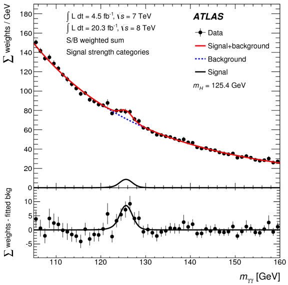
Hadronic and nuclear physics for BSM searches

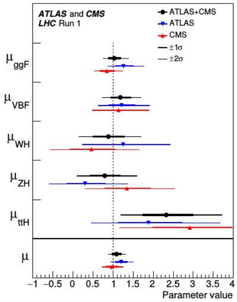
Emanuele Mereghetti

August 21st, 2019

18th International Conference on Hadron Spectroscopy and Structure, Guilin



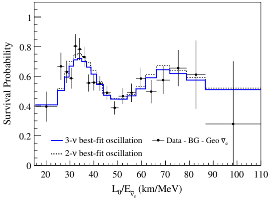
ATLAS collaboration, '14.



ATLAS & CMS, '16.

- the Standard Model works just fine
- last missing piece discovered @ LHC ... and looks SM-like

Introduction

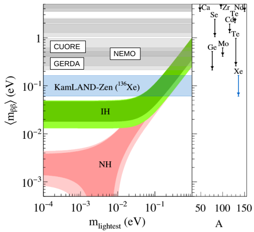


- neutrino masses

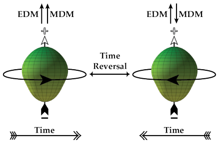
- baryogenesis

- dark matter

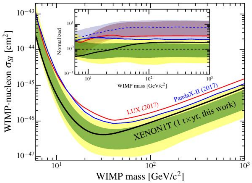
Introduction



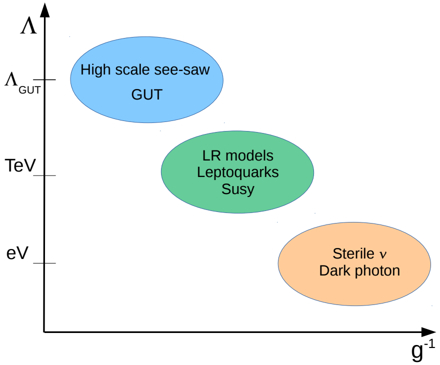
- neutrinoless double β



- EDM experiments

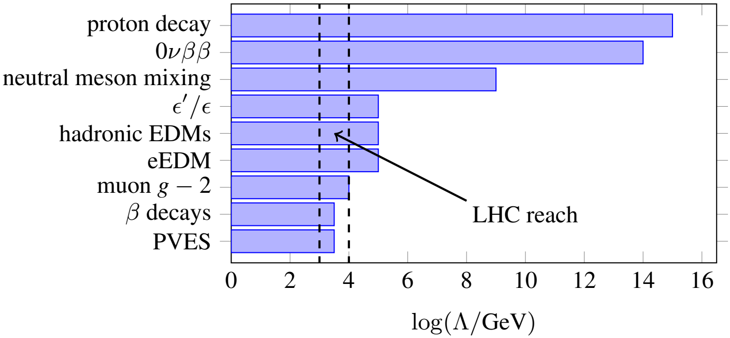


- DM direct detection



- large variety of BSM scenarios
- focus on heavy BSM physics $\Lambda \gg v = 246$ GeV

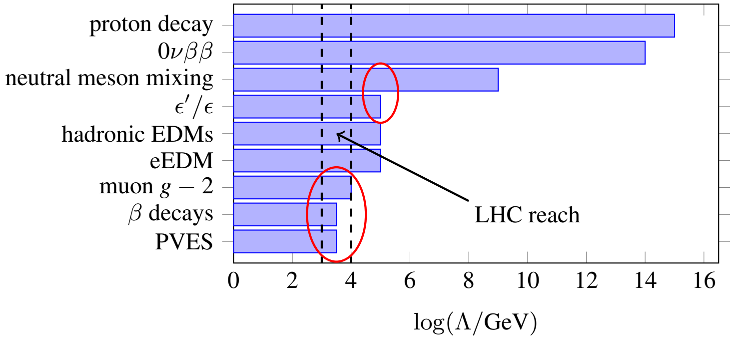
model-indep. EFT description



- large variety of BSM scenarios
- focus on heavy BSM physics $\Lambda \gg v = 246$ GeV
- low-energy experiments competitive & complementary to LHC

$\Rightarrow$ M. Zamkovsky, W. Qian and M. Saur's talks, Sat

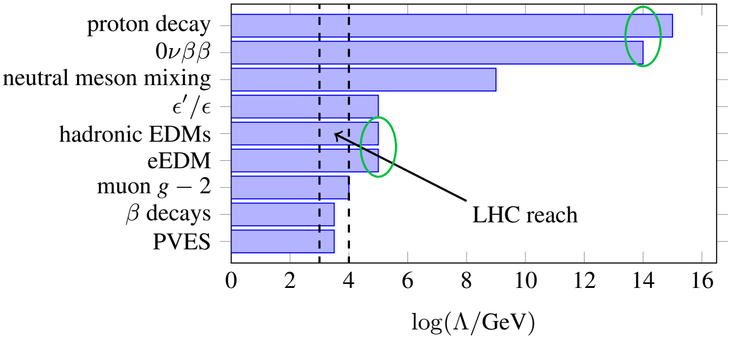
Hadronic and nuclear uncertainties



1. observables w. SM background

   precise SM background to claim discovery

Hadronic and nuclear uncertainties



1. observables w. SM background

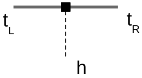
   precise SM background to claim discovery

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

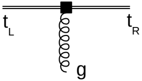
   extract microscopic symmetry violation params ($\bar{\theta}$, $m_{\beta\beta}$,...)

   compare w. high-energy exp. & disentangle BSM scenario

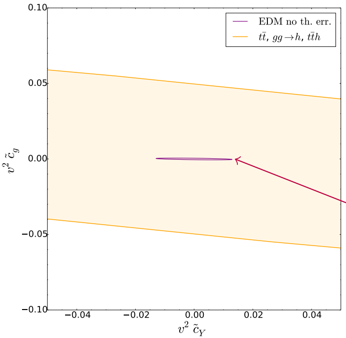
Hadronic and nuclear uncertainties

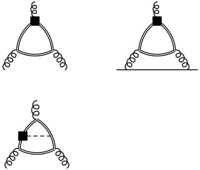


$\frac{m_t\, v}{\Lambda^2}\, \bar{t}_L t_R h$



$\frac{m_t}{\Lambda^2} \bar{t}_L \sigma^{\mu\nu} t_R G_{\mu\nu}$

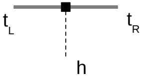




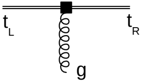
one/two-loop running to gCEDM, qCEDM

- important if baryogenesis comes from top sector
- EDM bounds much stronger than collider

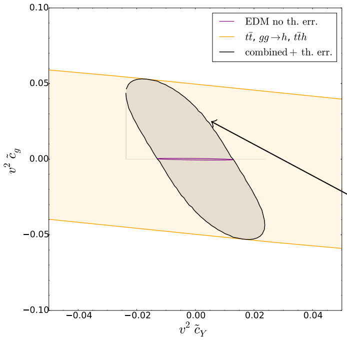
Hadronic and nuclear uncertainties

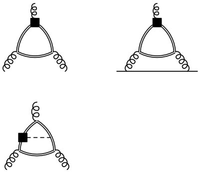


$$\frac{m_t v^2}{\Lambda^2} \bar{t}_L t_R h$$



$$\frac{m_t}{\Lambda^2} \bar{t}_L \sigma^{\mu\nu} t_R G_{\mu\nu}$$

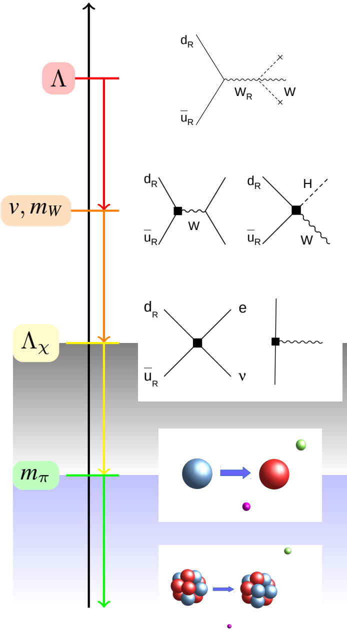




- important if baryogenesis comes from top sector
- EDM bounds much stronger than collider
- . . . but hadronic & nuclears uncertainties weaken bounds

$$\langle n | J^{\mu}_{\rm em}\, G\tilde{G} | n \rangle = ? \qquad \langle {}^{225}{\rm Ra} | J^{\mu}_{\rm em}\, G\tilde{G} | {}^{225}{\rm Ra} \rangle = ?$$

Effective Field Theories



new physics $\Lambda \gg v$

SM-EFT operators

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

non perturbative QCD

Chiral Effective Theory

strong nuclear interactions

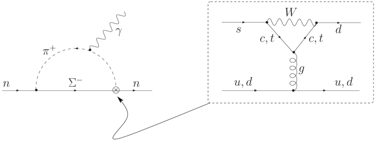
Many body

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

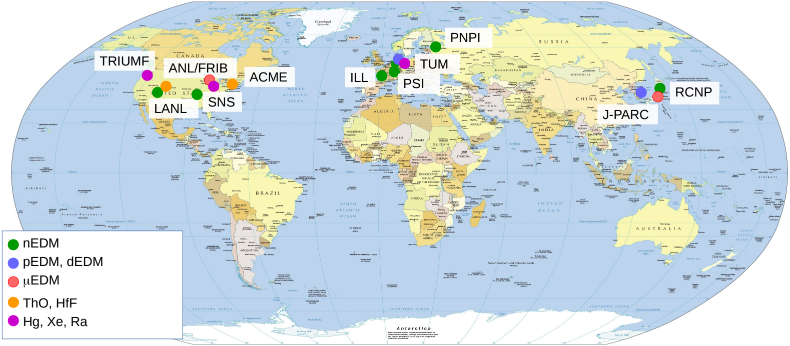


current bound
$|d_n| < 3.0 \cdot 10^{-13}\, e$ fm
J. M. Pendlebury *et al.*, '15

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

- large window & strong motivations for new physics!

EDM experiments worldwide



- goals for the next EDM generation

$$\begin{array}{llll} d_e & < 1.0 \cdot 10^{-17}\ e\ \text{fm} & d_n & < 1.0 \cdot 10^{-15}\ e\ \text{fm} \\ d_d & < 1.0 \cdot 10^{-16}\ e\ \text{fm} & d_{^{225}\text{Ra}} & < 1.0 \cdot 10^{-14}\ e\ \text{fm} \\ d_p & < 1.0 \cdot 10^{-16}\ e\ \text{fm} & & \ldots \end{array}$$

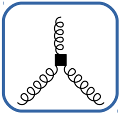
Low-energy EFT for flavor-diagonal T violation

After integrating out heavy SM d.o.f.

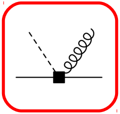
- one dim-4 operator: QCD $\bar{\theta}$ term

$$\mathcal{L}_{\not{T}\,4} = m_* \bar{\theta} \bar{q} i \gamma_5 q$$

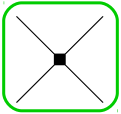
- 9 (+ 10 w. strangeness) hadronic operators @ $\mathcal{O}(v^2/\Lambda^2)$:



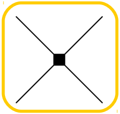
gluon CEDM
$C_{\tilde{G}}$



quark (C)EDM
$c_{g,\gamma}^{(u,d,s)}$

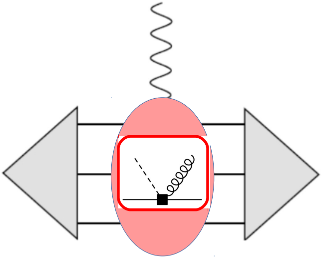


LL RR 4-quark
$\Xi_{ud,us,ds}^{(1,8)}$



LR LR 4-quark
$\Sigma_{ud,us}^{(1,8)}$, $\Sigma_{us,S}^{(1,8)}$

how many observables to pinpoint $\bar{\theta}$ term?
how to disentangle BSM mechanisms?

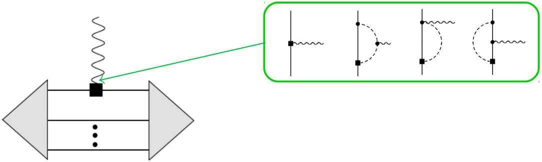


- nucleon and nuclear EDMs as a function of quark/gluon operators?

Chiral EFT

- systematic expansion of π, π-N interactions
  NN potentials and currents in $\epsilon_\chi \equiv \{Q, m_\pi\}/\Lambda_\chi,\ \ \Lambda_\chi \sim 1$ GeV

$\Rightarrow$ Lisheng Geng's talk, Tue



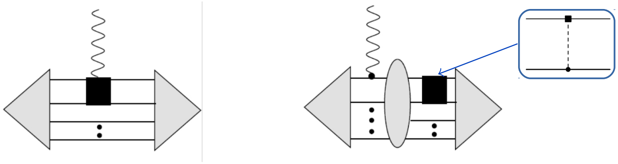
$$\mathcal{L}_{\not{T}} \quad = \quad -2\bar{N}\left(\bar{d}_0 + \bar{d}_1\tau_3\right) S^\mu v^\nu N F_{\mu\nu} - \frac{\bar{g}_0}{F_\pi}\bar{N}\boldsymbol{\pi}\cdot\boldsymbol{\tau}N - \frac{\bar{g}_1}{F_\pi}\pi_3\bar{N}N + \dots$$

- operators in $\mathcal{L}_{\not{T}}$ & scaling of couplings dictated by chiral symmetry

$\bar{d}_0, \bar{d}_1$ neutron & proton EDM,
one-body contribs. to A $\geq$ 2 nuclei

$\bar{g}_0, \bar{g}_1$ pion loop to nucleon & proton EDMs, leading OPE $\not{T}$ potential

relative size of the couplings
depends on chiral/isospin properties of $\not{T}$ source



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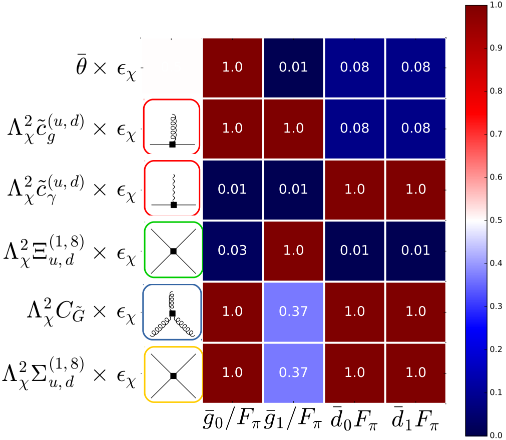
Hadronic EFTs

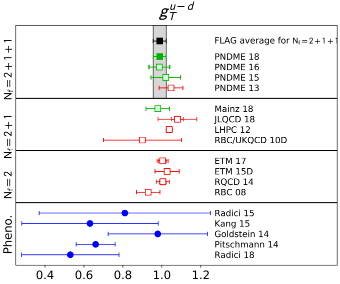


WARNING
naive dim. analysis!

- chiral breaking operators generate large $\bar g_0$
- chiral & isospin breaking large $\bar g_1$
- can we be more precise?

Hierarchies observable in experiment

Nucleon EDM from qEDM



FLAG 2019

modified by R. Gupta

$$\mathcal{L}_{\text{qEDM}} = m_q \tilde{c}_q \, \bar{q} \sigma_{\mu\nu} q \, \varepsilon^{\alpha\beta\mu\nu} F_{\mu\nu} \quad \Longrightarrow \quad d_N \propto \langle N | \bar{q} \sigma^{\mu\nu} q | N \rangle \equiv g_T$$

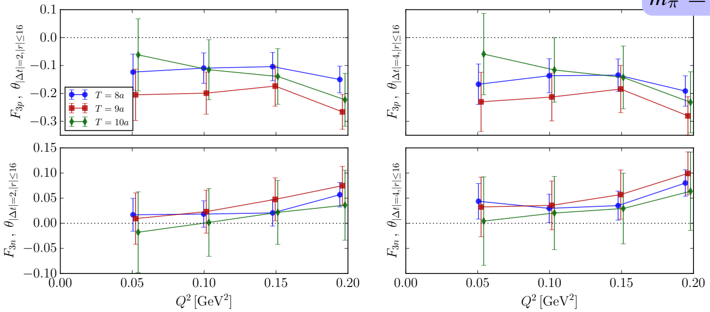
- single nucleon charges well determined by LQCD
- $\sim 5\%$ uncertainty on u, d
- first signal for s, $g_T^s = -0.0027 \pm 0.0016$

discrepancy with transversity?

$\Rightarrow$ Z. Kang and Z. Zhao's talks, Tue

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

$m_\pi = 139$ MeV



S. Syritsyn, T. Izubuchi, H. Ohki, '19

$$d_N \propto \langle N|G\tilde{G}(x)J^\mu_{\rm em}(y)|N\rangle$$

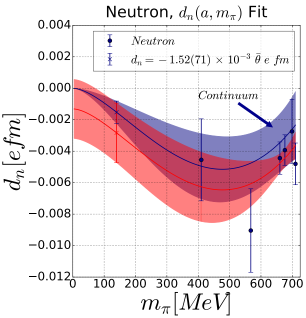
- sustained effort from LQCD

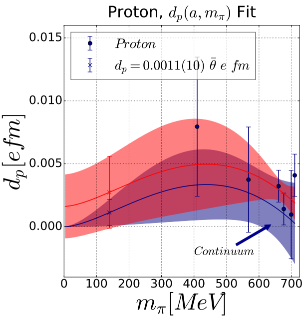
  S. Syritsyn *et al* @ RIKEN-BNL; A. Shindler *et al* @ MSU; T. Bhattacharya *et al*, LANL; ...

- no signal at physical pion mass, preliminary results @ heavier pions

  expect results on experiment timescale

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





J. Dragos, T. Luu, A. Shindler, J. de Vries, A. Yousif, '19

$$d_N \propto \langle N | G\tilde{G}(x) J^{\mu}_{\text{em}}(y) | N \rangle$$

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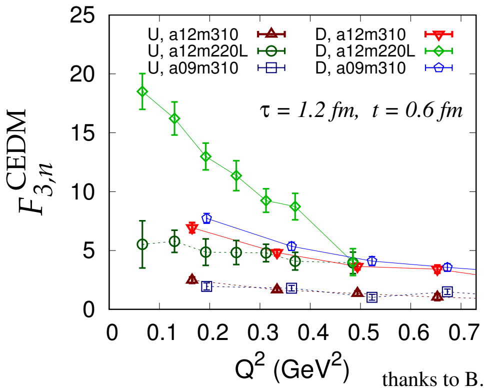
Nucleon EDM from dim. 6 hadronic operators

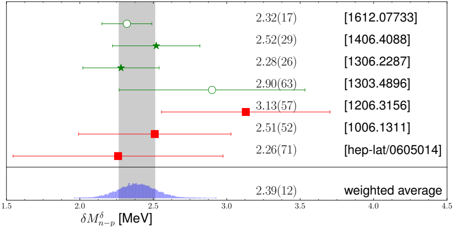


thanks to B. Yoon and T. Bhattacharya

- qCEDM more promising

  but still preliminary, e.g no renormalization
- gCEDM, 4-quark operators . . . work in progress

CPV pion nucleon couplings



thanks to A. Walker-Loud

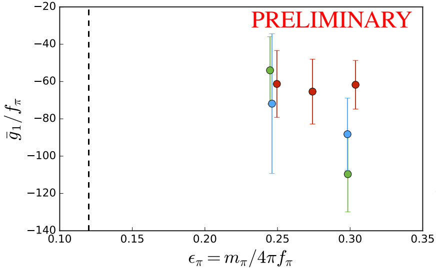
- π-N couplings crucial for nuclear EDMs & Schiff moments
- χ-symmetry relates π-N couplings to spectral properties

e.g. for $\bar{\theta}$: $\quad \bar{q}i\gamma_5 q \Longrightarrow \bar{q}\tau_3 q$

$$\frac{\bar{g}_0}{F_\pi}(\bar{\theta}) = \frac{(m_n - m_p)|_{\text{str}}}{F_\pi}\frac{1-\varepsilon^2}{2\varepsilon}\bar{\theta} = (15.5 \pm 2.0 \pm 1.6)\cdot 10^{-3}\bar{\theta}$$

LQCD $\qquad$ N^2LO χPT

CPV pion-nucleon couplings. qCEDM



thanks to D. Brantley, CalLat coll.

- can use similar relations to spectrum

$$\bar{g}_0 = (m_u\tilde{c}_g^{(u)} + m_d\tilde{c}_g^{(d)})\left(\sigma_C^3 - r\sigma^3\right), \qquad r = \frac{\langle 0|g_s\bar{q}\sigma\cdot Gq|0\rangle}{2\langle 0|\bar{q}q|0\rangle}$$

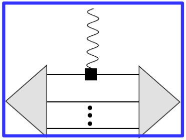
$$\bar{g}_1 = (m_u\tilde{c}_g^{(u)} - m_d\tilde{c}_g^{(d)})\left(\sigma_C^0 - r\sigma^0\right), \qquad \sigma_C^{0,3} = \langle N|g_s\bar{q}\sigma\cdot G\{1,\tau^3\}q|N\rangle/2$$

$$\sigma^{0,3} = \langle N|\bar{q}\{1,\tau^3\}q|N\rangle$$

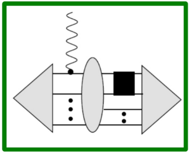
- any other handles on generalized sigma terms? higher-twist chiral-odd distributions?

C. Y. Seng, '18

From nucleons to nuclei: light nuclei as “chiral filters”



One-body $\not{T}$ current



NN $\not{T}$ potential

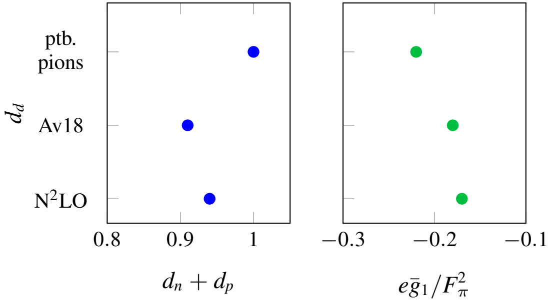
$$d_A = \alpha_n d_n + \alpha_p d_p + a_0 e \frac{\bar{g}_0}{F_\pi^2} + a_1 e \frac{\bar{g}_1}{F_\pi^2}, \qquad \alpha_{n,p} \sim a_{0,1} = \mathcal{O}(1)$$

- EDM of light nuclei enhanced w.r.t. d_n, d_p for χ-breaking sources

  $$d_A = \mathcal{O}(\epsilon_\chi^{-2}) d_n$$

  if $a_{0,1} = \mathcal{O}(1)$ & $\bar{g}_{0,1}$ follow NDA
- different nuclei have different sensitivities to $\bar{g}_{0,1}$
  e.g. $a_0 = 0$ for d_d

Ab initio calculations of d_d

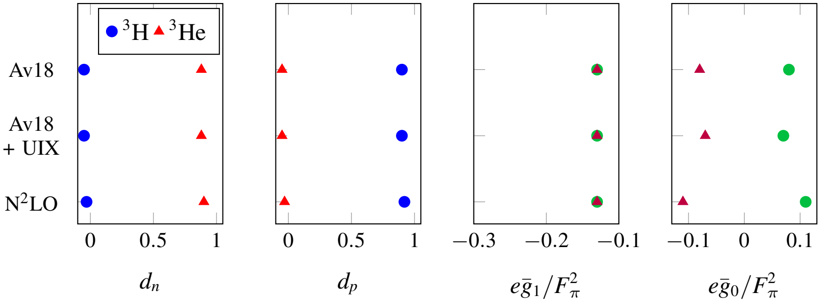


- several calculations pheno & chiral T-conserving potentials

C. P. Liu and R. Timmermans, ‘05; J. de Vries *et al*, ‘11;
J. Bsaisou *et al*, ‘13, J. Bsaisou *et al*, ‘15;
N. Yamanaka and E. Hiyama, ‘15

- one-body & $\not{T}$ OPE contribution not affected by different potentials

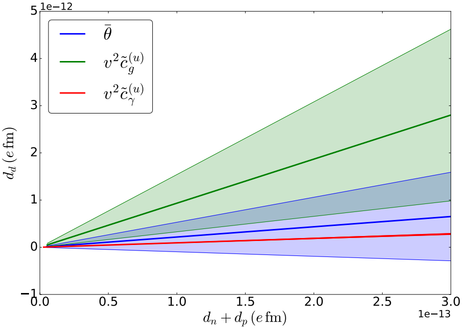
EDM of ^{3}He and ^{3}H



- additonal texture from ^{3}H, ^{3}He $\Longrightarrow$ sensitive to $\bar{g}_0$
- one-body not affected by different potentials
- OPE agrees well with ptb. pion counting

$$< 10\% \text{ error on } \bar{g}_1$$
$$\sim 30\% \text{ error on } \bar{g}_0$$

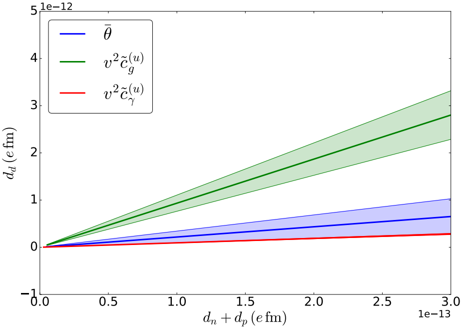
Disentangling $\not{T}$ mechanisms



- $d_d \gg d_n + d_p$ isospin-breaking sources
  $d_d \sim d_n + d_p$ QCD $\bar{\theta}$ term
  $d_d = d_n + d_p$ qEDM

  …but swamped by current theory uncertainties
- $\mathcal{O}(20\%)$ uncertainties sufficient to discriminate!

Disentangling $\not{T}$ mechanisms



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Neutrinoless double beta decay

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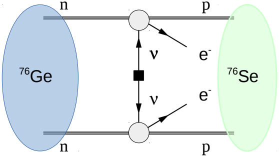
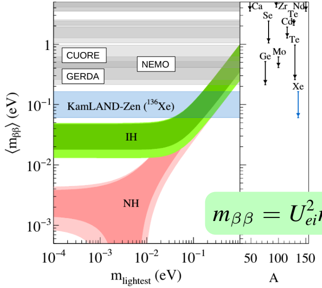




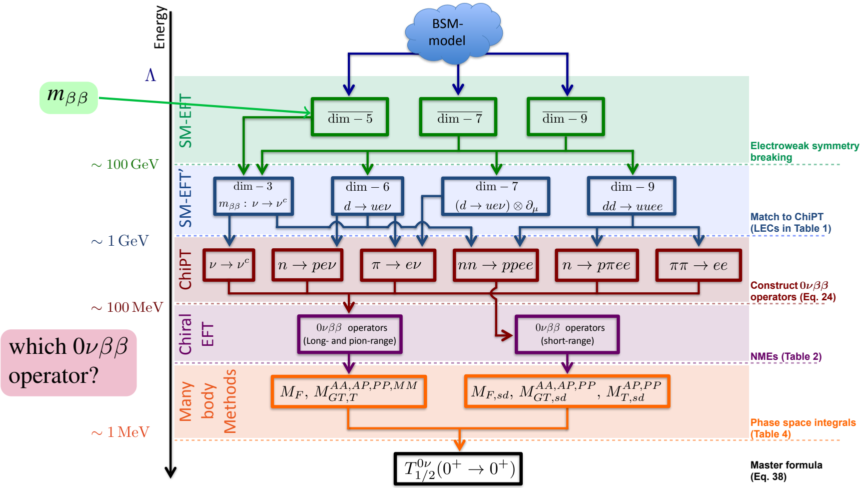
$$m_{\beta\beta} = U_{ei}^2 m_i$$

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

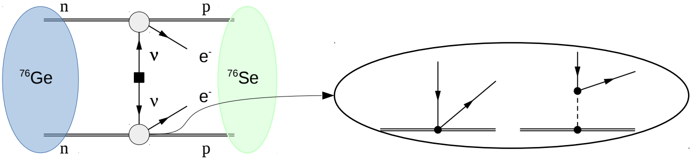
  possible iff νs have a Majorana mass

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

EFT approach to LNV



Light-ν exchange mechanism in chiral EFT



- LO $0\nu\beta\beta$ operator is two-body

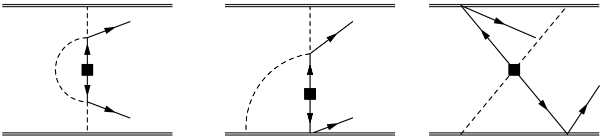
$$V_\nu = \mathcal{A}\tau^{(1)+}\tau^{(2)+}\frac{1}{\mathbf{q}^2}\left\{\mathbf{1}^{(a)}\times\mathbf{1}^{(b)} - g_A^2\boldsymbol{\sigma}^{(a)}\cdot\boldsymbol{\sigma}^{(b)}\left(\frac{2}{3}+\frac{1}{3}\frac{m_\pi^4}{(\mathbf{q}^2+m_\pi^2)^2}\right)+\dots\right\}.$$

$$\mathcal{A} = 2G_F^2 m_{\beta\beta}\,\bar{e}_L C\,\bar{e}_L^T$$

agree with all $0\nu\beta\beta$ literature

- Coulomb-like long-range component determined by nucleon axial and vector FF

Light-ν exchange mechanism. Higher orders



V. Cirigliano, W. Dekens, EM, A. Walker-Loud, '17

At N^2LO $\quad \mathcal{O}(\mathbf{q}^2/\Lambda_\chi^2)$, $\quad \Lambda_\chi = 4\pi F_\pi \sim 1$ GeV

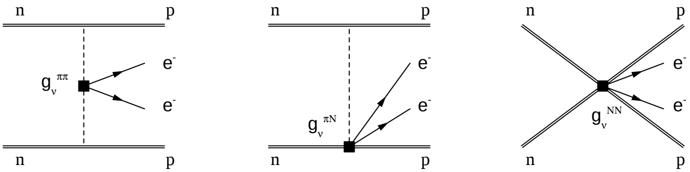
1. correction to the one-body currents (magnetic moment, radii, ...)

$$g_A(\mathbf{q}^2) = g_A\left(1 - r_A^2\,\frac{\mathbf{q}^2}{6} + \ldots\right)$$

2. two-body corrections to V and A currents
3. pion-neutrino loops & local counterterms

UV divergences signal short-range sensitivity at N^2LO
$g_\nu^{\pi\pi}$, $g_\nu^{\pi N}$ and g_ν^{NN} require new calculations

Light-ν exchange mechanism. Higher orders



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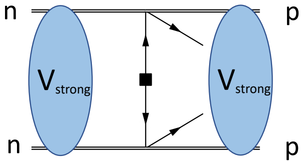
UV divergences signal short
$g_\nu^{\pi\pi}$, $g_\nu^{\pi N}$ and $g_\nu^{\rm NN}$ require ne

WARNING: based on naive dimensional analysis "Weinberg's counting"

Is Weinberg's counting consistent for $0\nu\beta\beta$



- Weinberg's counting fails in $^1S_0$ channel   D. Kaplan, M. Savage, M. Wise, '96
- study $nn \to ppe^-e^-$ with LO χEFT strong potential

$$V_{\text{strong}}(r) = \tilde{C}\,\delta^{(3)}(\mathbf{r}) + \frac{g_A^2 m_\pi^2}{16\pi F_\pi^2}\frac{e^{-m_\pi r}}{4\pi r}$$

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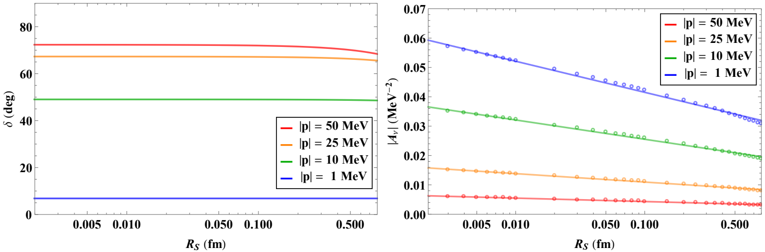

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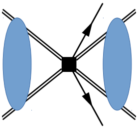
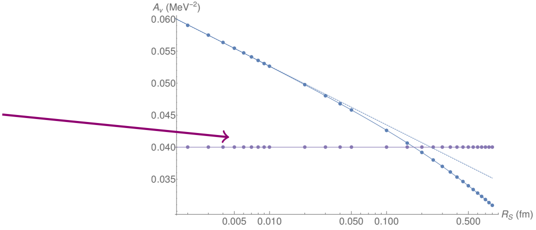
1. regulate $\tilde{C}$ & fit to ${}^1S_0$ scattering length
2. then compute $\mathcal{A}_\nu = \int d^3\mathbf{r}\,\psi^{-\,*}_{\mathbf{p}'}(\mathbf{r})V_\nu(\mathbf{r})\psi^{+}_{\mathbf{p}}(\mathbf{r})$

$\mathcal{A}_\nu$ is log divergent!

Light-ν exchange mechanism



$nn \to ppe^- e^-$



V. Cirigliano, *et al*, ‘18, ‘19

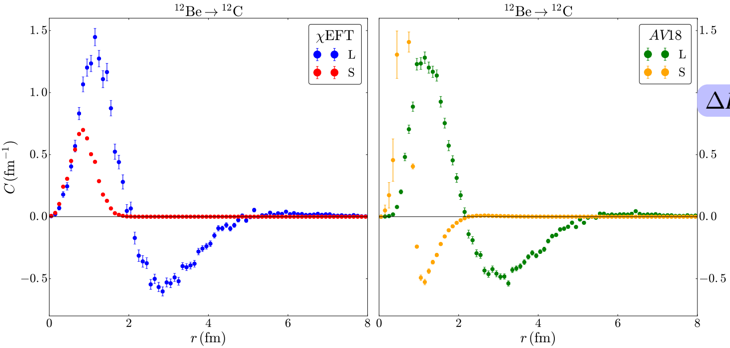
- renormalization requires $g_\nu^{\rm NN}$ to be promoted to LO

spectacular failure of Weinberg's counting
g_ν^{NN} absent in standard $0\nu\beta\beta$ calculations!

- RGE of $g_\nu^{\rm NN}$ is known, finite piece?
- exploit approx. symmetry relation to short-distance CIB in *NN* scattering

$$V_{\rm CIB,S} = -\frac{e^2}{4}(\mathcal{C}_1 + \mathcal{C}_2), \qquad g_\nu^{\rm NN} = \mathcal{C}_1$$

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



$\Delta I = 2$

thanks to M. Piarulli and S. Pastore

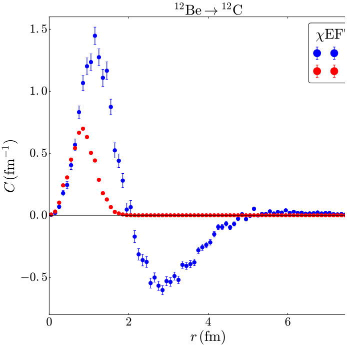
- *ab initio* calculations of ^{6}He $\rightarrow$ ^{6}Be and ^{12}Be $\rightarrow$ ^{12}C
- large corrections to $\Delta I = 2$ transitions

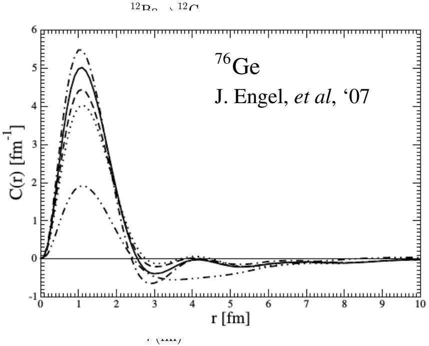
$$\text{AV18:} \quad M_L = 0.653, \quad M_S = 0.518$$
$$\chi\text{EFT:} \quad M_L = 0.725, \quad M_S = 0.533$$

$>$ 50% corrections

- …but uncontrolled theory error from $\mathcal{C}_1 = \mathcal{C}_2$

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





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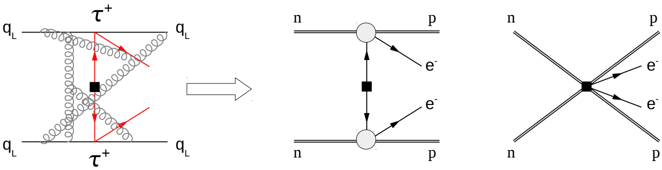
Light-ν exchange mechanism



- need two-nucleon ME of double current insertion

$$4G_F^2 m_{\beta\beta} \int d^4x d^4y S(x-y) \langle pp|T\left(J^\mu(x) J_\mu(y)\right)|nn\rangle \langle ee|\bar{e}_L(x) C e_L^T(y)|0\rangle$$

$$S(x) = \int \frac{d^4k}{(2\pi)^4} \frac{e^{iq\cdot x}}{q^2 + i\varepsilon}$$

& match to chiral EFT

- initial results for $\pi^- \to \pi^+ e^- e^-$ with light-ν

X. Feng *et al*, '18, D. Murphy *et al*, '19.

- detailed study for $2\nu\beta\beta$ at heavy pion mass

B. Tiburzi, *et al*, NPLQCD coll., '17

Conclusion

- BSM searches with nuclei are complementary
  & very competitive with the energy frontier

$0\nu\beta\beta$, EDMs, DM, β decay ...

- but need to control QCD & nuclear theory !

EFTs & LQCD

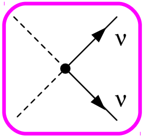
- LQCD necessary to match quark- and nucleon-level descriptions
- EFTs necessary to go from one to few-nucleons
- and to provide input for many-body calculations

$0\nu\beta\beta$ potentials, DM-nucleon currents, ...

- coupled with progress in many-body methods
  full *ab initio* description of low-energy probes of BSM physics!

Backup

Effective operators for LNV



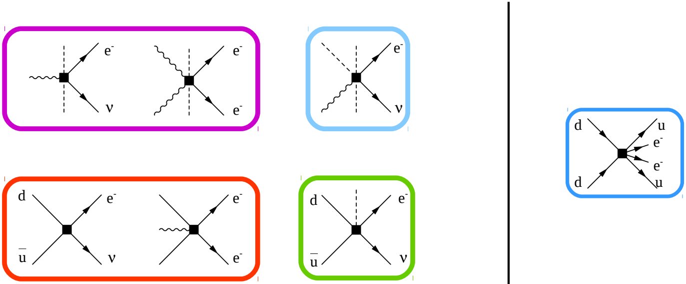
$\left(\frac{v}{\Lambda}\right)$

- no ν-mass operator in the SM
- **one** dimension 5 operator S. Weinberg, '79

$$\frac{1}{\Lambda}\varepsilon_{ij}\varepsilon_{mn}L_i^T C L_m H_j H_n \rightarrow \frac{v^2}{\Lambda}\nu_L^T C \nu_L$$

neutrino masses and mixings

Effective operators for LNV

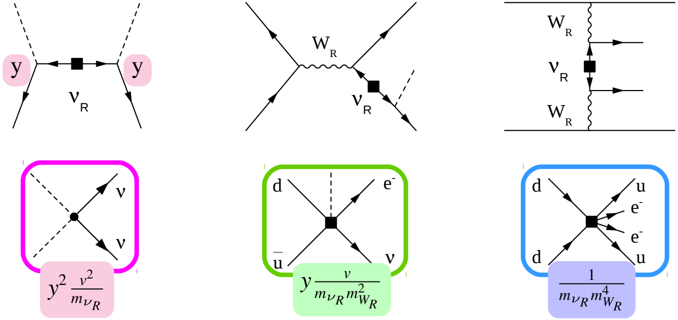


$\left(\frac{v}{\Lambda}\right)^3$ $\left(\frac{v}{\Lambda}\right)^5$

- **one** dimension 5 operator S. Weinberg, '79
- dim.7 operators mostly induce β decay with "wrong" ν

  $\Longrightarrow$ long range contribs. to $0\nu\beta\beta$
- dim. 9 induce short-range contributions to $0\nu\beta\beta$

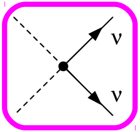
TeV-scale contributions to $0\nu\beta\beta$



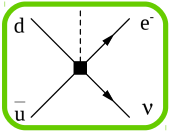
- light-ν mechanism dominates if $y \sim \mathcal{O}(1)$, $m_{\nu_R} \gg 1$ TeV
- but not if new-physics is light and weakly coupled $y \sim \mathcal{O}(m_e/v)$, $m_{\nu_R} \sim 1$ TeV

e. g. LR symmetric model

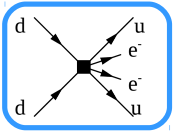
Effective operators for LNV



$\frac{v}{\Lambda}$



$\frac{v^3}{\Lambda^3}$



$\frac{v^3}{\Lambda^3}, \frac{v^5}{\Lambda^5}$

- **one** dim-5 @ EW scale, several dim. 7 and 9
- at GeV scale

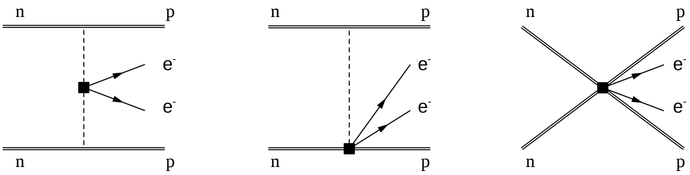
$$\mathcal{L}_{\Delta L=2}(\nu, e, u, d) = -\frac{1}{2}(m_\nu)_{ij}\nu^{Tj}C\nu^i + C_\Gamma\, \nu^T C\,\Gamma e\, \mathcal{O}_\Gamma + C_{\Gamma'} e^T C\,\Gamma' e\, \mathcal{Q}_{\Gamma'}$$

quark bilinear   four-quark

- match onto a EFT for nucleons

what's the form of $0\nu\beta\beta$ operator?
what's the needed hadronic input?

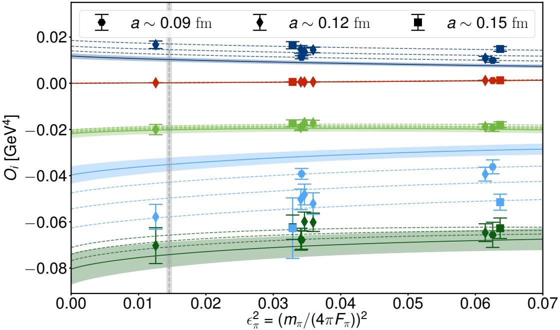
Dim. 9 operators



1. LL LL : $\mathcal{O}_1 = \bar{u}_L \gamma^\mu d_L \, \bar{u}_L \, \gamma_\mu d_L$
2. LR LR : $\mathcal{O}_2 = \bar{u}_L d_R \, \bar{u}_L \, d_R,$ $\mathcal{O}_3 = \bar{u}_L^\alpha d_R^\beta \, \bar{u}_L^\beta \, d_R^\alpha$
3. LL RR : $\mathcal{O}_4 = \bar{u}_L \gamma^\mu d_L \, \bar{u}_R \, \gamma_\mu d_R,$ $\mathcal{O}_5 = \bar{u}_L^\alpha \gamma^\mu d_L^\beta \, \bar{u}_R^\beta \, \gamma_\mu d_R^\alpha$

- induce $\pi\pi$, πN and NN LNV couplings
- same set of operators in BSM K-$\bar{K}$ mixing
- for $\mathcal{O}_2$– $\mathcal{O}_5$, $\pi\pi$ dominates (in Weinberg's counting)

$\pi\pi$ matrix elements



$g_1^{\pi\pi} = +0.4$

$g_2^{\pi\pi} = -(1.8\,\text{GeV})^2$

$g_3^{\pi\pi} = +(1.0\,\text{GeV})^2$

$g_4^{\pi\pi} = -(1.7\,\text{GeV})^2$

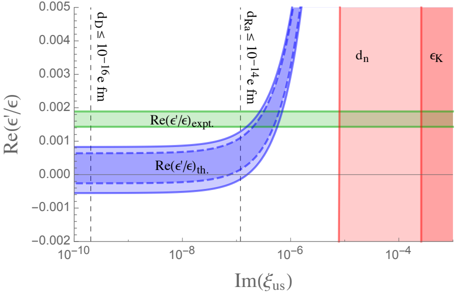
$g_5^{\pi\pi} = -(3.6\,\text{GeV})^2$

A. Nicholson *et al.*, CalLat collaboration, '18

- $\pi\pi$ matrix elements well determined in LQCD

  good agreement with NDA & K-$\bar{K}$ ME
- ...but same failure of Weinberg's counting, need g_i^{NN} at LO
- $nn \to ppe^-e^-$ to determine g_i^{NN} and test power counting!

Disentangling $\not{T}$ mechanisms



$$(\epsilon'/\epsilon)_{\rm expt} = (16.6 \pm 2.3) \cdot 10^{-4}$$

$$(\epsilon'/\epsilon)_{\rm LQCD} = (1.4 \pm 6.9) \cdot 10^{-4}$$

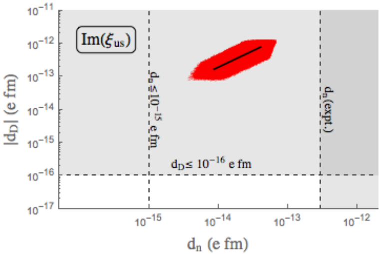
- to lift degeneracy $\Longrightarrow$ additional flavor or collider observables
  e.g. ϵ'/ϵ, $B \to X_s\gamma$, K-$\bar{K}$ oscillations
- explain LQCD/experiment discrepancy with tiny right-handed currents

$$\mathcal{L} = \frac{g}{\sqrt{2}} \left(\xi_{ud}\, \bar{u}_R \gamma^\mu d_R + \xi_{us}\, \bar{u}_R \gamma^\mu s_R\right) W_\mu + \text{h.c.}$$

- in this scenario: d_n, d_d and $d_{\rm Ra}$ in the next generation of experiments
- and correlated!

falsify with better hadronic and nuclear input

Disentangling $\not{T}$ mechanisms



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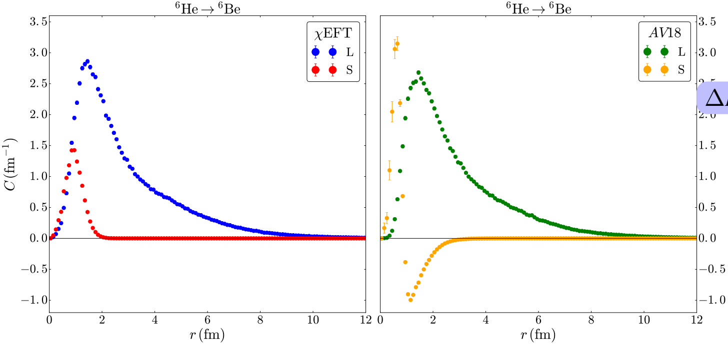
Impact on $0\nu\beta\beta$ nuclear matrix elements



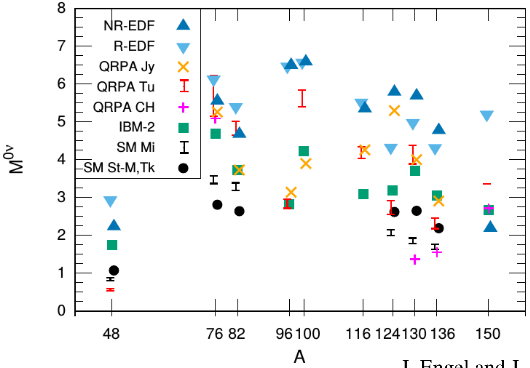
$\Delta I = 0$

- extract CIB potential V^S_{CIB} from AV18 or χEFT (rescaled by c_{LNV}/c_{e^2}) & *ab initio* calculations of nuclear w.f. with same potentials

$$\text{AV18:} \quad M_L = 7.45, \quad M_S = 0.48$$
$$\chi\text{EFT:} \quad M_L = 7.82, \quad M_S = 1.15$$

$\sim$ 10% corrections

Light-ν exchange and chiral EFT



J. Engel and J. Menéndez, ‘16

- a new source of theory uncertainties on $M^{0\nu}$
- can help convergence between methods?