Measuring the neutron charge radius from electron scattering experiments

Michael Paolone, New Mexico State University

PREN2022: Paris, France 06/23/22

Neutron Considerations

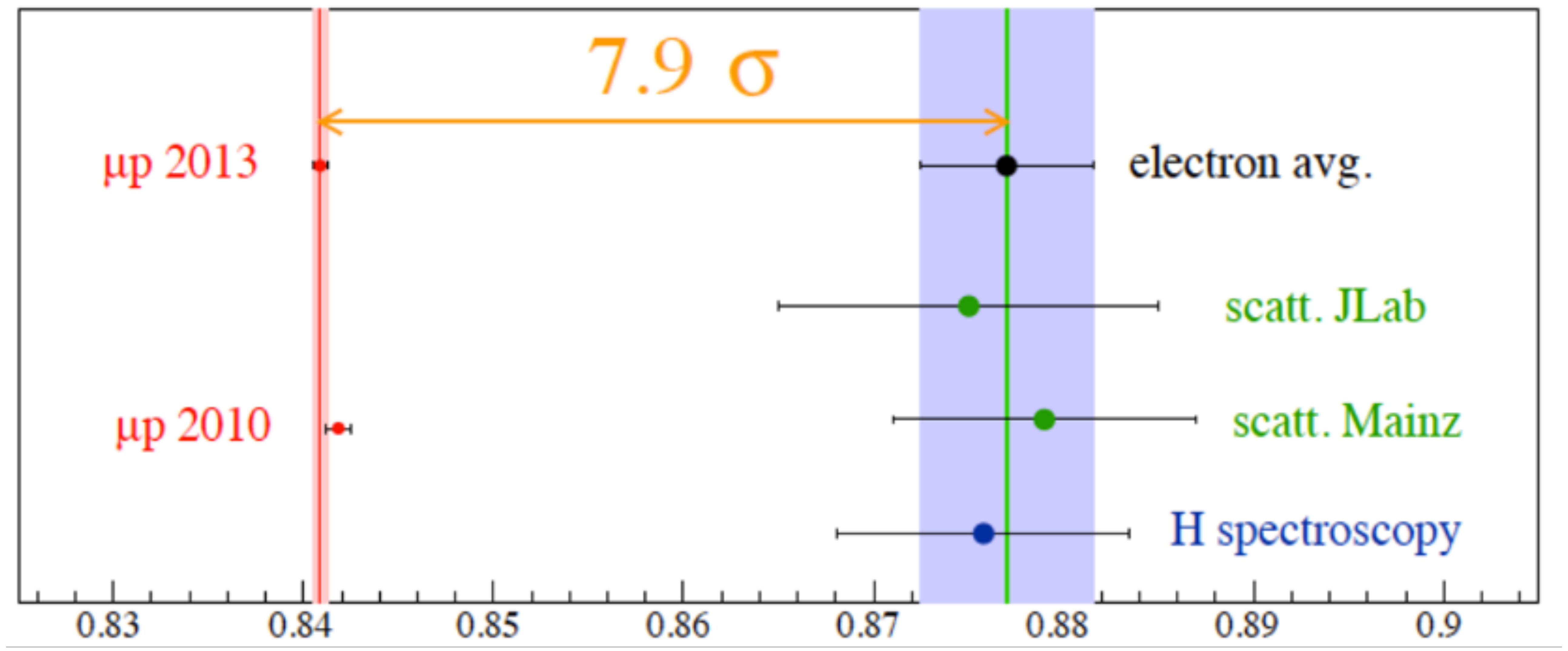
The fundamental properties of the neutron play a significant role in our understanding of nature. Compared to the proton, those properties have been notoriously more difficult to measure.

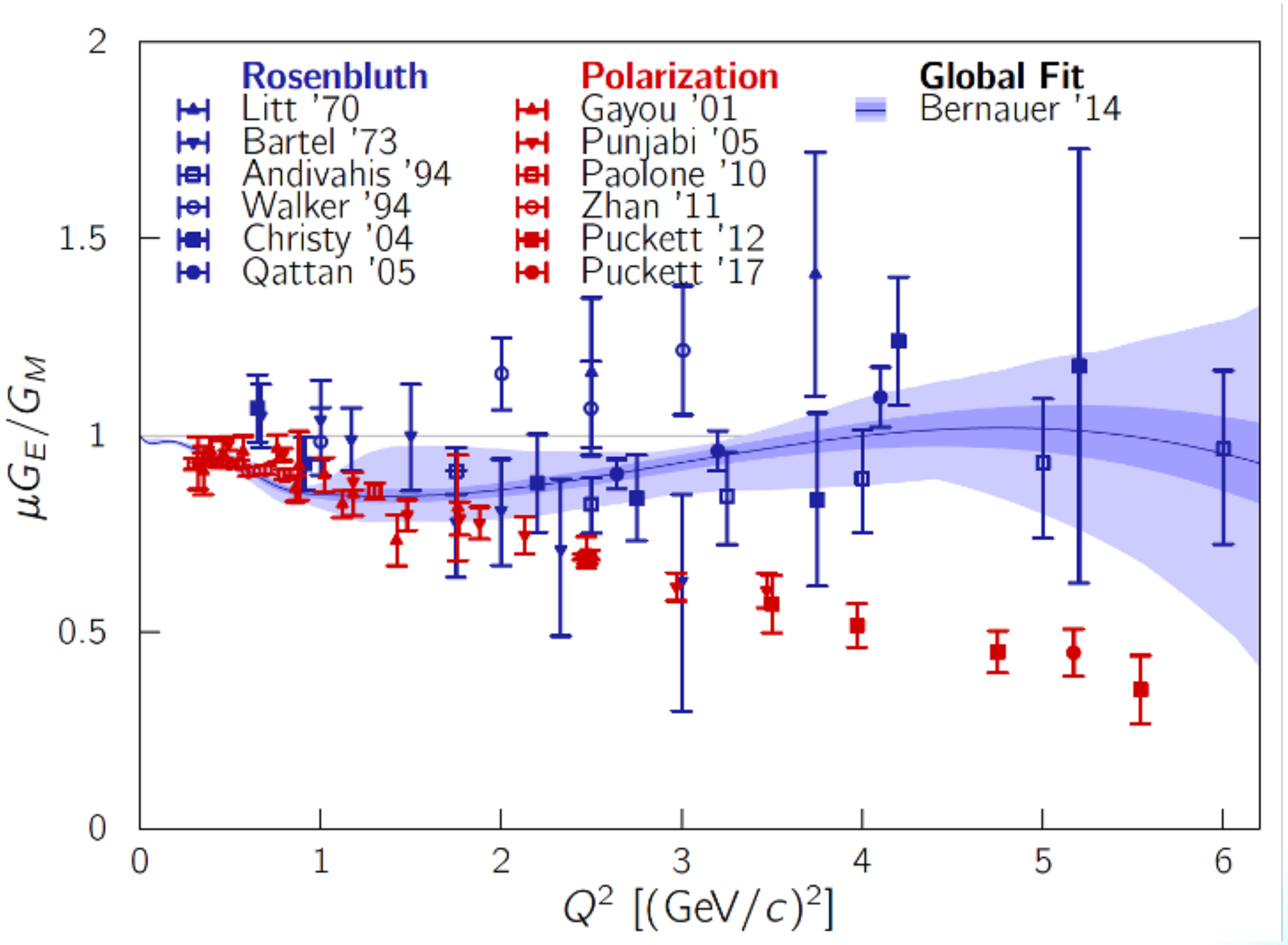
- **The significance of understanding the neutron cannot be overstated:**
  - A cornerstone in the understanding of the hadronic structure.
  - Plays a central role in cosmological theories: it’s properties offer valuable constraints in searches for new physics.
- **Precision is key:**
  - It is required in the determination of its properties in order to achieve the required level of understanding – consequence of the system dynamics & the interactions of the constituents
- **What if…**
  - … the proton-neutron mass difference (~0.1%) were swapped?
    - There would be no hydrogen, water, stable long-lived stars which use hydrogen as a nuclear fuel… The universe would be drastically different.

Bottom line: A precise understanding of the neutron's basic properties is critical.
The charge radius is one of those properties.

Surprises with the proton

- **We have been startled twice concerning the fundamental properties of the proton over the last 20 years!**
  - First concerning the electro-magnetic structure…
  - And more recently concerning the charge radius!



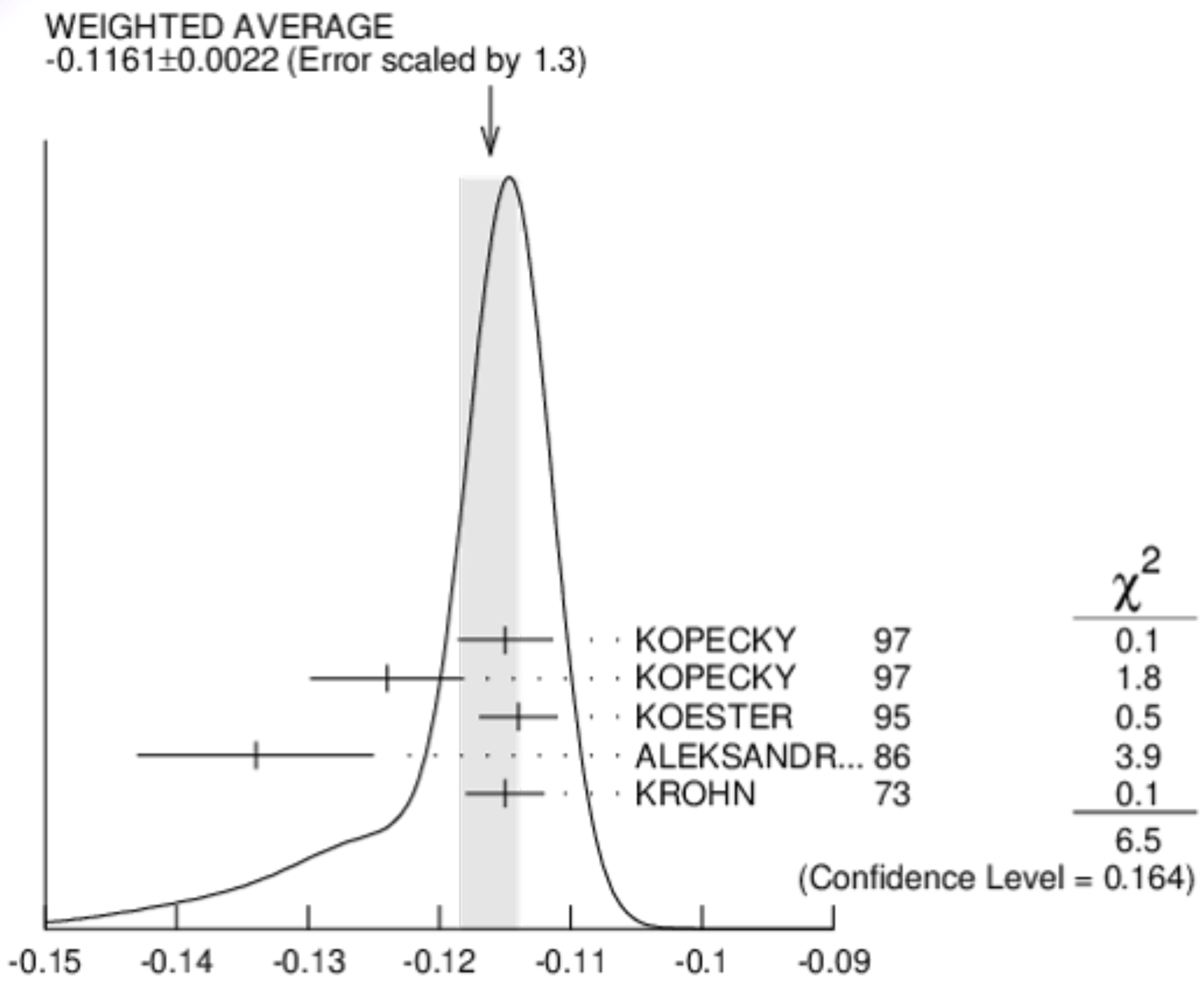


These issues concerning our understanding of the basic proton properties would have not have come to light when they did unless alternative measurement methods were considered and employed!!!!

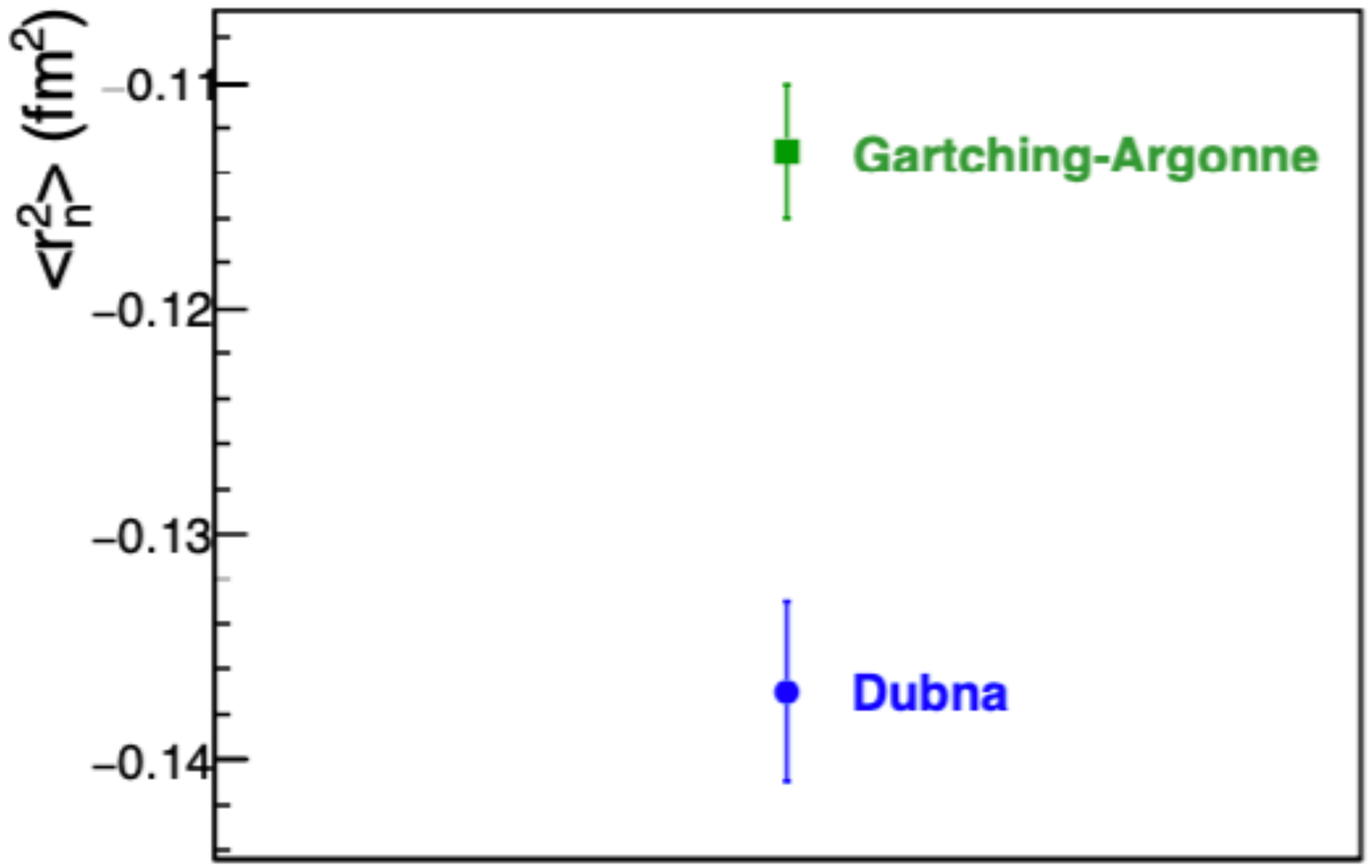
Alternative measurement methodologies are crucially important!

Our current understanding of the neutron charge radius

The value of $< r_n^2 >$ is based on one method of extraction → measurement of b_{ne} using Pb, Bi, …(very indirect method)



- **Some details on the PDG compiled neutron radius:**
  - Most recent measurements over 2 decades old.
  - Some world data is omitted.
  - Input data shows significant tension
    - Simply averaging data with significant discrepancies can be misleading.



The world data results essentially come from two research groups: Gartching-Argonne and Dubna

With a 5σ tension between them!!!

PRC 56, 2229 (1997) ; Annu. Rev. Nucl. Part. Sci. 55, 27 (2005) ; PRD 77 034020 (2008) …

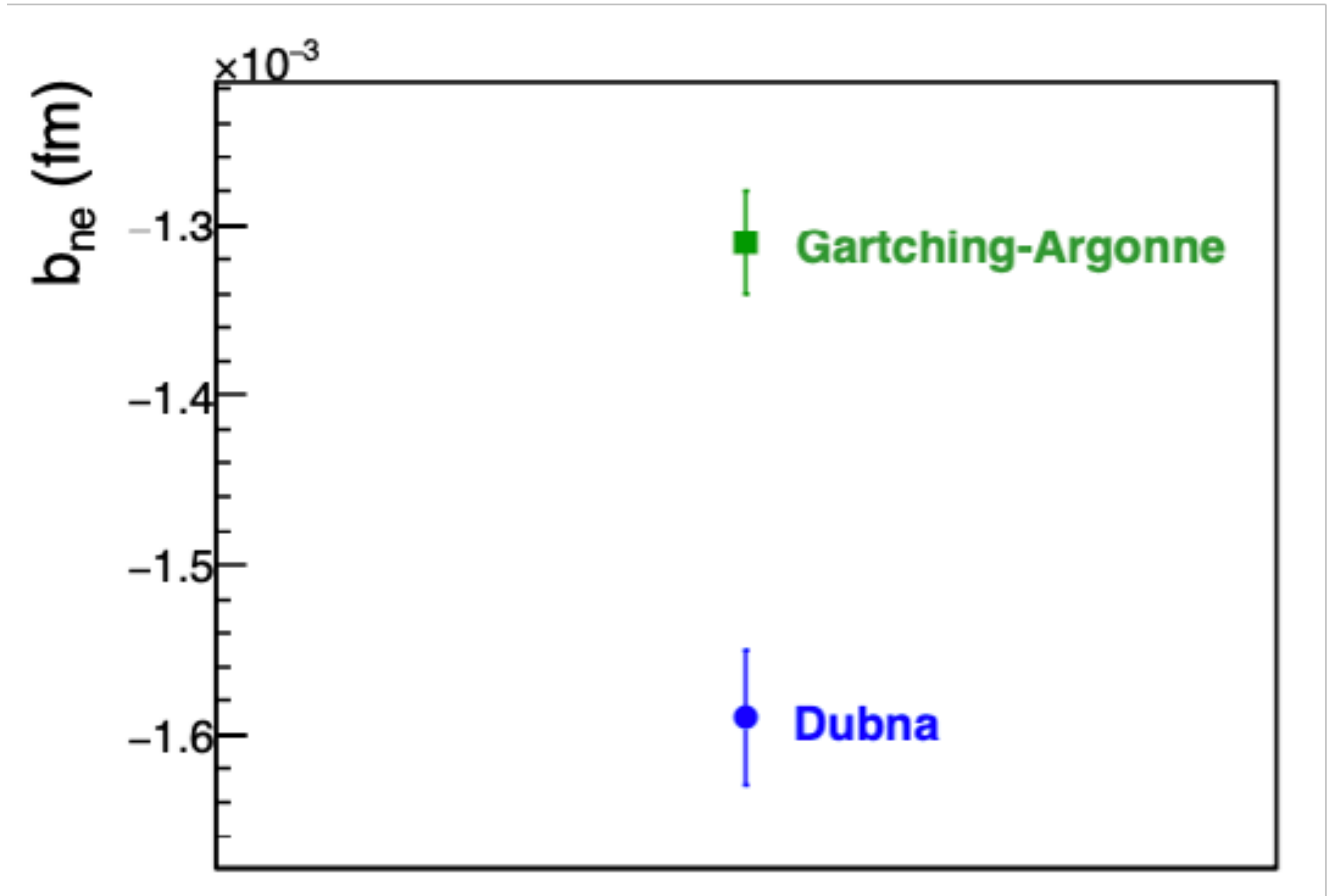
Our current understanding of the neutron charge radius

The value of $< r_n^2 >$ is based on one method of extraction → measurement of b_{ne} using Pb, Bi, …(very indirect method)

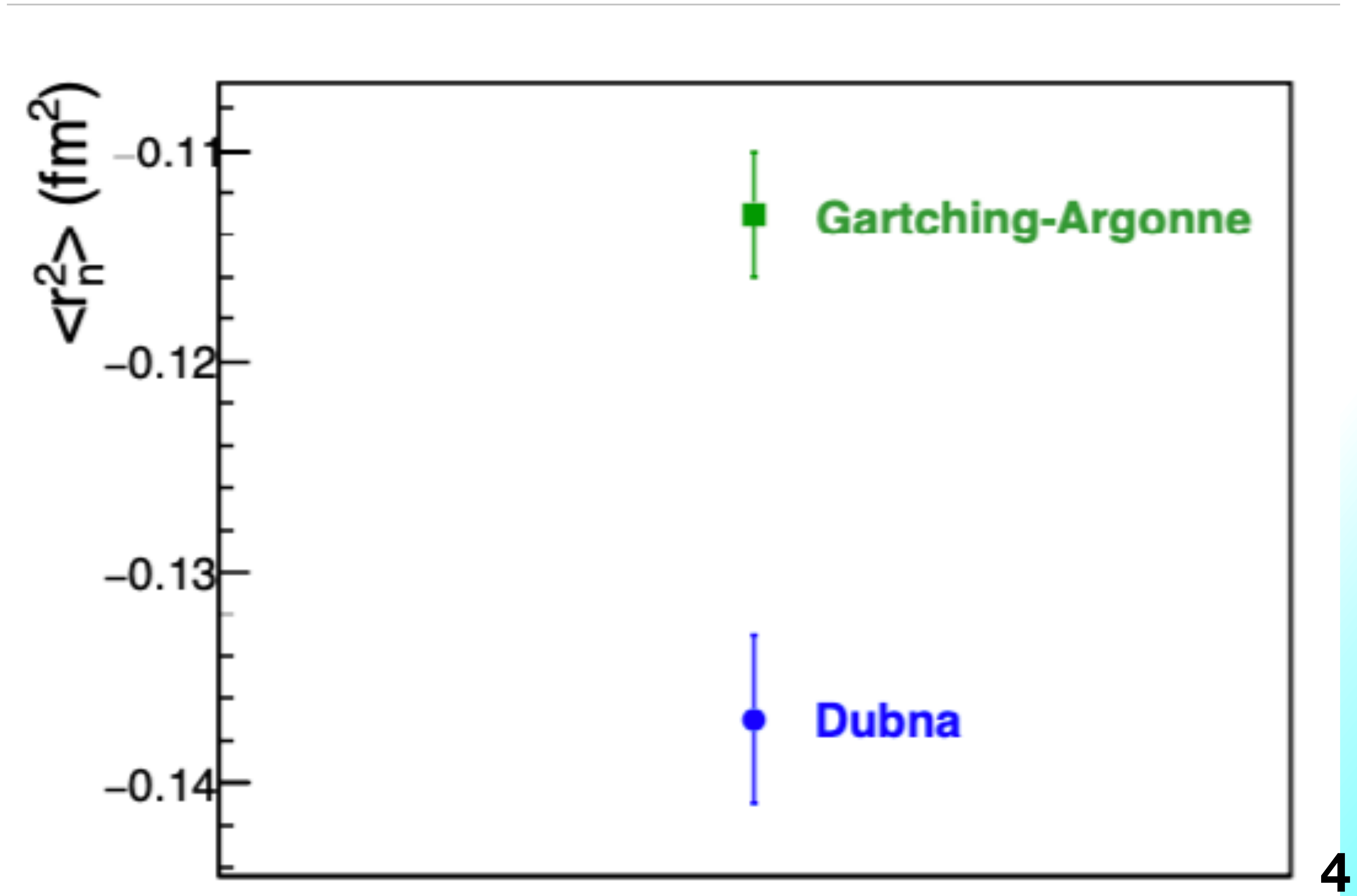
The same methodology is used in each group's radius extraction: a measurement of b_{ne}

A 5σ discrepancy most likely implies an underestimation of systematic uncertainty associated with the methodology

This is a long standing discrepancy and there is NO obvious path using neutron scattering alone that can resolve this.



$< r_n^2 > = 3(m_e a_0/m_n)\, b_{ne}$



Some consequences of the current precision

PHYSICAL REVIEW D 77, 034020 (2008)

Neutron scattering and extra-short-range interactions

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(Received 14 November 2007; published 25 February 2008)

The available data on neutron scattering were reviewed to constrain a hypothetical new short-range interaction. We show that these constraints are several orders of magnitude better than those usually cited in the range between 1 pm and 5 nm. This distance range occupies an intermediate space between collider searches for strongly coupled heavy bosons and searches for new weak macroscopic forces. We emphasize the reliability of the neutron constraints insofar as they provide several independent strategies. We have identified a promising way to improve them.

PHYSICAL REVIEW D 77, 034020 (2008)

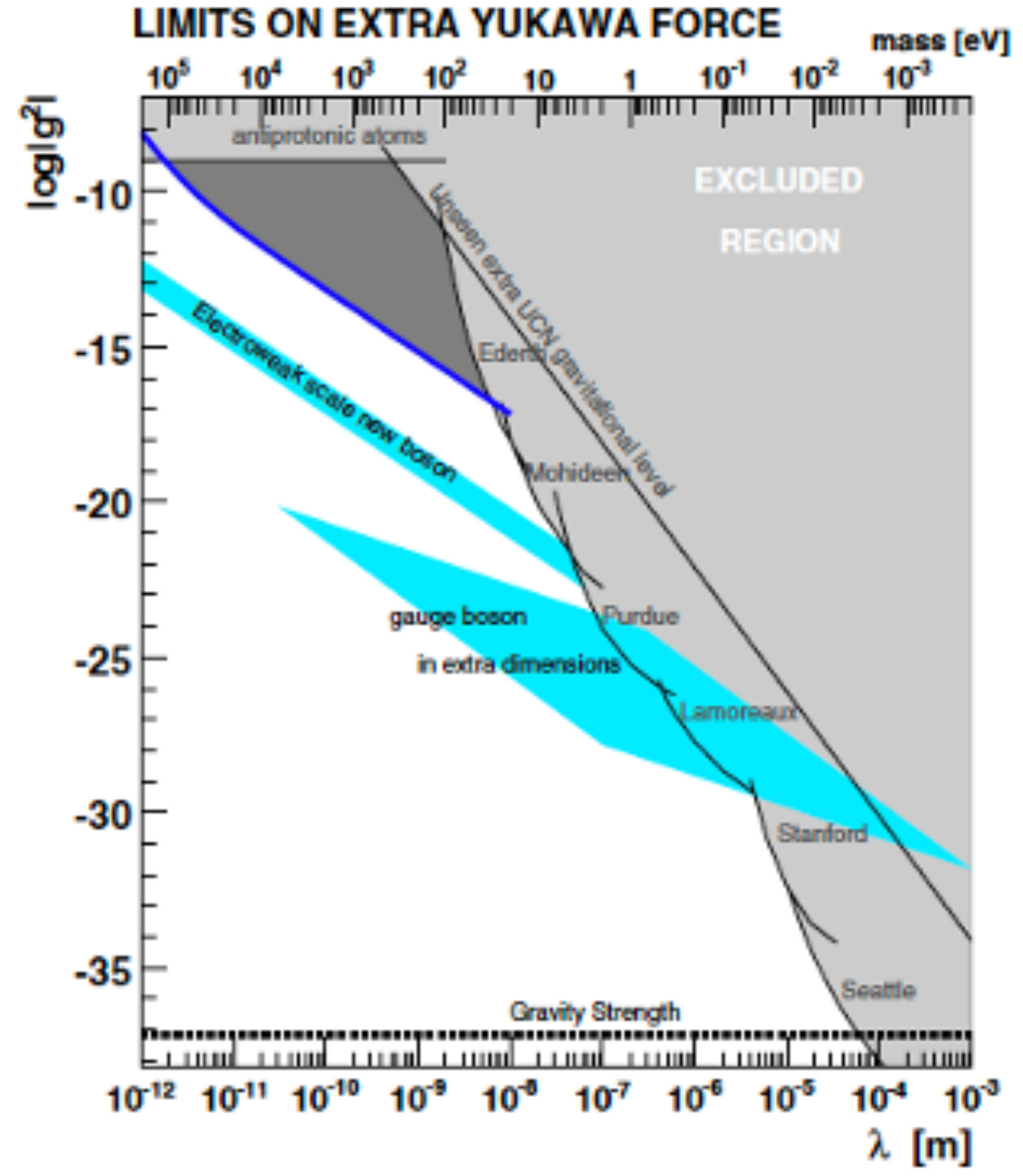


FIG. 8 (color online). Experimental limits on extra interactions including the best neutron constraint obtained in this article (bold line). Two theoretical regions of interest are shown: a new boson with mass induced by electroweak symmetry breaking [10], and a new boson in extra large dimensions [4].

BSM physics: constrains on forces due to new bosons modeled by a Yukawa-type scattering potential: $f(q) = f_{\rm nucl}(q) + f_{ne}(q) + f_{\rm new}(q)$

Depends on b_{ne} , limited by precision

Unfortunately, there is very clear disagreement between the two groups of values for $b_{ne}^{\rm exp} = \frac{b(1\ {\rm eV}) - b(0)}{Z}$ known as the Garching-Argonne and Dubna values [27]

$$b_{ne}^{\rm exp} = (-1.31 \pm 0.03) \times 10^{-3}\ {\rm fm} \quad [\text{Gartching-Argonne}]$$
$$b_{ne}^{\rm exp} = (-1.59 \pm 0.04) \times 10^{-3}\ {\rm fm} \quad [\text{Dubna}]. \qquad (18)$$

The discrepancy is much greater than the quoted uncertainties of the experiments and there evidently an unaccounted for systematic error in at least one of the experiments.

→

In order to overcome this difficulty we could determine b_{ne} from the experimental data on the neutron form factor (5). The simplest way to do this consists in using a commonly accepted general parametrization of the neutron form factor [28]:

$$G^n \rightarrow r_n \rightarrow b_{ne}$$

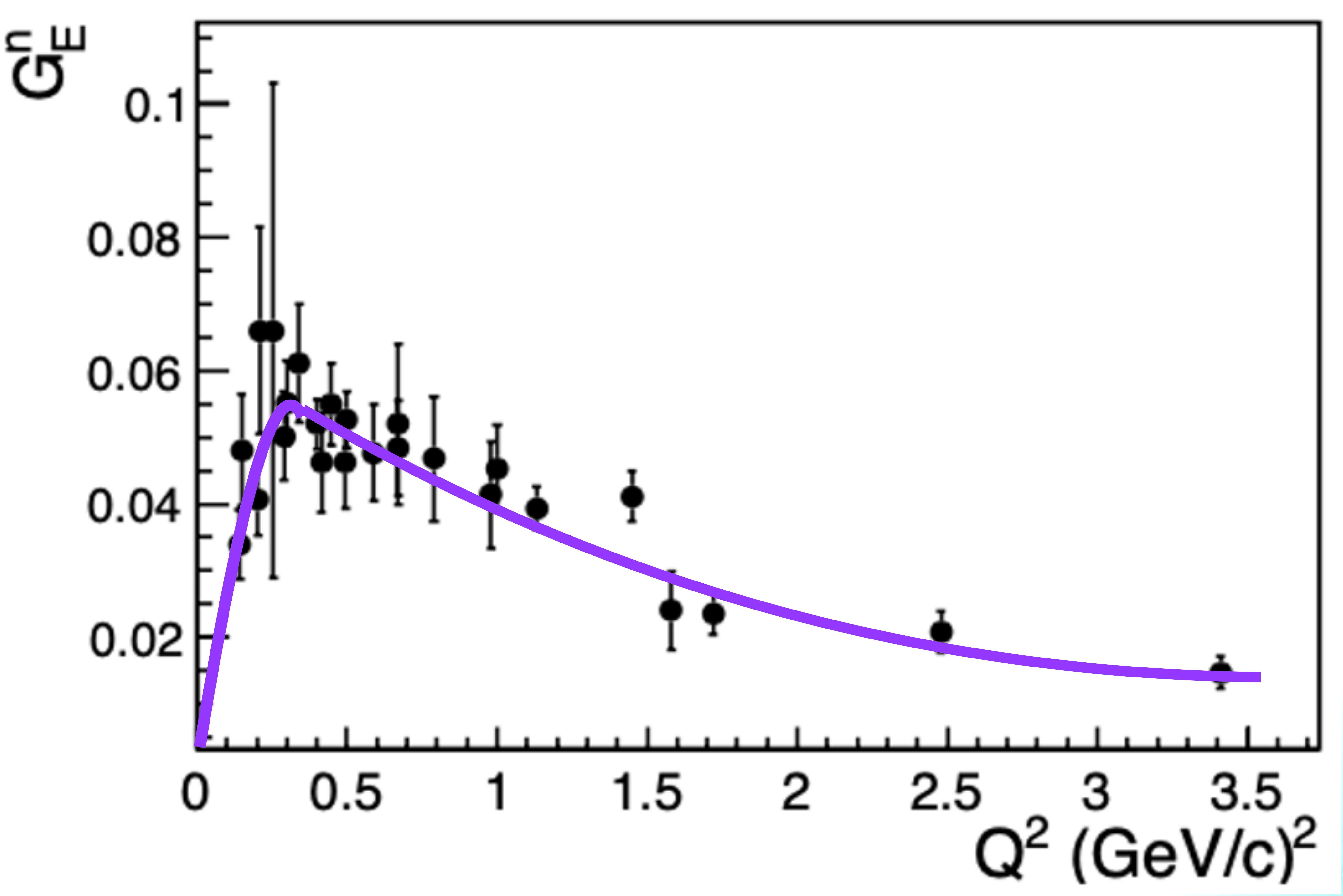
→

Our principal conclusion consists of the observation of (underestimated) systematical uncertainties in the presented experiments. Therefore a single experiment/method cannot be used for any reliable constraint. A conservative estimate of the precision of the b_{ne} value could be obtained from analyzing the discrepancies in the results obtained by different methods; it is equal to $\Delta b_{ne} \lesssim 6 \times 10^{-4}$ fm. The

An alternative method to measure the neutron charge radius

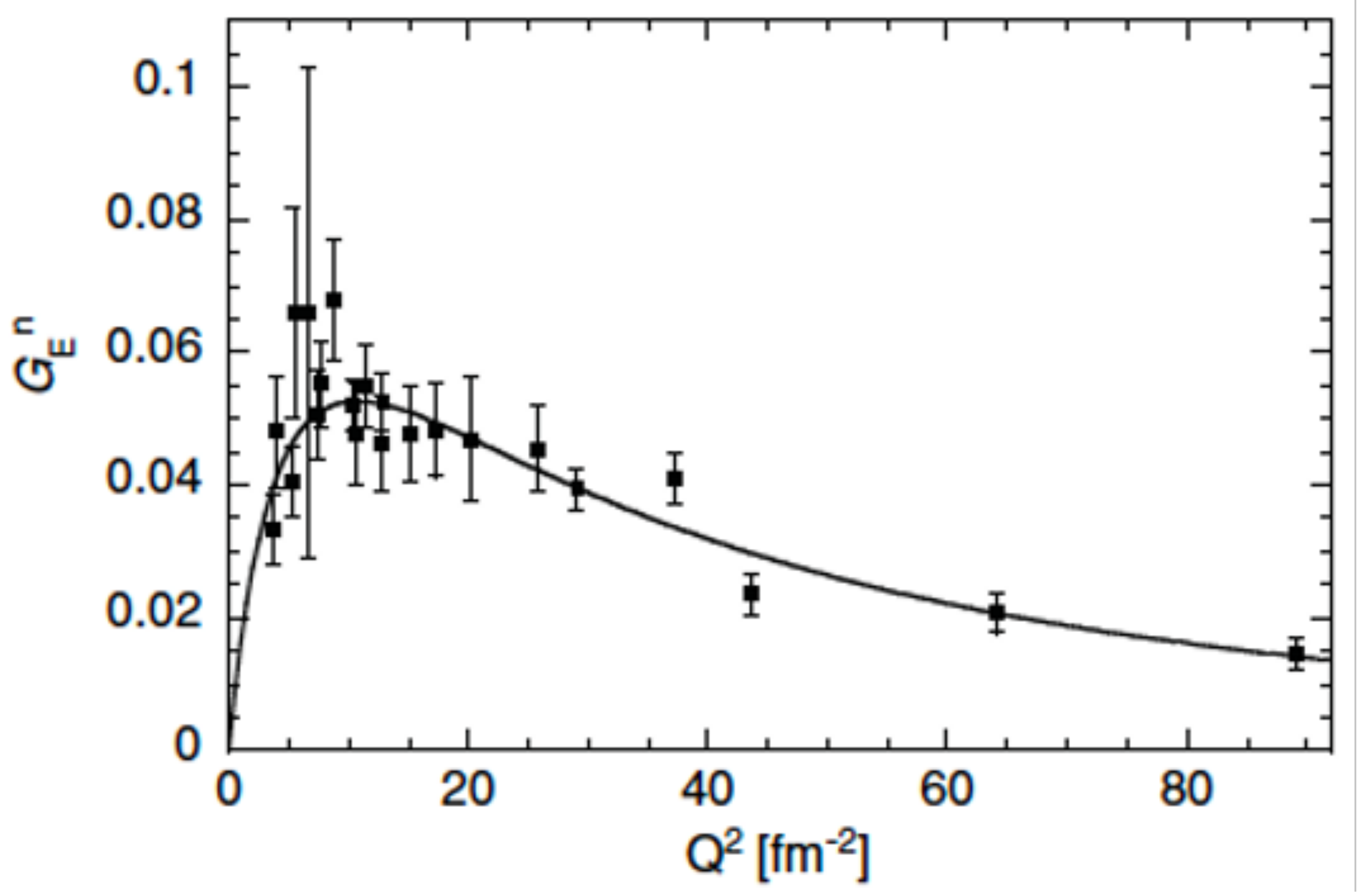
$$\langle r_n^2 \rangle = -6 \frac{dG_E^n(Q^2)}{dQ^2}\bigg|_{Q^2 \to 0}$$

- **Historical G_E^n measurements:**
  - No truly "free" neutron target
  - Polarized ^2H, ^3He targets & polarized electron beam
  - Quasi-elastic electron scattering
  - Double polarization observables
- **A fit is needed for $Q^2 \to 0$**
  - Relies on precision of measurements



An alternative method to measure the neutron charge radius

T.R. Gentile & C.B. Crawford
PRC 83, 055203 (2011)



- **Parameterizations of the fit forms are not well constrained as $Q^2 \to 0$**
  - Recent attempts using quasi-free neutron target measurements of G_E^n have yielded radii ~33% from pdg values.
- **Bottom Line:** Current landscape of G_E^n from electron + quasi-free neutron scattering is not sufficient.

TABLE I. Results of fitting G_E^n with the Galster form. For this table and Table II, the column labelled "$\langle r_n^2 \rangle^d$" lists the reference for the $\langle r_n^2 \rangle$ datum included in the fit, χ^2_{red} is the reduced χ^2 for the fit and "dof" refers to the number of degrees of freedom for each fit. The parameters A and B are listed, along with the resulting value for $\langle r_n^2 \rangle$.

Form	Eq.	$\langle r_n^2 \rangle^d$	A	B	$\langle r_n^2 \rangle$ (fm^2)	χ^2_{red}	dof
Galster	(1)	–	1.409(82)	2.09(39)	–0.0935(54)	0.90	20

TABLE II. Results of fitting G_E^n with the Bertozzi and mod-Ber (modified Bertozzi) forms. The parameters $\langle r_n^2 \rangle$, r_{av}, and a are listed (for the Bertozzi form the normalization parameter a is fixed at unity).

Form	Eq.	$\langle r_n^2 \rangle^d$	r_{av} (fm)	a	$\langle r_n^2 \rangle$ (fm^2)	χ^2_{red}	dof
Bertozzi	(3)	–	0.709(19)	1	–0.0906(64)	0.94	20

Radius extraction through flavor decomposition

- **Instead, one can consider doing a model independent transverse mean square flavor decomposition:**
  - $\langle r_p^2 \rangle = 2\langle b_u^2 \rangle - \frac{1}{2}\langle b_d^2 \rangle + \frac{3}{2}\frac{\kappa_N}{M_N^2}$
  - $\langle r_n^2 \rangle = \langle b_d^2 \rangle - \langle b_u^2 \rangle + \frac{3}{2}\frac{\kappa_N}{M_N^2}$
  - One can determine a global $\langle b_u^2 \rangle$ and $\langle b_d^2 \rangle$ and then simultaneously extract the proton and neutron charge radius.

Flavor decomposition at large Q^2

PRL 106, 252003 (2011) PHYSICAL REVIEW LETTERS week ending 24 JUNE 2011

Flavor Decomposition of the Elastic Nucleon Electromagnetic Form Factors

G. D. Cates,[1] C. W. de Jager,[2] S. Riordan,[3] and B. Wojtsekhowski[2,*]

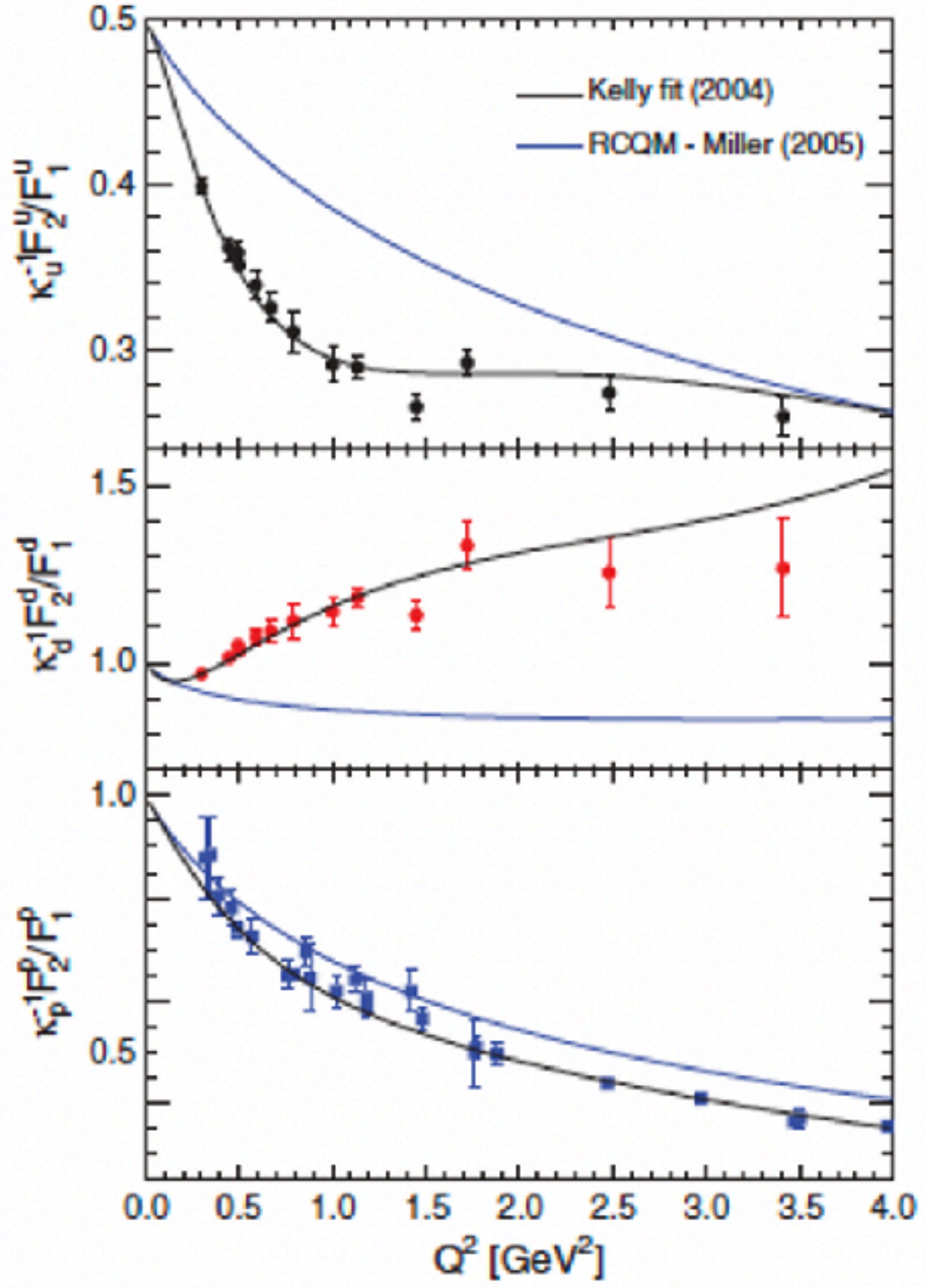


FIG. 2 (color). The ratios $\kappa_d^{-1}F_2^d/F_1^d$, $\kappa_u^{-1}F_2^u/F_1^u$, and $\kappa_p^{-1}F_2^p/F_1^p$ vs momentum transfer Q^2. The data and curves are described in the text.

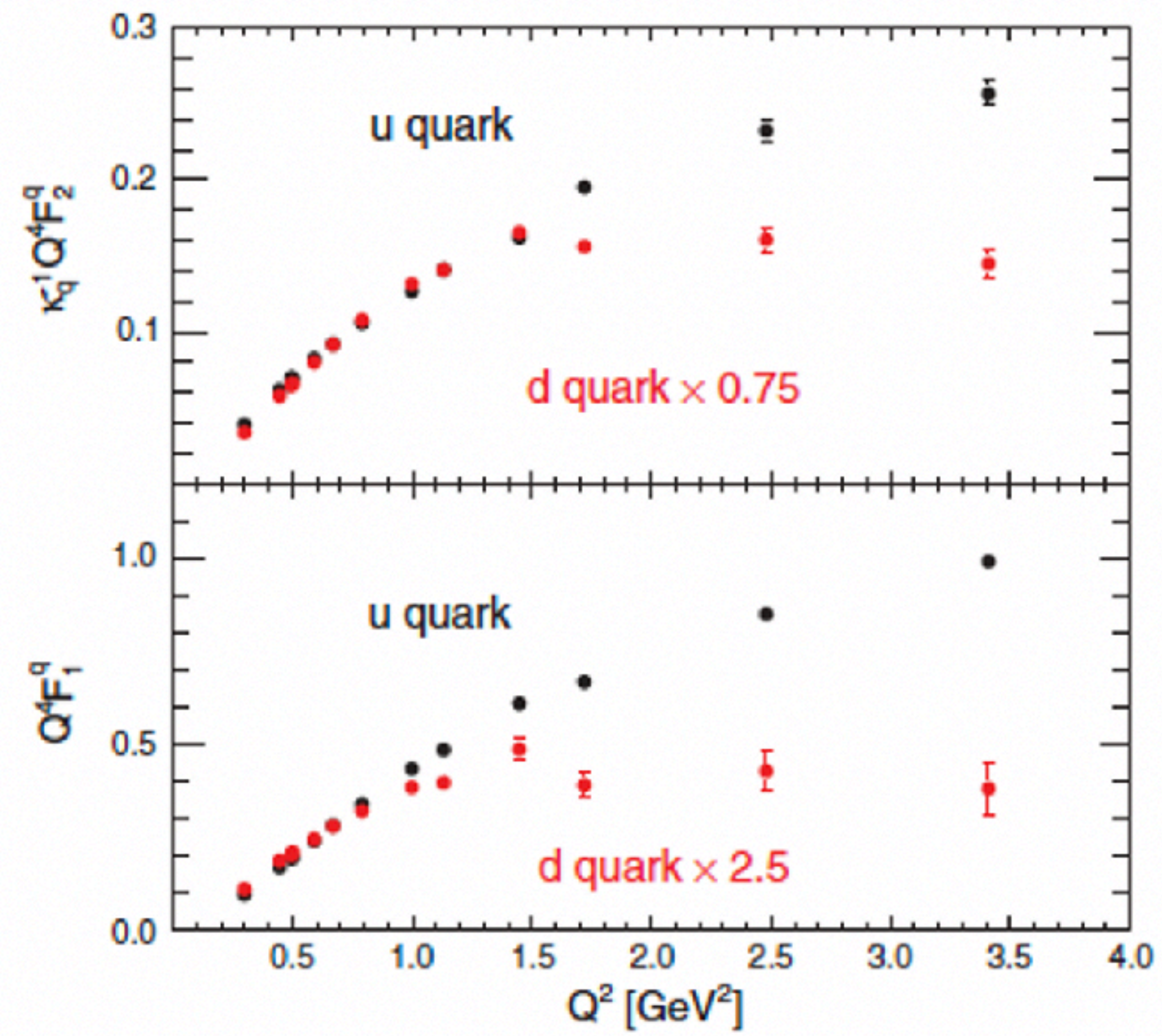
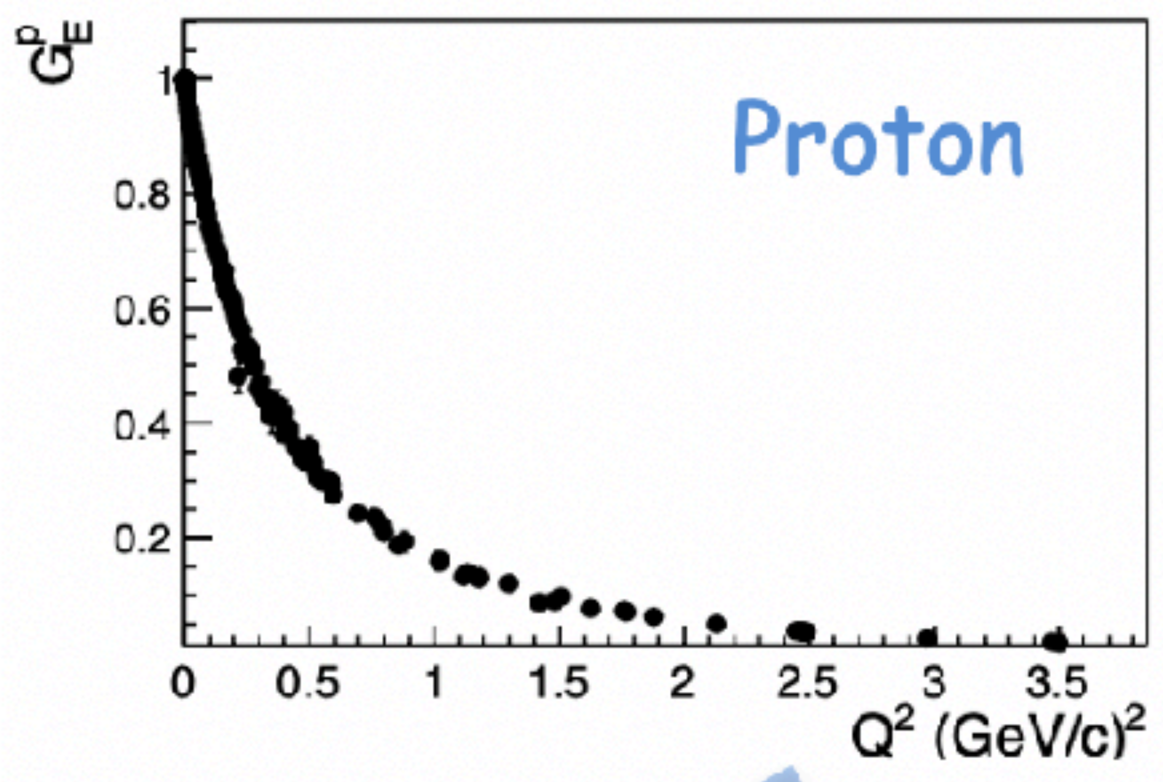
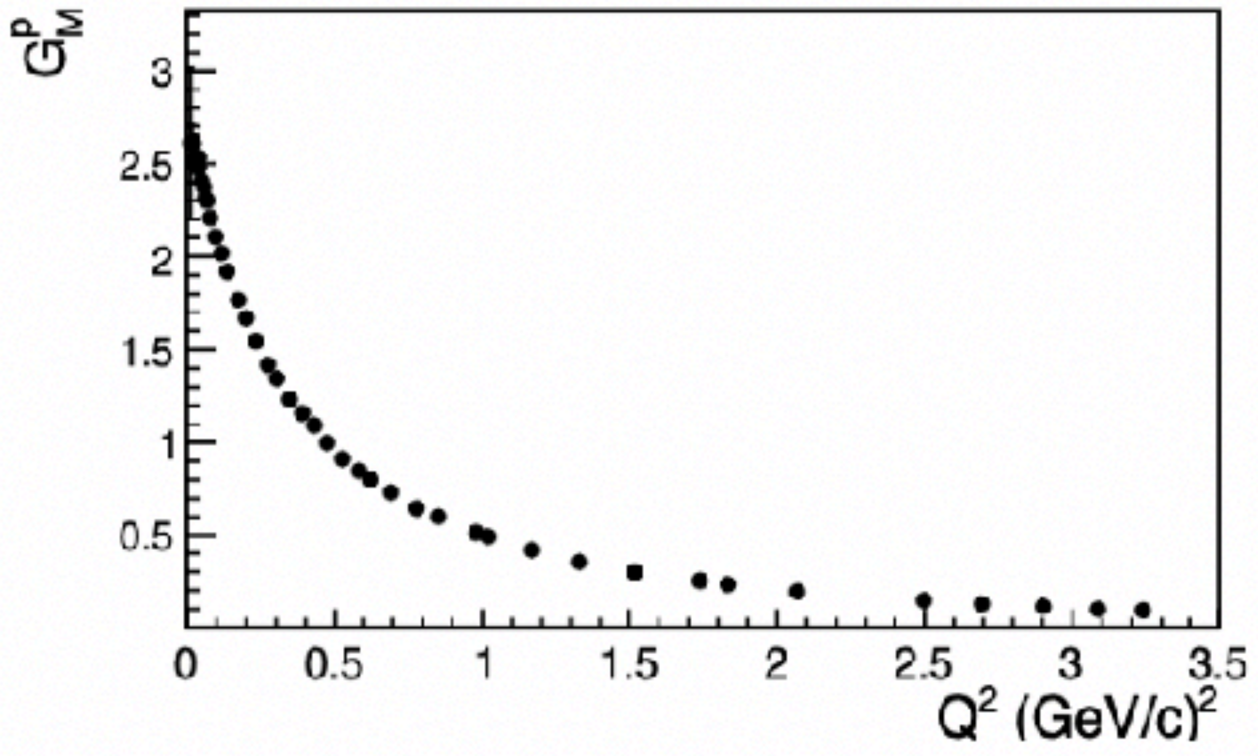


FIG. 3 (color). The Q^2 dependence for the u and d contributions to the proton form factors (multiplied by Q^4). The data points are explained in the text.

- Not a new concept.
  - Has previously been used to study high Q2 and scaling

Flavor decomposition at low Q2

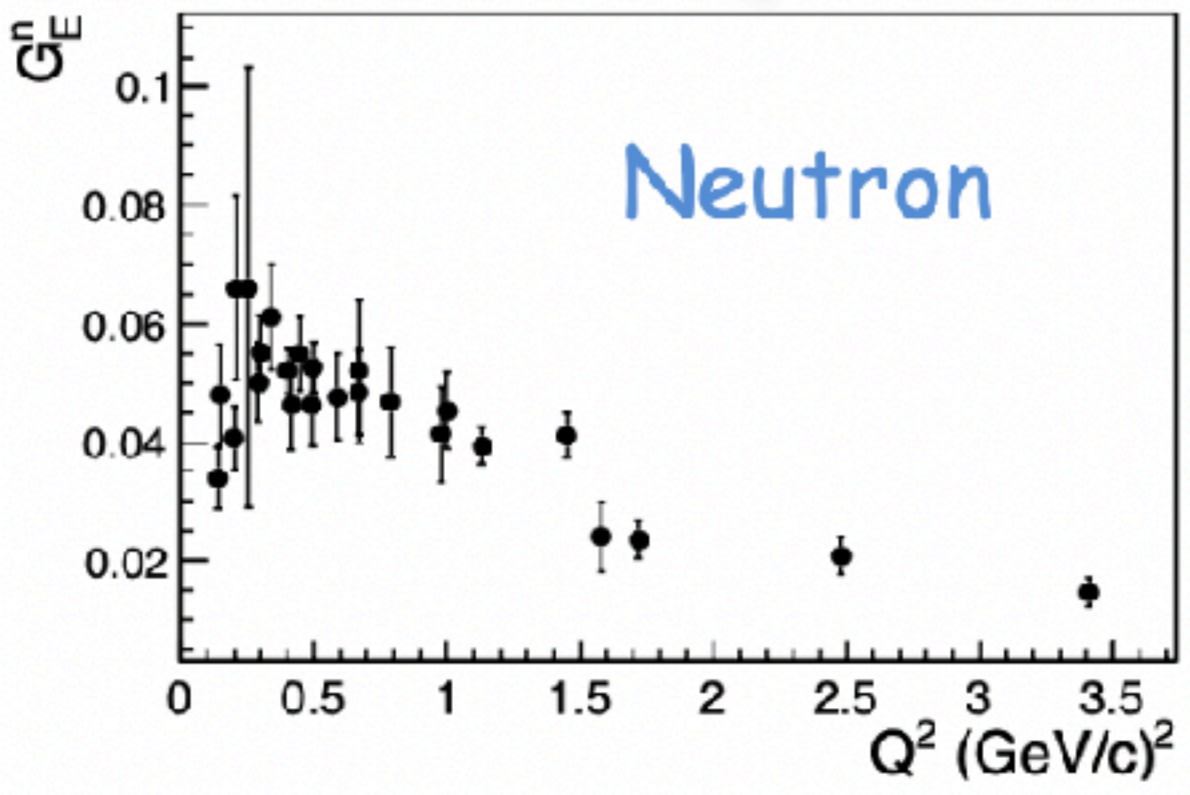


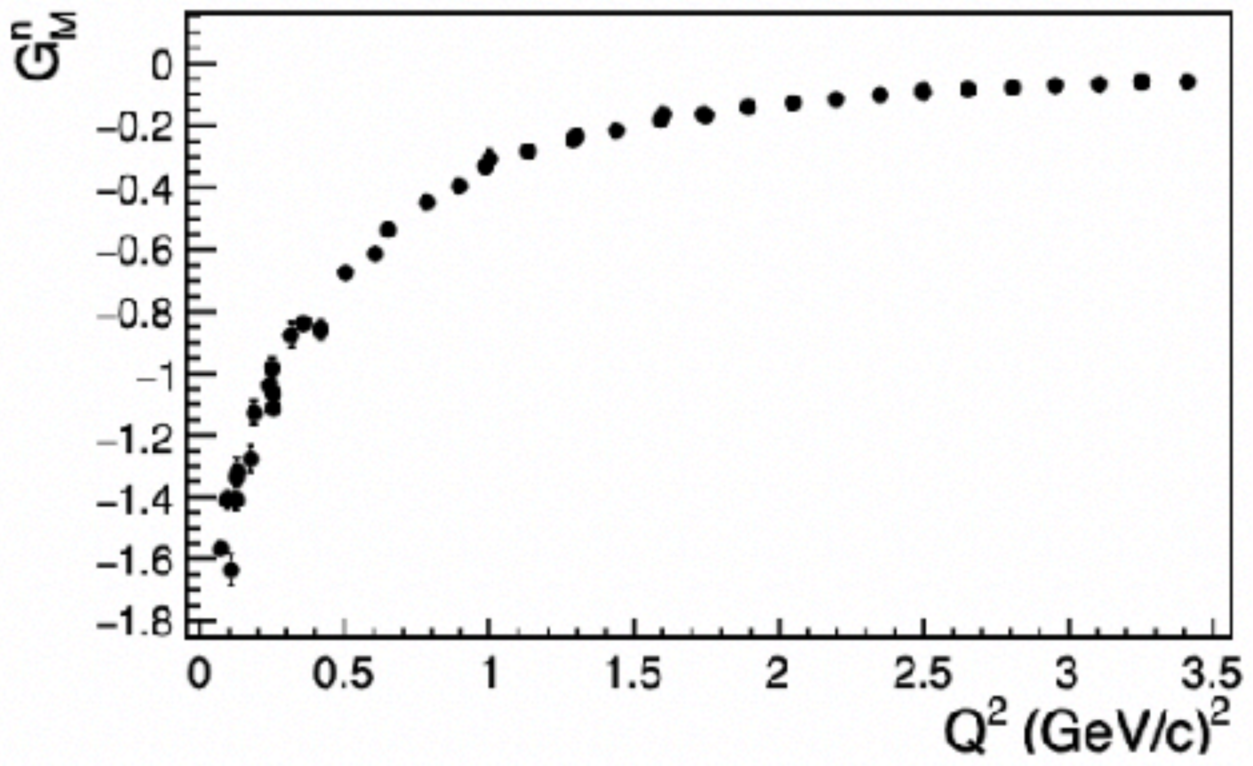


$$F_1 = (G_E + \tau G_M)/(1+\tau)$$

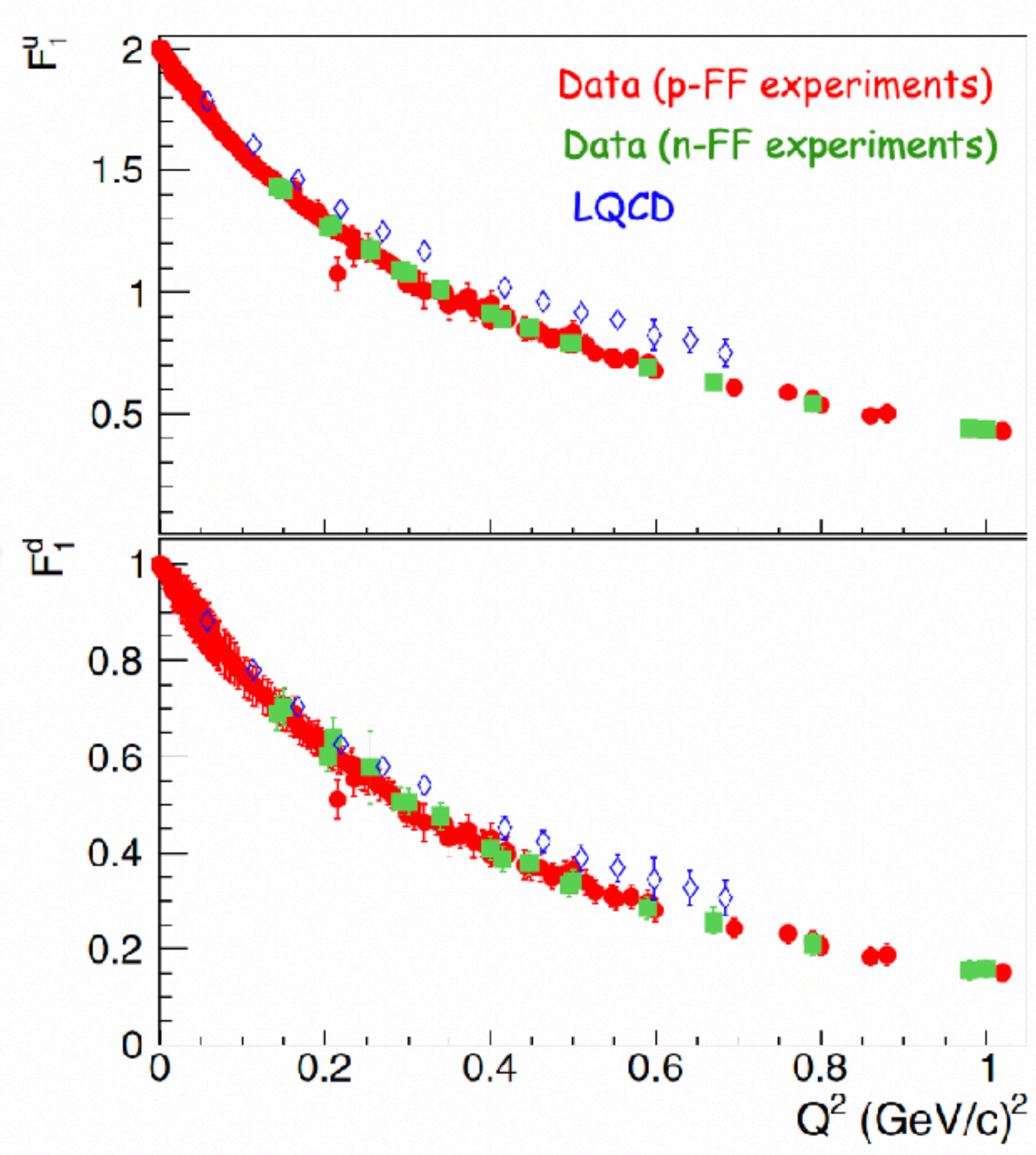
$$F_1^u = 2\,F_1^p + F_1^n$$

$$F_1^d = 2\,F_1^n + F_1^p$$



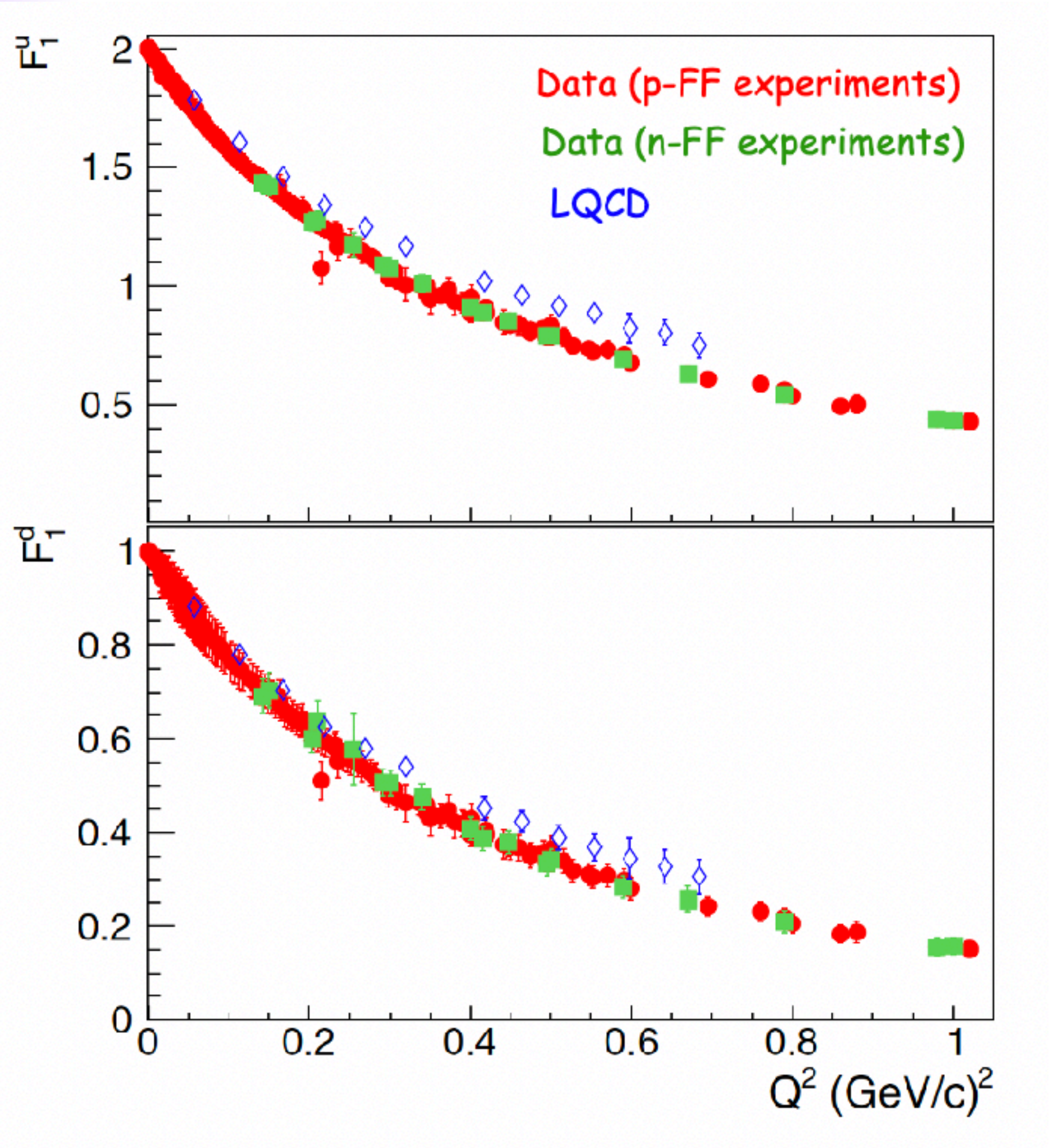


Eur. Phys. J. A 57, 65 (2021)

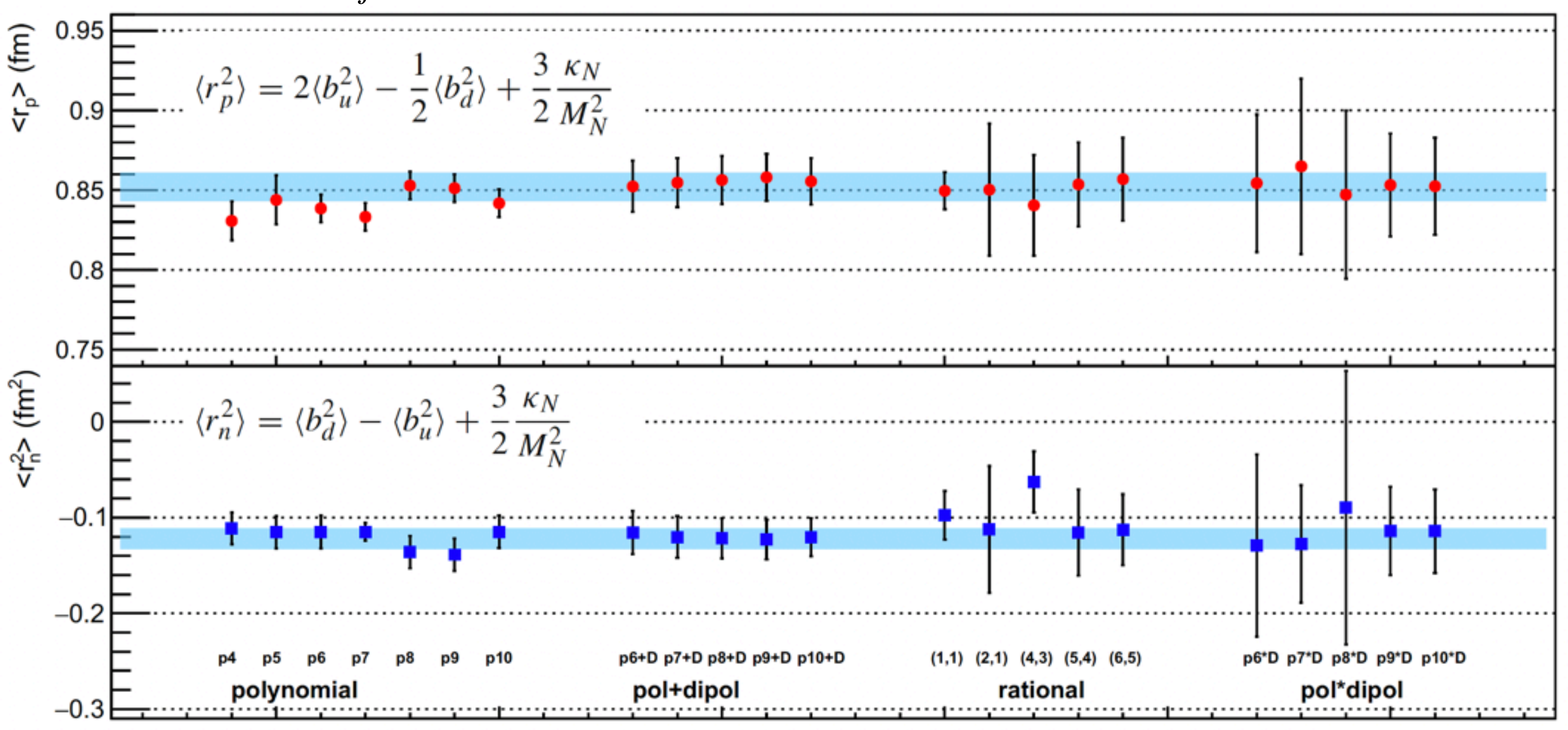


- Same procedure, but at low Q2

Radius extraction through flavor decomposition

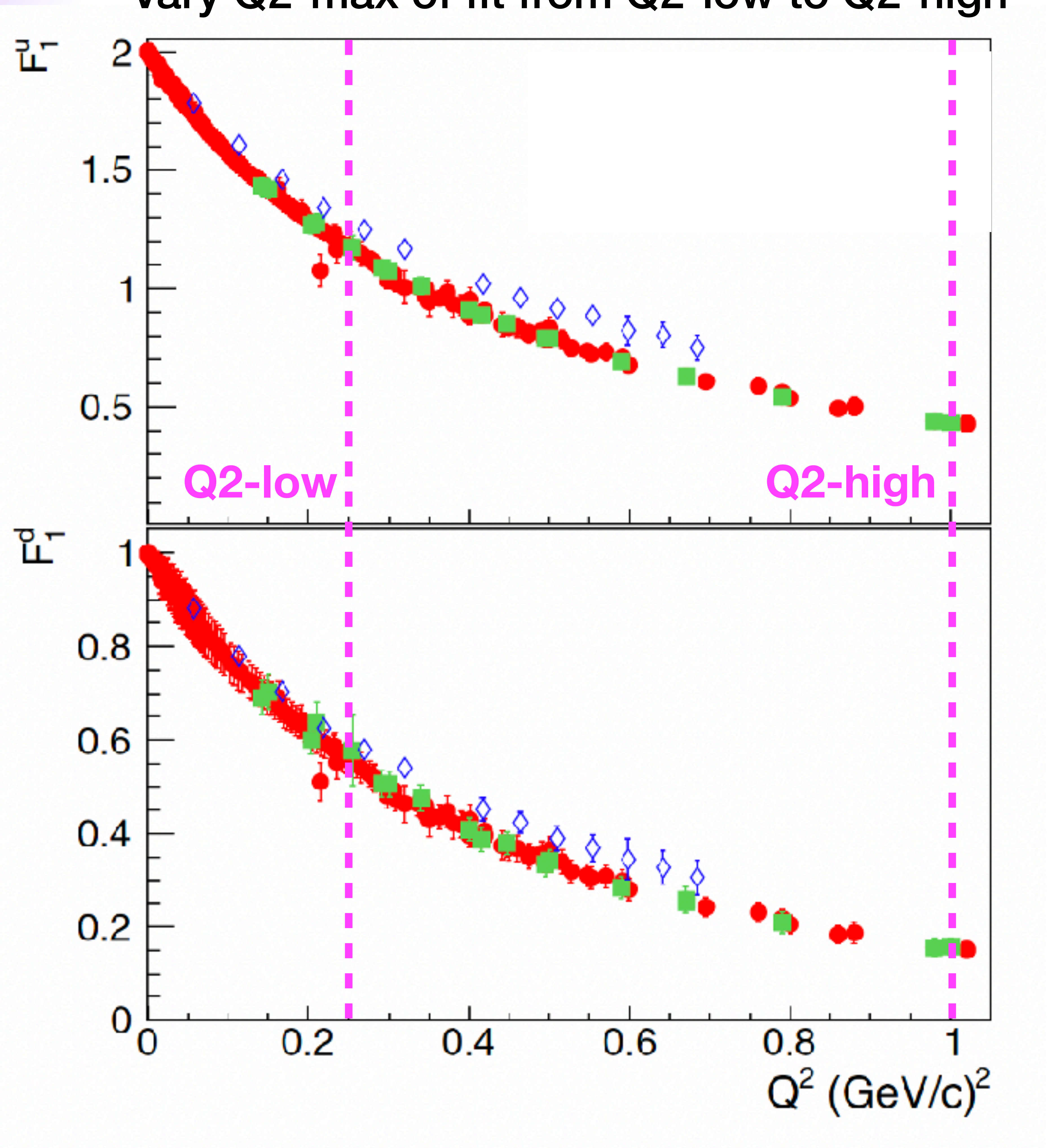


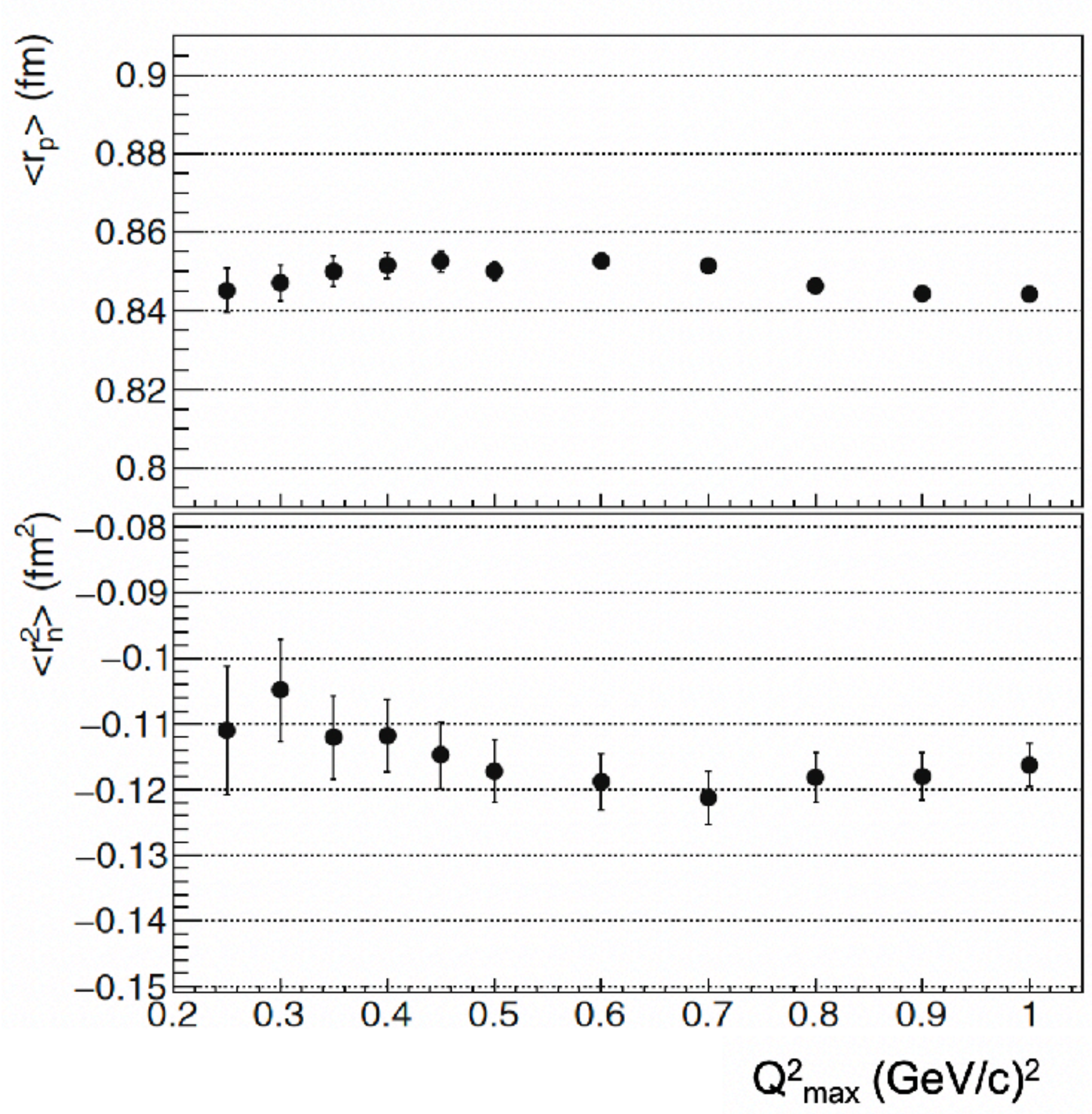
- Extract transverse quark radii: $\langle b^2_{u(d)} \rangle = \frac{-4}{F_1^{u(d)}(0)} \frac{dF_1^{u(d)}(Q^2)}{dQ^2}\Big|_{Q^2 \to 0}$
- Fit F_1^u and F_1^d simultaneously using same functional form.
- Consider continuous forms: polynomial, polynomial + dipole, rational $\frac{\sum_i \alpha_i (Q^2)^i}{1 + \sum_j \beta_j (Q^2)^j}$, polynomial time dipole.



Radius extraction through flavor decomposition

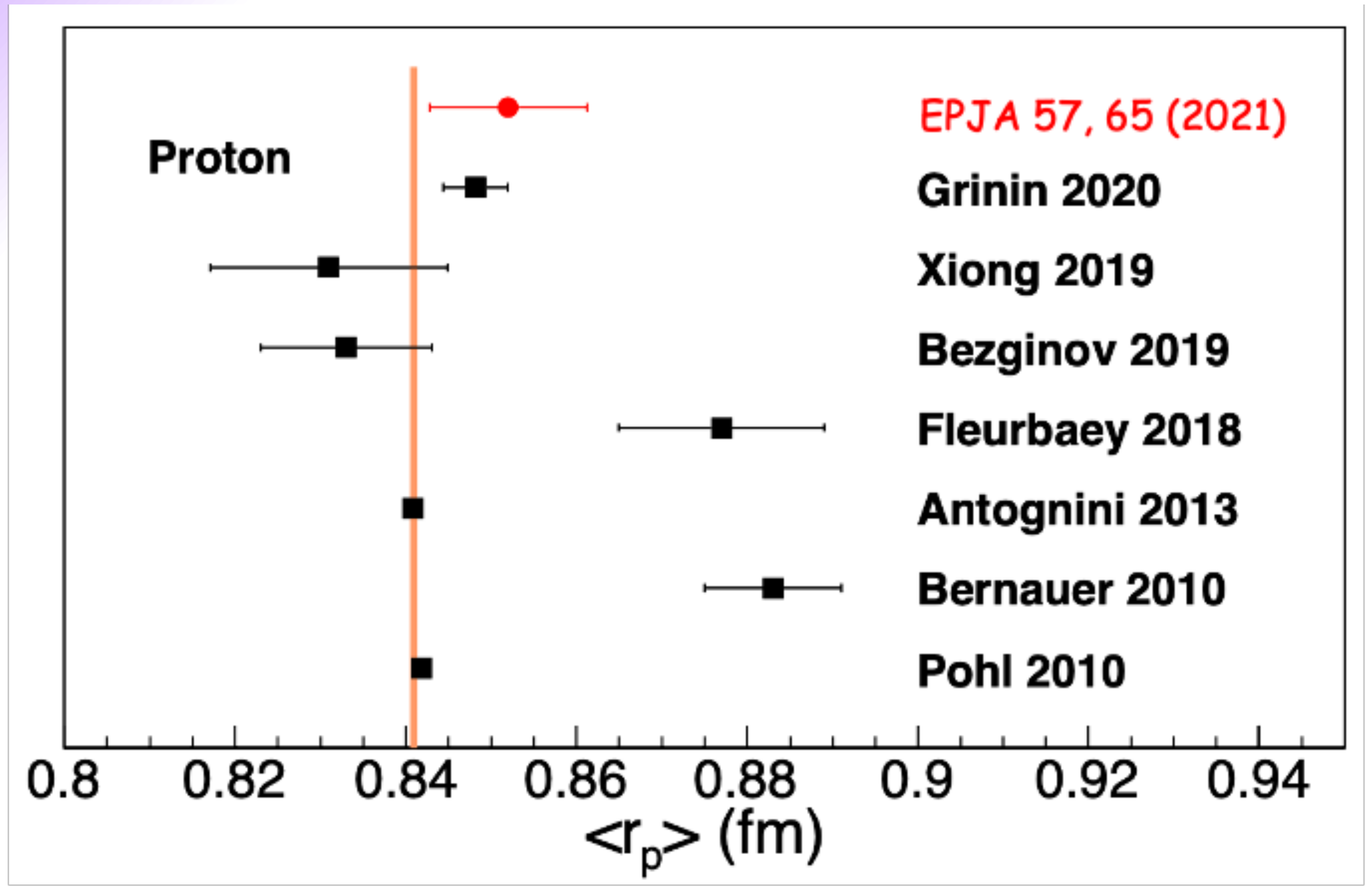
Vary Q2-max of fit from Q2-low to Q2-high

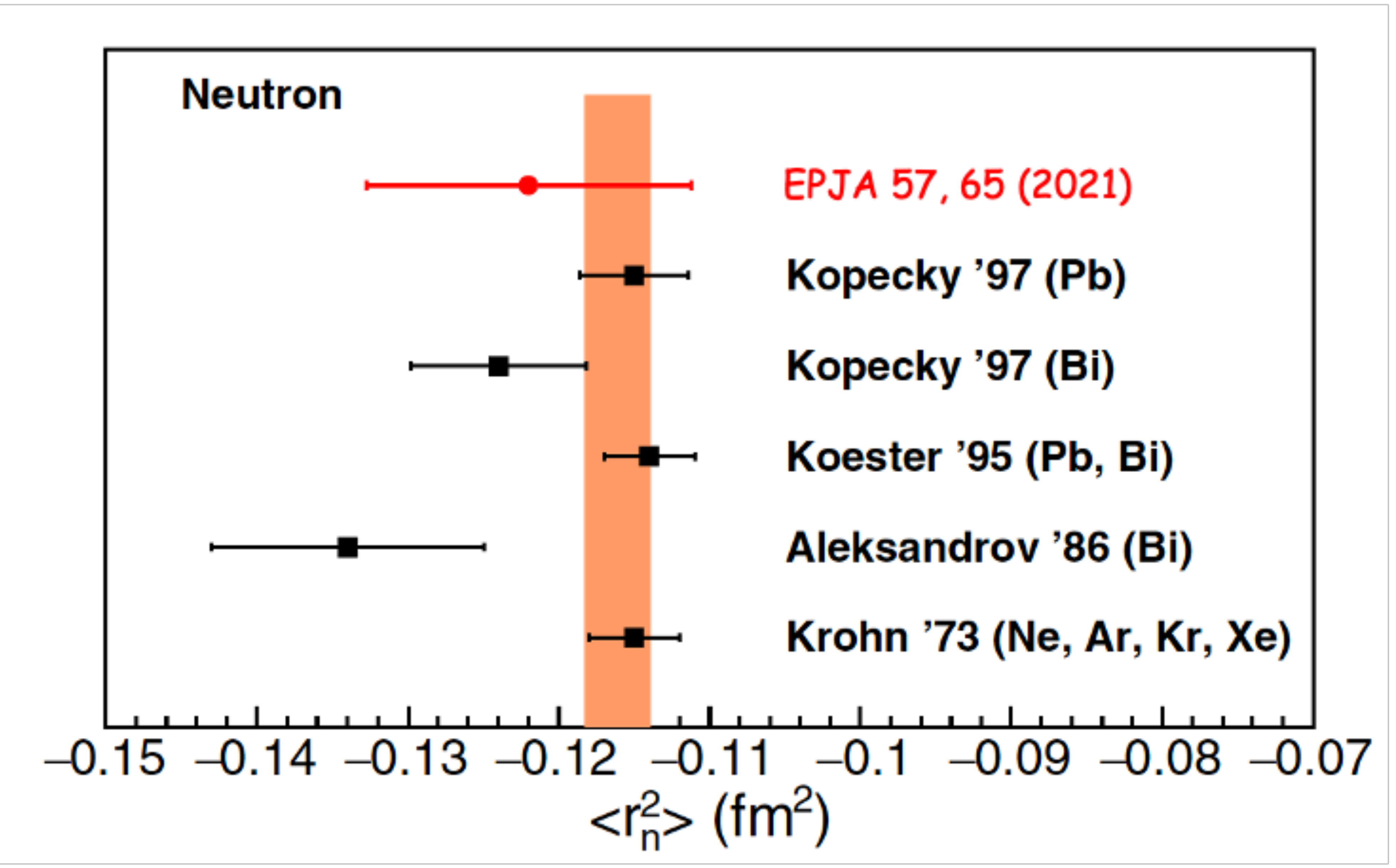




Variance in fit-function and fit range are considered in the total systematic uncertainty

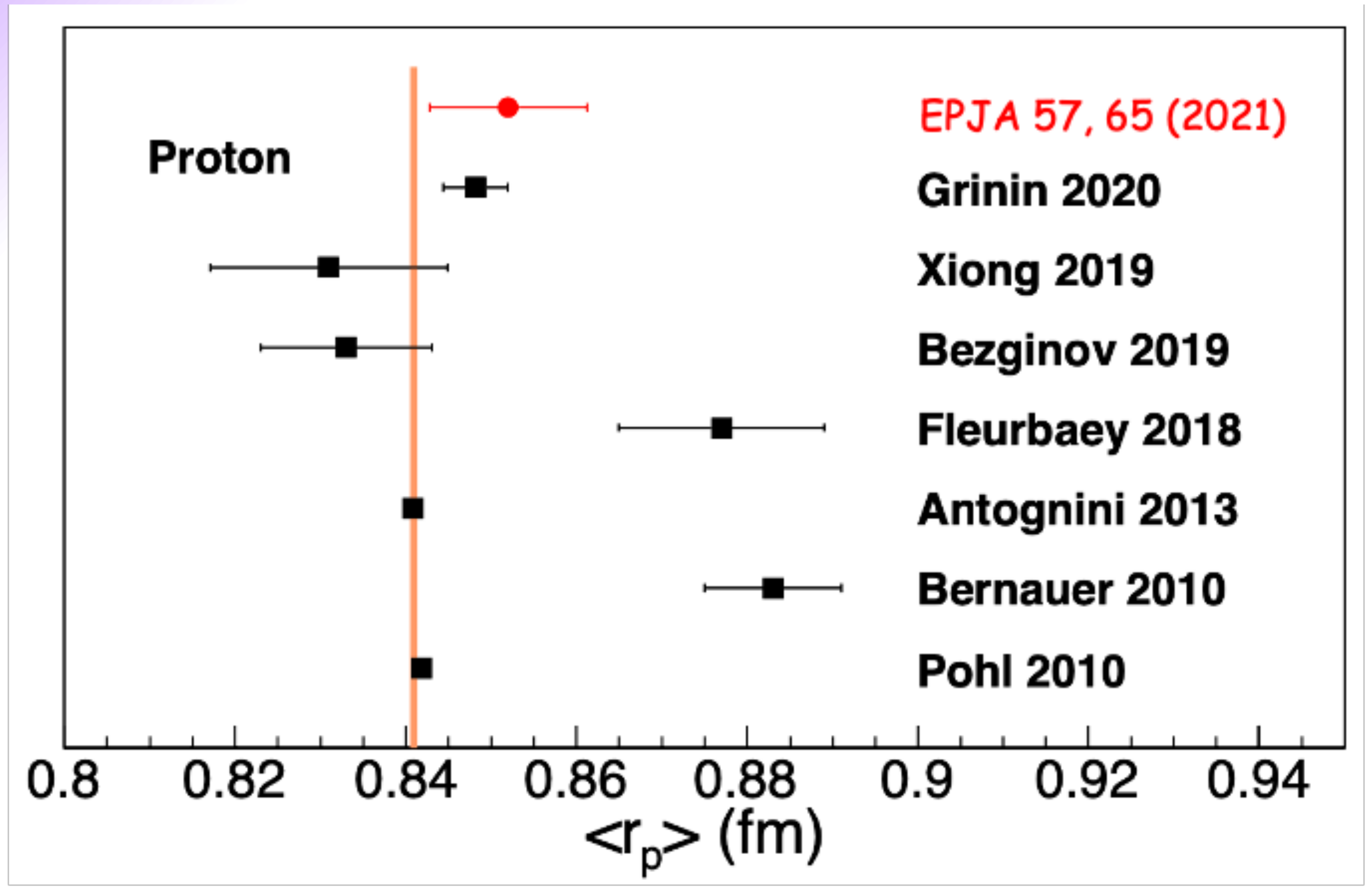
Radius extraction through flavor decomposition

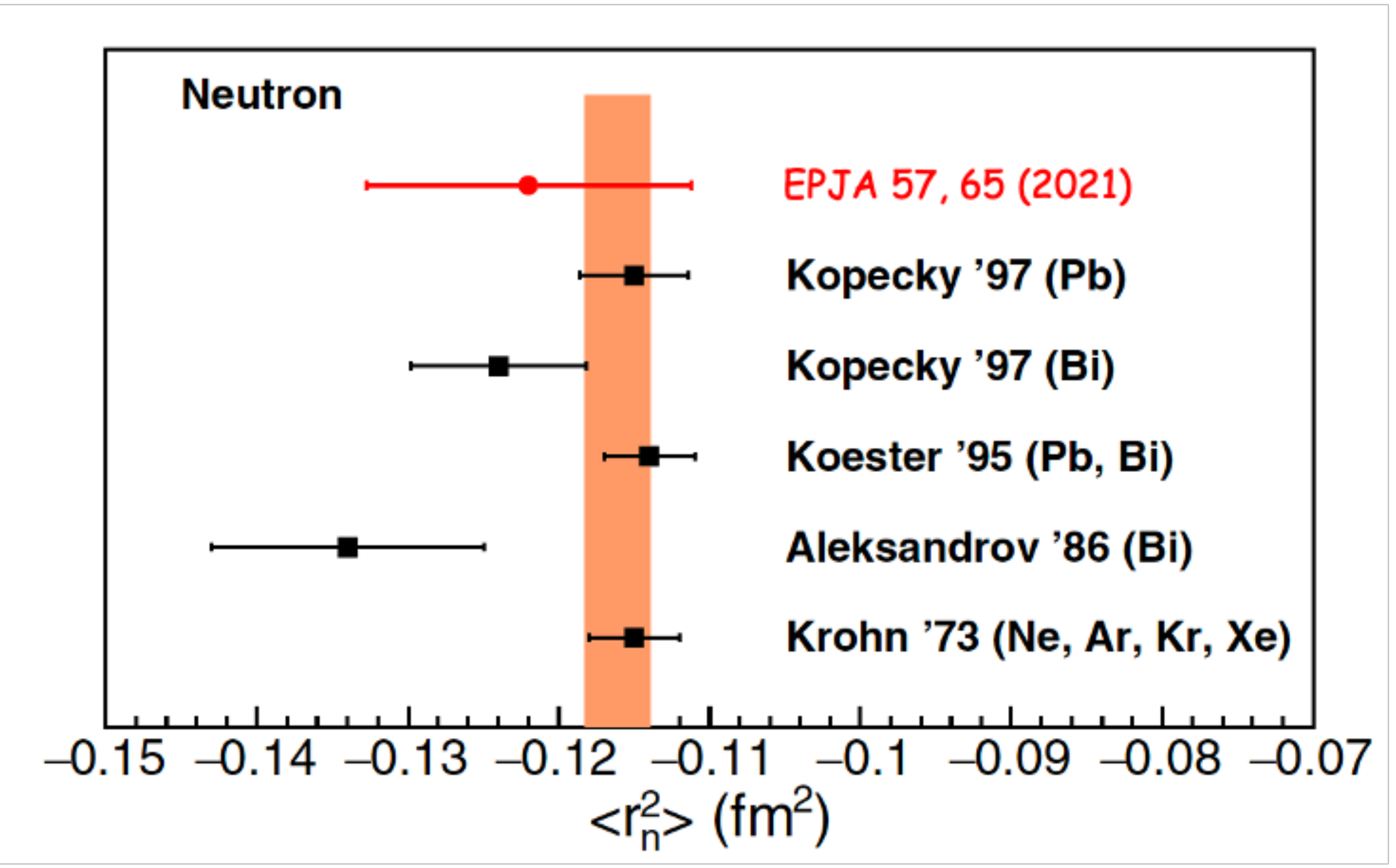




- Eur. Phys. J. A 57, 65 (2021), H. Atac, M. Constantinou, Z.E. Meziani, M. Paolone, N. Sparveris:
  - $\langle r_p \rangle = 0.852 \pm 0.002_{(\text{stat.})} \pm 0.009_{(\text{syst.})}$ (fm)
  - $\langle r_n^2 \rangle = -0.122 \pm 0.004_{(\text{stat.})} \pm 0.010_{(\text{syst.})}$ (fm^2)

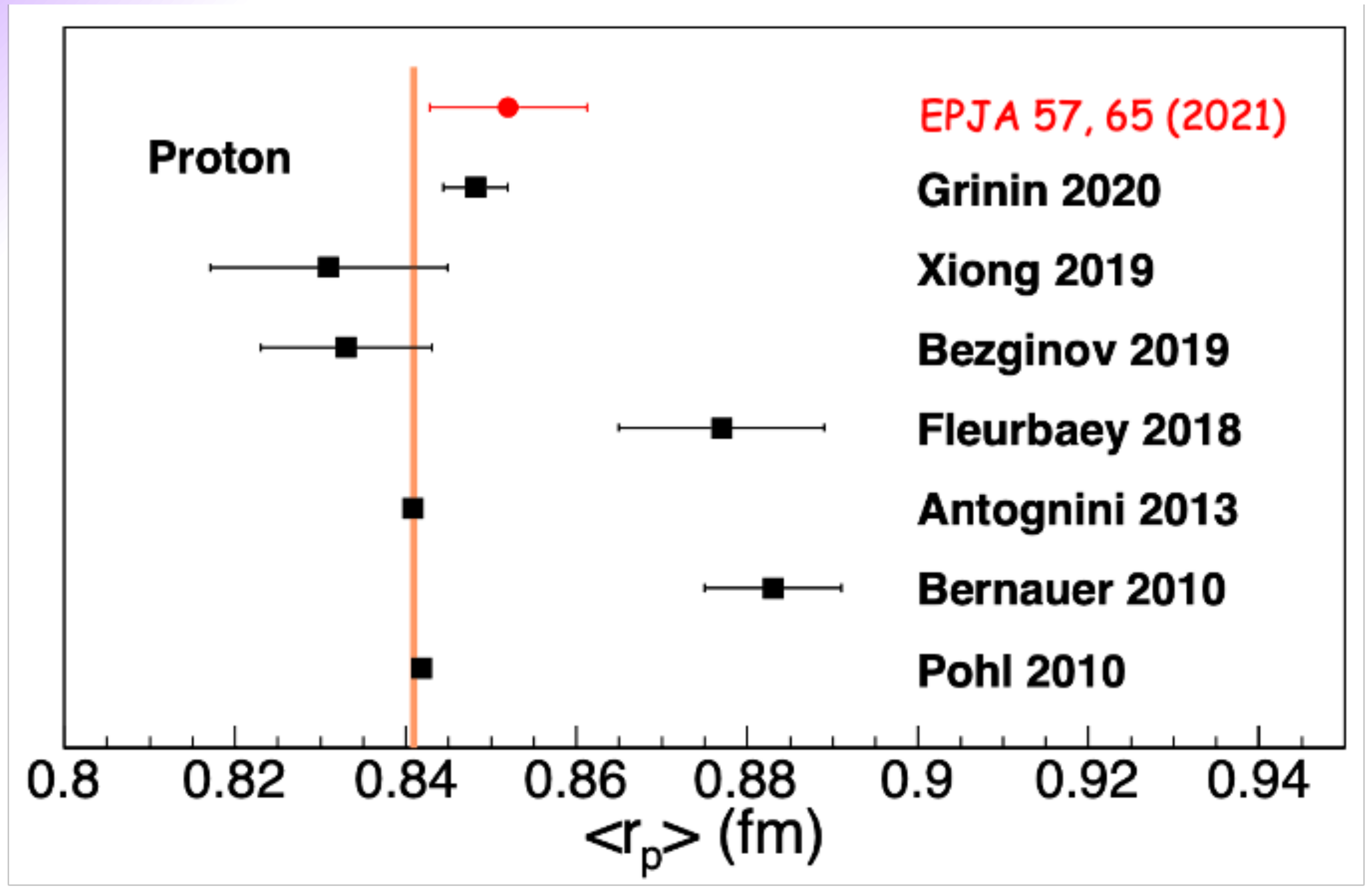
Radius extraction through flavor decomposition

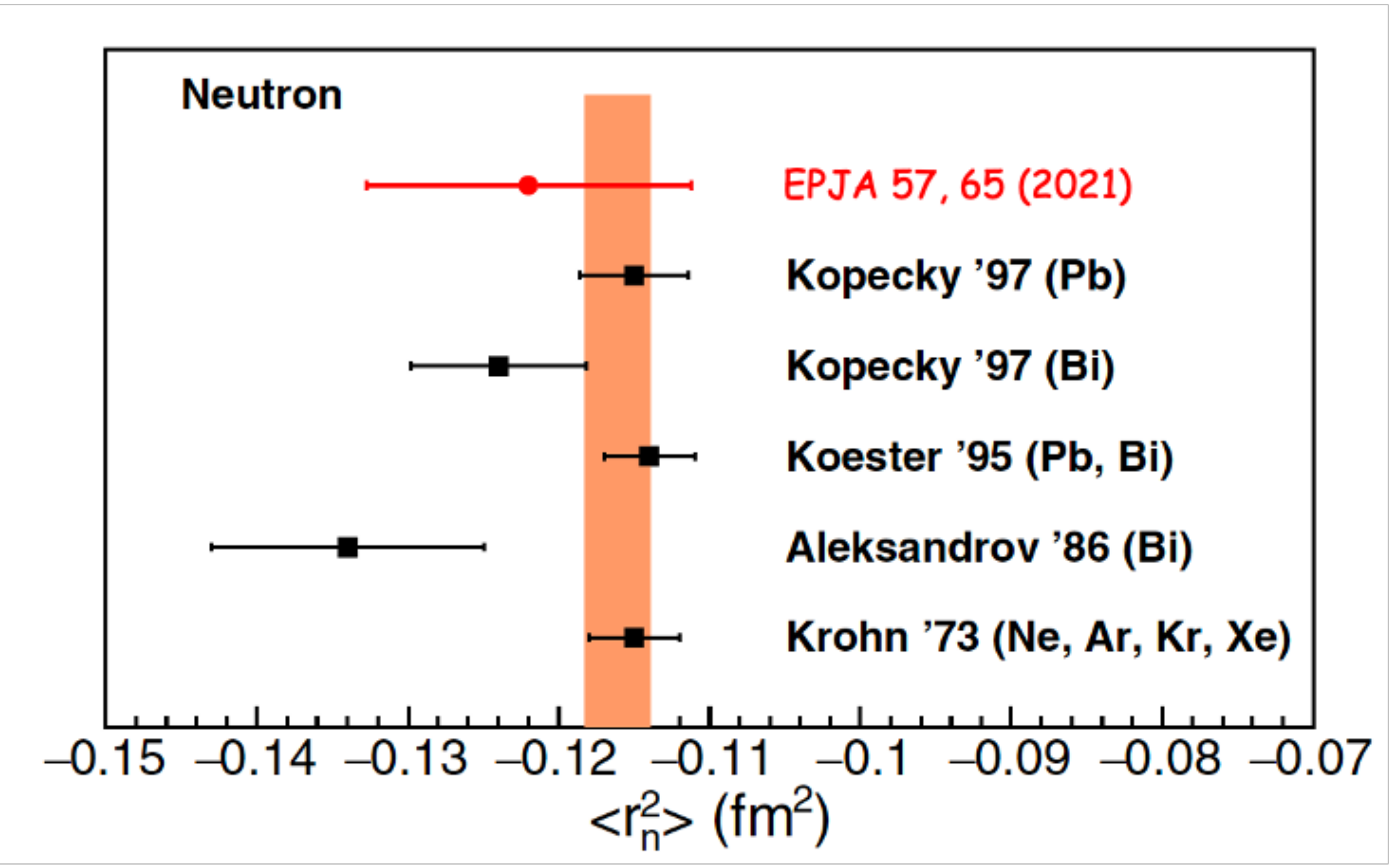




- **Note on Mainz vs PRad proton radius:**
  - The extraction is done on Mainz + PRad data:
    - $\langle r_p \rangle_{\text{Mainz+PRad}} = 0.852(10)$ fm
  - But also on the Mainz data alone:
    - $\langle r_p \rangle_{\text{Mainz}} = 0.857(13)$ fm
  - No significant difference between the proton radius with or without PRad (2019) data.
  - Both results are consistent with "smaller" proton radius.

Radius extraction through flavor decomposition





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  - No significant difference between the proton radius with or without PRad (2019) data.
  - Both results are consistent with "smaller" proton radius.

- **Provides new nucleon radii points:**
  - Neutron precision (~9%) remains inadequate to reconcile discrepancies.
  - Needs more leverage at low Q² for G_E^n

A path to extend our low Q^2 reach for G_E^n

PHYSICAL REVIEW D 76, 111501(R) (2007)

Large-N_c relations for the electromagnetic nucleon-to-Δ form factors

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(Received 3 November 2006; published 6 December 2007)

We examine the large-N_c relations which express the electromagnetic N-to-Δ transition quantities in terms of the electro… relation between th… derived large-N_c rel… Extending these rel… electromagnetic N… which may be ascri… for the $N \to \Delta$ gen…

VOLUME 93, NUMBER 21 PHYSICAL REVIEW LETTERS week ending 19 NOVEMBER 2004

Electromagnetic $N \to \Delta$ Transition and Neutron Form Factors

A. J. Buchmann*
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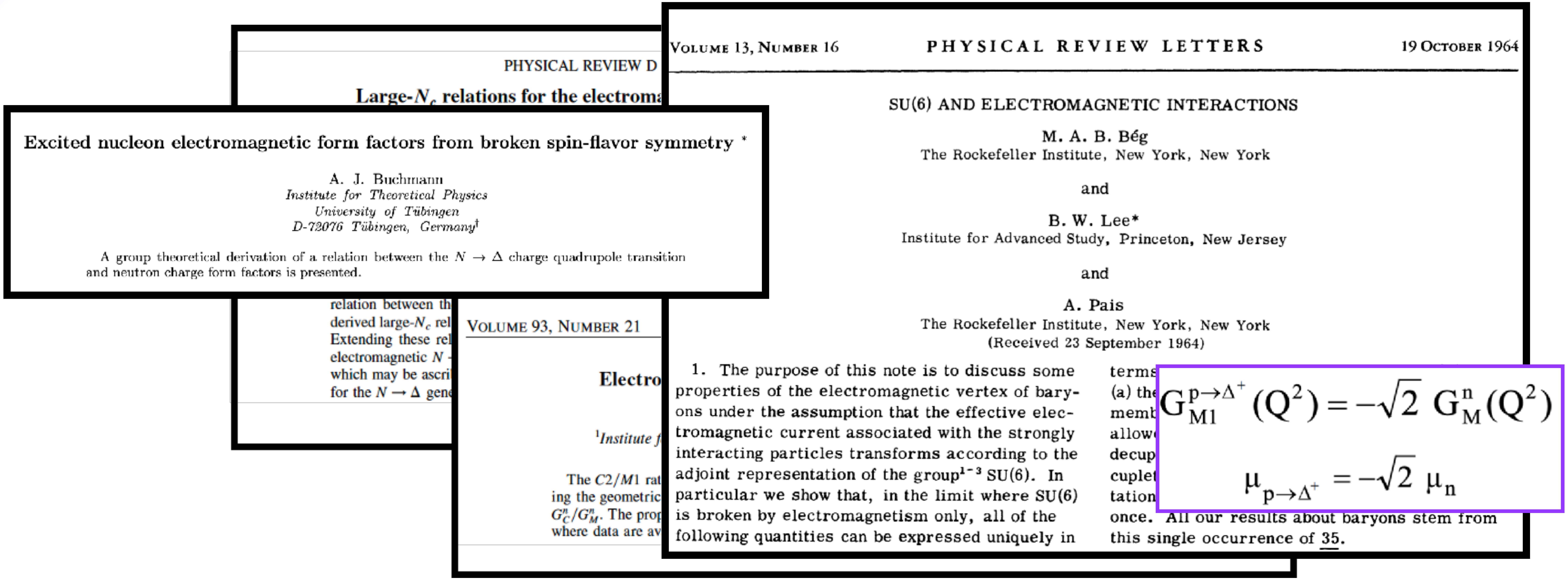
(Received 10 July 2004; published 17 November 2004)

The $C2/M1$ ratio of the electromagnetic $N \to \Delta(1232)$ transition, which is important for determining the geometric shape of the nucleon, is shown to be related to the neutron elastic form factor ratio G_C^n/G_M^n. The proposed relation holds with good accuracy for the entire range of momentum transfers where data are available.

- **It has been long known that there is a correlation between the N-Δ TFFs and G_E^n**
  - Initially exploited in reverse to infer information for the N-Δ TFFs, while they were not yet very well measured.
  - 15 years later: the N-Δ TFFs can be accessed at lower Q^2 and with higher precision, compared to the current G_E^n measurements

A path to extend our low Q^2 reach for G_E^n


PHYSICAL REVIEW D

Large-N_c relations for the electroma

Excited nucleon electromagnetic form factors from broken spin-flavor symmetry *

A. J. Buchmann
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D-72076 Tübingen, Germany†

A group theoretical derivation of a relation between the $N \to \Delta$ charge quadrupole transition and neutron charge form factors is presented.

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VOLUME 13, NUMBER 16 — PHYSICAL REVIEW LETTERS — 19 OCTOBER 1964

SU(6) AND ELECTROMAGNETIC INTERACTIONS

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and

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The Rockefeller Institute, New York, New York
(Received 23 September 1964)

1. The purpose of this note is to discuss some properties of the electromagnetic vertex of baryons under the assumption that the effective electromagnetic current associated with the strongly interacting particles transforms according to the adjoint representation of the group[1-3] SU(6). In particular we show that, in the limit where SU(6) is broken by electromagnetism only, all of the following quantities can be expressed uniquely in

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once. All our results about baryons stem from this single occurrence of 35.

$$G_{M1}^{p\to\Delta^+}(Q^2) = -\sqrt{2}\; G_M^n(Q^2)$$

$$\mu_{p\to\Delta^+} = -\sqrt{2}\;\mu_n$$

- **It has been long known that there is a correlation between the N-Δ TFFs and G_E^n**
  - Initially exploited in reverse to infer information for the N-Δ TFFs, while they were not yet very well measured.
  - 15 years later: the N-Δ TFFs can be accessed at lower Q^2 and with higher precision, compared to the current G_E^n measurements

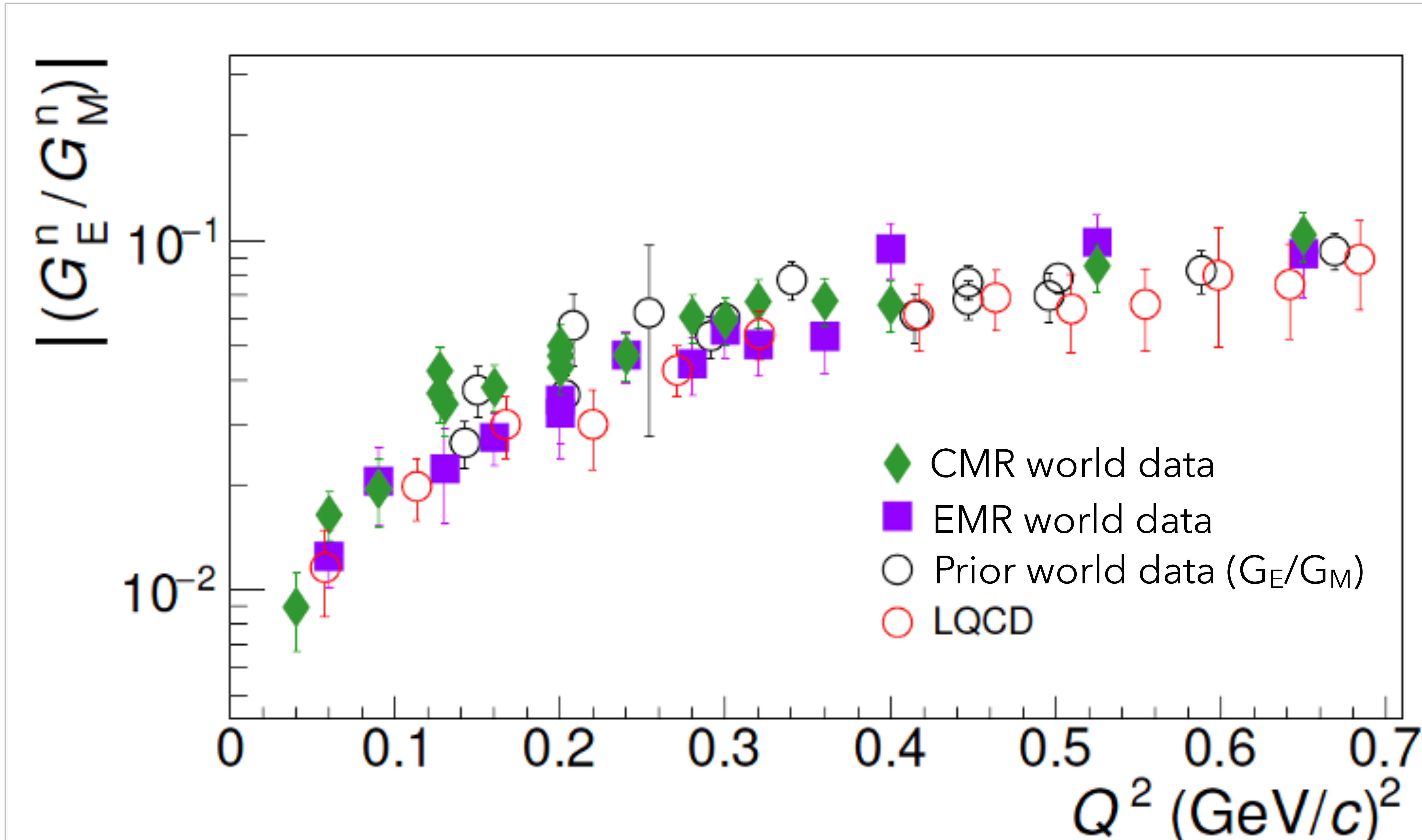
A path to extend our low Q^2 reach for G_E^n

Large-N$_c$ Relations (Pascalutsa & Vanderhaeghen)
Phys. Rev. D76. 93, 111501(R) (2007)

$$\frac{E2}{M1}(Q^2) = \left(\frac{M_N}{M_\Delta}\right)^{3/2} \frac{M_\Delta^2 - M_N^2}{2Q^2} \frac{G_E^n(Q^2)}{F_2^p(Q^2) - F_2^n(Q^2)}$$

$$\frac{C2}{M1}(Q^2) = \left(\frac{M_N}{M_\Delta}\right)^{3/2} \frac{Q_+ Q_-}{2Q^2} \frac{G_E^n(Q^2)}{F_2^p(Q^2) - F_2^n(Q^2)}$$

- **Large-Nc relations:**
  - Carry about 15% theoretical uncertainty.
  - Two relations (CMR and EMR) can be used to cross-check validity.

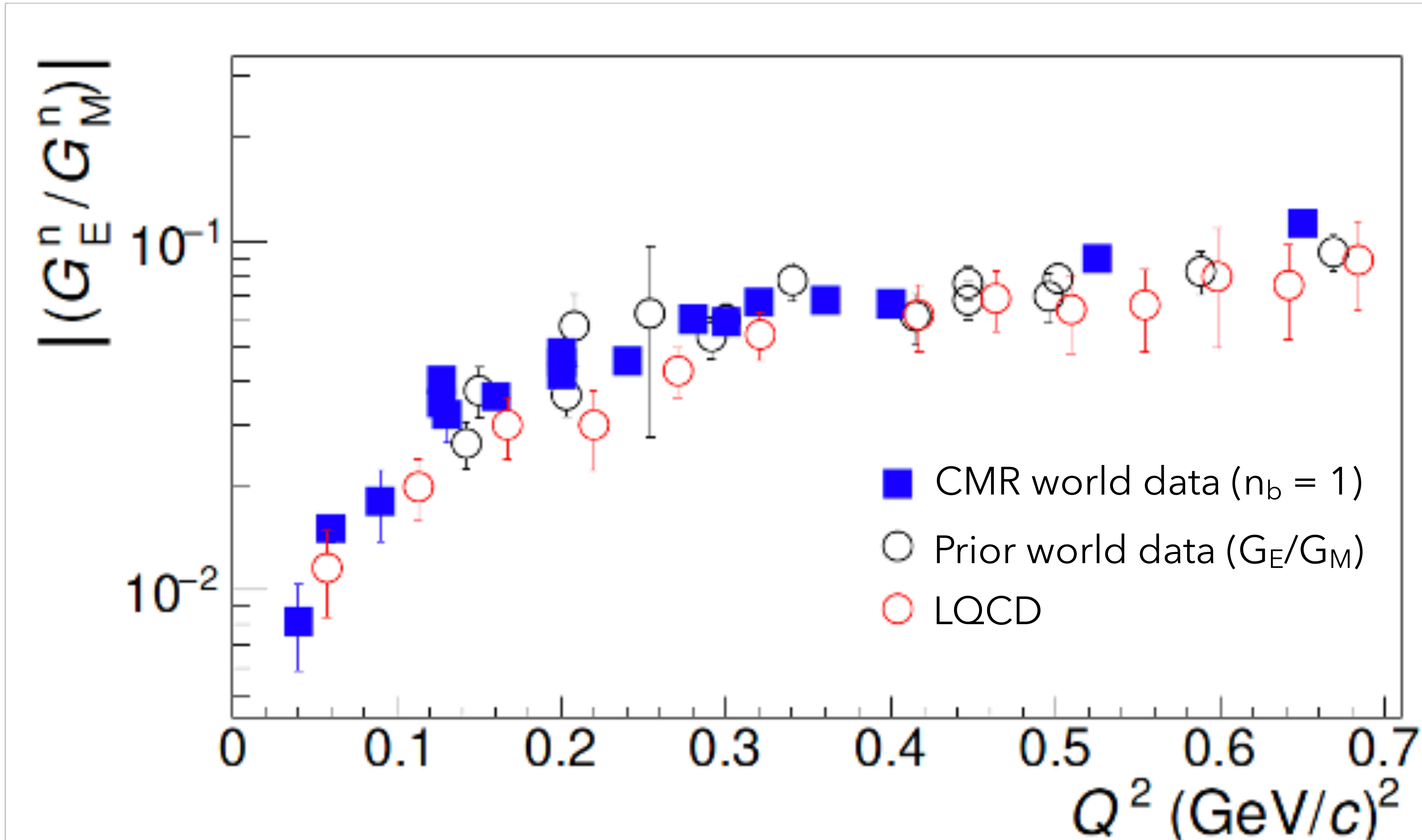


A path to extend our low Q^2 reach for G_E^n

A. J. Buchmann
Phys. Rev. Lett. 93, 212301 (2004)

$$\frac{G_E^n(Q^2)}{G_M^n(Q^2)} = \frac{Q}{|\mathbf{q}|}\frac{2Q}{M_N}\frac{1}{n_b(Q^2)}\frac{C2}{M1}(Q^2)$$

- **Buchmann SU(6) form:**
  - Ratios are related due to the underlying spin-flavor symmetry and its breaking by spin-dependent two- and three-quark currents
  - Theoretical correction (n_b) is ~10% (i.e. it reduces the G_E^n/G_M^n ratio by n_b~1.1) mainly due to third order SU(6) breaking terms (three-quark currents) omitted in the relation between G_M^n and $G_{M1}^{N\to\Delta}$



A path to extend our low Q^2 reach for G_E^n

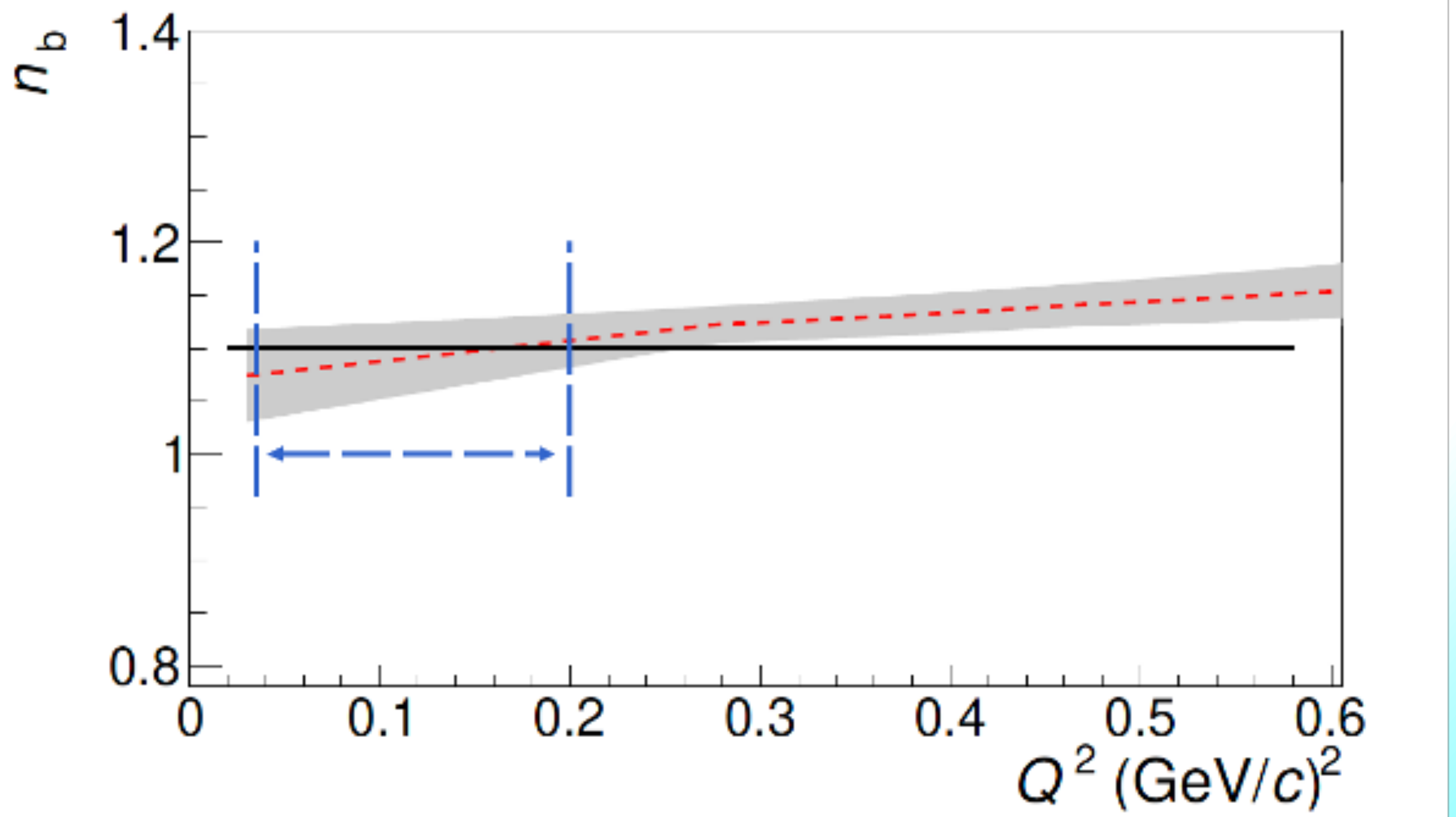
A. J. Buchmann
Phys. Rev. Lett. 93, 212301 (2004)

$$\frac{G_E^n(Q^2)}{G_M^n(Q^2)} = \frac{Q}{|\mathbf{q}|}\frac{2Q}{M_N}\frac{1}{n_b(Q^2)}\frac{C2}{M1}(Q^2)$$

This uncertainty can be parameterized from world CMR and ratio data

$$n_b(Q^2) = \frac{\frac{Q}{|\mathbf{q}|}\frac{2Q}{M_N}\frac{C2}{M1}(Q^2)}{\frac{G_E^n(Q^2)}{G_M^n(Q^2)}}$$

- **Buchmann SU(6) form:**
  - Ratios are related due to the underlying spin-flavor symmetry and its breaking by spin-dependent two- and three-quark currents
  - Theoretical correction (n_b) is ~10% (i.e. it reduces the G_E^n/G_M^n ratio by n_b~1.1) mainly due to third order SU(6) breaking terms (three-quark currents) omitted in the relation between G_M^n and $G_{M1}^{N\rightarrow\Delta}$



A path to extend our low Q^2 reach for G_E^n

A. J. Buchmann
Phys. Rev. Lett. 93, 212301 (2004)

$$\frac{G_E^n(Q^2)}{G_M^n(Q^2)} = \frac{Q}{|\mathbf{q}|}\frac{2Q}{M_N}\frac{1}{n_b(Q^2)}\frac{C2}{M1}(Q^2)$$

This uncertainty can be parameterized from world CMR and ratio data

$$n_b(Q^2) = \frac{\frac{Q}{|\mathbf{q}|}\frac{2Q}{M_N}\frac{C2}{M1}(Q^2)}{\frac{G_E^n(Q^2)}{G_M^n(Q^2)}}$$

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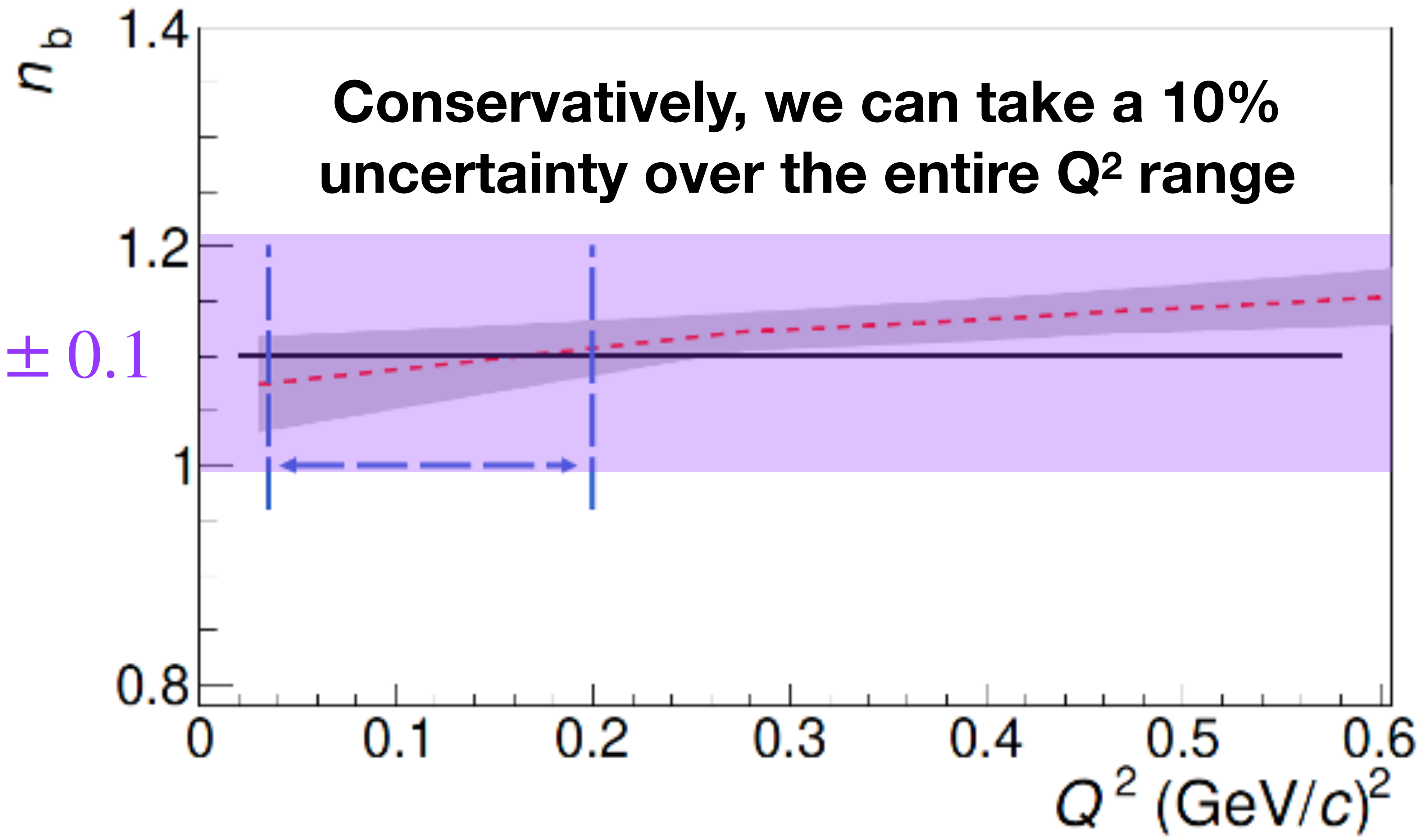
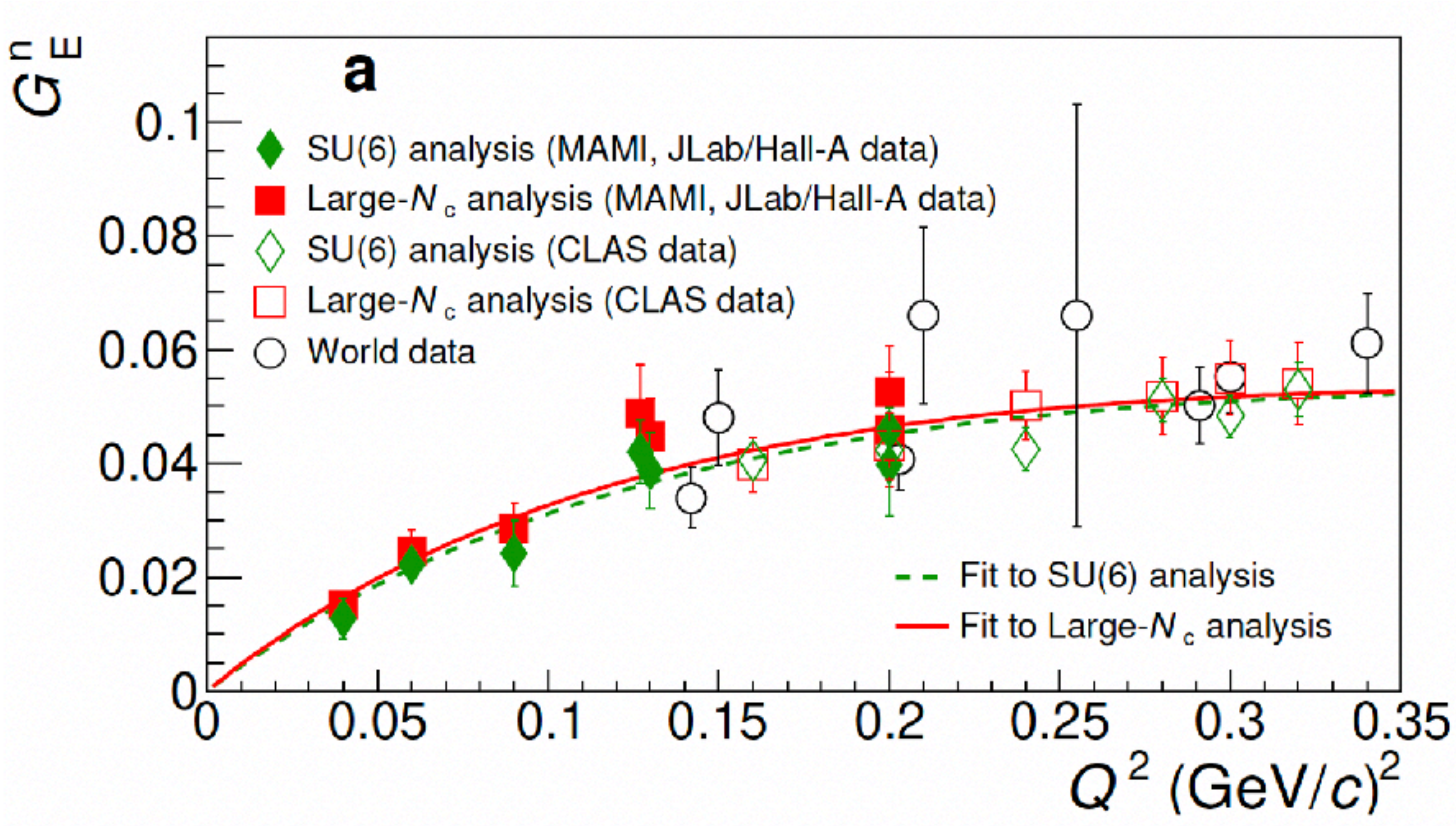
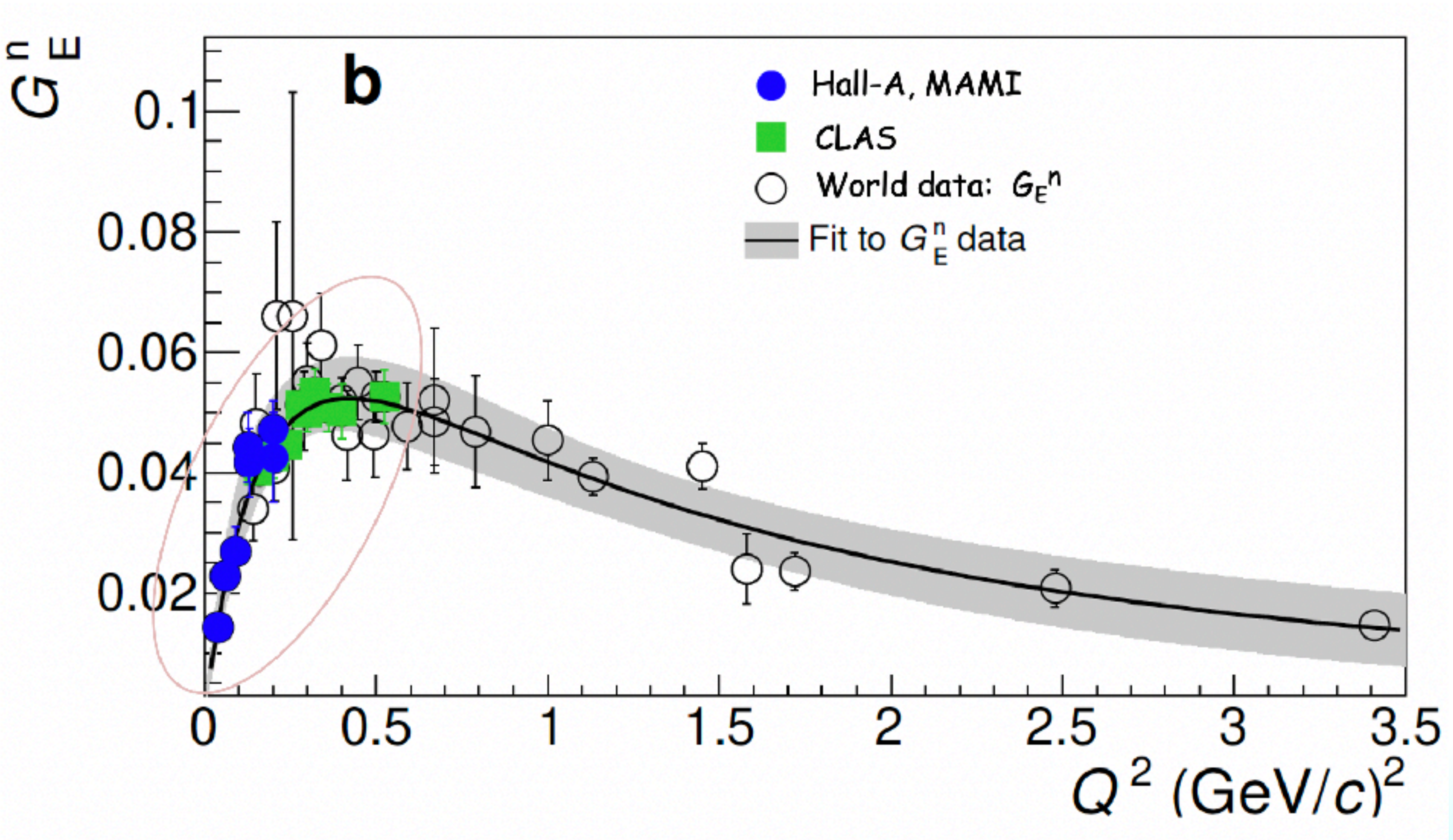
$n_b = 1.1 \pm 0.1$



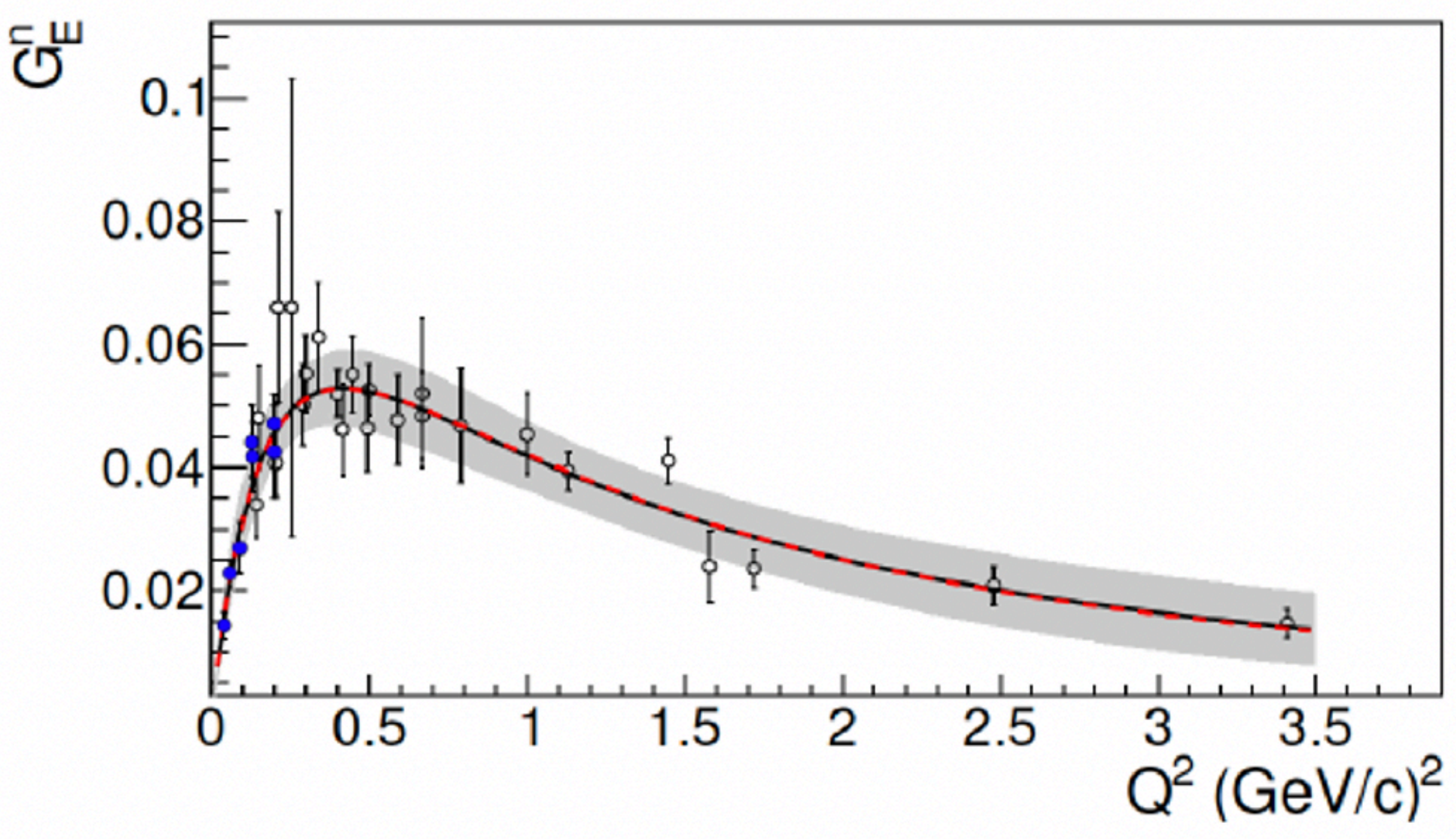
A path to extend our low Q^2 reach for G_E^n





A path to extend our low Q^2 reach for G_E^n

A note on form: Two common parameterizations
(Galster and 2-dipole) give near identical fits and radius:



Galster

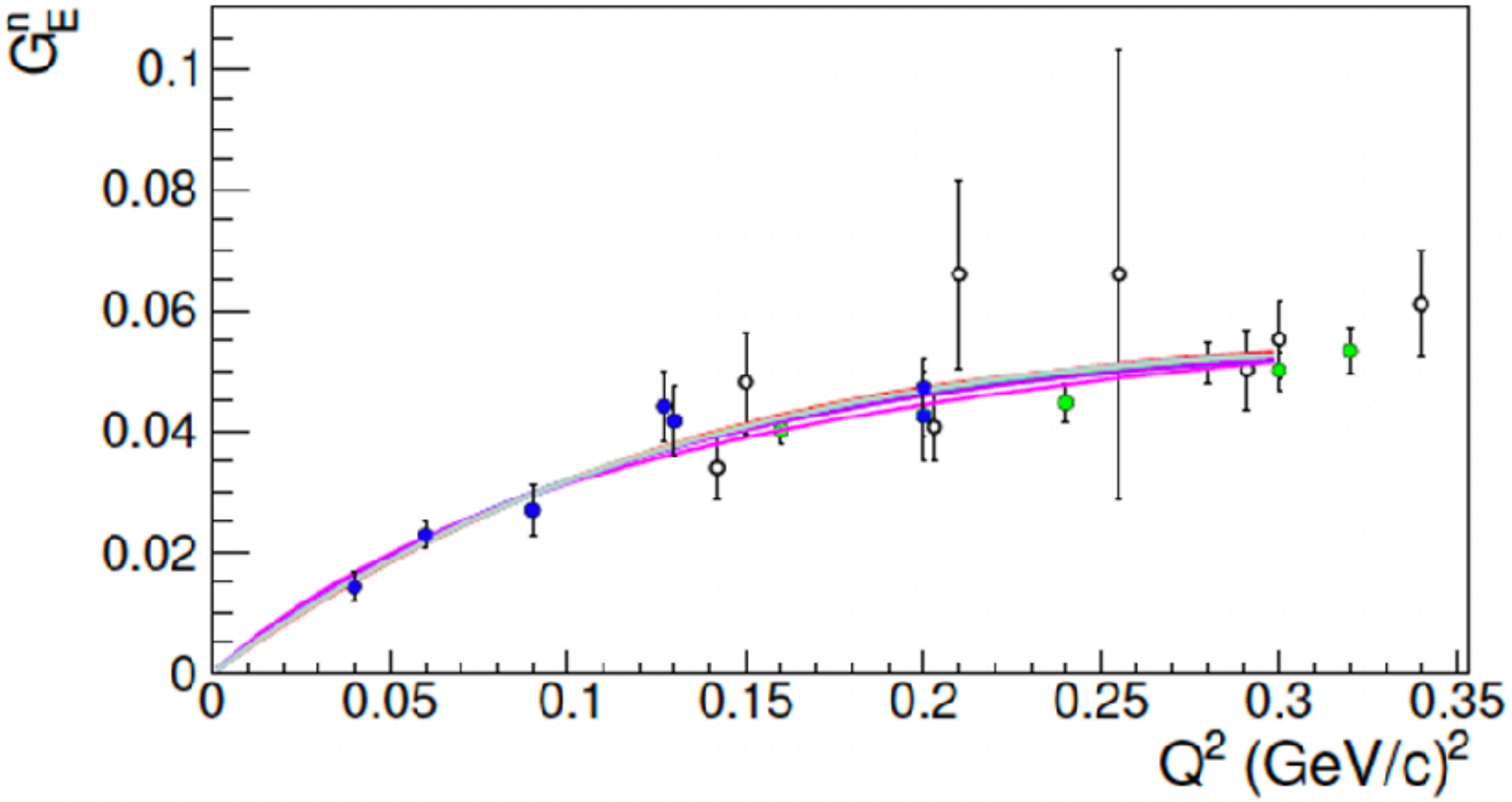
$$G_E^n(Q^2) = (1 + Q^2/A)^{-2} \frac{B\tau}{1 + C\tau}$$

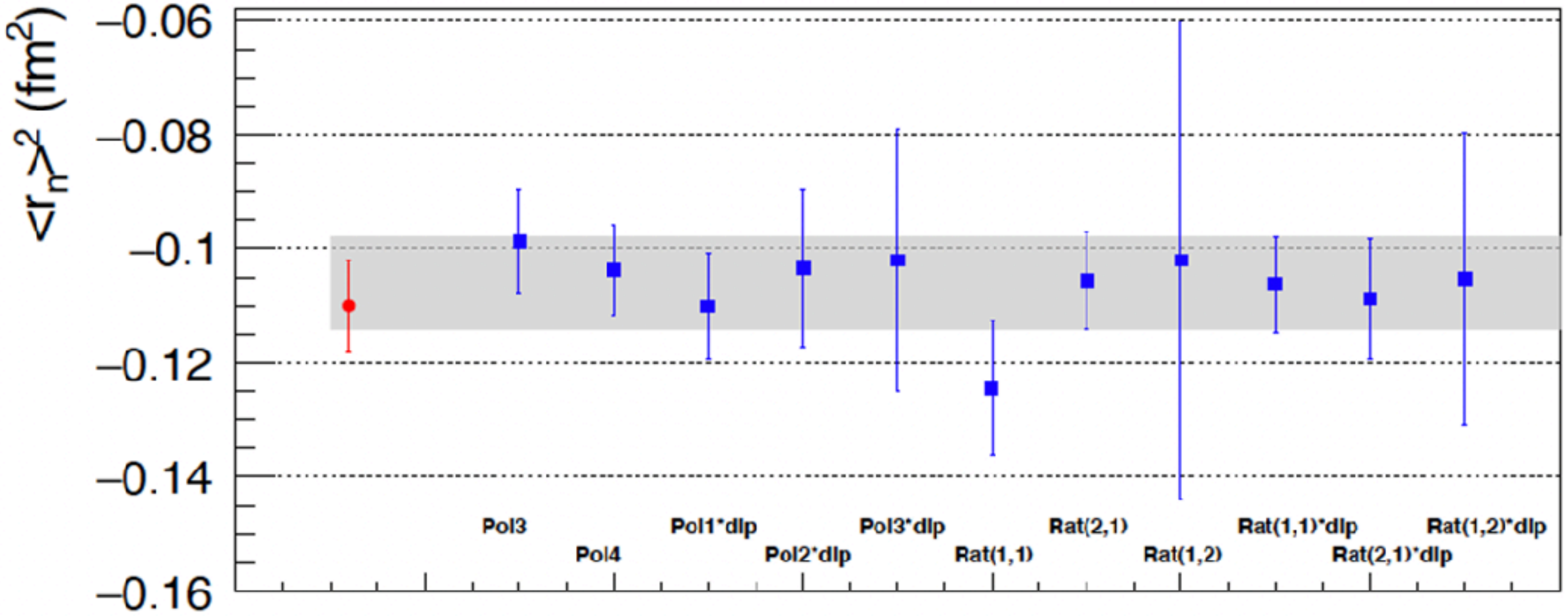
2-dipole

$$G_E^n(Q^2) = \frac{A}{(1 + \frac{Q^2}{B})^2} - \frac{A}{(1 + \frac{Q^2}{C})^2}$$

$$\langle r_n^2 \rangle = -6 \frac{dG_E^n(Q^2)}{dQ^2}\bigg|_{Q^2 \to 0} \to -0.110 \pm 0.008 \text{ fm}^2$$

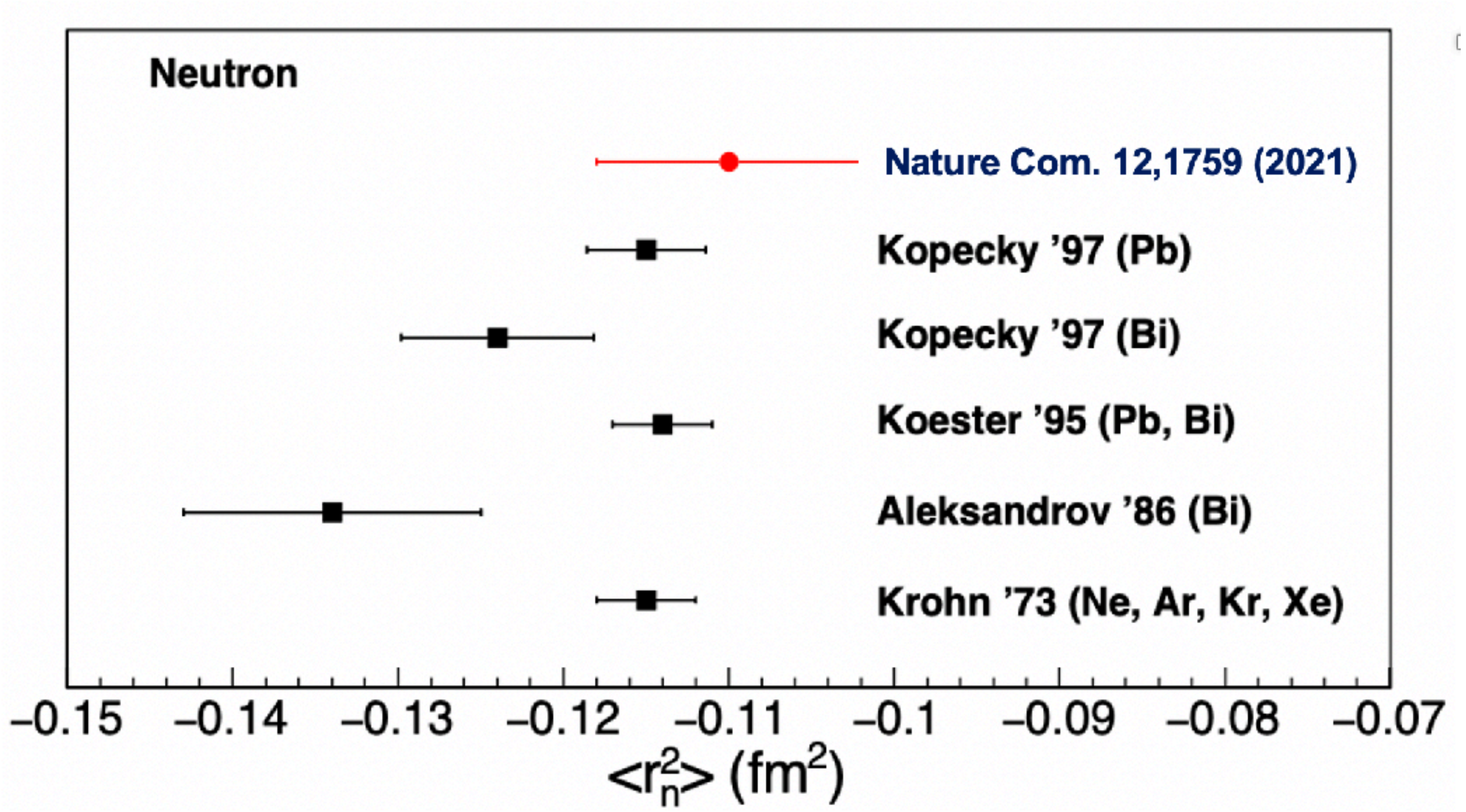
A path to extend our low Q^2 reach for G_E^n





	[0 - 0.3 (GeV/c)^2]	[0 - 0.4 (GeV/c)^2]
Polynomial group	$\langle r_n^2 \rangle = -0.107 \pm 0.006 \pm 0.001_{\text{mod}}$ (fm^2)	$\langle r_n^2 \rangle = -0.104 \pm 0.004 \pm 0.004_{\text{mod}}$ (fm^2)
Rational group	$\langle r_n^2 \rangle = -0.115 \pm 0.006 \pm 0.002_{\text{mod}}$ (fm^2)	$\langle r_n^2 \rangle = -0.115 \pm 0.005 \pm 0.007_{\text{mod}}$ (fm^2)
$\langle r_n^2 \rangle = -0.111 \pm 0.006 \pm 0.002_{\text{mod}} \pm 0.004_{\text{group}}$ (fm^2)		

A path to extend our low Q^2 reach for G_E^n



Agrees with the Gartching-Argonne results

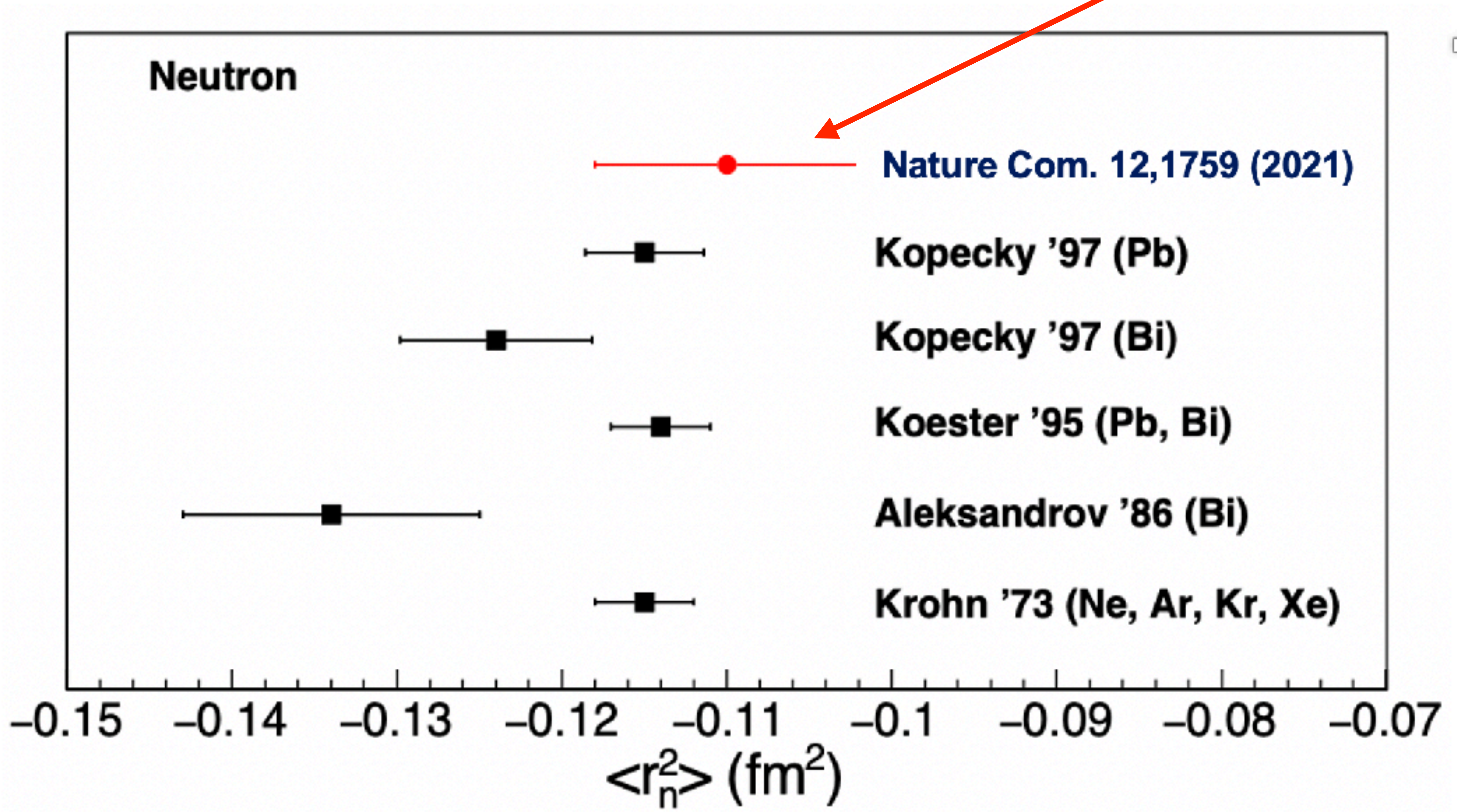
Updates the world data average:

$$\langle r_n^2 \rangle = -0.1152 \pm 0.017 \text{ fm}^2$$

Improves the uncertainty by 23%

A path to extend our low Q^2 reach for G_E^n

We could reduce uncertainty by a factor of 2 with new low Q2 TFF measurements!



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JLAB PAC49 (2021) Proposal: Measurement of the neutron charge radius through the study of the nucleon excitation

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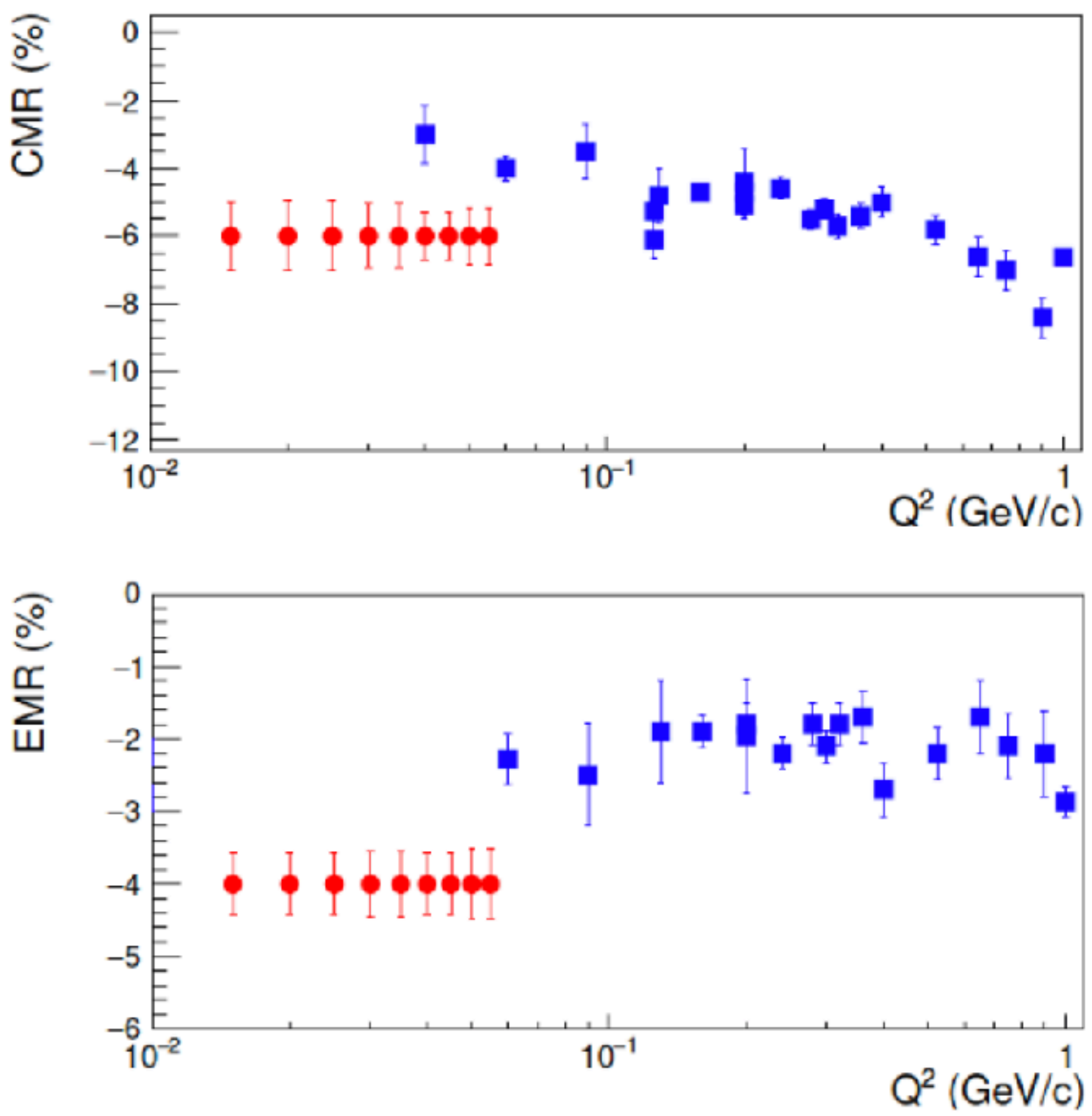
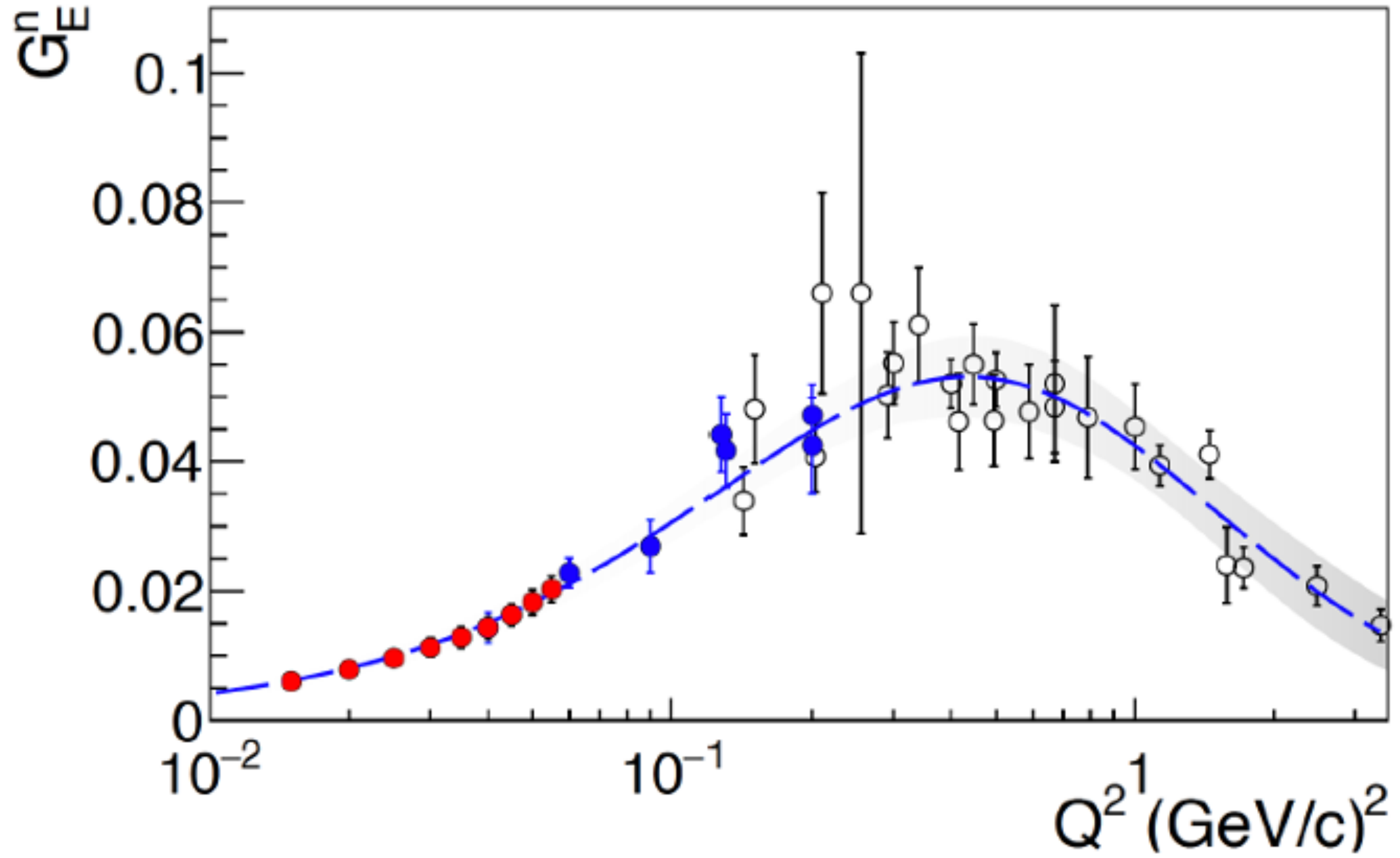
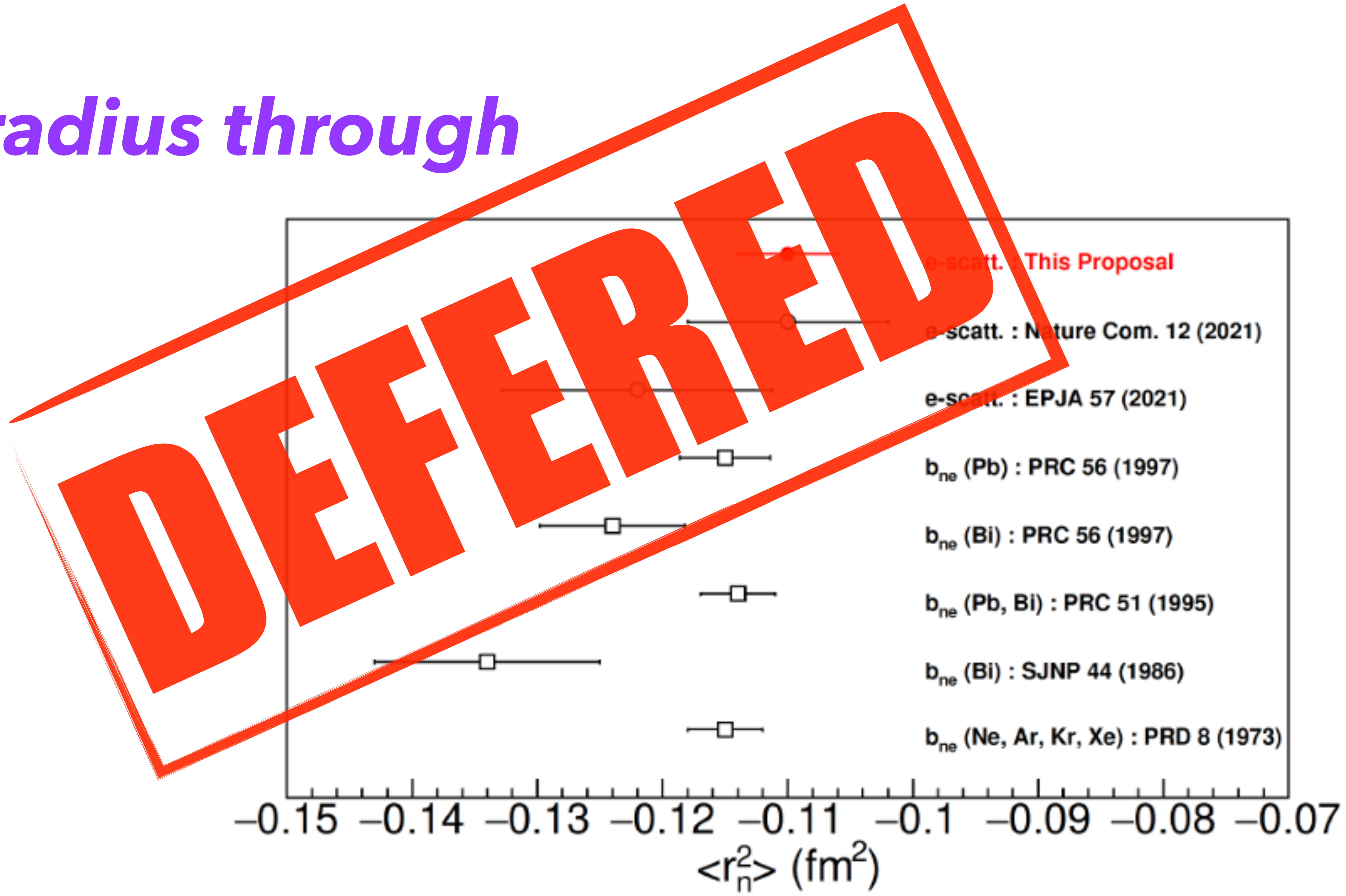
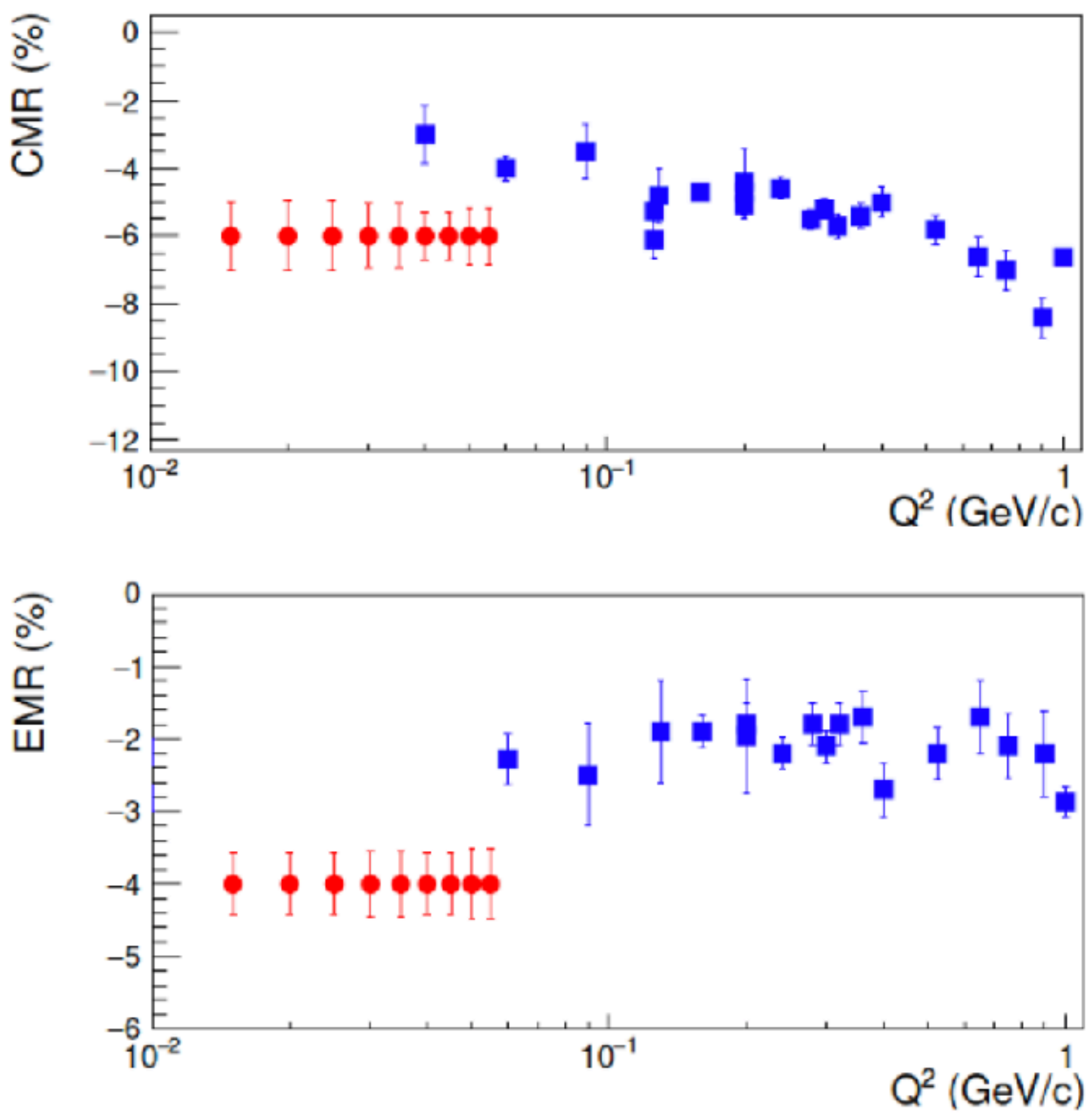






JLAB PAC49 (2021) Proposal: Measurement of the neutron charge radius through the study of the nucleon excitation



DEFERED

Comments from reviewers:

Uncertainties (and corrections) of Buchmann (CQM + 2b) or large-Nc are not well (enough) quantified for very low Q2.

BUT

TFFs at low-Q2 are very interesting (in their own right).

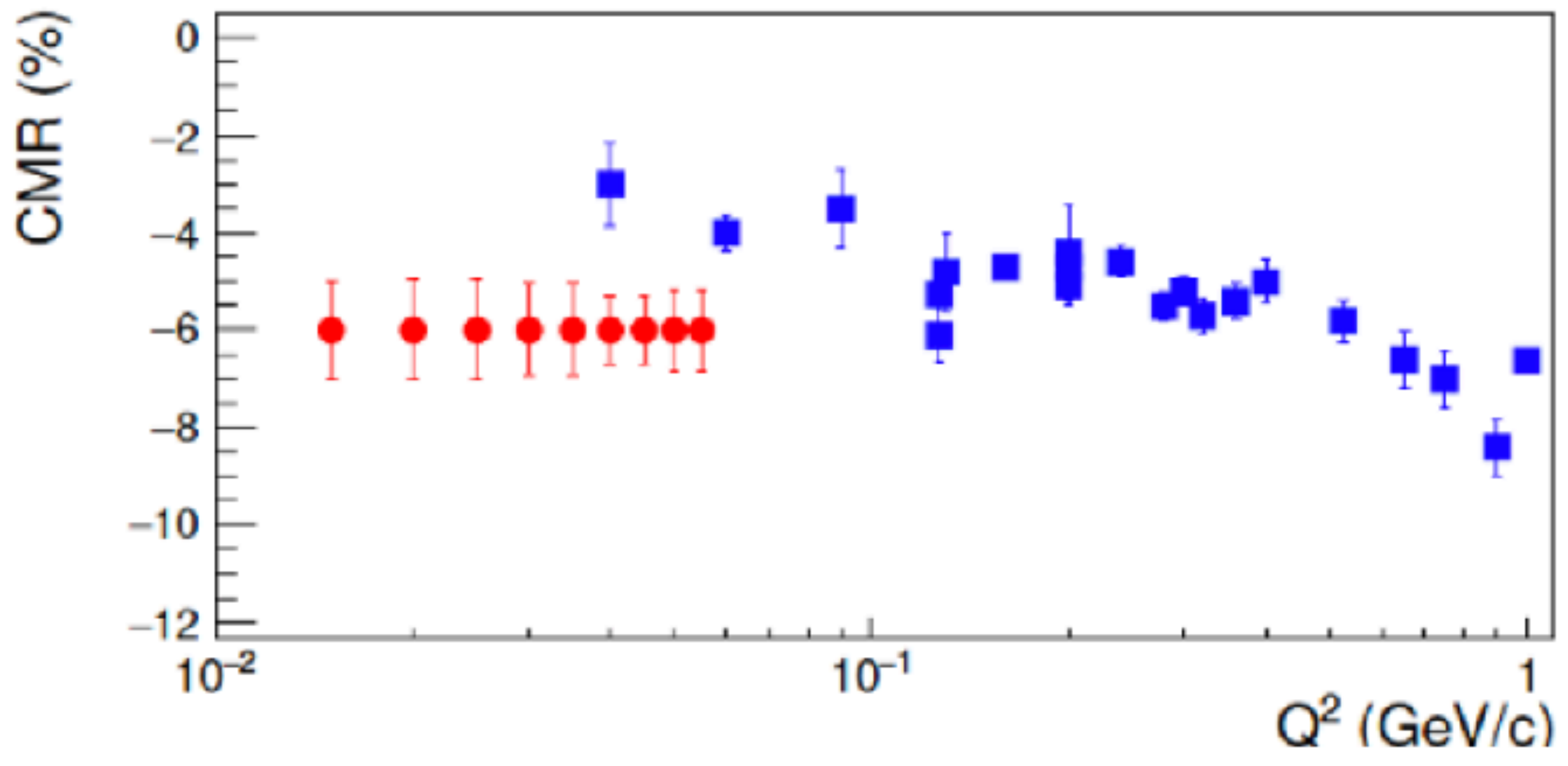
AND

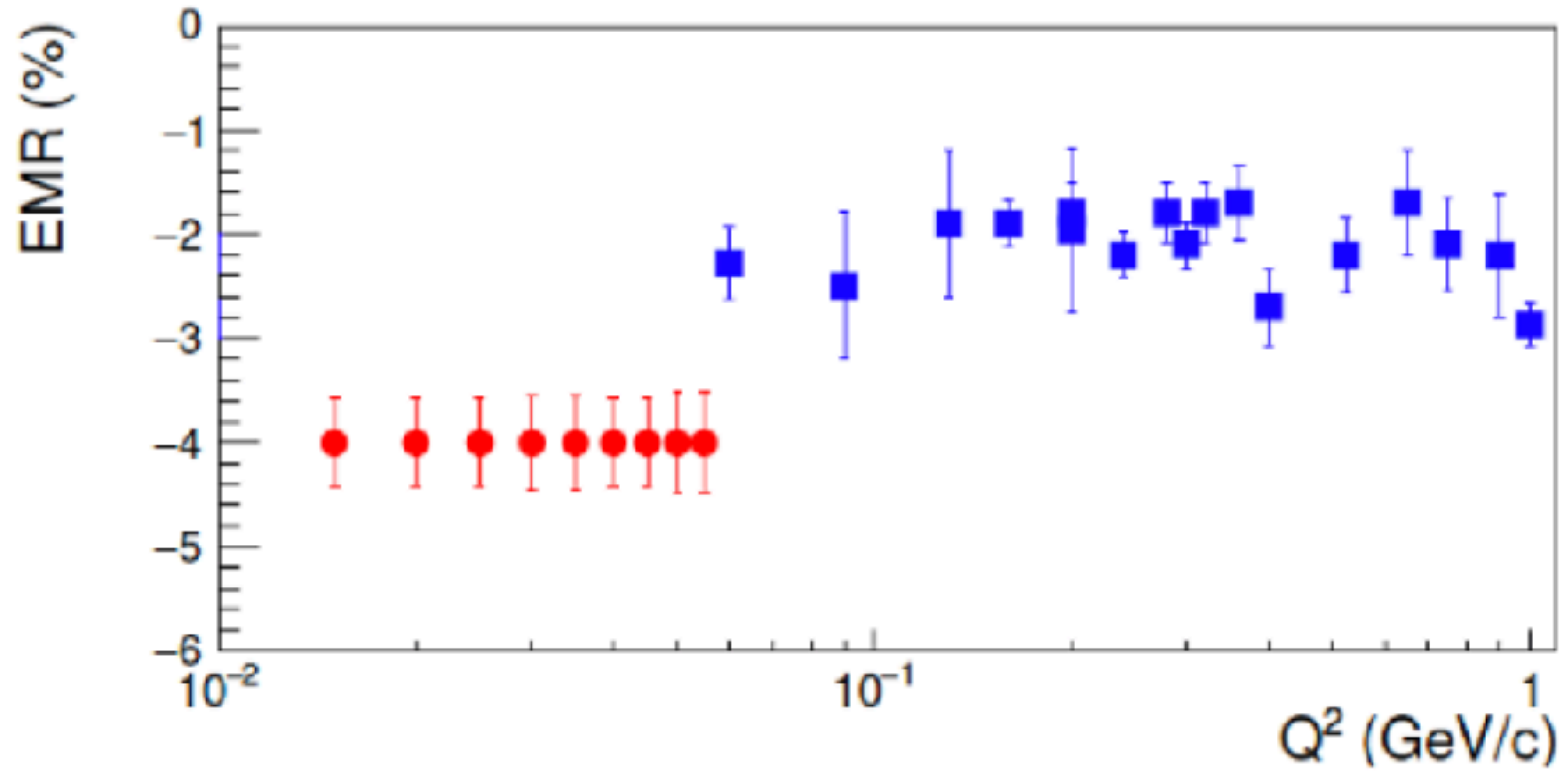
A combined framework of ChPT and large-Nc can test corrections vs low Q2 measurements.

Recommendation: Change the focus to low Q2 TFFs (only)

~~JLAB PAC49 (2021) Proposal: Measurement of the neutron charge radius through the study of the nucleon excitation~~

Exact same proposed measurements

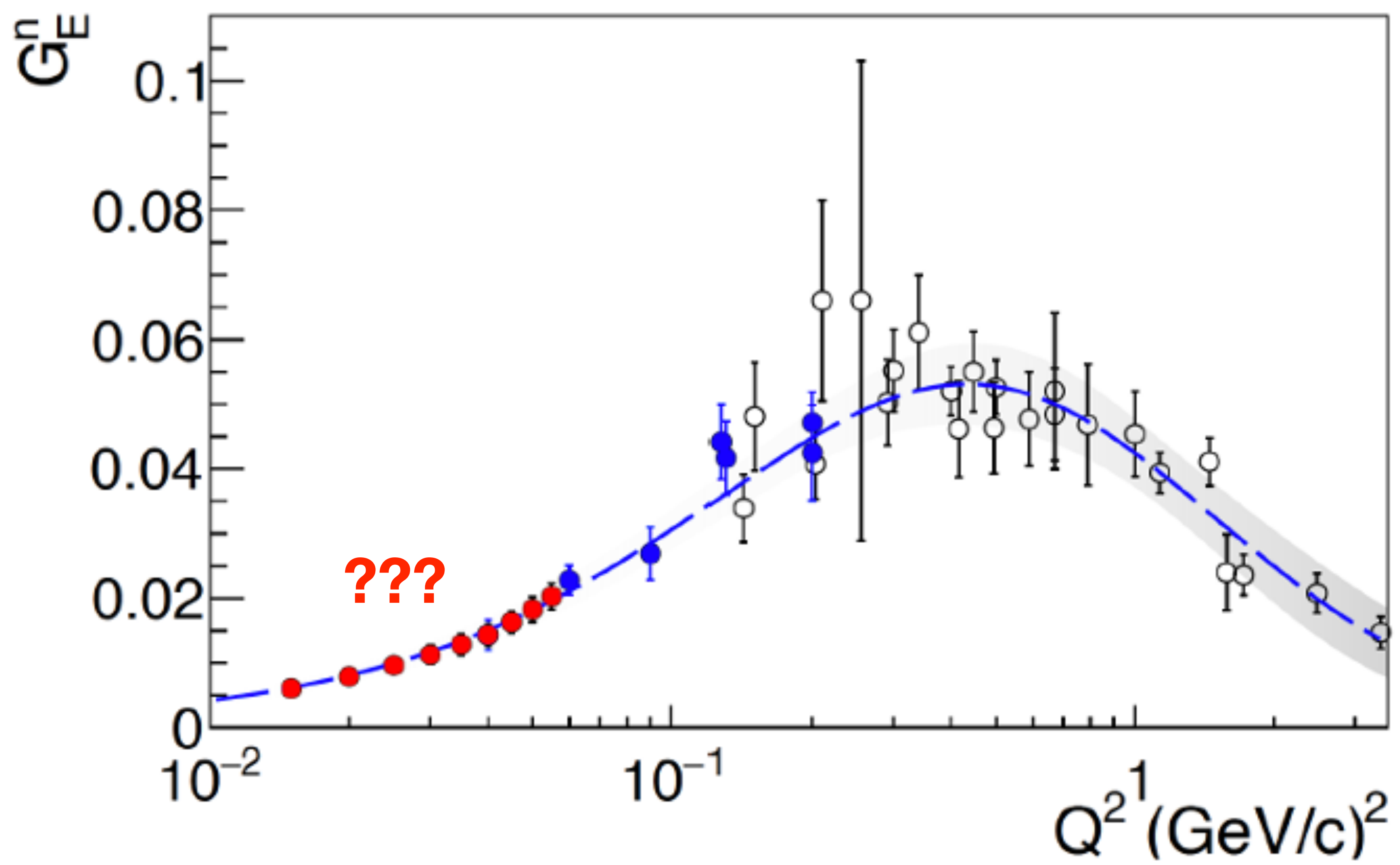




JLAB PAC50 (2022) Proposal: Measurement of the N→Δ Transition Form Factors at low Q2

So far: Theory report on proposal is very supportive!

A more rigorous study of theoretical uncertainties.



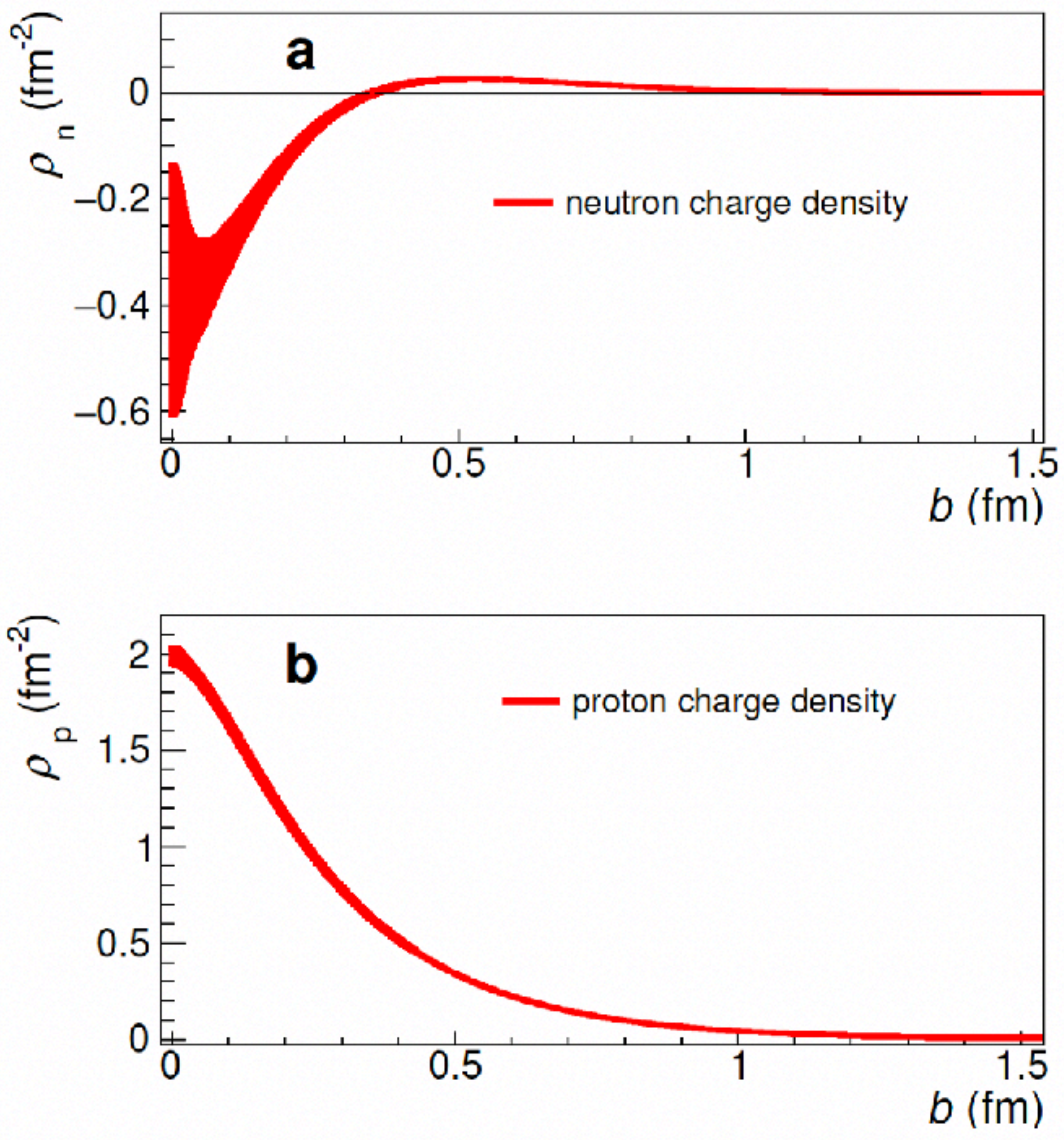
Fun things to do with global analysis of proton and neutron FFs.

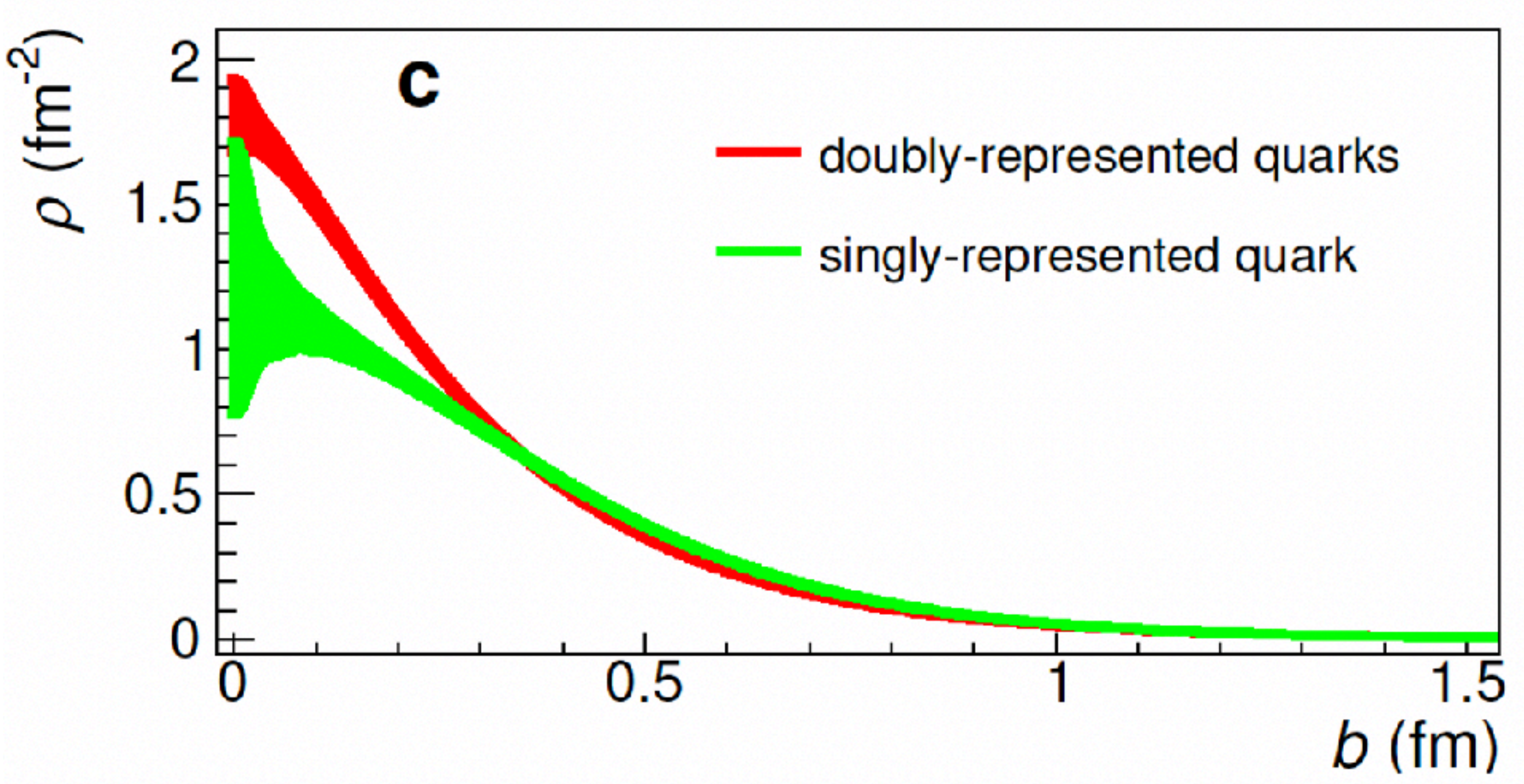
Spatial charge density distributions

$$\rho(b) = \int_0^\infty \frac{dQ\,Q}{2\pi} J_0(Qb) \frac{G_E(Q^2) + \tau G_M(Q^2)}{1+\tau}$$

$$\rho_u(b) = \rho_p(b) + \rho_n(b)/2$$

$$\rho_d(b) = \rho_p(b) + 2\rho_n(b)$$





Summary

- **After 2 decades of stagnation, there is progress in the determination of the neutron charge radius**
  - We now have an alternative path to access this quantity;
    - Important, considering the $\langle r_n^2 \rangle$ discrepancies, as well as our recent experience with the proton

- **A path for the further improvement of the $\langle r_n^2 \rangle$ extraction has been presented**
  - Future experiments may be able to help at low-Q2 and include precision.

- **Accessing the neutron & proton charge radius through the TMSR of the quark distributions appears to be a robust way for the charge radius extraction from the FF data.**

Thank you!