Disentangling physics beyond the SM with EDMs

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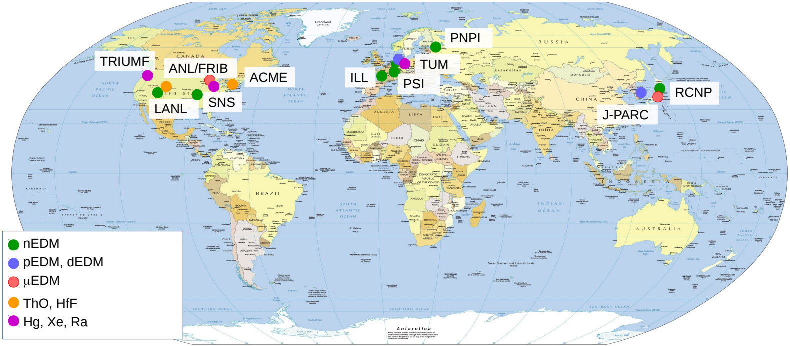
Neutron Electric Dipole Moment: from theory to experiment, ECT*
August 1st – August 5th, 2022

Los Alamos NATIONAL LABORATORY EST.1943

EDM experiments worldwide



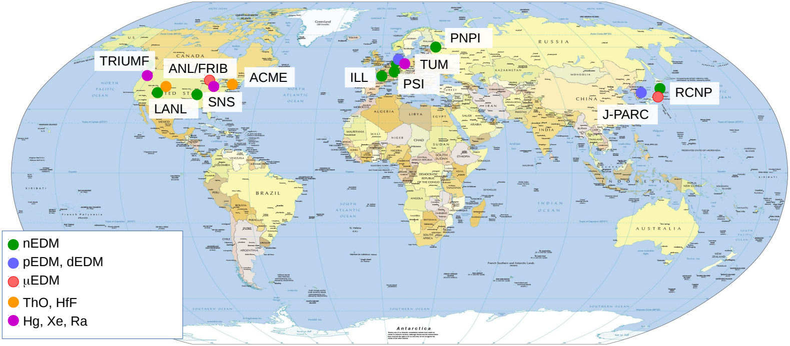
- current EDM bounds

$$
\begin{aligned}
d_e &< 1.0 \cdot 10^{-16}\ e\ \text{fm} \qquad & d_n &< 1.8 \cdot 10^{-13}\ e\ \text{fm} \\
d_{^{225}\text{Ra}} &< 1.2 \cdot 10^{-10}\ e\ \text{fm} \qquad & d_{^{199}\text{Hg}} &< 6.2 \cdot 10^{-17}\ e\ \text{fm}
\end{aligned}
$$

$$d_f \sim \frac{1}{(4\pi)^n} \frac{g_f v}{\Lambda^2}$$

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

EDM experiments worldwide

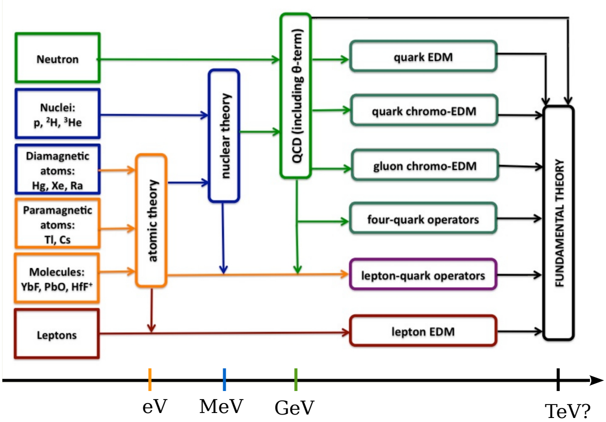


- goals for the next EDM generation

$$d_e \quad < 1.0 \cdot 10^{-17}\ e\ \text{fm} \qquad d_n \quad < 1.0 \cdot 10^{-15}\ e\ \text{fm}$$
$$d_p \quad < 1.0 \cdot 10^{-16}\ e\ \text{fm} \qquad d_{^{225}\text{Ra}} \quad < 1.0 \cdot 10^{-14}\ e\ \text{fm}$$

$d_d,\ d_{^3He}/d_p$?

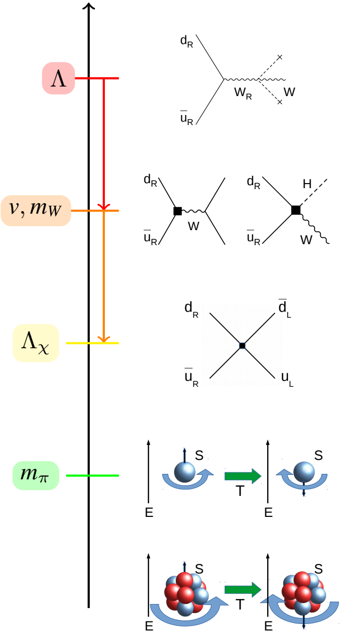
EDMs and new physics



thanks to J. de Vries

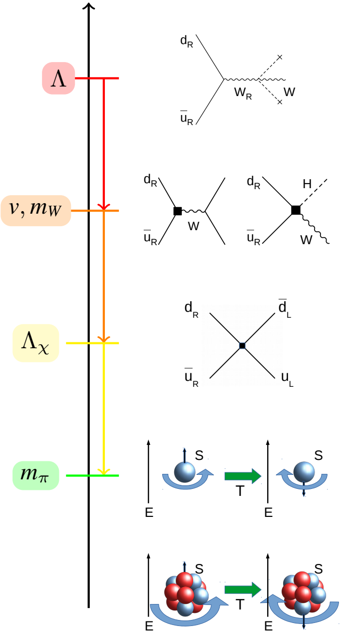
- measuring EDMs in different systems crucial to pinpoint BSM
- what's the max info on BSM physics that we can extract from EDMs?

Effective field theories for EDMs



1. correlate an EDM signal with colliders?

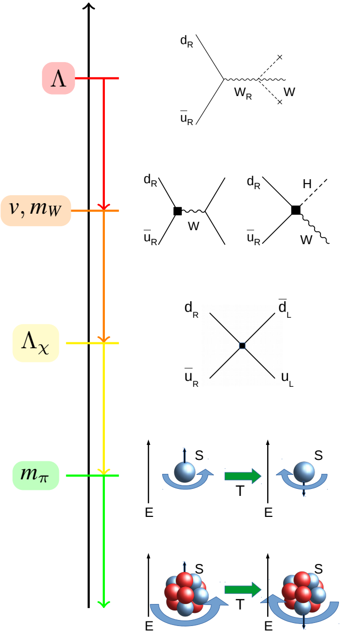
Effective field theories for EDMs



1. correlate an EDM signal with colliders?

2. hadronic uncertainties.
   Impact on interpretation of EDM exps.?

Effective field theories for EDMs



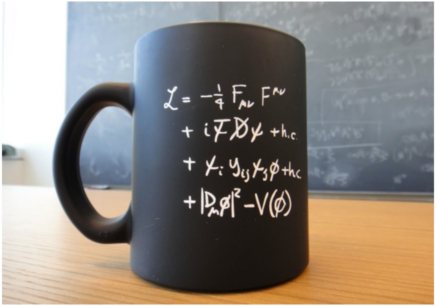
1. correlate an EDM signal with colliders?

2. hadronic uncertainties.
Impact on interpretation of EDM exps.?

3. nuclear uncertainties.
Reliably predict EDMs of light/heavy nuclei?

CP violation in the SM(EFT) & collider constraints

CP violation in the SM(EFT)



- two CPV sources in SM

$$\mathcal{L}_{\text{CPV}}^{(4)} = -\theta \frac{g_s^2}{64\pi^2} \varepsilon^{\alpha\beta\mu\nu} G_{\mu\nu} G_{\alpha\beta} + \bar{u}_L^i \left[V_{\text{CKM}}\right]_{ij} \gamma^\mu d_L^j W_\mu$$

CP violation in the SM(EFT)

X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar l_p e_r \varphi)$
$Q_{\widetilde G}$	$f^{ABC} \widetilde G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p u_r \widetilde\varphi)$
Q_W	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star \left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$
$Q_{\widetilde W}$	$\varepsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				

$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger \varphi\, G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eW}	$(\bar l_p \sigma^{\mu\nu} e_r) \tau^I \varphi W_{\mu\nu}^I$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar l_p \gamma^\mu l_r)$
$Q_{\varphi\widetilde G}$	$\varphi^\dagger \varphi\, \widetilde G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eB}	$(\bar l_p \sigma^{\mu\nu} e_r) \varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi)(\bar l_p \tau^I \gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger \varphi\, W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uG}	$(\bar q_p \sigma^{\mu\nu} T^A u_r) \widetilde\varphi\, G_{\mu\nu}^A$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar e_p \gamma^\mu e_r)$
$Q_{\varphi\widetilde W}$	$\varphi^\dagger \varphi\, \widetilde W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uW}	$(\bar q_p \sigma^{\mu\nu} u_r) \tau^I \widetilde\varphi\, W_{\mu\nu}^I$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar q_p \gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger \varphi\, B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar q_p \sigma^{\mu\nu} u_r) \widetilde\varphi\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi)(\bar q_p \tau^I \gamma^\mu q_r)$
$Q_{\varphi\widetilde B}$	$\varphi^\dagger \varphi\, \widetilde B_{\mu\nu} B^{\mu\nu}$	Q_{dG}	$(\bar q_p \sigma^{\mu\nu} T^A d_r) \varphi\, G_{\mu\nu}^A$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar u_p \gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger \tau^I \varphi\, W^I_{\mu\nu} B^{\mu\nu}$	Q_{dW}	$(\bar q_p \sigma^{\mu\nu} d_r) \tau^I \varphi\, W_{\mu\nu}^I$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar d_p \gamma^\mu d_r)$
$Q_{\varphi\widetilde WB}$	$\varphi^\dagger \tau^I \varphi\, \widetilde W^I_{\mu\nu} B^{\mu\nu}$	Q_{dB}	$(\bar q_p \sigma^{\mu\nu} d_r) \varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu \varphi)(\bar u_p \gamma^\mu d_r)$

$(\bar LL)(\bar LL)$		$(\bar RR)(\bar RR)$		$(\bar LL)(\bar RR)$	
Q_{ll}	$(\bar l_p \gamma_\mu l_r)(\bar l_s \gamma^\mu l_t)$	Q_{ee}	$(\bar e_p \gamma_\mu e_r)(\bar e_s \gamma^\mu e_t)$	Q_{le}	$(\bar l_p \gamma_\mu l_r)(\bar e_s \gamma^\mu e$ [illegible]
$Q_{qq}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar q_s \gamma^\mu q_t)$	Q_{uu}	$(\bar u_p \gamma_\mu u_r)(\bar u_s \gamma^\mu u_t)$	Q_{lu}	$(\bar l_p \gamma_\mu l_r)(\bar u_s \gamma$ [illegible]
$Q_{qq}^{(3)}$	$(\bar q_p \gamma_\mu \tau^I q_r)(\bar q_s \gamma^\mu \tau^I q_t)$	Q_{dd}	$(\bar d_p \gamma_\mu d_r)(\bar d_s \gamma^\mu d_t)$	Q_{ld}	$(\bar l_p \gamma_\mu l_r)(\bar d_s \gamma$ [illegible]
$Q_{lq}^{(1)}$	$(\bar l_p \gamma_\mu l_r)(\bar q_s \gamma^\mu q_t)$	Q_{eu}	$(\bar e_p \gamma_\mu e_r)(\bar u_s \gamma^\mu u_t)$	Q_{qe}	$(\bar q_p \gamma_\mu q_r)(\bar e_s \gamma^\mu e_t)$
$Q_{lq}^{(3)}$	$(\bar l_p \gamma_\mu \tau^I l_r)(\bar q_s \gamma^\mu \tau^I q_t)$	Q_{ed}	$(\bar e_p \gamma_\mu e_r)(\bar d_s \gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar u_s \gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar u_p \gamma_\mu u_r)(\bar d_s \gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar q_p \gamma_\mu T^A q_r)(\bar u_s \gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar u_p \gamma_\mu T^A u_r)(\bar d_s \gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar d_s \gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar q_p \gamma_\mu T^A q_r)(\bar d_s \gamma^\mu T^A d_t)$

$(\bar LR)(\bar RL)$ and $(\bar LR)(\bar LR)$		B-violating	
Q_{ledq}	$(\bar l_p^j e_r)(\bar d_s q_t^j)$	Q_{duq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(q_s^{\gamma j})^T C l_t^k\right]$
$Q_{quqd}^{(1)}$	$(\bar q_p^j u_r)\varepsilon_{jk}(\bar q_s^k d_t)$	Q_{qqu}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{quqd}^{(8)}$	$(\bar q_p^j T^A u_r)\varepsilon_{jk}(\bar q_s^k T^A d_t)$	$Q_{qqq}^{(1)}$	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\varepsilon_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$Q_{lequ}^{(1)}$	$(\bar l_p^j e_r)\varepsilon_{jk}(\bar q_s^k u_t)$	$Q_{qqq}^{(3)}$	$\varepsilon^{\alpha\beta\gamma}(\tau^I\varepsilon)_{jk}(\tau^I\varepsilon)_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$Q_{lequ}^{(3)}$	$(\bar l_p^j \sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar q_s^k \sigma^{\mu\nu} u_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$

$\mathcal{O}\left(\frac{v^2}{\Lambda^2}\right)$

Grzadkowski *et al.* ‘10

- two CPV sources in SM

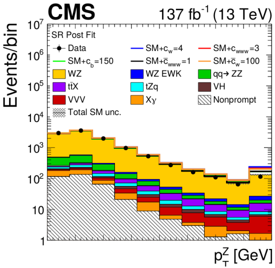
$$\mathcal{L}_{\rm CPV}^{(4)} = -\theta \frac{g_s^2}{64\pi^2} \varepsilon^{\alpha\beta\mu\nu} G_{\mu\nu} G_{\alpha\beta} + \bar u_L^i \, [V_{\rm CKM}]_{ij} \, \gamma^\mu d_L^j W_\mu$$

- 53 (1350) CP-even, 23 (1149) CP-odd dimension-6 operators ($\mathcal{O}(v^2/\Lambda^2)$)

  Buchmuller & Wyler ‘86, Weinberg ‘89, de Rujula *et al.* ‘91, Grzadkowski *et al.* ‘10 . . .

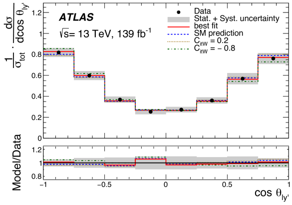
- number flavor-diagonal CPV operators still limited
  6 Higgs-gauge, 9 Yukawas, 24 dipoles, 9 right-handed currents . . .

diboson production



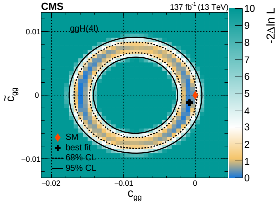
ATLAS 1905.04242,
CMS 2110.11231

top sector



ATLAS 2202.11382,
CMS 1907.03729

Higgs sector



CMS 2104.12152

- used to be an afterthought, more an more analyses coming up

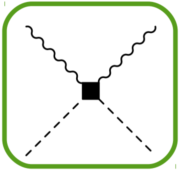
  mostly based on SMEFT

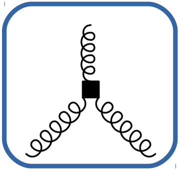
- most studies involve heavy SM particles

  WW and *WZ*, single *t* and $\bar{t}t$, Higgs properties

See A. Gritsan et al, 2109.13363 and 2205.07715 for HL-LHC study

Higgs-gauge operators

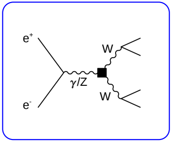


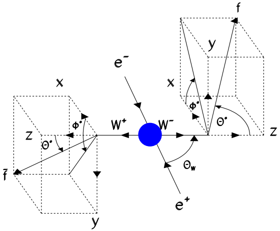


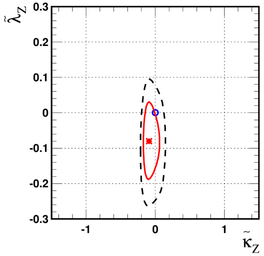
$$\mathcal{L} = -g^2 C_{\varphi\tilde{W}}\, \varphi^\dagger \varphi\, \tilde{W}^i_{\mu\nu} W_i^{\mu\nu} - g'^2 C_{\varphi\tilde{B}}\, \varphi^\dagger \varphi\, \tilde{B}_{\mu\nu} B^{\mu\nu} - g g' C_{\varphi\tilde{W}B}\, \varphi^\dagger \tau^i \varphi\, \tilde{W}^i_{\mu\nu} B^{\mu\nu}$$
$$- g_s^2 C_{\varphi\tilde{G}}\, \varphi^\dagger \varphi G^a_{\mu\nu} \tilde{G}_a^{\mu\nu} + \frac{C_{\tilde{G}}}{3}\, g_s f_{abc} \tilde{G}^a_{\mu\nu} G_b^{\nu\rho} G_\rho^{c\,\mu} + \frac{C_{\tilde{W}}}{3}\, g \epsilon_{ijk} \tilde{W}^i_{\mu\nu} W_j^{\nu\rho} W_\rho^{k\,\mu}\,,$$

- $C_{\varphi\tilde{W}}$, $C_{\varphi\tilde{B}}$, $C_{\varphi\tilde{W}B}$: corrections to $H \to \gamma\gamma, \gamma Z, ZZ^*, WW^*$, and H production (VBF and VH)
- $C_{\varphi\tilde{G}}$: corrections to $gg \to H$, $H \to gg$
- $C_{\varphi\tilde{W}B}$, $C_{\tilde{W}}$: anomalous $WW\gamma$ and WWZ couplings

Higgs-gauge operators. LEP







Delphi Collaboration, '08

- W polarization measurements at LEP2
- constrain anomalous $WW\gamma$ and WWZ couplings

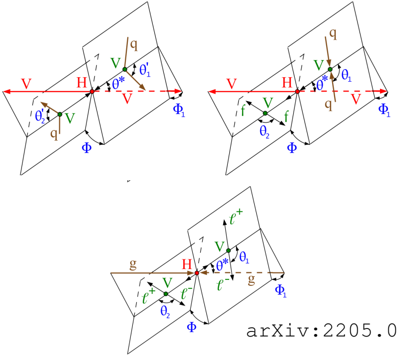
$$\tilde{\kappa}_Z = -0.12^{+0.06}_{-0.04} \qquad \tilde{\lambda}_Z = -0.09^{+0.07}_{-0.07}$$

- can be mapped onto $\varphi^\dagger \varphi \tilde{W} B$ and $WW\tilde{W}$ SMEFT operators

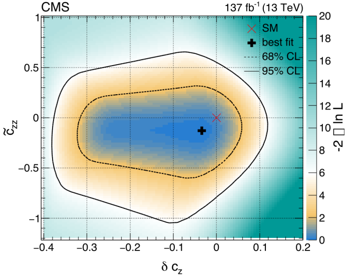
$\Lambda \sim 250 - 350$ GeV

sensitive to EW scale physics

Higgs-gauge operators. LHC



arXiv:2205.07715

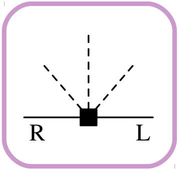


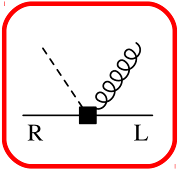
CMS arXiv:2104.12152

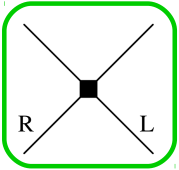
- CP-sensitive observables can be built in $pp \to H + 2j$, HV and $H \to 4\ell$

$$\tilde{c}_{ZZ} = -4\left(c_w^4 v^2 C_{\varphi\tilde{W}} + s_w^4 v^2 C_{\varphi\tilde{B}} + c_w^2 s_w^2 v^2 C_{\varphi\tilde{W}B}\right)$$

- with 13 TeV and 137 fb^{-1}, $\Lambda \sim 500$ GeV





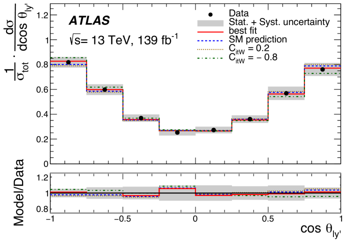


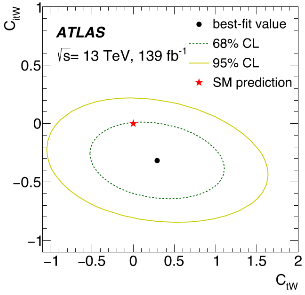
- focused on chiral-breaking operators

$$\mathcal{L} = -\frac{g'}{\sqrt{2}}\,\bar{q}_L\sigma^{\mu\nu}B_{\mu\nu}\,\Gamma^u_B\,u_R\,\tilde{\varphi} - \frac{g_s}{\sqrt{2}}\,\bar{q}_L\sigma^{\mu\nu}G^a_{\mu\nu}t^a\,\Gamma^u_g\,u_R\,\tilde{\varphi} - \sqrt{2}\varphi^\dagger\varphi\,\bar{q}_L\,Y'_u\,u_R\,\tilde{\varphi}$$
$$-\frac{g}{\sqrt{2}}\,\bar{q}_L\sigma^{\mu\nu}W^a_{\mu\nu}\tau^a\,\Gamma^u_W\,u_R\,\tilde{\varphi} - \frac{g}{\sqrt{2}}\,\bar{q}_L\sigma^{\mu\nu}W^a_{\mu\nu}\tau^a\,\Gamma^d_W\,d_R\,\varphi + (4\mathrm{f}) + \mathrm{h.c.}.$$

- including Higgs-gauge, closed set under renormalization
- corrections to $t\bar{t}$, $t\bar{t}h$ and single top production

Single top



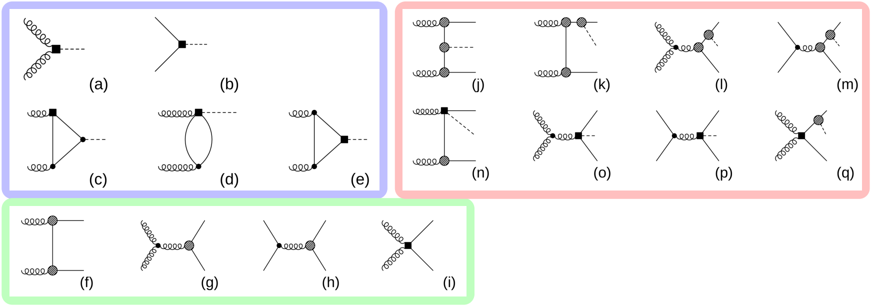


ATLAS 2202.11382

- angular distributions allow to access triple correlation $\vec{S}_t \cdot (\vec{p}_\ell \times \vec{p}_j)$

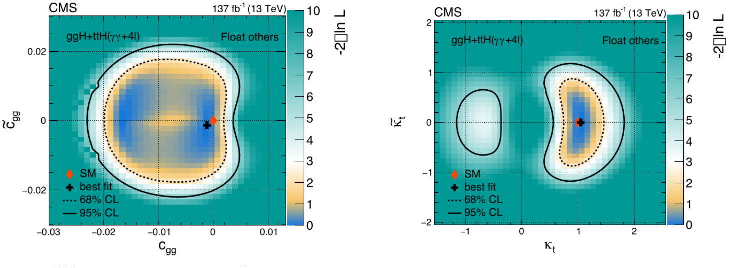
  analogous to "D coefficient" in β decays
- $\Lambda \sim 1.4$ TeV with polarization observables alone

$gg \to H$, $t\bar{t}$ and $t\bar{t}H$



- very sensitive to top couplings, at tree and loop level

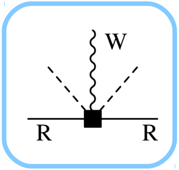
$gg \to H$, $t\bar{t}$ and $t\bar{t}H$



CMS arXiv:2104.12152

- very sensitive to top couplings, at tree and loop level
- $gg \to H$ loop suppressed in the SM $\Longrightarrow$ strong constraint on $\tilde{c}_{gg}$
- top dipole gets competitve constraints from $t\bar{t}$ and H processes
- $\mathcal{O}(1)$ top non-standard Yukawa still allowed

Right-handed currents

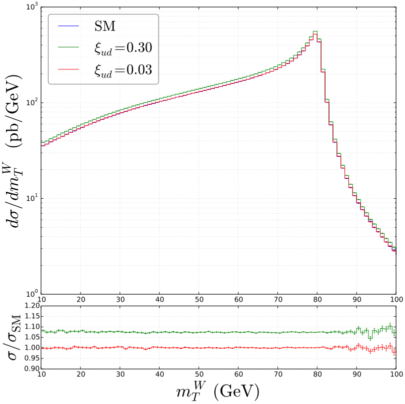


$$\xi = \begin{pmatrix} \xi_{ud} & \xi_{us} & \xi_{ub} \\ \xi_{cd} & \xi_{cs} & \xi_{cb} \\ \xi_{td} & \xi_{ts} & \xi_{td} \end{pmatrix}$$

$$\mathcal{L} = \frac{2}{v^2} i\tilde{\varphi}^\dagger D_\mu \varphi \, \bar{u}_R^i \gamma^\mu \, \xi_{ij} d_R^j + \text{h.c.}$$

- affect all charged-current processes
- at high-energy, Drell-Yan, Higgs and diboson production
- at low energy, EDMs, ϵ'/ϵ, β decays & B decays

Collider constraints on RH currents. Drell-Yan



$$\sqrt{S} = 13 \text{ TeV}$$

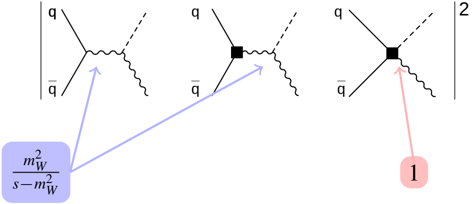
$$(m_T^W)^2 = 2|p_{T\,l}||p_{T\,\nu}|(1 - \cos\Delta\phi_{l\nu})$$

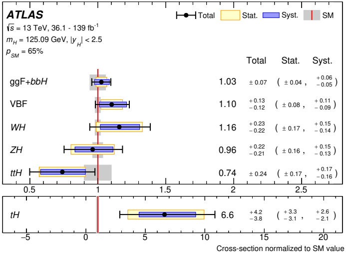
- $pp \to \ell\nu$, $pp \to WH$, VBF, at NLO in QCD
  with parton showering and hadronization in POWHEG

S. Alioli, W. Cirigliano, W. Dekens, J. de Vries, EM, '17,
S. Alioli, W. Dekens, M. Girard, EM, '18

- exact same shape as the SM, very hard to constrain

Associated production of Higgs and W





- contact quark-Higgs-W vertex enhances ξ contrib.

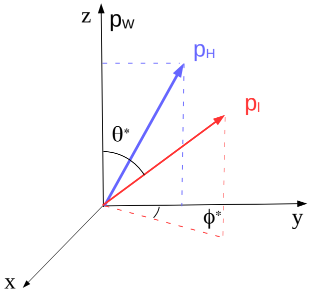
$$\mu_W = 1 + \frac{\sigma^{\xi}(pp \to e^+\nu_e)}{\sigma^{\rm SM}(pp \to e^+\nu_e)} = 1 + 0.9|\xi_{ud}|^2 + \dots$$

$$\mu_{WH} = 1 + \frac{\sigma^{\xi}(pp \to WH)}{\sigma^{\rm SM}(pp \to WH)} = 1 + 456|\xi_{ud}|^2 + \dots$$

$$|\xi_{ud}| < 0.04 \text{ at } 95\% \text{ CL}$$

- even stronger dependence at high p_T, m_{Vh}

Angular distributions in HW production



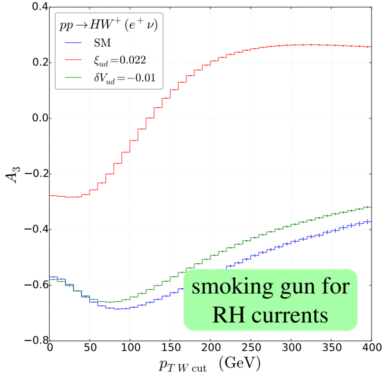
$\sin\theta^* \sin\phi^* \propto \vec{p}_\ell \cdot (\vec{p}_W \times \vec{p}_H)$

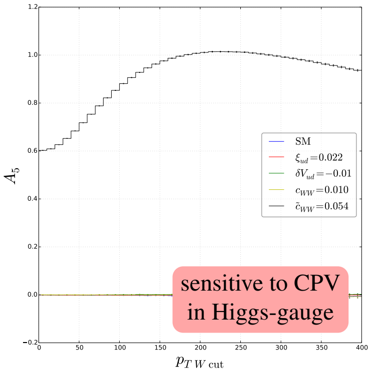
- angular distributions of charged lepton in W decay

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta^*\, d\phi^*} = \frac{3}{16\pi}\Big[1+\cos^2\theta^* + \frac{A_0}{2}(1-3\cos^2\theta^*) + A_1 \sin 2\theta^* \cos\phi^* + \frac{A_2}{2}\sin^2\theta^* \cos 2\phi^*$$
$$+ A_3 \sin\theta^* \cos\phi^* + A_4 \cos\theta^* + A_5 \sin\theta^* \sin\phi^* + A_6 \sin 2\theta^* \sin\phi^* + A_7 \sin^2\theta^* \sin 2\phi^*\Big].$$

- A_0-A_7 parameterize W spin-density matrix and carry info on the production mechanism

ϕ^* distribution in HW production





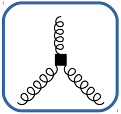
- ϕ^* distribution very sensitive to ξ,
  already at small p_T, even more at high p_T
- big qualitative difference between RH and LH currents
- sensitive to CPV from operators that interfere with the SM

Low-energy EFT for flavor-diagonal CPV

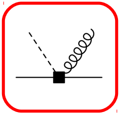
- one dim-4 operator: QCD $\bar{\theta}$ term

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

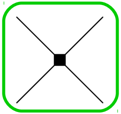
- 9 (+ 10 w. strangeness) hadronic operators @ $\mathcal{O}(v^2/\Lambda^2)$:



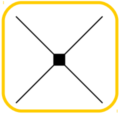
gluon CEDM $C_{\tilde{G}}$



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



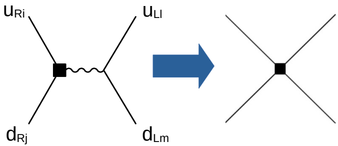
LL RR 4-quark $\Xi_{ud,us,ds}^{(1,8)}$



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

- SMEFT operators have different chiral/isospin transformations
- 3 lepton EDM + 3 semileptonic operators

Matching & running to low energy



- full one-loop matching between SMEFT and LEFT done!

  W. Dekens and P. Stoffer, '19

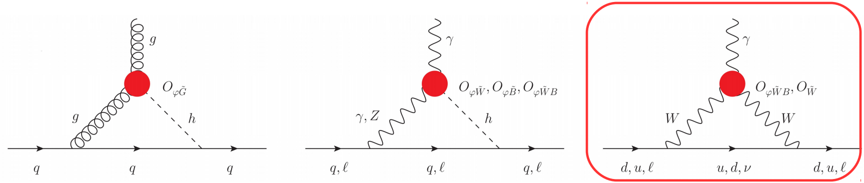
- LL running in SMEFT & LEFT known

  E. Jenkins, A. Manohar and M. Trott, '13, '14; + R. Alonso '14;
  E. Jenkins, A. Manohar and P. Stoffer, '19

Tree level path

- open to RH currents, leading to $\Delta F = 0$ and $\Delta F = 1$ observables
- different chiral structure and much more CP violation than in the SM

Matching & running to low energy



One loop path:

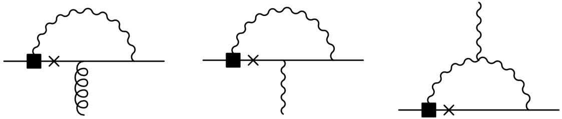
- $C_{\varphi\tilde{W}}, C_{\varphi\tilde{W}B}, C_{\varphi\tilde{B}}$ and $C_{\tilde{W}} \Longrightarrow$ lepton & quark EDM @ 1 EW loop

$$\tilde{c}_{\gamma}^{(e,q)} \sim \frac{\alpha_{\rm em}}{4\pi} C_{\tilde{X}} \sim \left\{10^{-2} C_{\varphi\tilde{X}}, 10^{-3} C_{\tilde{W}}\right\}$$

- gluonic operators $\Longrightarrow$ qCEDM and gCEDM @ $\mathcal{O}(\alpha_s)$
- $C_{\varphi\tilde{W}B}$ and $C_{\tilde{W}}$ match on flavor-changing dipoles

same chiral and flavor structure as SM
(same CKM suppression in $B \to X_s \gamma \ldots$)

Matching & running to low energy



One loop path:

- $C_{\varphi\tilde{W}}$, $C_{\varphi\tilde{W}B}$, $C_{\varphi\tilde{B}}$ and $C_{\tilde{W}}$ $\Longrightarrow$ lepton & quark EDM @ 1 EW loop

$$\tilde{c}_{\gamma}^{(e,q)} \sim \frac{\alpha_{\rm em}}{4\pi} C_{\tilde{X}} \sim \left\{10^{-2} C_{\varphi\tilde{X}}, 10^{-3} C_{\tilde{W}}\right\}$$

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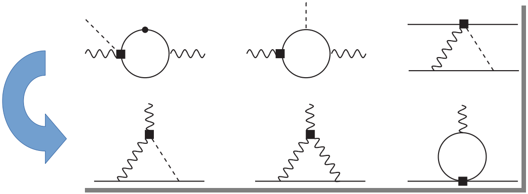
- $C_{\varphi\tilde{W}B}$ and $C_{\tilde{W}}$ match on flavor-changing dipoles

same chiral and flavor structure as SM
(same CKM suppression in $B \to X_s\gamma \ldots$)

- for RH currents and top dipoles, chiral structure lead to chiral enhancements

$$\left[v^2 c_g^{(d)}\right]_{i\ell} \propto \frac{1}{(4\pi)^2} \frac{m_t}{m_{d_\ell}} \xi_{t\ell} V_{ti}^*$$

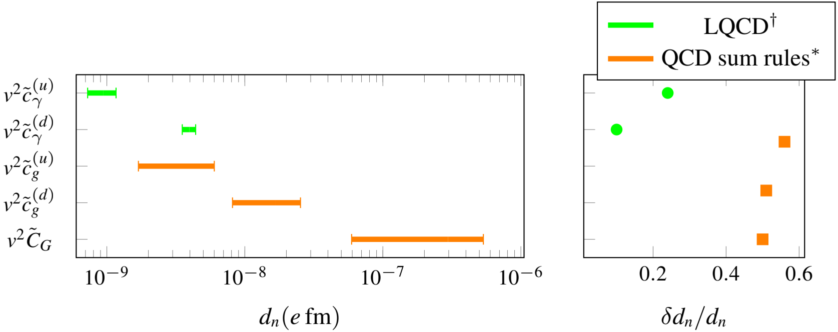


Two loop (LL) path:

- top dipoles $\Longrightarrow$ Higgs-gauge $\Longrightarrow$ fermion dipoles
- sizable mixing of the t EDM (weak EDM) onto eEDM

$$\tilde{c}_{\gamma}^{(e)} \sim \frac{\alpha}{4\pi} \frac{y_t^2}{(4\pi)^2} \log^2 \frac{\Lambda^2}{m_t^2} \tilde{c}_{\gamma}^{(t)} \sim 10^{-4} \tilde{c}_{\gamma}^{(t)}$$

Nucleon EDM matrix elements



† FLAG '21

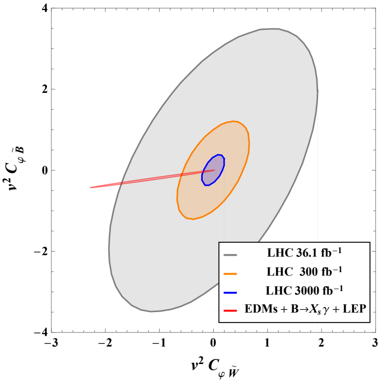
* Pospelov and Ritz, '05, Haisch and Hala, '19

- small error on the eEDM and ThO precession frequency

$$d_e = em_e\tilde{c}_\gamma^{(e)} \sim 1.7 \cdot 10^{-9}(v^2\tilde{c}_\gamma^{(e)})\, e\,\text{fm}$$

- tensor charges control qEDMs
- large (uncontrolled) errors on purely hadronic operators

Constraints on weak gauge-Higgs operators



marginalized

$\varphi^\dagger\varphi\tilde{W}W$, $\varphi^\dagger\varphi\tilde{B}B$,
$\varphi^\dagger\varphi\tilde{W}B$, $WW\tilde{W}$

V. Cirigliano, EM *et al*, '19

LHC projections of Bernlochner *et al*, '18

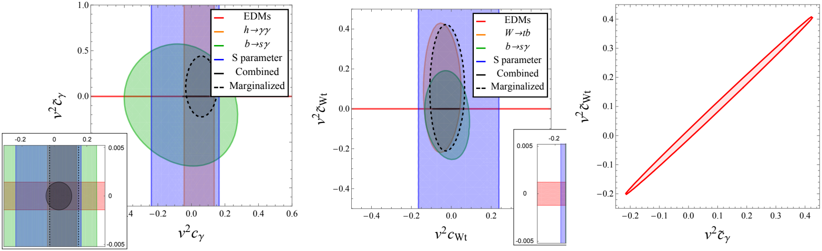
- dominant constraint from eEDM
- EDMs constrain 2 directions

d_n, $d_{\rm Hg}$ and $d_{\rm Ra}$ largely degenerate

- need LEP, $B \to X_s\gamma$ or LHC to close free directions

strong correlations to avoid EDMs

Top dipole operators

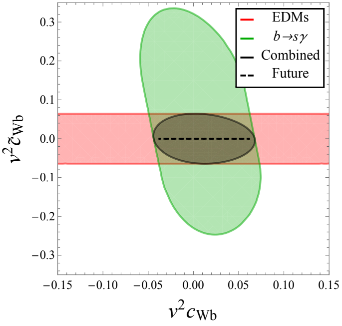


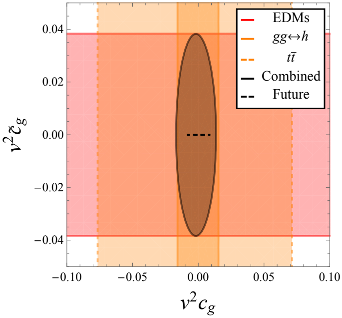
V. Cirigliano, W. Dekens, J. de Vries, EM, '16

marginalized over 5 chiral breaking t ops

- γ and W dipoles have sizable mixing with lepton EDMs
- strong constraints from eEDM, not affected by theory uncertainties
- free direction closed by CPV observables in single top production
- CP-even bounds typically a factor of ~ 100 weaker than CP-odd (loop dominated in the case of c_γ)

Top dipole operators





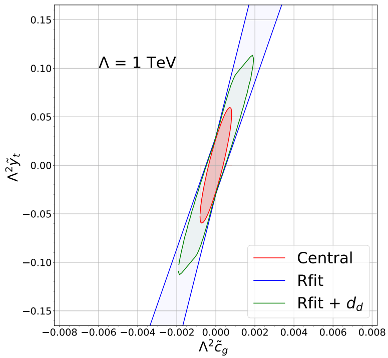
- $\tilde{c}_{Wb}$ and $\tilde{c}_g$ don't generate large eEDM
- $\tilde{c}_{Wb}$ constrained by nEDM and CP asymmetry in $B \to s\gamma$
- bound on gluonic dipole $\tilde{c}_g$ dominated by nEDM

  via qCEDM and gCEDM

- hadronic uncertainties weaken bounds by factors of 10 /100

  similar constraints on real and imaginary part

Top dipole, Yukawa and Higgs-glue operators



marginalized

$$\varphi^\dagger\varphi\tilde{G}G,\ \varphi^\dagger\varphi\bar{q}_L\varphi t_R,\ \bar{q}_L\sigma\cdot G\gamma_5 t_R$$

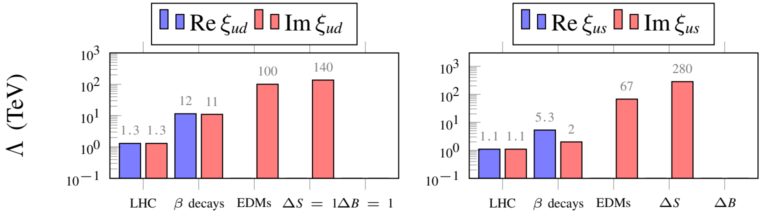
include d_e, d_n, $d_{\rm Hg}$, $d_{\rm Xe}$ and $d_{\rm Ra}$

Central: no theory errors
Rfit: vary ME in allowed ranges
Rfit + d_d : assume 10% *nuclear* errors

- naive analysis gives constraints out of LHC's reach
- analysis crucially depends on theory errors

  e.g. Hg and Xe bounds drop out in Rfit strategy
- EDMs of light nuclei provide orthogonal constraints

Constraints on right-handed currents



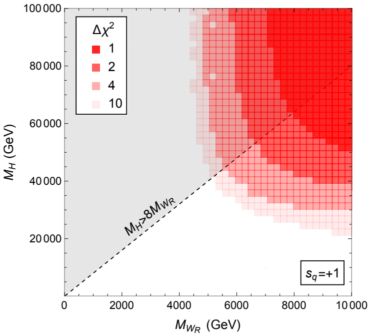
- tree level contributions to nEDM and ϵ'/ϵ
- enhanced by large mesonic matrix elements

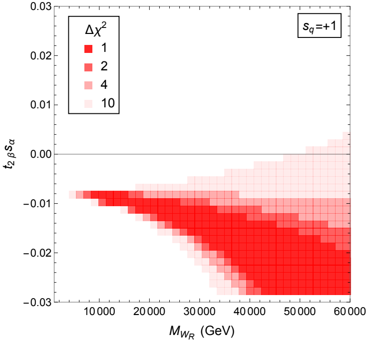
$$\{\bar{q}_L \gamma^\mu t^a \bar{q}_L \; \bar{q}_R \gamma_\mu t^b q_R, \bar{q}_{L\alpha} \gamma^\mu t^a \bar{q}_{L\beta} \; \bar{q}_{R\beta} \gamma_\mu t^b q_{R\alpha}\} \longrightarrow \frac{F_0^4}{4} \,\mathrm{Tr}\left(U^\dagger t^b U t^a\right) \{\mathcal{A}_{1\,LR}, \mathcal{A}_{2\,LR}\}$$

computed on the lattice for $K \to \pi\pi$ or K-$\bar{K}$ oscillations

- good β decay constraints
- correlation between ϵ'/ϵ, nEDM and atomic EDMs hallmark of RH currents

EDMs in the Left-Right symmetric model

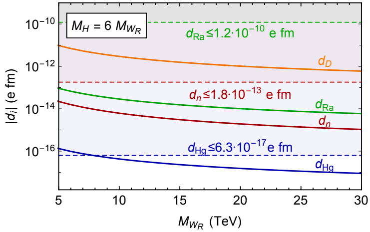




W. Dekens, L. Andreoli, F. Oosterhof *et al*, '21

- LR model with P symmetry; M_H, M_{W_R}, W_L-W_R mixing ξ, phase α
- global fit including $\Delta F = 0$, $\Delta F = 1$ and $\Delta F = 2$ observables
- B-$\bar{B}$, K-$\bar{K}$ oscillations enforce $M_{W_R} \gtrsim 5$ TeV
- relative large phase and mixing in "low" mass region

EDMs in the Left-Right symmetric model



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- B-$\bar{B}$, K-$\bar{K}$ oscillations enforce $M_{W_R} \gtrsim 5$ TeV
- relative large phase and mixing in “low” mass region

param. space will be significantly cut in the next gen. of experiments.

Summary

1. in a single coupling analysis, eEDM and nEDM dominate most of the flavor diagonal CPV parameters in the SMEFT

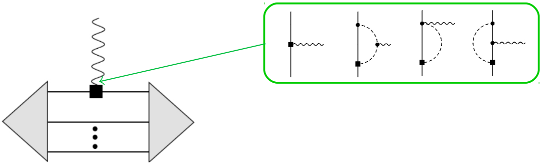
   . . . also in top, Higgs, W and Z sectors
2. theory errors weaken limits on some hadronic operators

   t and b Yukawa, chromoEDM, pure glue operators, . . .
3. beyond single couplings, EDMs of course will leave free directions
   . . . but they enforce correlations between different SMEFT coefficients

- correlated signals in different probes needed to solve the "inverse problem" (. . . after we see one signal . . .)

Hadronic uncertainties

CPV in chiral perturbation theory. One-body sector

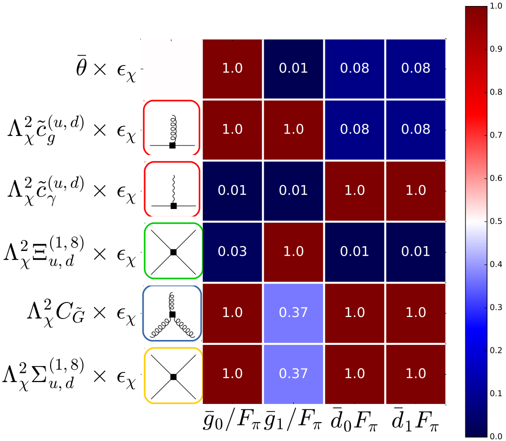


- power counting unambigous in the one-body sector

$$\mathcal{L}^{(1)}_{\not{T}} = \bar{N}\left(\bar{d}_n \frac{1-\tau_3}{2} + \bar{d}_p \frac{1+\tau_3}{2}\right) \boldsymbol{\sigma} \cdot \mathbf{E}\, N - \frac{\bar{g}_0}{2F_\pi} \bar{N} \boldsymbol{\pi} \cdot \boldsymbol{\tau} N - \frac{\bar{g}_1}{2F_\pi} \pi_3 \bar{N} N + \dots$$

- for all CPV sources $\bar{d}_n \sim \bar{d}_p$
- for $\not{\chi}$, $I = 0$ operators, long-range π loop contribute to nEDM at LO
- $\bar{g}_{0,1}$ induce π-range TV NN potential $\Longrightarrow$ nuclear EDMs and Schiff moments

Hadronic couplings in χPT

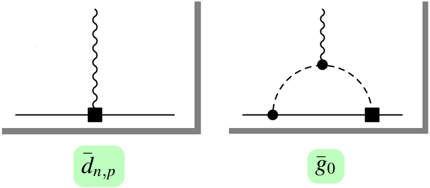


WARNING
naive dim. analysis!

- hierarchy of hadronic couplings strongly depends on CPV sources
- couplings can be in principle determined by lattice 2-, 3- and 4-point functions

Constantia, Boram, Andre, Keh-Fei, and Gerrit's talks

The neutron EDM in χPT



$$\left.\frac{F_3(Q^2)}{2m_N}\right|_n = d_n + S_n \frac{Q^2}{m_\pi^2} + H_n\left(\frac{Q^2}{m_\pi^2}\right)$$

- for isoscalar sources, tree-level and $\bar{g}_0$ loop of the same size ($\bar{g}_1$ suppressed)
- loop diagram controls chiral log

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

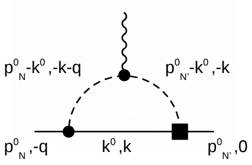
R. J. Crewther, P. di Vecchia, G. Veneziano and E. Witten, ‘79

- and momentum dependence

$$S_n = -\frac{1}{6}\frac{e g_A \bar{g}_0}{(4\pi F_\pi)^2}\left(1 - \frac{5\pi}{4}\frac{m_\pi}{m_N}\right)$$

U. van Kolck, W. Hockings, ‘05

Excited state contamination in χPT

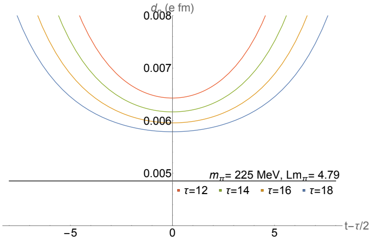


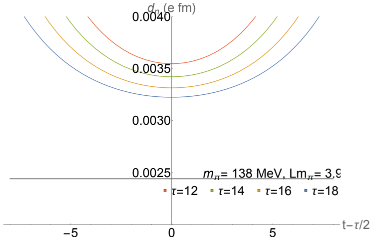
- the same diagram controls the ESC and finite volume corrections. At $Q = 0$

$$\frac{F_3(0,t,\tau)}{2m_N} = \bar{d}_n - e\frac{g_A\bar{g}_0}{(4\pi F_\pi)^2}\left(\ln\frac{\mu^2}{m_\pi^2}\right.$$

$$\left. + \sum_{\vec{k}=0}^{\infty}\frac{4\pi^2}{(m_\pi L)^3}\frac{m_\pi^3}{E_\pi^3}\left(e^{-E_\pi t} + e^{-E_\pi(\tau-t)} - e^{-E_\pi\tau}\right) + \sum_{\vec{n}\neq 0}^{\infty} 2K_0(Lm_\pi|\vec{n}|)\right)$$

- dominated by $\vec{k} = 0$, $E_\pi = \sqrt{k^2 + m_\pi^2} = m_\pi$, and first few momentum states
- ESC contribution not suppressed w.t.r chiral log





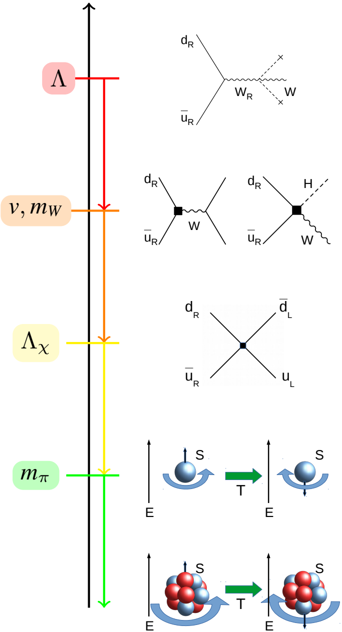
$\bar{\theta}$ term

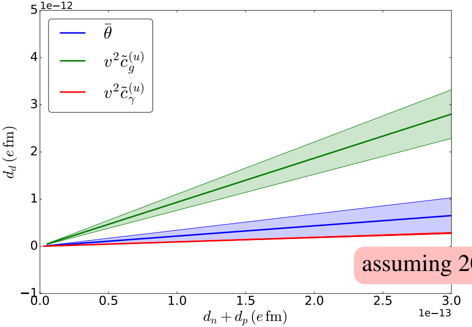
- large ESC at physical pion mass

  factor of ~ 1.4 for lattice used in `arXiv:2101.07230`
- still important at $m_\pi \sim 220$ MeV
- FV correction between 5% and 10%

are the systematics fully accounted for?

Nuclear EDMs in Effective Field Theories





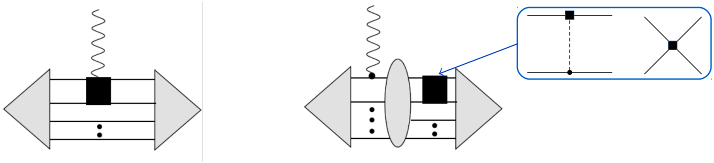
assuming 20% had/nuc errors

1. experimental proposals for $d_p \lesssim 10^{-16}$ e fm (possibly d_d and $d_{^3\mathrm{He}}/d_p$)

   see Snowmass White Paper `arXiv:2203.08103`

2. different nuclei probe different combinations d_n, d_p, $\bar{g}_0$, $\bar{g}_1$

can disentangle BSM scenarios with enough theory accuracy



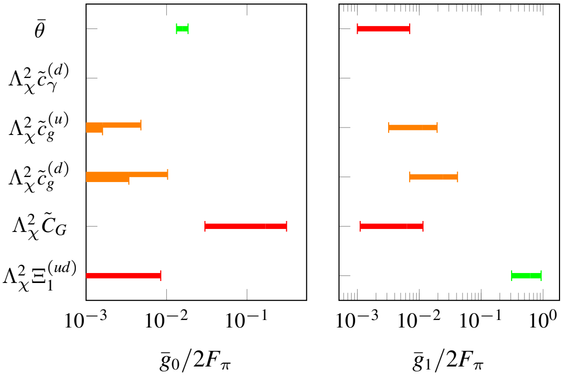
- in Weinberg's counting, TV potential dominated by OPE

need only 1-body input!

- for a small class of operators ($GG\tilde{G}$), four-nucleon operators a LO

$$\mathcal{L}_{\not{T}}^{(2)} = \tilde{C}_{^3S_1-^1P_1}\left(N^T P^i_{^3S_1} N\right)^\dagger N^T P^i_{^1P_1} N + \tilde{C}^{(0)}_{^1S_0-^3P_0}\left(N^T P^a_{^1S_0} N\right)^\dagger N^T P^a_{^3P_0} N$$

Determination of the TV potential



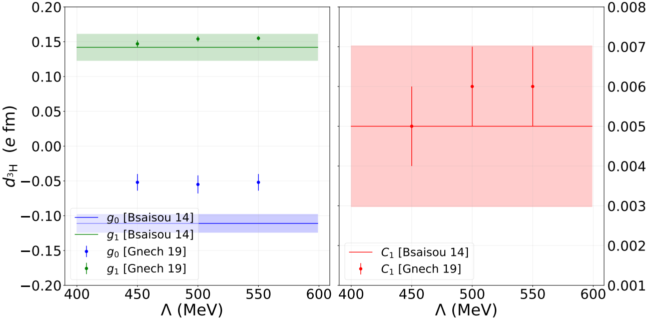
* Pospelov and Ritz, '05

- large theory error on LECs from most operators
- ideas for LQCD extractions of πN couplings

J. de Vries, EM, C. Y. Seng, A. Walker-Loud, '16

- no work yet on NN interactions

Chiral EFT calculations



- several "hybrid" calculations of d_d, $d_{^3\mathrm{H}}$, $d_{^3\mathrm{He}}$

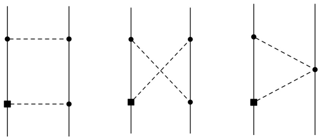
  C. P. Liu and R. Timmermans, '05; J. de Vries *et al*, '11; Y. H. Song, R. Lazauskas, V. Gudkov, '13, N. Yamanaka and E. Hiyama, '15, P. Froese and P. Navratil, '21

- two "fully chiral", with N^{2}LO chiral potential and LO or NLO TV potential

  J. Bsaisou *et al*, '14; A. Gnech and M. Viviani, '19

- uncertainty from spread of different calculations $\sim 10\%$

no full error analysis from EFT truncation



- form of the N^2LO potential in Weinberg's counting known for all CPV sources

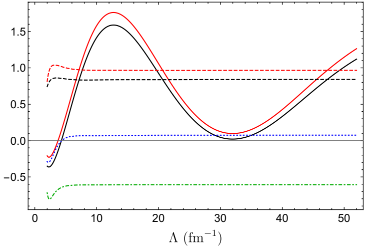
  C. Maekawa, EM, J. de Vries, U. van Kolck, '11; J. Bsaisou, C. Hanhart, S. Liebig, U. G. Meißner, A. Nogga, A. Wirzba, '12; A. Gnech and M. Viviani, '19

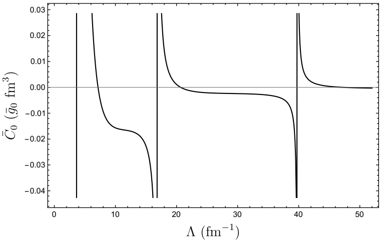
- need two-pion exchanges and $I = 0$ and $I = 1$ NN CPV interactions
- only one EFT calculation with N^2LO potentials
- large TPE contribution, reduces LO by a factor of 2

  A. Gnech and M. Viviani, '19

- LQCD determination of C_{S-P} needed for N^2LO (and truncation error) analysis

The problem with renormalization



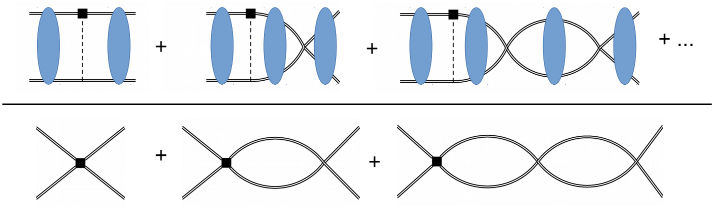


J. de Vries, A. Gnech, S. Shain, ‘20

- both $\bar{g}_0$ and $\bar{g}_1$ act in the $^3P_0$ channel
- the scattering amplitude $\mathcal{A}_{\not{T}}(^1S_0 \rightarrow ^3 P_0)$ shows strong cut-off dependence
- absorbed by promoting $C^{(0,1)}_{^1S_0-^3P_0}$ to LO
- cut-off dependence does not affect the deuteron
- should be visible in ^{3}H and ^{3}He

existing calculations have very limited ranges in Λ!
is the $\sim 10\%$ theory uncertainty estimated correctly?

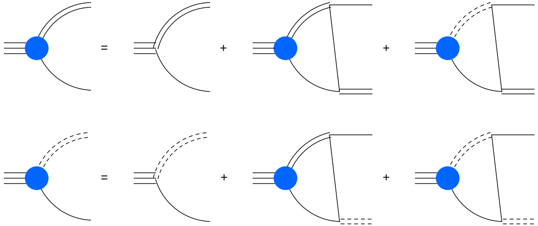
CPV in pionless EFT



- one-body CPV Lagrangian contains neutron/proton EDMs
- 5 S to P transitions in two-body Lagrangian
  $\Delta T = 0$: $C_{^3S_1-^1P_1}$, $C^{(0)}_{^1S_0-^3P_0}$; $\Delta T = 1$: $C_{^3S_1-^3P_1}$, $C^{(1)}_{^1S_0-^3P_0}$,
  $\Delta T = 0$: $C^{(2)}_{^1S_0-^3P_0}$
- scaling determined by NDA + matching to χPT
- match directly to lattice $NN \to NN$ amplitudes?

if isospin a good symmetry
2 LECs for each SMEFT op.

Trimer fields and three-body forces



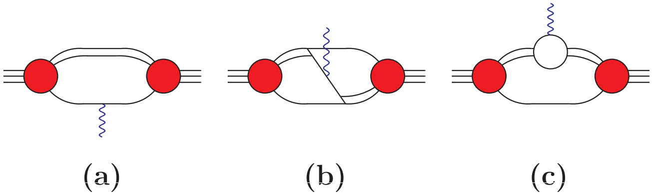
- introduce dimer fields (t, s) for NN in $^3S_1$, $^1S_0$
- calculation of 3-nucleon properties simplified by introducing trimer field

$$\psi = (\psi_{^3\mathrm{He}}, \psi_{^3\mathrm{H}})$$

follow closely J. Vanasse, '15

- ψ enter the Lagrangian via a LO 3-body force, determined by ^{3}H binding energy
- resum the series of LO diagrams via integral equation

Form factor calculation with a trimer field



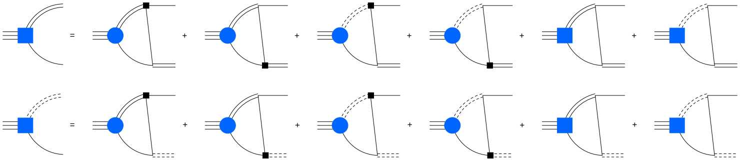
J. Vanasse, '15

Form factor calculation:

1. compute "trimer irreducible" diagrams
2. and the residue of the trimer propagator at B

$$Z_\psi = \frac{\pi}{\Sigma_0'(B)}$$

T-odd vertex functions



Z. Yang, EM, L. Platter, M. Schindler, J. Vanasse, '20

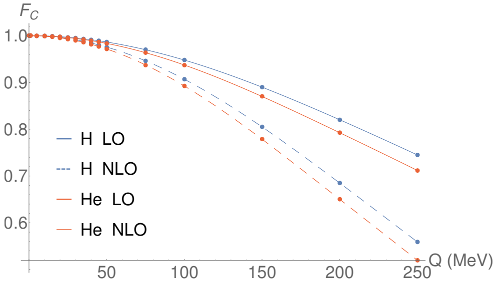
- in full generality, we can introduce 6 T-odd vertex functions
- 2 spin triplet components $\mathcal{T}_{t0}$ and $\mathcal{T}_{t1}$

  couple ψ to N-t in $S = 1/2, I = 1/2$
- 4 isospin triplet components, $\mathcal{T}_{s0}, \ldots, \mathcal{T}_{s3}$

  couple ψ to N-s in $S = 1/2, I = 1/2$ and $I = 3/2$
- follow similar integral equations

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

Charge form factor



$$F_C(q^2) \quad = \quad Z\left(1 - \frac{q^2}{6}\langle r_c^2\rangle + \frac{1}{5!}\langle r_c^4\rangle q^4 + \dots\right) \; ,$$

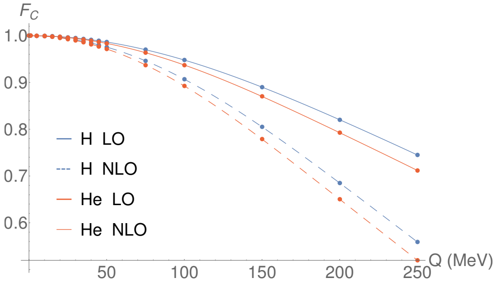
- at LO

$$\langle r_c^2(^3\mathrm{H})\rangle = 1.28\,\mathrm{fm}^2\;, \qquad \langle r_c^2(^3\mathrm{He})\rangle = 1.56\,\mathrm{fm}^2\;, \qquad \langle r_c^2(^3\mathrm{H})\rangle_{\mathrm{exp}} = 2.55\,\mathrm{fm}^2$$

- in the $SU(4)$ limit

$$F_C^{^3\mathrm{He}}(q^2) = 2\,F_C^{^3\mathrm{H}}(q^2) \qquad \langle r_c^2\rangle = 1.32\,\mathrm{fm}^2$$

Charge form factor



$$F_C(q^2) = Z\left(1 - \frac{q^2}{6}\langle r_c^2\rangle + \frac{1}{5!}\langle r_c^4\rangle q^4 + \ldots\right),$$

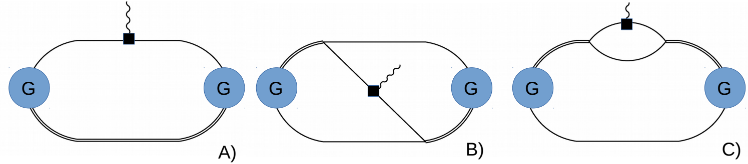
- at NLO

$$\langle r_c^2(^3\mathrm{H})\rangle = 2.30\,\mathrm{fm}^2\,, \qquad \langle r_c^2(^3\mathrm{He})\rangle = 2.69\,\mathrm{fm}^2\,, \qquad \langle r_c^2(^3\mathrm{H})\rangle_{\mathrm{exp}} = 2.55\,\mathrm{fm}^2$$

- in the $SU(4)$ limit

$$F_C^{^3\mathrm{He}}(q^2) = 2\,F_C^{^3\mathrm{H}}(q^2) \qquad \langle r_c^2\rangle = 2.46\,\mathrm{fm}^2$$

EDFF. One-body component



$$F_i(q^2, C) = d_i(C)\left(1 - \frac{q^2}{6}\langle r^2_{d,\,i}(C)\rangle + \frac{1}{5!}\langle r^4_{d,\,i}(C)\rangle q^4 + \dots\right),$$

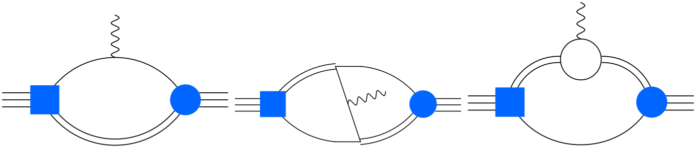
$$S_i(C) = -\frac{d_i(C)}{6}\left(\langle r^2_{d,\,i}(C)\rangle - \langle r^2_c\rangle\right),$$

- EDM of ^{3}H (^{3}He) determined by d_p (d_n)

$$d_{\rm I}(^3{\rm H}) = 0.99\, d_p \qquad d_{\rm I}(^3{\rm He}) = 0.99\, d_n$$

- the Schiff moment of ^{3}H vanishes (within errors). ^{3}He is small
- can be understood in the $SU(4)$ limit

$$F_I(q^2, {}^3{\rm H}) = d_p F_C(q^2), \qquad F_I(q^2, {}^3{\rm He}) = d_n F_C(q^2)$$



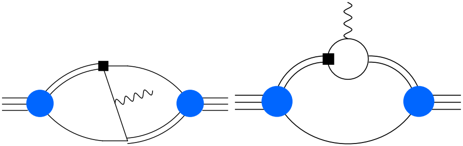
Two sets of diagrams

- three involve T-odd vertex functions

same topologies as charge form factors

- two more cannot be absorbed in $\mathcal{T}$
- no corrections to Z_ψ

EDFF. Two-body component



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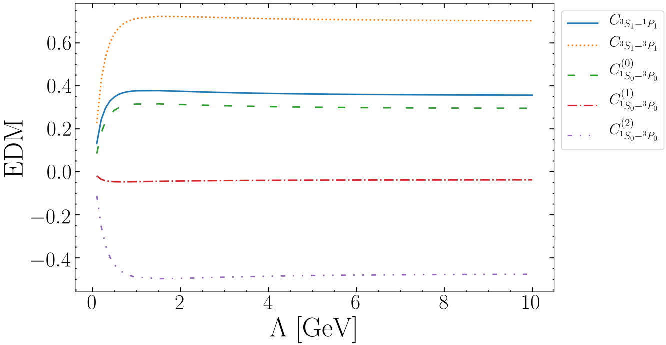
EDM. Two-body component



- EDM and EDFF are explicitly cut-off independent
- still some dependence at relative large scales ~ 1 GeV
- stronger dependence than $F_C(q^2)$

EDM. Two-body component

$$
\begin{aligned}
d_{\mathrm{II}}(^3\mathrm{H}) &= -0.36 C_{^3S_1-^1P_1} + 0.71 C_{^3S_1-^3P_1} - 0.30 C^{(0)}_{^1S_0-^3P_0} + 0.48 C^{(2)}_{^1S_0-^3P_0}, \\
d_{\mathrm{II}}(^3\mathrm{He}) &= +0.36 C_{^3S_1-^1P_1} + 0.71 C_{^3S_1-^3P_1} + 0.30 C^{(0)}_{^1S_0-^3P_0} - 0.48 C^{(2)}_{^1S_0-^3P_0}.
\end{aligned}
$$

- EDMs of natural size $\sim \mathcal{O}(1)$

  except $C^{(1)}_{^1S_0-^3P_0}$, which is suppressed
- isospin relations between ^{3}He and ^{3}H at $q^2 = 0$
- error from residual cut-off dependence & numerics smaller than last digit
- error from missing orders $(Z_t - 1)/2 \approx 0.4$

EDFF in the $SU(4)$ limit

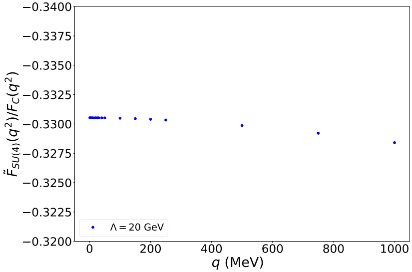
		$C_{^3S_1-^1P_1}$	$C_{^3S_1-^3P_1}$	$C^{(0)}_{^1S_0-^3P_0}$	$C^{(2)}_{^1S_0-^3P_0}$
$\langle r^2_{d,\,\mathrm{II}}(^3\mathrm{H})\rangle$	(fm^2)	1.31	1.30	1.24	1.19
$\langle r^2_{d,\,\mathrm{II}}(^3\mathrm{He})\rangle$	(fm^2)	1.90	1.50	1.83	1.19
$\langle r^2_{d,\,\mathrm{II}}(^3\mathrm{H})\rangle - \langle r^2_c(^3\mathrm{H})\rangle$	(fm^2)	0.03	0.02	-0.05	0.09
$\langle r^2_{d,\,\mathrm{II}}(^3\mathrm{He})\rangle - \langle r^2_c(^3\mathrm{He})\rangle$	(fm^2)	0.34	-0.06	0.27	-0.37

- dipole radii quite similar to charge $\Longrightarrow$ big suppression in the Schiff moment

In SU(4)

$$F_{\mathrm{II}}(q^2,{}^3\mathrm{H}) \xrightarrow{SU(4)} \tilde{F}_{SU(4)}(q^2)\left(C_{^3S_1-^1P_1} + C^{(0)}_{^1S_0-3P_0} - 2C^{(2)}_{^1S_0-^3P_0} - 2C_{^3S_1-^3P_1}\right),$$

$$F_{\mathrm{II}}(q^2,{}^3\mathrm{He}) \xrightarrow{SU(4)} -\tilde{F}_{SU(4)}(q^2)\left(C_{^3S_1-^1P_1} + C^{(0)}_{^1S_0-3P_0} - 2C^{(2)}_{^1S_0-^3P_0} + 2C_{^3S_1-^3P_1}\right),$$



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In SU(4)

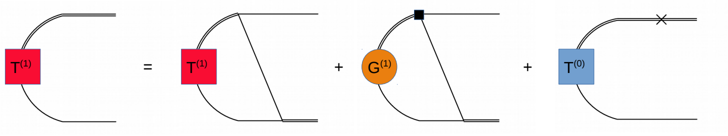
$$F_{\rm II}(q^2, {}^3{\rm H}) \xrightarrow{SU(4)} \tilde{F}_{SU(4)}(q^2)\left(C_{{}^3S_1-{}^1P_1} + C^{(0)}_{{}^1S_0-3P_0} - 2C^{(2)}_{{}^1S_0-{}^3P_0} - 2C_{{}^3S_1-{}^3P_1}\right),$$

$$F_{\rm II}(q^2, {}^3{\rm He}) \xrightarrow{SU(4)} -\tilde{F}_{SU(4)}(q^2)\left(C_{{}^3S_1-{}^1P_1} + C^{(0)}_{{}^1S_0-3P_0} - 2C^{(2)}_{{}^1S_0-{}^3P_0} + 2C_{{}^3S_1-{}^3P_1}\right),$$

- "empirically"

$$\frac{\tilde{F}_{SU(4)}(q^2)}{F_C(q^2)} = \text{constant} = -\frac{1}{3}$$

CP violation at NLO



- working to extend to NLO
- might need CP-odd photon-dimer interactions

$$\mathcal{L} \propto D_{1\gamma}\, t_j^\dagger t_i \varepsilon^{ijk} E_k + D_{2\gamma}\, t_j^\dagger s_3 E_j$$

- do we need a CP-odd three-nucleon interaction?

Conclusions

EDM are powerful probes of BSM physics
To disentangle BSM scenarios:

1. complementary systems and correlations with flavor and collider processes
2. better control on both hadronic and nuclear uncertainties
3. lattice program in 1- and 2-body sector
   & more systematic nuclear uncertainties