Measurement of the neutron charge radius from electron scattering data

Nikos Sparveris

9th Workshop of the APS Topical Group on Hadron Physics

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Temple University

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Neutron

Central role in nature; equivalent to that of 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: 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

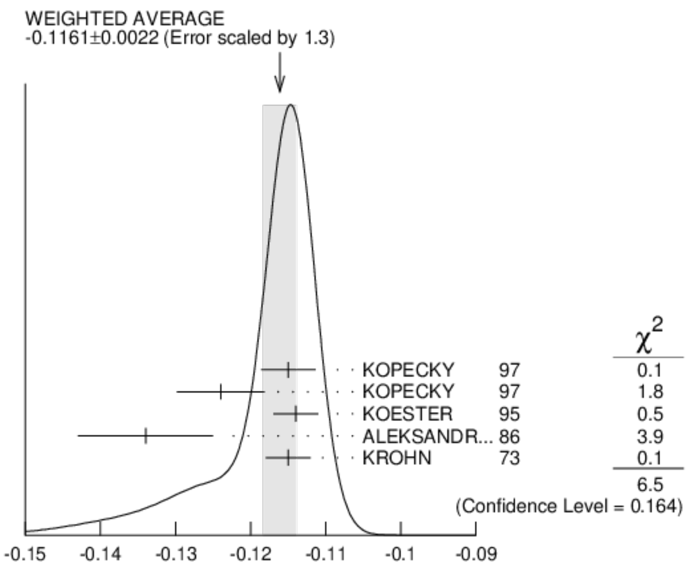
This talk: Status of the neutron charge radius measurements

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:

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

Measurements are old;
PDG value remains unchanged for 2 decades

PDG data exhibit large tensions → systematics

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

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

World data results are compiled in two groups:

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

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

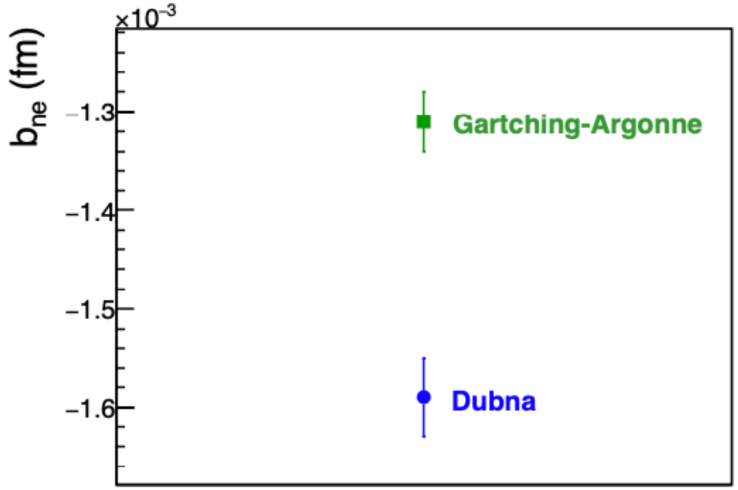
5σ unresolved discrepancies

e.g. PRC 56, 2229 (1997) ; Annu. Rev. Nucl. Part. Sci. 55, 27 (2005) ; PRD 77 034020 (2008) ; Nucl. Phys. A819 1 (2009) ; …

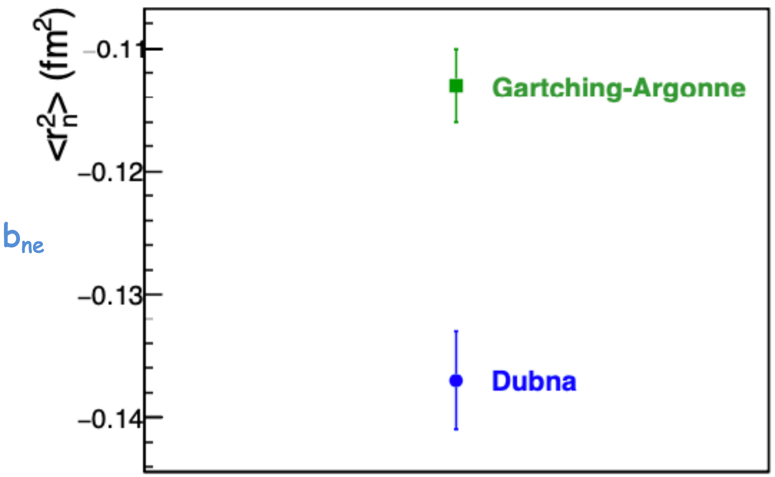
→ **Translated directly into $\langle r_n^2 \rangle$ extraction discrepancies**

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

5σ unresolved discrepancies in b_{ne}



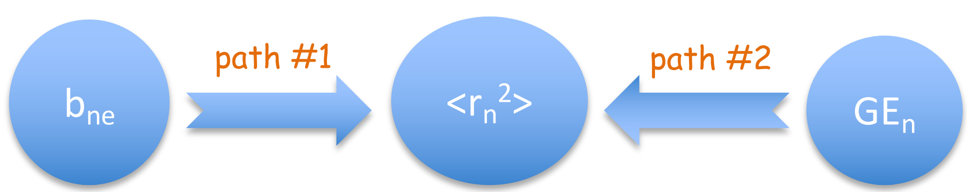
$\langle r_n^2 \rangle = 3\ (m_e\ a_o/m_n)\ b_{ne}$



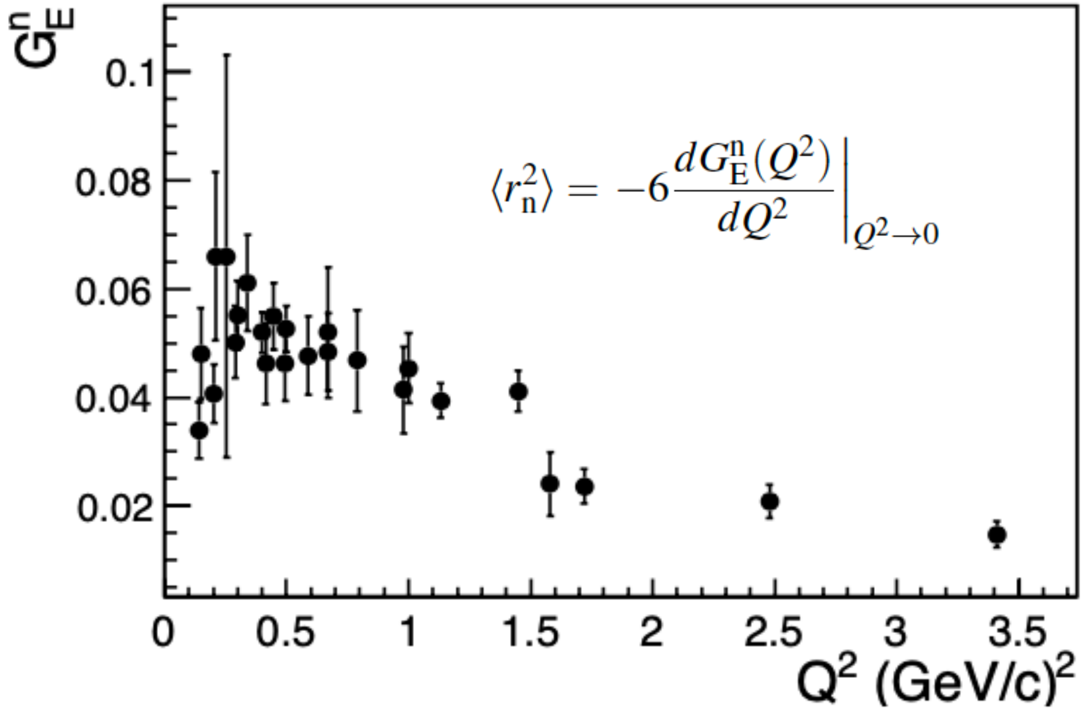
➔ Translated directly into $\langle r_n^2 \rangle$ extraction discrepancies

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



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 $\langle r_n^2 \rangle$

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)

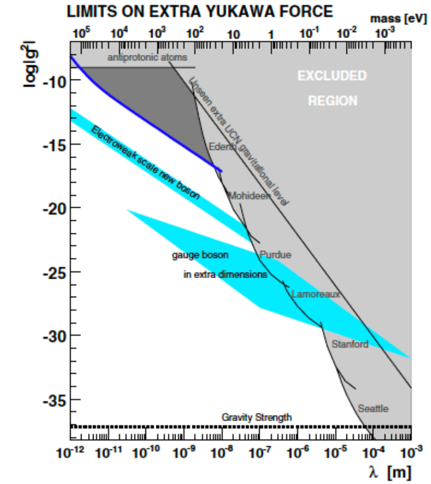


FIG. 8 (color online). Experimental limits on extra interactions including the best neutron constraint obtained in this article (bold line). Two theoretical regions of interest are shown: a new boson with mass induced by electroweak symmetry breaking [10], and a new boson in extra large dimensions [4].

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]

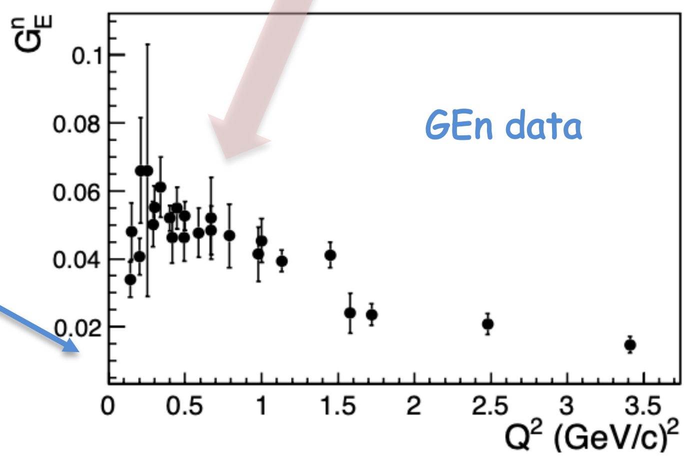
$$b_{ne}^{\rm exp} = (-1.31 \pm 0.03)\times 10^{-3}~{\rm fm} \quad [\text{Gartching-Argonne}]$$
$$b_{ne}^{\rm exp} = (-1.59 \pm 0.04)\times 10^{-3}~{\rm fm} \quad [\text{Dubna}]. \qquad (18)$$

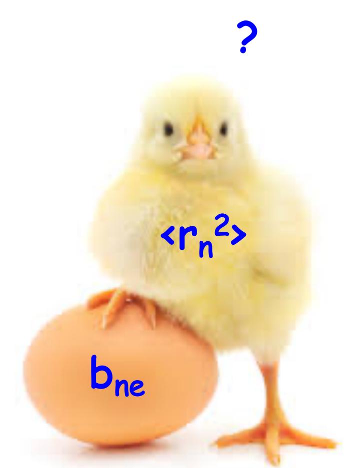
The discrepancy is much greater than the quoted uncertainties of the experiments and there evidently an unaccounted for systematic error in at least one of the experiments.

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,*]

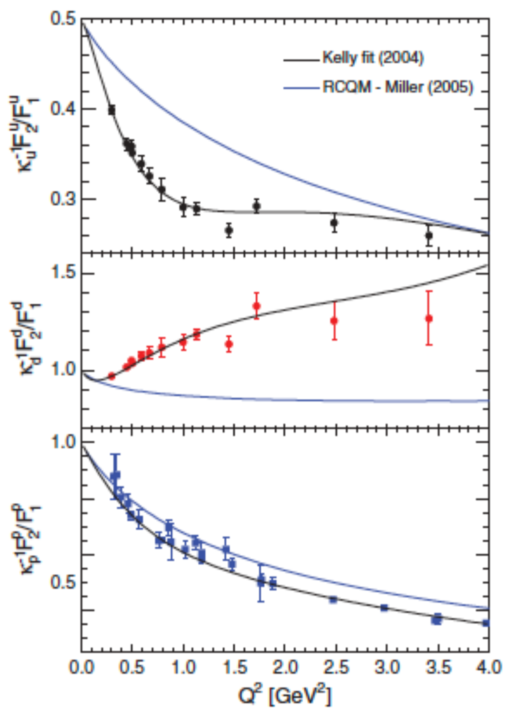


FIG. 2 (color). The ratios $\kappa_d^{-1}F_2^d/F_1^d$, $\kappa_u^{-1}F_2^u/F_1^u$, and $\kappa_p^{-1}F_2^p/F_1^p$ vs momentum transfer Q^2. The data and curves are described in the text.

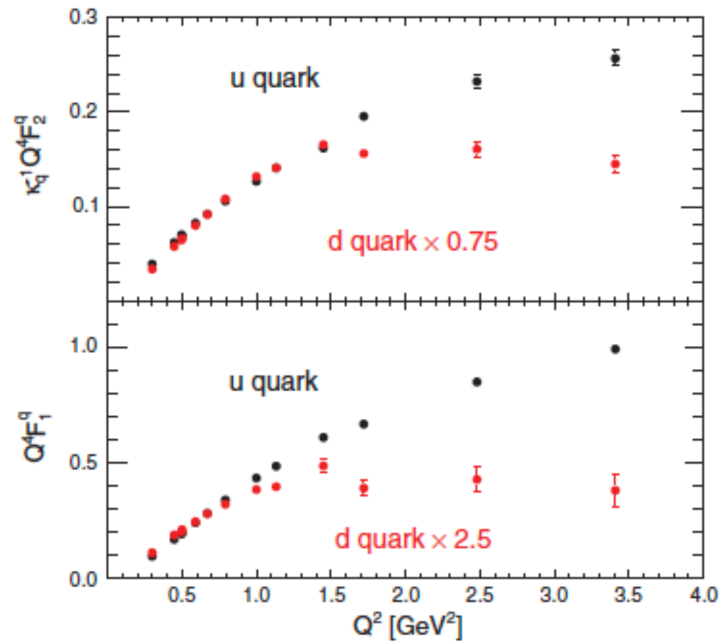
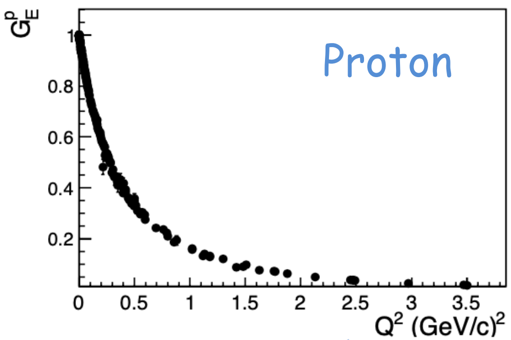
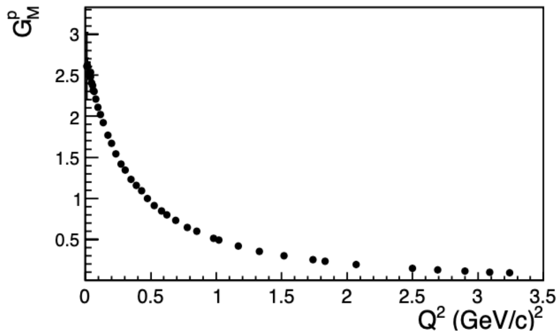


FIG. 3 (color). The Q^2 dependence for the u and d contributions to the proton form factors (multiplied by Q^4). The data points are explained in the text.

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

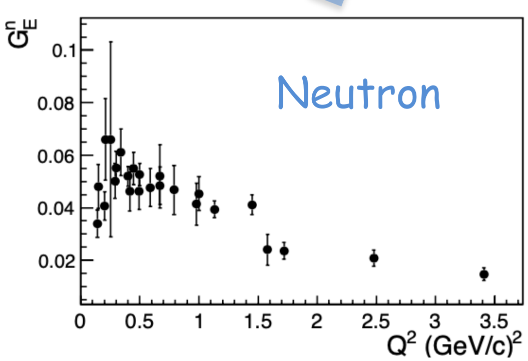


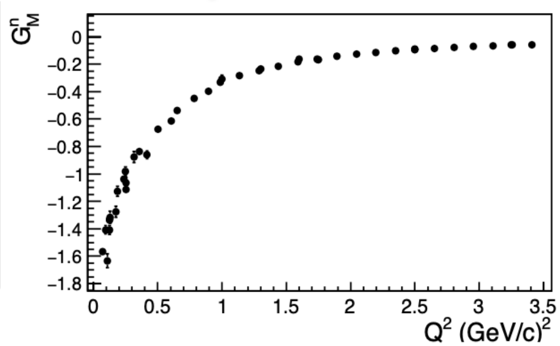


$$F_1 = (G_E + \tau G_M)/(1+\tau)$$

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

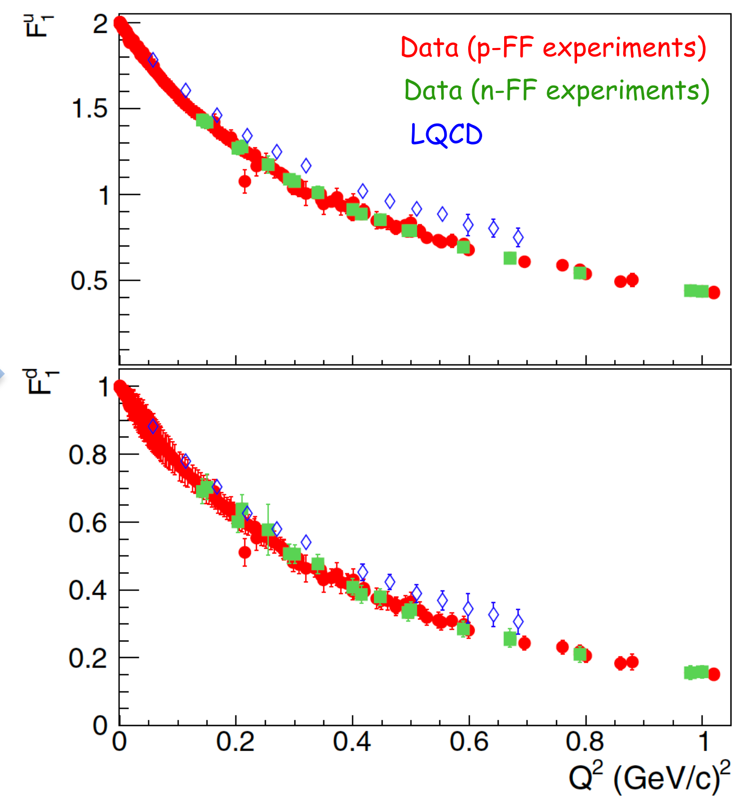
$$F_1^d = 2\,F_1^n + F_1^p$$



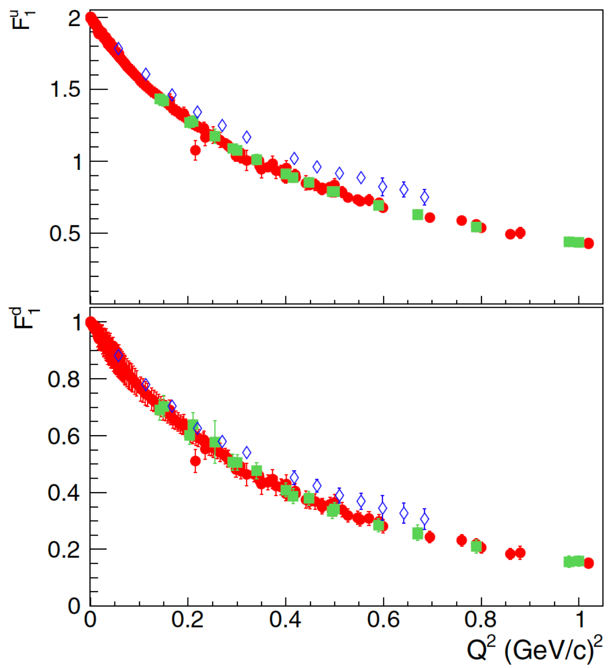


Same procedure but focusing at low-Q^2

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 $\langle b^2_{u(d)} \rangle$

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

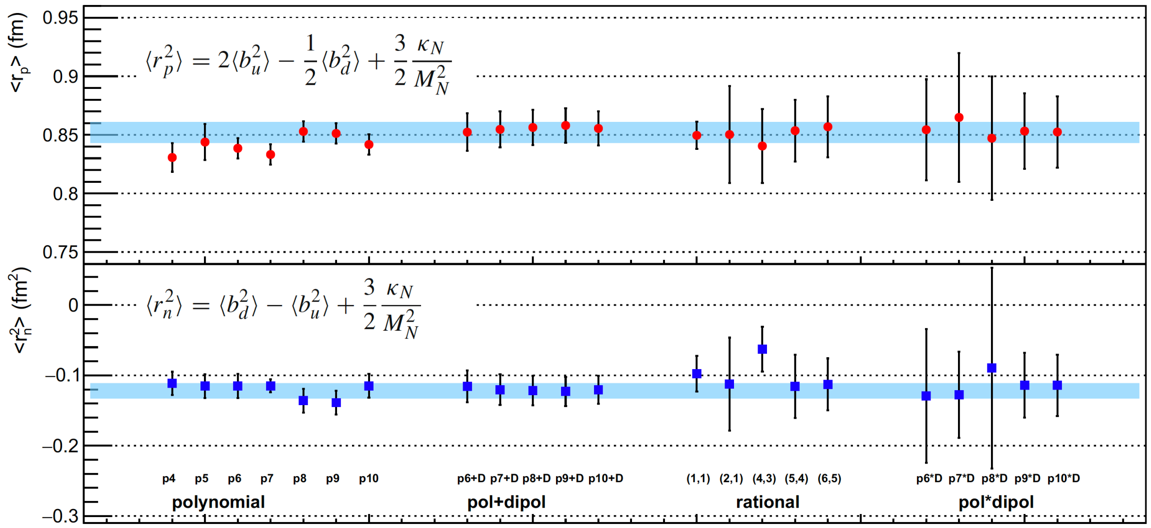
A variety of functional forms is employed to fit the data:

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**

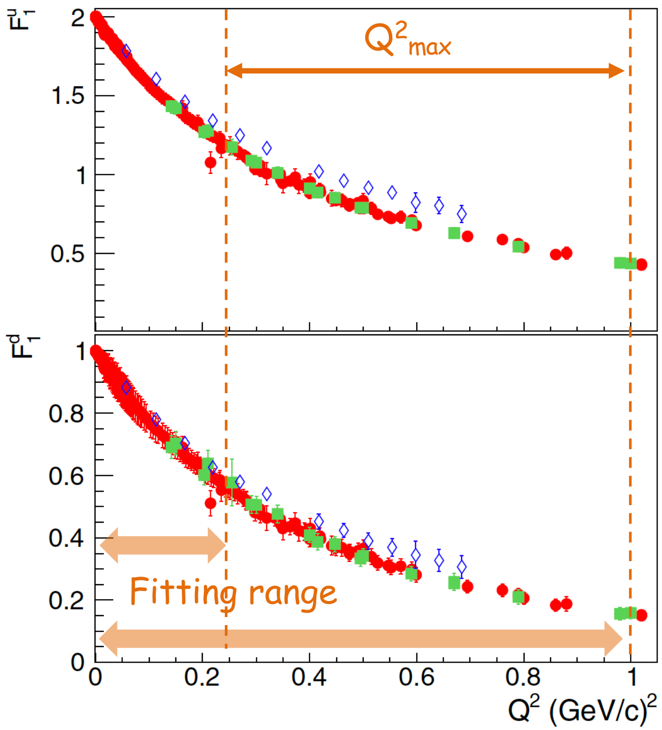
Stability of fits is observed for different orders in the fitted functions

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

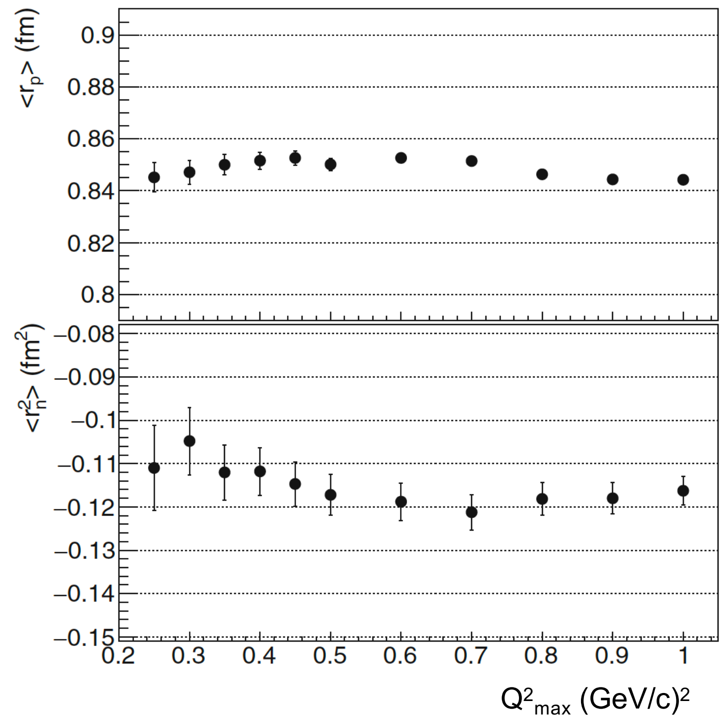


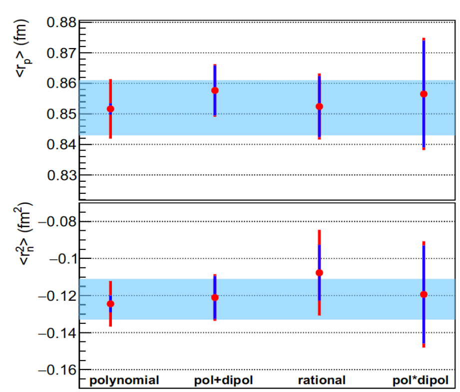
Flavor decomposition of the elastic nucleon EM FFs at low Q^2

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



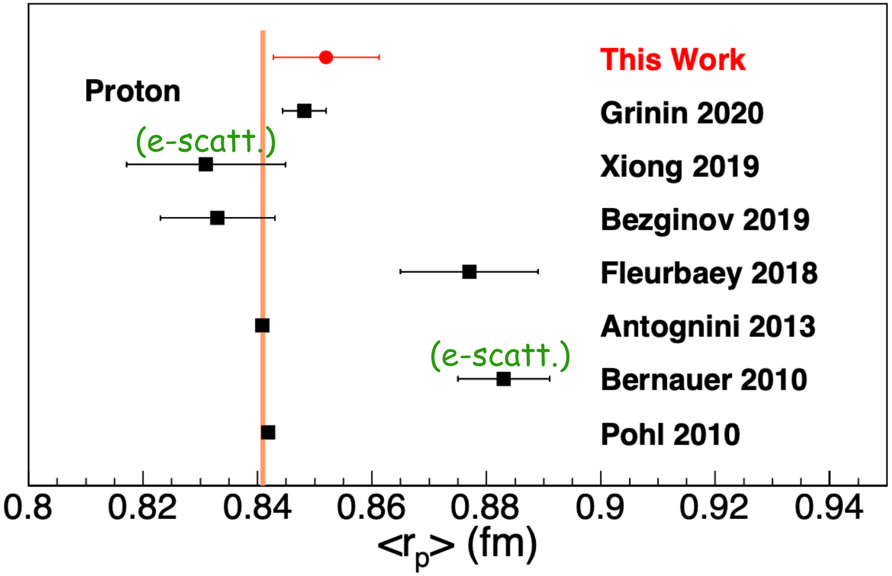
A systematic uncertainty is quantified from the variance of the fitted results for a varying Q^2_{max}





Fitted results per group of functions

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



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

Fitting **without the PRad data**:

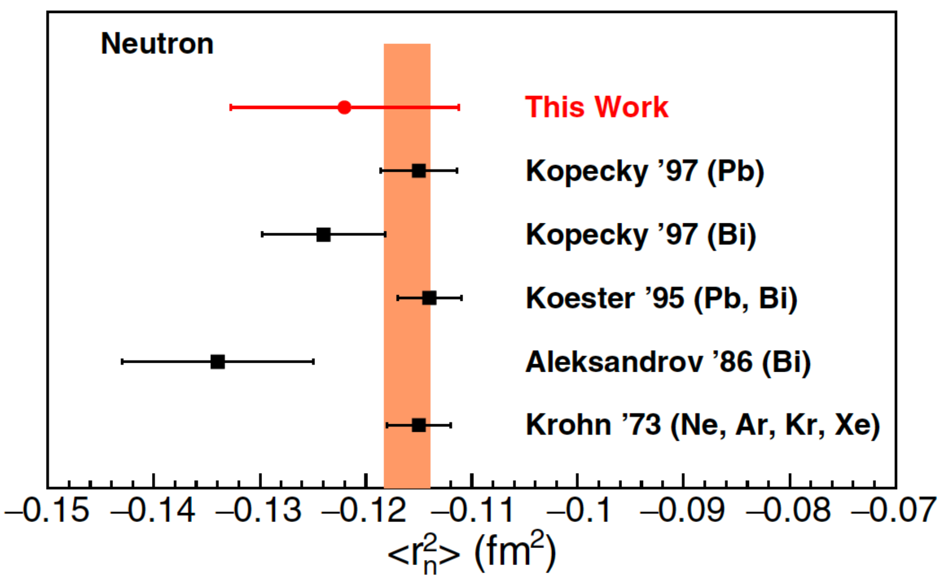
fit is driven primarily by the MAMI data

$\langle r_p \rangle$=0.857(13) (fm)

A small $\langle r_p \rangle$ is derived:

no discrepancy is observed in the extraction from the different e-scattering experiments (i.e. MAMI vs PRad)

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



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

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

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

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

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.

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 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.

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

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

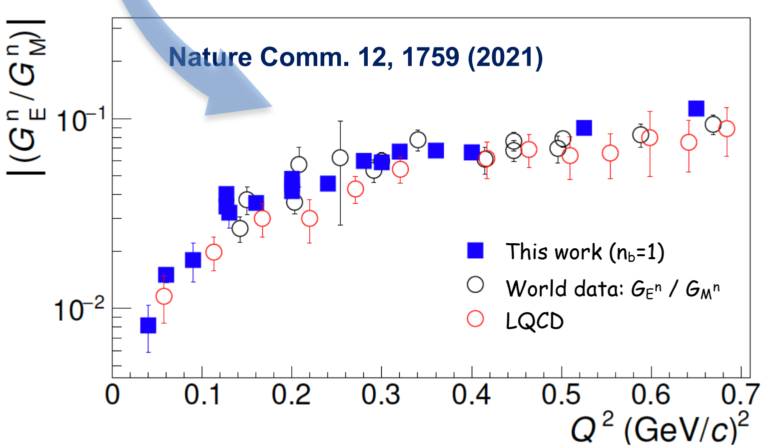
$$\frac{G_E^n(Q^2)}{G_M^n(Q^2)} = \frac{Q}{|\mathbf{q}|}\frac{2Q}{M_N}\frac{1}{n_b(Q^2)}\frac{C2}{M1}(Q^2)$$

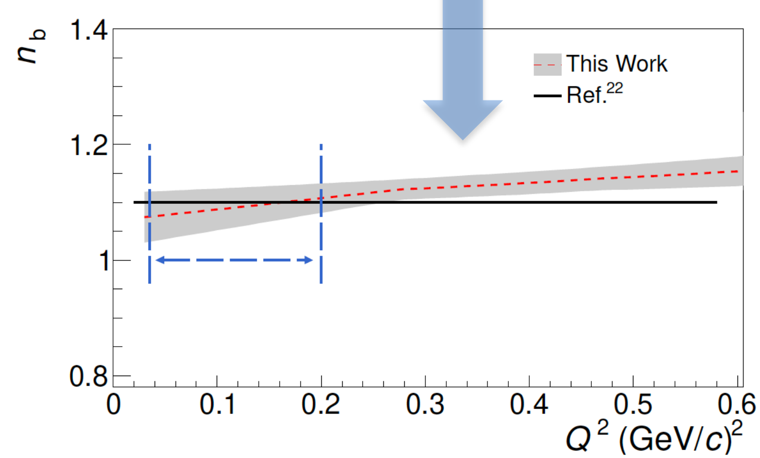
Theoretical correction (n_b) is ~10% (i.e. it reduces the G_E^n/G_M^n ratio by n_b~1.1) mainly due to third order SU(6) breaking terms (three-quark currents) omitted in the relation between G_M^n and $G_{M1}^{N-\Delta}$

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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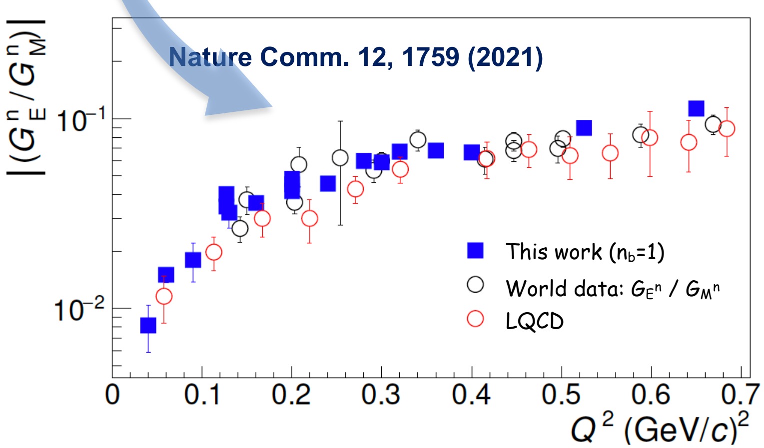
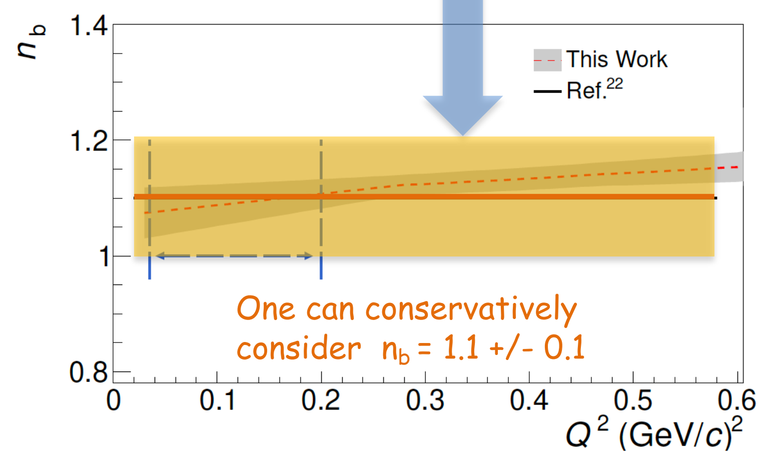




Connection between the GEn and the N-to-Δ FFs

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

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

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

Large-N_c relations (Pascalutsa & Vanderhaeghen)

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

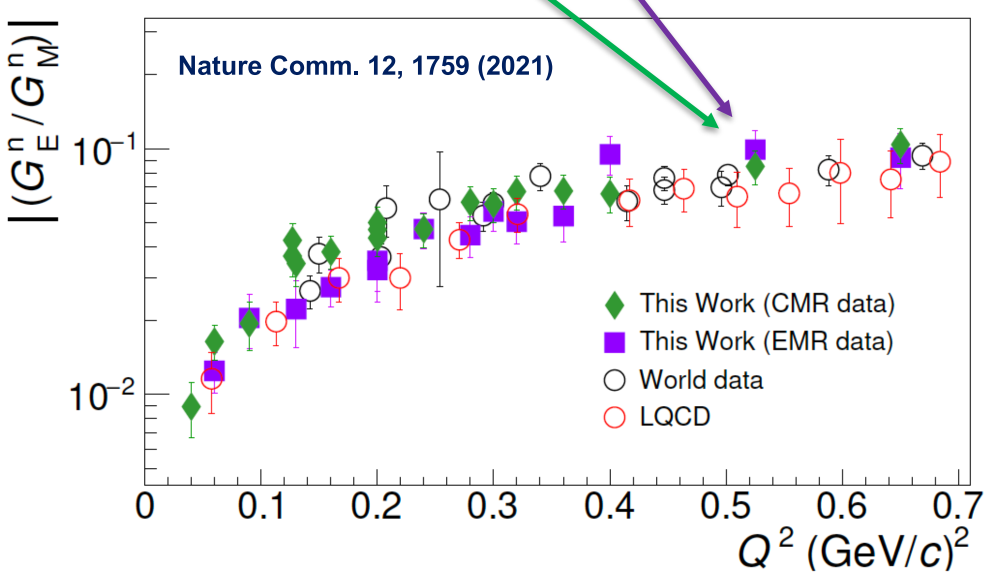
$$\frac{C2}{M1}(Q^2) = \left(\frac{M_N}{M_\Delta}\right)^{3/2} \frac{Q_+ Q_-}{2Q^2} \frac{G_E^n(Q^2)}{F_2^p(Q^2) - F_2^n(Q^2)}$$

Theoretical uncertainty ~15%

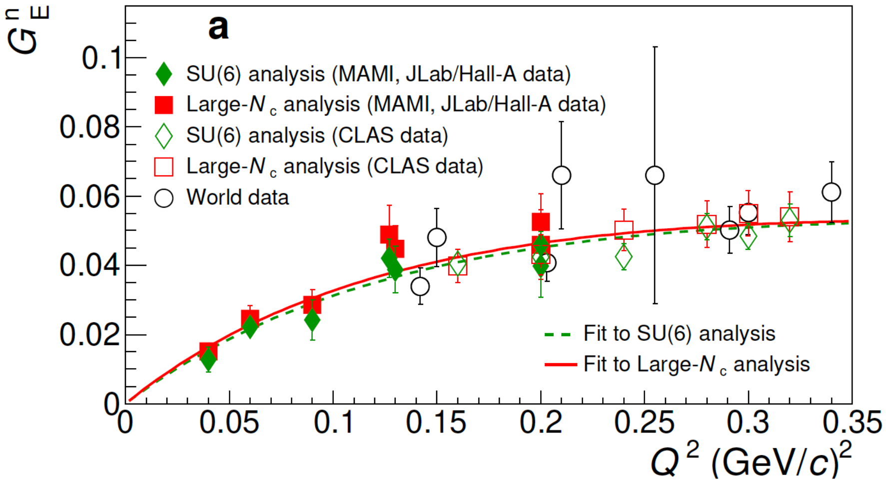
→ Propagates to a GEn uncertainty

Two relations involving 2 different observables

→ allows to check the validity of the theoretical framework



GEn extraction from N-to-Δ TFFs

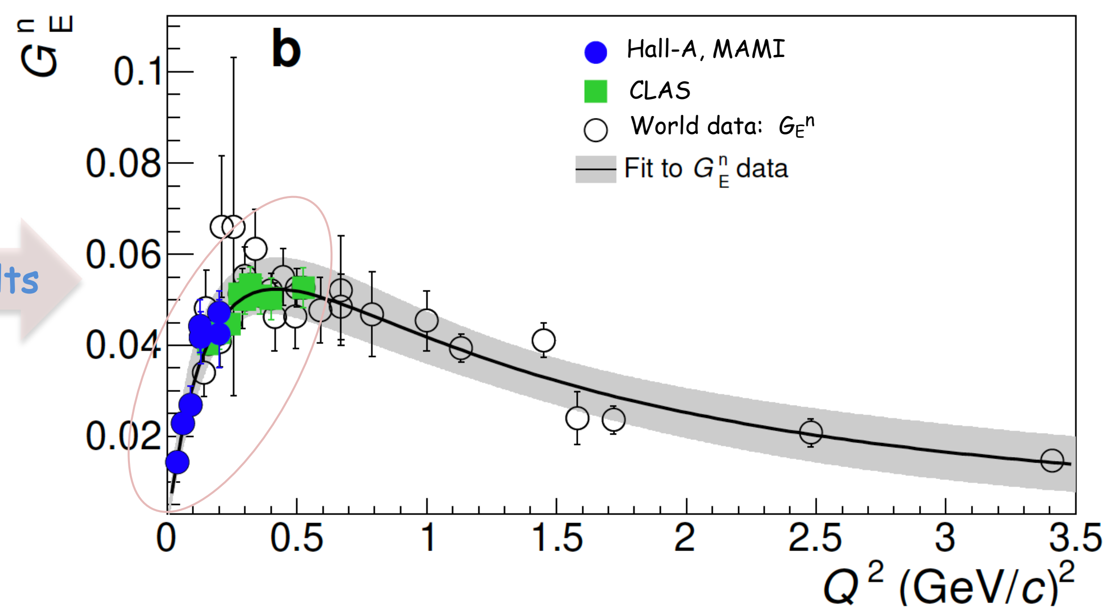


◆ ■	Hall-A, MAMI
◇ □	CLAS

Variance of the results is quantified as theoretical δG_E^n

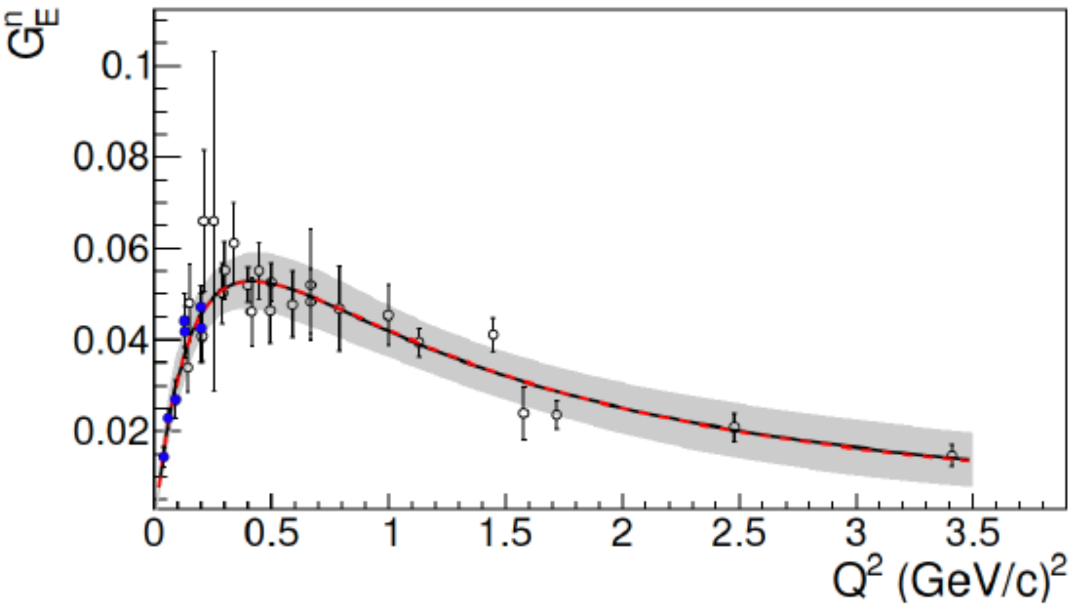
Final Results

Nature Comm. 12, 1759 (2021)



$\langle r_n^2 \rangle$ extraction

$$\langle r_{\mathrm{n}}^2 \rangle = -6 \frac{dG_{\mathrm{E}}^{\mathrm{n}}(Q^2)}{dQ^2}\Bigg|_{Q^2 \to 0}$$



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

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

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

Fits nearly indistinguishable

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

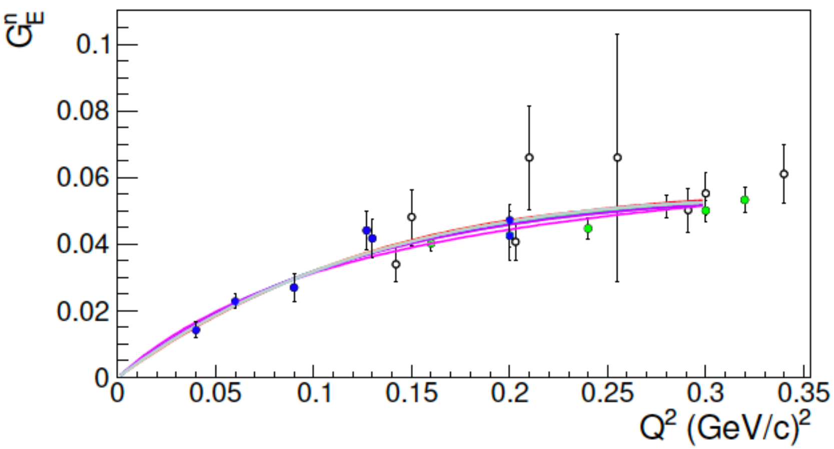
$\langle r_n^2 \rangle$ extraction with fits constrained at low Q^2

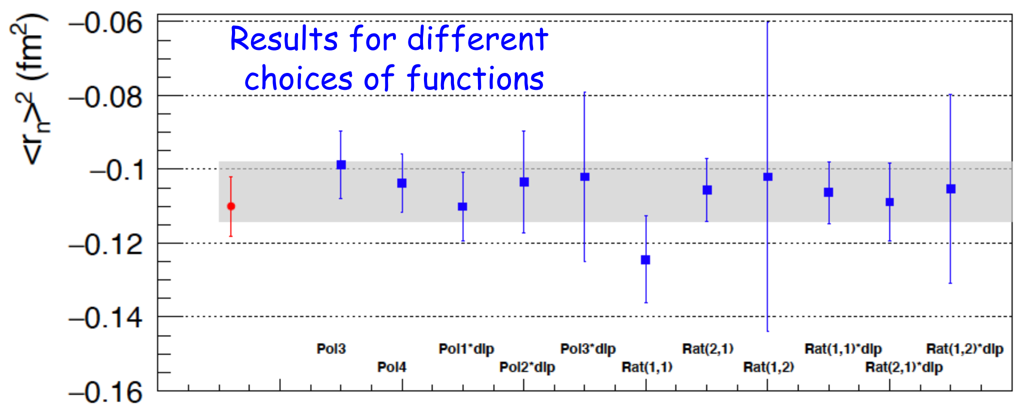
$$\langle r_{\rm n}^2 \rangle = -6 \frac{dG_{\rm E}^{\rm n}(Q^2)}{dQ^2}\bigg|_{Q^2 \to 0}$$

Fit within a Q^2 range where GEn is monotonic

Explore a variety of functional forms

Explore a varying fitting range in Q^2

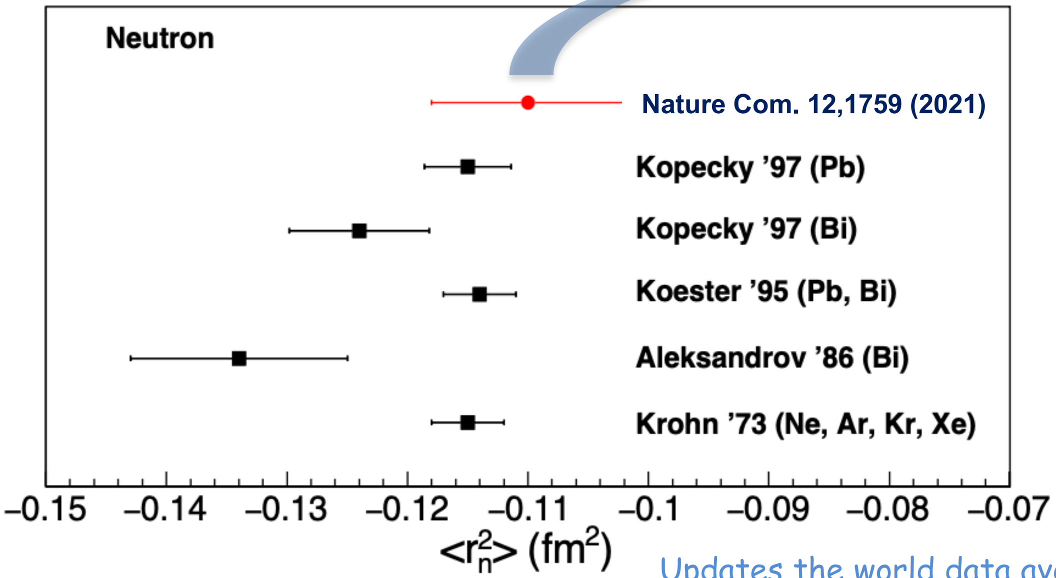




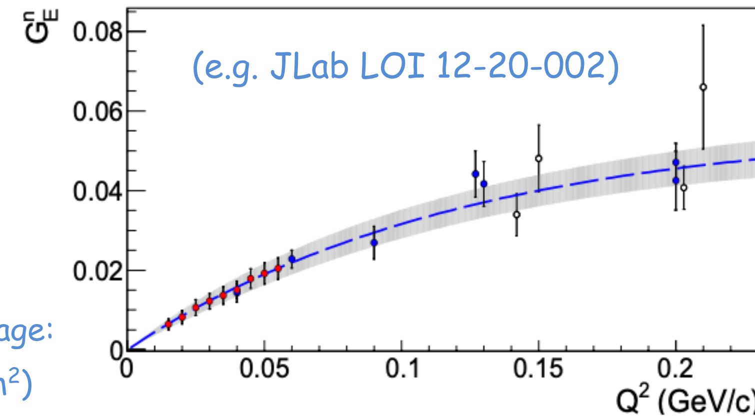
	[0 - 0.3 (GeV/c)^2]	[0 - 0.4 (GeV/c)^2]
Polynomial group	$\langle r_{\rm n}^2 \rangle = -0.107 \pm 0.006 \pm 0.001_{\rm mod}$ (fm^2)	$\langle r_{\rm n}^2 \rangle = -0.104 \pm 0.004 \pm 0.004_{\rm mod}$ (fm^2)
Rational group	$\langle r_{\rm n}^2 \rangle = -0.115 \pm 0.006 \pm 0.002_{\rm mod}$ (fm^2)	$\langle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

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

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



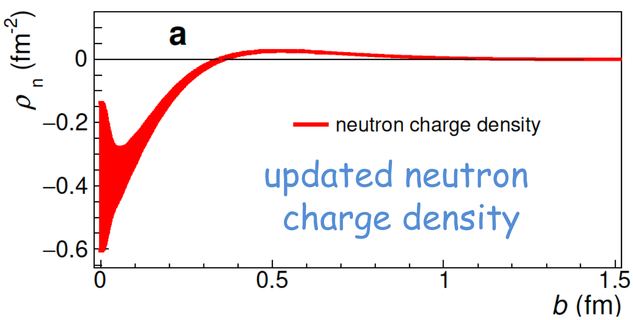
Can be further improved by a factor of 2 with new measurements at JLab (Hall-C) or/and MAMI-A1

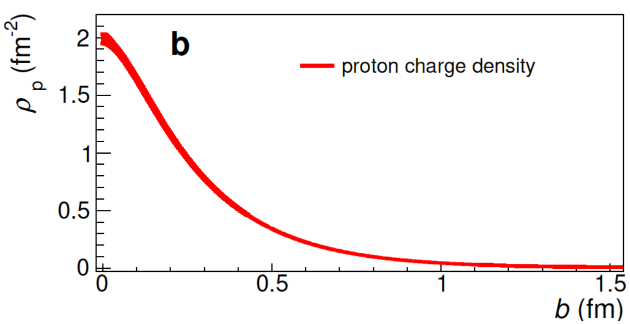


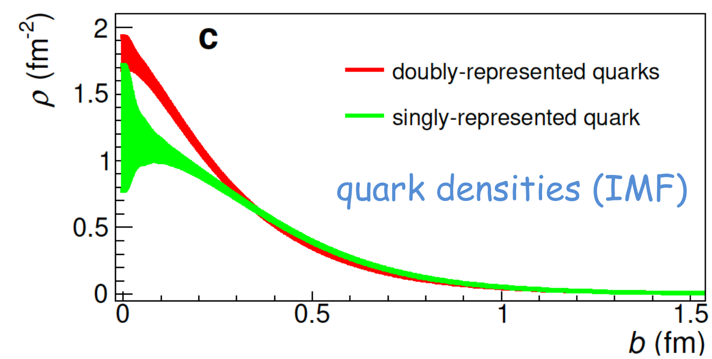
Updates the world data average:

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

Improves the uncertainty by 23%







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

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

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

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

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

A path for the further improvement of the $\langle r_n^2 \rangle$ extraction has been presented;

New experimental measurements have been proposed

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

Thank you!