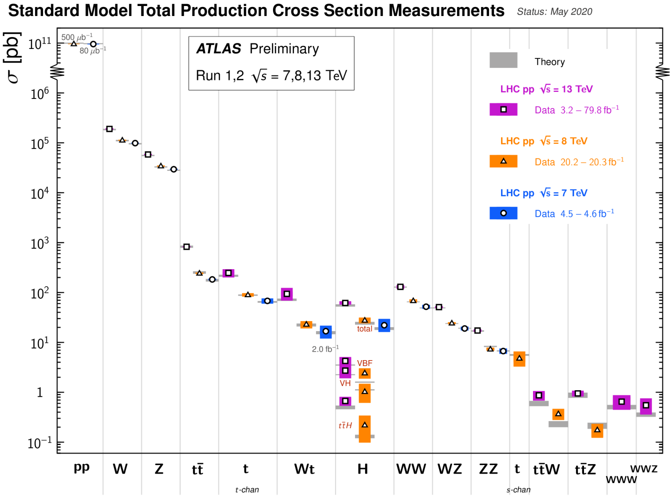
Phenomenology and EDMs

Emanuele Mereghetti

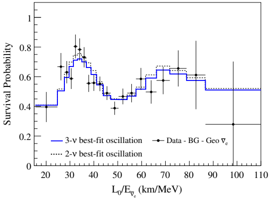
September 15th, 2020

Workshop on Electric and Magnetic Moments

Los Alamos
NATIONAL LABORATORY
EST. 1943



- SM works just fine, over wide energy range



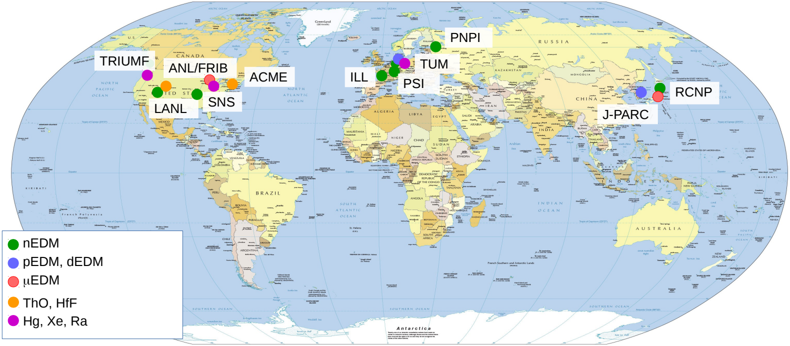
- neutrino masses

- baryogenesis

- dark matter

need new sources of CPV

EDM experiments worldwide



- current EDM bounds

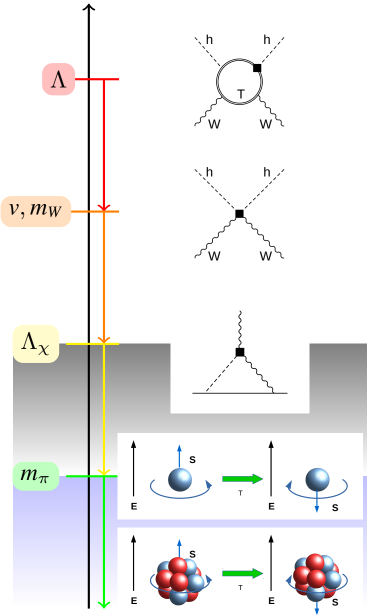
$$
\begin{aligned}
d_e &< 1.0 \cdot 10^{-16}\, e\ \text{fm} & \qquad d_n &< 1.8 \cdot 10^{-13}\, e\ \text{fm} \\
d_{^{225}\text{Ra}} &< 1.2 \cdot 10^{-10}\, e\ \text{fm} & \qquad d_{^{199}\text{Hg}} &< 6.2 \cdot 10^{-17}\, e\ \text{fm}
\end{aligned}
$$

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

EDM & pheno: some questions

1. complementarity/competition between collider and low-energy?
   - can EDMs/flavor physics guide direct collider searches?
2. what is the minimal set of observables to identify BSM CPV?
   - determine/exclude QCD $\bar{\theta}$ term?
   - disentangle key features of microscopic CPV mechanisms
3. what theoretical accuracy is necessary not to dilute EDM constraints?
   - Lattice QCD, chiral EFT, nuclear models, ...
4. can HL-LHC, next generation EDMs rule out EWBG?

CP violation in EFTs



new physics $\Lambda \gg v$

SM-EFT operators

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

non perturbative QCD

Chiral Effective Theory

strong nuclear interactions

Many body

CPV at colliders

SMEFT at dimension 6

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

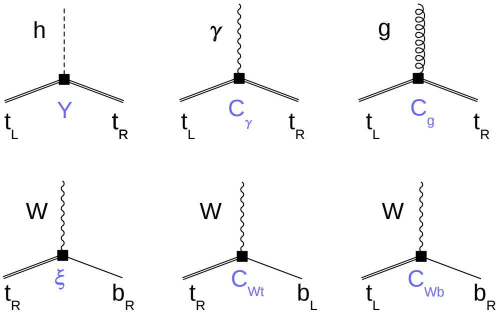
$(\bar LL)(\bar LL)$		$(\bar RR)(\bar RR)$		$(\bar LL)(\bar RR)$	
Q_{ll}	$(\bar l_p\gamma_\mu l_r)(\bar l_s\gamma^\mu l_t)$	Q_{ee}	$(\bar e_p\gamma_\mu e_r)(\bar e_s\gamma^\mu e_t)$	Q_{le}	$(\bar l_p\gamma_\mu l_r)(\bar e_s\gamma^\mu e_t)$
$Q_{qq}^{(1)}$	$(\bar q_p\gamma_\mu q_r)(\bar q_s\gamma^\mu q_t)$	Q_{uu}	$(\bar u_p\gamma_\mu u_r)(\bar u_s\gamma^\mu u_t)$	Q_{lu}	$(\bar l_p\gamma_\mu l_r)(\bar u_s\gamma^\mu u_t)$
$Q_{qq}^{(3)}$	$(\bar q_p\gamma_\mu \tau^I q_r)(\bar q_s\gamma^\mu \tau^I q_t)$	Q_{dd}	$(\bar d_p\gamma_\mu d_r)(\bar d_s\gamma^\mu d_t)$	Q_{ld}	$(\bar l_p\gamma_\mu l_r)(\bar d_s\gamma^\mu d_t)$
$Q_{lq}^{(1)}$	$(\bar l_p\gamma_\mu l_r)(\bar q_s\gamma^\mu q_t)$	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}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$		

Grzadkowski *et al.* ‘10

- full set of dimension 5 and 6 operator known

  Buchmuller & Wyler ‘86, Weinberg ‘89, de Rujula *et al.* ‘91, Grzadkowski *et al.* ‘10 . . .
- 53 (1350) CP-even, 23 (1149) CP-odd dimension 6 operators
- CPV in light quarks strongly suppressed at colliders, $\sim m_q/v$
- focus on top, gauge boson and Higgs operators

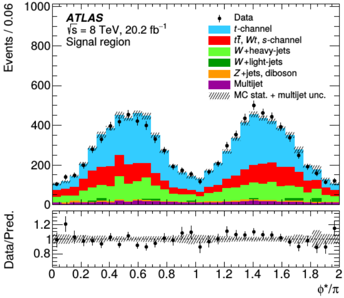
CPV in the top sector

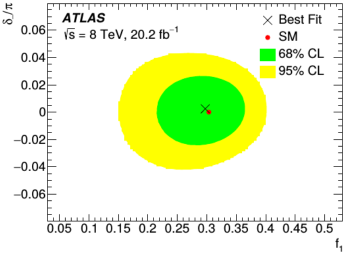


V. Cirigliano, W. Dekens, J. de Vries, EM, '16

- chirality flipping Yukawa (Y) and dipole (C_G, C_γ, C_{Wt}, C_{Wb}) operators & RH current (ξ)
- affect a variety of top and Higgs production/decay processes
  - $t\bar{t}$, $t\bar{t}\gamma$, $t\bar{t}Z$
  - $t\bar{t}h$
  - single top
  - $h \to \gamma\gamma$, $gg \to h$

Direct CPV probes in the top sector





ATLAS `arXiv:1707.05393`

LHC can probe naively T-odd correlations

- $\boldsymbol{\sigma}_t \cdot (\mathbf{p}_e \times \mathbf{p}_\nu)$ in single top production

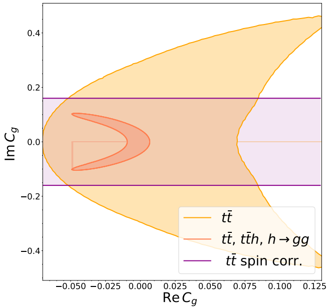
J. Boudreau,*et al* ‘13

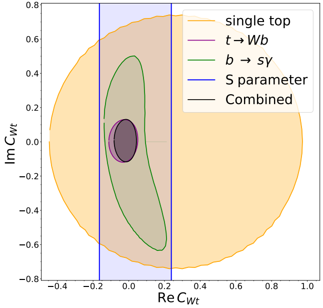
- spin correlations $(\boldsymbol{\sigma}_t \times \boldsymbol{\sigma}_{\bar{t}}) \cdot \mathbf{p}_t$ in $t\bar{t}$ production

W. Bernreuther, D. Heisler, Z.-G. Si, ‘15

- small backgrounds from absorptive SM diagrams

Direct CPV probes in the top sector

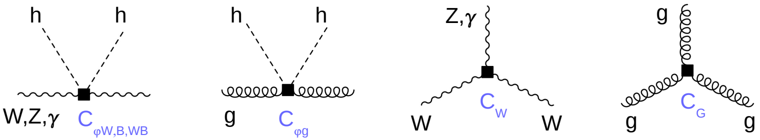




- total and differential t cross sections probe scales in 0.5-1 TeV range
- sensitive loop-level observables at colliders

  $gg \to h$, $h \to \gamma\gamma$, EW precision
- spin/momentum correlations clean probes of dim-6 CPV operators

  CMS, `arXiv:1601.01107`, ATLAS `arXiv:1707.05393`
- limited by statistics & systematics, could reach % level at HL-LHC

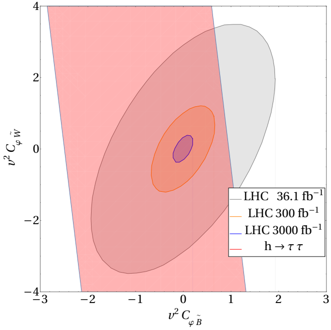


- four $\varphi^\dagger\varphi X^{\mu\nu}\tilde{X}_{\mu\nu}$ operators, two $XX\tilde{X}$ operators
- $C_{\tilde{W}}$ and $C_{\varphi W\tilde{B}}$ modify WWZ and WWγ couplings

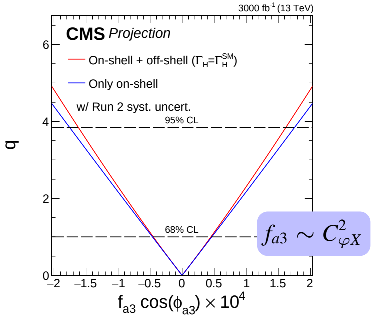
  already probed at LEP, in *WW* spin correlations
- $C_{\varphi,\tilde{X}}$ affect Higgs production and decay

  $h \to ZZ^* \to 4\ell$, $gg \to h$
- CPV probed in angular distributions in $pp \to h + 2j$, $pp \to Vh$, $h \to 4\ell$
- $C_{\tilde{G}}$ difficult to probe directly, $pp \to 3j$?

Higgs and gauge bosons



Bernlochner *et al*, '19, Cirigliano *et al*, '19

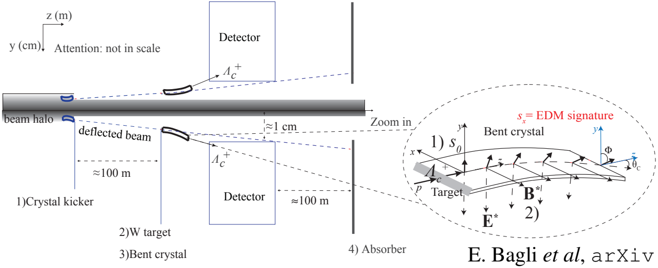


HL-LHC report `arXiv:1902.00134`

- current limits $\Lambda \sim v$
- HL-LHC will improve by a factor of 10

start pushing into TeV scale

EDMs of heavy quarks and leptons



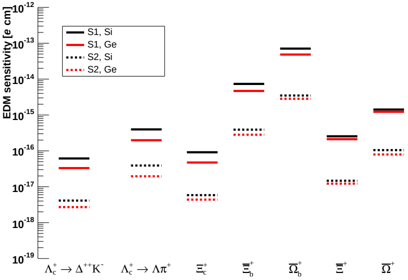
E. Bagli *et al*, arXiv:1708.08483

- Belle II will improve τ EDM by a factor of 40

$$-2.2 \cdot 10^{-4} < d_\tau < 4.5 \cdot 10^{-4}\, e\,\text{fm} \rightarrow 10^{-5}\, e\,\text{fm}$$

- new ideas to measure EDMs of c and b baryons at LHCb
- measure spin precession of Λ_c channeled in bent crystals
- first direct probe of heavy baryon EDMs

EDMs of heavy quarks and leptons



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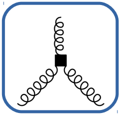
CPV at low-energy

Low-energy EFT for flavor-diagonal CPV

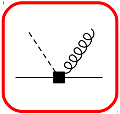
- one dim-4 operator: QCD $\bar{\theta}$ term

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

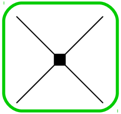
- 9 (+ 10 w. strangeness) hadronic operators @ $\mathcal{O}(v^2/\Lambda^2)$:



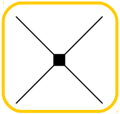
gluon CEDM
$C_{\tilde{G}}$



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



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

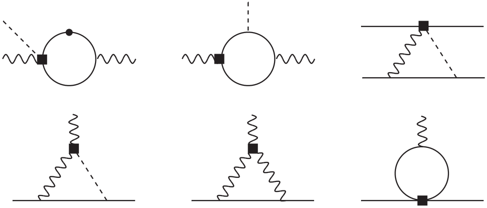


LR LR 4-quark
$\Sigma_{ud,us}^{(1,8)}$, $\Sigma_{us,S}^{(1,8)}$

- leptonic operators

$$\mathcal{L} = \sum_{\ell=e,\mu,\tau} \frac{m_l}{v^2} \tilde{c}_\gamma^{(\ell)} \bar{\ell} \sigma^{\mu\nu} \gamma^5 \ell \, F_{\mu\nu} + C_S \bar{q} q \, \bar{\ell} i \gamma_5 \ell + \dots$$

Running to low energy



- one-loop matching and running of SMEFT onto low-energy known

W. Dekens and P. Stoffer, '19

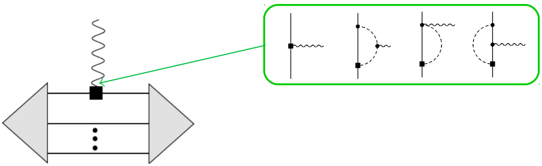
- Higgs operators contribute at one EW loop

$$\tilde{c}_\gamma^{(e)} = \left(-1.4 \mathrm{Im}\, C_{\varphi\tilde{B}} - 1.5 \mathrm{Im}\, C_{\varphi\tilde{W}} + 3.3 \mathrm{Im}\, C_{\varphi\tilde{W}B} + 0.14 \mathrm{Im}\, C_{\tilde{W}}\right) \cdot 10^{-2}$$

- top operators at one/two-loop

$$\tilde{c}_\gamma^{(e)} = (3.8 \mathrm{Im}\, C_{\gamma t} - 4.4 \mathrm{Im}\, C_{Wt} + 0.4 \mathrm{Im}\, Y) \cdot 10^{-4}$$
$$C_{\tilde{G}} = -8.8 \cdot 10^{-4}\, \mathrm{Im}\, C_{gt}$$

From quarks to nucleons



- only a handful of operators at LO in chiral/pionless EFT

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

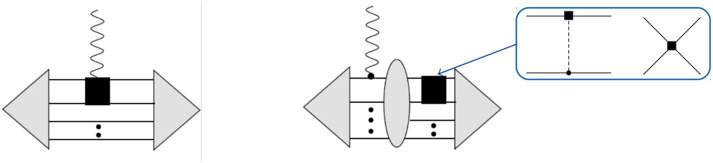
$\bar{d}_n, \bar{d}_p$ neutron & proton EDM,

$\bar{g}_0, \bar{g}_1$ pion loop to nucleon & proton EDMs,

- determine EDMs of nucleons, light nuclei,
  Schiff moments of heavy nuclei

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

From quarks to nucleons



- only a handful of operators at LO in chiral/pionless EFT

$$\mathcal{L}_{\not{T}}^{(2)} \;=\; C({}^{2S+1}S_J, {}^{2S'+1}P_J)\, (N^T P_{{}^{2S+1}S_J} N)^\dagger\, N^T P_{{}^{2S'+1}P_J} N$$

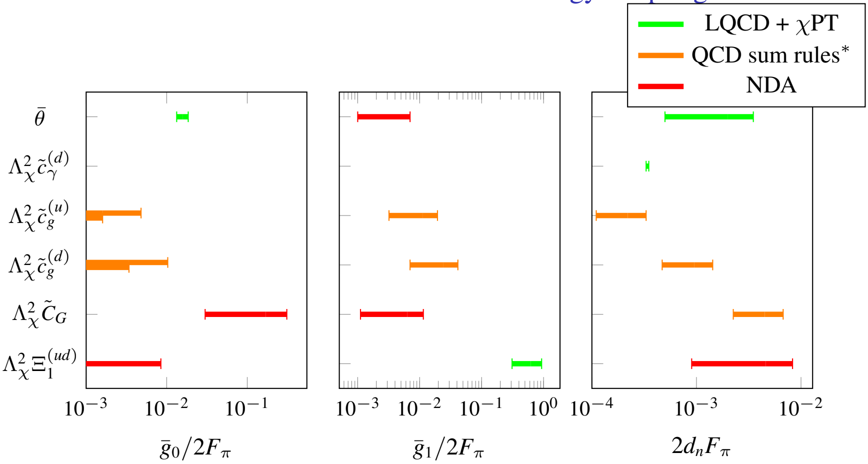
$\bar{g}_0, \bar{g}_1$ pion-range TV potential

C short-range TV potential in 5 S-P transition channels

- determine EDMs of nucleons, light nuclei,
  Schiff moments of heavy nuclei

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

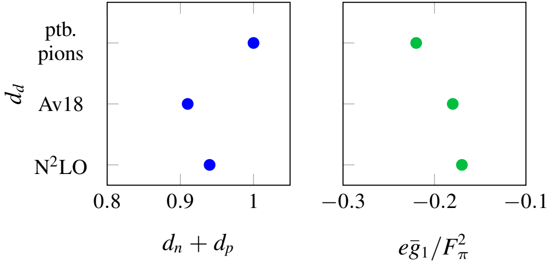
Status of low-energy couplings



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

- large theory error on LECs from most operators, but strong LQCD effort on $d_{n,p}$, $\bar{g}_{0,1}$ — see Boram Yoon's talk
- nucleon-nucleon not yet in reach

Nuclear EDMs as “chiral filters”



- nuclear EDMs sensitive to one- and two-body CPV couplings

$$d_A = \alpha_n(A)d_n + \alpha_p(A)d_p + a_0(A)e\frac{\bar{g}_0}{F_\pi^2} + a_1(A)e\frac{\bar{g}_1}{F_\pi^2} + \dots$$

- different nuclei have different sensitivities to $\bar{g}_{0,1}$, C
  e.g. $a_0(d) = 0$
- d_d: good agreement between different pheno & chiral nuclear potentials
  C. P. Liu and R. Timmermans, ‘05; J. de Vries *et al*, ‘11; J. Bsaisou *et al*, ‘13, J. Bsaisou *et al*, ‘15;
  N. Yamanaka and E. Hiyama, ‘15, M. Viviani and A. Gnech, ‘19
- larger uncertainties in the three-nucleon system

J. de Vries, A. Gnech, S. Shain, ‘20

EDMs of diamagnetic atoms

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

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

- EDM depends on nuclear Schiff moment

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

- π-N contribs. affected by large theory uncertainties
- no *ab initio* calculations at the moment

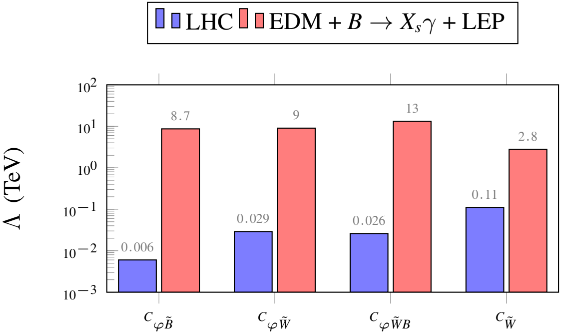
hard calculations!

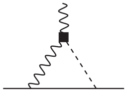
- single nucleon contrib. know at 5% accuracy

V. F. Dmitriev and R. A. Senkov, '03

EDM bounds on top and Higgs CPV

Constraints on weak gauge-Higgs operators



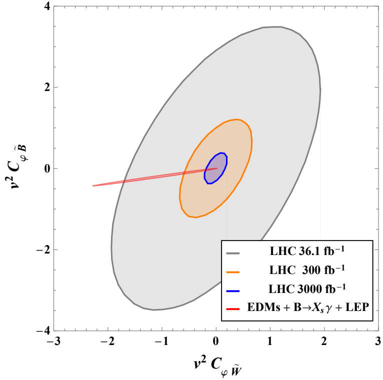


$$d_e = \frac{m_e}{v^2}\tilde{c}_\gamma^{(e)} < 1.0 \cdot 10^{-16}\ e\ \text{fm}$$

$$C_X = \frac{1}{(4\pi\Lambda)^2}$$

- low-energy observables not affected by large theory uncertainties
- eEDM dominates single coupling analysis
- collider not competitive

Constraints on weak gauge-Higgs operators

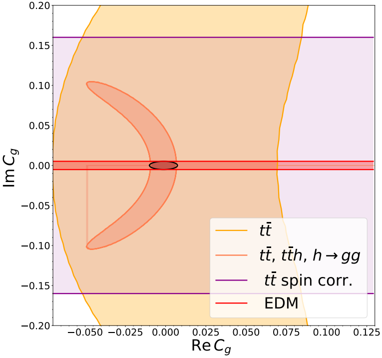


marginalized

- EDMs constrain 2 directions
  d_n, d_{Hg} and d_{Ra} largely degenerate
- need LEP, $B \to X_s\gamma$ or LHC to close free directions

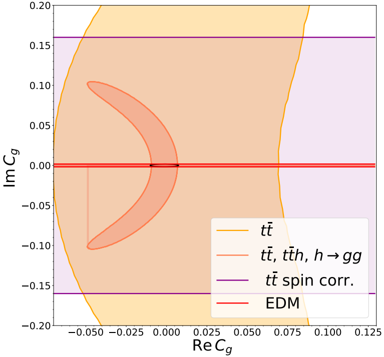
strong correlations to avoid EDMs

EDM bounds on top chromo-dipole moment



- strong cancellations between Weinberg and qCEDM contribs. to d_n with current theory errors
- no limit from d_n, $|\mathrm{ImC_g}| < 5 \cdot 10^{-3}$ from d_e

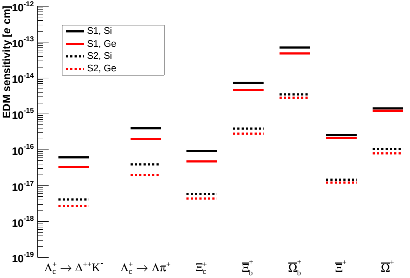
EDM bounds on top chromo-dipole moment

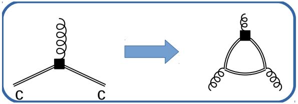


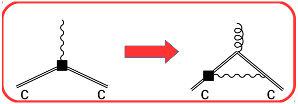
$$|\mathrm{Im}C_g| < 0.002$$
$$\Lambda = 6.0\ \mathrm{TeV}$$

- strong cancellations between Weinberg and qCEDM contribs. to d_n with current theory errors
- no limit from d_n, $|\mathrm{ImC_g}| < 5 \cdot 10^{-3}$ from d_e
- reducing error on Weinberg ME from 90% to 50% has dramatic effects

EDMs of charmed baryons







E. Bagli *et al*, `arXiv:1708.08483`

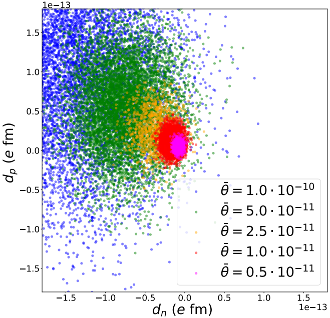
- charmed baryon EDMs could originate from variety of sources
- charm (chromo-)EDM induces Weinberg three-gluon at two (one) loop, severely constrained by d_n

$$|\tilde{d}_c| \lesssim 1.0 \cdot 10^{-22}\,\text{cm}, \qquad |d_c| \lesssim 1.5 \cdot 10^{-21}\,e\,\text{cm}$$

F. Sala, '13; H. Gisbert and J. Ruiz Vidal, '20

Disentangling CPV sources at low-energy

Disentangling CPV mechanisms: $\bar{\theta}$ term



$$d_n = -(1.5 \pm 0.7) \cdot 10^{-3}\, \bar{\theta}\, e\, \text{fm}$$
$$d_p = (1 \pm 1) \cdot 10^{-3}\, \bar{\theta}\, e\, \text{fm}$$

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

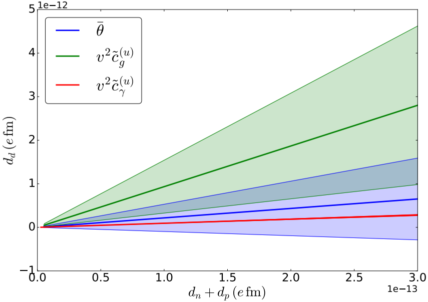
Q1: is a QCD $\bar{\theta}$ term?

- d_n and d_p can rule out $\bar{\theta}$

need to reduce LQCD uncertainties!

- light nuclear/atomic EDMs can show source-specific patterns
- $\mathcal{O}(20\%)$ uncertainties sufficient to discriminate!

Disentangling CPV mechanisms: $\bar{\theta}$ term



$d_d \gg d_n + d_p$ isospin-breaking CPV

$d_d \sim d_n + d_p$ QCD $\bar{\theta}$ term

$d_d = d_n + d_p$ qEDM

but swamped by th. uncertainties

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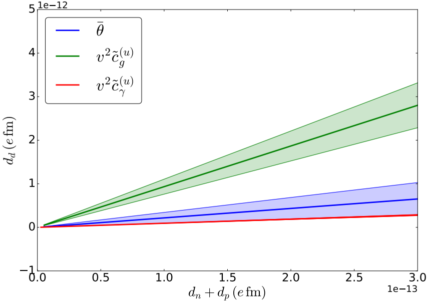

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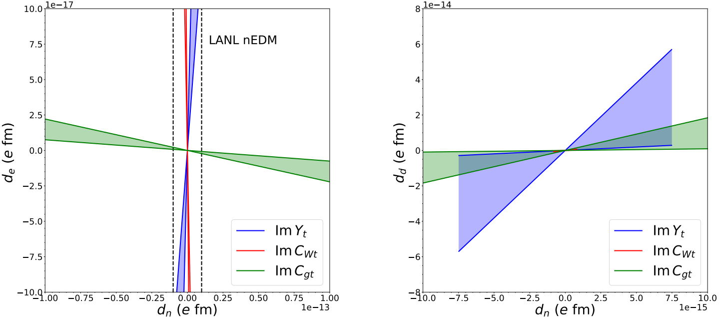
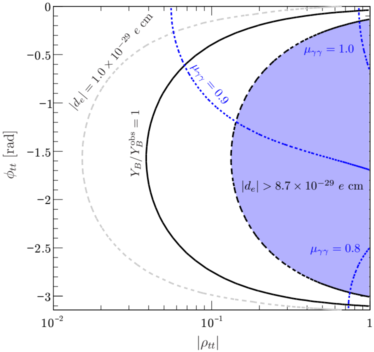
Disentangling CPV mechanisms: top couplings



- observation of d_e and d_n in next generation of experiments: no CPV top Yukawa or top weak dipole moment
- d_e and large $d_d \sim 5 d_n$ could signal Y_t

need large number of sensitive EDM experiments
and precise nuclear/hadronic theory!

EDMs and EW Baryogenesis

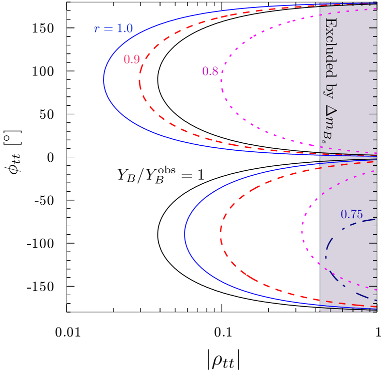


2HDM with CPV top Yukawa ρ_{tt}

K. Fuyuto, W.-S. Hou, E. Senaha, '17

- EDMs provide a severe challenge
- need cancellations between large CPV couplings responsible for EWBG & small 1st generation couplings
- can be falsified with improved neutron/nuclear EDMs

EDMs and EW Baryogenesis



2HDM with CPV top Yukawa ρ_{tt}
avoid eEDM with electron ρ_{ee}

$$\mathrm{Im}\,\rho_{ee} = r\frac{y_e}{y_t}\mathrm{Im}\,\rho_{tt}$$

K. Fuyuto, W.-S. Hou, E. Senaha, ‘19

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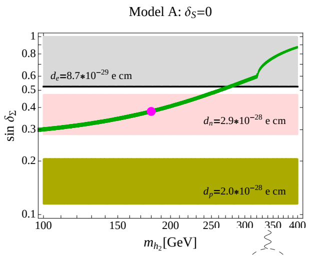
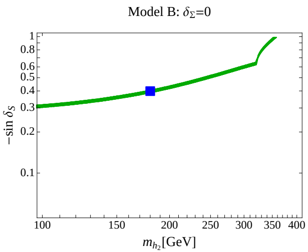
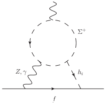
EDMs and EW Baryogenesis





scalar triplet Σ



scalar singlet S

S. Inoue, G. Ovanesyan, M. J. Ramsey-Musolf, '15

- EWBG requires new light dofs to trigger first order phase transition
- CP asymmetry cannot be studied in SMEFT

J. de Vries, M. Postma, J. van de Vis, G. White, '17

- possible to hide CPV in new sector with very small couplings to SM

Conclusion

CPV at colliders

- HL-LHC will reach % level accuracy in CP-sensitive observables
- LHCb, Belle 2 will explore CPV in heavy quark/leptons sector
- naively less sensitive than d_e, d_n,
  but study cancellation regions, free directions

Lattice QCD

- bring theoretical error on d_n, d_p, $\bar{g}_{0,1}$ under control
- longer time-frame for four-nucleon operators

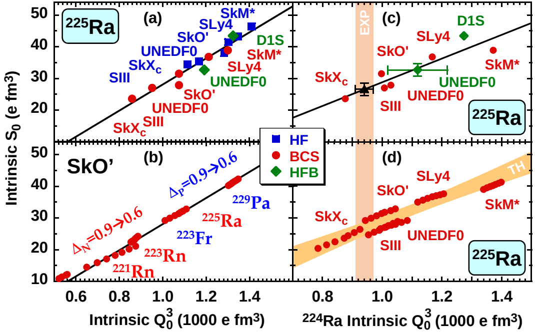
direct calculations of light-nuclear EDMs?
TV *NN* scattering in S-P transitions?

Nuclear theory

- investigate theory error in $A \geq 3$, push *ab initio* to larger A
- can *ab initio* methods help the calculation of Schiff moments?

Backup

EDMs of diamagnetic atoms

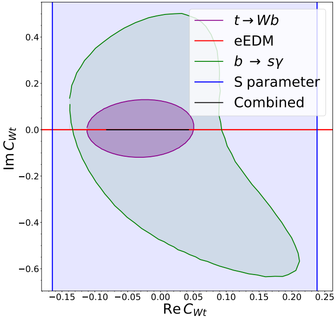


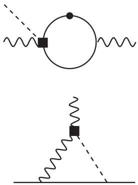
J. Dobaczewski, J. Engel,
M. Kortelainen, P. Becker, '18

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

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

EDM bounds on the top weak-dipole C_{Wt}





$$|\mathrm{Im} C_{Wt}| < 1.5 \cdot 10^{-3}$$

- very strong constraints from d_e even at two-loop weak running!
- constraints essentially free on nuclear/hadronic uncertainties