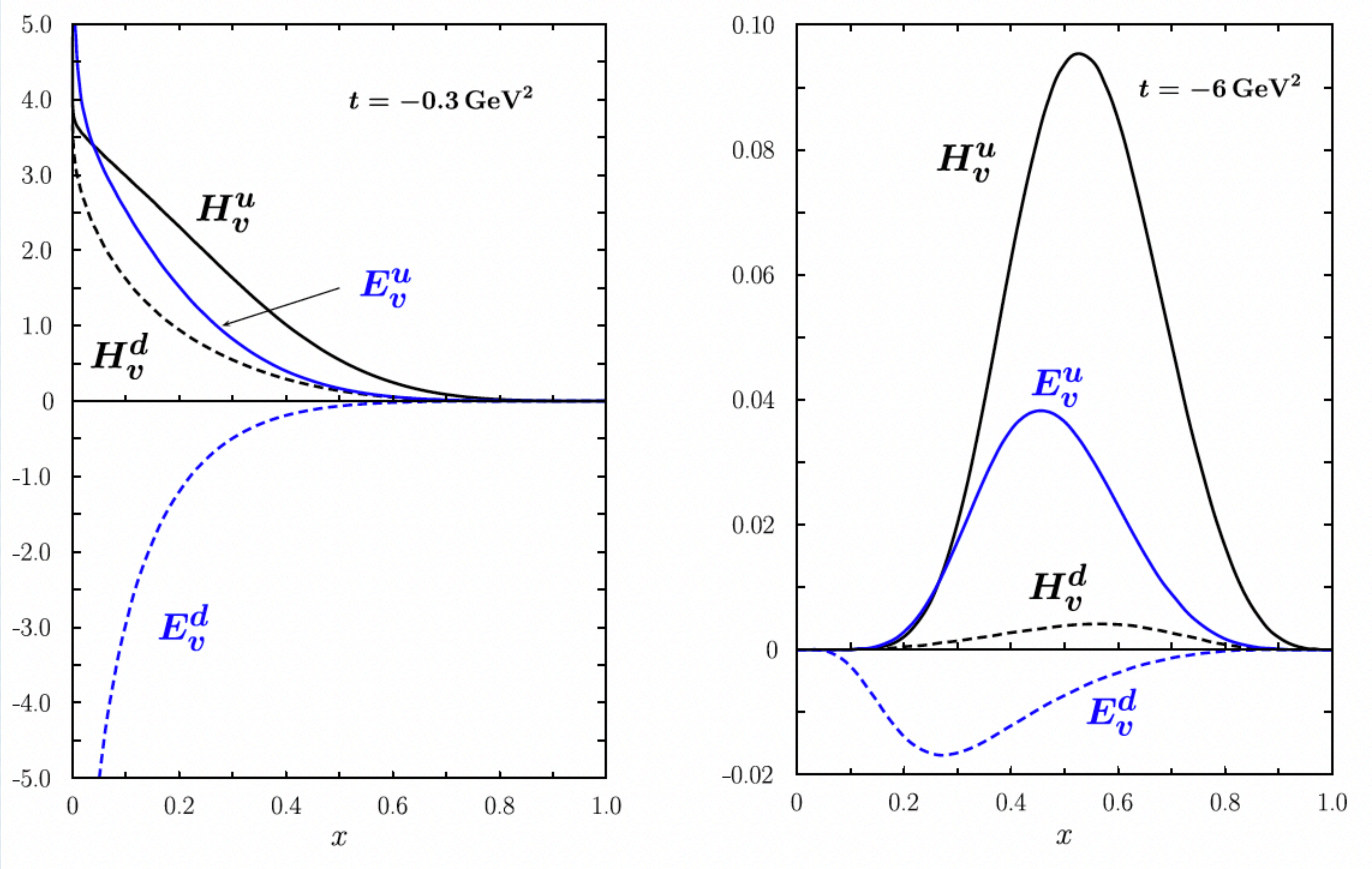
Nucleon form factors, generalized parton distributions and quark orbital angular momentum

Eur. Phys. J. C (2013) 73:2397

Markus Diehl[1,a], Peter Kroll[2,3]

$$F_1^q(t) = \int_0^1 dx\, H_v^q(x,t), \qquad F_2^q(t) = \int_0^1 dx\, E_v^q(x,t)$$

GPD's are determined by assuming a particular form and constraining them at each value of t according to the equations above. Shown are the resulting GPD's for two values of t.



Nucleon form factors, generalized parton distributions and quark orbital angular momentum

Eur. Phys. J. C (2013) 73:2397

Markus Diehl[1,a], Peter Kroll[2,3]

With the GPD's determined (such as they are in this work) one can calculated the angular momentum associated with the quarks using Ji's sum rule:

$$J^q = \frac{1}{2} \int_{-1}^{1} x\, dx\, \left[H^q(x,\xi,0) + E^q(x,\xi,0) \right]$$

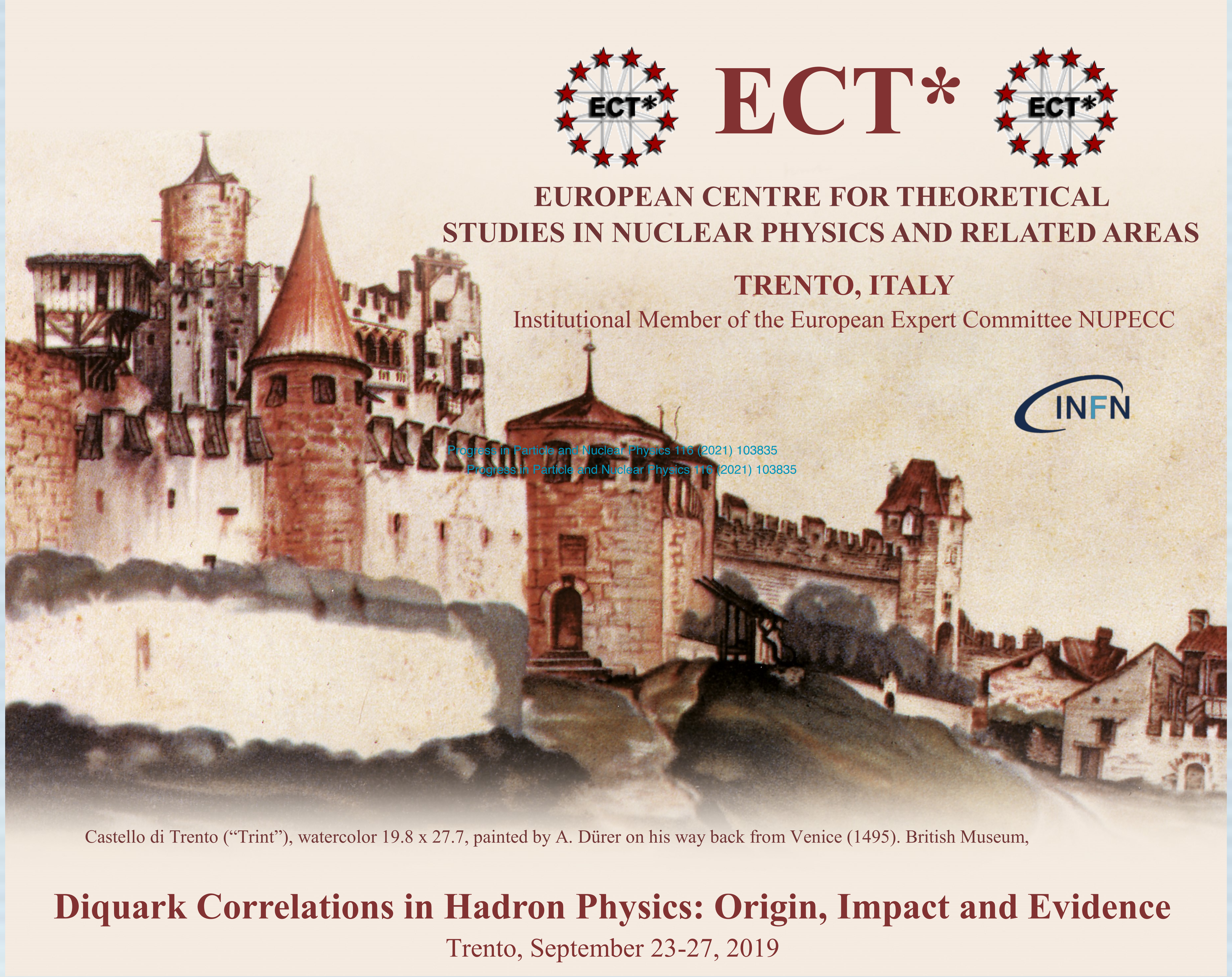
The result is:

$$J_v^u = 0.230^{+0.009}_{-0.024} \text{ and } J_v^d = -0.004^{+0.010}_{-0.016}$$

We should note that these values include both angular momentum due to spin as well as orbital angular momentum.

Workshop on diquarks at ECT* in Trento

(September 2019)



Review article grew out of the workshop: "Diquark Correlations in Hadron Physics: Origin, Impact and Evidence", Progress in Particle and Nuclear Physics 116 (2021) 103835".

Summary

- The SBS form factor measurements will tell us critical information about the structure of the nucleon.
- There are specific predictions from various models that WILL be tested by our experiments.
- Among other things, the SBS form factor measurements will confirm whether diquark correlations are indeed responsible for the different Q^2 behavior between the u- and d-quark contributions to the form factors.