Hints for Flavorful New Physics?

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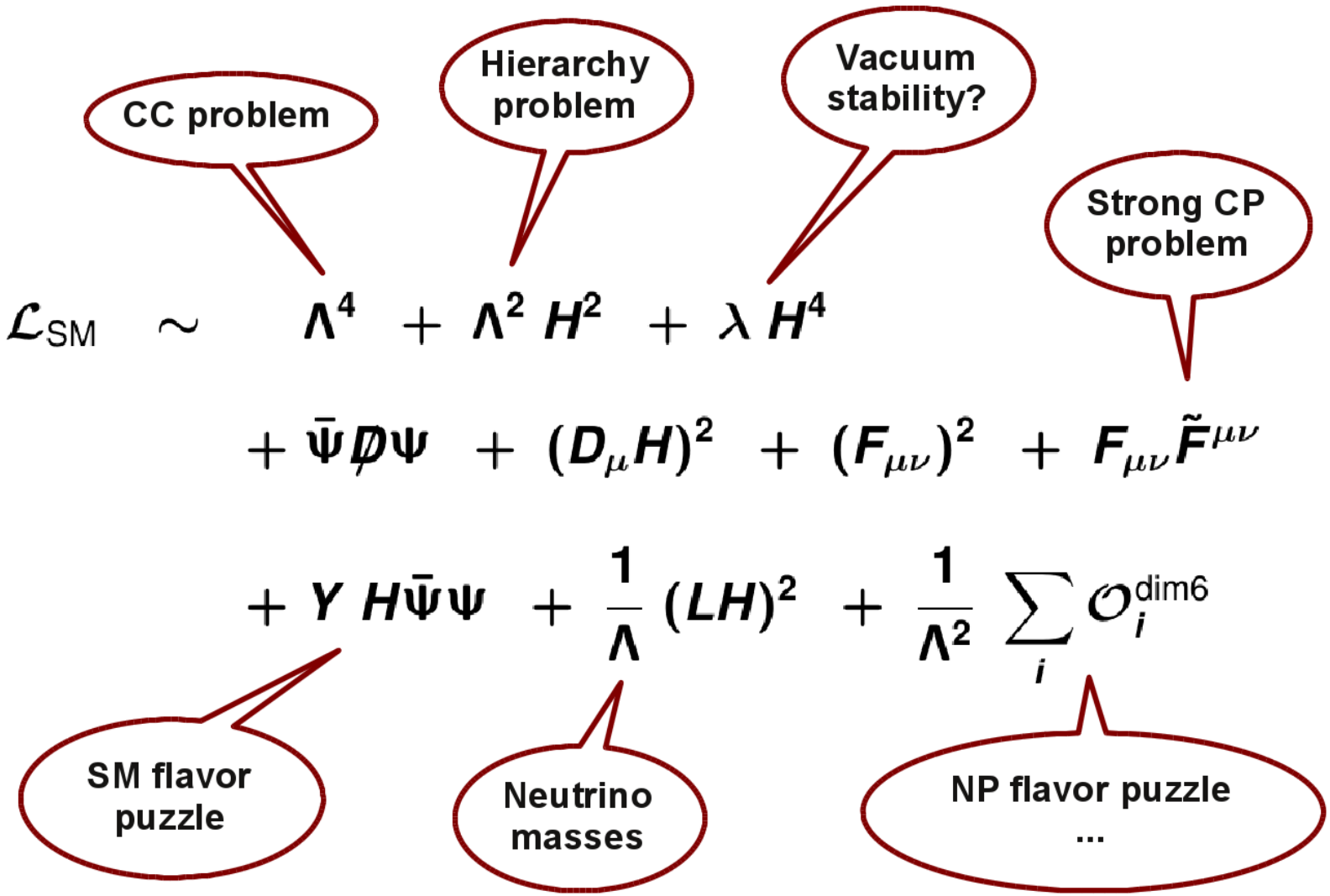
The Standard Model as Effective Theory

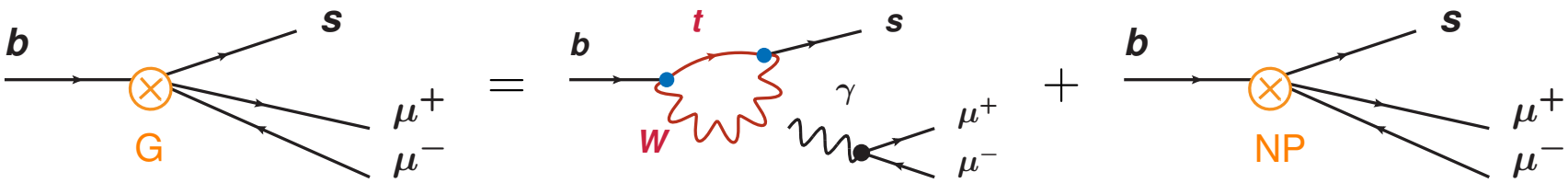
$$\mathcal{L}_{\text{SM}} \sim \Lambda^4 + \Lambda^2 H^2 + \lambda H^4$$
$$+ \bar{\Psi} \not{D} \Psi + (D_\mu H)^2 + (F_{\mu\nu})^2 + F_{\mu\nu} \tilde{F}^{\mu\nu}$$
$$+ Y H \bar{\Psi} \Psi + \frac{1}{\Lambda} (LH)^2 + \frac{1}{\Lambda^2} \sum_i \mathcal{O}_i^{\text{dim6}}$$

The Standard Model as Effective Theory



What is the New Physics scale Λ ?

Indirect Tests of New Physics



$$G \sim \frac{1}{16\pi^2} \frac{g^4}{m_W^2} \frac{m_t^2}{m_W^2} V_{tb} V_{ts}^* + \frac{C_{NP}}{\Lambda_{NP}^2}$$

measure precisely	calculate precisely the SM contribution	get information on NP coupling and scale

Dimension Six Interactions

$1 : X^3$	
Q_G	$f^{ABC} G^{A\nu}_{\mu} G^{B\rho}_{\nu} G^{C\mu}_{\rho}$
$Q_{\widetilde{G}}$	$f^{ABC} \widetilde{G}^{A\nu}_{\mu} G^{B\rho}_{\nu} G^{C\mu}_{\rho}$
Q_W	$\epsilon^{IJK} W^{I\nu}_{\mu} W^{J\rho}_{\nu} W^{K\mu}_{\rho}$
$Q_{\widetilde{W}}$	$\epsilon^{IJK} \widetilde{W}^{I\nu}_{\mu} W^{J\rho}_{\nu} W^{K\mu}_{\rho}$

$2 : H^6$	
Q_H	$(H^\dagger H)^3$

$3 : H^4 D^2$	
$Q_{H\Box}$	$(H^\dagger H) \Box (H^\dagger H)$
Q_{HD}	$\left(H^\dagger D_\mu H\right)^* \left(H^\dagger D_\mu H\right)$

$5 : \psi^2 H^3 + \text{h.c.}$	
Q_{eH}	$(H^\dagger H)(\bar{l}_p e_r H)$
Q_{uH}	$(H^\dagger H)(\bar{q}_p u_r \widetilde{H})$
Q_{dH}	$(H^\dagger H)(\bar{q}_p d_r H)$

$4 : X^2 H^2$	
Q_{HG}	$H^\dagger H\, G^A_{\mu\nu} G^{A\mu\nu}$
$Q_{H\widetilde{G}}$	$H^\dagger H\, \widetilde{G}^A_{\mu\nu} G^{A\mu\nu}$
Q_{HW}	$H^\dagger H\, W^I_{\mu\nu} W^{I\mu\nu}$
$Q_{H\widetilde{W}}$	$H^\dagger H\, \widetilde{W}^I_{\mu\nu} W^{I\mu\nu}$
Q_{HB}	$H^\dagger H\, B_{\mu\nu} B^{\mu\nu}$
$Q_{H\widetilde{B}}$	$H^\dagger H\, \widetilde{B}_{\mu\nu} B^{\mu\nu}$
Q_{HWB}	$H^\dagger \tau^I H\, W^I_{\mu\nu} B^{\mu\nu}$
$Q_{H\widetilde{W}B}$	$H^\dagger \tau^I H\, \widetilde{W}^I_{\mu\nu} B^{\mu\nu}$

$6 : \psi^2 X H + \text{h.c.}$	
Q_{eW}	$(\bar{l}_p \sigma^{\mu\nu} e_r) \tau^I H W^I_{\mu\nu}$
Q_{eB}	$(\bar{l}_p \sigma^{\mu\nu} e_r) H B_{\mu\nu}$
Q_{uG}	$(\bar{q}_p \sigma^{\mu\nu} T^A u_r) \widetilde{H}\, G^A_{\mu\nu}$
Q_{uW}	$(\bar{q}_p \sigma^{\mu\nu} u_r) \tau^I \widetilde{H}\, W^I_{\mu\nu}$
Q_{uB}	$(\bar{q}_p \sigma^{\mu\nu} u_r) \widetilde{H}\, B_{\mu\nu}$
Q_{dG}	$(\bar{q}_p \sigma^{\mu\nu} T^A d_r) H\, G^A_{\mu\nu}$
Q_{dW}	$(\bar{q}_p \sigma^{\mu\nu} d_r) \tau^I H\, W^I_{\mu\nu}$
Q_{dB}	$(\bar{q}_p \sigma^{\mu\nu} d_r) H\, B_{\mu\nu}$

$7 : \psi^2 H^2 D$	
$Q^{(1)}_{Hl}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{l}_p \gamma^\mu l_r)$
$Q^{(3)}_{Hl}$	$(H^\dagger i \overleftrightarrow{D}^I_\mu H)(\bar{l}_p \tau^I \gamma^\mu l_r)$
Q_{He}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{e}_p \gamma^\mu e_r)$
$Q^{(1)}_{Hq}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{q}_p \gamma^\mu q_r)$
$Q^{(3)}_{Hq}$	$(H^\dagger i \overleftrightarrow{D}^I_\mu H)(\bar{q}_p \tau^I \gamma^\mu q_r)$
Q_{Hu}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{u}_p \gamma^\mu u_r)$
Q_{Hd}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{d}_p \gamma^\mu d_r)$
$Q_{Hud} + \text{h.c.}$	$i(\widetilde{H}^\dagger D_\mu H)(\bar{u}_p \gamma^\mu d_r)$

$8 : (\bar{L}L)(\bar{L}L)$	
Q_{ll}	$(\bar{l}_p \gamma_\mu l_r)(\bar{l}_s \gamma^\mu l_t)$
$Q^{(1)}_{qq}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{q}_s \gamma^\mu q_t)$
$Q^{(3)}_{qq}$	$(\bar{q}_p \gamma_\mu \tau^I q_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$
$Q^{(1)}_{lq}$	$(\bar{l}_p \gamma_\mu l_r)(\bar{q}_s \gamma^\mu q_t)$
$Q^{(3)}_{lq}$	$(\bar{l}_p \gamma_\mu \tau^I l_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$

$8 : (\bar{R}R)(\bar{R}R)$	
Q_{ee}	$(\bar{e}_p \gamma_\mu e_r)(\bar{e}_s \gamma^\mu e_t)$
Q_{uu}	$(\bar{u}_p \gamma_\mu u_r)(\bar{u}_s \gamma^\mu u_t)$
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$Q^{(1)}_{ud}$	$(\bar{u}_p \gamma_\mu u_r)(\bar{d}_s \gamma^\mu d_t)$
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Q_{le}	$(\bar{l}_p \gamma_\mu l_r)(\bar{e}_s \gamma^\mu e_t)$
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Q_{qe}	$(\bar{q}_p \gamma_\mu q_r)(\bar{e}_s \gamma^\mu e_t)$
$Q^{(1)}_{qu}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{u}_s \gamma^\mu u_t)$
$Q^{(8)}_{qu}$	$(\bar{q}_p \gamma_\mu T^A q_r)(\bar{u}_s \gamma^\mu T^A u_t)$
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$8 : (\bar{L}R)(\bar{R}L) + \text{h.c.}$	
Q_{ledq}	$(\bar{l}^j_p e_r)(\bar{d}_s q_{tj})$

$8 : (\bar{L}R)(\bar{L}R) + \text{h.c.}$	
$Q^{(1)}_{quqd}$	$(\bar{q}^j_p u_r)\epsilon_{jk}(\bar{q}^k_s d_t)$
$Q^{(8)}_{quqd}$	$(\bar{q}^j_p T^A u_r)\epsilon_{jk}(\bar{q}^k_s T^A d_t)$
$Q^{(1)}_{lequ}$	$(\bar{l}^j_p e_r)\epsilon_{jk}(\bar{q}^k_s u_t)$
$Q^{(3)}_{lequ}$	$(\bar{l}^j_p \sigma_{\mu\nu} e_r)\epsilon_{jk}(\bar{q}^k_s \sigma^{\mu\nu} u_t)$

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$Q^{(1)}_{lq}$	$(\bar{l}_p \gamma_\mu l_r)(\bar{q}_s \gamma^\mu q_t)$
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Q_{uH}	$(H^\dagger H)(\bar{q}_p u_r \widetilde{H})$
Q_{dH}	$(H^\dagger H)(\bar{q}_p d_r H)$

$4: X^2 H^2$	
Q_{HG}	$H^\dagger H\, G^A_{\mu\nu} G^{A\mu\nu}$
$Q_{H\widetilde{G}}$	$H^\dagger H\, \widetilde{G}^A_{\mu\nu} G^{A\mu\nu}$
Q_{HW}	$H^\dagger H\, W^I_{\mu\nu} W^{I\mu\nu}$
$Q_{H\widetilde{W}}$	$H^\dagger H\, \widetilde{W}^I_{\mu\nu} W^{I\mu\nu}$
Q_{HB}	$H^\dagger H\, B_{\mu\nu} B^{\mu\nu}$
$Q_{H\widetilde{B}}$	$H^\dagger H\, \widetilde{B}_{\mu\nu} B^{\mu\nu}$
Q_{HWB}	$H^\dagger \tau^I H\, W^I_{\mu\nu} B^{\mu\nu}$
$Q_{H\widetilde{W}B}$	$H^\dagger \tau^I H\, \widetilde{W}^I_{\mu\nu} B^{\mu\nu}$

$6: \psi^2 X H + \text{h.c.}$	
Q_{eW}	$(\bar{l}_p \sigma^{\mu\nu} e_r) \tau^I H W^I_{\mu\nu}$
Q_{eB}	$(\bar{l}_p \sigma^{\mu\nu} e_r) H B_{\mu\nu}$
Q_{uG}	$(\bar{q}_p \sigma^{\mu\nu} T^A u_r) \widetilde{H} G^A_{\mu\nu}$
Q_{uW}	$(\bar{q}_p \sigma^{\mu\nu} u_r) \tau^I \widetilde{H} W^I_{\mu\nu}$
Q_{uB}	$(\bar{q}_p \sigma^{\mu\nu} u_r) \widetilde{H} B_{\mu\nu}$
Q_{dG}	$(\bar{q}_p \sigma^{\mu\nu} T^A d_r) H G^A_{\mu\nu}$
Q_{dW}	$(\bar{q}_p \sigma^{\mu\nu} d_r) \tau^I H W^I_{\mu\nu}$
Q_{dB}	$(\bar{q}_p \sigma^{\mu\nu} d_r) H B_{\mu\nu}$

$7: \psi^2 H^2 D$	
$Q^{(1)}_{H\ell}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{l}_p \gamma^\mu l_r)$
$Q^{(3)}_{H\ell}$	$(H^\dagger i \overleftrightarrow{D}^I_\mu H)(\bar{l}_p \tau^I \gamma^\mu l_r)$
Q_{He}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{e}_p \gamma^\mu e_r)$
$Q^{(1)}_{Hq}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{q}_p \gamma^\mu q_r)$
$Q^{(3)}_{Hq}$	$(H^\dagger i \overleftrightarrow{D}^I_\mu H)(\bar{q}_p \tau^I \gamma^\mu q_r)$
Q_{Hu}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{u}_p \gamma^\mu u_r)$
Q_{Hd}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{d}_p \gamma^\mu d_r)$
$Q_{iHud} + \text{h.c.}$	$i(\widetilde{H}^\dagger D_\mu H)(\bar{u}_p \gamma^\mu d_r)$

$8: (\bar{L}L)(\bar{L}L)$	
Q_{ll}	$(\bar{l}_p \gamma_\mu l_r)(\bar{l}_s \gamma^\mu l_t)$
$Q^{(1)}_{qq}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{q}_s \gamma^\mu q_t)$
$Q^{(3)}_{qq}$	$(\bar{q}_p \gamma_\mu \tau^I q_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$
$Q^{(1)}_{lq}$	$(\bar{l}_p \gamma_\mu l_r)(\bar{q}_s \gamma^\mu q_t)$
$Q^{(3)}_{lq}$	$(\bar{l}_p \gamma_\mu \tau^I l_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$

$8: (\bar{R}R)(\bar{R}R)$	
Q_{ee}	$(\bar{e}_p \gamma_\mu e_r)(\bar{e}_s \gamma^\mu e_t)$
Q_{uu}	$(\bar{u}_p \gamma_\mu u_r)(\bar{u}_s \gamma^\mu u_t)$
Q_{dd}	$(\bar{d}_p \gamma_\mu d_r)(\bar{d}_s \gamma^\mu d_t)$
Q_{eu}	$(\bar{e}_p \gamma_\mu e_r)(\bar{u}_s \gamma^\mu u_t)$
Q_{ed}	$(\bar{e}_p \gamma_\mu e_r)(\bar{d}_s \gamma^\mu d_t)$
$Q^{(1)}_{ud}$	$(\bar{u}_p \gamma_\mu u_r)(\bar{d}_s \gamma^\mu d_t)$
$Q^{(8)}_{ud}$	$(\bar{u}_p \gamma_\mu T^A u_r)(\bar{d}_s \gamma^\mu T^A d_t)$

$8: (\bar{L}L)(\bar{R}R)$	
Q_{le}	$(\bar{l}_p \gamma_\mu l_r)(\bar{e}_s \gamma^\mu e_t)$
Q_{lu}	$(\bar{l}_p \gamma_\mu l_r)(\bar{u}_s \gamma^\mu u_t)$
Q_{ld}	$(\bar{l}_p \gamma_\mu l_r)(\bar{d}_s \gamma^\mu d_t)$
Q_{qe}	$(\bar{q}_p \gamma_\mu q_r)(\bar{e}_s \gamma^\mu e_t)$
$Q^{(1)}_{qu}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{u}_s \gamma^\mu u_t)$
$Q^{(8)}_{qu}$	$(\bar{q}_p \gamma_\mu T^A q_r)(\bar{u}_s \gamma^\mu T^A u_t)$
$Q^{(1)}_{qd}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{d}_s \gamma^\mu d_t)$
$Q^{(8)}_{qd}$	$(\bar{q}_p \gamma_\mu T^A q_r)(\bar{d}_s \gamma^\mu T^A d_t)$

$8: (\bar{L}R)(\bar{R}L) + \text{h.c.}$	
Q_{ledq}	$(\bar{l}^j_p e_r)(\bar{d}_s q_{tj})$

$8: (\bar{L}R)(\bar{L}R) + \text{h.c.}$	
$Q^{(1)}_{quqd}$	$(\bar{q}^j_p u_r)\epsilon_{jk}(\bar{q}^k_s d_t)$
$Q^{(8)}_{quqd}$	$(\bar{q}^j_p T^A u_r)\epsilon_{jk}(\bar{q}^k_s T^A d_t)$
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$Q^{(3)}_{lequ}$	$(\bar{l}^j_p \sigma_{\mu\nu} e_r)\epsilon_{jk}(\bar{q}^k_s \sigma^{\mu\nu} u_t)$

2499 baryon and lepton number conserving dim. 6 operators

Grzadkowski et al. 1008.4884,
Alonso et al 1312.2014

flavor violation from

4 fermion interactions

dipole transitions

Z-penguins

Dimension Six Interactions

$1: X^3$	
Q_G	$f^{ABC} G^{A\nu}_{\mu} G^{B\rho}_{\nu} G^{C\mu}_{\rho}$
$Q_{\widetilde{G}}$	$f^{ABC} \widetilde{G}^{A\nu}_{\mu} G^{B\rho}_{\nu} G^{C\mu}_{\rho}$
Q_W	$\epsilon^{IJK} W^{I\nu}_{\mu} W^{J\rho}_{\nu} W^{K\mu}_{\rho}$
$Q_{\widetilde{W}}$	$\epsilon^{IJK} \widetilde{W}^{I\nu}_{\mu} W^{J\rho}_{\nu} W^{K\mu}_{\rho}$

$2: H^6$	
Q_H	$(H^\dagger H)^3$

$3: H^4 D^2$	
$Q_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$
Q_{HD}	$(H^\dagger D_\mu H)^* (H^\dagger D_\mu H)$

$5: \psi^2 H^3 + \text{h.c.}$	
Q_{eH}	$(H^\dagger H)(\bar{l}_p e_r H)$
Q_{uH}	$(H^\dagger H)(\bar{q}_p u_r \widetilde{H})$
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$Q_{H\widetilde{B}}$	$H^\dagger H\, \widetilde{B}_{\mu\nu} B^{\mu\nu}$
Q_{HWB}	$H^\dagger \tau^I H\, W^I_{\mu\nu} B^{\mu\nu}$
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$6: \psi^2 X H + \text{h.c.}$	
Q_{eW}	$(\bar{l}_p \sigma^{\mu\nu} e_r) \tau^I H W^I_{\mu\nu}$
Q_{eB}	$(\bar{l}_p \sigma^{\mu\nu} e_r) H B_{\mu\nu}$
Q_{uG}	$(\bar{q}_p \sigma^{\mu\nu} T^A u_r) \widetilde{H} G^A_{\mu\nu}$
Q_{uW}	$(\bar{q}_p \sigma^{\mu\nu} u_r) \tau^I \widetilde{H} W^I_{\mu\nu}$
Q_{uB}	$(\bar{q}_p \sigma^{\mu\nu} u_r) \widetilde{H} B_{\mu\nu}$
Q_{dG}	$(\bar{q}_p \sigma^{\mu\nu} T^A d_r) H G^A_{\mu\nu}$
Q_{dW}	$(\bar{q}_p \sigma^{\mu\nu} d_r) \tau^I H W^I_{\mu\nu}$
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Q_{Hu}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{u}_p \gamma^\mu u_r)$
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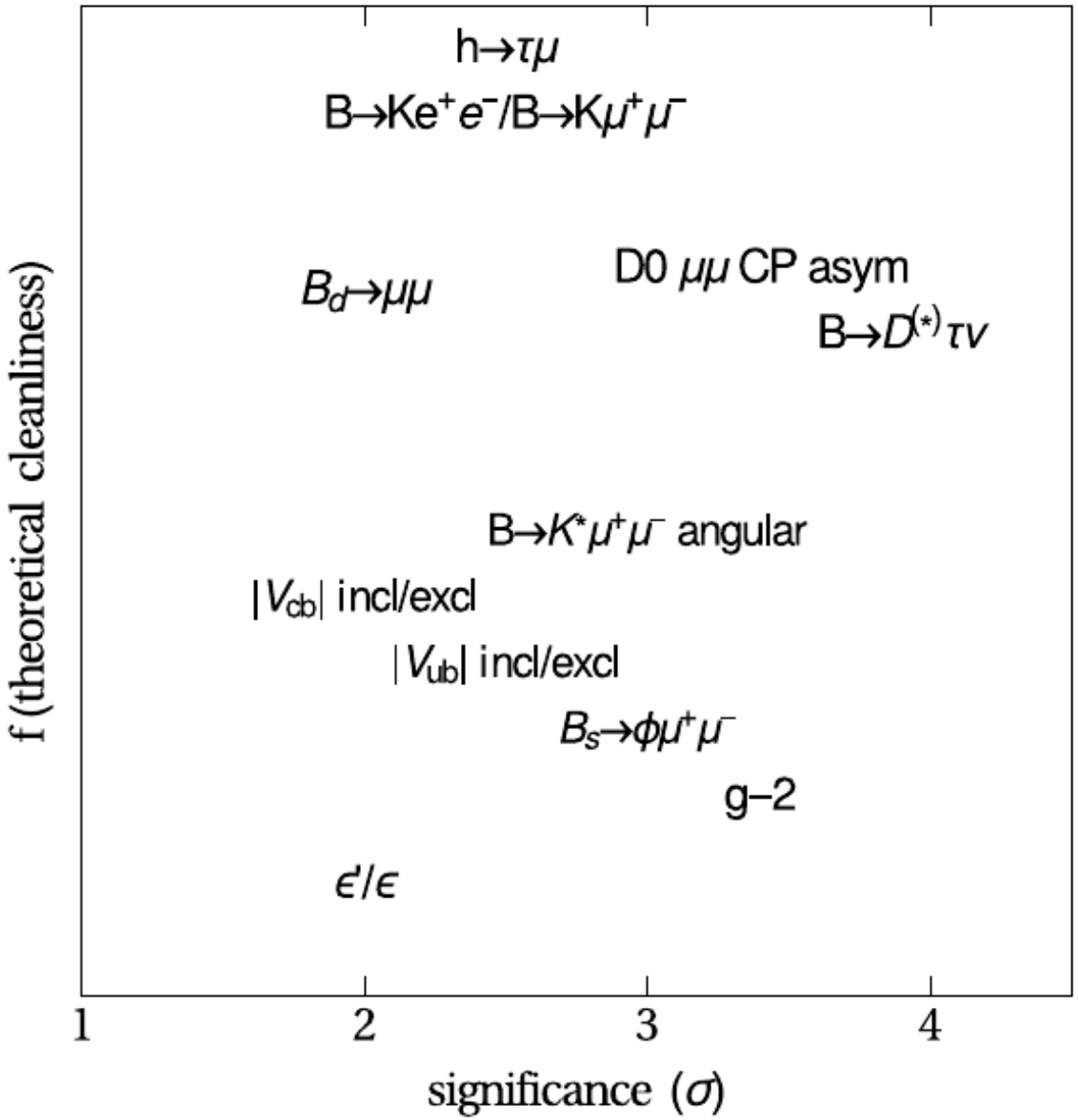
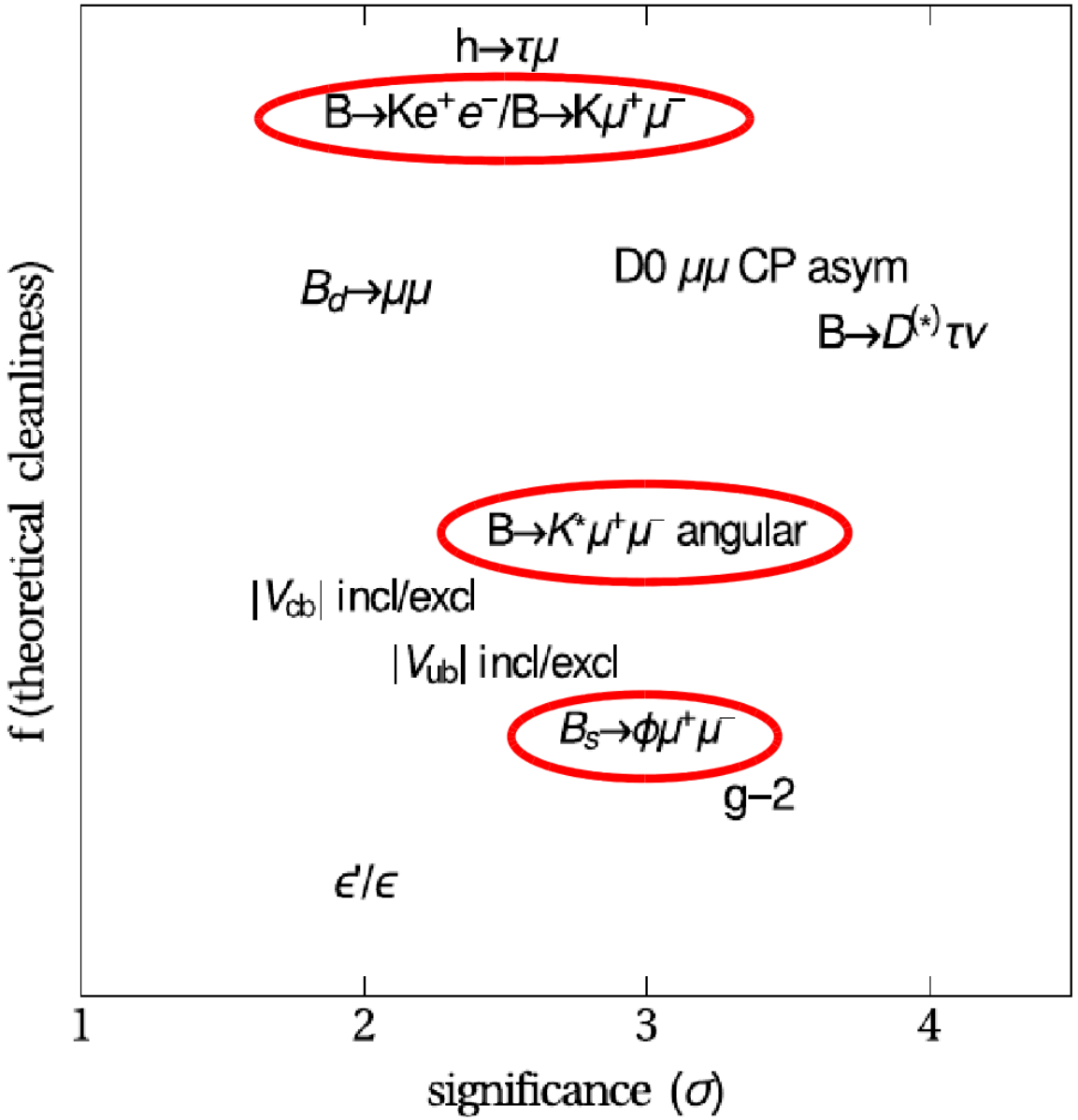
Higgs penguins

Hints For Flavorful New Physics?



Z. Ligeti

Hints For Flavorful New Physics?



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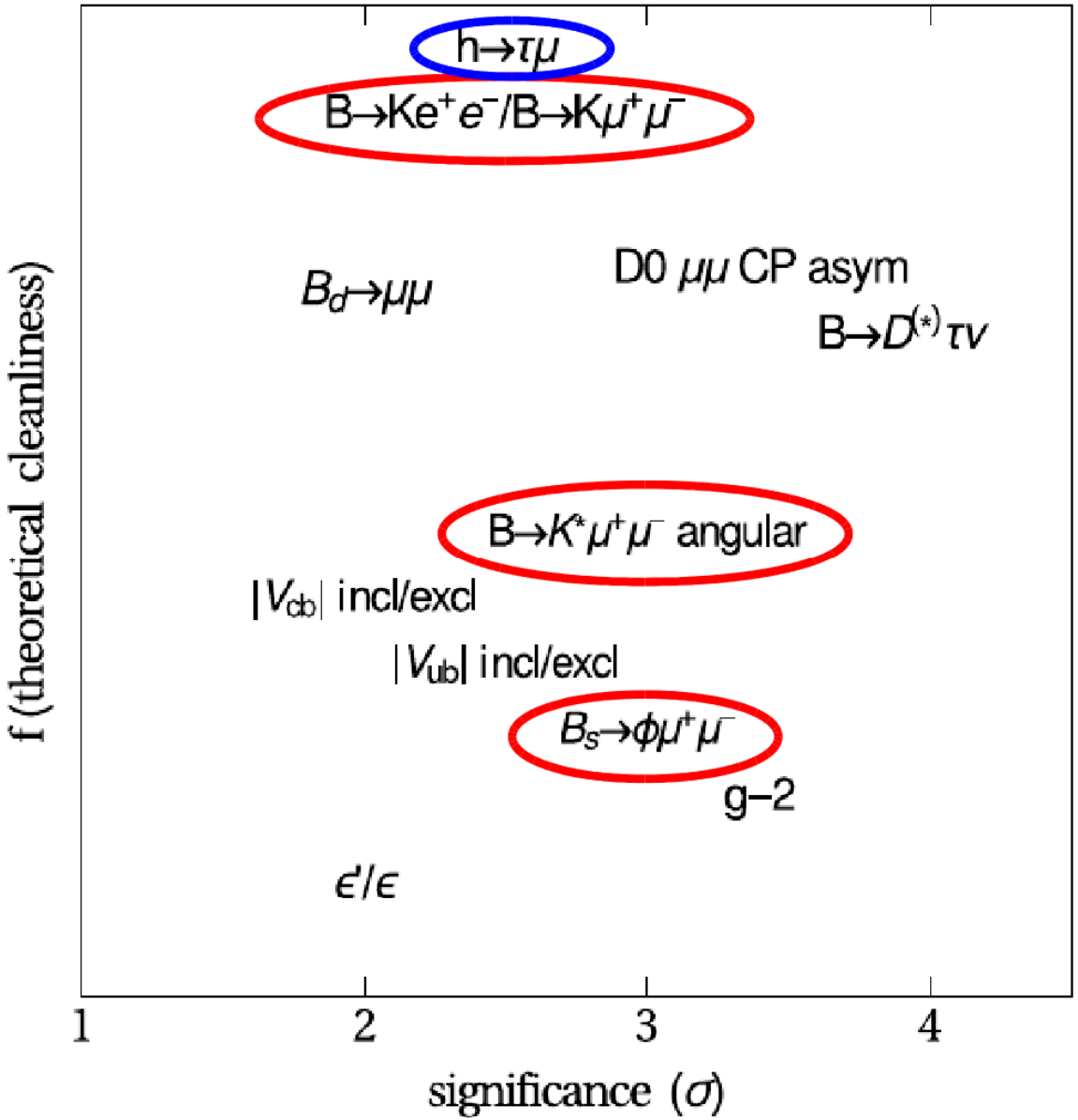
Hints For Flavorful New Physics?

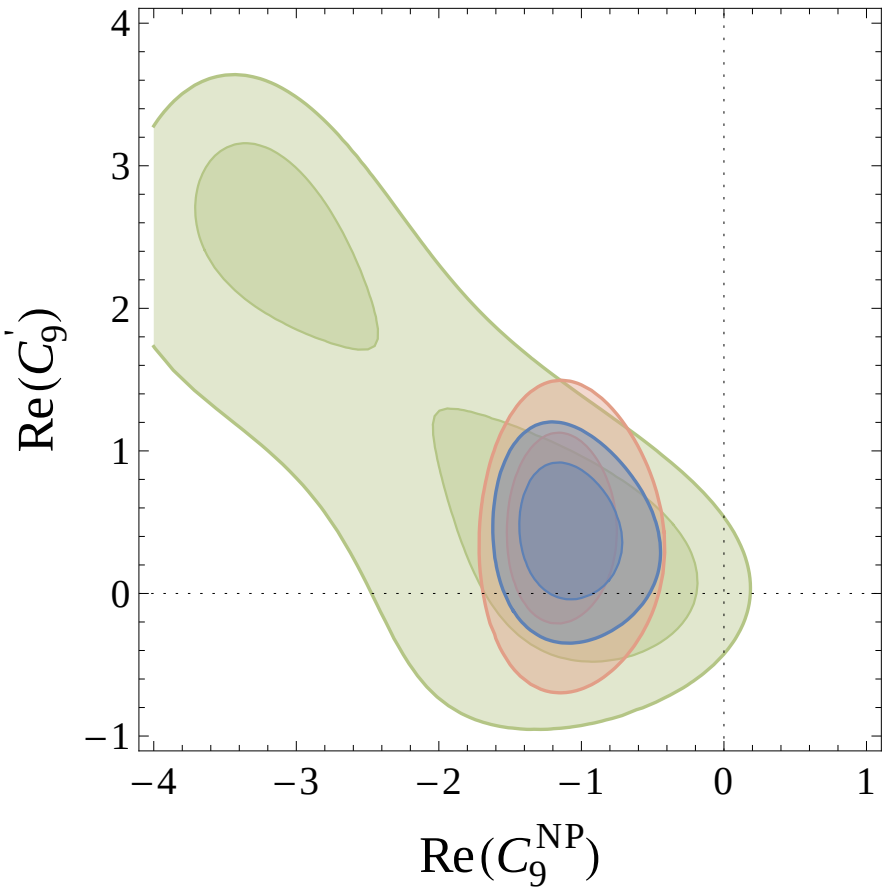


Z. Ligeti

New Physics in Rare B Decays

Global Fits of Rare B Decay Data

$$\mathcal{H}_{\text{eff}}^{b\to s} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \frac{e^2}{16\pi^2} \sum_i \left(C_i \mathcal{O}_i + C_i' \mathcal{O}_i' \right)$$



add new physics in form of
4 fermion contact interactions

$$O_9 \propto (\bar{s}\gamma_\mu P_L b)(\bar{\mu}\gamma^\mu \mu)$$

$$O_9' \propto (\bar{s}\gamma_\mu P_R b)(\bar{\mu}\gamma^\mu \mu)$$

muonic vector current

(global fit taking into account all
relevant data on radiative,
semi-leptonic and leptonic B decays)

WA, Straub 1411.3161/1503.06199 (also Descotes-Genon et al. 1510.04239; Hurth et al. 1603.00865)

Implications for the New Physics Scale

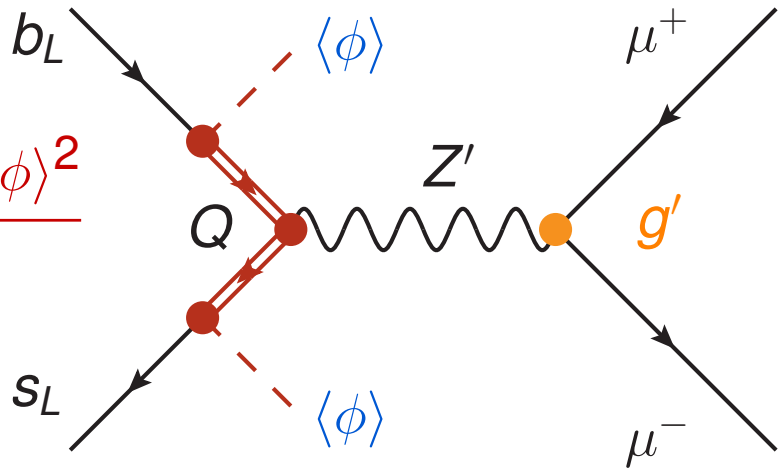
generic tree	$\frac{1}{\Lambda_{\rm NP}^2}(\bar{s}\gamma_\nu P_L b)(\bar{\mu}\gamma^\nu \mu)$	$\Lambda_{\rm NP} \simeq 35\ {\rm TeV} \times (C_9^{\rm NP})^{-1/2}$
MFV tree	$\frac{1}{\Lambda_{\rm NP}^2}\, V_{tb}V_{ts}^*\, (\bar{s}\gamma_\nu P_L b)(\bar{\mu}\gamma^\nu \mu)$	$\Lambda_{\rm NP} \simeq 7\ {\rm TeV} \times (C_9^{\rm NP})^{-1/2}$
generic loop	$\frac{1}{\Lambda_{\rm NP}^2}\frac{1}{16\pi^2}(\bar{s}\gamma_\nu P_L b)(\bar{\mu}\gamma^\nu \mu)$	$\Lambda_{\rm NP} \simeq 3\ {\rm TeV} \times (C_9^{\rm NP})^{-1/2}$
MFV loop	$\frac{1}{\Lambda_{\rm NP}^2}\frac{1}{16\pi^2}\, V_{tb}V_{ts}^*\, (\bar{s}\gamma_\nu P_L b)(\bar{\mu}\gamma^\nu \mu)$	$\Lambda_{\rm NP} \simeq 0.6\ {\rm TeV} \times (C_9^{\rm NP})^{-1/2}$

(MFV = Minimal Flavor Violation)

My Favorite Model

Z' based on gauging $L_\mu - L_\tau$
with effective flavor violating couplings to quarks

WA, Gori, Pospelov, Yavin 1403.1269

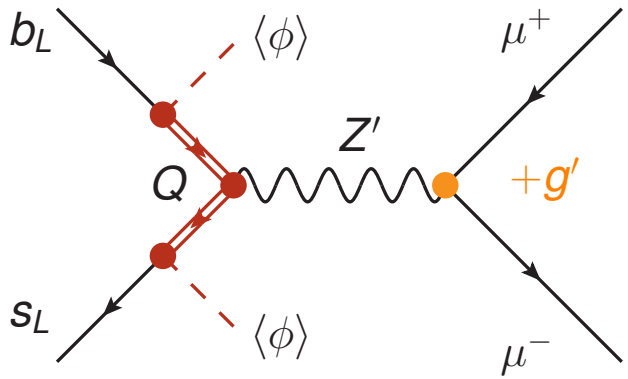


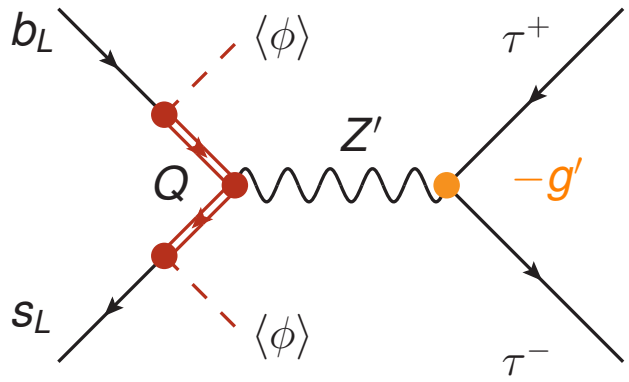
$$\frac{g' Y_{Qb} Y^*_{Qs} \langle\phi\rangle^2}{2m_Q^2}$$

$$C_9 = \frac{Y_{Qb} Y^*_{Qs}}{2m_Q^2}$$

Q: heavy vector-like fermions
ϕ: scalar that breaks $L_\mu - L_\tau$

$L_\mu - L_\tau$ and Lepton Flavor Universality





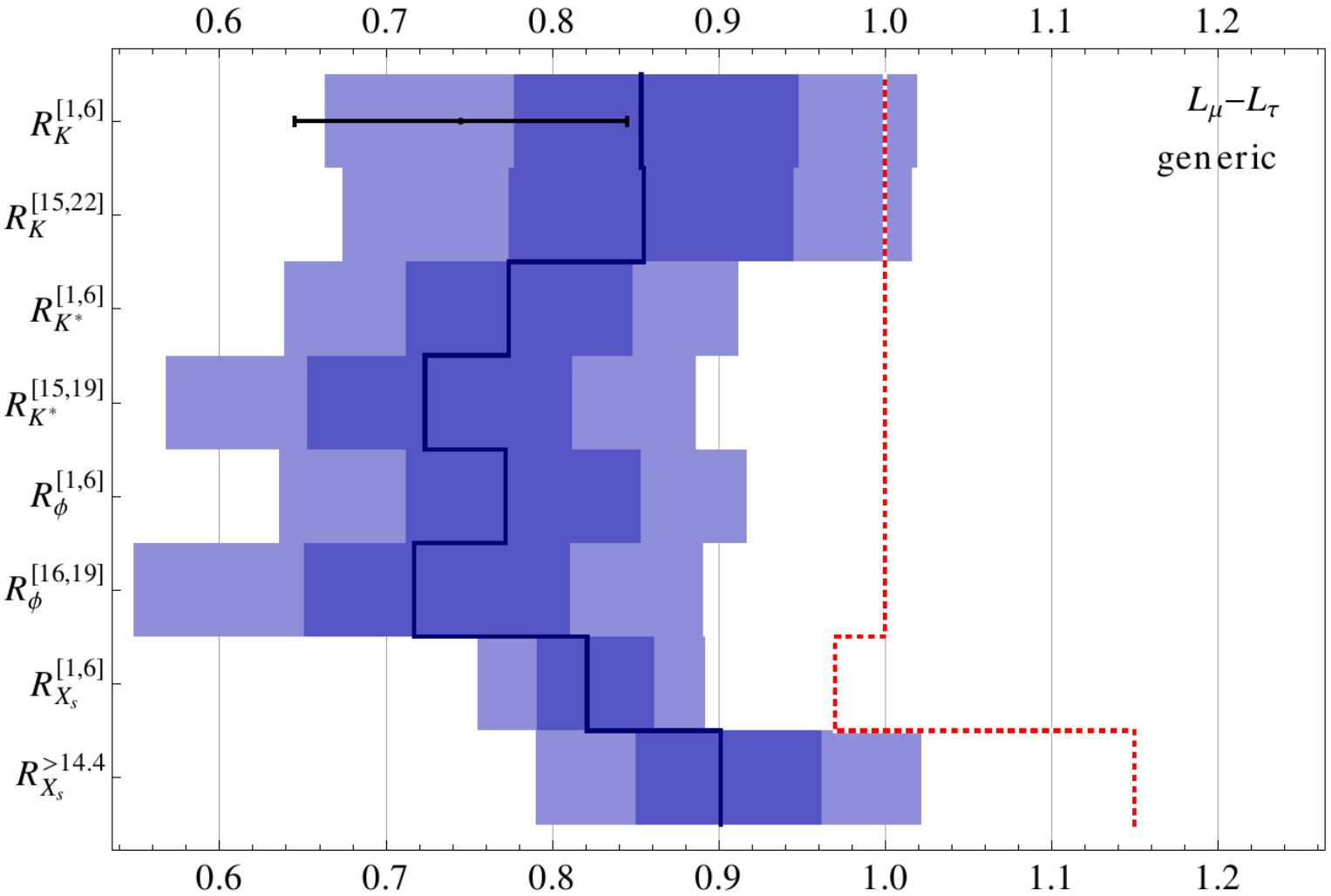
the Z' model based on gauged $L_\mu - L_\tau$ predicts:

1) opposite effects in the $\mu^+\mu^-$ and $\tau^+\tau^-$ final state

2) no effect in the e^+e^- final state

Predictions for LFU Ratios

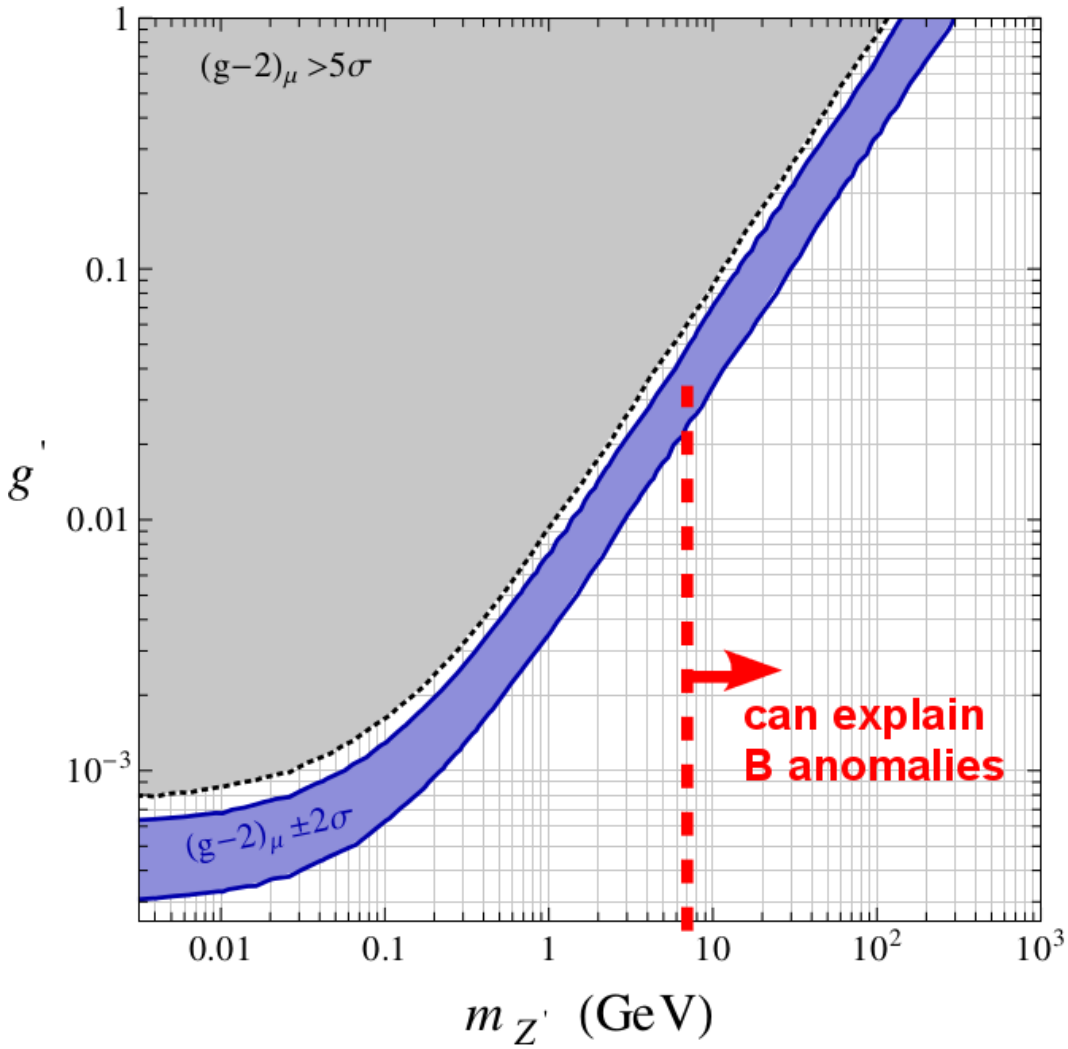
WA, Yavin 1508.07009



Probing the Z' Gauge Boson

muon $g-2$

WA, Gori, Pospelov, Yavin, 1406.2332



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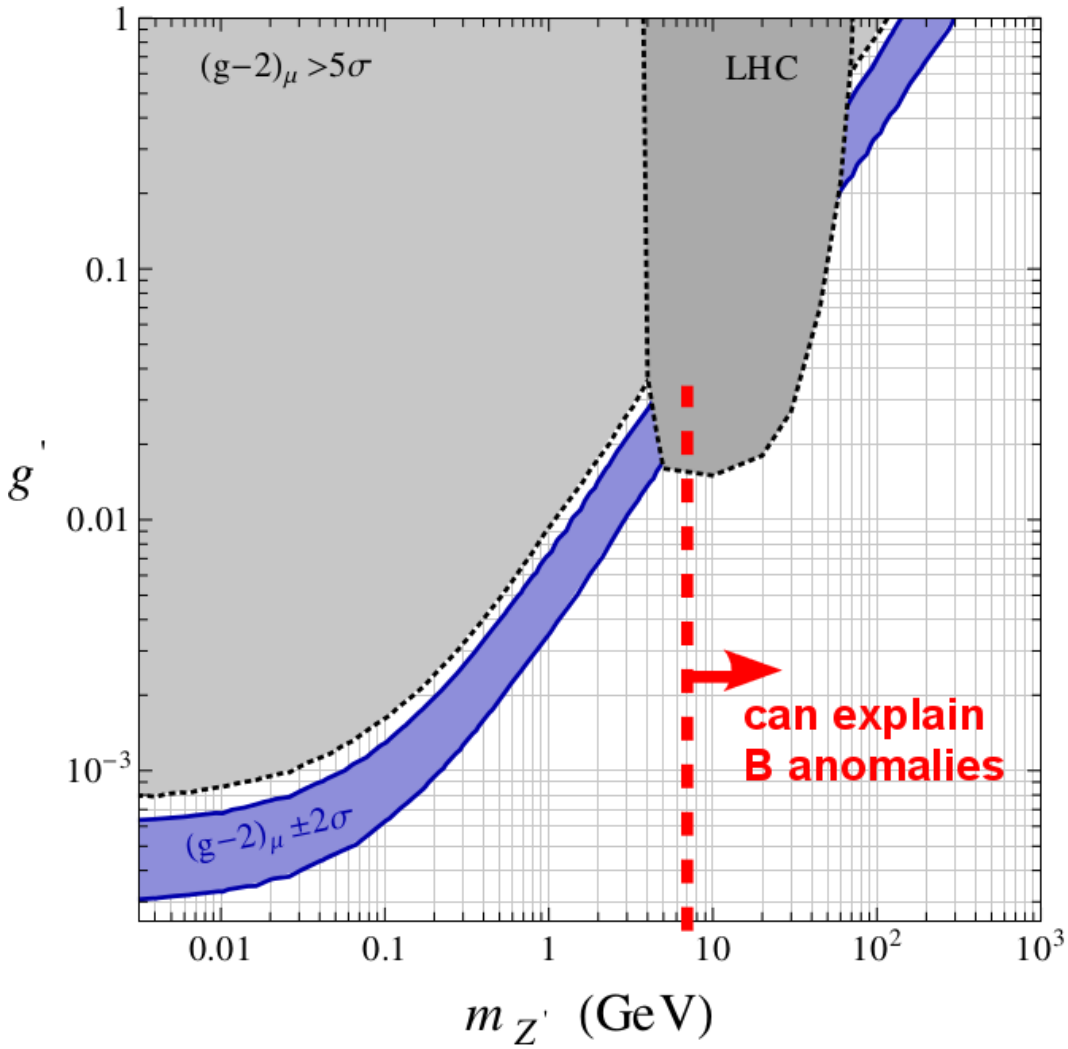
$Z \to 4\mu$ branching ratio

WA, Gori, Pospelov, Yavin, 1406.2332



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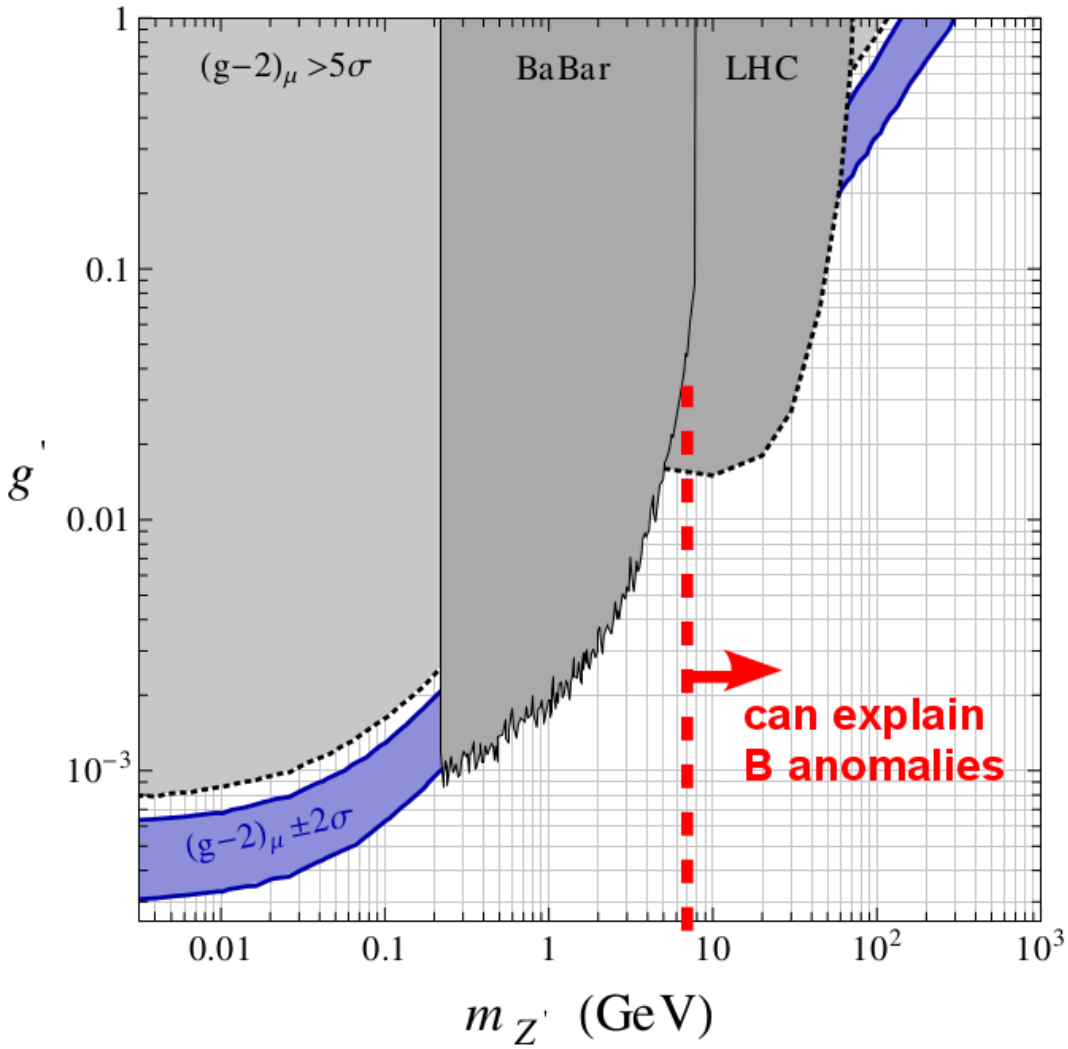
(BaBar 1606.03501)

WA, Gori, Pospelov, Yavin, 1406.2332



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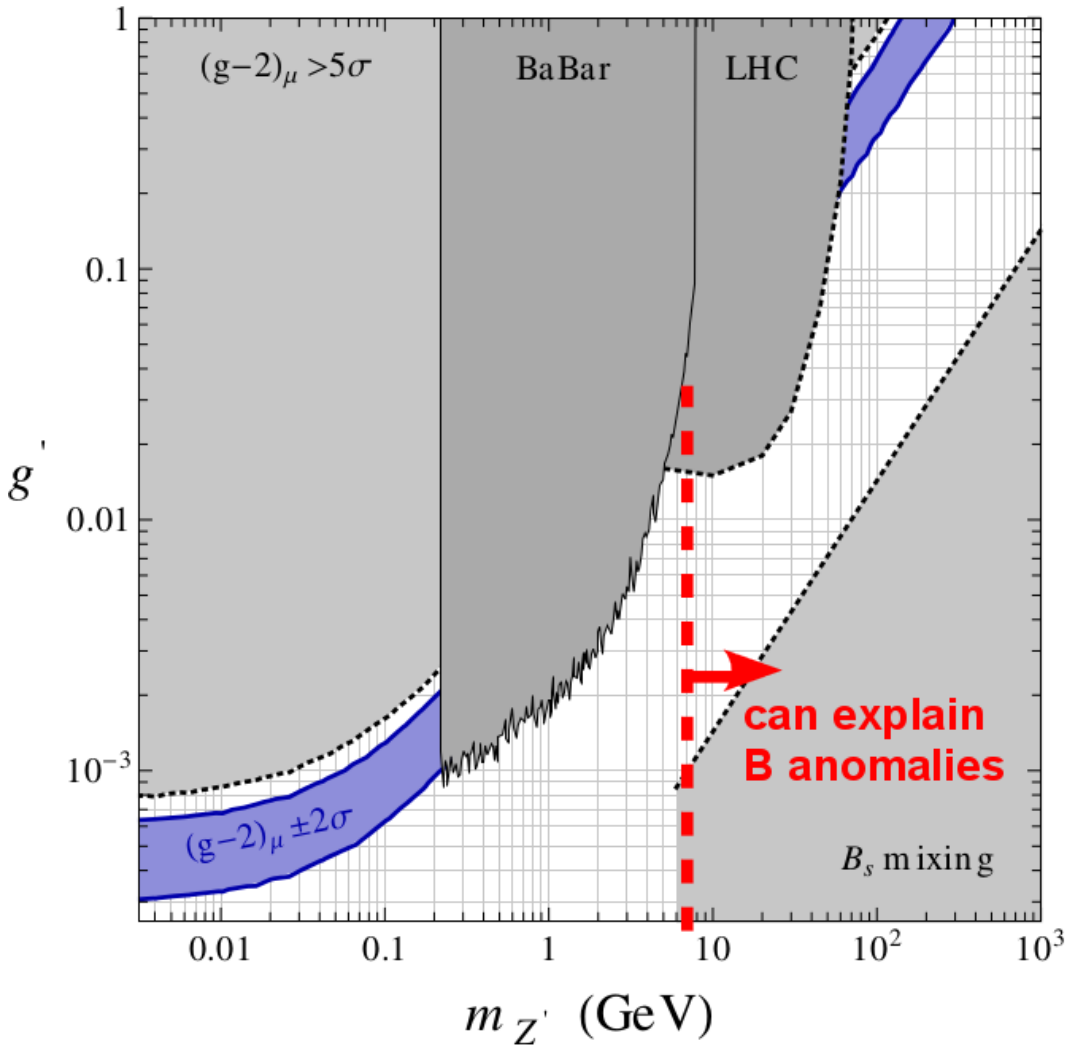
B_s mixing

WA, Gori, Pospelov, Yavin, 1406.2332



Probing the Z' Gauge Boson

muon $g-2$

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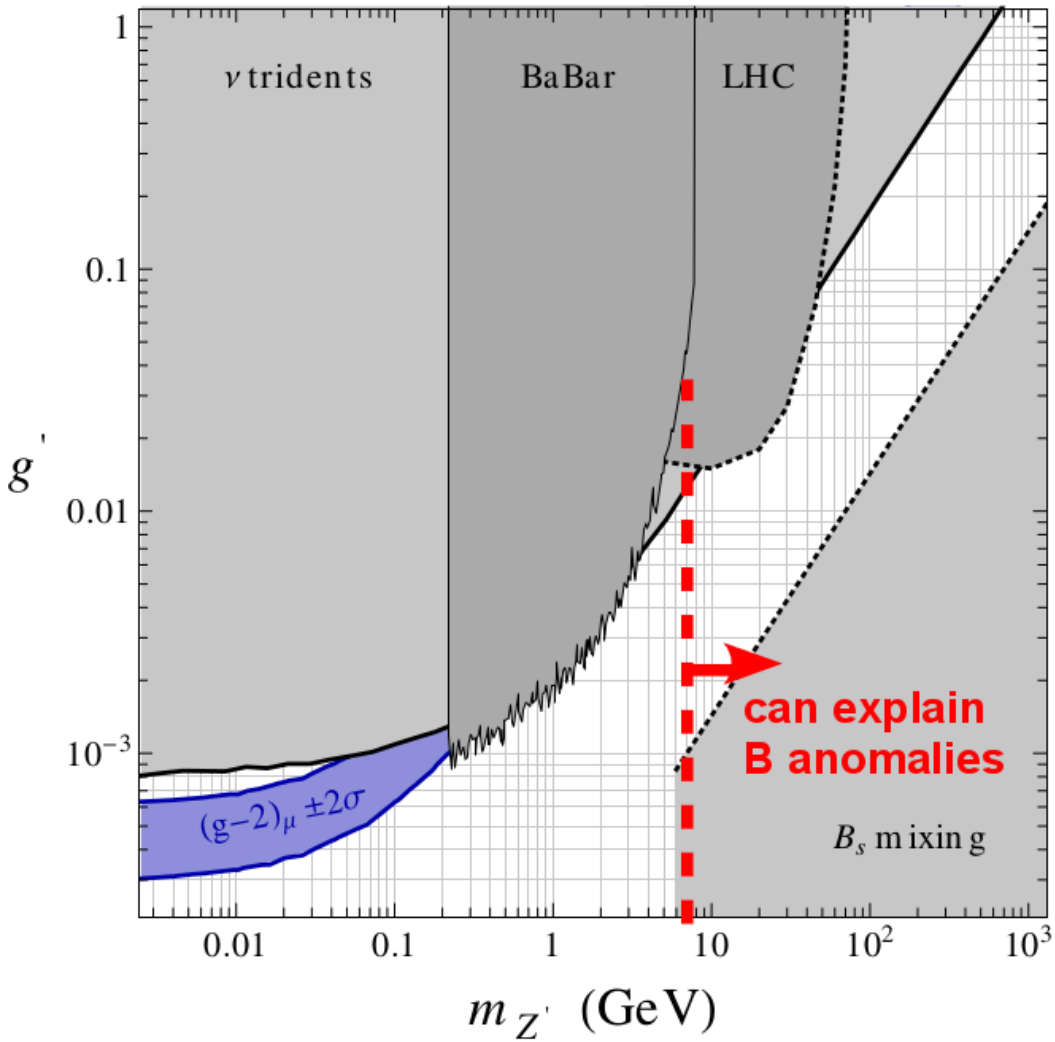
B_s mixing

neutrino tridents

WA, Gori, Pospelov, Yavin, 1406.2332



Flavor Violating Higgs Decays

Flavor Violating Higgs in the EFT

$$\mathcal{L} = Y\ \bar{\psi}\psi\ H + \frac{\tilde{Y}}{\Lambda^2}\ \bar{\psi}\psi H^3$$

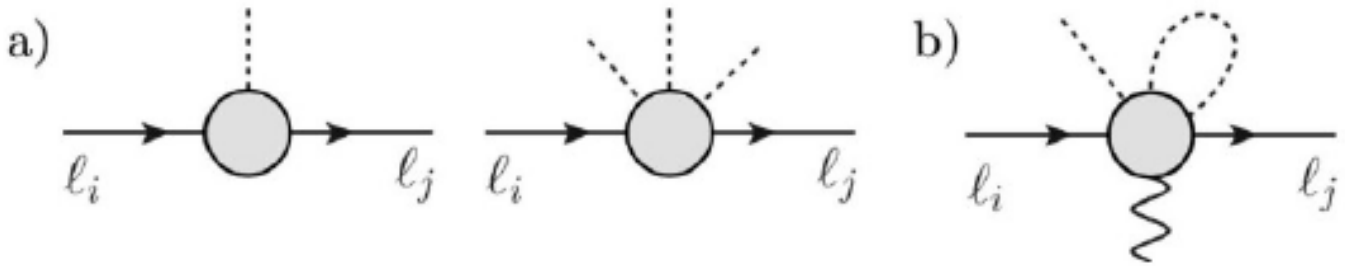
flavor violating higgs couplings if Y and $\tilde{Y}$ are not aligned

Flavor Violating Higgs in the EFT

$$\mathcal{L} = Y\ \bar{\Psi}\Psi\ H + \frac{\tilde{Y}}{\Lambda^2}\ \bar{\Psi}\Psi H^3 + \frac{c}{\Lambda^2}\ \bar{\Psi}\sigma_{\mu\nu}\Psi\ H\ F^{\mu\nu}$$

flavor violating higgs couplings if Y and $\tilde{Y}$ are not aligned

generically one also expects flavor violating dipoles at dim. 6 level



Contributions to lepton Yukawa couplings (a) , electromagnetic dipole (b)

WA, Gori, Kagan, Silvestrini, Zupan 1507.07927

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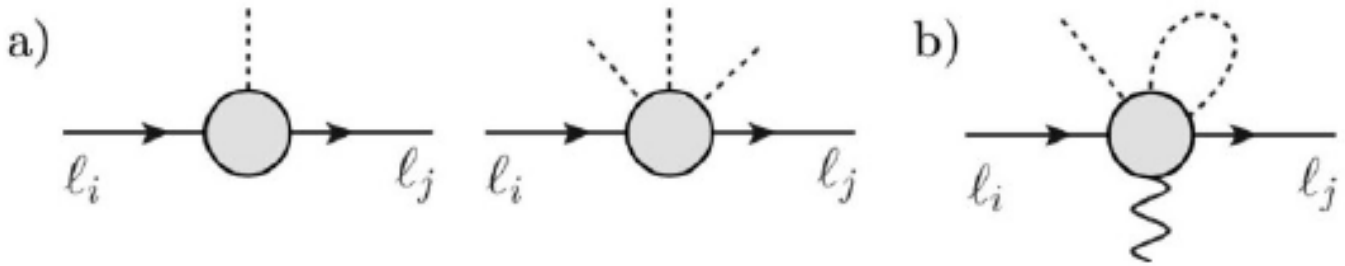
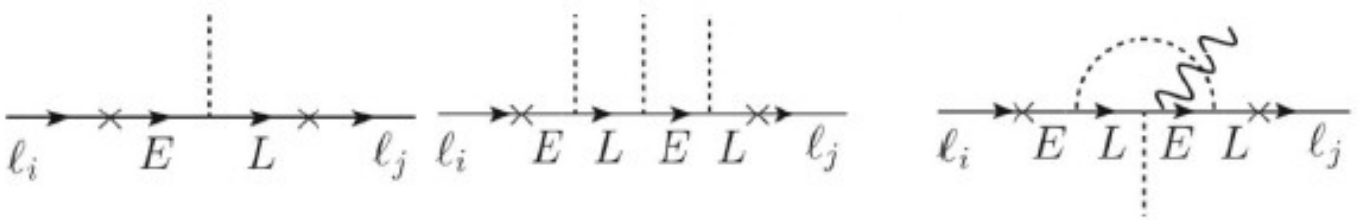


Contributions to lepton Yukawa couplings (a) , electromagnetic dipole (b)

Example for a realization:



WA, Gori, Kagan, Silvestrini, Zupan 1507.07927

"Bound" on $h \to \tau\mu$

$$\mathcal{L} = Y\ \bar{\Psi}\Psi\ H + \frac{\tilde{Y}}{\Lambda^2}\ \bar{\Psi}\Psi H^3 + \frac{c}{\Lambda^2}\ \bar{\Psi}\sigma_{\mu\nu}\Psi\ H\ F^{\mu\nu}$$

generically we expect $c \sim \tilde{Y}\frac{e}{16\pi^2}$

can derive a "generic upper bound"

$$\text{BR}(h \to \tau\mu) \sim 26 \times \text{BR}(\tau \to \mu\gamma) \lesssim 10^{-6}$$

(orders of magnitude below current and future sensitivities)

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Avoiding the Bound

Fine tune away $\tau \to \mu\gamma$

Clever model building

Additional source of EWSB / fermion masses

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$$+\frac{\tilde{Y}}{\Lambda_1^2}\ \bar{\Psi}\Psi H^3 + \frac{C}{\Lambda_2^2}\ \bar{\Psi}\sigma_{\mu\nu}\Psi\ H\ F^{\mu\nu}$$

arrange the new physics sector such that $\Lambda_1 \ll \Lambda_2$

WA, Carena, Crivellin 1604.08221

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Additional source of EWSB / fermion masses

$$\mathcal{L} = Y\ \bar{\Psi}\Psi\ H$$

$$+\tilde{Y}\ \bar{\Psi}\Psi\langle X\rangle + \frac{c}{\Lambda^2}\ \bar{\Psi}\sigma_{\mu\nu}\Psi\ H\ F^{\mu\nu}$$

can decouple the dipole

WA, Gori, Kagan, Silvestrini, Zupan 1507.07927

“Sequestered” Fermion Masses

let’s entertain the idea of a second source of fermion masses

$$\mathcal{M} = \mathcal{M}_0 + \Delta\mathcal{M}$$

- $\mathcal{M}_0$: due to the (main component of the) 125 GeV Higgs
  provides the bulk of the 3rd generation masses
- $\Delta\mathcal{M}$: due to some other source
  mainly responsible for the 1st and 2nd generation masses

WA, Gori, Kagan, Silvestrini, Zupan 1507.07927; Ghosh et al. 1508.01501; Botella et al. 1602.08011

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is easily realized in a 2HDM, if one Higgs has a rank 1 Yukawa coupling

$$\mathcal{M}_0 \simeq \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & m_\tau \end{pmatrix}, \quad \Delta\mathcal{M} \simeq \begin{pmatrix} m_e & O(m_e) & O(m_e) \\ O(m_e) & m_\mu & O(m_\mu) \\ O(m_e) & O(m_\mu) & O(m_\mu) \end{pmatrix}$$

(similar in the quark sector)

WA, Gori, Kagan, Silvestrini, Zupan 1507.07927; Ghosh et al. 1508.01501; Botella et al. 1602.08011

Flavor Violating Couplings of the Higgs

in general the fermion masses and the h couplings cannot be diagonalized simultaneously

e.g. $$\frac{y_{\mu\tau}}{y_\mu^{\rm SM}} = -\frac{\Delta\mathcal{M}_{\mu\tau}}{m_\mu}\frac{\cos(\beta-\alpha)}{\sin\beta\cos\beta}$$

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generic expectations for lepton flavor violating Higgs decays

$$\begin{aligned}
\text{BR}(h\to\tau\mu) &\sim \frac{m_\mu^2}{3m_b^2}\sim 10^{-3}\\
\text{BR}(h\to\tau e) &\sim \frac{m_e^2}{3m_b^2}\sim 10^{-7}\\
\text{BR}(h\to\mu e) &\sim \frac{m_e^2 m_\mu^2}{3m_\tau^2 m_b^2}\sim 10^{-10}
\end{aligned}$$

Additional Flavor Violating Signatures

flavor violating
rare top decays with
branching ratios as large as

$$\mathrm{BR}(t \to ch) \sim |V_{cb}|^2 \sim 10^{-3}$$

$$\mathrm{BR}(t \to uh) \sim |V_{ub}|^2 \sim 10^{-5}$$

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WA, Gori, Kagan, Silvestrini, Zupan 1507.07927 + in preparation

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lepton flavor violating
rare B meson decays
with sizable branching ratios

$$\text{BR}(B_s \to \tau\mu) \sim \text{few} \times 10^{-7}$$

$$\text{BR}(B \to K\tau\mu) \sim \text{few} \times 10^{-7}$$

$$\text{BR}(B \to K^*\tau\mu) \sim \text{few} \times 10^{-7}$$

LHCb might be sensitive
to the K^* and K rates

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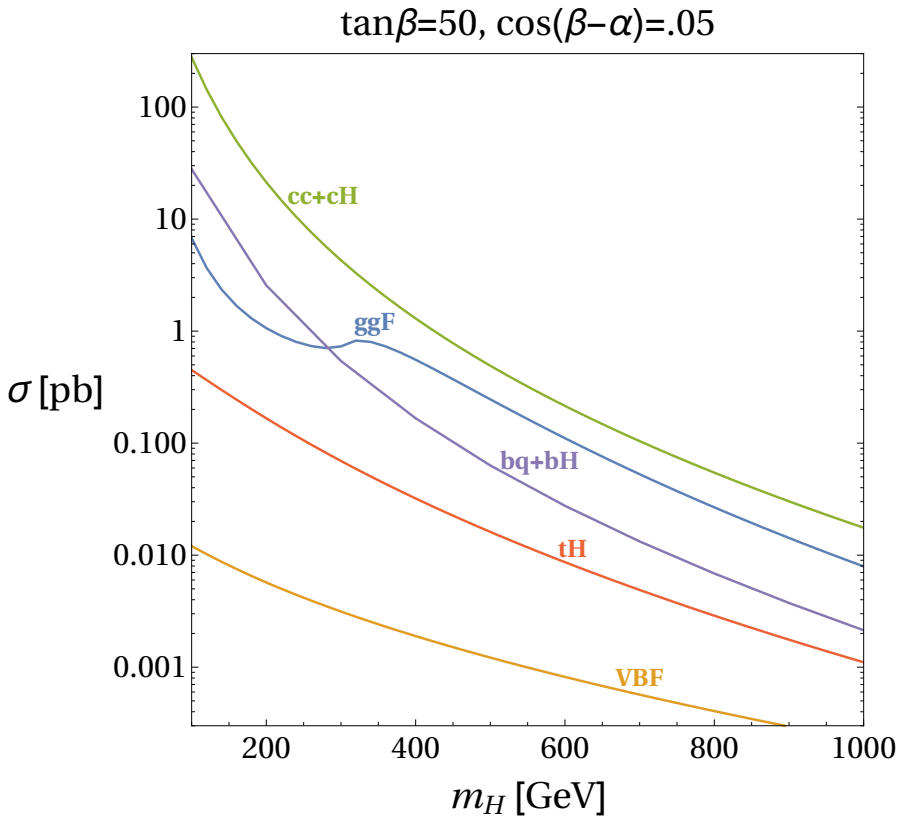
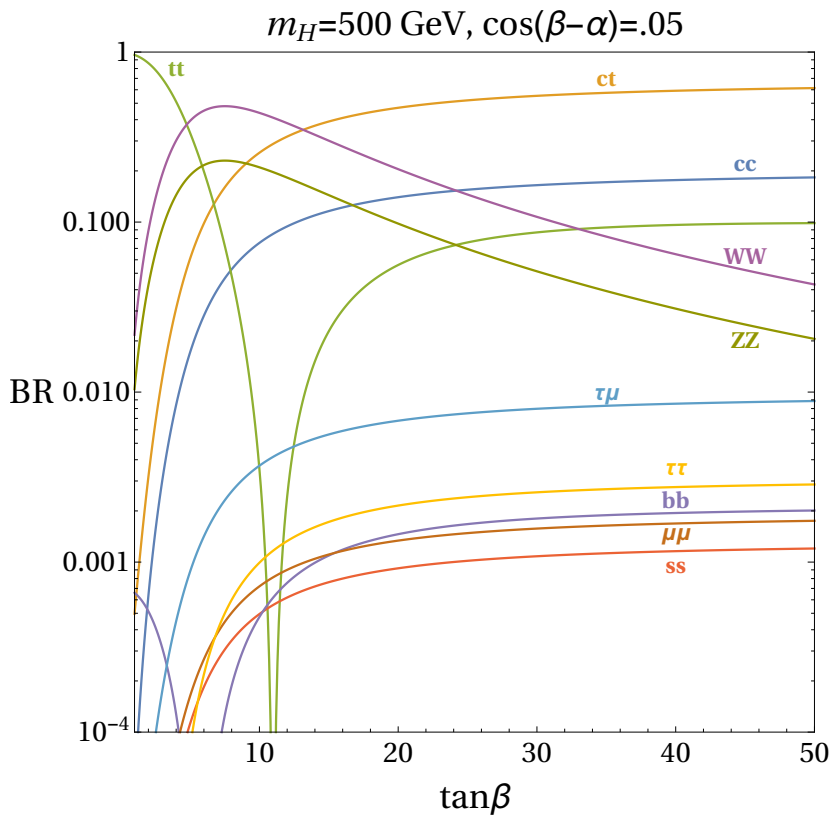
Heavy Higgs Production and Decays

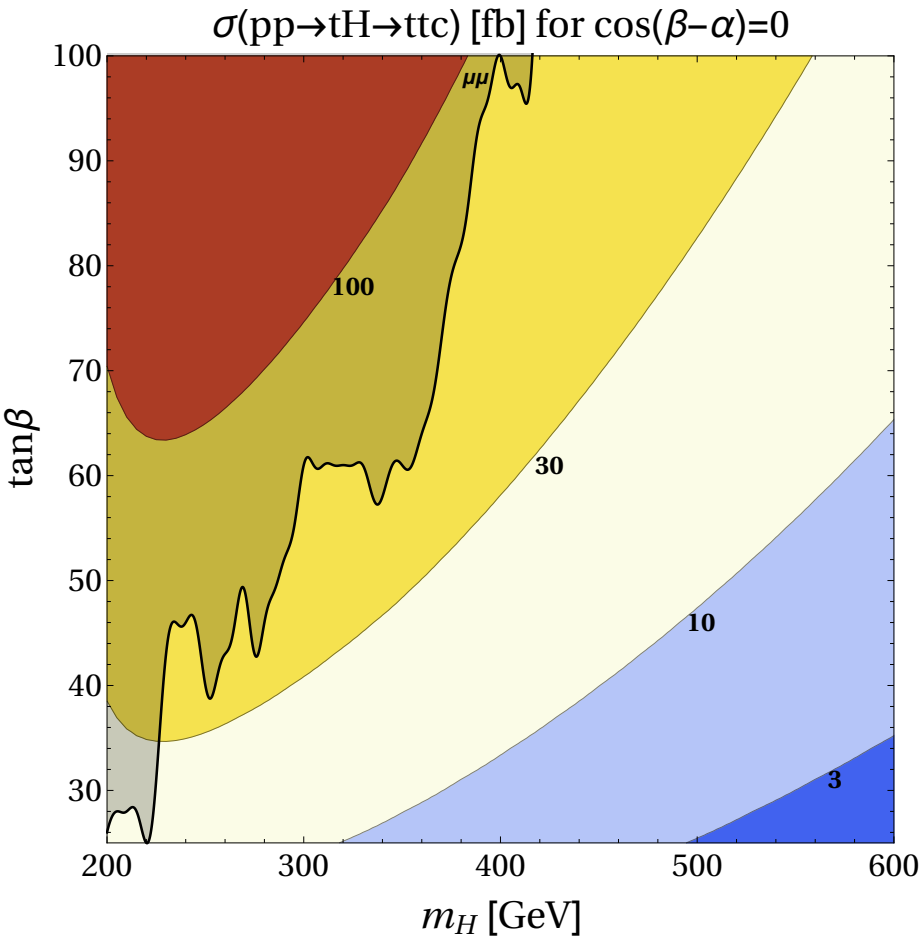
most important production and decay modes involve 2nd gen. fermions





WA, Eby, Gori, Lotito, Martone, Tuckler 1610.02398

Interesting Collider Signatures



current most stringent constraint:
di-muon resonance searches
(gray shaded region)

Interesting signatures include:

same sign tops
$pp \to tH/A \to tt\bar{c}$

di-jet resonances that are produced in association with a top
$pp \to tH/A \to tc\bar{c}$
$pp \to tH^{\pm} \to tcs$

flavor violating heavy Higgses
$pp \to H/A \to \tau\mu$

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Conclusions

- Several anomalies exist in flavor observables

  Statistical fluctuations? Hadronic uncertainties? New Physics?

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- Anomalies in rare B decays can be consistently described by New Physics in form of a four fermion contact interaction $C_9(\bar{s}\gamma_\alpha P_L b)(\bar{\mu}\gamma^\alpha \mu)$ at a scale as high as 35 TeV

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- Flavor violating Higgs decays at an observable level point to a second source of electro-weak symmetry breaking

  $\rightarrow$ a flavorful 2HDM with non-standard collider signatures