EDMs and CP violation in the Higgs sector

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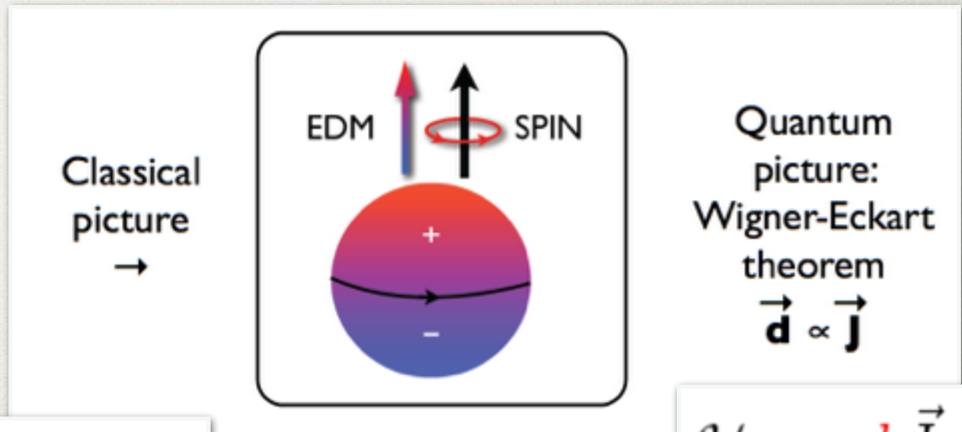
borrowed heavily from talks by V. Cirigliano and J. Brod

Higgs Tasting , Benasque, May 17 2016

EDMs

- electric dipole moments (EDMs) violate both P and CP
- e.g., electron EDM is dim-5 operator



$$\mathcal{H} \sim d\,\vec{J}\cdot\vec{E}$$

$$\mathcal{L}_{\text{eff}} = -d_e\,\frac{i}{2}\,\bar{e}\,\sigma^{\mu\nu}\gamma_5\,e\,F_{\mu\nu}\,,$$

- many complementary probes
  - **n**,p
  - light nuclei: ^{2}H, ^{3}He, ^{3}H, …
  - atoms: diamagnetic (^{129}**Xe**, ^{199}**Hg**, ^{225}Ra,…); paramagnetic (^{205}**Tl**, ...)
  - polar molecules: **YbF, ThO**, ...

EDMs

- the measured EDMs of the probe need to be related to fundamental EDMs

see a review by Dzuba, Flambaum, Roberts, 1412.6644

- for instance eEDM induces an EDM in an atom or molecule

$$D = K d_e$$

atom EDM **electron EDM**

- K calculated from atomic physics
  - for paramagnetic atoms $K \sim 10^2$-10^3 (e.g. has $K_{Tl} \sim -600$)
  - for diamagnetic atoms K is small (e.g. $K_{Hg} \sim 10^{-2}$)
  - for polar molecules $K \sim 10^7$–10^{11} possible (e.g. electric field in ThO ~84 GV/cm, one of largest known)

EDMs

- a big gap between present bounds and the SM “floor”
- significant exp progress predicted in the “near” future

EDMs in $e \cdot cm$

System	current	projected	SM (CKM)
e	$\sim 10^{-28}$	10^{-31}	$\sim 10^{-38}$
μ	$\sim 10^{-19}$	10^{-21}	$\sim 10^{-35}$
τ	$\sim 10^{-16}$		$\sim 10^{-34}$
n	$\sim 10^{-26}$	10^{-28}	$\sim 10^{-31}$
p	$\sim 10^{-23}$	10^{-29} **	$\sim 10^{-31}$
^{199}Hg	$\sim 10^{-29}$	10^{-30}	$\sim 10^{-33}$
^{129}Xe	$\sim 10^{-27}$	10^{-29}	$\sim 10^{-33}$
^{225}Ra	$\sim 10^{-23}$	10^{-26}	$\sim 10^{-33}$
...	...		...

talk by V. Cirigliano at MIAPP workshop, July 2015+ additions

OUTLINE

- CP violating couplings of the Higgs
  - couplings to fermions
  - couplings to gauge bosons

CPV in Higgs couplings to leptons

CPV Higgs Yukawas

- Higgs is our new window to NP
- if SM an EFT, then Yukawas get corrected by higher dim. ops

$$\mathcal{L}_{SM} = -\left[\lambda_{ij}(\bar{f}_L^i f_R^j)H + h.c.\right]$$

$$\Delta\mathcal{L}_Y = -\frac{\lambda'_{ij}}{\Lambda^2}(\bar{f}_L^i f_R^j)H(H^\dagger H) + h.c. + \cdots$$

  - decouples mass terms from yukawas

$$\mathcal{L}_Y = -m_i \bar{f}_L^i f_R^i - Y_{ij}(\bar{f}_L^i f_R^j)h + h.c. + \cdots,$$

- can lead to flavor violating Higgs decays
- can lead to CPV Higgs decays
  - how tight are constraints from EDMs?

CPV Higgs couplings

- the notation

$$\mathcal{L} \supset -\frac{y_f}{\sqrt{2}} \left(\kappa_f \bar{f} f + i \tilde{\kappa}_f \bar{f} \gamma_5 f \right) h$$

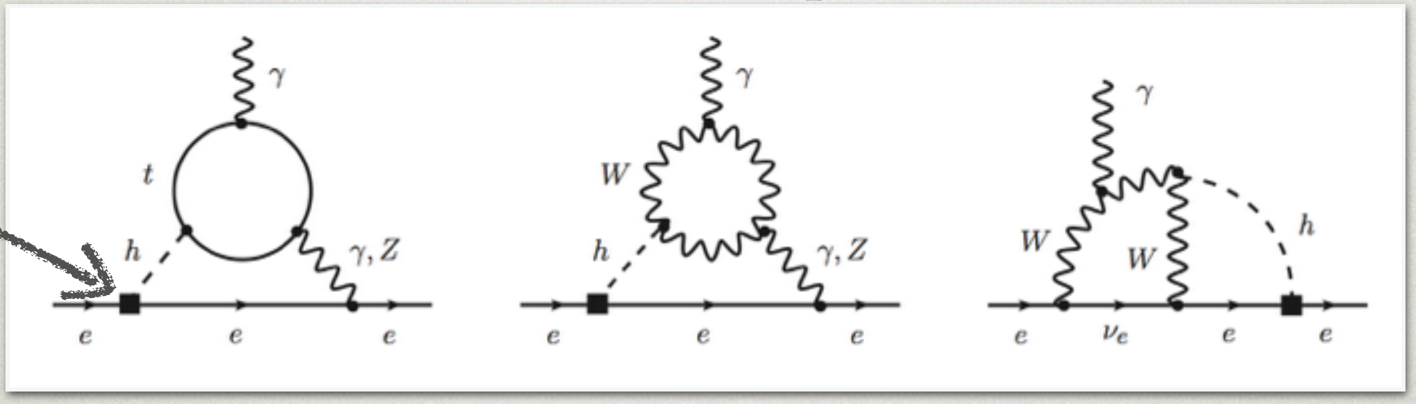
- will cover CPV couplings to all SM fermions

ELECTRON YUKAWA

- $\tilde{\kappa}_e \neq 0$ induces electron EDM
- dominant contributions at 2-loop

Altmannshofer, Brod, Schmaltz, 1503.04830

CPV



- several checks: $\kappa_e = 1$ reproduces Higgs contrib. contributions in muon g-2 (first indep. check)
  - agree with Barr-Zee contrib.
  - analytic results with an internal Z boson are new
    - parametric expressions available before, but numerically 10% difference with these

Gribouk, Czarnecki, hep-ph/0509205

Barr, Zee, Phys.Rev.Lett. 65:21, 1990

Leigh, Paban, Xu, Nucl.Phys. B352:45, 1991

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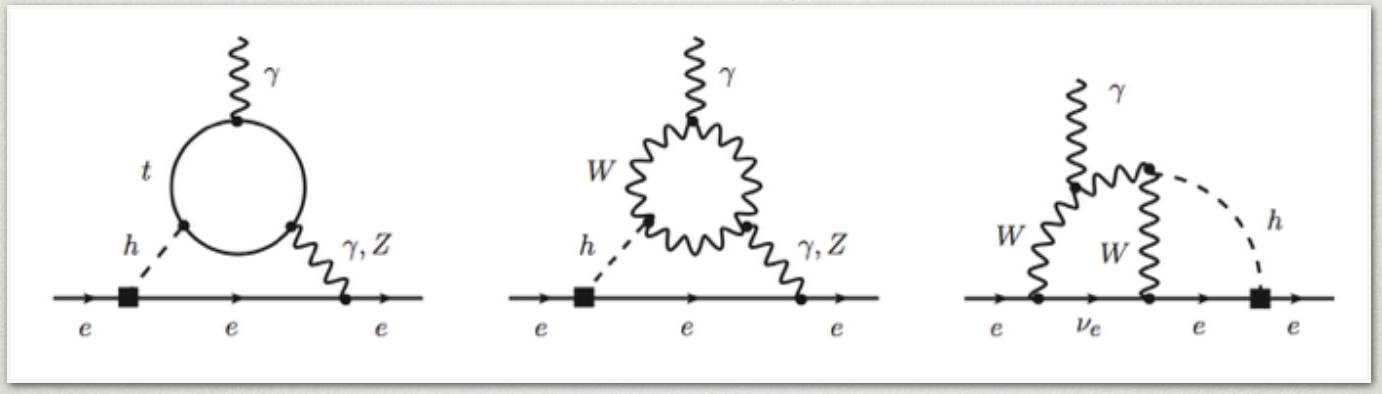


- experimental bound

ACME coll., 1310.7534

$$\left|\frac{d_e}{e}\right|_{\rm exp} < 8.7 \times 10^{-29}\ {\rm cm} \quad @\ 90\%\ {\rm C.L.}\,,$$

$$|\tilde{\kappa}_e| < 1.7 \times 10^{-2}$$

- for $c_0 = i \Rightarrow M > 1000\ TeV$

$$g_{eeh} = y_e + \frac{3c_0}{2}\frac{v^2}{M^2} = \frac{\sqrt{2}m_e}{v} + c_0\frac{v^2}{M^2}\,.$$

- compare with

CMS-HIG-13-007

$$\mathrm{Br}(h \to e^+e^-) < 0.0019 \quad @\ 95\%\ \mathrm{C.L.}\,.$$

$$\sqrt{|\kappa_e|^2 + |\tilde{\kappa}_e|^2} < 611$$

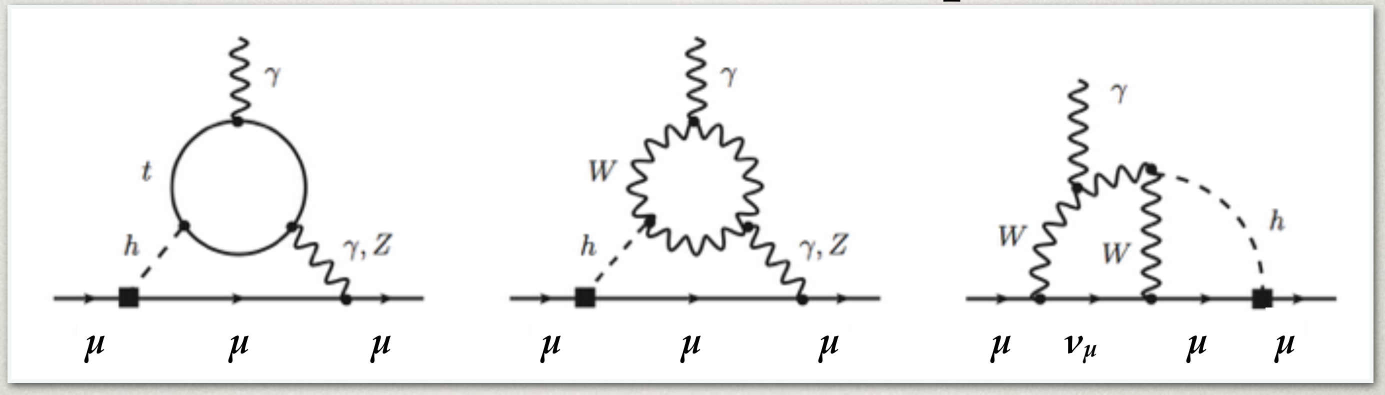
COMMENTS

- there is always ambiguity in low energy observables
  - need to assume which Yukawa(s) CP violating
  - in complete theories there are other contributions to EDMs
- in principle one could cancel Higgs and other contribs.
  - here always assume no such cancellations

MUON YUKAWA

thanks to J. Brod

- similarly, $\tilde{\kappa}_\mu \neq 0$ induces muon EDM
  - dominant contributions at 2-loop



- experimental bound Muon (g-2) Collaboration, 0811.1207

$$|d_\mu| < 1.9 \times 10^{-19} \; e\cdot\text{cm} \; (95\% \text{ C.L.}).$$

$$|\tilde{\kappa}_\mu| < 1.8 \times 10^5$$

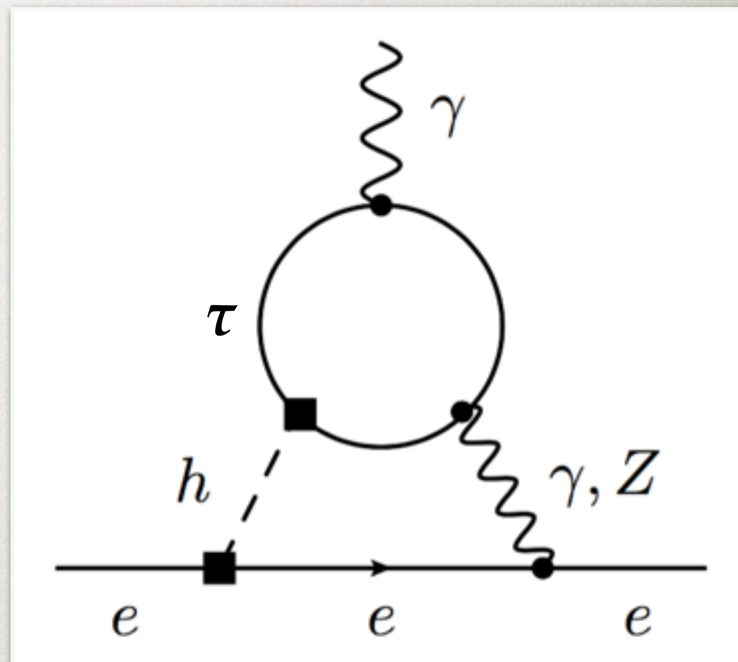
- compare with CMS-HIG-13-007; ATLAS 1406.7663

$$Br(h \to \mu^+\mu^-) < 1.5 \times 10^{-3}$$

$$\sqrt{|\kappa_\mu|^2 + |\tilde{\kappa}_\mu|^2} < 7.0$$

TAU YUKAWA

- electron EDM can also constrain tau $\tilde{\kappa}_\tau$
- need to assume the value for electron Yukawa
  - here: $\kappa_e=1$, $\tilde{\kappa}_e=0$
  - present exp. eEDM constr. then give



Brod, Haisch, JZ, 1310.1385

$$\left|\frac{d_e}{e}\right|_{\rm exp} < 8.7\times10^{-29}\ {\rm cm} \quad @\ 90\%\ {\rm C.L.}\,,$$

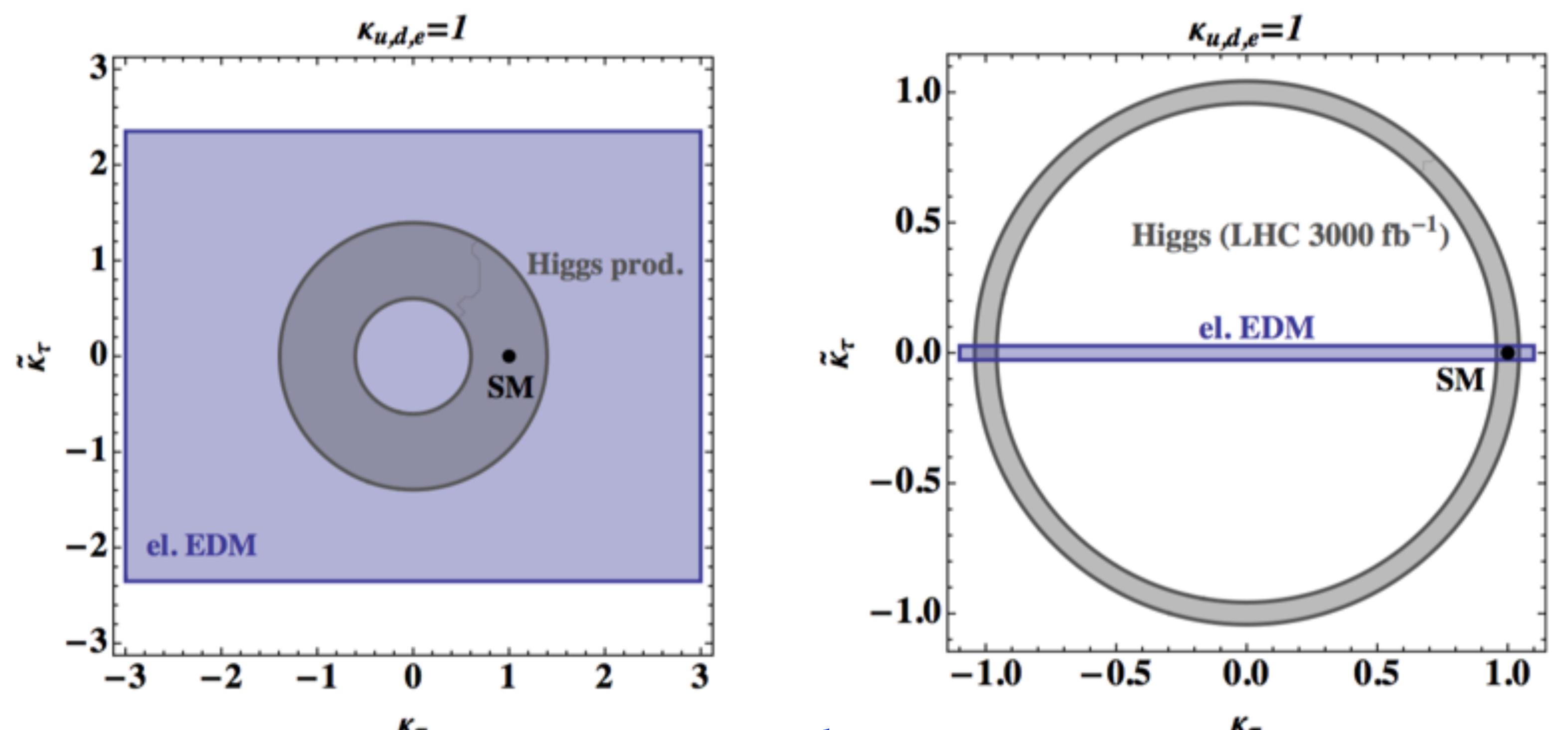
$$|\tilde{\kappa}_\tau| \lesssim 2$$

CPV coupling to τ

- impressive improvement in el. EDM is projected
  - 3 orders of magnitude
- in the plot no direct CPV measnt. at the LHC is assumed

Harnik, Martin, Okui, Primulando, Yu, 1308.1094

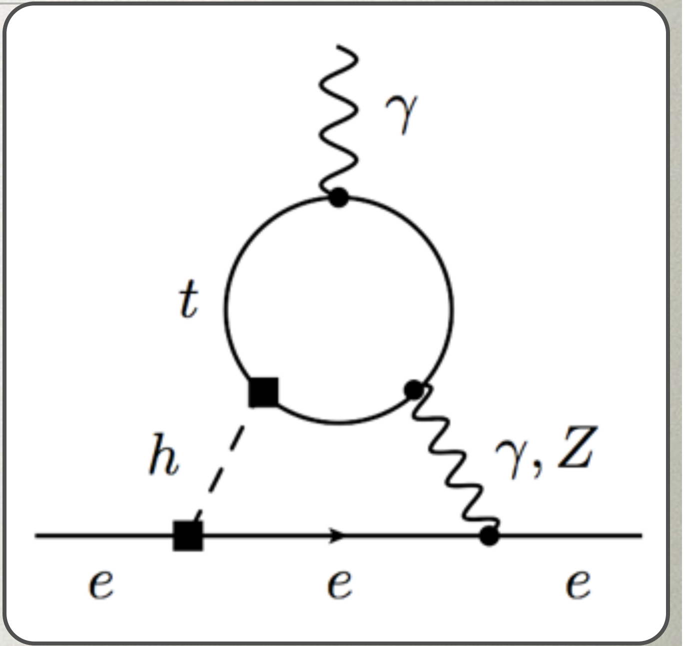
  - *O(0.2)* measrmnt. on $\tilde{\kappa}_\tau$ maybe possible (at LHC 3 ab^{-1})



Brod, Haisch, JZ, 1310.1385

CPV in Higgs couplings to quarks

GENERAL COMMENTS



- at 2-loops sensitivity to quark Yukawas from electron EDM
  - requires assumptions about electron Yukawa
- from neutron EDM, Hg EDM, … also constrains on quark EDMs
  - requires control of nuclear physics
- will take top CPV yukawa as a working example
  - then comments on all the other quarks

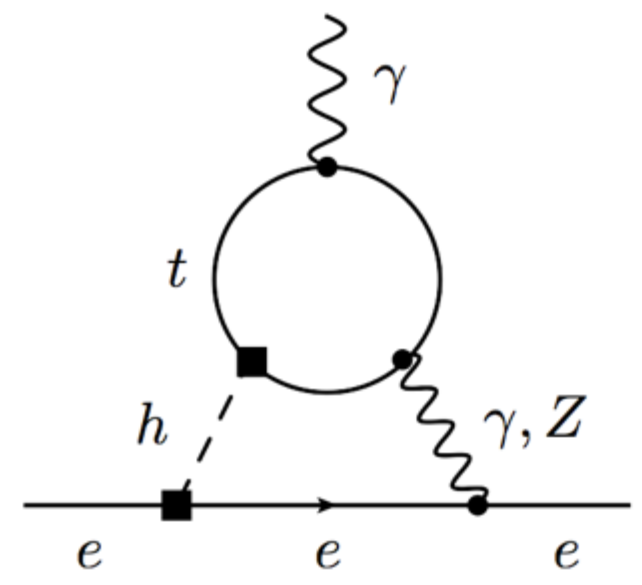
electron EDM

- dominant contribution from 2-loop Barr-Zee type diagram

$$\mathcal{L}_{\rm eff} = -d_e\,\frac{i}{2}\,\bar{e}\,\sigma^{\mu\nu}\gamma_5\,e\,F_{\mu\nu}$$

- depends on electron yukawa

$$\frac{d_e}{e} = 3.49\cdot 10^{-27}\,{\rm cm}\;\kappa_e\tilde{\kappa}_t\,f_1(x_{t/h}) = 9.6\cdot 10^{-27}\,{\rm cm}\;\kappa_e\tilde{\kappa}_t$$



- setting κ_e=1 is then quite constraining

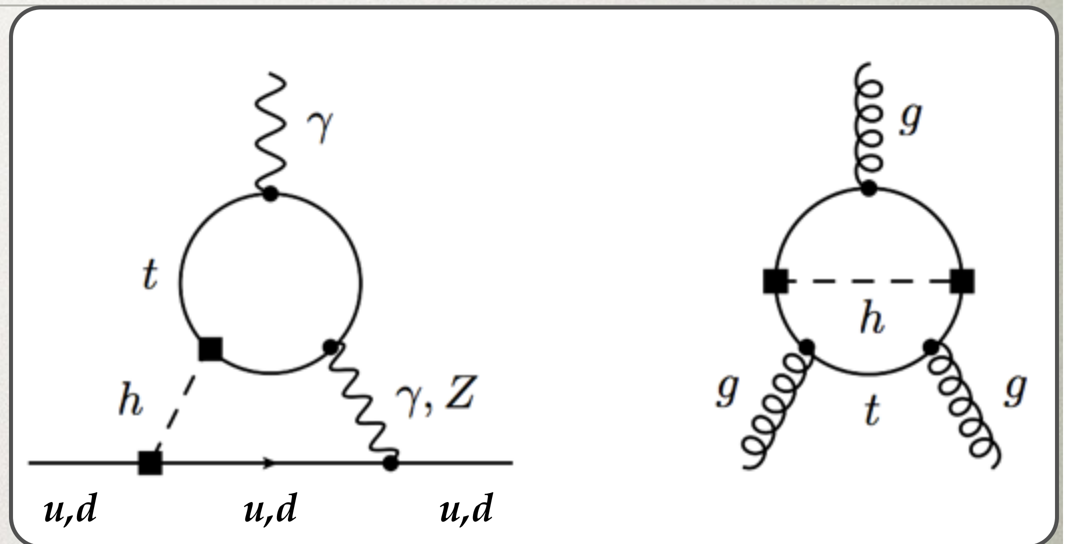
$$\left|\frac{d_e}{e}\right| < 8.7\cdot 10^{-29}\,{\rm cm}\,, \qquad |\tilde{\kappa}_t| < 0.01\,,$$

Brod, Haisch, JZ, 1310.1385

- the constraint vanishes, if the Higgs does not couple to electrons
  - e.g. if it only couples to the 3rd gen.

NEUTRON AND MERCURY EDM

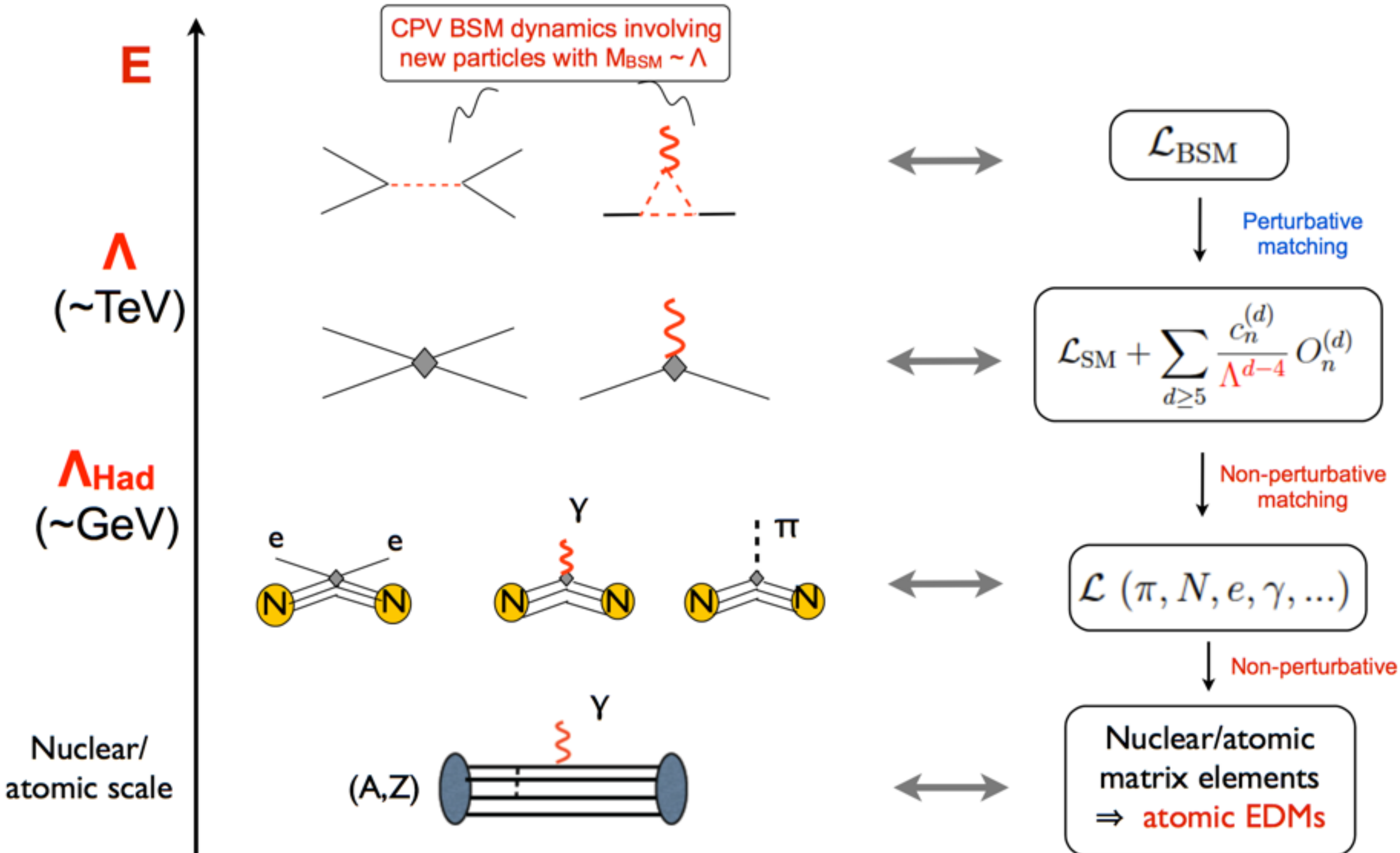
- neutron and Hg EDM also dominated by Barr-Zee type diagrams (SM-like couplngs. of the Higgs to light quarks)



$$\mathcal{L}_{\rm eff} = -d_q \frac{i}{2}\bar{q}\sigma^{\mu\nu}\gamma_5 q\, F_{\mu\nu} - \tilde{d}_q \frac{i g_s}{2}\bar{q}\sigma^{\mu\nu}T^a\gamma_5 q\, G^a_{\mu\nu} - w\,\frac{1}{3} f^{abc}\, G^a_{\mu\sigma} G^{b,\sigma}_{\nu} \widetilde{G}^{c,\mu\nu}$$

- however, an important difference is that at 2-loop also Weinberg operator is generated
    - is nonzero also, if CPV <u>is only</u> in the Higgs couplings to the 3rd gen. quarks!

Connecting EDMs to BSM CPV



talk by V. Cirigliano at MIAPP workshop, July 2015

HADRONIC MATRIX ELEMENTS

talk by V. Cirigliano at MIAPP workshop, July 2015

- important improvements recently in nonpert. matching at ChPT scale
  - at hadronic ~1GeV scale

$$\mathcal{L}_{\rm CPV} = -\frac{i}{2}\sum_{i=u,d,s} d_i\, \bar\psi_i \sigma_{\mu\nu}\gamma_5 \psi_i\, F^{\mu\nu} - \frac{i}{2} g_s \sum_{i=u,d,s} \tilde d_i\, \bar\psi_i \sigma_{\mu\nu}\gamma_5 T^a \psi_i\, G^{\mu\nu,a}$$

$$+ \frac{c_w}{\Lambda^2}\, f^{abc} G^a_{\mu\nu} \tilde G^{\nu\beta,b} G^{\mu,c}_{\beta} \qquad + \text{4−fermion}$$

  - Leading pion-nucleon CPV interactions characterized by few LECs

no info. from symmetries — well determined from symmetries

$$\mathcal{L}_{\rm CPV} = -\frac{i}{2}\bar N\, \bar d_N\, \sigma_{\mu\nu}\gamma_5\, N\, F^{\mu\nu} - \bar N \left[\bar g_0\, \vec\tau\cdot\vec\pi + \bar g_1\, \pi^0\right] N - \frac{\bar\Delta}{F_\pi}\, \pi^0\, \vec\pi\cdot\vec\pi + \ldots$$

Nucleon EDM $\bar d_N = \begin{pmatrix} \bar d_p & 0 \\ 0 & \bar d_n \end{pmatrix}$

T-odd P-odd pion-nucleon couplings

Short-range 4N and 2N2e coupling

HADRONIC MATRIX ELEMENTS

talk by V. Cirigliano at MIAPP workshop, July 2015

- At LO all hadronic EDMs are expressed in terms of these LECs

$$d^A = c_n^A\, d_n + c_p^A\, d_p + c_0^A\, \bar{g}_0 + c_1^A\, \bar{g}_1 + c_\Delta^A\, \bar{\Delta} + \dots$$

  - light nuclei *d, He3, t,…*: chiral EFT calc. ⇒ *O(10%)* uncertainty
  - diamagnetic atoms (^{199}Hg,...): *O(1-10)* uncertainties

- recent first LQCD determ. of neutron and proton tensor charges

$$d_n = d_u\, g_T^{(n,u)} + d_d\, g_T^{(n,d)} + d_s\, g_T^{(n,s)}$$

$$g_T^{(n,u)} = -0.23(3) \qquad g_T^{(n,d)} = 0.77(7) \qquad g_T^{(s)} = 0.008(9)$$

$$\langle N|\, \bar{q}\sigma_{\mu\nu} q\, |N\rangle \equiv g_T^{(N,q)}\; \bar{\psi}_N \sigma_{\mu\nu} \psi_N$$

  - still missing pieces: cEDM ops., Weinberg operator

$$d_n = (-0.22 \pm 0.03)\, d_u + (0.74 \pm 0.07)\, d_d + (0.008 \pm 0.010)\, d_s$$

$$+ (-0.55 \pm 0.28)\, e\tilde{d}_u + (-1.1 \pm 0.55)\, e\tilde{d}_d + (\pm(50 \pm 40)\,\text{MeV})\, e d_W$$

Pospelov-Ritz hep-ph/0504231

QCD Sum Rules (50%)

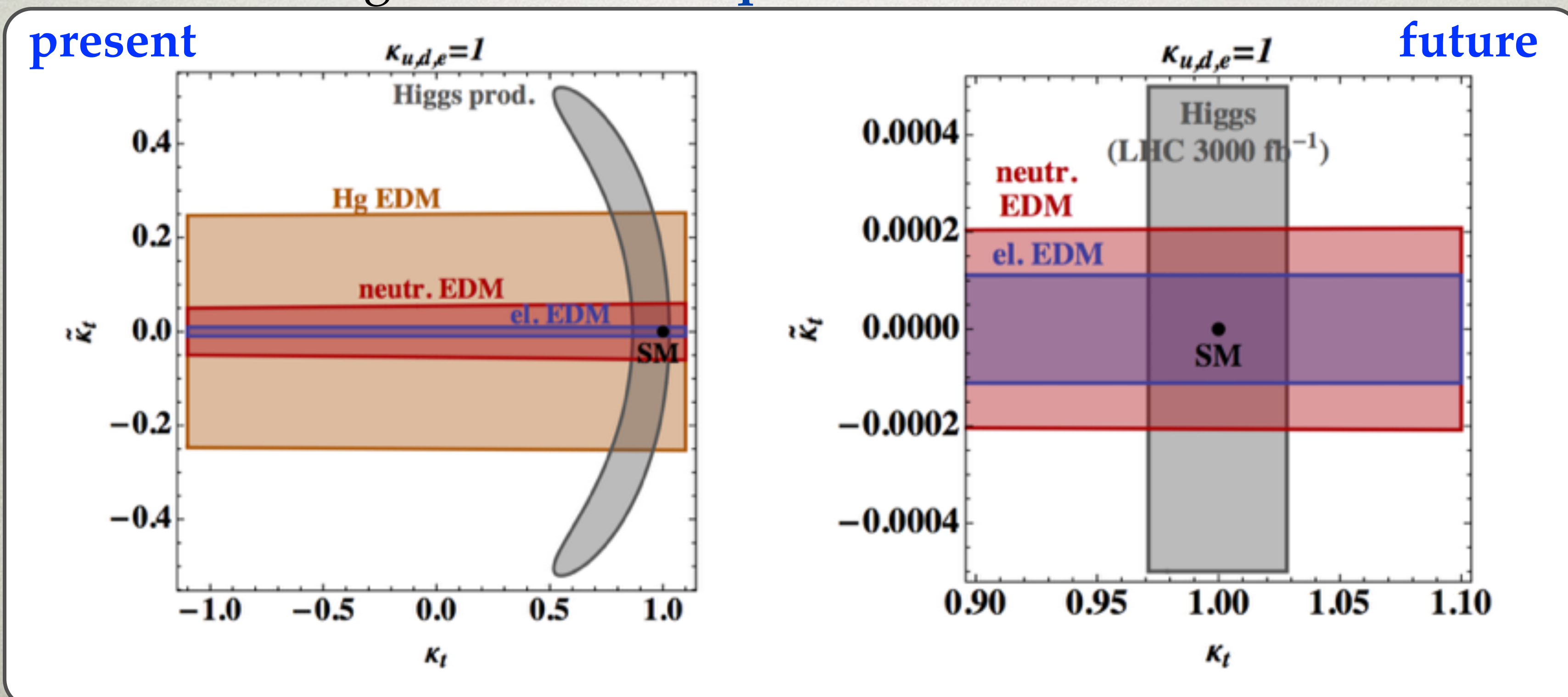
QCD Sum Rules + NDA (~100%)

CPV coupling to top

- comparing with the LHC reach

  Brod, Haisch, JZ, 1310.1385
  see also Cirigliano, de Vries, Dekens, Mereghetti, 1603.03049
  - assuming that no CPV measurements at the LHC
  - central values only for hadronic matrix elements

  Pospelov-Ritz hep-ph/0504231
- for 1st gen. Yukawas **equal to the SM**

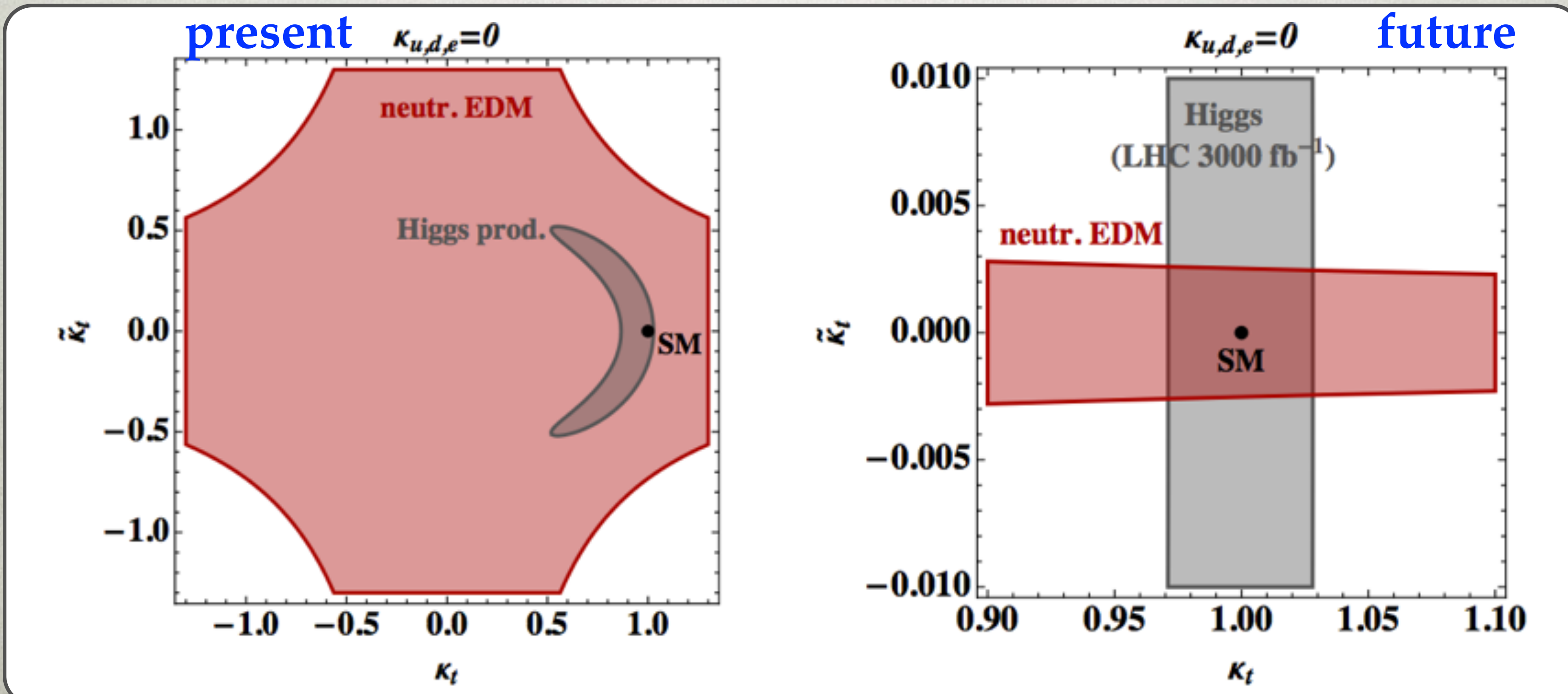


CPV coupling to top

- comparing with the LHC reach

Brod, Haisch, JZ, 1310.1385

  - assuming that no CPV measurements at the LHC
  - central values only for hadronic matrix elements
- 1st gen. Yukawas **set to zero**

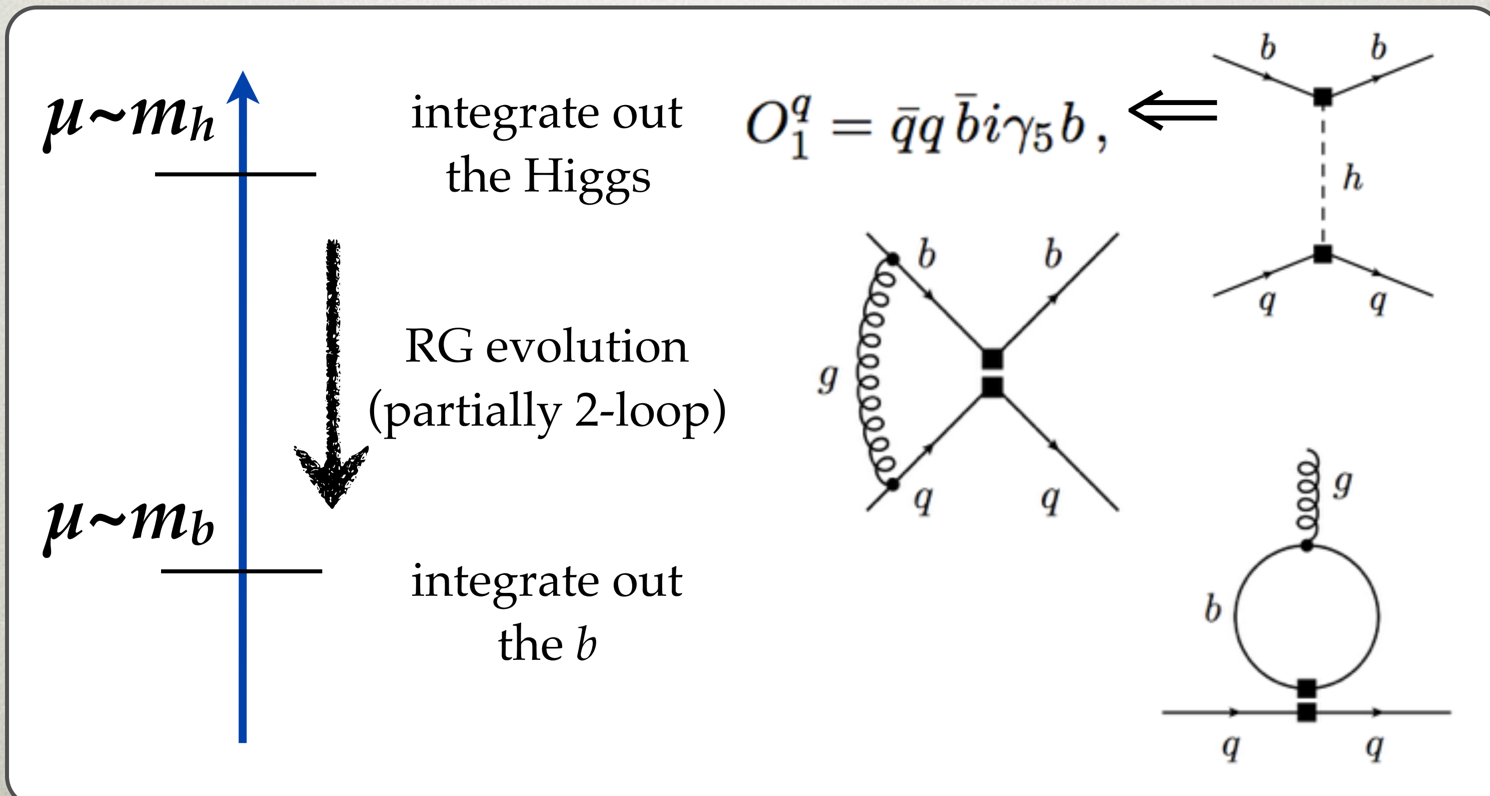


LIGHT QUARK YUKAWAS

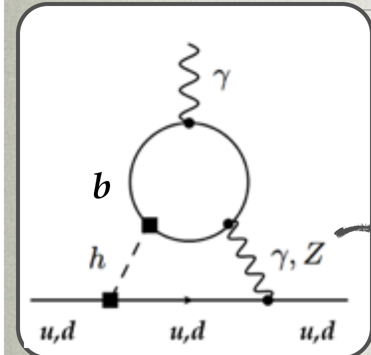
- for CPV light quark Yukawas: b,c,s,d,u
  - need to run down to lower energies
  - b integrated out at $\mu \sim m_b$
  - c integrated out at $\mu \sim m_c$
  - nonperturbative matching at $\mu \sim 1 GeV$

CPV COUPLING TO b QUARK

- here one extra scale $m_b \ll m_h$
  - need to re-sum $\alpha_s log(x_{b/h})$ (here $x_{b/h}=m_b^2/m_h^2$)



RESUMMATION



- only one relevant entry of anomalous dimension not known previously, $\gamma_{59}^{(1)}$

$$O_5^q = -\frac{i}{2} e Q_b \frac{m_b}{g_s^2}\, \bar{q}\sigma^{\mu\nu}\gamma_5 q\, F_{\mu\nu}\,,$$

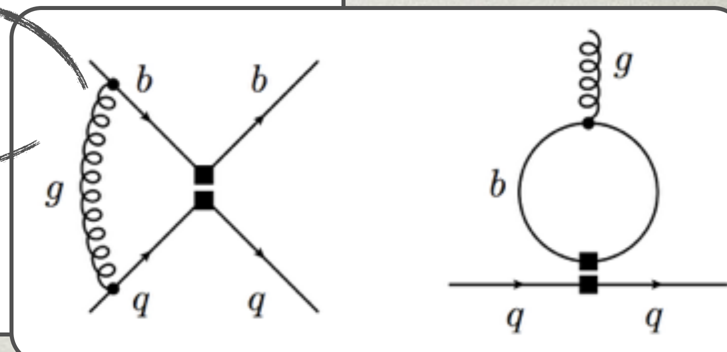
$$O_6^q = -\frac{i}{2}\frac{m_b}{g_s}\, \bar{q}\sigma^{\mu\nu}T^a\gamma_5 q\, G^a_{\mu\nu}\,,$$

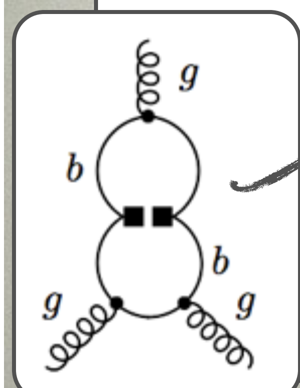
$$O_7 = -\frac{1}{3g_s} f^{abc}\, G^a_{\mu\sigma} G^{b,\sigma}_{\nu} \widetilde{G}^{c,\mu\nu}\,,$$

$$C_5^q(\mu_b) \simeq -4\,\frac{\alpha\alpha_s}{(4\pi)^2}\, Q_q \ln^2 x_{b/h} + \left(\frac{\alpha_s}{4\pi}\right)^3 \frac{\gamma_{14}^{(0)}\gamma_{48}^{(0)}\gamma_{87}^{(0)}}{48}\ln^3 x_{b/h} + \mathcal{O}(\alpha_s^4)$$

$$C_6^q(\mu_b) \simeq \left(\frac{\alpha_s}{4\pi}\right)^2 \frac{\gamma_{14}^{(0)}\gamma_{48}^{(0)}}{8}\ln^2 x_{b/h} + \mathcal{O}(\alpha_s^3)$$

$$C_7(\mu_b) \simeq \left(\frac{\alpha_s}{4\pi}\right)^2 \frac{\gamma_{59}^{(1)}}{2}\ln x_{b/h} + \mathcal{O}(\alpha_s^3)$$





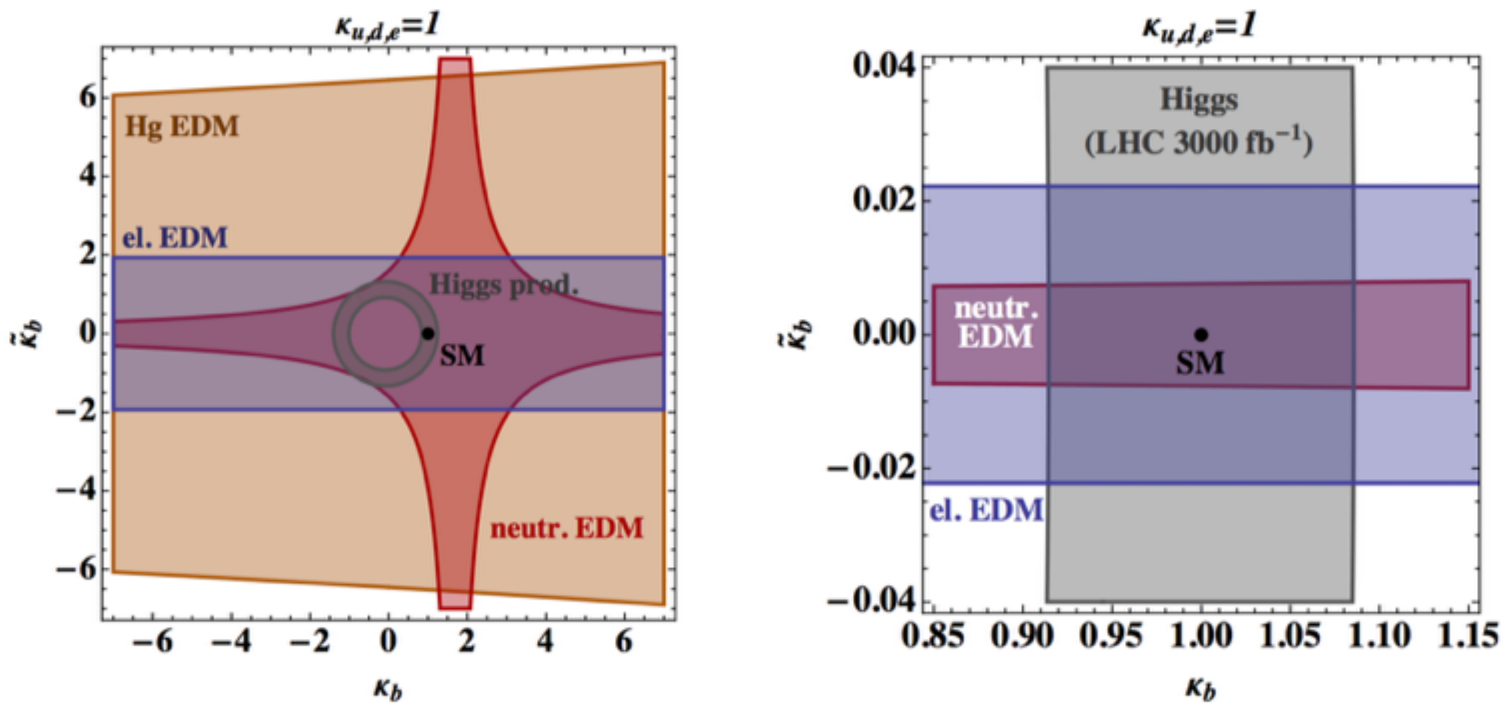
- resummation numerically important
  - without it a factor of ~3 ambiguity in nEDM

CPV coupling to b quark

- the EDM constraints on CPV Higgs coupling to b quark are weaker than the LHC data

Brod, Haisch, JZ, 1310.1385

  - this can change in the future
  - EDMs scale linearly with $\tilde{\kappa}_b$



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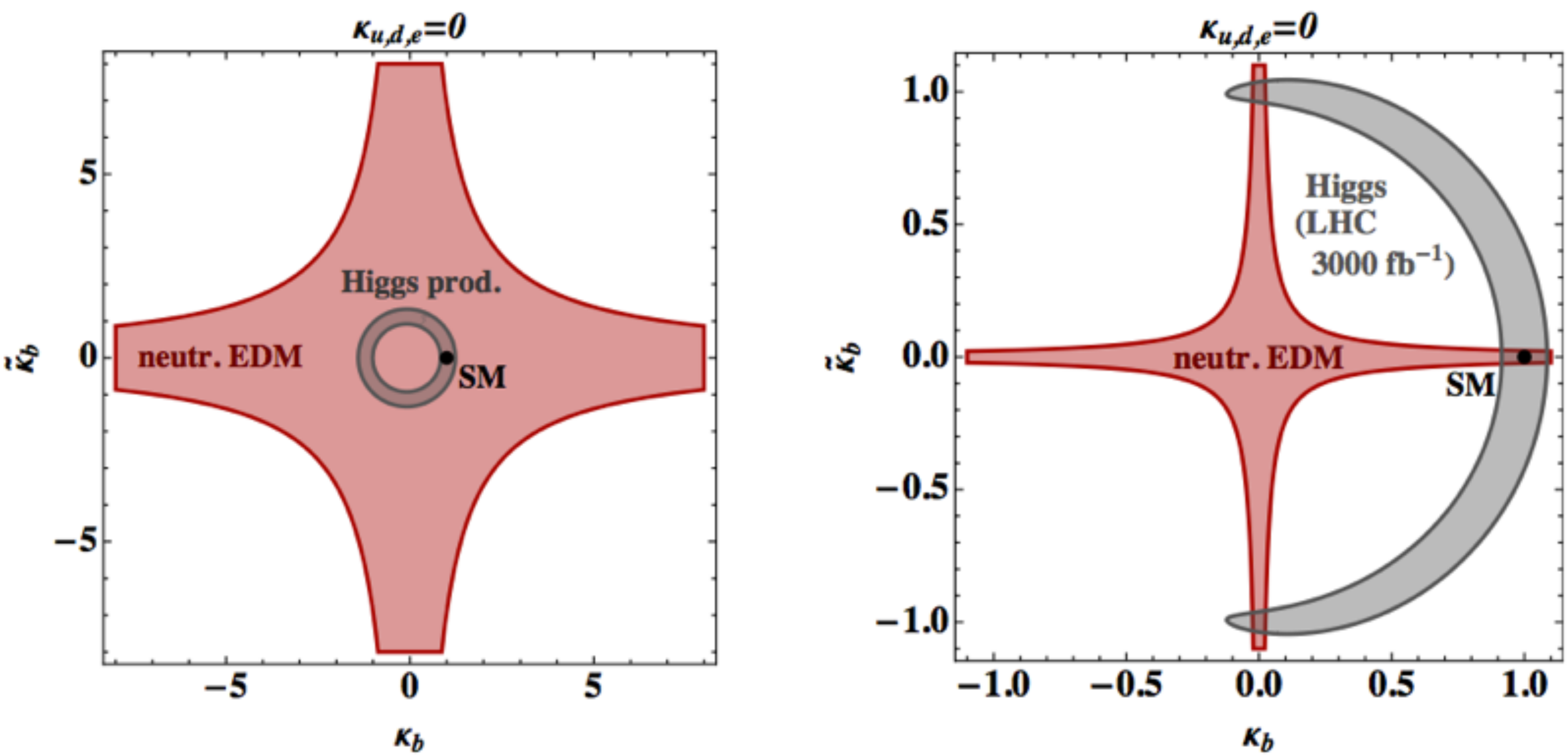
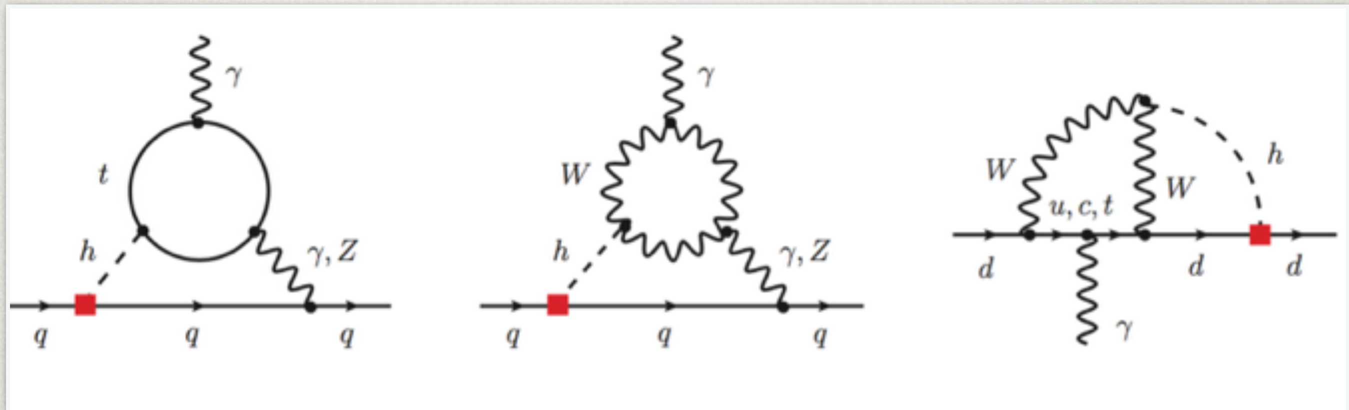


LIGHT QUARK YUKAWAS

- for light quarks need to include 2-loop matching at EW scale



- without resummation gives bounds

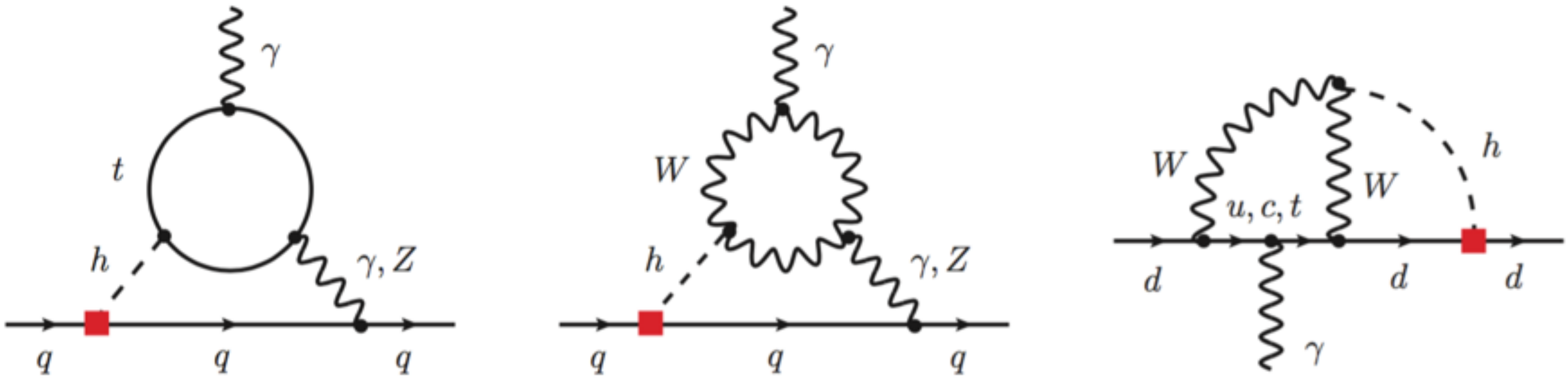
Chien, Cirigliano, de Vries, Dekens, Mereghetti, 1510.00725

$\tilde{\kappa}_u < 0.56 \qquad \tilde{\kappa}_d < 0.13 \qquad \tilde{\kappa}_c < 2.4 \qquad \tilde{\kappa}_s < 25$

	$v^2 \text{Im}\, Y_u'$	$v^2 \text{Im}\, Y_d'$	$v^2 \text{Im}\, Y_c'$	$v^2 \text{Im}\, Y_s'$
d_e	x	x	0.022	0.42
d_n Con.	$2.8 \cdot 10^{-6}$	$1.4 \cdot 10^{-6}$	$6.1 \cdot 10^{-3}$	$5.1 \cdot 10^{-3}$
d_{Hg} Con.	$1.6 \cdot 10^{-5}$	$2.9 \cdot 10^{-6}$	0.015	0.011

- however, resummation can be important

LIGHT QUARK YUKAWAS



talk by J. Brod at Beauty 2016

- Complete analytic result [work in progress]
- PRELIMINARY results:

$$\frac{d_n}{e} = (1.0 \pm 0.5)\,[0.36\,\tilde{\kappa}_u + 1.70\,\tilde{\kappa}_d]\,\kappa_t \times 10^{-25}\,\mathrm{cm}\,.$$

- $\Rightarrow |\tilde{\kappa}_u| \lesssim 0.8\,, \quad |\tilde{\kappa}_d| \lesssim 0.2$

CPV in Higgs couplings to W, Z, γ

CPV terms

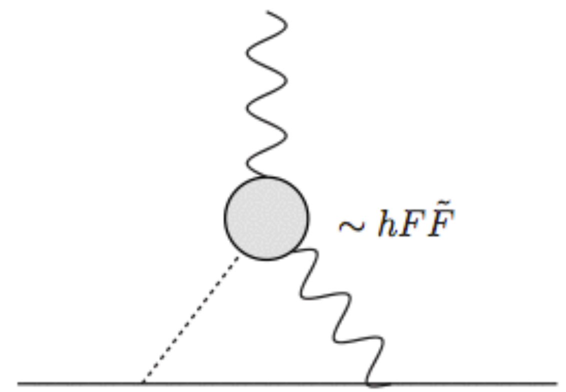
- the HEFT Lagrangian contains CPV couplings to gauge fields

$$\mathcal{L}_{\rm eff} \supset \tilde{c}_{\gamma\gamma}\frac{\alpha}{2\pi v} h F_{\mu\nu}\tilde{F}^{\mu\nu} + \tilde{c}_{\gamma Z}\frac{\alpha}{2\pi v} h F_{\mu\nu}\tilde{Z}^{\mu\nu} + \tilde{c}_{ZZ}\frac{\alpha}{2\pi v} h Z_{\mu\nu}\tilde{Z}^{\mu\nu} + \tilde{c}_{WW}\frac{\alpha}{2\pi v} h W_{\mu\nu}\tilde{W}^{\mu\nu}$$

- each of these induces EDMs
- much less work has been done on these

EDM CONSTRAINTS

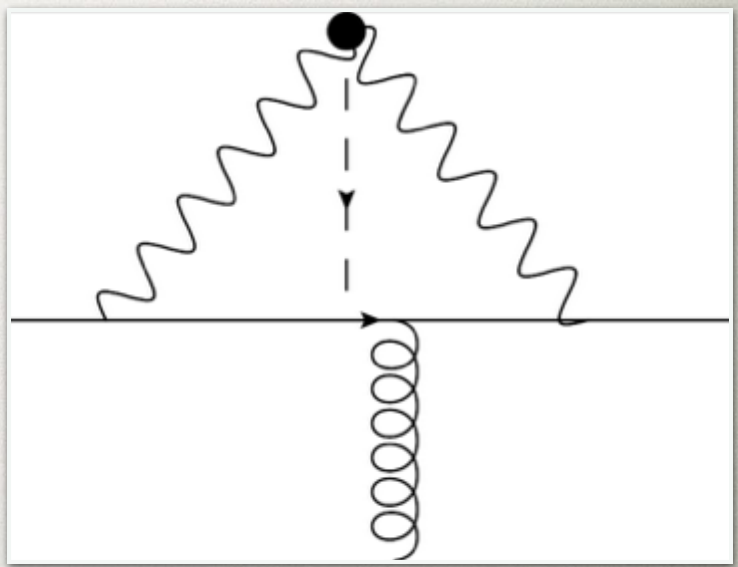
- constraint on $\kappa_e \tilde{c}_{\gamma\gamma}$ from electron EDM



McKeen, Pospelov, Ritz, 1208.4597

- gives $\tilde{c}_{\gamma\gamma} \lesssim 0.3$ for SM electron yukawa, similar bound for $\tilde{c}_{\gamma Z}$
  - vanishes if the Higgs does not couple to e^-
  - or if there is cancel. with CPV coupling to e^-
  - $\tilde{c}_{\gamma\gamma} \lesssim 30$ from nEDM, requires SM u,d yukawas
- note this is a divergent diagram
  - μ scale dependent, requires a counter term
  - the bound should be interpreted only as rough (NDA) estimate

EDM CONSTRAINS



- from $\tilde{c}_{ZZ}$,$\tilde{c}_{WW}$, chromo EDM at 2-loop
- *u,d,s* cEDM suppressed
- by light yukawa
- *b (t)* cEDM from $\tilde{c}_{WW}$ ($\tilde{c}_{ZZ}$) chirality flip from top internal line
- contributes at 1-loop to Weinberg operator
- resulting constraints on $\tilde{c}_{ZZ}$,$\tilde{c}_{WW}$ of ~$O(10^7)$

CONCLUSIONS

- EDMs important constraints on new physics models
- here: interpreted as nontrivial constraints on CPV Higgs yukawa couplings

BACKUP SLIDES

MOTIVATION

- compare NP contribs. to $h \to \gamma\gamma$ and $h \to ZZ$

$$\mathcal{L}_{\rm eff} \supset c_V \frac{m_Z^2}{v} h Z^\mu Z_\mu + \hat{c} \frac{\alpha}{\pi v} h F_{\mu\nu} F^{\mu\nu} + \hat{c}_{ZZ} \frac{\alpha}{\pi v} h Z^{\mu\nu} Z_{\mu\nu} + \tilde{c}_{ZZ} \frac{\alpha}{2\pi v} h Z_{\mu\nu} \tilde{Z}^{\mu\nu} + \tilde{c} \frac{\alpha}{2\pi v} h F_{\mu\nu} \tilde{F}^{\mu\nu},$$

- 0^+ Higgs: $\tilde{c}$ and $\tilde{c}_{ZZ}$ ops. are P and CP violating
- CPV only in dim 5 ops., generated at 1-loop from NP
- in $h \to \gamma\gamma$ the CP conserving (SM) at 1-loop
  - large $O(1)$ CPV effects possible
- unlike $h \to ZZ$ which has a tree level c_V
  - to see CPV in $h \to ZZ$ need a measrmnt. at $O(10^{-2})$-$O(10^{-3})$

LECs: symmetry relations

- **Prototype:** theta term and mass splitting are chiral partners

$$\begin{pmatrix} \bar{q} i \gamma_5 q \\ \bar{q} \boldsymbol{\tau} q \end{pmatrix} \xrightarrow{SU_A(2)} \begin{pmatrix} -\bar{q} \boldsymbol{\alpha} \cdot \boldsymbol{\tau} q \\ \boldsymbol{\alpha}\, \bar{q} i \gamma_5 q \end{pmatrix}$$

- Nucleon matrix elements are related. At LO (soft pion theorem)

$$\langle N_f \pi^a | \bar{q} i \gamma_5 q | N_i \rangle \;\propto\; F_\pi^{-1} \, \langle N_f | \bar{q}\, \tau^a \, q | N_i \rangle$$

Crewther-DiVecchia-Veneziano-Witten 1979

$$\Downarrow$$

$$\boxed{\bar{g}_0 = \frac{\delta M_{n-p}^{m_d - m_u}}{m_d - m_u} \frac{2 m_d m_u}{m_d + m_u} \bar{\theta}}$$

$$\frac{\bar{g}_0}{F_\pi} = (15 \pm 2) \cdot 10^{-3} \sin \bar{\theta}$$

(with LQCD input)

- Corrections appear at NNLO, not log enhanced

Mereghetti, van Kolck 1505.06272 and refs therein

talk by V. Cirigliano at MIAPP workshop, July 2015

- Summary of chiral symmetry constraints:

Mereghetti, & van Kolck 1505.06272, and references therein

$\bar{\theta}$	$\bar{g}_0$ from $\bar{\theta}$ determined by $(m_n - m_p)_{st}$
qCEDM	$\bar{g}_0$ and $\bar{g}_1$ determined by corrections to meson and baryon spectrum induced by CP-even qCMDM
4-quark	$\bar{g}_0$, $\bar{g}_1$ & $\bar{\Delta}$ determined by CP-even 4-q chiral partner

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- No info from symmetry on 4-N
- No info from symmetry on d_n, d_p
- Large uncertainties from QCD/model estimates [O(1)→O(10)] greatly dilute impact of experimental searches

Example: neutron EDM

$$d_n = \alpha_N \bar{\theta} + \beta_q d_q + \tilde{\beta}_q \tilde{d}_q + \beta_w \left(\frac{v}{\Lambda}\right)^2 c_w$$

Ranges from Engel, van Kolck, Ramsey-Musolf, 1303.2371

α_N	β_q	$\tilde{\beta}_q$	β_w
(0.5 - 4) *10^{-3} e*fm	- (0.17 - 0.52) (q=u) + 0.7 - 2.1 (q=d)	0.09 - 0.9 (q=u) 0.2 - 1.8 (q=d)	(0.2 - 40)*10^{-7} e*fm

- Lattice QCD can play a key role: recent progress on theta term

α_N = -3.8(2)$_{stat}$(9)$_{fit}$ *10^{-3} e*fm — Guo et al., 1502.02295

α_N = -2.7 (1.2) *10^{-3} e*fm; — Akan et al., 1406.2882 Fit to RBC-UKQCD data