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Precision calculations of charge radii of light nuclei

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in collaboration with

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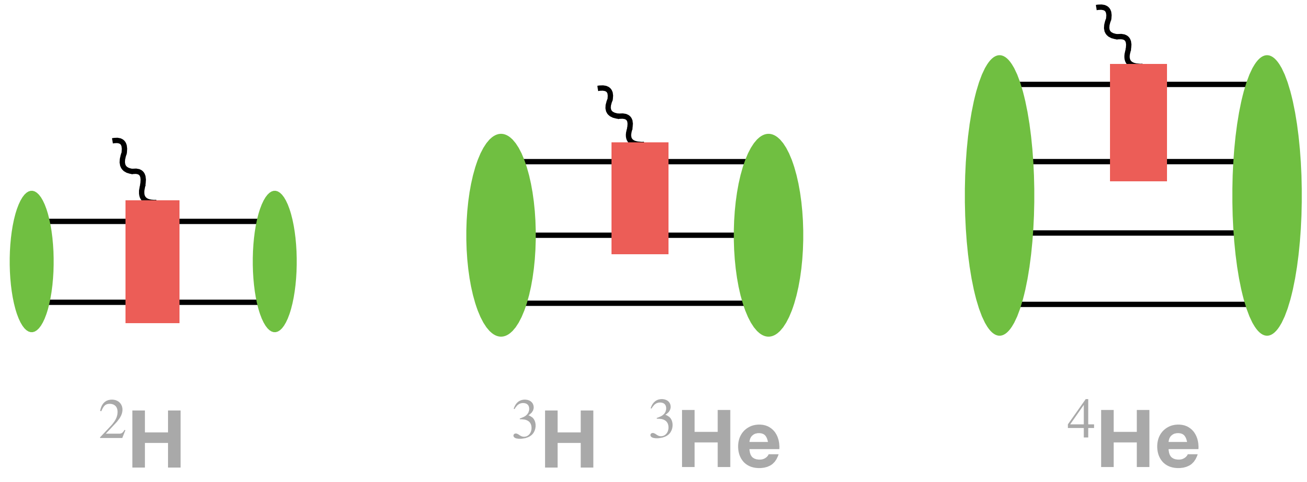
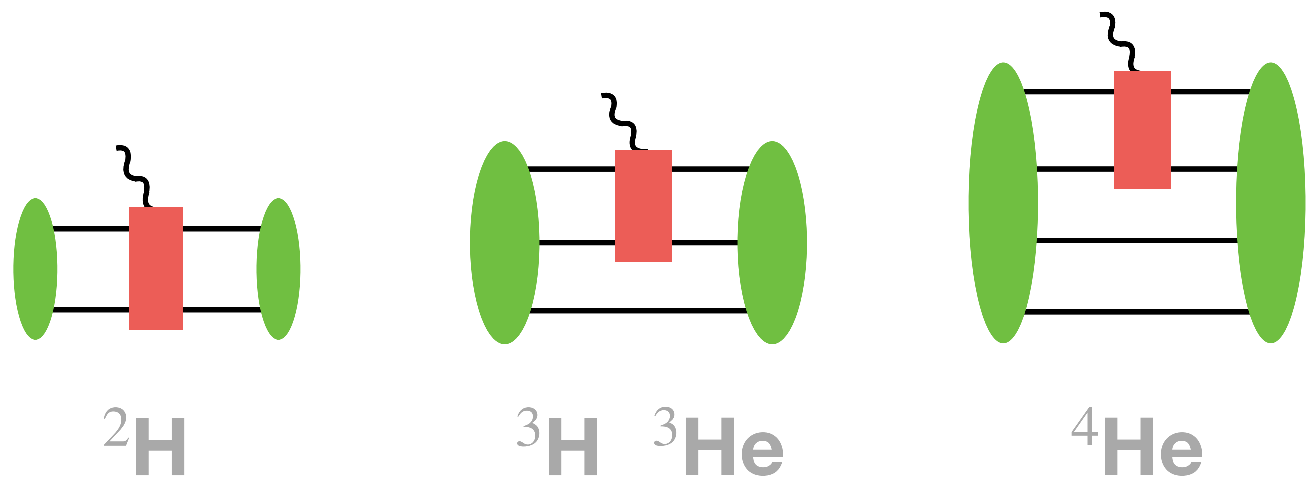


PRL 124 082501 (2020)
Phys.Rev.C 103 024313 (2021)

Precision calculations of charge radii of light nuclei



Motivation:

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

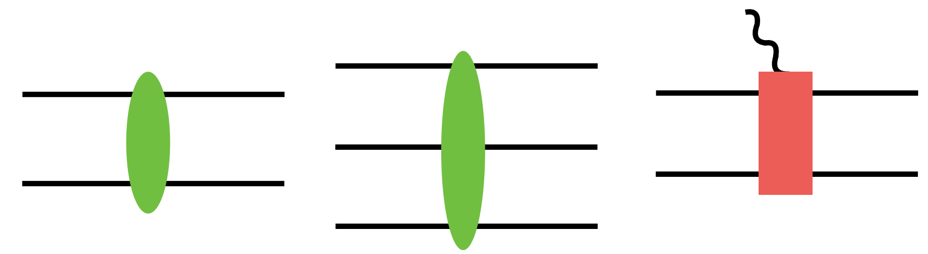
- Help to resolve long-standing issue with **underpredicted radii of medium-mass and heavy nuclei**

- More applications:
  - A new way to **extract the neutron and the proton charge radii** from few-nucleon data
  - Search for **Beyond-Standard-Model** physics

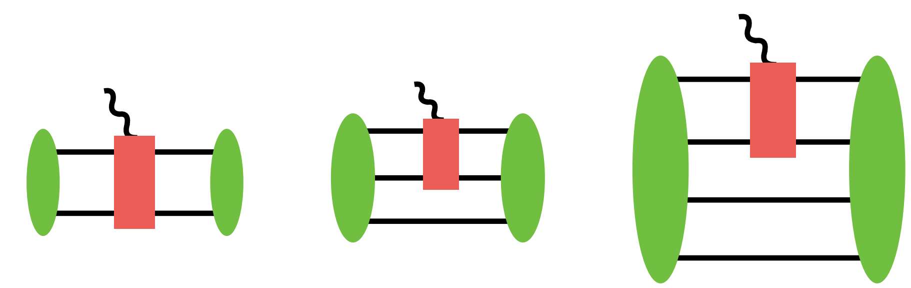
Precision calculations of charge radii of light nuclei

Introduction

- precision measurements of charge radii A<=4
- precision and accuracy of chiral EFT

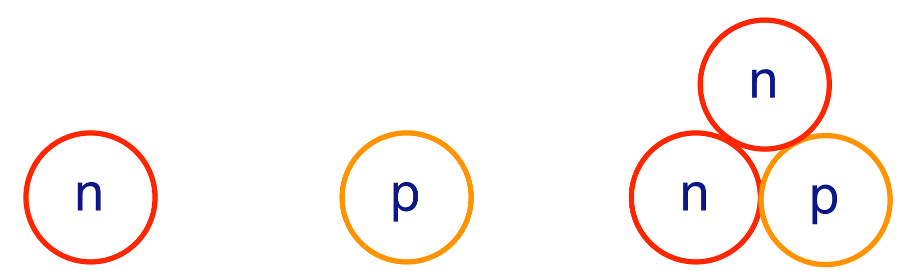


Results for A=2,3,4 charge form factors and radii



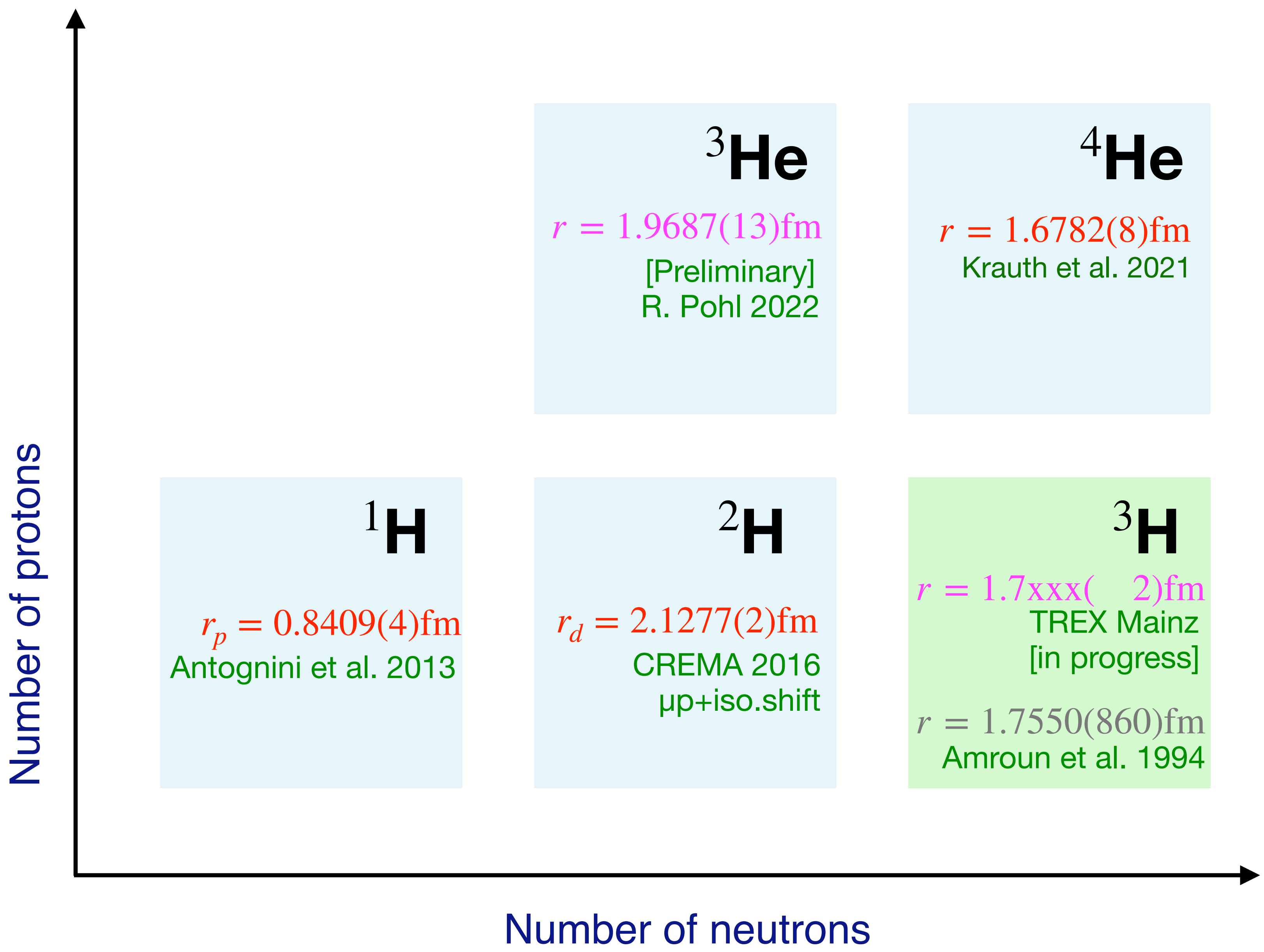
Applications and tests

- extraction of the neutron and proton charge radii
- predictions for 3N structure radii



Takeaway from A=2,3,4 calculations

Precision measurements of charge radii for A = 1, 2, 3, 4 nuclei



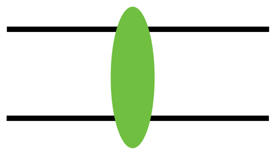
Pohl:2013yb,
CREMA:2016idx,
Pohl:2016glp,
Schmidt:2018kjc,
Krauth:2021foz
...

Data from isotope shift

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

Pachucki et al. 2018
Jentschura et al. 2011

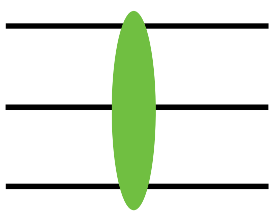
Chiral effective field theory - **precise, accurate** and **consistent**



N^4LO^+

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

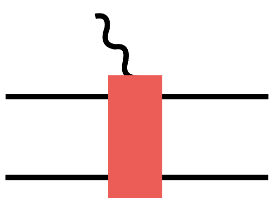
- Nearly perfect description of pp and pn scattering data up to pion production threshold



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, **talk by Hermann**



N^2LO

Isoscalar: N^4LO^-

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

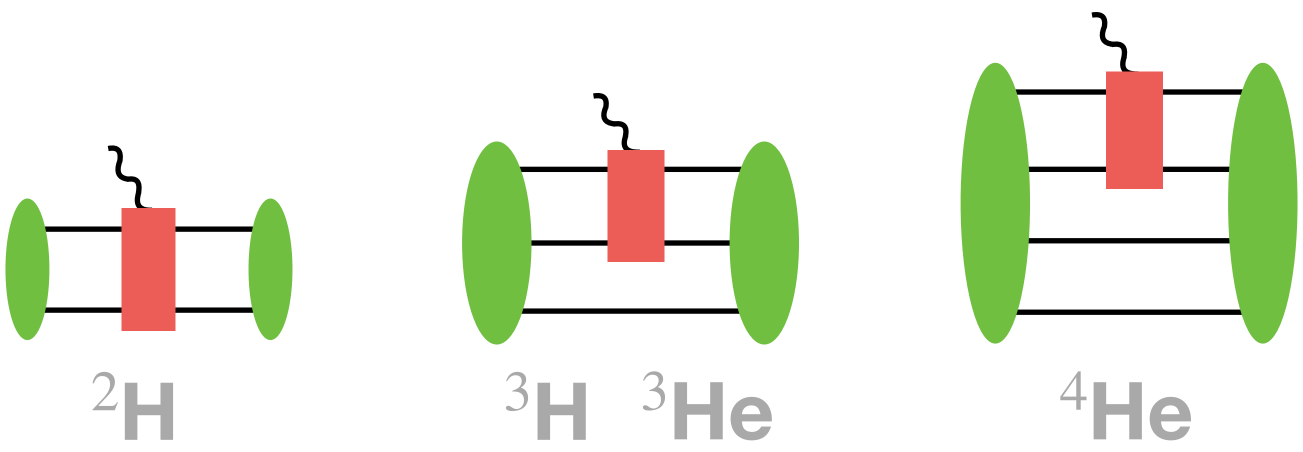
- N^2LO (**isoscalar N^4LO^-**) is derived and regularised consistently with the chiral NN forces
- Consistent regularisation of N^3LO (isovector) is in progress

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

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), ...

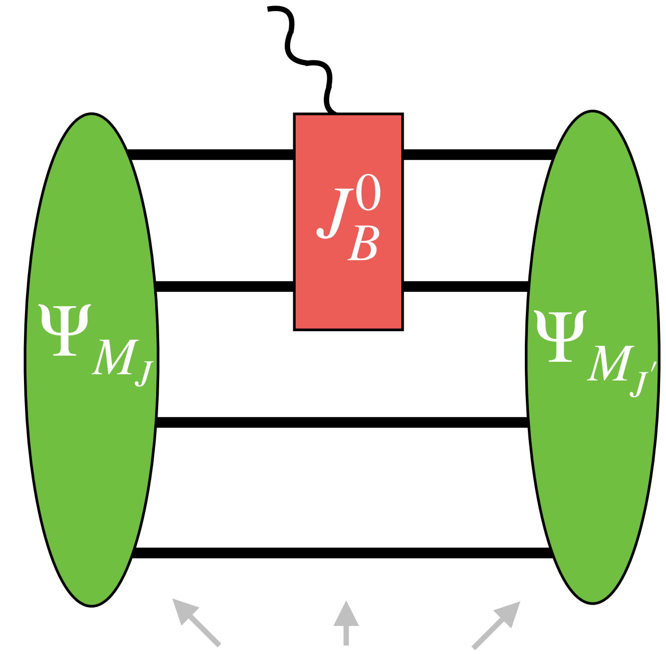
Chiral EFT calculation of charge radii



Goals:

- **consistent** calculation of **isoscalar** charge radii of A = 2, 3, 4 nuclei
- **aim at N^{4}LO level of accuracy** even when not all forces are available at N^{4}LO
- careful estimation of uncertainties (truncation, statistical, incompleteness of 3NFs, ...)

Chiral EFT calculation of the nuclear charge radius



calculated **consistently**

in chiral EFT

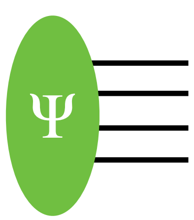
Charge radius r_C is related to the charge form factor $F_C(Q)$

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

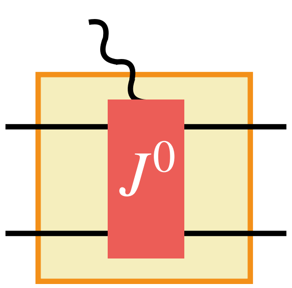
Charge form factor F_C can be computed (in the Breit frame) as

$$F_C(Q^2) = \frac{1}{2J+1}\sum_{M_J} < P', M_J | J_B^0 | P, M_J >$$

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

Wave functions of A=2,3,4 nuclei

A=2,3,4 wave functions - solutions of Schrödinger / FY equations in the partial wave basis

— 2N forces at N^4LO^+

— 3N forces at N^2LO LECs cD and cE (N^2LO) are fitted to RIKEN Nd DCS data and ^3He binding energy

Extra 3N forces at N^4LO:

— added selected 3NF at N^4LO (cE1 or cE3) (tree-level & regularised consistently)

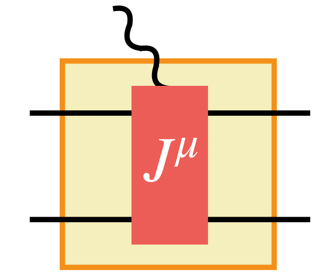
— fitted LEC cE1 **or** cE3 to exactly reproduce ^4He physical BE

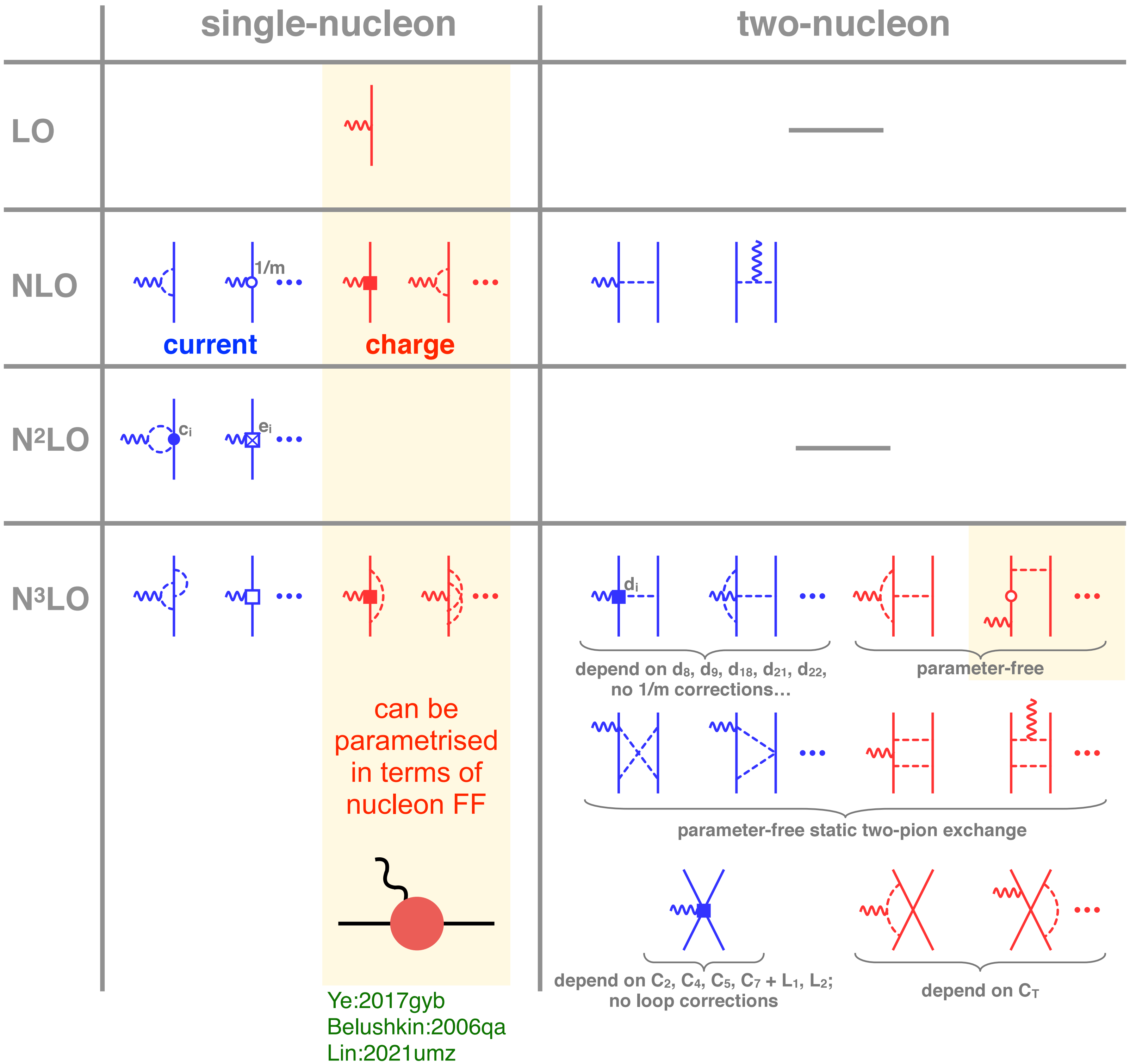
In progress

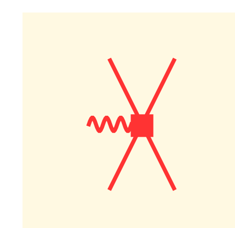
— relativistic treatment of 3N and 4N equations (talk by Anderas)

Nuclear electromagnetic currents

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





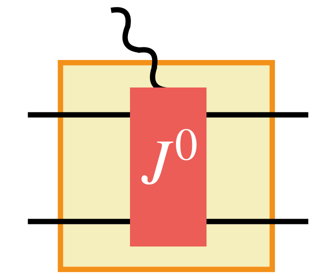


depend on **3 LECs**
$^3S_1$-$^3S_1$ - can be fitted to deuteron FF data
$^3S_1$-$^3D_1$ - this one too
$^1S_0$-$^1S_0$ - can be fitted to ^{4}He FF data

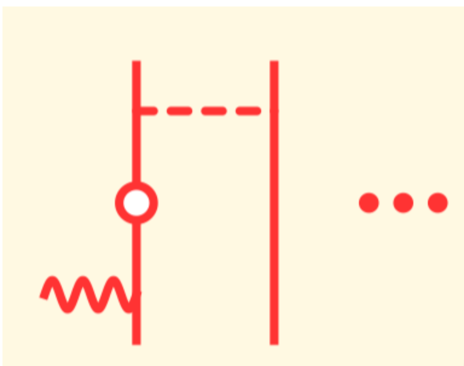
Chen, Rupak, Savage '99;
Phillips '07
AF et al. '20

three-nucleon isoscalar charge operators are beyond N⁴LO

2N Charge density operators (N^{3}LO)



Isoscalar 2N one-pion exchange charge density



— **parameter free**

— **regularised consistently** with NN forces

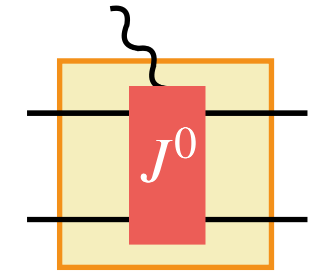
— **local** operator (simple PWD)

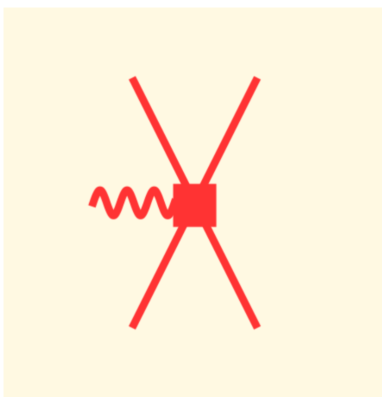
— depends on the off-shell parameters β_8, β_9

β_8, β_9 are chosen consistently with NN potential and checked

$$\rho_{2\mathrm{N}}^{1\pi,\,\mathrm{reg}} = (1-2\bar{\beta}_9) G_{\mathrm{E}}^{S}(Q^2) \frac{e g_A^2}{16 F_\pi^2 m_N} (\boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_2) \frac{(\boldsymbol{\sigma}_1 \cdot \boldsymbol{k})(\boldsymbol{\sigma}_2 \cdot \boldsymbol{q}_2)}{\boldsymbol{q}_2^2 + M_\pi^2} \exp\left(-\frac{\boldsymbol{q}_2^2 + M_\pi^2}{\Lambda^2}\right)$$
$$+ (2\bar{\beta}_8 - 1) G_{\mathrm{E}}^{S}(Q^2) \frac{e g_A^2}{16 F_\pi^2 m_N} (\boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_2)(\boldsymbol{\sigma}_1 \cdot \boldsymbol{q}_2)(\boldsymbol{\sigma}_2 \cdot \boldsymbol{q}_2)(\boldsymbol{q}_2 \cdot \boldsymbol{k}) \left(\frac{1}{\left(\boldsymbol{q}_2^2 + M_\pi^2\right)^2} + \frac{1}{\Lambda^2 \left(\boldsymbol{q}_2^2 + M_\pi^2\right)}\right) \exp\left(-\frac{\boldsymbol{q}_2^2 + M_\pi^2}{\Lambda^2}\right)$$

2N Charge density operators (N^3LO)





Isoscalar 2N contact charge density

— **3 LECs** which we fit to reproduce the deuteron and 4He form factors

— **regularised consistently** with NN forces

— **separable** operator (also simple PWD)

$$\rho_{\rm Cont} = 2eG_{\rm E}^{S}(\boldsymbol{k}^2)\Big[\Big(A+B+\frac{C}{3}\Big)\frac{\boldsymbol{\sigma}_1\cdot\boldsymbol{\sigma}_2+3}{4}\,\frac{1-\boldsymbol{\tau}_1\cdot\boldsymbol{\tau}_2}{4}\boldsymbol{k}^2$$

$^3S_1$-$^3S_1$ LEC

$$+\,C\,\frac{1-\boldsymbol{\tau}_1\cdot\boldsymbol{\tau}_2}{4}\Big((\boldsymbol{k}\cdot\boldsymbol{\sigma}_1)(\boldsymbol{k}\cdot\boldsymbol{\sigma}_2)-\frac{1}{3}\boldsymbol{k}^2(\boldsymbol{\sigma}_1\cdot\boldsymbol{\sigma}_2)\Big)$$

$^3S_1$-$^3D_1$ LEC

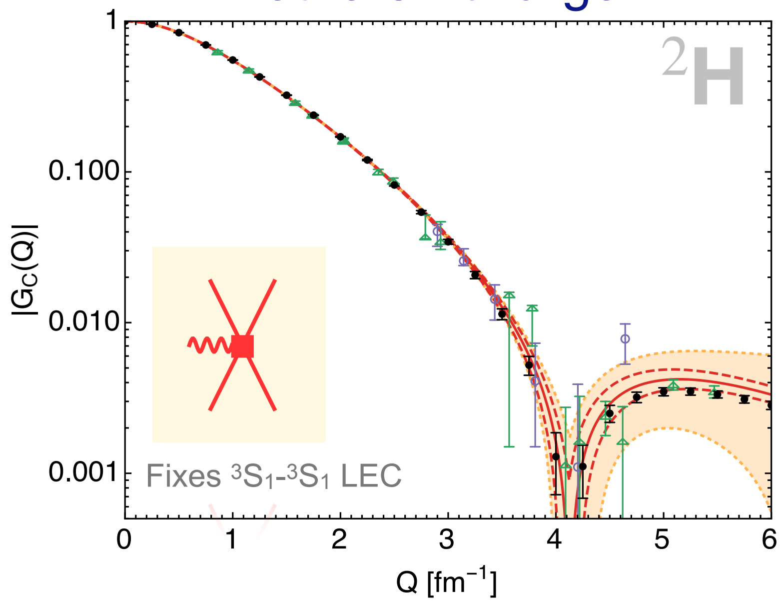
$$+\,(A-3B-C)\,\frac{1-\boldsymbol{\sigma}_1\cdot\boldsymbol{\sigma}_2}{4}\,\frac{\boldsymbol{\tau}_1\cdot\boldsymbol{\tau}_2+3}{4}\boldsymbol{k}^2\Big]$$

$^1S_0$-$^1S_0$ LEC

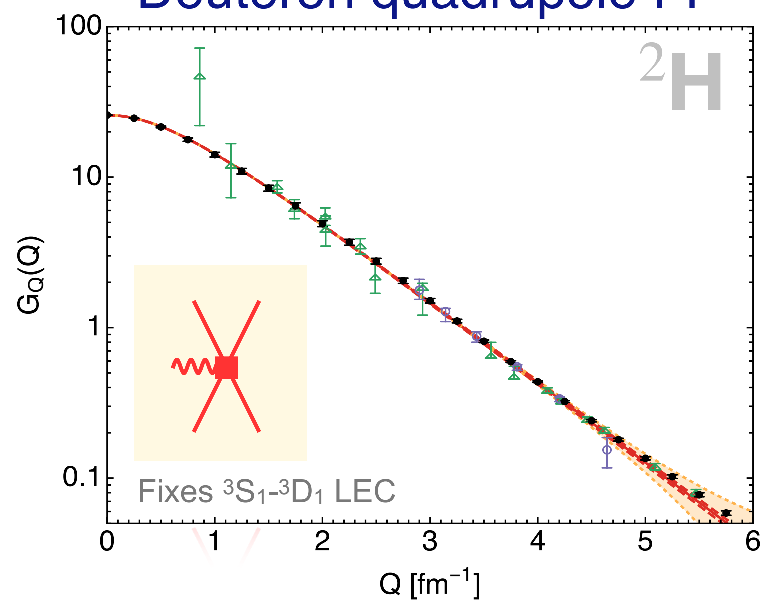
(regulator not shown)

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

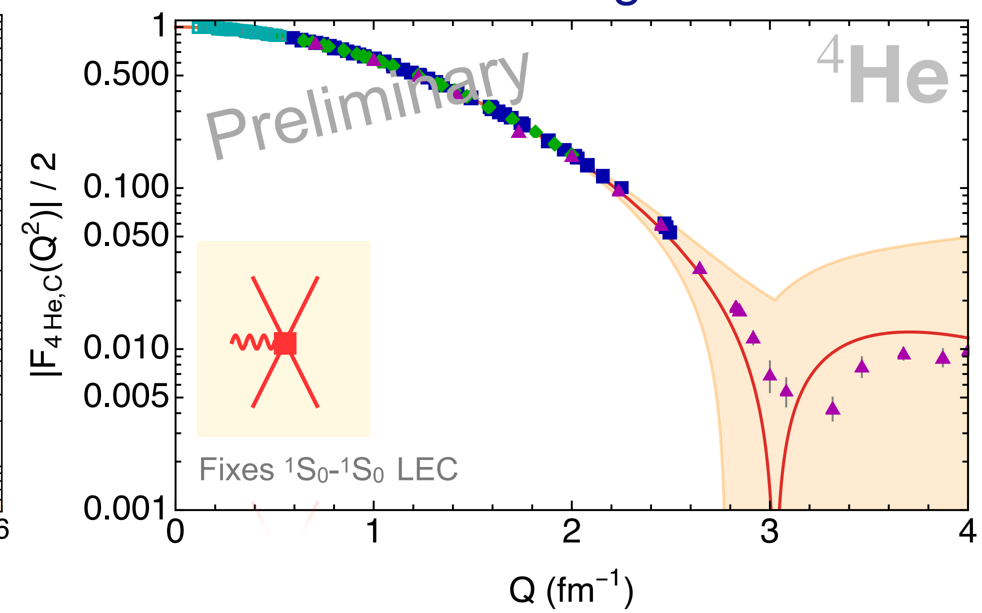
Deuteron charge FF

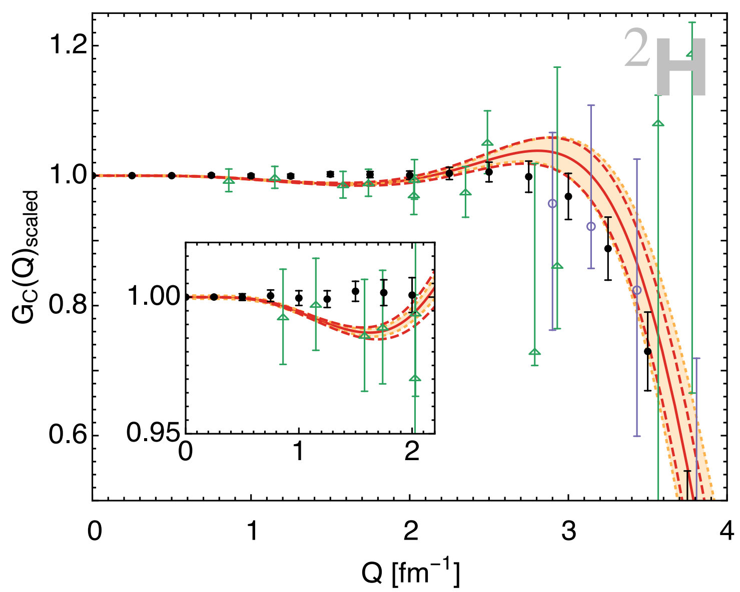


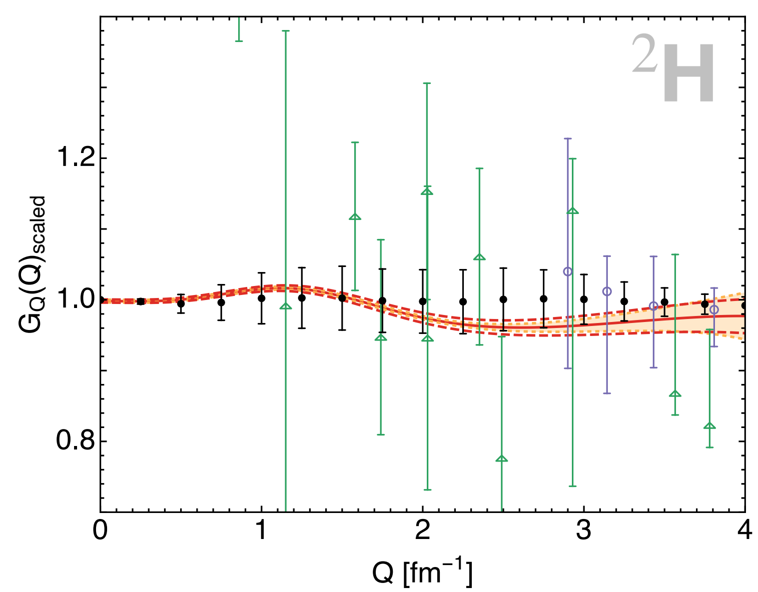
Deuteron quadrupole FF

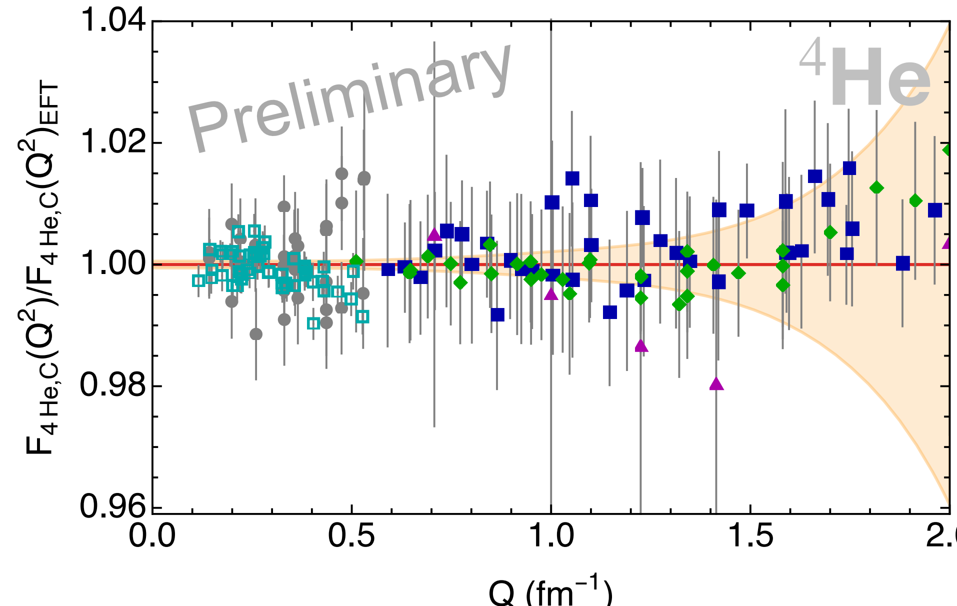


4He charge FF









^{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 LECs in J^0 are fixed from the form factor data of deuteron and ^{4}He

Parameter-free prediction of structure radii

After all three LECs in charge density operators are fixed we get predictions for the structure radii

$$r_{str}(^2\mathbf{H}) = 1.9729 \pm 0.0006_{\rm trunc}\,{}^{+0.0012}_{-0.0008\,\rm stat}\,fm$$

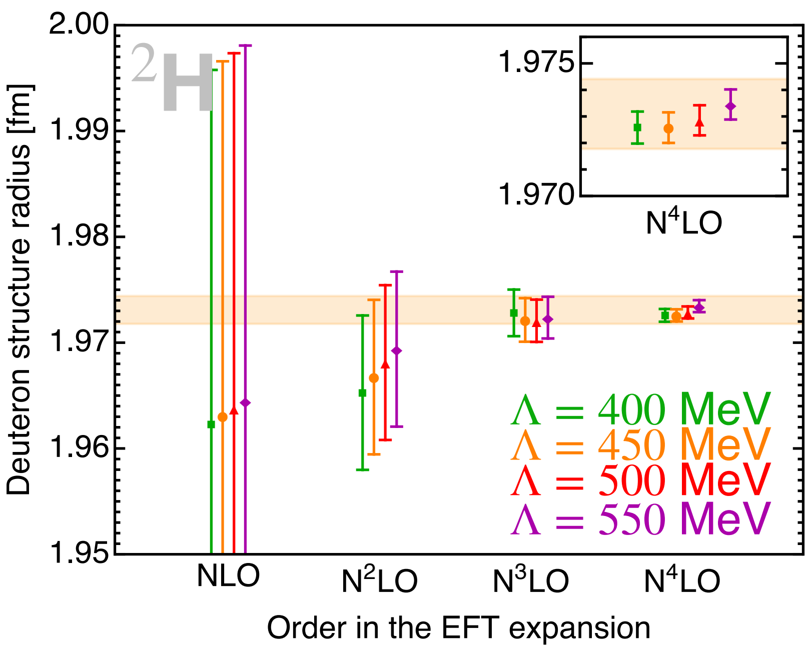
AF, Möller, Baru, Epelbaum, Krebs, Reinert, PRL 124 (2020) 082501; PRC 103 (2021) 024313

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

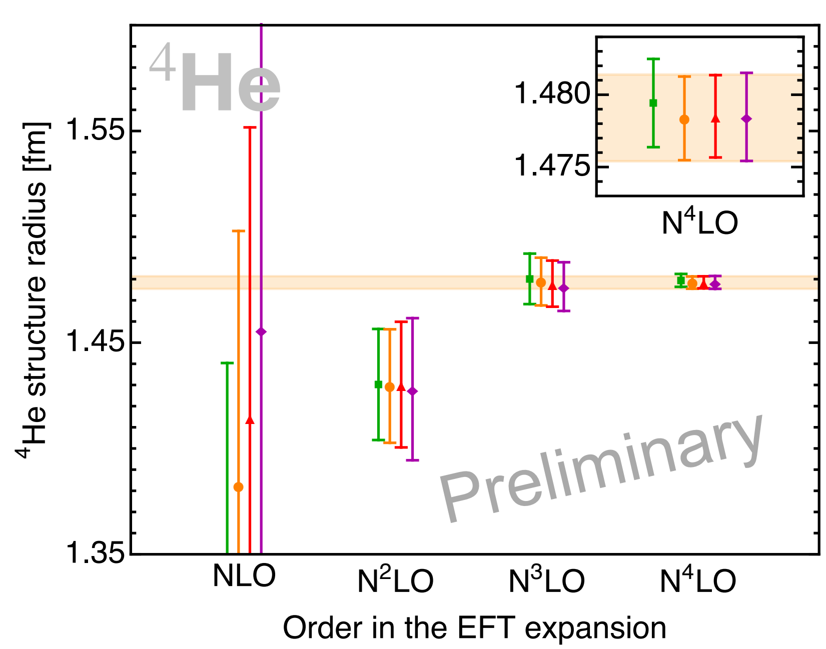
$$r_{str}(\mathbf{Isoscalar\ 3N}) = 1.7309 \pm 0.0020_{\rm trunc} \pm 0.0006_{\rm stat} \pm 0.0002_{\rm iso-v} \pm 0.0003_{\rm num}$$ (Preliminary)

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

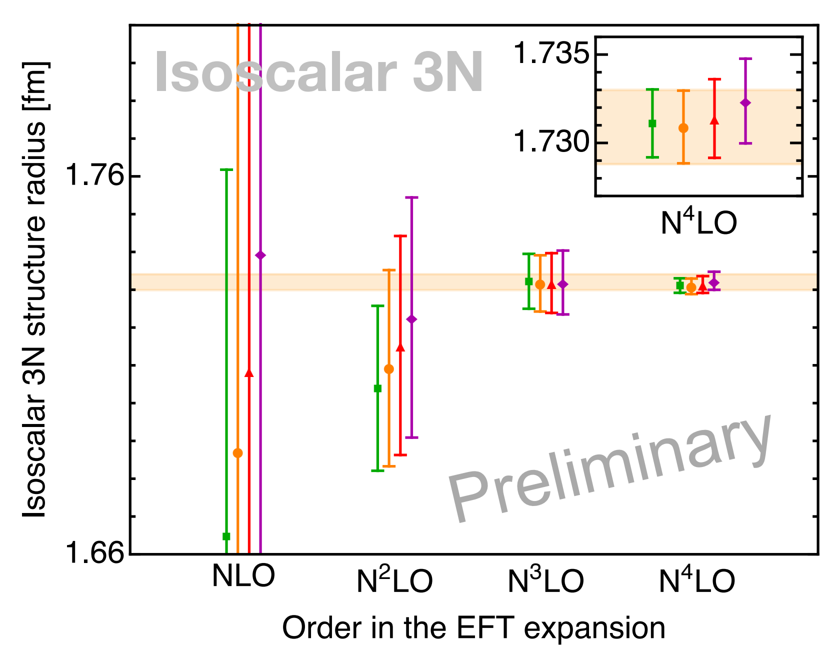
Deuteron structure radius



4He structure radius



Isoscalar 3N structure radius



error bands = χEFT truncation uncertainty

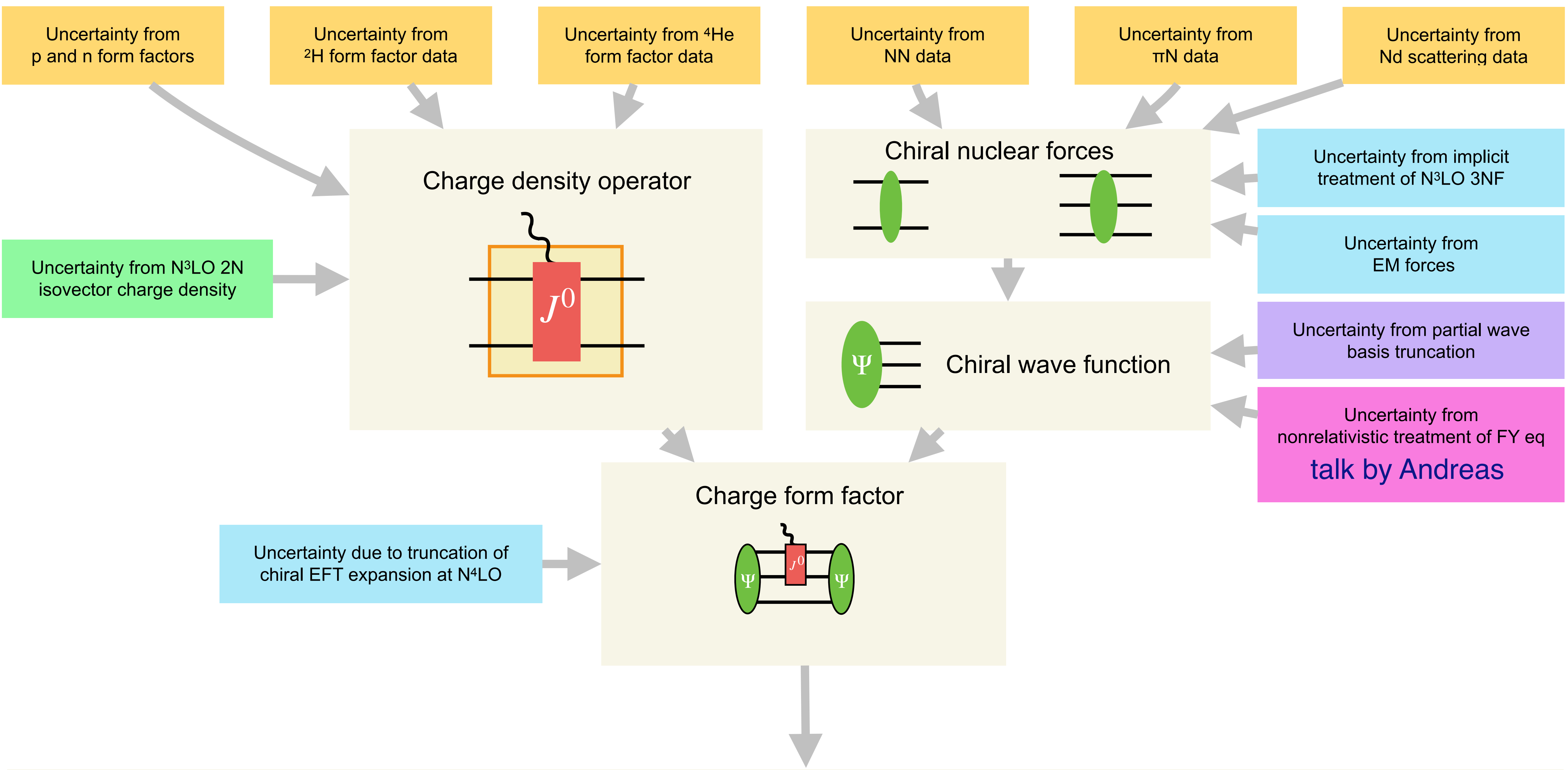
orange band = our prediction ± total uncertainty

Chiral EFT expansion converges well

Regulator dependence is smaller than the truncation uncertainty

Extensive uncertainty analysis

Propagation of uncertainties from data and theory



Uncertainty of the structure radius

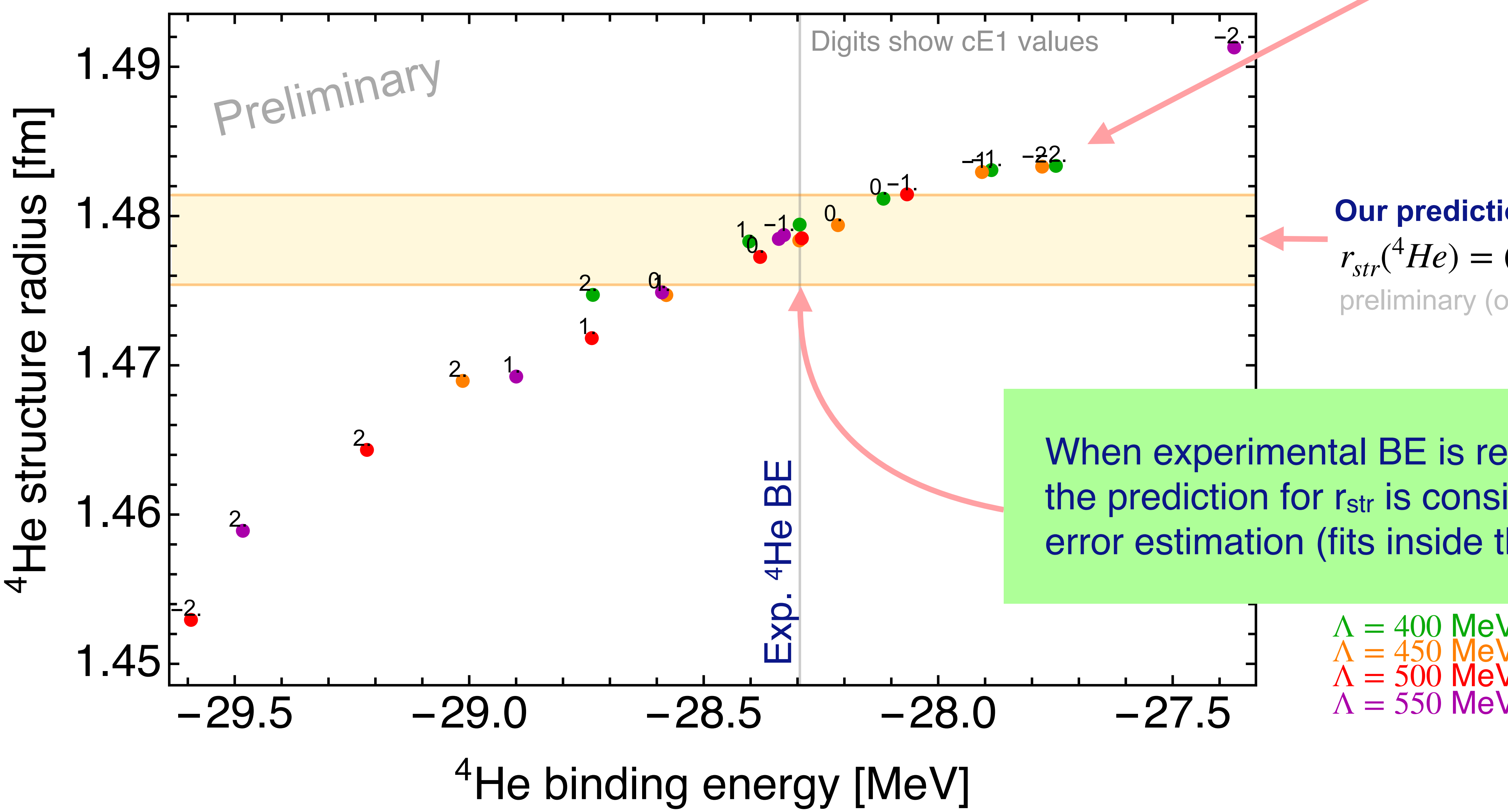
$$r_{str}(\mathrm{Isoscalar3N}) = 1.7309 \pm 0.0020_{\mathrm{trunc}} \pm 0.0006_{\mathrm{stat}} \pm 0.0002_{\mathrm{iso-v}} \pm 0.0003_{\mathrm{num}} \quad ?$$

(Preliminary)

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

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

^{4}He structure radius vs BE



^{4}He **binding energy** and $\mathbf{r_{str}}$ are **strongly correlated**!

Our prediction for ^{4}He structure radius:

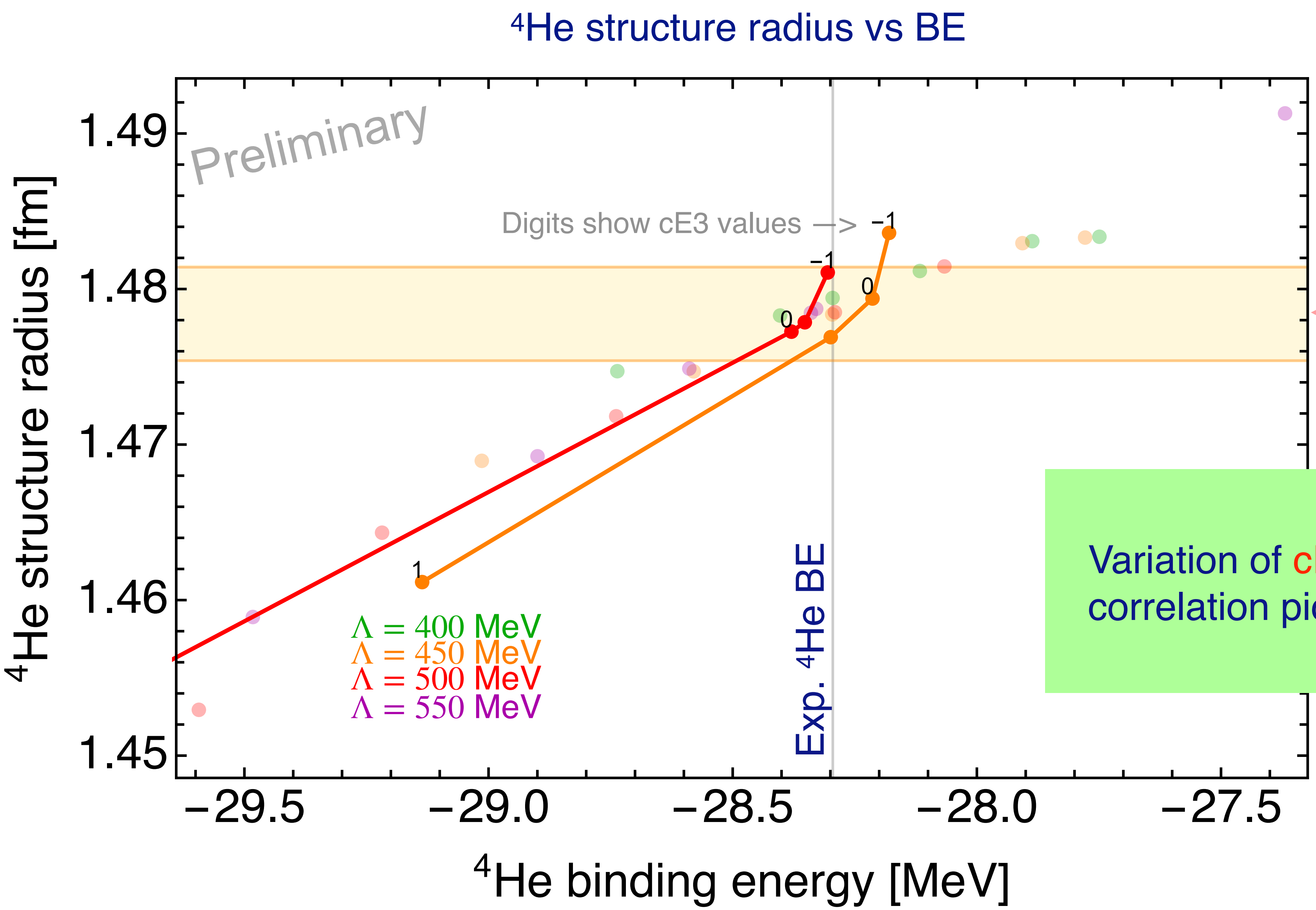
$$r_{str}(^4He) = (1.4784 \pm 0.0030_{trunc})\, fm$$

preliminary (only truncation error is shown)

When experimental BE is reproduced the prediction for r_{str} is consistent with our error estimation (fits inside the orange band)

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

using variation of **cE3** (N^4LO 3NF LEC)



Our prediction for ^{4}He structure radius:

$$r_{str}(^4He) = (1.4784 \pm 0.0030_{trunc})\,fm$$

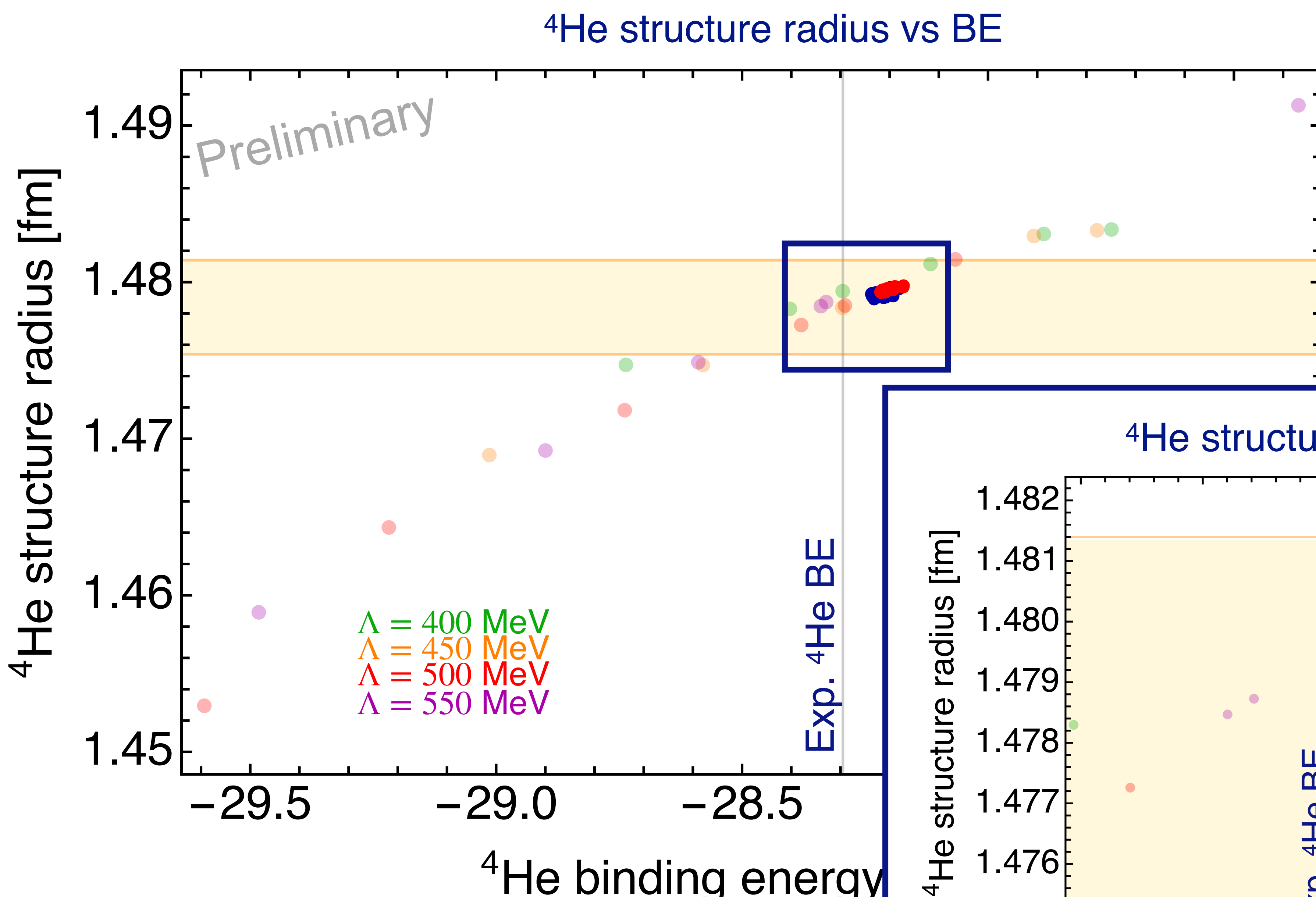
preliminary (only truncation error is shown)

Variation of cE3 LEC produces same correlation picture as variation of cE1

r-BE correlations help to precisely extract r_{str} even with incomplete 3NF!

Propagation of uncertainty from πN and NN LECs

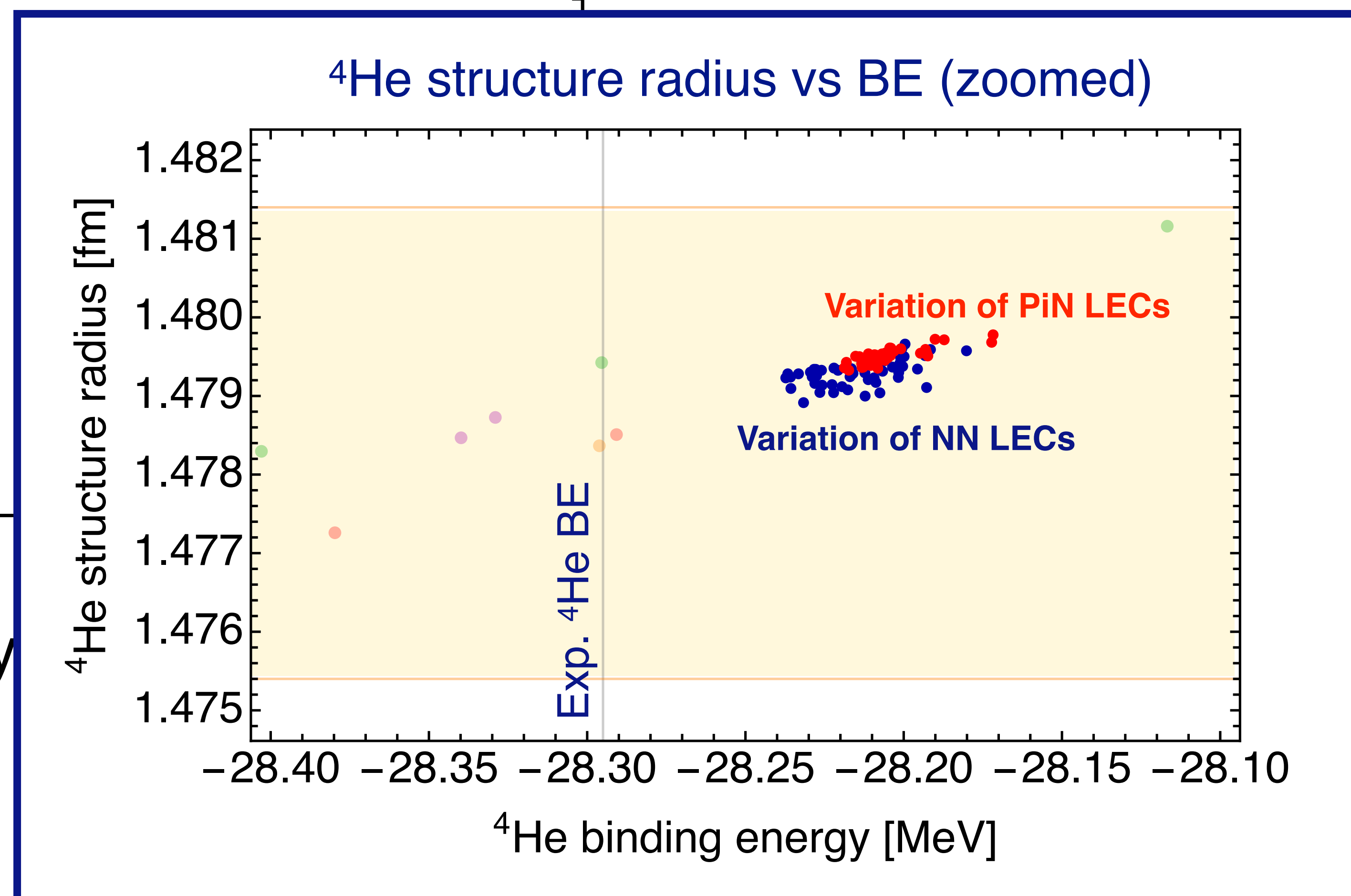
Prepared **50 sets of NN LECs** and **50 sets of piN LECs** correlation information from NN and RS analysis
Full calculation is repeated from scratch for each set



Notes:

Deuteron BE is always re-fitted

^{4}He BE is not fine-tuned (computational expensive)



Small uncertainty from πN and NN LECs

Applications

Relation between charge and structure radii

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

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

We focus on isoscalar A=2,3,4 radii

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

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

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

Some applications of the accurate **χEFT calculation** of the **nuclear structure** radii:

— extract proton and neutron charge radii from precisely measured nuclear charge radii

— **predict** other nuclear charge radii

Extraction of the neutron charge radius

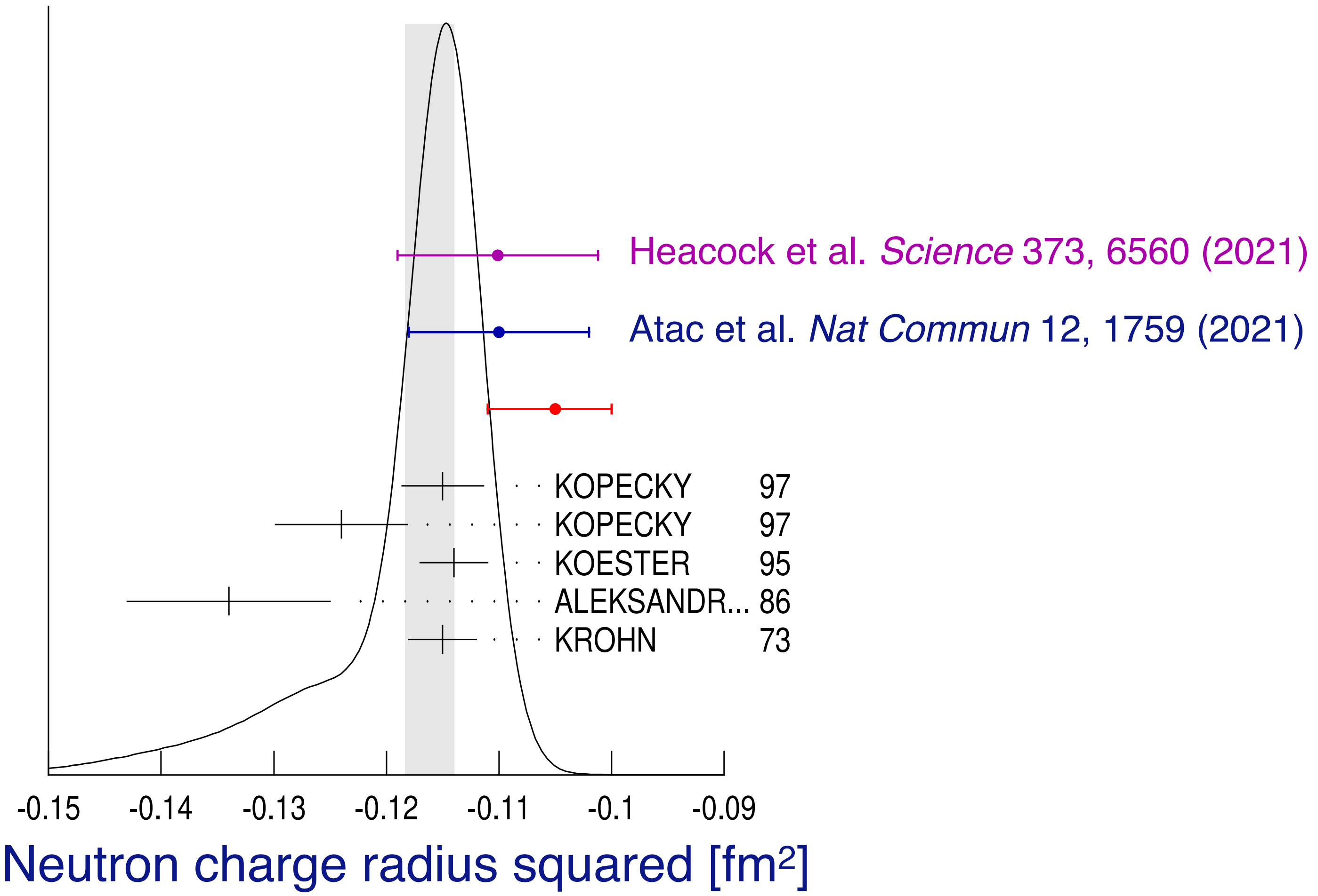
$$r_d^2 = r_{str}^2(^2\text{H}) + \left(r_p^2 + \frac{3}{4m_p^2}\right) + r_n^2 \quad \rightarrow \quad r_n^2 = (r_d^2 - r_p^2) - \frac{3}{4m_p^2} - r_{str}^2$$

$r_{str} = 1.9729^{+0.0015}_{-0.0012} fm$
our prediction

Extraction of the neutron radius from $(r_d^2 - r_p^2) = 3.82070(31) fm^2$ (atomic spectroscopy + QED corrections)

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

~2σ deviation from the PDG (2020) weighted average $r_n^2 = -0.1161(22) fm^2$



Neutron charge radius in PDG 2022

Citation: R.L. Workman *et al.* (Particle Data Group), to be published (2022)

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: effective field theory and experiment

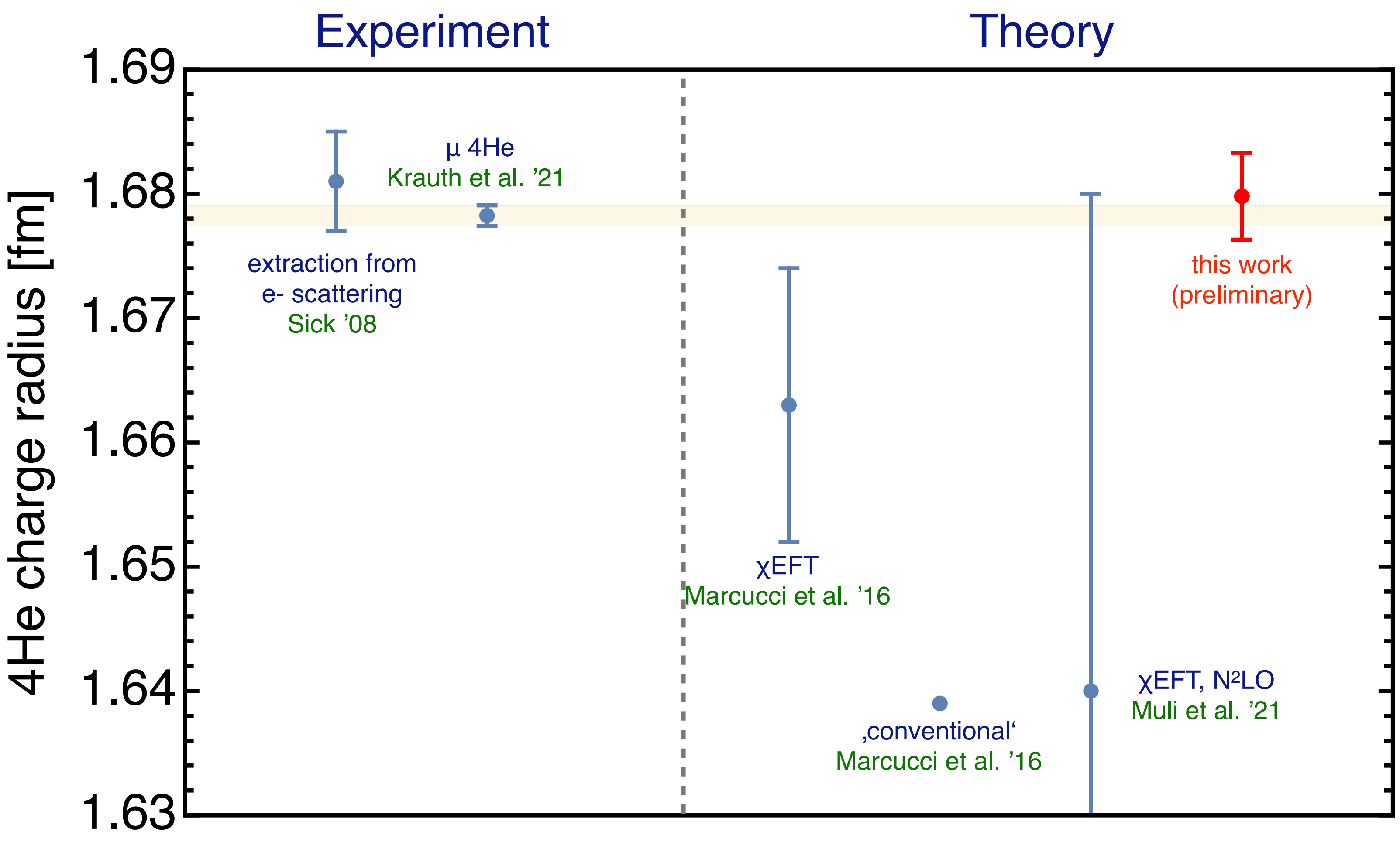
$$r_C(^4\mathbf{He}) = r_{str}^2(^4\mathbf{He}) + \left(r_p^2 + \frac{3}{4m_p^2}\right) + r_n^2$$

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

$$r_C(^4\mathbf{He}) = (1.6798 \pm 0.0035)\, fm$$

preliminary, using CODATA 2018 r_p and own determination of r_n

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



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

Indications of BSM physics in ^{4}He ?

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 BSM physics in ^{4}He at this accuracy level

Isoscalar nucleon charge radius from experimental ^{4}He charge radius

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

^{4}He charge radius experimental data

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

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

New method of determination

of the isoscalar nucleon charge radius

$$(r_n^2 + r_p^2) = (0.597 \pm 0.009)\, fm$$

preliminary

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

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

preliminary

Proton charge radius from isoscalar nucleon radius

Our determination of the

isoscalar nucleon charge radius from ^{4}He

$$(r_n^2 + r_p^2) = (0.597 \pm 0.009)\, fm^2$$ preliminary

Our determination of the

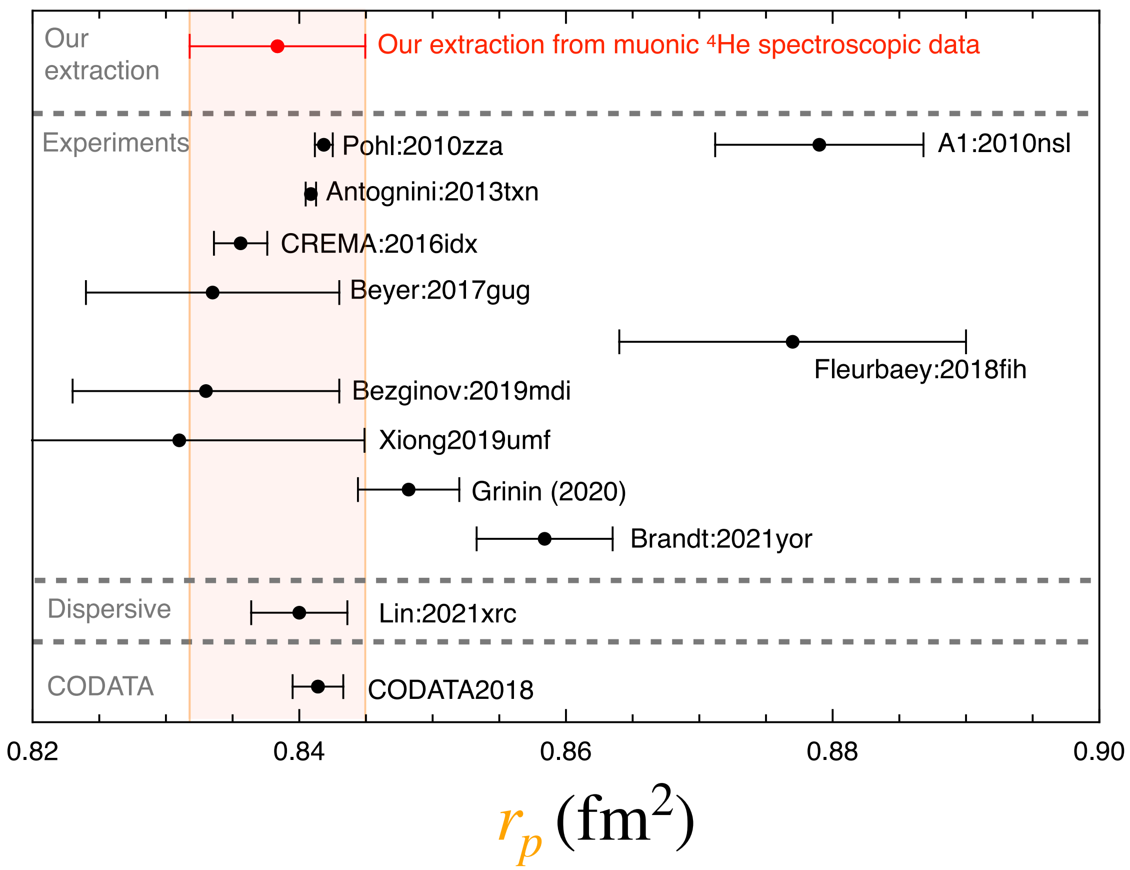
neutron charge radius from ^{2}H

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

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

New determination of the proton charge radius: $r_p = (0.838 \pm 0.007)\, fm$

preliminary



Our extraction supports the „small“ proton radius

Our uncertainty is comparable with the experimental one

Prediction for isoscalar 3N charge radius

With all LECs being fixed, we can predict the isoscalar 3N charge radius:

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

$$r_C^{isoscalar3N} = \sqrt{\frac{r_C^2(^3\mathbf{H}) + 2r_C^2(^3\mathbf{He})}{3}} = (1.9058 \pm 0.0026)\, fm$$

preliminary, using CODATA 2018 r_p and own determination of r_n

Our result is **10x more precise** than current experimental data: $r_{C,\,exp.}^{isoscalar3N} = (1.9030 \pm 0.0290)\, fm$

using muonic ^{3}He and old ^{3}H:

$r_C^{3He} = (1.9687 \pm 0.0013)\, fm$ Pohl '20 (preliminary)

$r_C^{3H} = (1.7550 \pm 0.0860)\, fm$ Amroun et al. '94 (world average)

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!**

Estimation of ^{3}H charge radius

Our **isoscalar 3N charge** radius calculation:

$$r_C^{isoscalar3N} = \sqrt{\frac{r_C^2(^3\mathbf{H}) + 2r_C^2(^3\mathbf{He})}{3}} = (1.9058 \pm 0.0026)fm$$

preliminary, using CODATA 2018 r_p and own determination of r_n

Preliminary **^{3}He charge radius** [Pohl et al.]

$$r_C^{3He} = (1.9687 \pm 0.0013)fm$$

^{3}H charge 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: $$r_C^{(3H)} = (1.7734 \pm 0.0088)fm$$

preliminary

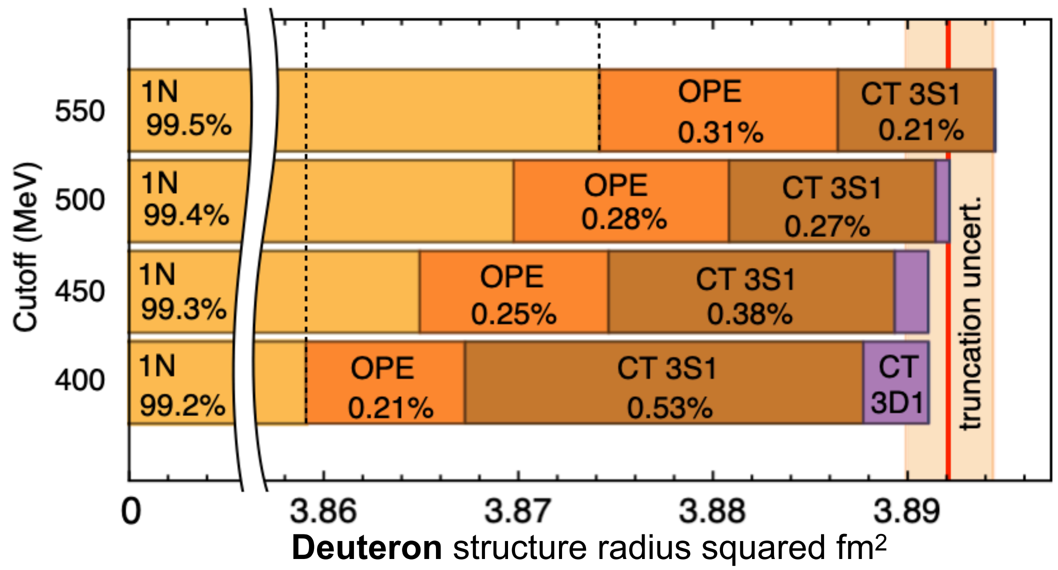
This estimation is 10x more precise than e$^-$ data $r_C^{3H} = (1.7550 \pm 0.0860)\,fm$ Amroun et al. '94 (world average)

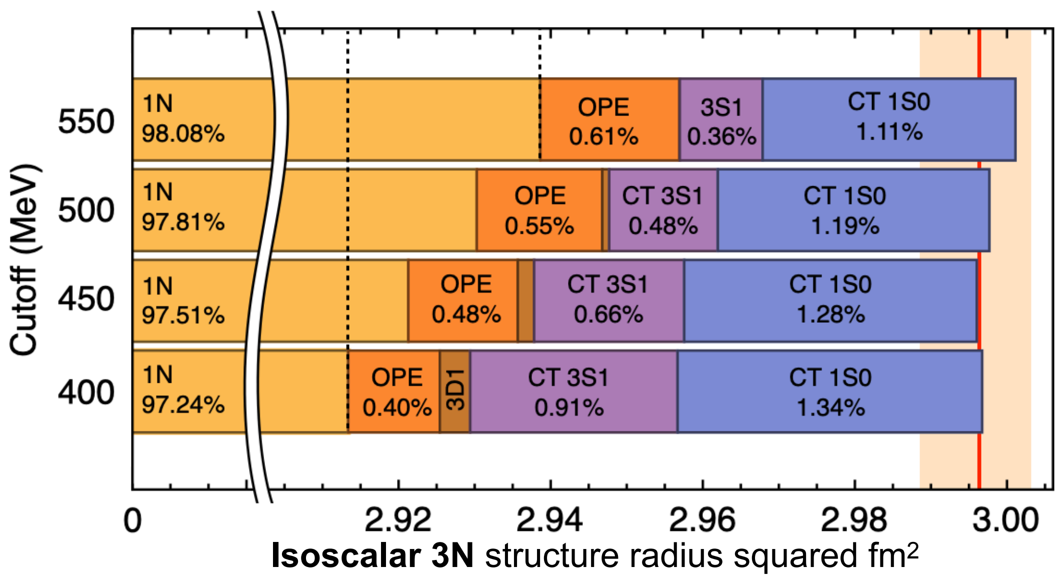
But it suffers from parametric amplification of uncertainties (both from theory and from ^{3}He data)

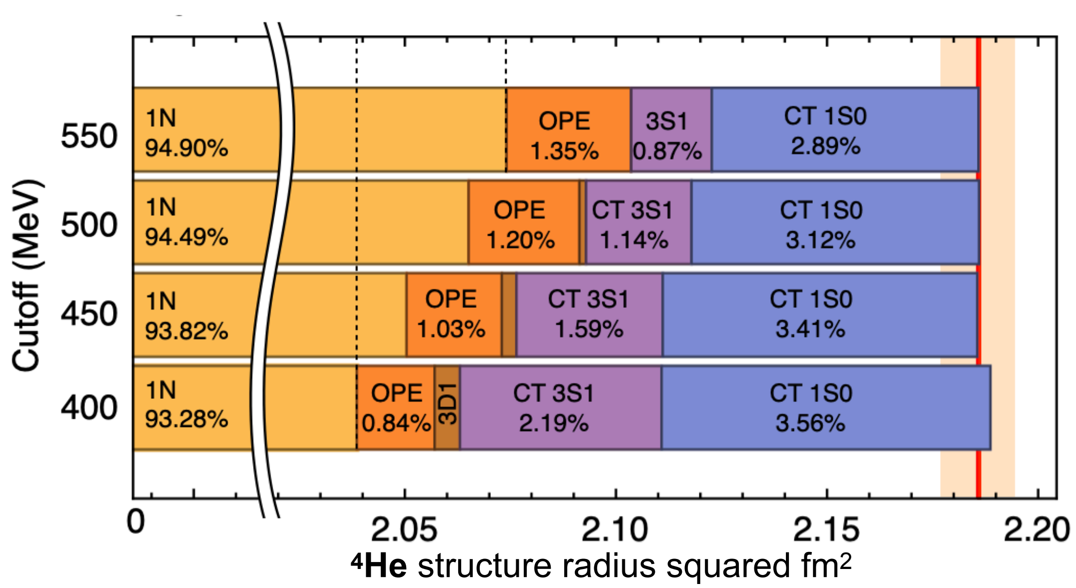
=> isoscalar 3N charge radius should be used for precision tests

Takeaway from A=2,3,4 calculations

Importance of 2N charge density







Individual contributions to A=2,3,4 stucture 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:

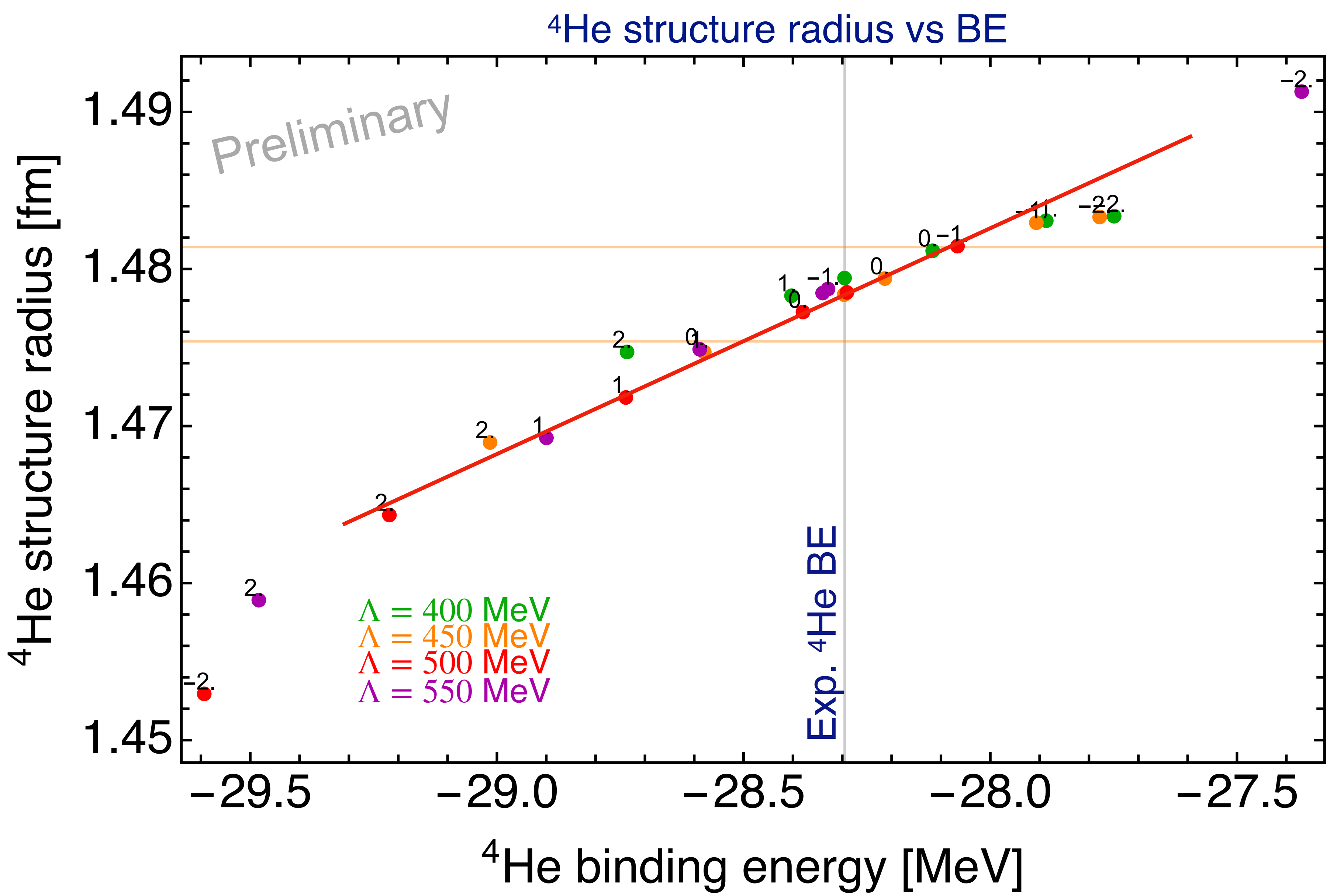
deuteron ~ 0.7%

isoscalar 3N ~ 2.5%

^{4}He ~ 6%

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

Importance of correct binding energy



Charge radius is correlated with BE

— correlation helps to calculate radii with incomplete 3NFs

— effects of over/underbinding cannot be compensated by short range charge density

Summary

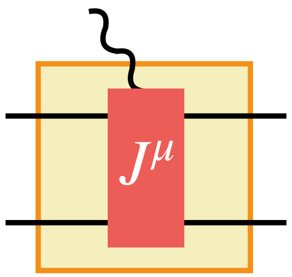
Precise calculation of A = 2, 3, 4 charge radii in chiral effective field theory & **uncertainty analysis**

Isoscalar 2N charge density operators

— derived, regularized, PW-decomposed and **LECs are fixed**

— produce important contributions to A=2,3,4 structure radii (**importance grows with A**)

— can be used to calculate corrections to charge radii of A>4 nuclei



Applications and tests: preliminary

^{4}He:

- calculated ^{4}He charge radius (0.2% accuracy) agrees with the new μ^{4}He measurement

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

- 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

p and **n** charge radii 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

Outlook

— estimation of the effects from non-relativistic treatment of the SE (talk by Anderas)

— Analysis of **magnetic form factors** of ^2H, ^3H and ^3He (talk by Daniel)

— **Consistent** inclusion of **N^3LO, N^4LO three-nucleon forces**

— **Consistent** inclusion of **isovector currents** (individual predictions for ^3H and ^3He)

— Application to processes with two photons (**polarizabilities**, ...)