Disentangling physics beyond the Standard Model with EDMs

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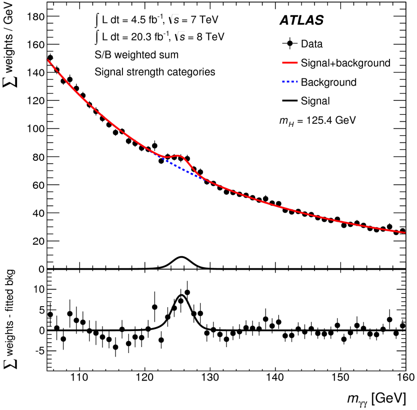
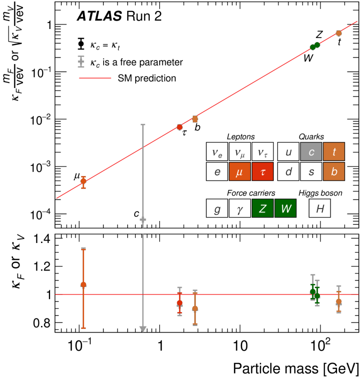
The 5th Workshop on Searches for a Neutron Electric Dipole Moment
November 6^{th}, 2023, Santa Fe.

Introduction





The Standard Model of Particle Physics

- describes nature in a economic and elegant way
- validated over a wide variety of scales
- last missing ingredient was discovered at LHC, and looks SM-like

The matter-antimatter asymmetry

$$\frac{n_B}{n_\gamma} = 6 \cdot 10^{-10}$$

- why is there more matter than antimatter?

Sakharov conditions

- C and CP violation
- baryon number violation
- deviation from thermal equilibrium

The matter-antimatter asymmetry

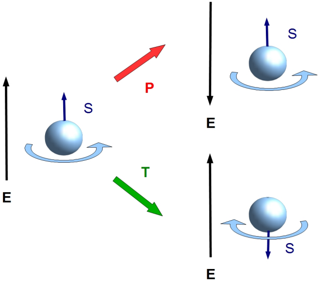
$$\frac{n_B}{n_\gamma} = 6 \cdot 10^{-10}$$

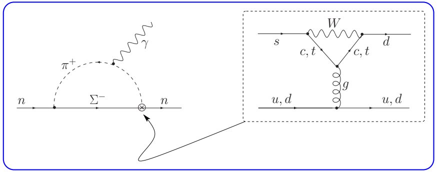
- why is there more matter than antimatter?

Sakharov conditions

- C and CP violation — × yes, but not enough
- baryon number violation — ✓
- deviation from thermal equilibrium — × not for $m_H = 125$ GeV

Electric dipole moments





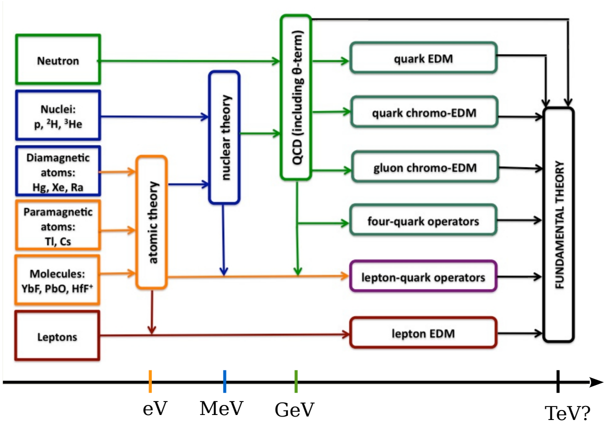
- signal of T and P violation (CP)
- insensitive to CP violation in the SM
- BSM CP violation needed for baryogenesis

neutron $d_n|_{\mathrm{SM}} \sim 10^{-32}\, e\,\mathrm{cm}$ $\ll$ $|d_n|_{\mathrm{exp}} < 1.8 \cdot 10^{-26}\, e\,\mathrm{cm}$

M. Pospelov and A. Ritz, '05; C. Y. Seng, '14; nEDM Collaboration, '20

large window & strong motivations for new physics!

EDMs and BSM physics



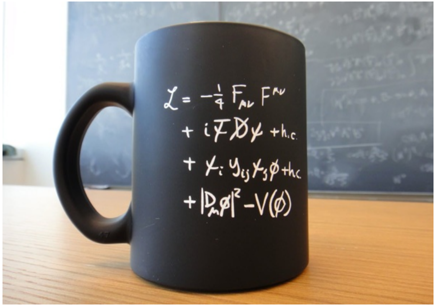
Non-zero EDM in **any** system will be revolutionary

thanks to J. de Vries

- different systems crucial to pinpoint BSM
- need atomic, nuclear, hadronic theory to identify CPV at quark level
- need to correlate with flavor physics and LHC to identify BSM

CP violation in the SM(EFT)

CP violation in the SM(EFT)



- two CPV sources in SM

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

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}	$(\bar l_p \sigma^{\mu\nu} e_r)\tau^I \varphi W^I_{\mu\nu}$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar l_p \gamma^\mu l_r)$
$Q_{\varphi\widetilde G}$	$\varphi^\dagger\varphi\, \widetilde G^A_{\mu\nu} G^{A\mu\nu}$	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}	$(\bar q_p \sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu \varphi)(\bar u_p \gamma^\mu d_r)$

$(\bar LL)(\bar LL)$		$(\bar RR)(\bar RR)$		$(\bar LL)(\bar$	
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}	$(\bar l_p \gamma_\mu l_r$
$Q_{qq}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar q_s \gamma^\mu q_t)$	Q_{uu}	$(\bar u_p \gamma_\mu u_r)(\bar u_s \gamma^\mu u_t)$	Q_{lu}	$(\bar l_p \gamma_\mu l_r)(u_s \gamma^\mu u_t)$
$Q_{qq}^{(3)}$	$(\bar q_p \gamma_\mu \tau^I q_r)(\bar q_s \gamma^\mu \tau^I q_t)$	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}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$

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

Grzadkowski *et al.* ‘10

- two CPV sources in SM

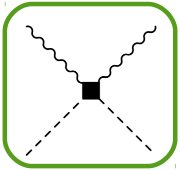
$$\mathcal{L}^{(4)}_{\rm CPV} = -\theta \frac{g_s^2}{64\pi^2}\varepsilon^{\alpha\beta\mu\nu} G_{\mu\nu} G_{\alpha\beta} + \bar u^i_L \left[V_{\rm CKM}\right]_{ij} \gamma^\mu d^j_L W_\mu$$

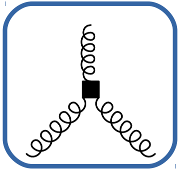
- 53 (1350) CP-even, 23 (1149) CP-odd dimension-6 operators ($\mathcal{O}(v^2/\Lambda^2)$)

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

- number flavor-diagonal CPV operators still limited

CP-violation in SMEFT: Higgs-gauge operators

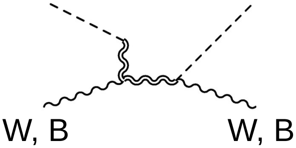


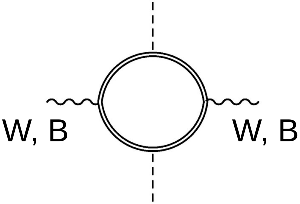


$$\mathcal{L} = -g^2 C_{\varphi\tilde{W}}\, \varphi^\dagger\varphi\, \tilde{W}^i_{\mu\nu} W_i^{\mu\nu} - g'^2 C_{\varphi\tilde{B}}\, \varphi^\dagger\varphi\, \tilde{B}_{\mu\nu} B^{\mu\nu} - gg' C_{\varphi\tilde{W}B}\, \varphi^\dagger\tau^i\varphi\, \tilde{W}^i_{\mu\nu} B^{\mu\nu} + \frac{C_{\tilde{W}}}{3}\,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

- $C_{\varphi\tilde{W}}$, $C_{\varphi\tilde{B}}$, $C_{\varphi\tilde{W}B}$ $C_{\tilde{W}}$ are CP-odd partners of operators contributing to EWPO
- $C_{\varphi\tilde{W}B}$, $C_{\tilde{W}}$: anomalous $WW\gamma$ and WWZ couplings, WZ, WW production at LHC
- $C_{\varphi\tilde{W}}$, $C_{\varphi\tilde{B}}$, $C_{\varphi\tilde{W}B}$: Higgs production and decay ($h \to \gamma\gamma$, $h \to \gamma Z$, $h \to ZZ^*$, $h \to WW^*$ ...)
- $C_{\varphi\tilde{G}}$: corrections to $gg \to h$, $h \to gg$

Higgs-gauge operators





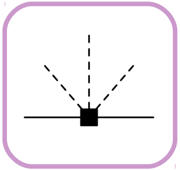
- induced at tree level in models with new vector bosons
- but more often at one loop

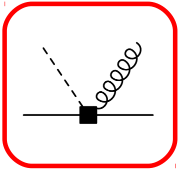
$>$ 2 families of vector-like fermions, vector-like fermions + scalars

J. de Blas, J. C. Criado, M. Pérez-Victoria, J. Santiago, '17; G. Guedes, P. Olgoso, J. Santiago, '23

- correlated with CP-even corrections to EW propagators

CP-violation in SMEFT: chiral-breaking bilinears





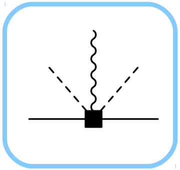
$$\mathcal{L} = \left(\varphi^\dagger \varphi\right) \left[\bar{q}_L C_{u\varphi} u_R \tilde{\varphi} + \bar{q}_L C_{d\varphi} d_R \varphi\right]$$

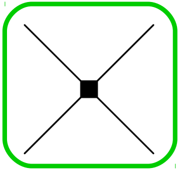
$$+ \bar{q}_L \sigma^{\mu\nu} \left(C_{uG} G_{\mu\nu} + C_{uW} W_{\mu\nu} + C_{uB} B_{\mu\nu}\right) u_R \tilde{\varphi} + \bar{q}_L \sigma^{\mu\nu} \left(C_{dG} G_{\mu\nu} + C_{dW} W_{\mu\nu} + C_{dB} B_{\mu\nu}\right) d_R \varphi$$

- 6 flavor-diagonal non-standard quark Yukawas

  directly testable in Higgs properties $pp \to tth$, $h \to bb$, ...
- often generated at tree-level — vector-like quarks, 2 Higgs doublet model ...
- 6 gluon + 6 photon + 6 Z quark dipole couplings
  typically arise at one-loop

CP-violation in SMEFT: Right-handed charged current & four-fermion operators





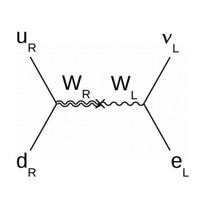
$$\mathcal{L} = \tilde{\varphi}^\dagger D_\mu \varphi \, \bar{u}_R \gamma_\mu \left[C_{\varphi ud}\right] d_R \to \frac{v^2}{2} g \, \bar{u}_R \gamma^\mu \left[C_{\varphi ud}\right] d_R W_\mu$$

- gives rise to a right-handed CKM matrix, with 9 independent phases
- coupled with SM left-handed CKM $\Longrightarrow$ low-energy $\Delta F = 0$, $\Delta F = 1$ CP-violating processes

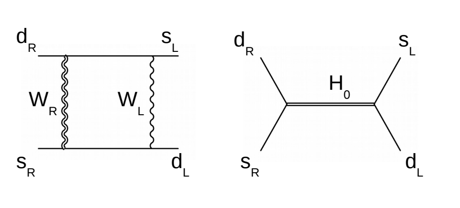
$$\mathcal{L} = \left[C^{(1)}_{quqd}\right]_{prst} \bar{q}^i_{Lp} u_{Rs} \, \bar{q}^j_{Ls} d_{Rt} + \left[C^{(1)}_{Qu}\right]_{prst} \bar{q}_{Lp} \gamma^\mu q_{Lr} \bar{u}_{Rs} \gamma_\mu u_{Rt} + \left[C^{(1)}_{Qd}\right]_{prst} \bar{q}_{Lp} \gamma^\mu q_{Lr} \bar{d}_{Rs} \gamma_\mu d_{Rt} + (1 \to 8)$$

- the scalar op. $C^{(1)}_{quqd}$ is always CP-odd, vector operators $p = t$, $r = s$, $p \neq r$

Right-handed charged current & four-fermion operators



$$\sim \frac{m_{W_L}^2}{m_{W_R}^2} \frac{\xi}{1+\xi^2} \sin\alpha$$



$$\sim \frac{m_{W_L}^2}{m_{H_0}^2} Y^2$$

Left-right symmetric model

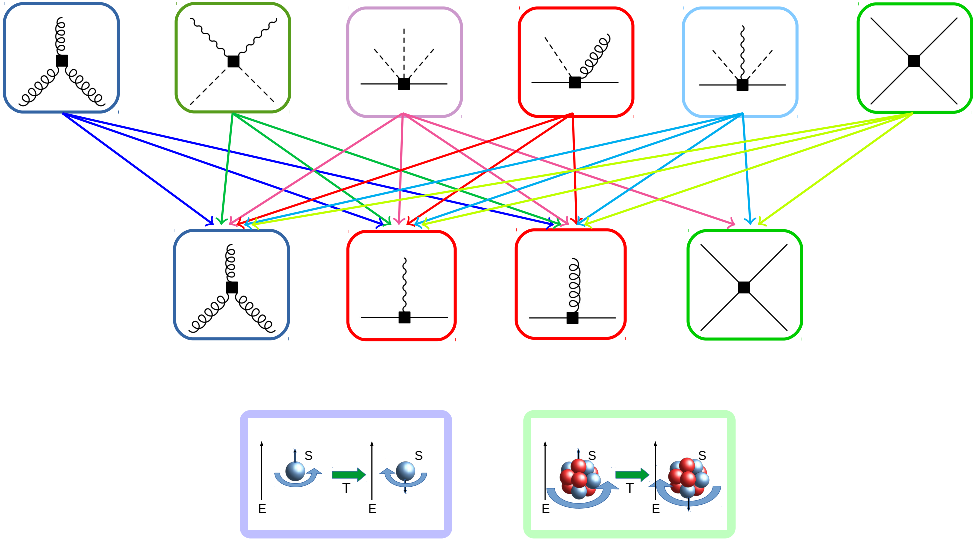
- extend SM symmetry to $SU(2)_L \times SU(2)_R \times U_{B-L}(1)$

  $\Longrightarrow$ heavy gauge boson (W_R) and Higgs fields (H_0, $H^{\pm}$)
- induces $C_{\varphi ud}$ prop. to W_L-W_R mixing α,

  EDMs correlated with direct CPV in kaon decays (ϵ'/ϵ)
- and $C_{quqd}^{(1,8)}$, $C_{qd}^{(1,8}$, $C_{qu}^{(1,8)}$ via heavy Higgs or W_R exchange

  correlated with $\Delta F = 2$ observables Δm_{B_d}, Δm_{B_s}, ϵ_K

Connecting SMEFT CP-violation to EDMs



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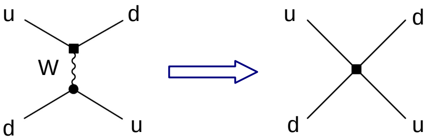


- CPV in SMEFT involves Higgs, heavy gauge bosons, and heavy quarks need to integrate them out!
- full one-loop matching between SMEFT and LEFT ✓

W. Dekens and P. Stoffer, '19

- LL running in SMEFT and LEFT ✓

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

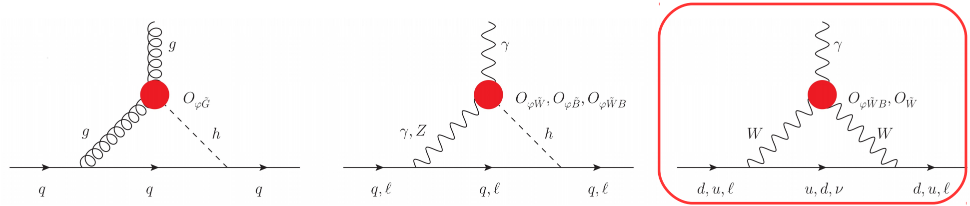
Tree level path:

- applies to all operators with light fermions or gluons

gluon CEDM, light quark EDM, CEDM and Yukawa, RHCC & four-fermion

- might not be the most efficient path (e.g. when involving small SM couplings)

Connecting SMEFT CP-violation to EDMs



One loop path:

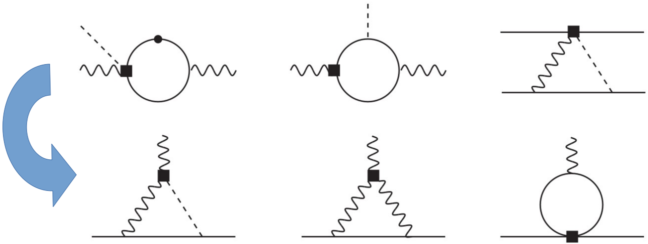
- applies to electroweak Higgs-gauge operators, four-fermion operators with 2 heavy quarks
- typical suppression 10^{-2} - 10^{-3}
- e.g. $C_{\varphi\tilde{W}}$, $C_{\varphi\tilde{W}B}$, $C_{\varphi\tilde{B}}$ and $C_{\tilde{W}}$ $\Longrightarrow$ lepton & quark EDM @ 1 EW loop

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

- gluonic operators $\Longrightarrow$ qCEDM and gCEDM @ $\mathcal{O}(\alpha_s)$
- preserve link to other low-energy observables. E.g. $C_{\varphi\tilde{W}B}$ and $C_{\tilde{W}}$ match on flavor-changing dipoles

correlations with $B \to X_s\gamma$, $K_L \to \pi^0 e^+ e^-$

Connecting SMEFT CP-violation to EDMs



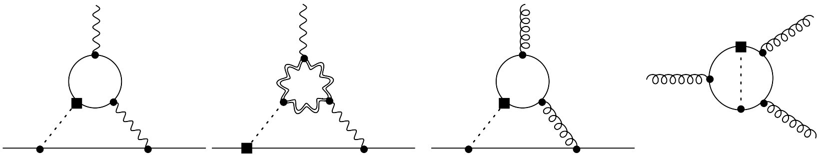
Two loop paths:

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

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

V. Cirigliano, W. Dekens, J. de Vries, EM, '16; K. Fuyuto and M. R. Musolf, '17

Connecting SMEFT CP-violation to EDMs



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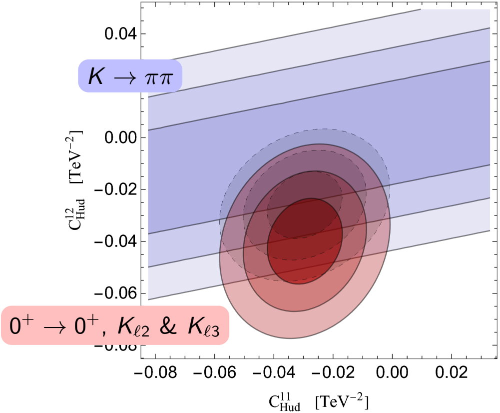
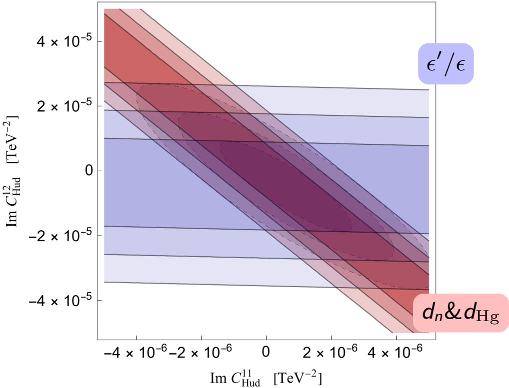
V. Cirigliano, W. Dekens, J. de Vries, EM, '16; K. Fuyuto and M. R. Musolf, '17

- for light-quark Yukawa, two-loop path is more efficient than tree level

CPV in the SMEFT: EDMs vs high-energy

Tree level path. Right handed charged currents



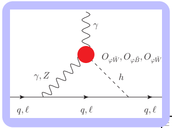


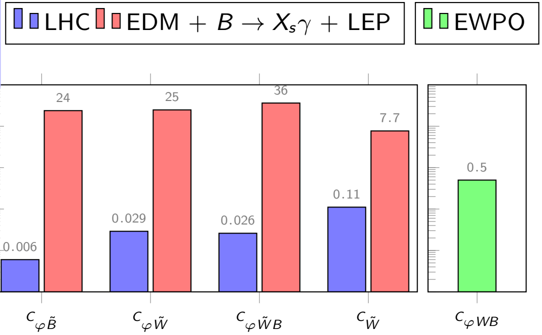
V. Cirigliano *et al*, '23

- RHCC are a popular explanation of tensions in β decay experiments
- pointing to new physics scale of $\Lambda \sim 10$ TeV
- RHCC induce nEDM, Hg EDM and ϵ'/ϵ at tree level

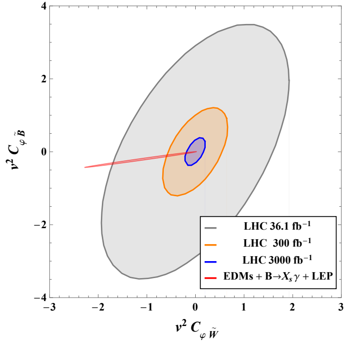
$\Lambda \gtrsim 200$ TeV!

One loop path. Higgs-gauge operators





V. Cirigliano, A. Crivellin, W. Dekens, J. de Vries, M. Hoferichter, EM, ‘19

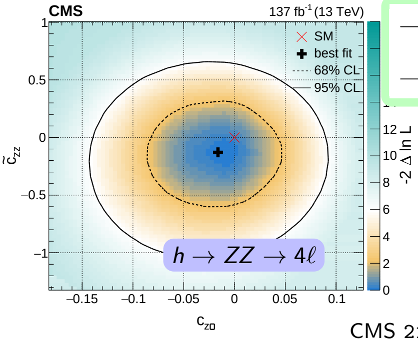


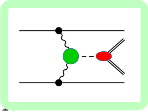
LHC projections of Bernlochner *et al*, ‘18

- eEDM dominates single coupling analysis
- hadronic 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

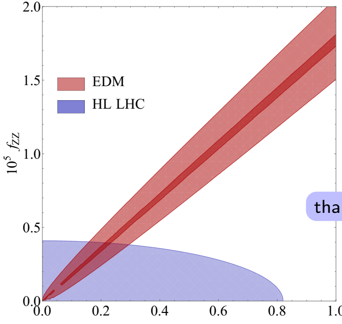
strong correlations to avoid EDMs

Constraints on weak gauge-Higgs operators





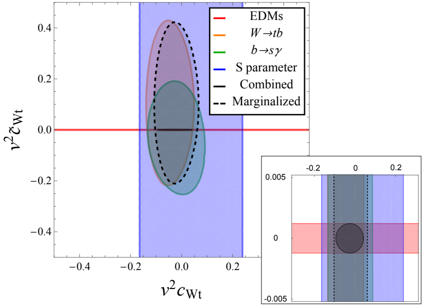
CMS 2104.12152



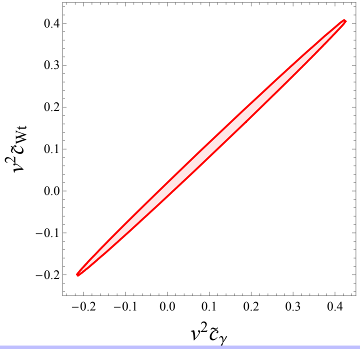
HL LHC projections from 2205.07715

- since then, a good number of dedicated CPV@LHC analyses came out with similar sensitivity $\Lambda \sim 100$ GeV
- HL-LHC can play a role to close free directions
- expect correlated signals in ZZ, $\gamma\gamma$, γZ

Two-loop path. Top dipole couplings



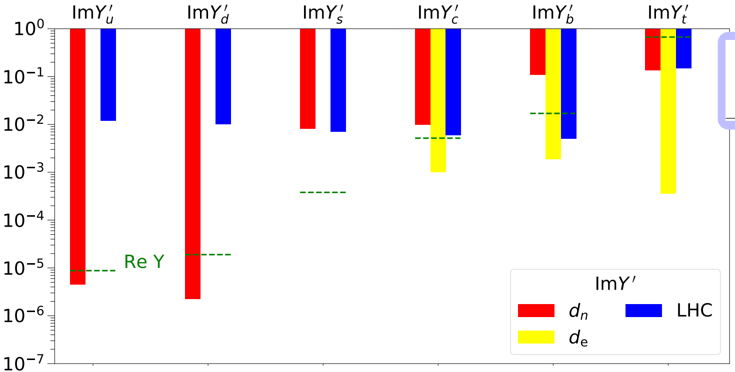
V. Cirigliano, W. Dekens, J. de Vries, EM, '16

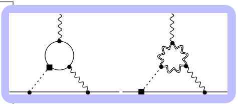


marginalized over 5 chiral breaking t ops

- γ and W dipole have sizable mixing with lepton EDMs
- strong constraints from eEDM, not affected by th. uncertainties
- free direction in $\tilde{c}_\gamma$-$\tilde{c}_{Wt}$ plane closed by CPV in single top
- CP-even bounds typically a factor of 100 weaker than CP-odd

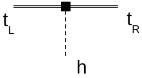
Two-loop path. CP-odd Yukawa couplings



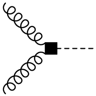


- neutron EDM best probe of the imaginary part of u, d and s Yukawa couplings
- eEDM wins on heavy quarks
- nEDM probes light quark Yukawas as small as SM Yukawas (not directly accessible in any CP-even probe!)

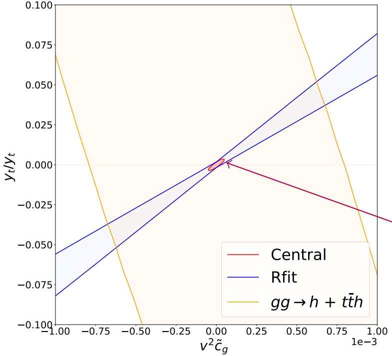
The role of theory uncertainties: top-Higgs and Higgs-gluon operators

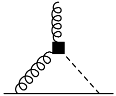


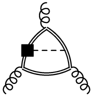
$(y_t + i\tilde{y}_t)\bar{t}_L t_R h$



$\tilde{c}_{gg} vhG\tilde{G}$





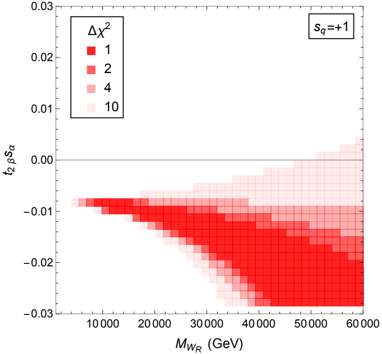


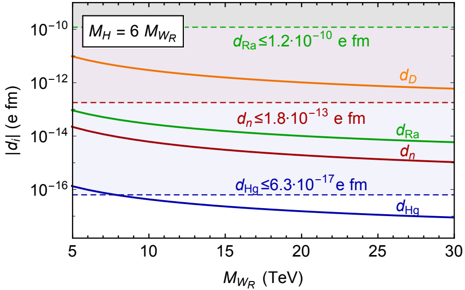
one/two-loop running to gCEDM, qCEDM

- affect $gg \to h$, $pp \to t\bar{t}$ and $pp \to t\bar{t}h$
- naively, eEDM, nEDM and Hg outperform direct constraints
- bounds depend strongly on treatment of the large hadronic uncertainties
- same conclusions for the $\bar{t}tg$ dipole interactions

need improved LQCD & nuclear theory calculations

EDMs in the Left-Right Symmetric Model



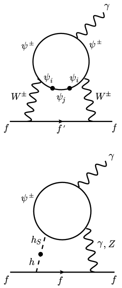


W. Dekens, L. Andreoli, J. de Vries, EM, F. Oosterhof, '21; M. J. Ramsey-Musolf and J. C. Vasquez, '21

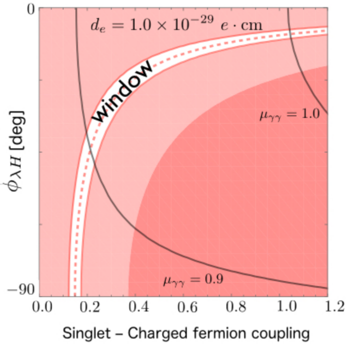
EFT analysis easily generalized to models, e.g. Left-Right Symmetric Model

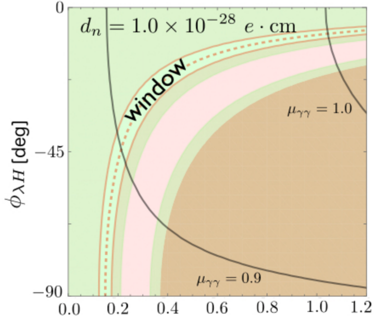
- $\sim$ few TeVs direct limits on W_R, H
- EDMs & $\Delta F = 2$ at tree and 1-loop level
- cancellations in contribs. to K-$\bar{K}$ oscillations $\Longrightarrow$ low-mass W_R still allowed
- "cancellation region" probed by next generation of EDMs, in particular atomic EDMs

Low-energy CPV and EWBG



thanks to K. Fuyuto





- eEDM, nEDM put simplest EWBG models under pressure
- w. multiple CP phases, can evade EDM bounds and are testable in near future

K. Fuyuto, J. Hisano, E. Senaha, ‘15, K. Fuyuto, W.-S. Hou, E. Senaha, ‘19

- identify signatures of EWBG at LHC and future colliders

Snowmass white paper `arXiv:2203.10184`, M. J. Ramsey-Musolf, ‘19

- improve calculations of CP asymmetries

V. Cirigliano, C. Lee, S. Tulin, ‘11

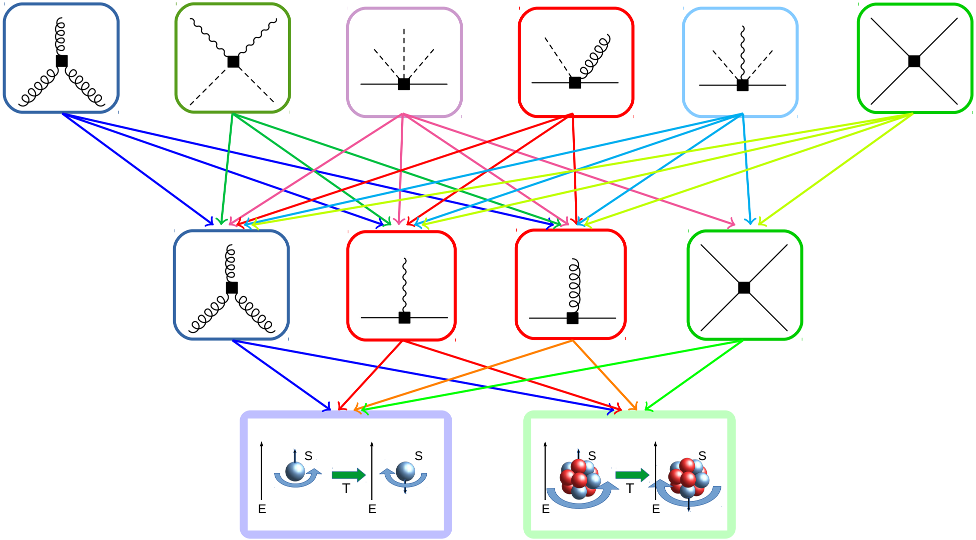
Preliminary Summary

1. in a single coupling analysis, eEDM and nEDM dominate most of the flavor-diagonal CPV parameters in SMEFT
2. theory errors weaken the limits on some hadronic operators

   t and b Yukawas and chromo-EDMs, pure glue operators
3. beyond single coupling, EDMs of course will leave free directions,
   . . . but enforce correlations between different SMEFT coefficients

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

Patterns of CP violation at low-energy



Low-energy EFT for flavor-diagonal CPV

What's the max. amount of info we can extract from EDM experiments?

- in the leptonic and semileptonic sector

$$\mathcal{L} = \frac{e}{2} m_\ell \tilde{c}_\ell \bar{\ell} \sigma^{\mu\nu} \gamma_5 \ell \, F_{\mu\nu} - \frac{G_F}{\sqrt{2}} \Big(\bar{\ell}\ell \bar{N} i\gamma_5 (C_P^{(0)} + C_P^{(1)} \tau_3) N + \bar{\ell} i \gamma_5 \ell \, \bar{N} (C_S^{(0)} + C_S^{(1)} \tau_3) N \Big)$$

$$\Longrightarrow d_e \sim e m_e \tilde{c}_e = 1.7 \cdot 10^{-22} (v^2 \tilde{c}_e) \, e\,\mathrm{cm}$$

- the dependence of $\tilde{c}_\ell$, $C_P^{(0,1)}$, $C_S^{(0,1)}$ on SMEFT operators is well understood ✓

Low-energy EFT for flavor-diagonal CPV

What's the max. amount of info we can extract from EDM experiments?

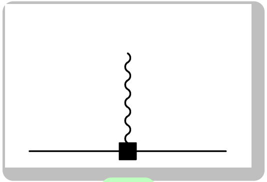
- in the hadronic sector, at the single nucleon level we can generate $N\pi$ and $N\gamma$ couplings

$$\mathcal{L}^N = \bar{N}\left(\bar{d}_n \frac{1-\tau_3}{2} + \bar{d}_p \frac{1+\tau_3}{2}\right) \boldsymbol{\sigma}\cdot \mathrm{E} N - \frac{\bar{g}_0}{2F_\pi}\bar{N}\boldsymbol{\pi}\cdot\boldsymbol{\tau}N - \frac{\bar{g}_1}{2F_\pi}\pi_3 \bar{N}N$$

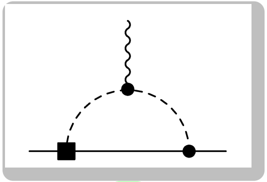
- the isotensor coupling $\bar{g}_2$ is usually suppressed
- at the two-nucleon level, 5 S to P transitions
  $\Delta T = 0$: $C_{^3S_1-^1P_1}$, $C^{(0)}_{^1S_0-^3P_0}$; $\Delta T = 1$: $C_{^3S_1-^3P_1}$, $C^{(1)}_{^1S_0-^3P_0}$, $\Delta T = 2$: $C^{(2)}_{^1S_0-^3P_0}$
- can be parameterized in terms of contact interactions or meson exchange couplings

1. The relative importance of these couplings depends on chiral/isospin properties of CPV ops.
2. Neutron, light-nuclei and atomic EDM experiments can identify these patterns
3. The dependence of hadronic couplings on SMEFT operators is **not** well understood.

Neutron (and proton) EDMs



$\bar{d}_{n,p}$



$\bar{g}_0$

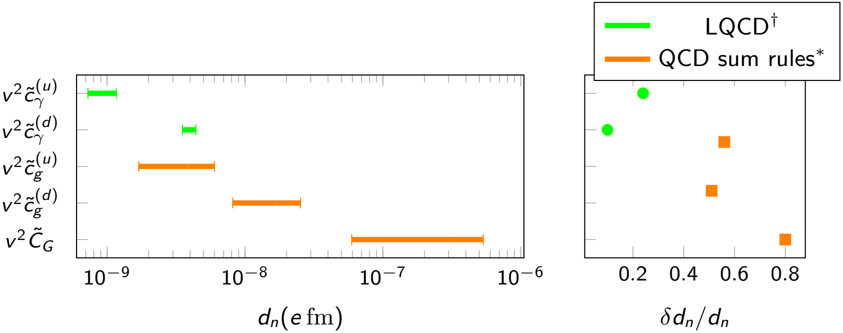
$$\frac{F_3(Q^2)}{2m_N} = d_N + S_N \frac{Q^2}{m_\pi^2} + \dots$$

- for isoscalar source, tree level and $\bar{g}_0$ loop of the same size ($\bar{g}_1$ suppressed)
- loop diagram control chiral log & momentum dependence

$$d_{n,p} = \bar{d}_{n,p}(\mu) \mp e \frac{g_A \bar{g}_0}{(4\pi F_\pi)^2} \ln \frac{\mu^2}{m_\pi^2}, \qquad S_n = \mp \frac{1}{6} \frac{e g_A \bar{g}_0}{(4\pi F_\pi)^2}$$

- for all sources, $d_n \sim d_p$. The exact ratio requires Lattice QCD calculations.

Nucleon EDM matrix elements



† FLAG '21

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

- qEDM contributions are mediated by nucleon tensor charges
  $g_T^{(u)}$, $g_T^{(d)}$ known with $< 10\%$ from LQCD, $g_T^{(s)}$ more uncertain
- contributions from $\bar{\theta}$ term and hadronic operators
  has large and (uncontrolled) errors

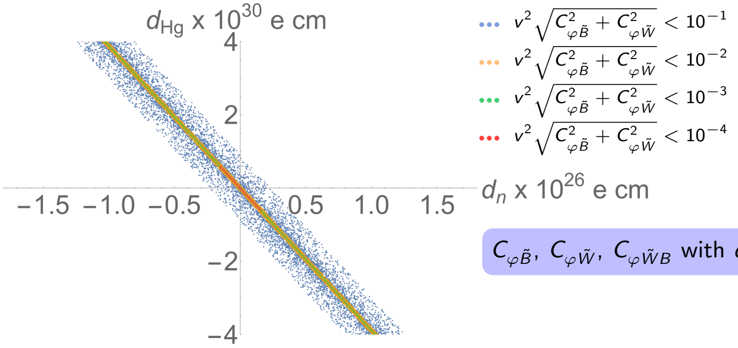
Nuclear EDMs and Schiff moments

	A_{Schiff}	α_n	α_p	a_0 (e fm)	a_1 (e fm)	a_2 (e fm)
^{199}Hg	$-(2.1 \pm 0.5) \cdot 10^{-4}$	1.9 ± 0.1	0.20 ± 0.06	$0.13^{+0.5}_{-0.07}$	$0.25^{+0.89}_{-0.63}$	$0.09^{+0.17}_{-0.04}$
^{129}Xe	$-(0.33 \pm 0.05) \cdot 10^{-4}$	–	–	$0.10^{+0.53}_{-0.037}$	$0.076^{+0.55}_{-0.038}$	
^{225}Ra	$7.7 \cdot 10^{-4}$	–	–	2.5 ± 7.5	-65 ± 40	14 ± 6.5
d	1	0.9	0.9	0	-0.100	0
^{3}He	1	0.9	0	-0.027	-0.079	-0.060
^{3}H	1	0	0.9	0.027	-0.079	0.060

$$d_{A_X} = A_{\text{Schiff}} \left(\alpha_n d_n + \alpha_p d_p + a_0 \frac{\bar{g}_0}{F_\pi} + a_1 \frac{\bar{g}_1}{F_\pi} + a_2 \frac{\bar{g}_2}{F_\pi} \right)$$

- for light ions, the nuclear theory input is under control (at the $\sim 10\%$ level)
- for diamagnetic atoms, Schiff moment calculations have large nuclear theory errors
- the couplings $\bar{g}_{0,1}$ are poorly known!

Identifying Higgs-gauge couplings



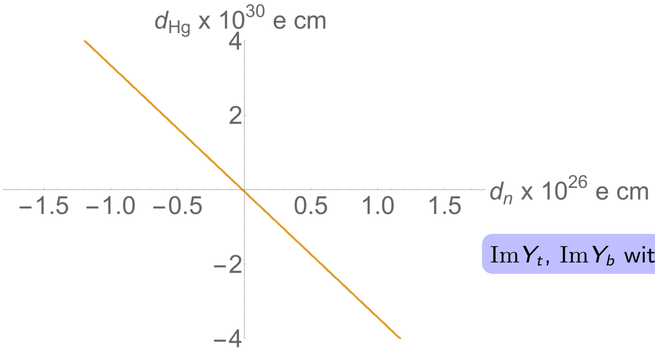
$C_{\varphi\tilde{B}}$, $C_{\varphi\tilde{W}}$, $C_{\varphi\tilde{W}B}$ with $d_e = 1 \cdot 10^{-30}$ e cm

- assume the 3 Higgs-gauge operators $C_{\varphi\tilde{B}}$, $C_{\varphi\tilde{W}}$ and $C_{\varphi\tilde{W}B}$ are active & and eEDM of 10^{-30} e cm is observed
- the combination

$$v^2\left(C_{\varphi\tilde{B}} + 1.1C_{\varphi\tilde{W}} - 2.3C_{\varphi\tilde{W}B}\right) \sim 10^{-6}$$

- if all the coefficients are of that size, no hadronic EDMs will be visible
- as they get larger, induce correlated signals in d_n, d_{Hg} and d_d

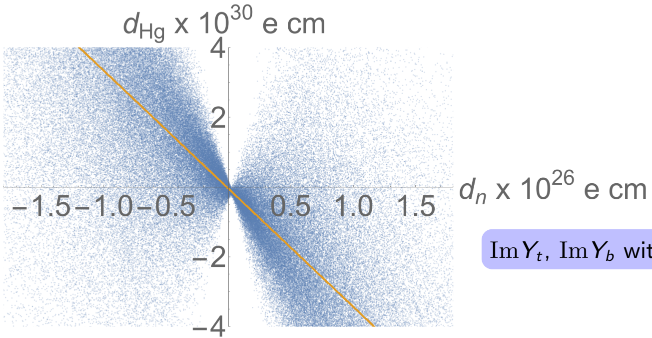
Identifying CP-odd Yukawa interactions



$\mathrm{Im}\, Y_t$, $\mathrm{Im}\, Y_b$ with $d_e = 1 \cdot 10^{-30}$ e cm

- assume the same eEDM signal is explained by non-standard t and b Yukawas
- if we neglect theory errors, clear prediction for d_n vs d_{Hg}

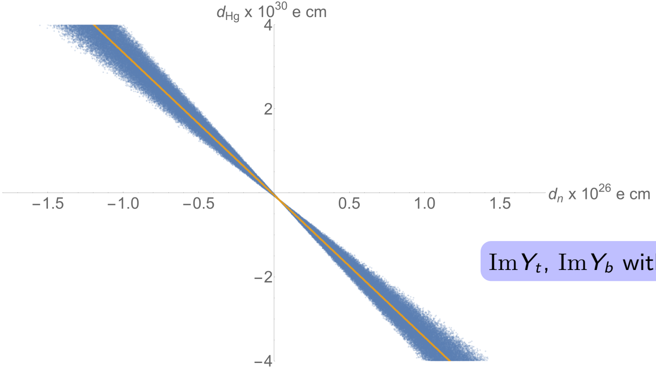
Identifying CP-odd Yukawa interactions



$\mathrm{Im}\, Y_t$, $\mathrm{Im}\, Y_b$ with $d_e = 1 \cdot 10^{-30}$ $e\,\mathrm{cm}$

- assume the same eEDM signal is explained by non-standard t and b Yukawas
- if we neglect theory errors, clear prediction for d_n vs d_{Hg}
- but large theory uncertainties spoil the picture!
- a reduction of th. errors to 10% of the current would greatly help!

Identifying CP-odd Yukawa interactions



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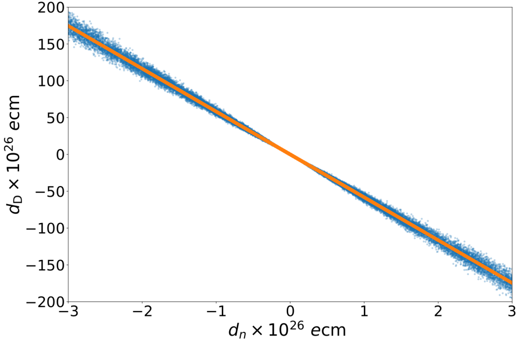
Identifying right-handed charged currents

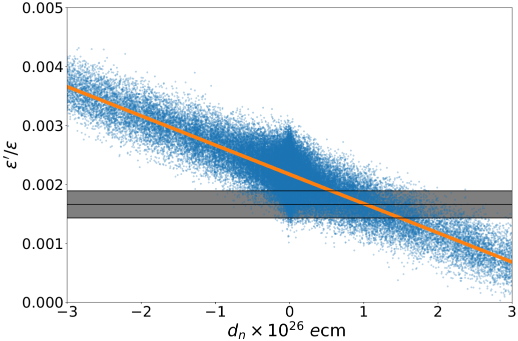


$[C_{Hud}]_{ud}$

assuming factor of 3 improvement on theory errors

- $u - d$ RHCC can explain Cabibbo anomaly
- eEDM is very small (two loop and light quark mass suppression)
- π-N contributions to nuclear and atomic EDMs enhanced
- an observation of d_n should lead to large expected deuteron EDM (or Hg and Ra)

Identifying right-handed charged currents



$[C_{Hud}]_{ud}$

assuming factor of 3 improvement
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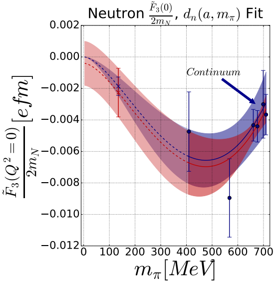
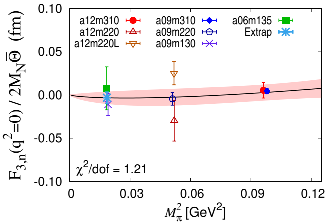
- $u - d$ RHCC can explain Cabibbo anomaly
- eEDM is very small (two loop and light quark mass suppression)
- π-N contributions to nuclear and atomic EDMs enhanced
- an observation of d_n should lead to large expected deuteron EDM (or *Hg* and *Ra*)
- but could lead to too large corrections to ϵ'/ϵ!

once again, important to reduce errors!

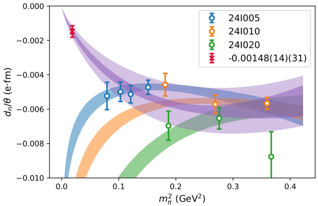
Lattice QCD calculations of nEDM. $\bar{\theta}$ term



J. Dragos, T. Luu, A. Shindler, *et al* '19



T. Bhattacharya, *et al*, '21



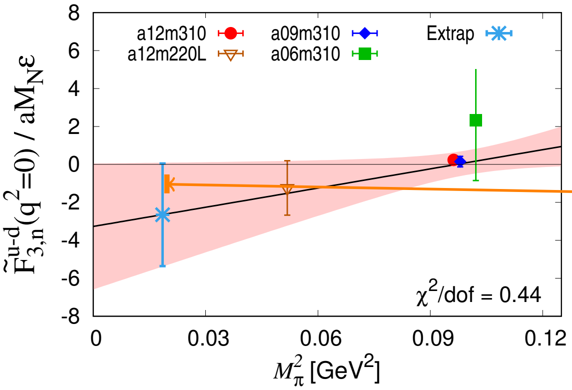
J. Liang, *et al* (χQCD Coll.), '23

- baseline for all nEDM calculations
- EDM from QCD $\bar{\theta}$ term extremely challenging

  vanishing signal at small m_π, large excited state contamination, ...
- published results compatible with zero at $\sim 2\sigma$
- approaching $d_n \sim 10^{-3}\,\bar{\theta}\ e\,\text{fm}$, size of "chiral log"

  Crewther, Di Vecchia, Veneziano and Witten, '79
- need more work to control all systematics

nEDM from dimension-6 operators



$\bar{q}\tau_3\sigma\tilde{G}q$

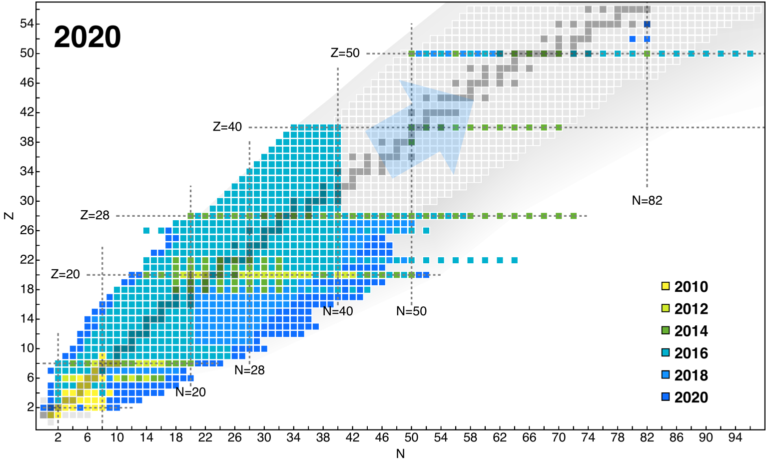
power div. subtracted

QCD sum rules

thanks to T. Bhattacharya and B. Yoon

- preliminary results for qCEDM and gCEDM
- error still a factor of 5 larger than QCD sum rule estimate
- ongoing efforts on π-N couplings

Nuclear Schiff moments



H. Hergert, `arXiv:2008.05061`

- need effort from nuclear theory community, with methods with different resolution scales
- tremendous advance of *ab initio* methods for β decays, $0\nu\beta\beta$, anapole moments

  S. Pastore *et al*, '17; P. Gysbers *et al*, '19; A. Belley, *et al*, '20; Y. Hao, P. Navratil *et al*, '20; R. Wirth *et al*, '21
- capabilities growing rapidly, and strong synergy with applications for "standard" NP

Conclusions

- EDM are powerful probes of BSM physics, which might lead to discovery of BSM CP-violation

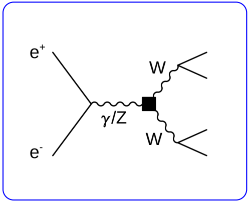
Disentangling BSM models requires:

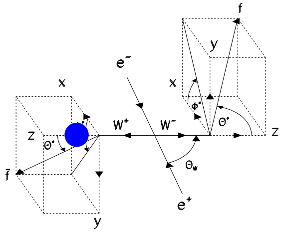
- multiple EDM observations
- improved nuclear and hadronic theory input
- correlations with flavor and collider probes
- and with well motivated baryogenesis scenarios

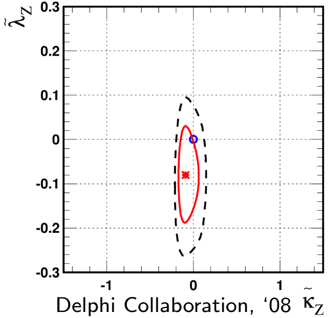
very important for these communties to keep talking!

Backup

Higgs-gauge operators. LEP







Delphi Collaboration, '08

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

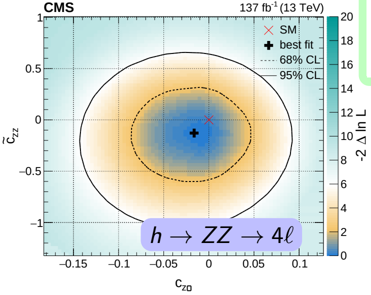
$$\tilde{\kappa}_Z = -0.12^{+0.06}_{-0.04} \qquad \tilde{\lambda}_Z = -0.09^{+0.07}_{-0.07}$$

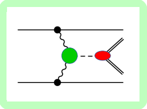
- can be mapped onto $\varphi^\dagger \varphi \tilde{W} B$ and $WW\tilde{W}$ SMEFT operators

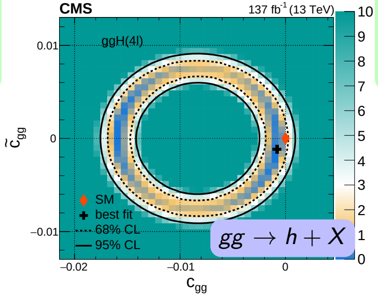
$\Lambda \sim 250 - 350$ GeV

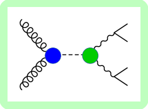
sensitive to EW scale physics

CPV in Higgs couplings. Collider constraints









CMS 2104.12152

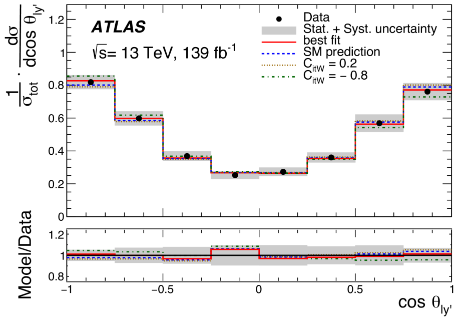
- more and more SMEFT analyses of CPV at LHC coming out

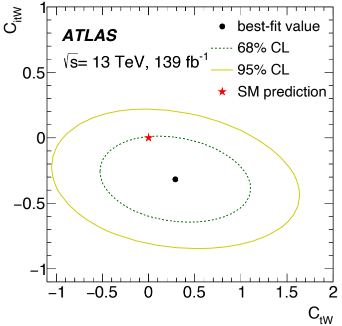
ATLAS: 1905.04242, 2202.11382, 2208.02338, ...
CMS: 1907.03729, 2110.11231, 2104.12152, ...

- Higgs-gauge couplings probed in WW, WZ, Higgs production and decay
- CPV-sensitive observables via angular correlations
- $\Lambda \lesssim 1 - 2$ TeV, larger sensitivity for loop-dominated processes

See A. Gritsan et al, 2104.12152, 2109.13363 and 2205.07715

Single top





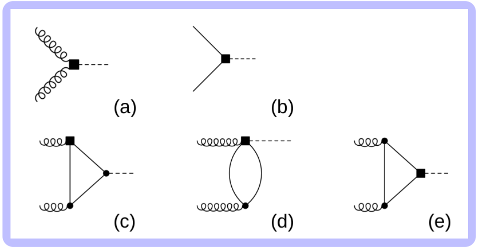
ATLAS 2202.11382

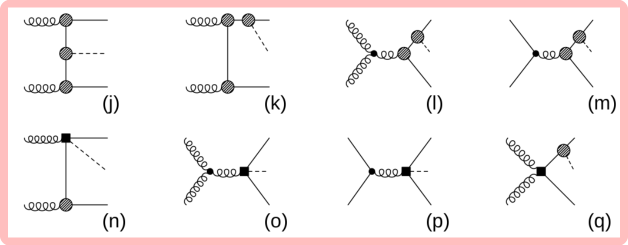
- angular distribution allow to access triple correlation $\vec{S}_t \cdot (\vec{p}_\ell \times \vec{p}_j)$

  analogous to "*D* coefficient" in β decays

- $\Lambda \sim 1.4$ TeV with polarization observables alone

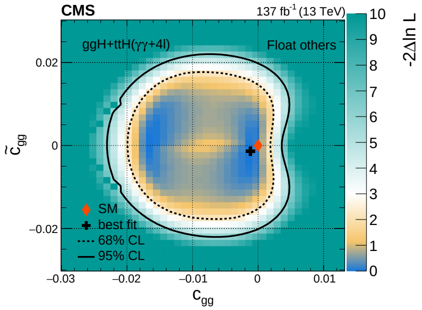
$gg \to h$, $t\bar{t}$ and $t\bar{t}h$

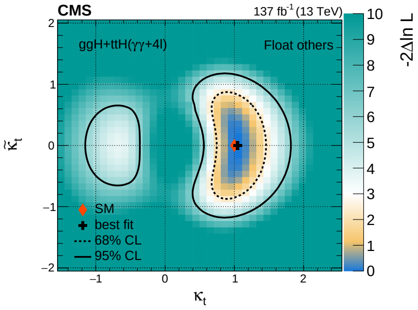




- very sensitive to top couplings, at tree and loop level

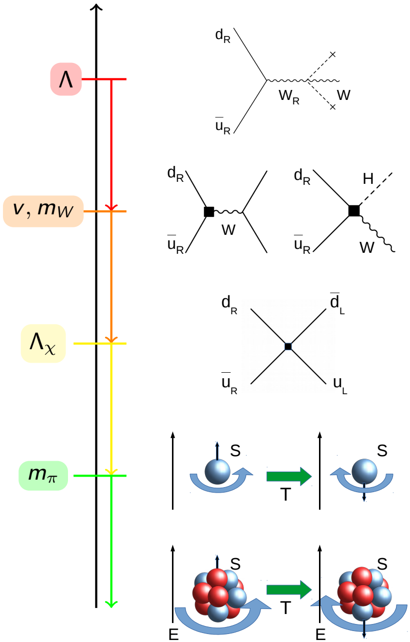
$gg \to h$, $t\bar{t}$ and $t\bar{t}h$





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

Effective field theories for EDMs



1. correlate an EDM signal with colliders/high energy physics?

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

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