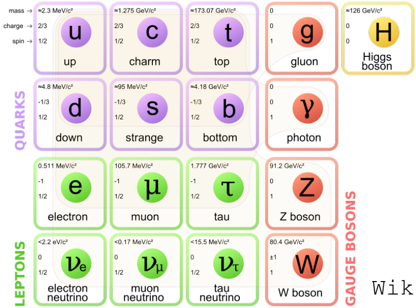
Fundamental Symmetries with Nucleons and Nuclei

Emanuele Mereghetti

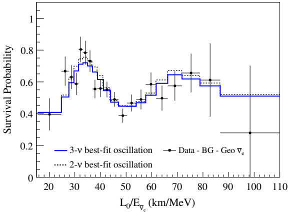
September 6th, 2022
Computational Nuclear Physics and AI/ML Workshop



Wikipedia

The Standard Model of Particle Physics

1. describes nature in a economic and elegant way (spontaneously broken) local gauge symmetry
2. validated over a wide variety of scales



- neutrino masses

- baryogenesis

- dark matter

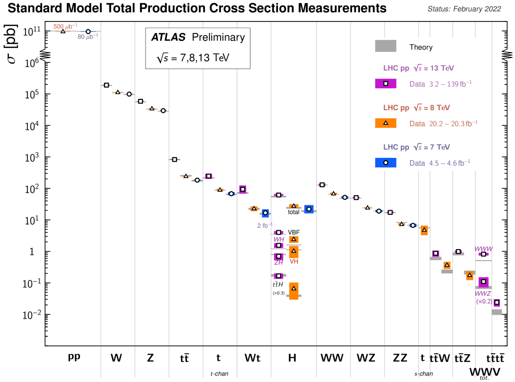
where can we look for BSM physics?

Finding new physics: the energy frontier

1. collide protons at high energy, and see what comes out

- create new particles **and/or**
  study their effects on rare processes

Finding new physics: the energy frontier



ATLAS, Standard Model Public Results

1. collide protons at high energy, and see what comes out

- create new particles **and/or**
  study their effects on rare processes

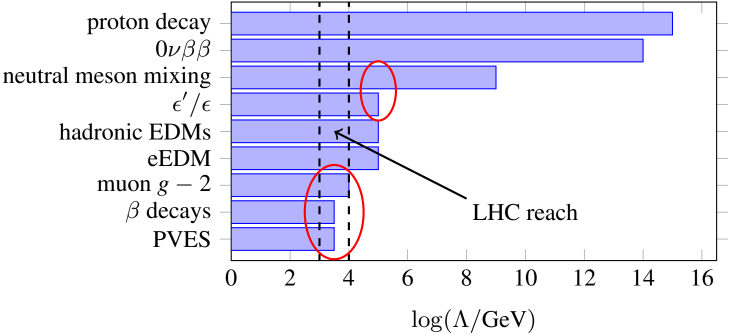
Finding new physics: the precision frontier

Majorana demonstrator

2. search for tiny indirect effects,
   with no (very precisely known) SM background

- electric dipole moments
- kaon physics
- rare B decays, $b \to s\gamma$
- muon and electron $g - 2$
- neutrinoless double β decay
- lepton flavor violation $\mu \to e\gamma$

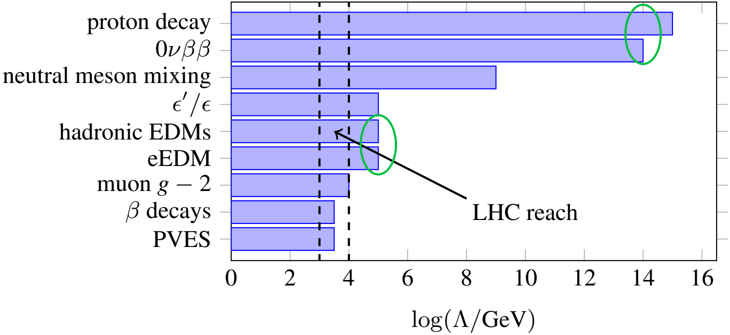
Finding new physics: the precision frontier



1. observables w. SM background

need precise SM background to claim discovery

Finding new physics: the precision frontier



1. observables w. SM background

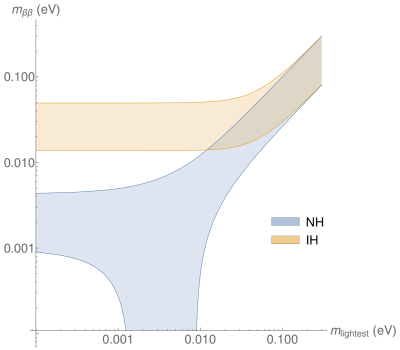
need precise SM background to claim discovery

2. observables w/o (w. negligible) SM background

precision to extract fundamental symmetry violation params ($\bar{\theta}$, $m_{\beta\beta}$,. . .)
& to connect with probes in other frontiers

- hadronic and nuclear theory crucial to this effort

The impact of hadronic and nuclear uncertainties: Neutrinoless double beta decay

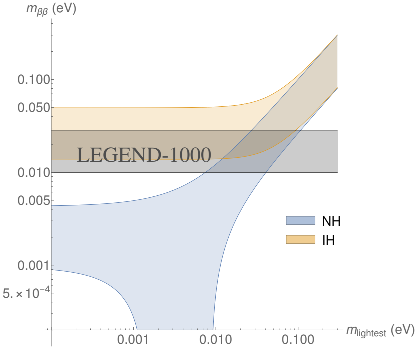


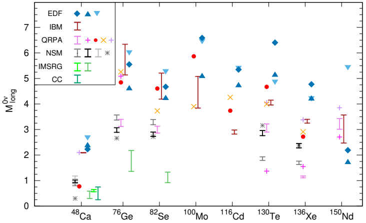
- in minimal scenario of light Majorana exchange

$$\left[T_{1/2}^{0\nu}\right]^{-1} = G_{01}\,\frac{m_{\beta\beta}^2}{m_e^2}\,g_A^2\left(M_{\text{long}}^{0\nu} + g_\nu^{\text{NN}} M_{\text{short}}^{0\nu}\right)^2, \qquad m_{\beta\beta} = \left|\sum_i U_{ei}^2 m_i\right|$$

g_A, g_ν^{NN}: 1- and 2-nucleon params, $M_{\text{long}}^{0\nu}$, $M_{\text{short}}^{0\nu}$: nuclear matrix elements

The impact of hadronic and nuclear uncertainties: Neutrinoless double beta decay





M. Agostini, G. Benato,
J. Detwiler, J. Menendez, F. Vissani '22

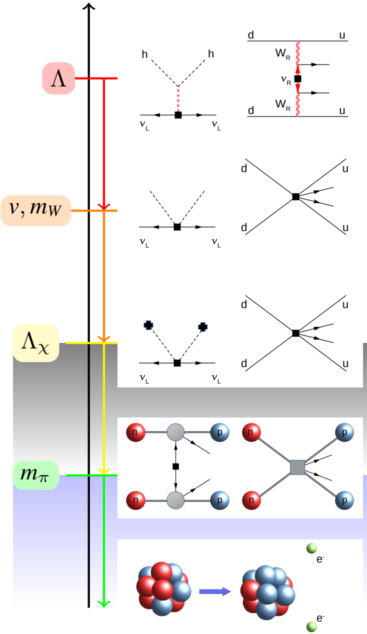
- in minimal scenario of light Majorana exchange

$$\left[T^{0\nu}_{1/2}\right]^{-1} = G_{01}\,\frac{m^2_{\beta\beta}}{m_e^2}\,g_A^2\left(M^{0\nu}_{\rm long} + g_\nu^{\rm NN} M^{0\nu}_{\rm short}\right)^2, \qquad m_{\beta\beta} = \left|\sum_i U_{ei}^2 m_i\right|$$

g_A, $g_\nu^{\rm NN}$: 1- and 2-nucleon params, $\quad M^{0\nu}_{\rm long}$, $M^{0\nu}_{\rm short}$: nuclear matrix elements

- impact of next gen. of experiments on neutrino physics affected by uncertainties

Effective Field Theories approach to BSM searches



new physics $\Lambda \gg v$

SMEFT operators

$SU(3)_c \times U(1)_{\rm em}$ operators

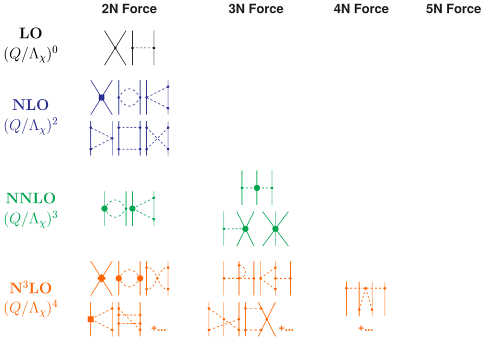
non perturbative QCD

Chiral Effective Theory

strong nuclear interactions

Many body

Chiral EFT



from D. R. Entem and R. Machleidt, '17

see also:

P. Reinert, H. Krebs, E. Epelbaum, '18

M. Piarulli *et al*, '16

M. Piarulli *et al*, '14

A. Nogga, R. Timmermans, B. van Kolck, '05

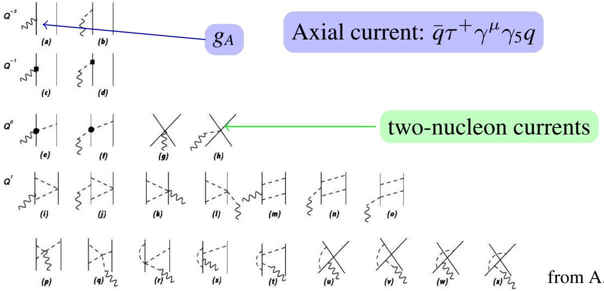
D. Kaplan, M. Savage, M. Wise, '96

Exploit QCD symmetries & scale separation in hadronic/nuclear physics

$$Q \sim m_\pi \ll \Lambda_\chi = 4\pi F_\pi \sim 1 \text{ GeV}$$

- expand *NN* potential and external currents in Q/Λ_χ
- LECs are fit to data in 2- and 3-nucleon systems
- reproduce well light-nuclear systems
- small expansion parameter allow for uncertainty estimation

External currents in chiral EFT



from A. Baroni *et al*, '16

- derive external currents consistent w. nuclear potential

  e.g. vector, axial, scalar, pseudoscalar, tensor

- framework can be applied to symmetry-breaking potentials

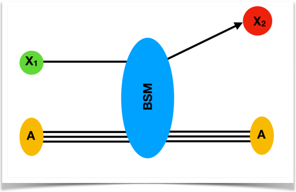
  e.g. neutrino potential in $0\nu\beta\beta$, P- and T-violating potentials

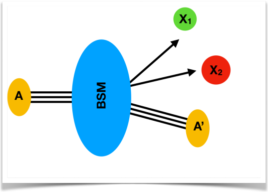
Outline

1. One-body currents
2. Two-current insertions
3. Electric dipole moments
4. Two-body operators

One-body currents

BSM processes dominated by 1-body currents

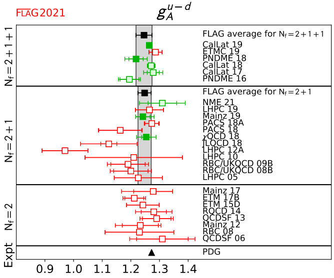


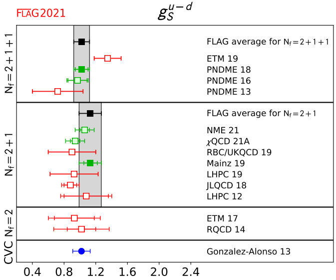


$$\mathcal{L}^{\text{BSM}} = \bar{q}\Gamma\tau^a q\mathcal{X}_a + \bar{q}\Gamma q\mathcal{X}_0 + \bar{s}\Gamma s\mathcal{X}_s, \qquad q = (u,d)^T, \qquad \Gamma = \{1, \gamma_5, \gamma^\mu, \gamma^\mu\gamma_5, \sigma^{\mu\nu}\}$$

- non-standard charged-currents in β decays $\qquad \mathcal{X}_+ = \bar{e}\,\Gamma\nu$
- coherent neutrino-nucleus scattering (CEνNS) $\qquad \mathcal{X}_{u,d,s} = \bar{\nu}\gamma_\mu\nu$
- $\mu \to e$ conversion in nuclei $\qquad \mathcal{X}_{u,d,s} = \bar{e}\Gamma\mu$
- dark-matter - nucleus scattering $\qquad \mathcal{X}_{u,d,s} = \bar{\chi}\Gamma\chi$
- neutron EDM from qEDM, molecular electric dipole moments $\qquad \mathcal{X}_{u,d,s} = \bar{e}\gamma_5 e,\ \tilde{F}_{\mu\nu}$

1-body currents





- chiral EFT construction of the currents at very high order

  S. Pastore *et al.*, '09; Kölling *et al.* '09, '16; A. Baroni *et al.*, '16; H. Krebs *et al.*, '17, '20; M. Hoferichter *et al.*, '15

- most important input from single nucleon charges

1. isovector charges very well determined on the lattice

$$g_A^{\mathrm{QCD}} = 1.264 \pm 0.009$$

A. Walker-Loud *e*t al (CalLat collaboration) '19

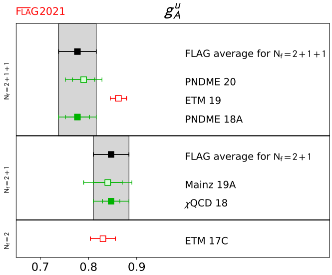
limited by QED and isospin breaking

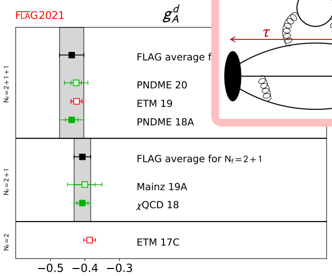
1-body currents

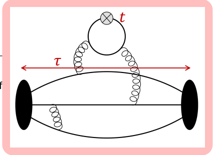
Collaboration	Ref.	N_f	publication status	continuum extrapolation	chiral extrapolation	finite volume	renormalization	excited states	g_A^{u-d}
CalLat 19	[148]	2+1+1	C	○	★	★	★	○	1.2642(93)
ETM 19	[149]	2+1+1	A	■	○	★	★	○	1.286(23)
PNDME 18[a]	[50]	2+1+1	A	★‡	★	★	★	○	1.218(25)(30)
CalLat 18	[51]	2+1+1	A	○	★	★	★	○	1.271(10)(7)
CalLat 17	[47]	2+1+1	P	○	★	★	★	○	1.278(21)(26)
PNDME 16[a]	[46]	2+1+1	A	○‡	★	★	★	○	1.195(33)(20)
NME 21[a]	[150]	2+1	P	○‡	★	★	★	○	1.31(6)(5)
LHPC 19	[13]	2+1	A	■‡	★	★	★	○	1.265(49)
Mainz 19	[84]	2+1	A	★	○	★	★	○	$1.242(25)(^{+0}_{-0.030})$
PACS 18A	[11]	2+1	A	■	★	★	★	○	1.273(24)(5)(9)
PACS 18	[9]	2+1	A	■	■	★	★	■	1.163(75)(14)
χQCD 18	[26]	2+1	A	○	★	★	★	○	1.254(16)(30)[$]
JLQCD 18	[60]	2+1	A	■	○	○	★	○	1.123(28)(29)(90)
LHPC 12A[b]	[151]	2+1	A	■‡	★	★	★	○	0.97(8)
LHPC 10	[68]	2+1	A	■	○	■	★	■	1.21(17)
RBC/UKQCD 09B	[53]	2+1	A	■	■	○	★	■	1.19(6)(4)
RBC/UKQCD 08B	[52]	2+1	A	■	■	○	★	■	1.20(6)(4)
LHPC 05	[152]	2+1	A	■	■	★	★	■	1.226(84)
Mainz 17	[36]	2	A	★	★	★	★	■	$1.278(68)(^{+0}_{-0.087})$
ETM 17B	[40]	2	A	■	○	○	★	○	1.212(33)(22)
ETM 15D	[38]	2	A	■	○	○	★	○	1.242(57)
RQCD 14	[34]	2	A	○	★	★	★	■	1.280(44)(46)
QCDSF 13	[32]	2	A	○	★	■	★	■	1.29(5)(3)
Mainz 12	[33]	2	A	★	○	○	★	■	$1.233(63)(^{+0.035}_{-0.060})$
RBC 08	[153]	2	A	■	■	■	★	■	1.23(12)
QCDSF 06	[30]	2	A	○	■	■	★	■	1.31(9)(7)

before ‘15
Long Range Plan

Isoscalar and strange matrix elements





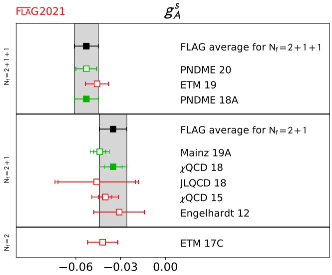


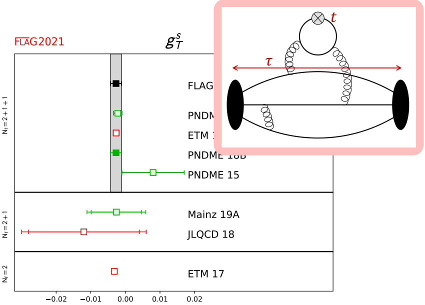
- needed for neutral current processes ($\mu \to e$, CEνNS, …) if BSM has generic couplings to quark flavors

2. sensitivity to disconnected diagrams increases uncertainties in u, d
3. s matrix elements not (yet) satisfactory

$$g_A^s \in [-0.061, -0.026], \qquad g_T^s = -0.0027(16)$$

Isoscalar and strange matrix elements





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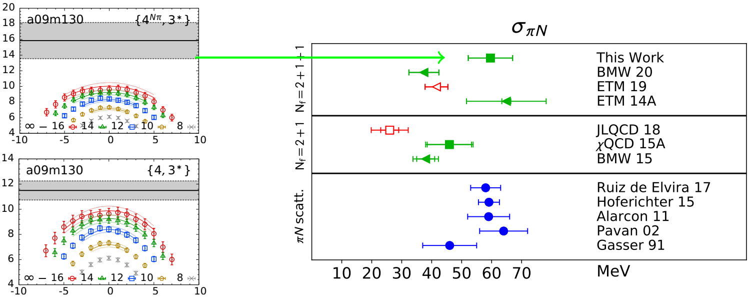
The nucleon σ term

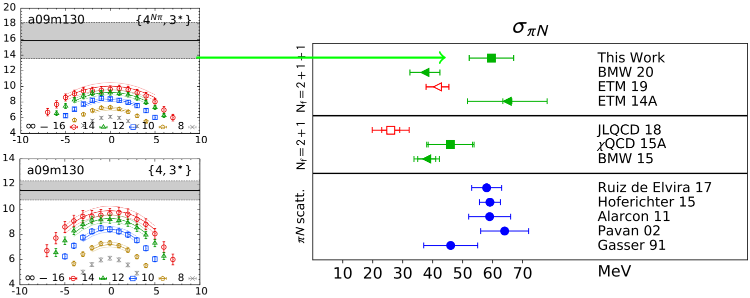


R. Gupta, *et al*, ‘21

- matrix element of the scalar charge, important for Higgs-mediated BSM
- long-standing discrepancy between LQCD and extractions from πN scattering
- very sensitive to low-lying excited state ($N\pi$ and $N\pi\pi$)
- $\sigma_{\pi N}$ compatible with πN scattering with narrow priors around $N\pi$

need better ESC control at small m_π!

The nucleon σ term



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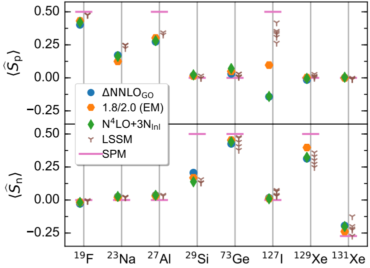
  need better ESC control at small m_π!
- new strategies for signal-to-noise problem?

  M. Wagman and M. Savage, '17; W. Detmold, G. Kanwar, H. Lamm, M. Wagman, N. Warrington, '21;
- variational methods?



B. S. Hu, J. Padua-Arguelles, S. Leutheusser, T. Miyagi, S. R. Stroberg, J. D. Holt, '21

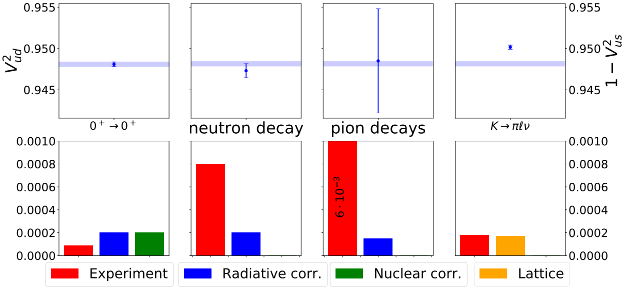
- several new shell-model calculations for DM, CEνNS and $\mu \to e$

  M. Hoferichter, J. Menéndez, A. Schwenk, '20; W. C. Haxton, E. Rule, M. J. Ramsey-Musolf, '22; M. Hoferichter, J. Menéndez, F. Noël, '22

- first *ab initio* calculation in good agreement with shell-model

Two-current insertions

CKM unitarity and the Cabibbo anomaly



- improved radiative corrections to $0^+ \to 0^+$ Fermi decays

  C. Y. Seng, M. Gorchtein, H. Patel, M. Ramsey-Musolf, '18;
  A. Czarnecki, W. Marciano, A. Sirlin, '19; J. C. Hardy and I. S. Towner, '20

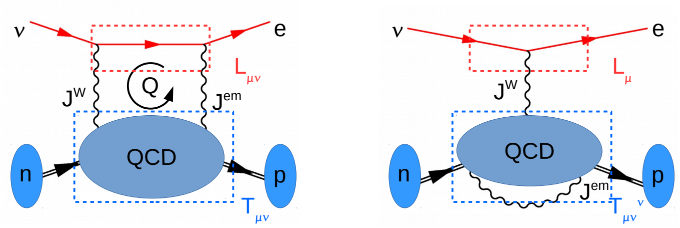
- high-precision lattice QCD calculations of f_K/f_π and $f_+(0)$

$$\Delta = 1 - |V_{ud}|^2 - |V_{us}|^2 - |V_{ub}|^2 = (1.5 \pm 0.7) \cdot 10^{-3}$$

2σ deviation!

- theory driven, needs to be validated

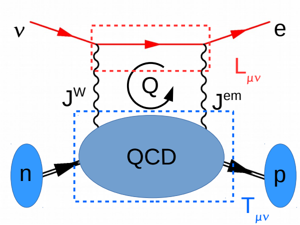
Radiative corrections to nucleon decay

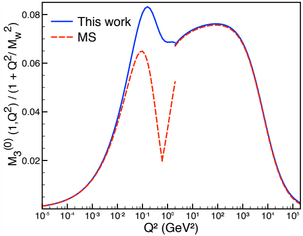


$$|V_{ud}|^2_{\text{neutron}} = \frac{5024.7\,\text{s}}{\tau_n(1+3g_A^2)(1+\delta_R(E_0)+\Delta_R^V)}, \qquad \Delta_R^V = \frac{\alpha}{2\pi}\left(4\ln\frac{m_Z}{m_p}+\Delta_{\text{np}}\right)$$

- $\delta_R(E_0)$ (universal soft photon emission) and ptb. log dominate EM corrections
- Δ_{np} is nonperturbative and small, but dominates the error
- for Fermi decays, Δ_{np} proportional to the $W-\gamma$ box

Radiative corrections to nucleon decay





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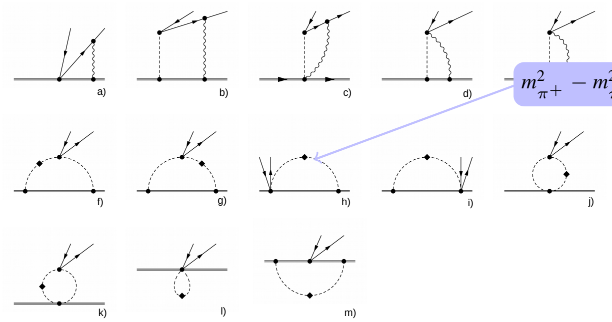
- Δ_{np} is nonperturbative and small, but dominates the error
- for Fermi decays, Δ_{np} proportional to the $W-\gamma$ box
- new dispersive analysis

$$\Delta_R^V = 0.02361(38) \to 0.02467(22)$$

C. Y. Seng, M. Gorchtein, M. Ramsey-Musolf, '18; + H. Patel, '18.

can be validated with LQCD?

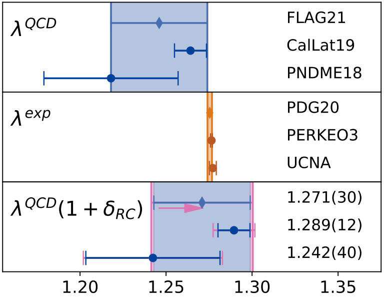
Radiative corrections to g_A



$$m_{\pi^+}^2 - m_{\pi^0}^2 = 2Z_\pi F_\pi^2 e^2$$

- chiral EFT analysis pointed out overlooked pion-mediated EM corrections

Radiative corrections to g_A



$$g_A = g_A^{\rm QCD}\left(1 + \frac{\alpha}{2\pi}\sum \Delta_{\rm em}^{(n)}\right)$$

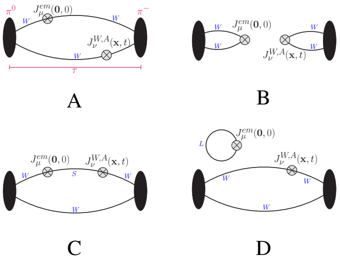
V. Cirigliano, J. de Vries, L. Hayen, EM, A. Walker-Loud, '22

- chiral EFT analysis pointed out overlooked pion-mediated EM corrections
- sizable, % level correction to g_A

$$\frac{\alpha}{2\pi}\left(\Delta_{\rm em}^{(0)} + \Delta_{\rm em}^{(1)}\right) = 1.9\% + \frac{\alpha}{2\pi}\hat{C}_A$$

- improved LQCD-data agreement, but need $\hat{C}_A$!
  $\Longrightarrow$ 2- and 3-current insertions

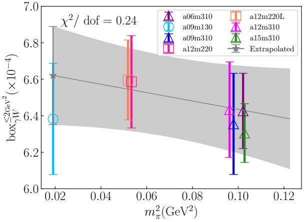
$W-\gamma$ box in Lattice QCD



thanks to B. Yoon and J. Yoo

- first calculations for $\pi^0 \to \pi^- e\nu$ & $K \to \pi\ell\nu$
- extra current insertion in C, D significantly raises the cost
- good agreement between LQCD & dispersive approach

$W-\gamma$ box in Lattice QCD



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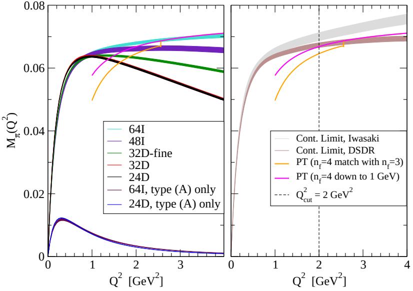

X. Feng, *et al*, '20; C. Y. Seng, *et al*, '20

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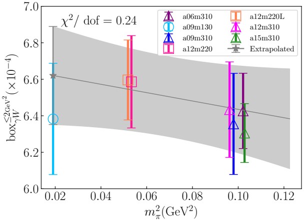

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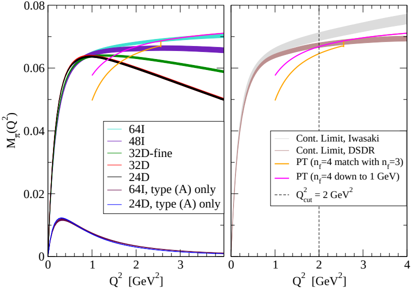

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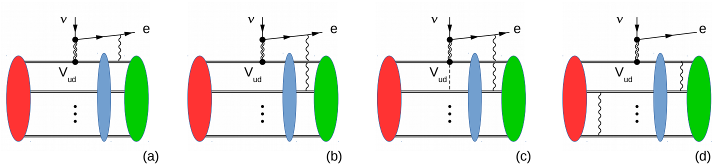
- extra current insertion in C, D significantly raises the cost
- good agreement between LQCD & dispersive approach
- first calculations for neutron decay are coming:

1. signal to noise?
2. excited state contamination?
3. beyond $W-\gamma$ box for GT ME?

Towards an EFT for radiative corrections



Δ_R^V, δ'_R δ_{NS} δ_C

$$|V_{ud}|^2_{0^+\to 0^+} = \frac{\log 2}{ft}\,\frac{\pi^3}{G_F^2 m_e^5}\,\frac{1}{1+\Delta_R^V+\delta'_R+\delta_C+\delta_{NS}}$$

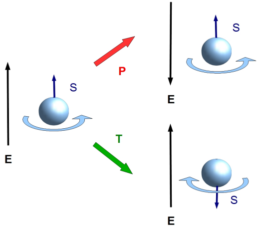
- nuclear corrections δ_{NS} and δ_C are mostly computed with nuclear models
- difficult to quantify uncertainties, can we use EFTs and *ab initio* methods?

1. construct EFT representation for δ_{NS}
2. test the formalism in simple systems, e.g. *pp* fusion, ^{3}H decay
3. use in lightest $0^+ \to 0^+$ (^{10}C $\to$ ^{10}B and ^{14}O $\to$ ^{14}N) with almost exact methods
4. extend to 23 transitions used by Towner and Hardy

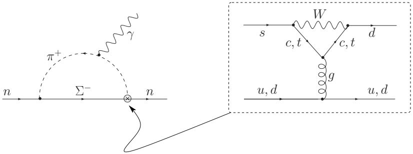
Electric dipole moments

A permanent Electric Dipole Moment (EDM)

- signal of T and P violation (CP)
- insensitive to CP violation in the SM
- BSM CP violation needed for baryogenesis



neutron

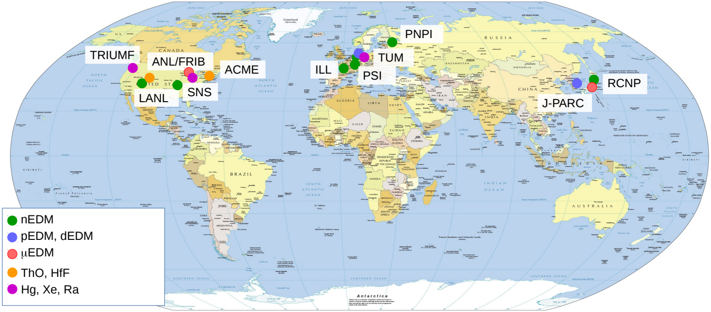


current bound
$|d_n| < 1.8 \cdot 10^{-13}\, e$ fm
nEDM Collaboration, '20

SM
$d_n \sim 10^{-19}\, e$ fm
M. Pospelov and A. Ritz, '05

- large window & strong motivations for new physics!

Electric dipole moments



- large worldwide experimental program

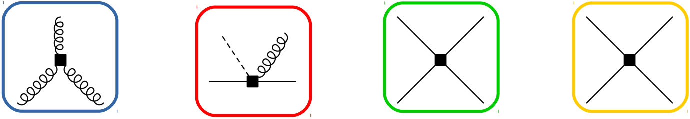
$$d_e < 1.0 \cdot 10^{-16}\, e\ \mathrm{fm} \qquad d_n < 1.8 \cdot 10^{-13}\, e\ \mathrm{fm}$$
$$d_{^{225}\mathrm{Ra}} < 1.2 \cdot 10^{-10}\, e\ \mathrm{fm} \qquad d_{^{199}\mathrm{Hg}} < 6.2 \cdot 10^{-17}\, e\ \mathrm{fm}$$

$\Lambda_{\mathrm{naive}} \sim$ 10-100 TeV

- orders of magnitude improvements in next generation of experiments
  nEDM@SNS, RaEDM at ANL/FRIB, LANL nEDM, ...

Low-energy EFT for flavor-diagonal CPV

- one dim-4 operator: QCD $\bar{\theta}$ term
- 9 (+ 10 w. strangeness) hadronic operators @ $\mathcal{O}(v^2/\Lambda^2)$:



gluon CEDM	quark (C)EDM	LL RR 4-quark	LR LR 4-quark
$C_{\tilde{G}}$	$c_{g,\gamma}^{(u,d,s)}$	$\Xi_{ud,us,ds}^{(1,8)}$	$\Sigma_{ud,us}^{(1,8)}$, $\Sigma_{us,S}^{(1,8)}$

- 3 lepton EDM + 3 semileptonic operators (hadronization well understood)

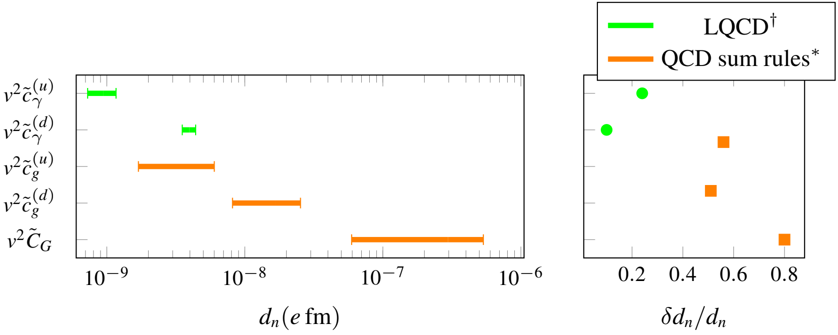
1. nucleon EDM?

$$\langle N | J_V^\mu(x) \int d^4y\, \mathcal{O}_{\not{T}}(y) | N \rangle$$

2. nucleon-nucleon TV potential?

$$\langle NN | \mathcal{O}_{\not{T}} | NN \rangle$$

Nucleon EDM matrix elements

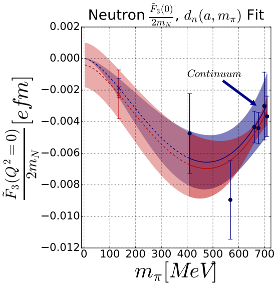


† FLAG '21

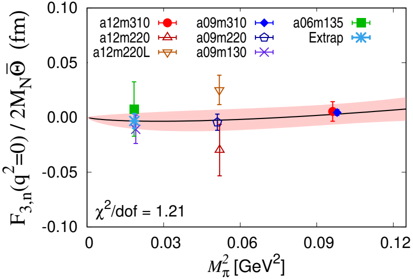
* Pospelov and Ritz, '05, Haisch and Hala, '19

- nucleon EDM from qEDM prop. to g_T
- large (uncontrolled) errors on purely hadronic operators

Lattice QCD calculations of EDMs



J. Dragos, T. Luu, A. Shindler, *et al* ‘19



T. Bhattacharya, *et al*, ‘21

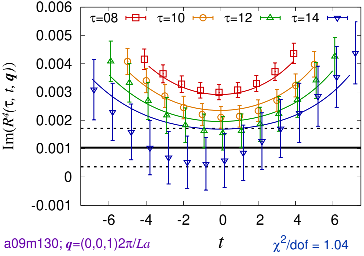
- EDM from QCD $\bar{\theta}$ term extremely challenging

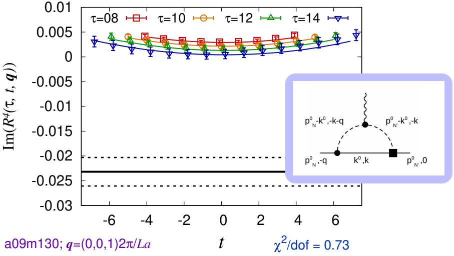
  small matrix element, vanishing signal as $m_\pi \to 0$, large excited state contamination

- published results compatible with zero, approaching $d_n \sim 10^{-3}\,\bar{\theta}\,e\,\text{fm}$

  “chiral log” prediction Crewther, Di Vecchia, Veneziano and Witten, ‘79

EDM from the QCD $\bar{\theta}$ term

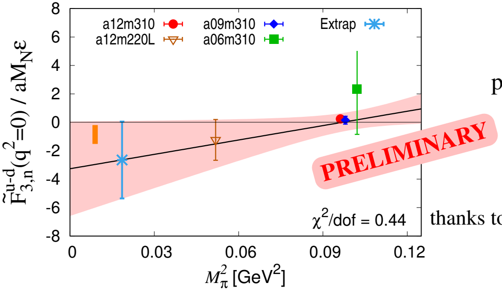




- even for $\bar{\theta} = 0.2$, signal is small $\ll \mathrm{Re}(R^4(\tau, t, \mathbf{q})) = \mathcal{O}(1)$
- EFT calculations predict $\mathcal{O}(1)$ corrections from $N(\mathbf{k})\pi(-\mathbf{k})$ and $N(\mathbf{0})\pi(-\mathbf{k})\pi(\mathbf{k})$ states
- χ^2 not enough to discriminate, leading to large error on extrapolated nEDM

5× more statistics coming soon

EDMs from dimension-6 operators



$\bar{q}\tau_3\sigma\tilde{G}q$

power div. subtracted

thanks to T. Bhattacharya and B. Yoon

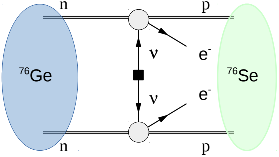
- preliminary results for qCEDM and gCEDM
- complicated by power divergences on the lattice
- error still a factor of 5 larger than QCD sum rule estimate

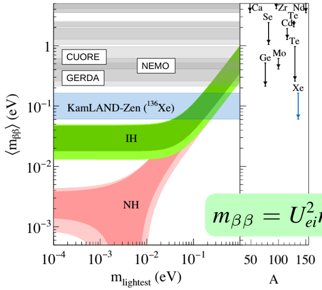
- ideas for LQCD calculations of TV (and PV) π-N couplings

J. de Vries, EM, C. Y. Seng, A. Walker-Loud, '16; X. Feng, F. K. Guo and C. Y. Seng, '17

Observables dominated by two-body operators

Neutrinoless double beta decay





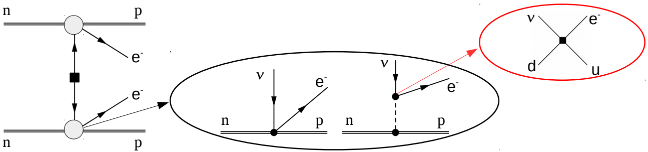
$$m_{\beta\beta} = U_{ei}^2 m_i$$

- $0\nu\beta\beta$ violates lepton number L by two units

  possible iff νs have a Majorana mass

- relation between m_ν and $0\nu\beta\beta$ depends on:
  1. assumptions on BSM physics
  2. nuclear matrix elements, e.g. $\langle {}^{76}\text{Ge} | V_{0\nu\beta\beta} | {}^{76}\text{Se} \rangle$

Consistent construction of the neutrino potential

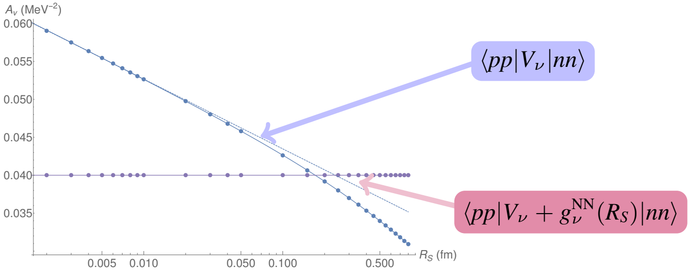


- long range ν-exchange, mediated by V, A 1-nucleon weak current
- Coulomb-like neutrino potential

$$V_\nu = G_F^2 m_{\beta\beta} \tau^{(1)+} \tau^{(2)+} \frac{1}{\mathbf{q}^2} \left\{ \mathbf{1}^{(a)} \times \mathbf{1}^{(b)} - \frac{2}{3} g_A^2 \boldsymbol{\sigma}^{(a)} \cdot \boldsymbol{\sigma}^{(b)} + \dots \right\}.$$

F. Šimkovic *et al*, '99

Consistent construction of the neutrino potential



V. Cirigliano, *et al*, '18

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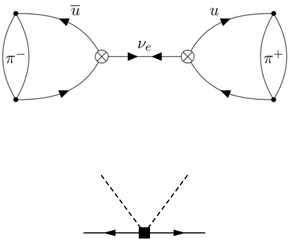
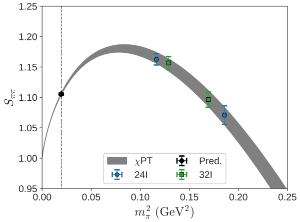
F. Šimkovic *et al*, '99

- NMEs from V_ν diverge logarithmically with the cut-off in nuclear interaction
- need to modify LO neutrino potential!

Evaluation of $g_\nu^{\rm NN}$





W. Detmold and D. Murphy, '20

- we know the RG evolution, not finite part of $g_\nu^{\rm NN}$
- LQCD offers the most direct avenue
- long distance contributions to π $0\nu\beta\beta$ already computed

$\lvert g_\nu^{\pi\pi}(\mu)\rvert_{\mu=m_\rho}$	$=$	-10.89 ± 0.79	X.-Y. Tuo, X. Feng and L.-C. Jin, '19
$\lvert g_\nu^{\pi\pi}(\mu)\rvert_{\mu=m_\rho}$	$=$	-10.78 ± 0.52	W. Detmold and D. Murphy, '20

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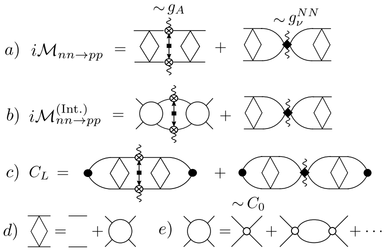
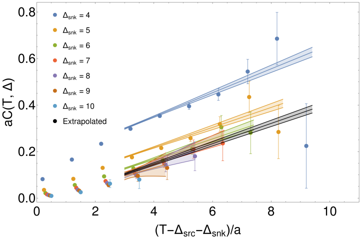


Z. Davoudi and S. Kadam, '20, '21



A. Grebe, W. Detmold, Z. Fu, D. Murphy, P. Oare, *in progress*

- need two nucleon matrix element!

$$\mathcal{A}_\nu(nn \to ppe^-e^-)$$

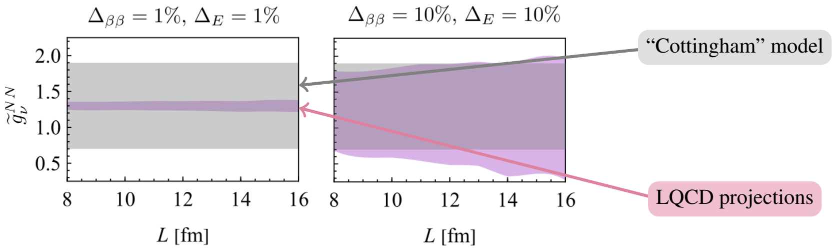
- formalism to match LQCD (euclidean, FV) to pionless EFT developed (at LO)
- preliminary calculations at heavy quark mass underway

A. Grebe, W. Detmold, Z. Fu, D. Murphy, P. Oare *in progress*

- accuracy requirements on LQCD two-nucleon MEs not too steep

Z. Davoudi, S. Kadam, '21

Evaluation of $g_\nu^{\rm NN}$



Z. Davoudi and S. Kadam, '20, '21

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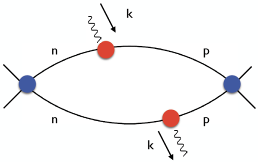
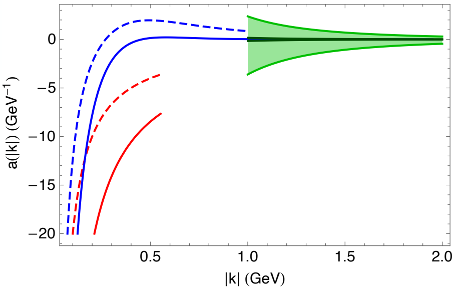
Z. Davoudi, S. Kadam, '21

“Cottingham” method



$$\mathcal{A}_\nu = \int_0^\Lambda d|\mathbf{k}|\, a_<(|\mathbf{k}|) + \int_\Lambda^{+\infty} d|\mathbf{k}|\, a_>(|\mathbf{k}|)$$



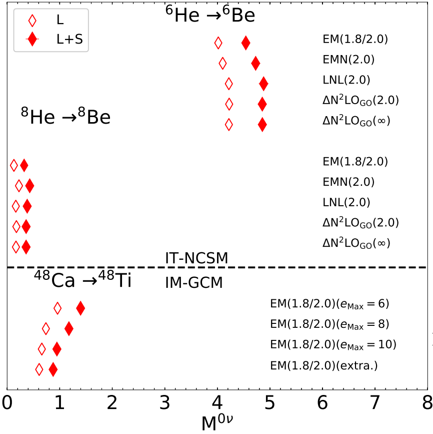
V. Cirigliano, W. Dekens, J. de Vries, M. Hoferichter, EM, ‘20, ‘21

- model the “forward Compton” scattering amplitude $W^+ nn \to W^- pp$ at small $|\mathbf{k}|$, and large $|\mathbf{k}|$

$$\tilde{g}_\nu^{\rm NN}(\mu = m_\pi) = 1.32(50)_{\rm inel}(20)_{\rm r}(5)_{\rm par} = 1.3(6)$$

- translate in scheme-independent amplitude and provide “synthetic datum” can be fit to any potential and used in *ab initio* calculations

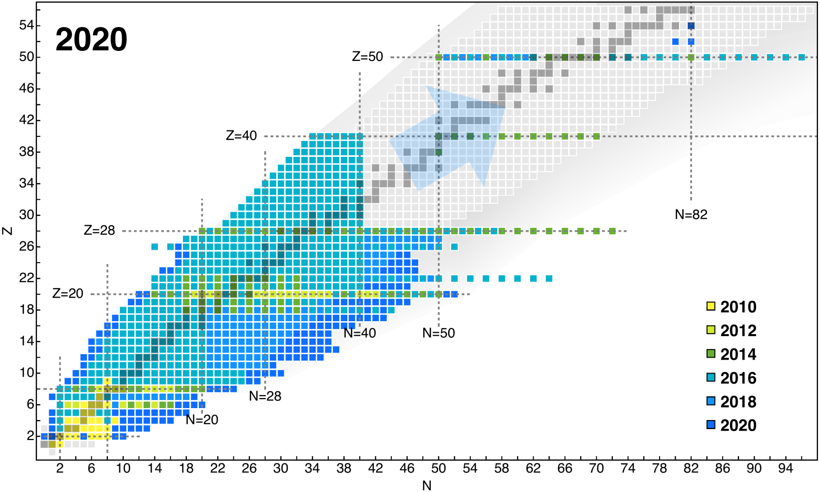
Impact on $0\nu\beta\beta$ nuclear matrix elements



R. Wirth, J. M. Yao, H. Hergert, ‘21

- short-range potential induces 40% - 50% shift

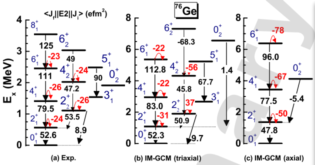
determination of g_ν^{NN} matters!

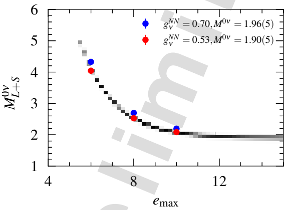


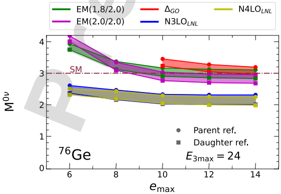
from H. Hergert, `arXiv:2008.05061`

- tremendous advance of *ab initio* methods

- **Multi-method Study of NMEs**
  - IM-GCM, VS-IMSRG - maybe more?
- **Status**
  - short-range contact ✓
  - triaxial deformation ✓
  - convergence w.r.t. basis size (✓)
  - correlations with other observables (✓)
  - **convergence of many-body expansion**
  - **parameter sensitivity analysis**
  - **uncertainty quantification**
  - currents, other mechanisms easy (can reuse computed wave functions)
- **Needs / Opportunities**
  - accelerate calculations
  - emulators for sensitivity analysis & UQ
- **Disclaimer: Status snapshot, changes with parameter analysis & UQ**







IM-GCM, EM1.8/2.0

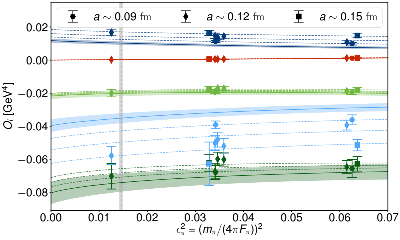
VS-IMSRG

Preliminary

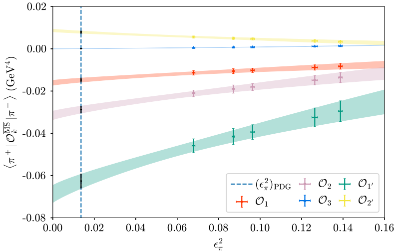
MSU, UNC-Chapel Hill, U Notre Dame, Sun Yat-Sen University, TRIUMF, CEA Saclay, UA Madrid

thanks to H. Hergert

BSM mechanisms



A. Nicholson *et al.*, CalLat coll., ‘18



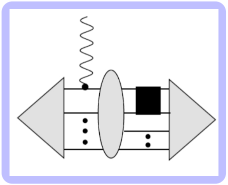
W. Detmold *et al.*, ‘22

- BSM mechanisms captured by dim-7 and dim-9 operators
- many-body input substantially the same
- but need several more meson, 1-nucleon and 2-nucleon matrix elements

$$\langle \pi^- | \bar{u}\Gamma d\, \bar{u}\Gamma d | \pi^+ \rangle$$

- lots of unjustified assumptions in the literature . . .
- and lots of progress on the lattice

Schiff moments of diamagnetic atoms



Nucl.	Best value			Range		
	a_0	a_1	a_2	a_0	a_1	a_2
^{199}Hg	0.01	$\pm$ 0.02	0.02	0.005 – 0.05	-0.03 – +0.09	0.01 – 0.06
^{129}Xe	-0.008	-0.006	-0.009	-0.005 – -0.05	-0.003 – -0.05	-0.005 – -0.1
^{225}Ra	-1.5	6.0	-4.0	-1 – -6	4 — 24	-3 – -15

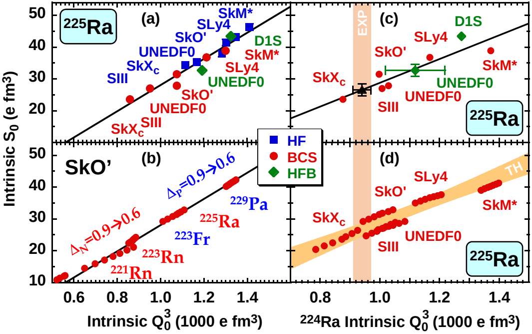
from M. Ramsey-Musolf, J. Engel, U. van Kolck, '13

- EDM depends on screening factor A and the Schiff moment

$$S = -\frac{m_N g_A}{F_\pi}\left(a_0 \frac{\bar{g}_0}{F_\pi} + a_1 \frac{\bar{g}_1}{F_\pi} + a_2 \frac{\bar{g}_2}{F_\pi}\right) e\,\mathrm{fm}^3 + (\alpha_n d_n + \alpha_p d_p)\,\mathrm{fm}^2$$

- π-N contribs. affected by large theory uncertainties
- complicate interpretation of ^{199}Hg and ^{129}Xe bounds

Schiff moments of diamagnetic atoms



J. Dobaczewski, J. Engel,
M. Kortelainen, P. Becker, '18

- error in ^{225}Ra reduced by correlations w. nuclear properties e.g. ^{224}Ra octupole moment

$$a_1 \in [4, 24] \Longrightarrow [1, 5]$$

1. can *ab initio* methods be applied?
2. can TV *NN* scattering amplitude be computed on the lattice?

Conclusion

Interpretation of next generation of Fundamental Symmetry experiments

- smooth connection between quark and hadron level pictures
- non-perturbative evalution of meson, 1-, 2-, . . ., n-nucleon matrix elements
- progress in many-body calculations
- deeper understanding of nuclear EFTs (convergence, renormalization)