INT Program INT-16-1 **Nuclear Physics from Lattice QCD** Week 7

Electroweak structure of A=2, 3 nuclei

האוניברסיטה העברית בירושלים
THE HEBREW UNIVERSITY OF JERUSALEM

Doron Gazit Racah Institute of Physics Hebrew University of Jerusalem

In collaboration with: Hilla Deleon (HUJI).

◆ Low energy electroweak observables A≤ 3 nuclei

K Low energy electroweak observables of light nuclei

- Typical momentum for $A{\le}4$: $Q_{typ} \approx \sqrt{2m_N B/A} \ll m_{\pi}$
	- Effective field theory without pions.

3

May 3, 2016

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Leutwyler, Gasser, Weinberg, Kaplan, Savage, Wise, van-Kolck, Birse, Meissner, Epelbaum, Machleidt, Chen, Park, Rho,...

The interaction of a nucleus with an external probe

"QCD"

Non-physical m_{p} , sign problem, statistics, configurations, finite volume...

Lattice formulation in a background field

Nuclear Matrix Element

Application in the EM sector (1)

Magnetic moments of light nuclei from lattice quantum chromodynamics

S.R. Beane,¹ E. Chang,^{1,2} S. Cohen,^{1,2} W. Detmold,³ H.W. Lin,¹ K. Orginos, 4,5 A. Parreño, 6 M.J. Savage, 1,2 and B.C. Tiburzi^{7,8,9} (NPLQCD Collaboration)

$$
\delta E^{(B)} = -2\mu \ |\mathbf{B}| + \gamma \ |\mathbf{B}|^3
$$

for
$$
m_{\pi} = 806 \,\text{MeV/c}^2
$$

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 $\frac{3}{H}$

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Application in the EM sector (2) H mulkeons are estentially independent of the nucleon T the pressure in units magnetons \mathcal{A} is plausible that L \mathcal{A}

PRL 115, 132001 (2015) PHYSICAL REVIEW LETTERS week ending

25 SEPTEMBER 2015 WIEW LETTERS week ending S of L¯ ¹ determined by the field-strength dependence fits

Ab initio Calculation of the $np \rightarrow d\gamma$ Radiative Capture Process
25 $\frac{1}{2}$ Ab initio Calculation of the $np \rightarrow d\gamma$ Radiative Capture Process \mathcal{W} and \mathcal{W}

> Silas R. Beane,¹ Emmanuel Chang,² William Detmold,³ Kostas Orginos,^{4,5} Assumpta Parreño,⁶ Martin J. Savage, 2 and Brian C. Tiburzi^{7,8,9} p etinoid, **N**ostas Orginos, Assumpta Parteno,

> > (NPLQCD Collaboration) statistical uncertainties, correlator fitting uncertainties,

 m_{π} [GeV-]

Institute for Nuclear Theory, University of Washington, Seattle, Washington 98195-1560, USA Center for Theoretical Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA Department of Physics, College of William and Mary, Williamsburg, Virginia 23187-8795, USA Jefferson Laboratory, 12000 Jefferson Avenue, Newport News, Virginia 23606, USA Departament d'Estructura i Constituents de la Matèria and Institut de Ciències del Cosmos, Universitat de Barcelona, Martí i Franquès 1, Barcelona, 08028, Spain 7 Department of Physics, The City College of New York, New York, New York 10031, USA 8 Graduate School and University Center, The City University of New York, New York, New York 10016, USA RIKEN BNL Research Center, Brookhaven National Laboratory, Upton, New York 11973, USA (Received 25 June 2015; revised manuscript received 14 August 2015; published 24 September 2015) Lattice QCD calculations of two-nucleon systems are used to isolate the short-distance two-body electromagnetic contributions to the radiative capture process np → dγ, and the photo-disintegration processes γð"Þd → np. In nuclear potential models, such contributions are described by phenomenological meson-exchange currents, while in the present work, they are determined directly from the quark and gluon interactions of QCD. Calculations of neutron-proton energy levels in multiple background magnetic fields are ² þ%%% ; ^ð1^Þ where X~ ^M¹ is the M1 amplitude, γ⁰ is the binding ΔE³S1; ¹S⁰ ^ðBÞ ¼ ²ðκ¹ ^þ ^γ0Z² d ~ l1Þ e ^M ^jB^j ^þ ^OðjB^j ²Þ; ^ð3^Þ where B is the background magnetic field. It is convenient to focus on the combination ^L¯ ¹ ^¼ ^γ0Z² d ~ l¹ that characterizes the two-nucleon contributions. Our LQCD calculations were performed on two ensembles of gauge-field configurations generated with a cloverimproved fermion action [36] and a Lüscher-Weisz gauge action [37]. The first ensemble had Nf ¼ 3 degenerate this leads to a value l lqcd ¹ ¼ −4.41ð þ15 [−]¹⁶ ^Þ fm. Future calculations with lighter quark masses will reduce both PRL 115, 132001 (2015) PHYSICAL REVIEW LETTERS week ending 25 SEPTEMBER 2015 ing, and the uncertainties in the mass extrapolation. Using the precise phenomenological values of γ⁰ ¼ 45.681 MeV, r¹ ¼ 2.73ð3Þ fm, r³ ¼ 1.749 fm, and κ¹ ¼ 2.35295 NM, (NPLQCD Collaboration) *¹Department of Physics, University of Washington, Box 351560, Seattle, WA 98195, USA ²Institute for Nuclear Theory, Box 351550, Seattle, WA 98195-1550, USA ³ Center for Theoretical Physics, Massachusetts Institute of Technology, Cambridge, MA 02139, USA ⁴Department of Physics, College of William and Mary, Williamsburg, VA 23187-8795, USA ⁵Je*↵*erson Laboratory, 12000 Je*↵*erson Avenue, Newport News, VA 23606, USA ⁶Dept. d'Estructura i Constituents de la Mat`eria. Institut de Ci`encies del Cosmos (ICC), Universitat de Barcelona, Mart´ı Franqu`es 1, E08028-Spain ⁷Department of Physics, The City College of New York, New York, NY 10031, USA ⁸Graduate School and University Center, The City University of New York, New York, NY 10016, USA ⁹RIKEN BNL Research Center, Brookhaven National Laboratory, Upton, NY 11973, USA* We present the results of lattice QCD calculations of the magnetic moments of the lightest nuclei, the deuteron, the triton and ³He, along with those of the neutron and proton. These calculations, performed at quark masses corresponding to *m*⇡ ⇠ 800 MeV, reveal that the structure of these nuclei at unphysically heavy quark masses closely resembles that at the physical quark masses. In particular, we find that the magnetic moment of ³He di↵ers only slightly from that of a free neutron,

extrapolated LQCD value of l

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mined nucleon isovector magnetic moment, and the above

context of nuclear potential models) that make significant contributions to the low-energy cross sections for np → dγ and \mathbf{z} \mathbf{z} effective field theory which provides a clean separation \mathbf{p}_i of long-distance and short-distance effects along with a concise analytic expression for the near-threshold cross sections. A (naive) extrapolation of the LQCD results to the physical pion mass is in agreement with the experimental determinations of the np → dγ cross section, within the uncertainties of the calculation and of the experiment. Calculations were performed at a single lattice spacing and volume, introducing systematic uncertainties in L¯ ¹ that are \mathbb{R}^n in comparison to \mathbb{R}^n

study, and a reduction of the uncertainties of the uncertainties of the uncertainties of the uncertainties of th section will require additional calculations at smaller lattice spacings and larger volumes, along with calculations at

 T present calculation demonstrates the power of lattices the power of lattices the power of lattices the power of lattices \mathcal{L} $\mathcal{L}(\mathcal{L})$ and input processes of importance

 \mathbb{R}^n

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smaller quark masses.

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Outline

\bullet EM:

- Calculate A=2, 3 magnetic moments, as well as $n+p$ capture, using consistent pionless EFT up to next-to-leading order (NLO).
	- Use A=3 magnetic moments to fix the EFT, and postdict A=2 observables.
	- Use $A=2$ observables to fix the EFT, and postdict $A=3$ observables.
- Show stability of the calculation, naturalness, power counting.
- **Confront with nature and lattice data.**
- **Give** *reliable* uncertainty estimate, especially for an n+p→d+γ postdiction, and check its validity!
- Weak interaction:
	- Calculate $3H$ decay and p+p fusion, using consistent pionless EFT up to next-to-leading order (NLO).
		- Use measured $3H$ decay rate to predict $p+p$ fusion.
	- Give *reliable* uncertainty estimate!

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Initial amplitude Final amplitude Scattering operator tude _o *M^N* 1*/at,s µ Ct,s* <u>2 = 4</u> *M^N* $\frac{1}{\sqrt{1-\frac{1}{2}}}$ 1*/at,s µ* ◆² ² (8)

Amplitudes (in a dibaryon formalism):

$$
\mathcal{L} = N^{\dagger} \left(i D_0 + \frac{D^2}{2M_N} \right) N - t^{\dagger \dagger} \left[\sigma_t + \left(i D_0 + \frac{D^2}{4M_N} \right) \right] t^i - s^{A \dagger} \left[\sigma_s + \left(i D_0 + \frac{D^2}{4M_N} \right) \right] s^A +
$$

$$
y_t \left[t^{\dagger \dagger} \left(N^T P_t^i N \right) + h.c \right] + y_s \left[s^{A \dagger} \left(N^T P_s^A N \right) + h.c \right],
$$

$$
y_{t,s}^2 = \frac{8\pi}{M_N^2 \rho_{t,s}}
$$

$$
\sigma_{t,s} = \frac{2}{M_N \rho_{t,s}} \left(\frac{1}{a_{t,s}} - \mu \right)
$$

ka Kaplan (1996), Beane, Savage (1999)

May 3, 2016 May 3, 2016

(~*s ·* ~⌧) *N*

(~*s ·* ~⌧) *N*

(25)

Deutron normalization (ANC):

\n
$$
Z_d^{-1} = i \frac{\partial}{\partial_{p_0}} \frac{1}{i \mathcal{D}_t(p_0, p)} \Big|_{p_0 = \frac{\gamma_t^2}{M_N}, p = 0}
$$

Range expansion:
$$
Z_d = \frac{1}{1 - \gamma_t \rho_t} = \underbrace{1}{\frac{1}{1 - \gamma_t \rho_t}} + \underbrace{\gamma_t \rho_t}_{NLO} + \underbrace{(\gamma_t \rho_t)^2}_{N^2LO} + \underbrace{(\gamma_t \rho_t)^3}_{N^3LO} + ... = 1.69
$$

Z-parameterization:

\n
$$
Z_d = \underbrace{1}_{\text{LO}} + \underbrace{Z_d - 1}_{\text{NLO}} + \underbrace{0}_{\text{N2LO}} + \underbrace{0}_{\text{N3LO}} + \dots = 1.69
$$

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These are two alternatives to arrange the FFT expansion. The are two alternatives to arrange the EFT expansion are their predictions is (one) measure of By using the earth in the earth capacity records of the expansion of that the deuteron (spin-triplet, *T*) pole residue *Z^d* = ¹ that the deuteron (spin-triplet, *T*) pole residue *Z^d* = ¹ = 1*.*69 is given correctly in an B_1 e B_2 e C_3 ective range expansion (ERE) parameterization we need to insures the insures B_4 = 1*.*69 is given correctly in an These are two alternatives to arrange the EFT ex
between their predictions is (one) measure of These are two alternatives to arrange the EFT expansion. The difference **between** *Moretical* uncertainty due to higher order corrections. ² *.* (29) In the following sections we will use both normalizations we will use \mathbb{R}^2 in order to \mathbb{R}^2 in order to \mathbb{R}^2

 $\sqrt{\frac{10}{\pi}}$ $\sum_{i=1}^{n}$ instead of the convergence displayed in eq. (2600) $\frac{1}{2}$ interpretation of the convergence displayed in eq. (26) $\frac{1}{2}$ we now have, by explicit construction of $\frac{1}{2}$ we now have $\frac{1}{2}$ and $\frac{1}{2}$ and $\frac{1}{2}$ and $\frac{1}{2}$ and $\frac{1}{2}$ and $\frac{1}{2}$ an Phillips, Rupak, Savage, Phys. Lett. **B473**, 209 (2000) Grießhammer, Nucl. Phys. **A744**, 192 (2004)

1⇢*^t*

1⇢*^t*

+*...* = 1*.*69 (28)

+*...* = 1*.*69 (28)

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17

 $\overline{1}$ *qkQ*⁰ ✓*q*² ⁺ *^k*² *^M^N ^E qk* ◆ ✓ *^y*² *^t · Dt*(*q*) 3*yty^s · Ds*(*q*) ◆ 3*yty^s · Dt*(*q*) *y*² ● A=3 Efimov effect: *triton at LO has strong cutoff dependence →add* ∙poay *3-body* contact at LO. prohibited by the Pauli principle. For the *nd* scattering we are setting : *ann* = *anp* = *a^t* imov effe Figure. 5 shows a diagrammatic representation of the coupled-channel integral equa-

³H-³He binding energy difference: E DINGHIS GHEFEV GIMEFENCE: **p** all the diagrams showld support survey.

• Since the typical momentum is $Q \ge \sqrt{M_N E_{\rm 3He}^B} \simeq 85 \text{MeV}$, then the Coulomb interaction is perturbative: $\sqrt{M_N E_{^3\text{He}}^B} \simeq 85\text{MeV}$, then the Coulomb

$$
\eta(Q)=\frac{\alpha M_N}{2Q}<<1
$$

- The pp propogator always has to be renormalized (as Q can be low). \log ator always rias to be reflorm
- two ways to find the $A=3$ b.e. difference:
	- Find the pole of a non-perturbative solution of the homogenous Fadeev equations with Coulomb (i.e., 3He w.f.).
	- Since Coulomb is perturbative in ³He, one can calculate the energy shift in the one photon approximation.

18

König, Hammer (2011-15), Vannase et al (2014), König et al (2014-2016) α , Hammer (2011-15), vannase et ar (2014), Konig et ar (2014) ⇥

The power counting for the diagram shown in $\mathcal{S}(\mathcal{S})$ are $\mathcal{S}(\mathcal{S})$ are $\mathcal{S}(\mathcal{S})$ are $\mathcal{S}(\mathcal{S})$

K Faddeev eq. for ³He

 $\boxed{7}$ $\boxed{3}$ $\boxed{3}$

 $\sqrt{S' \times \sqrt{S' \times \sqrt{$ \boxed{p} \cdots + \boxed{s} \cdots + \boxed{p} \cdots

\star ³H-³He binding energy difference:

NLO corrections

- NLO corrections to the amplitude include effective range (or Z_d) insertions.
- For $3H$, no need in a new 3NF (just a renormalization of the LO 3NF).
- For 3 He, NLO leads to a new isospin breaking force at NLO (Vanasse et al 2014).
	- See König et al (2016) for one possible solution.
- Normalization of amplitude is unchanged for $3H$, and changes insignificantly for 3 He.

May 3, 2016

May 3, 2016

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. *L*magnetic is written up to NLO where the first term which

to experiment once

In addition the three nucleons system contain also a disapplication, which also a disapplication, which is a disa

donate the one-body interaction is in LO and the other terms (ERE and *L*1*A*) which

Javier Menéndez (JSPS / U. Tokyo) Correlations and decay Jyväskylä, 1 June 2015 6 / 22

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. *L*magnetic is written up to NLO where the first term which

 x n+p \rightarrow d+γ ment of the deuteron. The diagrams for the *np* radiative capture (up to NLO) are showing μ mp μ grey solid line is the experiential data from \mathcal{P}_max and the data from \mathcal{P}_max line is the numerical results of 1-body NLO, the short dotted-dashed line is full NLO with *L*1*, L*² = 0. The red lines are the numerical results with ⇢*^t* = 1*.*765 fm, while the blue lines are numerical results after Z-parametrization with ⇢⁰ where *Y* is summation of all the diagrams from Fig. 18 and *p*=0.0034 MeV, is the momentum of each incoming nucleon in the center-of-mass frame [44, 66]. *Y* = r ⇡ *t M^N*

For low neutron energy:
$$
\sigma = \frac{\alpha (\gamma_t^2 + p^2)^3}{M_N^2 p} Y^2
$$

With:
\n
$$
Y = \sqrt{\frac{\pi}{\gamma_t}} \frac{\sqrt{Z_d}}{M_N} (\kappa_p - \kappa_n) \left[\left(\frac{1}{\gamma_t} - a_s \right) + \frac{a_s}{4} (\rho_t + \rho_s) - a_s \frac{M_N L_1}{2\pi (\kappa_p - \kappa_n)} \left(\mu - \frac{1}{a_t} \right) \left(\mu - \frac{1}{a_s} \right) \right]
$$

nber: $Z_d^{LO} = 1$ and $Z_d^{NLO} = (1 + \gamma \rho_t)$ P_0 are seek sec. Z_0 = 1 and Z_0 = (1 + α *t*) Remember:

$$
\sigma_{np} = \frac{\pi \alpha \gamma_t^5 a_s^2 (\kappa_p - \kappa_n)^2}{M_N^4 p} \left[\left(1 - \frac{1}{\gamma_t a_s} \right) \left(1 + \frac{1}{2} \gamma_t \rho_t \right) - \frac{\gamma_t}{4} (\rho_t + \rho_s) + \frac{\gamma_t M_N}{2\pi (\kappa_p - \kappa_n)} L_1 \left(\mu - \frac{1}{a_t} \right) \left(\mu - \frac{1}{a_s} \right) \right]^2
$$

 $T_{\rm eff}$ diagrams for the deuteron magnetic moment (up to \sim

showing in Fig. 18 where the *n* and *p* are in bound state. The magnet moment of the

showing in Fig. 18 where the *n* and *p* are in bound state. The magnet moment of the

 $\mathcal{N}(\mathcal{A})$

25

◆ *,*

(106)

(106)

 $\int_{\mathcal{A}} f(x) dx$

Deutron:

$$
\mu_d = \frac{e}{2M_N} \left(\kappa_n + \kappa_p \right) \left[1 + L_2 \frac{2M_N \gamma_t}{\pi \left(\kappa_n + \kappa_p \right)} \left(\mu - \frac{1}{a_t} \right)^2 \right]
$$

A=3:

\mathbf{A} =3 magnetic moments calculations:

- Natural NLO contributions. • All NLO contributions of the same order of magnitude $5-10%$ –
- Cutoff independence.
- When L_1 and L_2 are fixed **from A=2 observables**:

LO:	\n $\mu_{\text{3H}}^{LO} = 3.09 \pm_{Z_d} 0.01$ \n	\n $\mu_{\text{3He}}^{LO} = -2.455 \pm_{Z_d} 0.005$ \n
NLO:	\n $\mu_{\text{3H}}^{NLO} = 3.005 \pm_{Z_d} 0.01$ \n	\n $\mu_{\text{3He}}^{NLO} = -2.13 \pm_{Z_d} 0.01$ \n
exp:	\n $\mu_{\text{3H}}^{\text{exp}} = 2.9789...$ \n	\n $\mu_{\text{3He}}^{\text{exp}} = -2.1276...$ \n

2016

\star A=3 magnetic moments calculations:

• When L₁ and L₂ are fixed **from A=3 magnetic moments**:

Repeat using NPLQCD m.m. calculations

Magnetic moments of light nuclei from lattice quantum chromodynamics

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 $\delta E^{(B)} = -2\mu |\mathbf{B}| + \gamma |\mathbf{B}|^3$

*-preliminary

May 3, 2016

May 3, 2016 016 $\frac{3}{2}$ \mathfrak{D} in the phenomenological determination, the two-body \mathfrak{D} γ $\mathsf{E}_{\mathrm{max}}$

Using NPLQCD l_1 in our counting magnetons [41], so it is plant that L \mathcal{A} 1 also varies only \mathcal{A} <u>dir countinα</u> our counune t we extrapolate both linearly \overline{O} mass by resampling the probability distribution functions

Rho paramet.

paramet.

 $\frac{N}{2}$ $\frac{N}{2}$

L-paramet.

precision of the present work). In a pionless effective field

PRL 115, 132001 (2015) PHYSICAL REVIEW LETTERS week ending

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physical pion mass, where the uncertainty incorporates statistical uncertainties, correlator fitting uncertainties, field-strength dependence fitting uncertainties, lattice spac-

(blue points). The blue (green) shaded regions show the linear

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Ab initio Calculation of the $np \rightarrow d\gamma$ Radiative Capture Process $\frac{1}{2}$ is the contract of the state of the state $\frac{1}{2}$ and $\frac{1}{2}$ review $\$ value and uncertainties determined from the 0.17, 0.50, and

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> > (NPLQCD Collaboration)

$$
\Delta E_{^3S_1,^1S_0}(\mathbf{B})=2(\kappa_1+\gamma_0Z_d^2\tilde{l}_1)\frac{e}{M}|\mathbf{B}|+\mathcal{O}(|\mathbf{B}|^2),
$$

 $U_1 = -3.934 \, \text{Jm} \quad \text{S} \quad \text{O}_{np} = 322.9 \, \text{mJ} \quad \text{S}$ $(1 - 5.48 \text{ fm}) \rightarrow 7 - 342 \text{ fm}$ Lattice QCD calculations of two-nucleon systems are used to isolate the short-distance two-body \overline{a} processes $\mathfrak p$ and $\mathfrak p$ in nuclear potential models, such contributions are described by phenomenological models, such contributions are described by phenomenological models, and $\mathfrak p$

where B is the background magnetic field. It is convenient magnetic field. It is convenient of \mathbb{R}

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 $0.4\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$ $0.4\begin{bmatrix} \end{bmatrix}$

Universitat de Barcelona, Martí i Franquès 1, Barcelona, 08028, Spain ⁷ $L = -3.934$ fm \leftarrow $>$ $\sigma = 322.9$ mb $|^{0.3}|$

 $t_1 = -3.934 \text{ fm} \longrightarrow \sigma_{np} = 322.9 \text{ mb}$

 $l_1 = -3.934 fm$ \longrightarrow $\sigma_{np} = 322.9 mb$

 $l_1 = -5.48$ *fm* $\longrightarrow \sigma_{np} = 342.6 \text{ mJ}^2$

 $t_1 = -5.48$ fm $- \rightarrow \sigma_{np} = 34$

meson-exchange currents, while in the present work, they are determined directly from the quark and gluon interactions of QCD. Calculations of neutron-proton energy levels in multiple background magnetic fields are This could be regarded as a measure of the NPLQCD $\frac{0.0}{0.0}$ $\frac{0.0}{0.0}$ $\frac{0.0}{0.2}$ $\frac{0.2}{0.4}$ $\frac{0.6}{0.6}$ combined with pionless nuclear effective field theory to determine the amplitudes for th uncertainty in predicting n+p fusion, due to the EFT $\frac{m_{\pi}^{2} [GeV^{2}]}{m_{\pi}^{2} [GeV^{2}]}$ found at an incident neutron speed of v \mathcal{L}_1 \mathcal{L}_2 ; 200 m=s. Extrapolating the short-distance contribution to the short-distance contribution to the short-distance contribution to the short-distance contribution physical pion mass and combining the result with phenomenological scattering information and one-body center-of-mass frame. The ellipsis denotes the contribution **Expansion.** bles of gauge-field configurations generated with a clover-field configurations generated with a clover-field $\frac{1}{2}$ light-quark flavors with masses tuned to the physical strange quark mass (the physical value of ms is used, with α

30 \sim 1 \cup \parallel \mathcal{L}_C methods complex processes of importance

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section will require additional calculations at smaller lattice spacings and larger volumes, along with calculations at

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 $0.4\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$ $0.4\begin{bmatrix} \end{bmatrix}$

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þ5.2

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North Characterizes (1982)
North Characterizes (1982) $t_1 = -5.48$ fm $- \rightarrow \sigma_{np} = 34$ $\overline{\text{O}_{0.1}}$ $l_1 = -3.934 fm$ \longrightarrow $\sigma_{np} = 322.9 mb$ $l_1 = -5.48$ *fm* $\longrightarrow \sigma_{np} = 342.6 \text{ mJ}^2$ Rho paramet. paramet.

interactions of QCD. Calculations of neutron-proton energy levels in multiple background magnetic fields are This could be regarded as a measure of the NPLQCD $\frac{0.0}{0.0}$ $\frac{0.0}{0.0}$ $\frac{0.0}{0.2}$ $\frac{0.2}{0.4}$ $\frac{0.6}{0.6}$ combined with pionless nuclear effective field theory to determine the amplitudes for th uncertainty in predicting n+p fusion, due to the EFT $\frac{m_{\pi}^{2} [GeV^{2}]}{m_{\pi}^{2} [GeV^{2}]}$ found at an incident neutron speed of v \mathcal{L}_1 \mathcal{L}_2 ; 200 m=s. Extrapolating the short-distance contribution to the short-distance contribution to the short-distance contribution to the short-distance contribution physical pion mass and combining the result with phenomenological scattering information and one-body **Expansion.** light-quark flavors with masses tuned to the physical strange quark mass (the physical value of ms is used, with α May 3, 2016

 016 $\frac{3}{2}$ \mathfrak{D} in the phenomenological determination, the two-body \mathfrak{D} γ $\mathsf{E}_{\mathrm{max}}$

Calculations were performed at a single lattice spacing and

section will require additional calculations at smaller lattice

 \mathcal{L}_C methods complex processes of importance

31 spacings and larger volumes, along with calculations at s and de $\mathbf{I} = \mathbf{I}$

132001-4

 1.0

 0.8

Weak proton-proton fusion in the Sun constant. In order to evaluate has been constant. In order to energy dependence of

SFII - Adelberger et al., Rev. Mod. Phys. 83, 195 (2011)

- Cannot be measured terrestrially $$ depends on theory and the probability of several probability of several probability of several probability of s-• Very low proton-proton relative momentum ($E_{rel}^{}$ 6 keV). ϵ depend to measured to restrictly.
- $\begin{bmatrix} 1 & 1 & 1 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}$ is not otherwise explicitly treated accuracy: \sim 1%. t_{t} is the second increase in the S factor in the S t_{t}

 $\mathcal{L} = \mathcal{L} \left(\mathcal{L} \right)$ is the reaction cannot be measured in terrestrial behavior of the measured in terrest

laboratories, and it is necessary to relations. The many studies on the many studies on $\mathcal{L}_\mathcal{A}$

$$
\sigma(E) = \frac{S(E)}{E} \exp[-2\pi \eta(E)]
$$

momentum
$$
(E_{rel} \sim 6 \text{ keV})
$$
.
\nNeeded accuracy: ~1%.
\n
$$
\sigma(E) = \frac{S(E)}{E} \exp[-2\pi \eta(E)]
$$
\n
$$
S(O) + S'(O)E + S''(O)E^2 / 2 + \frac{1}{2} \text{ erg } \frac{1}{2} \text{ erg } \frac{1}{2}
$$

For such reactions it is helpful to remove much of the rapid

Weak proton-proton fusion in the Sun – theory standards 210 Adelberger et al.: Solar fusion cross ... In the pp chain ... In the pp chain ... In the pp chain ... In the p r_{\rm} in the ζ_{\rm} theory standards with ζ_{\rm} $\frac{1}{2}$ situation systems, but, as mentioned, the situation will be $\frac{1}{2}$

SFII – Adelberger et al., Rev. Mod. Phys. 83, 195 (2011) δ (2011) $\begin{array}{l} \text{Mod. Phys. 83, 195 (2011)} \ \textcolor{red}{\widehat{\mathcal{B}}} \end{array}$

$$
4.01(1 \pm 0.009) \times 10^{-25} \text{ MeV b} \quad \text{potential models,}
$$

$$
4.01(1 \pm 0.009) \times 10^{-25} \text{ MeV b} \quad \text{EFT}^*,
$$

$$
3.99(1 + 0.030) \times 10^{-25} \text{ MeV b} \quad \text{minless EFT}
$$

EFT*, we adopt as the recommended value

 $3.99(1 \pm 0.030) \times 10^{-25}$ MeV b pionless EFT.

The larger uncertainty in the pionless EFT result is due to the SFII recommended value (2011): $S_{11}(0) = 4.01(1 \pm 0.009) \times 10^{-25}$ MeV b.

cFFT calculation by Marcucci et al., Phys. Rev. Lett. (2013)[.] Use consistent ³H decay-rate to constrain consistently axial MEC^T (DG, Quaglioni, Navratil, PRL 2009), and predict pp-fusion rate. constrained by tritium α and agreement of a green agreement of agreement of agreement of agreement of agreement of *Modern cEFT calculation by Marcucci et al., Phys. Rev. Lett. (2013)*:

S00

$$
S(0) = (4.030 \pm 0.006) \times 10^{-23} \text{ MeV fm}^2
$$

uncertainty has been estimated using the same argument. Based on the result of the result of the result of the result of the potential model and position of the potential model and the position of t EFT: CHILD AND AND AND ON THE VIOLET AS Including: p-wave contribution (+0.005%), full EM (-0.0025-(-0.0075)%), on (10.0009%), fun EIVI (10.0020 (10.0079)%),
n 500 and 600 MeV cutoff and notential models Il 500 and 000 MCV caton and p difference between 500 and 600 MeV cutoff and potential models.

¹¹ð0Þ

(24)

The larger uncertainty in the pionless EFT result is due to the pionless EFT result is due to the pionless EFT

so be improved. The agreement of the agreement of the central values of the central values of $>$

 $\begin{bmatrix} 1 & 0 & 0 \ 0 & 0 & 0 \end{bmatrix}$ $\begin{bmatrix} 1 & 0 & 0 \ 0 & 1 & 0 \end{bmatrix}$

33

A. Data sets

 $\begin{bmatrix} 33 \end{bmatrix}$

As expected, the P-wave contributions become significant at higher values of E. From these

results, a least-squares polynomial fit to S(E) has been performed up to order O(E2), i.e., by

respectively.

May 3, 2016

modeling protostellar evolution.

 $\frac{1}{3}$, $\frac{1}{2}$

nucleosynthesis, which begins when the early Universe has

 $\mathcal{C}(\mathcal{C})$

pd reaction in the relevant energy window (25–120 keV)

The extensive experimental data sets for pd radiative

capture include total cross sections and spin polarization

in the light element primordial abundances, d,

The pd reaction also plays an important role in big bang

May 3, 2016 May 3, 2016

\star Precision, Uncertainty, and predictions

Advantages of p EFT UQ for proton-proton fusion: Small number of parameters.

- Two NLO p EFT set-ups.
- 3. A "cheat-sheet" in the electromagnetic sector.
- 4. Cutoff independence up to infinity.

We revisit the pp-fusion problem within pionless EFT, fixing the unknown LEC using triton decay.

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A fully perturbative pionless EFT A=2, 3 calculation @NLO

- LO Parameters:
	- nn and 2-np Scattering lengths: ${}^{3}S_{1}$, ${}^{1}S_{0}$.
	- pp scattering length.
	- Fine structure constant.
	- Three body force strength to prevent Thomas collapse.
- NLO parameters:
	- 2 effective ranges.
	- Renormalizations of pp and 3NF.
	- (isospin dependent 3NF to prevent logarithmic divergence in the binding energy of $3He$).
- Weak Interaction: LO $(g_A 1$ body), NLO $(L_{1A} 2$ body)
- *EM* Interaction: LO (k_s , k_v) 1 body), NLO (L_1 , L_2 –2 body)

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\sqrt{x} Triton decay – GT cutoff independence

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\sqrt{x} Triton decay – GT cutoff independence

Adding the NLO 1-body contributions

Triton decay - GT cutoff independence

All NLO contributions are of the same order,

one can estimate higher order effects as the NLO contribution.

\star Triton decay – GT cutoff independence

1st estimate of theoretical uncertainty: All NLO contributions are of the same order, one can estimate higher order effects as the NLO contribution.

\triangle So... is 3% too big to be called precision physics?

i.e., theoretical uncertainty of the same order of systematic experimental error encapsulated in g_A and ³H half life (2% total).

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Summary

- Pionless EFT reproduces low-energy electroweak observables to a very good precision $(^{21\%})$, even at NLO, and allows reliable uncertainty estimates.
- A coherent use of pionless EFT allows to estimate model uncertainty and higher order contribution.
- Pionless EFT allows assessing Lattice QCD calculations.
- Based on the EM sector, a theoretical prediction for pp fusion: $S_{\stackrel{}{pp}}(g_{\stackrel{}{A}}=1.2701)$ $=4.01\ \pm_{theory}\ 0.08\ \pm_{g_{\stackrel{}{A}}(1\sigma)}\quad 0.07\ \pm_{^3\text{H half life}}$ 0.04 $S_{pp}^{}(g_{\scriptscriptstyle{A}}^{} =\! 1.275) ~ = 4.12 ~ \pm_{\hbox{\scriptsize theory}}^{} 0.08 \pm_{g_{\scriptscriptstyle{A}}^{}(1\sigma)}^{} ~ ~ 0.07 ~ \pm_{^3\text{H half life}}^{}$ 0.04
- Better determination of g_A is necessary!
- $(3H \text{ half life is also an open exp. issue}).$