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Precision theory for charge radii of light nuclei

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in collaboration with

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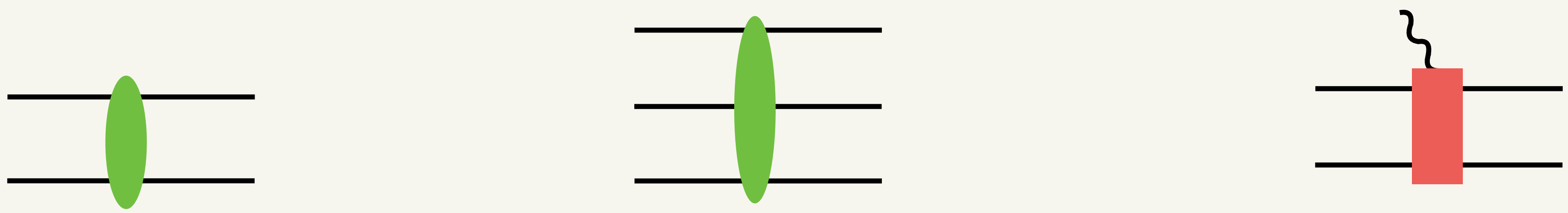
PRL 124 082501 (2020)

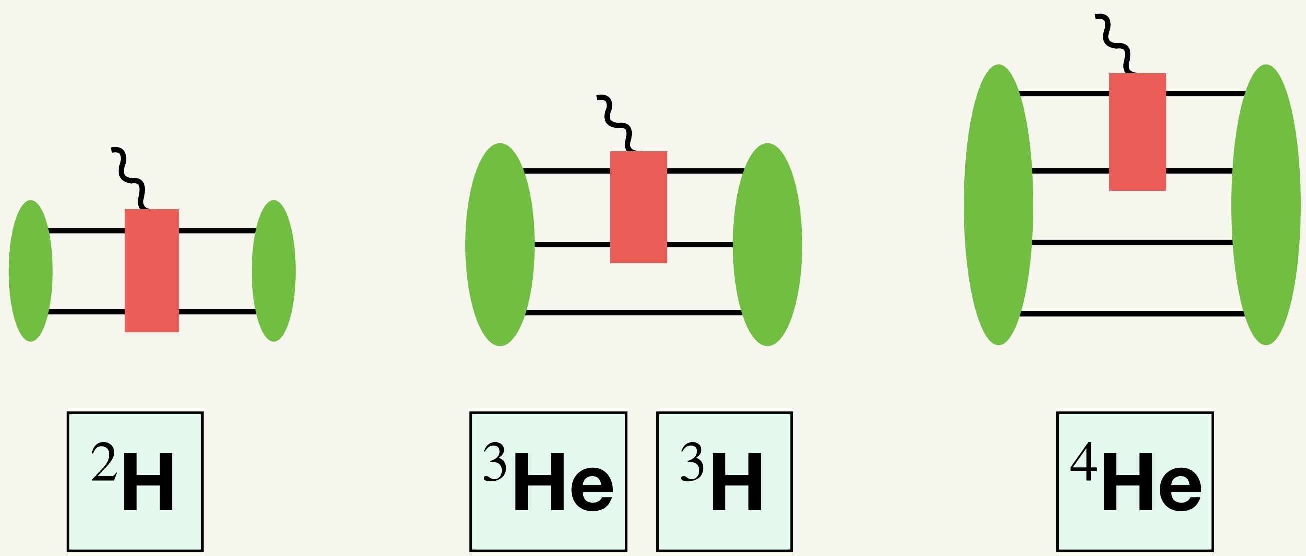
Phys.Rev.C 103 024313 (2021)

Nuclear structure using chiral effective field theory

Low-energy **chiral effective field theory** of the standard model



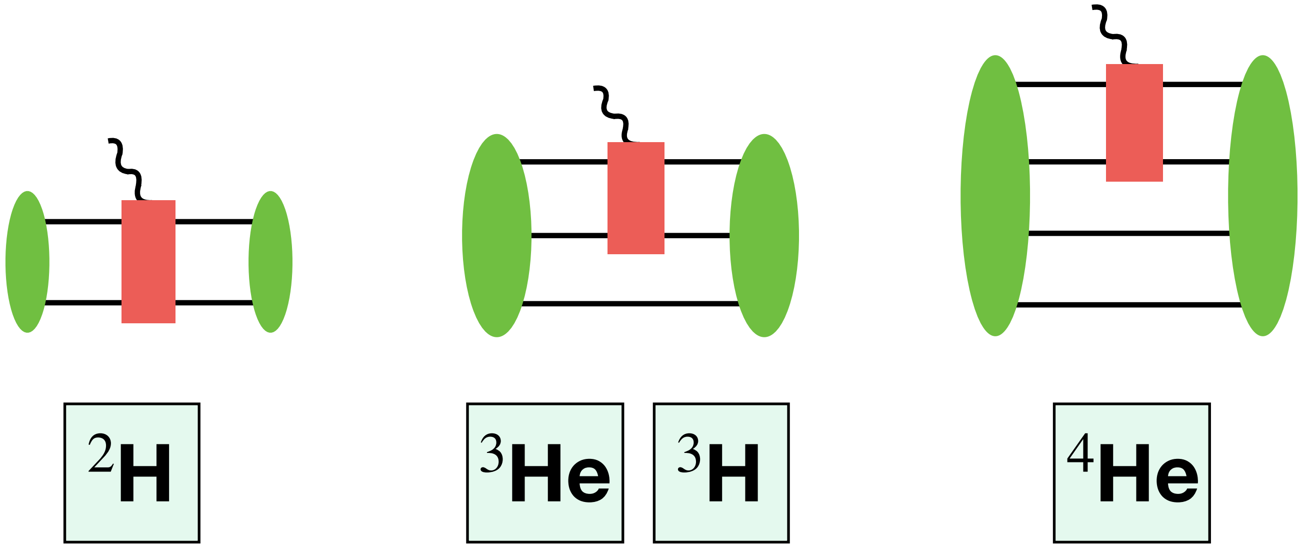
Chiral two-nucleon forces **Chiral three-nucleon forces** **Chiral electromagnetic currents**



Charge form factors and radii of super-light nuclei

structure of medium-mass nuclei

Precise calculations of charge radii of super-light nuclei



Motivation:

- Precision **tests of nuclear chiral effective field theory (Chiral EFT)**

- Help to resolve long-standing issue with **underpredicted radii of medium-mass and heavy nuclei**

- A new way to **extract the neutron and the proton charge radii** from few-nucleon data

- Search for **Beyond-Standard-Model** physics (lepton universality breaking)

Charge radii of A ≤ 4 nuclei — experimental data

^{3}He

$r = 1.97007(94)\text{fm}$

0.05 %

CREMA 2023
arXiv:2305.11679

^{4}He

$r = 1.6786(12)\text{fm}$

0.07 %

Krauth et al. 2021
Pachucki:2022tgl

Pohl:2013yb,
CREMA:2016idx,
Pohl:2016glp,
Schmidt:2018kjc,
Krauth:2021foz
...

^{1}H

$r_p = 0.8406(4)\text{fm}$

0.05 %

Antognini et al. 2013
Pachucki:2022tgl

^{2}H

$r_d = 2.12758(78)\ \text{fm}$

0.04 %

CREMA:2016idx
Pachucki:2022tgl

^{3}H

$r = 1.7xxx(\ \ 2)\text{fm}$

0.01 %

TREX Mainz
[in progress]

Data from isotope shift

$(r_d^2 - r_p^2) = 3.82070(31) fm^2$

0.01 %

Pachucki et al. 2018
Jentschura et al. 2011

n

$r_n^2 = -0.1155(17)\ \text{fm}^2$

1.5 %

PDG 2022

Number of protons Z

Number of neutrons N

Basic features of chiral effective field theory

Chiral effective field theory

- Low-energy **effective field theory of QCD**
- Degrees of freedom are **pions and nucleons**
- Most general Lagrangian consistent with **symmetries and symmetry-breaking pattern of QCD**
- Expansion parameter $Q = \frac{\max(m_\pi, p)}{\Lambda_\chi}$

m_π = pion mass

p = typical momentum scale

Λ_χ = chiral symmetry breaking scale

- **Systematically improvable**
- Observables are calculated order by order

  LO = Leading Order

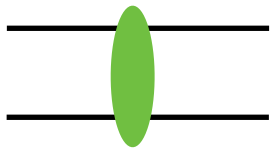
  NLO = Next-to-leading order

  N2LO = Next-to-next-to-leading order

  …

- Higher orders contain more free parameters, which have to be fitted to data

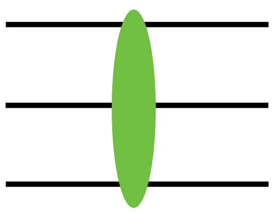
Chiral effective field theory - **precise, accurate** and **consistent**



N^4LO^+

New **high-precision chiral NN forces** (N^4LO^+) Reinert et al. PRL 126, 092501 (2021)

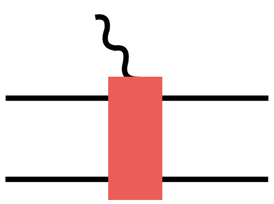
- Nearly perfect description of pp and pn scattering data up to pion production threshold



N^2LO

Chiral 3N forces (general N^2LO; selected terms at N^4LO) Epelbaum:2019kcf

- LECs cD and cE (N^2LO) are fitted to RIKEN Nd DCS data and ^{3}He binding energy
- **Consistent** regularisation of N^3LO is also in progress
- Charge radii of 3N and ^{4}He are not sensitive to 3N forces beyond N^2LO if binding energies of A=3, 4 are reproduced



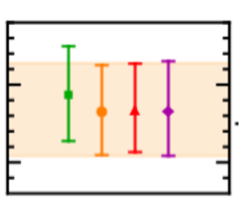
N^2LO

Isoscalar: N^4LO

2N Chiral electromagnetic currents (general N^2LO; isoscalar N^4LO)

Kolling:2009iq
Kolling:2012cs
Krebs:2019aka
Krebs:2020pii (Review)

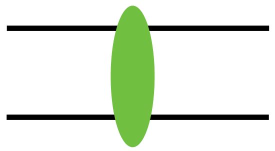
- N^2LO (**isoscalar N^4LO**) is derived and regularised consistently with the chiral NN forces
- Consistent regularisation of N^3LO (isovector) is in progress



Reliable methods to quantify truncation uncertainty of the EFT expansion

Epelbaum et al. EPJA 51 (2015); Furnstahl et al. PRC 92, 024005 (2015); Melendez et al. PRC 96, 024003 (2017), Wesolowski et al. J. Phys. G 46, 045102 (2019); Melendez et al. PRC 100, 044001 (2019), ...

Chiral effective field theory - **precise, accurate** and **consistent**



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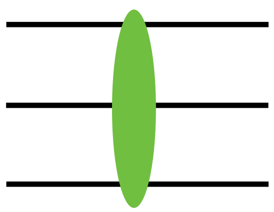

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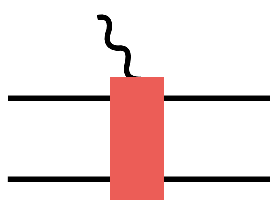

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- N^2LO (**isoscalar N^4LO**) is derived and regularised consistently with the chiral NN forces
- Consistent regularisation of N^3LO (isovector) is in progress

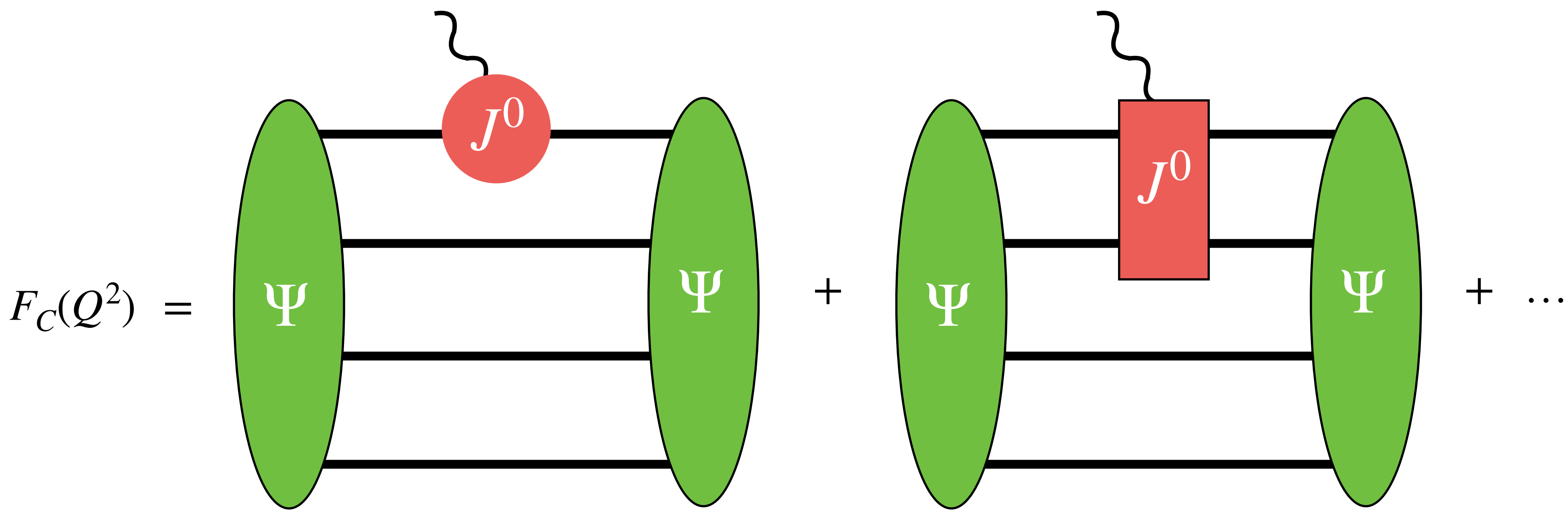
Goals of this study:

- consistent χEFT calculation of isoscalar structure radii of A = 2, 3, 4 nuclei
- aim at N^4LO level of accuracy even in the incomplete calculation
- careful estimation of uncertainties (truncation, statistical, numerical and other)

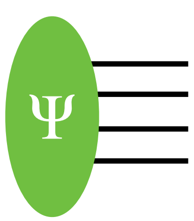
Chiral EFT calculation of the nuclear charge radius

Charge radius r_C is related to the charge form factor $F_C(Q^2)$

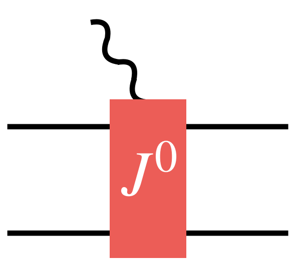
$$r_C^2 = (-6)\frac{\partial}{\partial Q^2} F_C(Q^2)\Big|_{Q=0}$$



The matrix element is a convolution of nuclear wave function and charge density operator



Nuclear wave function based on high-precision chiral EFT interactions



Charge density operator - consistent with chiral nuclear forces

Structure radius

Nuclear **charge radius** can be decomposed into structure, proton and neutron radii

$$r_C^2 = r_{str}^2 + \left(r_p^2 + \frac{3}{4m_p^2} \right) + \frac{N}{Z} r_n^2$$

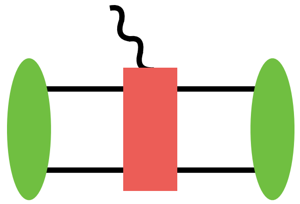
Nuclear structure radius

- depends on distribution of matter (proton and neutrons) inside the nuclei
- depends on many-body electromagnetic currents
- **can be accurately calculated using chiral nuclear forces and EM currents**

Structure radius = charge radius if protons and neutrons have point-like charge distributions

Deuteron structure radius

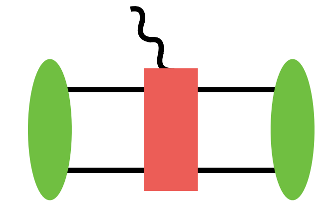
& extraction of the neutron charge radius

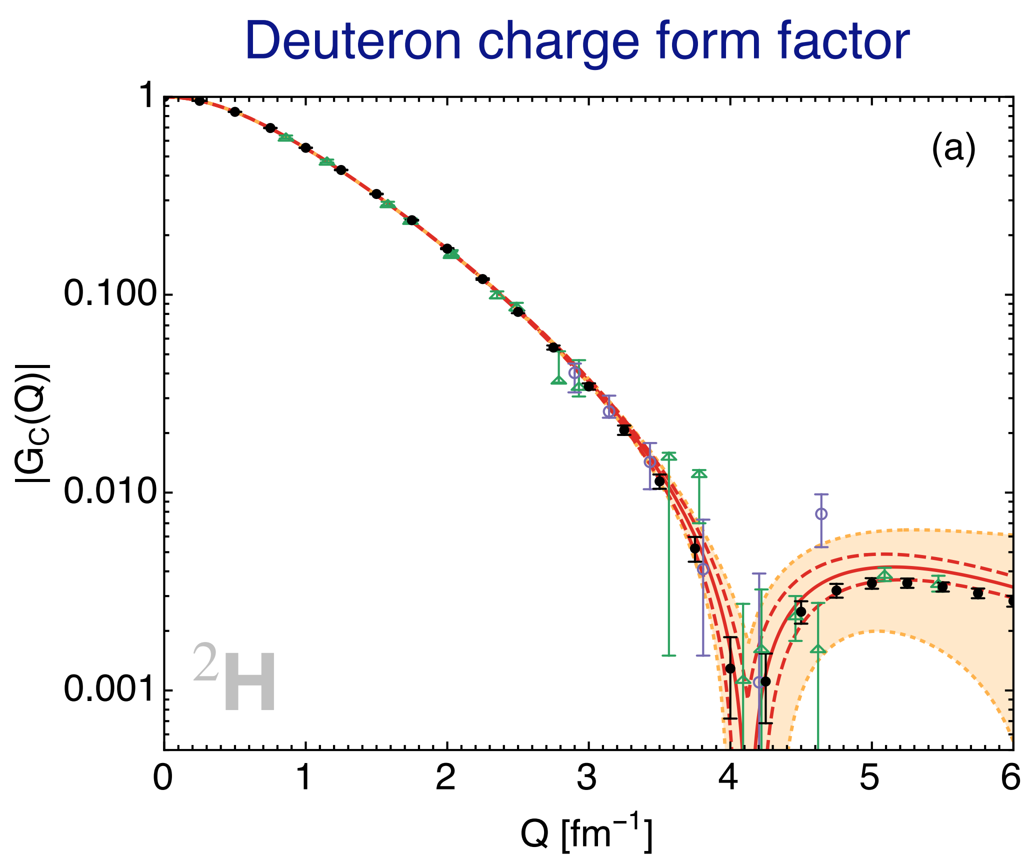


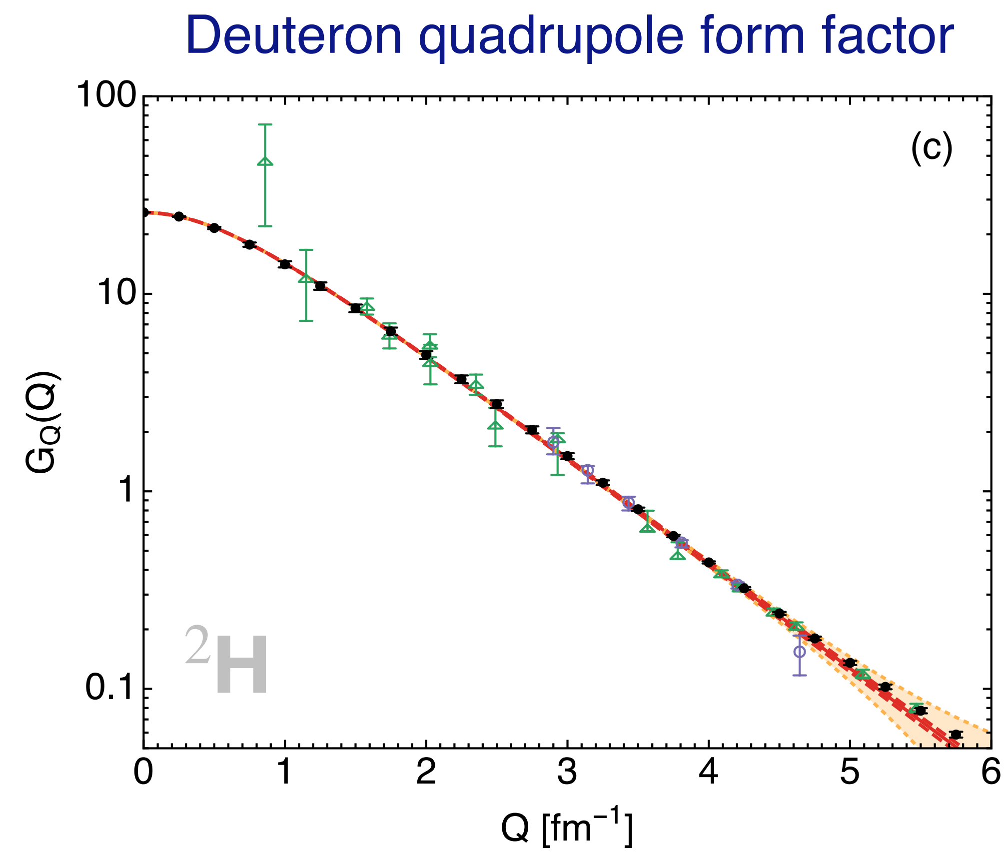
$^{2}\mathbf{H}$

PRL124 082501 (2020)
Phys.Rev.C 103, 024313 (2021)

Deuteron charge and quadrupole form factors







our result + N⁴LO truncation uncertainty

statistical uncertainty

Experimental data

Parameterisation by I.Sick (not used in the fit)

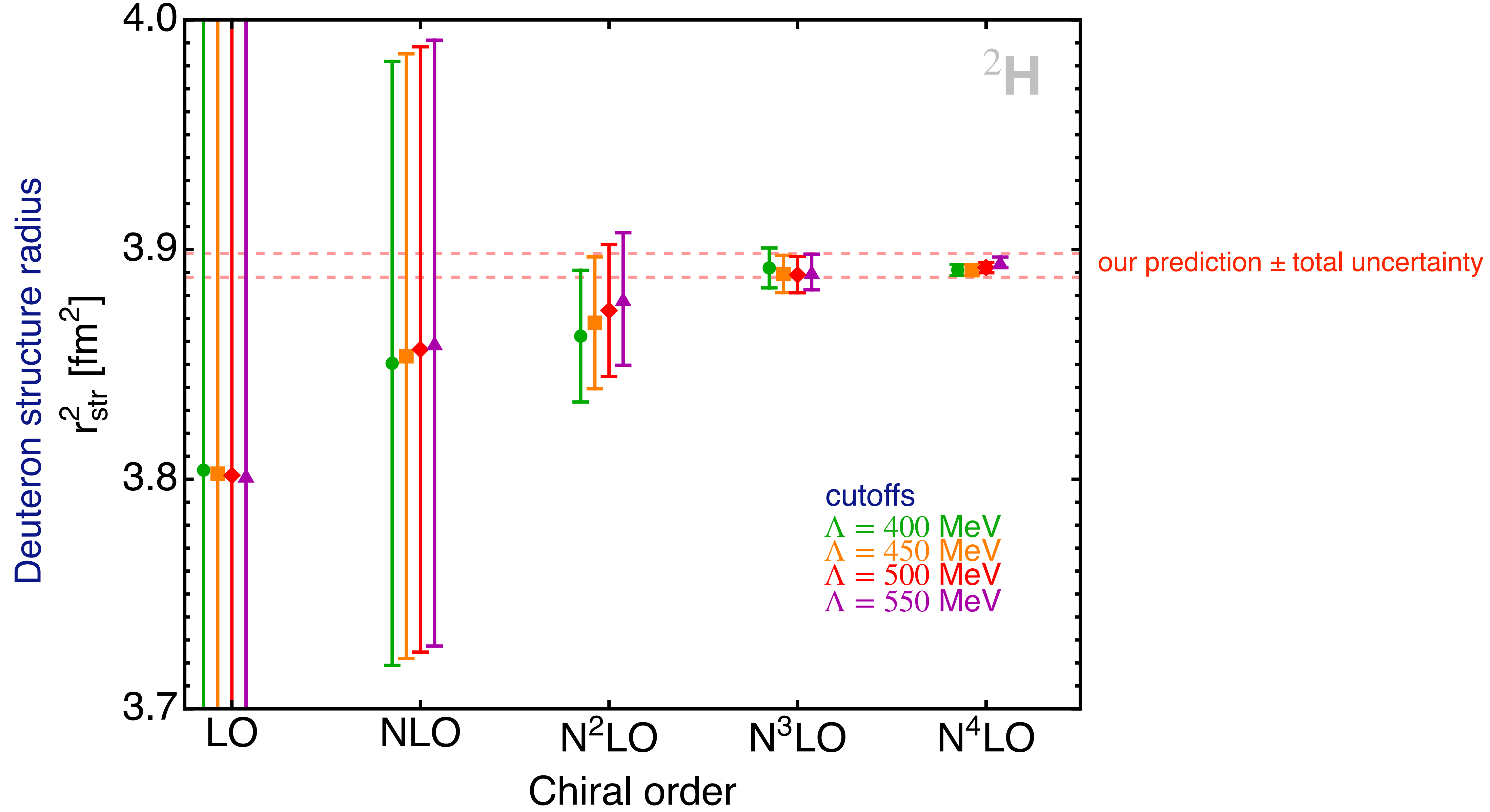
Extraction of deuteron structure radius and quadrupole moment

$$r_{str} = 1.9729^{+0.0015}_{-0.0012} fm \qquad Q_d = 0.2854^{+0.0038}_{-0.0017} fm^2$$

AF, Möller, Baru, Epelbaum, Krebs, Reinert, PRL 124 (2020) 082501; PRC 103 (2021) 024313

Truncation uncertainty of ^{2}H structure radius

Using Bayesian model to estimate truncation uncertainty at each order Epelbaum et al. EPJA 56, 92 (2020)

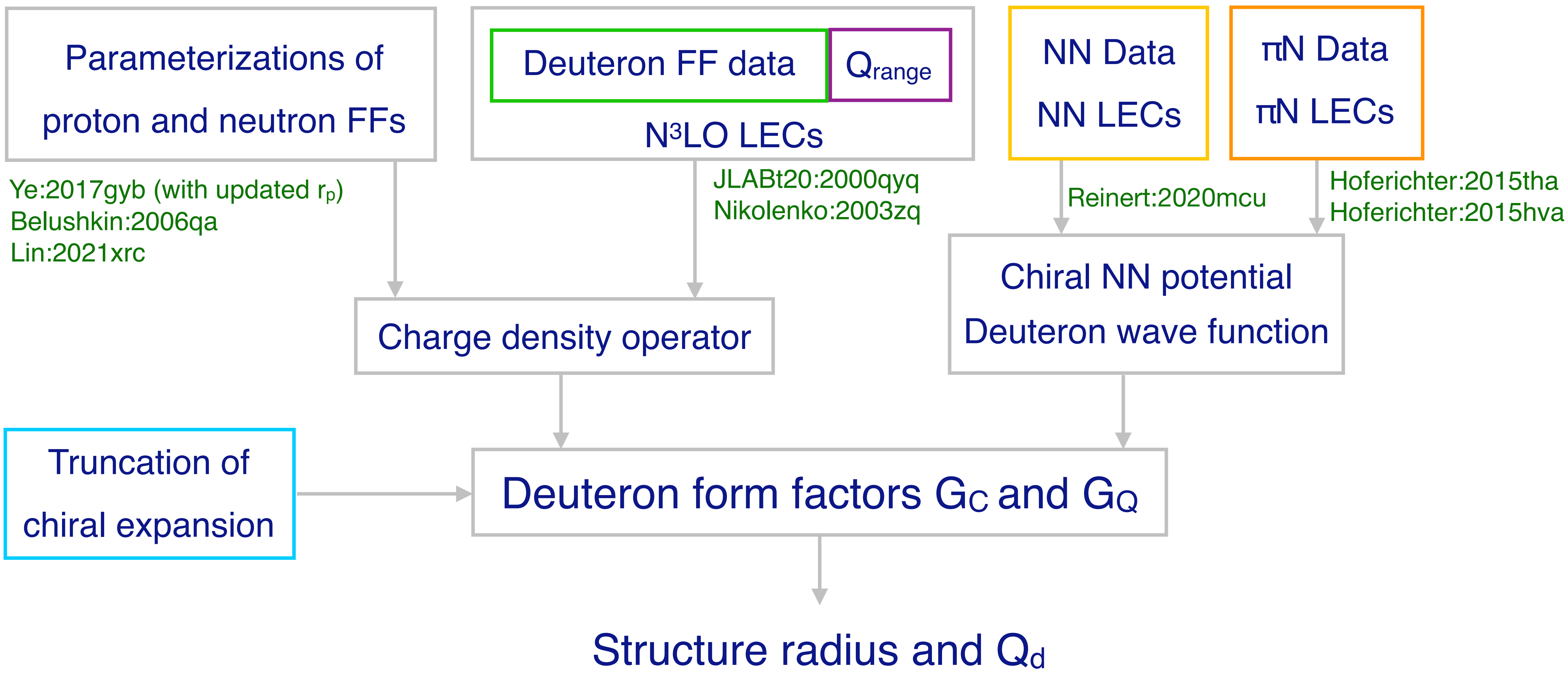


Chiral EFT expansion converges very well

Cutoff dependence is smaller than the truncation uncertainty

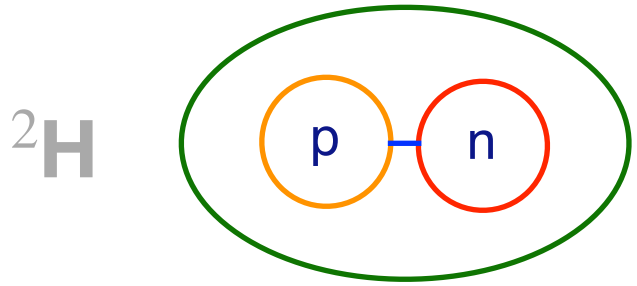
Uncertainty analysis of deuteron structure radius

We propagate uncertainties from multiple sources



	Central	Truncation	$\rho^{\mathrm{reg}}_{\mathrm{Cont}}$	πN LECs RSA	2N LECs and f_i^2	Q range	Total
r^2_{str} (fm^2)	3.8925	±0.0030	±0.0024	±0.0003	±0.0025	$^{+0.0035}_{-0.0005}$	$^{+0.0058}_{-0.0046}$
Q_d (fm^2)	0.2854	±0.0005	±0.0007	±0.0003	±0.0016	$^{+0.0035}_{-0.0005}$	$^{+0.0038}_{-0.0017}$

Neutron charge radius from high-accuracy χEFT calculation of deuteron structure radius



$$r_d^2 = r_{str}^2(^2\mathrm{H}) + \left(r_p^2 + \frac{3}{4m_p^2}\right) + r_n^2$$

Deuteron-proton radius difference

$$(r_d^2 - r_p^2) = 3.82070(31) fm^2$$

Atomic spectroscopy

Hydrogen-deuterium 1S-2S isotope shift

+ QED corrections

Pachucki et al., PRA 97, 062511 (2018)
Jentschura et al. PRA 83 (2011)

Our accurate **χEFT calculation** of the **deuteron structure** radius

New method of determination of the neutron charge radius

$$r_n^2 = (r_d^2 - r_p^2) - \frac{3}{4m_p^2} - r_{str}^2(^2\mathrm{H})$$

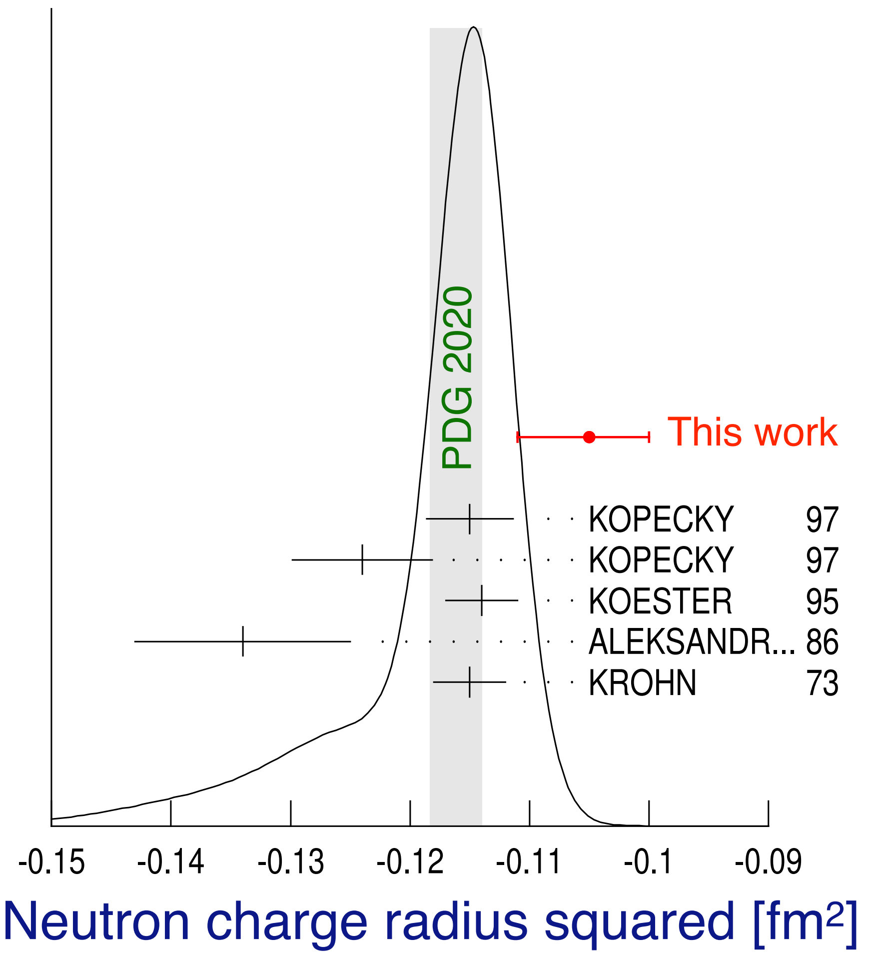
$$r_n^2 = -0.105^{+0.005}_{-0.006} fm^2$$

AF, Möller, Baru, Epelbaum, Krebs, Reinert,
PRL 124 (2020) 082501; PRC 103 (2021) 024313

Our extraction of the neutron charge radius

$$r_n^2 = -0.105^{+0.005}_{-0.006} fm^2$$

~2σ deviation from the PDG (2022) weighted average $r_n^2 = -0.1155(17) fm^2$



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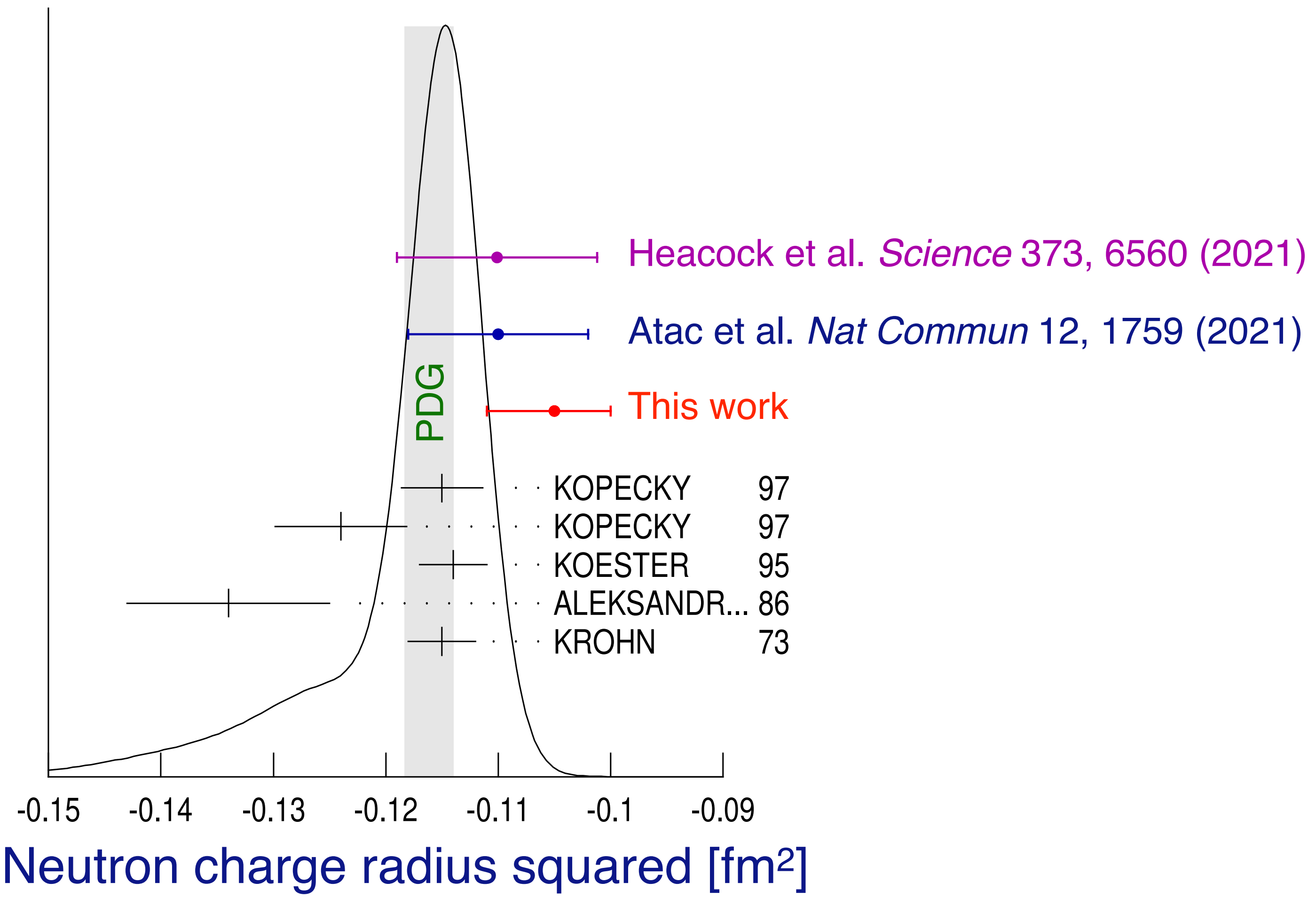


Neutron charge radius in PDG 2022

R.L. Workman et al. (Particle Data Group), Prog.Theor.Exp.Phys. 2022, 083C01 (2022) and 2023 update

n MEAN-SQUARE CHARGE RADIUS

VALUE (fm^2)			*DOCUMENT ID*		*COMMENT*
−0.1155±0.0017 OUR AVERAGE					
−0.115	±0.002	±0.003	KOPECKY	97	*n e* scattering (Pb)
−0.124	±0.003	±0.005	KOPECKY	97	*n e* scattering (Bi)
−0.114	±0.003		KOESTER	95	*n e* scattering (Pb, Bi)
−0.115	±0.003		[1] KROHN	73	*n e* scattering (Ne, Ar, Kr, Xe)
• • • We do not use the following data for averages, fits, limits, etc. • • •					
−0.1101	±0.0089		[2] HEACOCK	21	*n* interferometry
−0.106	$^{+0.007}_{-0.005}$		[3] FILIN	20	chiral EFT analysis
−0.117	$^{+0.007}_{-0.011}$		BELUSHKIN	07	Dispersion analysis
−0.113	±0.003	±0.004	KOPECKY	95	*n e* scattering (Pb)
−0.134	±0.009		ALEKSANDR...	86	*n e* scattering (Bi)
−0.114	±0.003		KOESTER	86	*n e* scattering (Pb, Bi)
−0.118	±0.002		KOESTER	76	*n e* scattering (Pb)
−0.120	±0.002		KOESTER	76	*n e* scattering (Bi)
−0.116	±0.003		KROHN	66	*n e* scattering (Ne, Ar, Kr, Xe)

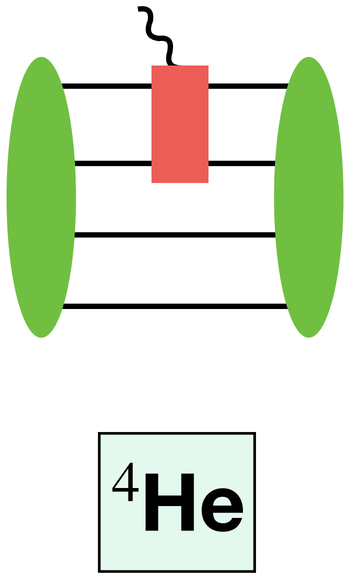
[1] KROHN 73 measured -0.112 ± 0.003 fm^2. This value is as corrected by KOESTER 76.

[2] HEACOCK 21 extract the value from Pendelloesung interferometry to measure the neutron structure factors of silicon. This value is strongly anti-correlated with the mean-square thermal atomic displacement.

[3] FILIN 20 extract the value based on their chiral-EFT calculation of the deuteron structure radius and use as input the atomic data for the difference of the deuteron and proton charge radii.

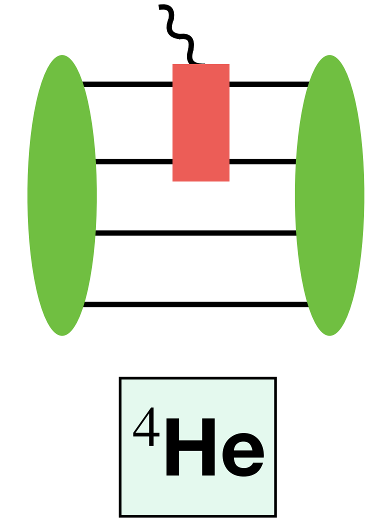
^{4}He charge radius

Precision test of the chiral EFT for ^{4}He



Preliminary results

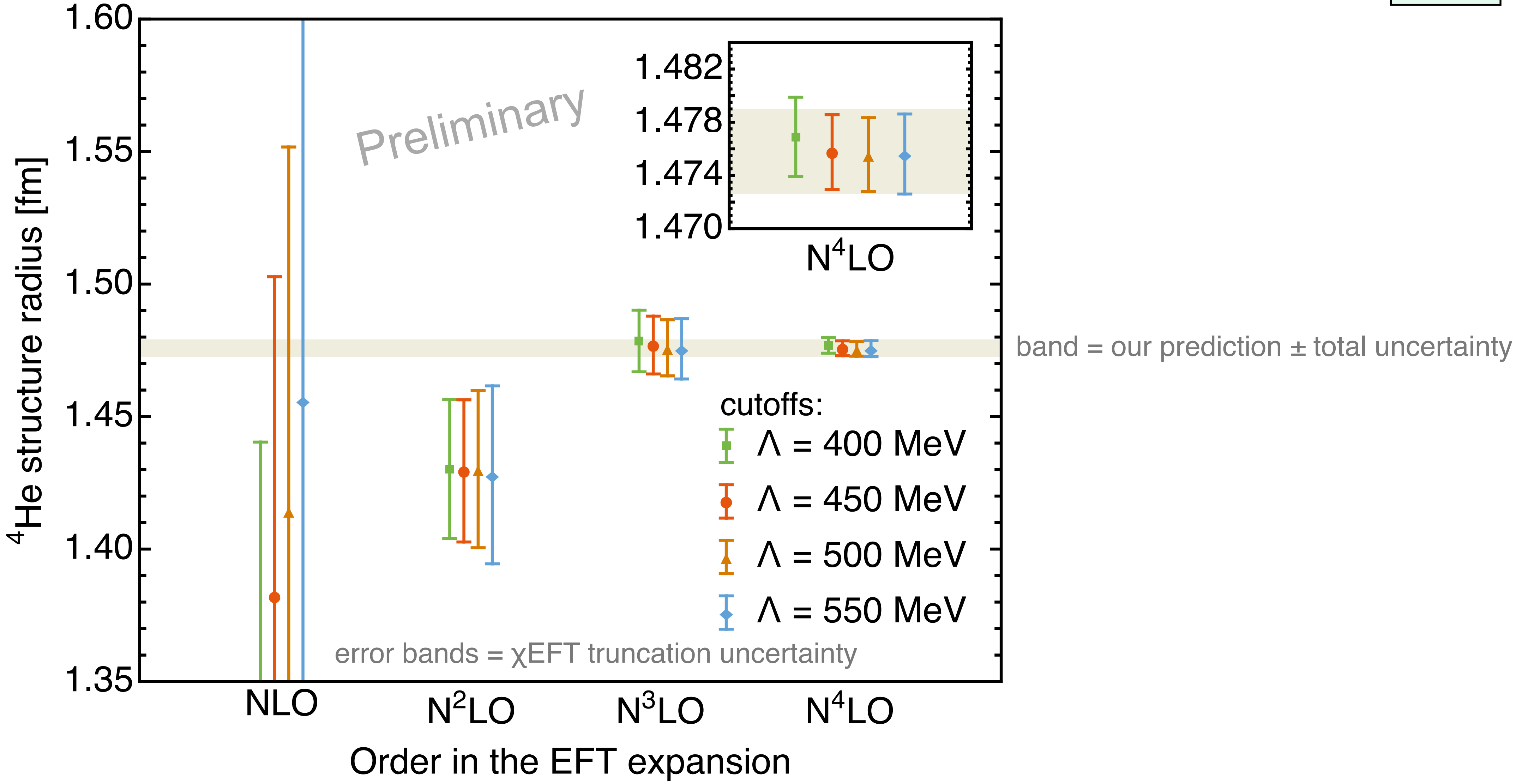
Prediction of 4He structure radius



Our preliminary prediction for 4He structure radius:

$$r_{str}(^4\mathbf{He}) = 1.4758 \pm 0.0028_{\rm trunc} \pm 0.0011_{\rm stat} \pm 0.0010_{\rm nuclFF}\ fm$$ (Preliminary)

Estimation of truncation error:

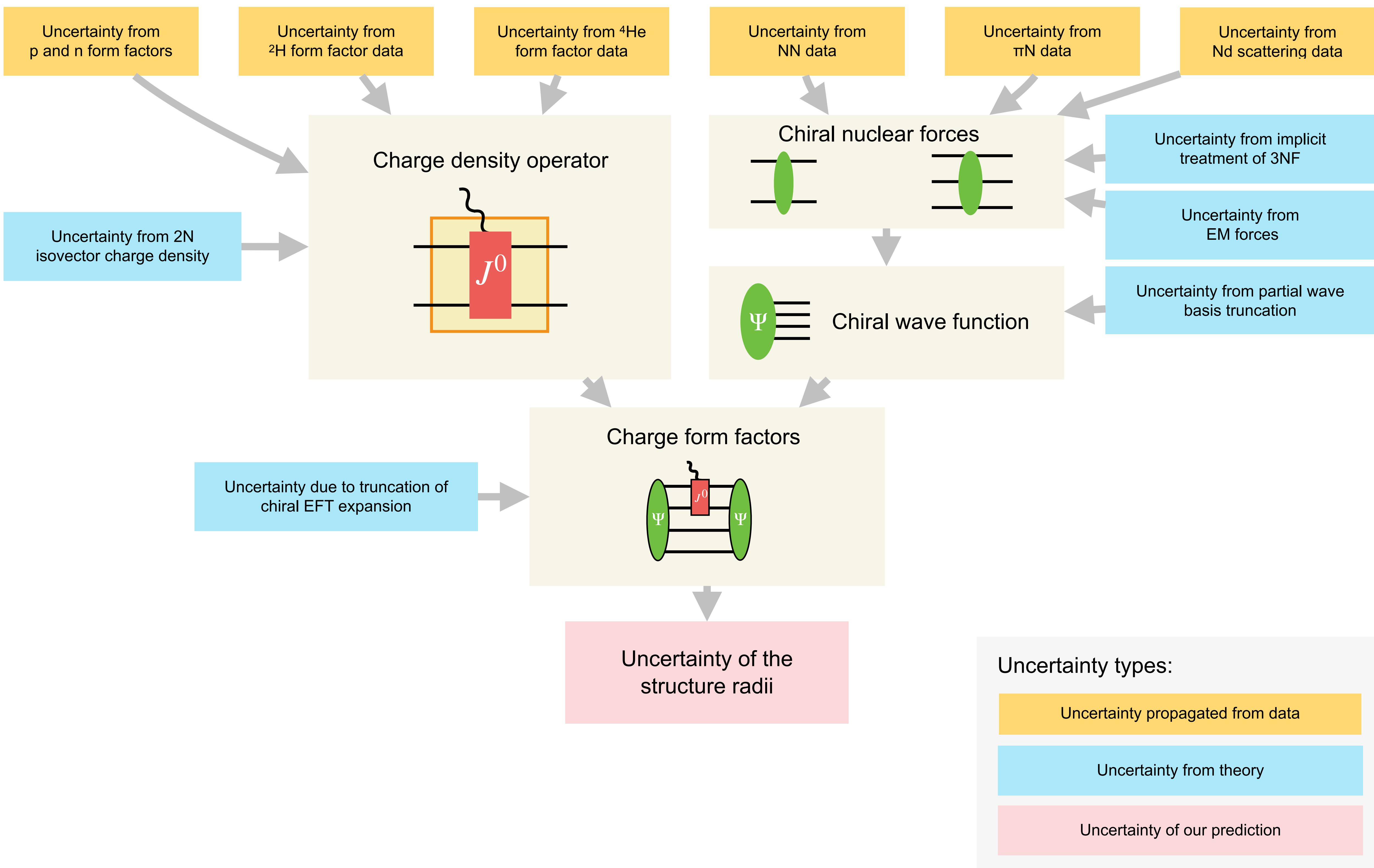


Cutoff dependence is smaller than the truncation uncertainty

Chiral EFT expansion converges well

Extensive uncertainty analysis

Propagation of uncertainties from data and theory



Prediction for ^{4}He charge radius

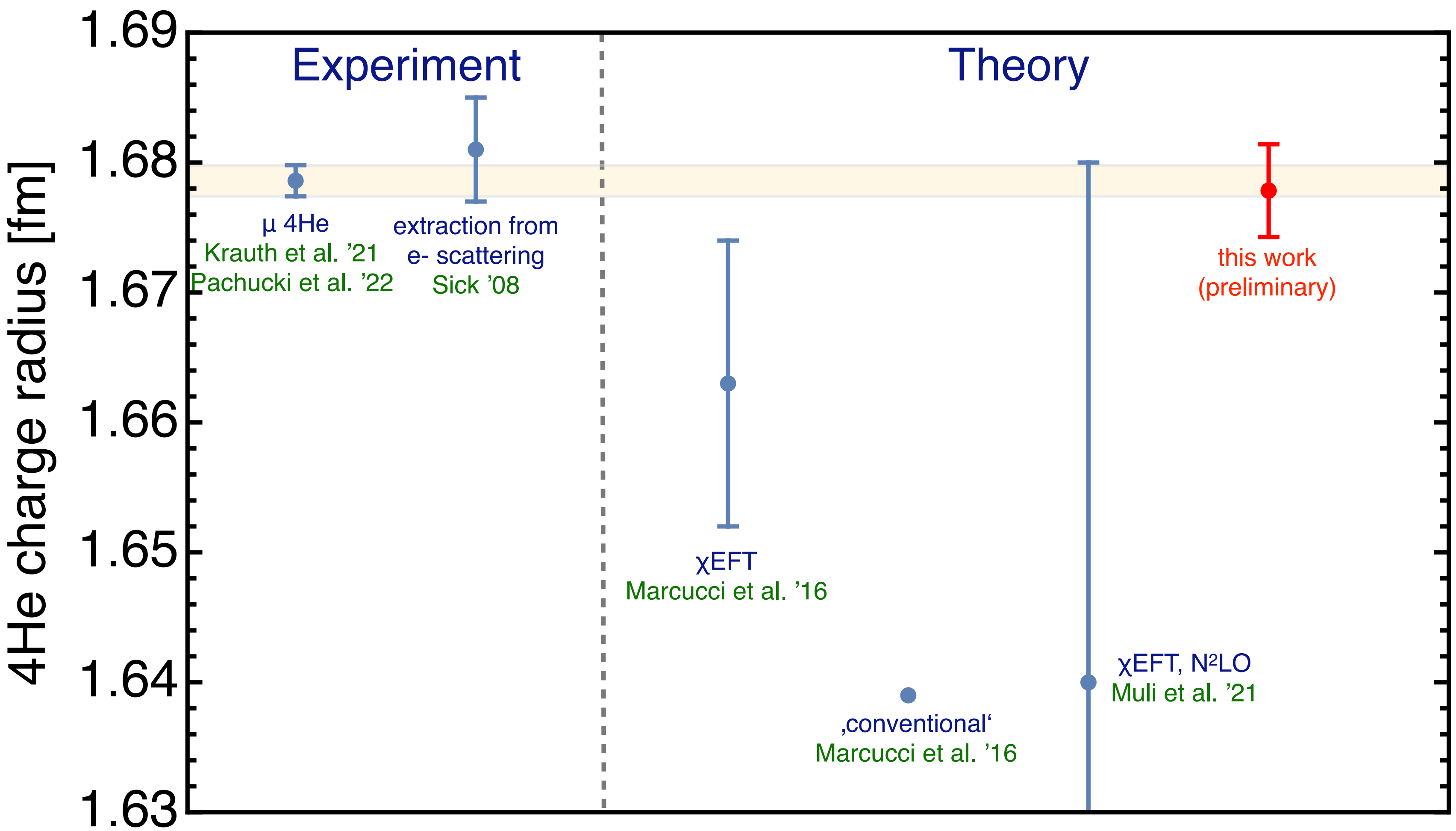
$$r_{str}(^4\mathbf{He}) = 1.4758 \pm 0.0028_{\text{trunc}} \pm 0.0011_{\text{stat}} \pm 0.0010_{\text{nuclFF}}\ fm$$ (Preliminary)

Our prediction for ^{4}He **charge** radius

$$r_C(^4\mathbf{He}) = (1.6775 \pm 0.0035)\, fm$$

preliminary, using CODATA 2018 r_p and own determination of r_n

$$r_C(^4\mathbf{He}) = r_{str}^2(^4\mathbf{He}) + \left(r_p^2 + \frac{3}{4m_p^2} \right) + r_n^2$$



Our prediction for ^{4}He charge radius is fully consistent with the muonic-atom spectroscopy

Indications of BSM physics?

All data used to constrain chiral EFT LECs are from strong interaction / electron-based experiments:

π N Roy-Steiner analysis Hoferichter:2015tha, Hoferichter:2015hva

NN pn and pp scattering data, deuteron BE Reinert:2020mcu

Deuteron charge and quadrupole FF data JLABt20:2000qyq, Nikolenko:2003zq

Deuteron-proton radii difference from atomic spectroscopy Pachucki:2018yxe, Jentschura et al. PRA 83 (2011)

Proton charge radius CODATA2018

^{4}He form factor data Erich:1971rhg, Mccarthy:1977vd, VonGunten:1982yna, Ottermann:1985km, Frosch:1967pz, Arnold:1978qs, Camsonne:2013df

Binding energies of ^{3}He and ^{4}He

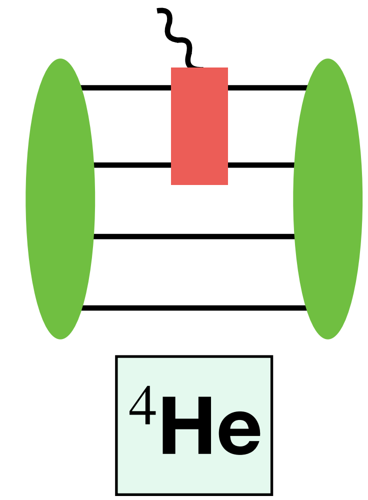
Nd DCS minimum @ 70 MeV RIKEN data

No muonic data is used in our chiral EFT predictions

Our prediction for ^{4}He charge radius is consistent with the muonic experiment

No indication of lepton universality breaking at this accuracy level

Isoscalar nucleon charge radius from data on ^{4}He



Our prediction for ^{4}He **structure** radius

Experimental ^{4}He charge radius
Krauth et al., Nature 589 (2021) 7843, 527-531
+ theory update from Pachucki et al. (2022)

$$r_C(^4\mathbf{He}) = r^2_{str}(^4\mathbf{He}) + \left(r_p^2 + \frac{3}{4m_p^2}\right) + r_n^2$$

Determination

of the isoscalar nucleon charge radius

$$(r_n^2 + r_p^2) = (0.607 \pm 0.010)\, fm^2$$

preliminary

Proton charge radius from isoscalar nucleon radius

Our determination of the

isoscalar nucleon charge radius from ^{4}He

$$(r_n^2 + r_p^2) = (0.607 \pm 0.010)\, fm^2$$ preliminary

Our determination of the

neutron charge radius from ^{2}H

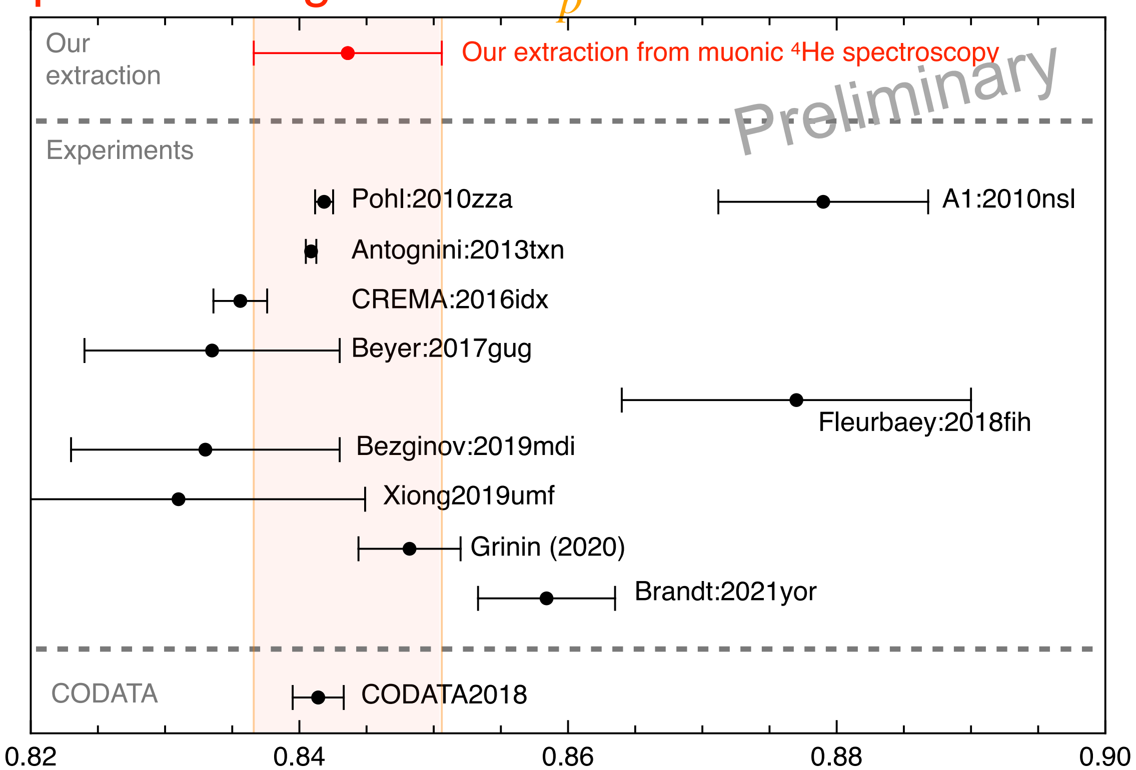
$$r_n^2 = -0.105^{+0.005}_{-0.006}\, fm^2$$

AF, Möller, Baru, Epelbaum, Krebs, Reinert,
PRL 124 (2020) 082501; PRC 103 (2021) 024313

New determination of the proton charge radius: $r_p = (0.844 \pm 0.007)\, fm$

preliminary

proton charge radius r_p



r_p (fm^2)

Our extraction supports the „small“ proton radius

Prediction for isoscalar 3N charge radius

With all LECs being fixed, we can predict the isoscalar 3N charge radius: $r_C^{isoscalar3N} = \sqrt{\frac{1}{3}(r_C^{3H})^2 + \frac{2}{3}(r_C^{3He})^2}$

$$r_C^{isoscalar3N} = (1.9061 \pm 0.0026)\, fm$$

preliminary, using CODATA 2018 r_p and own determination of r_n

Our result is 10x more precise than current experimental data:

the ^{3}H charge radius from e^- scattering experiments:	$r_C^{3H} = (1.7550 \pm 0.0860)\, fm$ (5 %)	Amroun et al. '94 (world average)
the ^{3}He charge radius from muonic ^{3}He:	$r_C^{3He} = (1.9701 \pm 0.0009)\, fm$ (0.05 %)	CREMA 2023 arXiv:2305.11679

Exp. **3N isoscalar charge radius**: (using muonic ^{3}He and old ^{3}H) $r_{C,\,exp.}^{isoscalar3N} = (1.9010 \pm 0.0260)\, fm$ (1.4 %)

T-REX experiment in Mainz [Pohl et al.] aims at measuring r_C^{3H} within ±0.0002 fm (400x more precise)

The isoscalar 3N radius will be then known within ±0.0009 fm

⇒ **precision tests of nuclear chiral EFT!**

Summary

Precise and accurate calculation of A = 2, 3, 4 isoscalar charge radii in chiral effective field theory

Extensive uncertainty analysis

Nuclear structure calculations with sub-percent accuracy!

Charge radii of neutron and proton from light nuclei:

- ^{2}H r_{str} combined with isotope-shift data => extracted the neutron charge radius (2σ tension with PDG)
- ^{4}He r_{str} combined with spectroscopic data => extracted isoscalar nucleon and proton charge radii preliminary

^{4}He calculation: preliminary

- calculated ^{4}He charge radius (0.2% accuracy) agrees with the new μ^{4}He measurement
- no indications of lepton universality breaking at this accuracy level

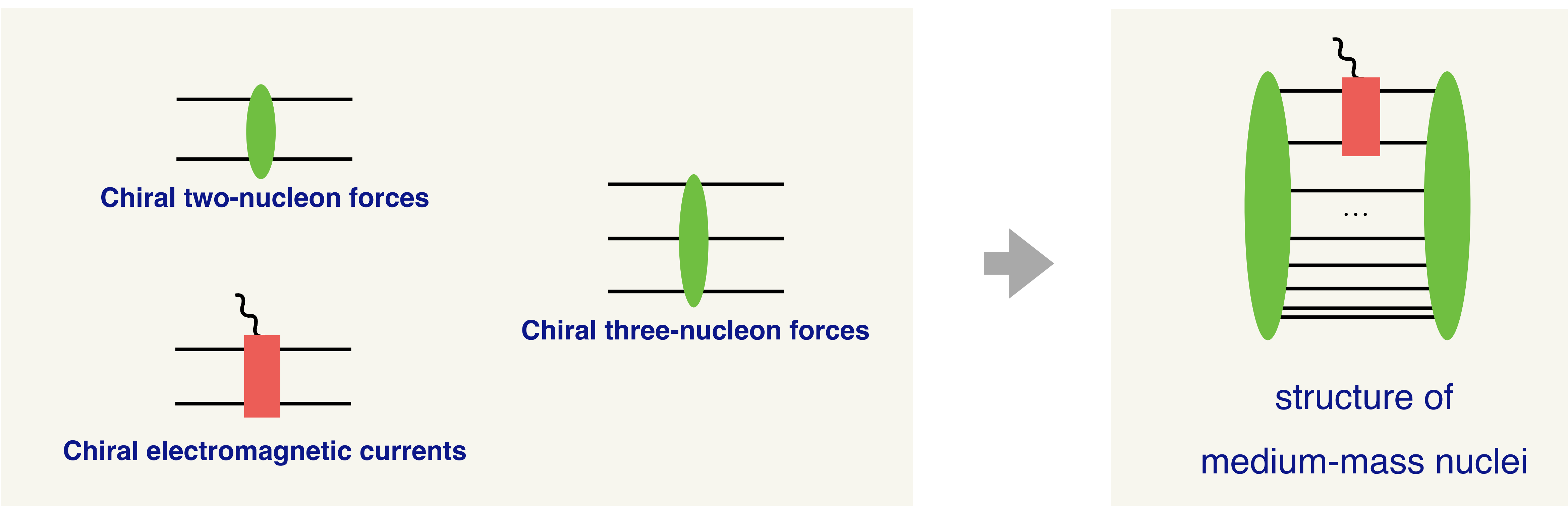
^{3}H-^{3}He: preliminary

- predicted the isoscalar 3N charge radius r_C (0.1% accuracy)
- our r_C is in agreement with the current exp. value (which has 10x larger errors)
- the ongoing T-REX (^{3}H) exp. in Mainz will allow for a precision test of nuclear chiral EFT

Outlook

In progress:

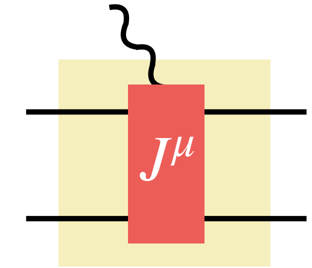
- **Consistent** inclusion of **isovector 2N currents at N^{3}LO** and **N^{4}LO**
- **Consistent** inclusion of **N^{3}LO** and **N^{4}LO three-nucleon forces**
- Analysis of **magnetic form factors**
- Application to processes with two photons (**polarizabilities**, ...)
- Calculation of isoscalar N4LO **charge radii for nuclei with A>4** (work in progress by LENPIC collaboration)

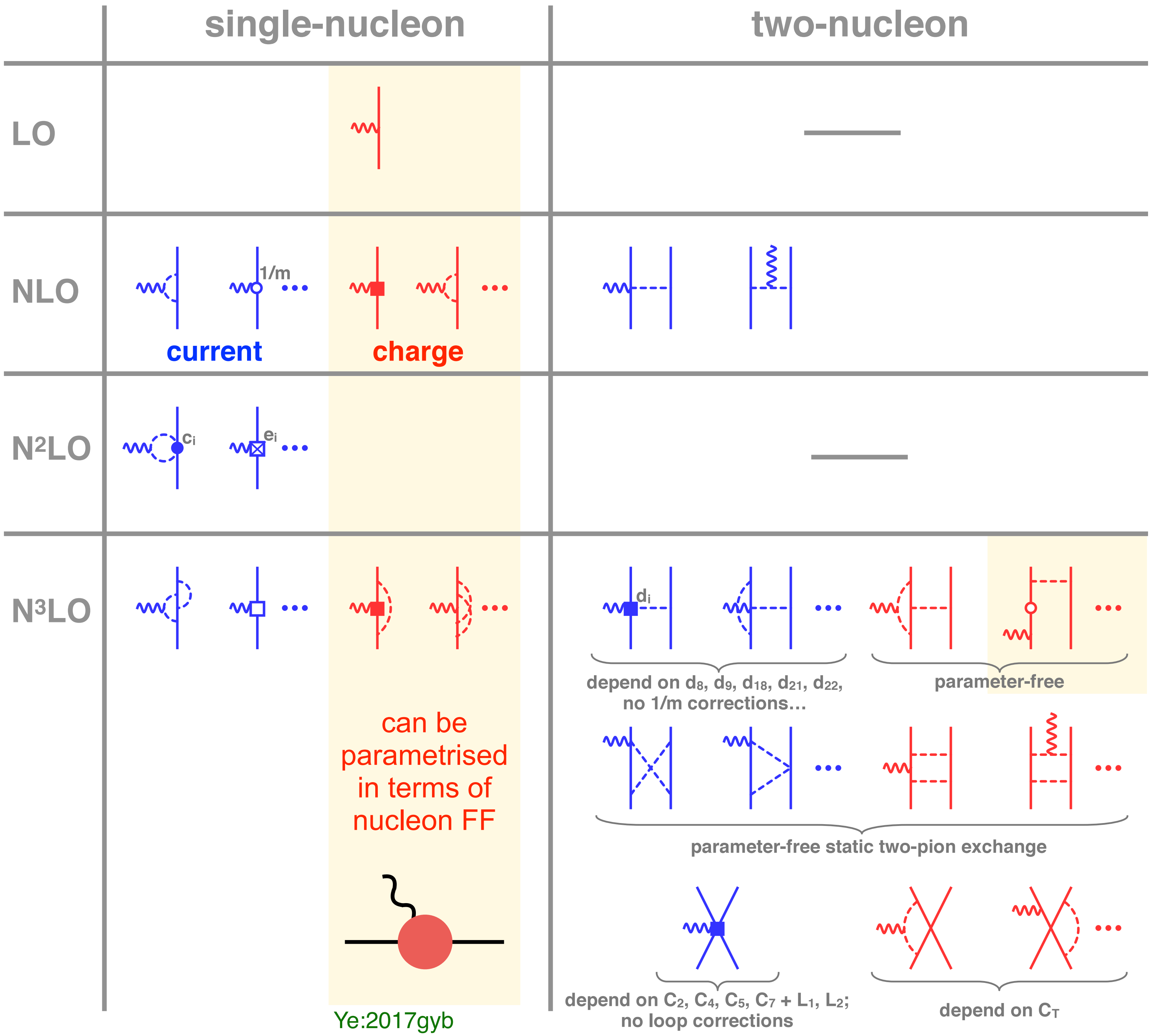


Spares

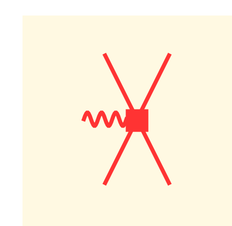
Nuclear electromagnetic currents

Kolling:2009iq, Kolling:2012cs, Krebs:2019aka
Review: H. Krebs, EPJA 56 (2020) 240





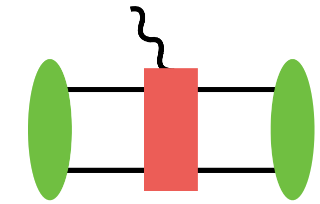
Ye:2017gyb
Belushkin:2006qa
Lin:2021umz



depend on **3 parameters (LECs)**
$^3S_1$-$^3S_1$ - can be fitted to deuteron FF data
$^3S_1$-$^3D_1$ - this one too
$^1S_0$-$^1S_0$ - can be fitted to ^{4}He FF data

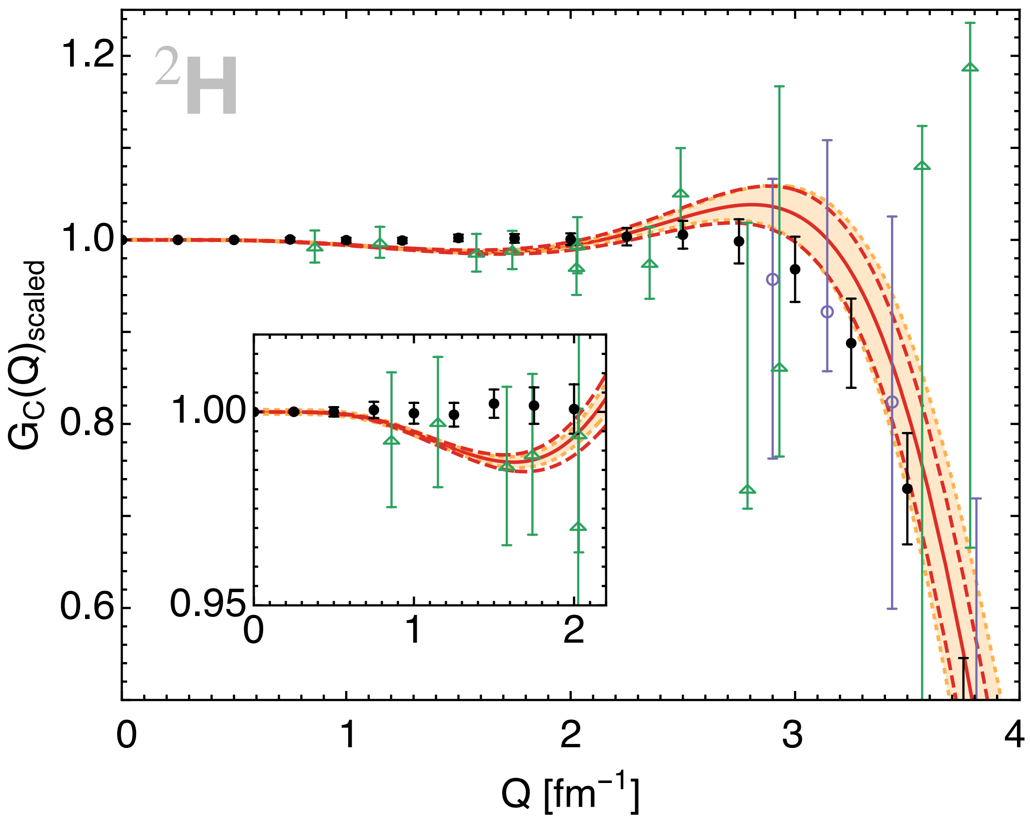
Chen, Rupak, Savage '99;
Phillips '07
AF et al. '20

Deuteron charge and quadrupole form factors

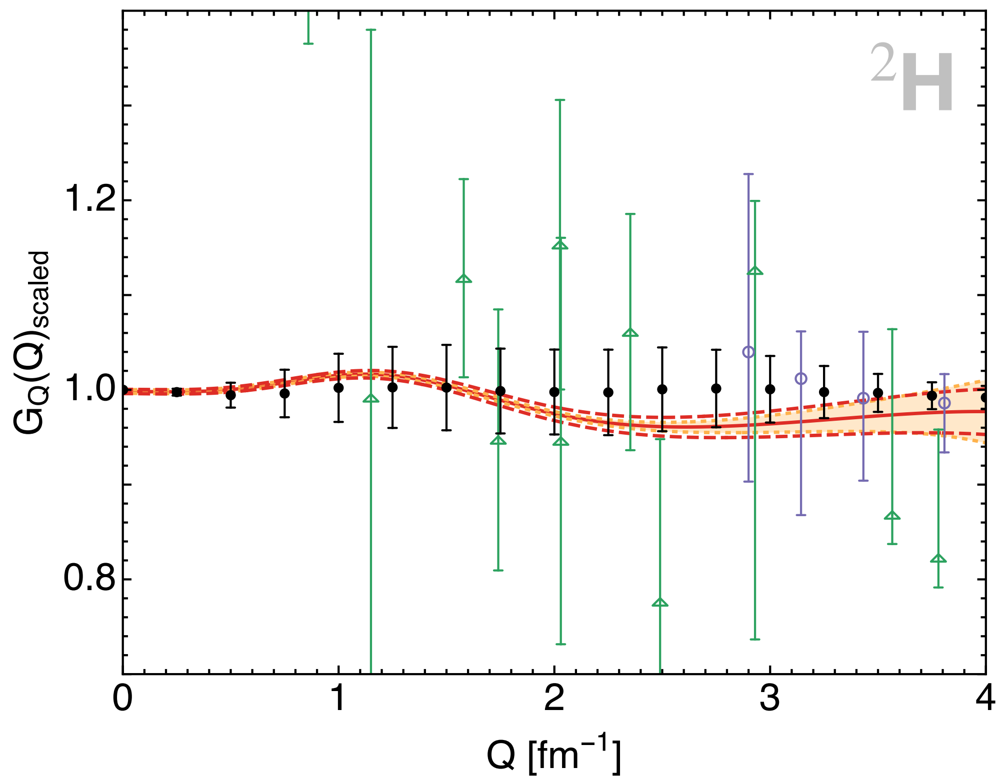


Deuteron form factors at low Q

Charge FF zoomed at low Q



Quadrupole FF zoomed at low Q



Deuteron charge FF can be used to extract neutron charge FF

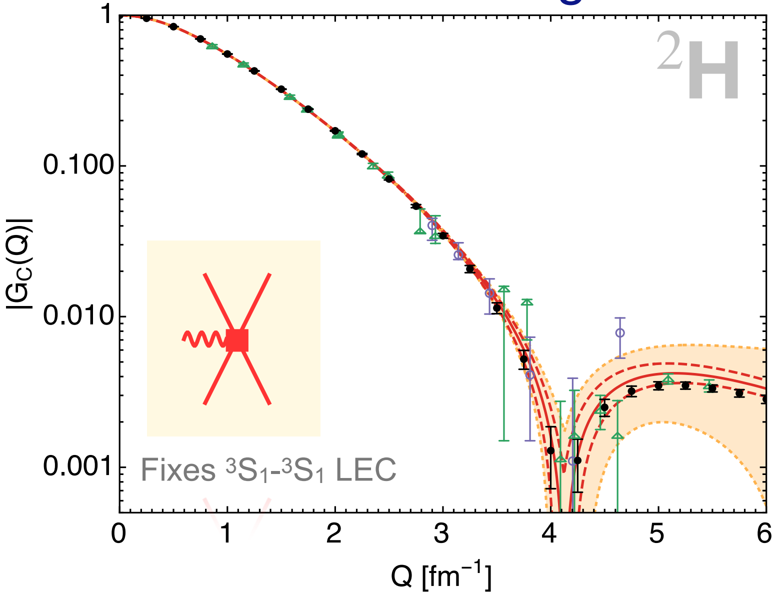
Extraction of deuteron structure radius and quadrupole moment

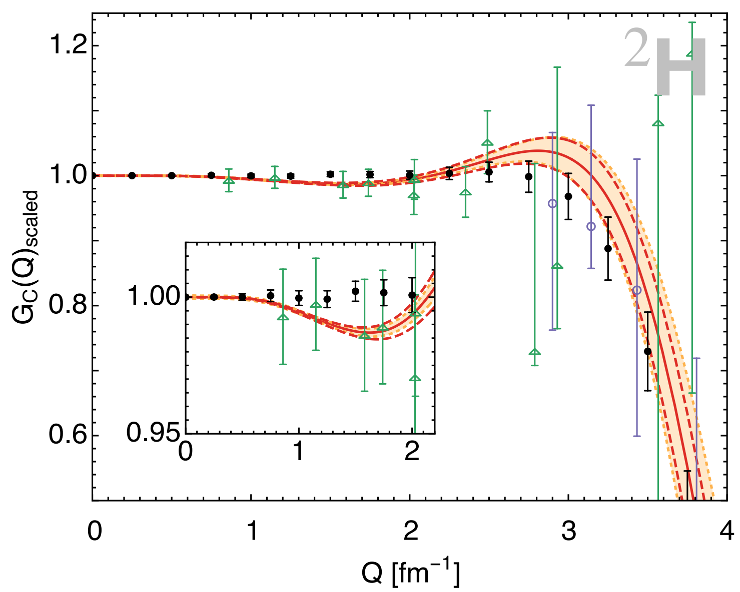
$$r_{str} = 1.9729^{+0.0015}_{-0.0012} fm \qquad Q_d = 0.2854^{+0.0038}_{-0.0017} fm^2$$

AF, Möller, Baru, Epelbaum, Krebs, Reinert, PRL 124 (2020) 082501; PRC 103 (2021) 024313

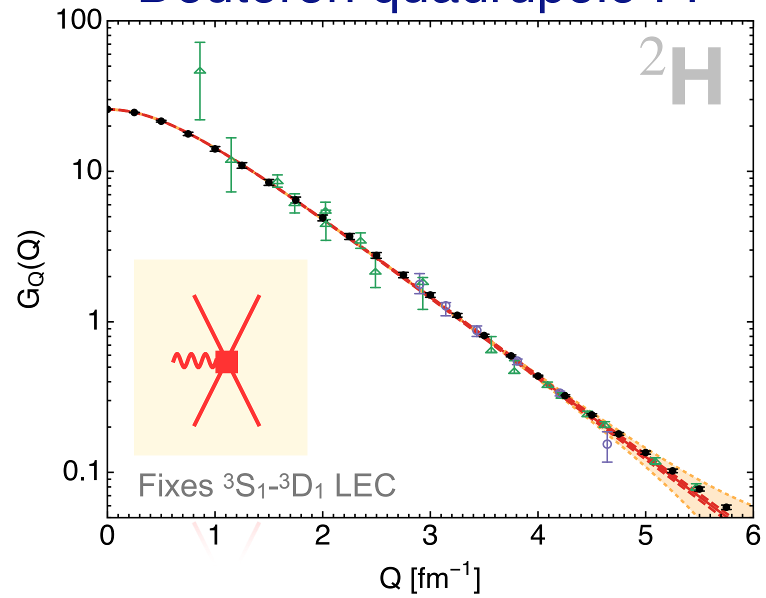
Low-energy constants from a fit to charge and quadrupole form factors

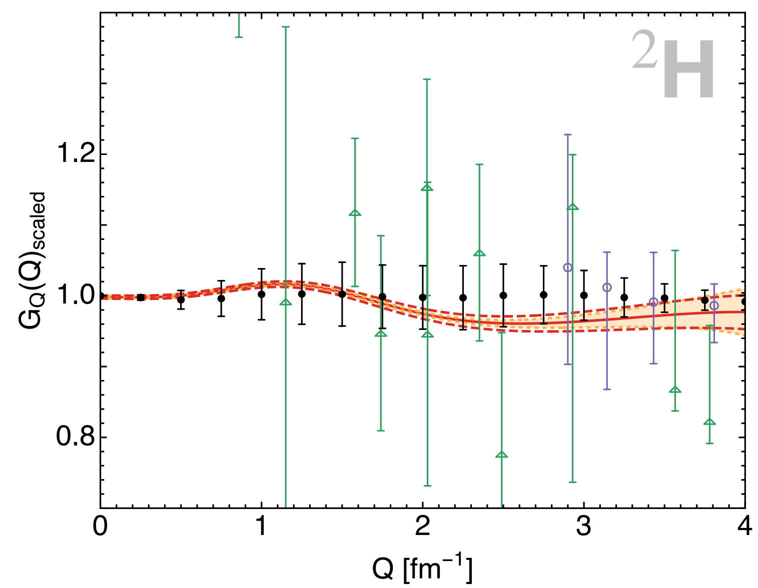
Deuteron charge FF



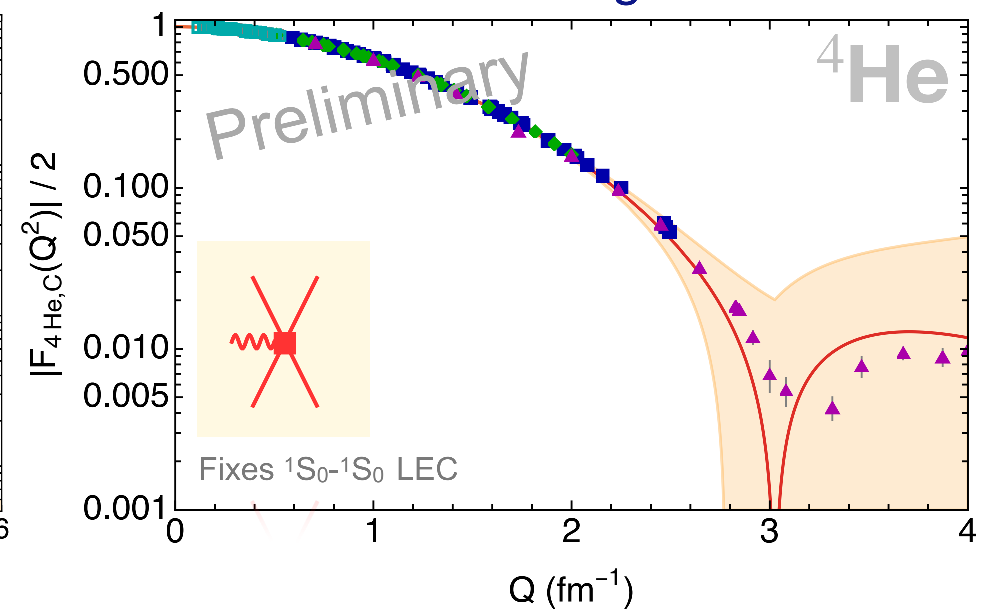


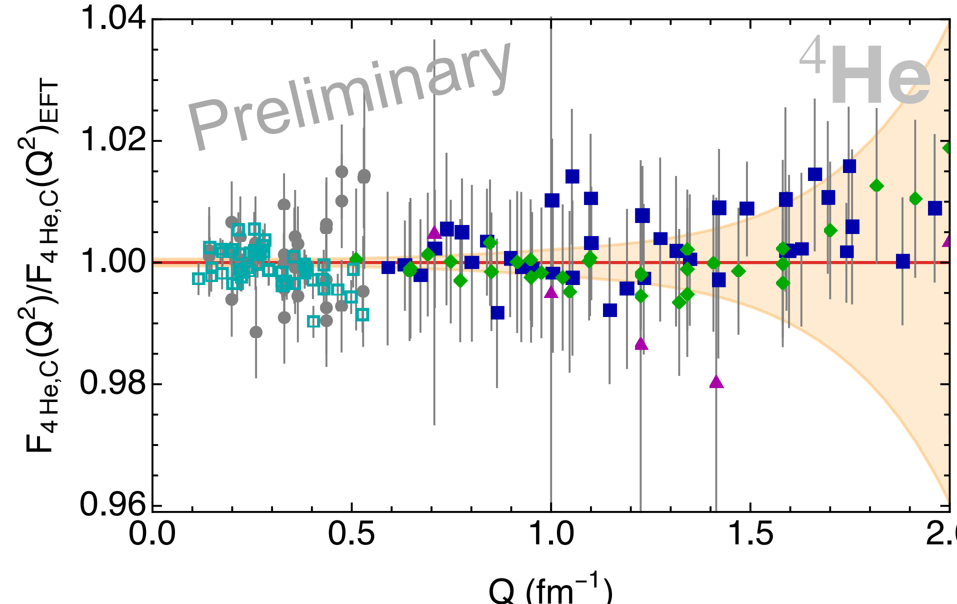
Deuteron quadrupole FF





4He charge FF





^{2}H:
AF, Möller, Baru, Epelbaum, Krebs, Reinert,
PRL 124 (2020) 082501; PRC 103 (2021) 024313

^{4}He: Preliminary

best fit + N^{4}LO truncation uncertainty

3 parameters (LECs) in 2N charge density J^0 are fixed from the form factor data of deuteron and ^{4}He

Prediction for ^{4}He charge radius

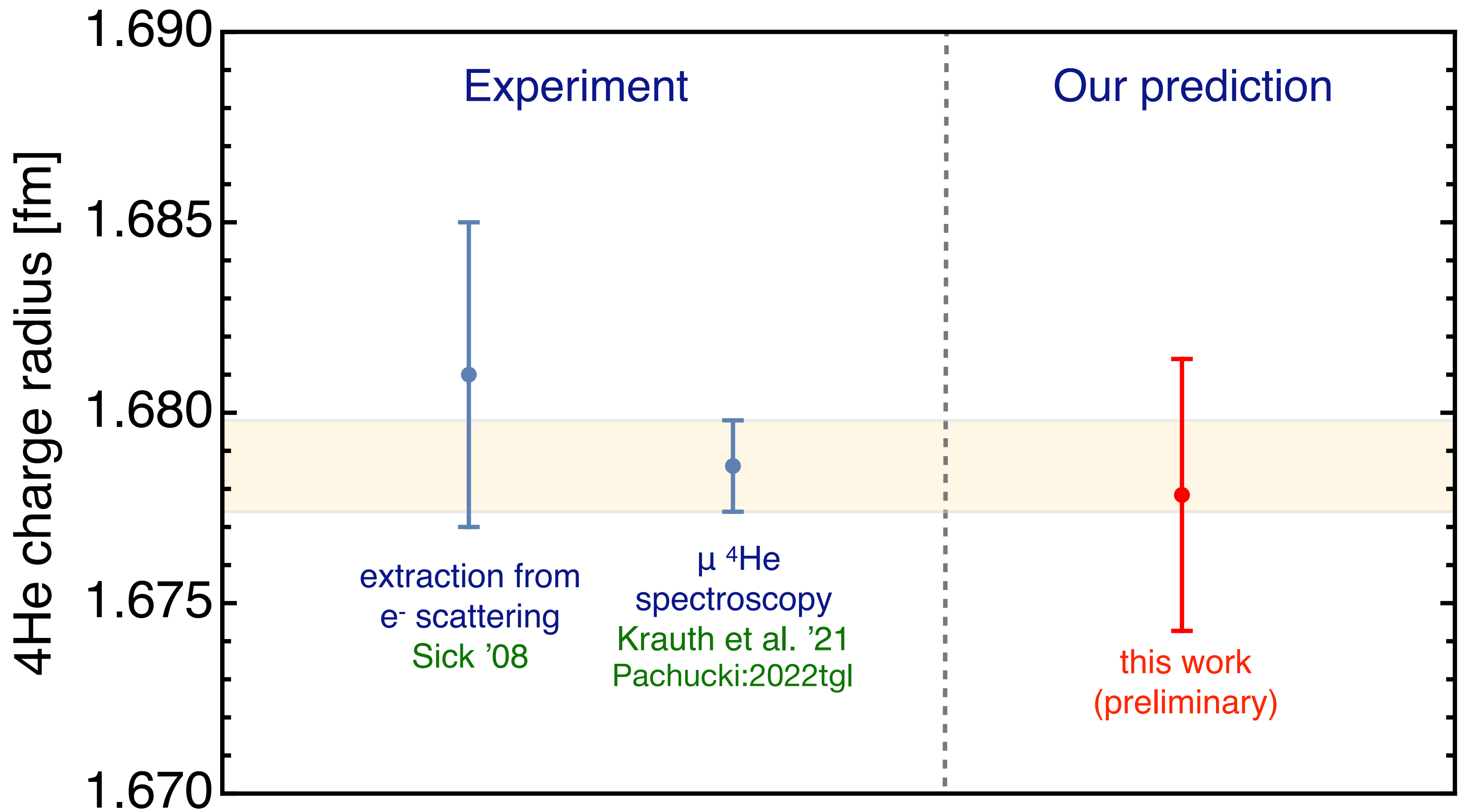
$r_{str}(^4\mathbf{He}) = 1.4758 \pm 0.0028_{\text{trunc}} \pm 0.0011_{\text{stat}} \pm 0.0010_{\text{nuclFF}}\ fm$ (Preliminary)

Our prediction for ^{4}He **charge** radius

$$r_C(^4\mathbf{He}) = (1.6775 \pm 0.0035)\, fm$$

preliminary, using CODATA 2018 r_p and own determination of r_n

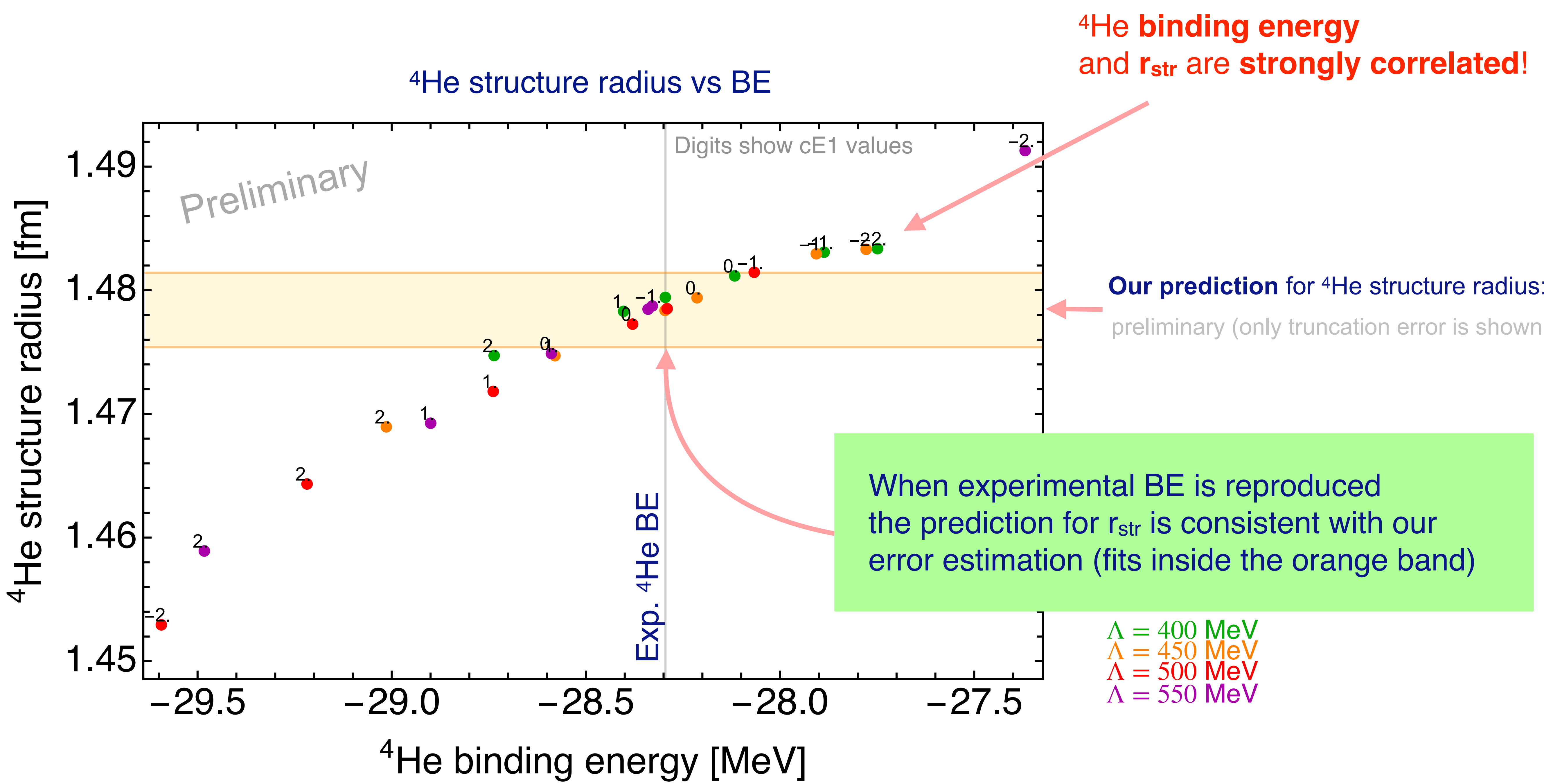
$$r_C(^4\mathbf{He}) = r^2_{str}(^4\mathbf{He}) + \left(r_p^2 + \frac{3}{4m_p^2} \right) + r_n^2$$



Our prediction for ^{4}He charge radius is fully consistent with the muonic-atom spectroscopy

Correlation between ^{4}He structure radius and binding energy

using variation of **cE1** (N^{4}LO contact 3NF LEC)



Many effects (higher-order 3NFs, some relativistic corrections) change BE and radius simultaneously.
Once BE is fitted back to physical value the residual effect is usually ver small.

Estimation of ^{3}H charge radius

Our preliminary prediction for **isoscalar** 3N **charge** radius:

$$r_C^{isoscalar3N} = (1.9061 \pm 0.0026)\, fm$$

preliminary, using CODATA 2018 r_p and own determination of r_n

^{3}He charge radius [CREMA 2023 2305.11679]

$$r_C^{3He} = (1.9701 \pm 0.0009) fm$$

Isoscalar 3N charge radius definition:

$$(r_C^{isoscalar3N})^2 = \frac{(r_C^{3H})^2 + 2\,(r_C^{3He})^2}{3}$$

Expression for ^{3}**H radius:**

$$(r_C^{3H})^2 = 3(r_C^{isoscalar3N})^2 - 2\,(r_C^{3He})^2$$

Coefficients 2 and 3 amplify both theoretical and experimental uncertainties

Our ^{3}H radius estimation:

$$r_C^{(3H)} = (1.7714 \pm 0.0087) fm$$

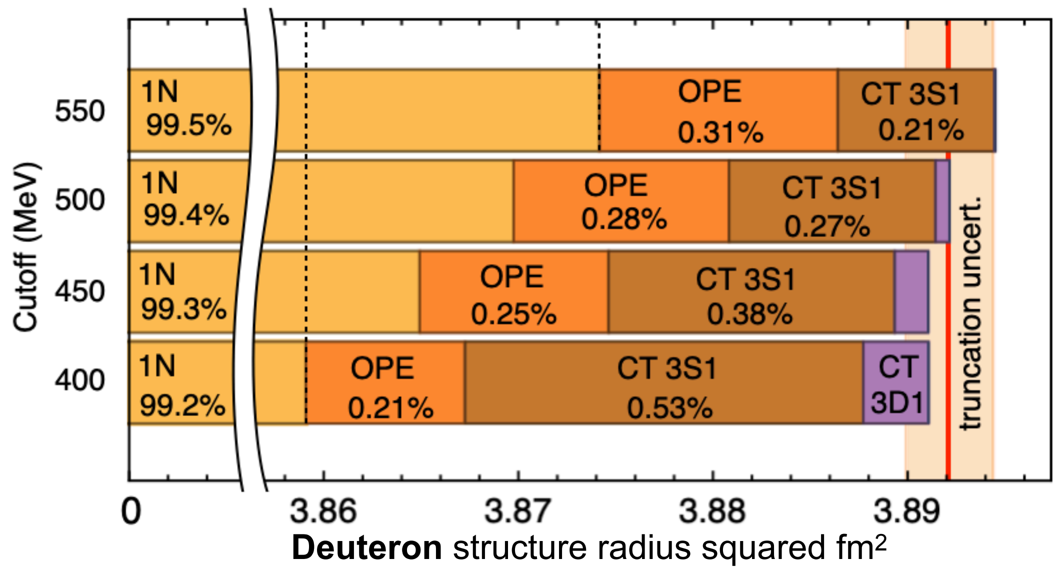
preliminary

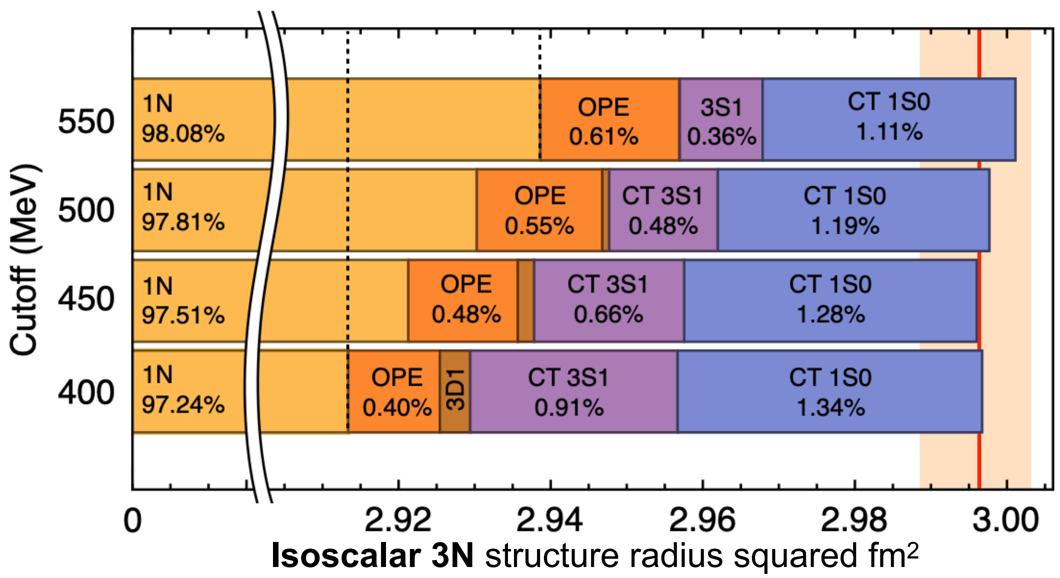
This estimation is 10x more precise than e$^-$ data $r_C^{3H} = (1.7550 \pm 0.0860)\, fm$ Amroun et al. '94 (world average)

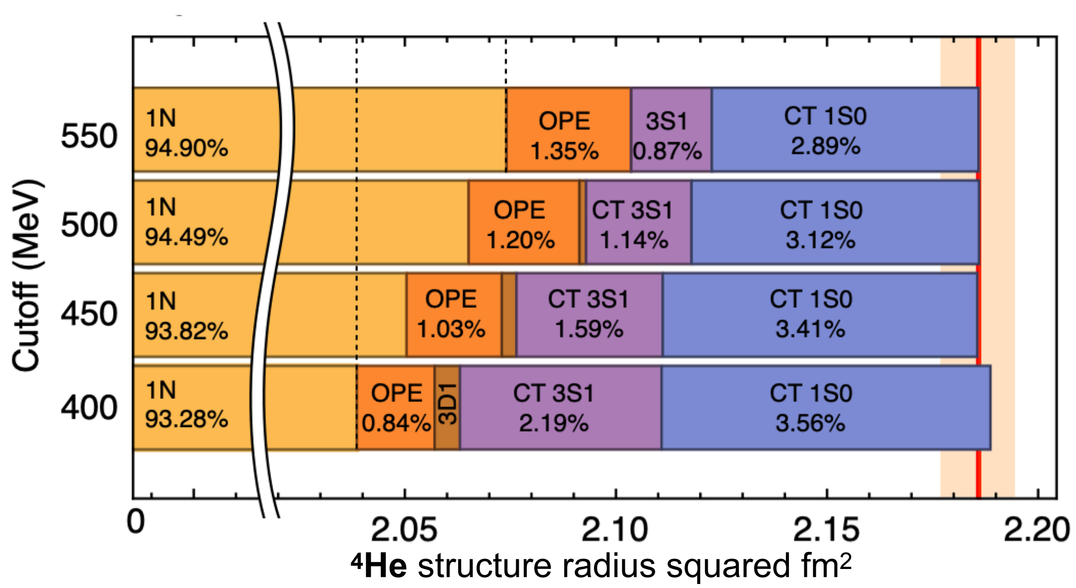
But it suffers from parametric amplification of uncertainties (both from theory and from ^{3}He data)

=> isoscalar 3N charge radius should be used for precision tests

Importance of 2N charge density







Individual contributions to A=2,3,4 structure radii from

- single-nucleon charge density (1N)
- 2N one-pion exchange density (OPE)
- 2N contact densities (CT 3S1, 3D1, 1S0)

2N charge density contribution to structure radii squared:

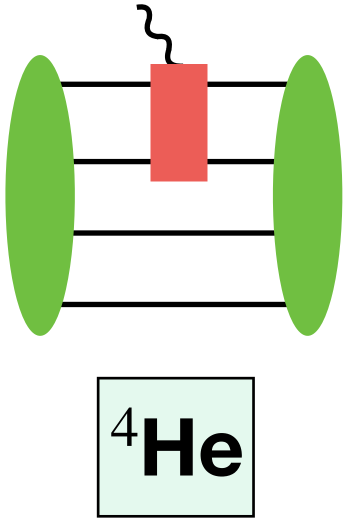
deuteron ~ 0.7%

isoscalar 3N ~ 2.5%

^{4}He ~ 6%

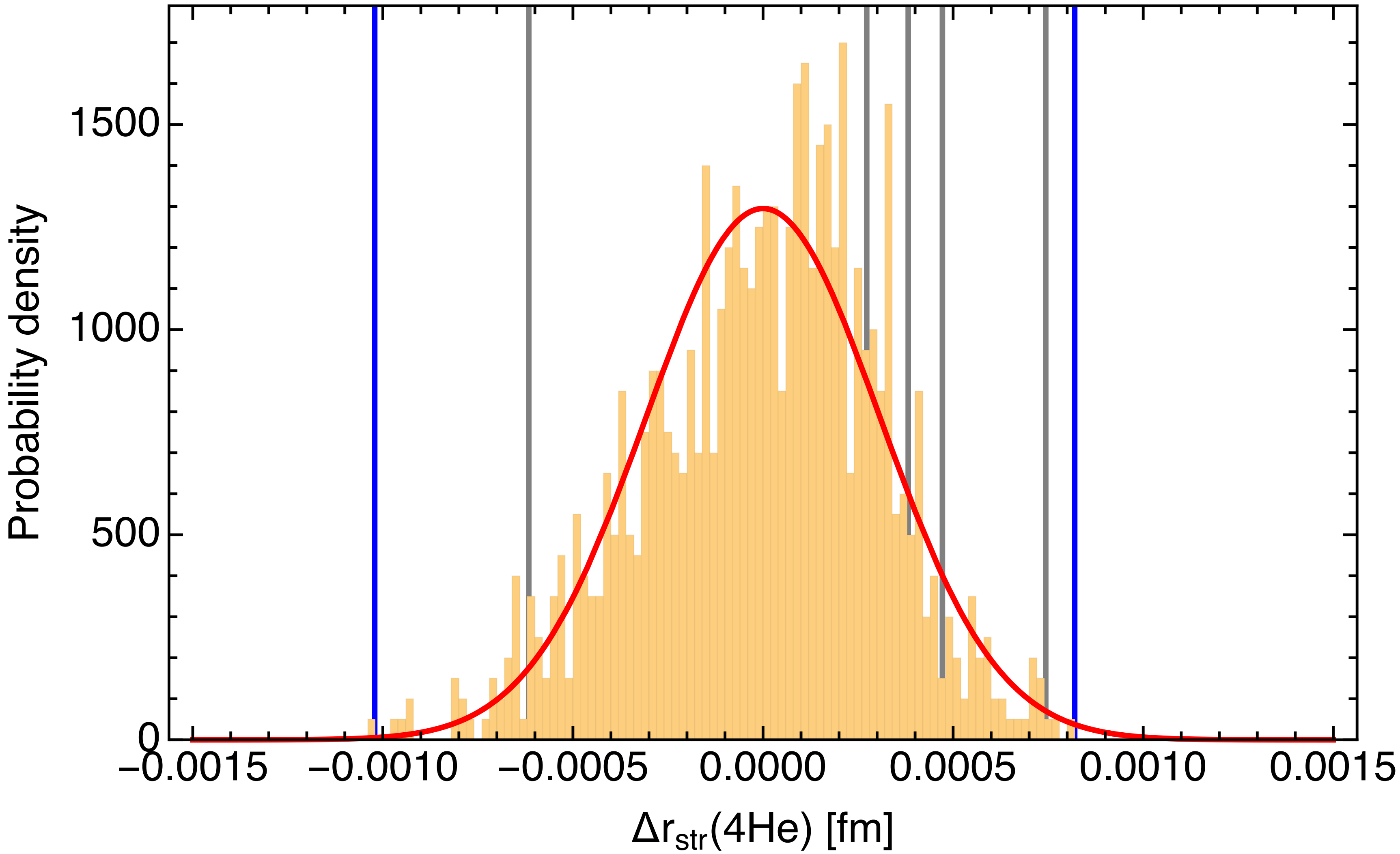
For A=2,3,4 importance of 2N charge grows with A

Sensitivity to nucleon FF parameterisation



Results for 4He structure radius fit with ~1000 variations of nucleon isoscalar FF

GES from dispersive analysis of Bonn group Lin, Hammer and Meißner, PRL 128 2022



Uncertainty from FF parametrisation:

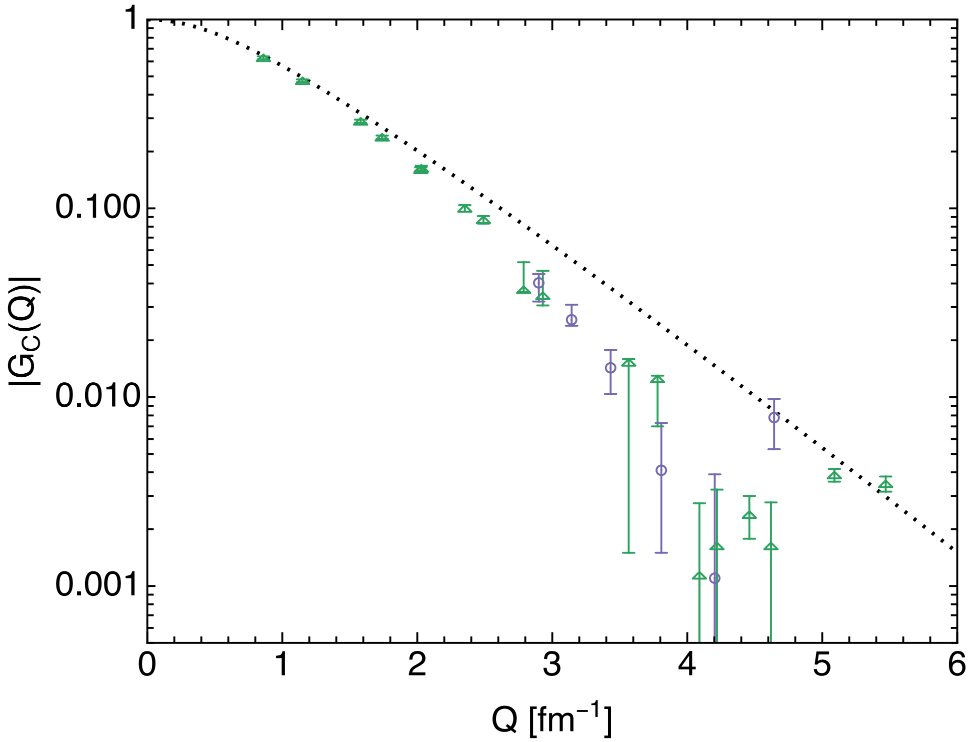
$$r_{str}(^4\mathbf{He}) = 1.4758 \pm 0.0010_{\text{nuclFF}}\ fm$$ (Preliminary)

We have also tested other modern nucleon FF parametrisations and they produce results in the same range

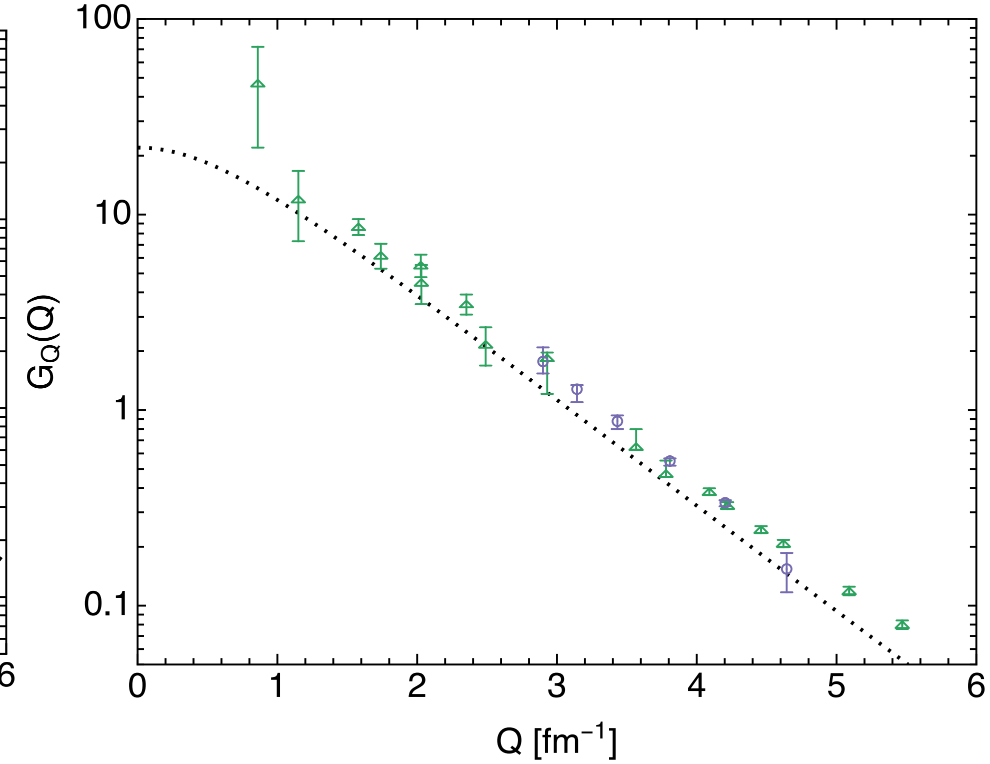
Deuteron charge and quadrupole form factors

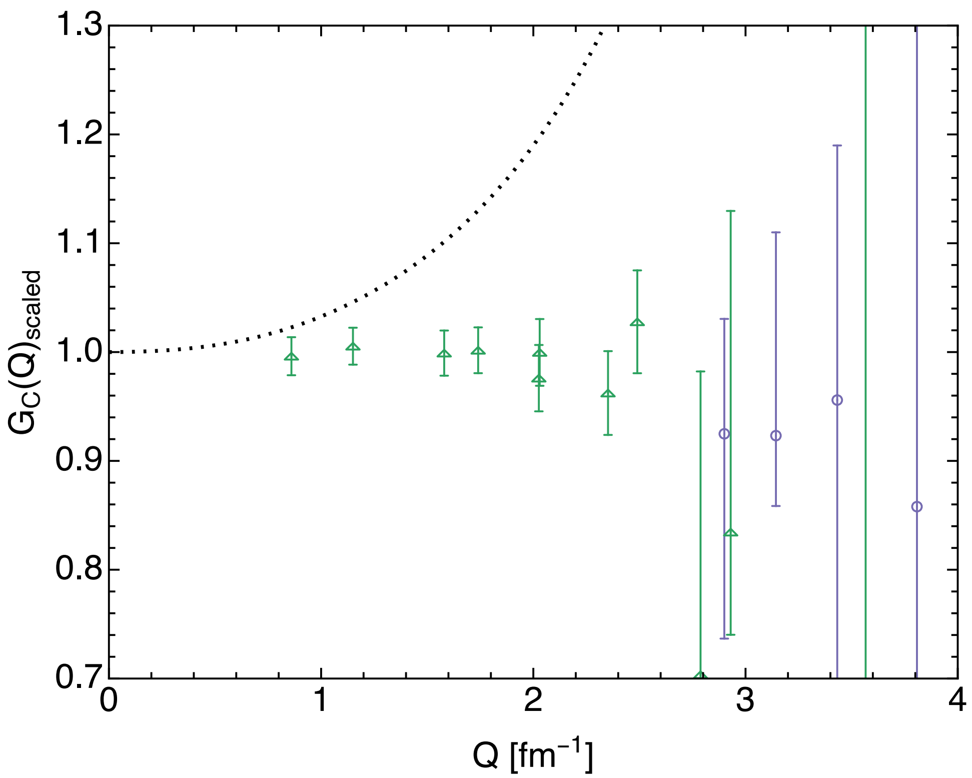
LO

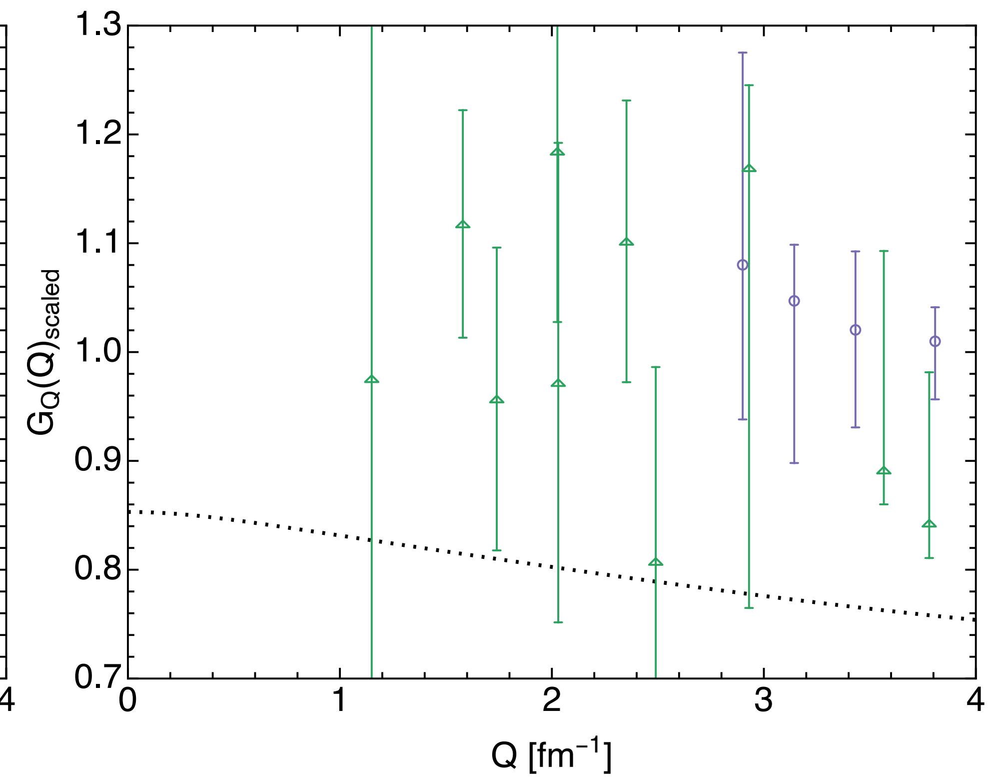
Deuteron charge form factor



Deuteron quadrupole form factor



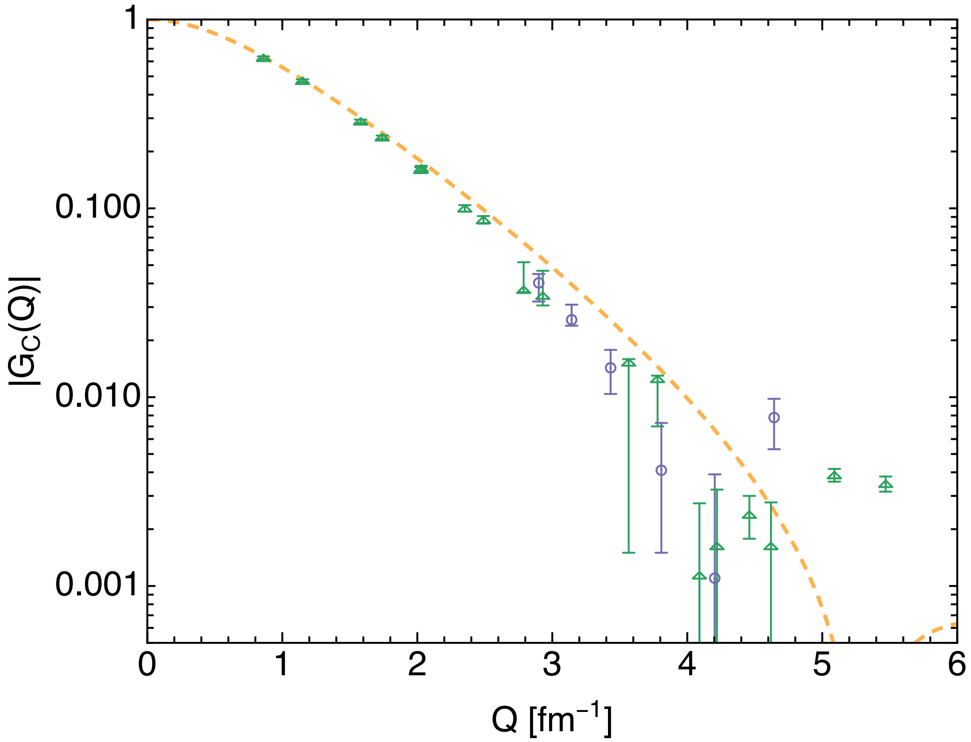




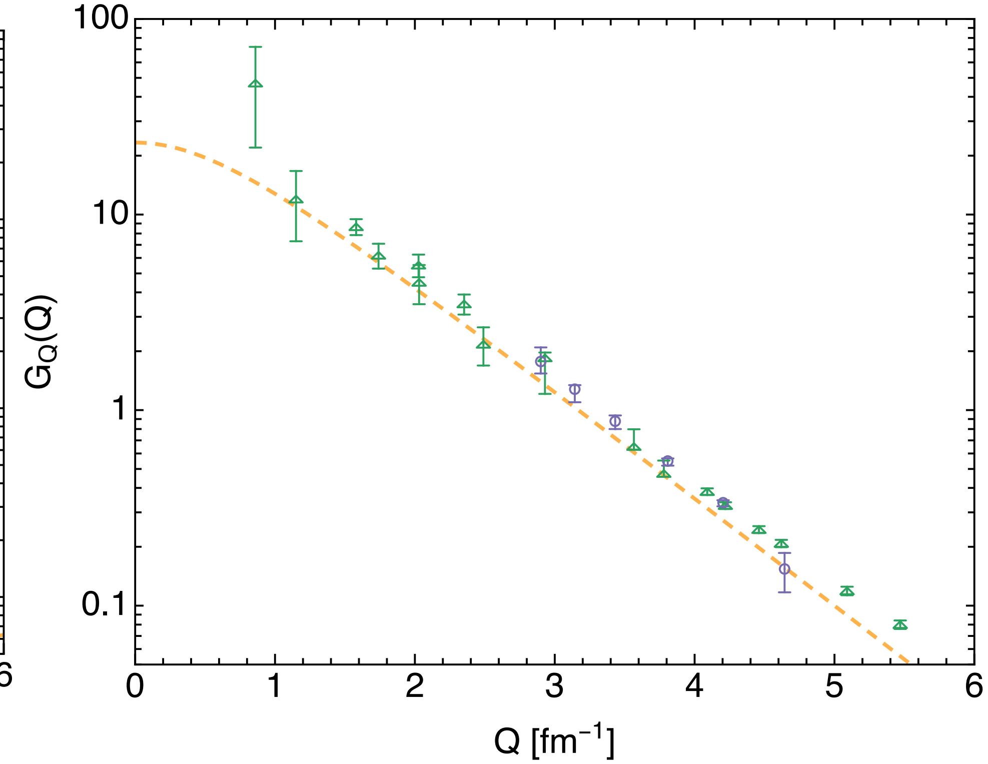
Deuteron charge and quadrupole form factors

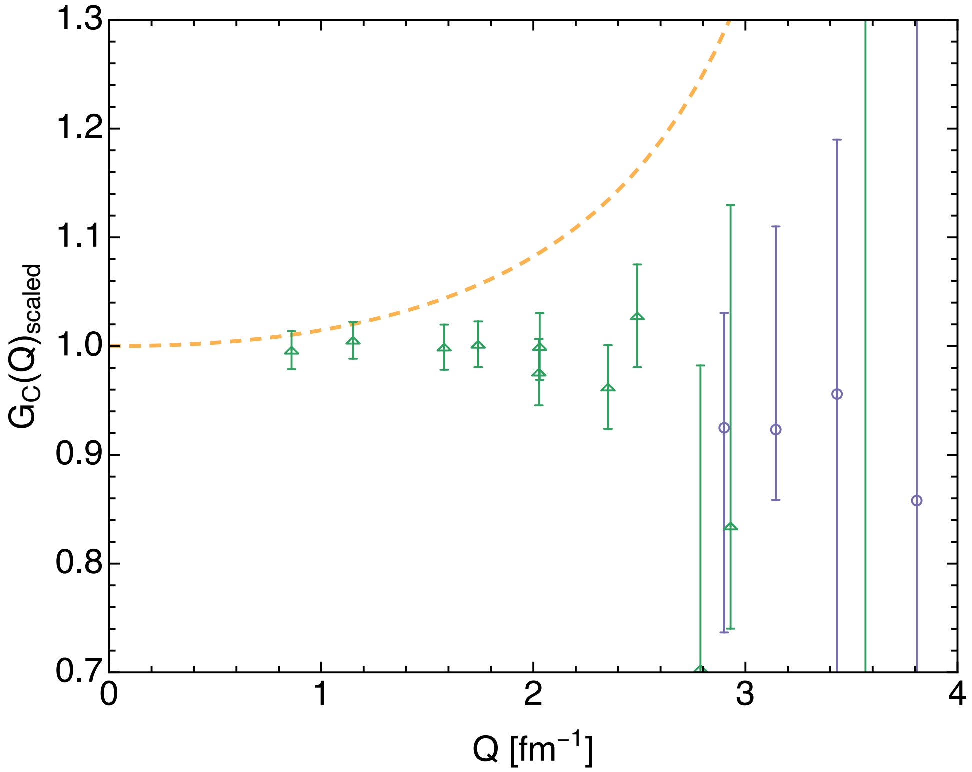
NLO

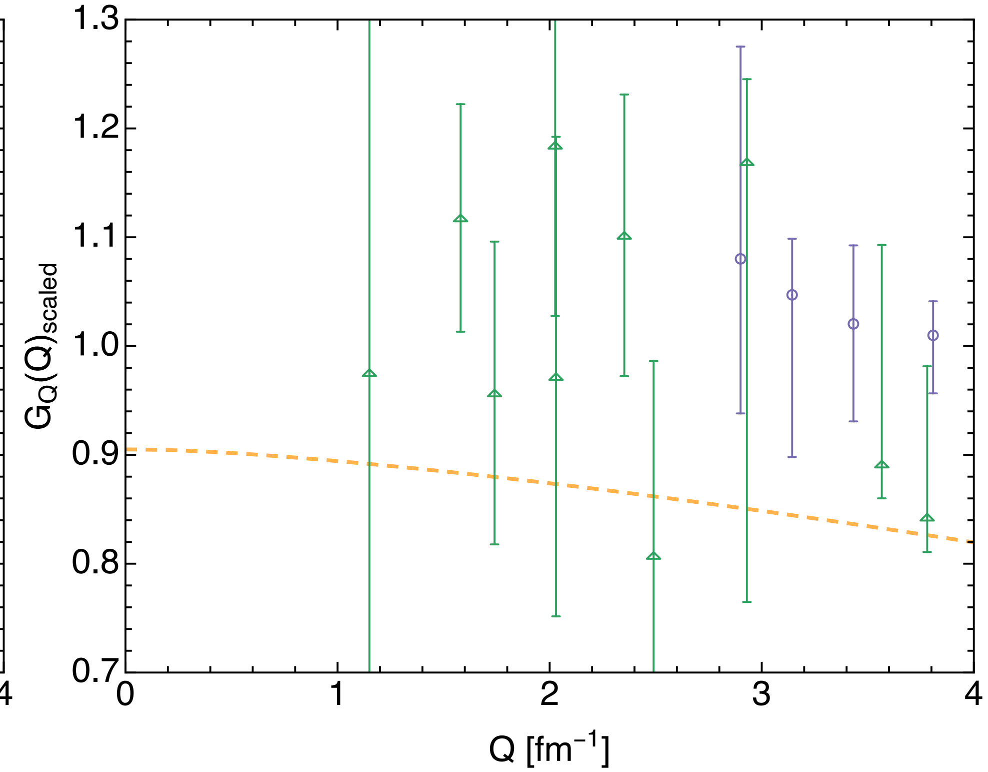
Deuteron charge form factor



Deuteron quadrupole form factor

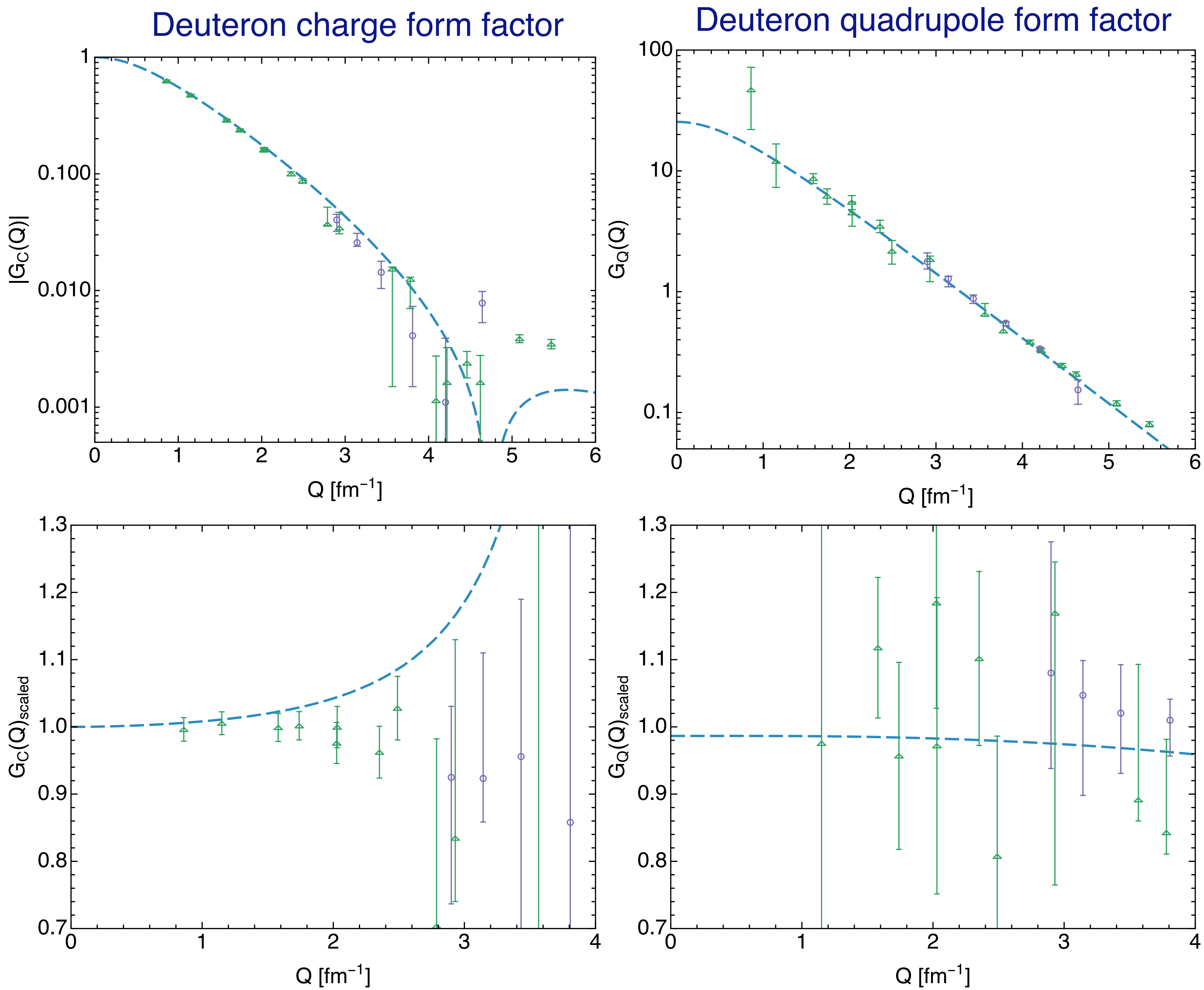






Deuteron charge and quadrupole form factors

N2LO

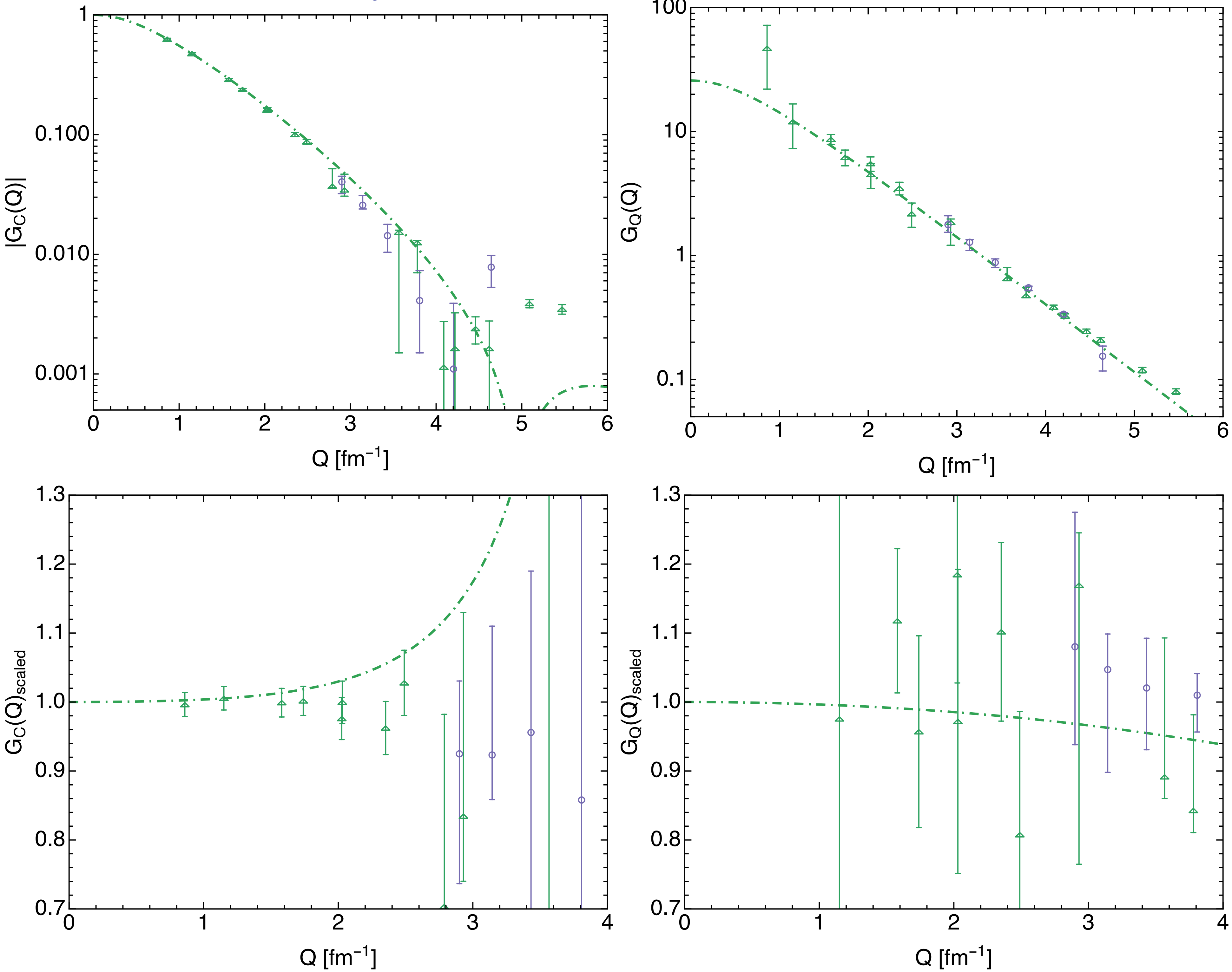


Deuteron charge and quadrupole form factors

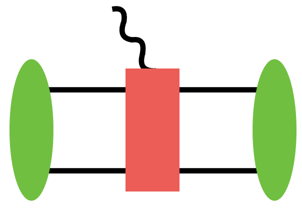
N3LO
without
2N charge
density

Deuteron charge form factor

Deuteron quadrupole form factor

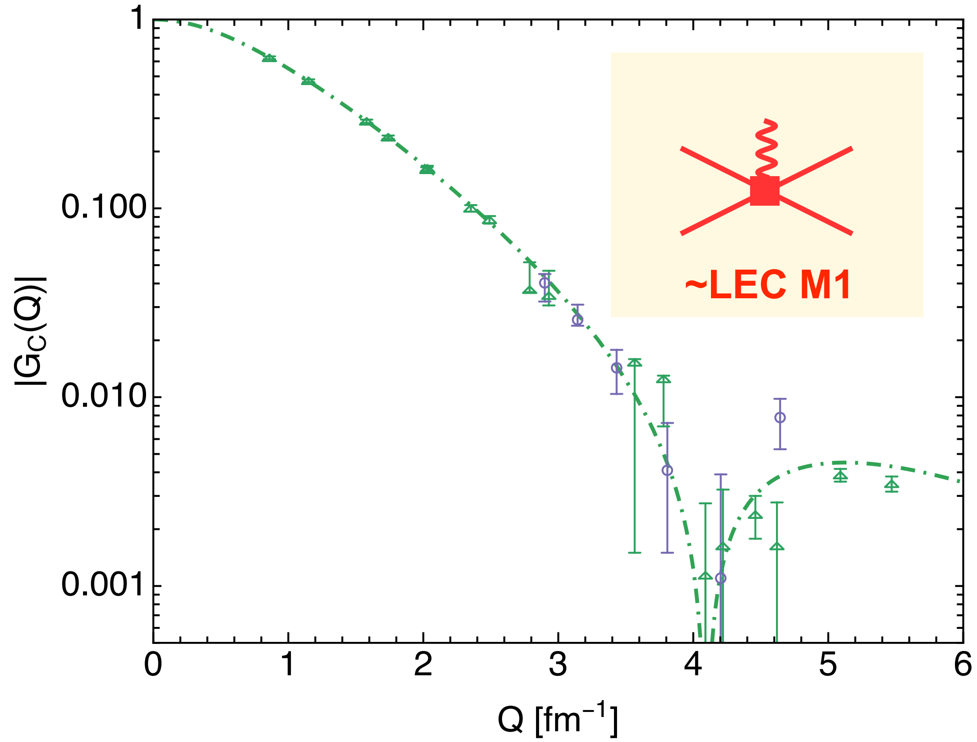


Deuteron charge and quadrupole form factors

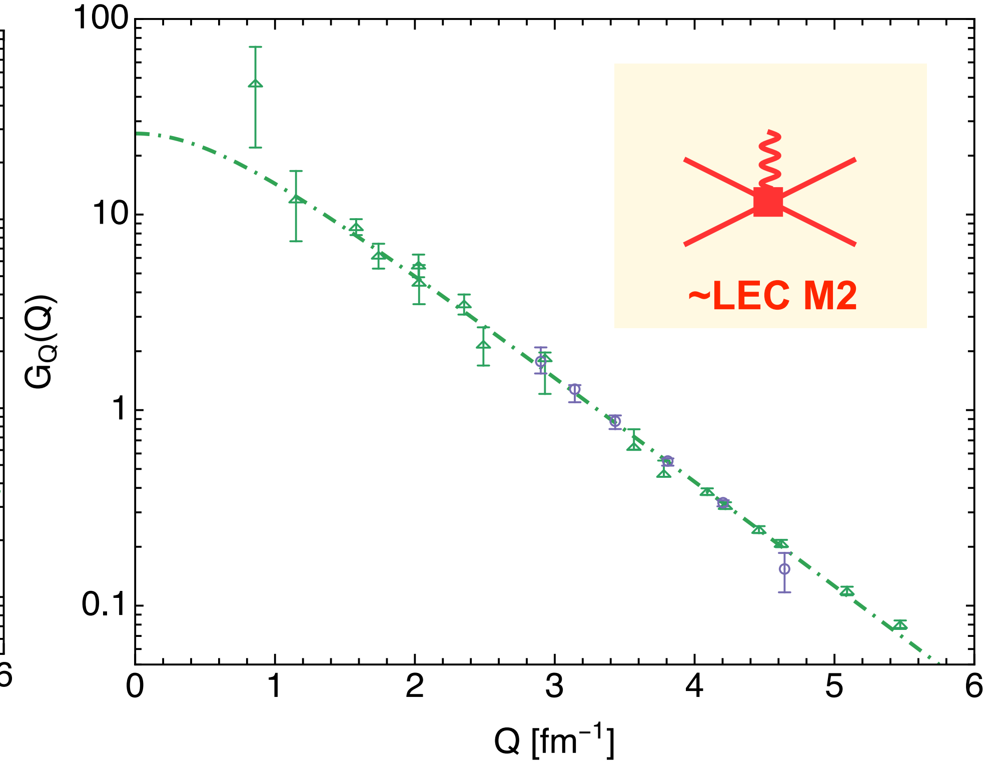


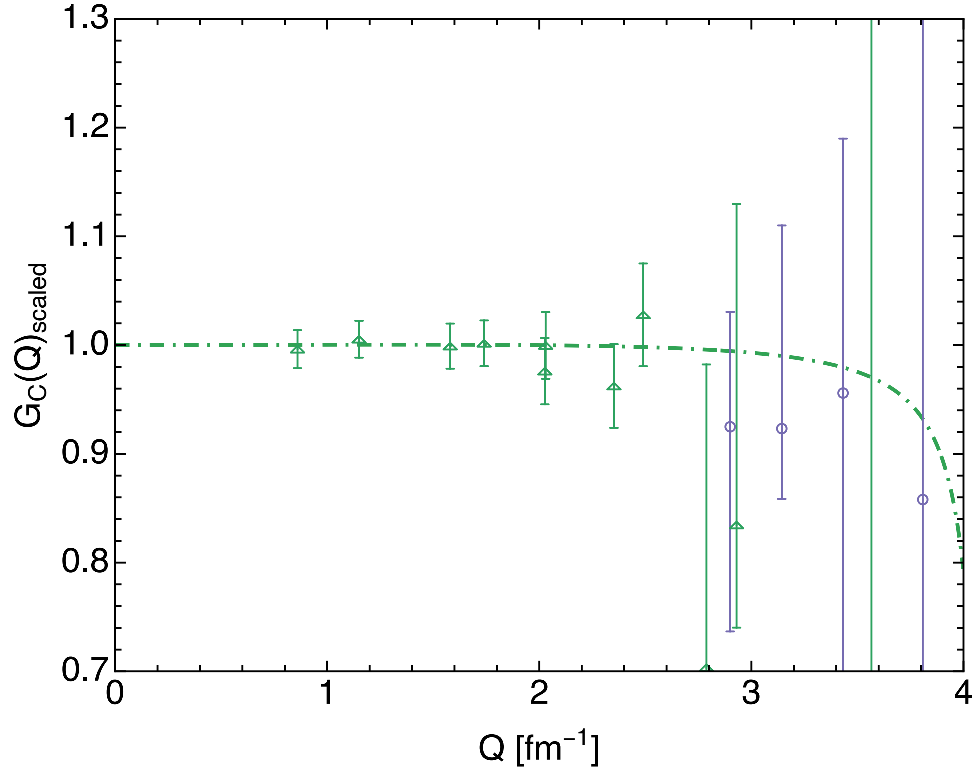
N3LO with 2N charge density

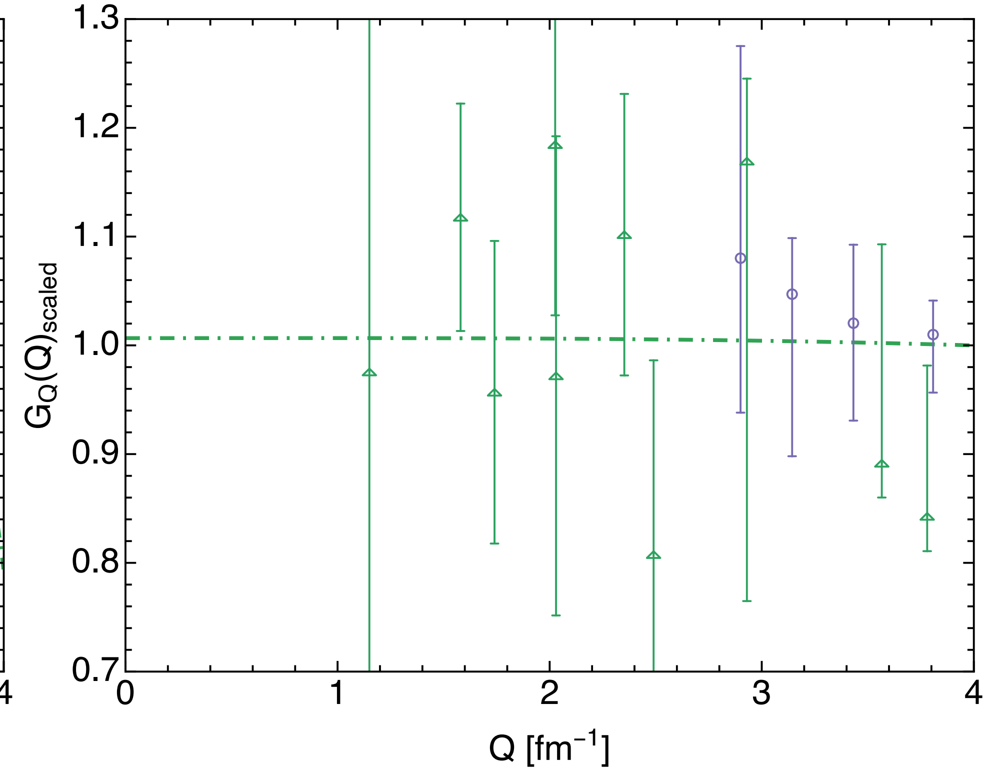
Deuteron charge form factor



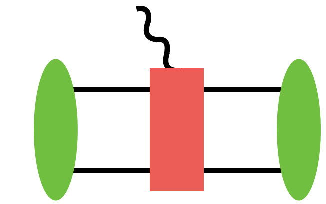
Deuteron quadrupole form factor





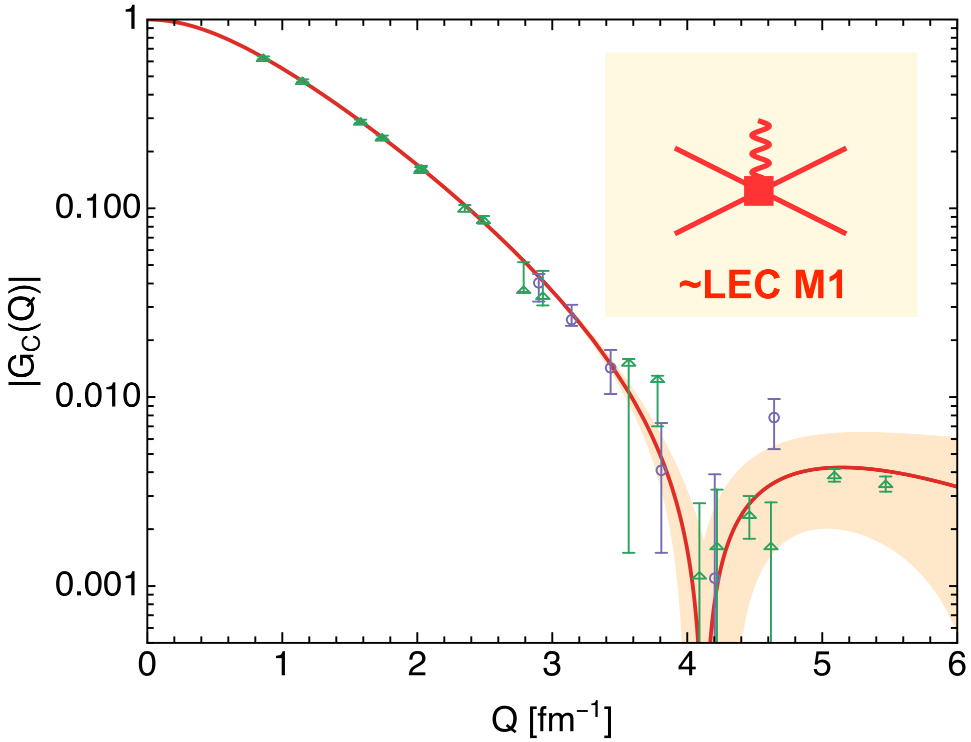


Deuteron charge and quadrupole form factors

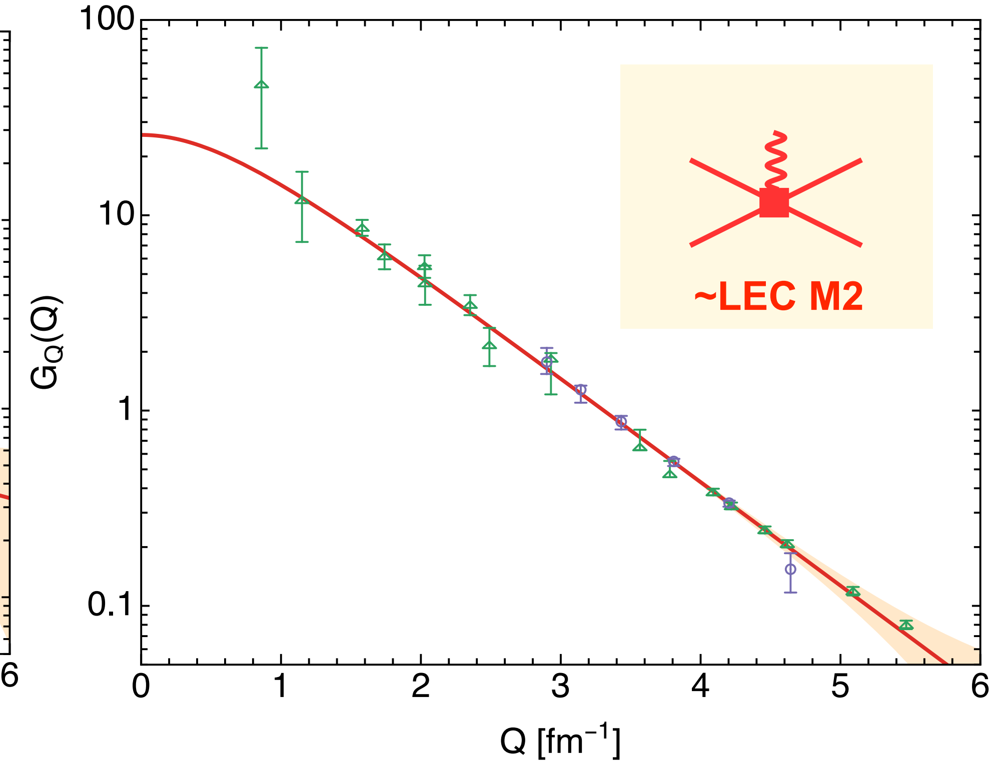


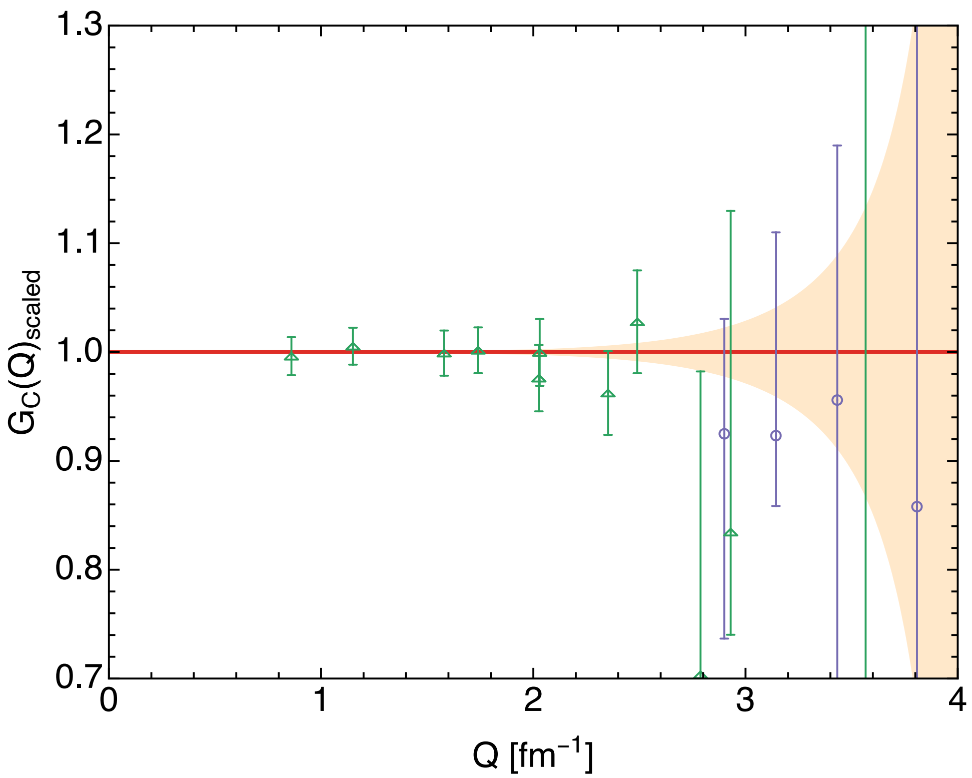
N4LO
with
2N charge
density

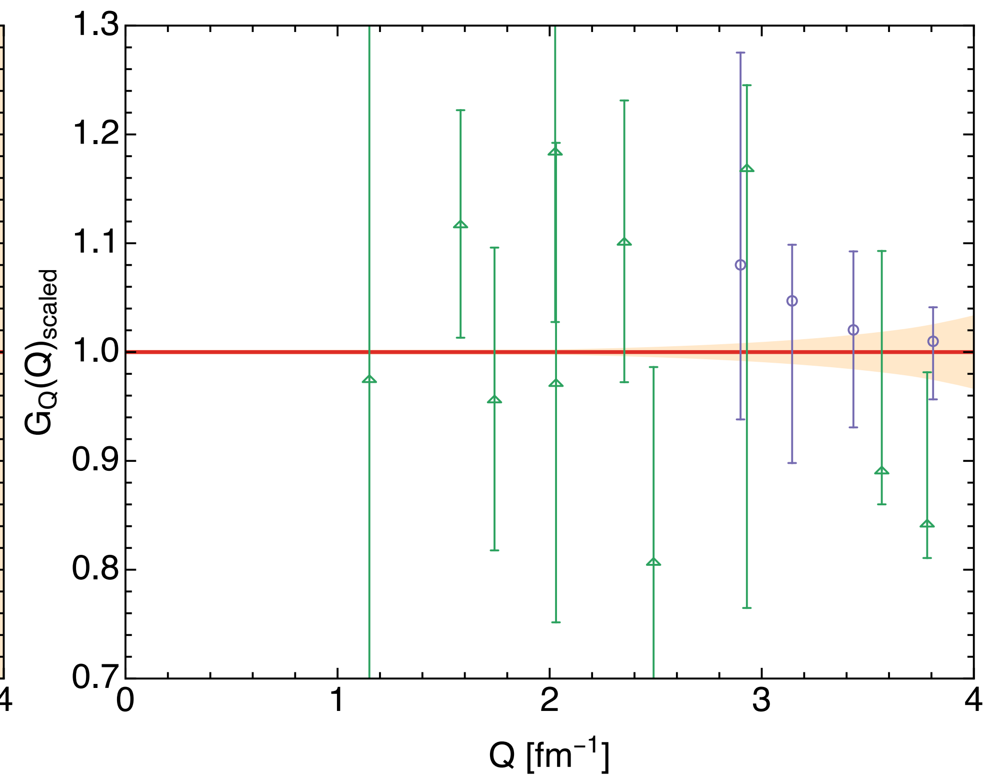
Deuteron charge form factor



Deuteron quadrupole form factor







LECs M1 and M2 are fitted to GC and GQ data

Good description of low-Q behaviour and also node position