CRC-TRR-257

The Top-Bottom Connection in SMEFT

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picture: www.westend61.de

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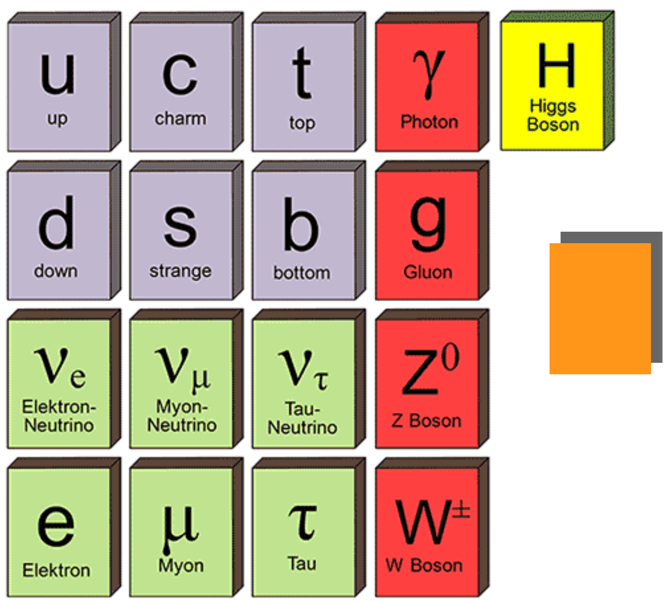
Adding the B to the SM



Standard Model as Effective Field Theory

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \frac{C^{(5)}}{\Lambda} O^{(5)} + \sum_i \frac{C_i^{(6)}}{\Lambda^2} O_i^{(6)} + \dots$$

Local operators preserve SM symmetries.

Where should we look for UV physics?

- high energies: $\frac{\text{BSM}}{\text{SM}} \sim C_i \frac{E^2}{\Lambda^2}$ LHC
- broken symmetries: $\frac{\text{BSM}}{\text{SM}} \sim C_i \frac{m_W^2}{m_b^2}, C_i \frac{4\pi}{\alpha V_{tb} V_{ts}^*}, \dots$ b factories

High energies

2-2 scattering amplitude (dim. 6): Hagiwara et al. 1987

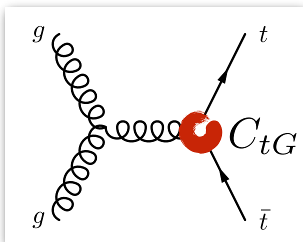
$$\mathcal{M} \sim \frac{v^m}{\Lambda^2} \frac{E^{2-m+n}}{m_V^n}$$

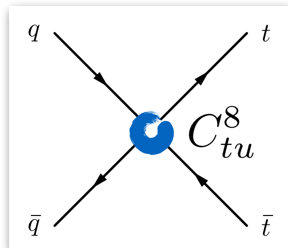
m vevs; *n* Goldstones

Maltoni, Mantani, Mimasu 1904.05637

- $O_{4f} = (\overline{f}\gamma_\mu f)(\overline{f}\gamma^\mu f) \quad \rightarrow \frac{E^2}{\Lambda^2}$ quadratic growth
- $O_{Hf} = (H^\dagger i D_\mu H)(\overline{f}\gamma^\mu f) \quad \rightarrow \frac{vE}{\Lambda^2}$ linear growth (longitudinal mode)
- $O_{fV} = (\overline{F}_L \sigma^{\mu\nu} f_R) H \, V_{\mu\nu} \quad \rightarrow \frac{m_f v}{\Lambda^2}$ helicity suppression (ffV)

Top pair production at high energies

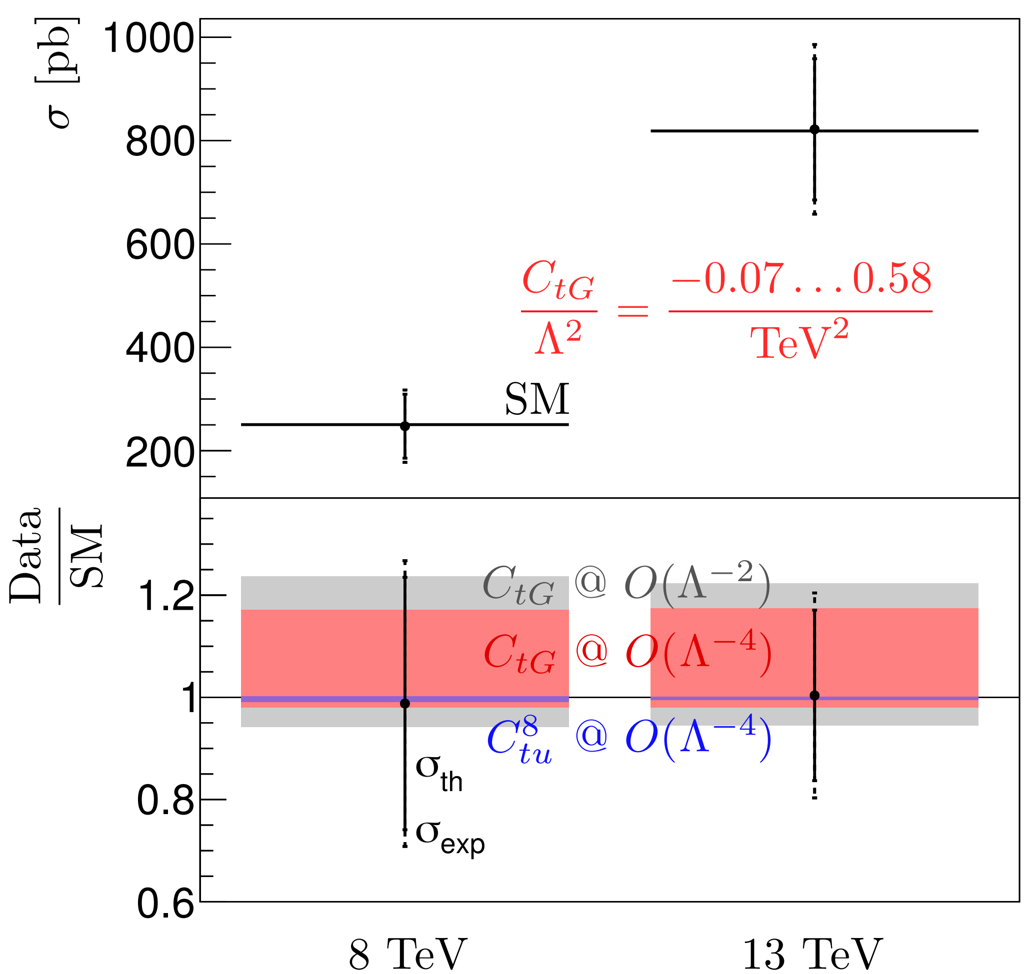


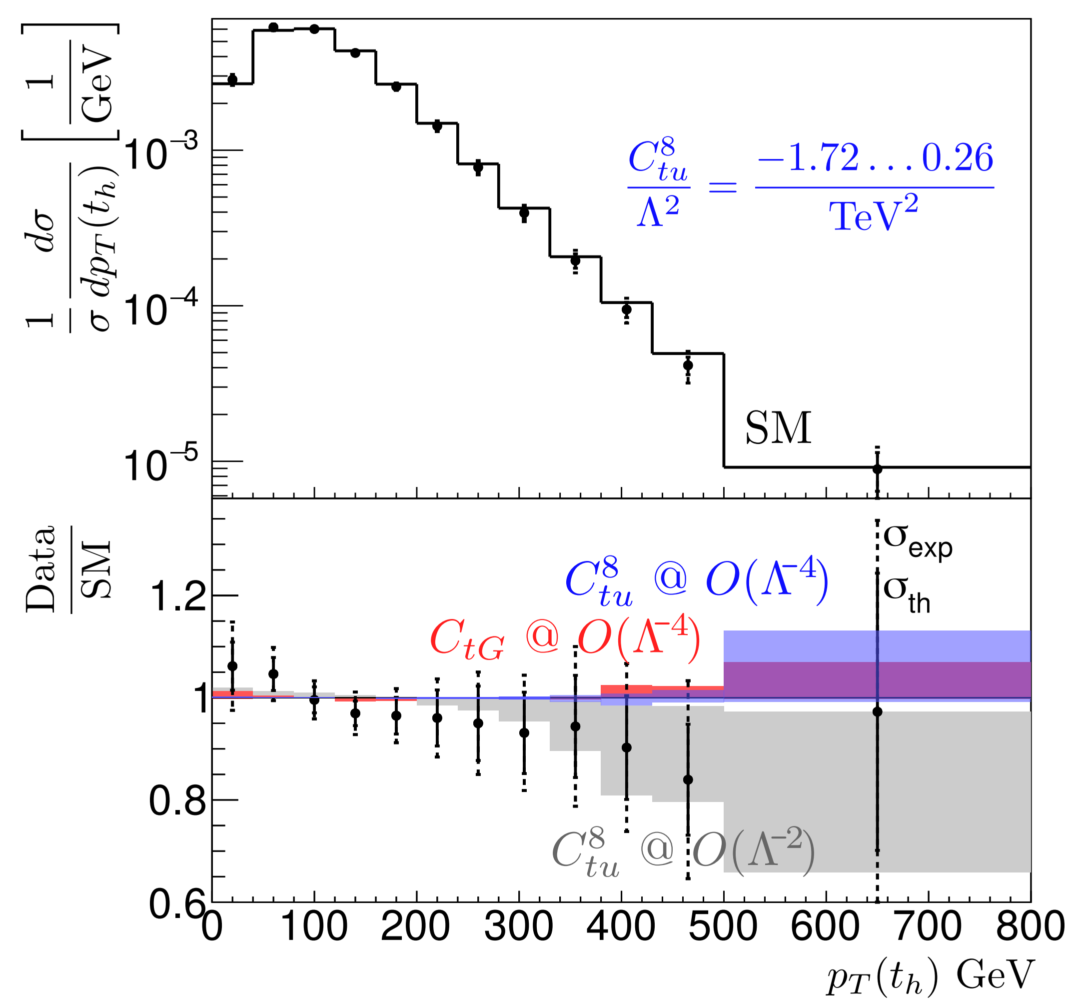


$$O_{tG} = (\overline{Q}_L \sigma^{\mu\nu} T^A t_R)\widetilde{H} G^A_{\mu\nu}$$

$$O^8_{tu} = (\bar{t}\gamma_\mu T^A t)(\bar{u}_i \gamma^\mu T^A u_i)$$

$$\sigma_{t\bar{t}}(s) \sim \sigma_{\rm SM}\left(1 + \frac{m_t v}{\Lambda^2} C_{tG} + \frac{s}{\Lambda^2} C^8_{tu} + \mathcal{O}\left(\frac{s^2}{\Lambda^4}\right) C_i C_j\right)$$





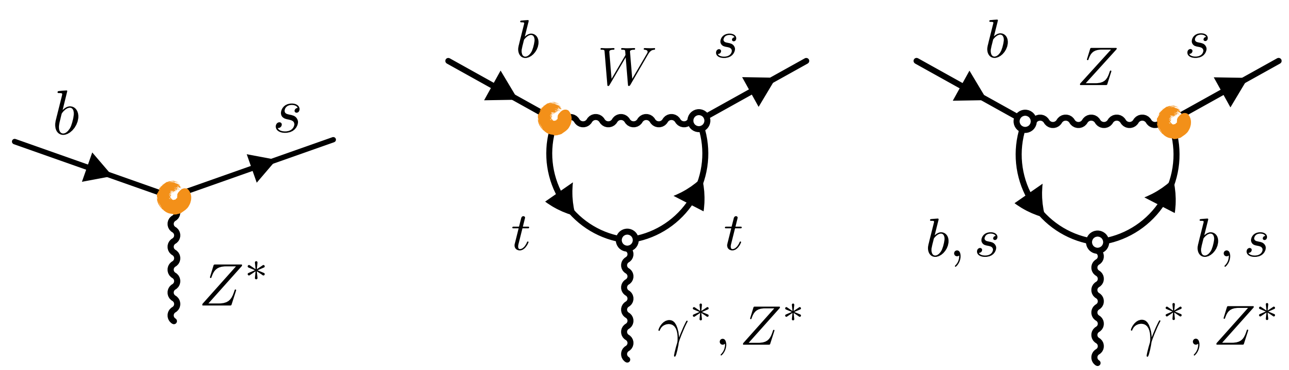
Brivio, Westhoff et al. 1910.03606; see also Englert et al. 1607.04304

Flavor breaking in down-quark FCNCs

W and Z couplings:

$$O_{\phi q}^{(1)} = (H^\dagger i\overleftrightarrow{D^\mu} H)(\overline{Q}\gamma_\mu Q)$$

$$O_{\phi q}^{(3)} = (H^\dagger i\overleftrightarrow{D^\mu} \tau^a H)(\overline{Q}\gamma_\mu \tau^a Q)$$



$$C_{\phi q}^{(1)} + C_{\phi q}^{(3)} \qquad \frac{\alpha}{4\pi} C_{\phi q}^{(3)} \qquad \frac{\alpha}{4\pi}(C_{\phi q}^{(1)} + C_{\phi q}^{(3)})$$

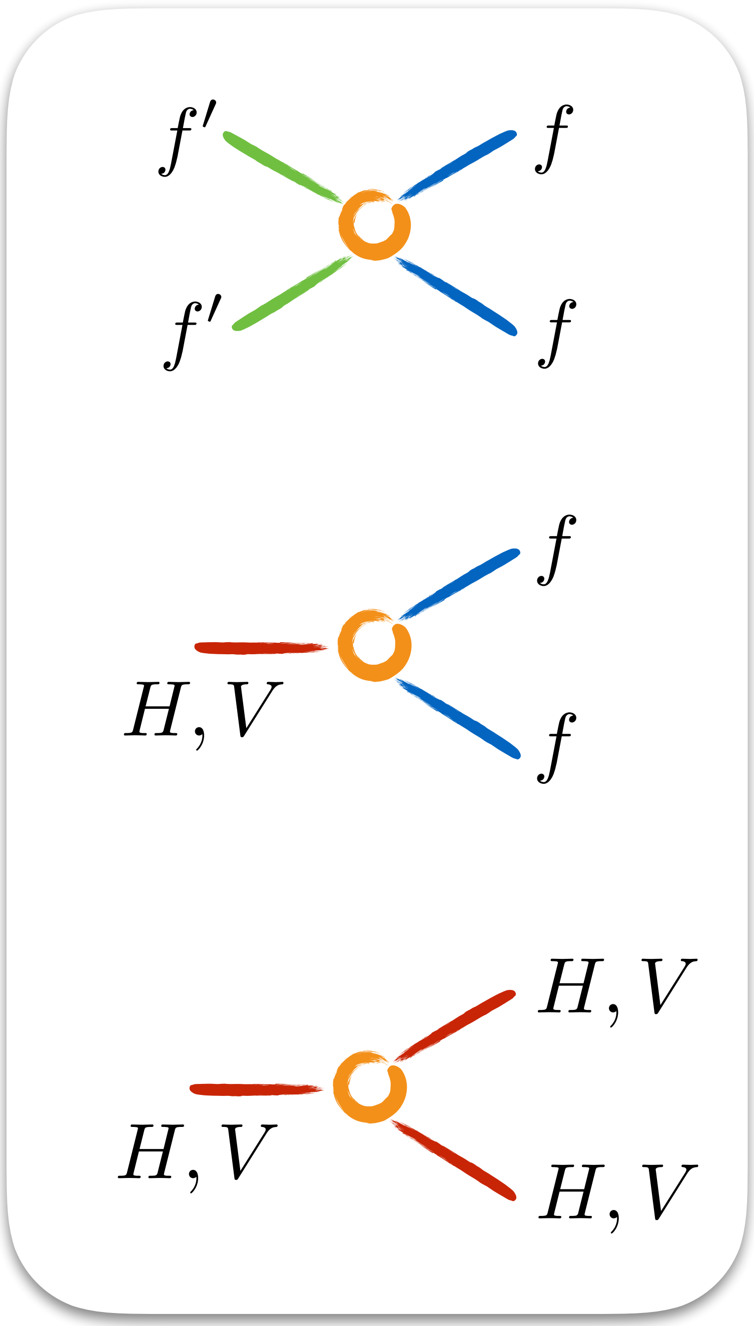
Flavor-breaking: $B \to X_s\gamma,\ B_s \to \mu^+\mu^-,\ B \to K^*\mu^+\mu^-$

kaon decays, meson mixing

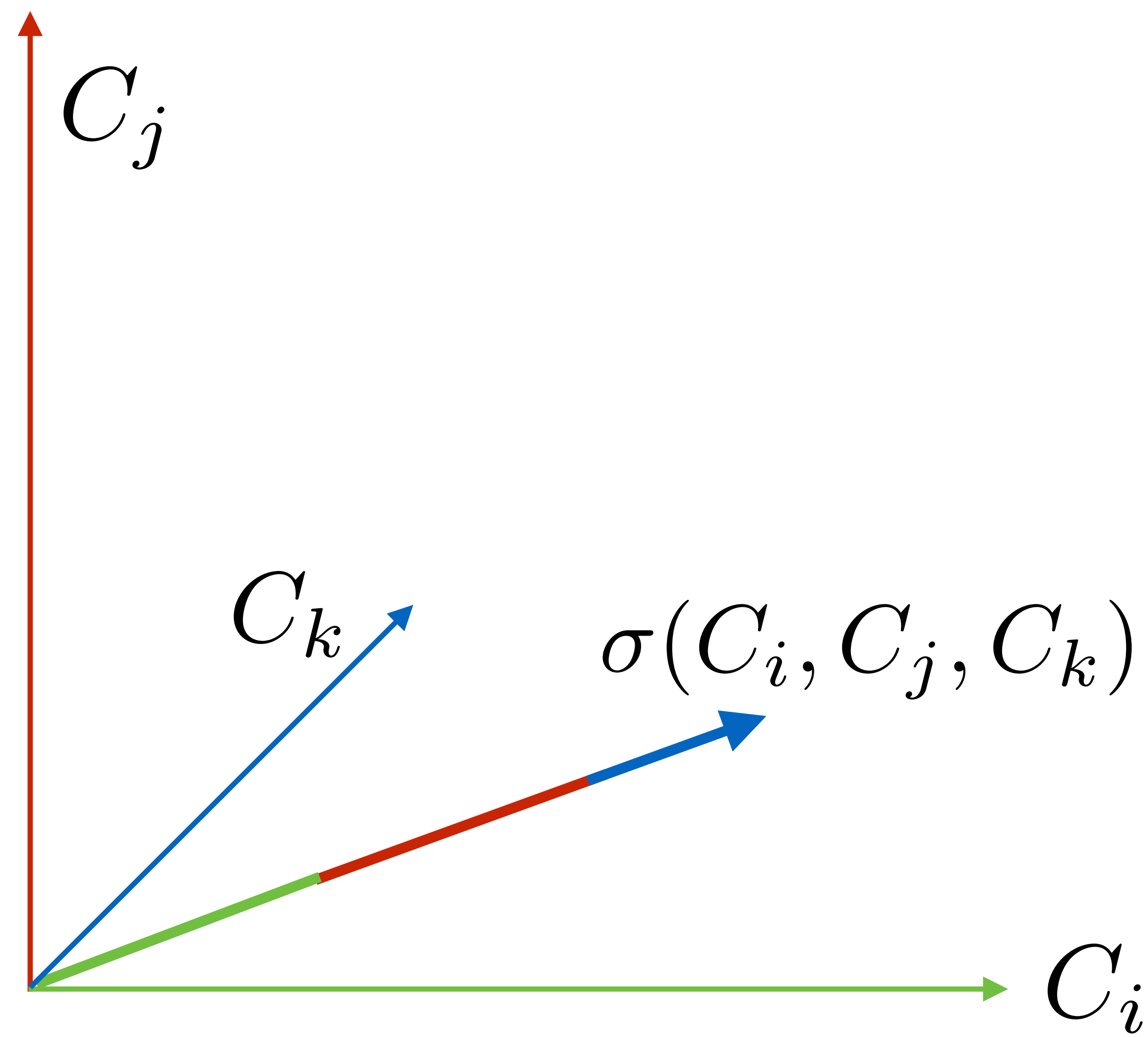
Flavor-diagonal: $Z \to b\bar{b}$ (LEP)

VBF @ high pT Araz, Banerjee, Gupta, Spannowsky 2011.03555

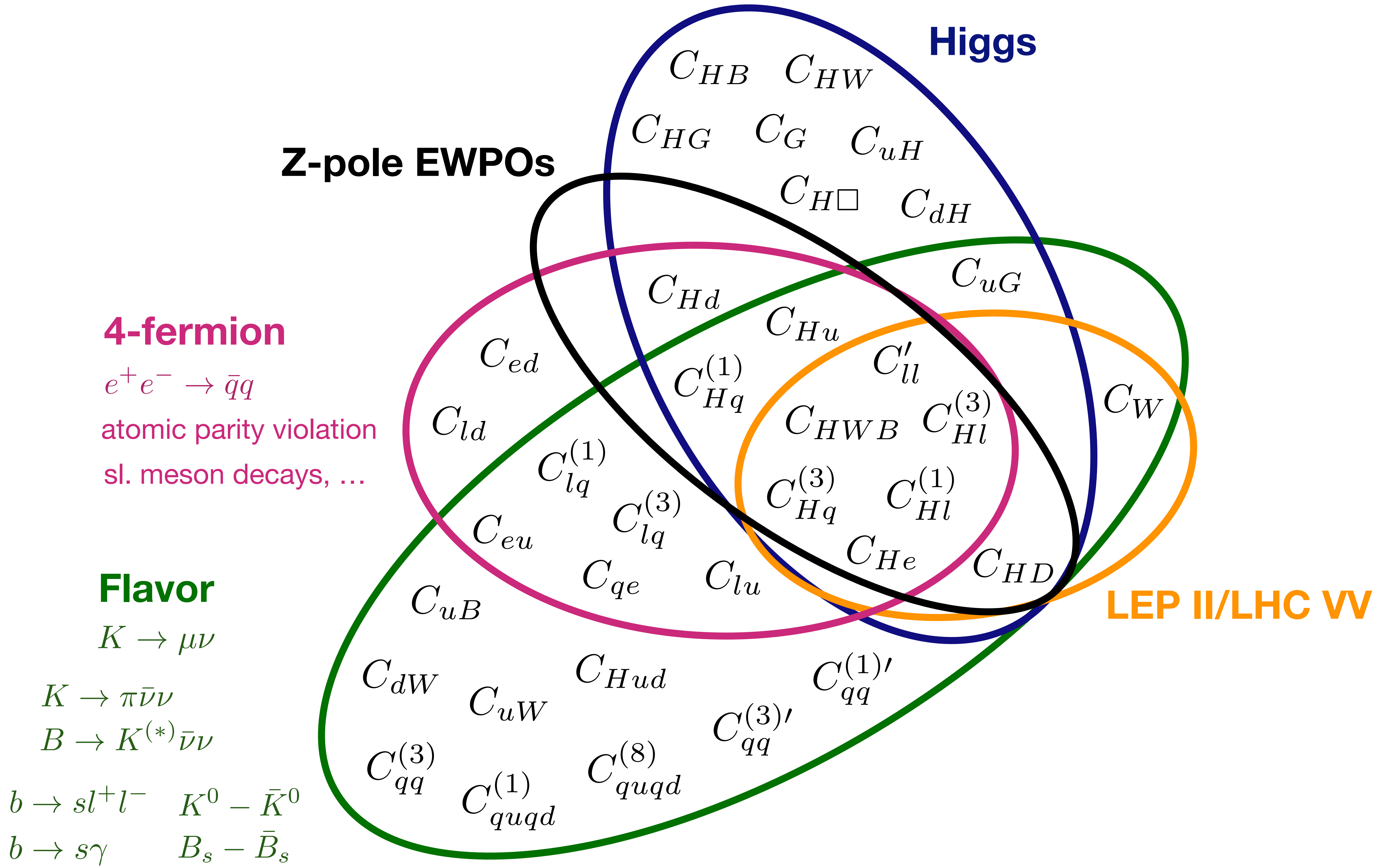
The vast space of UV physics



$$\sigma = \sigma_{\mathrm{SM}} + \sum_a \frac{C_a}{\Lambda^2}\sigma_a + \sum_{a,b} \frac{C_a C_b}{\Lambda^4}\sigma_{ab}$$

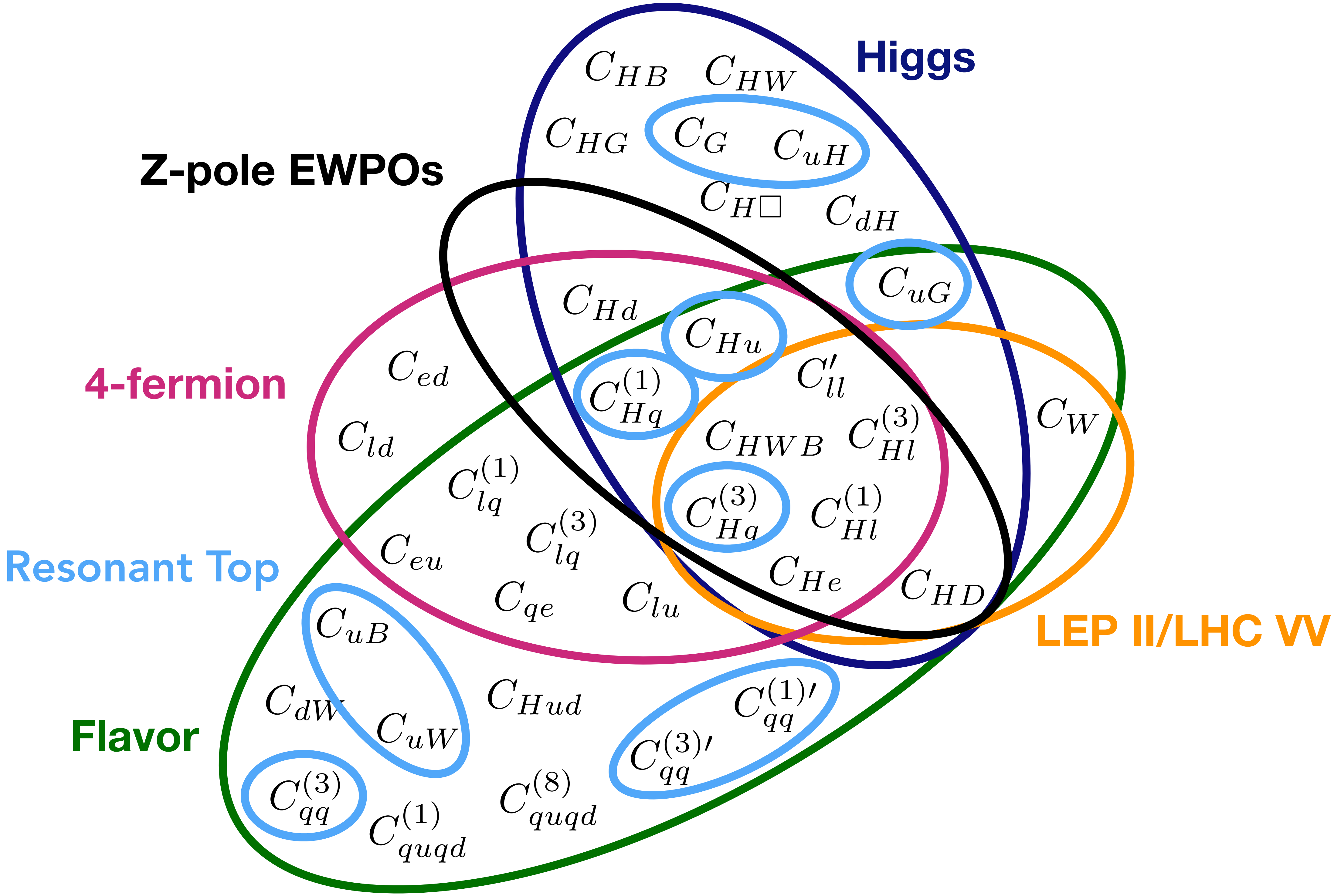


Probing the SMEFT at dim 6



Aoude, Hurth, Renner, Shepherd 2003.05432 (Warsaw basis)

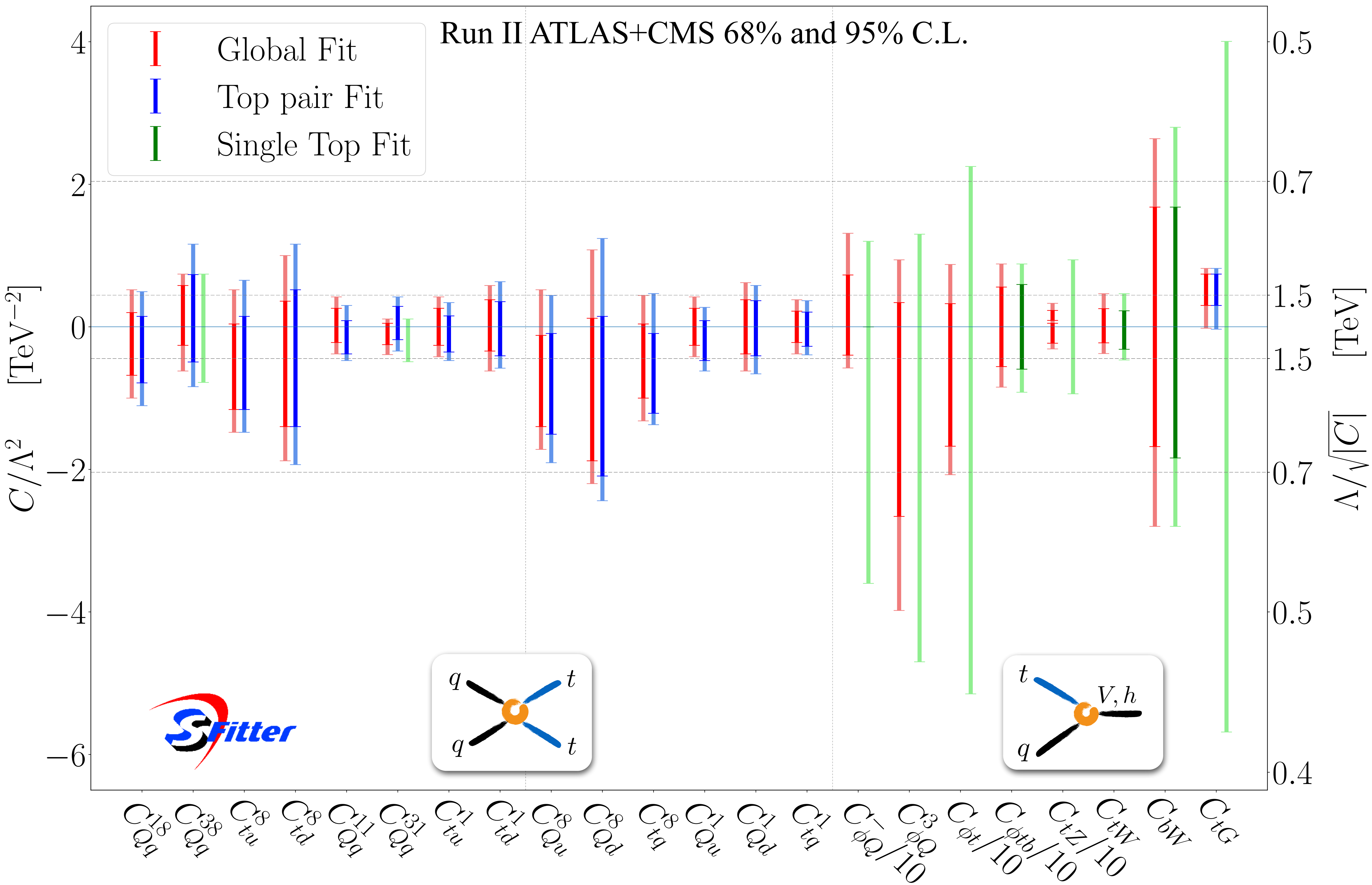
The role of the top



Top fits: Englert et al. 2016+, Hartland et al. 2019, Brivio et al. 2019, Ellis et al. 2020

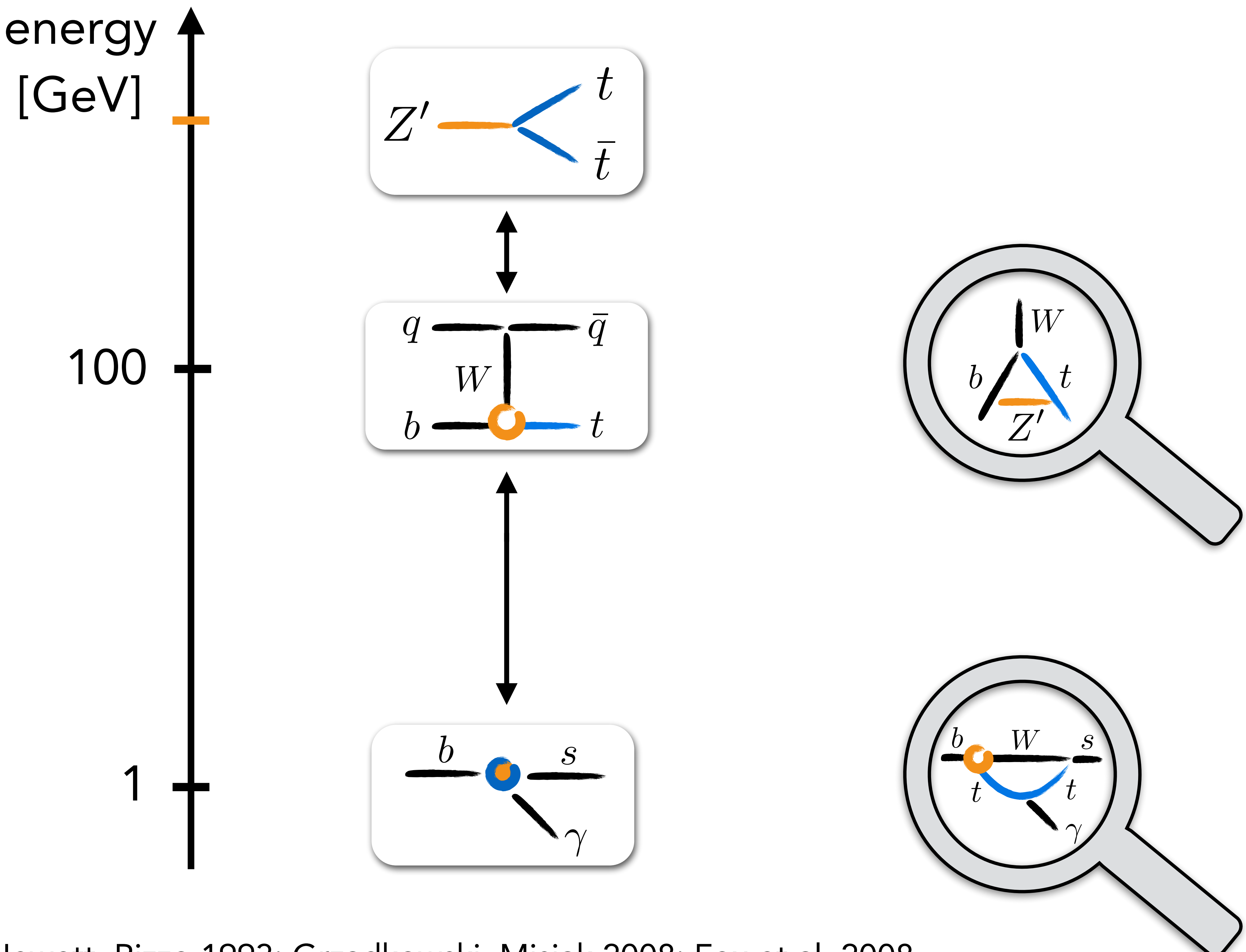
Top & flavor fits: Bissmann et al. 2019+, Bruggisser et al. 2021 Tops in EWPOs: Dawson, Giardino 2019

Global analysis of top LHC data



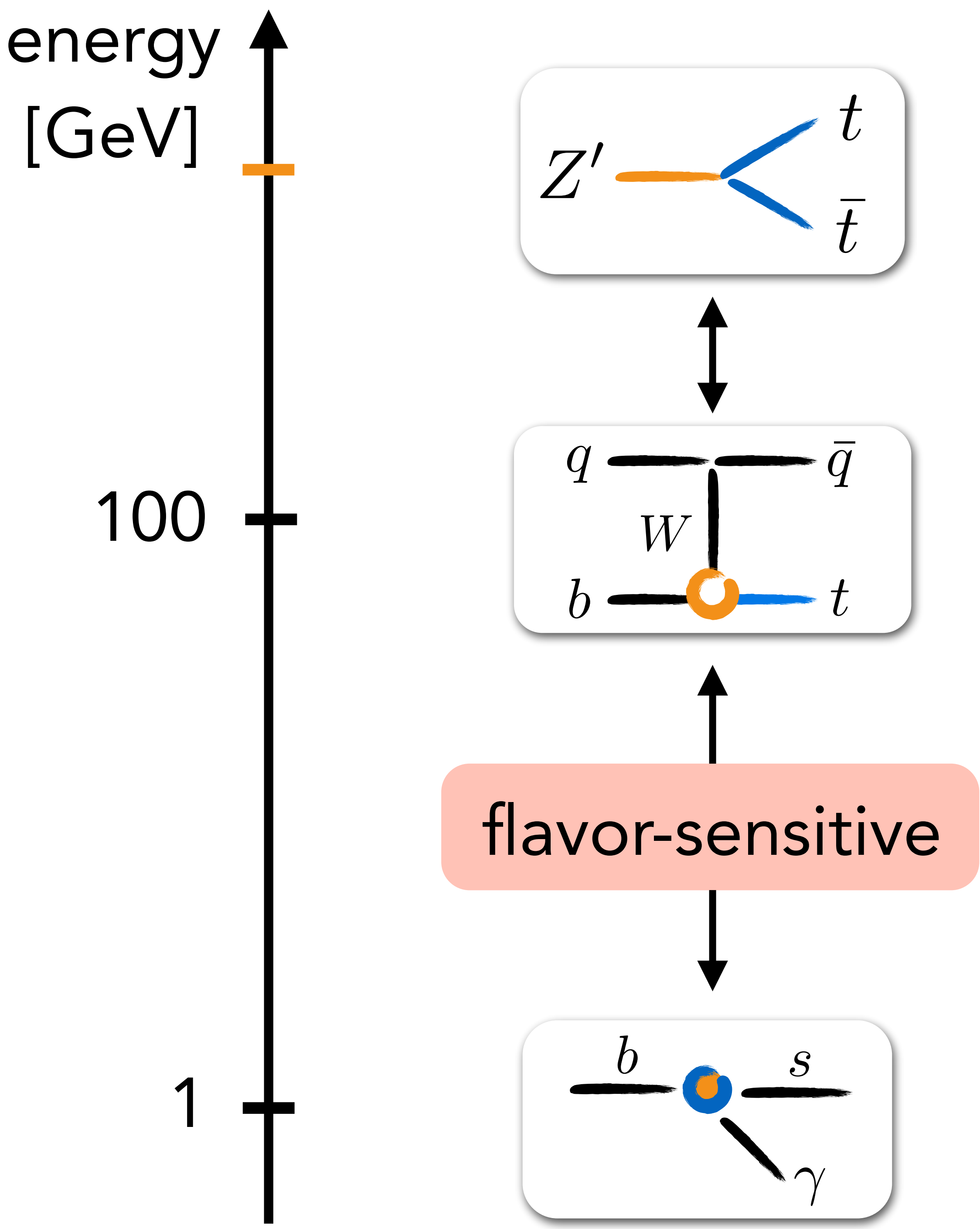
Brivio, Westhoff et al. 1910.03606

Top & Bottom



Hewett, Rizzo 1993; Grzadkowski, Misiak 2008; Fox et al. 2008
Brod et al. 2014; Cirigliano et al. 2016

Top & Bottom



$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{C_i}{\Lambda^2} O_i + \ldots$$

$$\mathcal{C}_a(m_b) = F(C_i(m_t))$$

match
&
run

$$\mathcal{L}_{\text{WET}} = \mathcal{L}_{\text{QCD}} + \mathcal{L}_{\text{QED}} + \sum_a \mathcal{C}_a \mathcal{O}_a + \ldots$$

Aebischer, Crivellin, Fael, Greub, Virto 2015 & 2017
Dekens, Jenkins, Manohar, Stoffer 2017 & 2019; Hurth, Renner, Shepherd 2019

Flavor structures

$$C_{\phi q}^{(1),kl} O_{\phi q}^{(1),kl} = C_{\phi q}^{(1),kl} (H^\dagger i \overleftrightarrow{D}^\mu H)(\overline{Q}^k \gamma_\mu Q^l)$$

Gauge sector: $U(3)_Q \times U(3)_U \times U(3)_D \times U(3)_L \times U(3)_E$

Minimal flavor violation:

$$C_{\phi q}^{(1)} = a\,\mathbf{1} + b\,Y_U Y_U^\dagger + c\,Y_D Y_D^\dagger + \ldots = \begin{pmatrix} a & & \\ & a & \\ & & A \end{pmatrix}_{A = a + b\, y_t^2} + \mathcal{O}(y_b^2)$$

Universality: $U(3)^5$

$$C_{\phi q}^{(1)} = \begin{pmatrix} a & & \\ & a & \\ & & a \end{pmatrix}$$

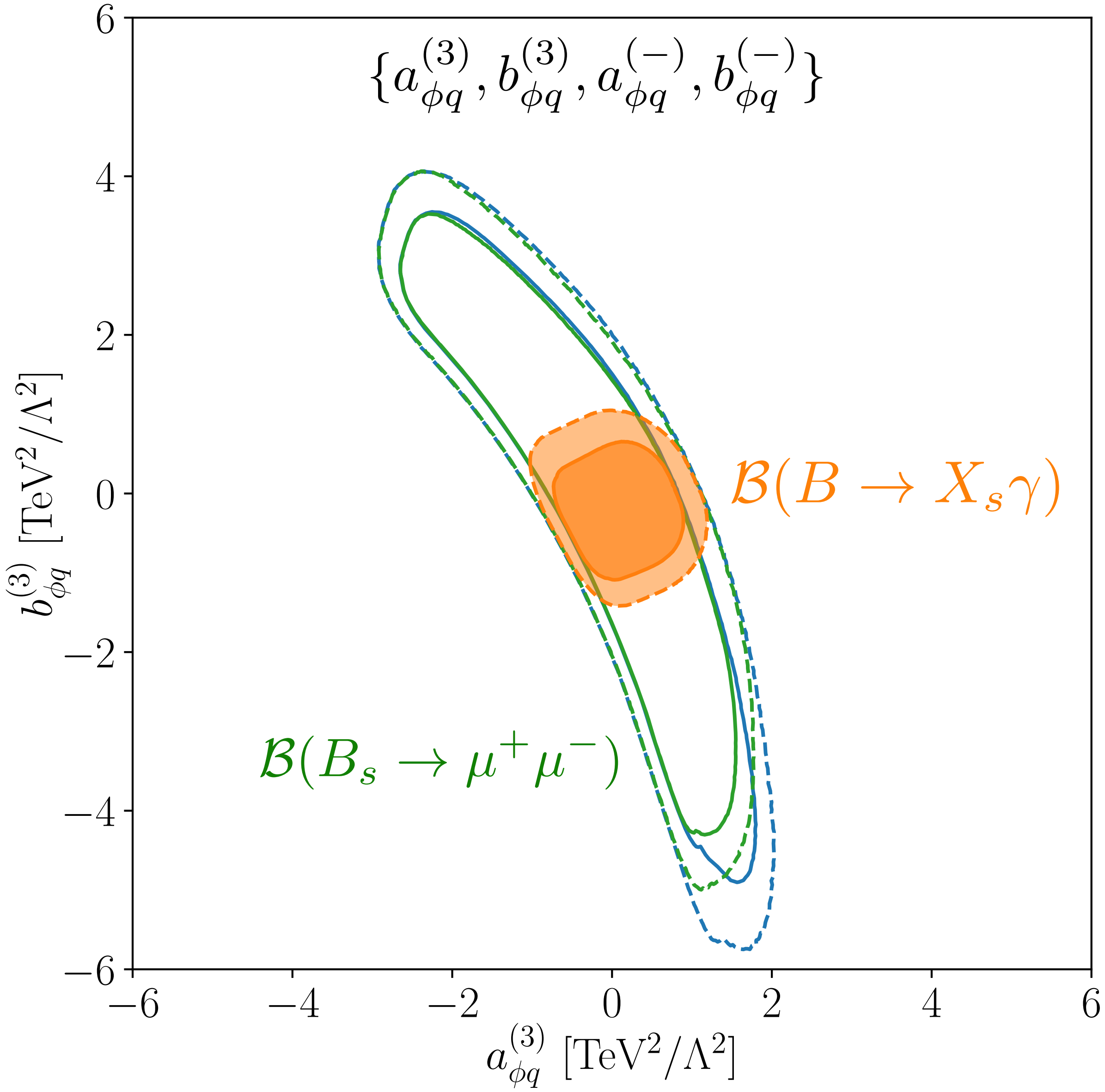
Misalignment: $U(2)^5$

$$C_{\phi q}^{(1)} = \begin{pmatrix} a & & b \\ & a & c \\ b & c & d \end{pmatrix}$$

universality & misalignment: see Aguilar-Saavedra et al. 2018, Faroughy et al. 2020

Flavor universality in W and Z couplings

$$\mathcal{B}(B \to X_s\gamma) \times 10^4 = 3.26 + 0.36\, a_{\phi q}^{(3)} - 0.76\, b_{\phi q}^{(3)}$$



top

$pp \to t\bar{t}$

$pp \to t\bar{t}Z, t\bar{t}W$

$pp \to tj, tZj$

$pp \to tW$

$t \to bW$

$$O_{\phi q}^{(1)} = (H^\dagger i\overleftrightarrow{D^\mu} H)(\overline{Q}\gamma_\mu Q)$$

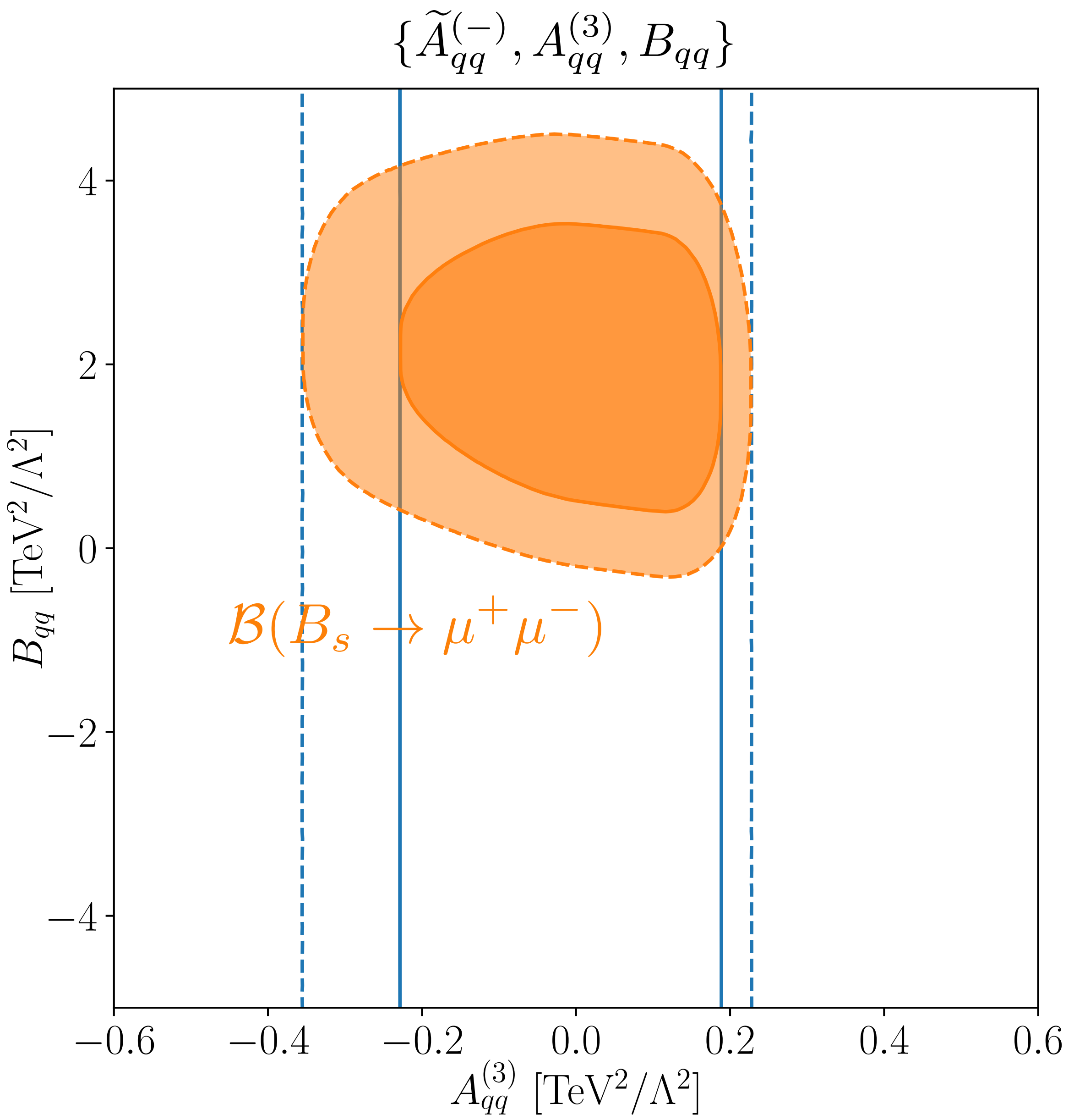
$$O_{\phi q}^{(3)} = (H^\dagger i\overleftrightarrow{D^\mu} \tau^a H)(\overline{Q}\gamma_\mu \tau^a Q)$$

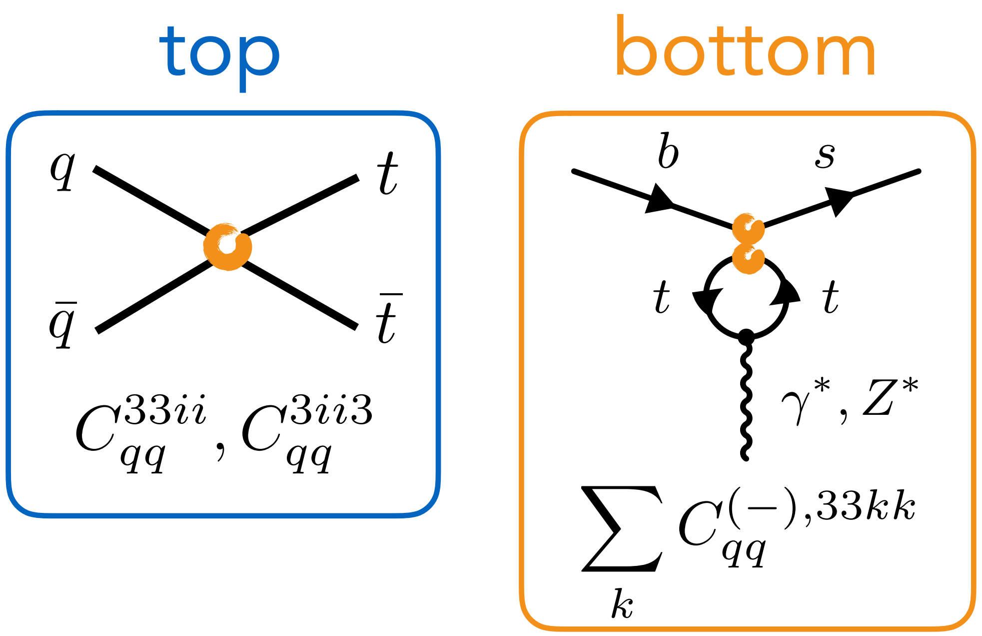
Top-bottom connection resolves flavor structure.

Bruggisser, Schäfer, van Dyk, Westhoff 2101.07273

Flavor breaking in four-quark couplings

$$\mathcal{C}_{10}(m_b) = 0.29\Big(A_{qq}^{(3)}(m_t) + B_{qq}^{(3)}(m_t)y_t^2\Big) + 0.03\Big(\widetilde{A}_{qq}^{(-)}(m_t) + B_{qq}^{(-)}(m_t)y_t^2\Big)$$





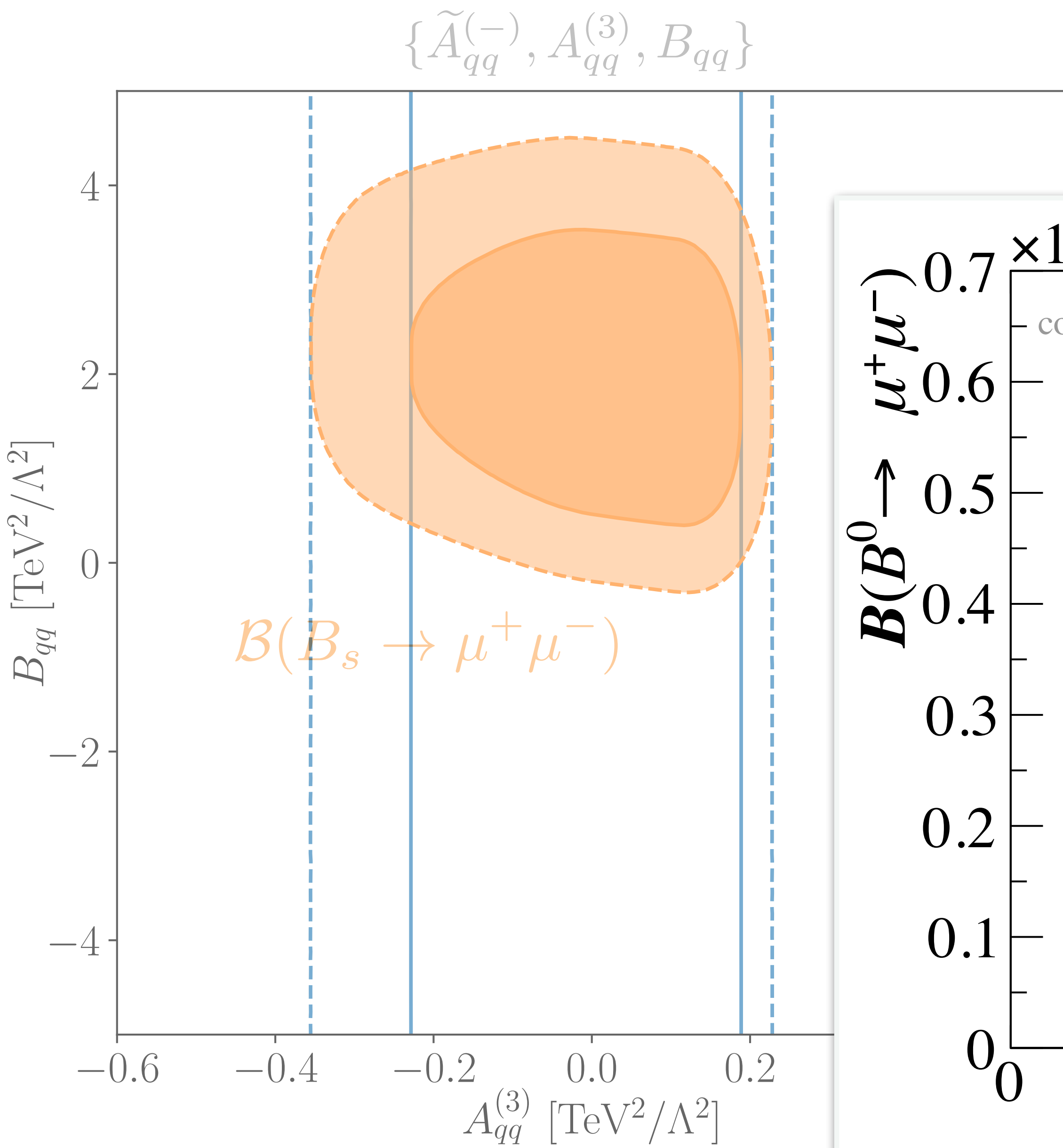
$$O_{qq}^{(1)} = (\overline{Q}\gamma_\mu Q)(\overline{Q}\gamma^\mu Q)$$

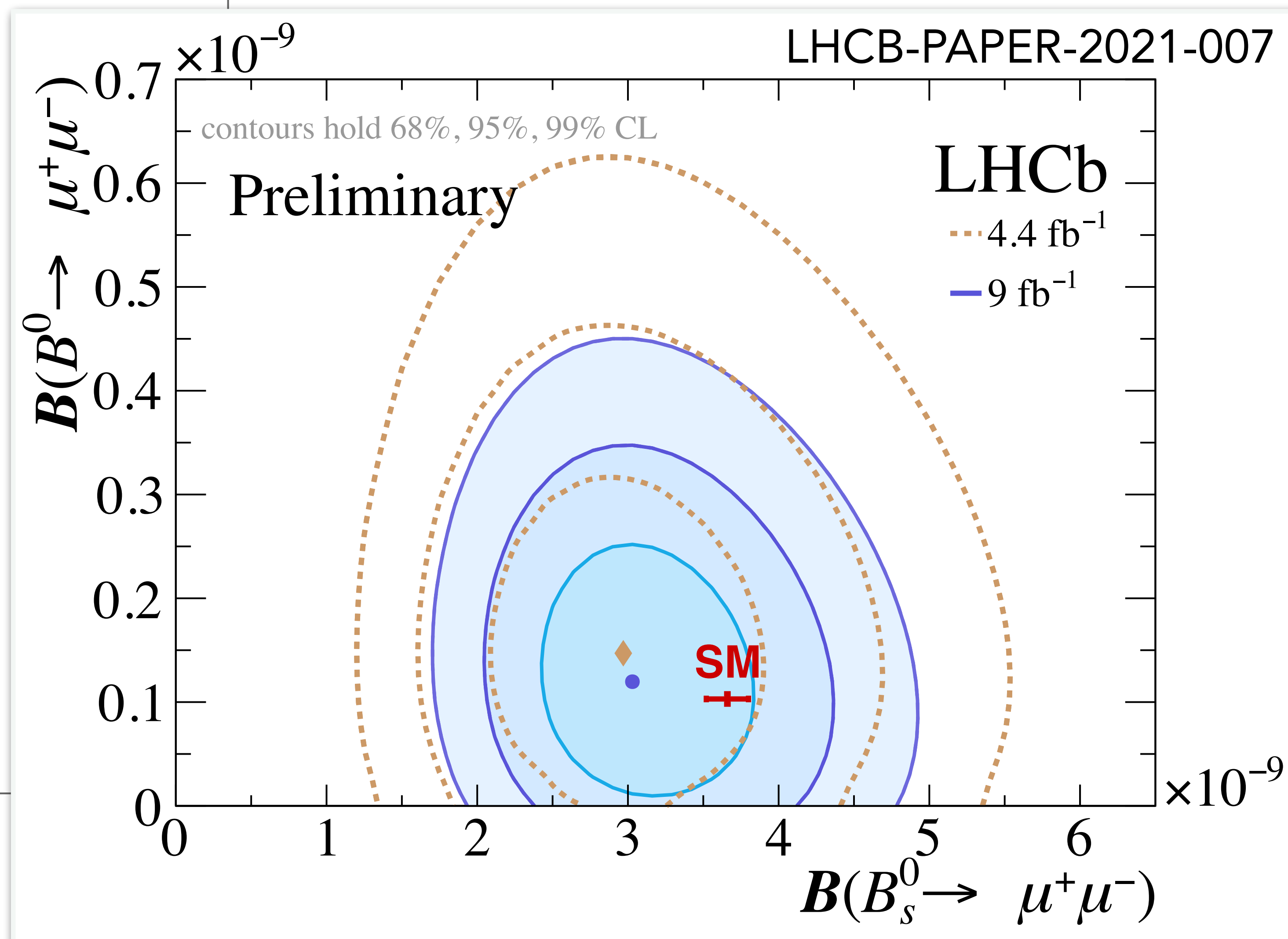
$$O_{qq}^{(3)} = (\overline{Q}\gamma_\mu \tau^a Q)(\overline{Q}\gamma^\mu \tau^a Q)$$

Bruggisser, Schäfer, van Dyk, Westhoff 2101.07273

Flavor breaking in four-quark couplings

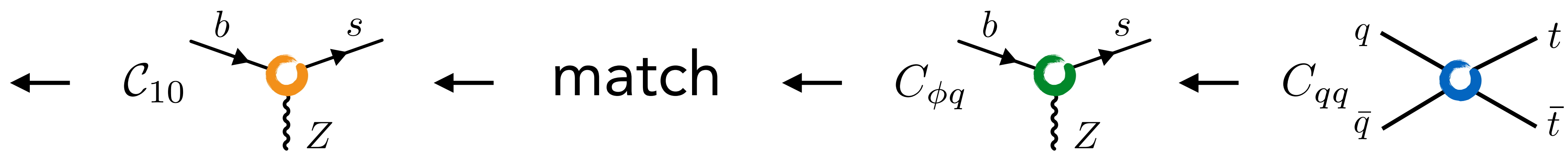
$$\mathcal{B}(B_s \to \mu^+\mu^-) \times 10^9 = 3.57 - 1.71\,\mathcal{C}_{10} + 0.21\,\mathcal{C}_{10}^2$$

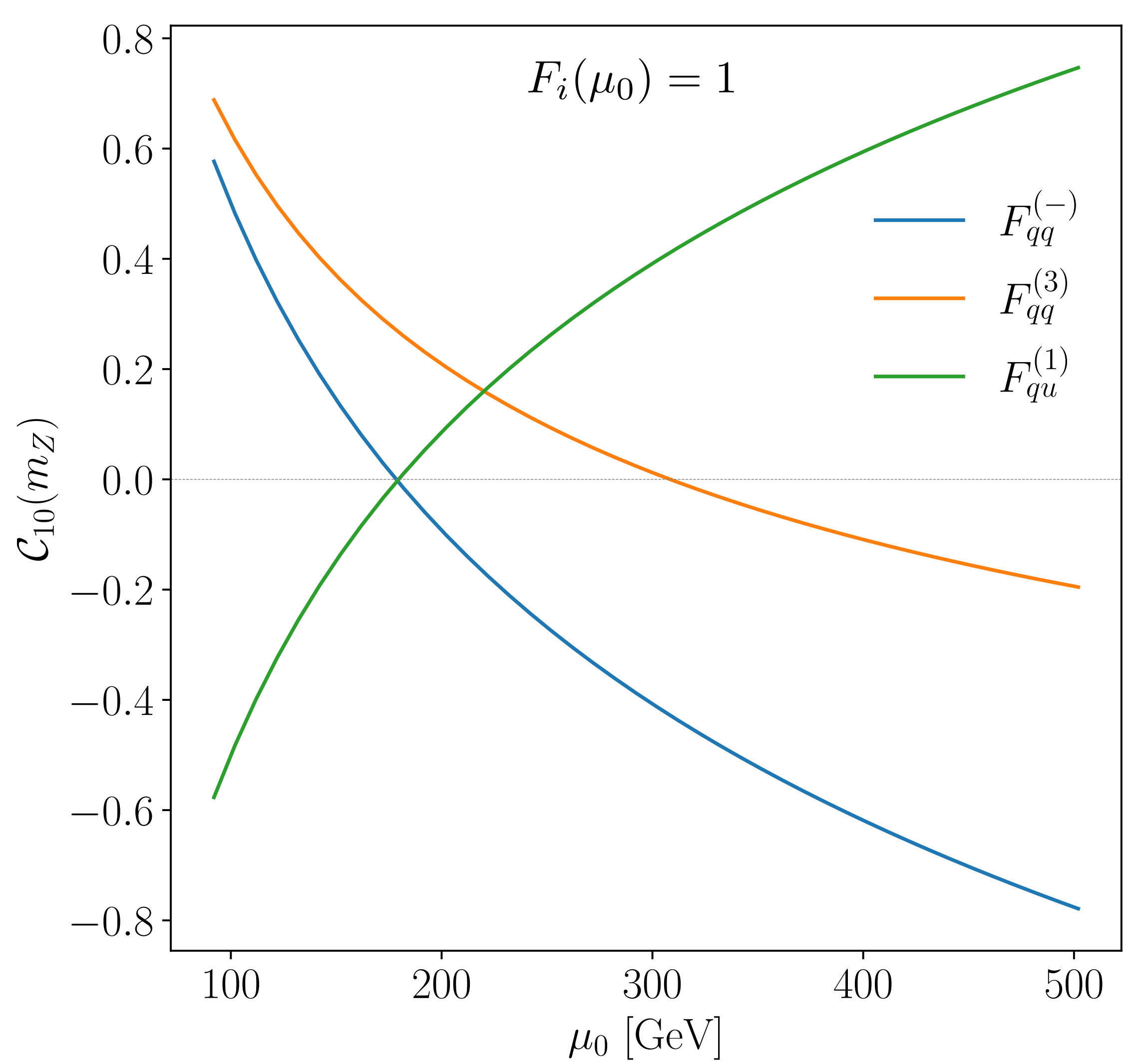


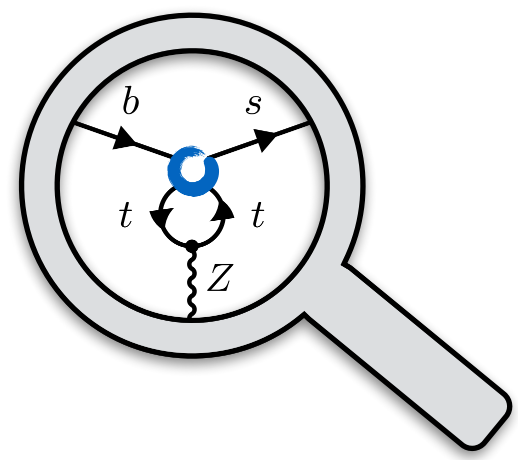


Operator mixing in SMEFT

$$\mathcal{C}_a(m_b) = \left(\mathcal{R}^{\mathrm{WET}}(m_b, m_Z)\right)_{ab} \left(\mathcal{M}(m_Z)\right)_{bc} \left(\mathcal{R}^{\mathrm{SMEFT}}(m_Z, m_t)\right)_{cd} C_d(m_t)$$







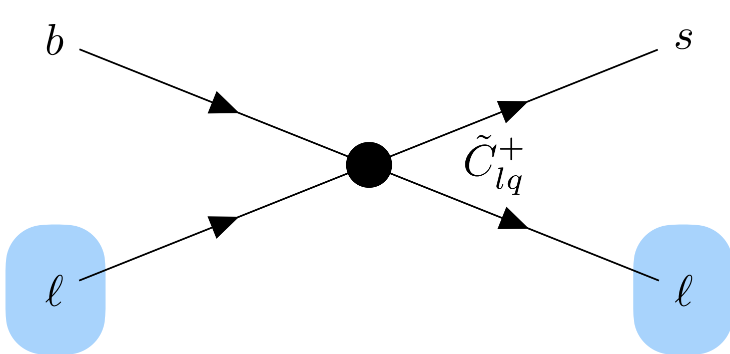
High sensitivity to operator mixing:

$$\mathcal{C}_{10} = F\left(\frac{4\pi}{\alpha} C_{\phi q}(m_t), C_{qq}(m_t)\right)$$

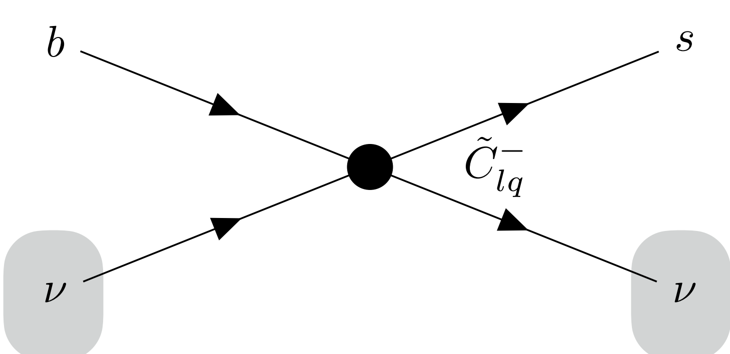
Bruggisser, Schäfer, van Dyk, Westhoff 2101.07273

Quark-lepton couplings

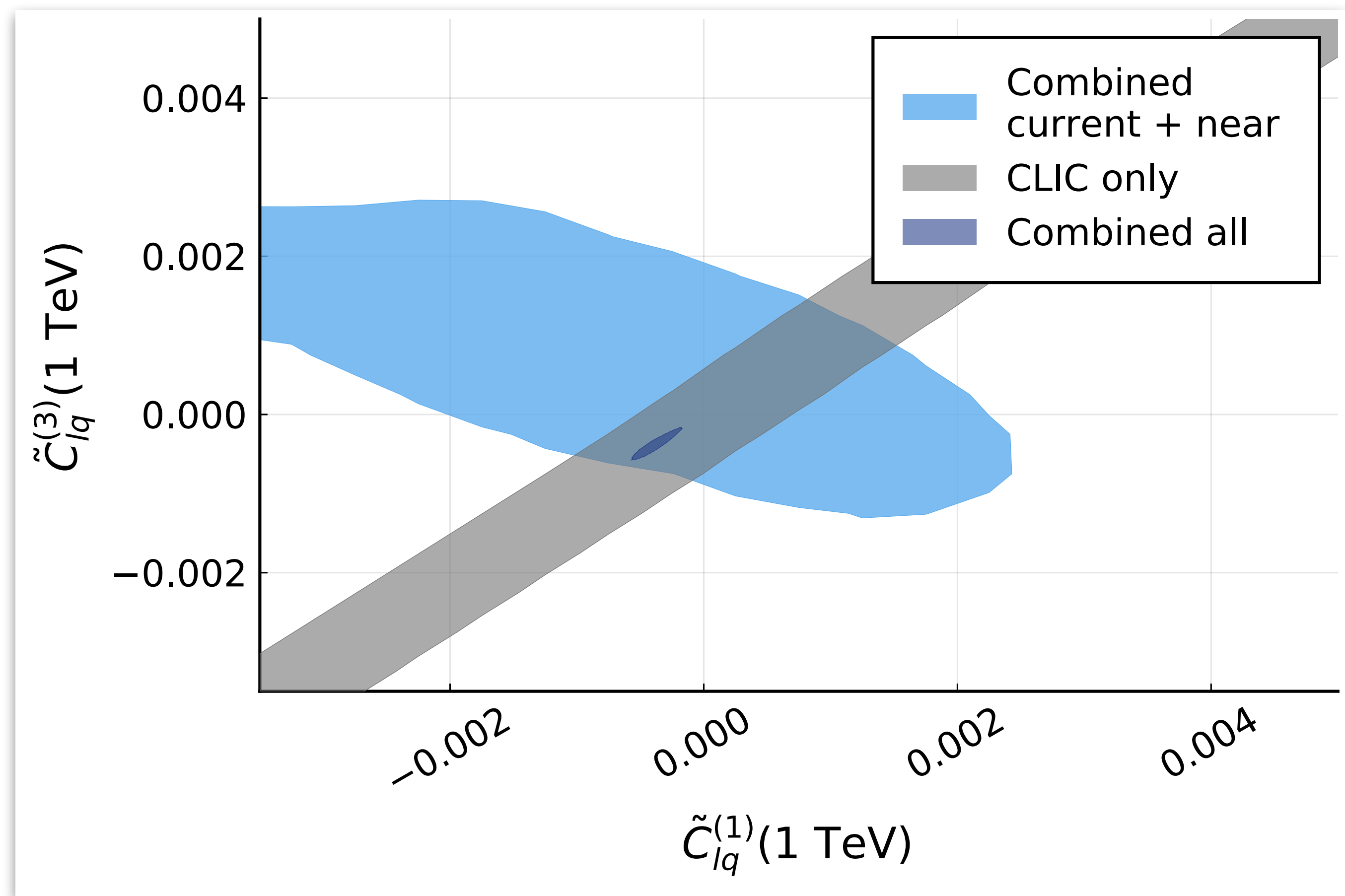
$$O_{lq}^{(1)} = (\bar{l}_L \gamma_\mu l_L)(\bar{q}_L \gamma^\mu q_L) \qquad O_{lq}^{(3)} = (\bar{l}_L \gamma_\mu \tau^I l_L)(\bar{q}_L \gamma^\mu \tau^I q_L)$$



$$C^{\pm} = C^{(1)} \pm C^{(3)}$$



sensitivity: rare B decays & top



Charged leptons and neutrinos probe orthogonal weak couplings.

Bissmann, Grunwald, Hiller, Kroeninger 2012.10456

Outlook

Flavor observables in global SMEFT fits:

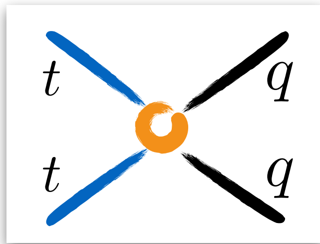
- high sensitivity to effective couplings and flavor breaking
- non-local contributions to Wilson coefficients C7, C9
- compatibility of flavor and LHC fit results

Probing the flavor structure in SMEFT:

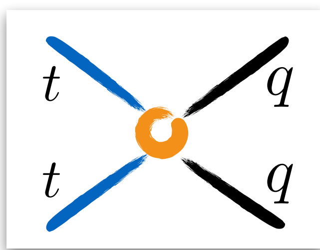
- top-bottom connection is flavor-sensitive
- interplay of kaons - jets
  bottom/charm - top
  leptons, neutrinos - electroweak, Higgs

Backup

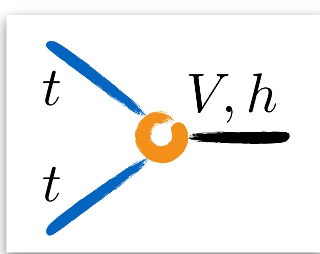
LHC processes in top EFT



LL, RR



LR, RL

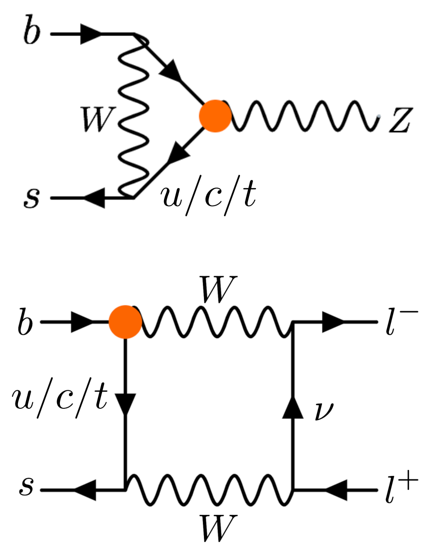


parameter	$t\bar{t}$	single t	tW	tZ	t decay	$t\bar{t}Z$	$t\bar{t}W$
$C_{Qq}^{1,8}$	Λ^{-2}	–	–	–	–	Λ^{-2}	Λ^{-2}
$C_{Qq}^{3,8}$	Λ^{-2}	Λ^{-4} $[\Lambda^{-2}]$	–	Λ^{-4} $[\Lambda^{-2}]$	Λ^{-4} $[\Lambda^{-2}]$	Λ^{-2}	Λ^{-2}
C_{tu}^{8}, C_{td}^{8}	Λ^{-2}	–	–	–	–	Λ^{-2}	–
$C_{Qq}^{1,1}$	Λ^{-4} $[\Lambda^{-2}]$	–	–	–	–	Λ^{-4} $[\Lambda^{-2}]$	Λ^{-4} $[\Lambda^{-2}]$
$C_{Qq}^{3,1}$	Λ^{-4} $[\Lambda^{-2}]$	Λ^{-2}	–	Λ^{-2}	Λ^{-2}	Λ^{-4} $[\Lambda^{-2}]$	Λ^{-4} $[\Lambda^{-2}]$
C_{tu}^{1}, C_{td}^{1}	Λ^{-4} $[\Lambda^{-2}]$	–	–	–	–	Λ^{-4} $[\Lambda^{-2}]$	–
C_{Qu}^{8}, C_{Qd}^{8}	Λ^{-2}	–	–	–	–	Λ^{-2}	–
C_{tq}^{8}	Λ^{-2}	–	–	–	–	Λ^{-2}	Λ^{-2}
C_{Qu}^{1}, C_{Qd}^{1}	Λ^{-4} $[\Lambda^{-2}]$	–	–	–	–	Λ^{-4} $[\Lambda^{-2}]$	–
C_{tq}^{1}	Λ^{-4} $[\Lambda^{-2}]$	–	–	–	–	Λ^{-4} $[\Lambda^{-2}]$	Λ^{-4} $[\Lambda^{-2}]$
$C_{\phi Q}^{-}$	–	–	–	Λ^{-2}	–	Λ^{-2}	–
$C_{\phi Q}^{3}$	–	Λ^{-2}	Λ^{-2}	Λ^{-2}	Λ^{-2}	–	–
$C_{\phi t}$	–	–	–	Λ^{-2}	–	Λ^{-2}	–
$C_{\phi tb}$	–	Λ^{-4}	Λ^{-4}	Λ^{-4}	Λ^{-4}	–	–
C_{tZ}	–	–	–	Λ^{-2}	–	Λ^{-2}	–
C_{tW}	–	Λ^{-2}	Λ^{-2}	Λ^{-2}	Λ^{-2}	–	–
C_{bW}	–	Λ^{-4}	Λ^{-4}	Λ^{-4}	Λ^{-4}	–	–
C_{tG}	Λ^{-2}	$[\Lambda^{-2}]$	Λ^{-2}	–	$[\Lambda^{-2}]$	Λ^{-2}	Λ^{-2}

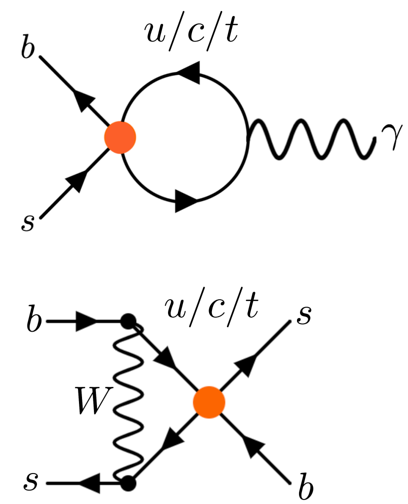
Hartland et al. 1901.05965; Brivio, SW et al. 1910.03606

Flavor observables in SMEFT

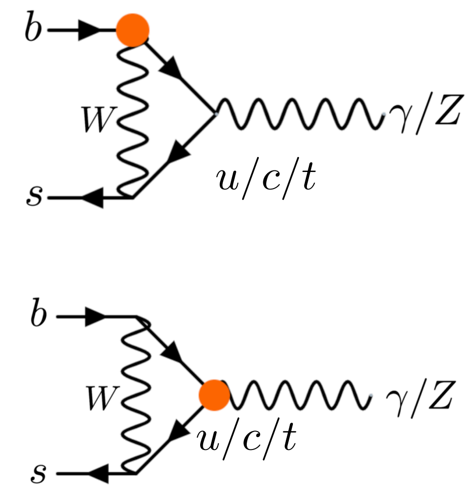
Higgs-quark



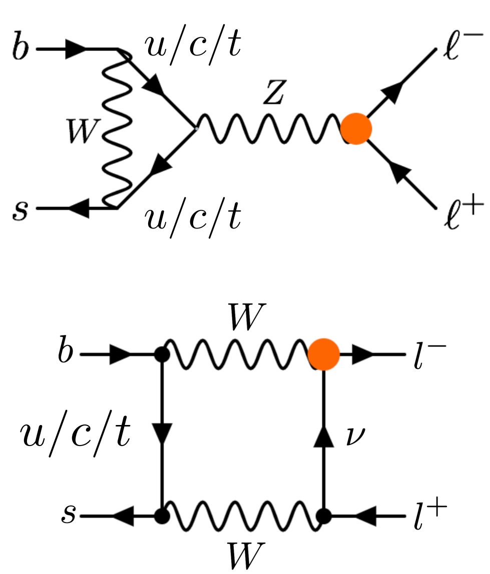
4-quark



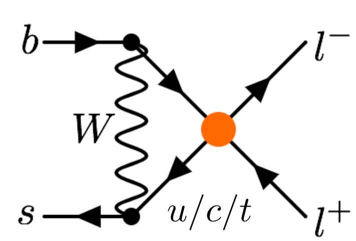
dipole



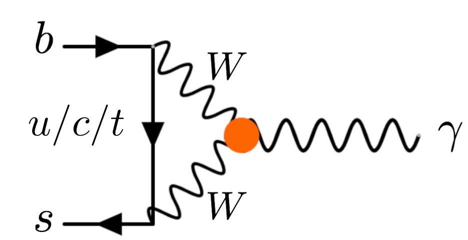
Higgs-lepton



2-quark 2-lepton



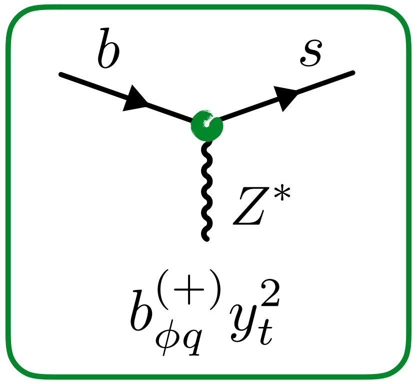
triple-gauge



Flavor in bottom observables

Tree level: flavor-breaking.

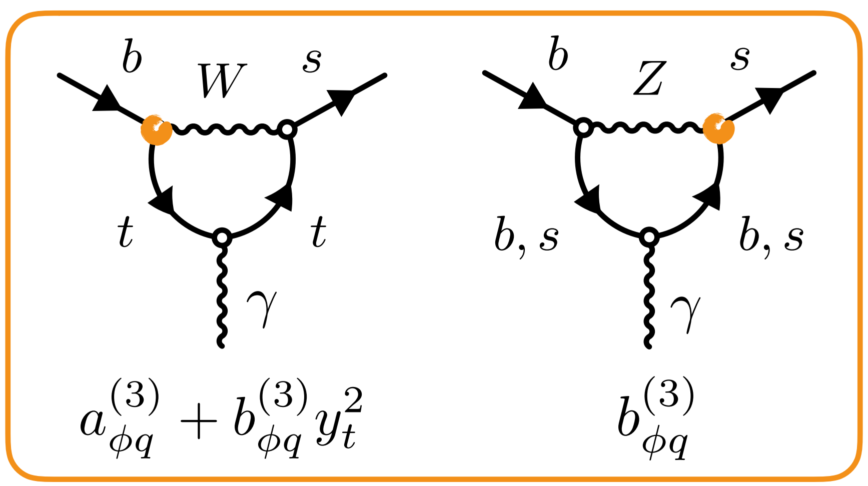
$$\sum (C_{\phi q}^{(1),kk} + C_{\phi q}^{(3),kk})\, V_{k3} V_{k2}^* \sim (b_{\phi q}^{(1)} + b_{\phi q}^{(3)}) y_t^2$$



$$\mathcal{O}_{10} = \frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \frac{\alpha_e}{4\pi} (\bar{s}\gamma_\mu P_L b)(\bar{\mu}\gamma^\mu \gamma_5 \mu)$$

$$\mathcal{B}(B_s \to \mu^+\mu^-) \times 10^9 = 3.57 - 41.0\, b_{\phi q}^{(+)} + 117.8 (b_{\phi q}^{(+)})^2$$

Loop level: flavor-diagonal & flavor-breaking.



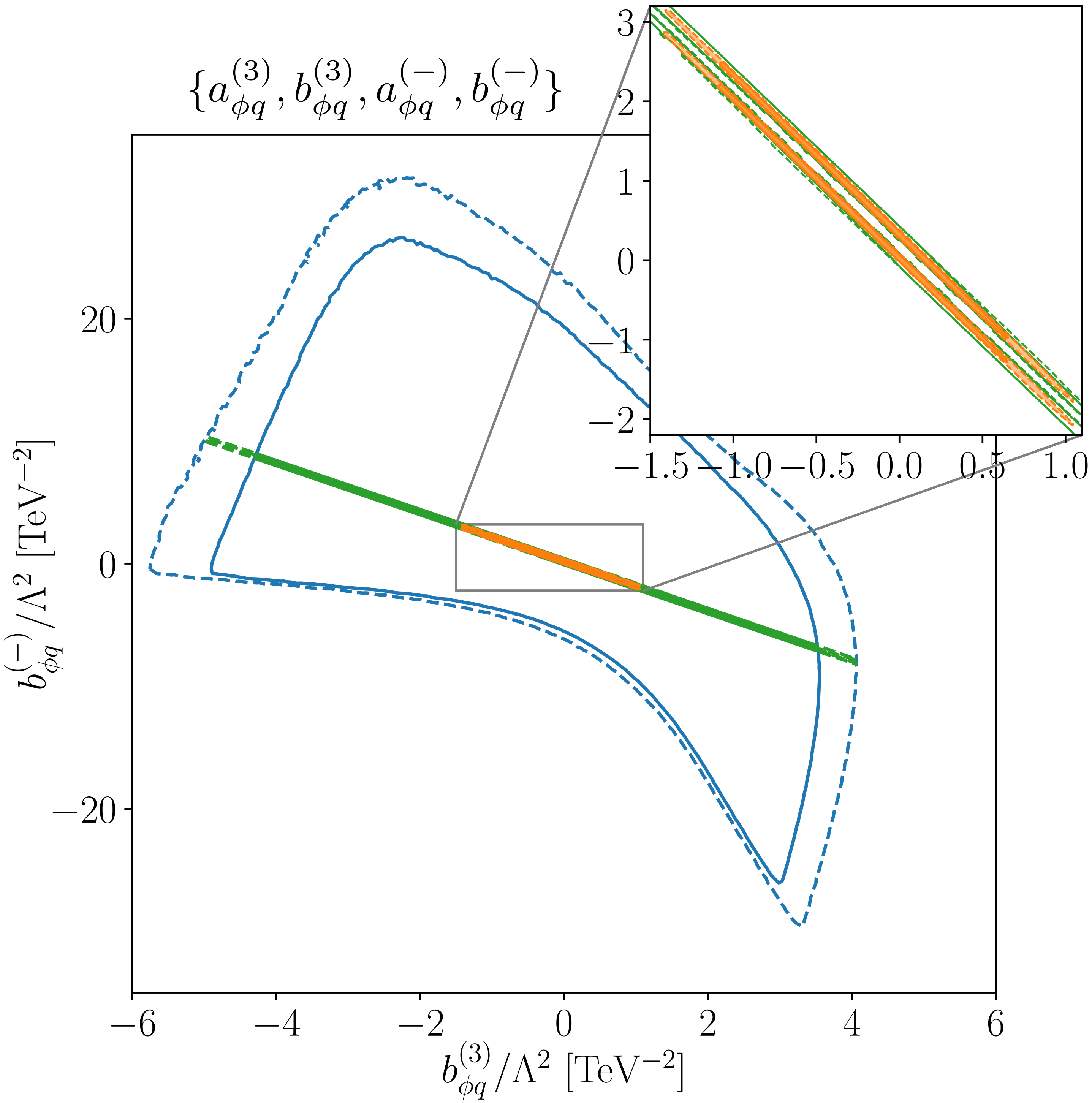
$$\mathcal{O}_7 = \frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \frac{e}{16\pi^2} m_b (\bar{s}\sigma^{\mu\nu} P_R b) F_{\mu\nu}$$

$$\mathcal{O}_8 = \frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \frac{g_s}{16\pi^2} m_b (\bar{s}\sigma^{\mu\nu} T^A P_R b) G_{\mu\nu}^A$$

$$\mathcal{B}(B \to X_s \gamma) \times 10^4 = 3.26 + 0.36\, a_{\phi q}^{(3)} - 0.76\, b_{\phi q}^{(3)}$$

Flavor breaking in W and Z couplings

Combined fit to top data & $\mathcal{B}(B_s \to \mu^+\mu^-)$ & $\mathcal{B}(B \to X_s\gamma)$



Bruggisser, Schäfer, van Dyk, Westhoff 2021

Flavor in four-quark couplings

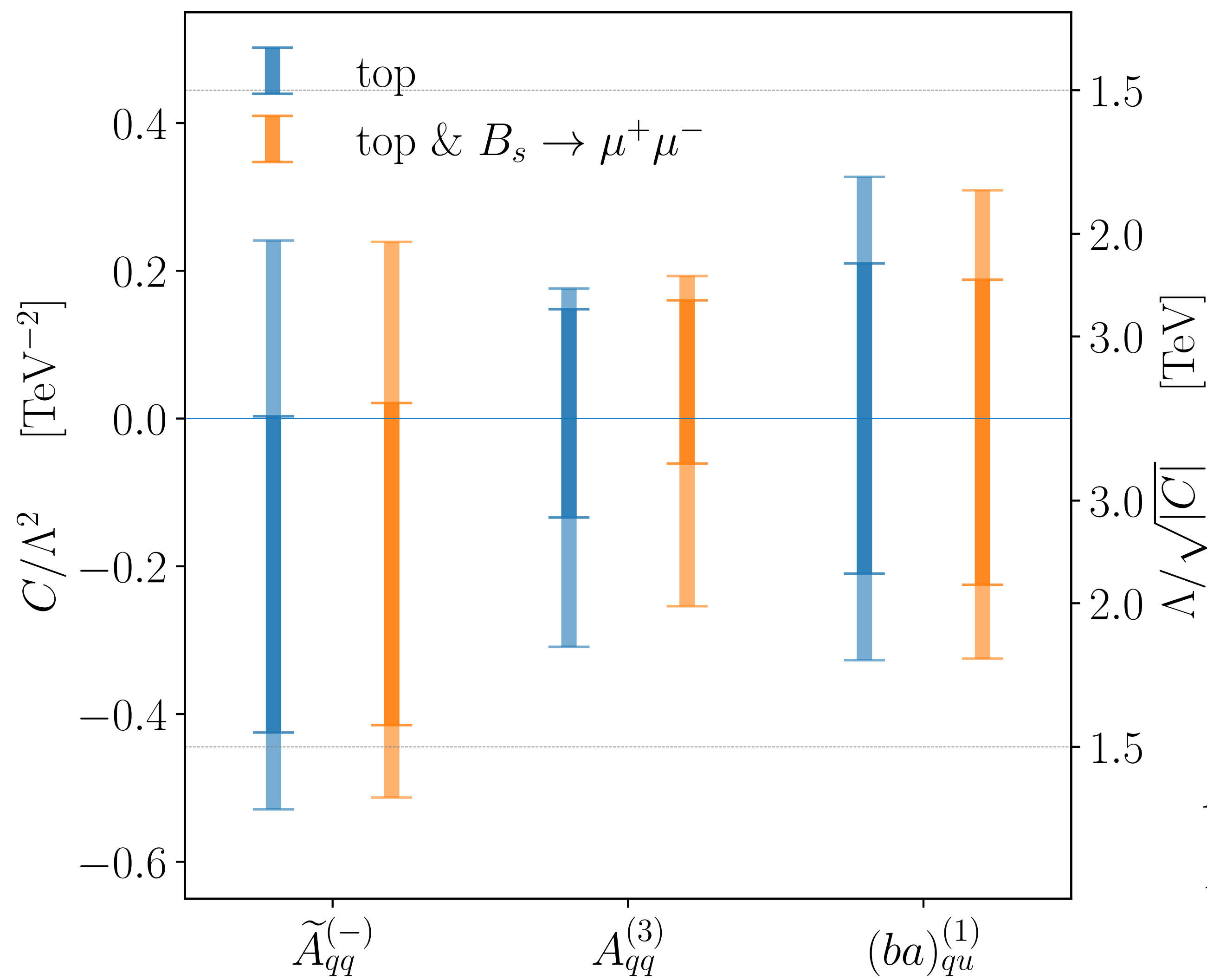
$$O_{qq}^{(1)} = (\overline{Q}\gamma_\mu Q)(\overline{Q}\gamma^\mu Q)$$

$$O_{qq}^{(3)} = (\overline{Q}\gamma_\mu \tau^a Q)(\overline{Q}\gamma^\mu \tau^a Q)$$

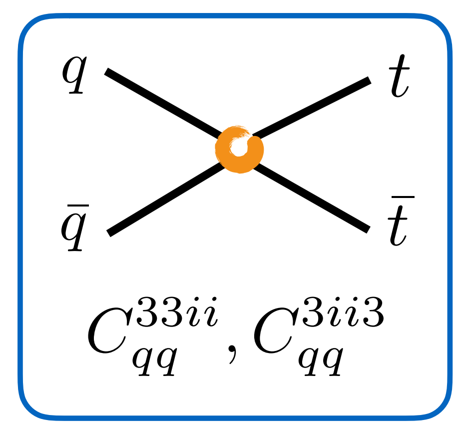
$(C_{qq})^{33ii} = A_{qq}$ color singlet

$(C_{qq})^{3ii3} = \widetilde{A}_{qq}$ color octet

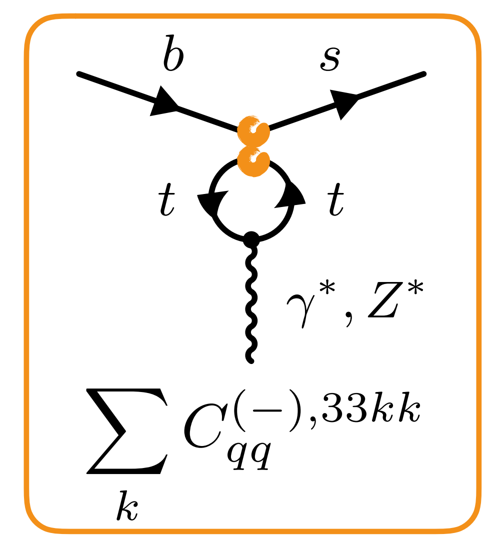
$$(C_{qq})^{3333} = A_{qq} + \widetilde{A}_{qq} + B_{qq}$$



top



bottom



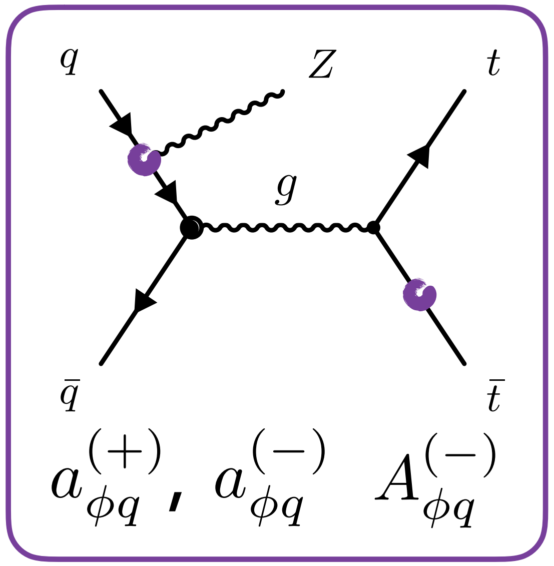
$$A_{qq} = (aa) + (ba)y_t^2$$

$$B_{qq} = (ba) + (\widetilde{ba})$$

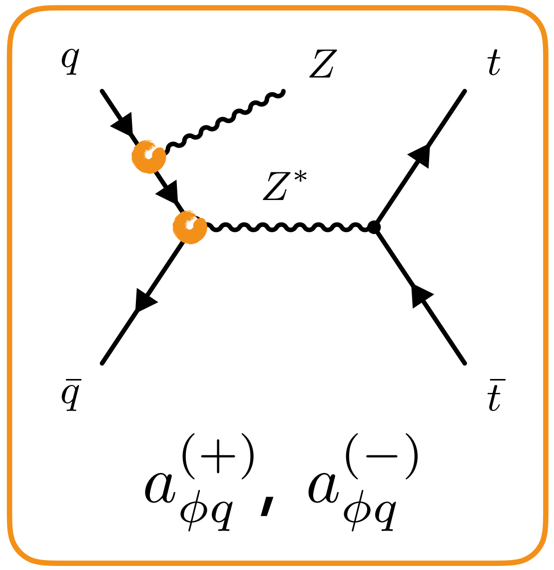
Bruggisser, Schäfer, van Dyk, Westhoff 2021

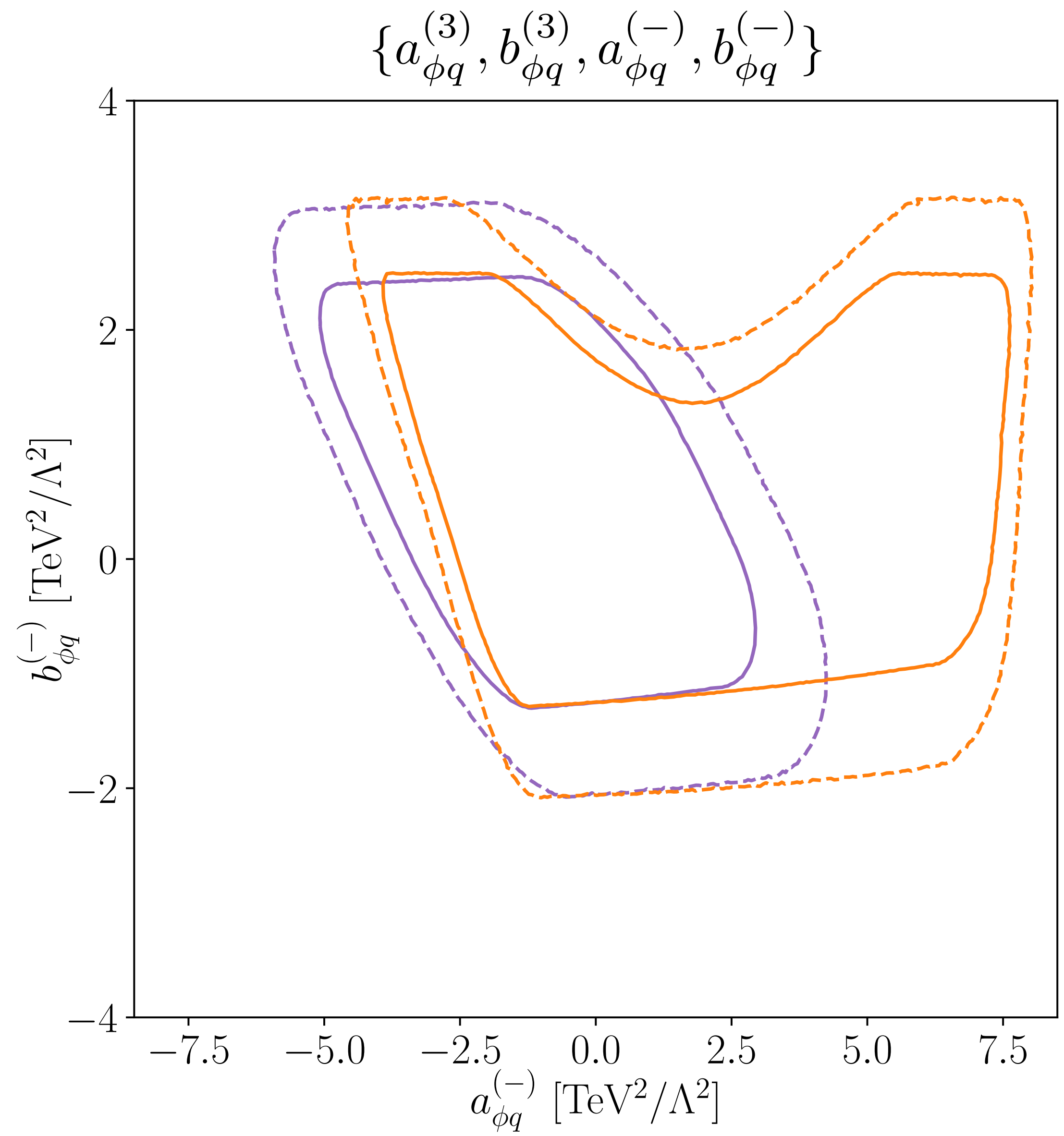
Flavor in top observables

Electroweak contributions matter!



+



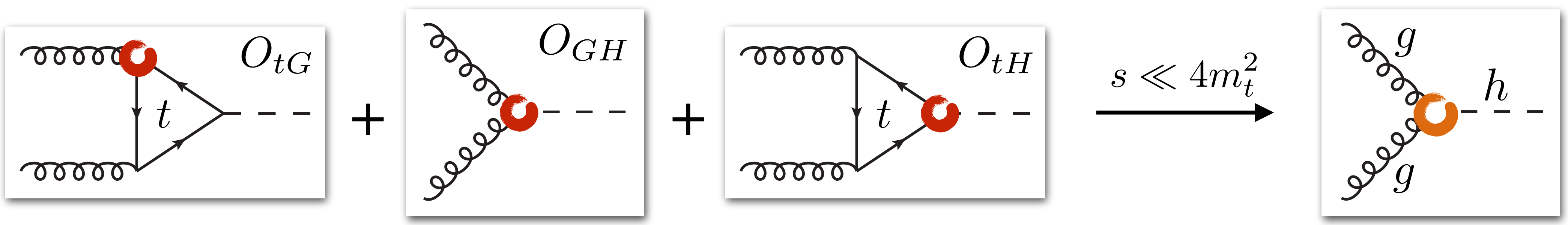


$$\sigma_{t\bar{t}Z}\,[\mathrm{pb}] = 0.679 + 0.023\,a_{\phi q}^{(3)} - 0.070 A_{\phi q}^{(-)}$$
$$+\,\mathbf{0.008}(a_{\phi q}^{(-)})^2 + \mathbf{0.004}(a_{\phi q}^{(+)})^2$$

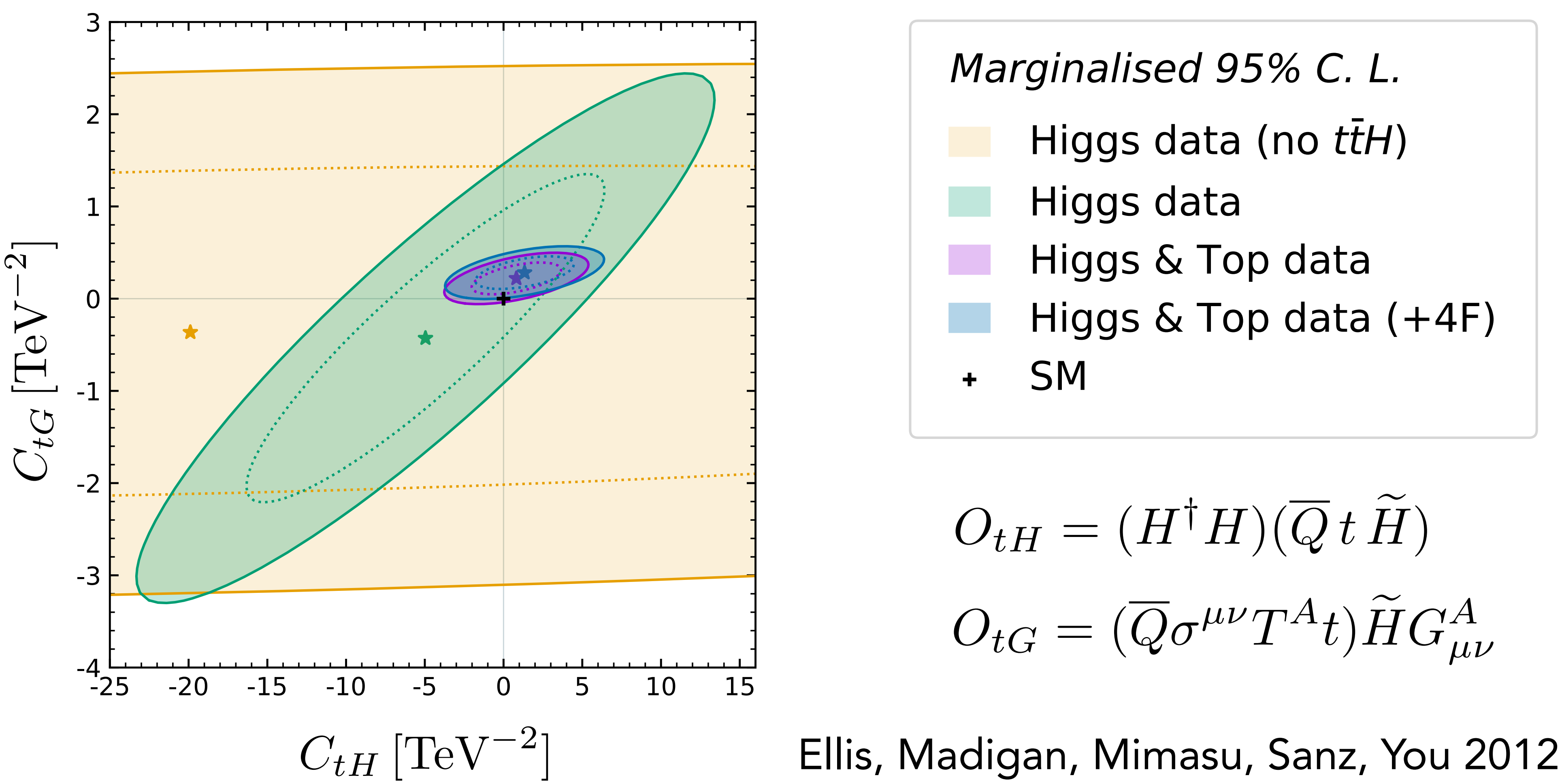
Top observables are flavor-sensitive. (against folklore)

Top & Higgs

Higgs production via gluon fusion:



Top resolves blind directions in Higgs data:



$$O_{tH} = (H^\dagger H)(\overline{Q}\, t\, \widetilde{H})$$

$$O_{tG} = (\overline{Q}\sigma^{\mu\nu}T^A t)\widetilde{H}G^A_{\mu\nu}$$

Ellis, Madigan, Mimasu, Sanz, You 2012.02779