Accessing the neutron charge radius through electron scattering

Nikos Sparveris

QCD Evolution 2021

Acknowledgements:

H. Atac, M. Constantinou, Z.E. Meziani, M. Paolone

Nature Comm. 12, 1759 (2021)

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

Temple University

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Neutron

Central role in the understanding of nature; equivalent to the proton, but a much more difficult system to study in the lab

Significance: cornerstone in the understanding of the hadronic structure, central role in cosmological theories, it's properties offer valuable constraints in searches for new physics

Precision 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

e.g. consider the delicate difference for the neutron – proton mass (~0.1%) ; tremendous consequences

was it the other way around, very much different Universe (without hydrogen, water, stable long-lived stars which use hydrogen as a nuclear fuel, …)

It is important to access the neutron properties with a high level of precision

The charge radius is one of the system's most basic properties

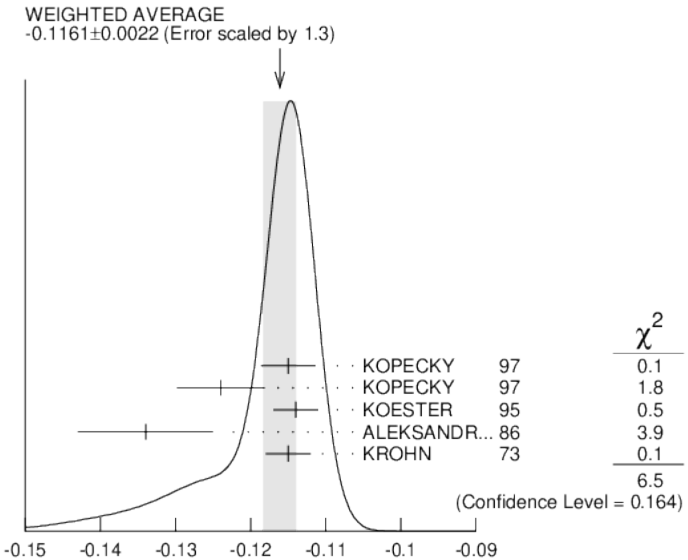
This talk: Status of the neutron charge radius measurements

New results

Prospects

Status of the $\langle r_n^2 \rangle$ measurments

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



PDG compilation:

Measurements are rather old;
PDG value remains the same for 2 decades

Only a fraction of the world data is considered (unclear why in some cases)

PDG data exhibit large tensions → systematics

PDG: averages measurements that disagree
→ PDG average $\langle r_n^2 \rangle$ uncertainty is elusive

Underestimated systematics of the b_{ne} method have been acknowledged in the literature

World data results are compiled in two groups:

$$b_{ne} = -(1.31 \pm 0.03) \cdot 10^{-3}\ \text{fm} \qquad \text{(Garching-Argonne)}$$

$$b_{ne} = -(1.59 \pm 0.04) \cdot 10^{-3}\ \text{fm} \qquad \text{(Dubna)}$$

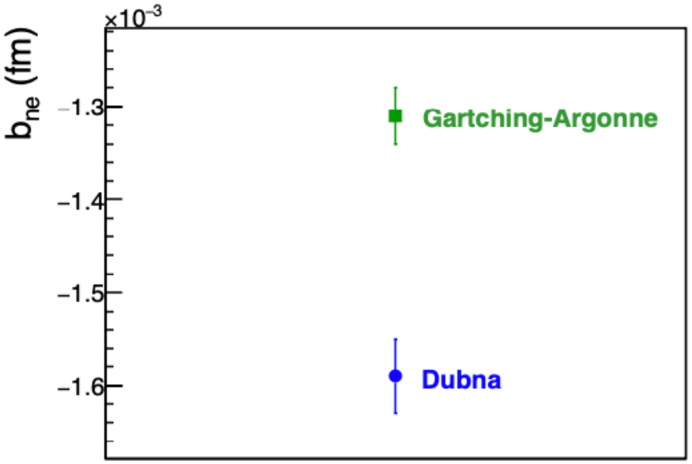
5σ unresolved discrepancies

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

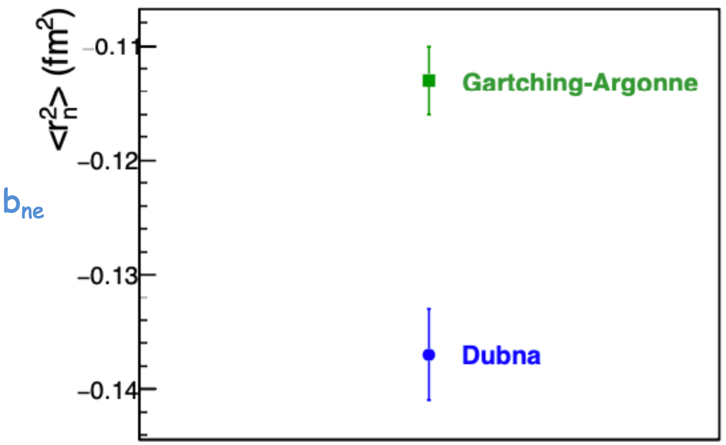
➔ **Translated directly into $\langle r_n^2 \rangle$ extraction discrepancies**

$\langle r_n^2 \rangle$ extraction from b_{ne}

5σ unresolved discrepancies in b_{ne}



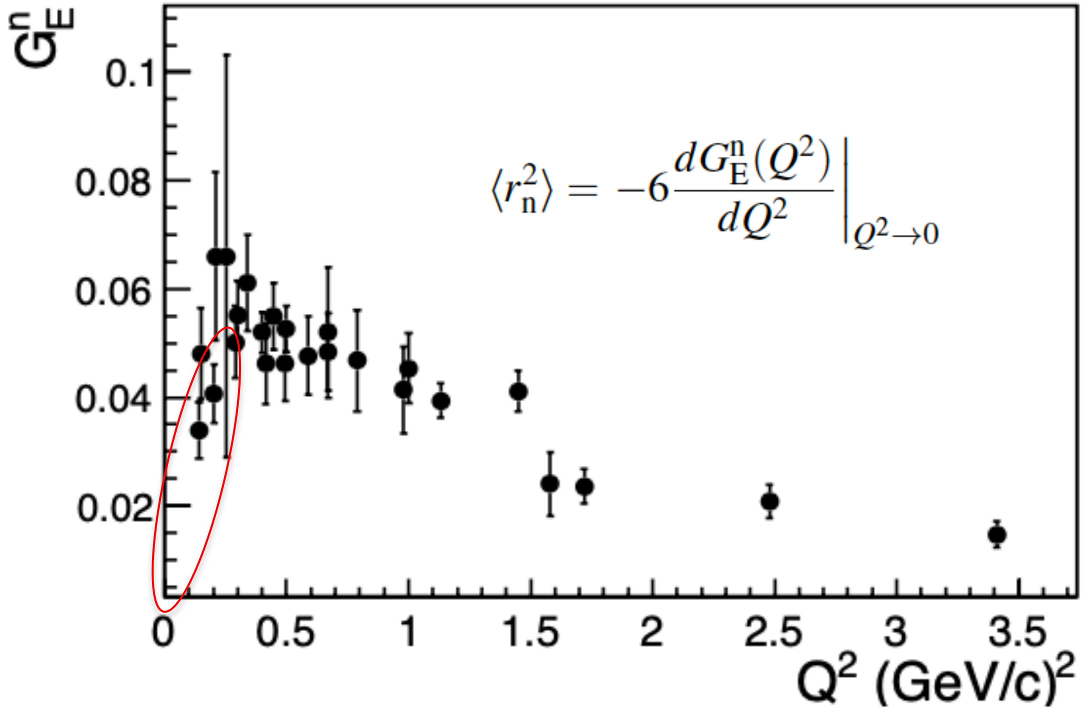
$\langle r_n^2 \rangle = 3\,(m_e\, a_o/m_n)\, b_{ne}$



➔ Translated directly into $\langle r_n^2 \rangle$ extraction discrepancies

Employing a different method to measure a quantity
ensures the "*honesty*" of the measurement, can resolve discrepancies, reveal surprises, …

$\langle r_n^2 \rangle$ extraction from GEn



What we need:
Fit G^n_E at $Q^2 \to 0$

GEn determination:

In the absence of
a free neutron target:

Polarized deuterium, ^{3}He targets & polarized electron beam

Quasi-elastic electron scattering

Double polarization observables

Limitations in the precision of the GEn measurements &
in the low Q^2 coverage towards a high precision extraction of $\langle r_n^2 \rangle$

$\langle r_n^2 \rangle$ extraction from GEn

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

Severe limitations in the $\langle r_n^2 \rangle$ extraction

Parametrizations do not have sufficient freedom to fit the radius, without constraining or compromising the fit.

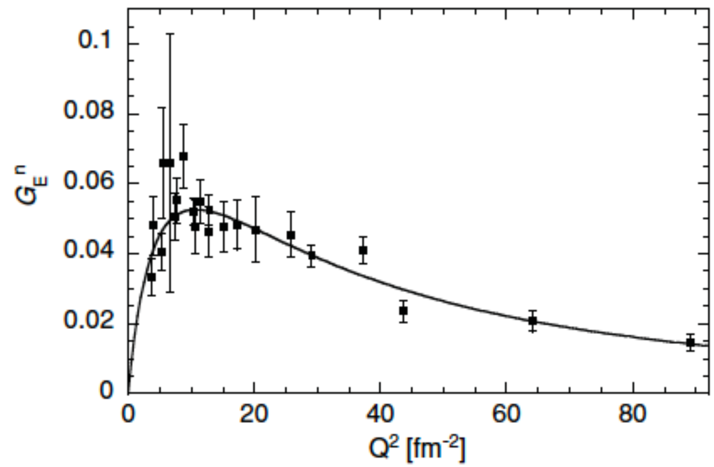


TABLE I. Results of fitting G_E^n with the Galster form. For this table and Table II, the column labelled "$\langle r_n^2 \rangle^d$" lists the reference for the $\langle r_n^2 \rangle$ datum included in the fit, χ^2_{red} is the reduced χ^2 for the fit and "dof" refers to the number of degrees of freedom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

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)

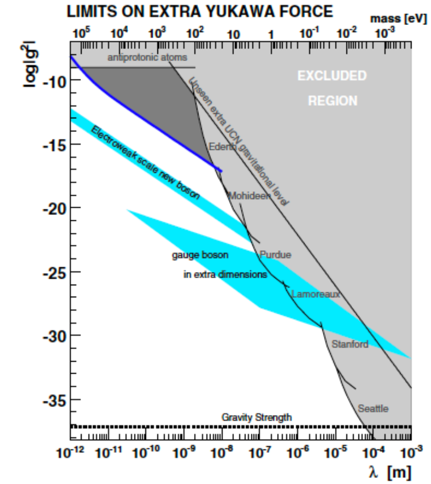


FIG. 8 (color online). Experimental limits on extra interactions including the best neutron constraint obtained in this article (bold line). Two theoretical regions of interest are shown: a new boson with mass induced by electroweak symmetry breaking [10], and a new boson in extra large dimensions [4].

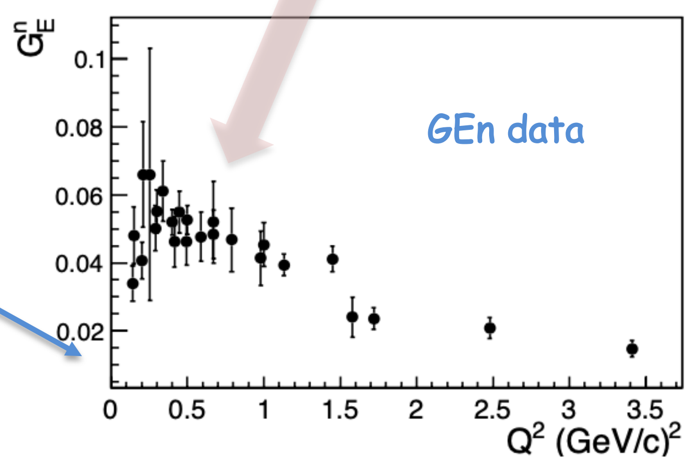
Unfortunately, there is very clear disagreement between the two groups of values for $b_{ne}^{\rm exp} = \frac{b(1\ {\rm eV}) - b(0)}{Z}$ known as the Garching-Argonne and Dubna values [27]

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

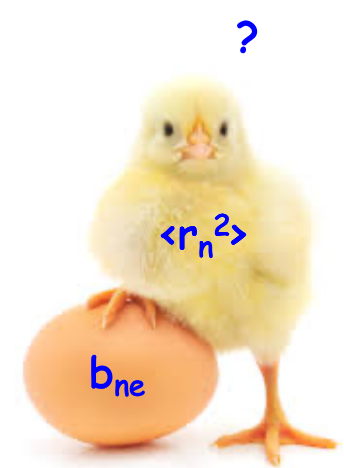
The discrepancy is much greater than the quoted uncertainties of the experiments and there evidently an unaccounted for systematic error in at least one of the experiments.

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]:

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



$\langle r_n^2 \rangle$ ↔ GEn slope at Q^2
cannot be precisely constrained



Nucleon charge radii from the u- and d-quark distributions

The neutron (and proton) charge radius is related in a **model independent way** to the transverse mean-square radii of the flavor dependent quark distributions

$$\langle r_p^2 \rangle = 2\langle b_u^2 \rangle - \frac{1}{2}\langle b_d^2 \rangle + \frac{3}{2}\frac{\kappa_N}{M_N^2}$$

$$\langle r_n^2 \rangle = \langle b_d^2 \rangle - \langle b_u^2 \rangle + \frac{3}{2}\frac{\kappa_N}{M_N^2}$$

The TMSR of the u- and d-quark distributions can be determined through a collective analysis of the G^p_E, G^p_M, G^n_E, G^n_M experimental data

Flavor decomposition of the nucleon EM form factors ➔ $\langle b^2_{u(d)} \rangle$

A path for the simultaneous extraction of $\langle r^2_p \rangle$ and $\langle r^2_n \rangle$

Flavor decomposition of the elastic nucleon EM FFs at high 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,*]

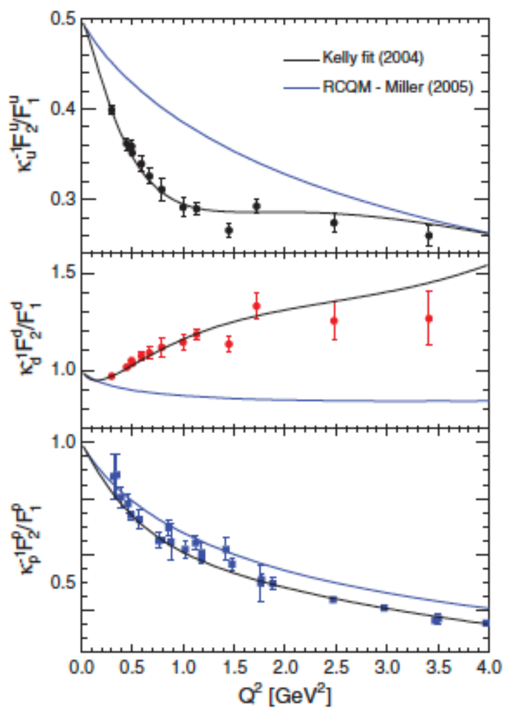


FIG. 2 (color). The ratios $\kappa_d^{-1}F_2^d/F_1^d$, $\kappa_u^{-1}F_2^u/F_1^u$, and $\kappa_p^{-1}F_2^p/F_1^p$ vs momentum transfer Q^2. The data and curves are described in the text.

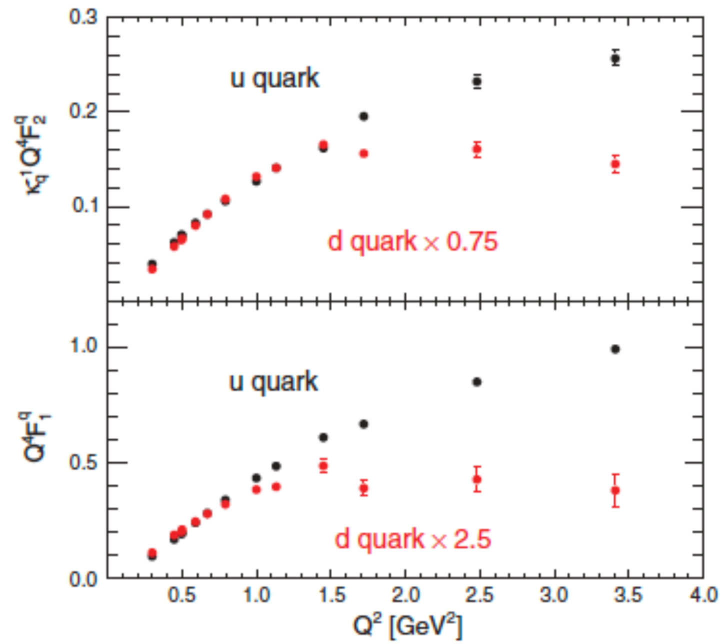
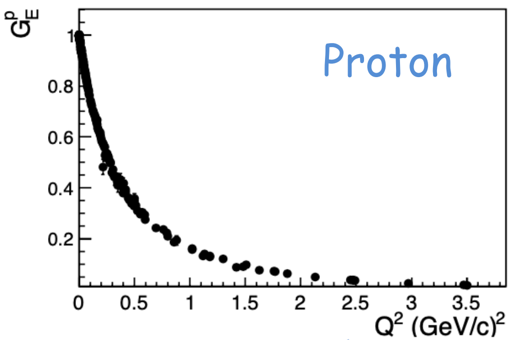
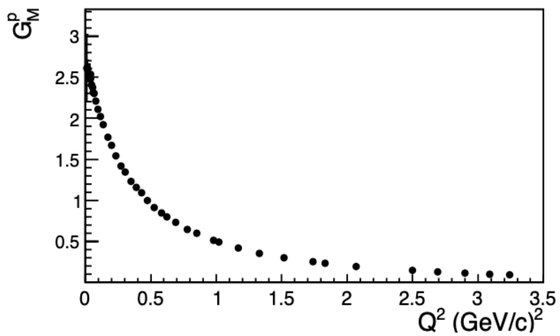


FIG. 3 (color). The Q^2 dependence for the u and d contributions to the proton form factors (multiplied by Q^4). The data points are explained in the text.

Focusing on the study of the u- and d-quark distributions at high-Q^2, scaling …

Flavor decomposition of the elastic nucleon EM FFs at low Q^2

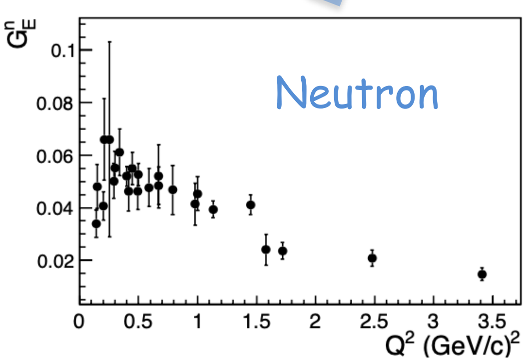


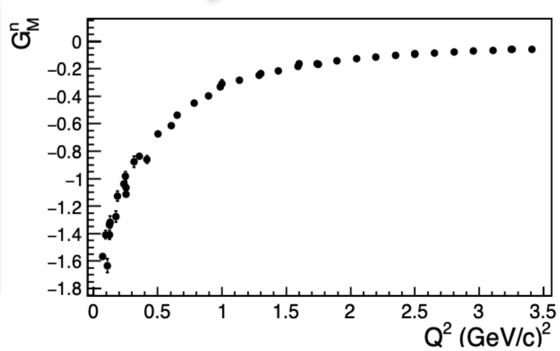


$$F_1 = (G_E + \tau G_M)/(1+\tau)$$

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

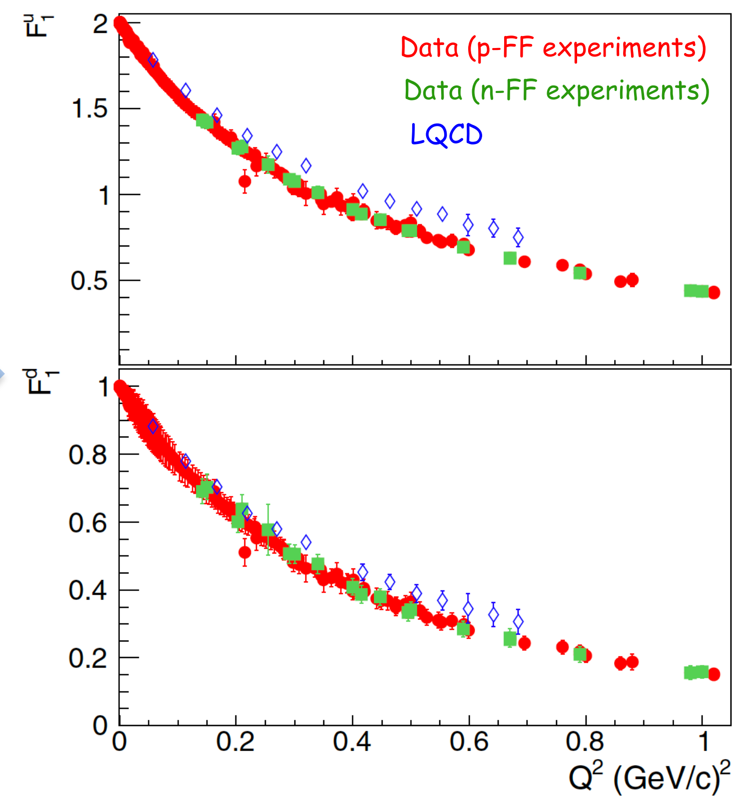
$$F_1^d = 2\,F_1^n + F_1^p$$



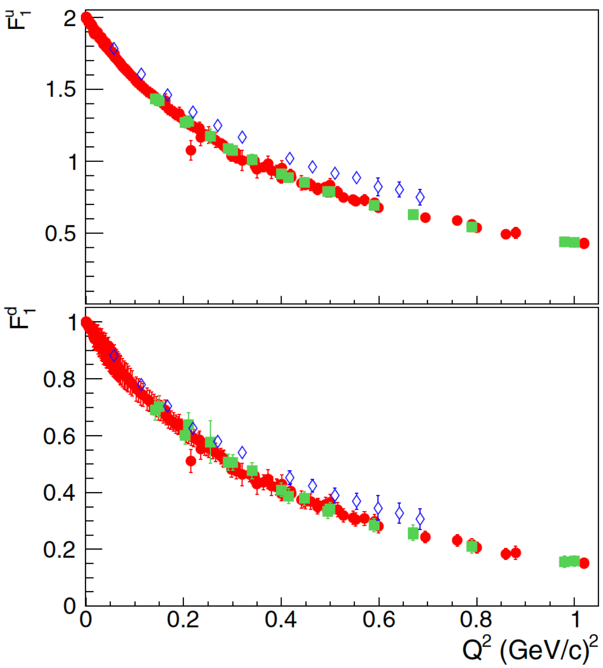


Same procedure but focusing at low-Q^2

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



Flavor decomposition of the elastic nucleon EM FFs at low Q^2



We need to determine the slope of $F_1^{u(d)}$ at $Q^2 \to 0$ so that we can derive the $\langle b^2_{u(d)} \rangle$

$$\langle b^2_{u(d)} \rangle = \frac{-4}{F_1^{u(d)}(0)} \frac{dF_1^{u(d)}(Q^2)}{dQ^2}\bigg|_{Q^2 \to 0}$$

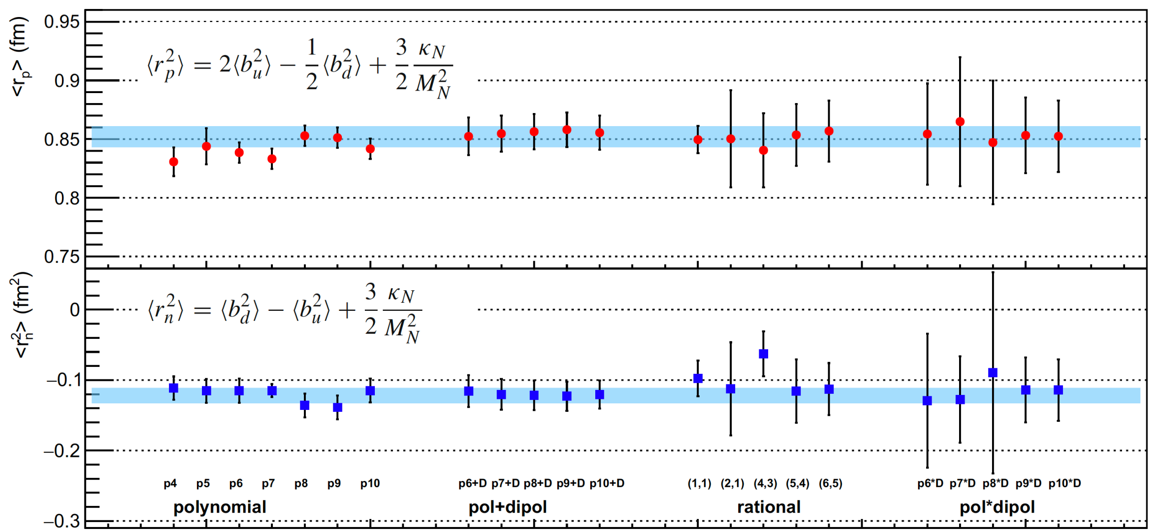
A variety of functional forms is employed to fit the data:

polynomial, (pol + dip), (pol x dip), rational $f(Q^2) = \frac{\alpha_0 + \sum_{i=1}^{n} \alpha_i Q^{2i}}{1 + \sum_{j=1}^{m} \beta_j Q^{2j}}$

F_1^u and F_1^d are **fitted simultaneously**, each time with the **same functional form**

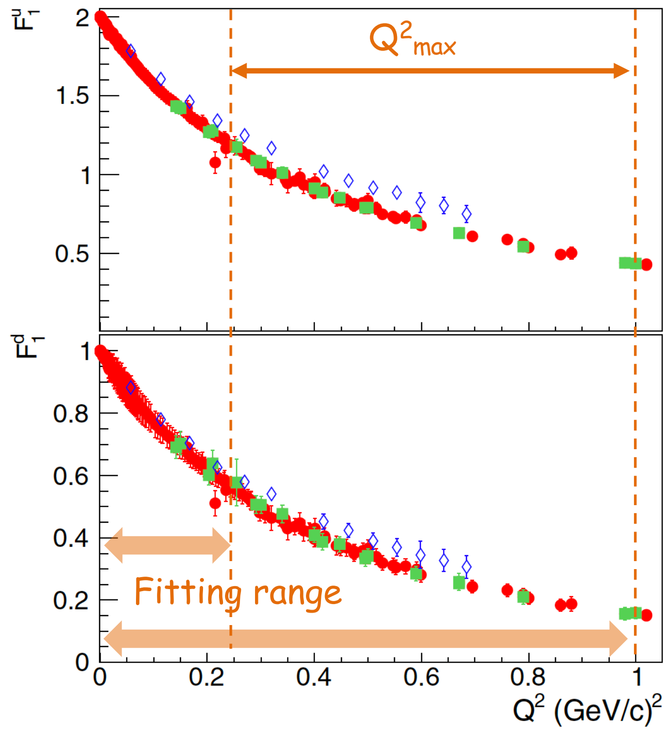
Stability of fits is observed for different orders in the fitted functions

A systematic uncertainty is quantified from the variance of the fitted results within each group of functions

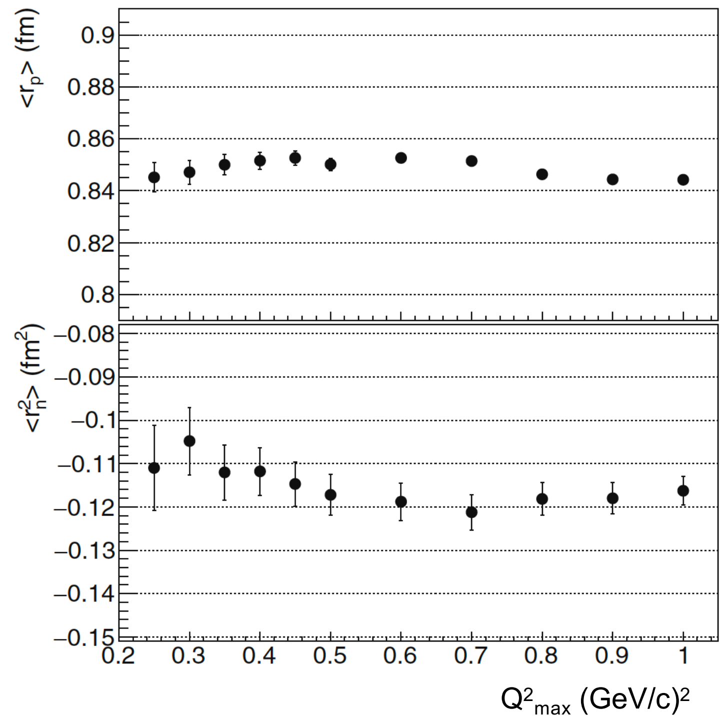


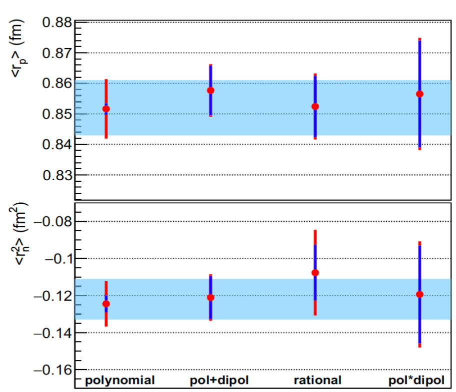
Flavor decomposition of the elastic nucleon EM FFs at low Q^2

Stability of the fits is observed for a varying fitting range: Q^2=0 to Q^2_{max}



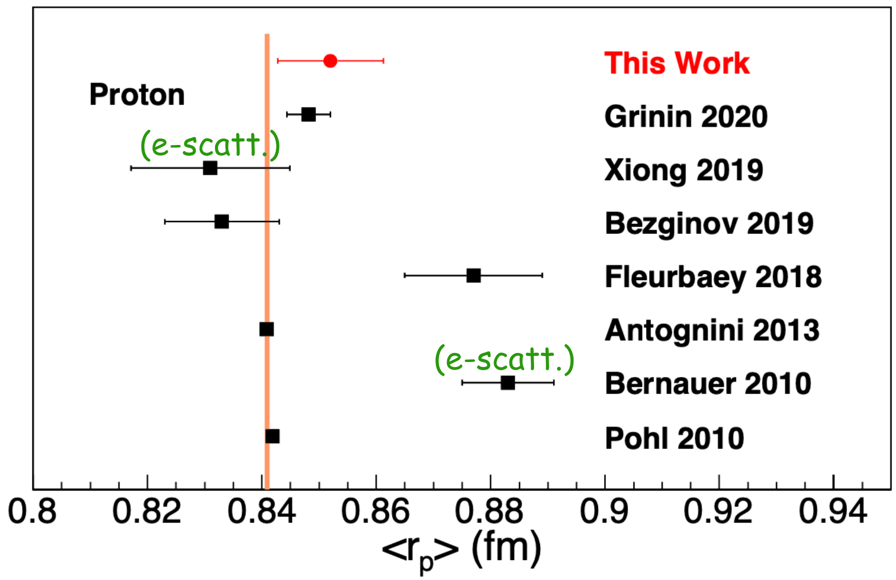
A systematic uncertainty is quantified from the variance of the fitted results for a varying Q^2_{max}





Fitted results per group of functions

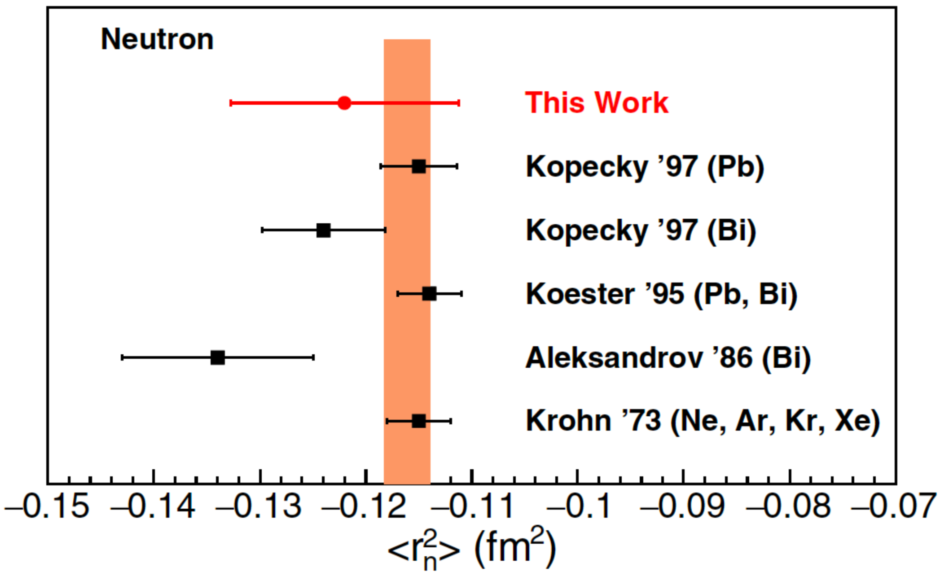
Flavor decomposition of the elastic nucleon EM FFs at low Q^2



$$\langle r_p \rangle = 0.852 \pm 0.002_{(stat.)} \pm 0.009_{(syst.)} \text{ (fm)}$$

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

H. Atac, M. Constantinou, Z.E. Meziani, M. Paolone, N.S

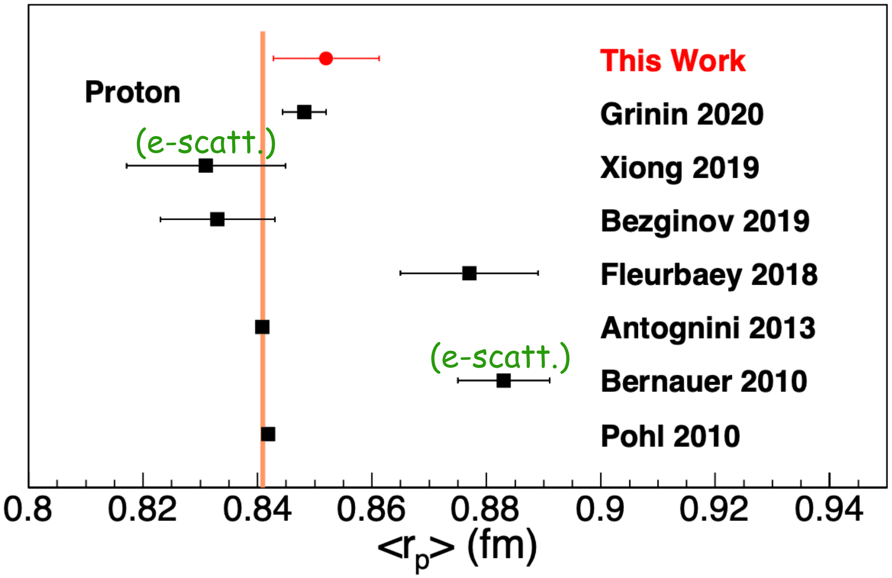


$$\langle r_n^2 \rangle = -0.122 \pm 0.004_{(stat.)} \pm 0.010_{(syst.)} \text{ (fm}^2\text{)}$$

The $\langle r^2_n \rangle$ is found in agreement with the results of the b_{ne} method

Precision is not sufficient to resolve among the discrepancies

Flavor decomposition of the elastic nucleon EM FFs at low Q^2

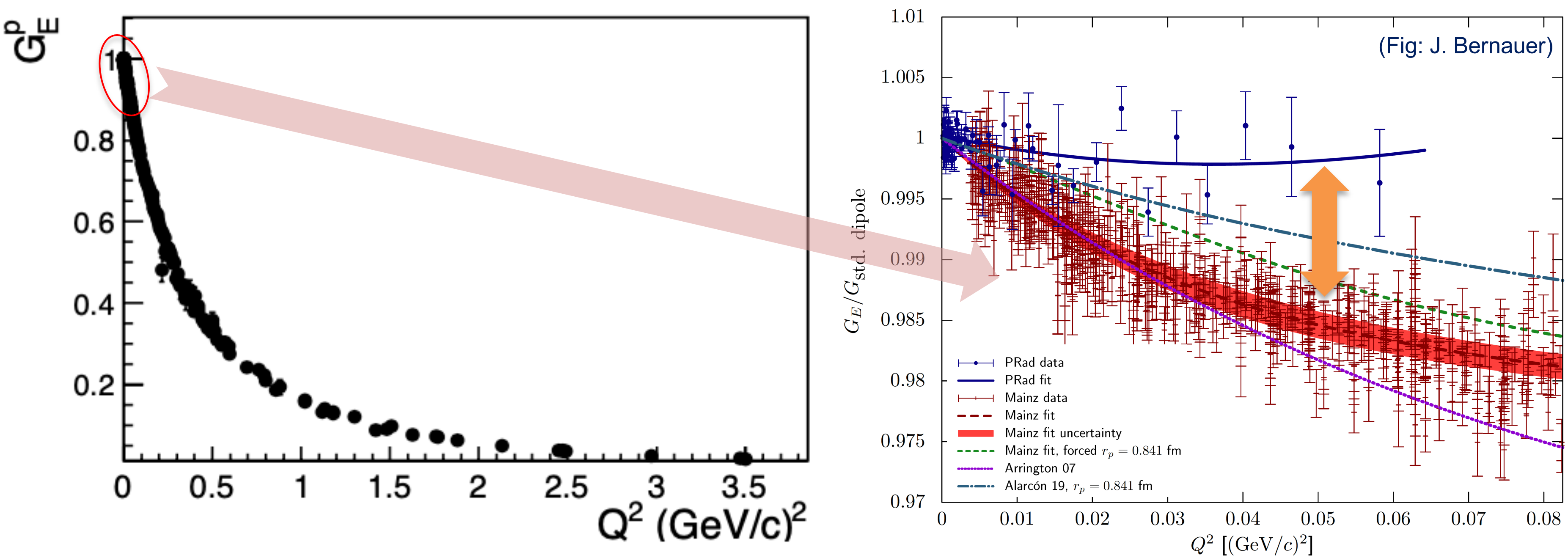


Eur. Phys. J. A 57, 65 (2021)

$$\langle r_p \rangle = 0.852 \pm 0.002_{(\text{stat.})} \pm 0.009_{(\text{syst.})} \text{ (fm)}$$

Fitting **without the PRad data**:
fit is driven primarily by the MAMI data
$<r_p>$=0.857(13) (fm)

A small $<r_p>$ is derived:
no discrepancy is observed in the extraction from the different e-scattering experiments (i.e. MAMI vs PRad)



An alternative path to access $\langle r_n^2 \rangle$

Long known connection between the GEn and the N-to-Δ quadrupole transition FFs

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

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

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and Theory Center, Thomas Jefferson National Accelerator Facility, Newport News, Virginia 23606, USA
(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 electromagnetic properties of the nucleon. These relations are based on the known large-N_c relation between the $N \to \Delta$ electric quadrupole moment and the neutron charge radius, and a newly derived large-N_c relation between the electric quadrupole ($E2$) and Coulomb quadrupole ($C2$) transitions. Extending these relations to finite, but small, momentum transfer, we find that the description of the electromagnetic $N \to \Delta$ ratios (R_{EM} and R_{SM}) in terms of the nucleon form factors predicts a structure which may be ascribed to the effect of the "pion cloud." These relations also provide useful constraints for the $N \to \Delta$ generalized parton distributions.

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

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

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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.

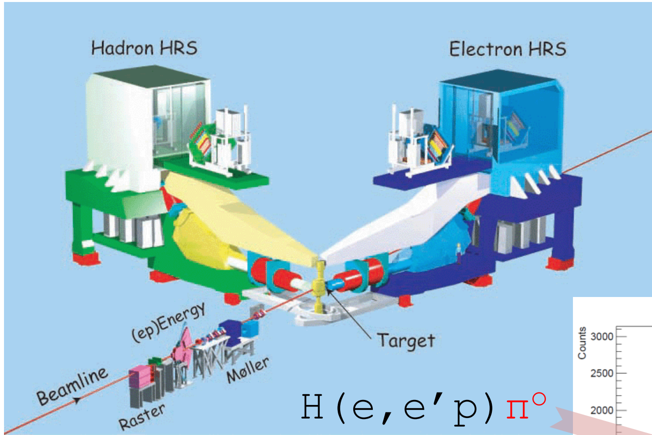
Was initially exploited in reverse

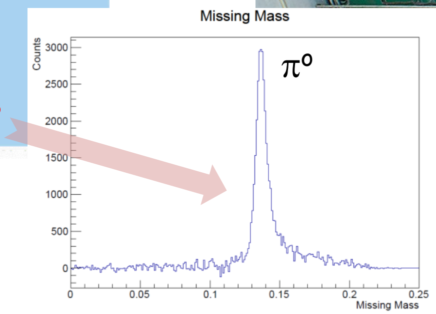
i.e. to infer information for the N-Δ transition FFs while they were not yet very well measured

15 years later: the N-Δ TFFs can be accessed at lower Q^2 and with higher precision, compared to the current GEn measurements

Multiple theoretical relations & experimental data allow the validation of the theoretical framework

N-to-Δ measurements at low Q^2

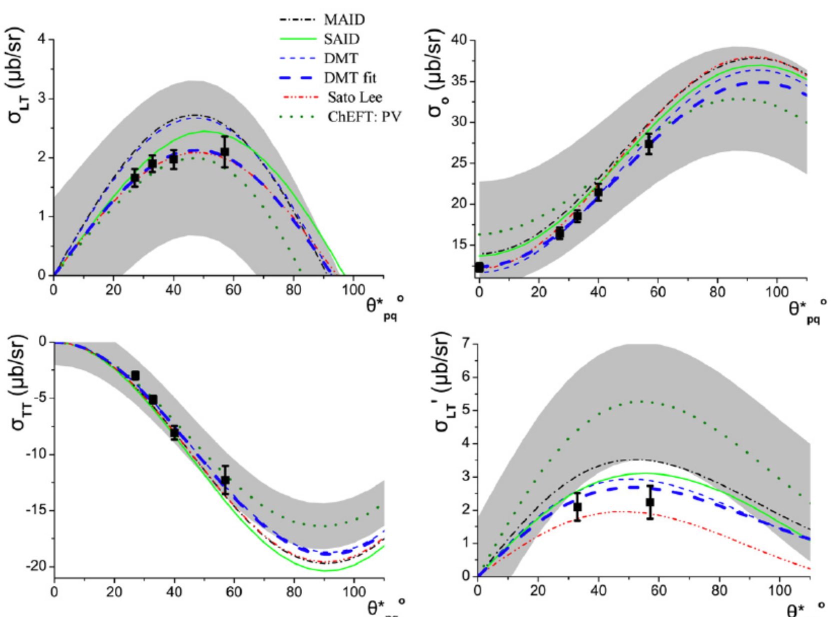


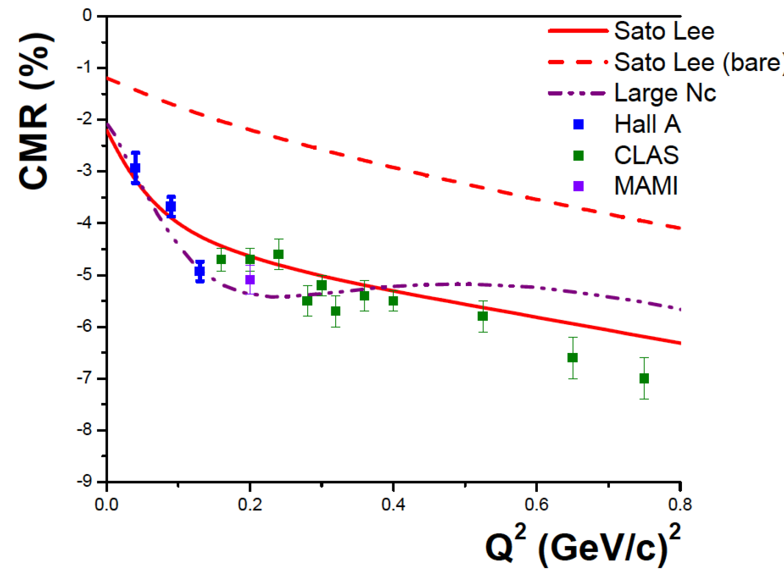


High resolution spectrometers

Sequential settings (θ, Φ)

High precision cross section measurements





Connection between the GEn and the N-to-Δ FFs

$G_E^n \longleftrightarrow (C2 / M1)$

$G_E^n \longleftrightarrow (E2 / M1)$

Phys. Rev. D76. 93, 111501(R) (2007)

Large-N_c relations (Pascalutsa & Vanderhaeghen)

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

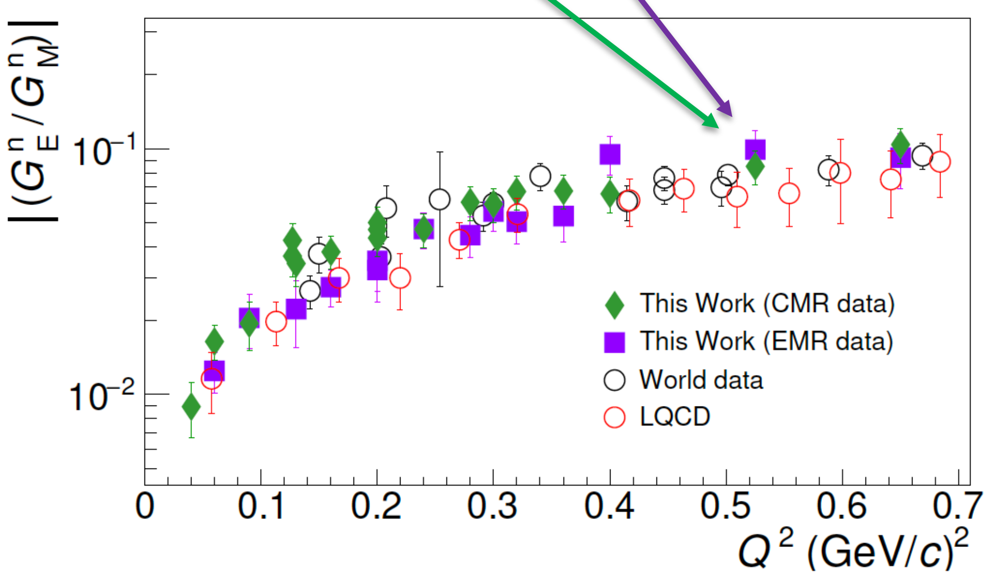
$$\frac{C2}{M1}(Q^2) = \left(\frac{M_N}{M_\Delta}\right)^{3/2} \frac{Q_+ Q_-}{2Q^2} \frac{G_E^n(Q^2)}{F_2^p(Q^2) - F_2^n(Q^2)}$$

Theoretical uncertainty ~15%

→ Propagates to a GEn uncertainty

Two relations involving 2 different observables

→ allows to check the validity of the theoretical framework



Connection between the GEn and the N-to-Δ FFs

$G_E^n / G_M^n \longleftrightarrow C2 / M1$ Phys. Rev. Lett. 93, 212301 (2004)

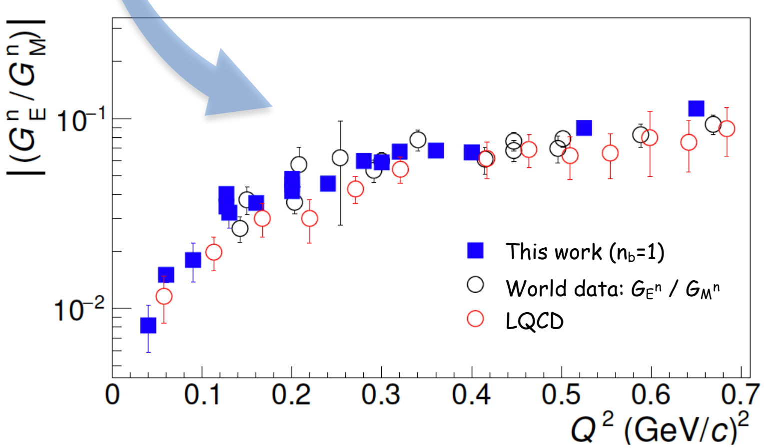
Ratios are related due to the underlying spin-flavor symmetry and its breaking by spin-dependent two- and three-quark currents

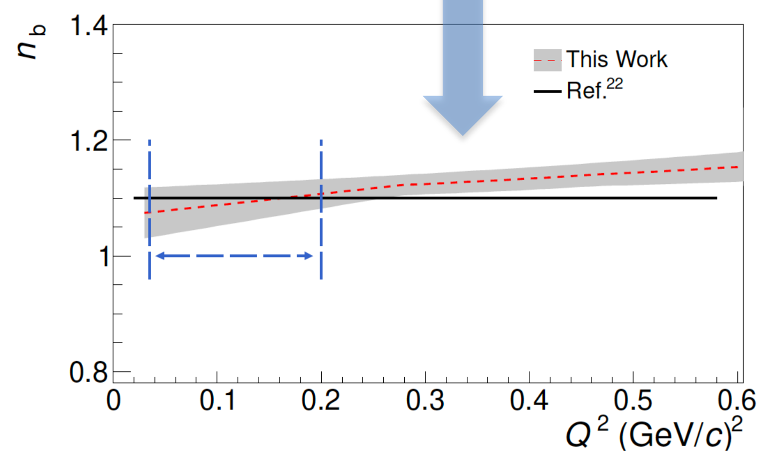
$$\frac{G_E^n(Q^2)}{G_M^n(Q^2)} = \frac{Q}{|\mathbf{q}|}\frac{2Q}{M_N}\frac{1}{n_b(Q^2)}\frac{C2}{M1}(Q^2)$$

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 $G_{M1}^{N\text{-}\Delta}$

This can be tested with the G_E^n/G_M^n and C2/M1 world data → parametrize the two world-data sets & derive $n_b(Q^2)$ →

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





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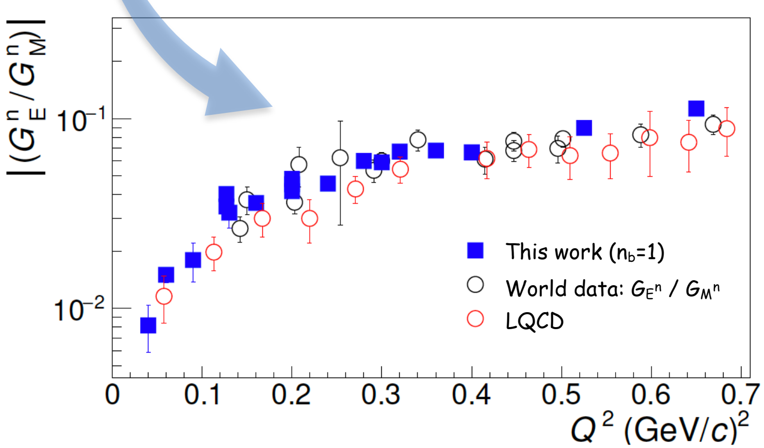
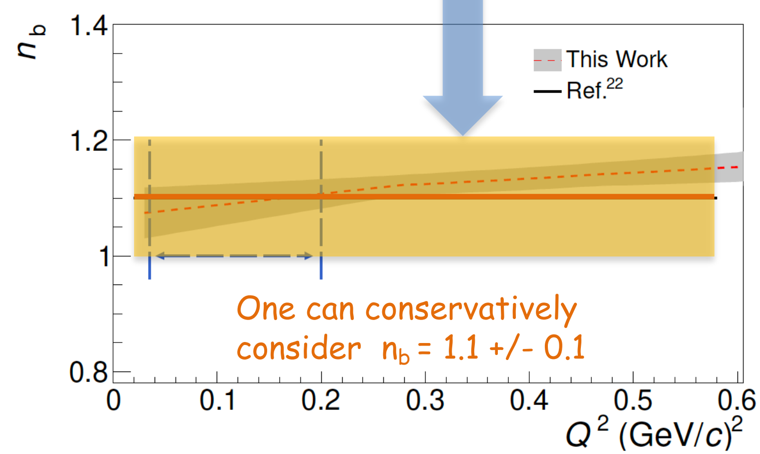
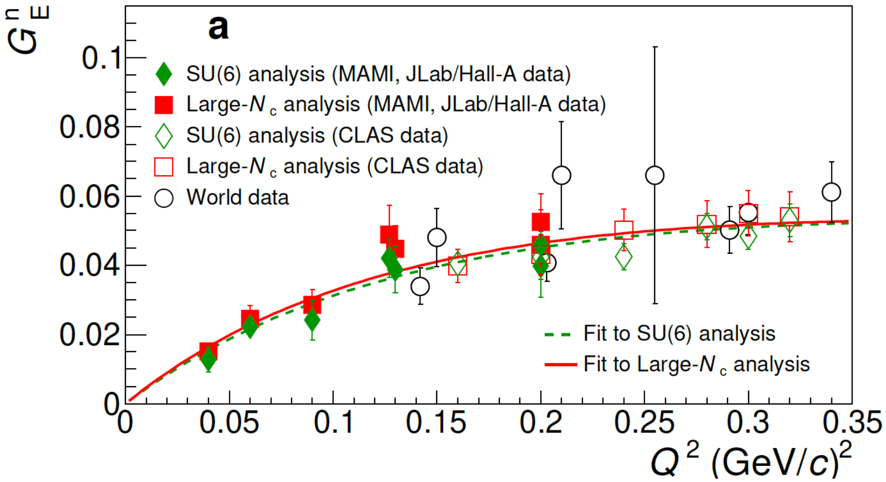
This can be tested with the G_E^n/G_M^n and C2/M1 world data → parametrize the two world-data sets & derive $n_b(Q^2)$ →

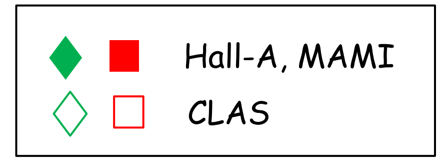
$$n_b(Q^2) = \frac{\frac{Q}{|\mathbf{q}|}\frac{2Q}{M_N}\frac{C2}{M1}(Q^2)}{\frac{G_E^n(Q^2)}{G_M^n(Q^2)}}$$







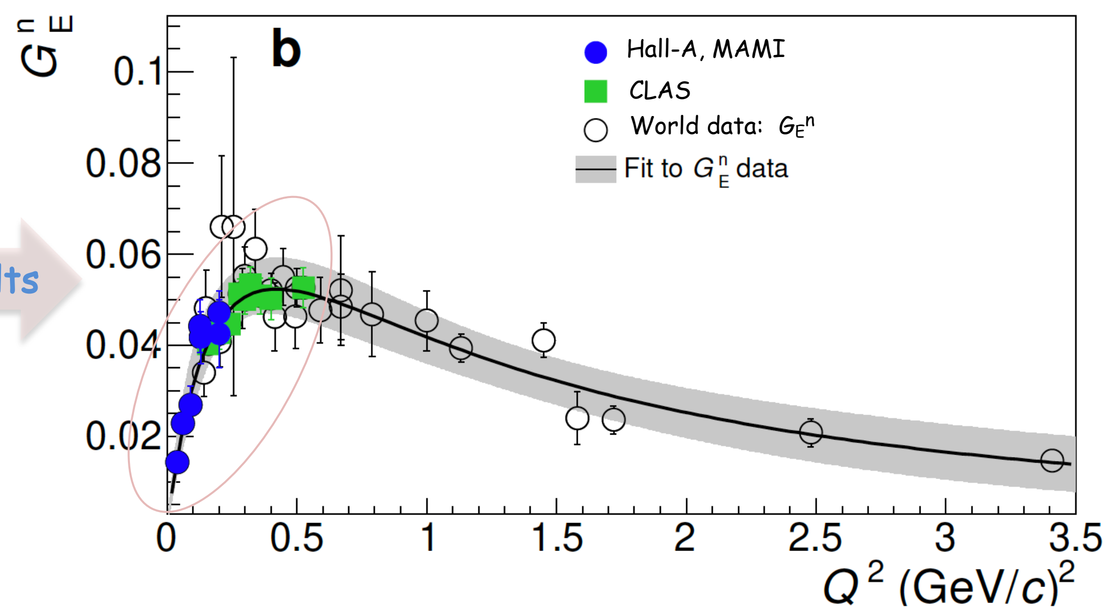
GEn extraction
from N-to-Δ TFFs



Nature Comm. 12, 1759 (2021)

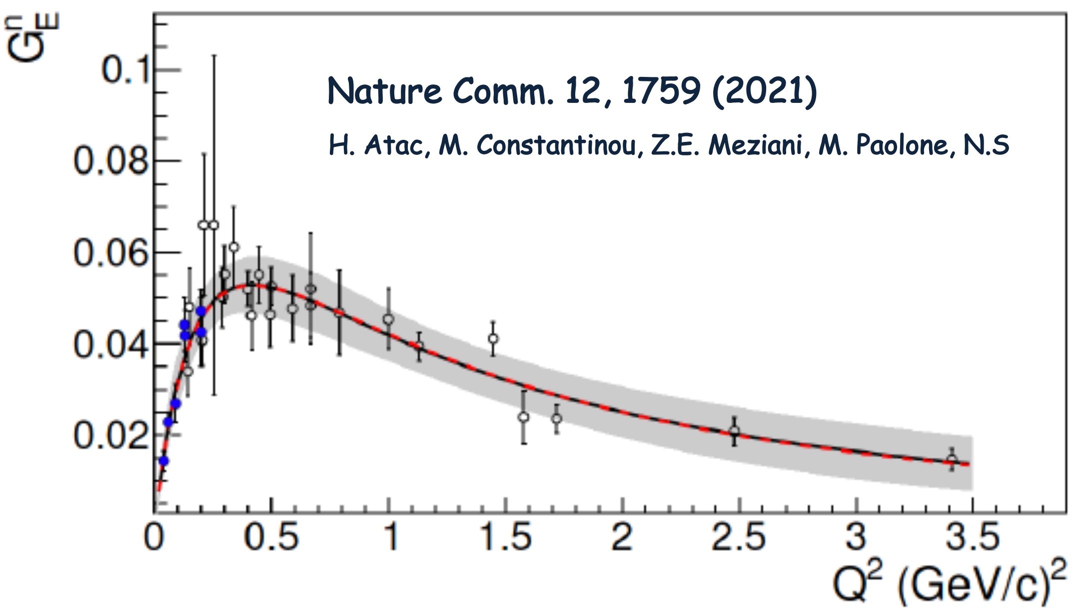
Theoretical variance of the results is quantified as δG_E^n

Final Results



$\langle r_n^2 \rangle$ extraction

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



We need to parametrize GEn so that we can fit to the data:

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

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

Fits nearly indistinguishable

$$\langle r_{\rm n}^2 \rangle = -0.110 \pm 0.008 \ ({\rm fm}^2)$$

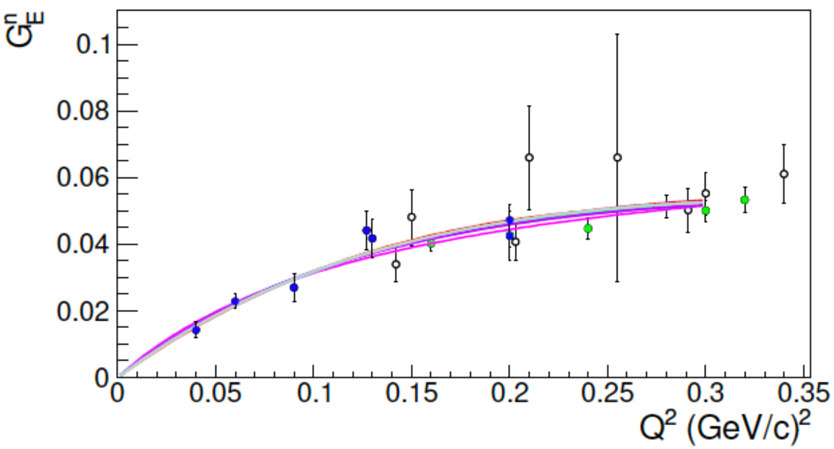
$\langle r_n^2 \rangle$ extraction with fits constrained at low Q^2

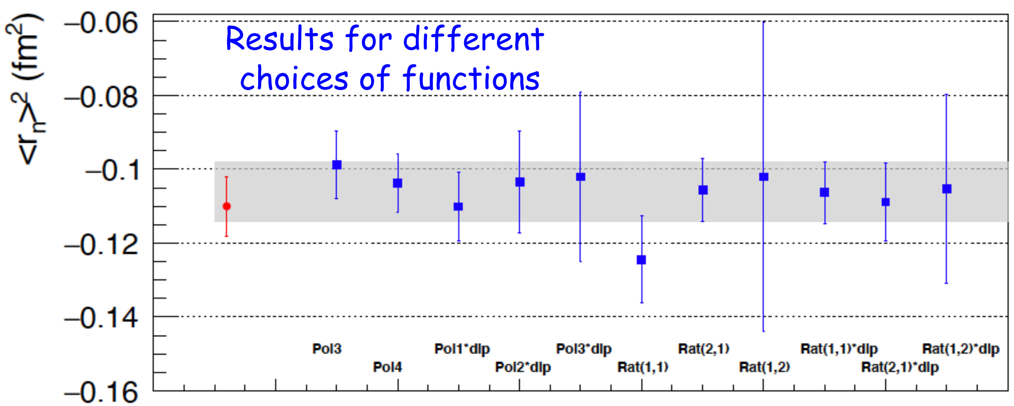
$$\langle r_{\rm n}^2 \rangle = -6 \frac{dG_E^n(Q^2)}{dQ^2}\bigg|_{Q^2 \to 0}$$

Fit within a Q^2 range where GEn is monotonic

Explore a variety of functional forms

Explore a varying fitting range in Q^2

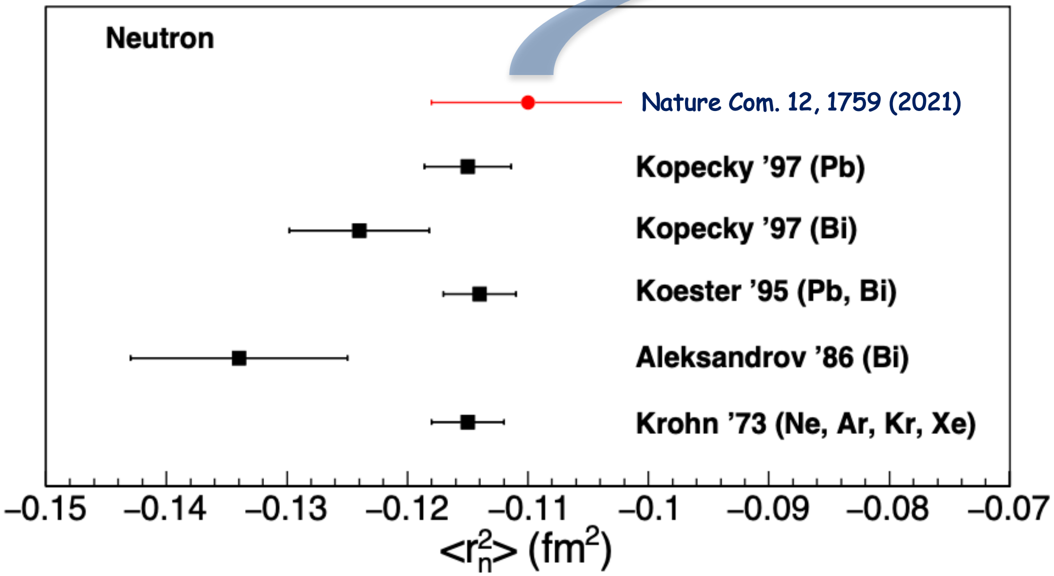




	[0 - 0.3 (GeV/c)^2]	[0 - 0.4 (GeV/c)^2]
Polynomial group	$\langle r_n^2 \rangle = -0.107 \pm 0.006 \pm 0.001_{\rm mod}$ (fm^2)	$\langle r_n^2 \rangle = -0.104 \pm 0.004 \pm 0.004_{\rm mod}$ (fm^2)
Rational group	$\langle r_n^2 \rangle = -0.115 \pm 0.006 \pm 0.002_{\rm mod}$ (fm^2)	$\langle r_n^2 \rangle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

Consistent result for $\langle r_n^2 \rangle$ but with larger uncertainties

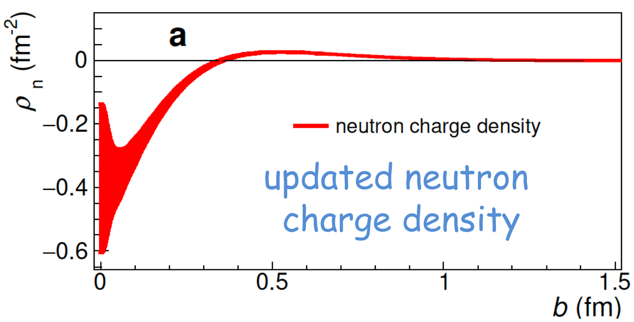
(model dependence due to the choice of the fitted functional form)

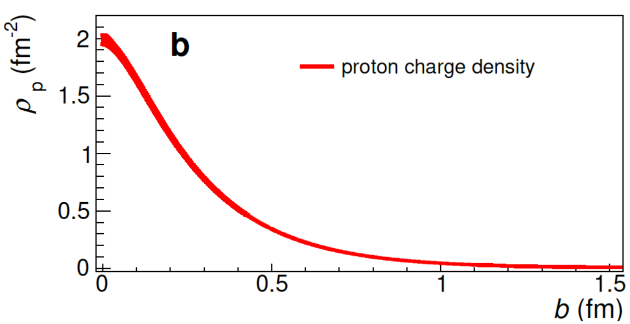


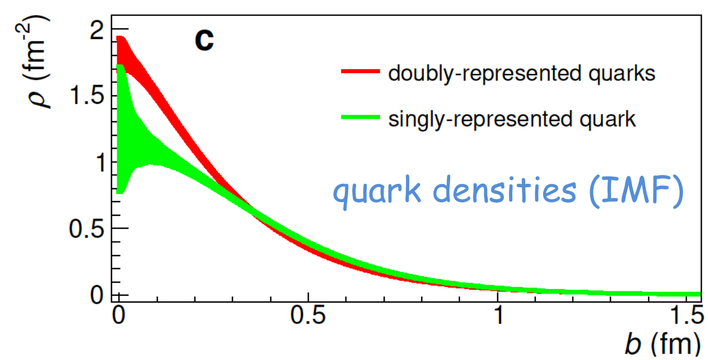
Updates the world data average:

$\langle r_n^2 \rangle$ = -0.1152 +/- 0.017 (fm^2)

Improves the uncertainty by 23%







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

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

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

Phys. Rev. Lett. 125, 232002 (2020)

C. Lorce'

Charge distributions of moving nucleons

The appearance of a negative region around the center of the neutron charge distribution is a manifestation of the contribution induced by the rest frame magnetization

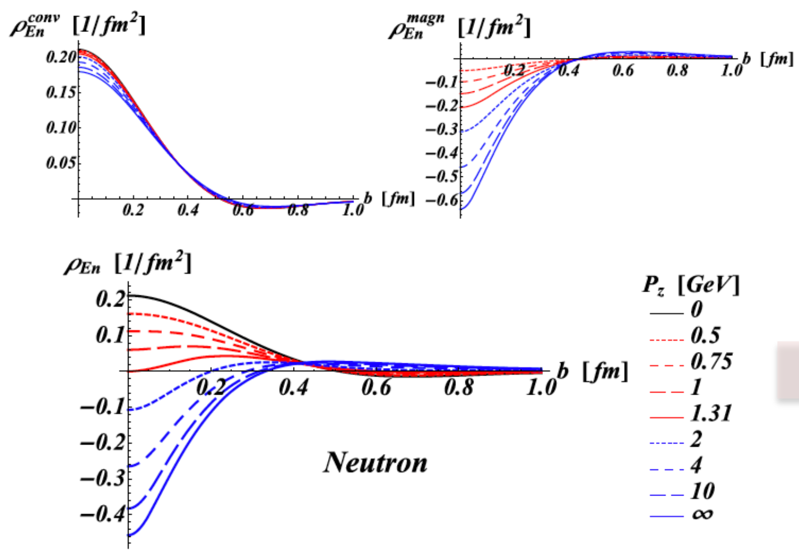
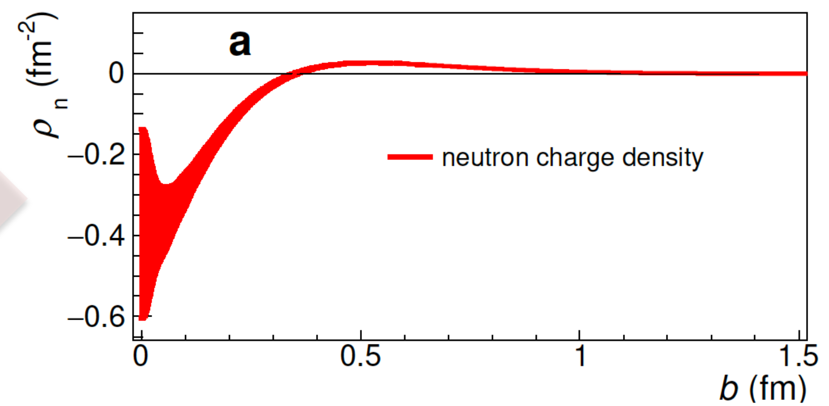


FIG. 3. Unpolarized neutron 2D charge quasidensity as a function of P_z (lower panel), decomposed into convection and magnetization contributions (upper panels). In the Breit or rest frame $P_z = 0$, the charge distribution is purely convective. As P_z increases, a large contribution induced by the rest-frame magnetization progressively pushes the positive charges away from the center. Based on the parametrization from Ref. [26].



<r_n^2> extraction from a precise calculation of the deuteron structure radius

PRL 124, 082501 (2020)

A.A. Filin, V. Baru, E. Epelbaum, H. Krebs, D. Moller, P. Reinert

Determination of the deuteron structure radius in chiral effective field theory

$$r_{\text{str}} = 1.9731^{+0.0013}_{-0.0018}\ \text{fm}$$

Employing atomic data for the difference of the deuteron and proton charge radii

$$r_d^2 - r_p^2 = 3.82070(31)\ \text{fm}^2$$ PRA 97, 062511 (2018)

$$r_{\text{str}}^2 = r_d^2 - r_p^2 - r_n^2 - \frac{3}{4m_p^2}$$

$$\Rightarrow \quad r_n^2 = -0.106^{+0.007}_{-0.005}\ \text{fm}^2$$

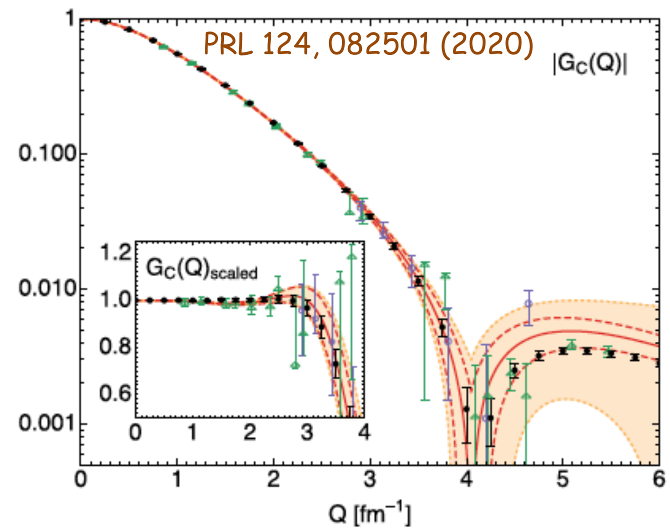
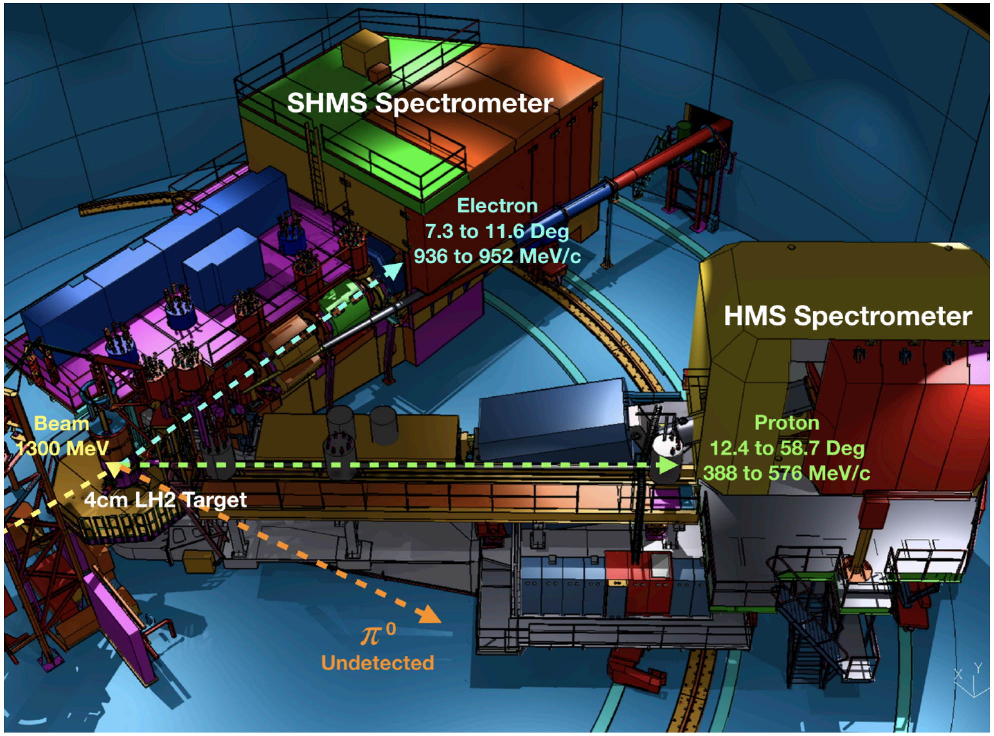
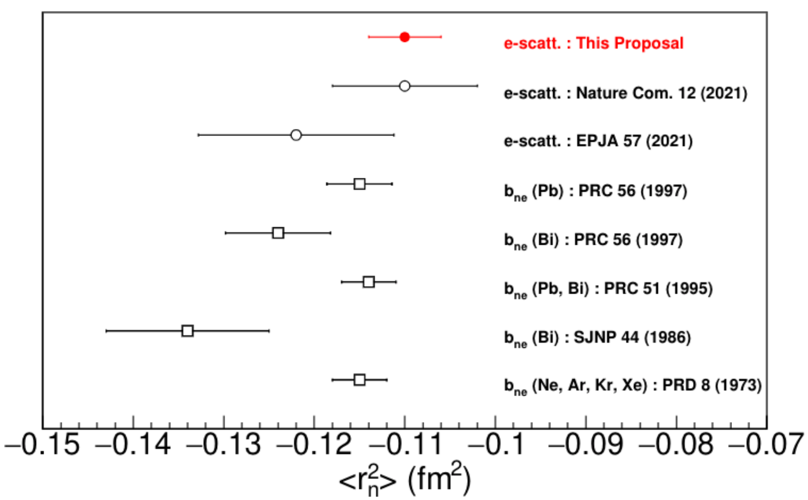


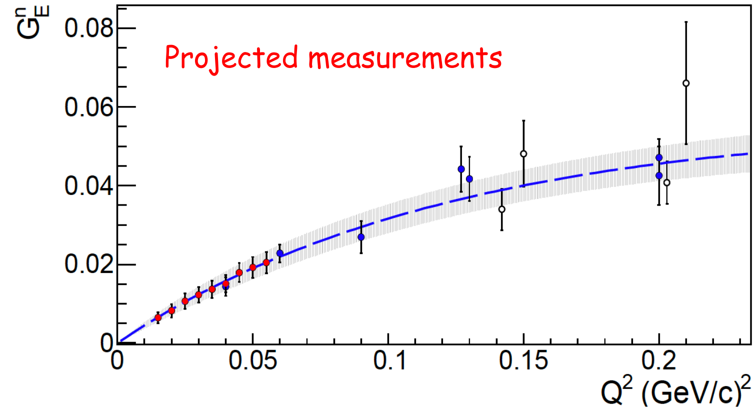
FIG. 1. Deuteron charge FF from the best fit to data up to $Q = 4\ \text{fm}^{-1}$ evaluated for the cutoff $\Lambda = 500$ MeV (solid red lines). Band between dashed (red) lines corresponds to a 1σ error in the determination of the short-range contribution to the charge density operator at N^{4}LO. Light-shaded (orange dotted) band corresponds to the estimated error (68% degree-of-belief) from truncation of the chiral expansion at N^{4}LO. Open violet circles and green triangles are experimental data from Ref. [45] and Refs. [46,47], respectively. Black solid circles correspond to the parametrization of the deuteron FFs from Refs. [16,52] which is not used in the fit and shown just for comparison. The rescaled charge FF of the deuteron, $G_C(Q)_{\text{scaled}}$, as defined in Ref. [16], is shown on a linear scale.

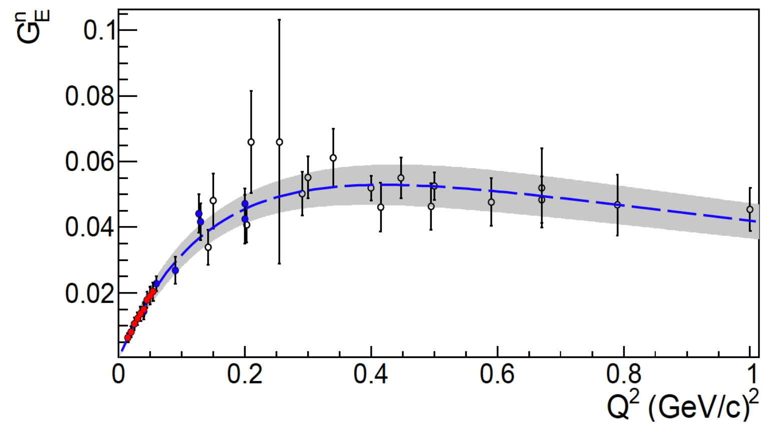
Future prospects

JLab LOI 12-20-002









Conclusion

✓ After 2 decades of stagnation, 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

Discrepancies in the $\langle r_n^2 \rangle$ extraction have been addressed

Path for the further improvement of the $\langle r_n^2 \rangle$ extraction; new experiments

✓ 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;

Resolves the $\langle r_p \rangle$ fitting discrepancies from the different e-scattering data-sets: no proton radius puzzle in e-scattering

Thank you!