

# Lattice QCD and nuclear EFT for BSM searches

Emanuele Mereghetti

July 23th, 2018

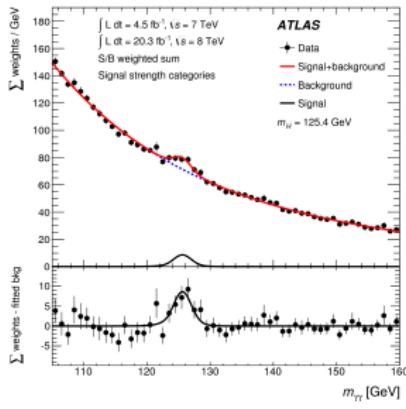
36<sup>th</sup> Annual International Symposium on Lattice Field Theory



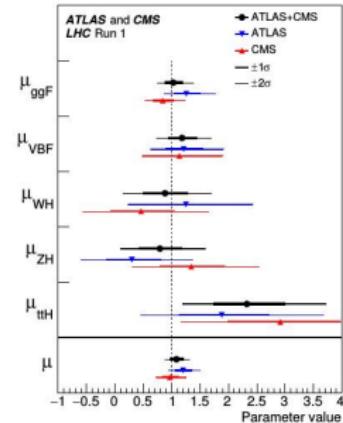
# Outline

- ① Introduction: BSM physics with nuclei
- ② Nuclear EFTs
- ③  $\beta$  decays and DM
- ④ Neutrinoless double beta decay
- ⑤ Electric dipole moments

# Introduction



ATLAS collaboration, '14.



ATLAS & CMS, '16.

- the Standard Model works just fine
- last missing piece discovered @ LHC

... and looks SM-like

# Introduction

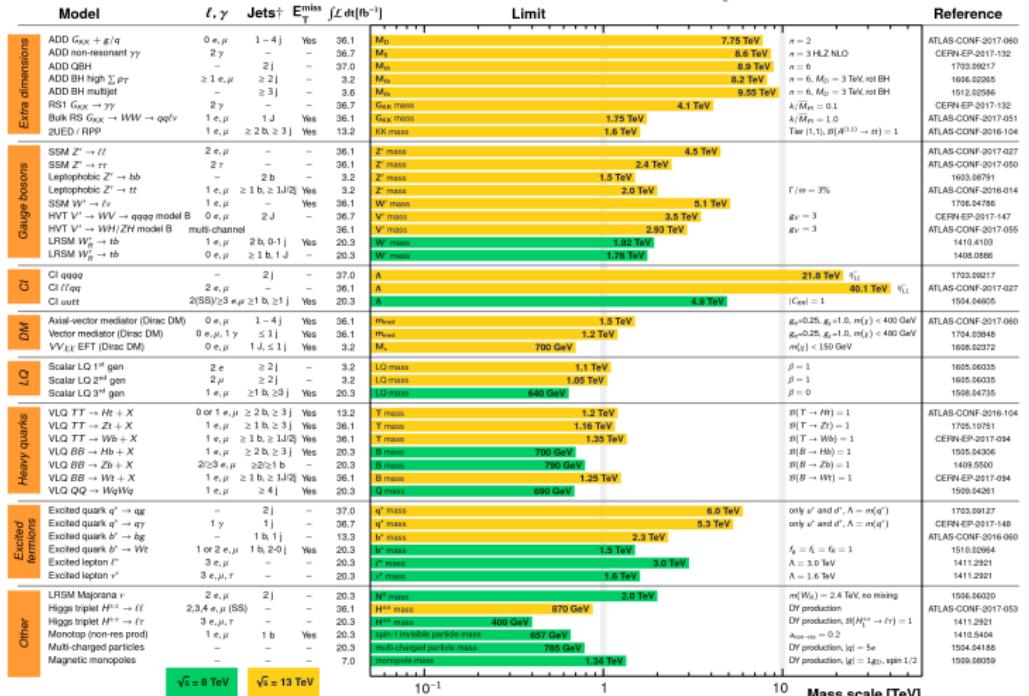
## ATLAS Exotics Searches\* - 95% CL Upper Exclusion Limits

Status: July 2017

ATLAS Preliminary

$$\int \mathcal{L} dt = (3.2 - 37.0) \text{ fb}^{-1}$$

$\sqrt{s} = 8, 13 \text{ TeV}$



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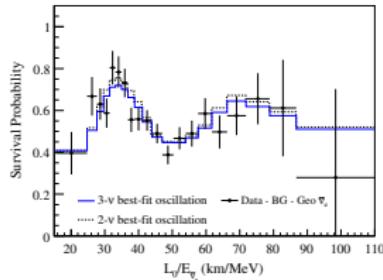
\*Only a selection of the available mass limits on new states or phenomena is shown.

†Small-radius (large-radius) jets are denoted by the letter j (J).

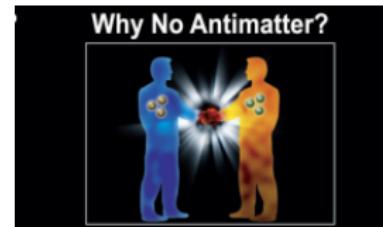
- a lot of work, no evidence for new particles

ATLAS Exotics summary plots

# Introduction



- neutrino masses

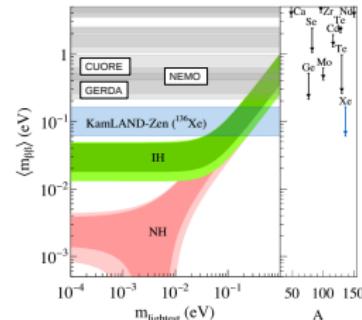


- baryogenesis

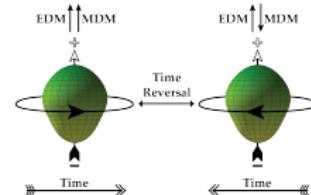


- dark matter

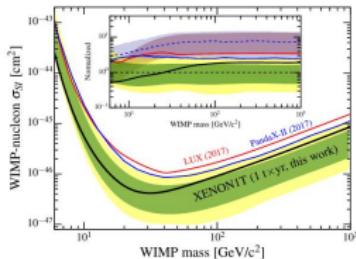
# Introduction



- neutrinoless double  $\beta$



- EDM experiments

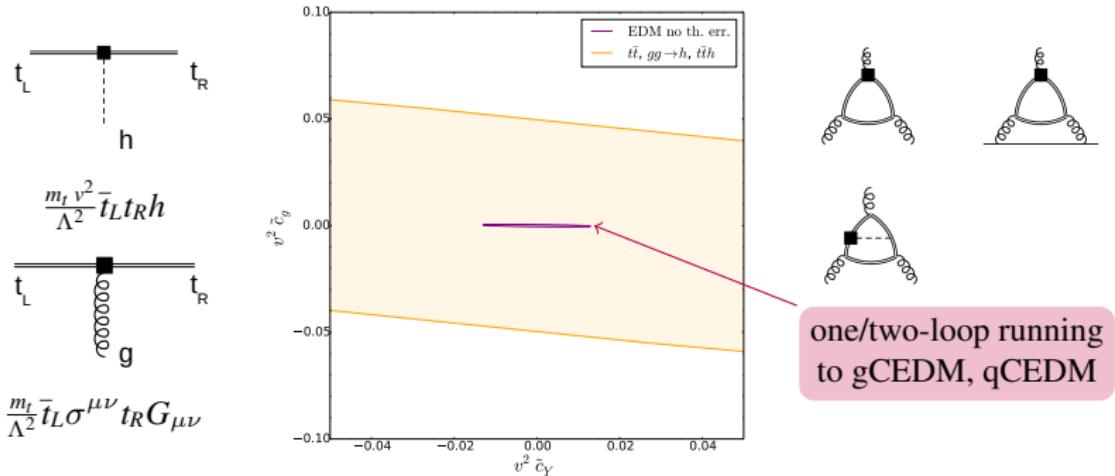


- DM direct detection

nuclei extremely sensitive probes

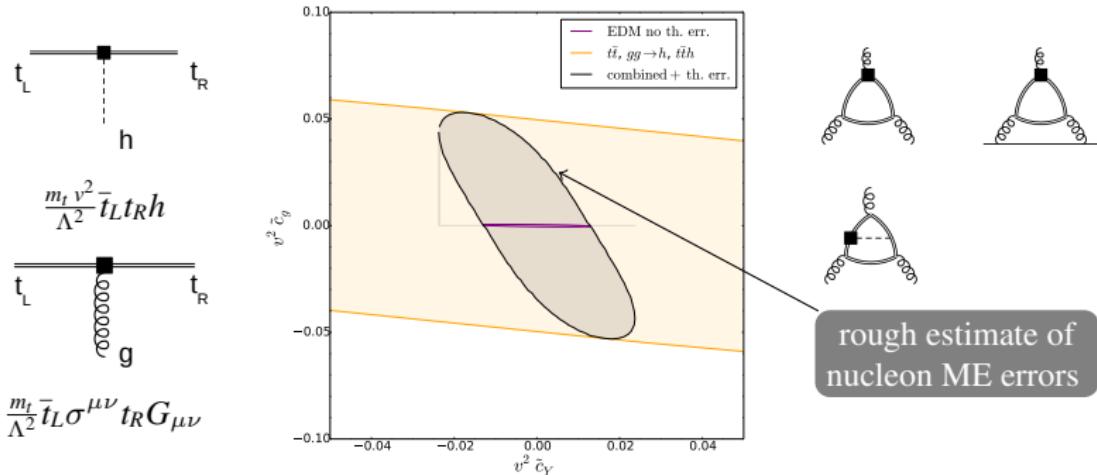
competitive & complementary to LHC

# Introduction



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

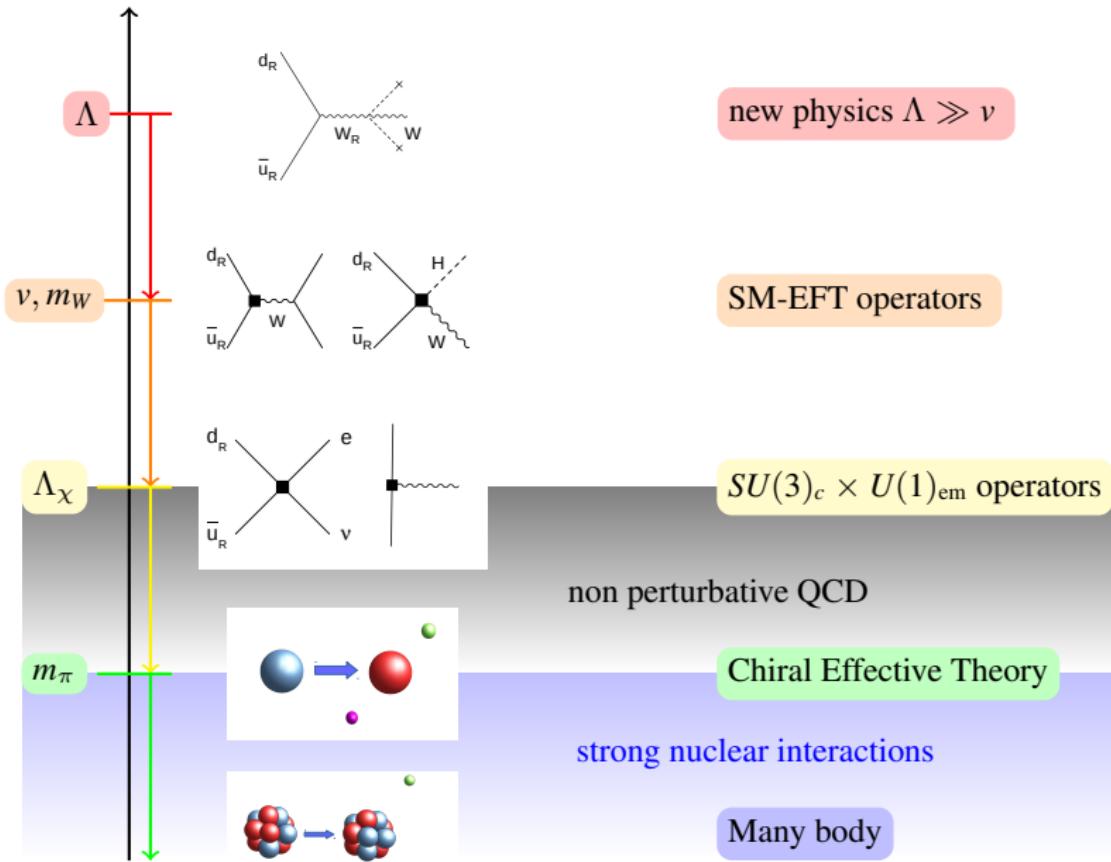
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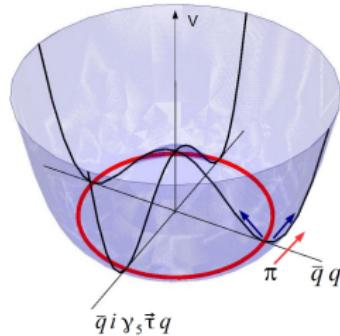


- important if baryogenesis comes from top sector
- EDM bounds much stronger than collider
- ... but hadronic & nuclear uncertainties weaken bounds

$$\langle n | J_{\text{em}}^\mu G G \tilde{G} | n \rangle = ? \quad \quad \langle {}^{225}\text{Ra} | J_{\text{em}}^\mu G G \tilde{G} | {}^{225}\text{Ra} \rangle = ?$$

# Effective Field Theories



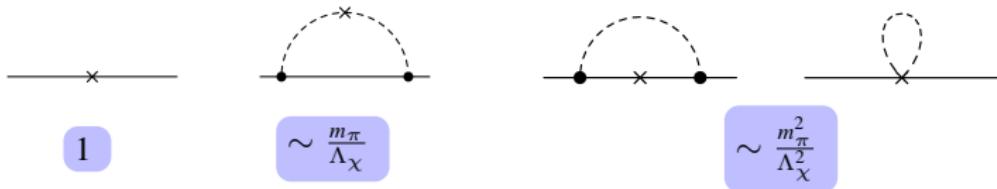


$$\mathcal{L} = -\frac{1}{4}G_{\mu\nu}^a G^{a\mu\nu} + \bar{q}_L i \not{D} q_L + \bar{q}_R i \not{D} q_R - \bar{q}_L \mathcal{M} q_R - \bar{q}_R \mathcal{M} q_L + \mathcal{L}_6 + \dots$$

Chiral symmetry & its spontaneous breaking:

- pions are pseudo-Goldstone
- light,  $m_\pi \ll \Lambda_\chi \sim 1 \text{ GeV}$
- and weakly coupled
- EFT expansion in powers of  $\{Q, m_\pi\}/\Lambda_\chi$

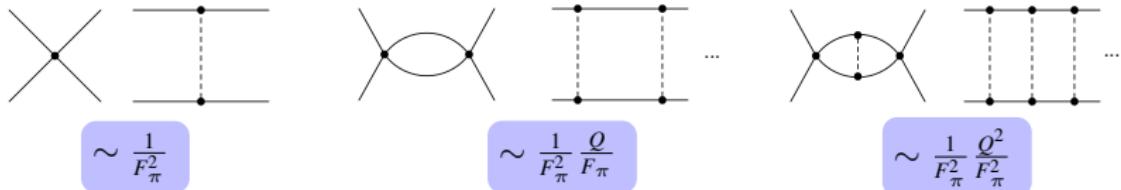
## Chiral Effective Theory



$$A = 1$$

- only one scale  $Q \sim m_\pi \ll \Lambda_\chi$
- observables have expansion in  $Q/\Lambda_\chi$

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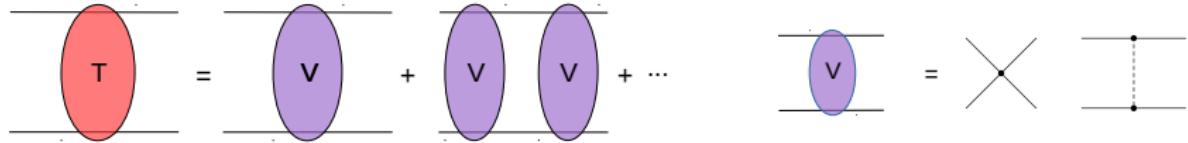
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$A \geq 2$

1. another scale in the problem  $Q^2/m_N$

- resum an infinite class of diagrams (Lippmann-Schwinger eq.)

## Chiral Effective Theory



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$$A \geq 2$$

1. another scale in the problem  $Q^2/m_N$

- resum an infinite class of diagrams (Lippmann-Schwinger eq.)

2.  $V$  is organized in powers of  $Q/\Lambda_\chi$

3. the LO potential is singular (“short-range core”)

- new divergences in solution of LS
- can invalidate power counting based on NDA

## Nuclear EFT(s)

	2N Force	3N Force	4N Force	5N Force
LO $(Q/\Lambda_\chi)^0$				
NLO $(Q/\Lambda_\chi)^2$				
NNLO $(Q/\Lambda_\chi)^3$				
$N^3\text{LO}$ $(Q/\Lambda_\chi)^4$				

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

see also:

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

M. Piarulli *et al*, '16

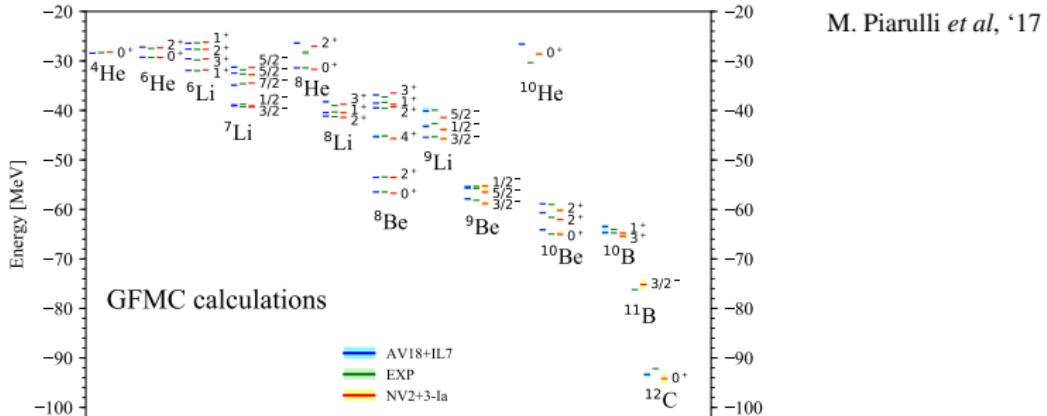
M. Piarulli *et al*, '14

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

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

- LECs are fit to data in 2- and 3-nucleon systems
- and predict light-nuclear observables

# Nuclear EFT(s)

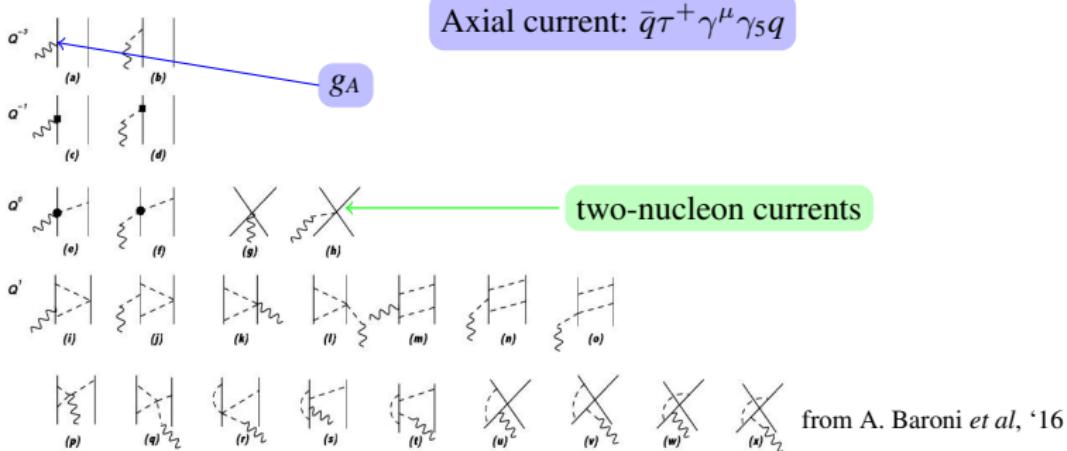


- LECs are fit to data in 2- and 3-nucleon systems
- and predict light-nuclear observables

**WARNING:** unresolved issues with power counting

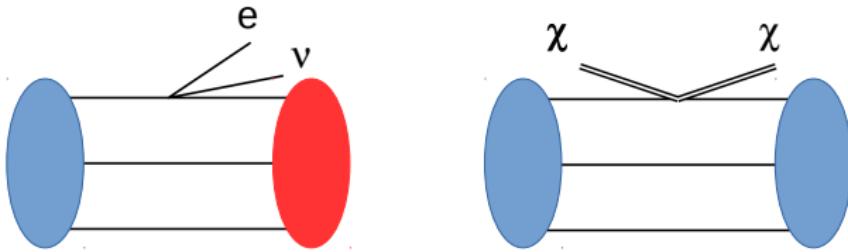
- alternatives: pionless EFT, phenomenological potentials (AV18), ...

## External currents in chiral EFT



- similar expansions for external currents
  - e.g. vector, axial, scalar, pseudoscalar, tensor
- for SM operators, LECs can be fit to data
- for BSM operators, need LQCD!

## $\beta$ decays and DM direct detections



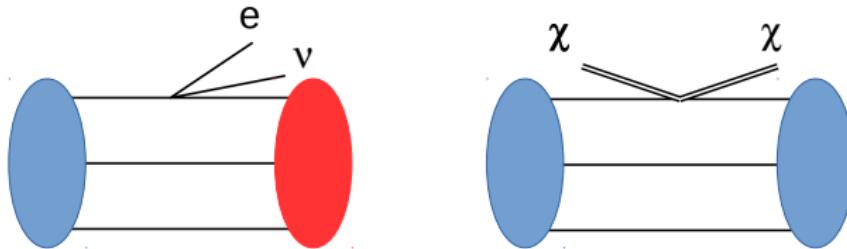
$$\mathcal{L}_\beta = -\frac{4G_F}{\sqrt{2}} V_{ud} \left\{ \epsilon_L \bar{\nu}_L \gamma^\mu e_L \bar{d}_L \gamma_\mu u_L + \frac{1}{2} \bar{\nu}_L e_R \left( (\epsilon_S - \epsilon_P) \bar{d}_R u_L + (\epsilon_S + \epsilon_P) \bar{d}_L u_R \right) + \epsilon_T \bar{\nu}_L \sigma^{\mu\nu} e_R \bar{d}_L \sigma_{\mu\nu} u_R \right\}, \quad \epsilon_{L,S,P,T} \sim \frac{v^2}{\Lambda^2}$$

- LO effects are one body

single-nucleon isovector & isoscalar charges  
 $s$  and  $c$  nucleon ME

- two-body effects suppressed by  $\mathcal{O}((Q/\Lambda_\chi)^n)$

## $\beta$ decays and DM direct detections



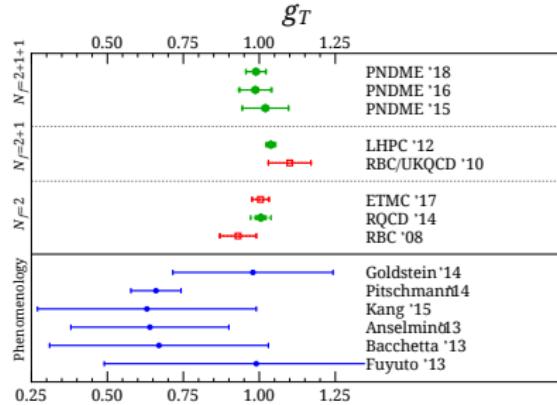
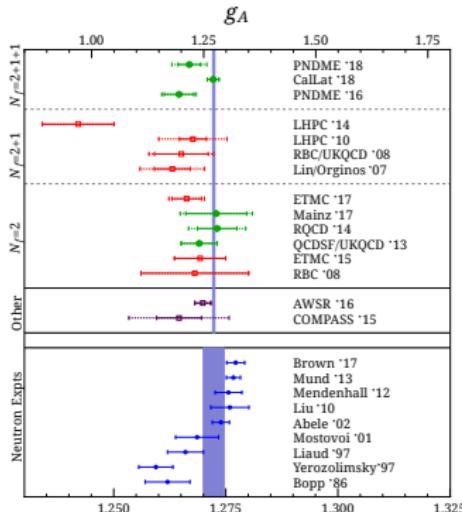
$$\begin{aligned}\mathcal{L}_\chi &= \frac{1}{\Lambda^2} \sum_q \left\{ C_q^{VV} \bar{\chi} \gamma^\mu \chi \bar{q} \gamma_\mu q + C_q^{VA} \bar{\chi} \gamma^\mu \chi \bar{q} \gamma_\mu \gamma^5 q + C_q^{AV} \bar{\chi} \gamma^\mu \gamma^5 \chi \bar{q} \gamma_\mu q + \dots \right\} \\ &\quad + \frac{1}{\Lambda^3} \sum_q m_q \left\{ C_q^{SS} \bar{\chi} \chi \bar{q} q + C_q^{SP} \bar{\chi} \chi \bar{q} \gamma^5 q + C_q^{PS} \bar{\chi} \gamma^5 \chi \bar{q} q + C_q^{PP} \bar{\chi} \gamma^5 \chi \bar{q} \gamma^5 q + \dots \right\}\end{aligned}$$

- LO effects are one body

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# $\beta$ decays and DM direct detections



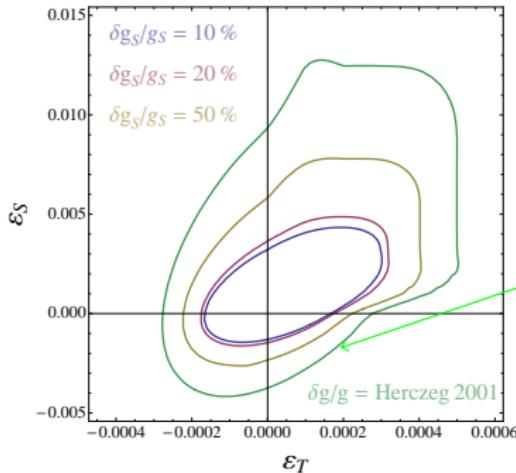
from R. Gupta *et al.*, '18

- isovector charges well determined by LQCD
- $\delta g_A/g_A \sim 1\%$ ,  $\delta g_T/g_T \sim 3\%$ ,  $\delta g_S/g_S \sim 10\%$
- larger uncertainties on  $s, c$  charges

J. Green, Fri, 10:00 am  
 S. Otha, Thu, 11:40 am  
 K. Ott nad, Thu, 12:00 pm  
 R. Gupta, Thu, 12:40 pm

...

## Non-standard charged current interactions



projected  $b < 10^{-3}$   
decay correlation @ 0.1%

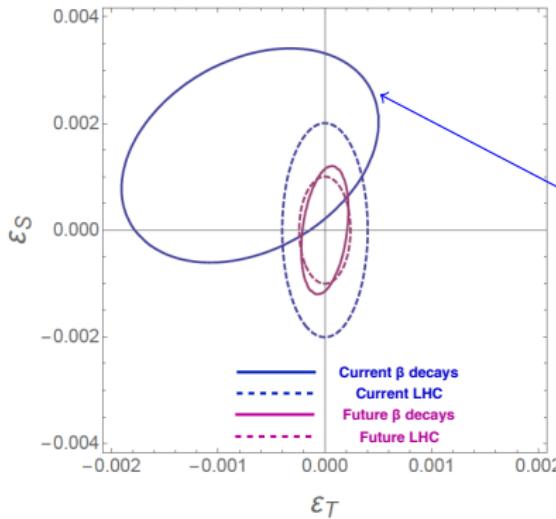
quark model, MIT bag

T. Bhattacharya *et al.*, '11

- precise determination of  $g_{T,S}$  necessary to compete with LHC
- comparable LHC & low-energy bounds
- Fierz interference term at  $10^{-4}$  gives low-energy an edge

$^6\text{He}$  little- $b$  coll. @ FRIB?

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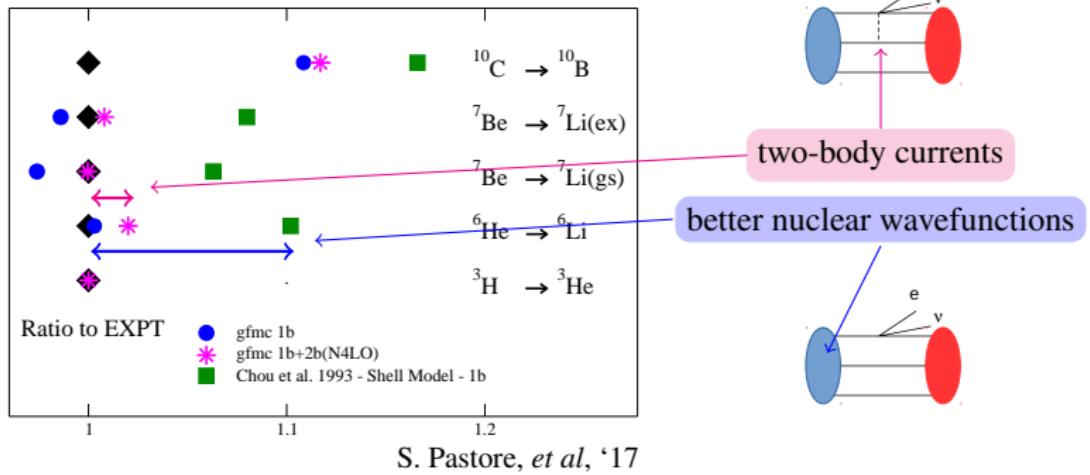
global fit to nuclear  $\beta$  decay  
M. González-Alonso, *et al.*, '18

R. Gupta *et al.*, '18

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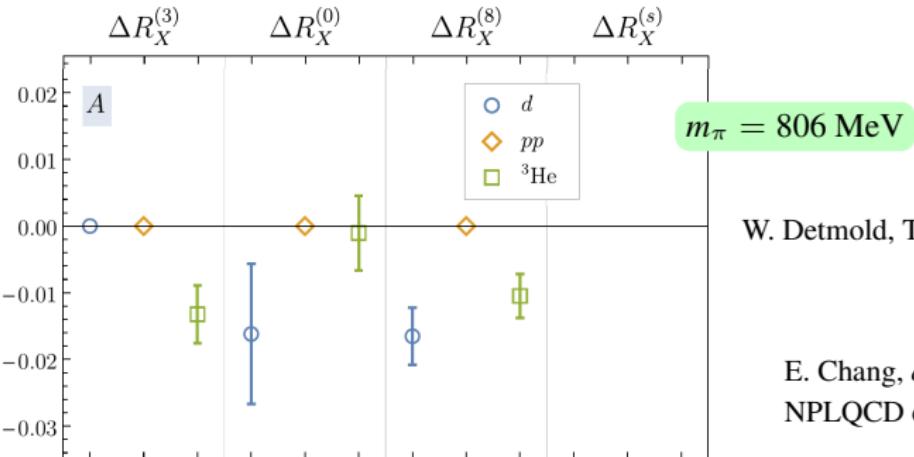
## Two-body currents



beyond one nucleon

- effects from solving few-body LS equation
- and from two-body, three-body, . . . currents

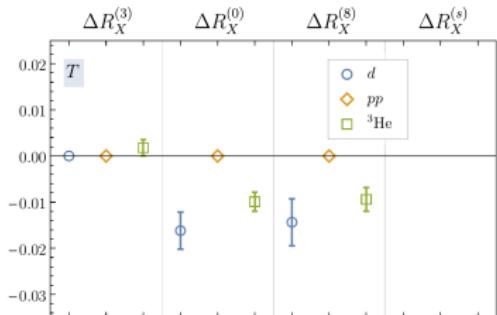
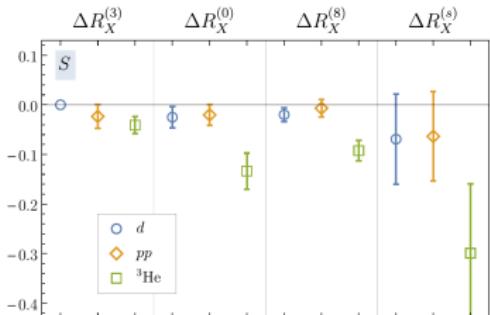
## Two-body currents



beyond one nucleon

- effects from solving few-body LS equation
- and from two-body, three-body, . . . currents
- results from LQCD starting to appear

# Nuclear scalar and tensor charges



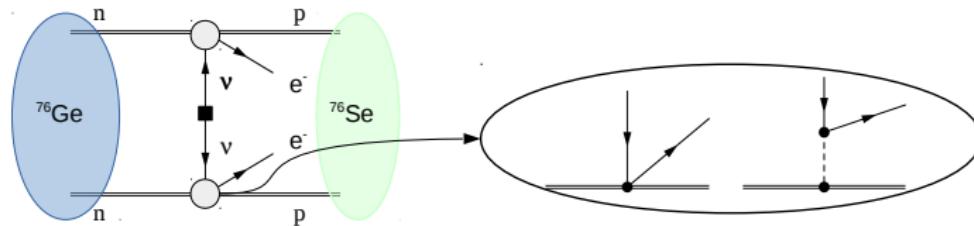
- relevant for DM,  $\beta$  decay, EDM
- two-body effects generally small (at small momentum)
- roughly agree with EFT

C. Körber, A. Nogga, J. de Vries, '17  
 M. Hoferichter, P. Klos, J. Menéndez, A. Schwenk, '16 & '17

- important to check the power-counting

# Neutrinoless double beta decay

## Light- $\nu$ exchange mechanism in chiral EFT

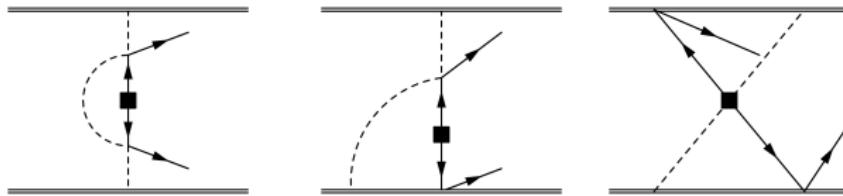


- double beta decay is rare doubly-weak decay process
- LO  $0\nu\beta\beta$  operator is two-body

$$V_\nu = \mathcal{A} \tau^{(1)} + \tau^{(2)} + \frac{1}{\mathbf{q}^2} \left\{ \mathbf{1}^{(a)} \times \mathbf{1}^{(b)} - g_A^2 \boldsymbol{\sigma}^{(a)} \cdot \boldsymbol{\sigma}^{(b)} \left( \frac{2}{3} + \frac{1}{3} \frac{m_\pi^4}{(\mathbf{q}^2 + m_\pi^2)^2} \right) + \dots \right\},$$
$$\mathcal{A} = 2G_F^2 m_{\beta\beta} \bar{e}_L C \bar{e}_L^T$$

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

## Light- $\nu$ exchange mechanism. Higher orders



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

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

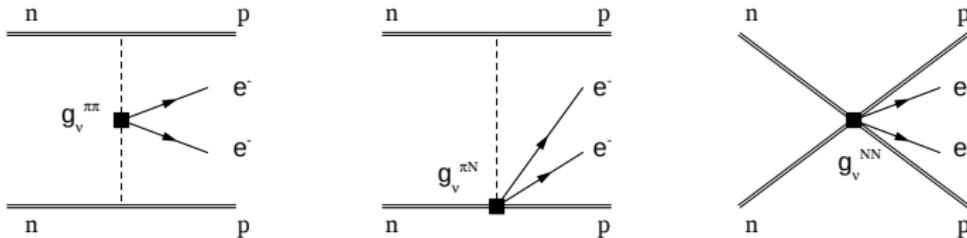
- ## 1. correction to the one-body currents (magnetic moment, radii, ...)

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

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

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

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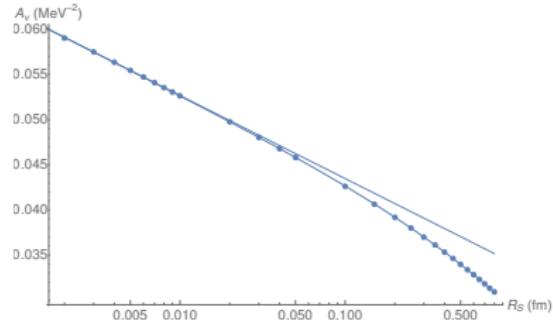
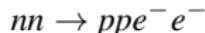
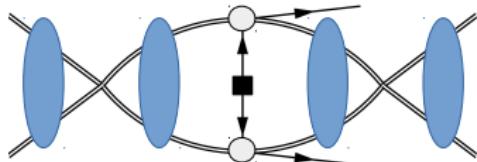
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UV divergences signal short  
 $g_\nu^{\pi\pi}$ ,  $g_\nu^{\pi N}$  and  $g_\nu^{NN}$  require ne

**WARNING:** based on naive  
dimensional analysis  
“Weinberg’s counting”

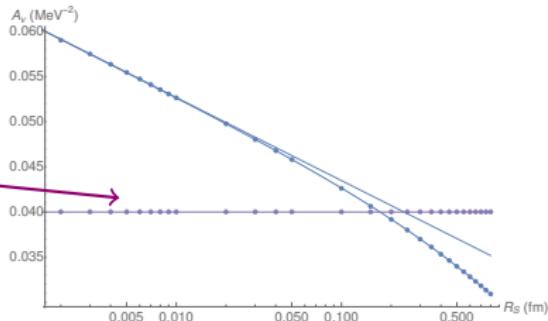
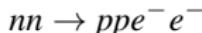
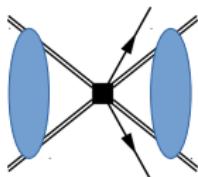
## Light- $\nu$ exchange mechanism



V. Cirigliano, *et al.*, '18

- ... but nuclear amplitudes computed with  $V_\nu$  are divergent  
short-range core of the nuclear force!
- renormalization requires  $g_\nu^{NN}$  to be promoted to LO  
spectacular failure of Weinberg's counting  
 $g_\nu^{NN}$  absent in standard  $0\nu\beta\beta$  calculations!

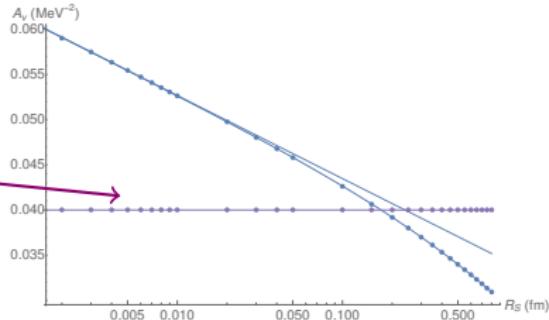
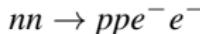
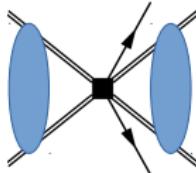
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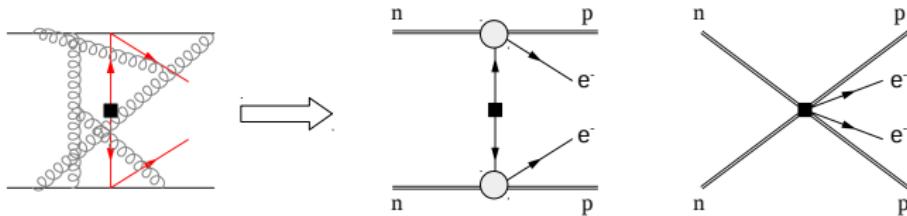


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 $g_\nu^{NN}$  absent in standard  $0\nu\beta\beta$  calculations!
- how to fix the finite piece?

$$g_\nu^{NN} = \left( \frac{m_N \tilde{C}}{4\pi} \right)^2 \left( a - \frac{1}{2} (1 + 2g_A^2) \log R_S \right), \quad a = ?$$

## Light- $\nu$ exchange mechanism



- need two-nucleon ME of double current insertion

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

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

& match to chiral EFT

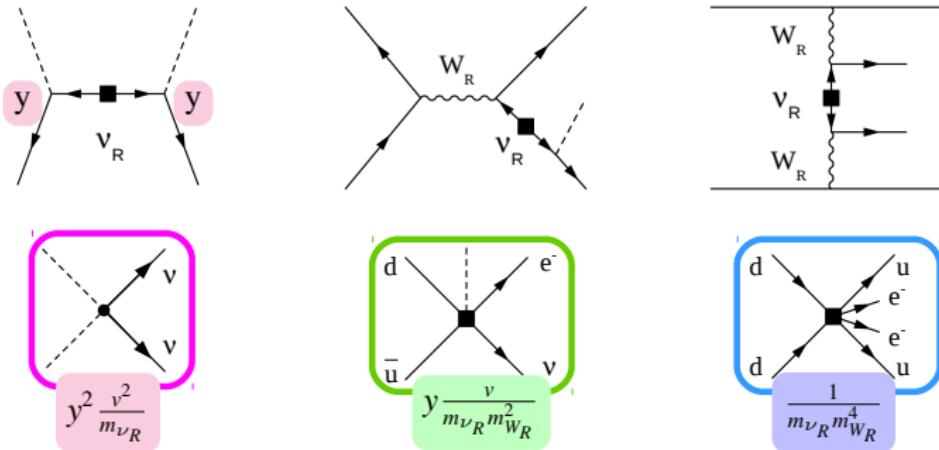
- initial results for  $\pi^- \rightarrow \pi^+ e^- e^-$  with light- $\nu$

D. Murphy, Tue, 3:00 pm  
X. Feng, Tue, 6:45 pm

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

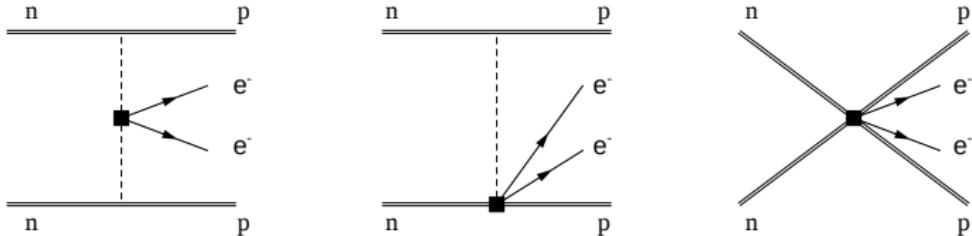
B. Tiburzi, *et al*, NPLQCD coll., '17

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



- light- $\nu$  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

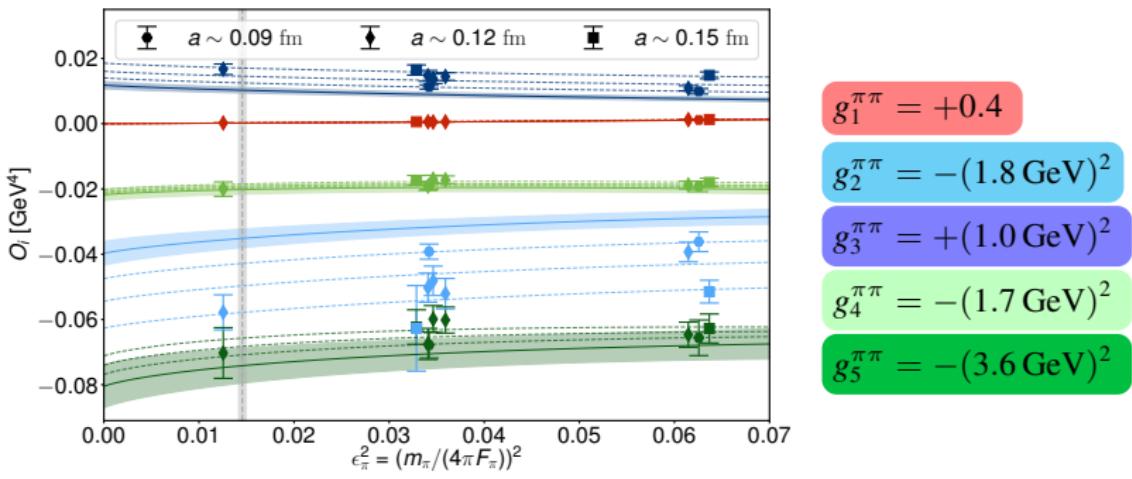
## Dim. 9 operators



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

- induce  $\pi\pi$ ,  $\pi N$  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

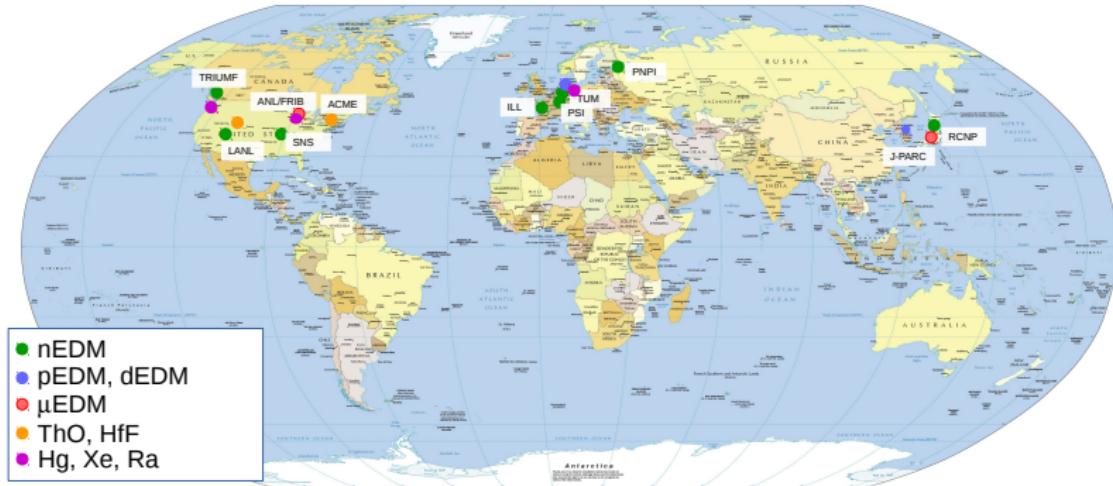


A. Nicholson *et al.*, CalLat collaboration, ‘18

- $\pi\pi$  matrix elements well determined in LQCD
    - good agreement with NDA &  $K\bar{K}$  ME  
H. Monge-Camacho, Tue, 3:20 pm
  - ... but same failure of Weinberg's counting, need  $g_i^{NN}$  at LO
  - $nn \rightarrow ppe^- e^-$  to determine  $g_i^{NN}$  and test power counting!

# Electric dipole moments

# EDM experiments worldwide



- current bounds

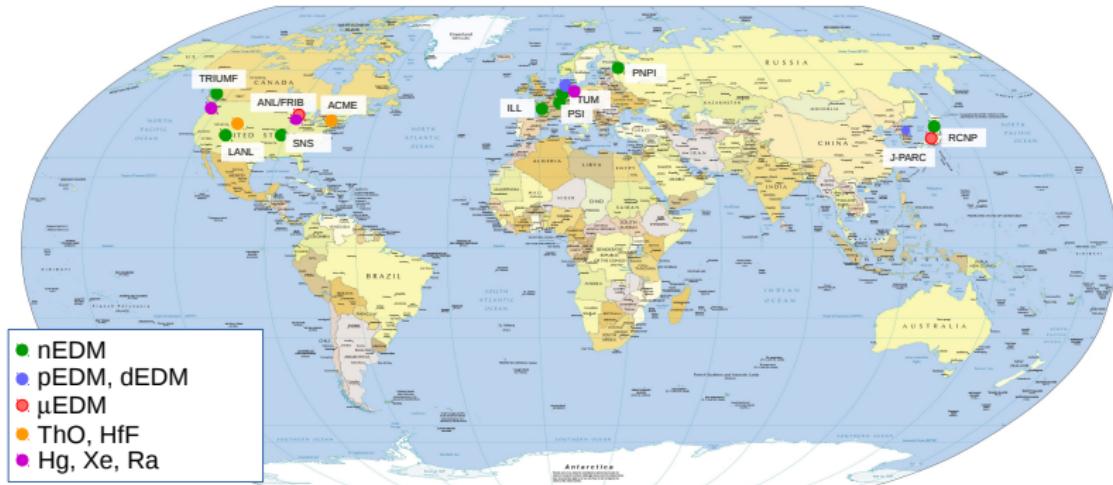
$$\begin{aligned}d_e &< 8.7 \cdot 10^{-16} \text{ e fm} \\d_n &< 3.0 \cdot 10^{-13} \text{ e fm} \\d_{^{199}\text{Hg}} &< 6.2 \cdot 10^{-17} \text{ e fm} \\d_{^{225}\text{Ra}} &< 1.2 \cdot 10^{-10} \text{ e fm}\end{aligned}$$

- SM

$$\begin{aligned}d_e &\sim 5.0 \cdot 10^{-25} \text{ e fm} \\d_n &\sim 1.0 \cdot 10^{-19} \text{ e fm}\end{aligned}$$

large window for BSM!

# EDM experiments worldwide



- current bounds

$$\begin{aligned}d_e &< 8.7 \cdot 10^{-16} e \text{ fm} \\d_n &< 3.0 \cdot 10^{-13} e \text{ fm} \\d_{^{199}\text{Hg}} &< 6.2 \cdot 10^{-17} e \text{ fm} \\d_{^{225}\text{Ra}} &< 1.2 \cdot 10^{-10} e \text{ fm}\end{aligned}$$

- future bounds

$$\begin{aligned}d_e &< 5.0 \cdot 10^{-17} e \text{ fm} \\d_n &< 1.0 \cdot 10^{-15} e \text{ fm} \\d_{^{199}\text{Hg}} &< 6.2 \cdot 10^{-17} e \text{ fm} \\d_{^{225}\text{Ra}} &< 1.0 \cdot 10^{-14} e \text{ fm}\end{aligned}$$

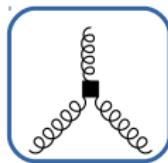
## EFT for T violations

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

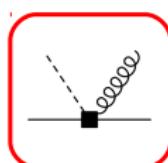
$$\mathcal{L}_{T4} = m_* \bar{\theta} \bar{q} i\gamma_5 q$$

in principle  $\bar{\theta} = \mathcal{O}(1)$   
... strong CP problem

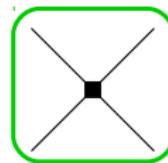
- 9 (+ 10 w. s quark) dim-6 hadronic operators:



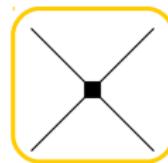
gluon CEDM  
 $C_{\tilde{G}}$



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



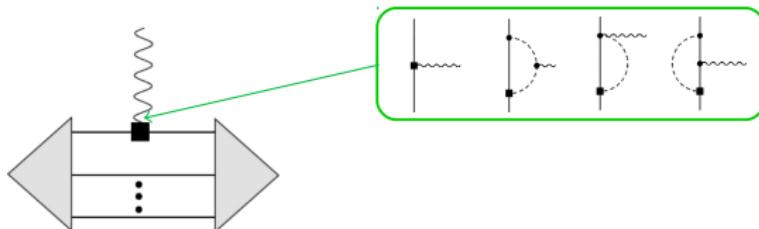
LL RR 4-quark  
 $\Xi_{ud,us,ds}^{(1,8)}$



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

- electron, muon EDMs and semileptonic operators

## From quarks to nucleons.



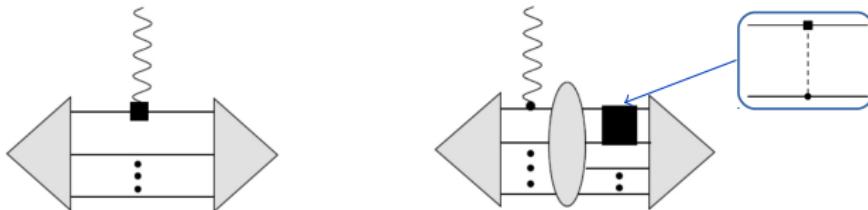
$$\mathcal{L}_T = -2\bar{N}(\bar{d}_0 + \bar{d}_1\tau_3)S^\mu v^\nu NF_{\mu\nu} - \frac{\bar{g}_0}{F_\pi}\bar{N}\boldsymbol{\pi} \cdot \boldsymbol{\tau} N - \frac{\bar{g}_1}{F_\pi}\pi_3\bar{N}N$$

- operators in  $\mathcal{L}_T$  & 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  $T$  OPE potential

1. relative size depends  
on chiral properties of  $T$  source

2. for  $\chi$ -breaking  $T$   
 $d_A$  gets large  $\pi$ -N contribs.

## From quarks to nucleons.



$$\mathcal{L}_T = -2\bar{N}(\bar{d}_0 + \bar{d}_1\tau_3)S^\mu v^\nu NF_{\mu\nu} - \frac{\bar{g}_0}{F_\pi}\bar{N}\boldsymbol{\pi} \cdot \boldsymbol{\tau} N - \frac{\bar{g}_1}{F_\pi}\pi_3\bar{N}N$$

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1. relative size depends  
on chiral properties of  $T$  source

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 $d_A$  gets large  $\pi$ -N contribs.

# From nucleons to nuclei. Light nuclei

	Potential (references)	$d_n$	$d_p$	$\bar{g}_0/F_\pi$	$\bar{g}_1/F_\pi$
$d_d$	Perturbative pion (141, 129)	1	1	—	-0.23
	Av18 (125, 130, 131, 86, 132)	0.91	0.91	—	-0.19
	N <sup>2</sup> LO (131, 86)	0.94	0.94	—	-0.18
$d_t$	Av18 (126, 130, 132)	-0.05	0.90	0.08	-0.14
	Av18+UIX (128, 86)	-0.05	0.90	0.07	-0.14
	N <sup>2</sup> LO (86)	-0.03	0.92	0.11	-0.14
$d_b$	Av18 (126, 130, 132)	0.88	-0.05	-0.08	-0.14
	Av18+UIX (128, 86)	0.88	-0.05	-0.07	-0.14
	N <sup>2</sup> LO (86)	0.90	-0.03	-0.11	-0.14

from EM and U.van Kolck, '15

- in storage ring experiments, constituent EDMs are not screened
- nuclear theory is well under control

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

- largest uncertainties from hadronization

$$d_n, d_p, \bar{g}_{0,1} \stackrel{?}{=} f \left( \bar{\theta}, c_g^{(u,d,s)}, \Xi, \Sigma, \dots \right)$$

## From nucleons to nuclei. Diamagnetic atoms

Nucl.	Range		Range	
	$a_0$	$a_1$	$\alpha_n$	$\alpha_p$
$^{199}\text{Hg}$	[-0.65 , 0.06]	[ -1.14 , 0.38]	[1.8 , 2.0]	[ 0.14 , 0.26]
$^{129}\text{Xe}$	[ 0.06 , 0.63]	[ 0.04 , 0.63]	[-0.34, -0.30]	0
$^{225}\text{Ra}$	[ -76, -13]	[51, 303]	$\mathcal{O}(1)$	$\mathcal{O}(1)$

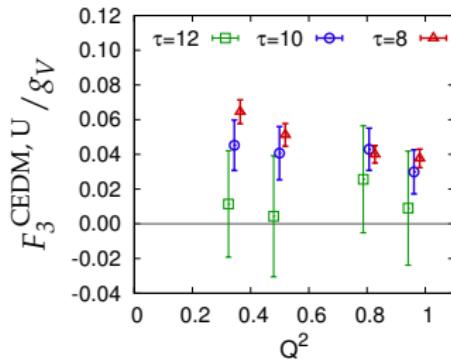
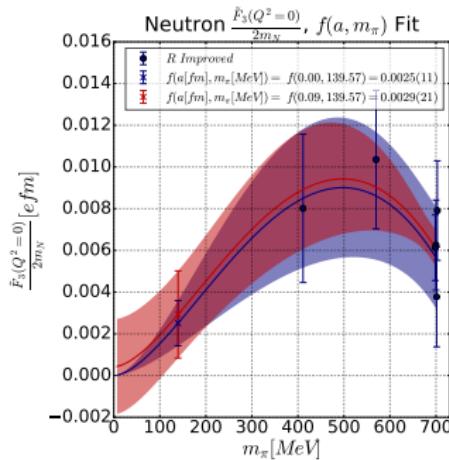
adapted from M. Ramsey-Musolf, J. Engel, U. van Kolck, '13

- constituent EDMs are screened
- atomic EDM depends on screening factor  $A \sim 10^{-4} \text{ fm}^2$  and the Schiff moment

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

- $\pi\text{-N}$  contribs. dominate,  
especially for  $^{225}\text{Ra}$ , octupole deformed nuclei
- ... but affected by large nuclear uncertainties

## Nucleon EDM



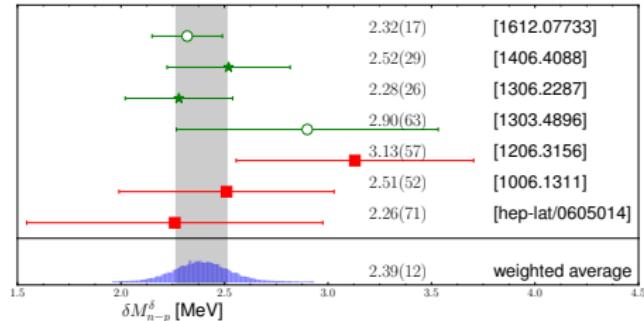
thanks to A. Shindler, S. Syritsyn, B. Yoon

$$d_{n,p}(\bar{\theta}, c_\gamma^{(u,d,s)}, c_g^{(u,d,s)}, C_{\tilde{G}}, \Xi, \Sigma)$$

- qEDM contribs. determined by  $g_T$   
 $\lesssim 5\%$  uncertainties!
- ongoing calculations of  $d_N$  from  $\bar{\theta}, \tilde{c}_g^{u,d}, C_{\tilde{G}}$
- four-quark next!

T. Bhattacharya, Mon 2:40 pm  
J. Dragos, Tue, 2:00 pm  
J. Kim, Tue, 2:20 pm  
S. Syritsyn, Thu, 8:50 am  
M. Rizik, Thu, 9:10 am  
J. Liang, Tue, 6:45 pm

## Pion-nucleon couplings. $\bar{\theta}$ term.

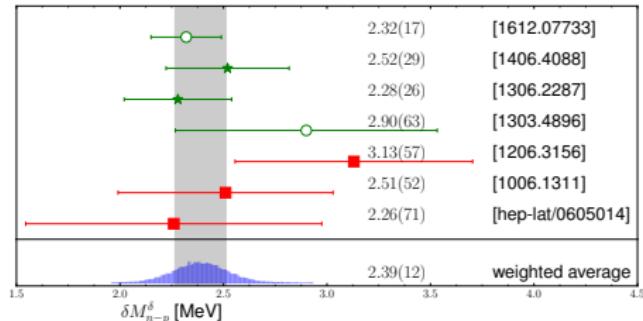


- $\chi$ -symmetry relates  $\pi$ -N couplings to spectral properties

$$\frac{\bar{g}_0}{F_\pi}(\bar{\theta}) = \frac{(m_n - m_p)|_{\text{str}}}{F_\pi} \frac{1 - \varepsilon^2}{2\varepsilon} \bar{\theta}, \quad \varepsilon = \frac{m_d - m_u}{m_d + m_u}$$

back to 2-point functions!

## Pion-nucleon couplings. $\bar{\theta}$ term.



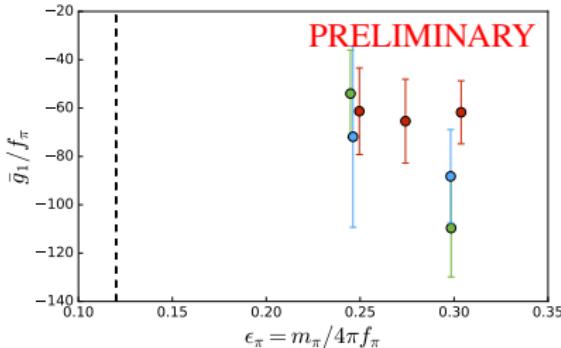
- $\chi$ -symmetry relates  $\pi$ -N couplings to spectral properties

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

LQCD      N<sup>2</sup>LO  $\chi$ PT

- LQCD calculations of  $m_n - m_p$  determines  $\bar{g}_0$
- precise prediction of chiral log in  $d_n(\bar{\theta})$  & form factor
- can be generalized to all  $\chi$ -breaking operators

# Pion-nucleon couplings. qCEDM



thanks to D. Brantley, CallLat  
see A. Walker-Loud, Wed, 4:10 pm

- $\bar{g}_{0,1}$  given by nucleon & pion “sigma terms”  
e.g. for qCEDM

$$\begin{aligned} \bar{g}_0 &= \tilde{d}_0 \left( \frac{d}{d\tilde{c}_3} - r \frac{d}{d\bar{m}\varepsilon} \right) (m_n - m_p) & \bar{g}_1 &= \tilde{d}_3 \left( \frac{d}{d\tilde{c}_0} + r \frac{d}{d\bar{m}} \right) (m_n + m_p) \\ r &= \frac{dm_\pi^2}{d\tilde{c}_0} \frac{d\bar{m}}{dm_\pi^2} \end{aligned}$$

$\tilde{c}_{0,3}$ : couplings of CP-even qCMDM

## Conclusion

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

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

- but need to control QCD & nuclear theory !

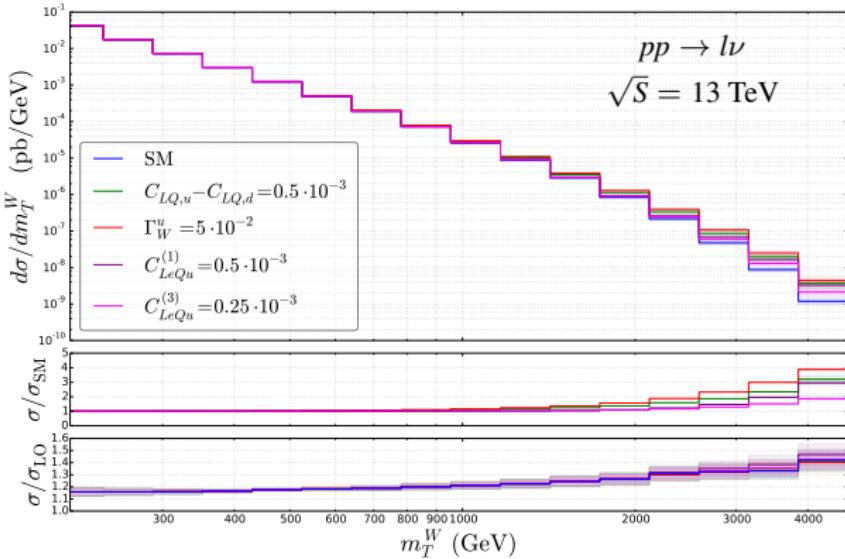
### EFTs & LQCD

- 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, ...

# Backup

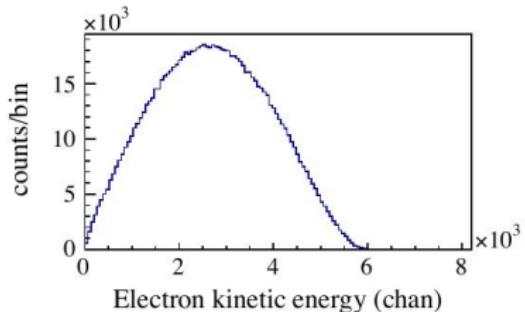
# Non-standard charged current interactions at the LHC



S. Alioli, W. Dekens, M. Girard, EM, '18

- look at the  $m_T^W$  spectrum in  $pp \rightarrow l\nu$  and  $m_{l+l-}$  in  $pp \rightarrow l^+l^-$

## One example



X. Huyan, M. Hughes,  
O. Naviliat-Cuncic, '18

$$w(\langle \mathbf{J} \rangle | E_e, \Omega_e, \Omega_\nu) = PS \times \xi \left\{ 1 + a \frac{\mathbf{p}_e \cdot \mathbf{p}_\nu}{E_e E_\nu} + b \frac{m_e}{E_e} + \dots \right\}$$

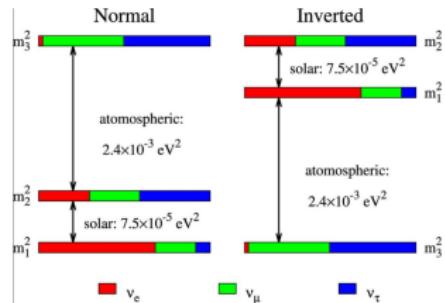
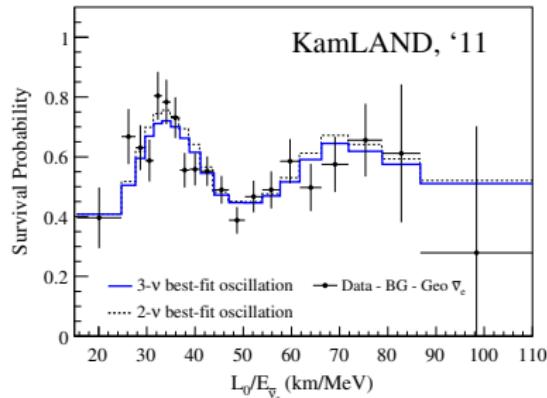
- $b$  Fierz interference term
- $b \sim 0$  in the SM, but sensitive to  $\epsilon_S$  and  $\epsilon_T$

$$b \sim \left| \frac{\langle {}^6\text{Li} | J_T | {}^6\text{He} \rangle}{\langle {}^6\text{Li} | J_A | {}^6\text{He} \rangle} \right| g_A g_T \epsilon_T, \quad \left| \frac{\langle {}^6\text{Li} | J_T | {}^6\text{He} \rangle}{\langle {}^6\text{Li} | J_A | {}^6\text{He} \rangle} \right| = 1 + \text{two-body} + \dots$$

figure with the impact of shrinking uncertainties on scalar/tensor charges

# Lepton number violation

## Lepton number violation



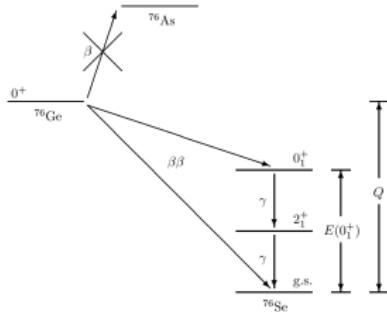
- neutrino have masses
- and know a great deal from oscillation
- what's the origin of neutrino masses?  
Dirac or Majorana?

BSM physics!

$$v_L \xrightarrow{} v_R \quad m_i \bar{\nu}_R^i \nu_L^i$$

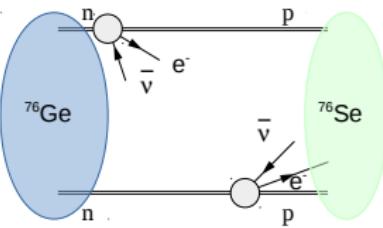
$$v_L \xrightarrow{} v_L \quad m_i \nu_L^{T^i} C \nu_L^i$$

## Lepton number violation



M. Duerr, M. Lindner, K. Zuber, '11

$$T_{1/2}^{2\nu} = (1.84^{+0.14}_{-0.10}) \times 10^{21} \text{ yr}$$

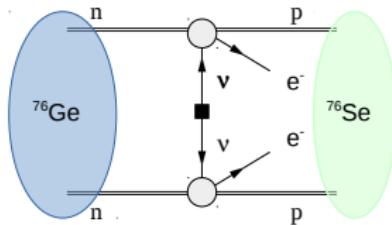
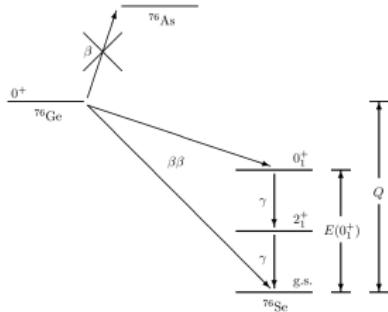


- double beta decay is rare doubly-weak decay process
- $2\nu\beta\beta$  allowed in SM
- $0\nu\beta\beta$  violates lepton number  $L$  by two units

$$(A, Z) \rightarrow (A, Z + 2) + e^- e^-$$

possible iff  $\nu$ s have a Majorana mass

## Lepton number violation



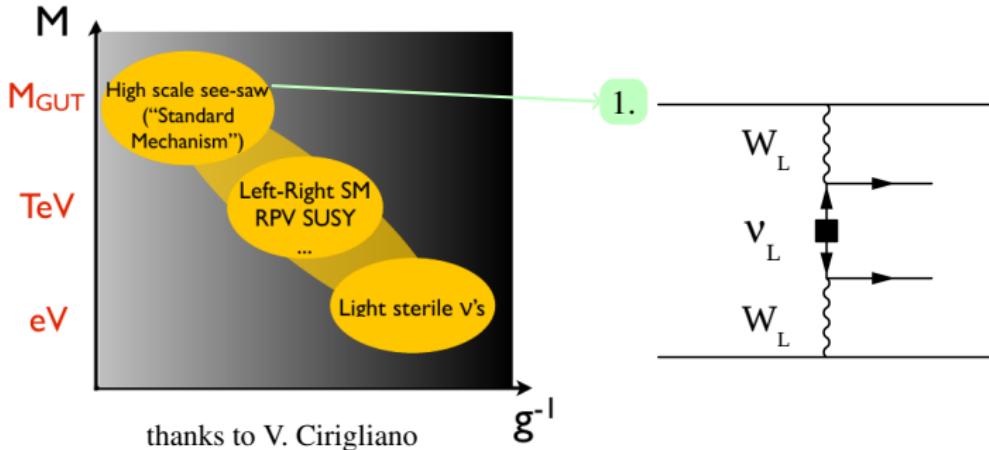
M. Duerr, M. Lindner, K. Zuber, '11

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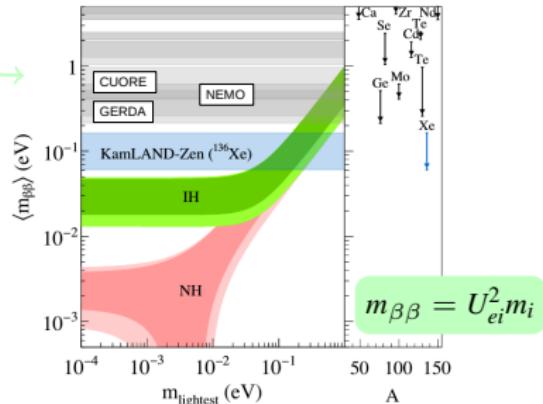
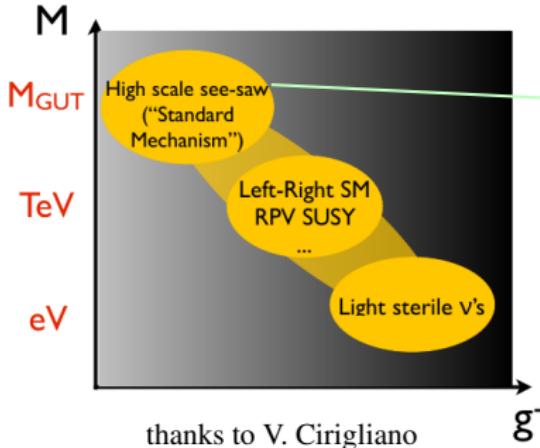
## Lepton number violation



Next generation of experiments sensitive to a variety of LNV scenarios

1. LNV originates at very high scales
  - $0\nu\beta\beta$  only relevant experiment
  - direct connection between  $\nu$  oscillations and  $0\nu\beta\beta$

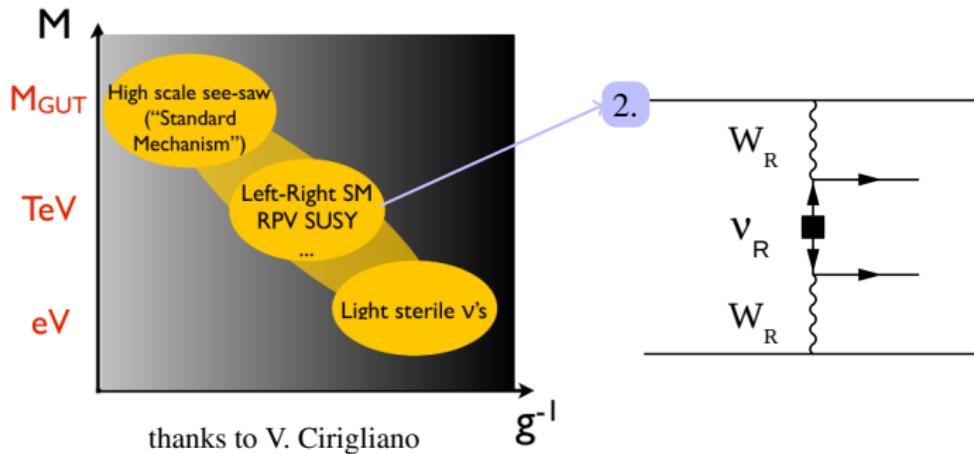
## Lepton number violation



Next generation of experiments sensitive to a variety of LNV scenarios

1. LNV originates at very high scales
  - $0\nu\beta\beta$  only relevant experiment
  - direct connection between  $\nu$  oscillations and  $0\nu\beta\beta$
  - clear goals: rule out inverted hierarchy

## Lepton number violation



Next generation of experiments sensitive to a variety of LNV scenarios

### 2. LNV at intermediate scales

- $0\nu\beta\beta$  is mediated by new particles
- could be accessible at colliders

## Lepton number violation

- experiments are done with  $^{76}\text{Ge}$ ,  $^{82}\text{Se}$ ,  $^{130}\text{Te}$ ,  $^{136}\text{Xe}$

What's the role of LQCD & nuclear EFTs?

- half-life anatomy

$$\left(T_{1/2}^{0\nu}\right)^{-1} = \frac{m_{\beta\beta}^2}{m_e^2} G_{01} g_A^4 |\langle 0^+ | V_\nu | 0^+ \rangle|^2 + \dots$$

- fundamental LNV parameters

classify with SM-EFT

- single nucleon input

need LQCD input for non-standard mechanism

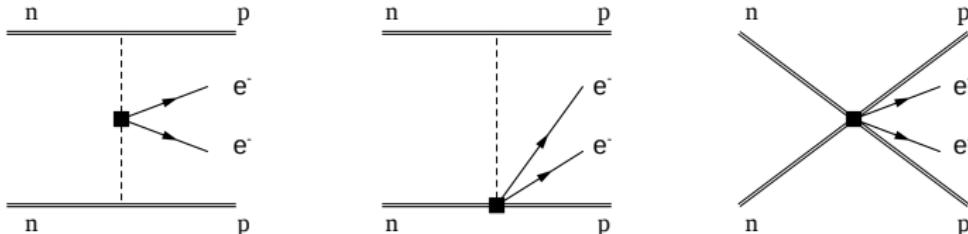
- $0\nu\beta\beta$  transition operator

two-body operator

can be systematically constructed in chiral EFTs

need LQCD both

## Dim. 9 operators



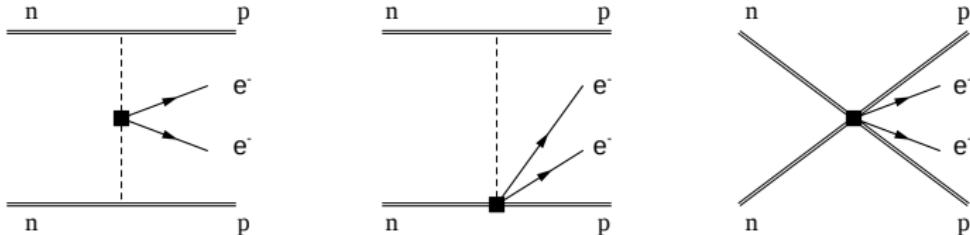
1. LL LL :  $\mathcal{O}_1 = \bar{u}_L \gamma^\mu d_L \bar{u}_L \gamma_\mu d_L$
2. LR LR :  $\mathcal{O}_2 = \bar{u}_L d_R \bar{u}_L d_R, \quad \mathcal{O}_3 = \bar{u}_L^\alpha d_R^\beta \bar{u}_L^\beta d_R^\alpha$
3. LL RR :  $\mathcal{O}_4 = \bar{u}_L \gamma^\mu d_L \bar{u}_R \gamma_\mu d_R, \quad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

- several unjustified assumptions in the literature . . .

e.g.  $\langle pp | \bar{u}_L \gamma^\mu d_L \bar{u}_R \gamma_\mu d_R | nn \rangle = \langle p | \bar{u}_L \gamma^\mu d_L | n \rangle \langle p | \bar{u}_R \gamma_\mu d_R | n \rangle = (1 - 3g_A^2)$

inconsistent with QCD, miss chiral dynamics

## LNV interactions from dim. 9 operators



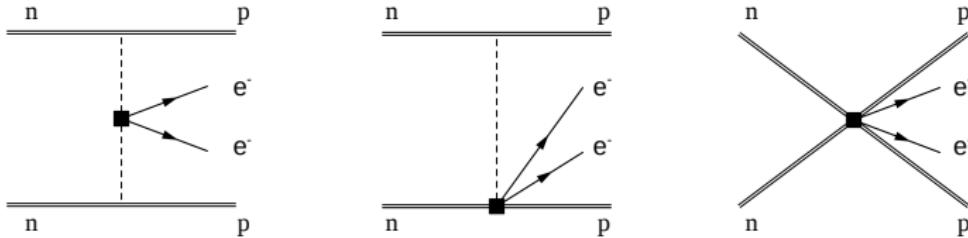
- $\pi\pi$  couplings

$$\begin{aligned} \mathcal{L}_\pi = & \frac{F_0^2}{2} \left[ \frac{5}{3} g_1^{\pi\pi} C_{1L}^{(9)} \partial_\mu \pi^- \partial^\mu \pi^- + \left( g_4^{\pi\pi} C_{4L}^{(9)} + g_5^{\pi\pi} C_{5L}^{(9)} - g_2^{\pi\pi} C_{2L}^{(9)} - g_3^{\pi\pi} C_{3L}^{(9)} \right) \pi^- \pi^- \right] \\ & \times \frac{\bar{e}_L C \bar{e}_L^T}{v^5} + (L \leftrightarrow R) + \dots \end{aligned}$$

- size depends on chiral properties of  $\mathcal{O}_{1,\dots,5}$

$$g_1^{\pi\pi} \sim \mathcal{O}(1), \quad g_{2,3,4,5}^{\pi\pi} \sim \mathcal{O}(\Lambda_\chi^2)$$

## LNV interactions from dim. 9 operators



- $\pi N$  couplings, only important for  $\mathcal{O}_1$

- $NN$  couplings

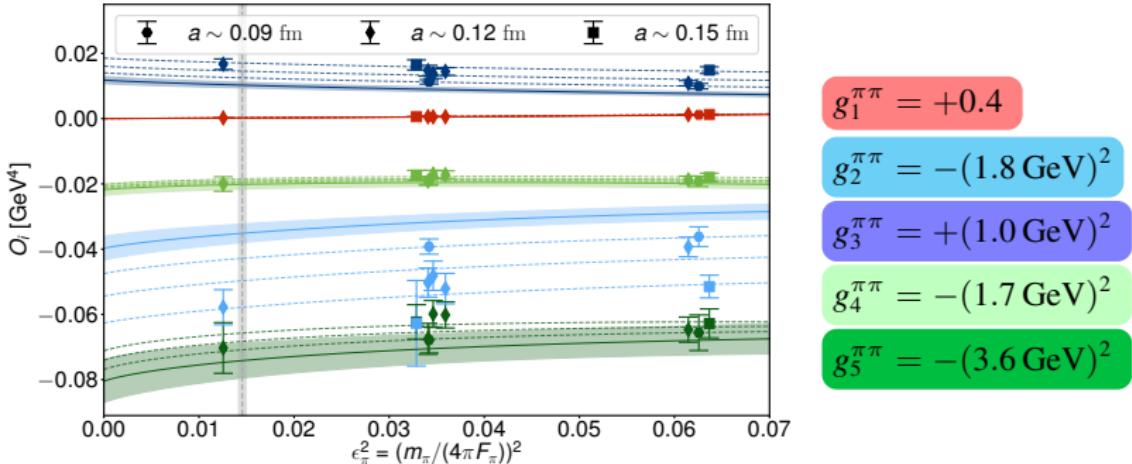
$$\mathcal{L}_{NN} = \left( g_1^{NN} C_{1L}^{(9)} + g_2^{NN} C_{2L}^{(9)} + g_3^{NN} C_{3L}^{(9)} + g_4^{NN} C_{4L}^{(9)} + g_5^{NN} C_{5L}^{(9)} \right) (\bar{p}n) (\bar{p}n) \frac{\bar{e}_L C e_L^T}{v^5}$$

- size depends on chiral properties of  $\mathcal{O}_{1,\dots,5}$

$$g_1^{NN} \sim \mathcal{O}(1), \quad g_{2,3,4,5}^{NN} \sim \mathcal{O}\left(\frac{\Lambda_\chi^2}{F_\pi^2}\right)$$

enhanced w.r.t NDA!

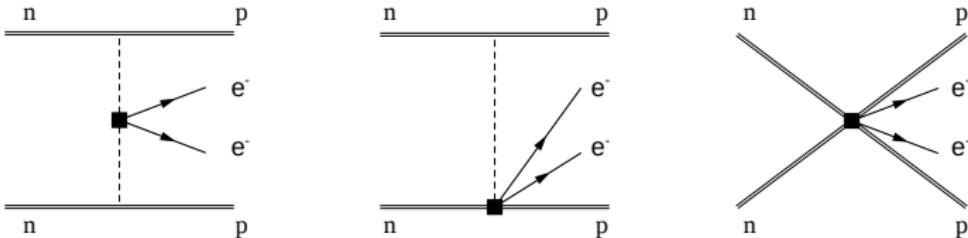
## $\pi\pi$ matrix elements



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

- $\pi\pi$  matrix elements well determined in LQCD  
good agreement with NDA
- $nn \rightarrow pp$  will allow to determine  $g_i^{NN}$   
and test the chiral EFT power counting

## $0\nu\beta\beta$ potential



- NME differ dramatically from factorization

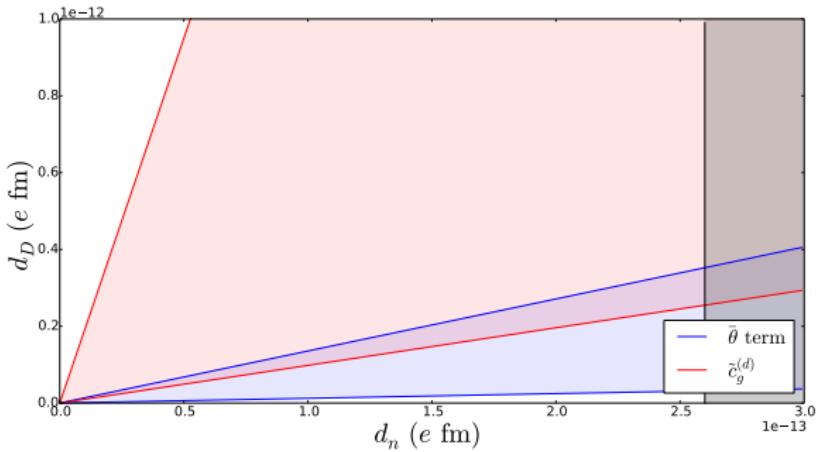
e.g  $C_4^{(9)}$

$$M = -\frac{g_A^{\pi\pi} C_4^{(9)}}{2m_N^2} \left( \frac{1}{2} M_{AP,sd}^{GT} + M_{PP,sd}^{GT} \right) \sim -0.60 C_4^{(9)}$$

$$M_{\text{fact}} = -\frac{3g_A^2 - 1}{2g_A^2} \frac{m_\pi^2}{m_N^2} C_4^{(9)} M_{F,sd} \sim -0.04 C_4^{(9)}$$

bigger error than from NMEs ...

## Impact of better LECs

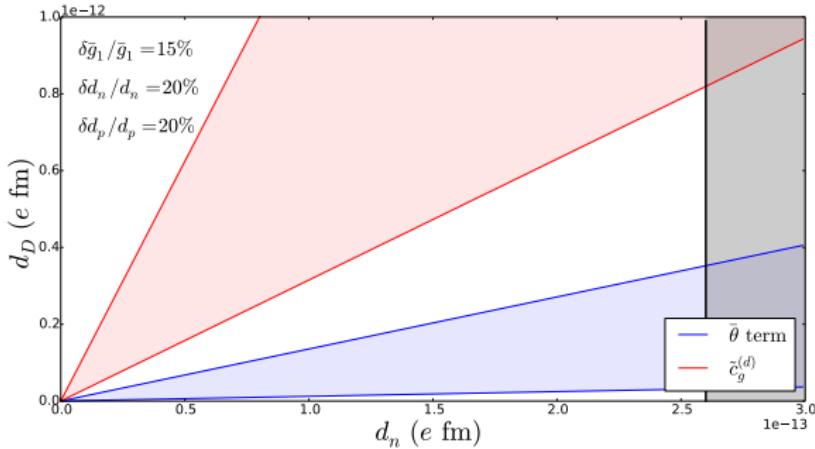


- chiral EFT predicts

$$d_D(\bar{\theta}) \sim d_n(\bar{\theta}), \quad d_D(\tilde{c}_d^{(g)}) \sim (5 - 10) d_n(\tilde{c}_d^{(g)})$$

murky with current LECs

## Impact of better LECs



- chiral EFT predicts

$$d_D(\bar{\theta}) \sim d_n(\bar{\theta}), \quad d_D(\tilde{c}_d^{(g)}) \sim (5 - 10) d_n(\tilde{c}_d^{(g)})$$

murky with current LECs

- reasonable improvement on  $\bar{g}_1, d_n, d_p$  has big impact

similar for  $^{225}\text{Ra}, ^{199}\text{Hg}$