WEINBERG POWER COUNTING AND BEYOND-THE-STANDARD-MODEL PHYSICS

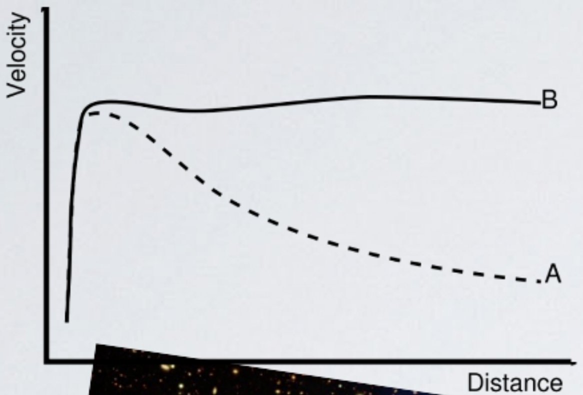
Jordy de Vries
University of Amsterdam & Nikhef

The impact of power counting on particle physics

Background and motivation

- Particle physics stands somewhat at a crossroads
- Large Hadron Collider will (very likely) not produce new particles on-shell
- Proposed future colliders typically pitched as 'Higgs factories' or 'precision machines'
- Exception perhaps ~100 TeV pp colliders (FCC-pp or CEPC) but longer time-scale
- **Problems of the Standard Model remain as persistent as ever**

Problems where we are kinda clueless

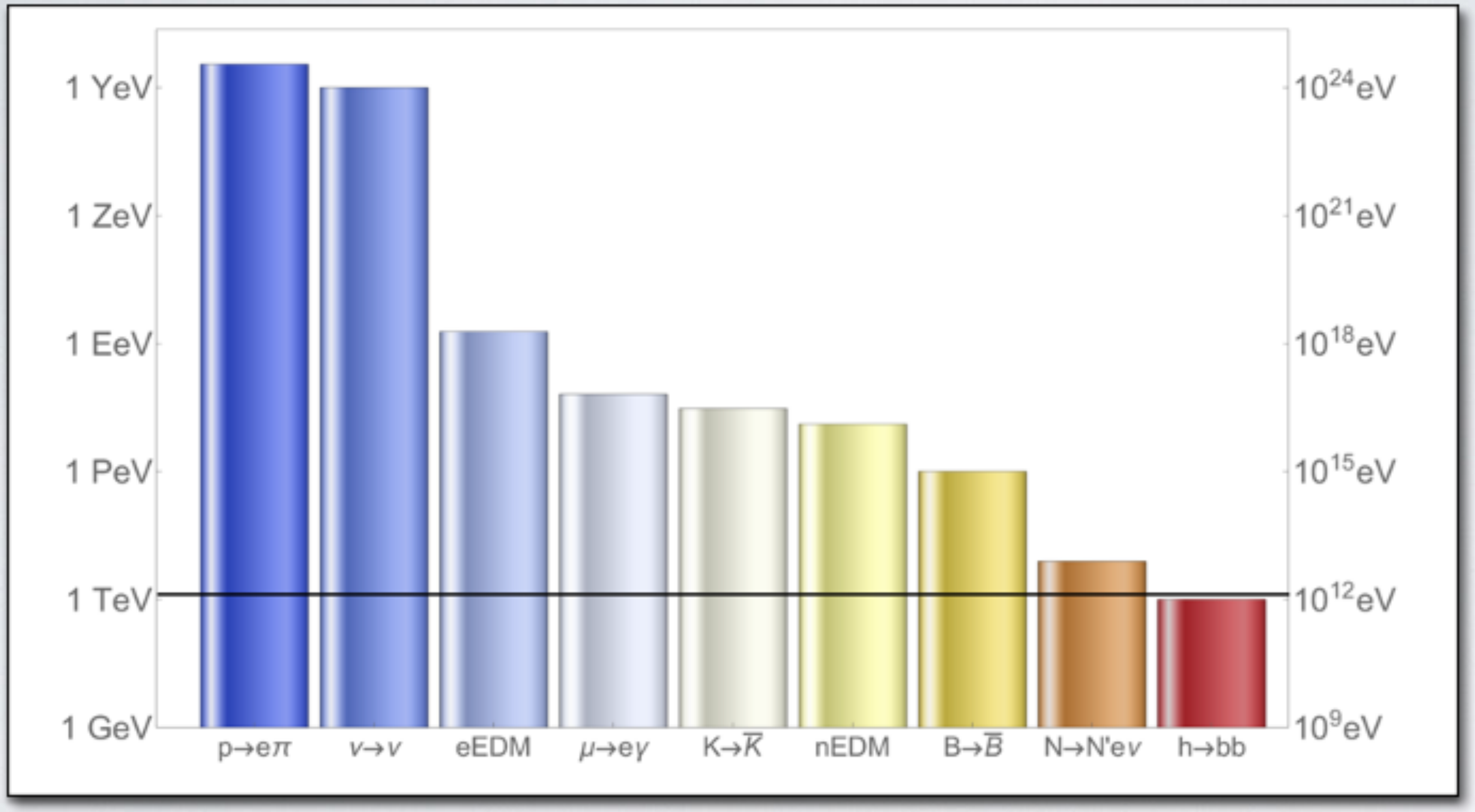


$$\frac{M_{\text{Higgs}}}{M_{\text{Planck}}} \ll 1 \qquad \bar{\theta} \ll 1 \qquad y_e \ll y_t$$

- Despite decades of model building and soul searching there are no answers
- *Note: not all problems are 'problems' per se*

- *Important: none of these problems (apart from hierarchy perhaps) point to beyond-the-Standard-Model physics at the TeV scale*

Reach of precision experiments



$$d_n \sim \frac{1}{\Lambda^2}$$

Figure made by Adam Falkowski

- Low-energy precision experiments (proton decay, 0vbb, EDMs, Lepton-flavor violation, Flavor Physics, beta decays) indirectly reach very high energy scales
- Many experiments involve nucleons and nuclei —> require nuclear physics
- Interpretation of experiments requires precise or semi-precise theory predictions
- **Chiral EFT can help —> but need to understand power counting**

Classes of experiments

Two types of precision tests of Standard Model physics

`Background Free'

Electric dipole moments (practically)
Proton decay
Neutron-antineutron oscillations
Neutrinoless double beta decay
Lepton flavor violation (practically)
DM direct detection
……………………..

`SM Background'

Beta decay
Flavor physics (most observables)
Muon and electron g-2
Atomic parity violation
……………………..

Theoretical accuracy arguably more important in right column
But not unimportant on the left: '*can we reach inverted hierarchy Majorana masses in next-gen experiments ?*' ' *What models of baryogenesis work ?*'

Chiral EFT and power counting

BSM observables can also help us probe the power counting !

BSM observables probe different aspects of nuclear physics and chiral interactions

Disadvantage: we often have no data (since SM works too well). Cannot verify our power counting assumptions.

But: sometimes there are ways around this

Chiral EFT and power counting

BSM observables can also help us probe the power counting !

BSM observables probe different aspects of nuclear physics and chiral interactions

Disadvantage: we often have no data (since SM works too well). Cannot verify our power counting assumptions.

But: sometimes there are ways around this

Advantage: we often have no data (since SM works too well). Cannot fit away problems and have to take them on the chin.

We have to *predict* something

The plan of attack

1. Introduction to why BSM is relevant for power counting

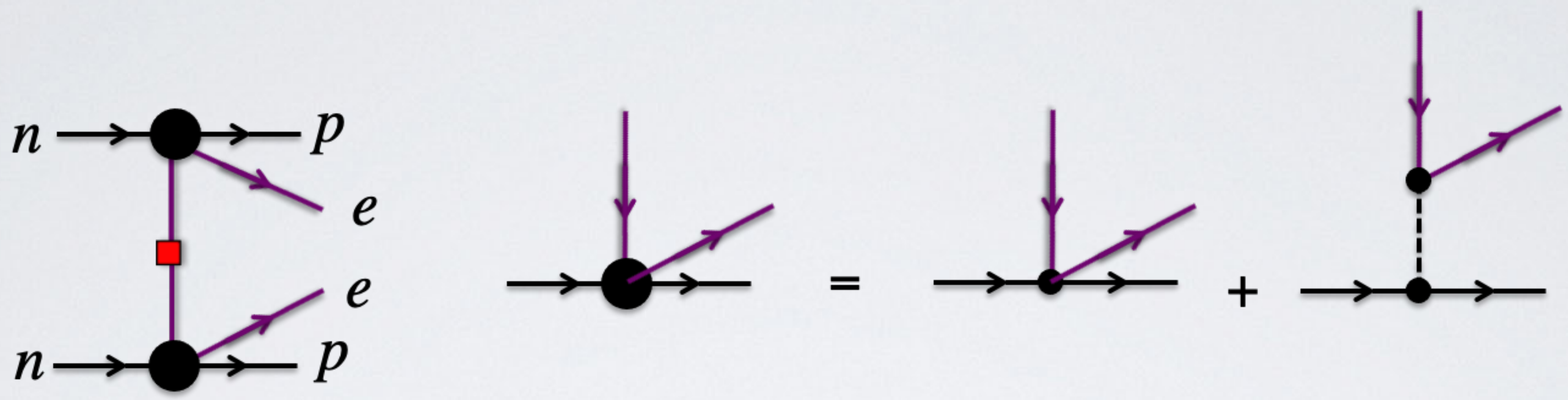
2. **0vbb from light Majorana neutrino exchange**

3. EDMs and the problems of S-P mixing

4. The confusing case of Dark Matter scattering

Case in point

- Maybe best example is neutrinoless double beta decay

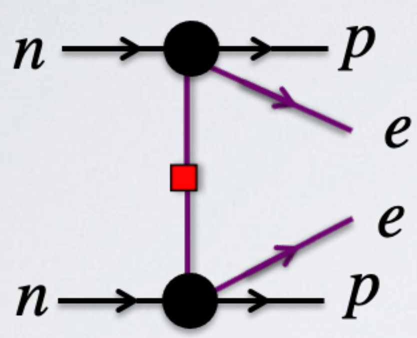


$$V_\nu({}^1S_0) = (2G_F^2 m_{\beta\beta})\tau_1^+\tau_2^+ \frac{1}{\mathbf{q}^2}\left[(1+2g_A^2) + \frac{g_A^2 m_\pi^4}{(\mathbf{q}^2+m_\pi^2)}\right] \otimes \bar{e}_L e_L^c$$

- This is the leading-order 'neutrino potential' in Weinberg counting
- Then insert this 'potential' between nuclear wave functions $A_\nu = \langle \Psi_f | V_\nu | \Psi_i \rangle$

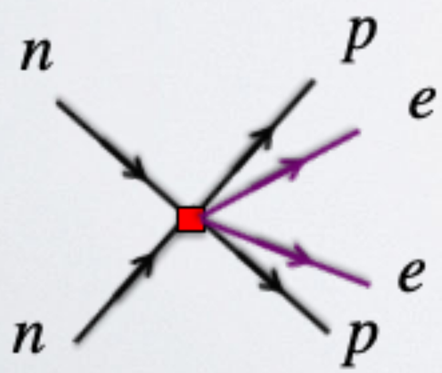
Case in point

- Maybe best example is neutrinoless double beta decay



$$V_\nu(^1S_0) = (2G_F^2 m_{\beta\beta})\tau_1^+\tau_2^+\frac{1}{\mathbf{q}^2}\left[(1+2g_A^2) + \frac{g_A^2 m_\pi^4}{(\mathbf{q}^2+m_\pi^2)}\right] \otimes \bar{e}_L e_L^c$$

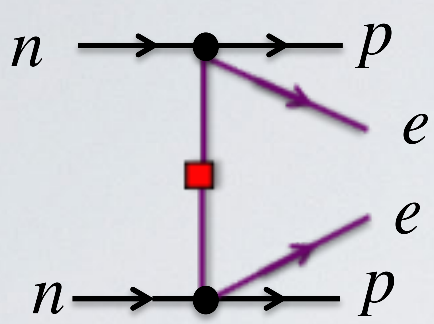
- This is the leading-order 'neutrino potential' in Weinberg counting
- Then insert this 'potential' between nuclear wave functions $A_\nu = \langle \Psi_f | V_\nu | \Psi_i \rangle$



- Contributions from virtual hard neutrinos $\mathbf{q} \sim \Lambda_\chi \sim 1\,\mathrm{GeV}$
- Naive-dimensional analysis tells us this is NNLO

$$V_\nu^{short} \sim \frac{m_{\beta\beta}}{\Lambda_\chi^2}$$

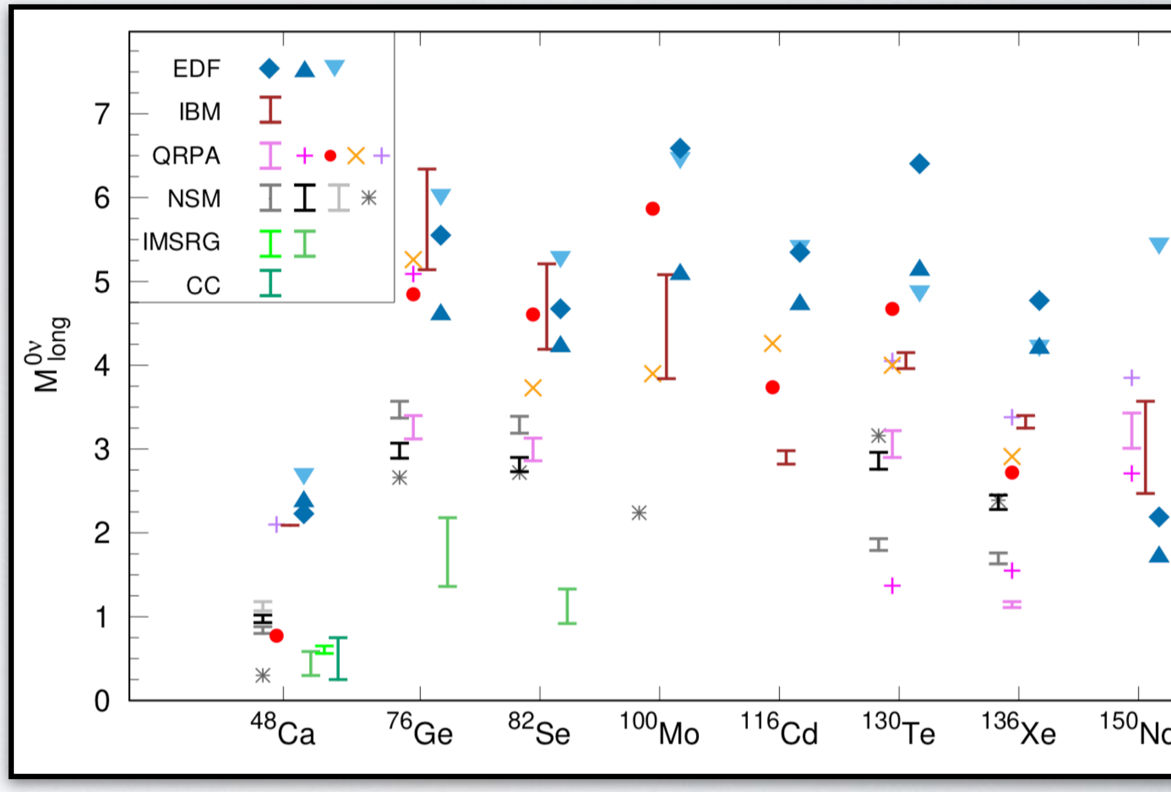
Leading-order transition currents



$$V_\nu = (2G_F^2 m_{\beta\beta})\tau_1^+\tau_2^+ \frac{1}{\mathbf{q}^2}\left[(1+2g_A^2) + \frac{g_A^2 m_\pi^4}{(\mathbf{q}^2+m_\pi^2)}\right] \otimes \bar{e}_L e_L^c$$

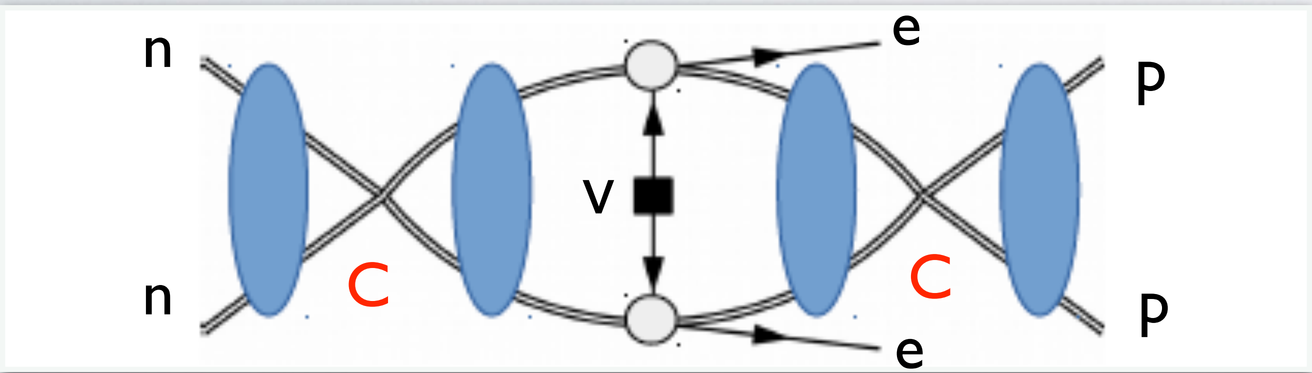
From: Menendez et al review '22

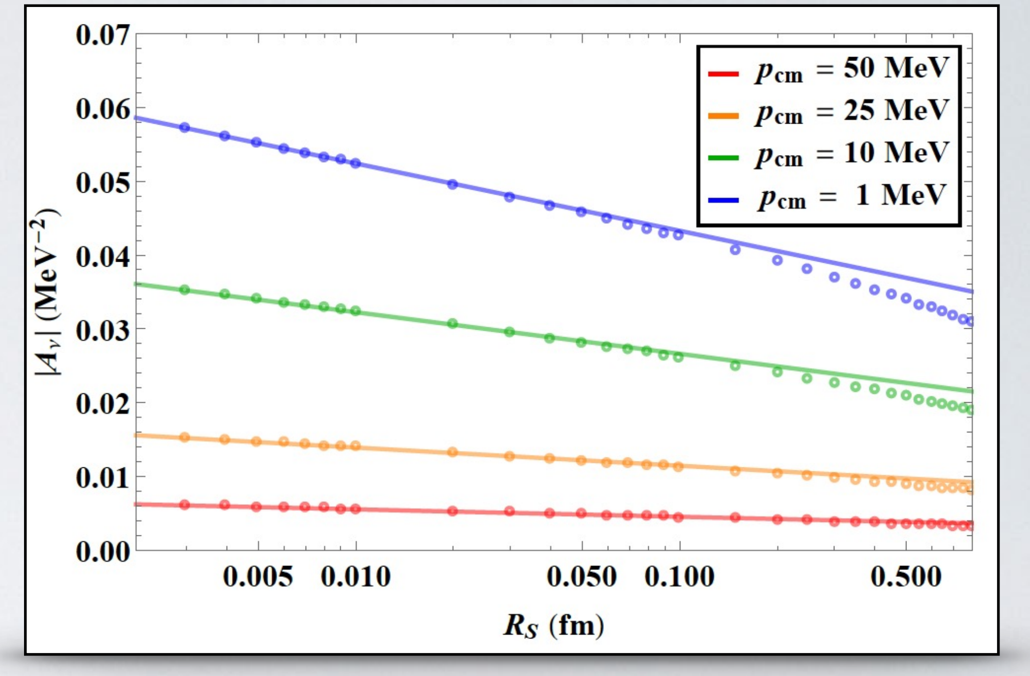
- Leading-order 0vbb current is very simple
- No unknown hadronic input ! Only unknown is $m_{\beta\beta}$
- ***Many-body methods disagree significantly***
- *Are we sure that the input is correct ?*



It doesn't work

Cirigliano et al '18

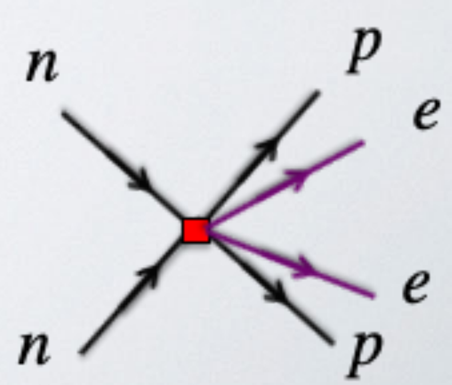




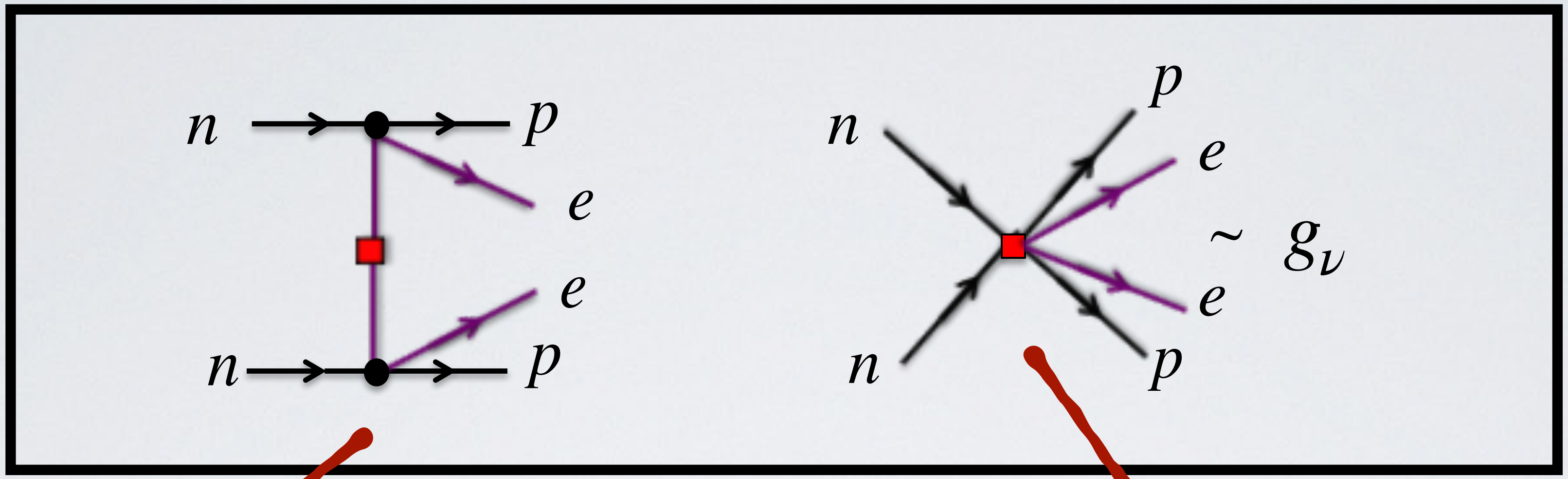
$$\sim (1 + 2g_A^2)\left(\frac{m_N C_0}{4\pi}\right)^2 \left(\frac{1}{\epsilon} + \log\frac{\mu^2}{p^2}\right)$$

New divergences

- **Logarithmic regulator dependence**
- Divergence indicates sensitivity to short-distance physics (hard-neutrino exchange)
- Suggests need a counter term: a short-range nn → pp + ee operator



A new leading-order contribution



'Long-range' neutrino-exchange

'Short-distance' neutrino exchange required by renormalization of amplitude

- **Short-distance piece depends on QCD matrix element** g_ν

- This was initially unknown but now been determined with some confidence (see next talks)

Cirigliano, Dekens, JdV, Hoferichter, Mereghetti PRC '19 PRL '21 JHEP '21

Davoudi, Kadam PRL '21 Briceno et al '19 '20

Van Groffier '24

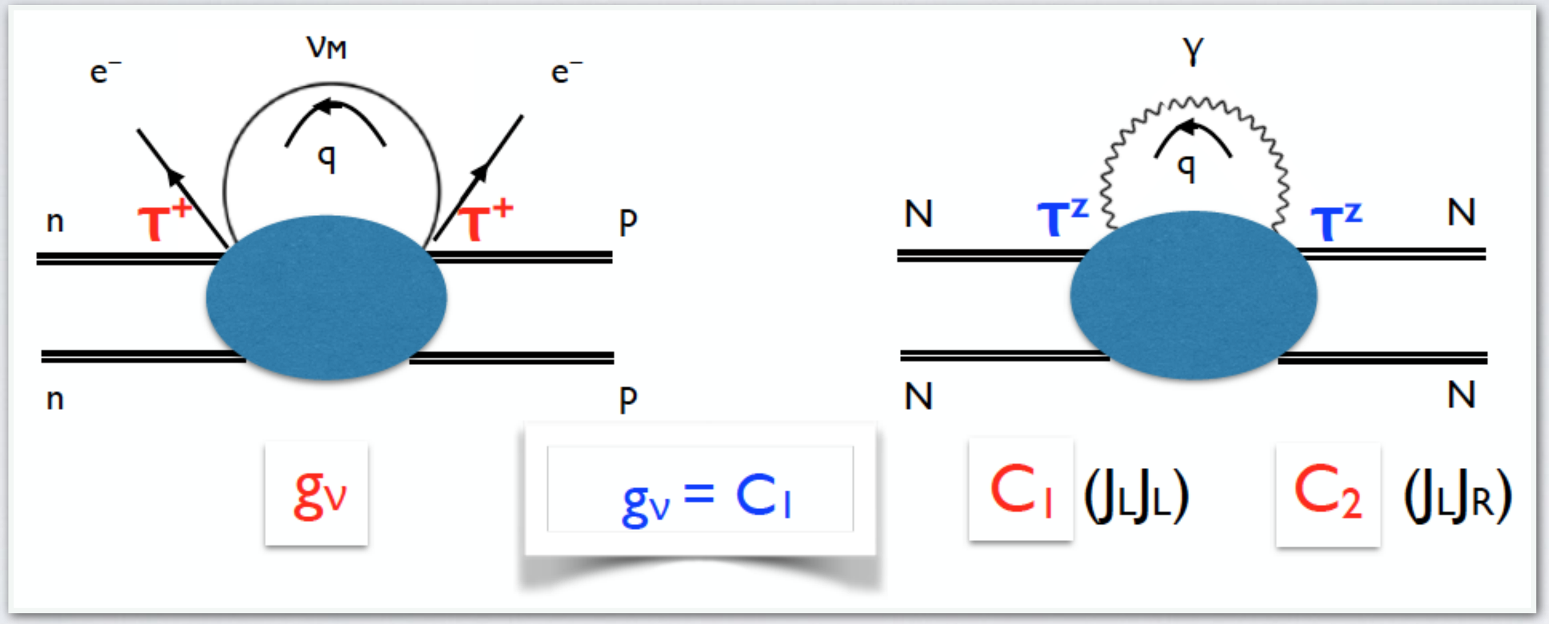
Richardson, Schindler, Pastore, Springer '21

Tuo et al. '19; Detmold, Murphy '20 '22

Yang, Zhao '23 '24

A connection to electromagnetism

- A neutrino-exchange process looks like a photon-exchange process



Cirigliano et al '19

Walzl, Meißner, Epelbaum '01

- **Chiral** connection between double-weak and double-EM NN interactions

- Isospin-breaking nucleon-nucleon scattering data determines **C_1+C_2**
- Electromagnetism conserves **parity** coupling and **g_ν~C_1** only

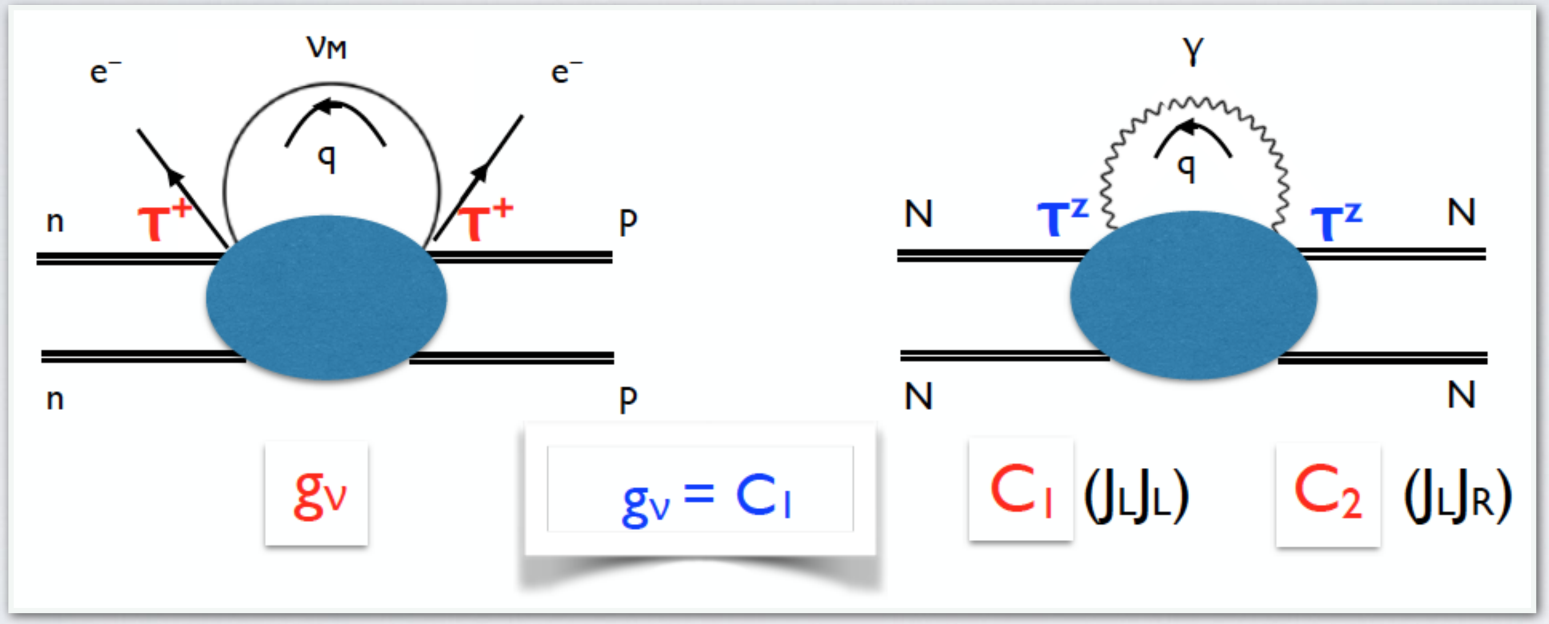
- Large-Nc arguments indicates $C_1 + C_2 \gg C_1 - C_2$ Richardson, Schindler, Pastore, Springer PRC'21

- This seems to work surprisingly well Cirigliano, Dekens, JdV, Hoferichter, Mereghetti PRL '21

Van Groffier '24 Yang, Zhao PLB '23 '24

A connection to electromagnetism

- A neutrino-exchange process looks like a photon-exchange process



Cirigliano et al '19

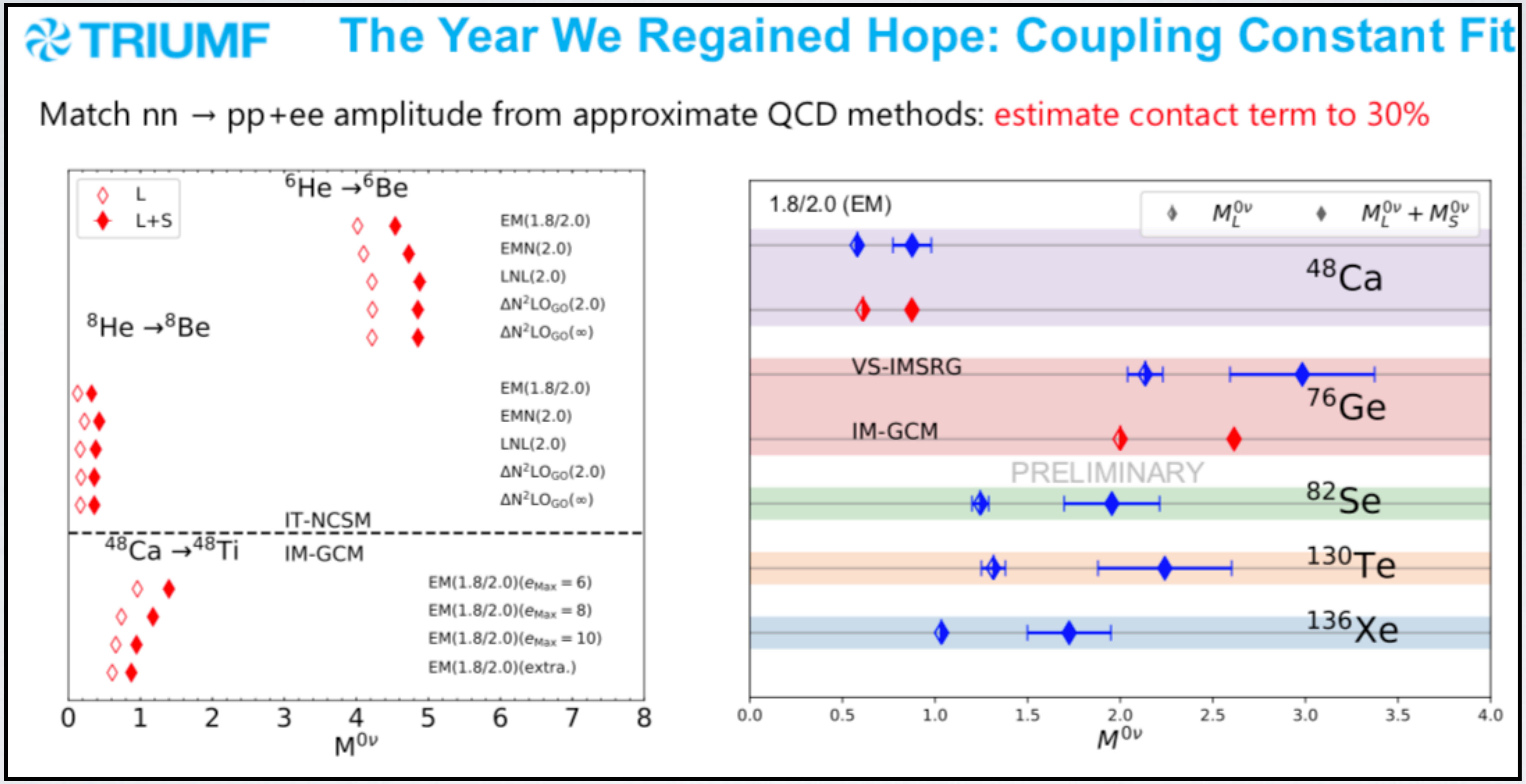
Model	Ref.	R_S (fm)	C_0^{IT} (fm^2)	$(\mathcal{C}_1+\mathcal{C}_2)/2$ (fm^2)	Model	Ref.	Λ (MeV)	$(\mathcal{C}_1+\mathcal{C}_2)/2$ (fm^2)
NV-Ia*	[37]	0.8	0.0158	−1.03	Entem-Machleidt	[33]	500	−0.47
NV-IIa*	[37]	0.8	0.0219	−1.44	Entem-Machleidt	[33]	600	−0.14
NV-Ic	[37]	0.6	0.0219	−1.44	Reinert *et al.*	[38]	450	−0.67
NV-IIc	[37]	0.6	0.0139	−0.91	Reinert *et al.*	[38]	550	−1.01
					NNLO$_{sat}$	[36]	450	−0.39

TABLE II. Values of $\mathcal{C}_1+\mathcal{C}_2$ obtained from the CIB contact interactions in various chiral potentials

- **Weinberg PC:** $$C_{1,2} \sim \frac{1}{\Lambda_\chi^2} \sim 0.04\,\mathrm{fm}^2$$

- Chiral potentials were never really consistent with this

Impact on realistic nuclei



- Slides from **Jason Holt** (TRIUMF) at Institute of Nuclear Physics Seattle (2023)
- Contact term increases ab initio NMEs and brings them closer to phenomenological calculations

***Ab initio* uncertainty quantification of neutrinoless double-beta decay in ^{76}Ge**

A. Belley,[1,2] J. M. Yao,[3] B. Bally,[4] J. Pitcher,[1,2] J. Engel,[5] H. Hergert,[6,7] J. D. Holt,[1,8] T. Miyagi,[9,10,11] T. R. Rodríguez,[12,13,14] A. M. Romero,[15,16] S. R. Stroberg,[17] and X. Zhang[3]

The plan of attack

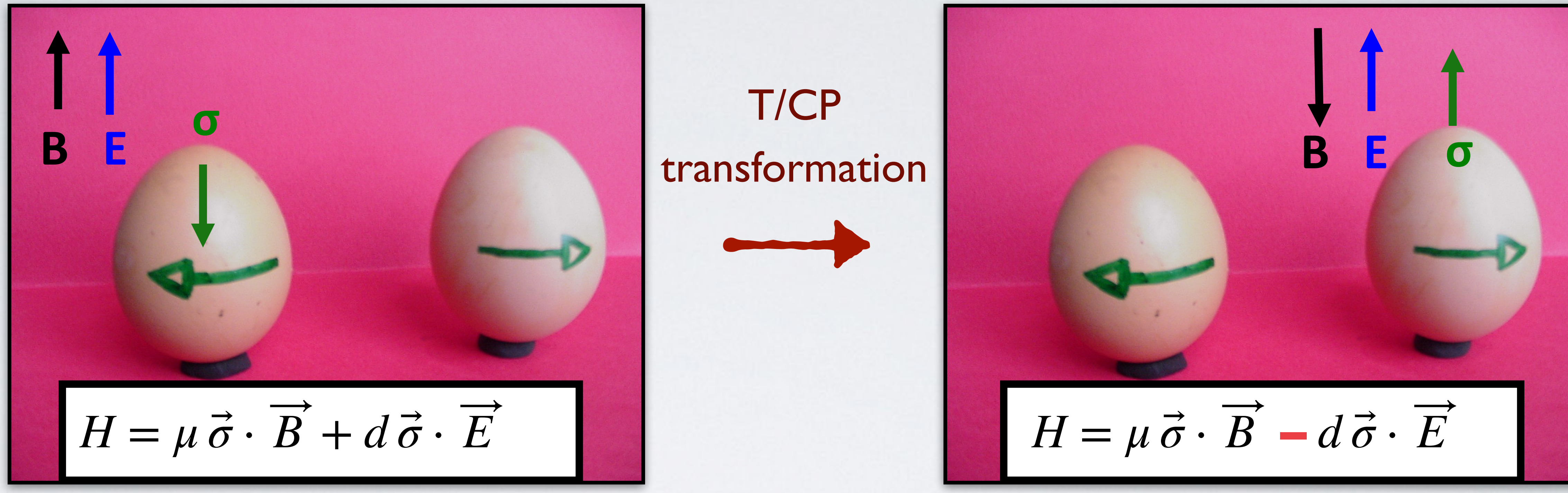
1. Introduction to why BSM is relevant for power counting

2. 0vbb from light Majorana neutrino exchange

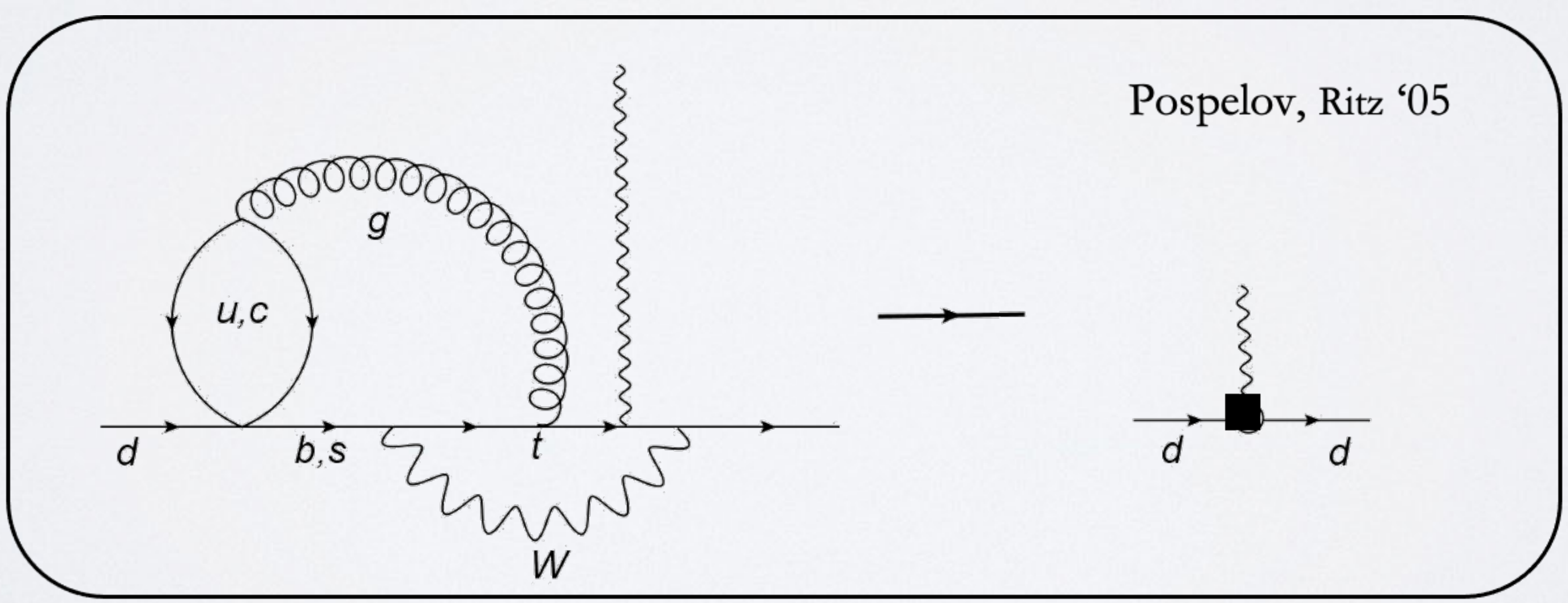
3. **EDMs and the problems of S-P mixing**

4. The confusing case of Dark Matter scattering

Electric dipole moments 101

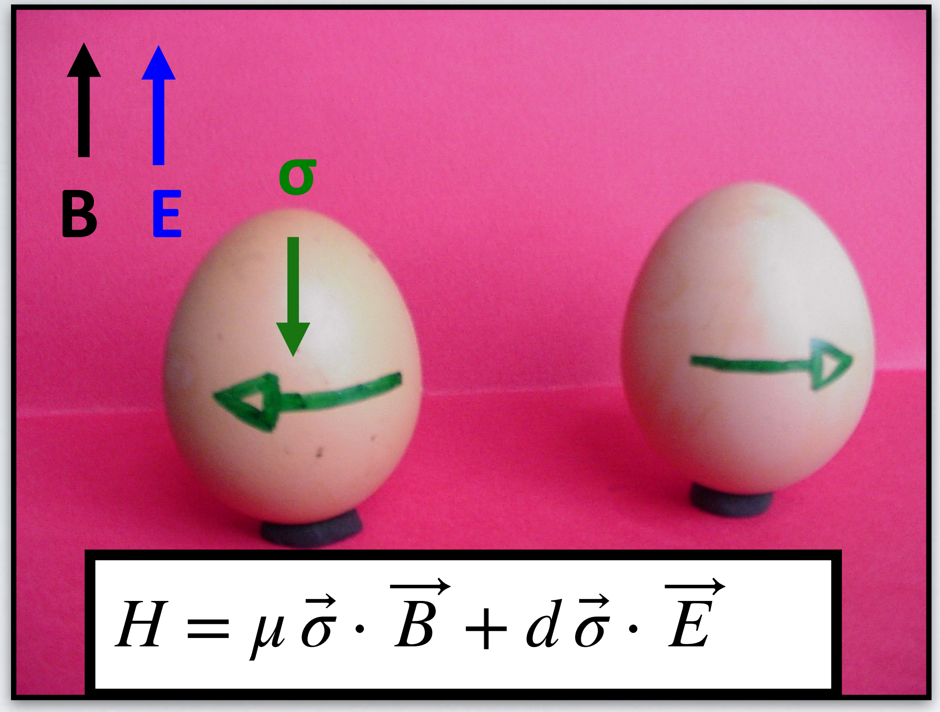


- EDMs from CKM phase only appear at high-loop level and are very suppressed !

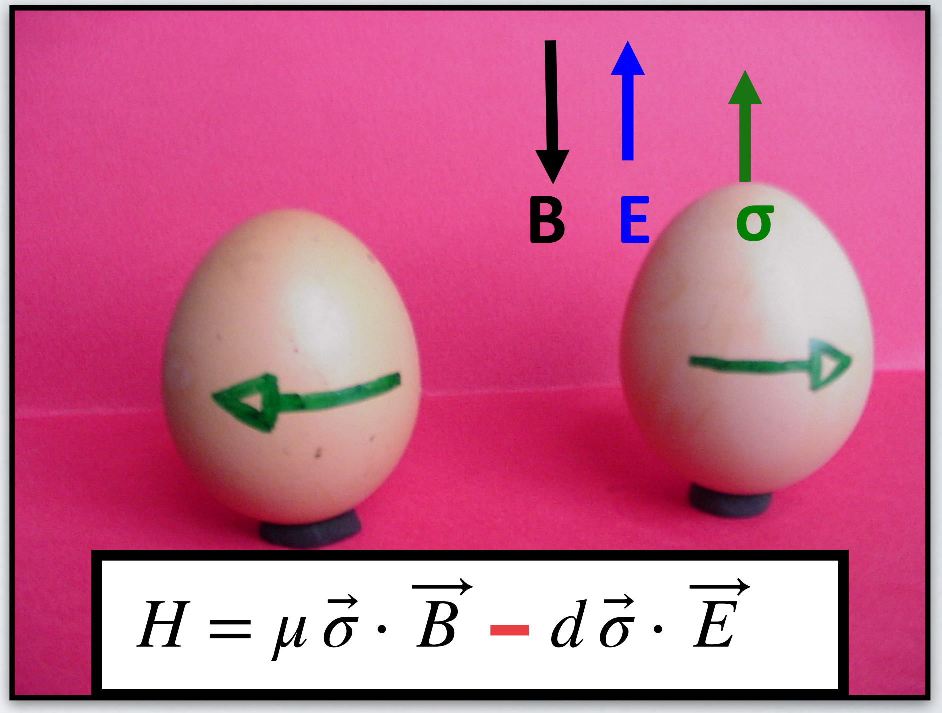


Hoogeveen '90, Khriplovich, Zhitnitsky '82, Czarnecki, Krause '97, Uraltsev '13, Seng '14

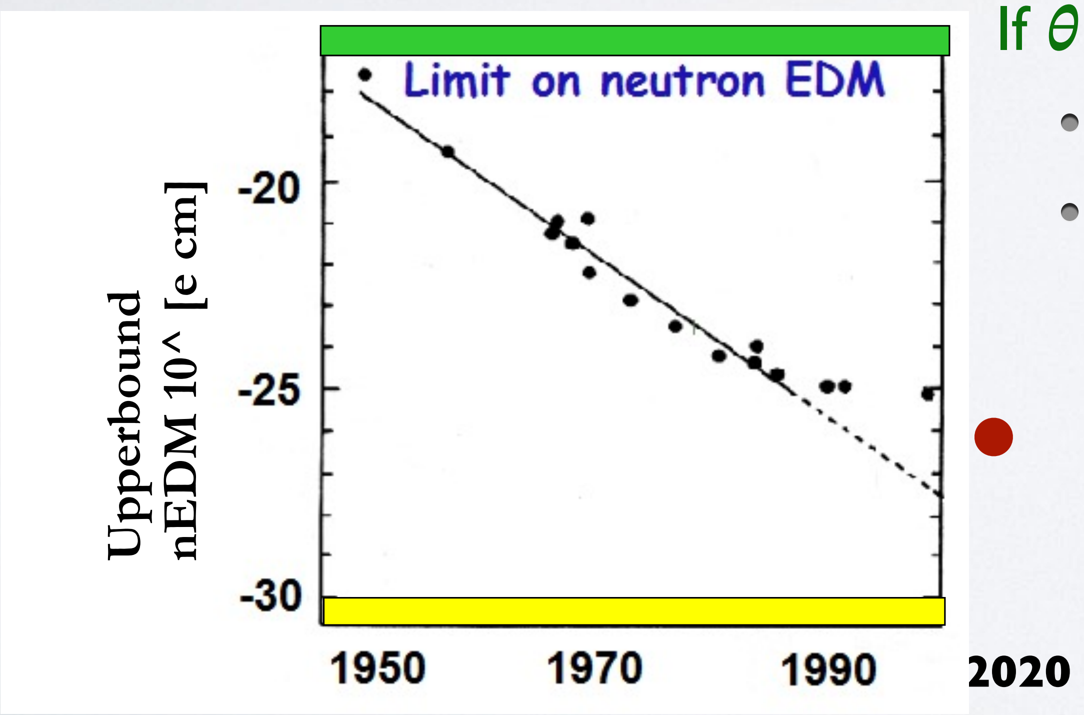
Electric dipole moments 101



T/CP transformation



- EDMs from CKM phase only appear at high-loop level and are very suppressed !



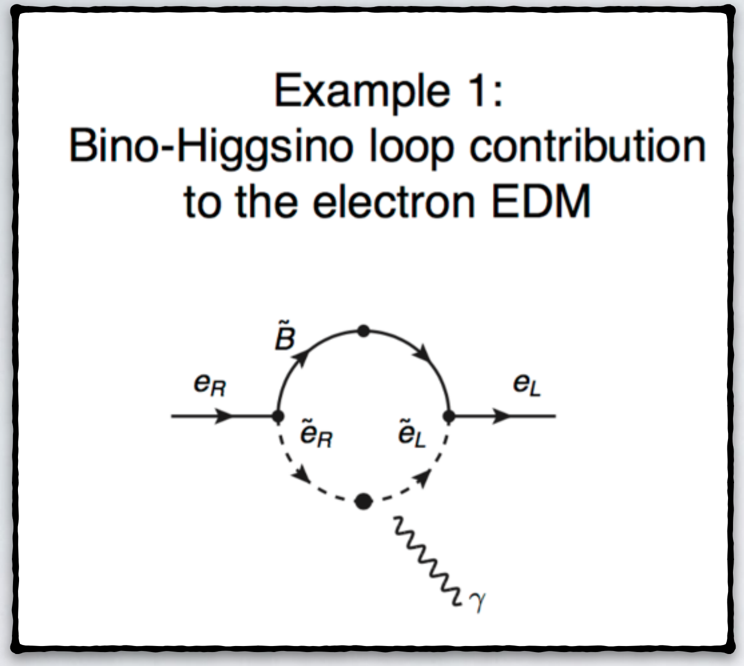
If $\theta \sim 1$

- SM prediction essentially out of reach
- EDMs can still arise from the QCD theta term

$$\mathcal{L}_\theta \sim \bar{\theta}\epsilon^{\mu\nu\alpha\beta}G^a_{\mu\nu}G^a_{\alpha\beta}$$

- Strong CP problem: $\theta < 0.0000000001$
- Sparked a lot of debate and theorizing

Electric dipole moments 101

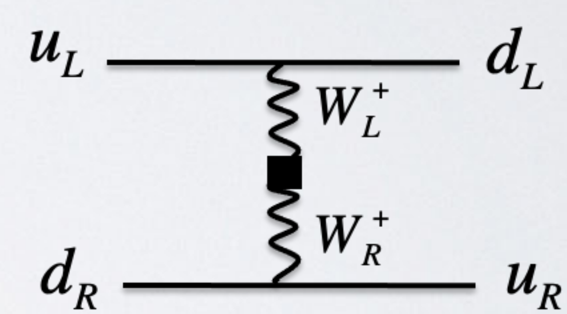


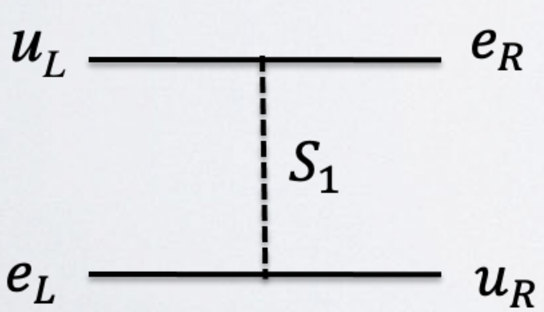
- Many BSM models: EDMs at zero-, one-, or two-loop

$$d_f \left(\frac{\alpha_{em}}{\pi}\right)^n \frac{m_e}{\Lambda^2} \sin\phi_{CPV}$$

- If phase ~ O(1), then Λ > 40 TeV (n=1), or Λ > 5 TeV (n=2)

- Certain models EDMs are induced without loop suppression !
- For example, in left-right symmetric models:
- CP-odd four-quark operators induce hadronic EDMs

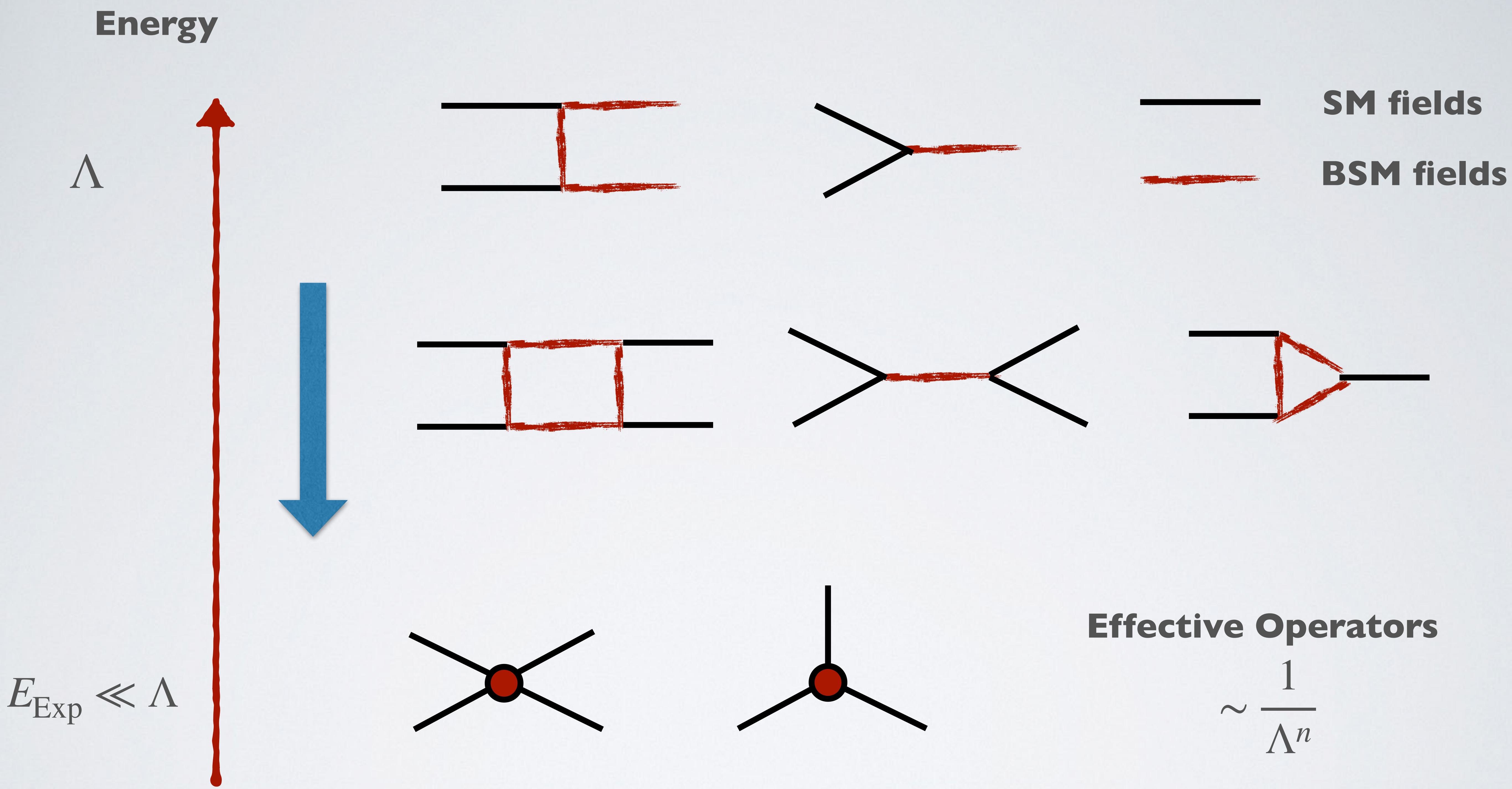




- Leptoquarks can induce CP-odd electron-quark interactions
- Induce atomic/molecular EDMs

- Tree-level CPV leads to Λ > 1000-10000 TeV if phases are O(1)

EDMs are low-energy experiments



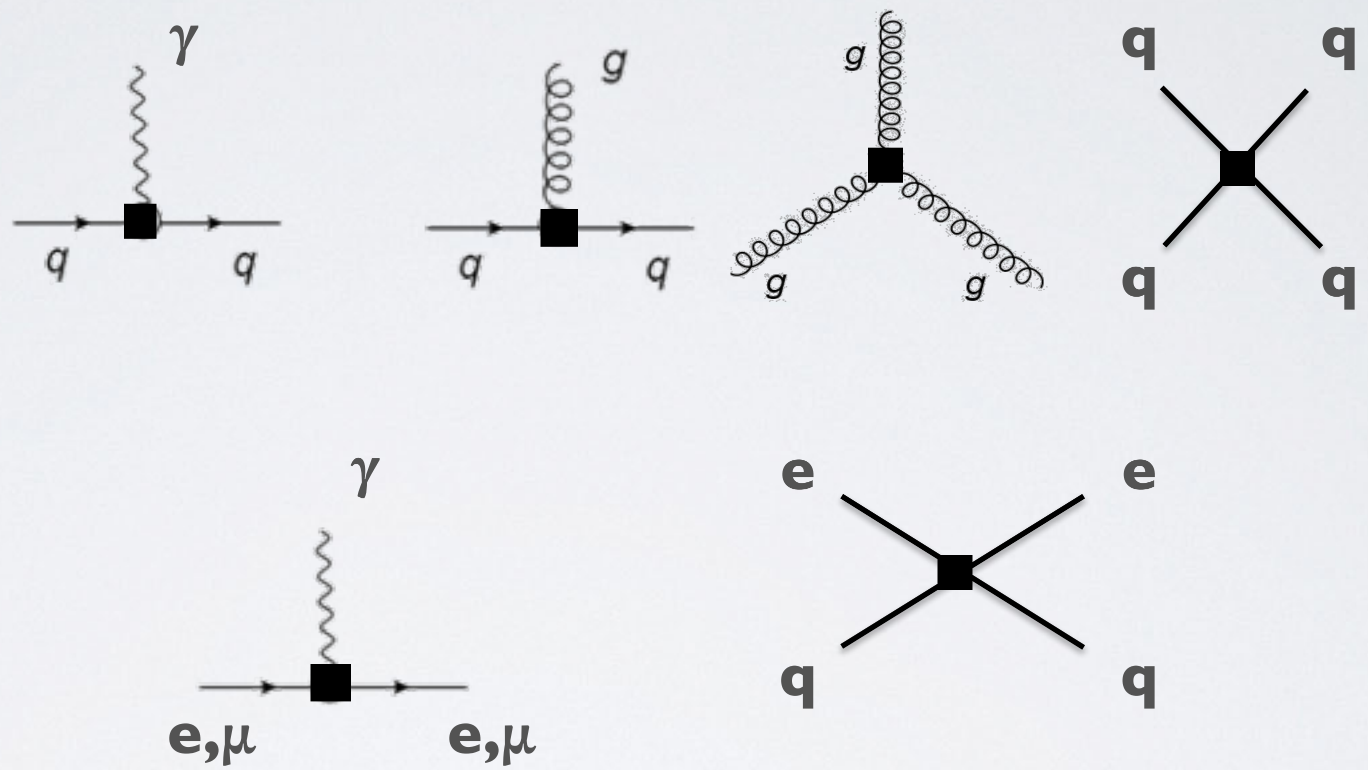
Effects of heavy BSM fields capture by local effective operators

For CP violation relevant operators start at dimension six

Strong CP violation

- Large number of **CP-odd** and **flavor-diagonal** dim-6 operators (unlike Standard Model)
- At energies around a few GeV: handful of operators left

$$\mathscr{L}_\theta \sim \bar{\theta}\epsilon^{\mu\nu\alpha\beta}G^a_{\mu\nu}G^a_{\alpha\beta}$$



- **Induce electric dipole moments of leptons, hadrons, nuclei, atoms, molecules**

Example: strong CP problem

- **Problem:** Calculate EDMs in terms of the theta angle
- First calculation Crewther et al '79, essentially leading-order Chiral perturbation theory.

$$\mathcal{L}_{QCD} = \mathcal{L}_{kin} - \bar{m}\bar{q}q - \varepsilon\bar{m}\bar{q}\tau^3 q \qquad + m_\star\bar{\theta}\bar{q}i\gamma^5 q$$

$$m_\star = \frac{m_u m_d}{m_u + m_d}$$

$$\bar{m} = (m_u + m_d)/2$$

$$\varepsilon\bar{m} = (m_d - m_u)/2$$

Example: strong CP problem

- **Problem:** Calculate EDMs in terms of the theta angle
- First calculation Crewther et al '79, essentially leading-order Chiral perturbation theory.

$$m_\star = \frac{m_u m_d}{m_u + m_d}$$

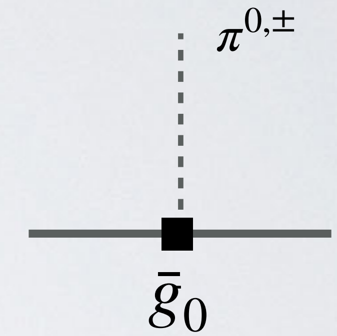
$$\bar{m} = (m_u + m_d)/2$$

$$\varepsilon\bar{m} = (m_d - m_u)/2$$

$$\mathscr{L}_{QCD} = \mathscr{L}_{kin} - \bar{m}\bar{q}q - \varepsilon\bar{m}\bar{q}\tau^3 q \qquad + m_\star \bar{\theta}\bar{q}i\gamma^5 q$$

$$\downarrow \quad \downarrow \qquad\qquad \downarrow$$

$$\mathscr{L}_{\chi+m} = \mathscr{L}_\chi - \frac{m_\pi^2}{2}\pi^2 - \delta m_N \bar{N}\tau^3 N \qquad + \bar{g}_0 \bar{N}\tau\cdot\pi N$$



Nucleon mass splitting (strong part, no EM)

CP-odd pion-nucleon

Example: strong CP problem

- **Problem:** Calculate EDMs in terms of the theta angle
- First calculation Crewther et al '79, essentially leading-order Chiral perturbation theory.

$$m_\star = \frac{m_u m_d}{m_u + m_d}$$

$$\bar{m} = (m_u + m_d)/2$$

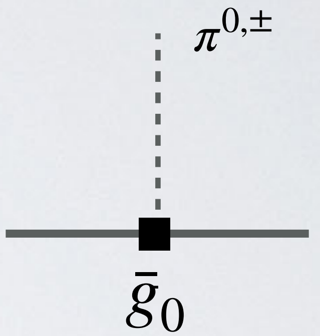
$$\varepsilon \bar{m} = (m_d - m_u)/2$$

$$\mathcal{L}_{QCD} = \mathcal{L}_{kin} - \bar{m}\bar{q}q - \varepsilon\bar{m}\bar{q}\tau^3 q \quad \longleftrightarrow \quad +m_\star \bar{\theta}\bar{q}i\gamma^5 q$$

SU$_A$(2) rotation

$$\downarrow \qquad\qquad \downarrow \qquad\qquad\qquad\qquad \downarrow$$

$$\mathcal{L}_{\chi+m} = \mathcal{L}_{\chi} - \frac{m_\pi^2}{2}\pi^2 - \delta m_N \bar{N}\tau^3 N \qquad\qquad +\bar{g}_0 \bar{N}\tau\cdot\pi N$$



Nucleon mass splitting (strong part, no EM) $\longleftrightarrow$ **CP-odd pion-nucleon**

$$\bar{g}_1/\bar{g}_0 \simeq -0.2$$

$$\bar{g}_0 = -\frac{\delta m_N}{2f_\pi}\frac{1-\varepsilon^2}{2\varepsilon}\,\bar{\theta} \quad = (15.5 \pm 2.5)\cdot 10^{-3}\,\bar{\theta}$$

δm_N from lattice-QCD

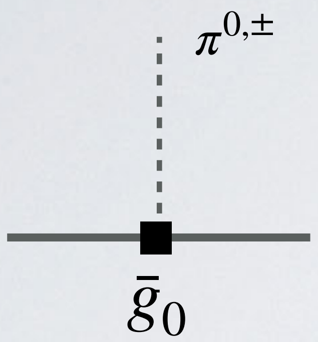
e.g. Borsanyi et al '14 but many more calculations

Relation valid up to N^{2}LO corrections

JdV, Mereghetti, Walker-Loud'15

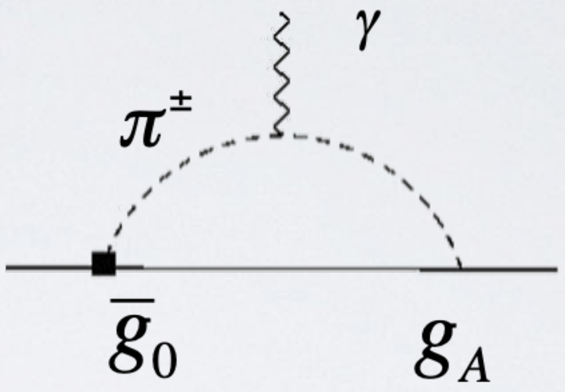
Quantifying the strong CP problem

- **Problem:** Calculate EDMs in terms of the theta angle
- First calculation Crewther et al '79, essentially leading-order Chiral perturbation theory.



Neutron EDM

at 1 loop

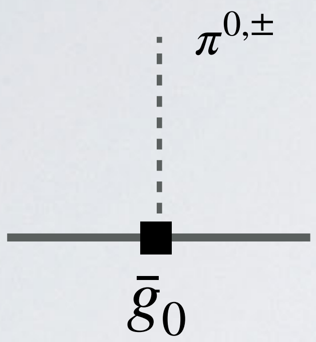


$$d_n = \bar{d}_n(\mu = m_N) - \frac{e g_A \bar{g}_0}{4\pi^2 F_\pi}\left(\ln \frac{m_\pi^2}{m_N^2} - \frac{\pi m_\pi}{2 m_N}\right)$$

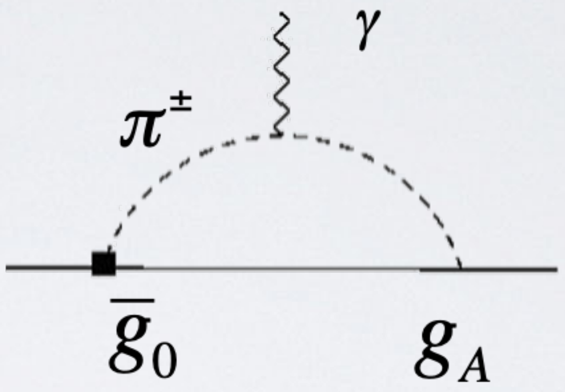
- The loop part gives $d_n \simeq -2.5 \cdot 10^{-16} e\,\mathrm{cm}$ $\longrightarrow$ $\bar{\theta} < 10^{-10}$

Quantifying the strong CP problem

- **Problem:** Calculate EDMs in terms of the theta angle
- First calculation Crewther et al '79, essentially leading-order Chiral perturbation theory.



Neutron EDM
at 1 loop



$$d_n = \bar{d}_n(\mu = m_N) - \frac{e g_A \bar{g}_0}{4\pi^2 F_\pi}\left(\ln \frac{m_\pi^2}{m_N^2} - \frac{\pi m_\pi}{2 m_N}\right)$$

- The loop part gives $d_n \simeq -2.5 \cdot 10^{-16} e\,\mathrm{cm}$ → $\bar{\theta} < 10^{-10}$
- Lattice QCD is needed for a full calculation.

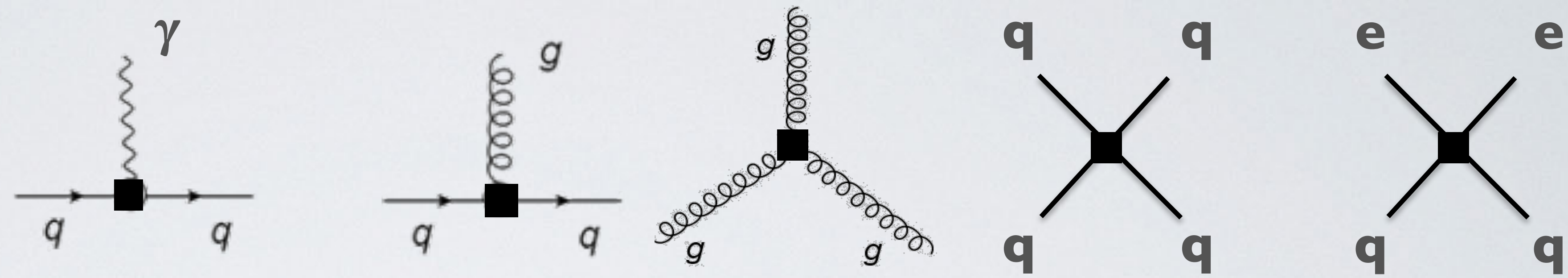
$d_n = -(1.5 \pm 0.8) \cdot 10^{-16} e\,\mathrm{cm}$ from Shindler et al '19

$d_n = -(1.4 \pm 0.51) \cdot 10^{-16} e\,\mathrm{cm}$ from Liang et al '23

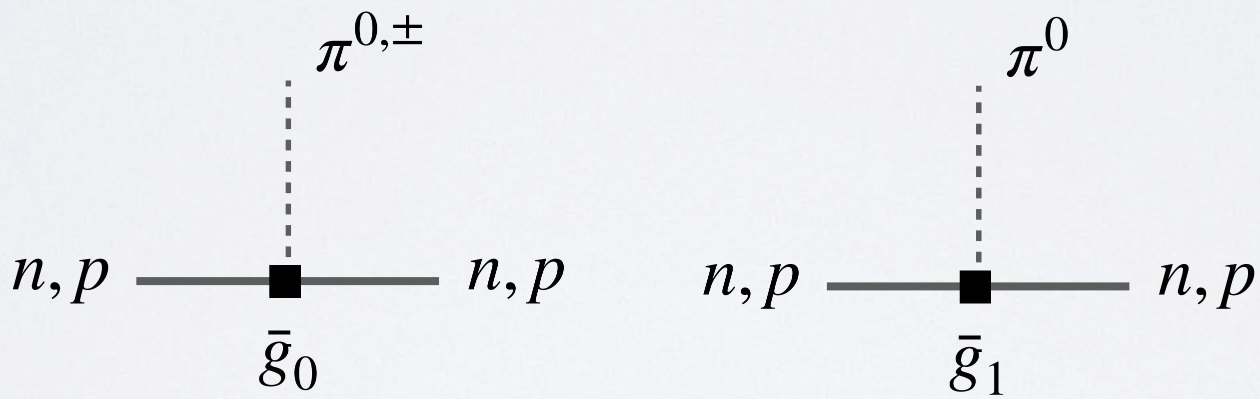
Neither confirmed by recent calculations from LANL lattice group '21

Patterns of EDMs

$$\mathcal{L}_\theta \sim \bar{\theta}\epsilon^{\mu\nu\alpha\beta}G^a_{\mu\nu}G^a_{\alpha\beta}$$



- They all break CP symmetry……
- But have different isospin and chiral symmetry properties → pattern of EDMs



- Ratios vary

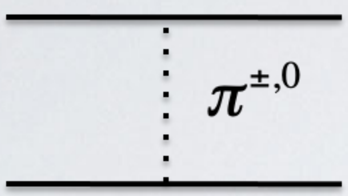
	Theta term	Quark CEDMs	FQLR	Quark EDM and Weinberg
$\frac{\bar{g}_1}{\bar{g}_0}$	–0.2	≈ 1	+50	Both couplings are suppressed !

JdV, Mereghetti, van Kolck, Timmermans '12

The original idea

CP-even

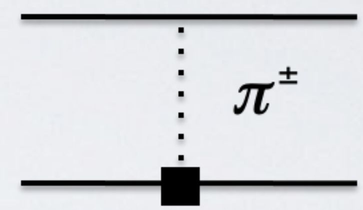
$$\frac{g_A}{2F_\pi}\bar{N}(\vec{\sigma}\cdot\vec{D}\pi^a)\tau^a N$$



$$\sim \frac{(g_A Q)^2}{Q^2} \sim Q^0$$

CP-odd

$$\bar{g}_0\bar{N}(\vec{\tau}\cdot\vec{\pi})N$$

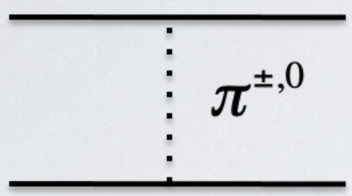


$$\sim \frac{(g_A Q)\bar{g}_0}{Q^2} \sim Q^{-1}$$

The original idea

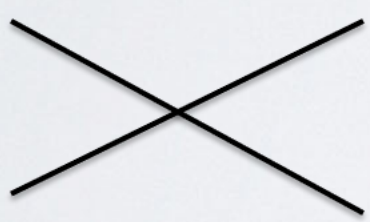
CP-even

$$\frac{g_A}{2F_\pi}\bar{N}(\vec{\sigma}\cdot\vec{D}\pi^a)\tau^a N$$



$$\sim \frac{(g_A Q)^2}{Q^2} \sim Q^0$$

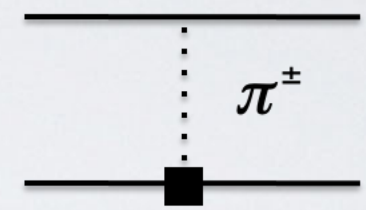
$$\bar{N}N\,\bar{N}N$$



$$\sim Q^0$$

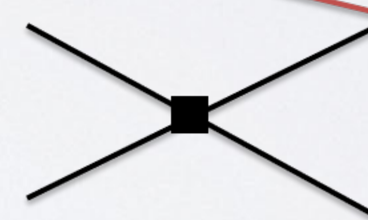
CP-odd

$$\bar{g}_0\bar{N}(\vec{\tau}\cdot\vec{\pi})N$$



$$\sim \frac{(g_A Q)\bar{g}_0}{Q^2} \sim Q^{-1}$$

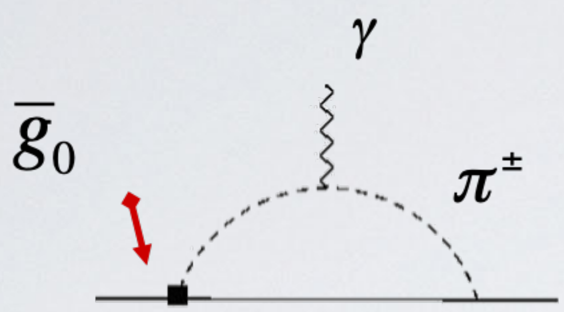
$$(\bar{N}N)\,\partial^i(\bar{N}\sigma^i N)$$

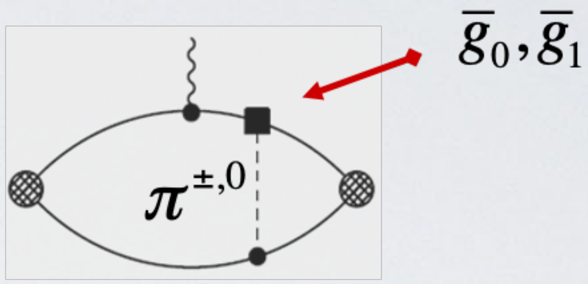


$$\sim Q^1$$

- In 'normal' nuclear forces, pions come with a derivative but contacts do not (S to S wave)
- Most CP-odd operators at dim-6 break chiral symmetry and then pion interactions have no derivative but contacts have one (S to P wave)

The deuteron EDM

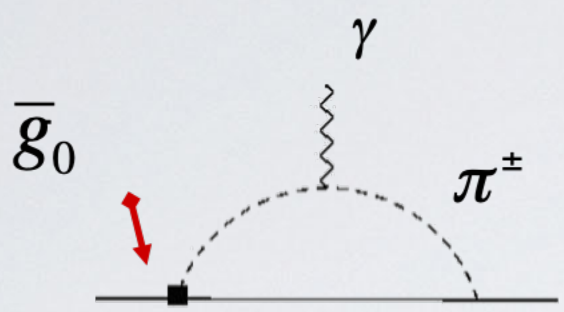


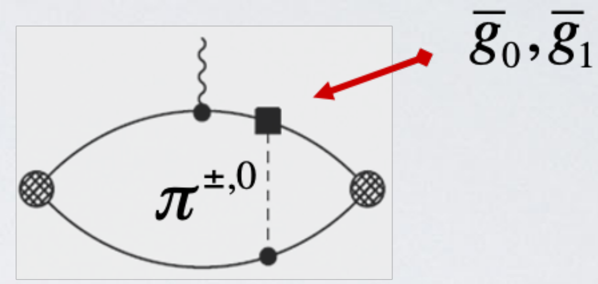


Khriplovich/Korkin '00
JdV, Mereghetti, Timmermans, van Kolck
PRL '11

- Nuclear CP violation can be larger than nucleon CP violation ! No chiral loop suppression !

The deuteron EDM





Khriplovich/Korkin '00
JdV, Mereghetti, Timmermans, van Kolck
PRL '11

- Nuclear CP violation can be larger than nucleon CP violation ! No chiral loop suppression !

$$^3S_1 \xrightarrow{\bar{g}_0,\, \bar{C}_{1,2}} {}^1P_1 \xrightarrow{\gamma} \cancel{{}^3S_1}$$

$$^3S_1 \xrightarrow{\bar{g}_1} {}^3P_1 \xrightarrow{\gamma} {}^3S_1$$

- Nice result with perturbative pions (KSW)

$$d_D = (d_n + d_p) + \frac{e g_A \bar{g}_1 m_N}{12\pi m_\pi F_\pi} \frac{1 + \gamma/m_\pi}{(1 + 2\gamma/m_\pi)^2} \simeq d_n + d_p + (0.23\, \bar{g}_1)\, e\, \mathrm{fm}$$

- Redone with chiral wave functions of various kinds —> stable results

$$d_D \simeq 0.95(d_n + d_p) + (0.18\, \bar{g}_1)\, e\, \mathrm{fm}$$

Computing atomic CP-odd moments

- Similar computation needed for diamagnetic atoms. For instance Hg

$$d_{\mathrm{Hg}} = -(2.1 \pm 0.5) \cdot 10^{-4} \left[(1.9 \pm 0.1) d_n + (0.20 \pm 0.06) d_p + \left(0.13^{+0.5}_{-0.07} \, \bar{g}_0 + 0.25^{+0.89}_{-0.63} \, \bar{g}_1 \right) e \, \mathrm{fm} \right]$$

- Large uncertainties for nuclear part.

$$d_{\mathrm{Ra}} = (-7.7 \pm 0.8) \cdot 10^{-4} \cdot [(-2.5 \pm 7.6) \; \bar{g}_0 + (63 \pm 38) \; \bar{g}_1] \, e \, \mathrm{fm}$$

Dobaczewski et al PRL '18

Computing atomic CP-odd moments

- Similar computation needed for diamagnetic atoms. For instance Hg

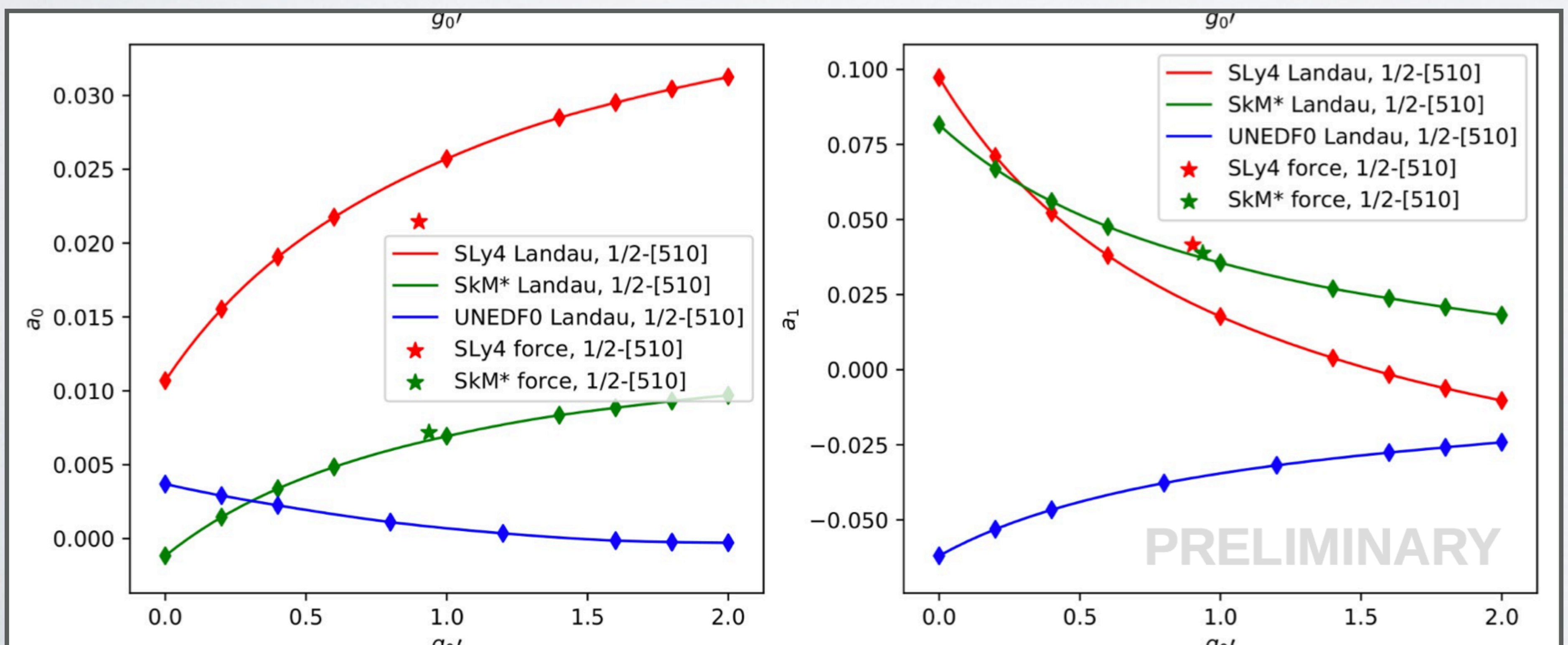
$$d_{\mathrm{Hg}} = -(2.1 \pm 0.5) \cdot 10^{-4} \left[(1.9 \pm 0.1) d_n + (0.20 \pm 0.06) d_p + \left(0.13^{+0.5}_{-0.07}\, \bar{g}_0 + 0.25^{+0.89}_{-0.63}\, \bar{g}_1 \right) e\,\mathrm{fm} \right]$$

- Large uncertainties for nuclear part.

$$d_{\mathrm{Ra}} = (-7.7 \pm 0.8) \cdot 10^{-4} \cdot [(-2.5 \pm 7.6)\ \bar{g}_0 + (63 \pm 38)\ \bar{g}_1]\, e\,\mathrm{fm}$$

Dobaczewski et al PRL '18

- Not a lot of progress in recent years on better calculations —> very important



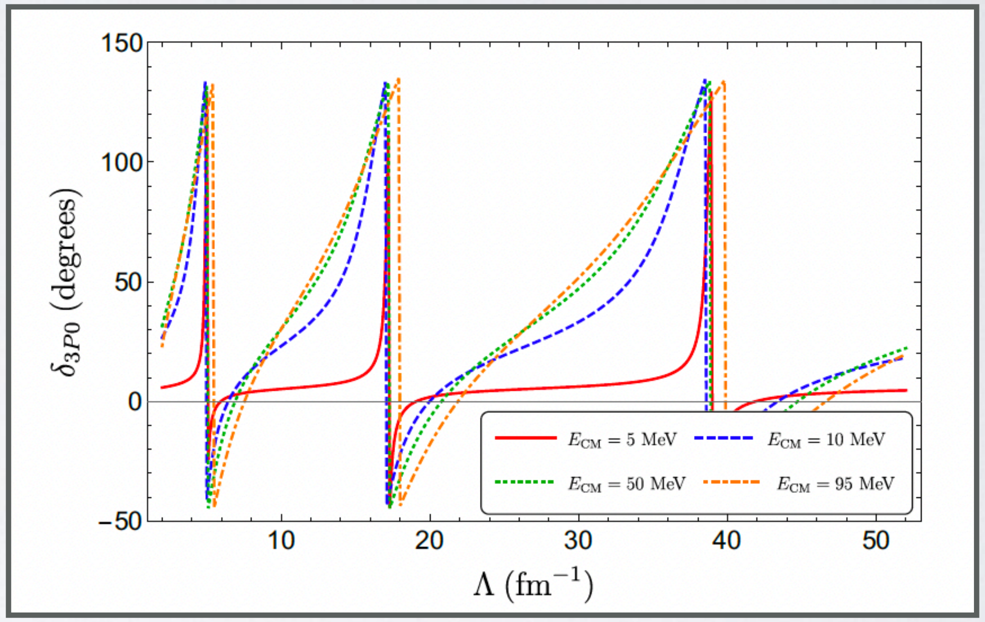
Talk by Markus Kortelainen at ECT* '24

Revisit CP-odd nuclear forces a la Nogga/van Kolck/Timmermans

- Revisited CP-odd forces with graduate student Sachin Shain
- Nogga/van Kolck/Timmermans: need counter terms at LO in attractive P-waves 3P0 and 3P2

Figures from dissertation Sachin Shain

$$V_{\mathrm{str},\pi} = -\frac{1}{(2\pi)^3}\left(\frac{g_A}{2F_\pi}\right)^2 \vec{\tau}_1 \cdot \vec{\tau}_2 \frac{(\boldsymbol{\sigma}_1 \cdot \mathbf{q})(\boldsymbol{\sigma}_2 \cdot \mathbf{q})}{\mathbf{q}^2 + m_\pi^2},$$



- Regulator to solve LS equation

$$f_\Lambda(p, p') = e^{-(\mathbf{p}/\Lambda)^4} e^{-(\mathbf{p}'/\Lambda)^4},$$

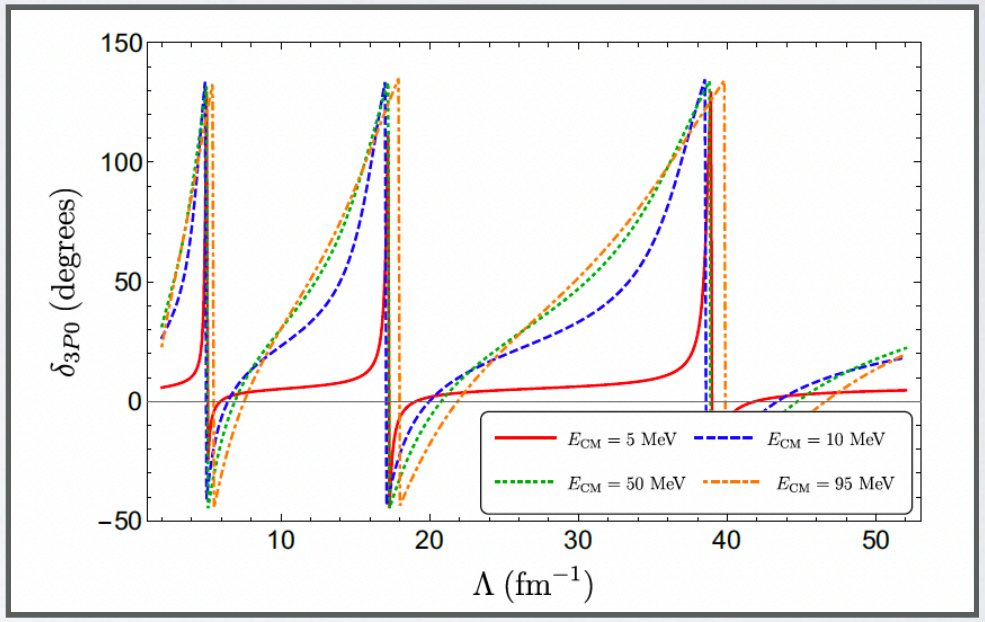
Revisit CP-odd nuclear forces a la Nogga/van Kolck/Timmermans

- Revisited CP-odd forces with graduate student Sachin Shain
- Nogga/van Kolck/Timmermans: need counter terms at LO in attractive P-waves 3P0 and 3P2

Figures from dissertation Sachin Shain

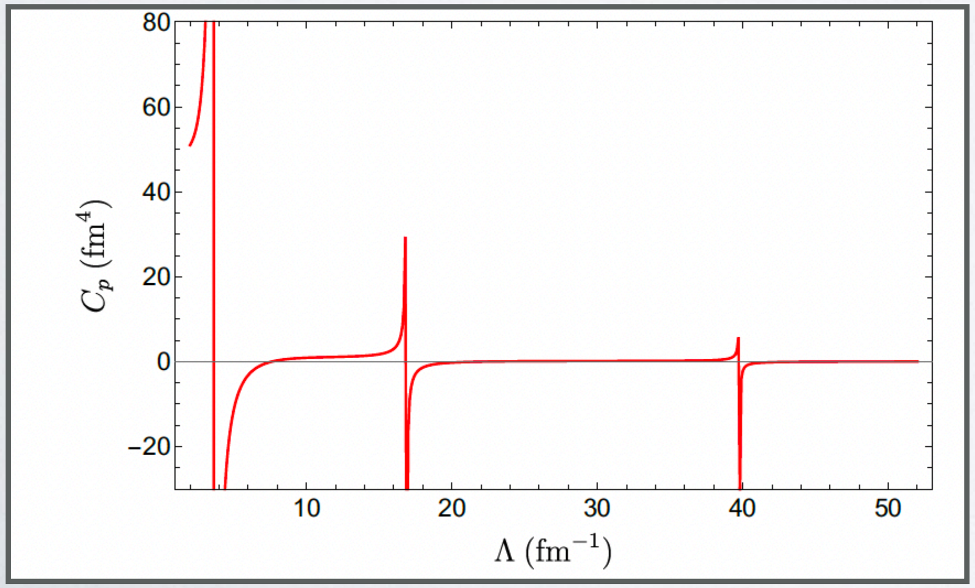
$$V_{\mathrm{str},\pi} = -\frac{1}{(2\pi)^3}\left(\frac{g_A}{2F_\pi}\right)^2 \vec{\tau}_1 \cdot \vec{\tau}_2 \frac{(\boldsymbol{\sigma}_1 \cdot \mathbf{q})(\boldsymbol{\sigma}_2 \cdot \mathbf{q})}{\mathbf{q}^2 + m_\pi^2},$$

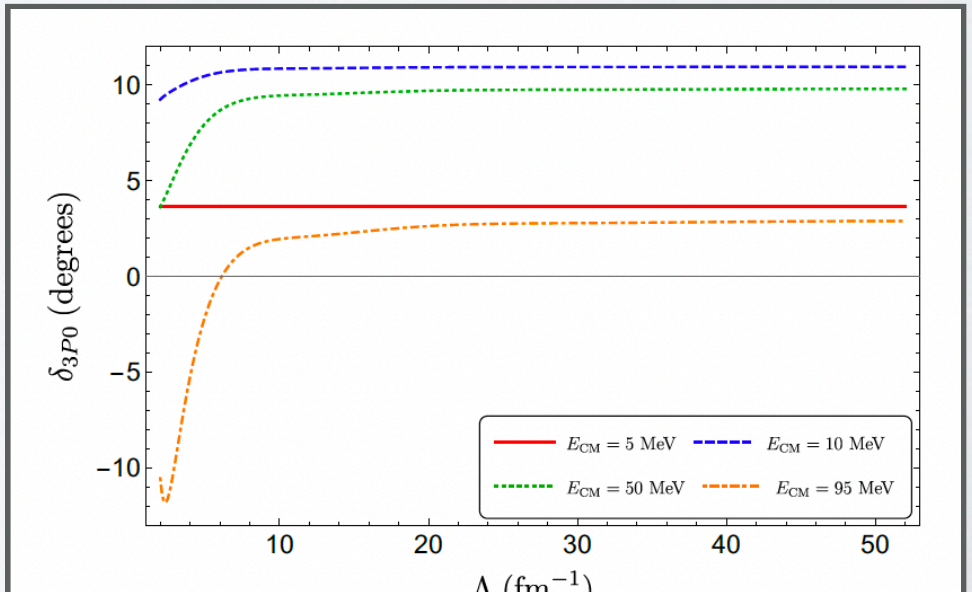
$$V_{\mathrm{str,sd}} = \frac{1}{(2\pi)^3}\left(C_s P_s + C_t P_t + \frac{1}{4} p p' \, C_P P_p\right)$$



- Regulator to solve LS equation

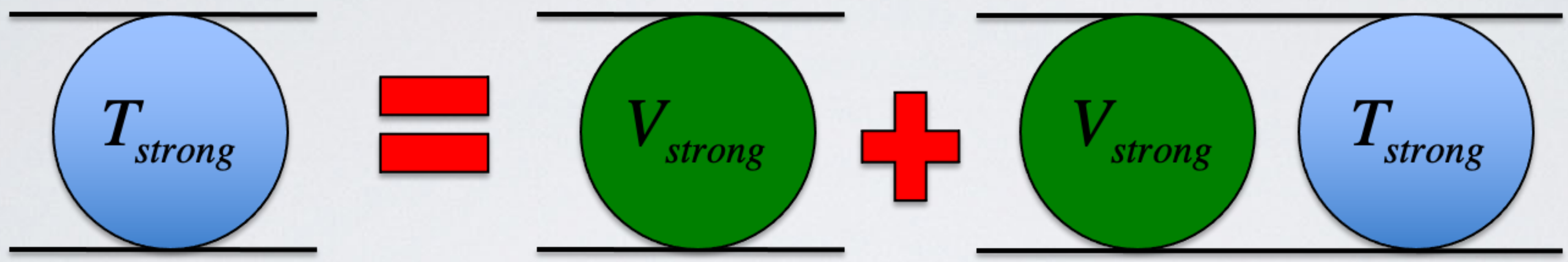
$$f_\Lambda(p, p') = e^{-(\mathbf{p}/\Lambda)^4} e^{-(\mathbf{p}'/\Lambda)^4},$$





Adding CP violation

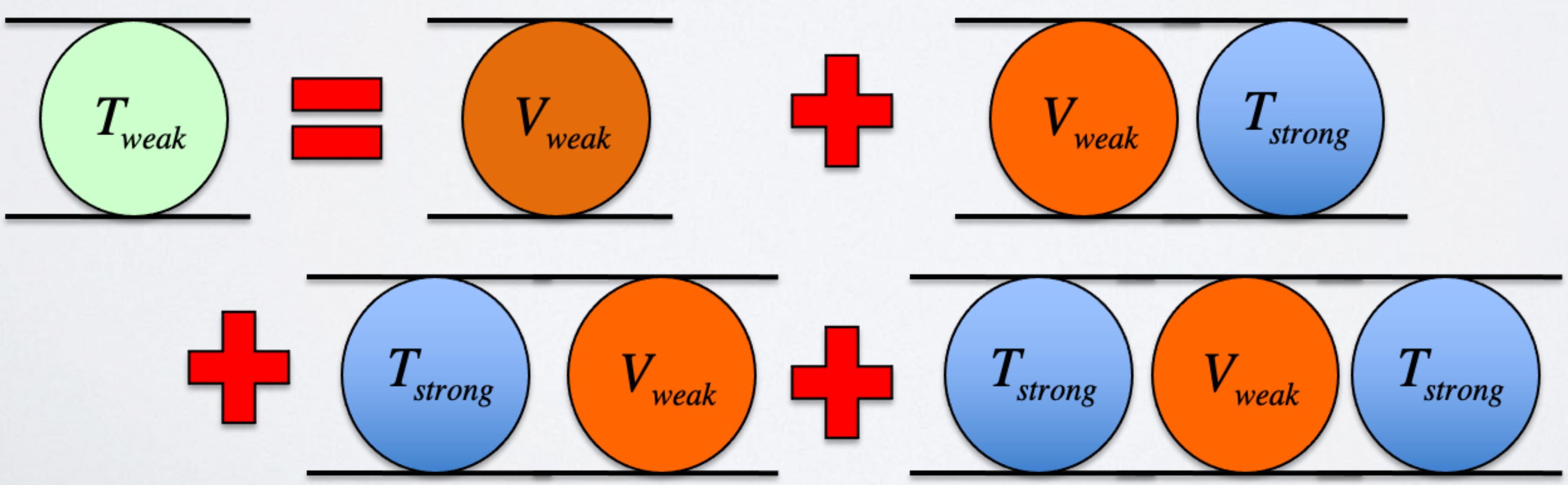
- Solved and renormalized strong scattering amplitude $T_{\rm strong} = V_{\rm strong} + V_{\rm strong}\, G_0\, T_{\rm strong}$



- Then solve in perturbation theory (CP violation is very very very weak)

$$T_{weak} = V_{weak} + V_{weak} G_0 T_{strong} + T_{strong} G_0 V_{weak} + T_{strong} G_0 V_{weak} G_0 T_{strong}$$

$$V_{\bar{g}_0} = -\frac{1}{(2\pi)^3}\frac{g_A \bar{g}_0}{2F_\pi}\vec{\tau}_1\cdot\vec{\tau}_2\frac{i(\boldsymbol{\sigma}_1-\boldsymbol{\sigma}_2)\cdot\mathbf{q}}{\mathbf{q}^2+m_\pi^2},$$

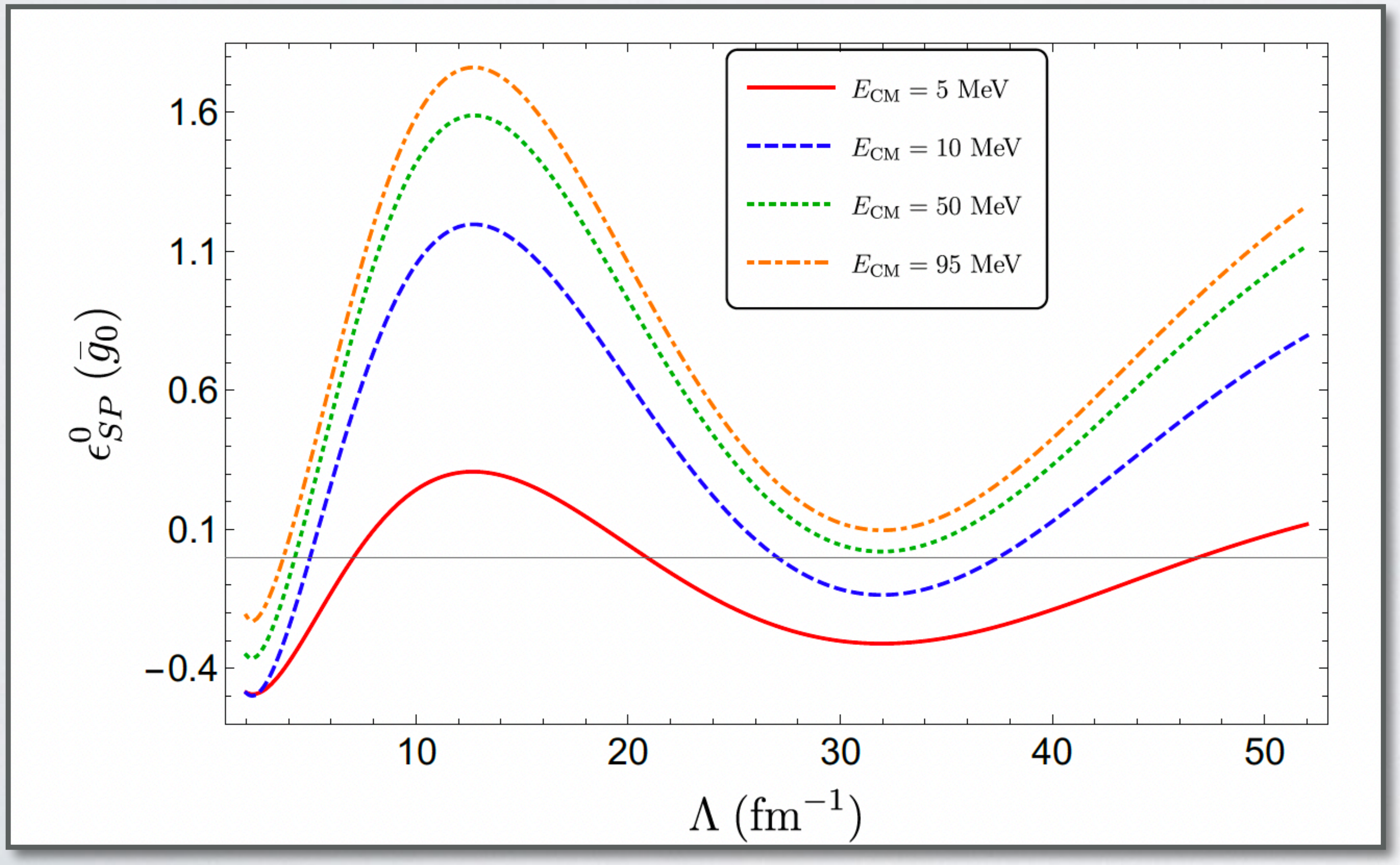


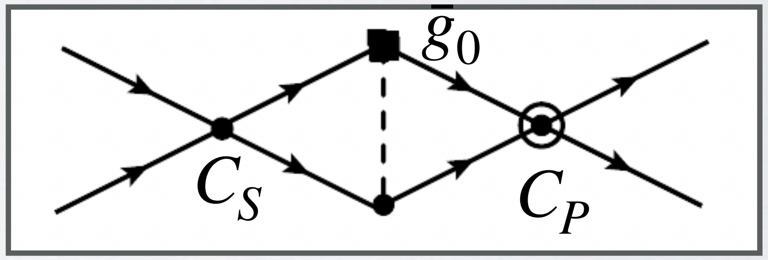
CP-odd phase shifts

- First consider j=0 states $^1S_0 \leftrightarrow {}^3P_0$
- CP-odd mixing angle in principle observable in spin rotations of polarized ultra cold neutrons on hydrogen target

$$S_{j=0} = \begin{pmatrix} e^{2i\delta_{1S_0}} & \epsilon^0_{\rm SP} e^{i[\delta_{1S_0}+\delta_{3P_0}]} \\ -\epsilon^0_{\rm SP} e^{i[\delta_{1S_0}+\delta_{3P_0}]} & e^{2i\delta_{3P_0}} \end{pmatrix}$$

- We compute the phase shifts in units of $\bar{g}_0$
- **Results are extremely cut-off dependent ! Driven by 3P0-3P0 counter term**





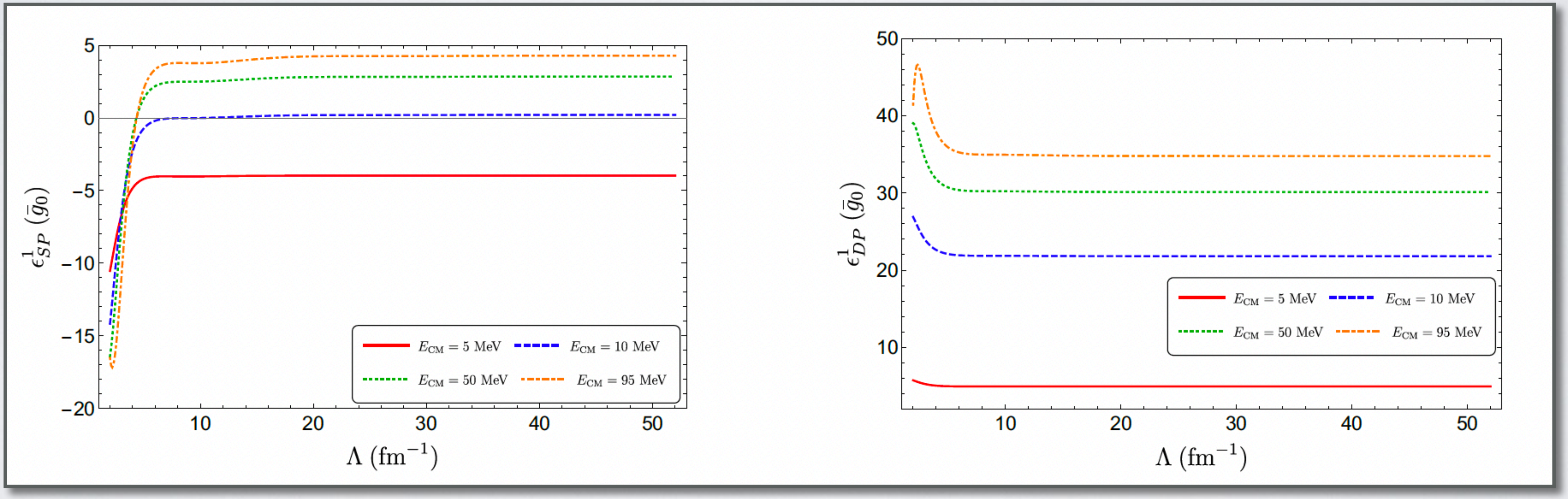
JdV, Gnech, Shain '20

CP-odd phase shifts

- Now consider j=1 states $^3S_1 \leftrightarrow {}^3P_1 \leftrightarrow {}^3D_1$

- Now there are 2 CP-odd mixing angles

- **Results quickly converge because the 3P1 channel is repulsive (no CT)**



- This means that the deuteron EDM is safe since only intermediate 3P1 states

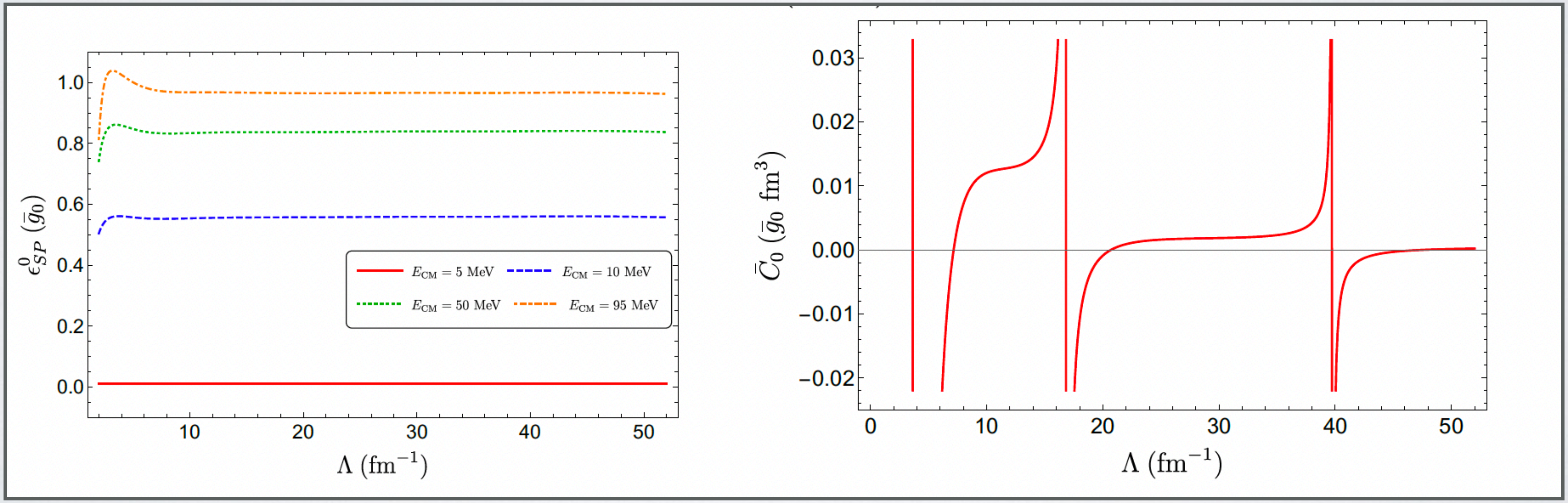
Lessons ?

- We probably need short-distance counter terms in certain CP-odd pion-induced transitions
- Let's add the 1S0-3P0 counter term

$$\mathcal{L}_{NN} = \bar{C}_0 \left[\bar{N}\boldsymbol{\sigma}N \cdot \boldsymbol{\nabla}(\bar{N}\,N) + \frac{1}{3}\bar{N}\vec{\tau}\boldsymbol{\sigma}N \cdot \boldsymbol{\nabla}(\bar{N}\vec{\tau}N) \right]$$

- And pretend we have some fake measurement of the mixing angle at some energy

$$\epsilon_{SP}(5\,\mathrm{MeV}) = 0.01\,\bar{g}_0$$



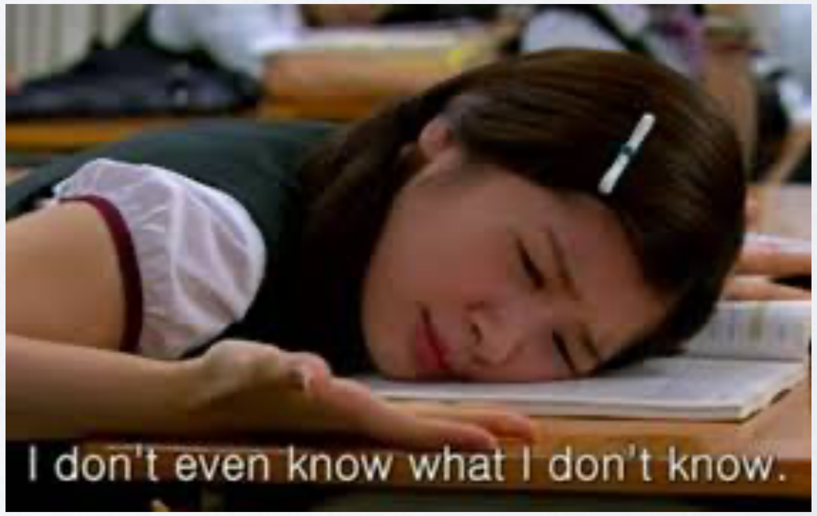
- It works…. But of course the outcome crucially depends on the fitting point (no prediction !)

So ?

- For a long time it has been thought that EDMs of nuclei and diamagnetic atoms can be computed from CP-odd pion exchange
- ***But if EDMs depend on 1S0 <-> 3P0 mixing this is probably not the case***
- The deuteron EDM is special (only intermediate 3P1 state) so calculation should be good
- *Not true for 3He or larger systems (unless there are selection rules)*
- Interesting to redo 3He EDM calculation in renormalized ChPT (we started 3He with Alex Gnech but did not finish due to numerical issues)

So ?

- For a long time it has been thought that EDMs of nuclei and diamagnetic atoms can be computed from CP-odd pion exchange
- ***But if EDMs depend on 1S0 <-> 3P0 mixing this is probably not the case***
- The deuteron EDM is special (only intermediate 3P1 state) so calculation should be good
- *Not true for 3He or larger systems (unless there are selection rules)*
- Interesting to redo 3He EDM calculation in renormalized ChPT (we started 3He with Alex Gnech but did not finish due to numerical issues)
- *Can counter terms help explain why Schiff moment computations are so hard ?*
- *Can we fix the CP-odd counter term ?*



Obtaining the counter term for theta term

- For general sources of CP violation (say quark chromo-EDM) even the pion-nucleon is hard….
- For theta term might be a way out. Remember :

$$\mathcal{L}_{QCD} = \mathcal{L}_{kin} - \bar{m}\bar{q}q - \varepsilon\bar{m}\bar{q}\tau^3 q \quad \longleftrightarrow \quad + m_\star \bar{\theta}\bar{q}i\gamma^5 q$$

Obtaining the counter term for theta term

- For general sources of CP violation (say quark chromo-EDM) even the pion-nucleon is hard….
- For theta term might be a way out. Remember :

JdV, Gnech, Shain '20

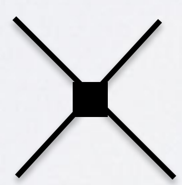
$$\mathscr{L}_{QCD} = \mathscr{L}_{kin} - \bar{m}\bar{q}q - \varepsilon\bar{m}\bar{q}\tau^3 q \quad \longleftrightarrow \quad + m_\star \bar{\theta}\bar{q}i\gamma^5 q$$

$$\mathcal{L}_{NN} = -\frac{iC_0}{8}\mathrm{Tr}[\chi_-]\left[\bar{N}\boldsymbol{\sigma}N\cdot\boldsymbol{\nabla}(\bar{N}N) + \frac{1}{3}\bar{N}\vec{\tau}\boldsymbol{\sigma}N\cdot\boldsymbol{\nabla}(\bar{N}\vec{\tau}N)\right]$$

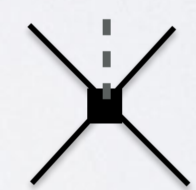
$$\chi = u^\dagger \chi u^\dagger - u\chi^\dagger u$$

$$\chi = 2B(M_q + im_* \bar{\theta})$$

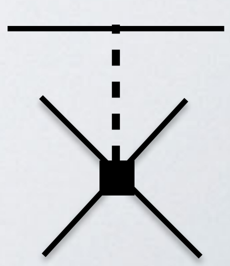
CP-odd counter term



CP-even isospin-breaking pion-nucleon-nucleon



- Task to do: fit to Charge-Symmetry-Breaking in measured $p + n \to d + \pi^0$ $\quad d + d \to \alpha + \pi^0$
- Work done by van Kolck, Hanhart et al ' 00, '06 but with Weinberg power counting
  - Also a new three-body force at N?LO ?



- ***In renormalized ChEFT the counter term appears at LO (can it be extracted ?)***

The plan of attack

1. Introduction to why BSM is relevant for power counting

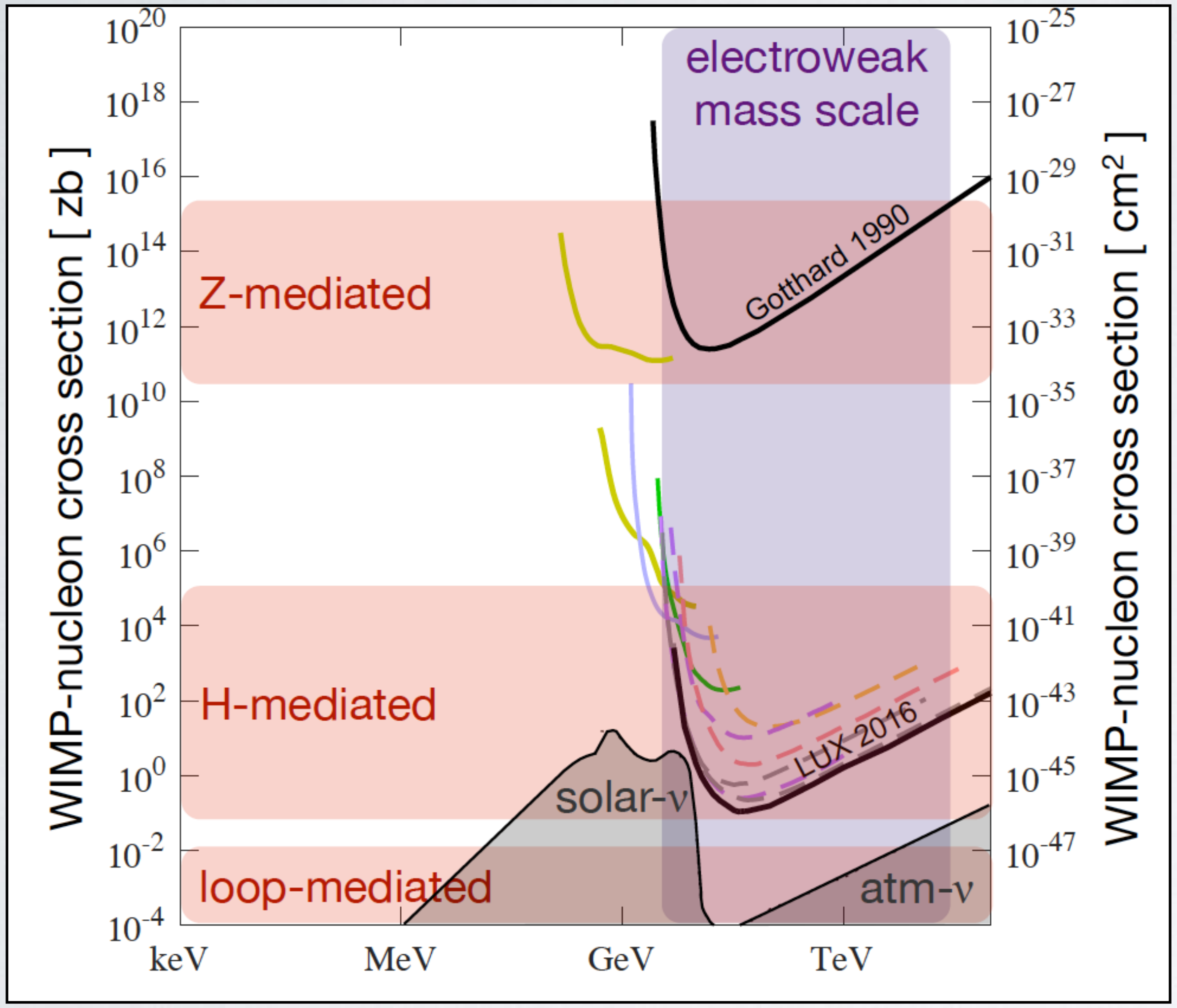
2. 0vbb from light Majorana neutrino exchange

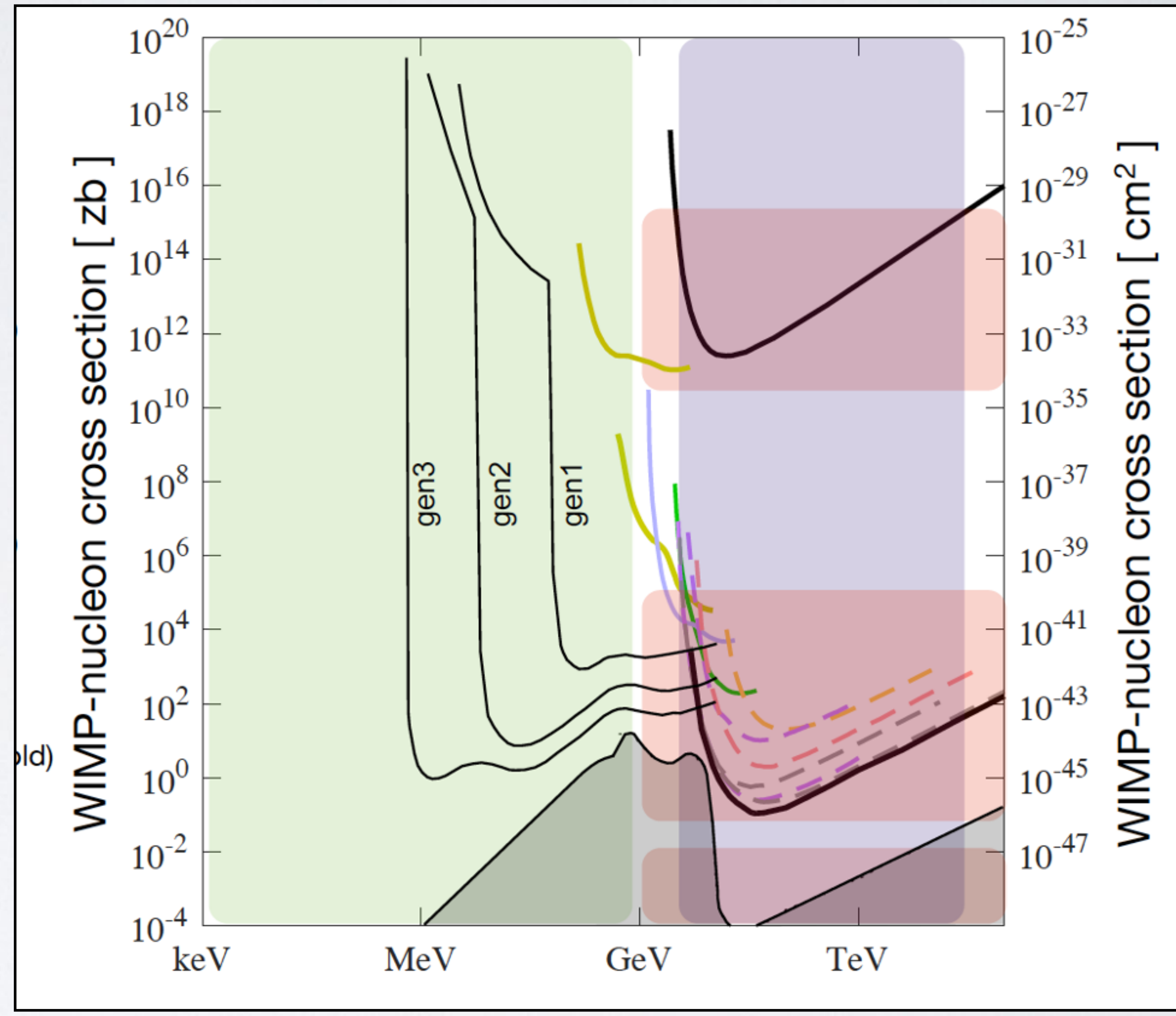
3. EDMs and the problems of S-P mixing

4. **The confusing case of Dark Matter scattering**

A quick discussion of Dark Matter detection

- We used to love WIMPs but now we don't anymore (we like axions now)
- Figures from Scott Hertell (UMass)





PHYSICAL REVIEW LETTERS **133,** 191001 (2024)

Editors' Suggestion | Featured in Physics

First Indication of Solar ^{8}B Neutrinos through Coherent Elastic Neutrino-Nucleus Scattering in PandaX-4T

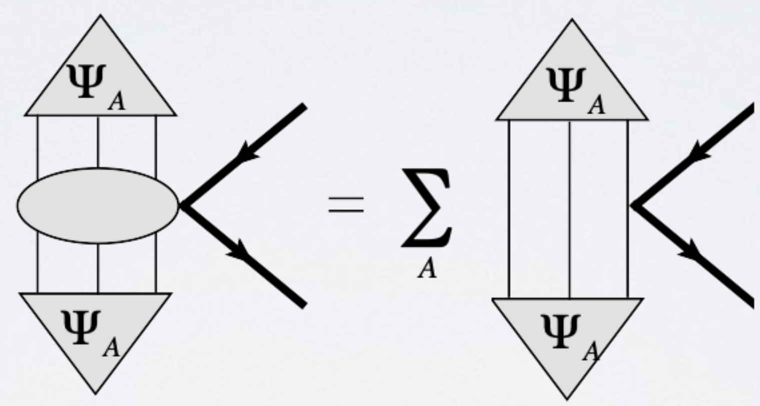
DM-quark interactions

- In scalar or Higgs mediated DM models, DM interactions with nuclei through scalar currents

$$\mathscr{L} = C_q\, \bar{\chi}\chi\, \bar{q}q$$

- For this talk, I focus on couplings to light quarks. ChPT gives $\mathscr{L} = C_q \dfrac{\sigma_N}{m_q} \bar{\chi}\chi\, \bar{N}N$

- Then spin-independent cross section of WIMP-nucleus scattering



$\sim A \cdot \sigma_{nucleon}$ X form factor

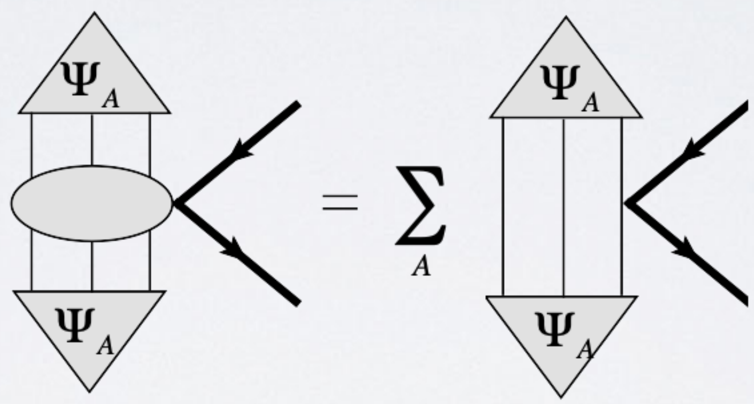
DM-quark interactions

- In scalar or Higgs mediated DM models, DM interactions with nuclei through scalar currents

$$\mathscr{L} = C_q\, \bar{\chi}\chi\, \bar{q}q$$

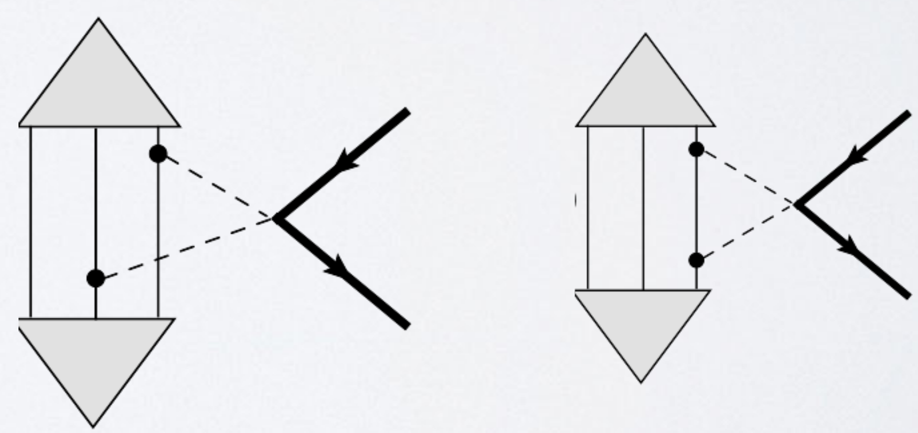
- For this talk, I focus on couplings to light quarks. ChPT gives $\mathscr{L} = C_q \frac{\sigma_N}{m_q} \bar{\chi}\chi\, \bar{N}N$

- Then spin-independent cross section of WIMP-nucleus scattering



$\sim A \cdot \sigma_{nucleon}$ X form factor

- At NLO $\mathscr{L} = C_q \frac{m_\pi^2}{m_q} \bar{\chi}\chi\, \pi^2$

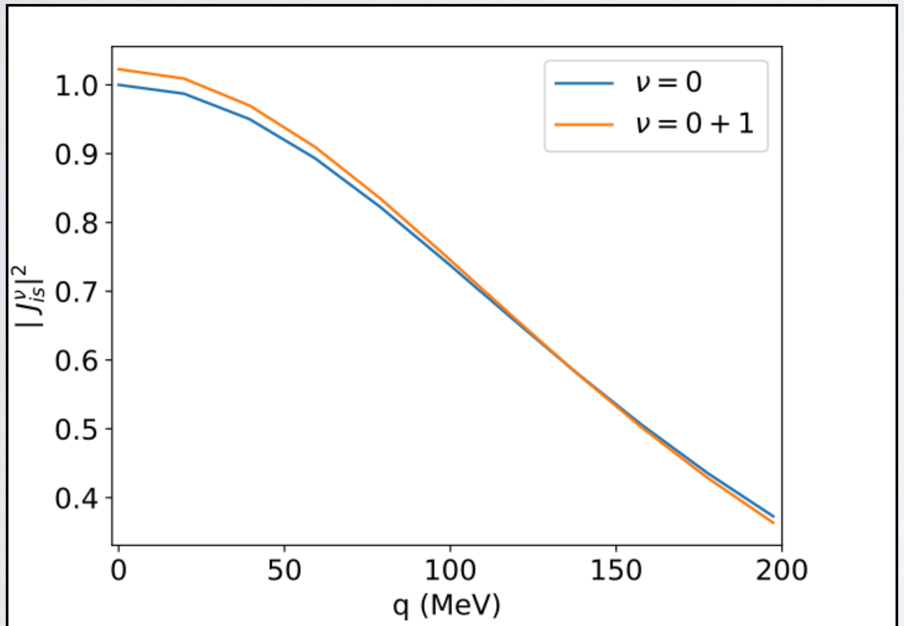


Prezau et al PRL '03, Cirigliano et al ' 13,
Hoferichter, Klos, Schwenk, Menendez ' 15 '16 '18

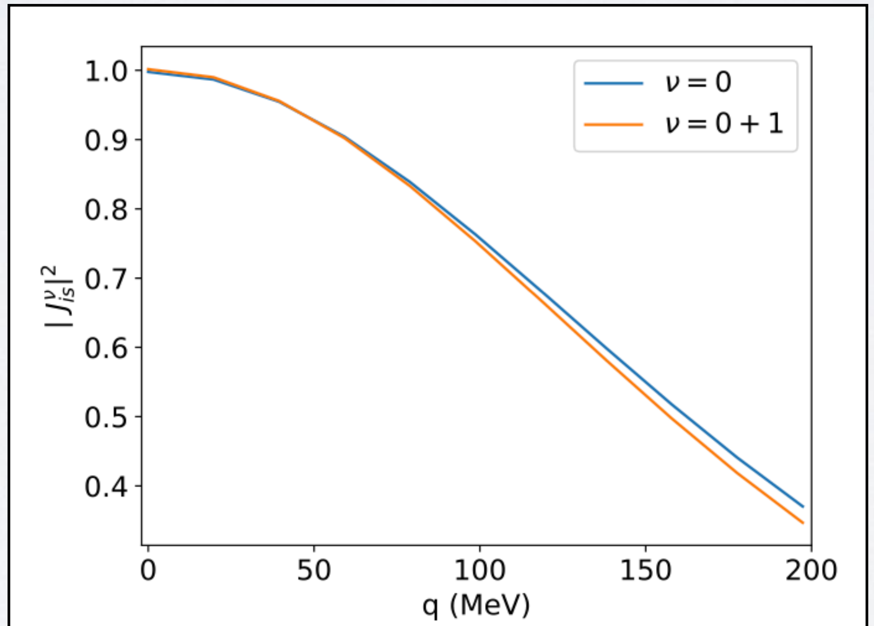
- The 'one-body' correction can be easily computed and I will not discuss them

DM-quark interactions

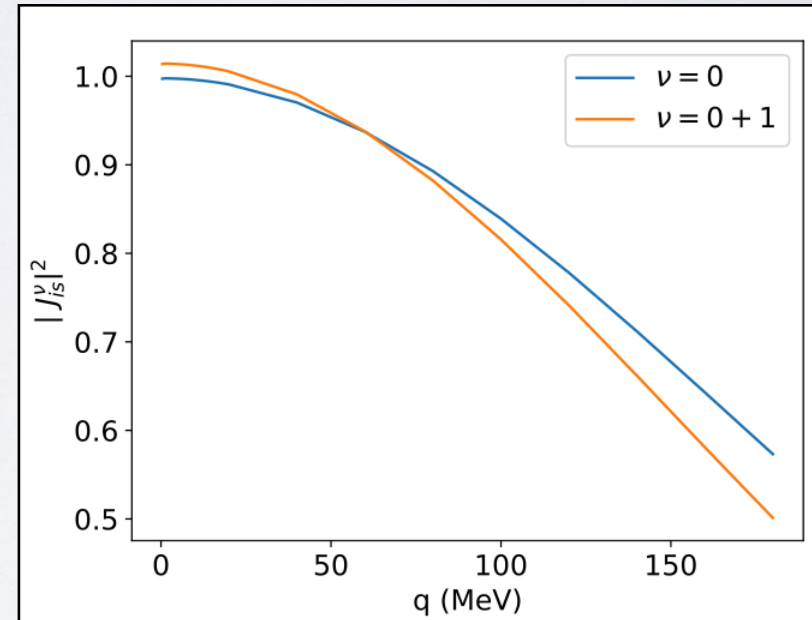
- With Andreas Nogga, Chris Korber, and Sachin Shain we investigated scattering off light nuclei
- Used Bochum/Bonn chiral EFT potentials from NLO to N5LO + 4 r-space cut-offs
- Made use of the density formalism from Phillips, McGovern, Nogga, Grießhammer ’20
- Main phenomenological findings: NLO scalar currents are only a few percent



(a) ^{2}H



(b) ^{3}He

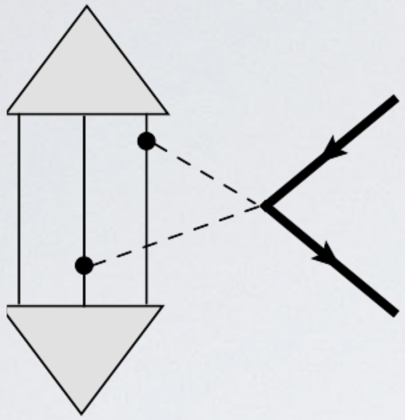


(c) ^{4}He

- Larger corrections for heavier nuclei (Xenon etc) but requires Shell Model computations

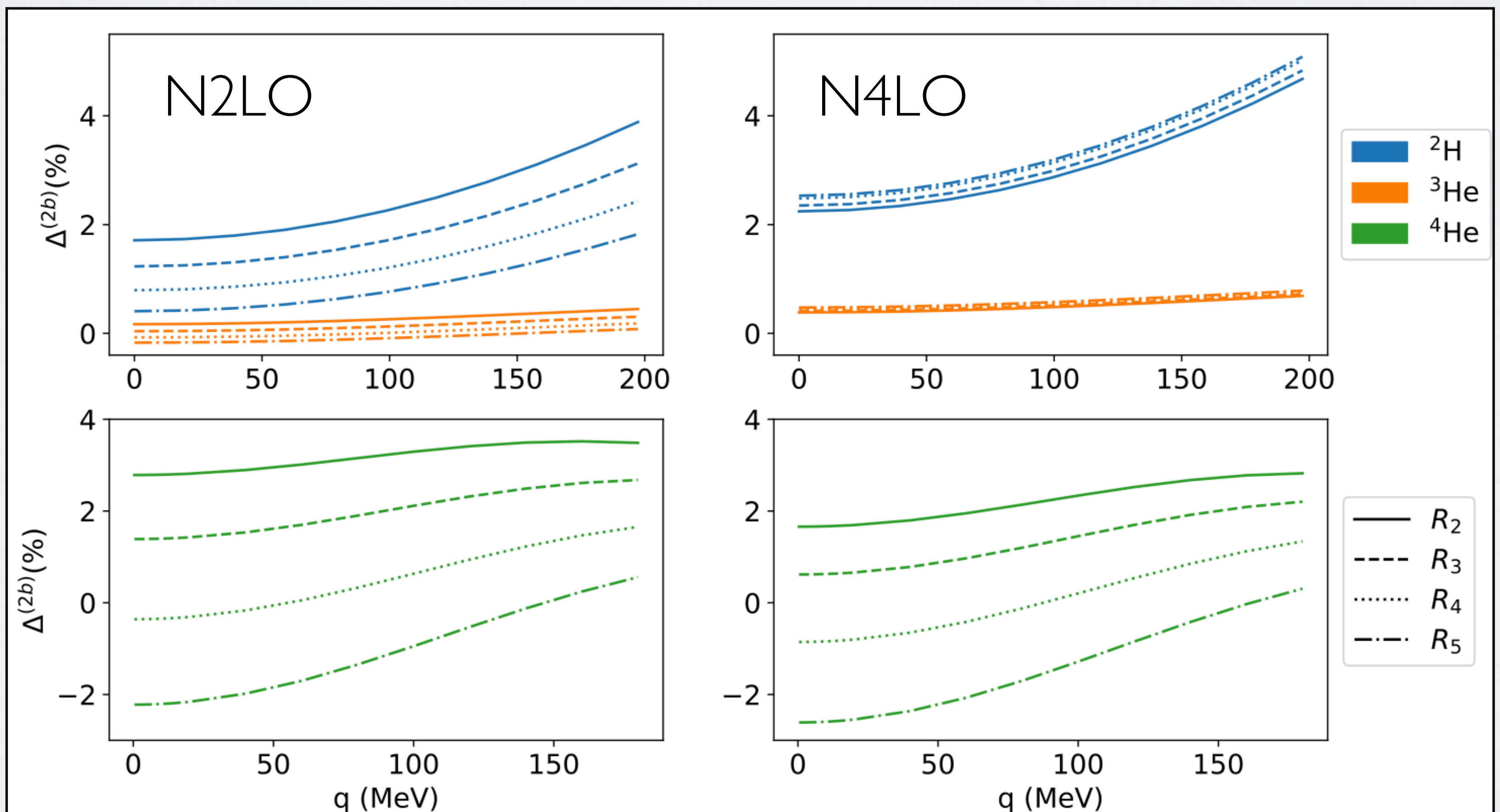
Hoferichter, Klos, Schwenk, Menendez ‘ 15 ’16 ‘18

DM-quark interactions



$$-c_q\, m_\pi^2 \left(\frac{g_A}{2 f_\pi}\right)^2 \frac{(\vec{\sigma}_1\cdot\vec{q}_1)(\vec{\sigma}_2\cdot\vec{q}_2)}{(\vec{q}_1^{\,2}+m_\pi^2)(\vec{q}_2^{\,2}+m_\pi^2)}\,\tau_1\cdot\tau_2$$

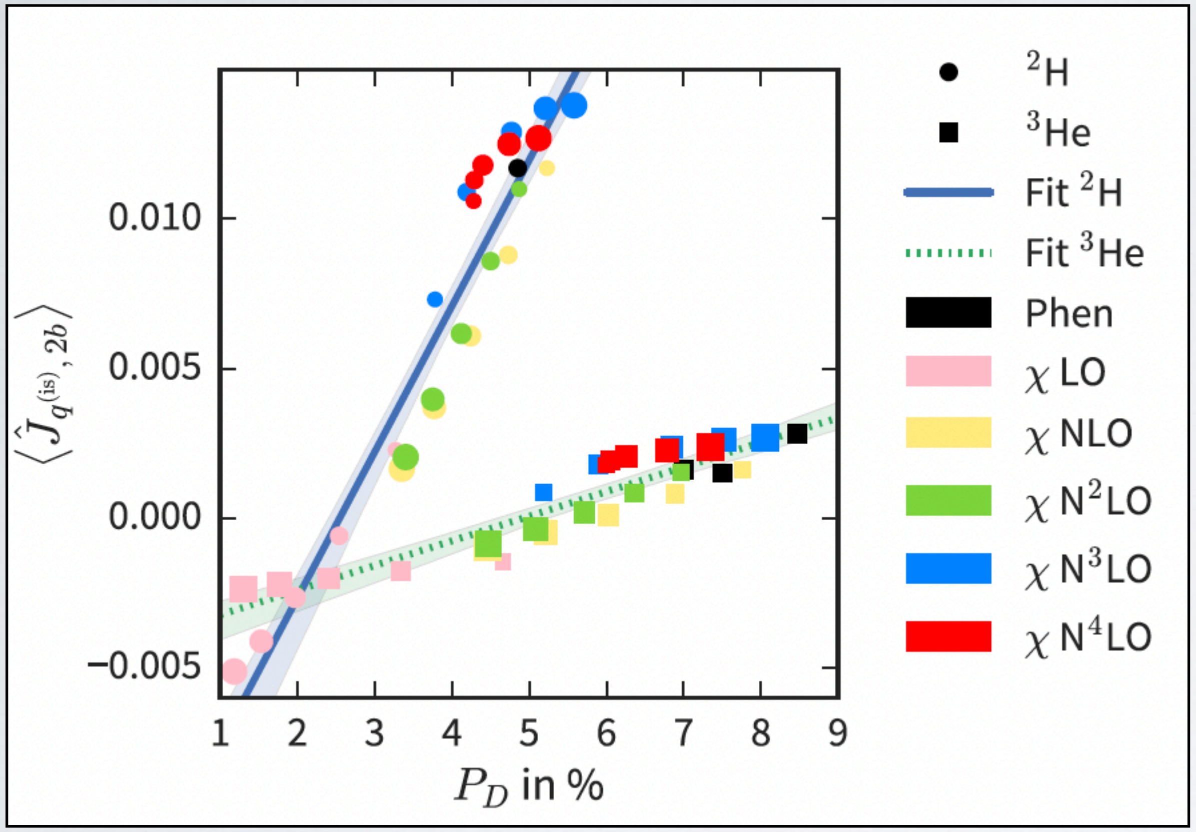
- Used Bochum/Bonn chiral EFT potentials from NLO to N5LO + 4 r-space cut-offs
- Two-body results are puzzling: small and large cut-off dependence

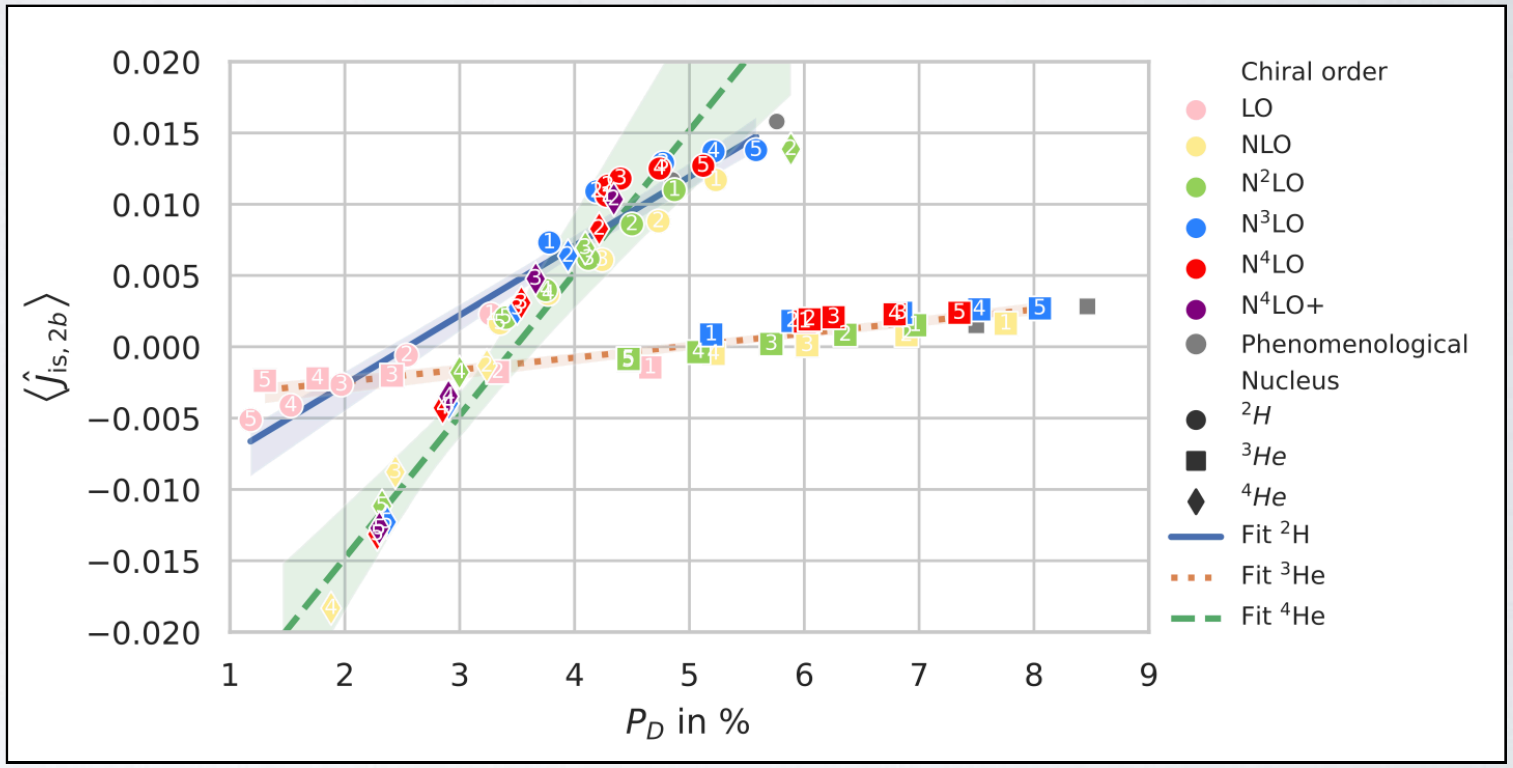


- Surprising to me that rather simple matrix elements depend so much on the wave function

D-wave correlation

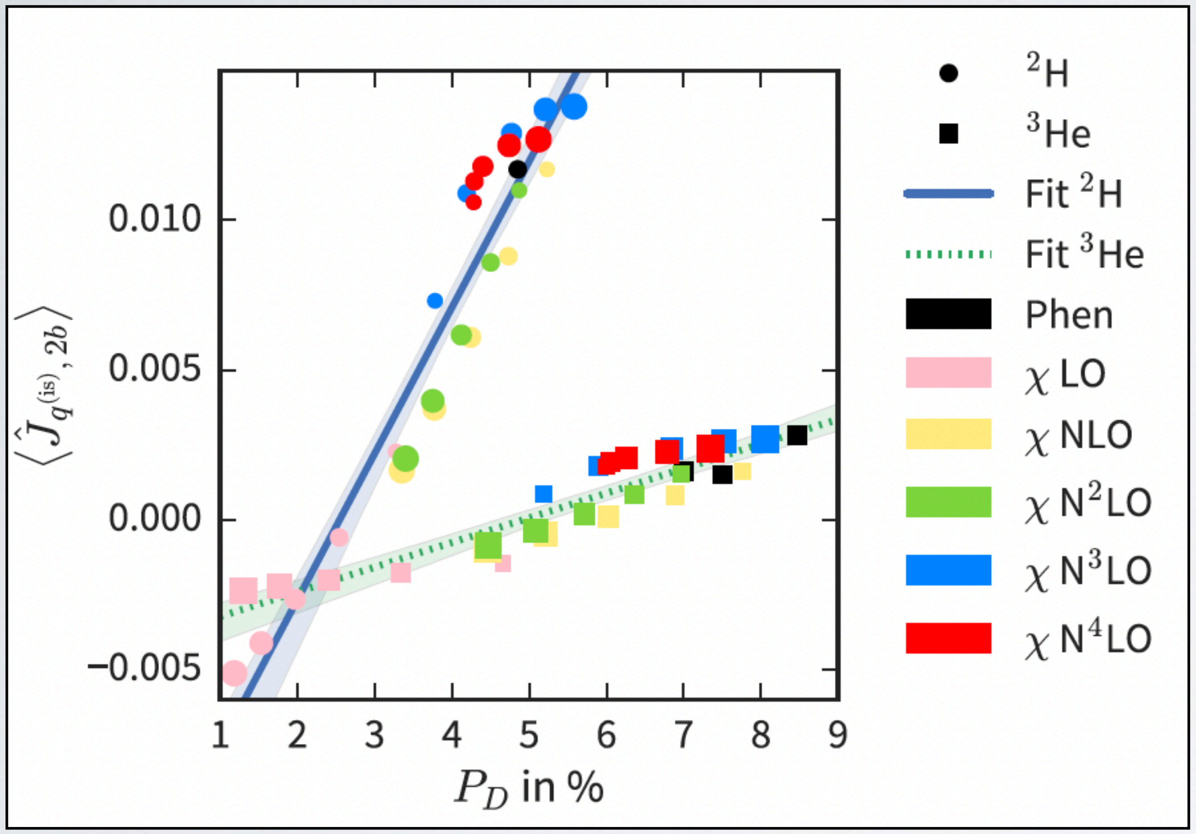
- By accident we found that matrix elements are correlated with D-wave admixture…
- But that is not an observable right ? (Friar' 79)

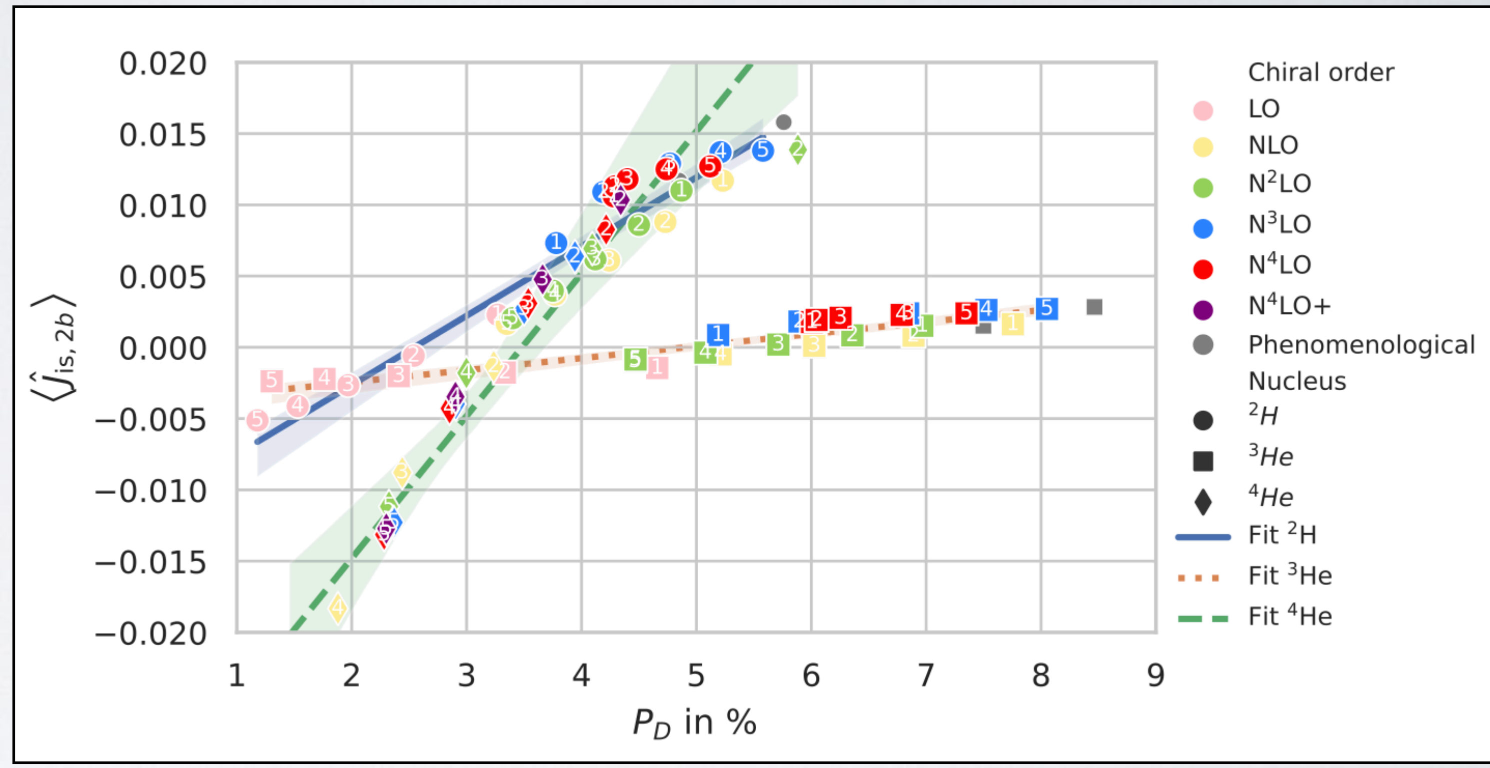




D-wave correlation

- By accident we found that matrix elements are correlated with D-wave admixture…
- But that is not an observable right ? (Friar ' 79)

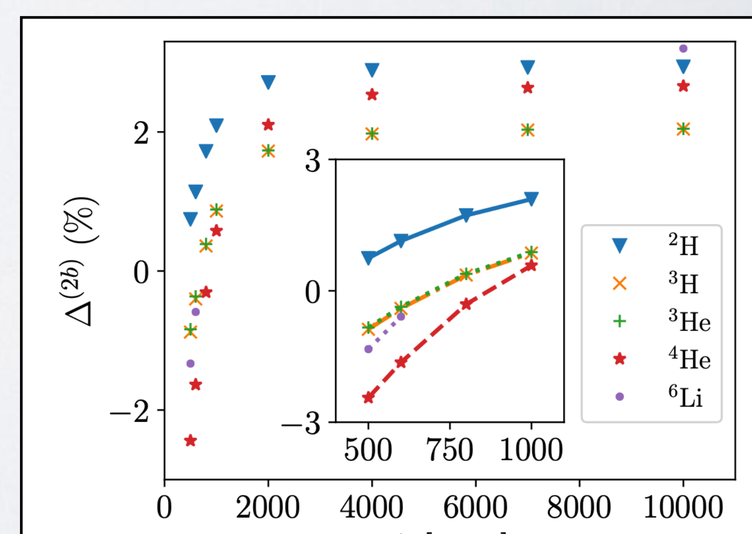




- Similar puzzling findings found by Andreoli et al '18 using phenomenological wave functions

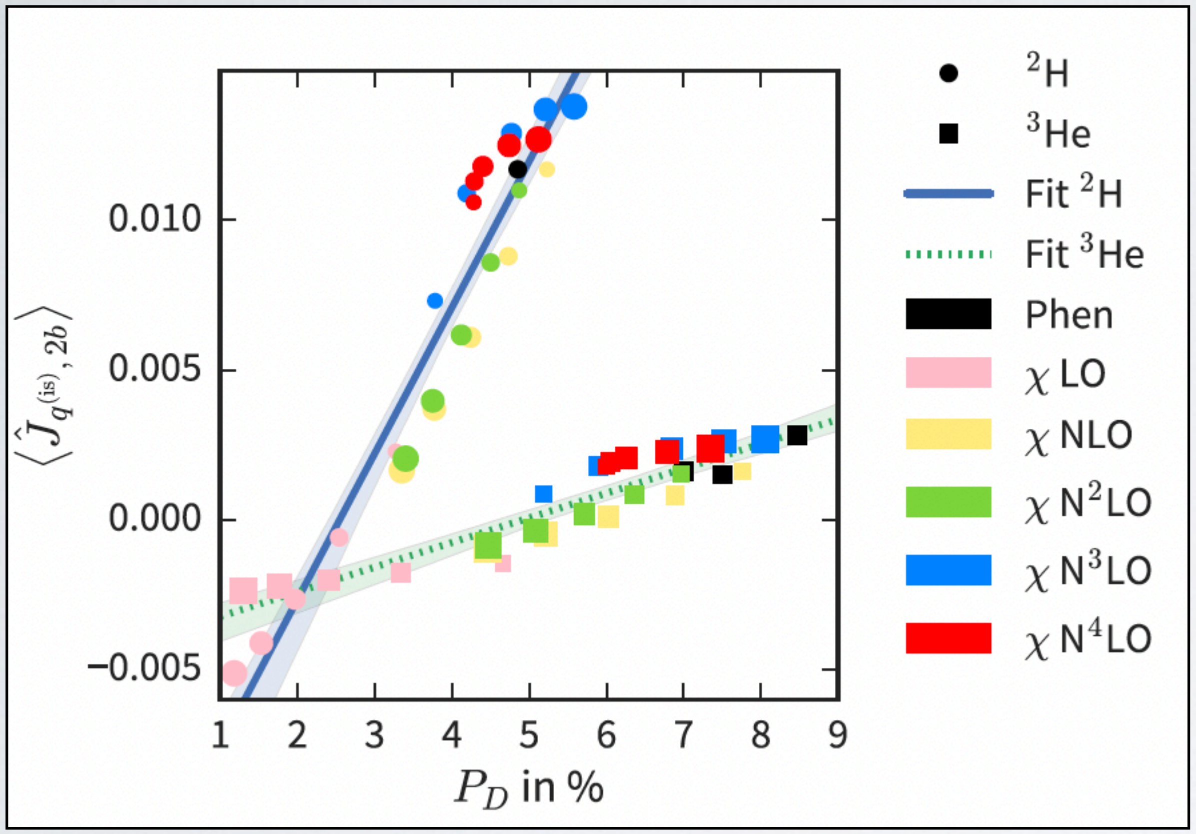
- Should we have scalar WIMP-nucleon-nucleon counter term ?

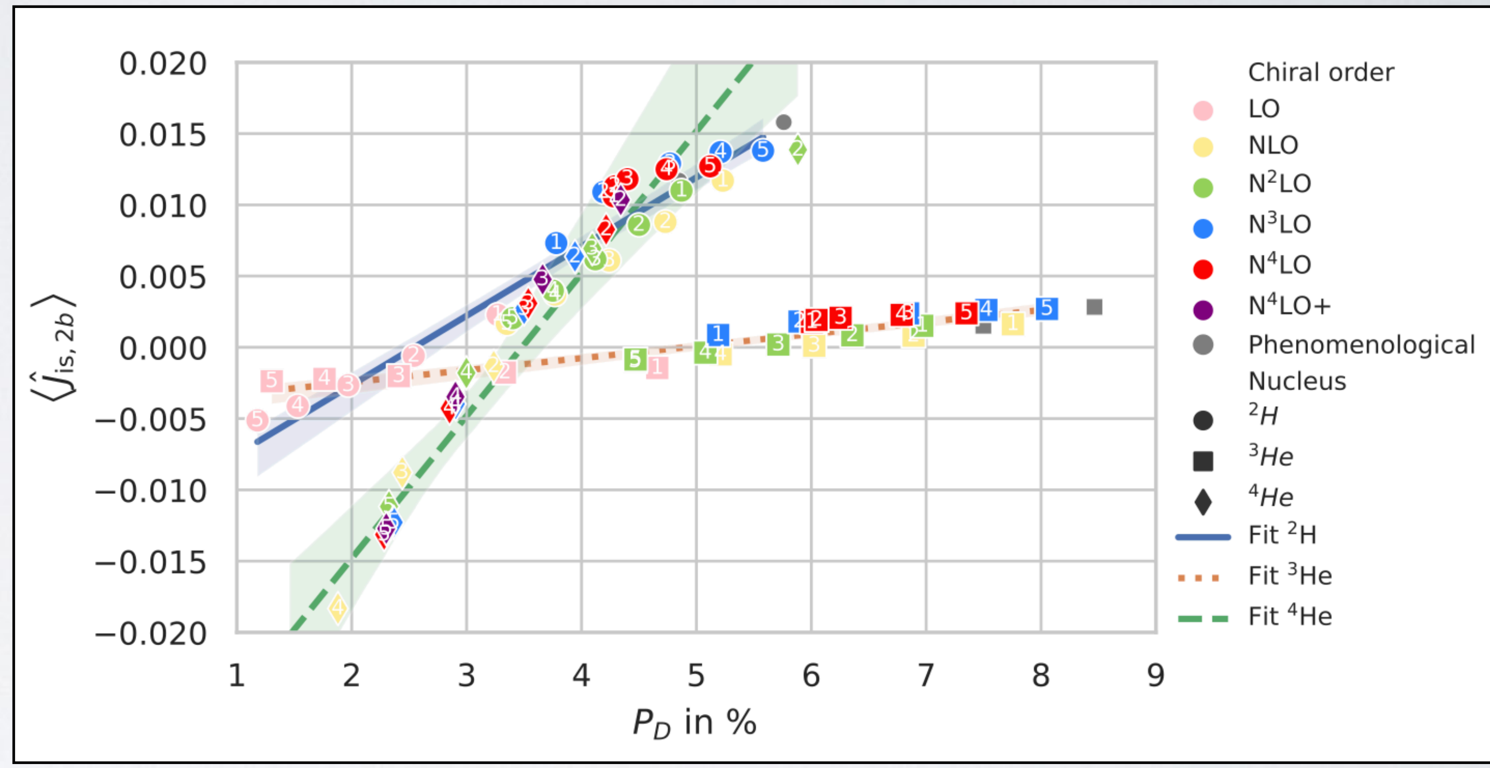
- Very similar to 0vbb but now also in 3S1. Phillips, Valderrama PRL '14



D-wave correlation

- By accident we found that matrix elements are correlated with D-wave admixture…
- But that is not an observable right ? (Friar ‘ 79)





- Fit to lattice Data (NPLQCD) ?

PHYSICAL REVIEW LETTERS **120,** 152002 (2018)

Scalar, Axial, and Tensor Interactions of Light Nuclei from Lattice QCD

Emmanuel Chang,[1] Zohreh Davoudi,[2,3] William Detmold,[4,3] Arjun S. Gambhir,[5,6] Kostas Orginos,[7,8] Martin J. Savage,[1,3] Phiala E. Shanahan,[7,8,3] Michael L. Wagman,[4,3] and Frank Winter[8]

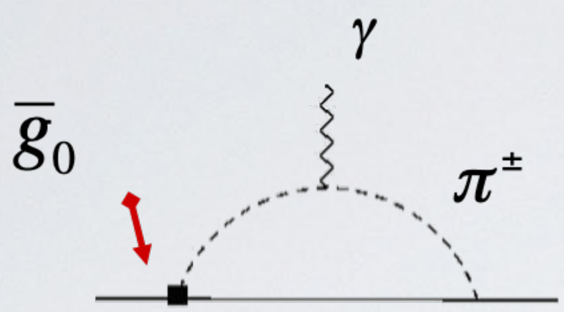
(NPLQCD Collaboration)

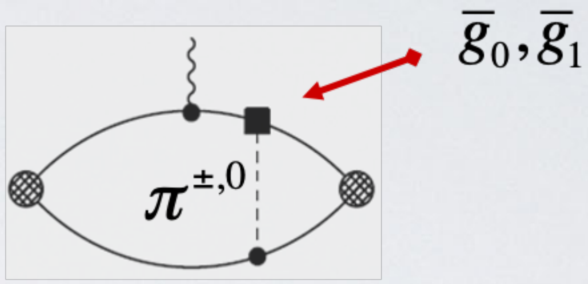
- If we need more CT’s this could affect the quark mass dependence of nuclear forces

Concluding remarks

- Very rich experimental program exploring BSM physics at low energies
- Low-energy searches very complementary and competitive with HEP experiments
- Interpretation of experiments involves hadronic and nuclear physics
- Weinberg PC issues play a remarkably large role !!

The deuteron MQM





Khriplovich/Korkin '00
JdV, Mereghetti, Timmermans, van Kolck PRL '11

- Nuclear CP violation can be larger than nucleon CP violation ! No chiral loop suppression !
- No selection rules for a magnetic quadrupole moment (deuteron has spin 1)

$$\mathcal{M}_D = -\frac{e g_A}{4\pi m_\pi F_\pi}\left[\bar{g}_0\kappa_0' + \frac{1}{3}\bar{g}_1\kappa_1'\right]\frac{1+\gamma/m_\pi}{(1+2\gamma/m_\pi)^2} \simeq (0.15\bar{g}_0\kappa_0' + 0.05\bar{g}_1\kappa_1')\, e\,\mathrm{fm}^2$$

- With non-perturbative pions we found

$$M_D \simeq \simeq (0.045\bar{g}_0\kappa_0' + 0.035\bar{g}_1\kappa_1')\, e\,\mathrm{fm}^2$$

C.P. Liu et al '12

- Agrees pretty well for the g1 coefficients but the g0 coefficient is very off

- Similar results for 3He and later in NCSM also 6Li and other light nuclei

Papenbrock et al '