Evgeny Epelbaum, Ruhr University Bochum

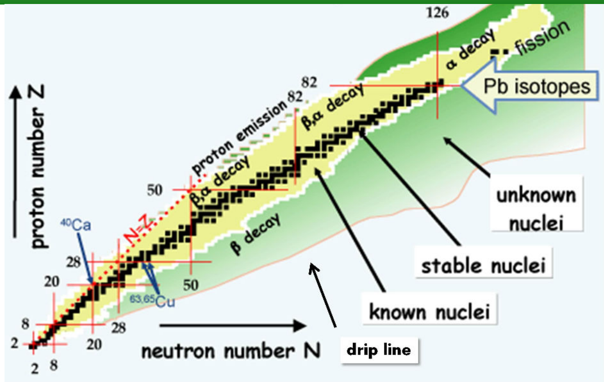
14th Conference on the Intersections of Particle & Nuclear Physics (CIPANP2022),
Lake Buena Vista, Florida, USA, Aug 29 — Sep 4, 2022

Chiral EFT for low-energy nuclear physics

- Introduction
- ChEFT for NN scattering
- Beyond the two-nucleon system
- Precision calculation of radii of $A \leq 4$ nuclei
- Summary and outlook

Bundesministerium für Bildung und Forschung
DFG Deutsche Forschungsgemeinschaft
erc European Research Council

Why (precision) nuclear physics?



After the discovery of Higgs boson,

the strong sector remains the only poorly understood part of the SM!

Interesting topic on its own. Some current frontiers:

— the nuclear chart and limits of stability FAIR, GANIL, ISOLDE,…

— EoS for nuclear matter (gravitational waves from n-star mergers) LIGO/Virgo,…

— hypernuclei (neutron stars) JLab, JSI/FAIR, J-PARC, MAMI, NICA, …

But also highly relevant for searches for BSM physics, e.g.:

— direct Dark Matter searches (WIMP-nucleus scattering)

— searches for $0\nu\beta\beta$ decays

— searches for nucleon/nuclear EDMs

— proton/deuteron radius puzzle (complementary experiments with light nuclei…)

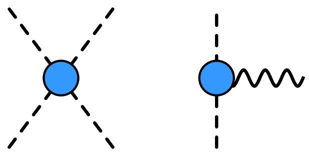
→ need a reliable approach to nuclear structure with quantified uncertainties:

Effective Field Theory

Chiral Effective Field Theory

GB dynamics

Weinberg, Gasser, Leutwyler, …

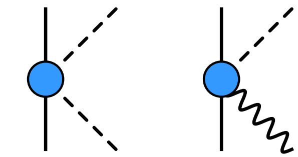


Chiral Perturbation Theory

$$Q = \frac{\text{momenta of particles or } M_\pi}{\text{breakdown scale } \Lambda_b} \sim \frac{1}{4} \cdots \frac{1}{3}$$

πN dynamics

Bernard-Kaiser-Meißner et al.



Effective Lagrangian:

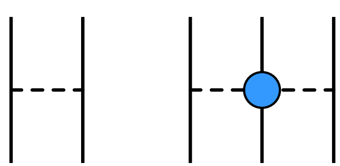
$$\mathcal{L}_\pi = \frac{F^2}{4}\mathrm{Tr}(\nabla^\mu U \nabla_\mu U^\dagger + \chi_+) + \ldots,$$

$$\mathcal{L}_{\pi N} = \bar{N}(iv\cdot D + g_A u\cdot S)N + \ldots,$$

$$\mathcal{L}_{NN} = -\frac{1}{2}C_S(\bar{N}N)^2 + 2C_T(\bar{N}SN)^2 + \ldots$$

Nuclear forces

Weinberg, van Kolck, Kaiser, EGM, …

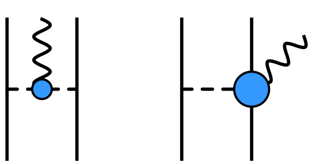


Combined with ab-initio few-body methods,
provide first-principle approach to nuclear systems

$\boxed{\text{Goal: chiral EFT as a precision tool}}$

Nuclear currents

Park et al, Bochum-Bonn, JLab-Pisa

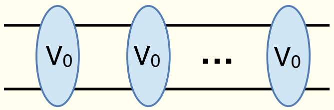


Re-summation of ladder diagrams

Certain terms in the amplitude must be re-summed (ladder-type graphs enhanced Weinberg '90, '91)

$$T_{\mathrm{LO}} = V_0 + V_0 G V_0 + V_0 G V_0 G V_0 + \ldots = \sum_{n=0}^{\infty} V_0 (G V_0)^n$$

order in the ChEFT expansion



$$T_{\mathrm{NLO}} = T_{\mathrm{LO}} + \sum_{m,n=0}^{\infty} (V_0 G)^m V_2 (V_0 G)^n + \underbrace{\mathcal{O}\left((V_2)^2\right)}$$

automatically included when solving
$T_{\mathrm{NLO}} = (V_0 + V_2) + (V_0 + V_2) G T_{\mathrm{NLO}}$

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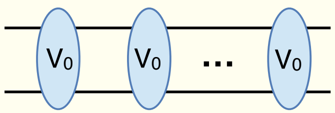

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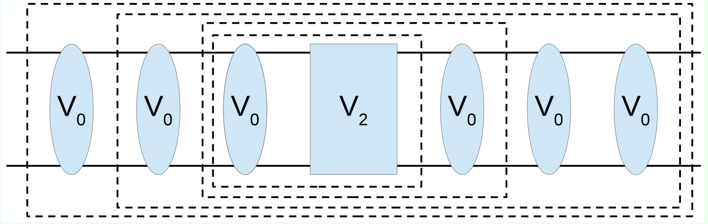
Divergent integrals in the Lippmann-Schwinger equation are usually regularized with a cutoff Λ:

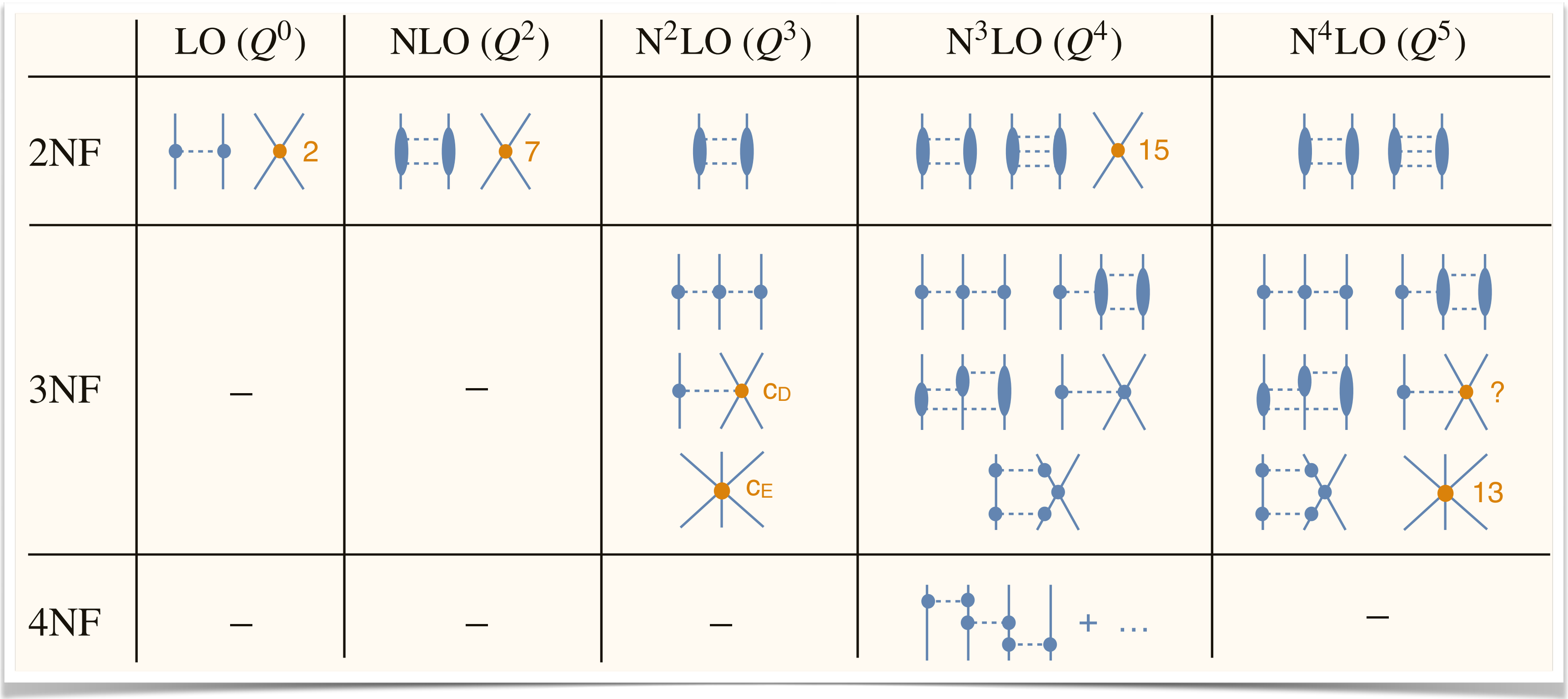
- the „RG invariant" approach with $\Lambda \gg \Lambda_b$: $T \sim 1 + \Lambda + \Lambda^2 + \ldots = (1 - \Lambda)^{-1}$ van Kolck, Long, Yang, …
  - — criticized in EE, Gegelia, EPJA 41 (09) 341; EE, Gasparyan, Gegelia, Meißner, EPJA 54 (18) 186
  - — in fact, not RG-invariant beyond LO Ashot Gasparyan, EE, to appear

- finite-Λ EFT with $\Lambda \lesssim \Lambda_b \sim 600$ MeV Lepage, EE, Gegelia, Meißner, Reinert, Entem, Machleidt, …
  - — phenomenologically successful; approximate Λ-independence verified a posteriori
  - — renormalizability (in the EFT sense) has been rigorously proven to NLO using the BPHZ subtraction method (forest formula)
    Ashot Gasparyan, EE, PRC 105 (2022) 024001; to appear



Chiral EFT expansion of the nuclear forces

Weinberg, van Kolck, Friar, Kaiser, EE, Krebs, Bernard, Meißner, Girlanda, …



ACCURACY …but also complexity and the number of LECs…

- πN LECs taken from the Roy-Steiner analysis ⇒ long-range topologies are pure predictions
- Loop diagrams in the 3NF calculated using dimensional regularization

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	LO (Q^0)	NLO (Q^2)	N^{2}LO (Q^3)	N^{3}LO (Q^4)	N^{4}LO (Q^5)
2NF	2	7		15	
3NF	–	–	c_D c_E		? 13
4NF	–	–	–	+ …	–

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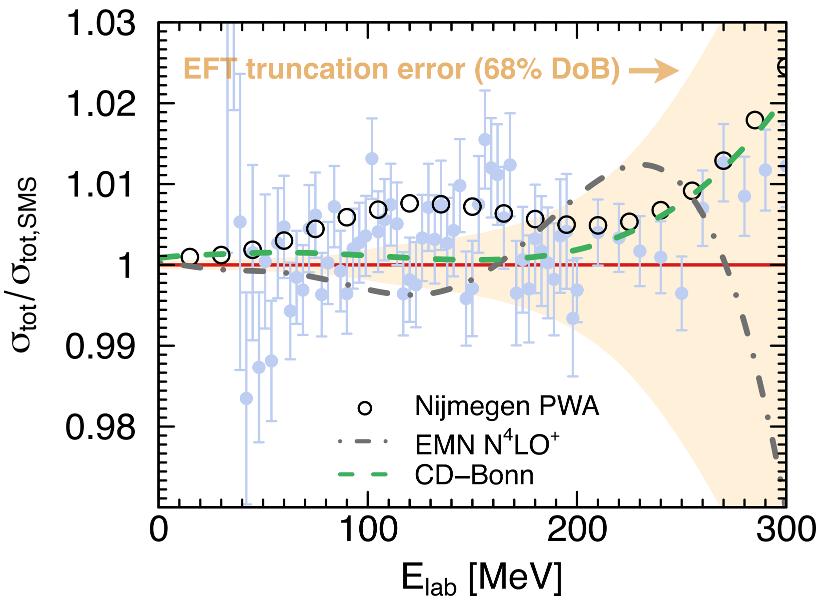
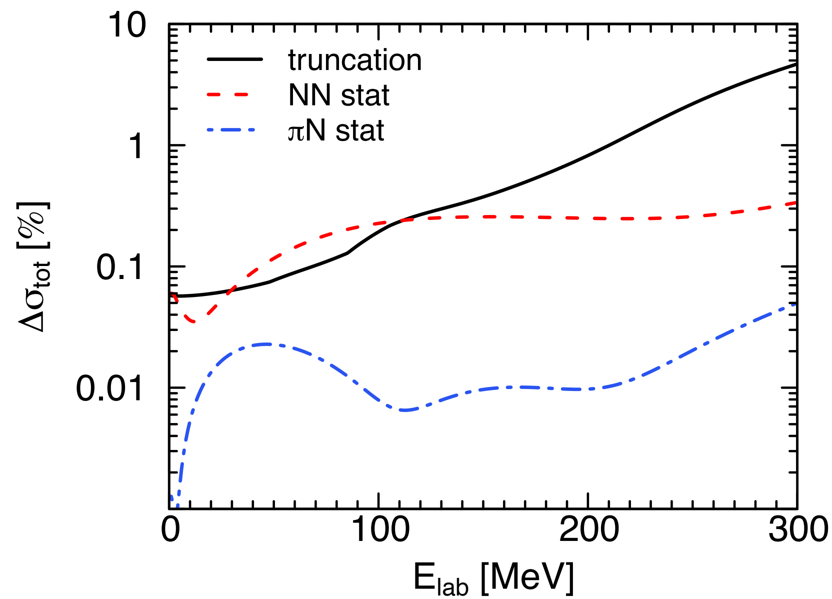
Chiral EFT for NN scattering

- Statistically perfect description of our own database of mutually consistent scattering data (2124 pp and 2935 np data below E_{lab} = 290 MeV) Reinert, Krebs, EE, PRL 126 (21) 092501

high-precision „realistic“ potentials				*Idaho χEFT*		*Bochum SMS χEFT*	
Nijm I	Nijm II	Reid93	CD Bonn	$N^4LO^+_{450}$	$N^4LO^+_{500}$	$\mathbf{N^4LO^+_{450}}$	$\mathbf{N^4LO^+_{500}}$
1.061	1.070	1.078	1.042	2.019	1.203	**1.013**	**1.015**

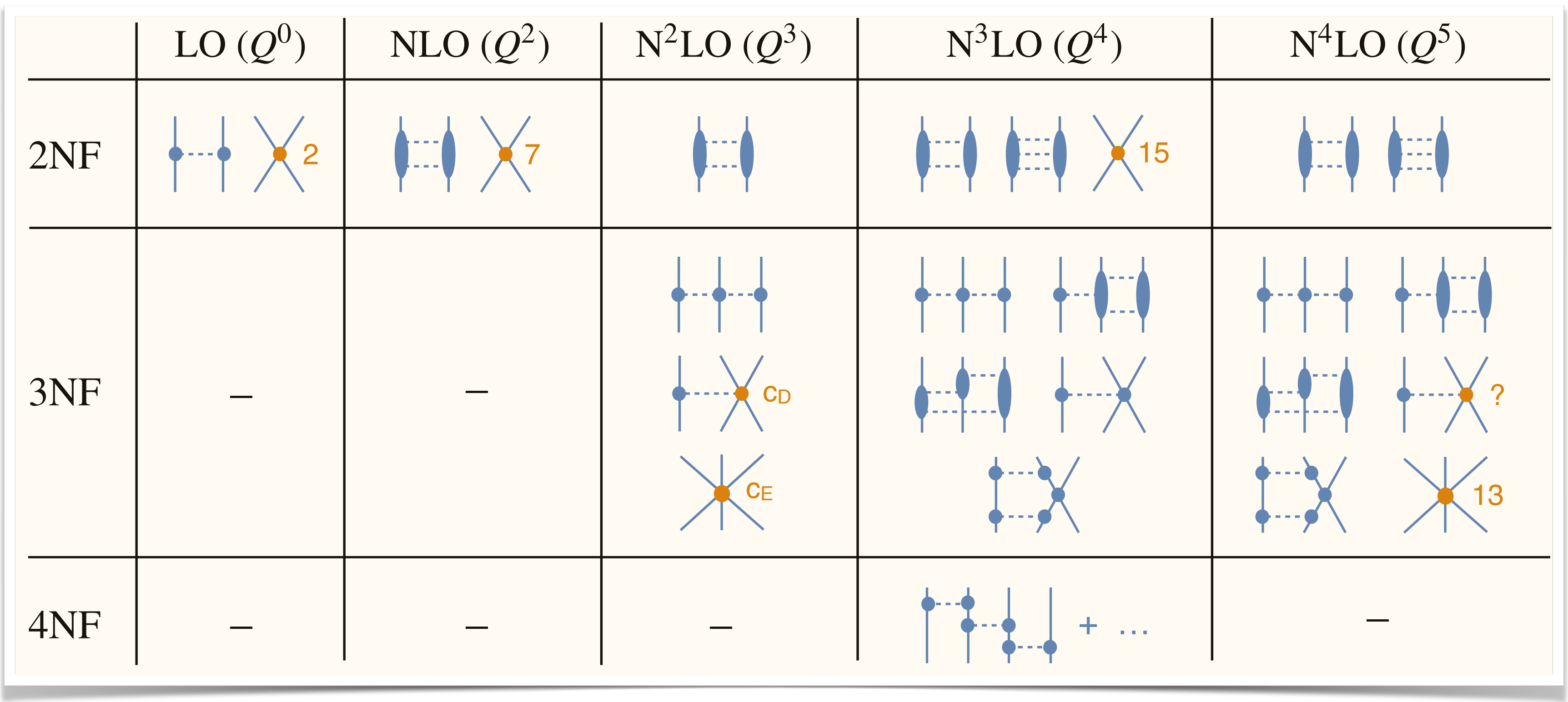
- Results for the np total cross section and the error budget:





- Our determination of $g_{\pi NN}$ from NN data, $g_{\pi NN} = 13.23 \pm 0.04$, is to be compared with PSI data $g_{\pi NN} = 13.10 \pm 0.10$ (from $\epsilon_{1s}^{\pi H}$, $\epsilon_{1s}^{\pi D}$) and $g_{\pi NN} = 13.24 \pm 0.10$ (from $\Gamma_{1s}^{\pi H}$) Hirtl et al.'21

Beyond the NN system



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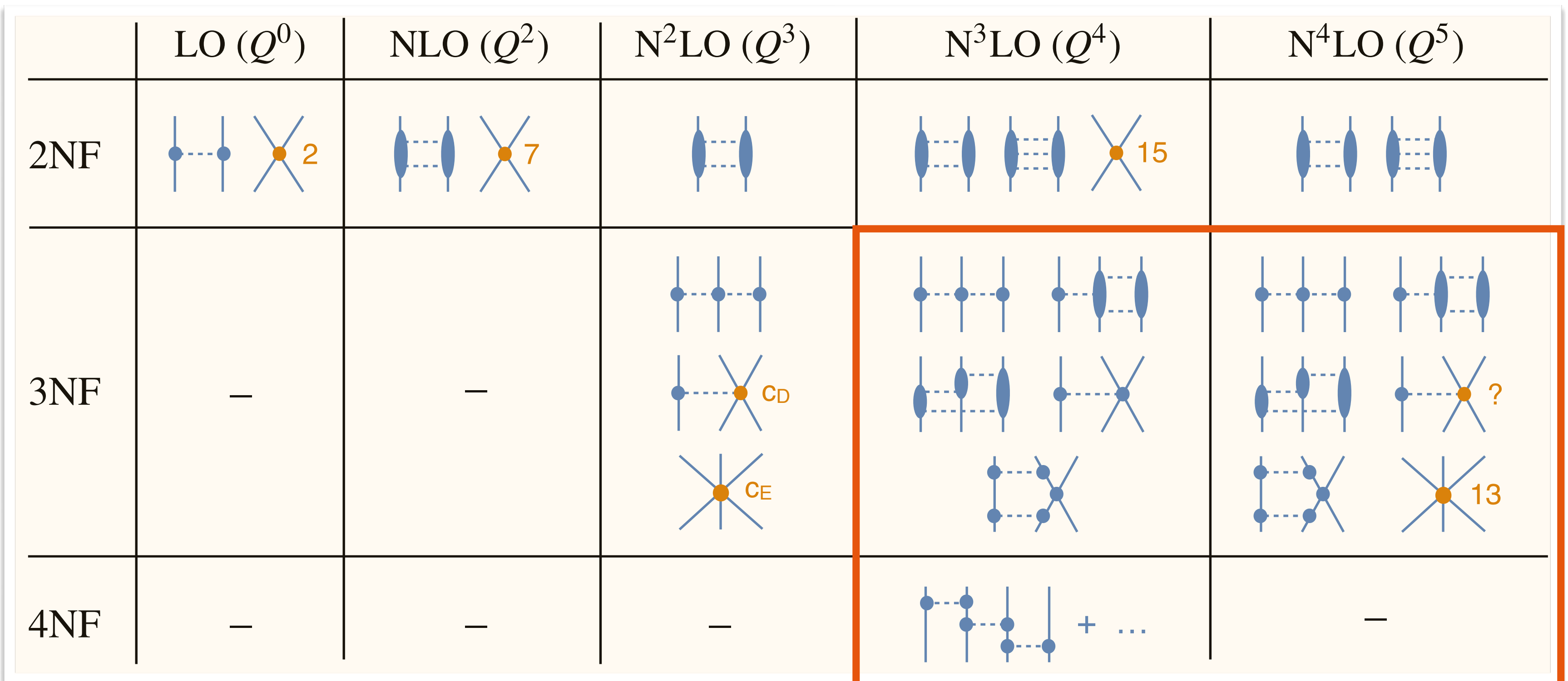
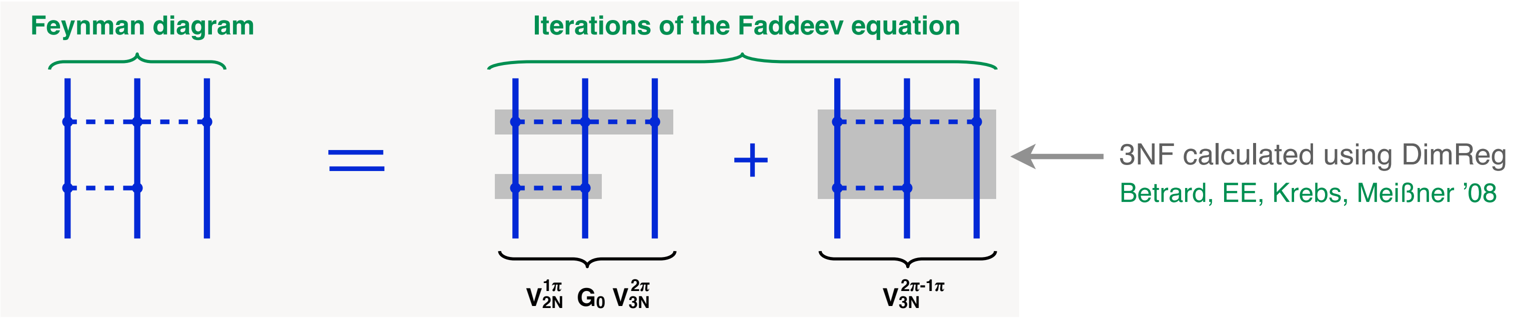


need to be re-derived using consistent cutoff regularization

3NF: the need for consistent regularization

Using DimReg to calculate loop diagrams in the 3NF + cutoff regularization in the dynamical equation violates the chiral symmetry.



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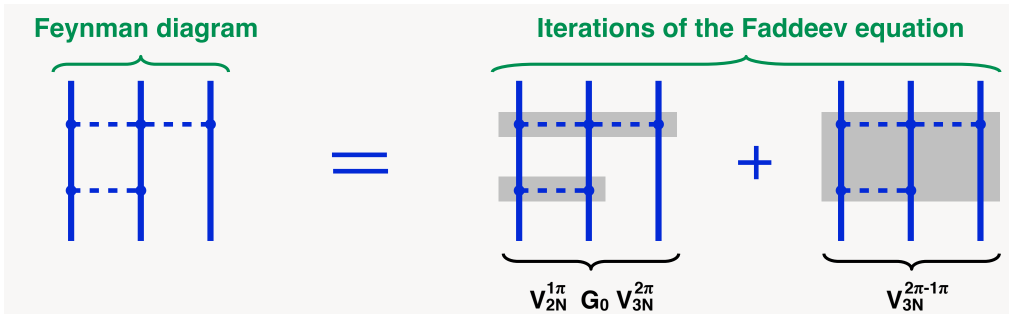
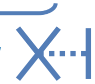


3NF calculated using DimReg
Betrard, EE, Krebs, Meißner ’08

- Using DimReg everywhere: l.h.s. = r.h.s. $\Rightarrow$ consistent
- Calculate the iterative diagram on the r.h.s. using cutoff regularization:

$$V_{2N,\,\Lambda}^{1\pi}\, G_0\, V_{3N,\,\Lambda}^{2\pi} = -\,\Lambda \frac{g_A^4}{96\sqrt{2\pi^3}F_\pi^6}\Bigg[\underbrace{\tau_1\cdot\tau_3\,(\vec{q}_3\cdot\vec{\sigma}_1)}_{\text{absorbable into } c_D:} - \underbrace{\frac{4}{3}(\tau_2\cdot\tau_3-\tau_1\cdot\tau_3)(\vec{q}_2\cdot\vec{\sigma}_3)}_{\text{violates chiral symmetry...}}\Bigg]\frac{\vec{q}_3\cdot\vec{\sigma}_3}{q_3^3+M_\pi^2} + \ldots$$



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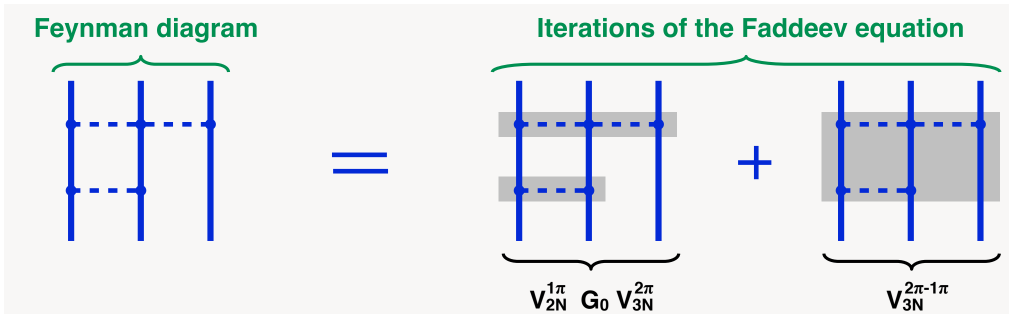

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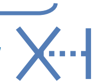

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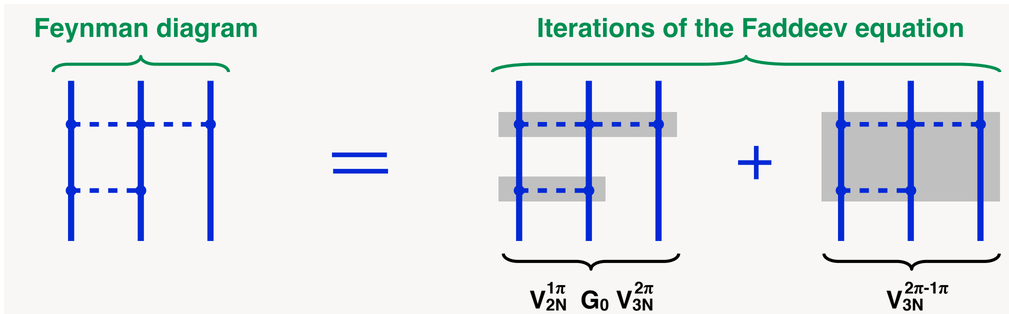

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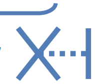

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$\Rightarrow$ 3NF and currents beyond N²LO must be re-derived using symmetry-preserving regulator

— e.g., the higher-derivative [Slavnov '71] or gradient flow regularization [Lüscher '10]

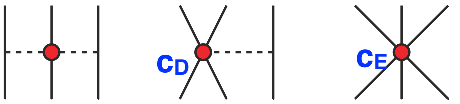
— a new path-integral approach to derive nuclear forces and currents [Krebs, EE, in preparation]

Few-N systems and light nuclei to N^{2}LO

P. Maris et al. (LENPIC), Phys. Rev. C 103 (2021) 5, 054001

V_{2N}: available to fifth order (Q^5, N^{4}LO)

V_{3N}: currently available only to third order (Q^3, N^{2}LO)



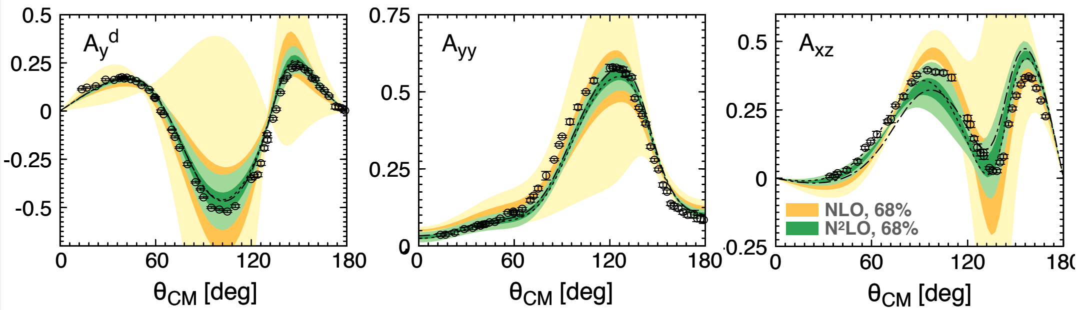
$\underbrace{\qquad\qquad\qquad}_{\text{fixed from 3N data}}$

$\Rightarrow$ test the χEFT Hamiltonian, fixed in $A \leq 3$ systems, in heavier nuclei

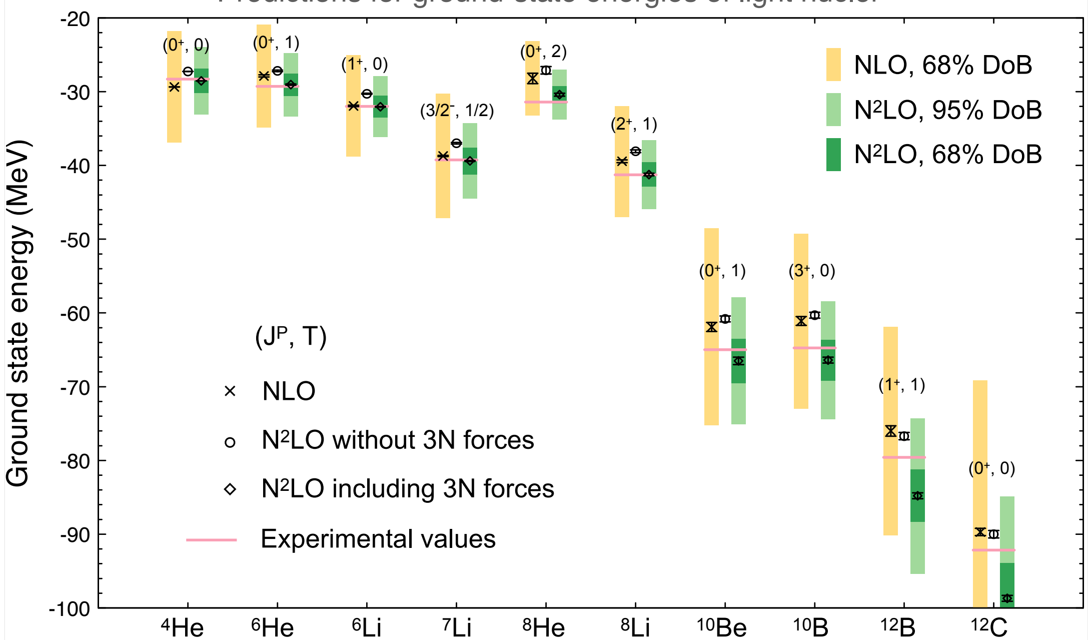
Few-N systems and light nuclei to N²LO

P. Maris et al. (LENPIC), Phys. Rev. C 103 (2021) 5, 054001

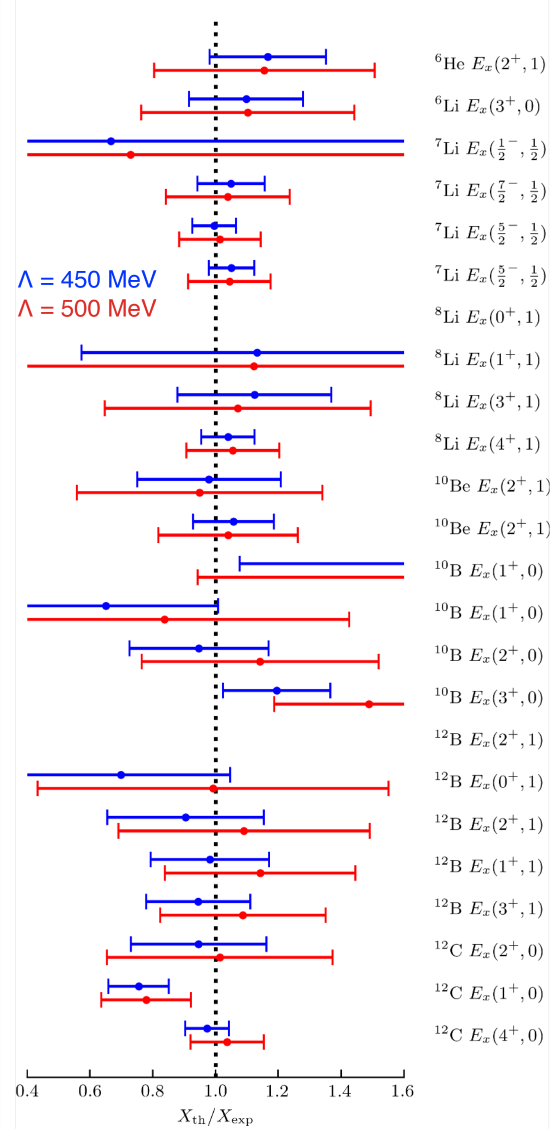
Tensor analyzing powers in Nd elastic scattering at 70 MeV



Predictions for ground-state energies of light nuclei



Excitation energies



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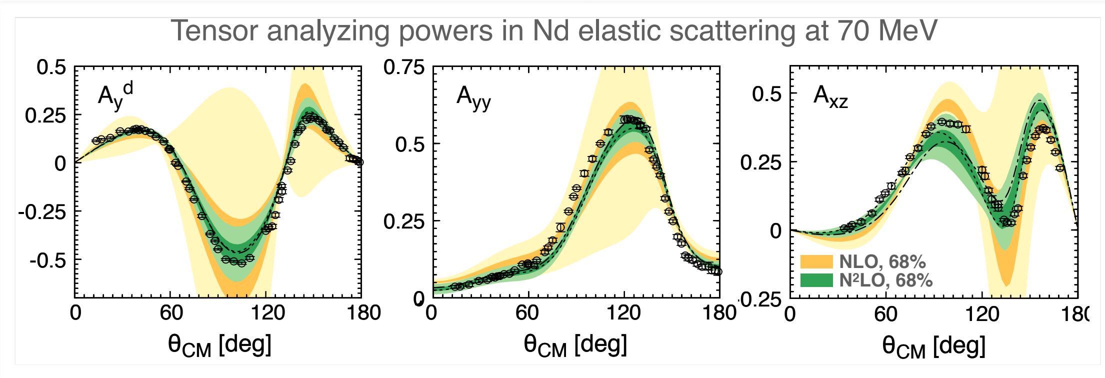
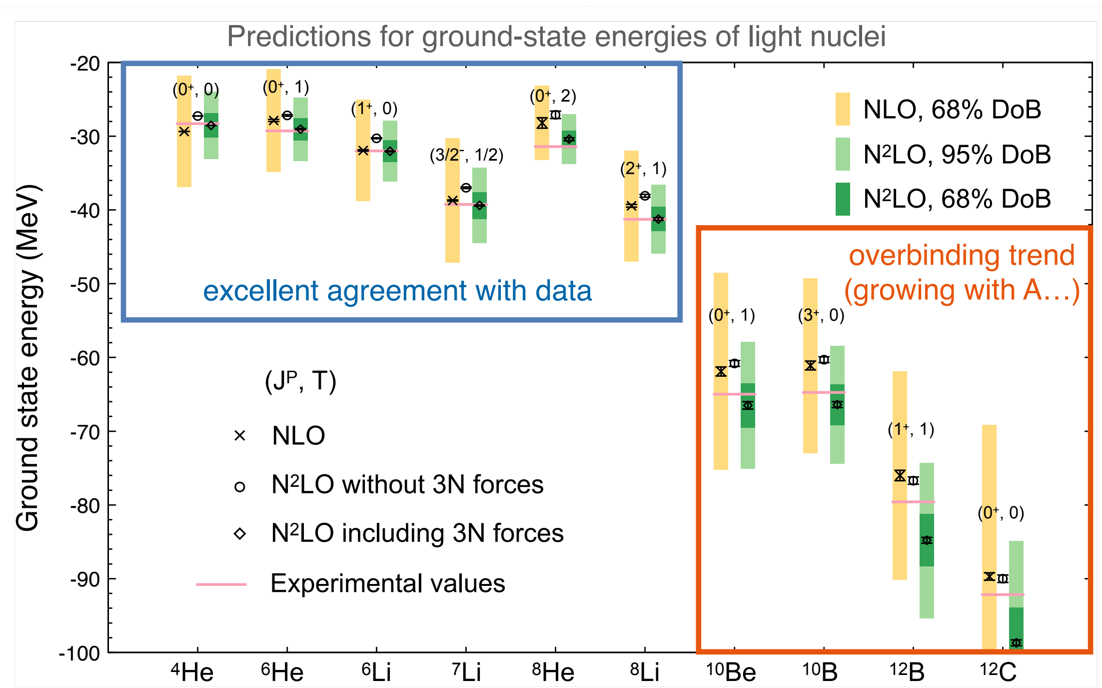
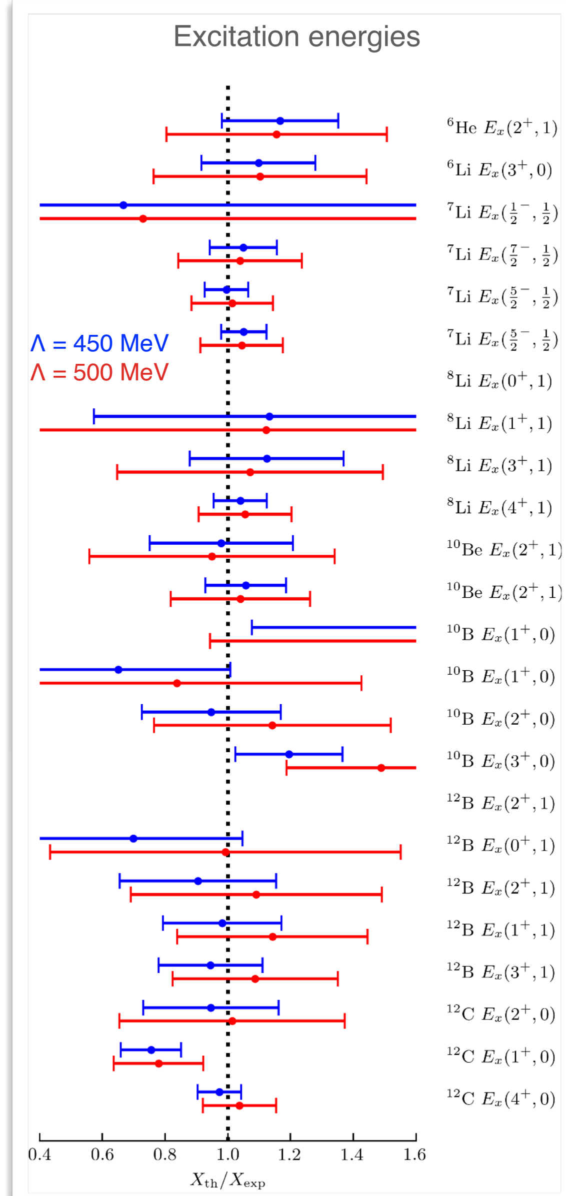
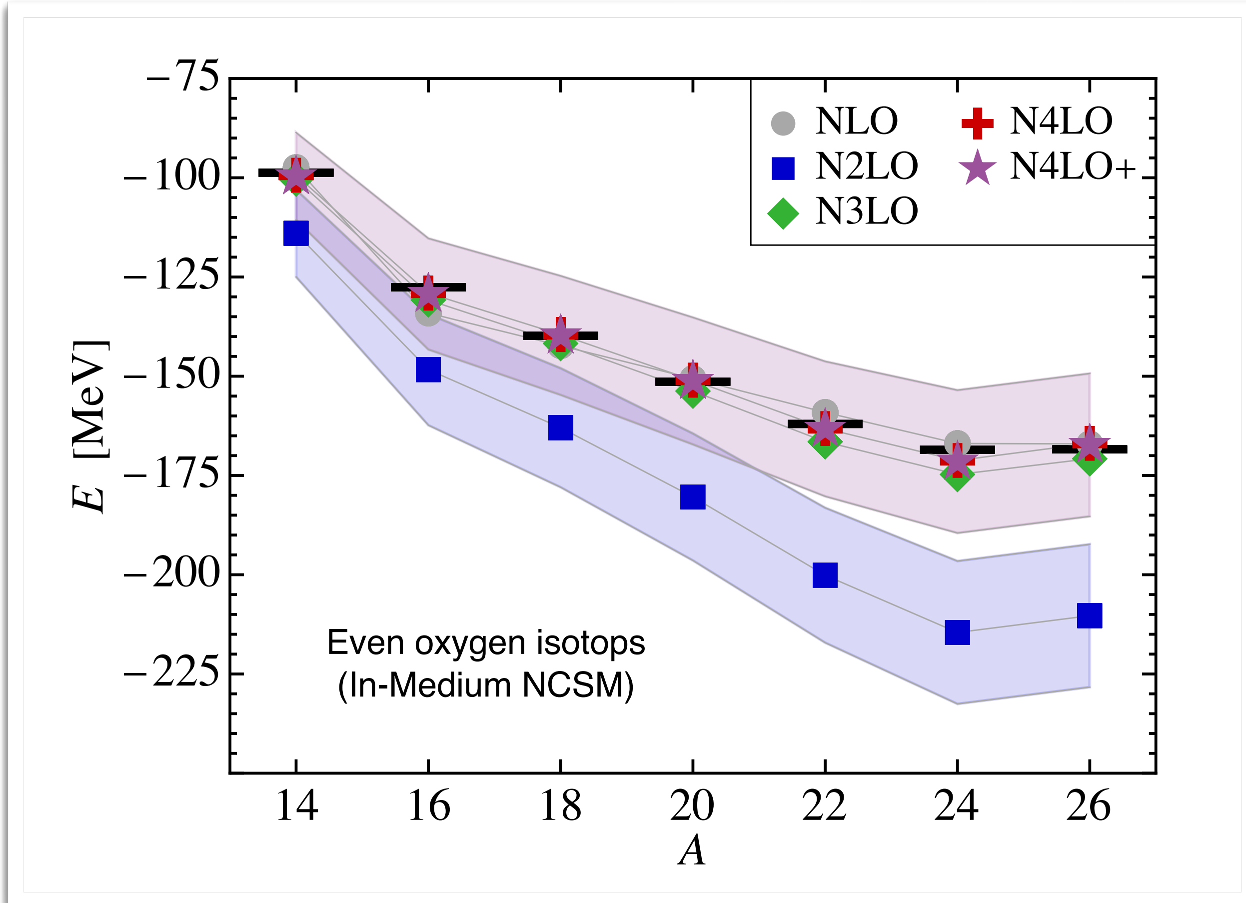






Few-N systems and light nuclei to N²LO

P. Maris et al. (LENPIC), e-Print: 2206.13303 [nucl-th]



A remarkable predictive power!

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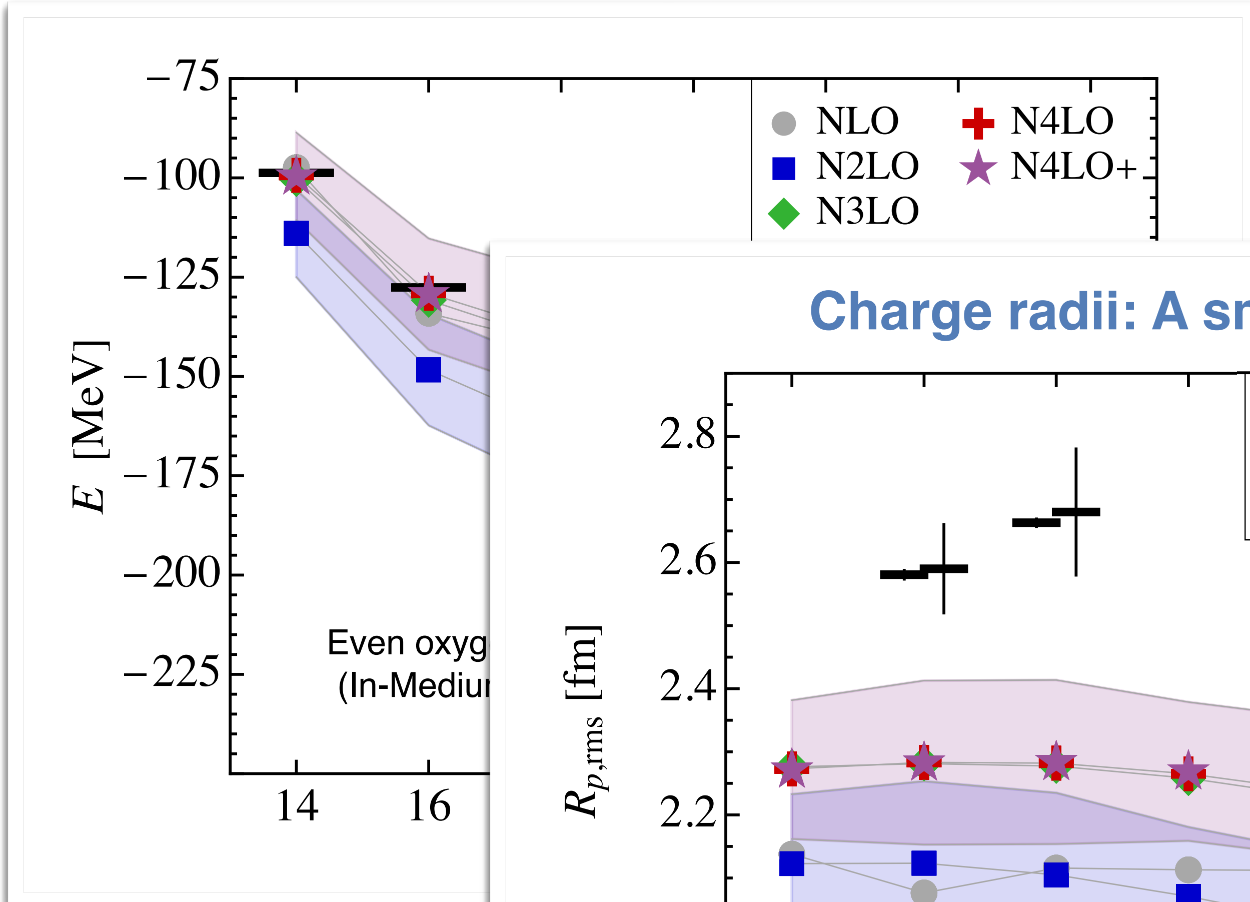

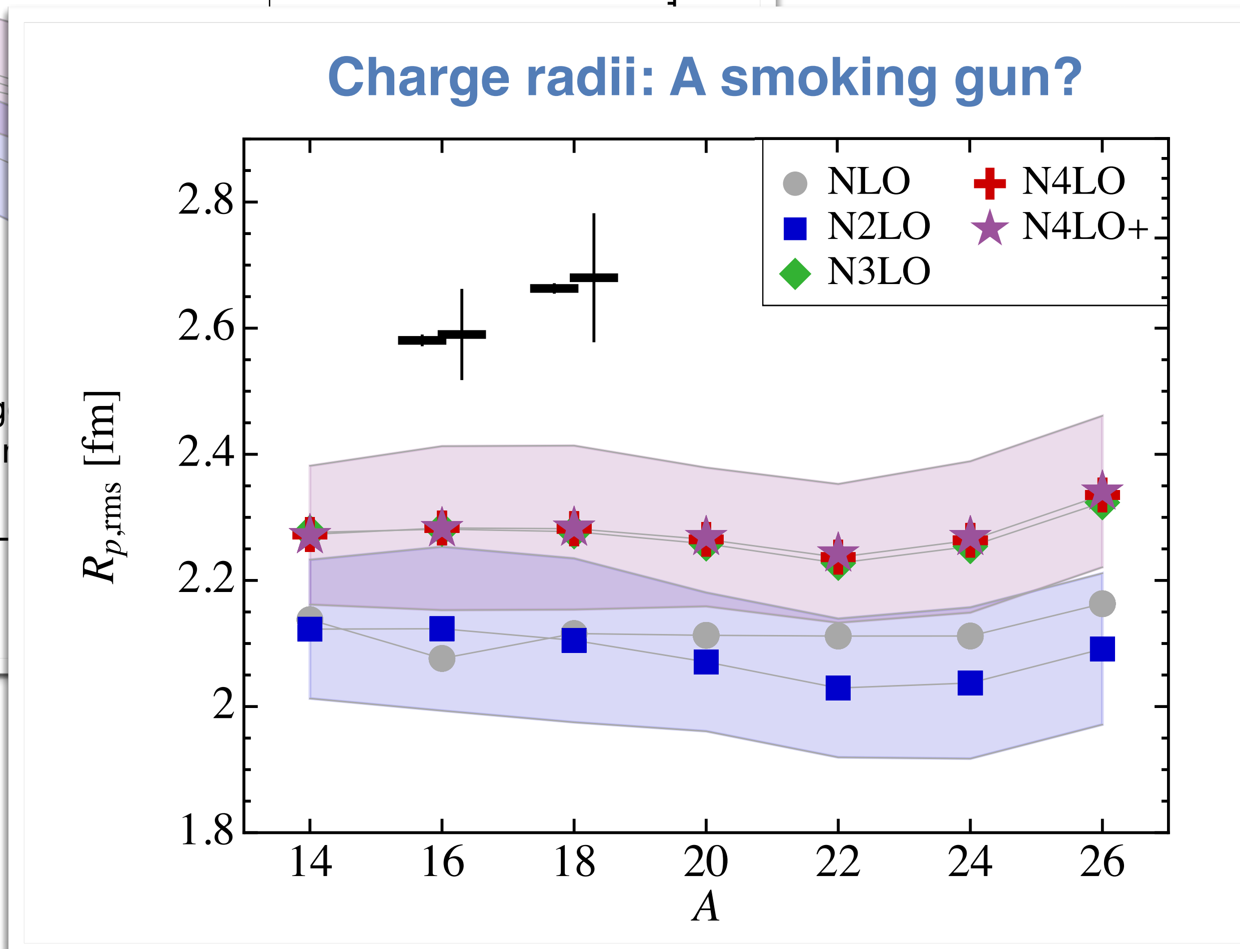

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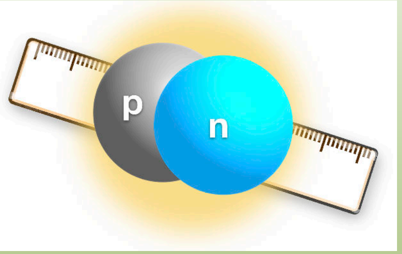

High-accuracy calculation of the deuteron charge and quadrupole FFs

Arseniy Filin, Vadim Baru, EE, Hermann Krebs, Daniel Möller, Patrick Reinert, Phys. Rev. Lett. 124 (2020) 082501;

Phys. Rev. C103 (2021) 024313

- provides a nontrivial test the new chiral NN interactions
- can shed new light on the long-standing issue with underpredicted radii of medium-mass and heavy nuclei
- opens a way to extract the neutron radius from few-N data

How big is a neutron?

Famous proton radius puzzle: pre-2010 electron-based experiments give the radius $> 7\sigma$ larger than muon-based experiments.

CODATA-2018 recommended value: $r_p = 0.8414 \pm 0.0019$ fm

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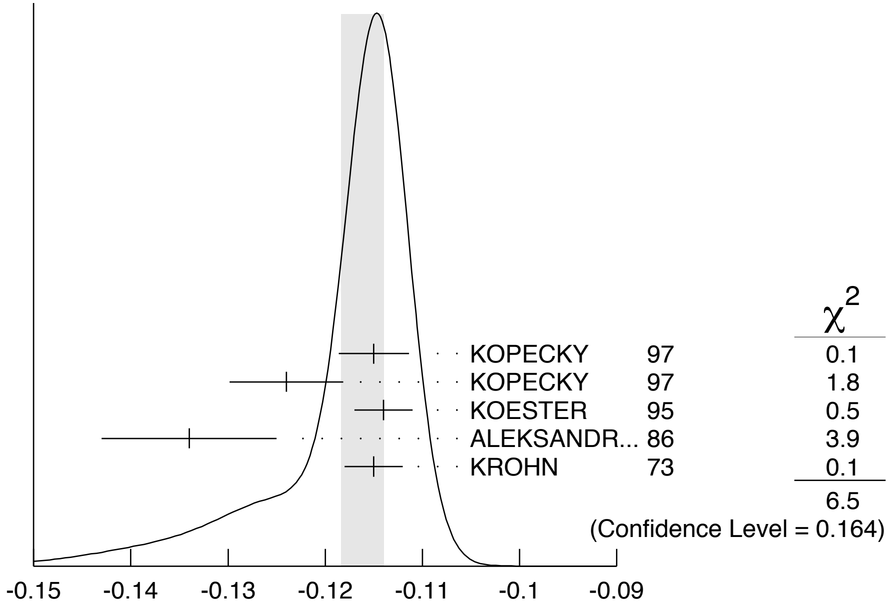
What do we know about the neutron radius?

— no neutron targets; extrapolations of $G_C^n(Q^2)$ extracted from ^{2}H not reliable…

— the only information comes from (old) n-scattering experiments on Pb, Bi, …

$\longrightarrow$ PDG (2020) recommended value: $r_n^2 = -0.1161 \pm 0.0022$ fm^2



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Idea: accurate calculation of the ^{2}H structure radius

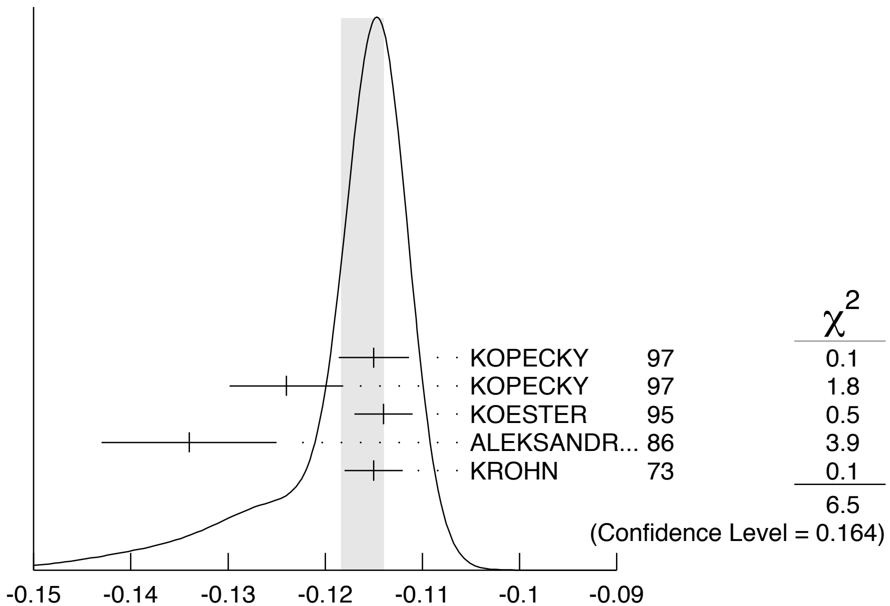
$$r_{\rm str}^2 = r_d^2 - r_p^2 - r_n^2 - \frac{3}{4m_p^2}$$

along with ^{1}H-^{2}H isotope shifts data

$$r_d^2 - r_p^2 = 3.82070(31)\ \text{fm}^2$$

Jentschura et al. ’11; Pachucki et al. ’18

can be used to extract r_n^2 !



Outline of the calculation

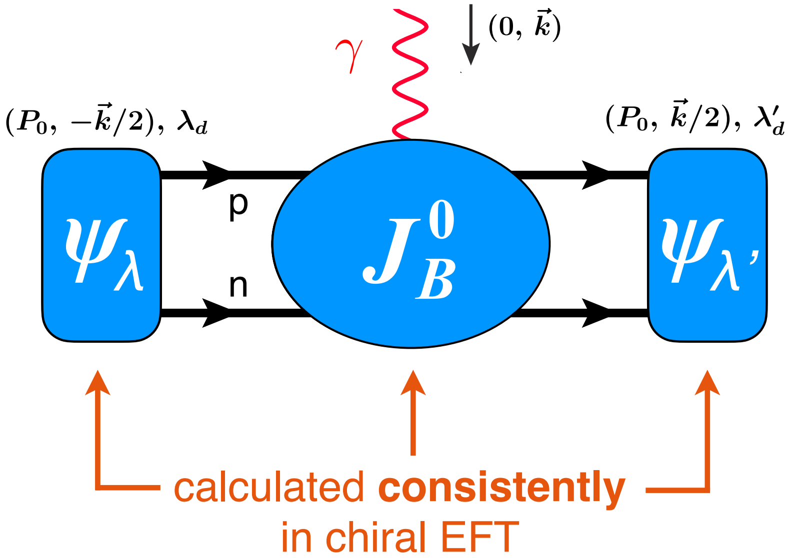
Calculation of the deuteron charge radius:

The deuteron charge radius is defined in terms of the charge form factor G_C

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

which can be computed as (in the Breit frame):

$$G_C(Q^2) = \frac{1}{3e}\frac{1}{2P_0}\sum_\lambda \langle P', \lambda | J_B^0 | P, \lambda\rangle$$



The matrix element is given by:

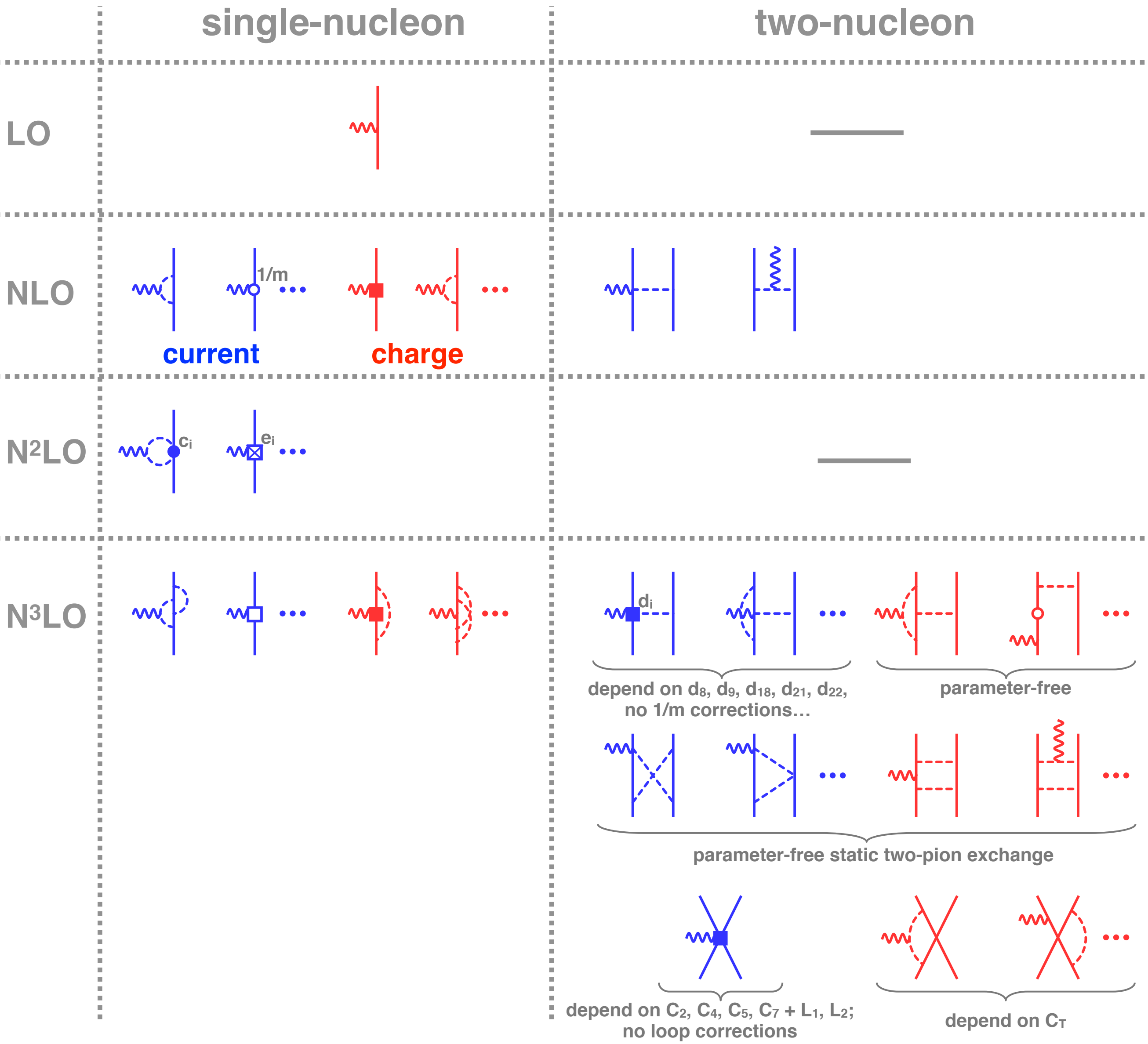
$$\frac{1}{2P_0}\langle P', \lambda' | J_B^\mu | P, \lambda\rangle = \int \frac{d^3 l_1}{(2\pi)^3}\frac{d^3 l_2}{(2\pi)^3}\, \psi_{\lambda'}^\dagger\left(\vec{l}_2 + \frac{\vec{k}}{4},\, \vec{v}_B\right) J_B^\mu\, \psi_\lambda\left(\vec{l}_1 - \frac{\vec{k}}{4},\, -\vec{v}_B\right)$$

Precision calculation of the deuteron charge radius in chiral EFT relies upon:

- — accurate, high-precision two-nucleon interactions
- — **consistent** charge density operator
- — careful error analysis

Nuclear electromagnetic currents

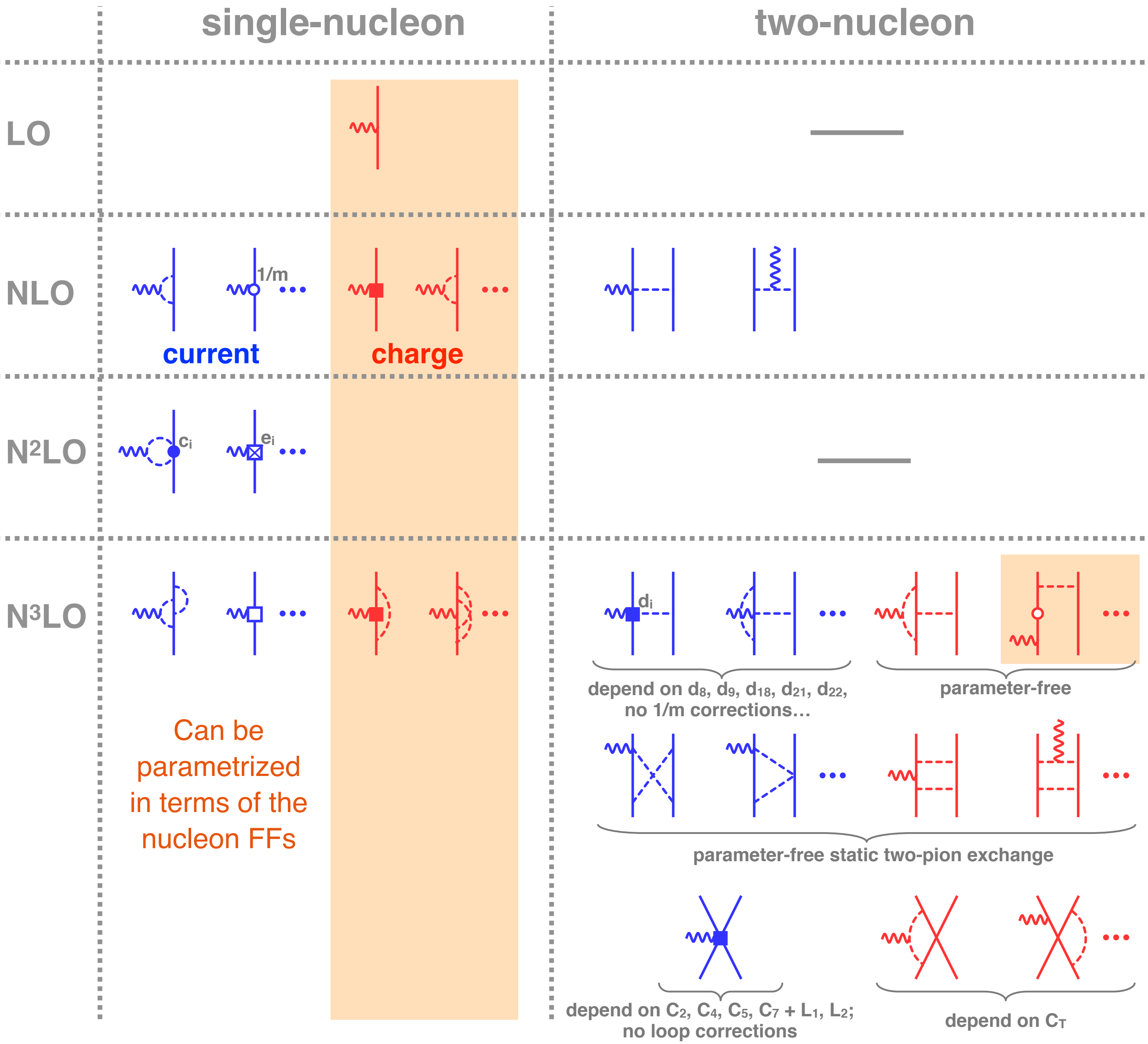
Kölling, EE, Krebs, Meißner, PRC 80 (09) 045502; PRC 86 (12) 047001; Krebs, EE, Meißner, FBS 60 (2019) 31



For review see:
H. Krebs, EPJA 56 (2020) 240

Nuclear electromagnetic currents

Kölling, EE, Krebs, Meißner, PRC 80 (09) 045502; PRC 86 (12) 047001; Krebs, EE, Meißner, FBS 60 (2019) 31



For review see:
H. Krebs, EPJA 56 (2020) 240

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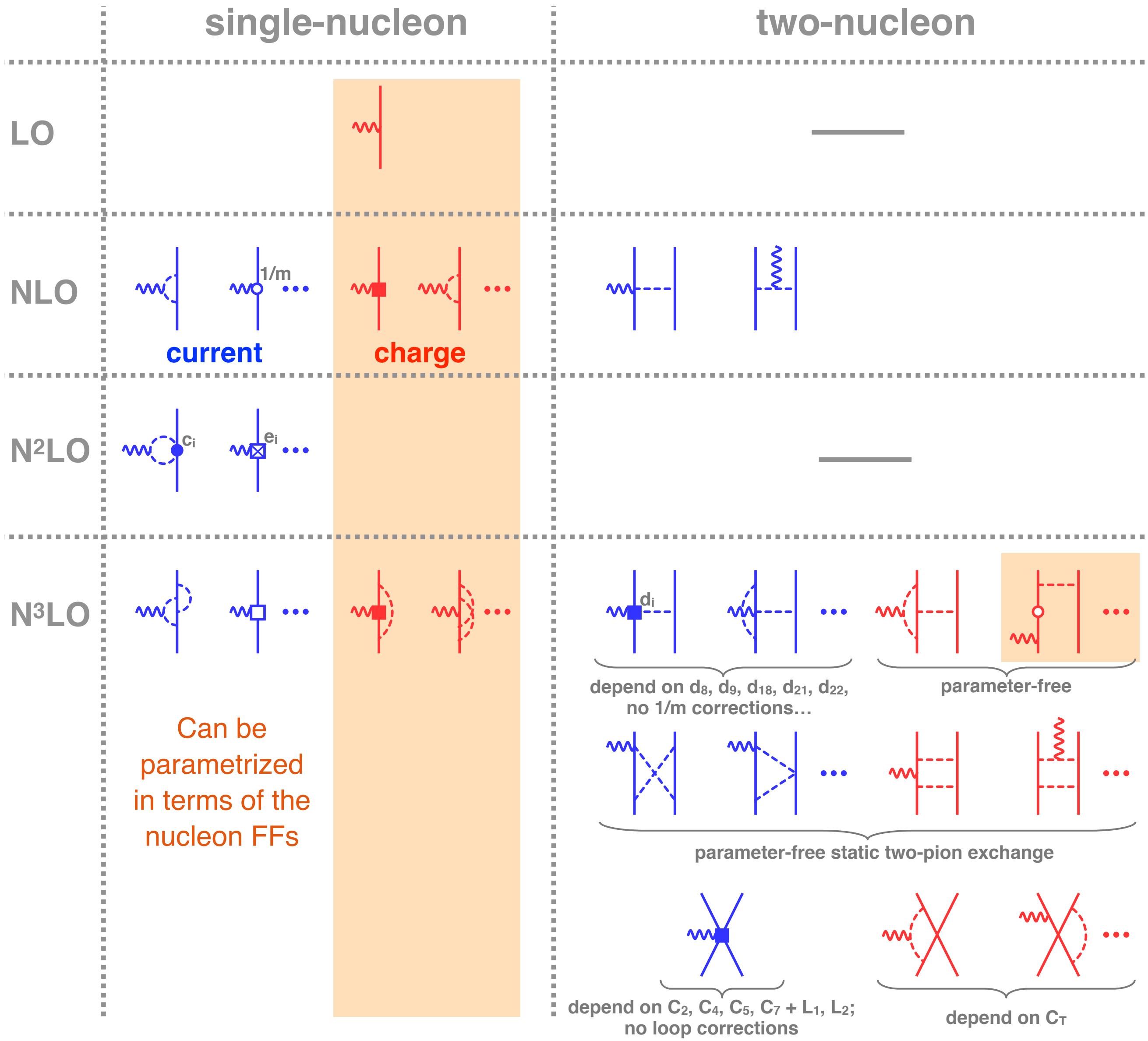

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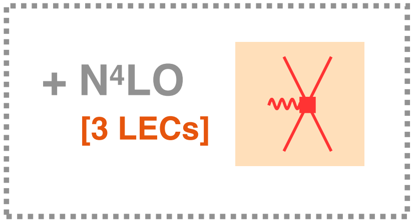
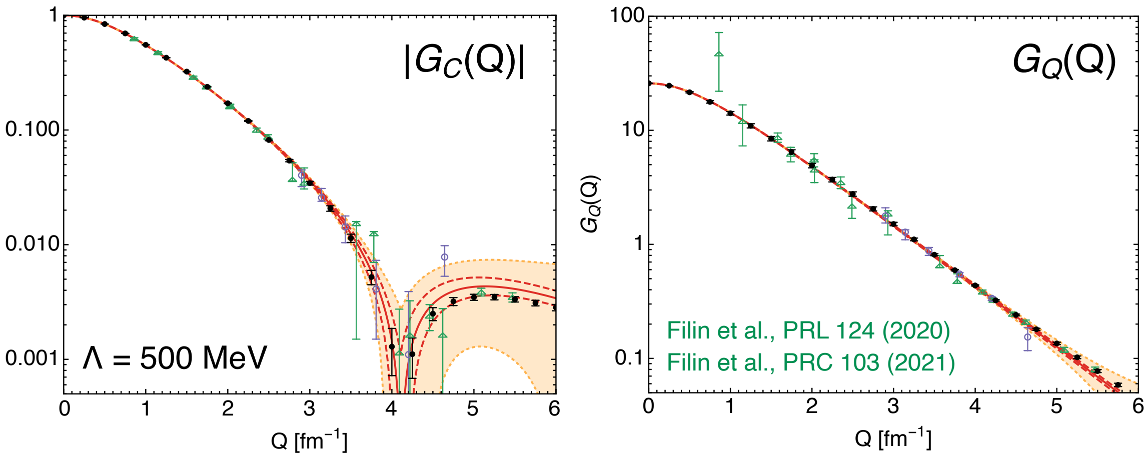


Deuteron charge and quadrupole FFs

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

The charge and quadrupole form factors of the deuteron at N⁴LO



The extracted structure radius and quadrupole moment:

$$r_{\rm str} = 1.9729^{+0.0015}_{-0.0012}\ \text{fm}$$

$$Q_{\rm d} = 0.2854^{+0.0038}_{-0.0017}\ \text{fm}^2$$

statistical and systematic errors due to the EFT truncation, choice of fitting range and πN LECs

The value of $Q_{\rm d}$ is to be compared with $Q_{\rm d}^{\rm exp} = 0.285\,699(15)(18)$ fm^2 Puchalski et al., PRL 125 (2020)

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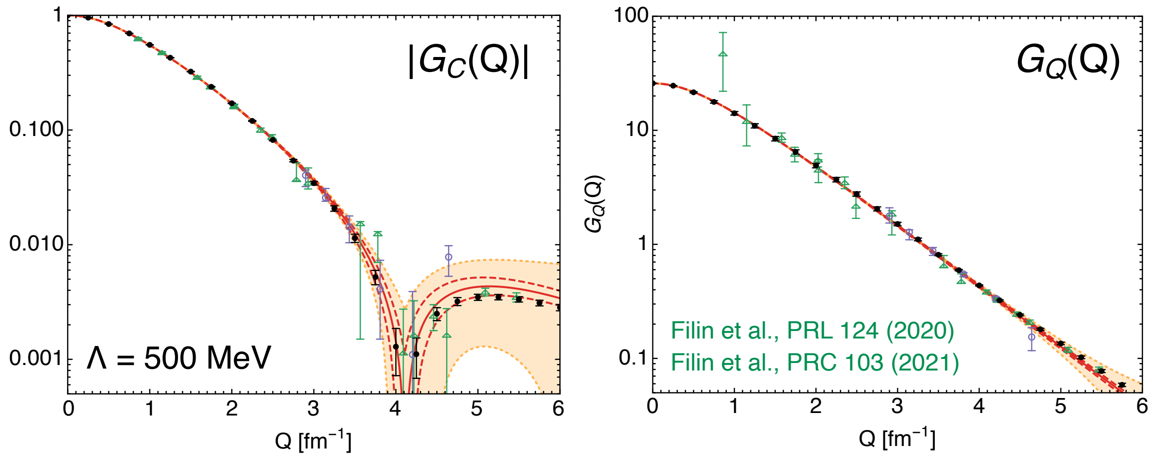

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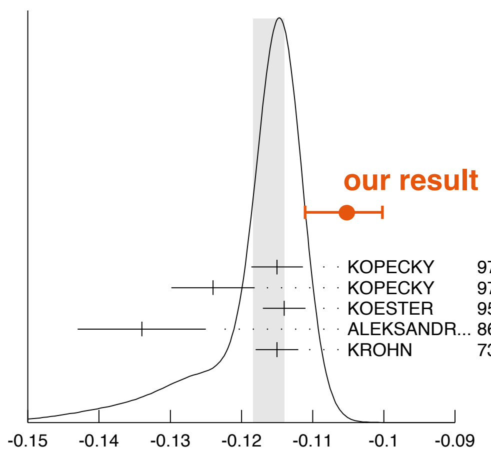
Combining our result for $r_{\rm str}^2 = r_d^2 - r_p^2 - r_n^2 - \dfrac{3}{4m_p^2}$ with the

¹H-²H isotope shift datum $r_d^2 - r_p^2 = 3.82070(31)\ \text{fm}^2$ leads

to the prediction for the neutron radius:

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



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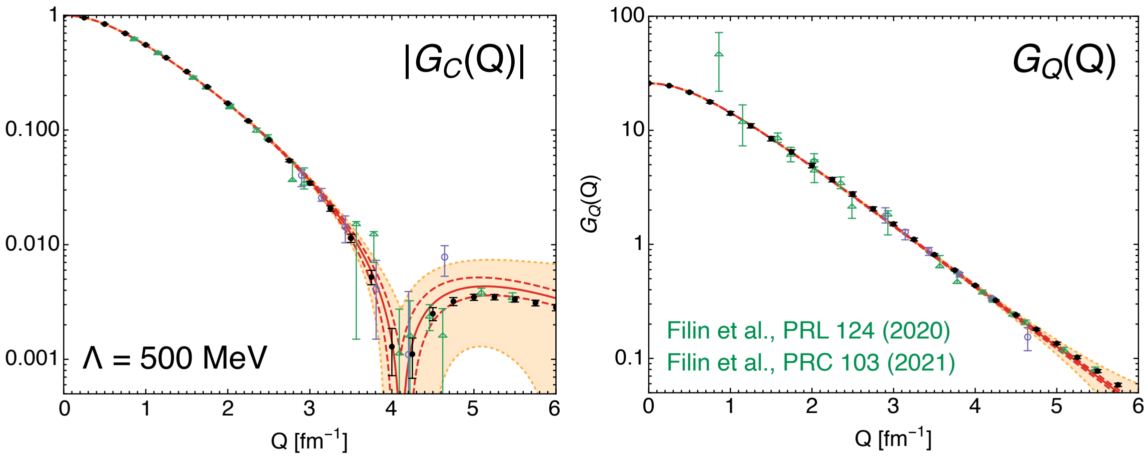

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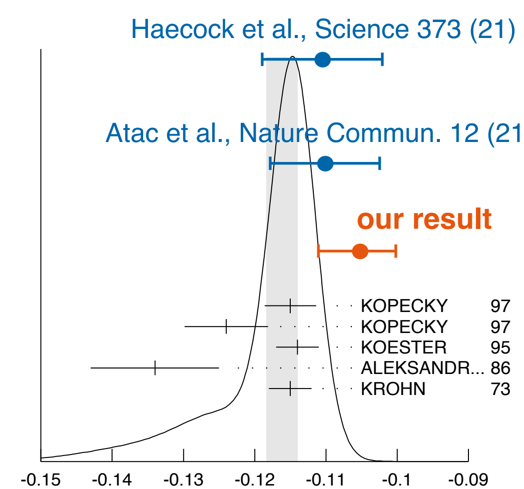


Preliminary results for the charge radius of A = 3,4 nuclei

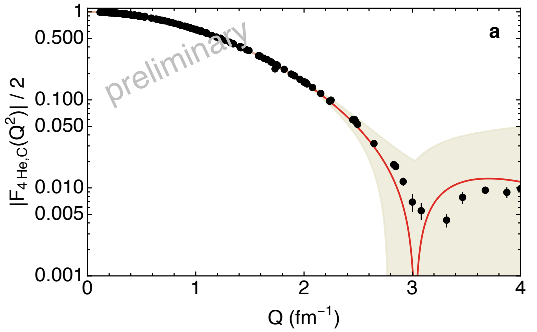
Arseniy Filin, Vadim Baru, EE, Christopher Körber, Hermann Krebs, Daniel Möller, Andreas Nogga, Patrick Reinert,
in preparation

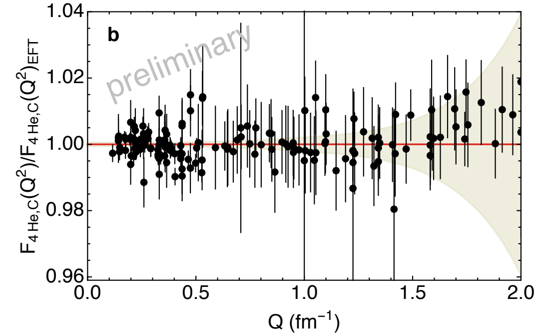
- precision test of the theory for ^{4}He
- focus on $T = 0$ nucleus (^{4}He) + isoscalar ^{3}H-^{3}He combination
- correlation between BE and r_{str} helps to account for missing 3NF beyond N^2LO
- theoretical prediction for the isoscalar ^{3}H-^{3}He charge radius 10 times more accurate than the current exp value — to be tested by CREMA soon!

Charge radii of light nuclei

Filin, Baru, EE, Körber, Krebs, Möller, Nogga, Reinert, in preparation

2 out of 3 LECs in the short-range 2N charge density already fixed from the ^{2}H FFs; the remaining one is determined from the ^{4}He FF (lots of low-energy data…) →





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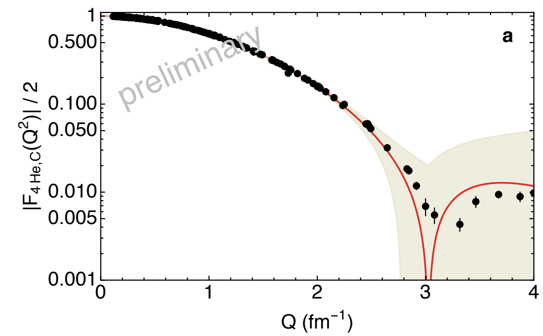
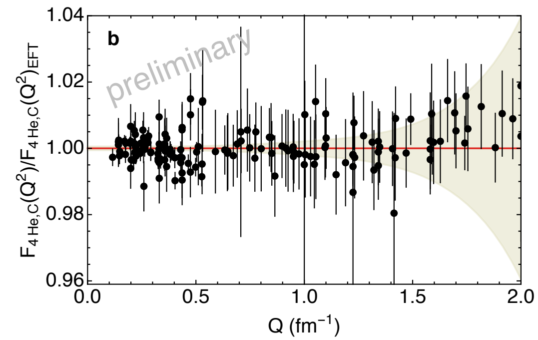


$$\boxed{r_{str}(^4He) = 1.4784 \pm 0.0030_{\text{trunc}} \pm 0.0013_{\text{stat}} \pm 0.0007_{\text{num}}\ fm}$$

preliminary; relativistic corrections still under investigation



$$\Rightarrow \quad \boxed{r_C(^4He) = 1.6798 \pm 0.0035\ fm}$$

using CODATA r_p and own determination of r_n

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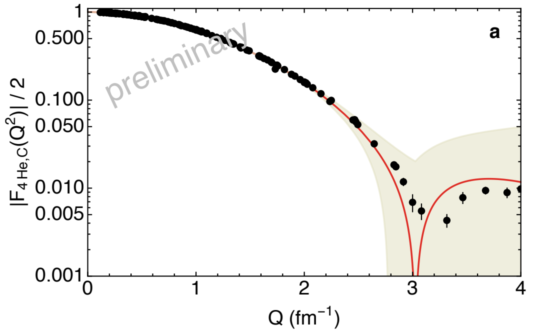

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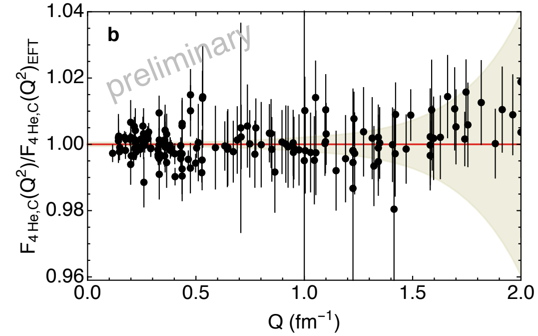

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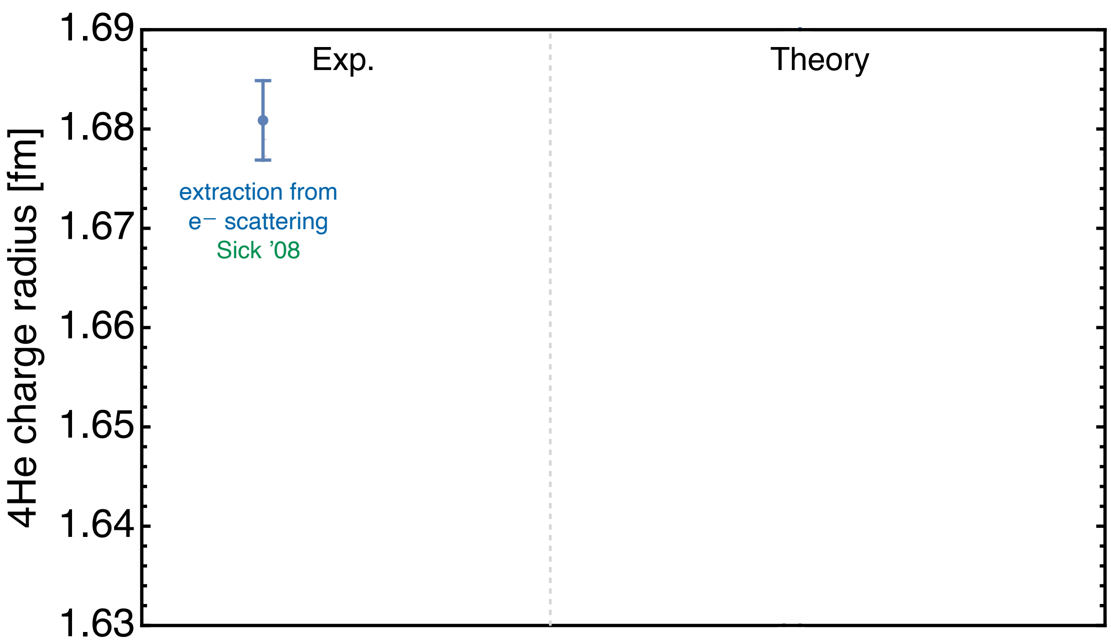

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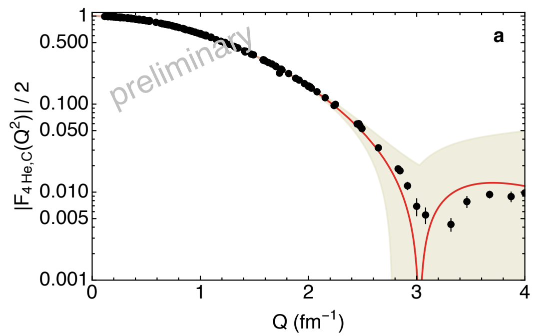

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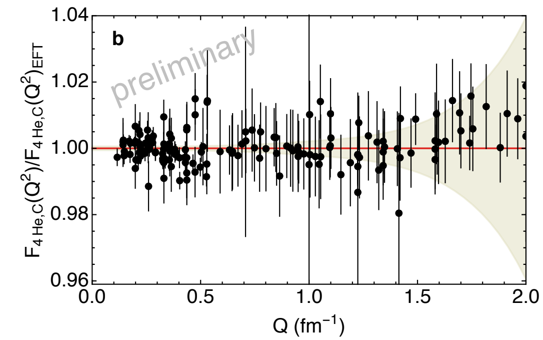

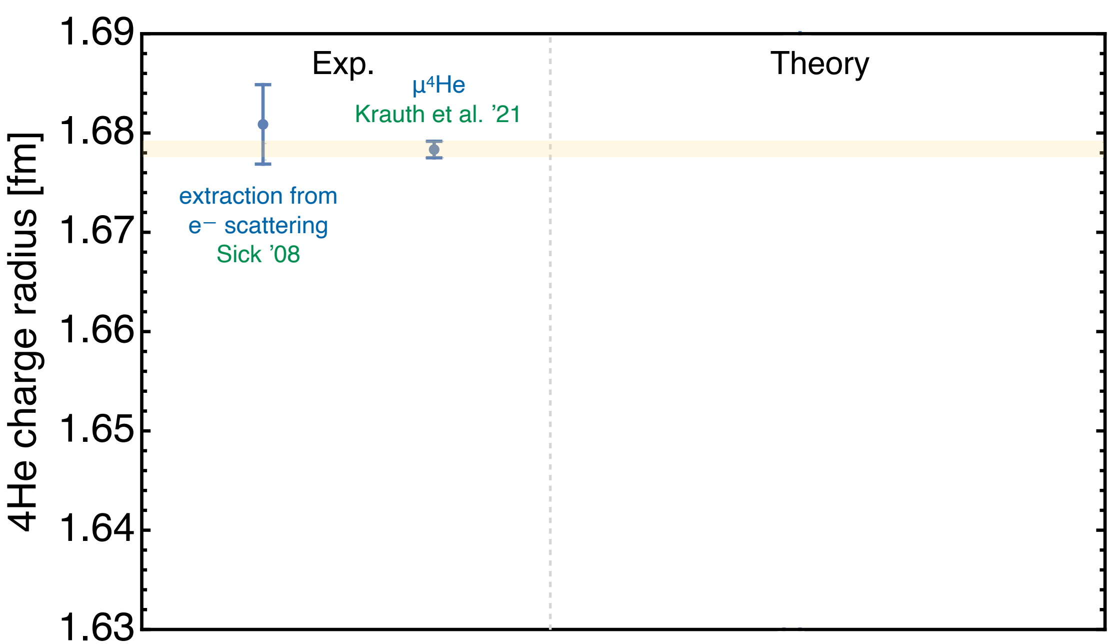

The μ 4He exp. value is:

$$r_C^{exp}(^4He) = (1.67824 \pm 0.00083)\, fm$$

Krauth et al., Nature 589 (2021) 7843, 527-531

Charge radii of light nuclei

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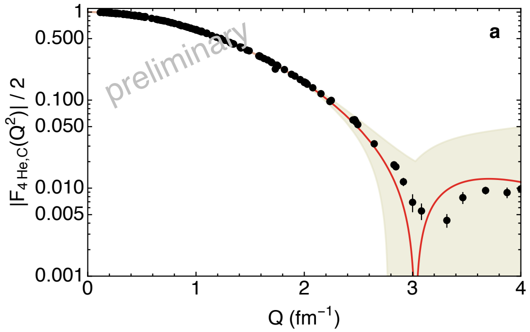

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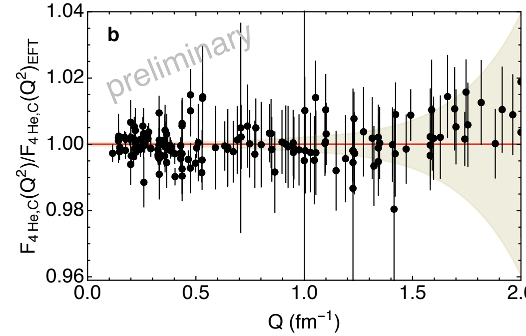

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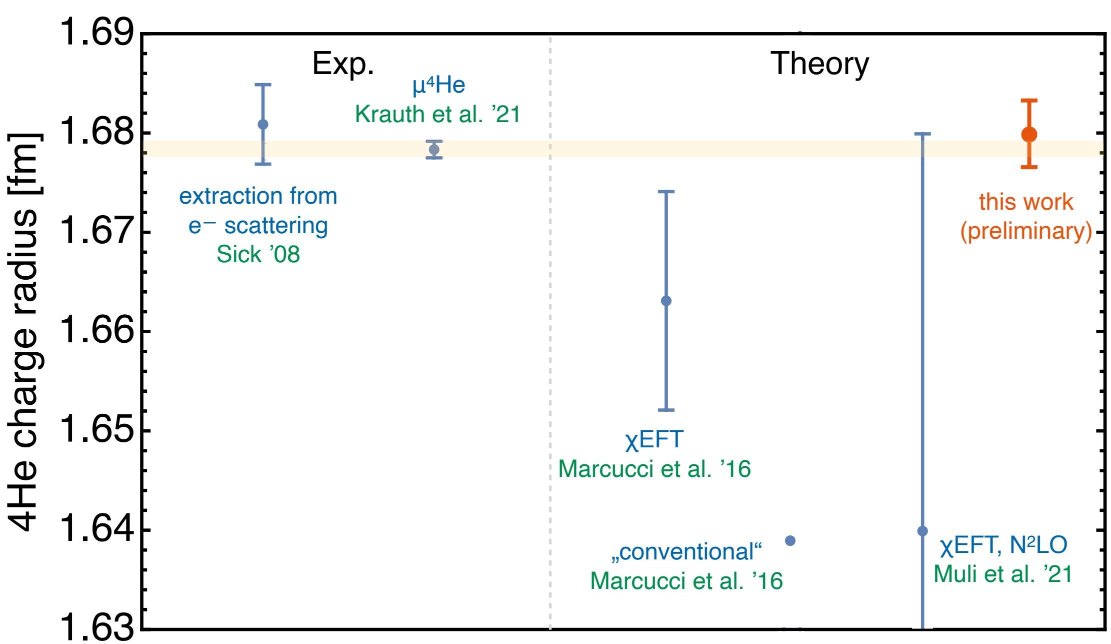

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Charge radii of light nuclei

Filin, Baru, EE, Körber, Krebs, Möller, Nogga, Reinert, in preparation

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

$$\boxed{r_C(3N_{\rm isoscalar}) \;=\; (1.9058 \pm 0.0026)\ \text{fm}}$$

preliminary, using CODATA-2018 r_p and own determination of r_n

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On the experimental side:

— the ^{3}H radius poorly known (5%) from e⁻ scattering exp.: $r_C^{^3\mathrm{H}} = (1.755 \pm 0.086)\, fm$

Amroun et al. '94 (world average)

— more (and more precise) measurements for ^{3}He

— e⁻ scattering experiments: $r_C^{^3\mathrm{He}} = (1.959 \pm 0.030)\, fm$ Amroun et al. '94 (world average)

$r_C^{^3\mathrm{He}} = (1.973 \pm 0.016)\, fm$ Sick '15 (world average)

— muonic ^{3}He (preliminary): $r_C^{^3\mathrm{He}} = (1.9687 \pm 0.0013)\, fm$ Pohl '22

⇒ the current exp. value for the isoscalar radius: $\boxed{r_C^{\exp}(3N_{\text{isoscalar}}) \;=\; (1.903 \pm 0.029)\ \text{fm}}$

Charge radii of light nuclei

Filin, Baru, EE, Körber, Krebs, Möller, Nogga, Reinert, in preparation

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$\Rightarrow$ the current exp. value for the isoscalar radius: $\boxed{r_C^{\rm exp}(3N_{\rm isoscalar}) \;=\; (1.903 \pm 0.029)\ \mathrm{fm}}$

The ongoing T-REX experiment in Mainz [Pohl et al.] aims at measuring $r_C^{^3\mathrm{H}}$ with $\pm 0.0002\, fm$, which would determine the isoscalar radius with $\pm 0.0009\, fm$ $\Rightarrow$ precision tests of nuclear chiral EFT!

Summary and outlook

The 2N sector

- statistically perfect description of NN scattering data at N^{4}LO$^+$

Heavier systems

- accuracy currently limited to N^{2}LO: 3NF need to be rederived using symmetry preserving cutoff regularization (work in progress)

Precision calculations of the charge radii of $A \leq 4$ nuclei

- Deuteron:
  - determined $r_{\rm str}$ (0.1% accuracy) and Q_d (1.4% accuracy)
  - combined with isotope-shift data, extracted the neutron radius

- ^{4}He: the extracted r_C (0.2% accuracy) agrees with the new μ^4He data

- ^{3}H-^{3}He: predicted the isoscalar r_C (0.1% accuracy) in agreement with the current exp. value (10 times bigger errors). The T-REX experiment in Mainz will allow for a precision test of nuclear chiral EFT

MEC contribution increases from ~0.3% for ^{2}H to ~3% for ^{4}He! Heavier nuclei in progress…