Indirect probes of Higgs effective theory

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UCL HEP Seminar,
19 February 2016

2500 – 1 = too many

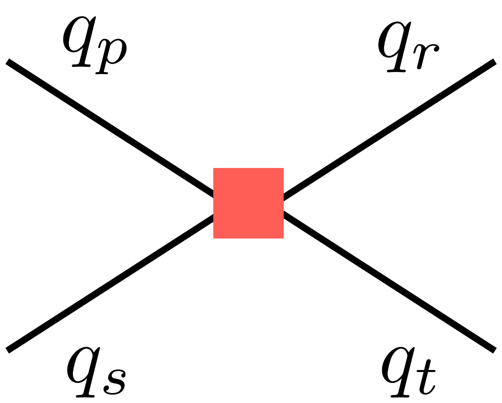
- Taking into account all possible flavour structures, complete set of dimension-6 Higgs effective theory (HEFT) operators consists of 1350 CP-even & 1149 CP-odd composites

[Buchmüller & Wyler, NPB (1986) 268; Grzadkowski et al., 1008.4884]

- Which are the dimension-6 operators that are most strongly (the least) constrained by existing data? In which cases can the LHC, in particular ATLAS & CMS, provide unique insights?

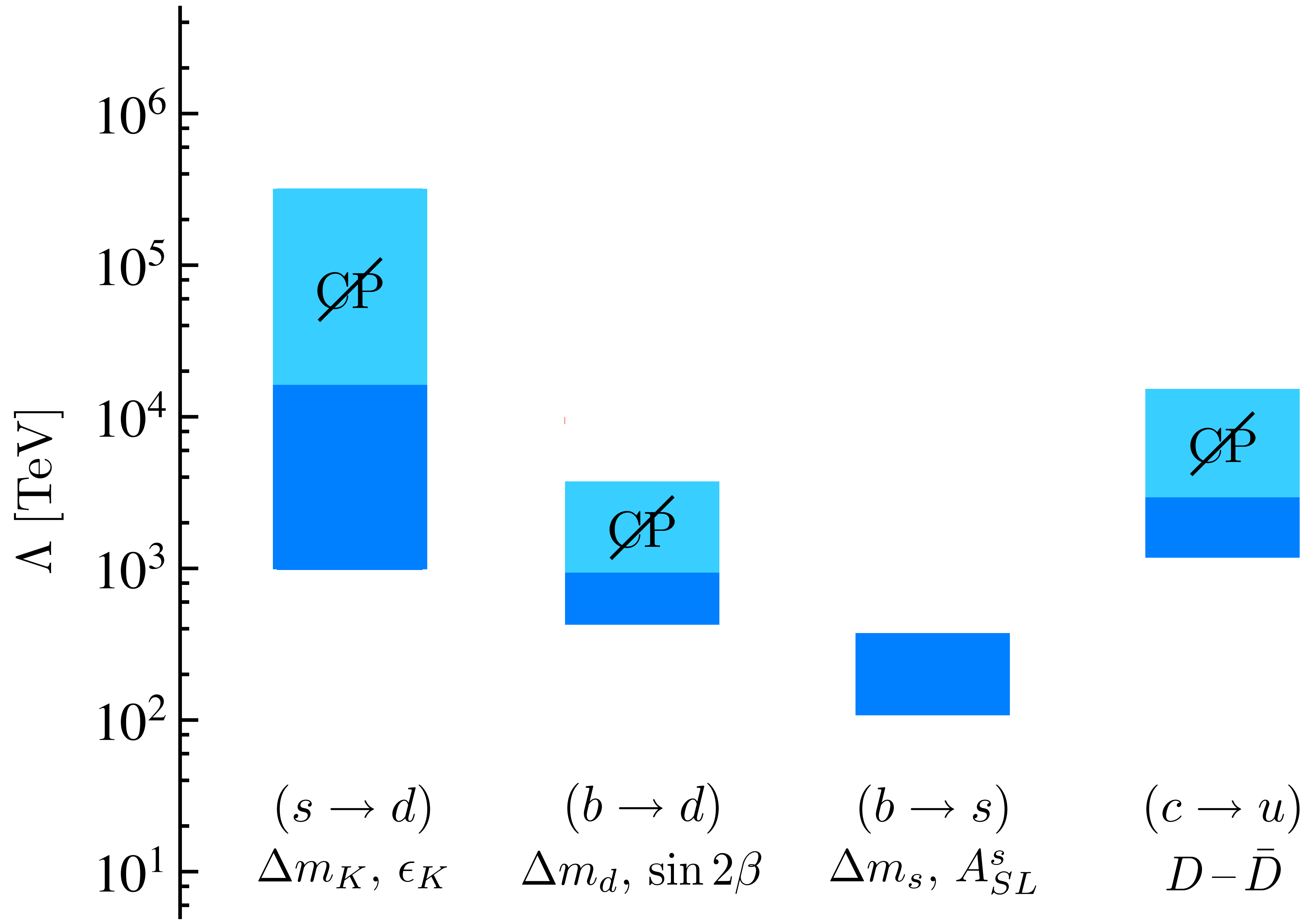
Operator classes

1) ψ^4: $Q_{LL}^{(1)} = (\bar{q}_p \gamma_\mu q_r)(\bar{q}_s \gamma^\mu q_t)\,, \ldots$



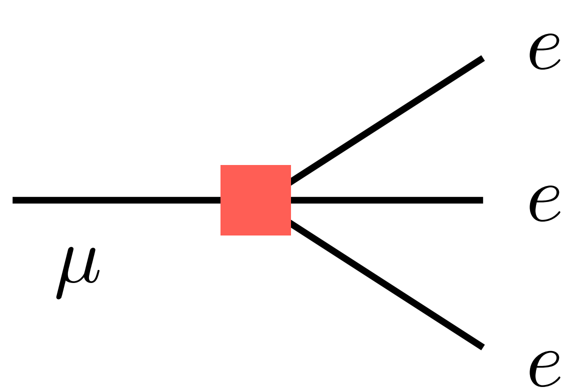
$$\mathcal{L}_{\text{HEFT}} \supset \frac{c_{LL}^{(1)}}{\Lambda^2} Q_{LL}^{(1)}$$

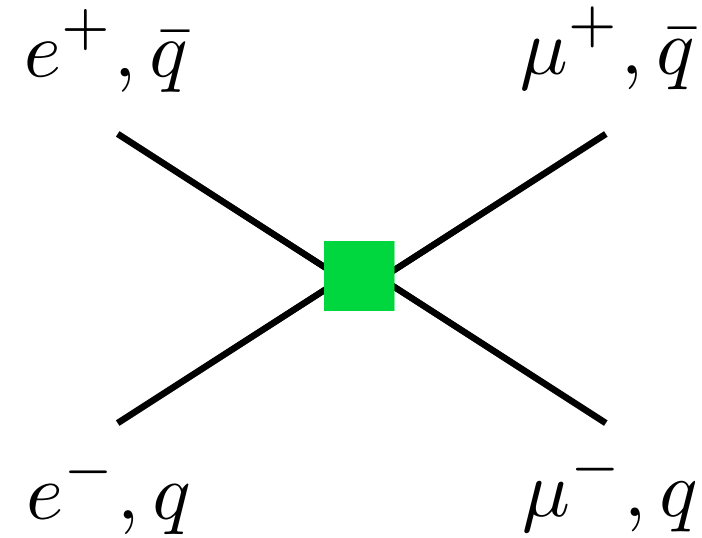
Bounds on ψ⁴ operators†



†figure assumes Wilson coefficients $c_{pr} = 1$, i.e. a generic flavour structure

Bounds on ψ^4 operators



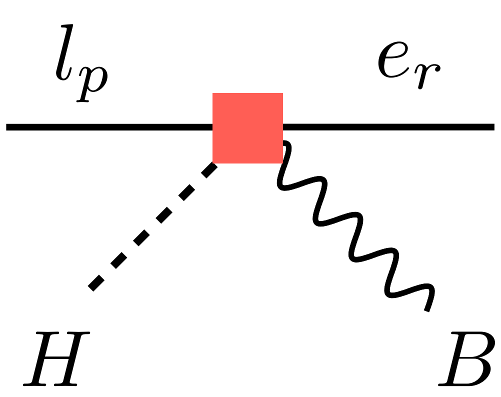


- (Multi-)TeV constraints also apply in case of lepton-flavour violating operators giving rise e.g. to $\mu \to 3e$ as well as contact interactions that lead to di-lepton & di-jet signatures. LHC will further tighten restrictions on all light-quark operators

Operator classes

1) ψ^4 : $Q_{LL}^{(1)} = (\bar{q}_p \gamma_\mu q_r)(\bar{q}_s \gamma^\mu q_t)$, ...

2) $\psi^2 H X$: $Q_{eB} = (\bar{l}_p \sigma_{\mu\nu} e_r) H B^{\mu\nu}$, ...



Bounds on $\psi^2 XH$ operators

$$\mathrm{Br}\left(\mu \to e\gamma\right) = 1.5 \cdot 10^8 \, \frac{|c_{eB}^{21}|^2}{\Lambda^4} \, \mathrm{TeV}^4 < 5.7 \cdot 10^{-13} \ (90\% \ \mathrm{CL})$$

[MEG, 1303.0754]

$$\Lambda \gtrsim 1.3 \cdot 10^5 \sqrt{|c_{eB}^{21}|} \, \mathrm{TeV} \simeq 1.3 \cdot 10^4 \, \mathrm{TeV} \ \ (\text{weak loop})^{\dagger}$$

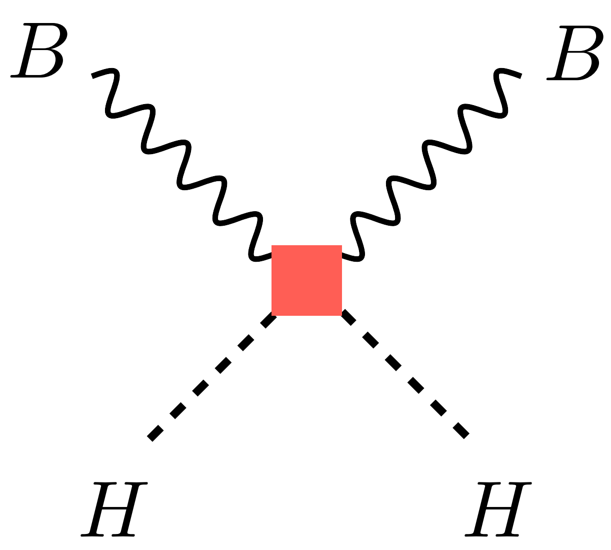
†applies to normal ultraviolet (UV) completions

Operator classes

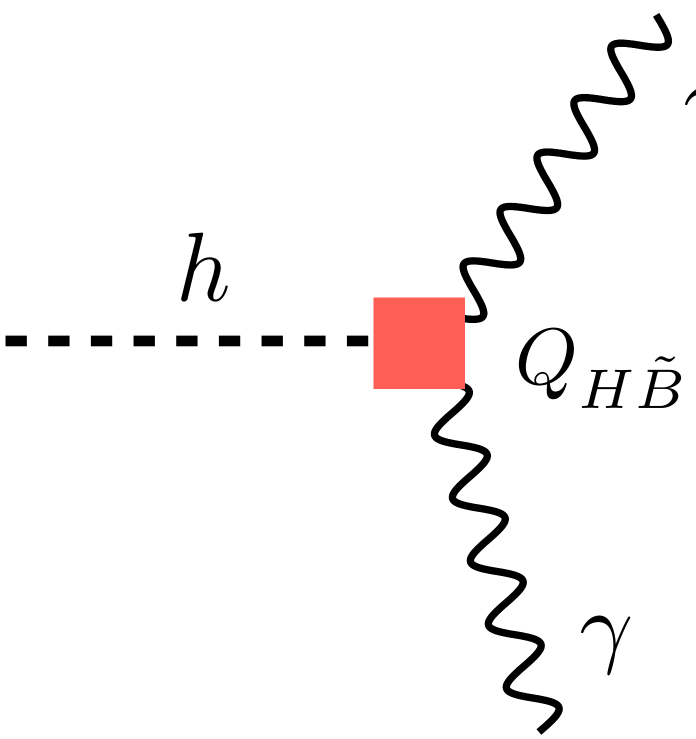
1) $\psi^4: \; Q_{LL}^{(1)} = (\bar{q}_p \gamma_\mu q_r)(\bar{q}_s \gamma^\mu q_t)\,, \ldots$

2) $\psi^2 H X: \; Q_{eB} = (\bar{l}_p \sigma_{\mu\nu} e_r) H B^{\mu\nu}\,, \ldots$

3) $X^2 H^2$: $Q_{HB} = (H^\dagger H) B_{\mu\nu} B^{\mu\nu},\; Q_{H\tilde{B}} = (H^\dagger H) B_{\mu\nu} \tilde{B}^{\mu\nu}\,, \ldots$



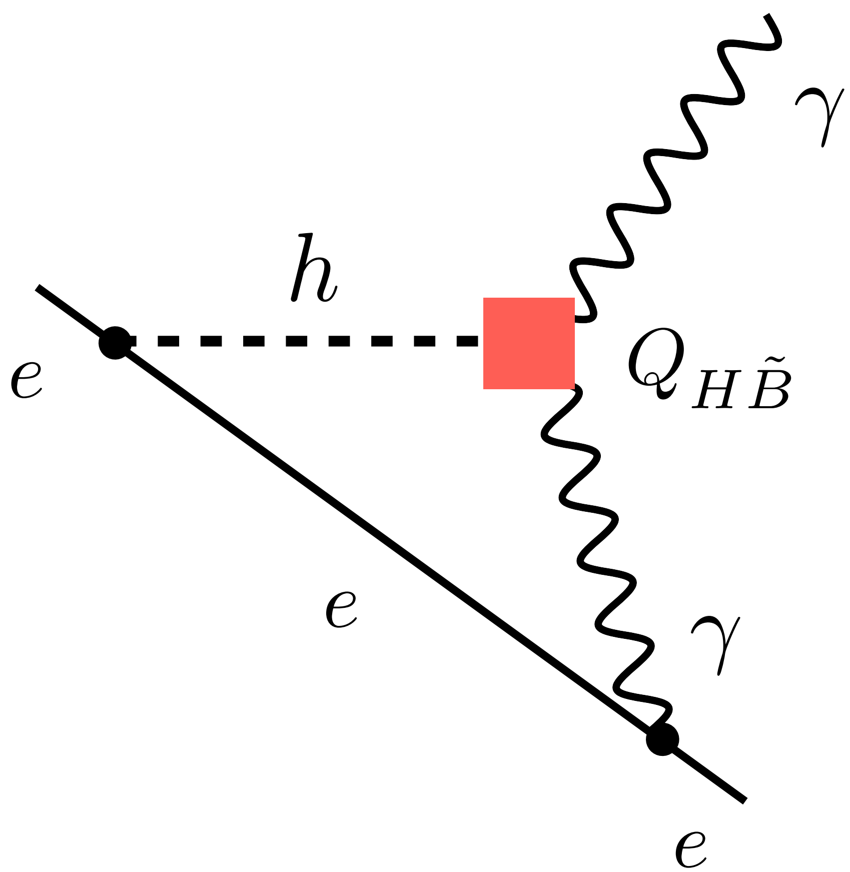
From h→γγ to …



- X^2H^2 operators alter Higgs physics. For instance di-photon decay:

$$\mathcal{L} \supset \frac{c_{H\tilde{B}}\, v}{\Lambda^2}\, h F_{\mu\nu} \tilde{F}^{\mu\nu}$$

… electron electric dipole moment



- X^2H^2 operators alter Higgs physics. For instance di-photon decay:

$$\mathcal{L} \supset \frac{c_{H\tilde{B}}\, v}{\Lambda^2}\, h F_{\mu\nu} \tilde{F}^{\mu\nu}$$

- Attaching electron line to $Q_{H\tilde{B}}$ generates electric dipole moment (EDM) for electron d_e. As SM background 3-loop suppressed, EDMs offer unique indirect probe of CP-violating (CPV) operators

Bounds on CP-odd X^2H^2 operators

$$\left|\frac{d_e}{e}\right| = \frac{|c_{H\tilde{B}}|}{\Lambda^2}\frac{m_e}{4\pi^2}\ \ln\frac{\Lambda^2}{m_h^2} < 8.7\cdot 10^{-29}\,\mathrm{cm}\ \ (90\%\,\mathrm{CL})$$

[ACME, 1310.7534]

⇓

$$\Lambda \gtrsim 200\sqrt{|c_{H\tilde{B}}|}\ \mathrm{TeV} \simeq 20\,\mathrm{TeV}\ \ (\text{weak loop})^\dagger$$

† applies to normal UV-complete theories

Bounds on CP-even X^2H^2 operators

$$\left|\frac{\Gamma(h\to\gamma\gamma)}{\Gamma(h\to\gamma\gamma)_{\rm SM}}-1\right|\simeq 530\;|c_{HB}|\;\frac{v^2}{\Lambda^2}\lesssim 20\%$$

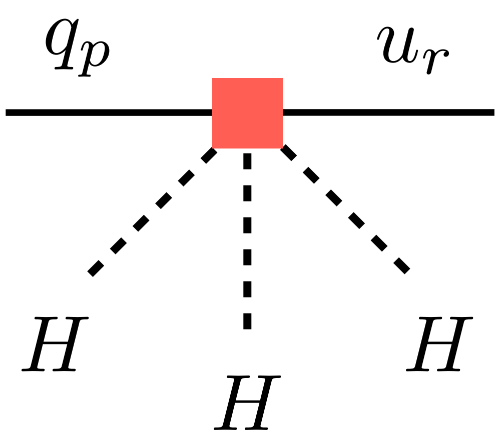
[ATLAS, 1507.04548; CMS-PAS-HIG-14-009]

$$\Lambda\gtrsim 13\sqrt{|c_{HB}|}\;\text{TeV}\simeq 1.3\,\text{TeV}\quad(\text{weak loop})^\dagger$$

†applies to normal UV-complete theories

Operator classes

4) $\psi^2 H^3$: $Q_{uH} = (H^\dagger H)(\bar{q}_p u_r \tilde{H})\,, \ldots$



Physics of ψ²H³ composites

- Adding ψ²H³ operators to SM will change Yukawa couplings & generically induce flavour-changing & CPV interactions:

$$\mathcal{L} = \mathcal{L}_{\rm SM} - \left(\frac{c_{pr}}{\Lambda^2} (H^\dagger H)(\bar{q}_p u_r \tilde{H}) + \text{h.c.} \right)$$

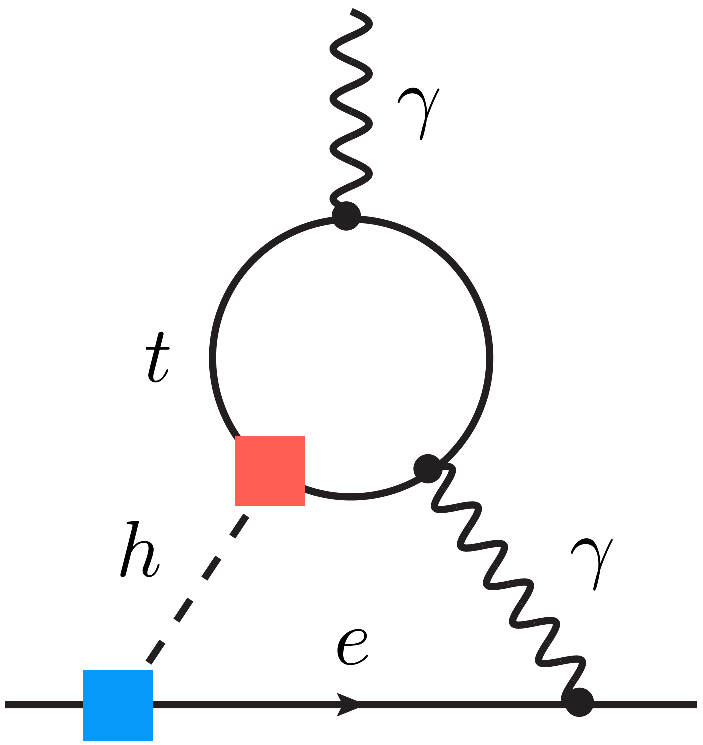
$$\Downarrow$$

$$\mathcal{L} \supset -\left(Y_{tu}\, \bar{t}_L u_R h + Y_{ut}\, \bar{u}_L t_R + \text{h.c.} \right)$$

$$Y_{pr} = \frac{m_p}{v} \delta_{pr} + \frac{v^2}{\sqrt{2}\Lambda^2} \tilde{c}_{pr} \,, \quad \tilde{c} = U_L c U_R^\dagger \not\propto \mathbf{1}$$

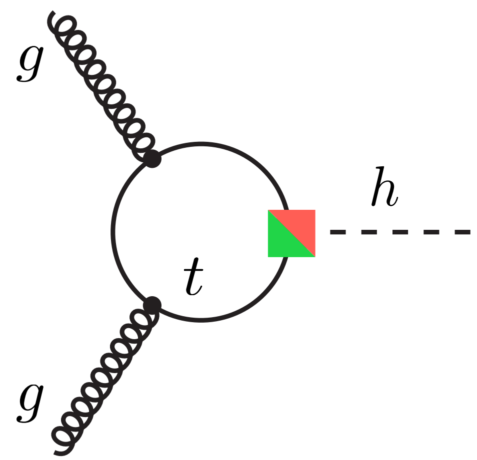
$h\bar{t}t$ couplings in d_e

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

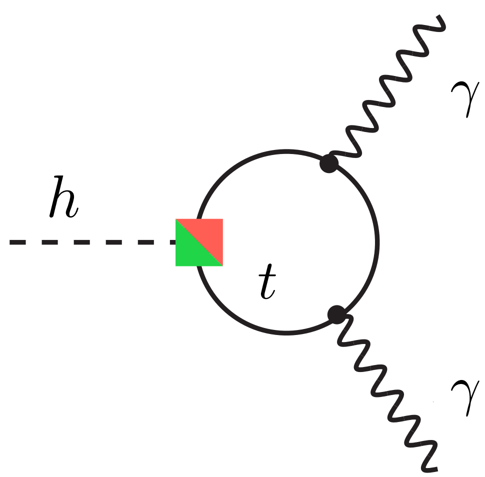


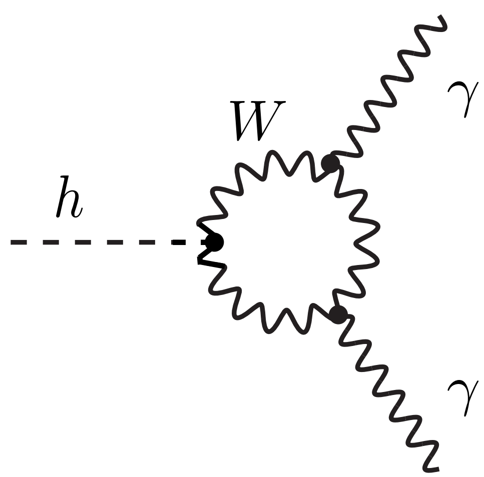
- d_e induced via two-loop diagrams of Barr-Zee type
- Constraint vanishes if Higgs does not couple to electron

h$\bar{t}$t couplings in Higgs physics



$$\frac{\sigma(gg \to h)}{\sigma(gg \to h)_{\rm SM}} \simeq \kappa_t^2 + 2.6\tilde{\kappa}_t^2 + 0.11\kappa_t(\kappa_t - 1)$$

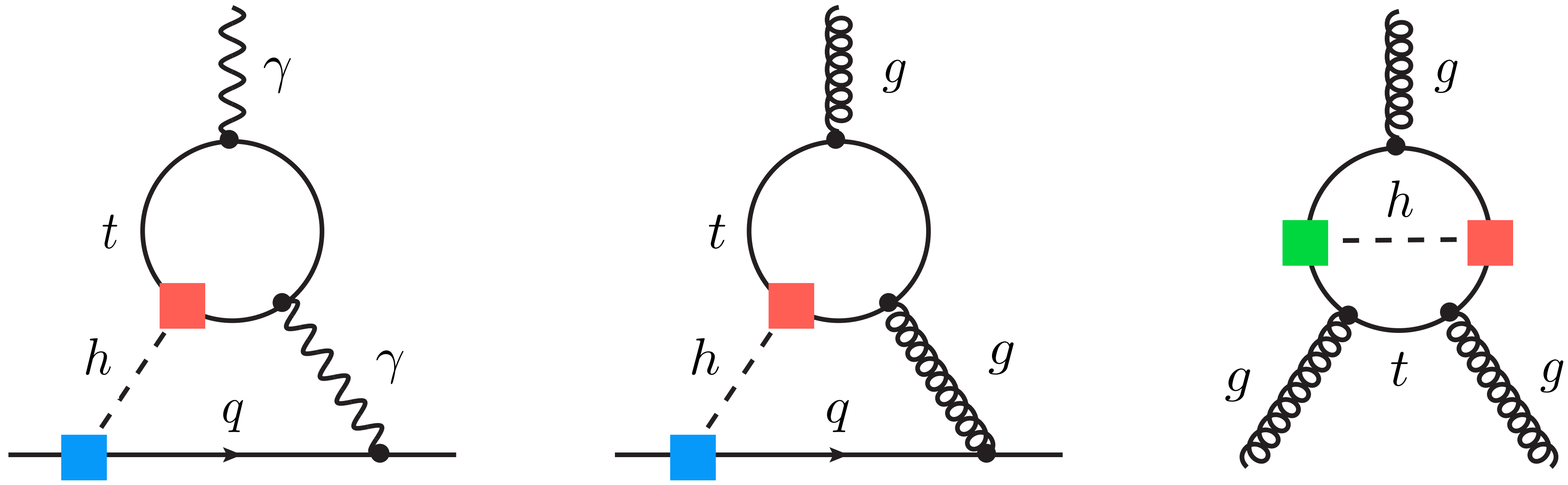




$$\frac{\Gamma(h \to \gamma\gamma)}{\Gamma(h \to \gamma\gamma)_{\rm SM}} \simeq (1.28 - 0.28\kappa_t)^2 + (0.43\tilde{\kappa}_t)^2$$

- CP-odd top-Higgs does not interfere with SM contributions

$h\bar{t}t$ couplings in neutron EDM (d_n)



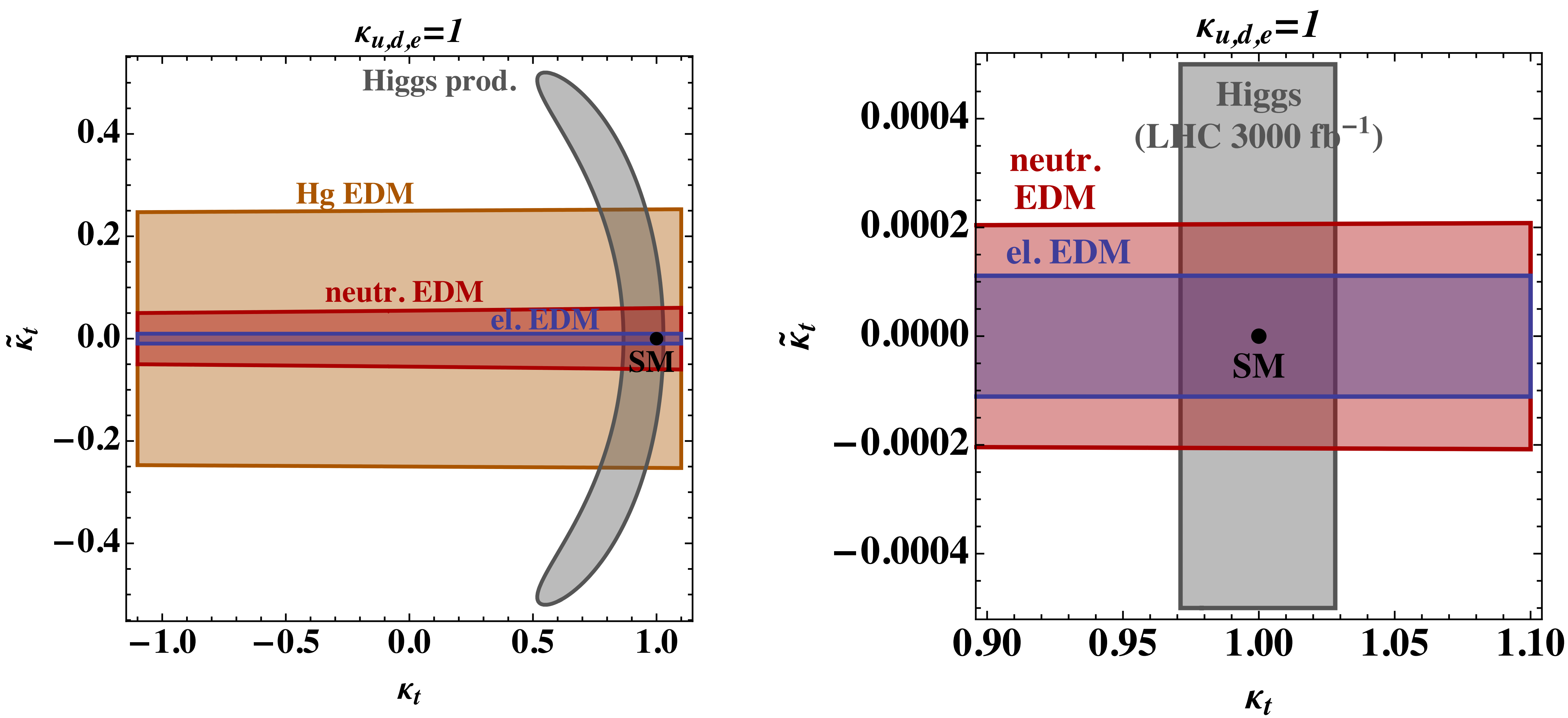
$$\frac{d_n}{e} = \Big\{(1.0 \pm 0.5)\left[-(1.0\,\kappa_u + 4.3\,\kappa_d)\,\tilde{\kappa}_t + 5.1 \cdot 10^{-2}\,\kappa_t\tilde{\kappa}_t\right]$$

$$+\,(22 \pm 10)\,1.8 \cdot 10^{-2}\,\kappa_t\tilde{\kappa}_t\Big\} \cdot 10^{-25}\,\text{cm}$$

- $\kappa_t\tilde{\kappa}_t$ contributions due to Weinberg operator subdominant
- At 90% CL have $|d_n/e| < 2.9 \cdot 10^{-26}$ cm **[Baker et al., hep-ex/0602020]**

Fits to $h\bar{t}t$ couplings

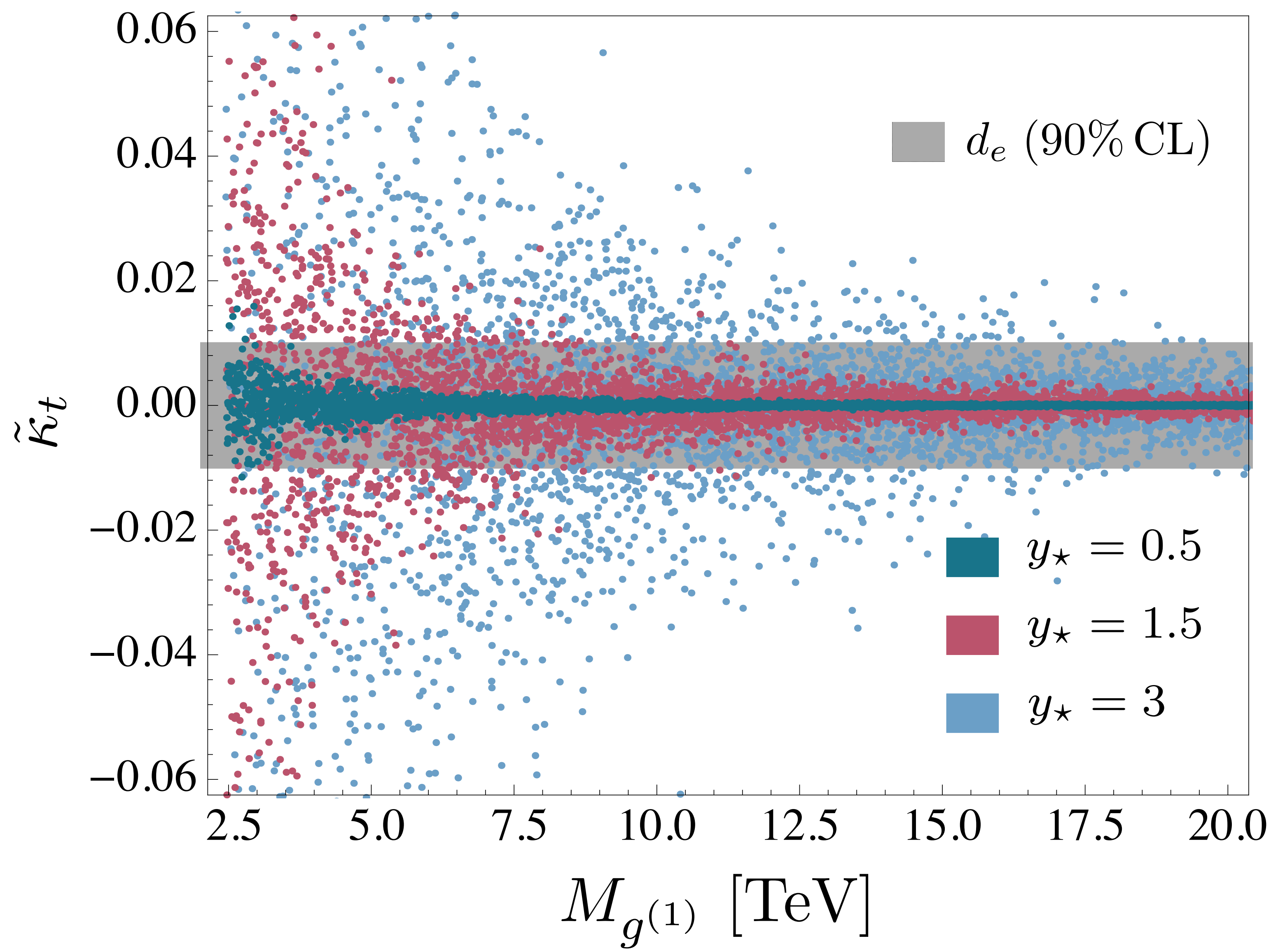
[Brod, UH & Zupan, 1310.1385]



- Projection for 3000 fb^{-1} at HL-LHC [Olsen, talk at Snowmass2013]
- Factor 90 (300) improvement on d_e (d_n) [Hewett et al., 1205.2671]

d_e in Randall-Sundrum models

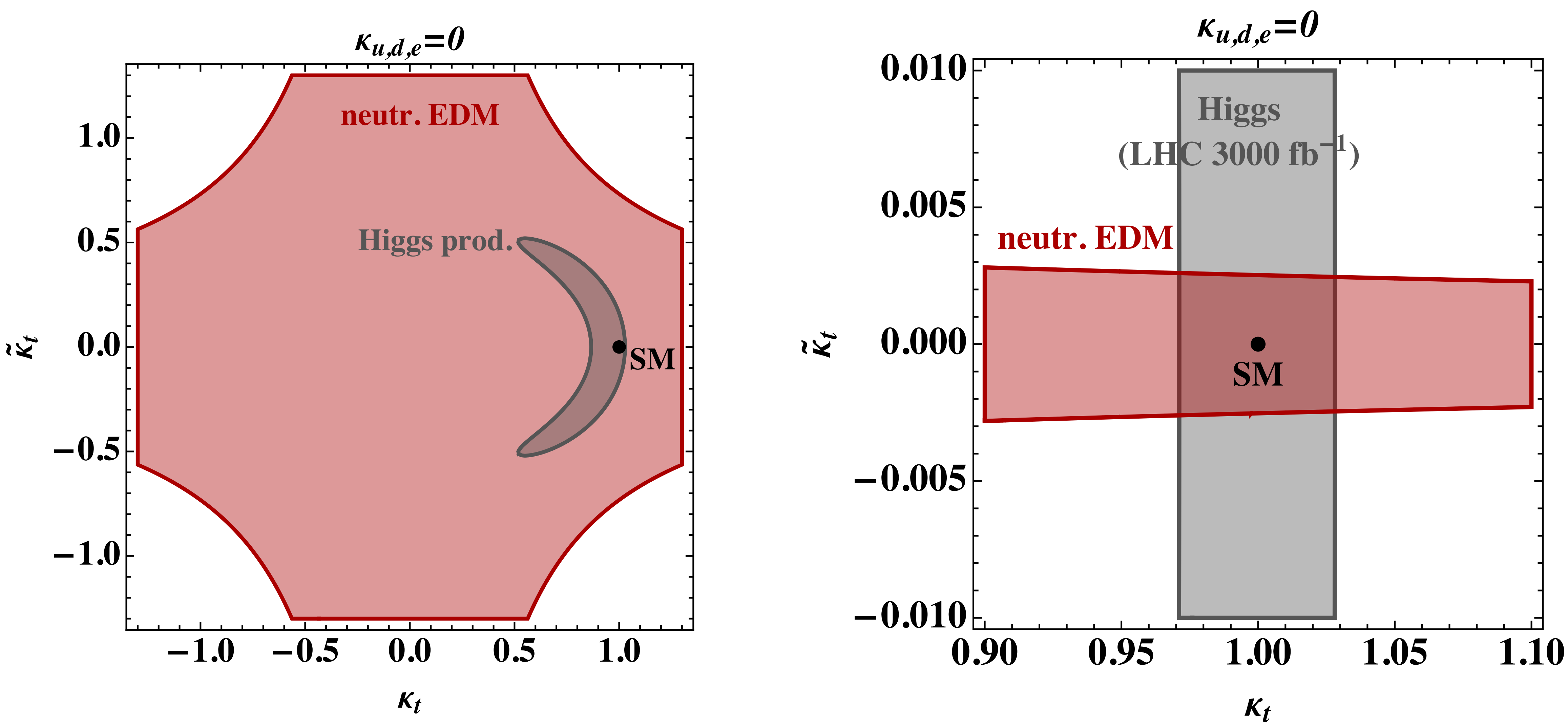
[Malm et al., 1408.4456]



- In flavour-anarchic custodial Randall-Sundrum model, existing d_e constraint on $\tilde{\kappa}_t$ probes multi-TeV Kaluza-Klein masses

Fits to $h\bar{t}t$ couplings

[Brod, UH & Zupan, 1310.1385]



- But even if electron & light-quark couplings vanish, effects due to Weinberg operator will lead to stringent future constraints

$h\bar{b}b$ couplings in d_n

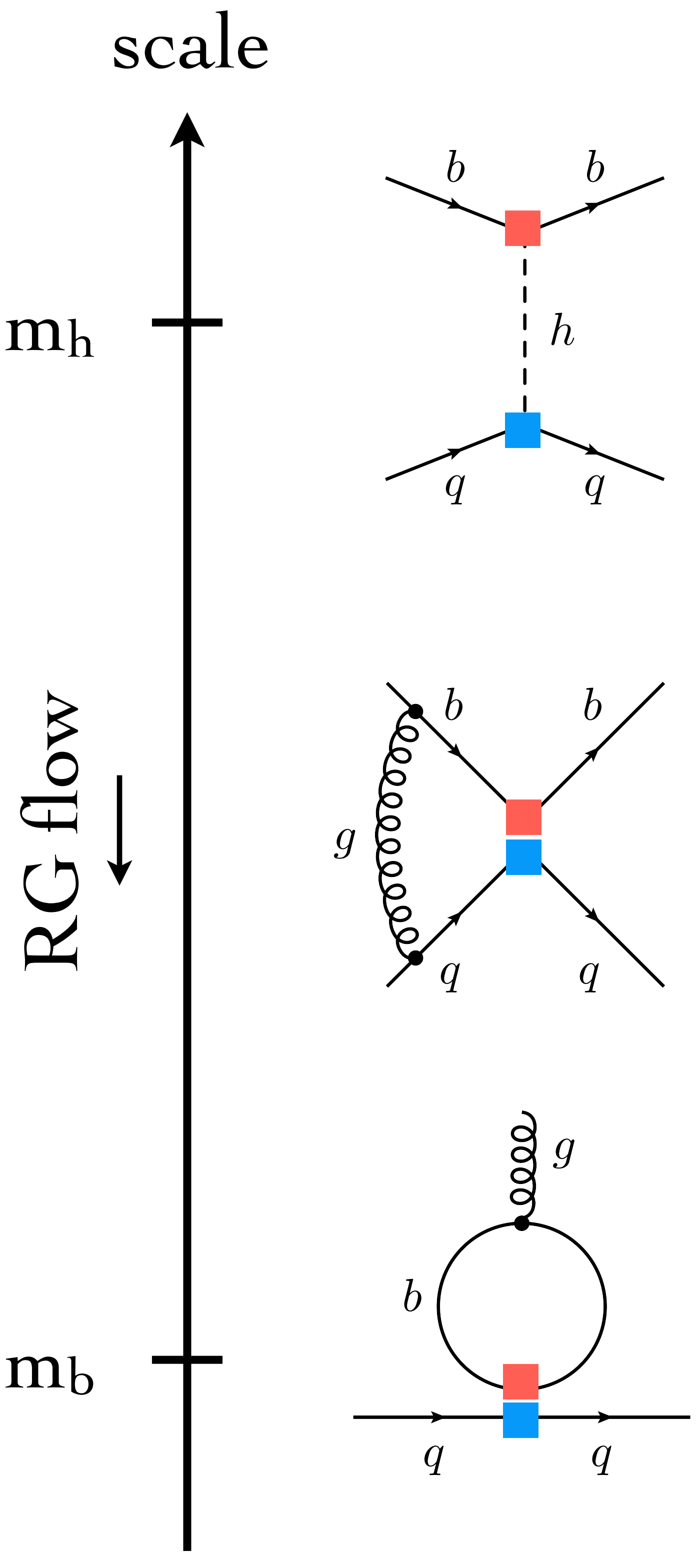
$$d_q(\mu_W) \simeq -4eQ_qN_cQ_b^2\,\frac{\alpha}{(4\pi)^3}\,\sqrt{2}G_F m_q\,\kappa_q\tilde{\kappa}_b\,\frac{m_b^2}{m_h^2}\,\ln^2\frac{m_b^2}{m_h^2},$$

$$\tilde{d}_q(\mu_W) \simeq -2\,\frac{\alpha_s}{(4\pi)^3}\,\sqrt{2}G_F m_q\,\kappa_q\tilde{\kappa}_b\,\frac{m_b^2}{m_h^2}\,\ln^2\frac{m_b^2}{m_h^2},$$

$$w(\mu_W) \simeq -g_s\,\frac{\alpha_s}{(4\pi)^3}\,\sqrt{2}G_F\,\kappa_b\tilde{\kappa}_b\,\frac{m_b^2}{m_h^2}\,\ln\frac{m_b^2}{m_h^2}$$

- d_n suppressed by small bottom-quark Yukawa coupling
- Prediction plagued by sizeable scale uncertainty (factor of 3). Calls for resummation of large logarithms $\alpha_s \ln(m_b^2/m_h^2)$

Renormalisation Group (RG): CEDM



matching → $\bar{q}q\,\bar{b}i\gamma_5 b$

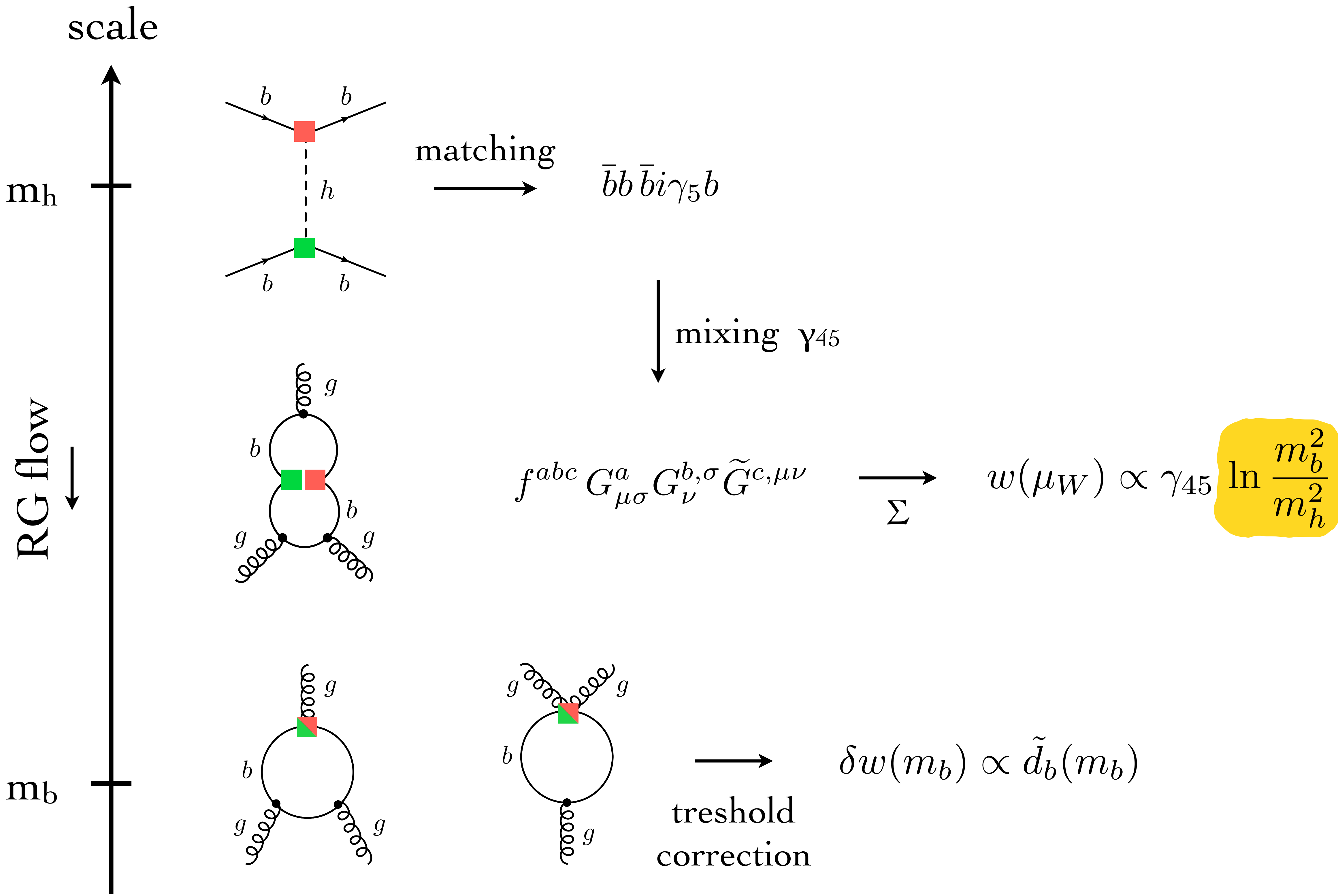
↓ mixing γ_{12}

$\bar{q}\sigma_{\mu\nu}t^a q\,\bar{b}i\sigma^{\mu\nu}\gamma_5 t^a b$

↓ mixing γ_{23}

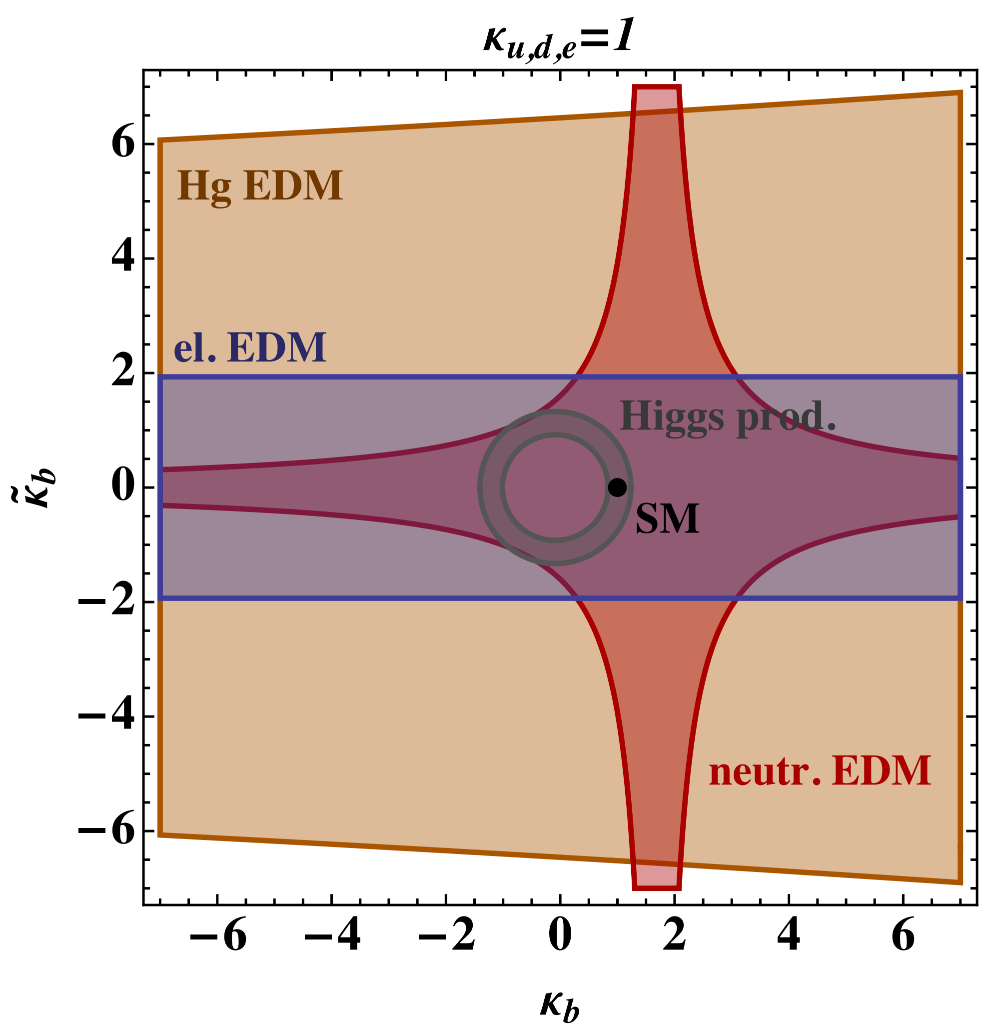
$im_b\,\bar{q}\sigma_{\mu\nu}t^a q\,G^{a,\mu\nu}$ $\xrightarrow{\Sigma}$ $\tilde{d}_q(\mu_W) \propto \gamma_{12}\gamma_{23}\ln^2\frac{m_b^2}{m_h^2}$

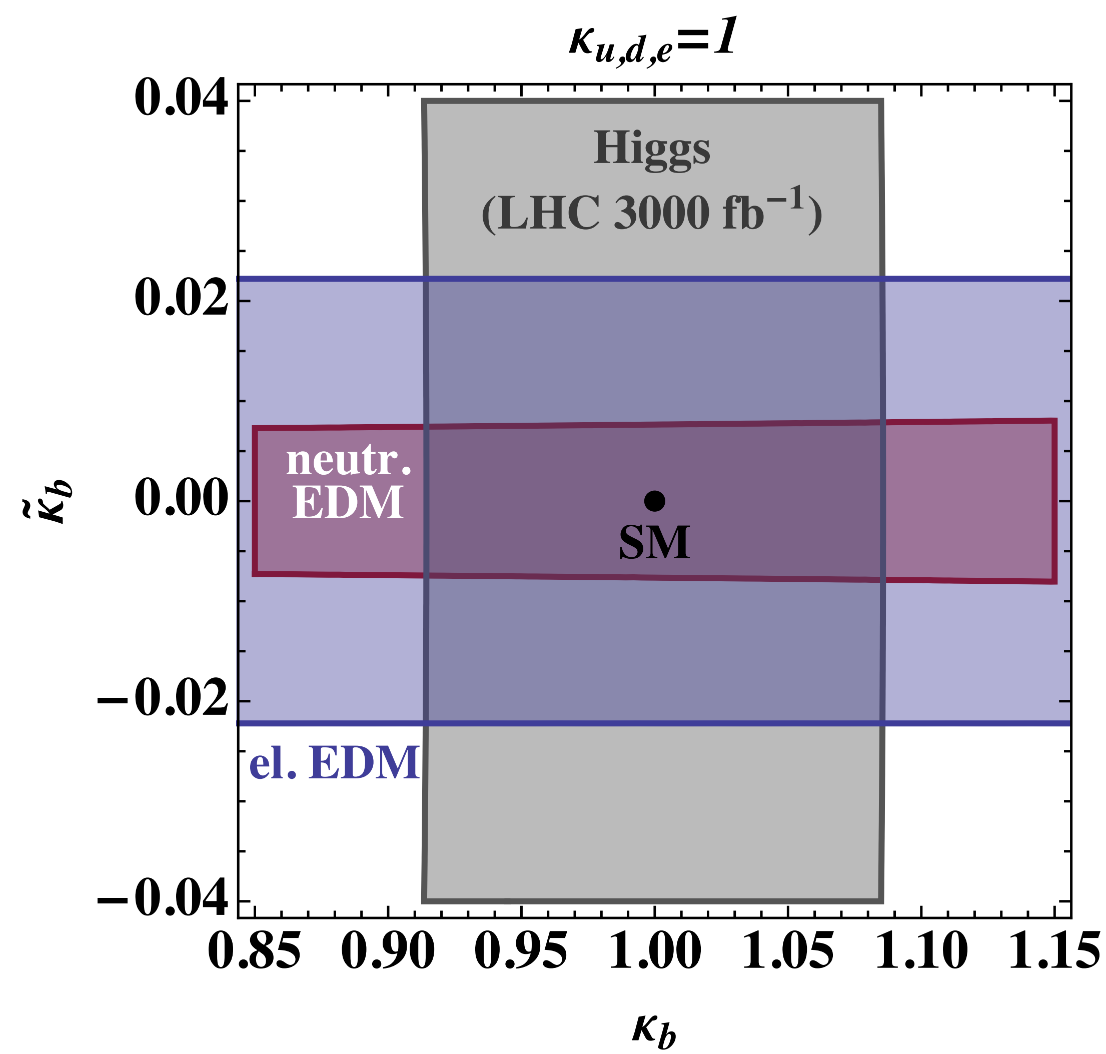
RG: Weinberg operator



Fits to $h\bar{b}b$ couplings

[Brod, UH & Zupan, 1310.1385]

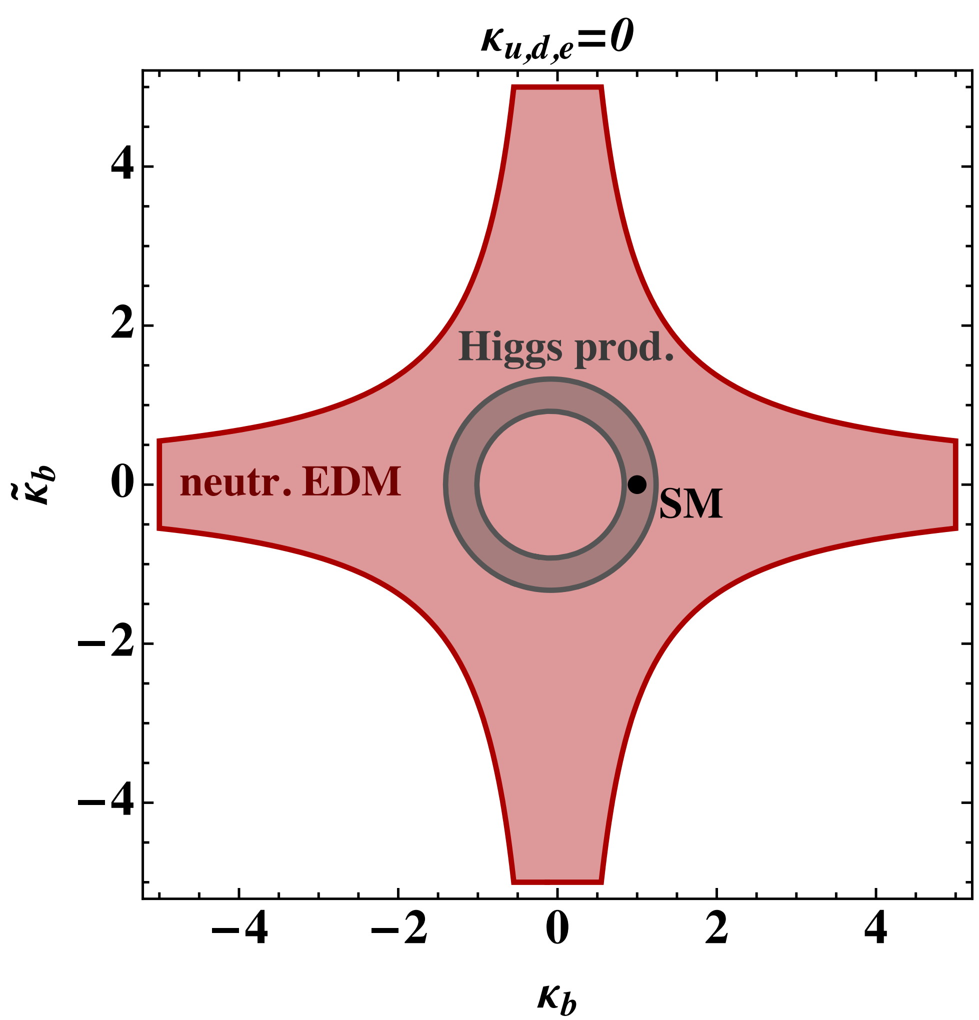


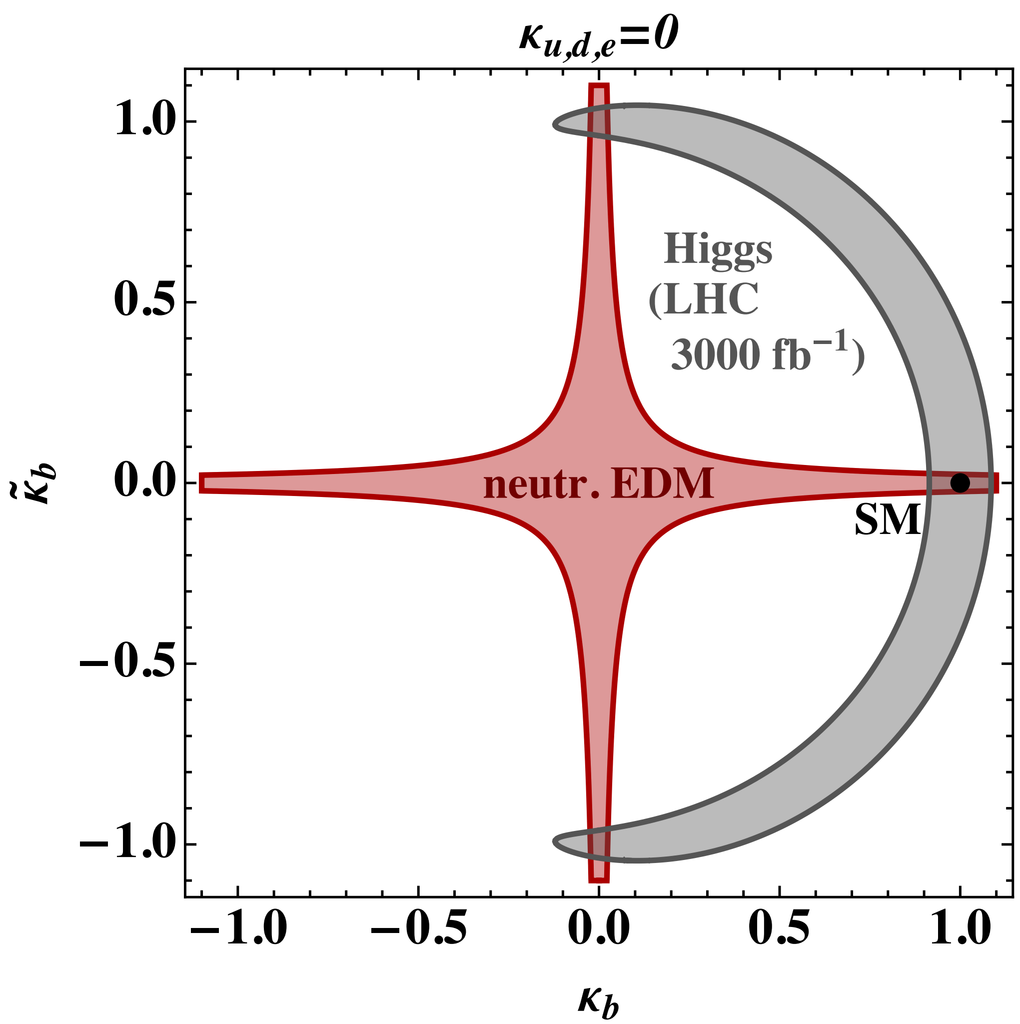


- If Higgs couples SM-like to electron & light quarks then future bounds from EDMs superior to HL-LHC constraints

Fits to $h\bar{b}b$ couplings

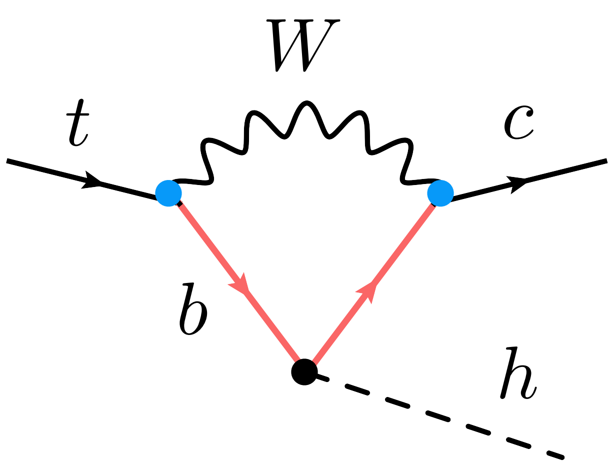
[Brod, UH & Zupan, 1310.1385]





- For $\kappa_{\rm e,d,u}=0$, contributions associated to Weinberg operator expected to lead to competitive constraints in future scenario

Top FCNCs

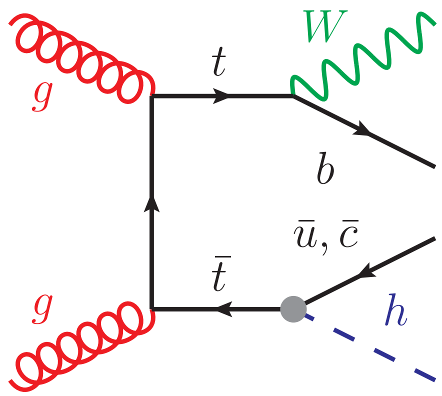


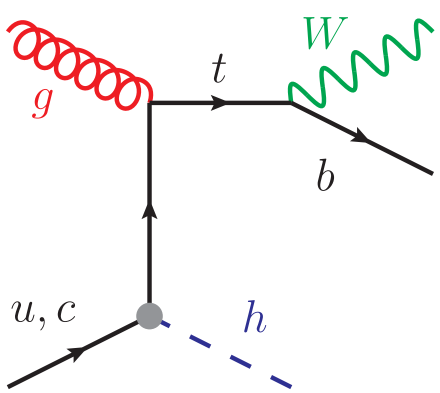
$$\mathcal{M} \simeq \frac{3}{32\sqrt{2}\pi^2} V_{tb}^* V_{cb}\, y_t\, \frac{m_b^2}{v^2}\, \bar{c}_L t_R h$$

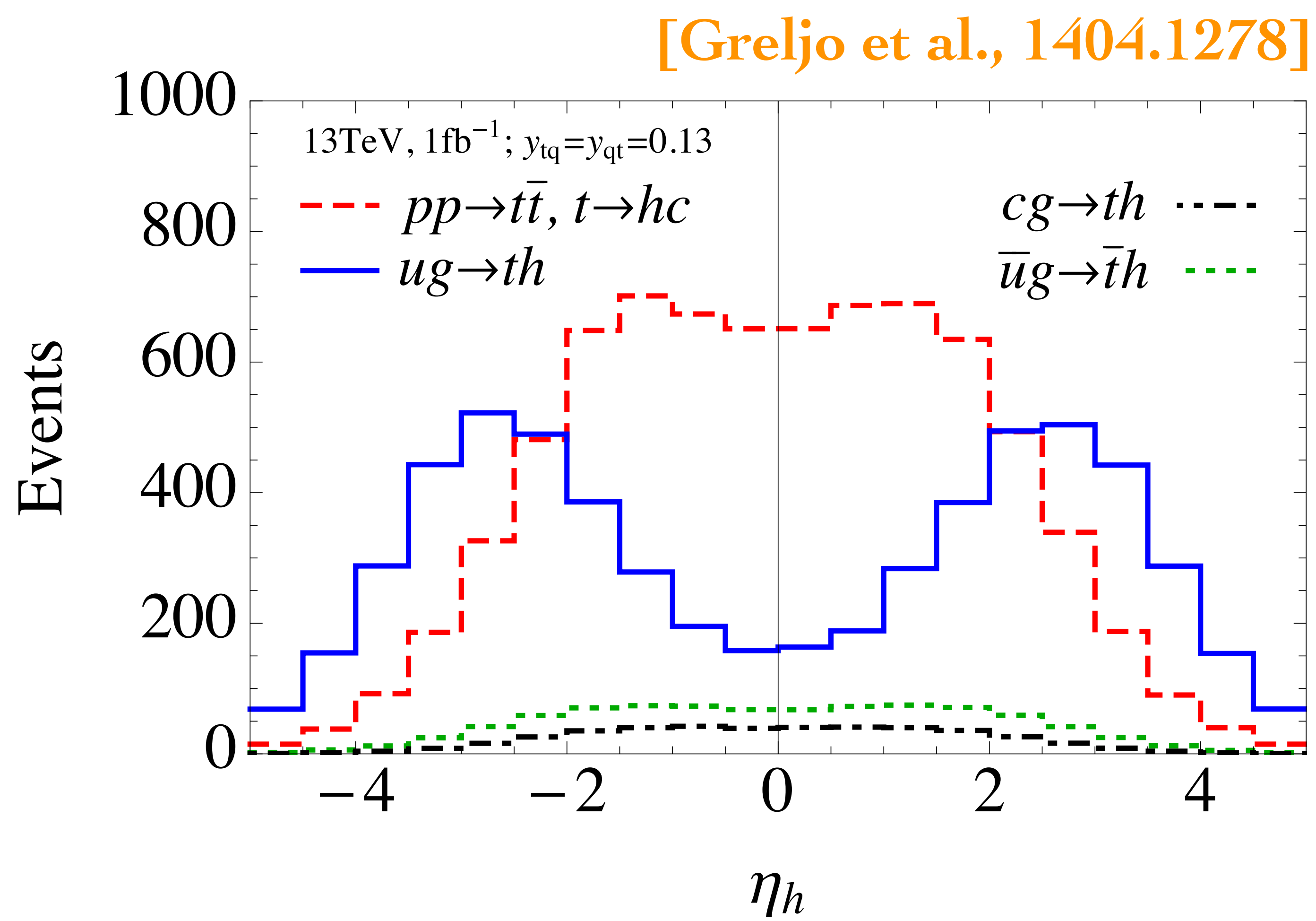
$$\mathrm{Br}(t \to ch) \simeq 3 \cdot 10^{-15}\,, \qquad \mathrm{Br}(t \to uh) \simeq 2 \cdot 10^{-17}$$

- In SM, flavour-changing neutral current (FCNC) top decays one-loop, GIM & CKM suppressed. Finding t→c(u)h, would thus imply new physics, presumably of TeV-scale origin

LHC searches

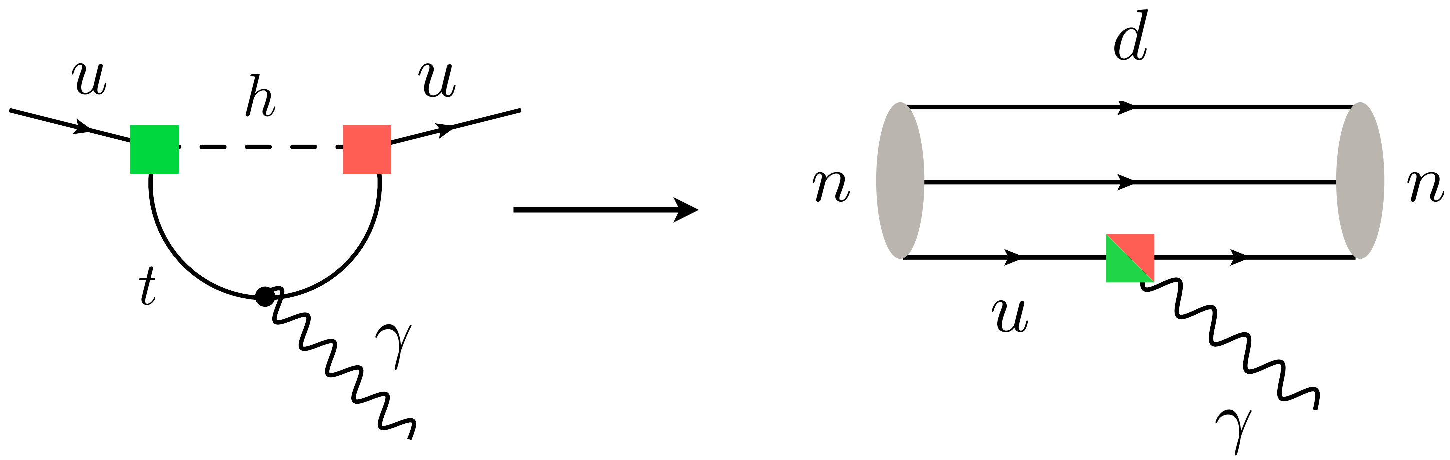


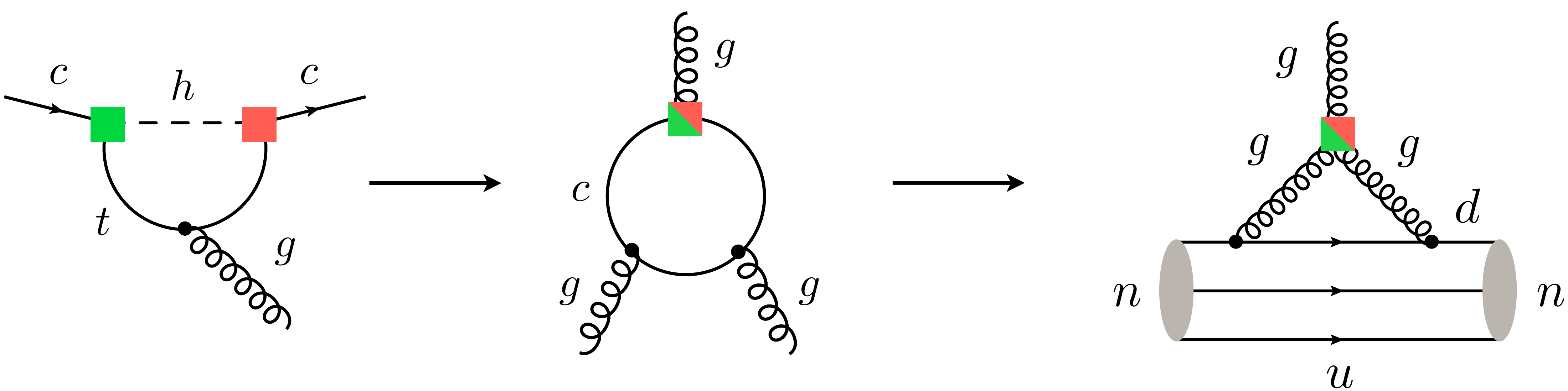




- tc(u)h couplings have been looked for in t̄t & single-top samples
- Best LHC Run I bound reads Br(t→qh) < 0.56% at 95% CL
- Can distinguish t→c/uh by e.g. Higgs rapidity or charm tagging

Y_{pr} contributions to d_n





- tuh interactions contribute to d_n at 1-loop level, while tch couplings first enter at 2-loop order (dominant effect due to charm threshold)

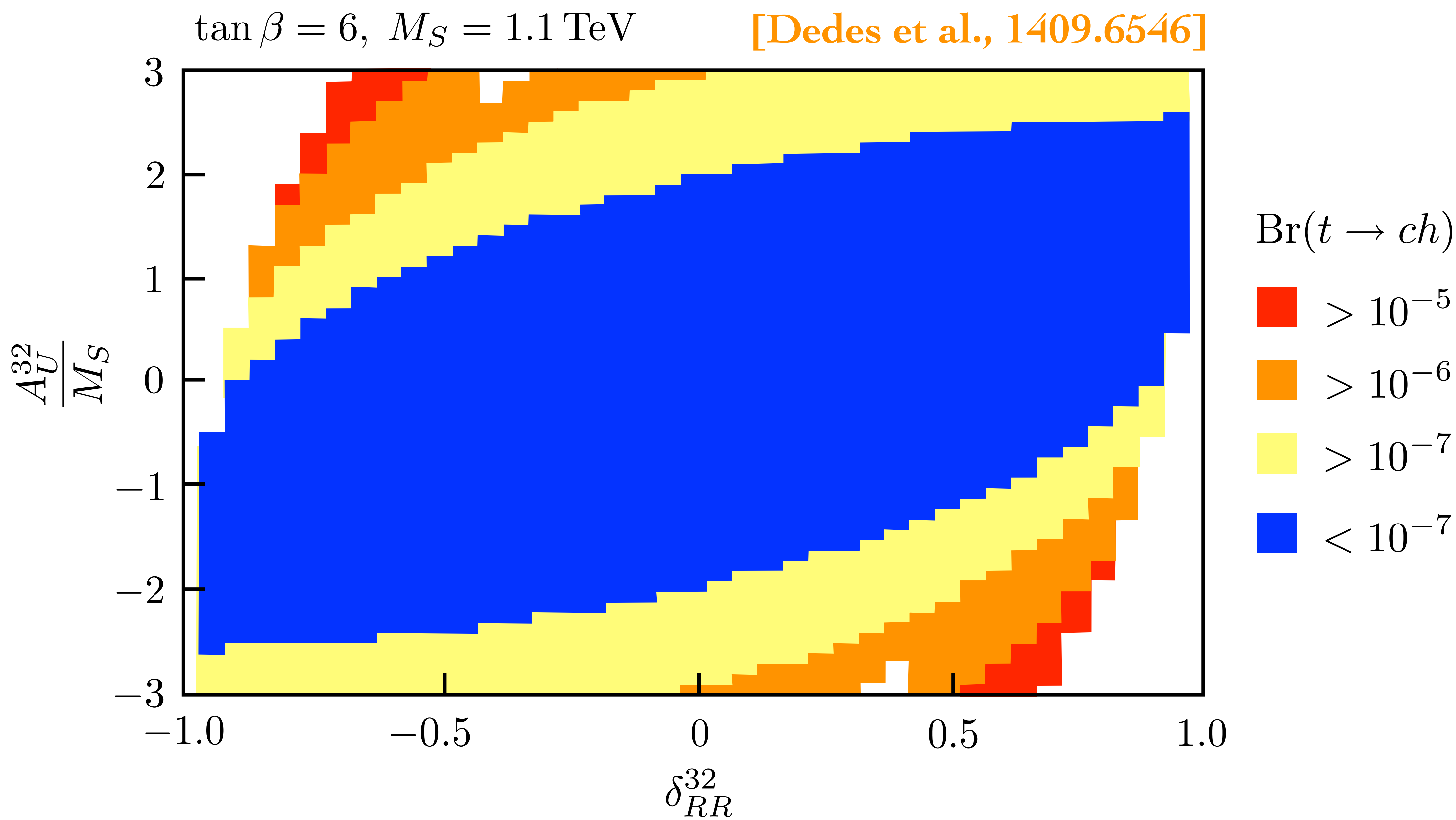
Summary of constraints on Y_{pr}

[Gorbahn & UH, 1404.4873]

Observable	Coupling	Present bound	Future sensitivity
LHC searches	$\sqrt{\lvert Y_{tc}\rvert^2 + \lvert Y_{ct}\rvert^2}$	0.14	$2.8 \cdot 10^{-2\,\dagger}$
	$\sqrt{\lvert Y_{tu}\rvert^2 + \lvert Y_{ut}\rvert^2}$	0.13	$2.8 \cdot 10^{-2\,\dagger}$
d_n	$\lvert \mathrm{Im}\,(Y_{tc} Y_{ct})\rvert$	$5.0 \cdot 10^{-4}$	$1.7 \cdot 10^{-6}$
	$\lvert \mathrm{Im}\,(Y_{tu} Y_{ut})\rvert$	$4.3 \cdot 10^{-7}$	$1.5 \cdot 10^{-9}$
d_D	$\lvert \mathrm{Im}\,(Y_{tc} Y_{ct})\rvert$	—	$1.7 \cdot 10^{-7}$
	$\lvert \mathrm{Im}\,(Y_{tu} Y_{ut})\rvert$	—	$1.7 \cdot 10^{-11}$
ΔA_{CP}	$\lvert \mathrm{Im}\,(Y_{ut}^* Y_{ct})\rvert$	$4.0 \cdot 10^{-4}$	—
D–$\bar{D}$ mixing	$\sqrt{\lvert \mathrm{Im}\,(Y_{tc}^* Y_{ut}^* Y_{tu} Y_{ct})\rvert}$	$4.1 \cdot 10^{-4}$	$1.3 \cdot 10^{-4}$

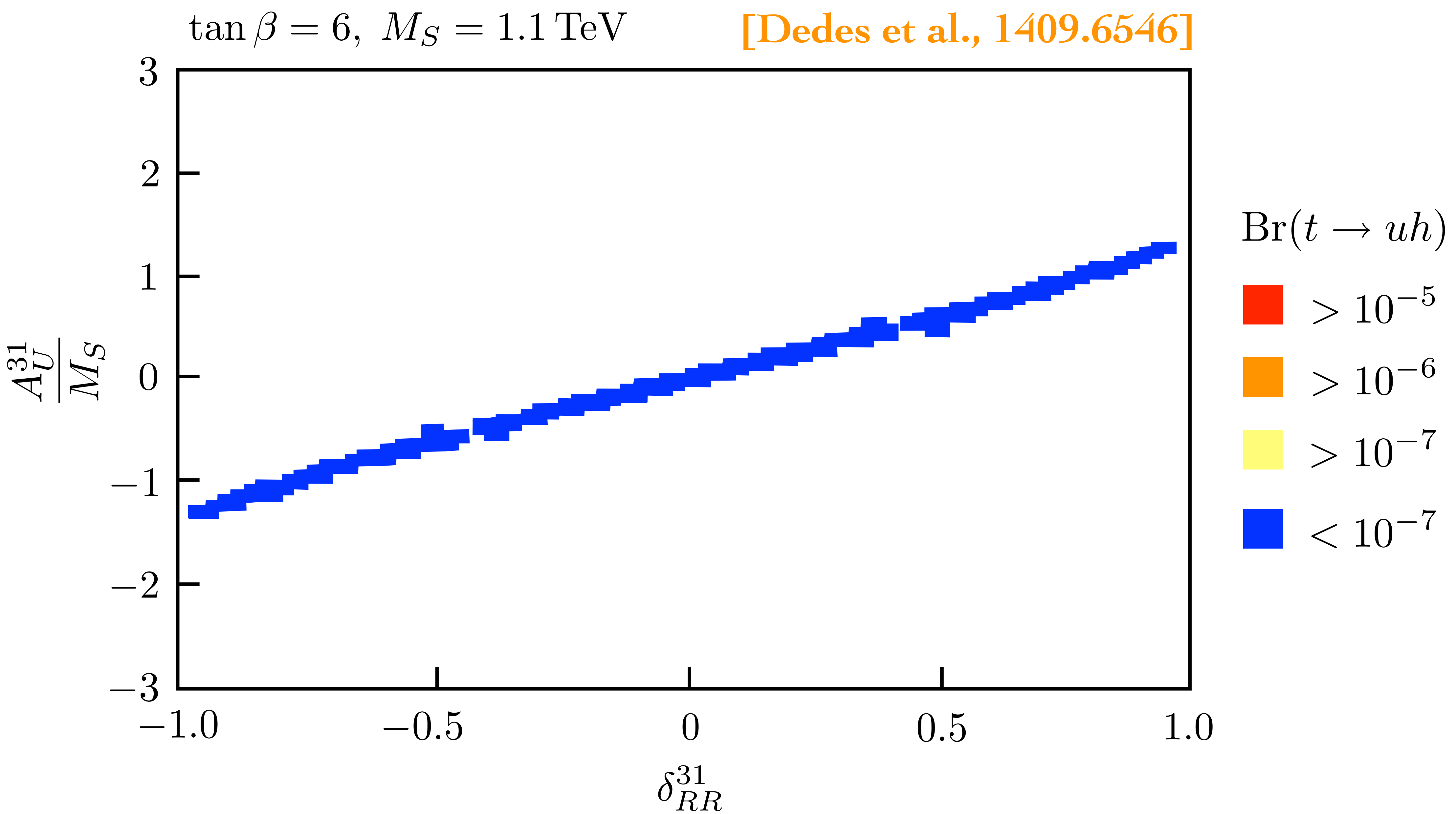
†based on projection Br(t→c/uh) < $2 \cdot 10^{-4}$ [Agashe et al., 1311.2028]

t→ch in MSSM



- Regions with Br(t→ch) > 10^{-6} require $|A_U^{32}| > 2M_S$. Such large A_U^{32} terms naively trigger colour & charge breaking minima

t→uh in MSSM

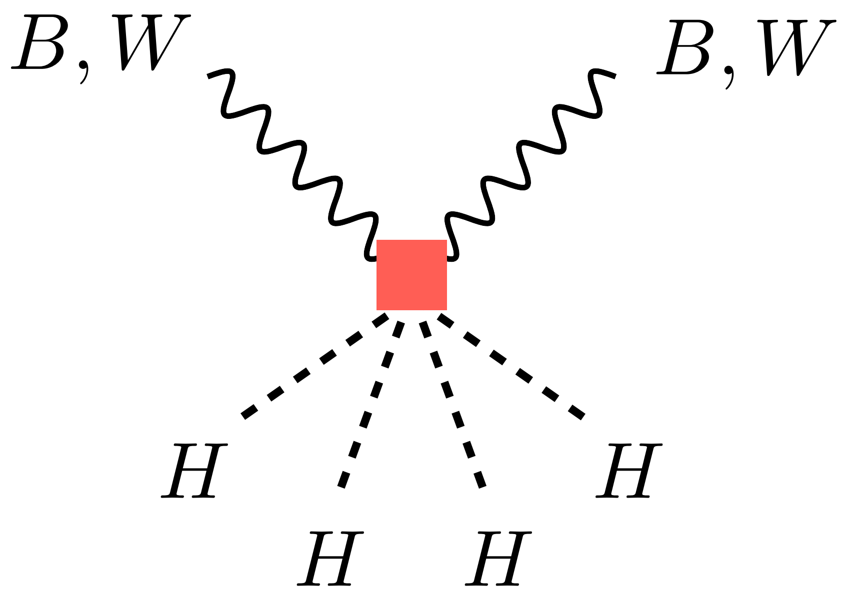


- Even for real A_U^{31} & δ_{RR}^{31}, higher-order terms in mass insertion expansion depend on δ_{CKM}. d_n rules out Br(t→uh) > 10^{-7}

Operator classes

4) $\psi^2 H^3$: $Q_{uH} = (H^\dagger H)(\bar{q}_p u_r \tilde{H})$, ...

5) $H^4 D^2$: $Q_T = (H^\dagger \overleftrightarrow{D}_\mu H)(H^\dagger \overleftrightarrow{D}^\mu H)$, ...



Bounds on H^4D^2 operators

$$\Delta\rho = \alpha T = \frac{v^2}{\Lambda^2}\, c_T \in [-1.5, 2.2]\cdot 10^{-3} \quad (95\%\,\mathrm{CL})$$

[Gfitter, 1209.2716]

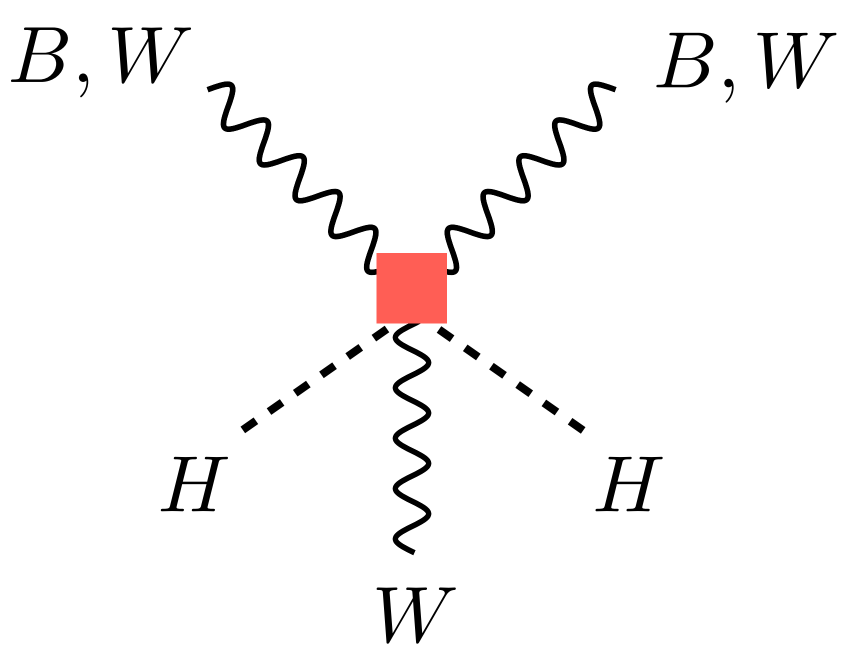
$$\Lambda \gtrsim 5.5\sqrt{|c_T|}\ \mathrm{TeV} \simeq \begin{cases} 5.5\,\mathrm{TeV} & \text{(tree level)} \\ 550\,\mathrm{GeV} & \text{(weak loop)} \end{cases}$$

Operator classes

4) $\psi^2 H^3$: $Q_{uH} = (H^\dagger H)(\bar{q}_p u_r \tilde{H})\,, \ldots$

5) $H^4 D^2$: $Q_T = (H^\dagger \overleftrightarrow{D}_\mu H)(H^\dagger \overleftrightarrow{D}^\mu H)\,, \ldots$

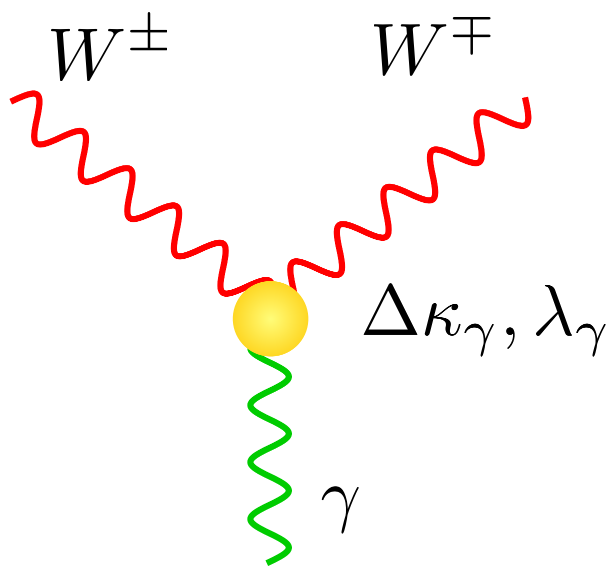
6) $H^2 D^2 X$: $Q_{HW} = (D_\mu H)^\dagger \tau^i (D_\nu H) W^{i,\mu\nu}\,, \ldots$

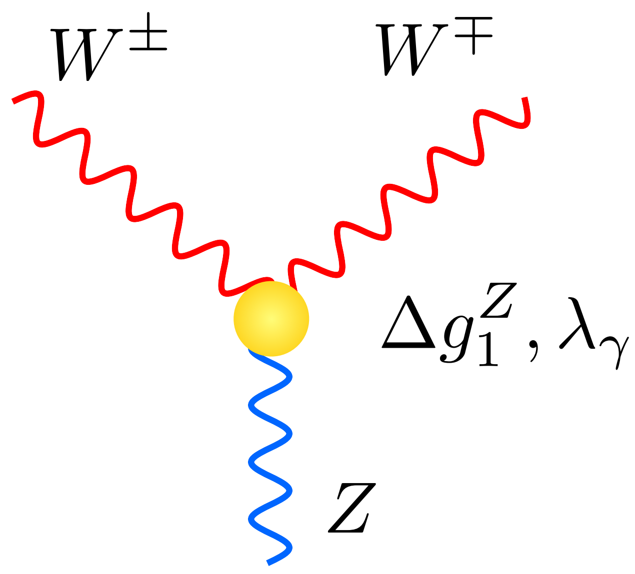


Triple gauge couplings

- $\mathrm{H^2D^2X}$ operators contribute to triple gauge couplings (TGCs):

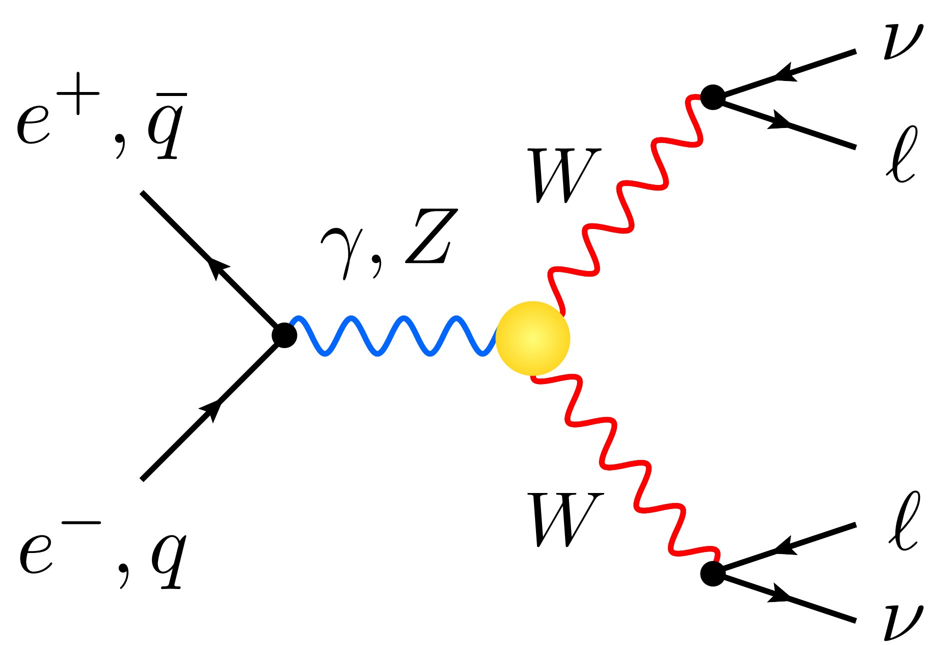
$$\mathcal{L}_{WWV} = -ig_{WWV}\Big[g_1^V\left(W^+_{\mu\nu}W^{-\,\mu}V^\nu - W^+_\mu V_\nu W^{-\,\mu\nu}\right) + \kappa_V W^+_\mu W^-_\nu V^{\mu\nu} + \frac{\lambda_V}{m_W^2} W^+_{\mu\nu} W^{-\,\nu\rho} V_\rho{}^\mu\Big]$$

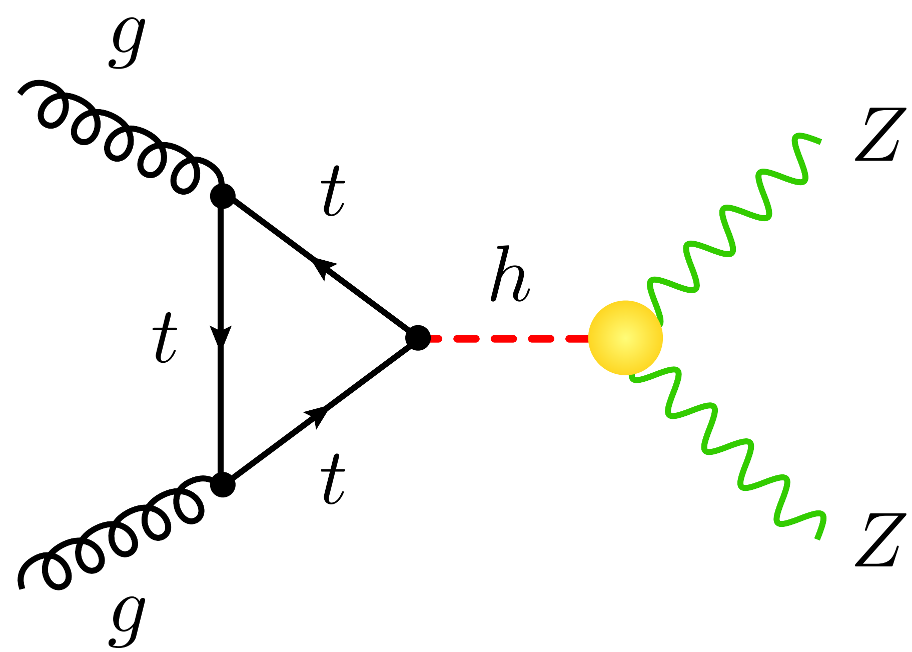




[Hagiwara et al., NPB (1987) 282; PRD (1993) 48]

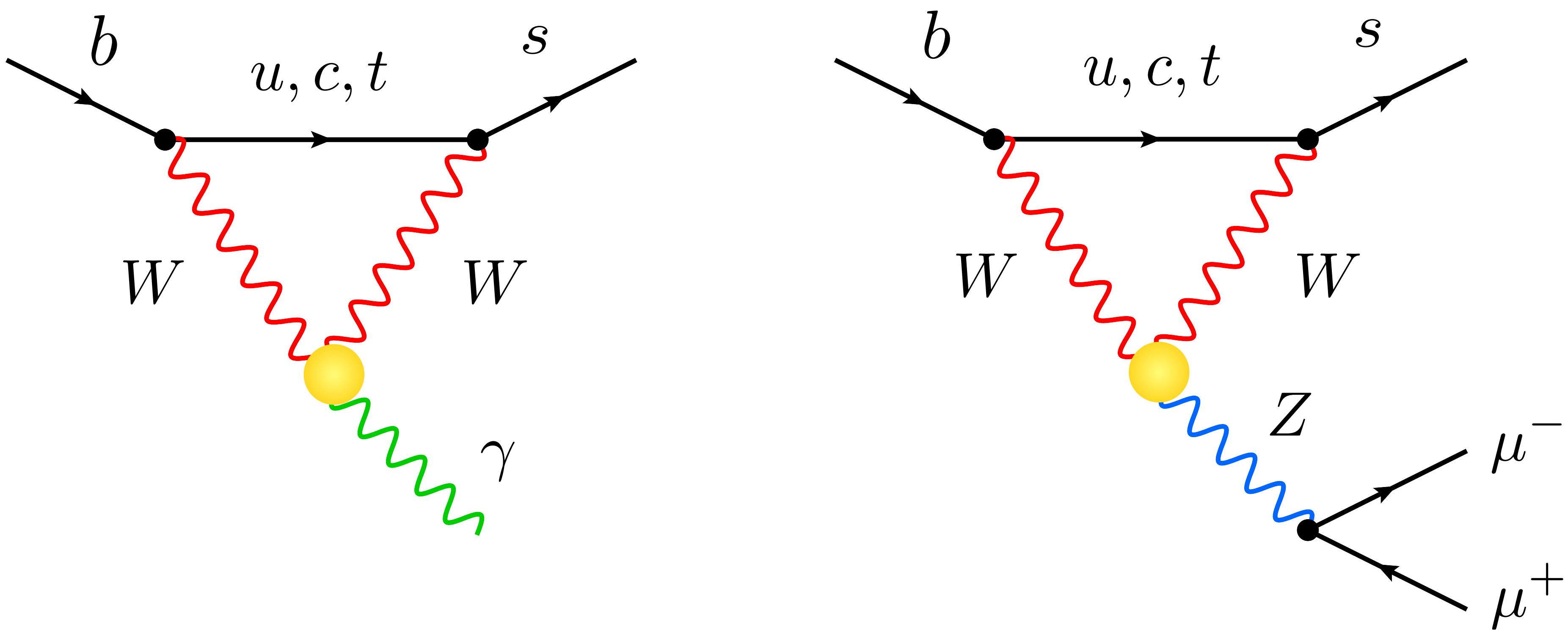
Direct probes of anomalous TGCs





- Searches for anomalous TGCs have been performed at LEP, Tevatron & LHC (WW, WZ, Wγ, Zγ, … production). They can also be probed in Higgs physics (pp→h→ZZ, …)

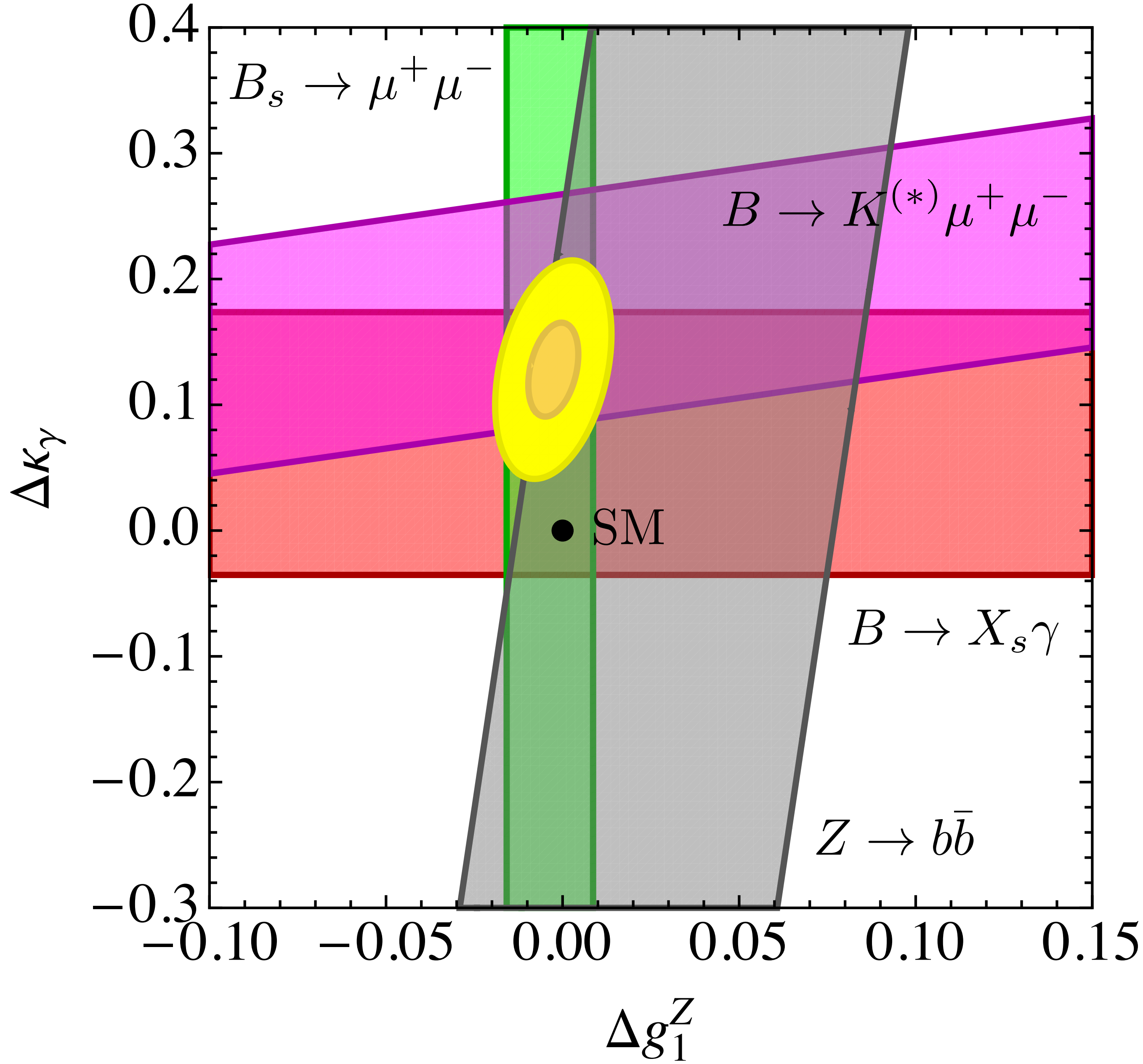
Indirect tests of anomalous TGCs



- Anomalous TGCs contribute to observables such as $B \to X_s \gamma$, $B \to K^* \mu^+ \mu^-$, $B_s \to \mu^+ \mu^-$, $K \to \pi \bar{\nu} \nu$ & ε'/ε as well as $Z \to \bar{b} b$ from 1-loop level & beyond

Anomalous TGCs from flavour

[Bobeth & UH, 1503.04829]



- $b \to s\mu^+\mu^-$ anomalies lead to 3σ deviation of best fit from SM

Bounds on H^2D^2X operators

[Falkowski et al., 1508.00581]

$$\Delta g_1^Z = \frac{M_Z^2}{2\Lambda^2}\, c_{HW} = \begin{cases} 0.017 \pm 0.023 & \text{(direct)} \\ -0.003 \pm 0.007 & \text{(indirect)} \end{cases}$$

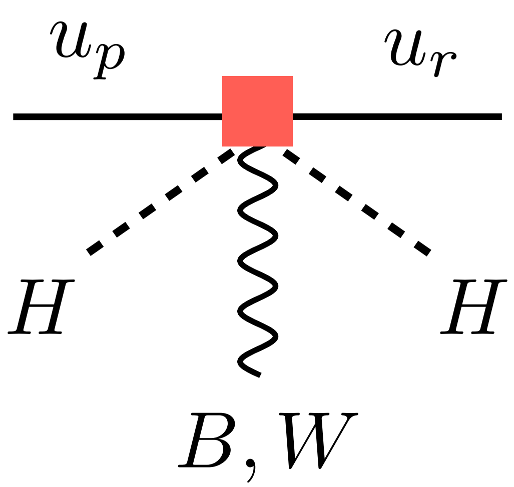
[Bobeth & UH, 1503.04829]

$$\Lambda \gtrsim 550\sqrt{|c_{HW}|}\,\text{GeV} \simeq 55\,\text{GeV} \quad \text{(weak loop)}^{\dagger}$$

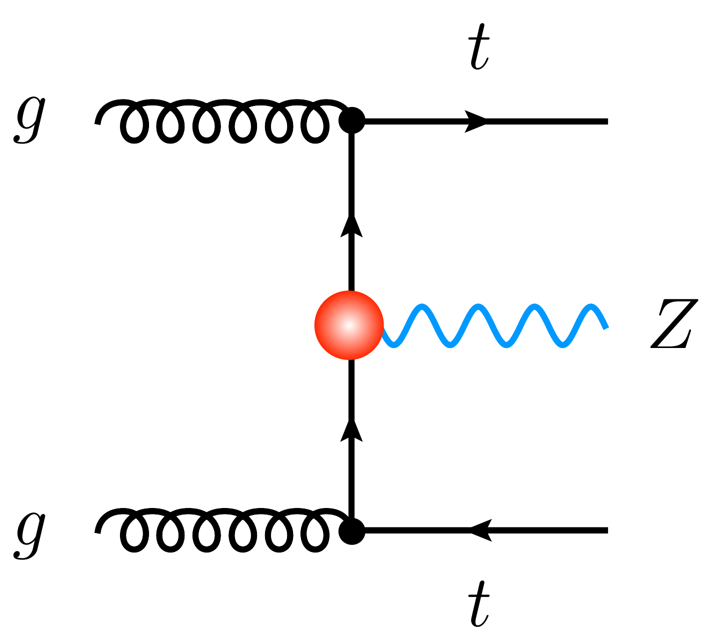
†applies to regular UV completions

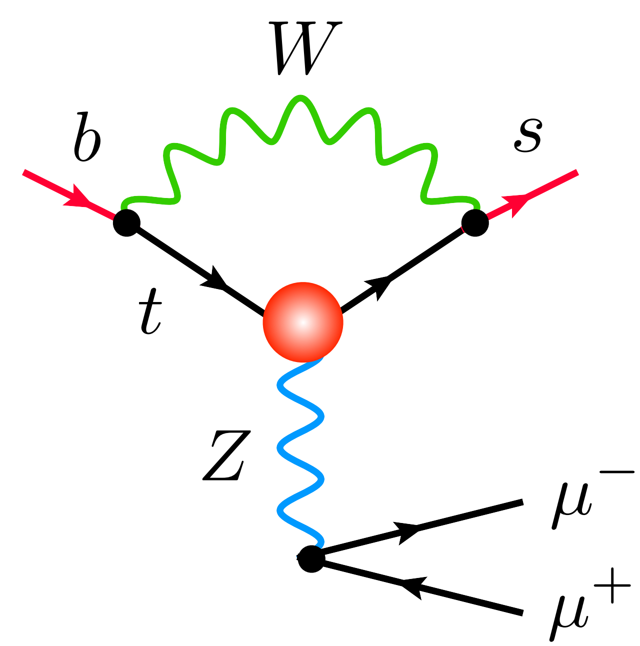
Operator classes

7) $\psi^2 H^2 D$: $Q_{Hu} = (H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{u}_p \gamma^\mu u_r)\,,\ \ldots$



Anomalous Z$\bar{t}$t couplings

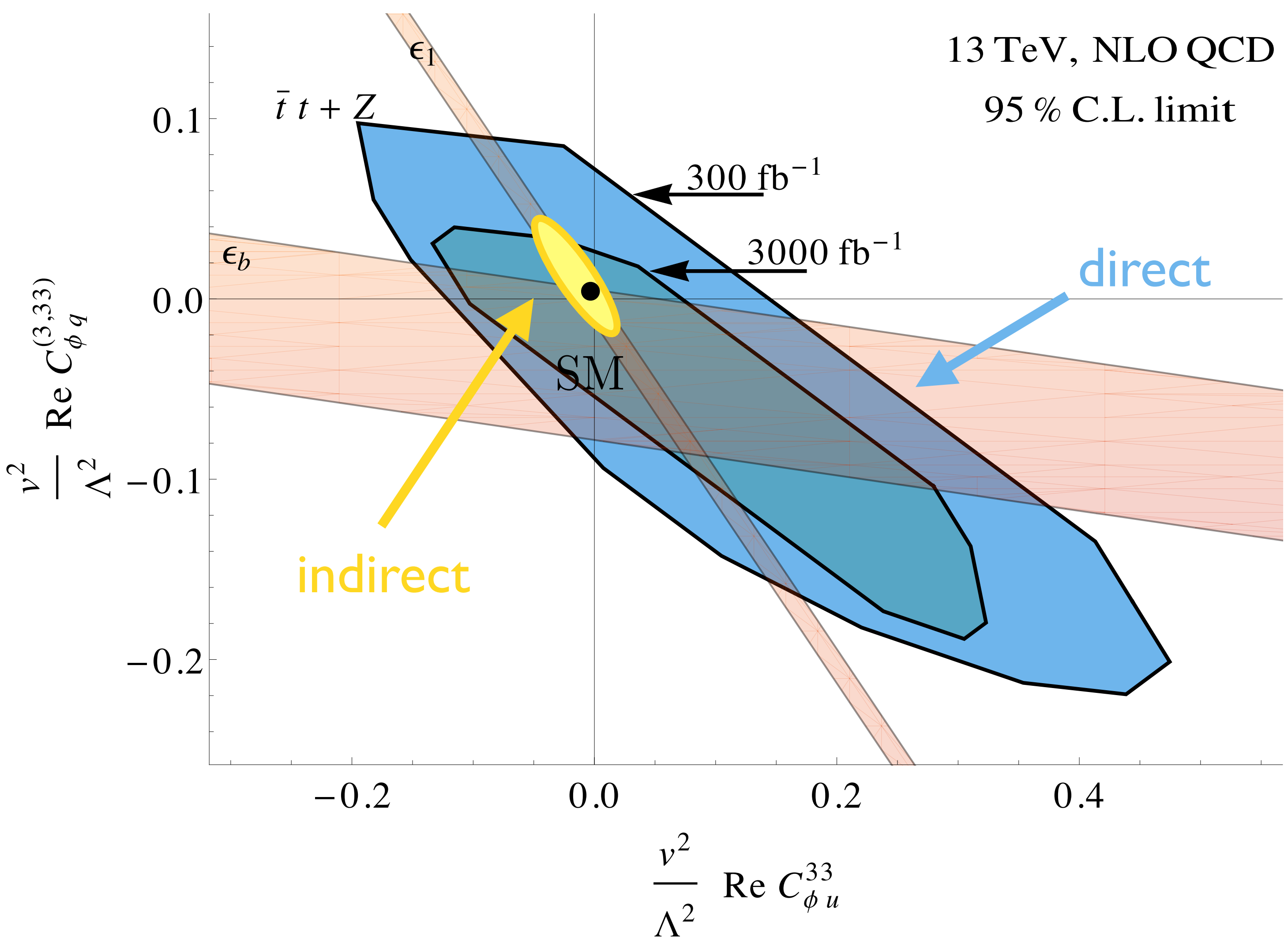




- $\psi^2 H^2 D$ composites involving 3rd generation quarks can be constrained directly (single-top production, pp→Z$\bar{t}$t, …), but also contribute to B & K decays, Z→$\bar{b}$b & T via loops

$Z\bar{t}t$ couplings: Comparison

[Röntsch & Schulze, 1404.1005; Brod et al., 1408.0792]



- Indirect bounds stronger than direct limits for $Z\bar{t}t$ couplings. Still worth looking at pp→$Z\bar{t}t$, as cancellation in former case possible

Bounds on t^2H^2D operators

$$\frac{v^2}{\Lambda^2}\,|c^{33}_{Hu}|\,\ln\frac{\Lambda^2}{M_W^2} \lesssim 2.5\cdot 10^{-2} \quad \text{(indirect)}$$

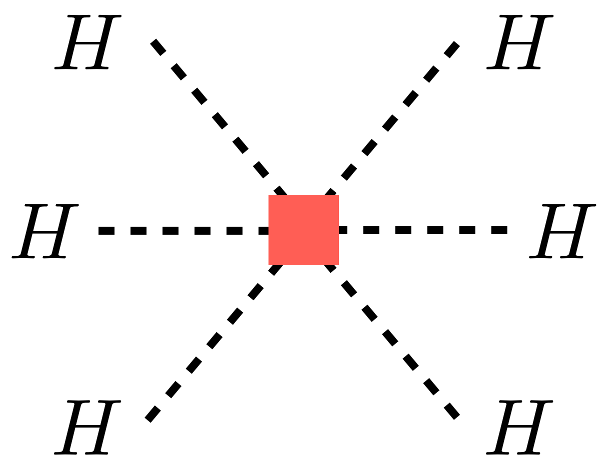
[Brod et al., 1408.0792]

$$\Lambda \gtrsim 2\sqrt{|c^{33}_{Hu}|}\,\text{TeV} \simeq 2\,\text{TeV} \quad \text{(tree level)}$$

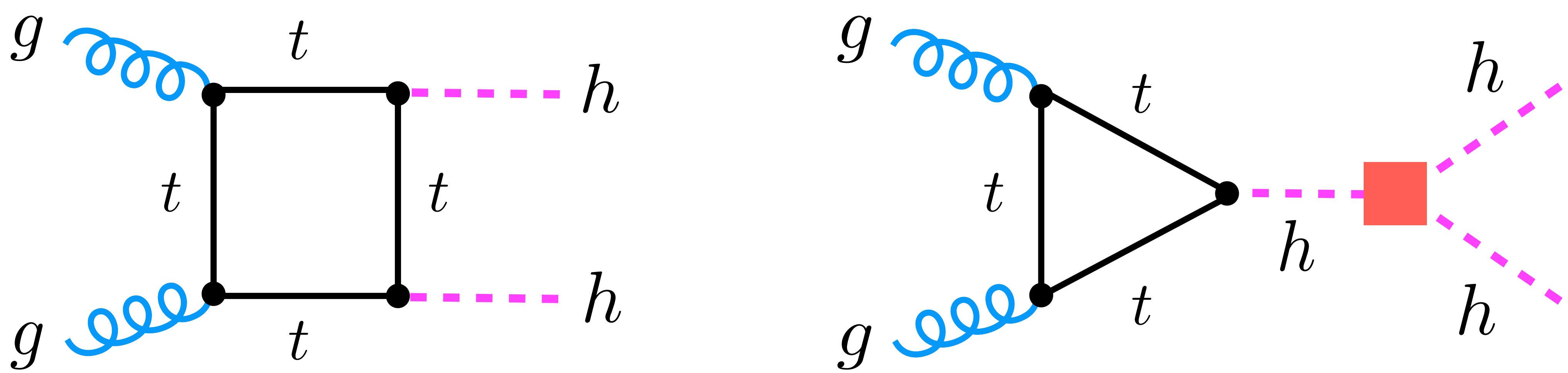
Operator classes

7) $\psi^2 H^2 D$: $Q_{Hu} = (H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{u}_p \gamma^\mu u_r)\,,\ \ldots$

8) H^6: $Q_6 = (H^\dagger H)^3$



Di-Higgs production



$$\sigma\,(pp \to 2h) \simeq (9.9 \pm 1.3)\left(1 - 0.87\bar{c}_6 + 0.33\bar{c}_6^2\right)\,\text{fb} \quad (\text{LHC 8 TeV})$$

$$\bar{c}_6 = -\frac{v^2}{\Lambda^2}\frac{c_6}{\lambda}\,, \qquad \lambda = \frac{m_h^2}{2v^2} \simeq 0.13$$

[de Florian & Mazzitelli, 1309.6594;
Gorbahn & UH, 16xx.xxxxx]

First bound on H^6 operator

$$\sigma\,(pp \to 2h) < 0.69\,\mathrm{pb} \quad (95\%\,\mathrm{CL})$$

[ATLAS, 1509.04670; Gorbahn & UH, 16xx.xxxxx]

$$\bar{c}_6 \in [-18.2, 15.6] \quad (95\%\,\mathrm{CL})$$

$$\Lambda \gtrsim 170\,\sqrt{|c_6|}\,\mathrm{GeV} \simeq 170\,\mathrm{GeV} \quad (\text{tree level})$$

HL-LHC bounds on H^6 operator

- At 14 TeV LHC with $3ab^{-1}$ may be possible to set a 95% CL bound on $\bar{c}_6$ of

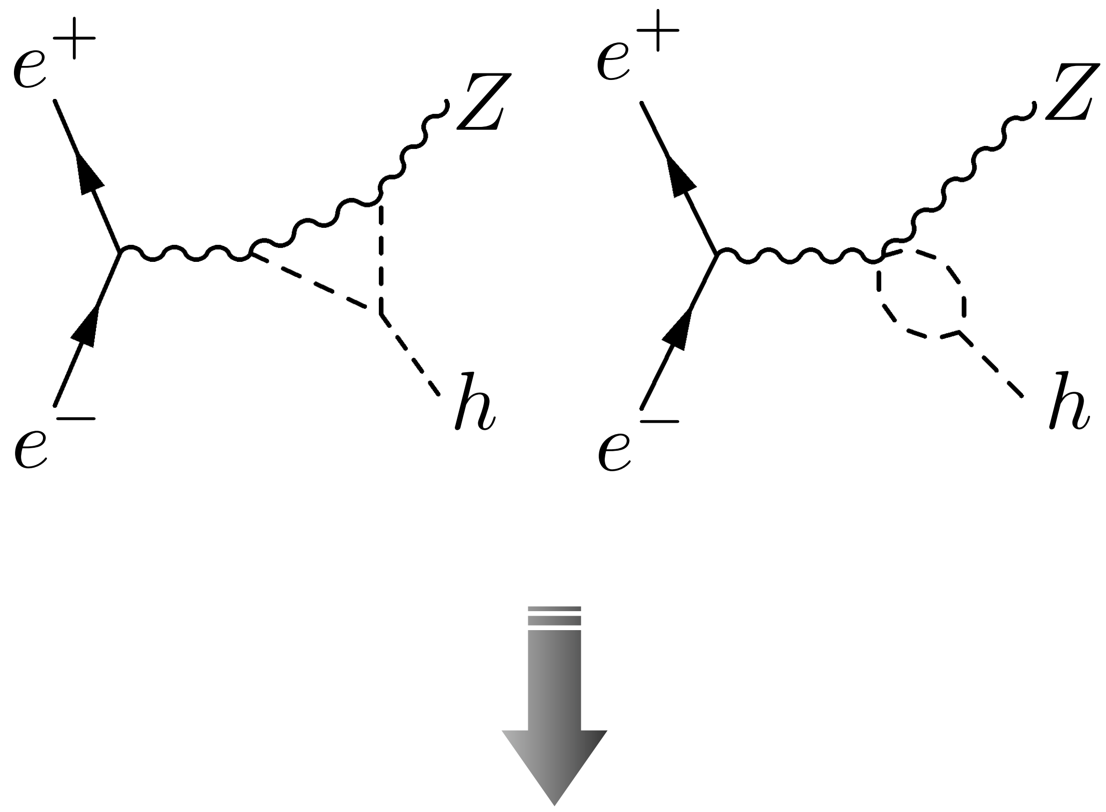
$$\bar{c}_6 \in [-0.9, 1.6] \cup [4.5, 6.9]$$

if Q_6 is only relevant operator If other operators like Q_{uH} contribute (i.e. top Yukawa deviates from SM) then limits on $\bar{c}_6$ typically worsen by a factor of a few. Removing non-SM solution seems also challenging at HL-LHC

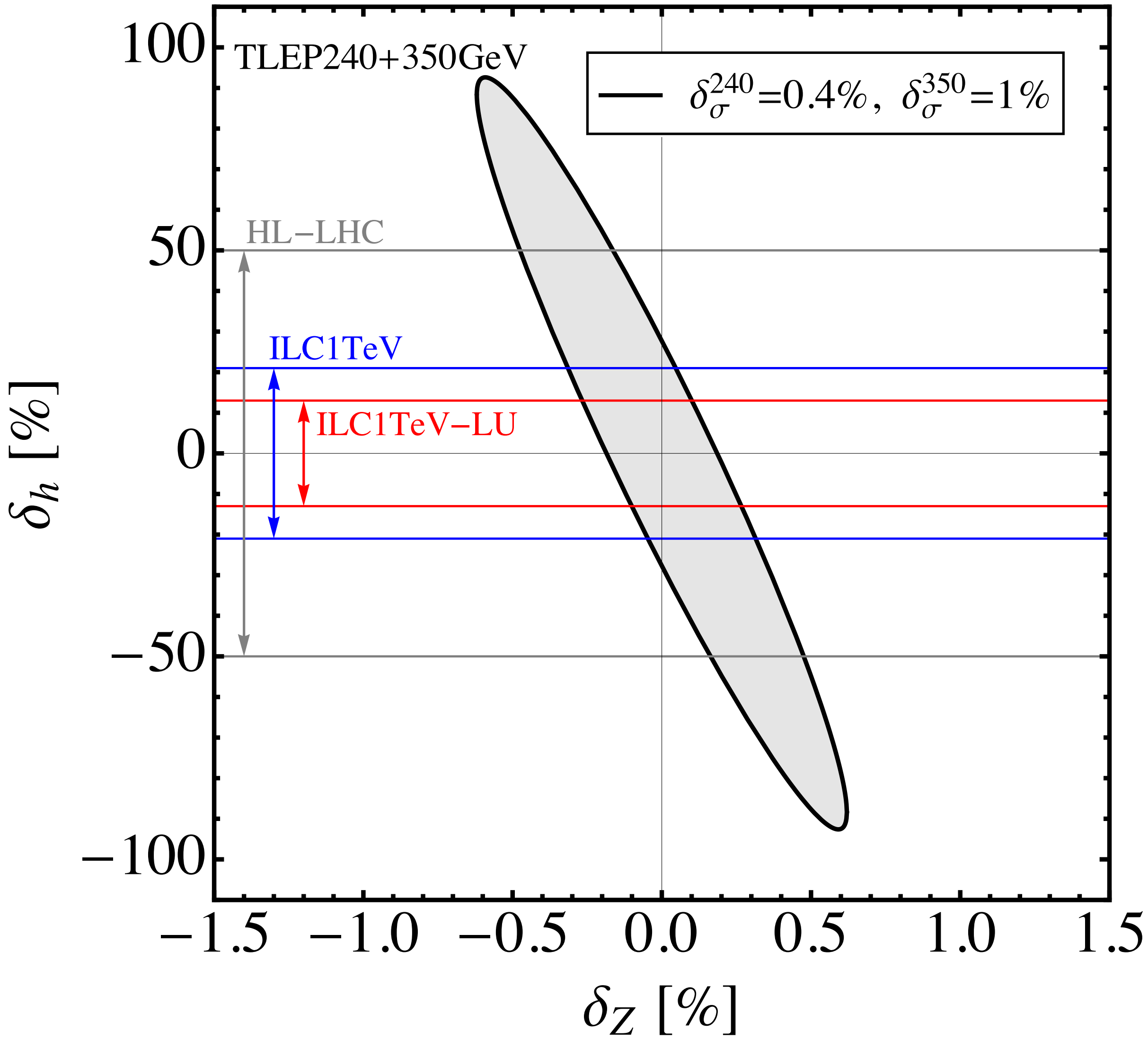
[an incomplete list of relevant references includes …; Goertz et al., 1410.3471; …; Azatov et al., 1502.00539; …]

Indirect bounds at e⁺e⁻ machines

[McCullough, 1312.3322]

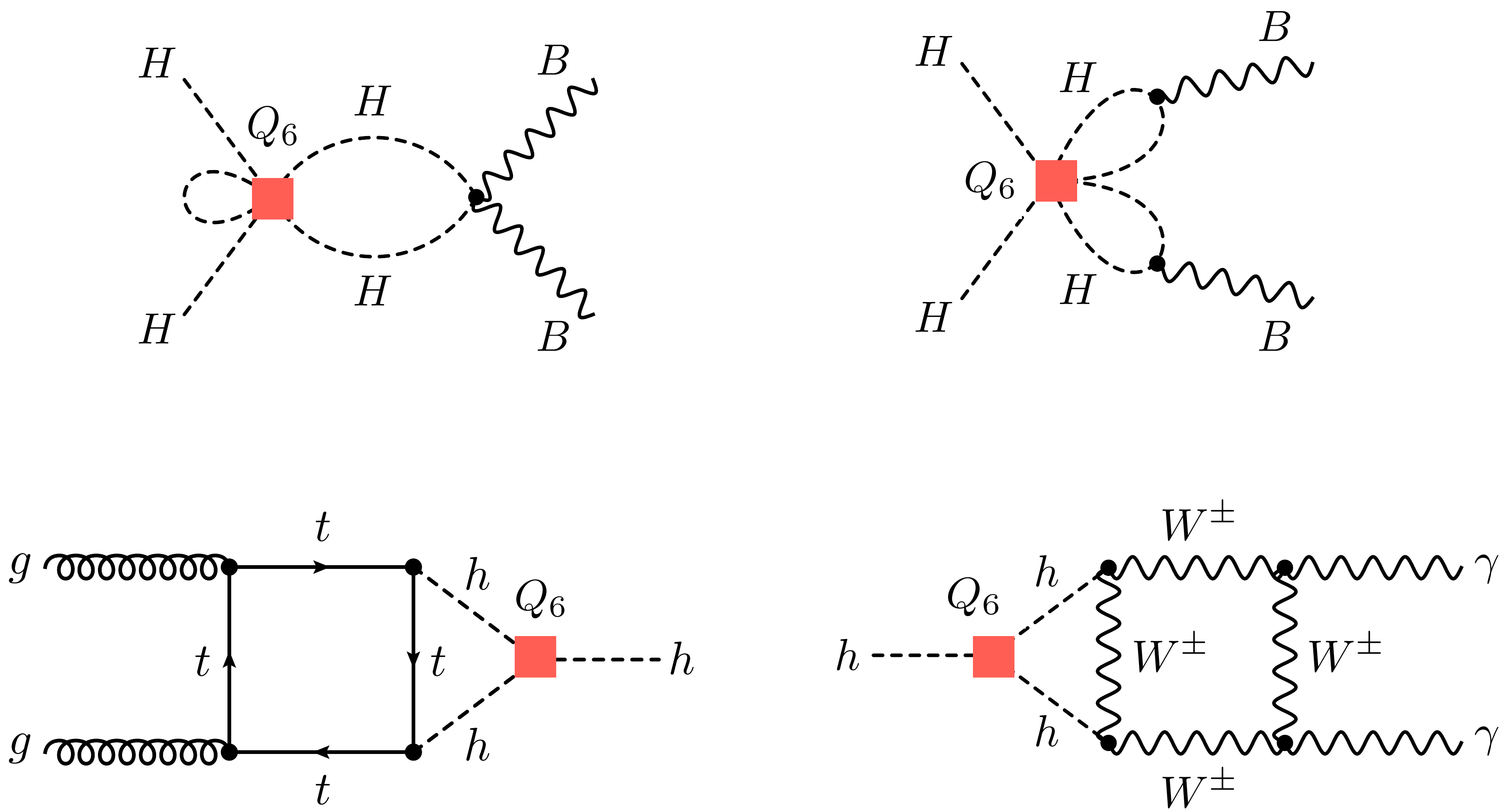


$$\delta_\sigma^{240} = 100\,(2\delta_Z + 0.014\delta_h)\,\%$$



- Precision measurement of associated hZ production at future e⁺e⁻ machines may also allow to test $\bar{c}_6$ values of O(1)

Indirect bounds at LHC



- Indirect bounds on Q_6 arise from gg→h & h→γγ at 2-loop level. Mixing vanishes, so need to calculate finite 2-loop matching

[Gorbahn & UH, 16xx.xxxxx]

Fits to LHC Run I Higgs data†

- Naive combination of ATLAS & CMS Run I Higgs signal strengths leads to:

$$\kappa_g = 0.98 \pm 0.08\,, \quad \kappa_\gamma = 1.07 \pm 0.09$$

$$\bar{c}_6 \in [-135, 76] \;\; (95\%\,\mathrm{CL})$$

†very preliminary results; bounds amazingly close to NDA limit $|\bar{c}_6| < (4\pi)^2/\lambda\ \delta\kappa$

Prospects of fits to Higgs data

- With $3ab^{-1}$ of HL-LHC data it may be possible to improve present knowledge of ggh & hγγ couplings by factor 3 to 4:

$$\kappa_g = 1.00 \pm 0.03\,, \quad \kappa_\gamma = 1.00 \pm 0.02$$

$$\Downarrow$$

$$|\bar{c}_6| \lesssim 16.9 \;\; (95\%\,\mathrm{CL})$$

Indirect probes of Q_6 via $gg \to h$ & $h \to \gamma\gamma$ not as strong as di-Higgs production, but maybe still useful to resolve blind directions

Conclusions

- Operators leading to flavour or CP violation have to be strongly suppressed to avoid stringent low-energy bounds. Limits range from 20 TeV (2-loop) to 10^5 TeV (tree level)
- Present bounds on operators modifying electroweak precision or Higgs observables in ballpark of a few TeV. HL-LHC will allow to improve some of these limits by a factor of O(2)
- Operators that give rise to anomalous triple gauge or Higgs couplings only have to be suppressed by O(100 GeV). New ideas of how to better bound these interactions very welcome

Taming d_e constraint

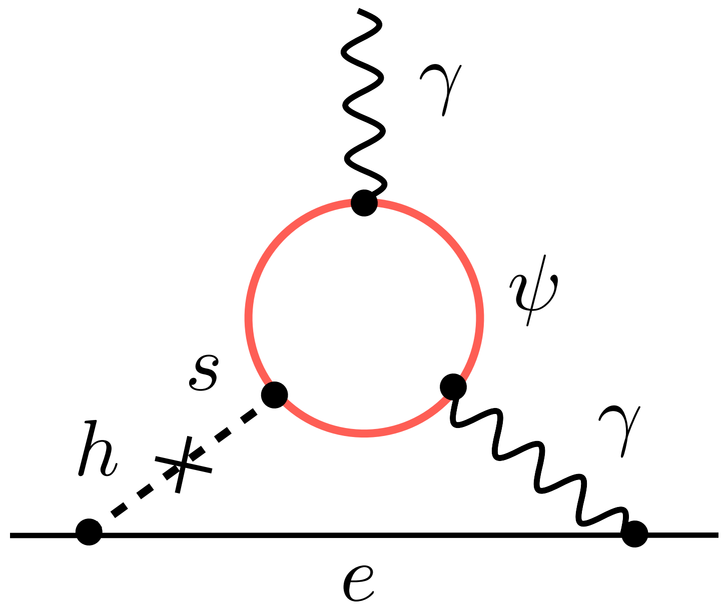
- Consider model with a vector-like hyper-charged fermion & a singlet scalar with a Higgs-portal coupling:

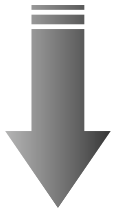
$$\mathcal{L} \supset -i\tilde{\kappa}_\psi \, \bar{\psi}\gamma_5\psi \, s - \mu_s \, (H^\dagger H) \, s$$

⇓

$$\begin{pmatrix} h_1 \\ h_2 \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}, \quad \sin(2\theta) = \frac{2\mu_s v}{m_{h_1}^2 - m_{h_2}^2}$$

Taming d_e constraint





$$\frac{d_e}{e} = \frac{\alpha m_e}{16\pi^3 v^2} Q_\psi^2 \tilde{\kappa}_\psi \frac{v}{m_\psi} \sin(2\theta) \left[g\left(\frac{m_\psi^2}{m_{h_1}^2}\right) - g\left(\frac{m_\psi^2}{m_{h_2}^2}\right) \right]$$

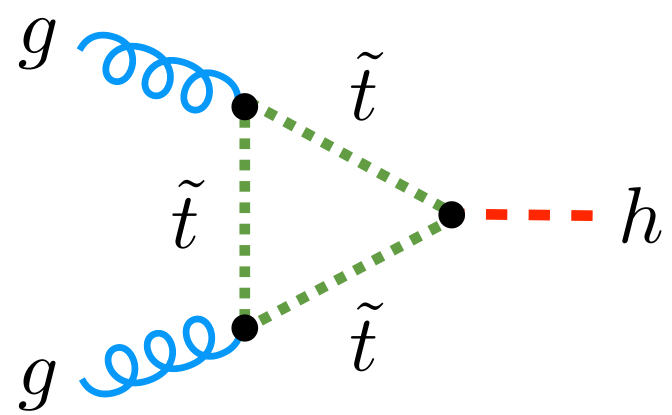
Taming d_e constraint

$$\frac{d_e}{e} \simeq \frac{\alpha m_e}{16\pi^3 v^2} Q_\psi^2 \tilde{\kappa}_\psi \frac{v}{m_\psi} \sin(2\theta) \cdot \begin{cases} \frac{1}{2} \ln \frac{m_{h_2}^2}{m_{h_1}^2} \, , & m_{h_2} \gg m_{h_1} \\ \frac{m_{h_2} - m_{h_1}}{m_{h_1}} \, , & m_{h_2} \simeq m_{h_1} \end{cases}$$

- In limit $m_\psi > m_{h_2} >> m_{h_1}$, one finds scaling as expected from HEFT analysis. Yet, if Higgs masses are close to degenerate, i.e. $m_\psi > m_{h_2} \simeq m_{h_1}$, one looses logarithm & contribution turns out to be suppressed by mass splitting $m_{h_2} - m_{h_1}$

B3/B25

Stop contribution to gg→h



$$\frac{\sigma(gg \to h)}{\sigma(gg \to h)_{\rm SM}} \simeq 1 + \frac{1}{2}\, m_t^2\, \frac{\partial}{\partial m_t^2}\ \ln\left[\det\left(\mathcal{M}^2_{\tilde{t}}\right)\right]$$

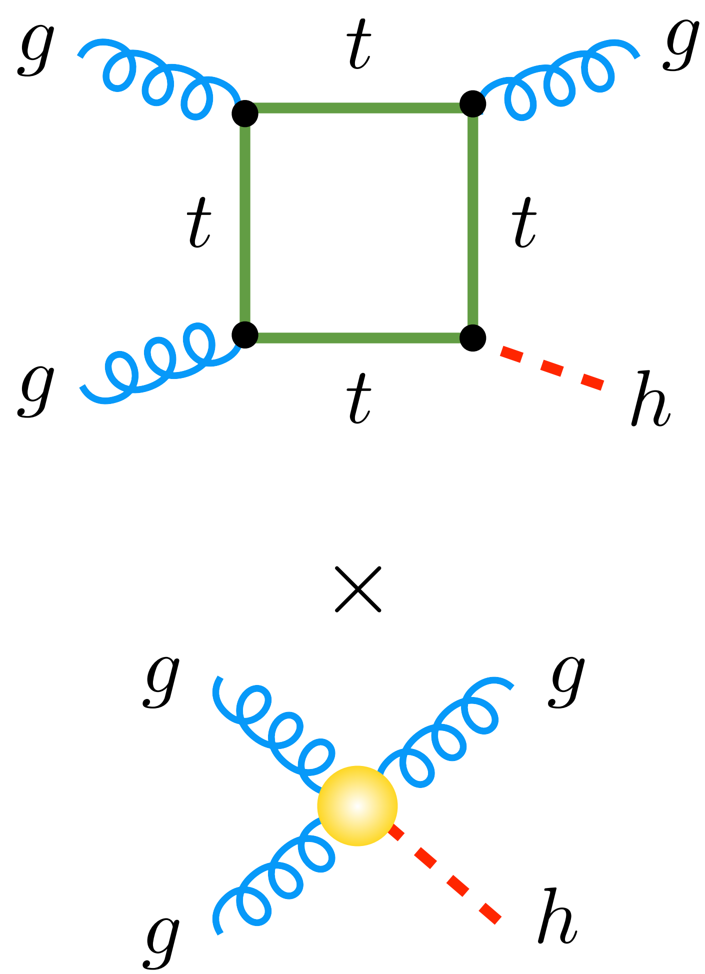
$$\simeq 1 + \frac{m_t^2}{2}\left(\frac{1}{m^2_{\tilde{t}_1}} + \frac{1}{m^2_{\tilde{t}_2}} - \frac{X_t^2}{m^2_{\tilde{t}_1}\, m^2_{\tilde{t}_2}}\right)$$

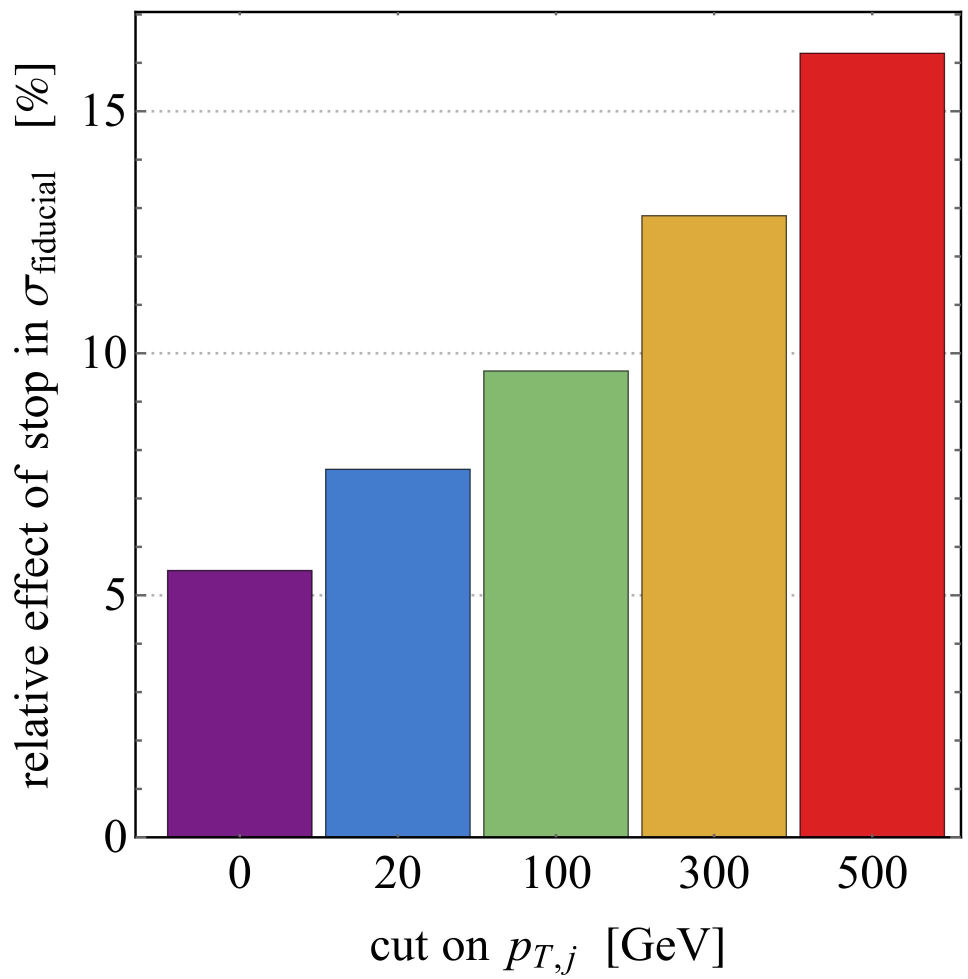
Stop contribution to gg→h

$$\frac{\sigma(gg \to h)}{\sigma(gg \to h)_{\rm SM}} \simeq \begin{cases} 1 + \dfrac{m_t^2}{m_{\tilde{t}}^2}\,, & X_t = 0 \\[2ex] 1 - 2\,\dfrac{m_t^2}{m_{\tilde{t}}^2}\,, & X_t = \sqrt{6}\, m_{\tilde{t}} \end{cases}$$

- In MSSM, correct Higgs mass easier to obtain for large stop-mixing X_t & as a result Higgs production typically suppressed compared to SM. In fact, can choose mixing such that even a very light stop will lead to no effect in σ(gg→h)

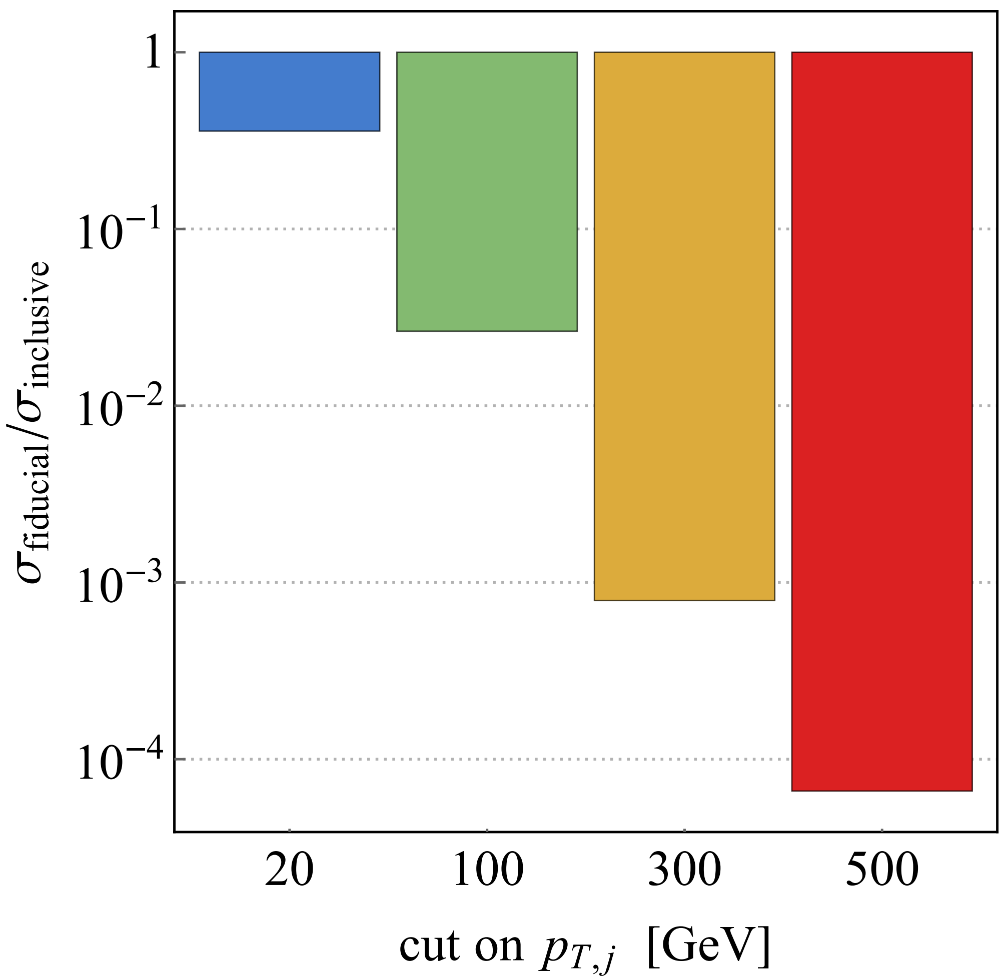
Stops in Higgs + jet

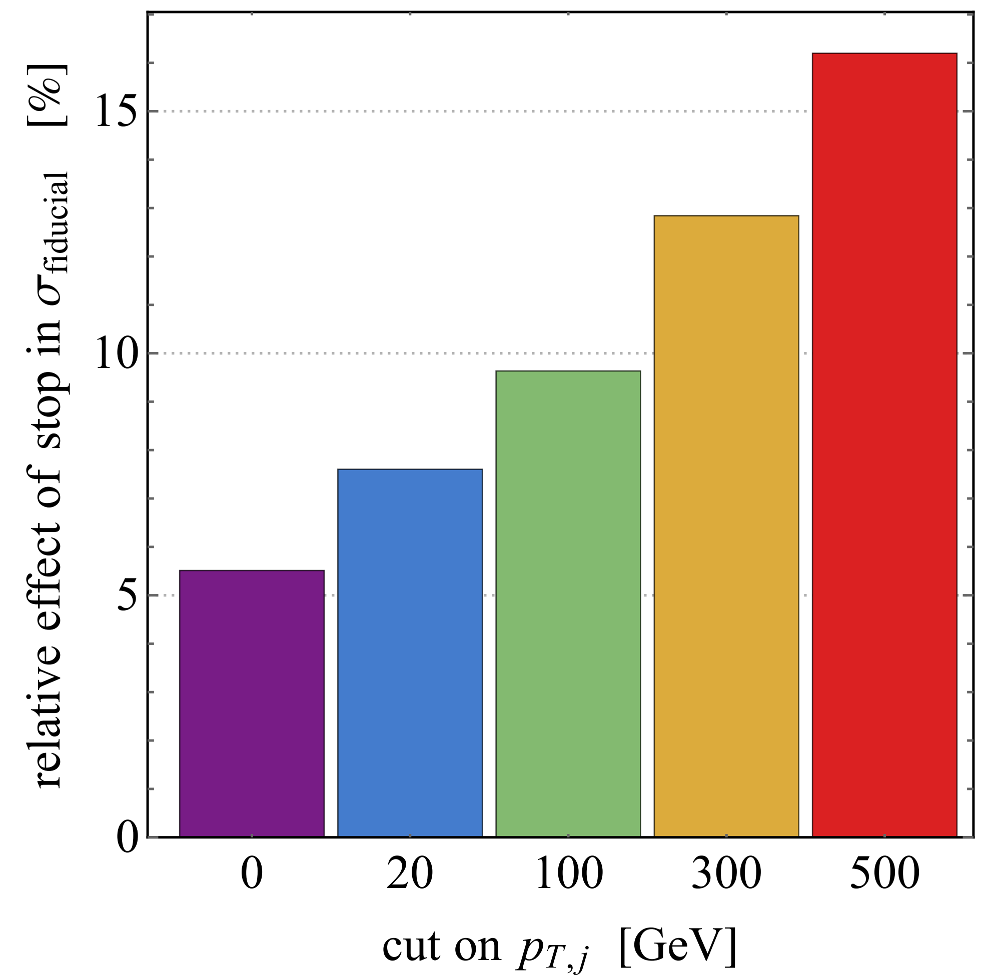




- Can use momentum dependence of h+j form factor in SM to gain higher sensitivity to new physics via interference effects

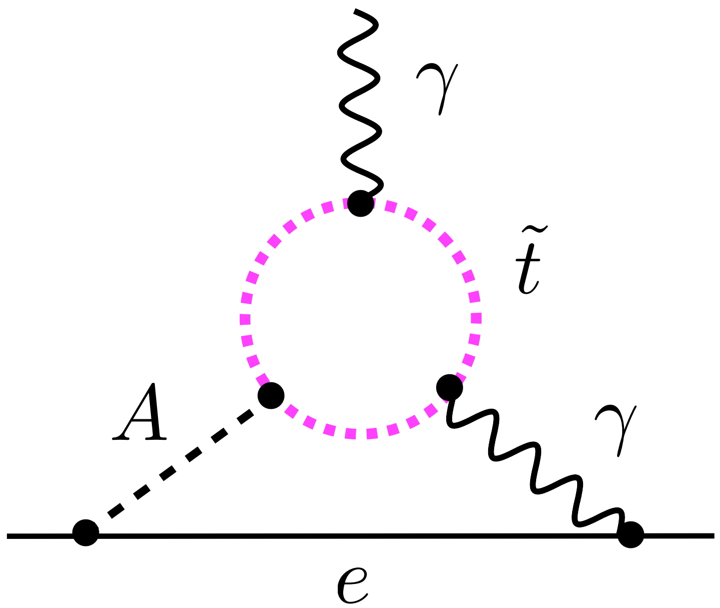
Stops in Higgs + jet





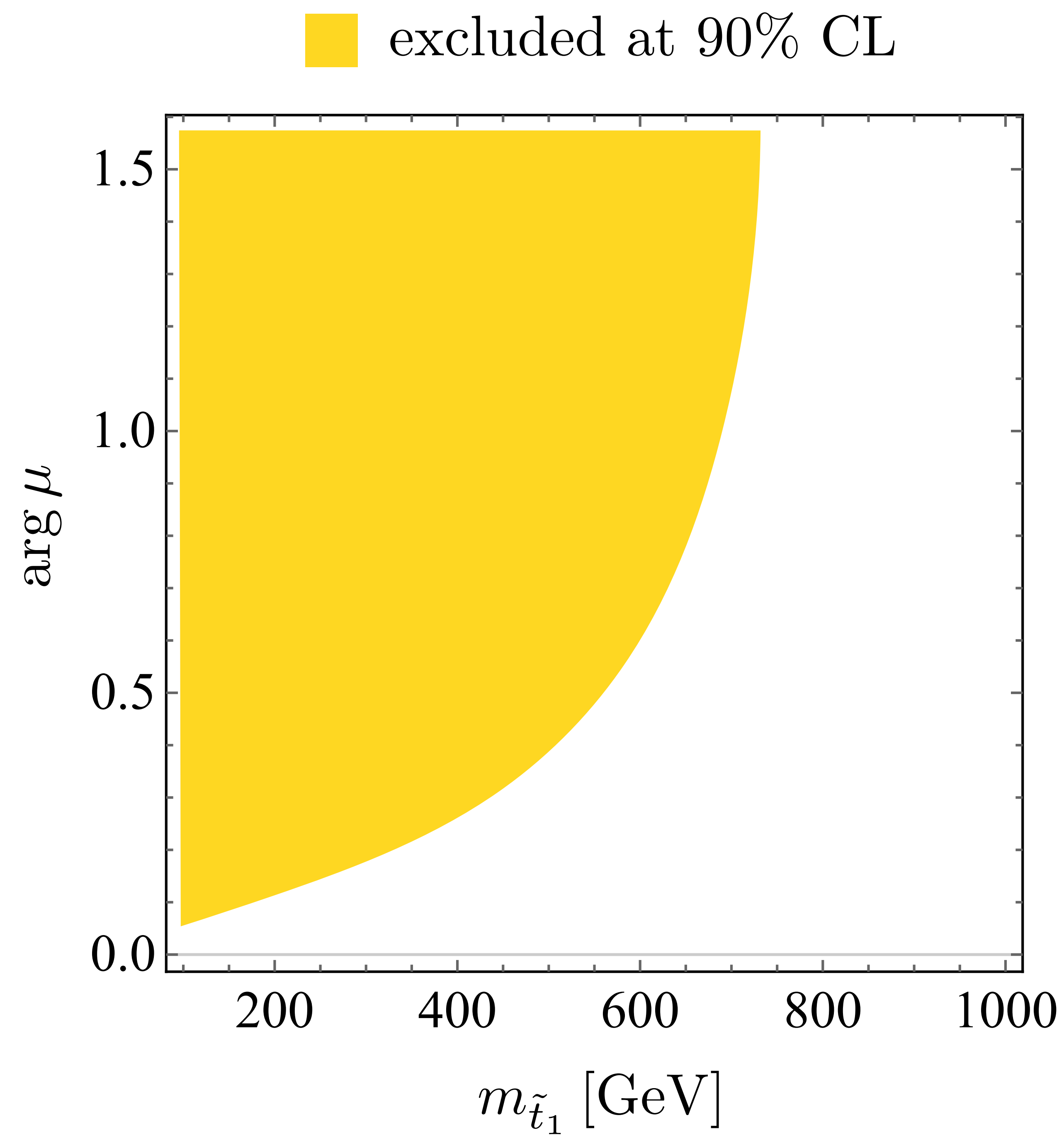
- Improvement in sensitivity to new physics has obvious price: strong cuts will lead to very small fiducial cross sections

Stop contribution to d_e

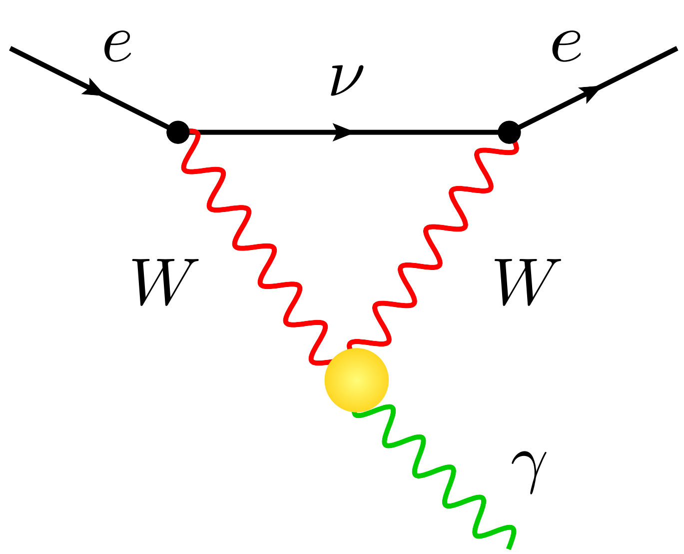


$$|\mu| = 200\,\text{GeV}\,,\ \tan\beta = 5\,,$$

$$m_{\tilde{t}_2} = m_A = 1\,\text{TeV}\,,\ \theta_{\tilde{t}} = \pi/4$$



Bounds on CP-odd TGCs



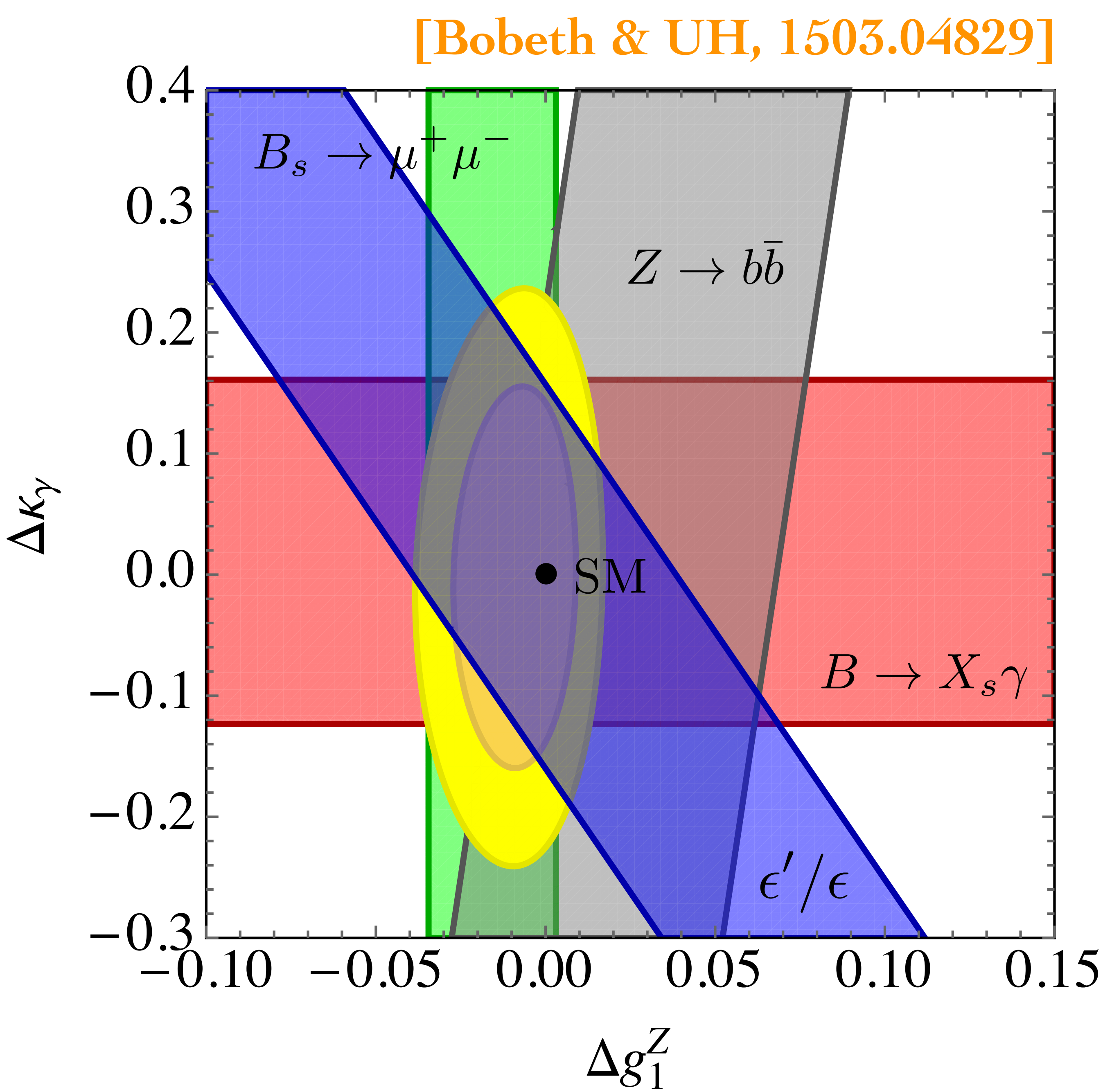
$$\left|\frac{d_e}{e}\right| \simeq \frac{|c_{H\tilde{W}}|}{\Lambda^2}\frac{\alpha m_e}{8\pi}\ln\frac{\Lambda^2}{m_h^2}$$

$$\left|\frac{d_e}{e}\right| < 8.7\cdot 10^{-29}\,\mathrm{cm}\quad (90\%\ \mathrm{CL})$$

$$\Lambda \gtrsim 13\sqrt{|c_{H\tilde{W}}|}\,\mathrm{TeV} \simeq 1.3\,\mathrm{TeV}\quad (\text{weak loop})^{\dagger}$$

†applies to regular UV completions

Anomalous TGCs from ε′/ε

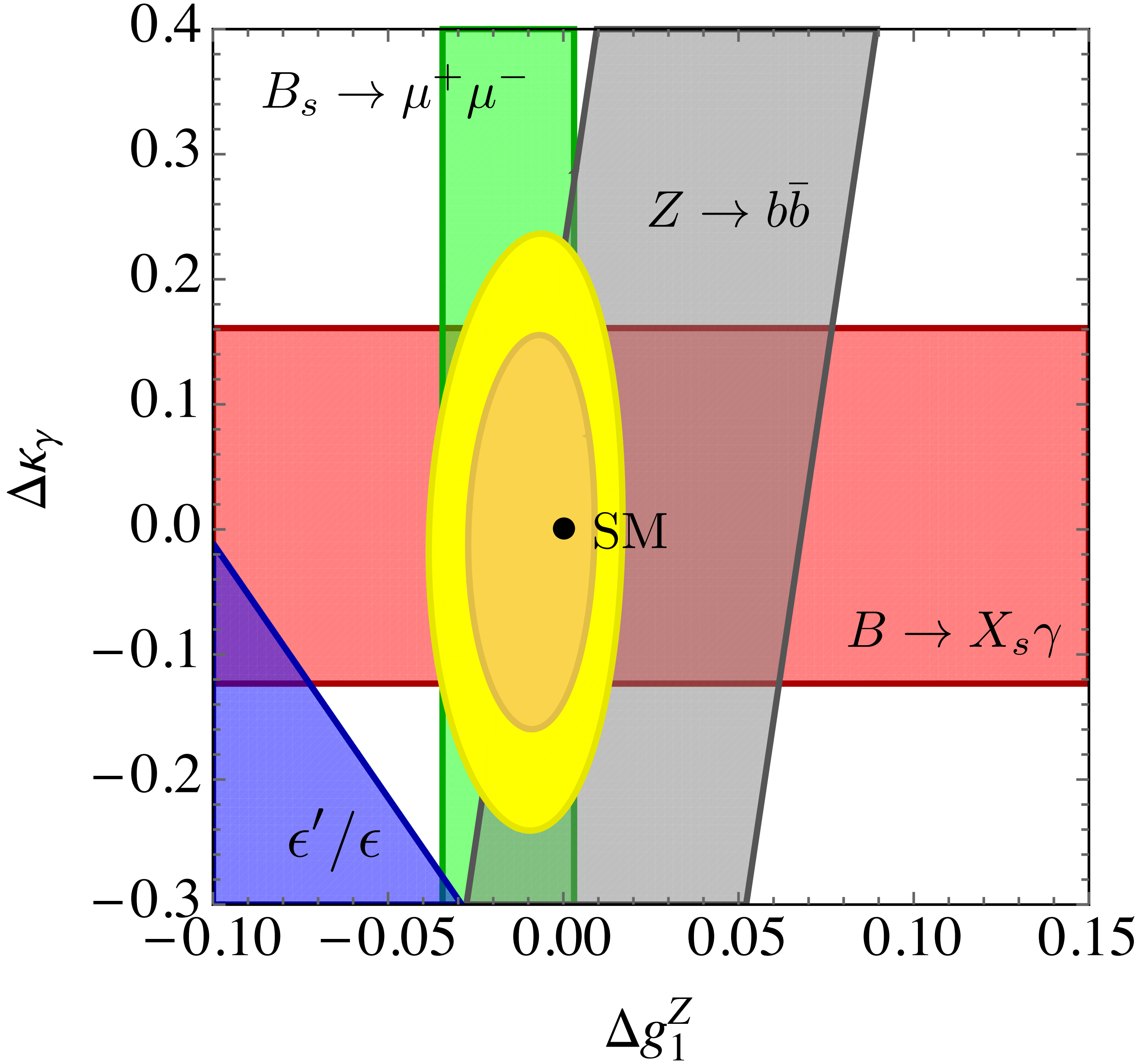


$$\left(\frac{\epsilon'}{\epsilon}\right)_{\rm SM} = (16.6 \pm 2.3)\cdot 10^{-4}$$

[NA48 & KTeV]

- ε′/ε can provide additional constraints on anomalous TGCs

Anomalous TGCs from ε′/ε



$$\left(\frac{\epsilon'}{\epsilon}\right)_{\rm SM} = (1.9 \pm 5.4) \cdot 10^{-4}$$

[Buras et al., 1507.06345]

- ε′/ε can provide additional constraints on anomalous TGCs

Anomalous tt̄Z couplings

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum_{i=\substack{(3)\\ \phi Q},\phi Q,\phi u} \frac{C_i}{\Lambda^2} O_i + \dots$$

$$O_{\phi Q}^{(3)} = \left(\phi^\dagger i \overleftrightarrow{D}_\mu \sigma^a \phi\right)\left(\bar{Q}_{L,3}\gamma^\mu \sigma^a Q_{L,3}\right),$$

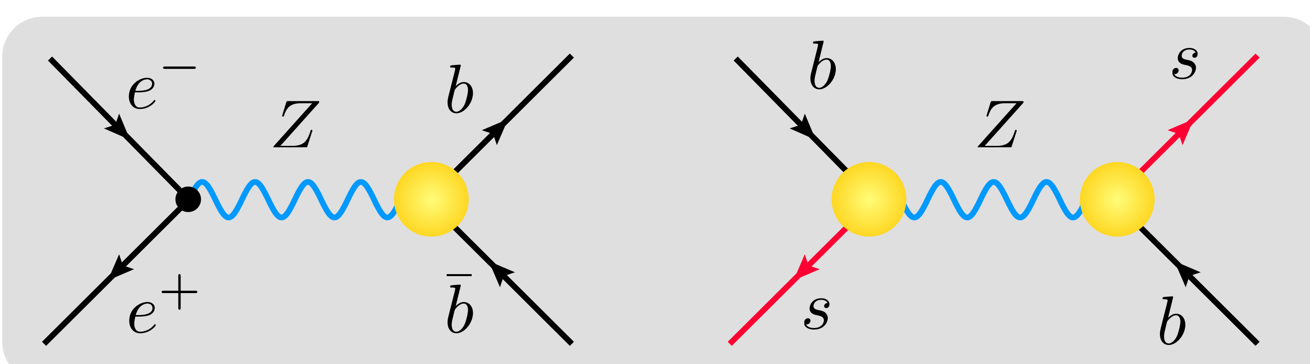
$$O_{\phi Q} = \left(\phi^\dagger i \overleftrightarrow{D}_\mu \phi\right)\left(\bar{Q}_{L,3}\gamma^\mu Q_{L,3}\right),$$

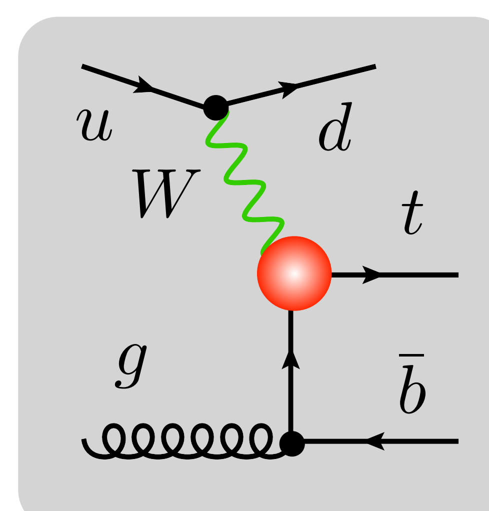
$$O_{\phi u} = \left(\phi^\dagger i \overleftrightarrow{D}_\mu \phi\right)\left(\bar{t}_R\gamma^\mu t_R\right)$$

Closed $t\bar{t}Z$ couplings

$$\mathcal{L}_{t\bar{t}Z} = g_L\,\bar{t}_L \not{Z} t_L + g'_L\, V^*_{ti} V_{tj} \bar{d}_{L,i} \not{Z} d_{L,j} + g_R \bar{t}_R \not{Z} t_R$$
$$+ \left(k_L\, \bar{t}_L \not{W}^+ b_L + \text{h.c.} \right)$$

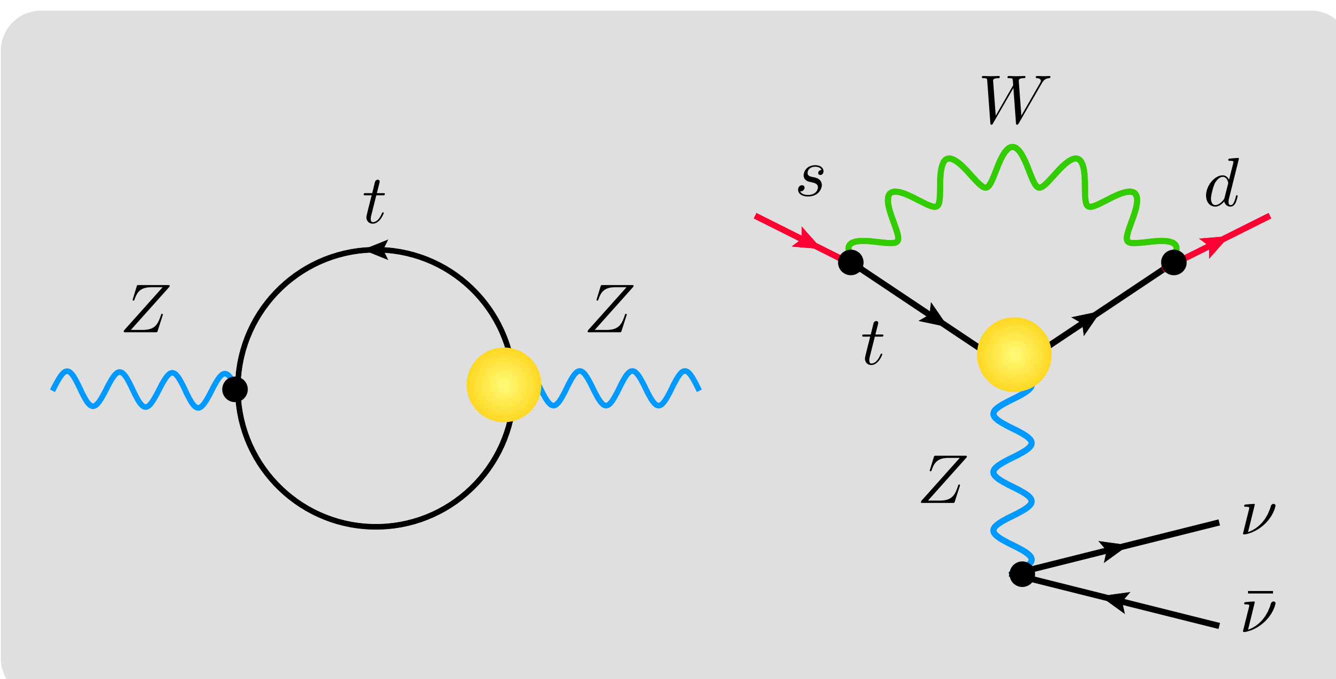
$$g'_L \propto \frac{v^2}{\Lambda^2} \left(C^{(3)}_{\phi Q} + C_{\phi Q} \right) \simeq 0\,, \qquad k_L \propto \frac{v^2}{\Lambda^2}\, C^{(3)}_{\phi Q} = -0.006 \pm 0.038$$

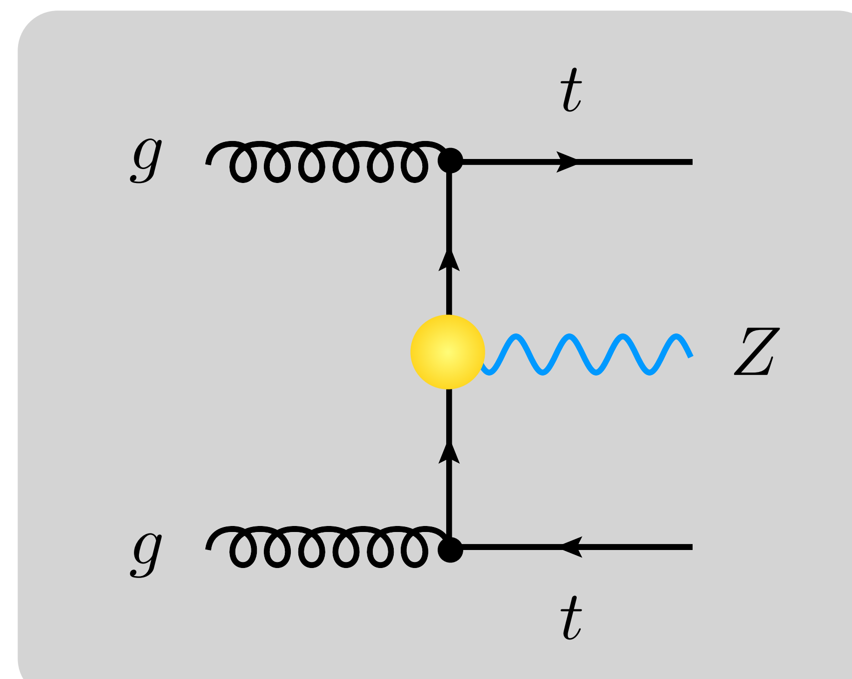




Open t$\bar{\mathrm{t}}$Z couplings

$$g_L \propto \frac{v^2}{\Lambda^2}\left(C^{(3)}_{\phi Q} - C_{\phi Q}\right)\,, \qquad g_R \propto \frac{v^2}{\Lambda^2} C_{\phi u}$$





B14/B25

Recent result on d_e

Order of Magnitude Smaller Limit on the Electric Dipole Moment of the Electron

The ACME Collaboration*: J. Baron[1], W. C. Campbell[2], D. DeMille[3], J. M. Doyle[1], G. Gabrielse[1], Y. V. Gurevich[1,**], P. W. Hess[1], N. R. Hutzler[1], E. Kirilov[3,#], I. Kozyryev[3,†], B. R. O'Leary[3], C. D. Panda[1], M. F. Parsons[1], E. S. Petrik[1], B. Spaun[1], A. C. Vutha[4], and A. D. West[3]

The Standard Model (SM) of particle physics fails to explain dark matter and why matter survived annihilation with antimatter following the Big Bang. Extensions to the SM, such as weak-scale Supersymmetry, may explain one or both of these phenomena by positing the existence of new particles and interactions that are asymmetric under time-reversal (T). These theories nearly always predict a small, yet potentially measurable (10^{-27}-10^{-30} e cm) electron electric dipole moment (EDM, d_e), which is an asymmetric charge distribution along the spin ($\vec{S}$). The EDM is also asymmetric under T. Using the polar molecule thorium monoxide (ThO), we measure $d_e = (-2.1 \pm 3.7_{\rm stat} \pm 2.5_{\rm syst}) \times 10^{-29}$ e cm. This corresponds to an upper limit of $|d_e| < 8.7 \times 10^{-29}$ e cm with 90 percent confidence, an order of magnitude improvement in sensitivity compared to the previous best limits. Our result constrains T-violating physics at the TeV energy scale.

The exceptionally high internal effective electric field ($\mathcal{E}_{\rm eff}$) of heavy neutral atoms and molecules can be used to precisely probe for d_e via the energy shift $U = -\vec{d}_e \cdot \vec{\mathcal{E}}_{\rm eff}$, where $\vec{d}_e = d_e \vec{S}/(\hbar/2)$. Valence electrons travel relativistically near the heavy nucleus, making $\mathcal{E}_{\rm eff}$ up to a million times larger than any static laboratory field[1–3]. The previous best limits on d_e came from experiments with thallium (Tl) atoms[4] ($|d_e| < 1.6 \times 10^{-27}$ e cm), and ytterbium fluoride (YbF) molecules[5,6] ($|d_e| < 1.06 \times 10^{-27}$ e cm). The latter demonstrated that molecules can be used to suppress the motional electric fields and geometric phases that

is prepared using optical pumping and state preparation lasers. Parallel electric ($\vec{\mathcal{E}}$) and magnetic ($\vec{\mathcal{B}}$) fields exert torques on the electric and magnetic dipole moments, causing the spin vector to precess in the xy plane. The precession angle is measured with a readout laser and fluorescence detection. A change in this angle as $\vec{\mathcal{E}}_{\rm eff}$ is reversed is proportional to d_e.

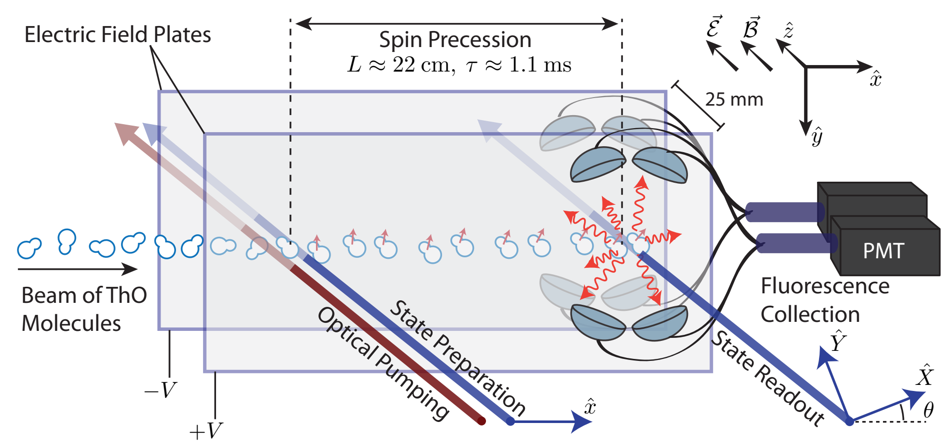
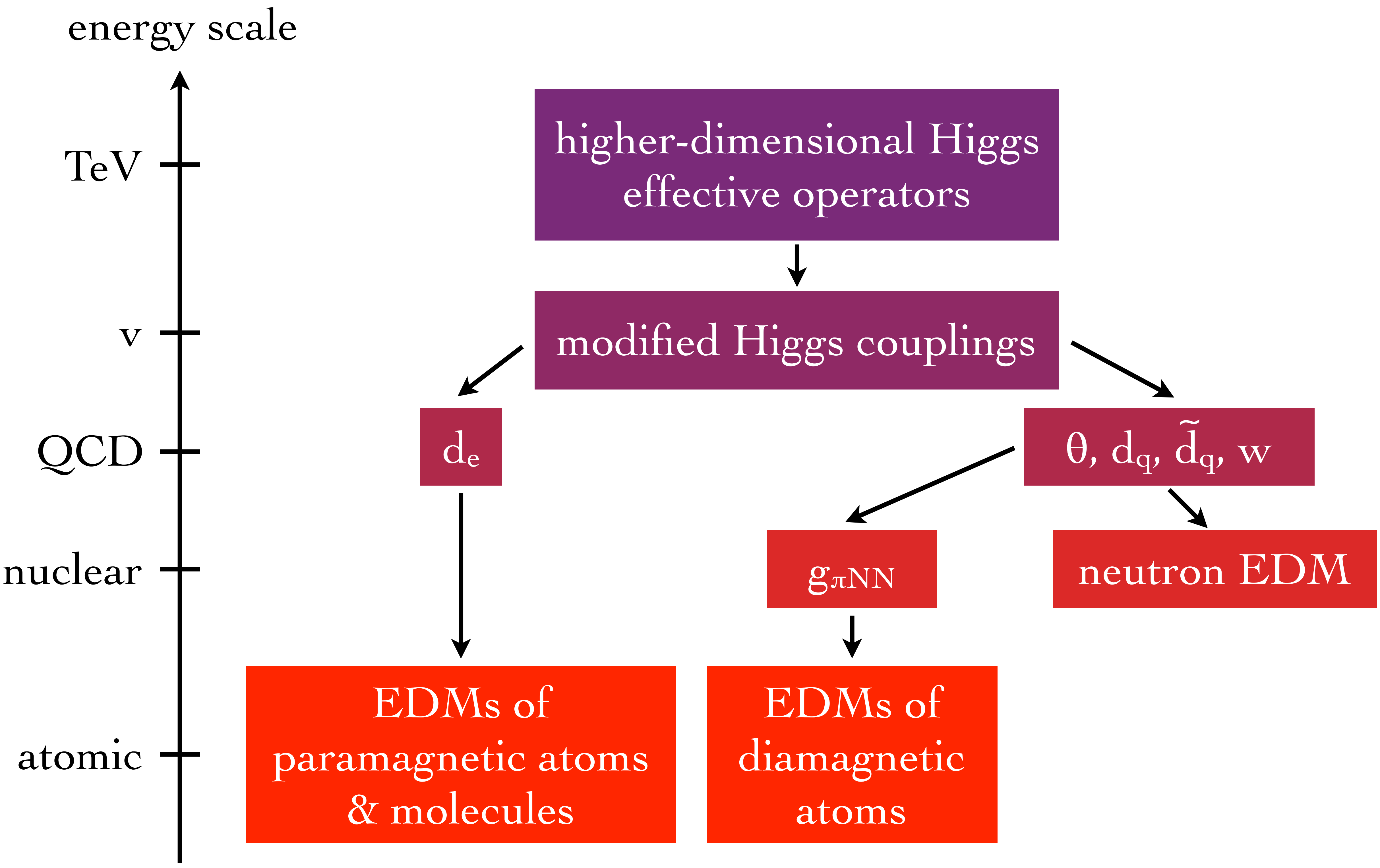


FIG. 1. Schematic of the apparatus (not to scale). A collimated pulse of ThO molecules enters a magnetically shielded region. An aligned spin state (smallest red arrows), prepared via optical pumping, precesses in parallel electric and magnetic fields. The final spin alignment is read out by a laser with rapidly alternating linear polarizations, $\hat{X}, \hat{Y}$, with the resulting fluorescence collected and detected with photomultiplier tubes (PMTs).

[ACME, 1310.7534]

Effective theory playground



B16/B25

Mercury EDM

$$\frac{d_{\rm Hg}}{e} \simeq -1.8 \cdot 10^{-4} \left(4^{+8}_{-2}\right) \left(\tilde{d}_u(\mu_H) - \tilde{d}_d(\mu_H)\right)$$

$$\simeq -\left(4^{+8}_{-2}\right) \left[3.1\, \tilde{\kappa}_t - 3.2 \cdot 10^{-2} \kappa_t \tilde{\kappa}_t\right] \cdot 10^{-29}\,\mathrm{cm}$$

- Dominant corrections from CP-odd isovector πNN interactions
- $\kappa_t \tilde{\kappa}_t$ contributions due to Weinberg operator subdominant
- $|d_{Hg}/e| < 3.1 \cdot 10^{-29}$ cm at 90% CL **[Griffith et al., PRL (2009) 102]**

Neutron & deuteron EDM

$$\frac{d_n}{e} = (1.0 \pm 0.5) \left\{ 1.4 \left[\frac{d_d(\mu_H)}{e} - 0.25 \, \frac{d_u(\mu_H)}{e} \right] + 1.1 \left[\tilde{d}_d(\mu_H) + 0.5 \, \tilde{d}_u(\mu_H) \right] \right\}$$

$$+ (22 \pm 10) \cdot 10^{-3} \, \mathrm{GeV} \, w(\mu_H)$$

$$\frac{d_D}{e} = (0.5 \pm 0.3) \left[\frac{d_d(\mu_H)}{e} + \frac{d_u(\mu_H)}{e} \right] + \left[5^{+11}_{-3} + (0.6 \pm 0.3) \right] \left(\tilde{d}_d(\mu_H) - \tilde{d}_u(\mu_H) \right)$$

$$- (0.2 \pm 0.1) \left(\tilde{d}_d(\mu_H) + \tilde{d}_u(\mu_H) \right) + (22 \pm 10) \cdot 10^{-3} \, \mathrm{GeV} \, w(\mu_H)$$

[Lebedev et al., hep-ph/0402023; Pospelov & Ritz, hep-ph/0504231]

$h\bar{b}b$ couplings in Higgs physics

- Corrections in gg→h & h→γγ due to κ_b, $\tilde{\kappa}_b$ subleading. Main effect from modifications of $\bar{b}b$ branching ratio/total rate:

$$\mathrm{Br}(h \to \bar{b}b) = \frac{\left(\kappa_b^2 + \tilde{\kappa}_b^2\right) \mathrm{Br}(h \to \bar{b}b)_{\mathrm{SM}}}{1 + \left(\kappa_b^2 + \tilde{\kappa}_b^2 - 1\right) \mathrm{Br}(h \to \bar{b}b)_{\mathrm{SM}}} \,,$$

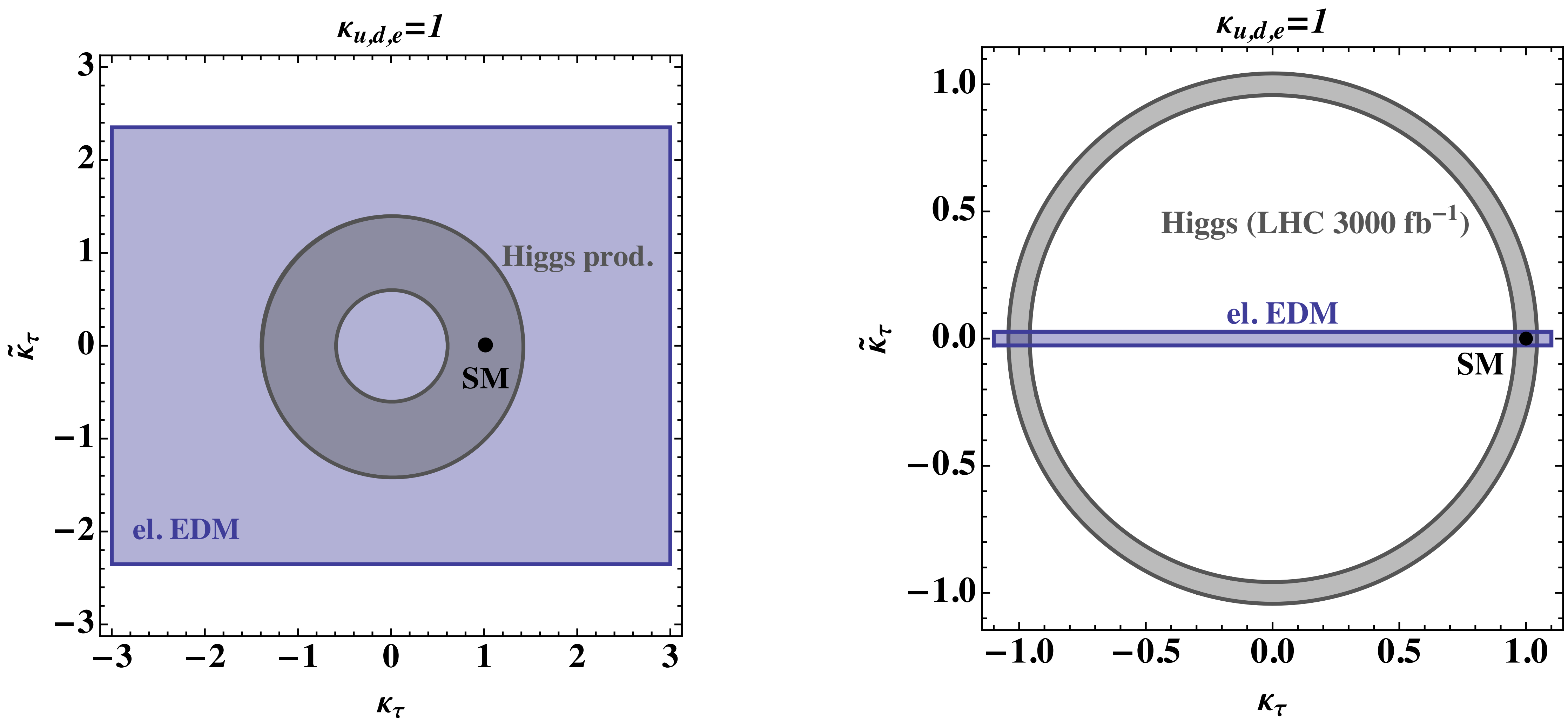
$$\mathrm{Br}(h \to X) = \frac{\mathrm{Br}(h \to X)_{\mathrm{SM}}}{1 + \left(\kappa_b^2 + \tilde{\kappa}_b^2 - 1\right) \mathrm{Br}(h \to \bar{b}b)_{\mathrm{SM}}}$$

$$\mu_{\bar{b}b} = 0.72 \pm 0.53 \,, \quad \mu_{\bar{\tau}\tau} = 1.02 \pm 0.35 \,, \quad \mu_{\gamma\gamma} = 1.14 \pm 0.20 \,,$$

$$\mu_{WW} = 0.78 \pm 0.17 \,, \quad \mu_{ZZ} = 1.11 \pm 0.23^{\dagger}$$

†values as of October 2013

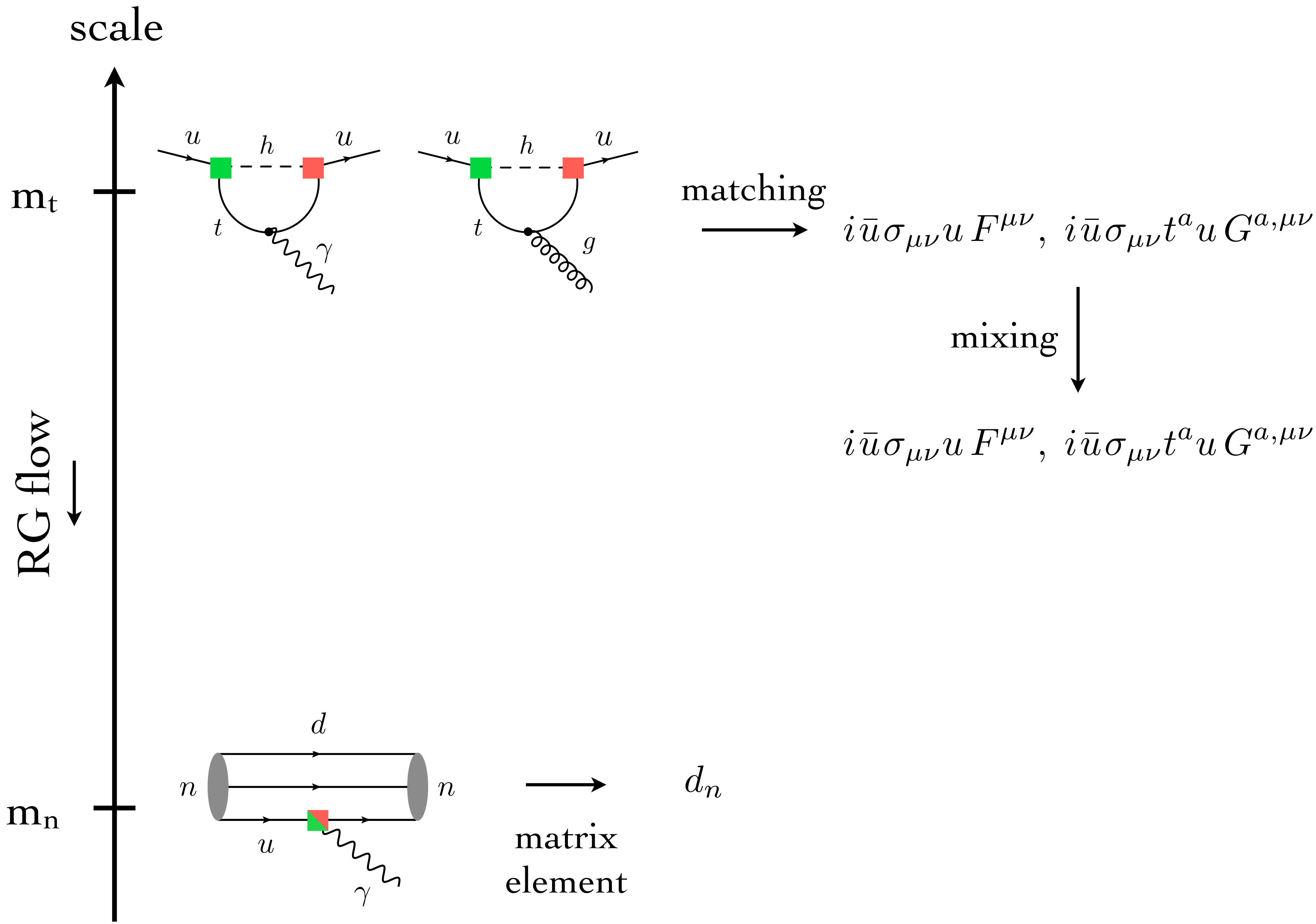
Fits to $h\bar{\tau}\tau$ couplings



- Via angular correlations in $h \to \bar{\tau}\tau$, LHC may be capable to probe $\tilde{\kappa}_\tau$ values of O(0.1) without assumption about $h\bar{e}e$ coupling

[Berge et al., 0801.2297, 0812.1910, 1108.0670; Harnik et al., 1308.1094]

Constraints from d_n on $t \to uh$



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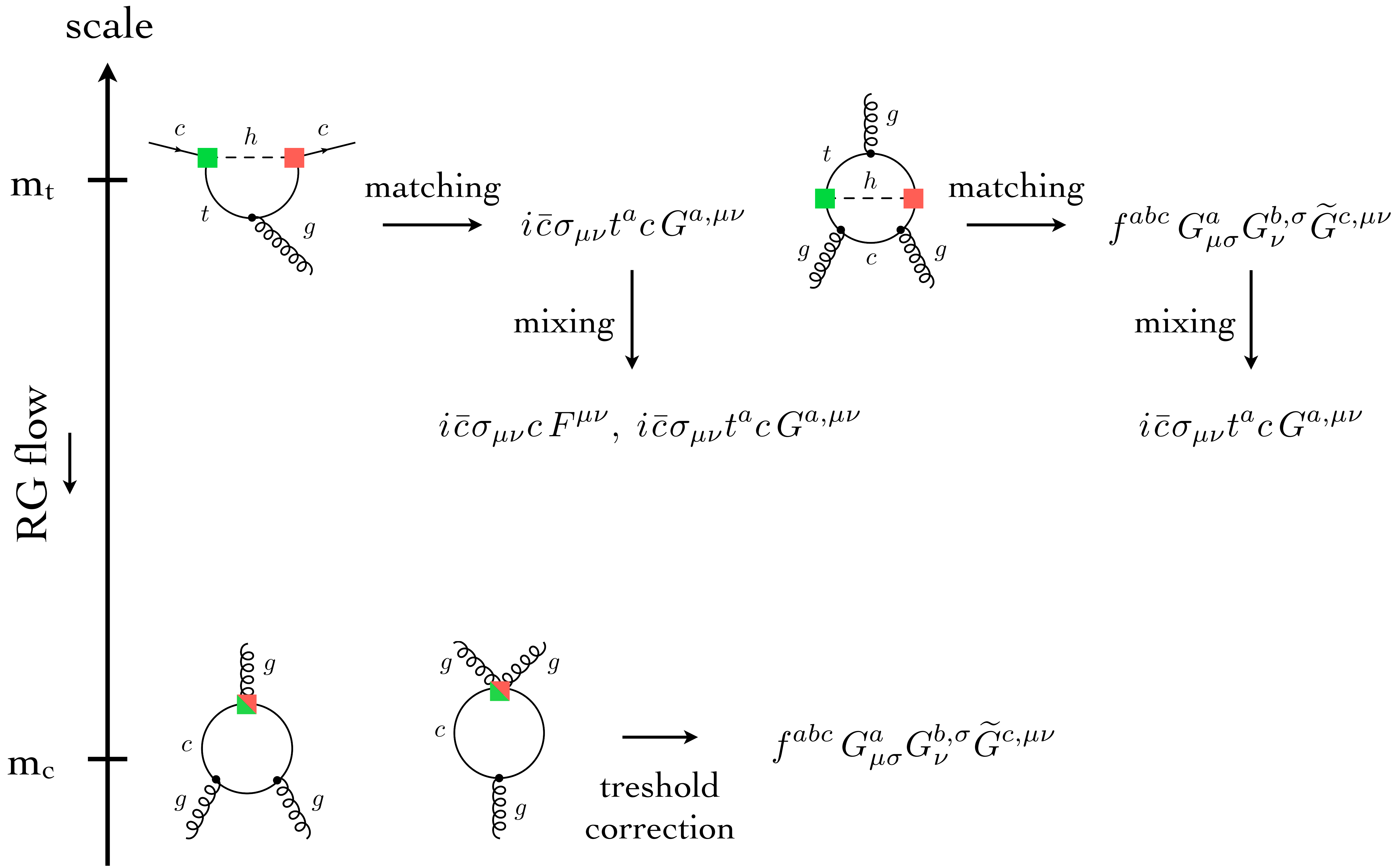
Constraints from d_n on $t\to ch$



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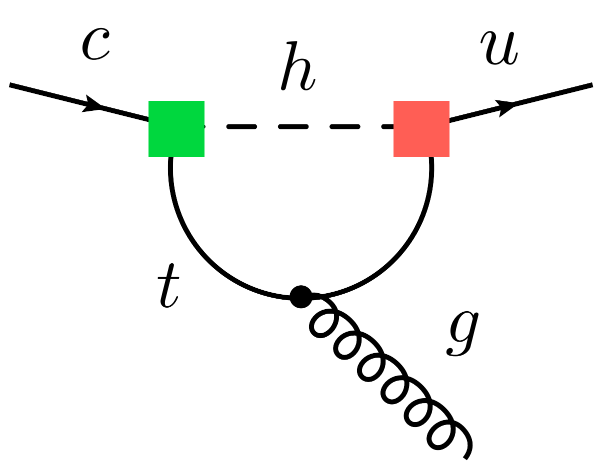
Constraints from D→π⁺π⁻,K⁺K⁻

- Top-Higgs couplings contribute to difference ΔA_{CP} between direct CP asymmetries in $D\to\pi^+\pi^-$ & $D\to K^+K^-$:



matching ⟶

$$Q_8 = \frac{g_s}{(4\pi)^2}\, m_c\, \bar{u}_L \sigma^{\mu\nu} t^a c_R G^a_{\mu\nu}$$

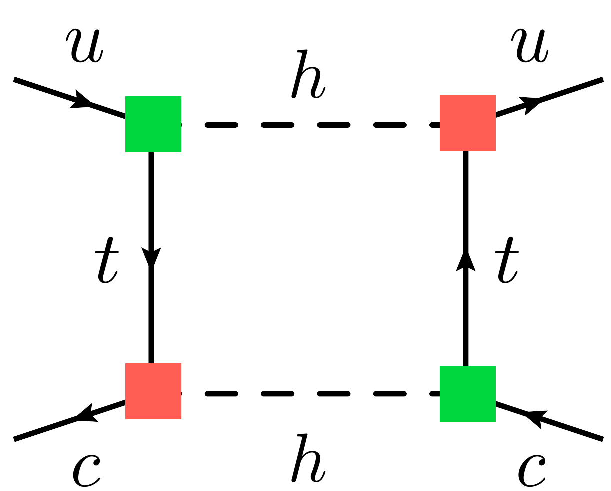
$$|\Delta A_{\rm CP}| \simeq \, {\rm Im}\big(\Delta C_8(m_t)\big) \simeq \frac{|{\rm Im}\,(Y^*_{ut} Y_{tc})|}{3.7 \cdot 10^{-4}}\,\% \lesssim 1\%$$

↑ **[HFAG]**

$$\Delta A_{\rm CP} = -(0.33 \pm 0.12)\%$$

Constraints from D-$\bar{\rm D}$ mixing

- Also D-$\bar{\rm D}$ mixing receives contribution from Higgs-top loops. Dominant effect due to mixed-chirality operator:



matching $\longrightarrow$ $Q_4 = (\bar{c}_L u_R)(\bar{c}_R u_L)$

$$\Delta C_4(m_t) \simeq \frac{1}{32\pi^2} \frac{\sqrt{2}}{4G_F} \frac{1}{3m_h^2} Y_{tc}^* Y_{ut}^* Y_{tu} Y_{ct}$$

[Gedalia et al., 0906.1879]

$$|\mathrm{Im}\,(\Delta C_4(m_t))\,| \lesssim 3.4 \cdot 10^{-10}$$

Present & future limits

$\mathrm{Br}\,(t \to qh)$	0.56%	$2 \cdot 10^{-4}$	[Agashe et al., 1311.2028]
$\left\lvert \frac{d_n}{e} \right\rvert$	$2.9 \cdot 10^{-26}\,\mathrm{cm}$	$10^{-28}\,\mathrm{cm}$	[Hewett et al., 1205.2671]
$\left\lvert \frac{d_D}{e} \right\rvert$	$-$	$10^{-29}\,\mathrm{cm}$	[Storage Ring EDM]
ΔA_{CP}	theory limited		
D–$\bar{D}$	$\mathcal{O}(10)$ improvement		[Belle & LHCb]