

# Constraints on CP-Violating Yukawa Couplings from EDMs

Joachim Brod & Emmanuel Stamou



Workshop “Testing CP-Violation for Baryogenesis”  
Amherst Center for Fundamental Interactions  
March 30, 2018

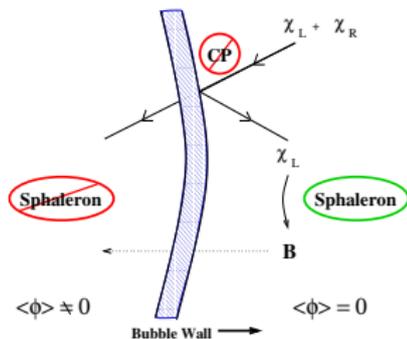
With Ulrich Haisch, Jure Zupan – [JHEP 1311 \(2013\) 180 \[arXiv:1310.1385\]](#)

With Wolfgang Altmannshofer, Martin Schmaltz – [JHEP 1505 \(2015\) 125 \[arXiv:1503.04830\]](#)

With Dimitrios Skodras – [work in progress](#)

# Motivation – Electroweak Baryogenesis

- Baryogenesis fails within the SM
  - Need strong first-order phase transition
  - Need more CP violation
- A minimal setup for electroweak baryogenesis:  
[Huber, Pospelov, Ritz, hep-ph/0610003]



[Image credit: Morrissey et al., 1206.2942]

$$\mathcal{L} = \frac{1}{\Lambda^2} (H^\dagger H)^3 + \frac{Z_t}{\Lambda^2} (H^\dagger H) \bar{Q}_3 H^c t_R$$

- $\Lambda \sim 500 - 800 \text{ GeV}$  gives correct baryon-to-photon ratio  $\eta_b$
- In principle, there are more operators  
[E.g., de Vries et al. 1710.04061]

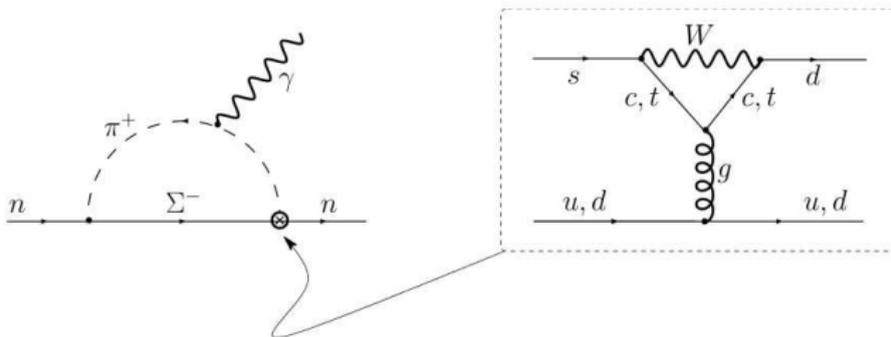
# Outline

- EDM overview
- EDM constraints on CP-violating Higgs couplings
  - Top Yukawa
  - Light-fermion Yukawas
  - Bottom & charm Yukawa → second half

# EDM Overview

# Sources of CP violation

- QCD is CP invariant...
  - ... apart from possible  $\theta$  term  $\propto \epsilon_{\mu\nu\alpha\beta} G^{\mu\nu} G^{\alpha\beta}$
  - Neglect for the purpose of this talk
- Microscopic origin of CP violation:
  - Weak interactions
  - New Physics
- E.g. neutron EDM: SM contribution is tiny,  $d_n^{SM} \sim 10^{-32} e \text{ cm}$   
[Khriplovich & Zhitnitsky, PLB 109 (1982) 490]



# EDM experiments, bounds

- Measure different EDMs
  - Elementary: neutron, proton, deuteron
  - Atomic: mercury, radium, xenon
  - Molecular: ThO (mainly electron)
- Current bounds and prospects:

[Hewett et al., 1205.2671; Baker et al., hep-ex/0602020; [ACME 2013]; Graner et al. 1601.04339]

	$d_e$ [e cm]	$d_n$ [e cm]	$d_{p,D}$ [e cm]
current	$8.7 \times 10^{-29}$	$2.9 \times 10^{-26}$	–
expected	$5.0 \times 10^{-30}$	$1.0 \times 10^{-28}$	$1.0 \times 10^{-29}$
	$d_{\text{Hg}}$	$d_{\text{Xe}}$	$d_{\text{Ra}}$
current	$7.4 \times 10^{-30}$	$5.5 \times 10^{-27}$	$4.2 \times 10^{-22}$
expected	–	$5.0 \times 10^{-29}$	$1.0 \times 10^{-27}$

# Low-energy operators

- At low scales, three types of operators contribute:

- qEDM:  $\bar{q}\sigma^{\mu\nu}\gamma_5 q F_{\mu\nu}$
- qCEDM:  $\bar{q}\sigma^{\mu\nu} T^a \gamma_5 q G_{\mu\nu}^a$
- Weinberg:  $f^{abc} \epsilon_{\mu\nu\alpha\beta} G_{\alpha\beta}^a G_{\mu\rho}^b G_{\nu}^{c,\rho}$

- Hadronic matrix elements:

- qEDM  $\rightarrow$  lattice

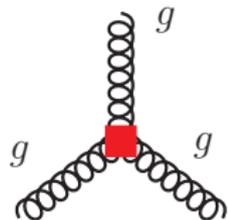
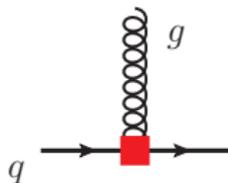
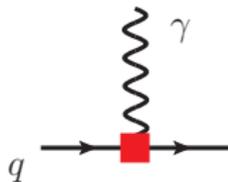
[Battacharya et al., 1506.04196, 1506.06411]

- qCEDM: ChPT and NDA

[E.g. Pospelov & Ritz, hep-ph/0504231]

- Weinberg: No systematic calculation exists, even sign unknown

[NDA: Weinberg PRL 63 (1989) 2333, Sum rules: Demir et al. hep-ph/0208257]



# Connection to Higgs

## MJRM Formula of Merit

$$d \sim (10^{-16} \text{ e cm}) \times (v / \Lambda)^2 \times \sin\phi \times y_f F$$

# MJRM Formula of Merit

$$d \sim (10^{-16} \text{ e cm}) \times (v / \Lambda)^2 \times \sin\phi \times y_f F$$

- We will look at modification

$$\mathcal{L}'_Y = -\frac{y_f}{\sqrt{2}} \kappa_f \bar{f} (\cos\phi_f + i\gamma_5 \sin\phi_f) f h$$

- Motivated by higher dimension operators

$$-\frac{\lambda}{\Lambda^2} |H|^2 \bar{Q}_L H d_R, \quad -\frac{\lambda'}{\Lambda^2} |H|^2 \bar{Q}_L \tilde{H} u_R$$

- In the SM,  $\kappa_f = 1$  and  $\phi_f = 0$

## MJRM Formula of Merit

$$d \sim (10^{-16} \text{ e cm}) \times (v / \Lambda)^2 \times \sin\phi \times y_f F$$

- We will look at modification

$$\mathcal{L}'_Y = -\frac{y_f}{\sqrt{2}} \kappa_f \bar{f} (\cos\phi_f + i\gamma_5 \sin\phi_f) f h$$

- Motivated by higher dimension operators

$$-\frac{\lambda}{\Lambda^2} |H|^2 \bar{Q}_L H d_R, \quad -\frac{\lambda'}{\Lambda^2} |H|^2 \bar{Q}_L \tilde{H} u_R$$

- In the SM,  $\kappa_f = 1$  and  $\phi_f = 0$

# MJRM Formula of Merit

$$d \sim (10^{-16} \text{ e cm}) \times (v / \Lambda)^2 \times \sin\phi \times y_f F$$

- We will look at modification

$$\mathcal{L}'_Y = -\frac{y_f}{\sqrt{2}} \kappa_f \bar{f} (\cos\phi_f + i\gamma_5 \sin\phi_f) f h$$

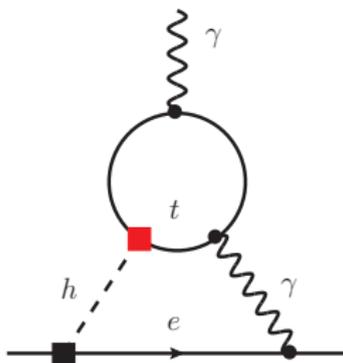
- Motivated by higher dimension operators

$$-\frac{\lambda}{\Lambda^2} |H|^2 \bar{Q}_L H d_R, \quad -\frac{\lambda'}{\Lambda^2} |H|^2 \bar{Q}_L \tilde{H} u_R$$

- In the SM,  $\kappa_f = 1$  and  $\phi_f = 0$

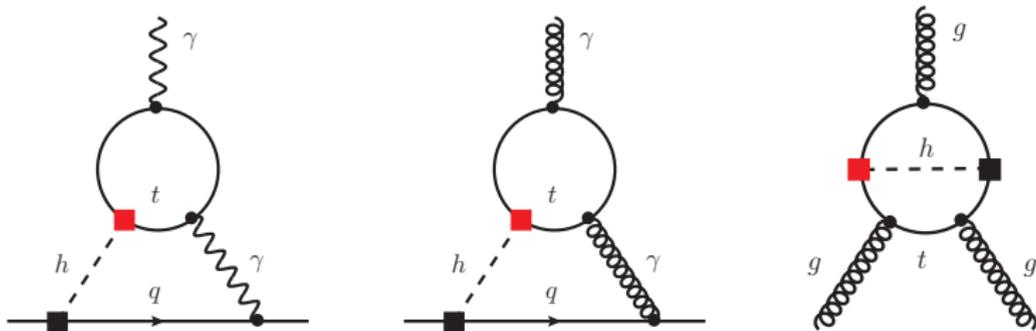
# Top Yukawa

# Electron EDM – Barr-Zee contributions



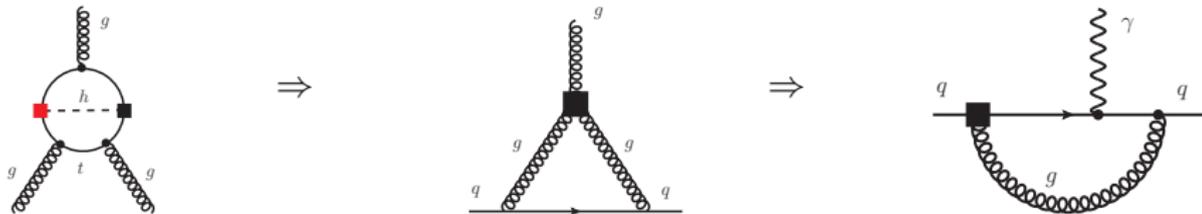
- “Barr-Zee” diagrams induce electron EDM  
[Weinberg PRL 63 (1989) 2333, Barr & Zee PRL 65 (1990) 21]
- $|d_e/e| < 8.7 \times 10^{-29}$  cm (90% CL) [ACME 2013]
- $\Rightarrow \kappa_t |\sin \phi_t| < 0.01$
- Constraint on  $\phi_t$  vanishes if the Higgs does not couple to the electron

# Neutron EDM – The Weinberg Operator



- Barr-Zee diagrams similar as in electron case
- Contribution of the Weinberg Operator: Higgs couples only to top quark
  - Get constraint even if couplings to light quarks vanish

# Neutron EDM – RG running



- Operator mixing:  $\mu \frac{d}{d\mu} \mathcal{C}(\mu) = \gamma^T \mathcal{C}(\mu)$

$$\gamma = \frac{\alpha_s}{4\pi} \begin{pmatrix} \frac{32}{3} & 0 & 0 \\ \frac{32}{3} & \frac{28}{3} & 0 \\ 0 & -6 & 14 + \frac{4N_f}{3} \end{pmatrix}$$

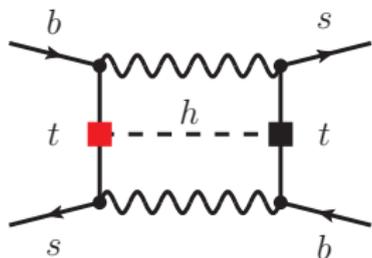
- Hadronic matrix elements are evaluated at  $\mu_H \sim 1$  GeV
- QCD sum rules (large  $\mathcal{O}(1)$  uncertainties!)  
[Pospelov, Ritz, hep-ph/0504231]

# Neutron EDM – Constraints on top Yukawa

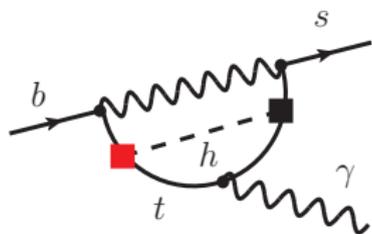
$$\frac{d_n}{e} = \kappa_t \left\{ -4.2 \sin \phi_t + 4.8 \cdot 10^{-2} \kappa_t \sin \phi_t \cos \phi_t \right. \\ \left. \pm (50 \pm 40) 1.9 \cdot 10^{-2} \kappa_t \sin \phi_t \cos \phi_t \right\} \cdot 10^{-25} \text{ cm}.$$

- Terms  $\propto \cos \phi_t$  subdominant, but proportional only to top Yukawa
- $|d_n/e| < 2.9 \times 10^{-26} \text{ cm}$  (90% CL) [Baker et al., hep-ex/0602020]
  - $|\sin \phi_t| \lesssim 0.1$  (0.06) – SM couplings to light quarks
  - $|\sin \phi_t| \lesssim 0.3$  (0.3) – only coupling to top quark

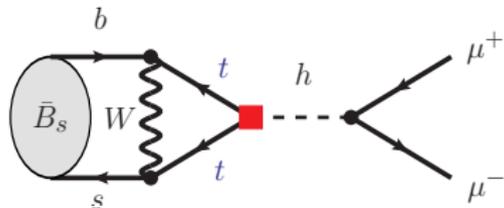
# Other low-energy constraints



- No effects in dim. six operators



- $\mathcal{O}(100)$  effects allowed by data



- $\mathcal{O}(100)$  effects allowed by data

# Connection to SM EFT

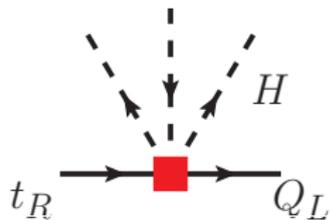
# Top-Higgs Sector in the SM EFT

- Five chirality flipping operators at dim. 6 without FCNC:

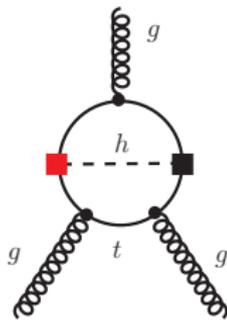
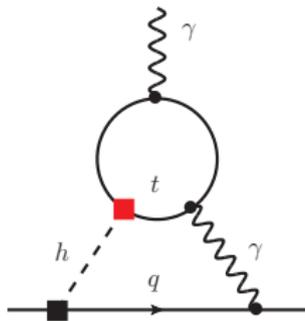
[Cirigliano, Dekens, Mereghetti, de Vries, 1603.03049, 1605.04311]

- $|H|^2 \bar{Q}_L \tilde{H} t_R$ ,
- $\bar{Q}_L \tilde{H} \sigma^{\mu\nu} T^a t_R G_{\mu\nu}^a$ ,
- $\bar{Q}_L \tilde{H} \sigma^{\mu\nu} t_R B_{\mu\nu}$ ,
- $\bar{Q}_L \tilde{H} \sigma^{\mu\nu} \tau^a t_R W_{\mu\nu}^a$ ,
- $\bar{Q}_L H \sigma^{\mu\nu} \tau^a b_R W_{\mu\nu}^a$

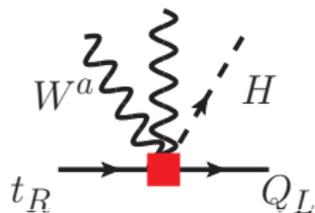
# $|H|^2 \bar{Q}_L \tilde{H} t_R$ – Barr-Zee & Weinberg



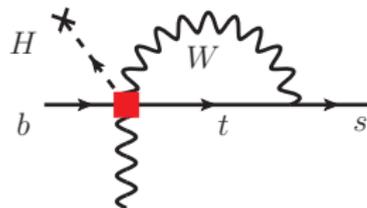
$\Rightarrow$



# $\bar{Q}_L H \sigma^{\mu\nu} \tau^a b_R W_{\mu\nu}^a$ – Flavor



$\Rightarrow$

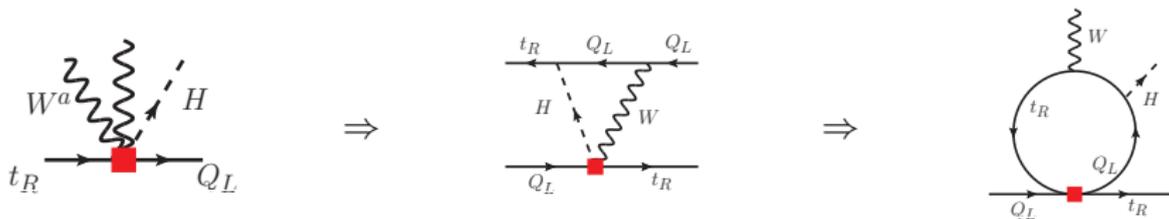


- $A_{CP}(b \rightarrow s\gamma) = 0.015 \pm 0.02$  [HFAG]
- $v^2 C_{Wt} \simeq 0.1$  [1605.04311]

# $\bar{Q}_L H \sigma^{\mu\nu} \tau^a b_R W_{\mu\nu}^a$ – EDMs

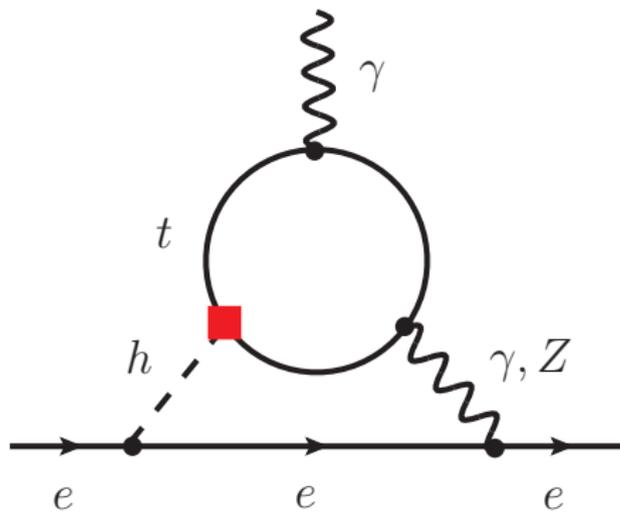


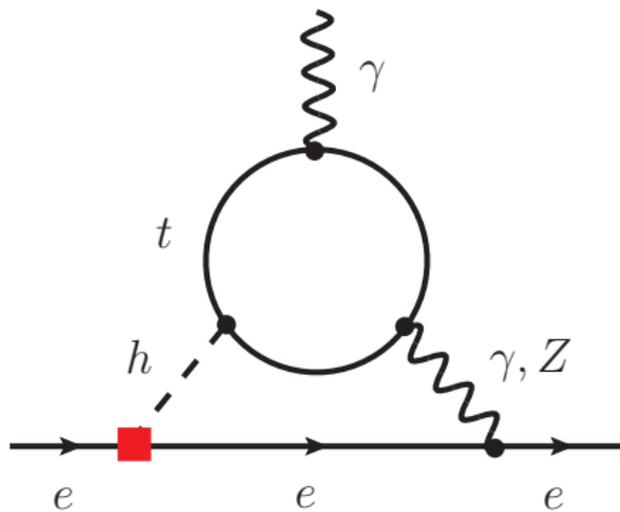
- Suppressed by  $|V_{td}|^2 \sim 6.7 \times 10^{-5}$

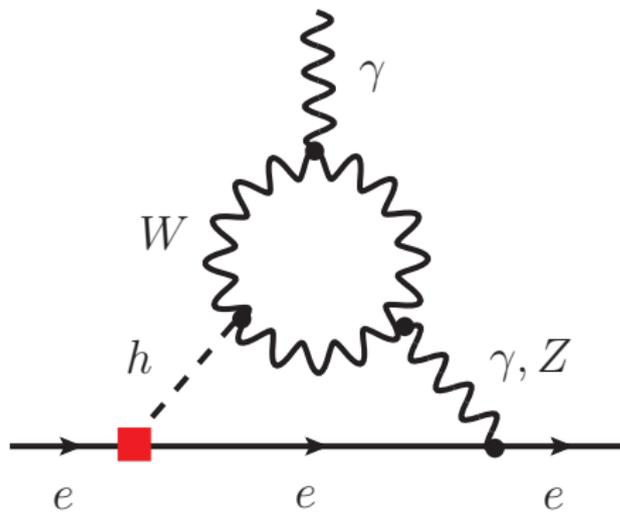


- Gives stronger bound than direct insertion by factor  $10^3$
- $v^2 C_{Wt} \simeq 0.001$  [Cirigliano, Dekens, Mereghetti, de Vries, 1605.04311]

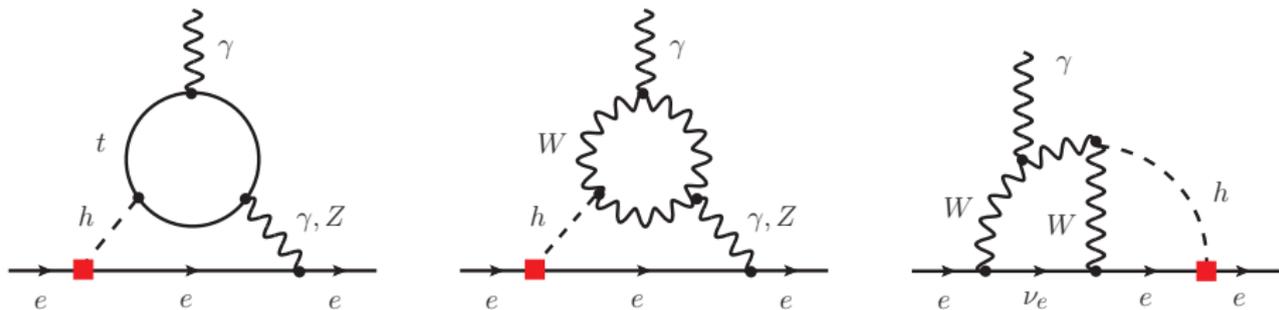
# Light-Fermion Yukawas





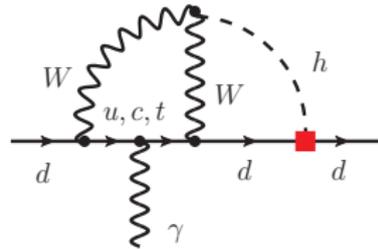
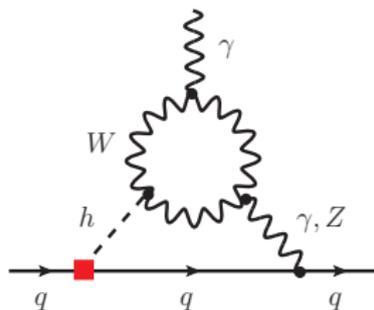
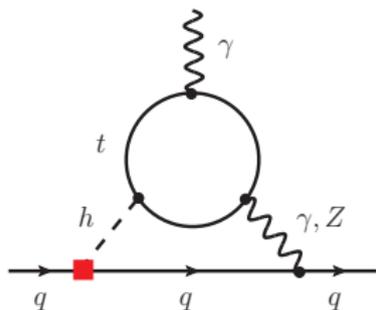


# Light fermions: electron



- ... + 117 more two-loop diagrams
- Complete analytic result [Altmannshofer, Brod, Schmaltz, 1503.04830]
  - See also [Czarnecki & Gribouk hep-ph/0509205]
- Electron EDM:  $|d_e/e| < 8.7 \times 10^{-29}$  cm (90% CL) [ACME 2013]
- ... leads to  $|\sin \phi_e| < 0.017$

# Light fermions: 1<sup>st</sup> generation quarks



- Complete analytic result [Brod, Skodras, work in progress]
- **PRELIMINARY** results:

$$\frac{d_n}{e} = (1.0 \pm 0.5) [0.36 \sin \phi_u + 1.70 \sin \phi_d] \times 10^{-25} \text{ cm} .$$

- $\Rightarrow |\sin \phi_u| \lesssim 0.8, \quad |\sin \phi_d| \lesssim 0.2$

# Joachim → Emmanuel



THE UNIVERSITY OF  
CHICAGO

arXiv:180x.xxxxx with Joachim Brod



- How are bottom and charm Yukawas different from top- and light-quark Yukawas?
- How precise are they being constrained at moment?
- How (and why) should we improve on theory uncertainties?
- *Emmanuel, why are you not showing us the final result?*

$$\mathcal{L} = -\frac{y_q^{\text{SM}}}{\sqrt{2}} \kappa_q \bar{q} (\cos \phi_q + i \sin \phi_q) q$$

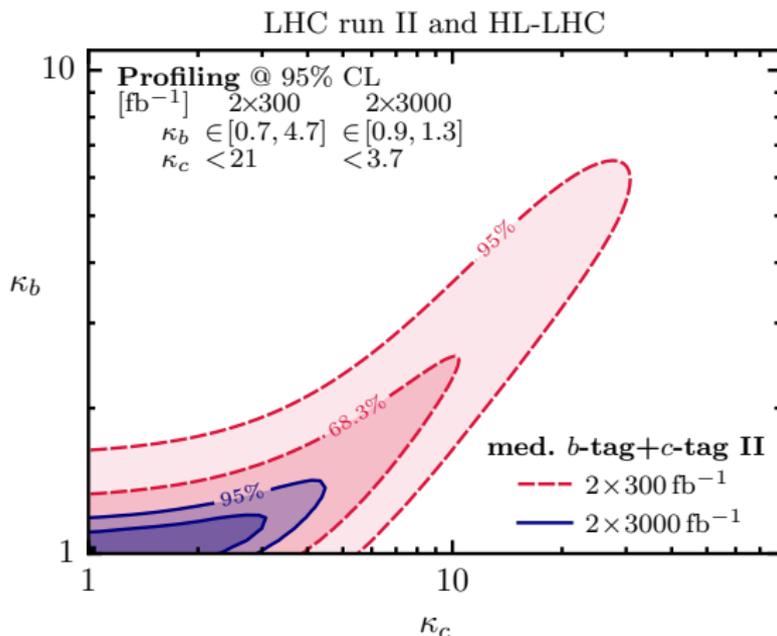
- $\kappa_q$  is a CP conserving NP parameter
- $\phi_q$  is a CP violating NP phase

## Collider

- On-shell production of Higgs / rate measurements probe typically only  $\kappa_q$ , **not**  $\phi_q$ .
- LHC's sensitivity to  $\phi_q$  is trickier (interference in loops, asymmetries, exclusive decays,...) [See Kazuki Sakurai's and Felix Yu's talk]

# Bottom and Charm Yukawas

## Example 1: HL-LHC with charm tagging



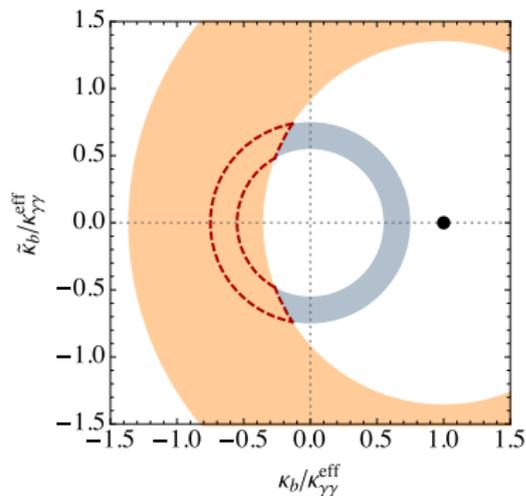
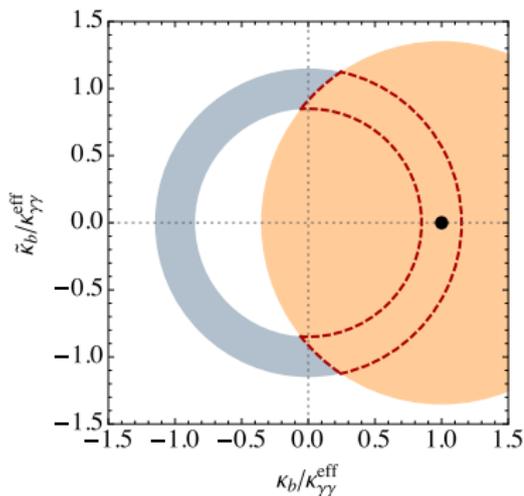
[Perez et al 15]

No information on  $\phi_b$  or  $\phi_c$ .

# Bottom and Charm Yukawas

**Example 2:** Interference in exclusive higgs decays, e.g.,  $h \rightarrow \Upsilon \gamma$

[Bodwin et al 13, Kagan et al 14, König et al 15]



[König et al 15]

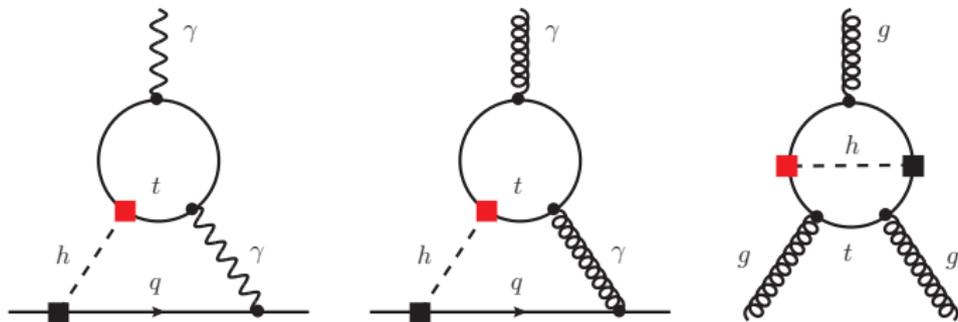
0 background hypothesis, sensitivity expected to be weaker [Perez et al 15]

**What about constraints from EDMs?**

# $t$ and light-quark VS $b$ and $c$ Yukawas I

- How are  $b$  and  $c$  Yukawas different from  $t$  and light-quark Yukawas?

**Top-quark:** leading contribution to neutron EDM



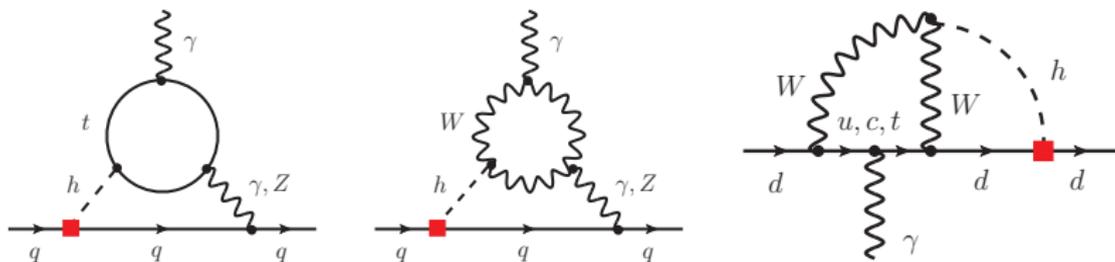
→ **Matching** at  $\mu_{ew}$  / integrating out higgs and top suffices

$$\frac{d_n}{e} = (\# + \# \log \frac{m_t}{m_h}) (\kappa_t^2 \sin \phi_t \cos \phi_t \text{ or } \kappa_t \kappa_q \sin \phi_t \cos \phi_q) \quad (1)$$

# $t$ and light-quark VS $b$ and $c$ Yukawas II

- How are  $b$  and  $c$  Yukawas different from  $t$  and light-quark Yukawas?

**Light-quarks:** leading contribution to neutron EDM



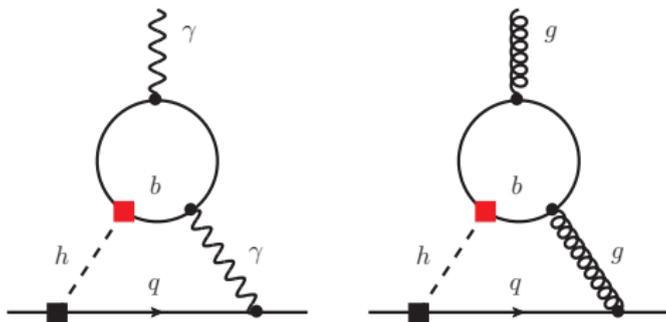
→ **Matching** at  $\mu_{ew}$  / integrating out higgs and top again suffices

$$\frac{d_n}{e} = (\# + \# \log \frac{m_{t,Z,W}}{m_h}) (\kappa_q \sin \phi_q) \quad (2)$$

# $t$ and light-quark VS $b$ and $c$ Yukawas II

- How are  $b$  and  $c$  Yukawas different from  $t$  and light-quark Yukawas?

**Bottom/Charm quark:** the “naive” contribution to neutron EDM



→ Matching dipoles at  $\mu_{ew}$  is a **bad** approximation

$$\tilde{d}_q = g_s^3 \left( \# + \# \log \frac{m_b}{m_h} \right) (\kappa_b \sin \phi_b) \quad (3)$$

Two very different scales in the problem → large logarithms

→ large uncertainties, e.g.,

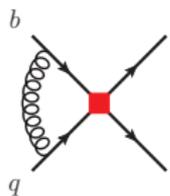
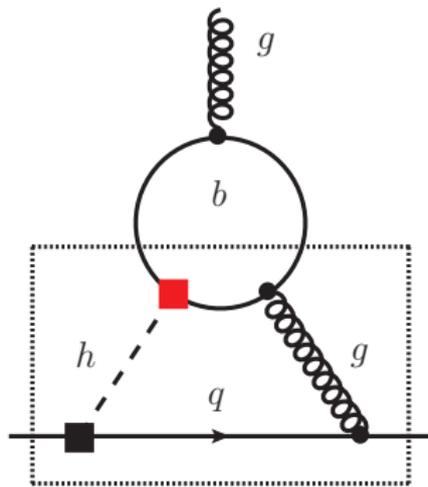
$$\alpha_s(m_h)^2 = 0.01? \quad \alpha_s(m_b)^2 = 0.045? \quad \alpha_s(2 \text{ GeV})^2 = 0.07?$$

- Factor  $\approx 5$  uncertainty in CEDM Wilson coefficient
- Multi-scale problem  $\rightarrow \alpha_s \log \frac{m_b}{m_h} \sim 1$
- Framework to control large logs: **EFT + RGE**
  - $\rightarrow$  Sum all  $\alpha_s^n \log^n m_b/m_h$  to all orders (LL) ✓
  - $\rightarrow$  Sum all  $\alpha_s^n \log^{n-1} m_b/m_h$  to all orders (NLL) ✗

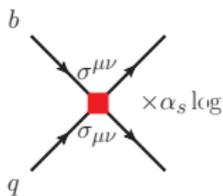
[Brod et al 13]

[in progress]

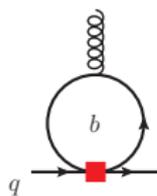
# What is the EFT + RGE doing for us?



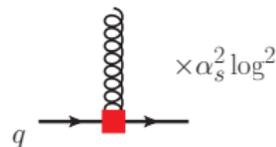
$\Rightarrow$



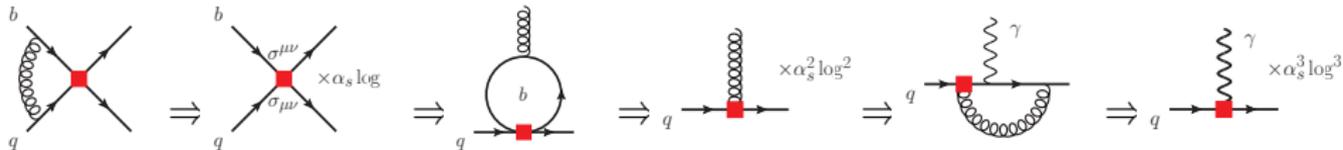
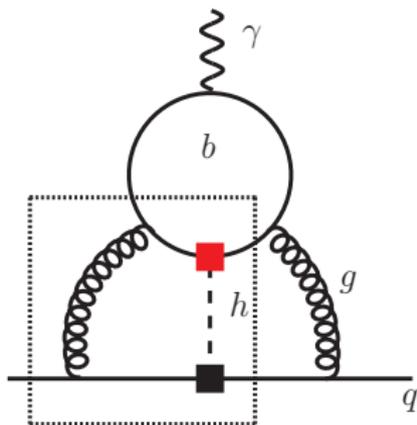
$\Rightarrow$



$\Rightarrow$



# What is the **EFT + RGE** doing for us?



- This “3-loop” contribution dominates over the two-loop Barr-Zee by a factor of  $\approx 10!$

# Loop strategy

1. Write all effective operators that contribute to quark EDMs below the EW scale (CP-odd).
2. Match at the tree-level and obtain the tree-level Wilson coefficients.
3. Compute the one-loop running.
4. Solve the RGE and check residual uncertainties.
5. **If** uncertainties larger than experimental or hadronic input **go back to 2.** and redo for one loop-order higher **else** stop.

# The effective CP-odd flavour-conserving Lagrangian

$$\mathcal{L}_{\text{eff}} = -\frac{\sqrt{2}G_F}{M_h^2} \left\{ m_q^2 \sum_{i=1,\dots,4} C_i^q O_i^q + C_5 O_5 \right. \\ \left. + \sum_{q \neq q'} m_q m_{q'} \left[ \sum_{i=1,2} C_i^{qq'} O_i^{qq'} + \frac{1}{2} \sum_{i=3,4} C_i^{qq'} O_i^{qq'} \right] \right\}$$

$$O_1^q = (\bar{q}q) (\bar{q} i\gamma_5 q)$$

$$O_1^{qq'} = (\bar{q}q) (\bar{q}' i\gamma_5 q')$$

$$O_2^q = (\bar{q}\sigma_{\mu\nu}q) (\bar{q} i\sigma^{\mu\nu} \gamma_5 q)$$

$$O_2^{qq'} = (\bar{q} T^a q) (\bar{q}' i\gamma_5 T^a q')$$

$$O_3^q = \frac{ieQ_q m_q}{2 g_s^2} \bar{q}\sigma^{\mu\nu} \gamma_5 q F_{\mu\nu}$$

$$O_3^{qq'} = (\bar{q}\sigma_{\mu\nu}q) (\bar{q}' i\sigma^{\mu\nu} \gamma_5 q')$$

$$O_4^q = -\frac{i}{2} \frac{m_q}{g_s} \bar{q}\sigma^{\mu\nu} T^a \gamma_5 q G_{\mu\nu}^a$$

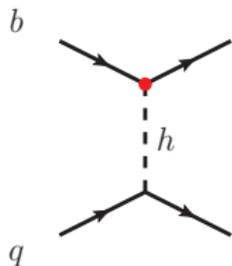
$$O_4^{qq'} = (\bar{q}\sigma_{\mu\nu} T^a q) (\bar{q}' i\sigma^{\mu\nu} \gamma_5 T^a q')$$

$$O_5 = -\frac{1}{3 g_s} f^{abc} G_{\mu\sigma}^a G_{\nu}^{b,\sigma} \tilde{G}^{c,\mu\nu}$$

In 5-flavour theory:  $20 + 6 \times 10 + 1$  operators

# One-loop leading-log resummation

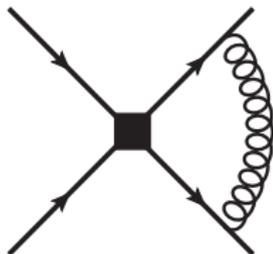
## Tree-level matching



$$C_1^q = -\kappa_q^2 \cos \phi_q \sin \phi_q$$

$$C_1^{qq'} = -\kappa_q \kappa_{q'} \cos \phi_q \sin \phi_{q'}$$

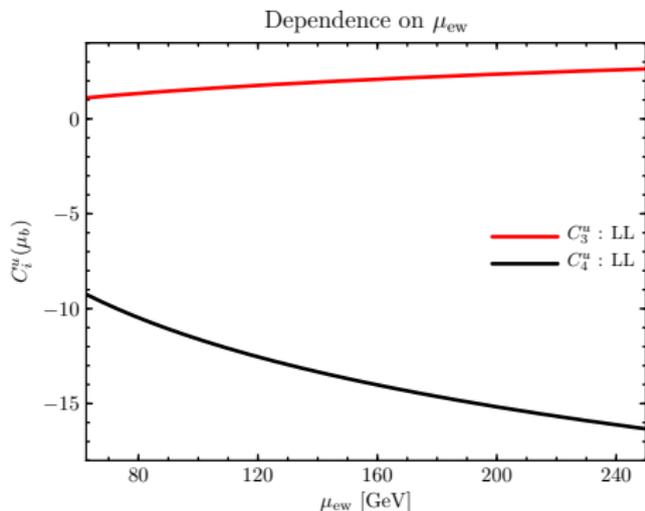
## One-loop mixing



[Hisano et al 12, Misiak et al 94]

# One-loop leading-log resummation

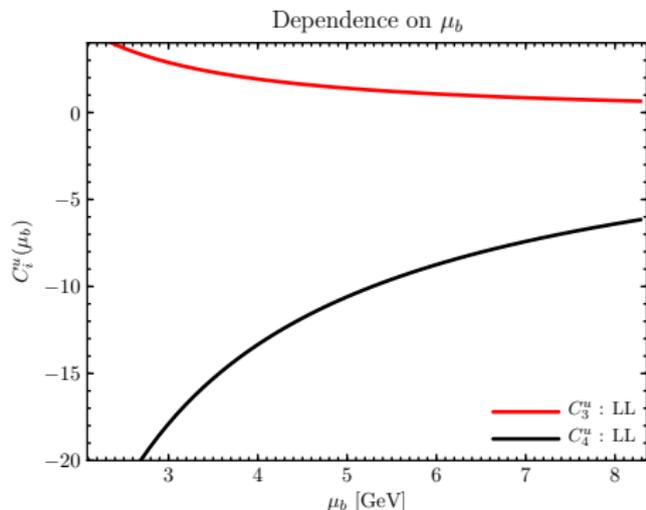
- **RGE evolution** from  $\mu_{ew}$  to  $\mu_b$
- Resumming all orders of  $\alpha_s^n \log^n$
- Value of **light-quark dipole** Wilson coefficients at  $\mu_b$  varying  $\mu_{ew}$



- Approximately **factor of 2 uncertainty** after LL resummation
  - CEDM ME uncertainty  $\approx 100\%$  and good prospects for its implementation on the lattice  
[Bhattacharya et al 15]
- NLL resummation required**

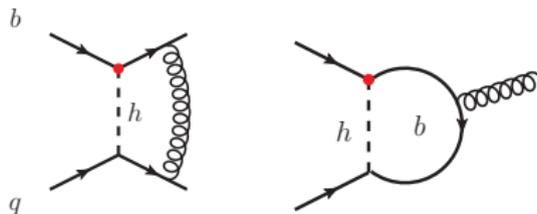
# One-loop leading-log resummation

- **RGE evolution** from  $\mu_{ew}$  to  $\mu_b$
- Resumming all orders of  $\alpha_s^n \log^n$
- Value of **light-quark dipole** Wilson coefficients at  $\mu_b$  varying  $\mu_{ew}$



- Approximately **factor of 2 uncertainty** after LL resummation
  - CEDM ME uncertainty  $\approx 100\%$  and good prospects for its implementation on the lattice  
[Bhattacharya et al 15]
- **NLL resummation required**

## ■ One-loop matching



$$C_1^q(\mu_{ew}) = - \left( 1 + \frac{\alpha_s}{4\pi} \left( \frac{9}{2} + 3 \log \frac{\mu_{ew}^2}{M_h^2} \right) \right) \kappa_q^2 \cos \phi_q \sin \phi_q$$

$$C_2^q(\mu_{ew}) = \frac{\alpha_s}{4\pi} \left( \frac{1}{8} + \frac{1}{12} \log \frac{\mu_{ew}^2}{M_h^2} \right) \kappa_q^2 \cos \phi_q \sin \phi_q$$

$$C_3^q(\mu_{ew}) = - \frac{\alpha_s}{4\pi} \left( 3 + 2 \log \frac{\mu_{ew}^2}{M_h^2} \right) \kappa_q^2 \cos \phi_q \sin \phi_q$$

$$C_4^q(\mu_{ew}) = - \frac{\alpha_s}{4\pi} \left( 3 + 2 \log \frac{\mu_{ew}^2}{M_h^2} \right) \kappa_q^2 \cos \phi_q \sin \phi_q$$

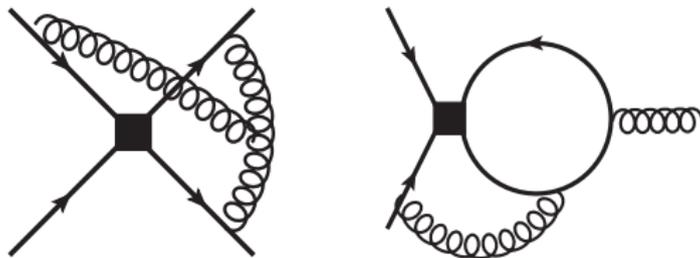
$$C_1^{qq'}(\mu_{ew}) = -\kappa_q \kappa_{q'} \cos \phi_q \sin \phi_{q'}$$

$$C_4^{qq'}(\mu_{ew}) = \frac{\alpha_s}{4\pi} \left( \frac{3}{2} + \log \frac{\mu_{ew}^2}{M_h^2} \right) \kappa_q \kappa_{q'} (\cos \phi_q \sin \phi_{q'} + \sin \phi_q \cos \phi_{q'})$$

## Two-loop mixing:

Renormalize/extract UV poles of 2-loop insertions of operators

in progress, partial results available [Misiak et al 94, Buras et al 00, Degrandi et al 05]



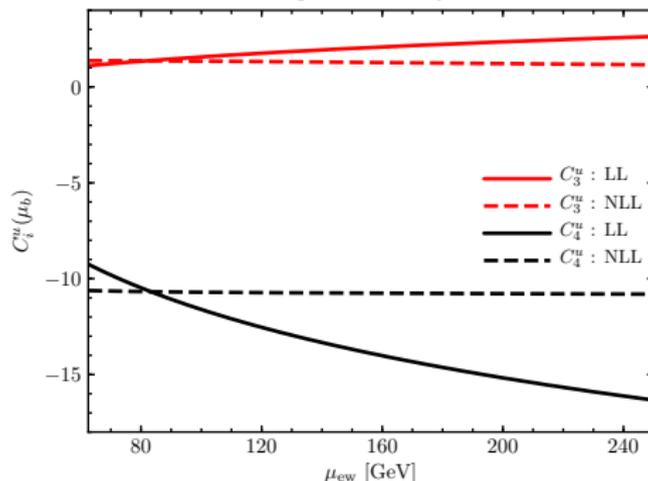
■ Sums  $\alpha_s^n \log^{n-1}$  to all orders

■ Cancels scheme dependence of one-loop Wilson coefficients

■ Cancels  $\mu_{ew}$  and  $\mu_b$  dependence up to higher orders in  $\alpha_s$

## Preliminary/incomplete/scheme-dependent result of the NLL resummation

Dependence on  $\mu_{ew}$



- Running (without the 2-loop mixing) illustrating the cancellation of scale uncertainties
- Why are we not done yet?*

# Peculiarities of the 2-loop computation I

- We extract UV poles of diagrams using *Dimensional regularization*

$$4 \rightarrow 4 - 2\epsilon$$

The basis of operators is then infinitely large, **evanescent operators**  
**Their definition affects the 2-loop ADM**

$$E_1^q = (\bar{q}T^a q)(\bar{q}i\gamma_5 T^a q) + \left(\frac{1}{4} + \frac{1}{2n_c}\right)O_1^q + \frac{1}{16}O_2^q$$

$$E_2^q = (\bar{q}\sigma^{\mu\nu}T^a q)(\bar{q}\sigma_{\mu\nu}i\gamma_5 T^a q) + 3O_1^q - \left(\frac{1}{4} - \frac{1}{2n_c}\right)O_2^q$$

$$E_3^q = (\bar{q}\gamma^{[\mu}\gamma^\nu\gamma^\rho\gamma^{\sigma]}q)(\bar{q}\gamma_{[\mu}\gamma_\nu\gamma_\rho\gamma_{\sigma]}i\gamma_5 q) - 24O_1^q$$

$$E_4^q = (\bar{q}\gamma^{[\mu}\gamma^\nu\gamma^\rho\gamma^{\sigma]}T^a q)(\bar{q}\gamma_{[\mu}\gamma_\nu\gamma_\rho\gamma_{\sigma]}i\gamma_5 T^a q) + 6\left(1 + \frac{2}{n_c}\right)O_1^q + \frac{3}{2}O_2^q$$

$$E_5^q = (\bar{q}\gamma^{[\mu}\gamma^\nu\gamma^\rho\gamma^\sigma\gamma^\tau\gamma^{\nu]}q)(\bar{q}\gamma_{[\mu}\gamma_\nu\gamma_\rho\gamma_\sigma\gamma_\tau\gamma_{\nu]}i\gamma_5 q)$$

$$E_6^q = (\bar{q}\gamma^{[\mu}\gamma^\nu\gamma^\rho\gamma^\sigma\gamma^\tau\gamma^{\nu]}T^a q)(\bar{q}\gamma_{[\mu}\gamma_\nu\gamma_\rho\gamma_\sigma\gamma_\tau\gamma_{\nu]}T^a i\gamma_5 q)$$

$$E_1^{qq'} = (\bar{q}\gamma^\mu\gamma^\nu\sigma^{\rho\tau}q)(\bar{q}'\gamma_\mu\gamma_\nu\sigma_{\rho\tau}i\gamma_5 q') + 24(O_1^{qq'} + O_1^{q'q}) - 12O_3^{qq'}$$

$$E_2^{qq'} = (\bar{q}\gamma^\mu\gamma^\nu\sigma^{\rho\tau}T^a q)(\bar{q}'\gamma_\mu\gamma_\nu\sigma_{\rho\tau}i\gamma_5 T^a q') + 24(O_2^{qq'} + O_2^{q'q}) - 12O_4^{qq'}$$

$$E_3^{qq'} = (\bar{q}\gamma^\mu\gamma^\nu\gamma^\rho\gamma^\sigma\sigma^{\tau\nu}q)(\bar{q}'\gamma_\mu\gamma_\nu\gamma_\rho\gamma_\sigma\sigma_{\tau\nu}i\gamma_5 q') + 384(O_1^{qq'} + O_1^{q'q}) - 192O_3^{qq'}$$

$$E_4^{qq'} = (\bar{q}\gamma^\mu\gamma^\nu\gamma^\rho\gamma^\sigma\sigma^{\tau\nu}T^a q)(\bar{q}'\gamma_\mu\gamma_\nu\gamma_\rho\gamma_\sigma\sigma_{\tau\nu}i\gamma_5 T^a q') + 384(O_2^{qq'} + O_2^{q'q}) - 192O_4^{qq'}$$

# Peculiarities of the 2-loop computation II

- In  $d = 4$

$$(\bar{q}\sigma^{\mu\nu}q)(\bar{q}'\sigma_{\mu\nu}i\gamma_5q') = (\bar{q}\sigma^{\mu\nu}i\gamma_5q)(\bar{q}'\sigma_{\mu\nu}) = (\bar{q}\sigma^{\mu\nu}q)(\bar{q}'\sigma^{\rho\tau}q')\epsilon_{e\mu\nu\rho\tau}$$

- In  $d = 4 - 2\epsilon$

$$(\bar{q}\sigma^{\mu\nu}q)(\bar{q}'\sigma_{\mu\nu}i\gamma_5q') \neq (\bar{q}\sigma^{\mu\nu}i\gamma_5q)(\bar{q}'\sigma_{\mu\nu}) \neq (\bar{q}\sigma^{\mu\nu}q)(\bar{q}'\sigma^{\rho\tau}q')\epsilon_{\mu\nu\rho\tau}$$

Operators differ by **evanescent** structures  $\rightarrow$  different ADM

- We have traces with  $\gamma_5$  for which  $[\gamma^\mu, \gamma_5] = 0$  (NDR) is **inconsistent**
- Need to use 't Hooft Veltman (HV) scheme with mixed (anti-) commutation relations

$$[\tilde{\gamma}^\mu, \gamma_5] = 0 \quad \{\hat{\gamma}^\mu, \gamma_5\} = 0$$

- **Make sure that physical results are independent of such choices**

# Conclusions

- **Higgs couplings** are presently being probed in both the **high-energy** and **high-intensity** frontier
- **Yukawa sector** and  $\theta_{\text{QCD}}$  are the only sources of CP violation in the SM
- EDMs strongly constrain new CP phases in the higgs sector  
(Using EFT we can identify the contributions that are “irreducible”)
- **Important goal for the high-intensity community**
  - Measure and combine info from many observables  
(neutron, proton, electron, atom, ... EDMs)
  - Control theory uncertainties, **lattice QCD** and **perturbative errors**  
(bottom/charm Yukawa example of such an interplay)