(Some title with "Flavor" and "violation" and minimal and maximal...)

Benjamín Grinstein

Aug 18, 2016

Current Themes in High Energy Physics and Cosmology

Mini-max Flavor Violation

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Current Themes in High Energy Physics and Cosmology

So far: 4 speakers, ...

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Work done with

Michele Redi and Giovani Villadoro, JHEP 1011 (2010) 067

Rodrigo Alonso and Jorge Martin-Camalich, Phys.Rev.Lett. 113 (2014) 24, 241802 (1407.7044); and 1505.05164

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$-1.$

Scale vs Conformal
(and an update on a-theorem in 6D)

Quiz

Directions: Select the best answer.

1. Which of the following is true:

A. The trace anomaly is $T^{\mu}_{\mu} = \beta_i \mathcal{O}_i$ (up to equations of motion)

B. A theory is conformal if and only if $\beta_i = 0$

C. Scale invariance does not imply conformal invariance

D. All of the above

E. None of of the above

Quiz Solutions & Explanations

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B. A theory is conformal if and only if $\beta_i = 0$ — $B_I = \beta_I - (Sg)_I = 0$

C. Scale invariance does not imply conformal invariance — Yes it does (at least perturbatively, in local, unitary, Poincare invariant QFTs)

D. All of the above

✓ E. None of the above

S is not formal gobbledygook.

In a 4D Yang-Mills, scalar+fermion theory with potential

$$V = \frac{1}{4!}\lambda_{abcd}\phi_a\phi_b\phi_c\phi_d + (\tfrac{1}{2}y_{a|ij}\phi_a\psi_i\psi_j + \text{h.c.}).$$

it first arises at 3-loops; in dim-reg (with symmetric wave-function renormalization):

$$(16\pi^2)^3 S_{ab} = \frac{5}{8}\,\text{tr}(y_a y_c^* y_d y_e^*)\lambda_{bcde} + \frac{3}{8}\,\text{tr}(y_a y_c^* y_d y_d^* y_b y_c^*) + \text{h.c.} - \{a \leftrightarrow b\}$$

Scale vs Conformal

If the current $D^\mu = x_\nu T^{\mu\nu} - V^\mu$ is conserved

and V^μ is a non-conserved current that does not depend explicitly on coordinates

then $T^\mu_\mu = \partial_\mu V^\mu \neq 0$ scale, but no conformal symmetry

This never happens for a unitary (+ Poincare invariant + no nonsense) QFT
... at least, not in Pert Th

Using EOM to expand in O_I $T^\mu_\mu = \partial_\mu V^\mu \quad \Rightarrow \quad \beta_I - (Sg)_I = (Rg)_I$

$\beta = (Qg) \; [\equiv ((S+R)g)]$ *Has RG cycles or fixed points as general solution*

On a cycle/FP $S = Q$ hence R = 0; done.

Proof: $8 B_I \partial_I \tilde{A} = \chi^g_{IJ} B_I B_J$ LHS vanishes on cycle/FP (by flavor symmetry)

$B_I = \beta_I - (Sg)_I$ $\chi^g_{IJ} B_I B_J = 0$ χ^g_{IJ} is positive definite in pert Th

Update: 6D

Weyl consistency conditions

BG, Stergiou, Stone, JHEP 1311,195 (2013), arXiv:1308.1096 [hep-th].

- 95 anomaly terms in 6D
- Explicit consistency conditions found
- Single condition emerges as candidate for *a*-theorem
- Calculation is sufficiently general: shows candidate for *a*-theorem in any (2*n*)D: it is always from relating Euler to Einstein (actually, Lovelock)

Perturbation theory: Full lowest non-trivial order renormalization

- multi-flavor scalar^3
- 2-loop computation
- 3-loop terms inferred from Weyl cc's
- no nontrivial fixed points
- *a*-increases towards IR

BG, Stergiou, Stone, Zhong, PRL 113, 231602 (2014), arXiv:1406.3626.
idem arXiv:1504.05959 [hep-th].

- 2-forms
- *a*-decreases towards IR

Osborn, Stergiou, arXiv:1501.01308.

⇒ No strong version of *a*-theorem. Weak version (compare *a* between fixed points) still possible.

0.

Lee-Wick TwoTevs

Question: Can the LWSM account for the ATLAS (CMS?) 2TeV-diboson?

Question: Can the LWSM account for the ATLAS (CMS?) 2TeV-diboson?

Answer: I don’t know.
Certainly in the expected mass range. But have not computed rates.

Magic!

Magic!

Happenings

You're going to be told lots of things.
You get told things every day that don't happen.

It doesn't seem to bother people, they don't—
It's printed in the press.
The world thinks all these things happen.
They never happened.

Everyone's so eager to get the story
Before in fact the story's there
That the world is constantly being fed
Things that haven't happened.

All I can tell you is,
It hasn't happened.
It's going to happen.

Donald Rumsfeld—Feb. 28, 2003, DoD briefing

Flavor

The Flavor Puzzle

- Why 3?
- Why *u* : *c* : *t, d* : *s* : *b, e* : ...
- Why $V_{KM} = 1$ (approx)
- but $(U_{PMNS})_{ij} = 1/\sqrt{3}$ (approx)

and more importantly

- Why have we made no progress?

An incomplete set of References

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2) Andreas Crivellin, Giancarlo D'Ambrosio, Julian Heeck. arXiv:1503.03477 [hep-ph].
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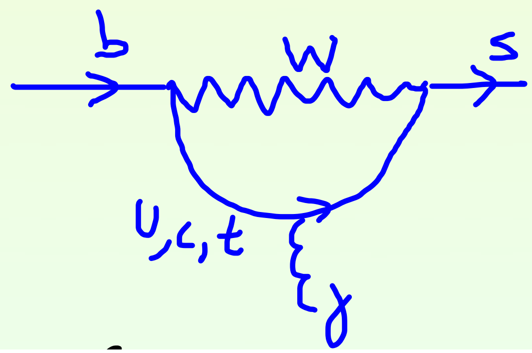
14) Andrzej J. Buras, Jennifer Girrbach-Noe, Christoph Niehoff, David M. Straub. arXiv:1409.4557 [hep-ph]. JHEP 1502 (2015) 184.
15) Andreas Crivellin. arXiv:1409.0922 [hep-ph].
16) Sanjoy Biswas, Debtosh Chowdhury, Sangeun Han, Seung J. Lee. arXiv:1409.0882 [hep-ph]. JHEP 1502 (2015) 142.
17) Diptimoy Ghosh, Marco Nardecchia, S.A. Renner. arXiv:1408.4097 [hep-ph].JHEP 1412 (2014) 131.
18) Gudrun Hiller, Martin Schmaltz. arXiv:1408.1627 [hep-ph]. Phys.Rev. D90 (2014) 5, 054014.

Rare B-meson Decays

In SM:



$$\sim \sum_{q=u,c,t} V_{qb} V_{qs}^* \, f\left(\frac{m_q^2}{M_W^2}\right)$$

- In SM:
  - Weak process (M ~ 100 GeV)
  - 1-loop suppressed
  - CKM suppressed
- Large number of processes and observables
- Pure leptonic or semi-leptonic are "reasonably well" predicted

☛ Tests of NP

Altmannshofer and Straub, 1411.3161

Examples:

$\bar{B}^0 \to \bar{K}^{*0}\gamma$

Obs.	SM pred.	measurement		pull
10^5 BR	4.21 ± 0.68	4.33 ± 0.15	HFAG	-0.2
S	-0.02 ± 0.00	-0.16 ± 0.22	HFAG	$+0.6$

$B_s \to \phi\mu^+\mu^-$

Obs.	q^2 bin	SM pred.	measurement		pull
$10^7 \frac{dBR}{dq^2}$	$[1, 6]$	0.48 ± 0.06	0.21 ± 0.15	CDF	$+1.7$
			0.23 ± 0.05	LHCb	**$+3.1$**
	$[16, 19]$	0.41 ± 0.05	0.80 ± 0.32	CDF	-1.2
			0.36 ± 0.08	LHCb	$+0.6$

$\bar{B}^0 \to \bar{K}^0\mu^+\mu^-$

Obs.	q^2 bin	SM pred.	measurement		pull
$10^8 \frac{dBR}{dq^2}$	$[0, 2]$	2.63 ± 0.49	2.45 ± 1.60	CDF	$+0.1$
	$[0.1, 2]$	2.71 ± 0.50	1.26 ± 0.56	LHCb	$+1.9$
	$[2, 4]$	2.76 ± 0.47	1.90 ± 0.53	LHCb	$+1.2$
	$[2, 4.3]$	2.77 ± 0.47	2.55 ± 1.74	CDF	$+0.1$
	$[4, 6]$	2.81 ± 0.46	1.76 ± 0.51	LHCb	$+1.5$
	$[15, 22]$	1.19 ± 0.15	0.96 ± 0.16	LHCb	$+1.1$
	$[16, 23]$	0.93 ± 0.12	0.37 ± 0.22	CDF	**$+2.2$**

$B \to X_s\gamma$

Obs.	SM pred.	measurement		pull
10^4 BR	3.15 ± 0.23	3.43 ± 0.22	HFAG	-0.9

$B_s \to \mu^+\mu^-$

Obs.	SM pred.	measurement		pull
10^9 BR	3.40 ± 0.23	2.90 ± 0.70	LHCb+CMS	$+0.7$

$B \to X_s\mu^+\mu^-$

Obs.	q^2 bin	SM pred.	measurement		pull
10^6 BR	$[1, 6]$	1.59 ± 0.11	0.72 ± 0.84	BaBar	$+1.0$
	$[14.2, 25]$	0.24 ± 0.07	0.62 ± 0.30	BaBar	-1.2

Note:

- Charmonium windows
- Improved prediction near $q^2_{\max}$

LE-EFT as parametrization

- SM described by EFT at low energies (or LE-EFT)
  (pedantic reminder: “low” is « M_W, “high” is M_W)
- Operators are Poincare and gauge invariant (QCD x EM) of dim 6
- It works pretty well ... (if you do your homework: NLL)
- Anomalies (if any) described by
  - ✳ Wilson coefficients modified w.r.t. SM
  - ✳ additional operators, absent from SM

In LE-EFT of the SM (10 operators):

SM: $$\mathcal{L}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} \sum_{p=u,c} \lambda_{ps} \left(C_1 \mathcal{O}_1^p + C_2 \mathcal{O}_2^p + \sum_{i=3}^{10} C_i \mathcal{O}_i \right)$$

Of particular interest for rare radiative decays:

$$\mathcal{O}_7 = \frac{e}{(4\pi)^2} \overline{m}_b [\bar{s}\sigma^{\mu\nu} P_R\, b] F_{\mu\nu}, \quad \mathcal{O}_9 = \frac{e^2}{(4\pi)^2} [\bar{s}\gamma_\mu P_L b][\bar{l}\gamma^\mu l], \quad \mathcal{O}_{10} = \frac{e^2}{(4\pi)^2} [\bar{s}\gamma_\mu P_L b][\bar{l}\gamma^\mu \gamma_5 l]$$

BSM include also $P_R \leftrightarrow P_L$ above, denote by adding a prime

and in addition 4 scalar and 2 tensor new operators:

$$\mathcal{O}_S^{(\prime)} = \frac{e^2}{(4\pi)^2}[\bar{s}P_{R(L)}b][\bar{l}l], \ \mathcal{O}_P^{(\prime)} = \frac{e^2}{(4\pi)^2}[\bar{s}P_{R(L)}b][\bar{l}\gamma_5 l],$$

$$\mathcal{O}_T = \frac{e^2}{(4\pi)^2}[\bar{s}\sigma_{\mu\nu}b][\bar{l}\sigma^{\mu\nu}l], \ \mathcal{O}_{T5} = \frac{e^2}{(4\pi)^2}[\bar{s}\sigma_{\mu\nu}b][\bar{l}\sigma^{\mu\nu}\gamma_5 l].$$

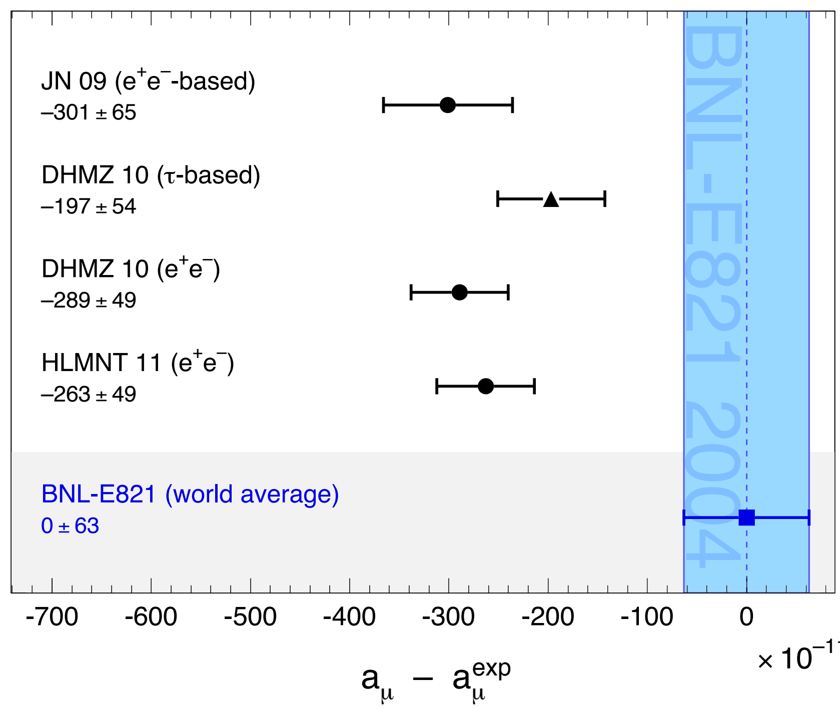

STORY
© 2009
THIS WASN T PREDICTED IN OUR MODEL — WHAT SHOULD WE DO ?
DON T SAY ANYTHING. MAYBE NO ONE WILL NOTICE.
LARGE HADRON COLLIDER
CERN
CERN

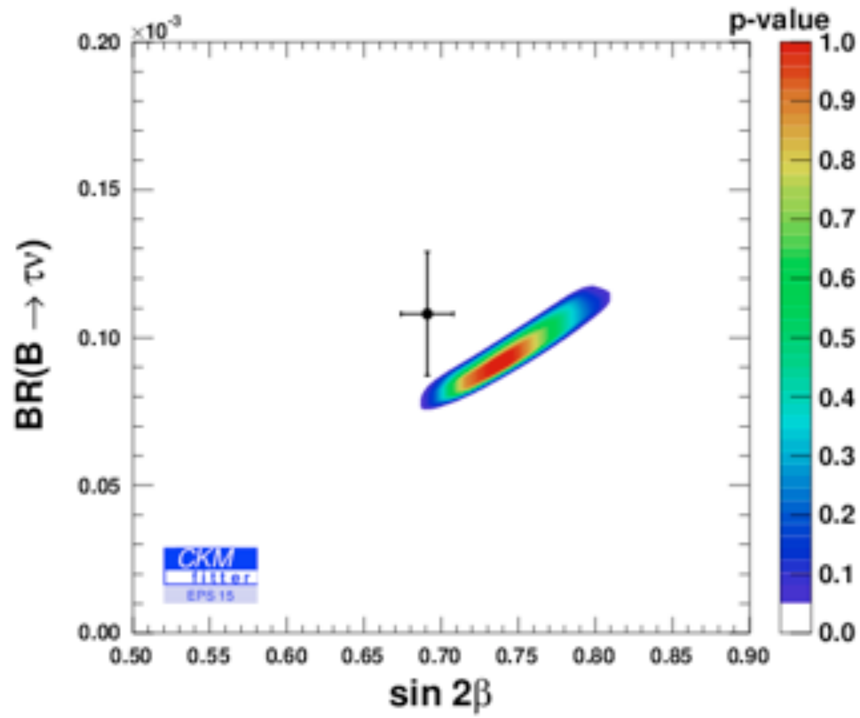
Quantity	Value	Standard Model	Pull
M_Z [GeV]	91.1876 ± 0.0021	91.1880 ± 0.0020	-0.2
Γ_Z [GeV]	2.4952 ± 0.0023	2.4955 ± 0.0009	-0.1
$\Gamma(\text{had})$ [GeV]	1.7444 ± 0.0020	1.7420 ± 0.0008	—
$\Gamma(\text{inv})$ [MeV]	499.0 ± 1.5	501.66 ± 0.05	—
$\Gamma(\ell^+\ell^-)$ [MeV]	83.984 ± 0.086	83.995 ± 0.010	—
σ_{had}[nb]	41.541 ± 0.037	41.479 ± 0.008	1.7
R_e	20.804 ± 0.050	20.740 ± 0.010	1.3
R_μ	20.785 ± 0.033	20.740 ± 0.010	1.4
R_τ	20.764 ± 0.045	20.785 ± 0.010	-0.5
R_b	0.21629 ± 0.00066	0.21576 ± 0.00003	0.8
R_c	0.1721 ± 0.0030	0.17226 ± 0.00003	-0.1
$A_{FB}^{(0,e)}$	0.0145 ± 0.0025	0.01616 ± 0.00008	-0.7
$A_{FB}^{(0,\mu)}$	0.0169 ± 0.0013		0.6
$A_{FB}^{(0,\tau)}$	0.0188 ± 0.0017		1.6
$A_{FB}^{(0,b)}$	0.0992 ± 0.0016	0.1029 ± 0.0003	-2.3
$A_{FB}^{(0,c)}$	0.0707 ± 0.0035	0.0735 ± 0.0002	-0.8
$A_{FB}^{(0,s)}$	0.0976 ± 0.0114	0.1030 ± 0.0003	-0.5
$\bar{s}_\ell^2$	0.2324 ± 0.0012	0.23155 ± 0.00005	0.7
	0.23176 ± 0.00060		0.3
	0.2297 ± 0.0010		-1.9

Conveniently ignoring?

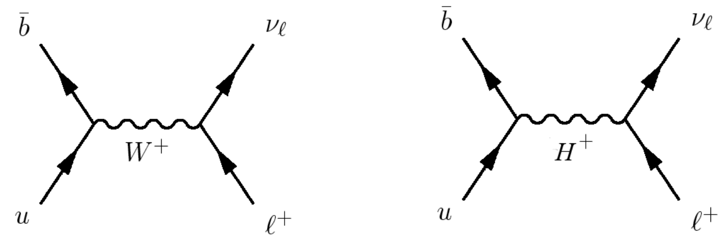
$(g\text{-}2)_\mu$

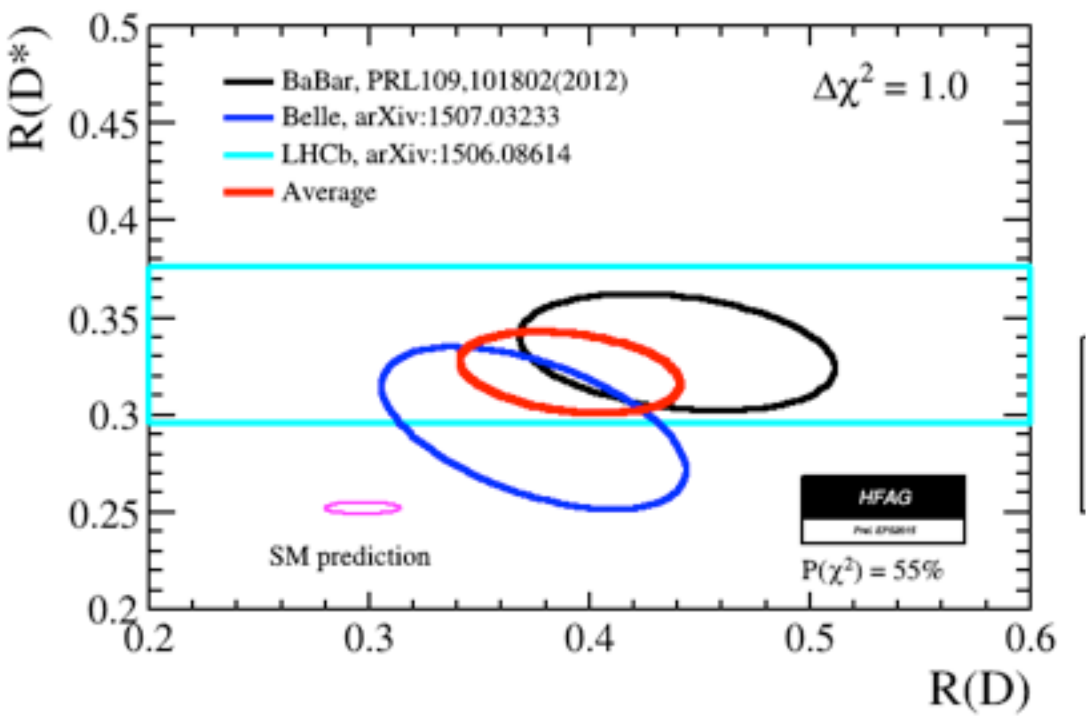
but not $(g\text{-}2)_e$





τ





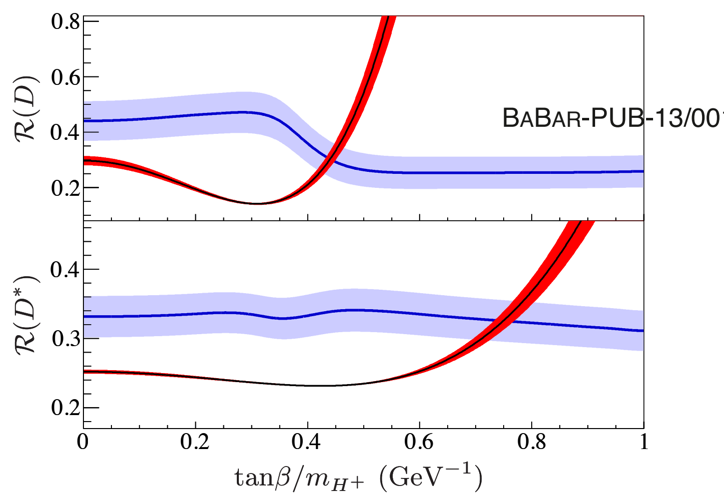
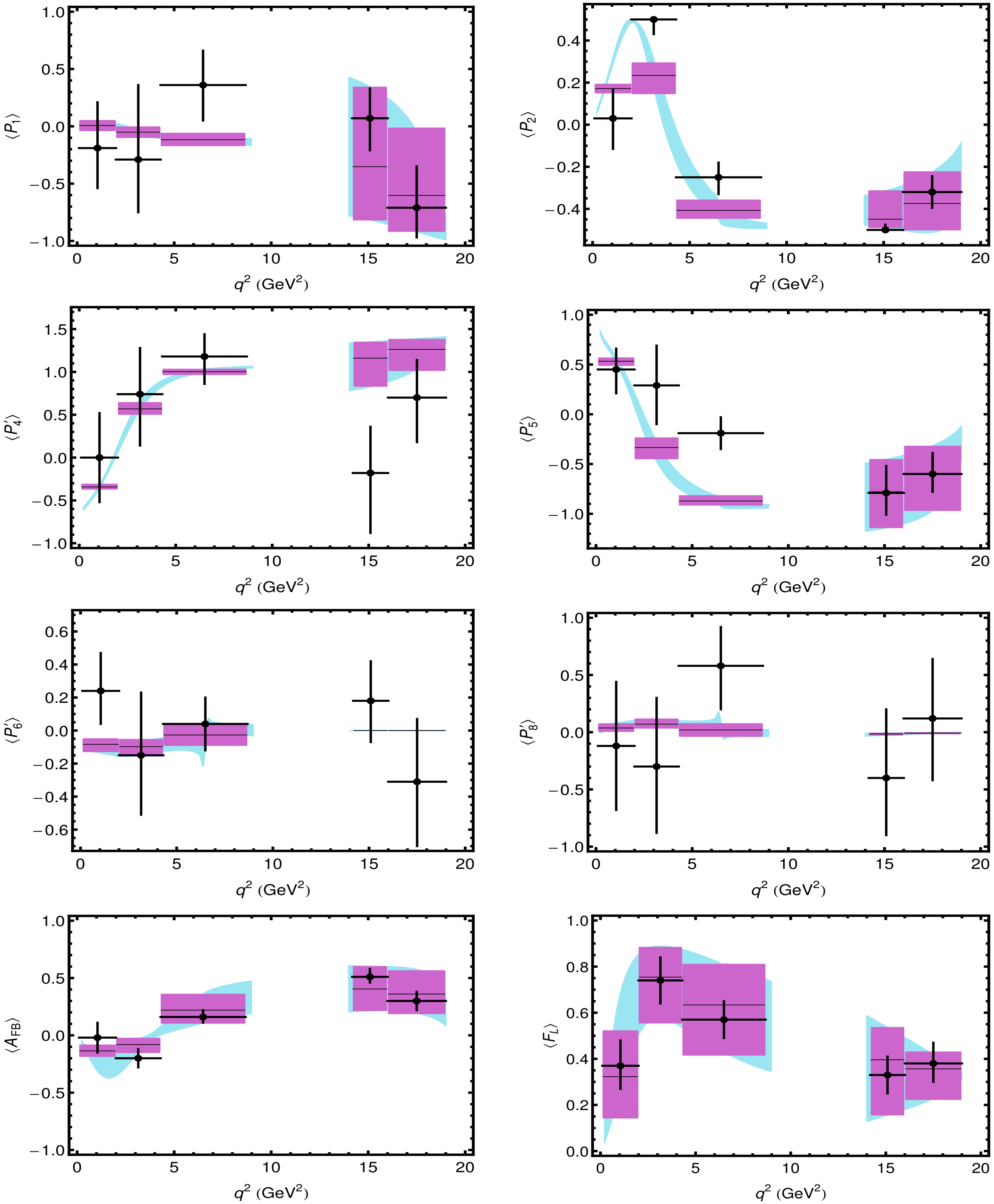


FIG. 20. (Color online). Comparison of the results of this analysis (light band, blue) with predictions that include a charged Higgs boson of type II 2HDM (dark band, red). The widths of the two bands represent the uncertainties. The SM corresponds to $\tan\beta/m_{H^+} = 0$.

$R(D^*) = BF(B \to D^* \tau \nu_\tau)/BF(B \to D^* \, l \, \nu_l)$ and $R(D) = BF(B \to D \tau \nu_\tau)/BF(B \to D \, l \, \nu_l)$.

Descotes-Genon, Matias and Virto,1307.5683
See also
Beaujean, Bobeth, and van Dyk, 1310.2478
Altmannshofer and Straub, 1411.3161 & 1308.1501
Hurth and Mahmoudi, 1312.5267
Jaeger and Martin-Camalich, 1412.3183

$$B \to K^* \mu^+ \mu^-$$



For example:

$$P_1 = \frac{-2\,\mathrm{Re}(H_V^+ H_V^{-*} + H_A^+ H_A^{-*})}{|H_V^+|^2 + |H_V^-|^2 + |H_A^+|^2 + |H_A^-|^2}$$

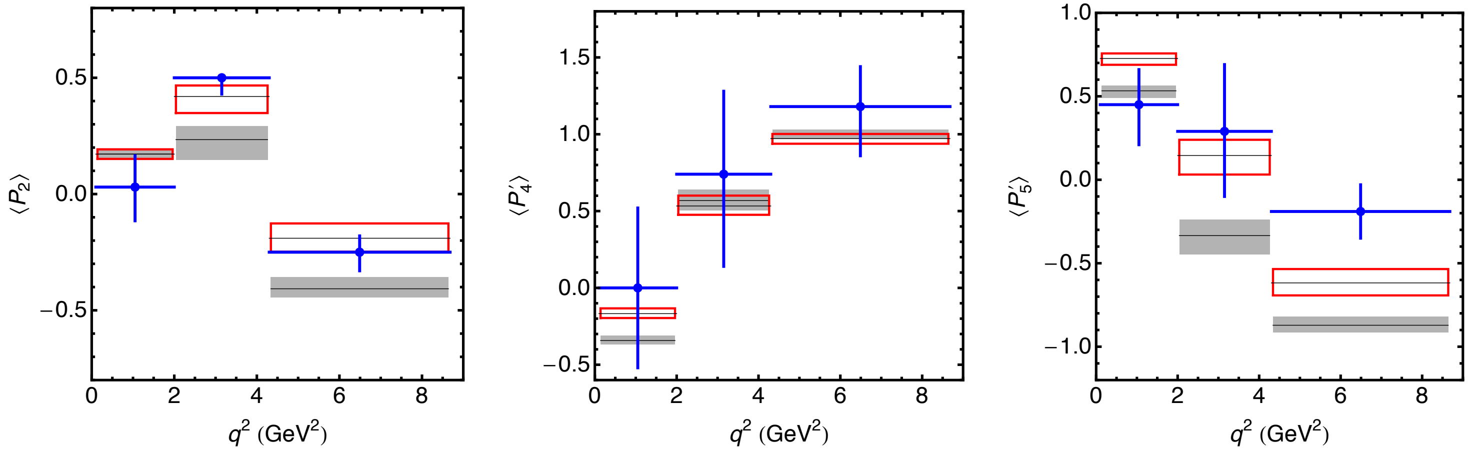
$$P_5' = \frac{\mathrm{Re}[(H_V^- - H_V^+)H_A^{0*} + (H_A^- - H_A^+)H_V^{0*}]}{\sqrt{(|H_V^0|^2 + |H_A^0|^2)(|H_V^+|^2 + |H_V^-|^2 + |H_A^+|^2 + |H_A^-|^2)}}$$

Neglect charm, use HQ/LE sym, neglect α_s

$$P_1 = 0.$$

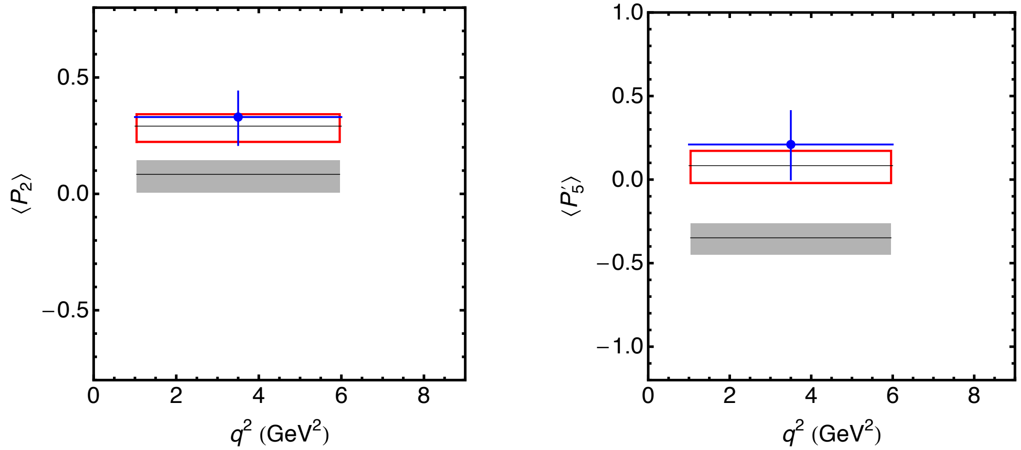
$$P_5' = \frac{\mathrm{Re}[C_{10}^* C_{9,\perp} + C_{9,\parallel}^* C_{10}]}{\sqrt{(|C_{9,\parallel}|^2 + |C_{10}|^2)(|C_{9,\perp}|^2 + |C_{10}|^2)}};$$

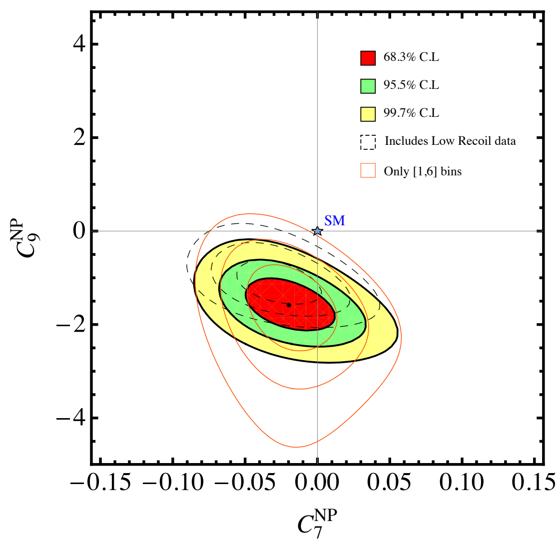
$$C_{9,\perp} = C_9^{\mathrm{eff}}(q^2) + \frac{2 m_b m_B}{q^2} C_7^{\mathrm{eff}},\ C_{9,\parallel} = C_9^{\mathrm{eff}}(q^2) + \frac{2 m_b}{m_B} C_7^{\mathrm{eff}}$$



SM

$\Delta C_9 = -1.5$





The R_K anomaly

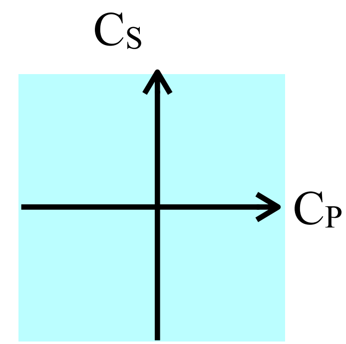
LHCb, 1406.6482

$$R_K \equiv \frac{\mathcal{B}\left(B^+ \to K^+\mu\mu\right)}{\mathcal{B}\left(B^+ \to K^+ee\right)} = 0.745^{+0.090}_{-0.074}(\text{stat}) \pm 0.036(\text{syst}).$$

q^2 in [1,6]GeV^2

SM gives 1.0 to good approximation
(you do not need a calculation, they do not need to employ you)

The Chase Begins



Model Independent approach: use LE-EFT

Problem: too many parameters,

Aha! We have seen the Higgs.

BSM: assume LE-EFT follows from HE-EFT:

assume EW-gap

+

linearized realization of EW symmetry

➥ SM + dim 6 operators

How can this matter?

In low energy (LE) EFT: Among several ops, find

$$[\bar{s}\sigma^{\mu\nu}b][\bar{e}\sigma_{\mu\nu}e] \quad \text{and} \quad [\bar{s}\sigma^{\mu\nu}b][\bar{e}\sigma_{\mu\nu}\gamma_5 e]$$

Now in full SM with heavy NP:

recall:

quarks: $q_L = 2_{\frac{1}{6}},\ u_R = 1_{\frac{2}{3}},\ d_R = 1_{-\frac{1}{3}}$

leptons: $\ell_L = 2_{-\frac{1}{2}},\ e_R = 1_{-1}$

Only gauge invariant LR combination:

$$[\bar{s}_R\sigma^{\mu\nu}q_L][\bar{\ell}_L\sigma_{\mu\nu}e_R]$$

Not only is there only one possibility (rather than 2), but in this case it vanishes!

(because $\sigma^{\mu\nu}(1-\gamma_5)\otimes\sigma_{\mu\nu}(1+\gamma_5)=0$ identically)

Full $b \to s\, l^+\, l^-$ story

With full SM symmetry, EW-gap (14 operators)

dipole like:

$$Q_{dW} = g_2(\bar{q}_s \sigma^{\mu\nu} b_R)\tau^I H\, W^I_{\mu\nu},\ \ Q_{dB} = g_1(\bar{q}_s \sigma^{\mu\nu} b_R) H B_{\mu\nu},$$

$$Q'_{dW} = g_2 H^\dagger \tau^I (\bar{s}_R \sigma^{\mu\nu} q_b) W^I_{\mu\nu},\ \ Q'_{dB} = g_1 H^\dagger (\bar{s}_R \sigma^{\mu\nu} q_b) B_{\mu\nu},$$

higgs-current

$$Q^{(1)}_{Hq} = \left(H^\dagger\, i \overleftrightarrow{D}_\mu H\right)(\bar{q}_s \gamma^\mu q_b)$$

$$Q^{(3)}_{Hq} = H^\dagger\, i(\tau^I \overrightarrow{D}_\mu - \overleftarrow{D}_\mu \tau^I) H (\bar{q}_s \tau^I \gamma^\mu q_b)$$

$$Q_{Hd} = \left(H^\dagger\, i \overleftrightarrow{D}_\mu H\right)(\bar{s}_R \gamma^\mu b_R)$$

4-fermion:

$$Q^{(1)}_{\ell q} = (\bar{\ell}\gamma_\mu \ell)(\bar{q}_s \gamma^\mu q_b),\qquad Q^{(3)}_{\ell q} = (\bar{\ell}\gamma_\mu \tau^I \ell)(\bar{q}_s \gamma^\mu \tau^I q_b),$$

$$Q_{ed} = (\bar{l}_R \gamma_\mu l_R)(\bar{s}\gamma^\mu b_R),\qquad Q_{\ell d} = (\bar{\ell}\gamma_\mu \ell)(\bar{s}\gamma^\mu b_R),$$

$$Q_{qe} = (\bar{q}_s \gamma_\mu q_b)(\bar{l}\gamma^\mu l_R),\qquad Q_{\ell edq} = (\bar{q}_s b_R)(\bar{l}_R \ell),$$

$$Q'_{\ell edq} = (\bar{\ell}\, l_R)(\bar{s}_R q_b),$$

LE-EFT coefficients given in terms of "high energy" coefficients.

Most interesting:

$$C_S^l = -C_P^l = \frac{4\pi^2}{e^2 \lambda_{ts}} \frac{v^2}{\Lambda^2} C_{\ell edq}$$

$$C_S^{l\prime} = C_P^{l\prime} = \frac{4\pi^2}{e^2 \lambda_{ts}} \frac{v^2}{\Lambda^2} C'_{\ell edq}$$

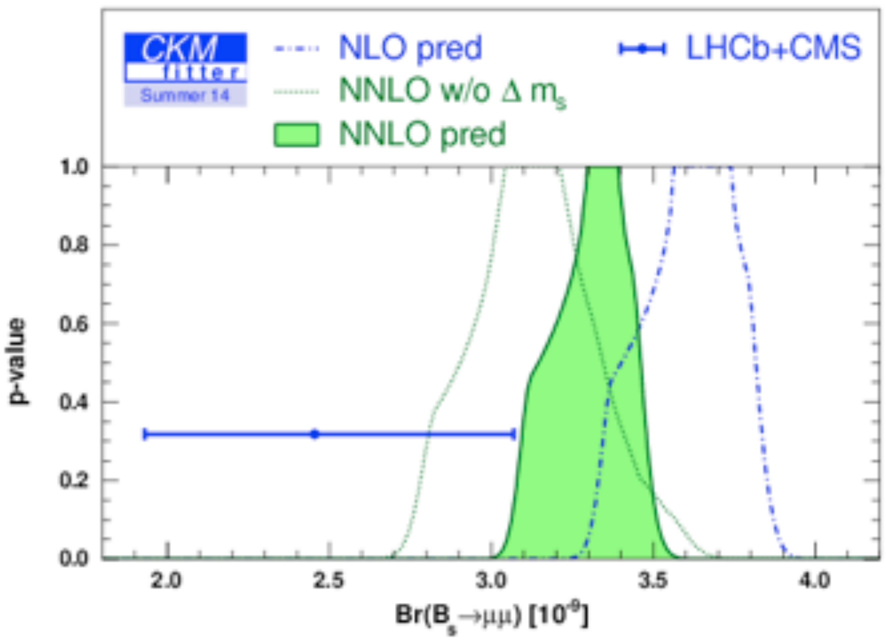
$$C_T = C_{T5} = 0$$

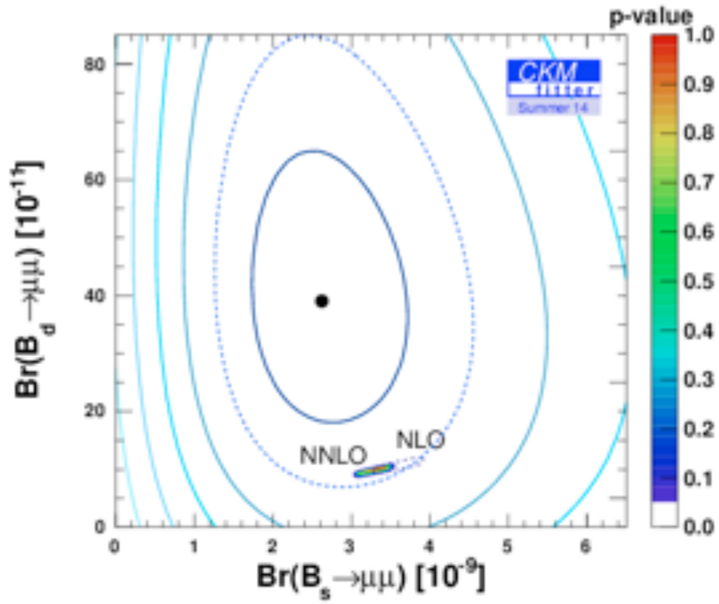
These are 6 LE-EFT-WC's in terms of 2 HE-EFT-WC's !

These are definite predictions that depend on very few assumptions:

- No new light states
- Linear realization
- Corrections of order $(M_{w,t,h} / \Lambda)^2$

$B^0_{s,d} \to l^+ l^-$



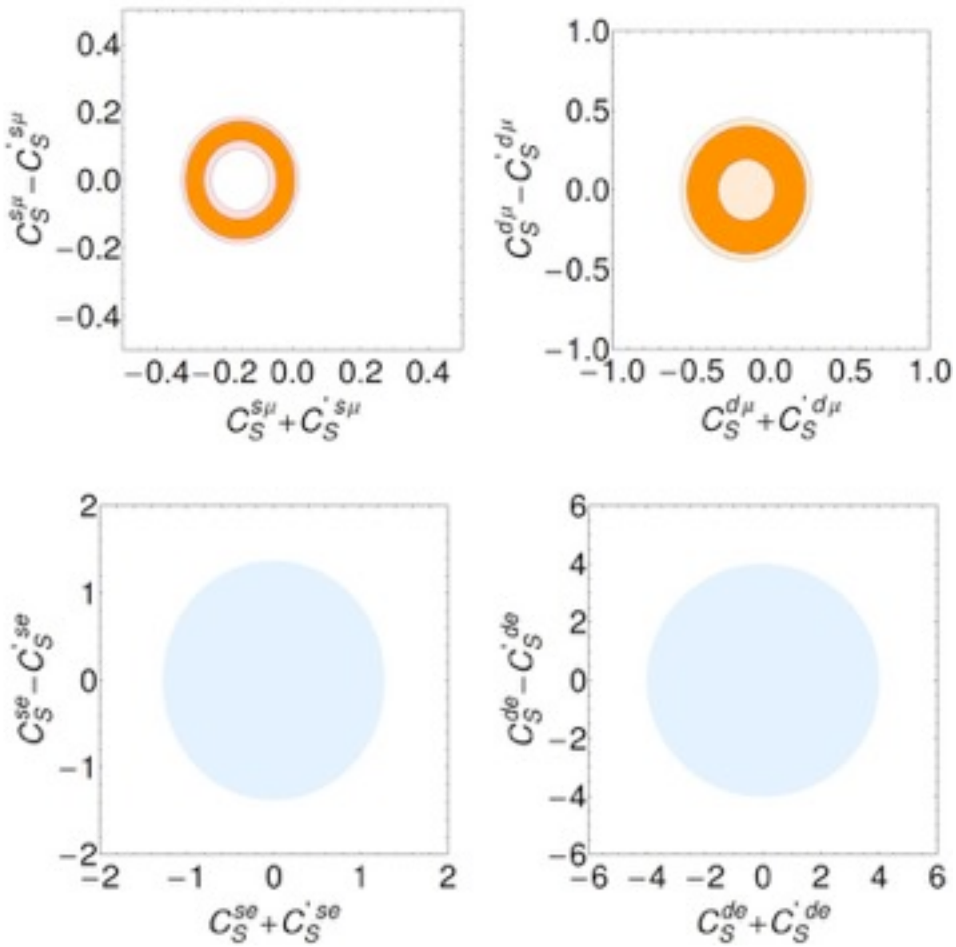


$$\frac{\overline{\mathcal{B}}_{ql}}{\left(\overline{\mathcal{B}}_{ql}\right)_{\mathrm{SM}}} = \frac{1 + \mathcal{A}^{ll}_{\Delta\Gamma}\, y_q}{1 + y_q} \left(|S|^2 + |P|^2\right),$$

$$S = \sqrt{1 - \frac{4m_l^2}{m_{B_q}^2}} \frac{C_S - C_S'}{r_{ql}}, \qquad P = \frac{C_{10} - C_{10}'}{C_{10}^{\mathrm{SM}}} + \frac{C_P - C_P'}{r_{ql}}, \qquad r_{ql} = \frac{2m_l\,(m_b + m_q)C_{10}^{SM}}{m_{B_q}^2}.$$

$$\hookrightarrow \quad \frac{C_S + C_S'}{r_{ql}}$$

$B^0_{s,d} \to l^+ l^-$



(1-σ and 3-σ)

(3-σ)

Moral: only "vector × vector" operators that contribute to R_K

R_K

$$\frac{d\Gamma}{dq^2} = \frac{G_F^2\,\alpha_e^2|\lambda_{ts}|^2\,m_B^3}{1536\pi^5}\,f_+^2\left(|C_9+C_9'+2\frac{\mathcal{T}_K}{f_+}|^2+|C_{10}+C_{10}'|^2\right)$$

$$\delta C_9^\mu - \delta C_9^e \in [-1,0], \qquad \delta C_{10}^\mu - \delta C_{10}^e \in [0,1],$$
$$\delta C_9^{\mu\prime} - \delta C_9^{e\prime} \in [-1,0], \qquad \delta C_{10}^{\mu\prime} - \delta C_{10}^{e\prime} \in [0,1].$$

P_5’

$$\delta C_9^\mu \simeq -1,$$

or for left-handed, this too:

$$\delta C_9^\mu = -\delta C_{10}^\mu \simeq -0.5,$$

Consistent with both

$$\delta C_9^\mu = -\delta C_{10}^\mu = -0.5,$$
$$\delta C_9^e = \delta C_{10}^e = 0.$$

LE-to-HE connection

$$\delta C_9 = \frac{4\pi^2}{e^2\lambda_{ti}}\frac{v^2}{\Lambda^2}\left(C_{qe}+C_{\ell q}^{(1)}+C_{\ell q}^{(3)}\right), \qquad \delta C_{10} = \frac{4\pi^2}{e^2\lambda_{ti}}\frac{v^2}{\Lambda^2}\left(C_{qe}-C_{\ell q}^{(1)}-C_{\ell q}^{(3)}\right),$$

$$\mathcal{B}(B^+\to K^+\nu\bar\nu) < 1.7\times10^{-5}$$
$$\mathcal{B}(B^0\to K^{*0}\nu\bar\nu) < 5.5\times10^{-5}$$
$$\mathcal{B}(B^+\to K^{*+}\nu\bar\nu) < 4.0\times10^{-5}$$

an order of magnitude larger than the SM

$$\mathcal{O}_\nu = \frac{e^2}{(4\pi)^2}[\bar d_i\gamma^\mu P_L b][\bar\nu\gamma^\mu(1-\gamma_5)\nu],$$

$$\delta C_\nu = \frac{4\pi^2}{e^2\lambda_{ti}}\frac{v^2}{\Lambda^2}\left(C_{\ell q}^{(1)}-C_{\ell q}^{(3)}\right)$$

eventually can nail down $C^{(1)}$ and $C^{(3)}$ separately

Flavor??? Completely model independent so far. Let’s assume ...

Minimal Flavor Violation

Minimal Flavor Violation (MFV)

Chivukula and Georgi, Phys.Lett. B188 (1987) 99
D'Ambrosio et al Nucl.Phys. B645 (2002) 155-187

- Premise: Unique source of flavor braking
- Quark sector in SM, in absence of masses has large flavor (global) symmetry:

$$G_F = SU(3)^3 \times U(1)^3$$

- In SM, symmetry is only broken by Yukawa interactions, parametrized by couplings Y_U and Y_D

$$\begin{aligned} -\mathcal{L}_{\text{Yuk}} &= H\bar{q}_L Y_U u_R + \tilde{H}\bar{q}_L Y_D d_R \\ &= \epsilon_U H\bar{q}_L \hat{Y}_U u_R + \epsilon_D \tilde{H}\bar{q}_L \hat{Y}_D d_R \end{aligned}$$

Normalize:
$$\text{tr}(\hat{Y}_U^\dagger \hat{Y}_U) = \text{tr}(\hat{Y}_D^\dagger \hat{Y}_D) = 1$$
Breaking of $U(1)_U$ characterized by ϵ_U, ϵ_D

- MFV: all breaking of G_F must transform as these
- When going to mass eigenstate basis, all mixing is parametrized by CKM and GIM is automatic
- Approach: via effective field theory: at low energies only SM fields
    - Note that many models are like this. For example, MSSM/gauge-mediation

How does this work?
Consider $K_L \to \pi\nu\bar{\nu}$

Recall, G_F breaking from: $$-\mathcal{L}_{\text{Yuk}} = \epsilon_U H \bar{q}_L \hat{Y}_U u_R + \epsilon_D \tilde{H} \bar{q}_L \hat{Y}_D d_R$$

Implications of G_F? use ***spurion*** method:

$$q_L \to e^{i\theta_q} V_L q_L \qquad \hat{Y}_U \to V_L \hat{Y}_U V_u^\dagger \qquad \epsilon_U \to e^{i(\theta_q - \theta_u)} \epsilon_U$$
$$u_R \to e^{i\theta_u} V_u u_R \qquad \hat{Y}_D \to V_L \hat{Y}_D V_d^\dagger \qquad \epsilon_D \to e^{i(\theta_q - \theta_d)} \epsilon_D$$
$$d_R \to e^{i\theta_d} V_d d_R$$

Effective Lagrangian $$\mathcal{L}_{\text{eff}} = \frac{1}{\Lambda^2} \sum C_i O_i$$

among the operators have, for example

$$O = \bar{q}_L (\hat{Y}_U \hat{Y}_U^\dagger) \gamma_\mu q_L \, \bar{\nu}_L \gamma^\mu \nu_L$$

In mass basis $$\Rightarrow \left(\sum_{q=u,c,t} V_{qs}^* V_{qd} \frac{m_q^2}{v^2} \right) \bar{s}_L \gamma_\mu d_L \, \bar{\nu}_L \gamma^\mu \nu_L$$

As needed it includes the factor

$$|V_{ts}^* V_{td}| m_t^2 / v^2 \approx A^2 \lambda^5 \approx 5 \times 10^{-4}$$

Minimal Lepton Flavor Violation
and
Lepton (non)-universality

Minimal Lepton Flavor Violation

Cirigliano et al, NPB728(2005)121, hep-ph/0507001

- Extension of MFV to lepton sector
- Need assumption on origin of neutrino masses: Dirac vs Majorana
- In charged lepton sector

$$-\mathcal{L}_{\text{Yuk}} = \epsilon_E \tilde{H} \bar{\ell}_L \hat{Y}_E e_R$$

$$G_F = SU(3)^2 \times U(1)^2$$

$$\ell_L \to e^{i\theta_\ell} V_\ell \ell_L \qquad \hat{Y}_E \to V_\ell \hat{Y}_E V_e^\dagger$$

$$e_R \to e^{i\theta_e} V_e e_R \qquad \epsilon_E \to e^{i(\theta_\ell - \theta_e)} \epsilon_E$$

- Ignoring neutrino masses (small!), a symmetry transformation

$$\hat{Y}_E \to V_\ell \hat{Y}_E V_e^\dagger = \frac{\sqrt{2}}{v|\epsilon_E|} \text{diag}(m_e, m_\mu, m_\tau)$$

- Unbroken symmetry

$$U(3)^2 \to U(1)_e \times U(1)_\mu \times U(1)_\tau$$

Flavor conservation without universality! (caveat, up to neutrino “Yukawas”)

Application: R_K anomaly.

There are claims that violation to lepton universality implies (unacceptably large) lepton flavor violation

Glashow, Guadagnoli & Lane, PRL114, 091801 (2015)

With MLFV lepton flavor violation is controlled by neutrino "Yukawas" (much as in SM+neutrinos) while lepton universality violation is controlled by charged lepton Yukawas

4-fermion operators inducing $b \to sll$

Alonso, BG, Martin Camalich, arXiv:1505.05164

$$Q_{\ell q}^{(1)} = (\bar{q}\gamma^\mu q_L)(\bar{\ell}\gamma_\mu \ell_L) \qquad Q_{\ell q}^{(3)} = (\bar{q}\vec{\tau}\gamma^\mu q_L)\cdot(\bar{\ell}\vec{\tau}\gamma_\mu \ell_L)$$

$$Q_{\ell d} = (\bar{d}\gamma^\mu d_R)(\bar{\ell}\gamma_\mu \ell_L) \qquad Q_{qe} = (\bar{q}\gamma_\mu q_L)(\bar{e}\gamma^\mu e_R)$$

$$Q_{ed} = (\bar{d}_R\gamma^\mu d_R)(\bar{e}\gamma_\mu e_R) \qquad Q_{\ell edq} = (\bar{\ell}_L e_R)(\bar{d}_R q) + \text{h.c.}$$

Coefficients constrained by MFV+MFLV

$$C_{\ell q}^{(1)} = c_{\ell q}^{(1)}\, \hat{Y}_u\hat{Y}_u^\dagger \otimes \hat{Y}_e\hat{Y}_e^\dagger, \qquad C_{\ell q}^{(3)} = c_{\ell q}^{(3)}\, \hat{Y}_u\hat{Y}_u^\dagger \otimes \hat{Y}_e\hat{Y}_e^\dagger,$$

$$C_{qe} = c_{qe}\, \hat{Y}_u\hat{Y}_u^\dagger \otimes \hat{Y}_e^\dagger\hat{Y}_e, \qquad C_{\ell edq} = c_{\ell eqd}\, \varepsilon_e\varepsilon_d^*\, \hat{Y}_d^\dagger\hat{Y}_u\hat{Y}_u^\dagger \otimes \hat{Y}_e.$$

Lessons: 1. Scalar operator additionally suppressed! 2. Prediction: τ-enhancement:

$$\overline{\mathcal{B}}_{s\tau} \simeq 1\times 10^{-3}, \qquad \mathcal{B}(B\to K\tau^-\tau^+) \simeq 2\times 10^{-4},$$

Enhancement shows up in b →sνν too. This sets $\left(C_q^{(1)} - C_q^{(3)}\right)_{sb} \lesssim 0.03\, \left(C_q^{(1)} + C_q^{(3)}\right)_{sb}$

looks fine tuned, but appears naturally in models

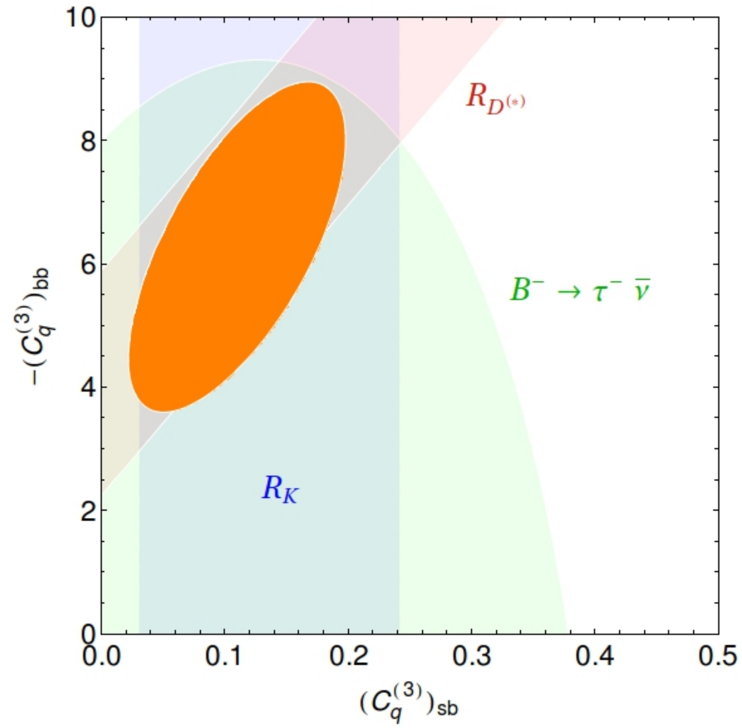
Charged currents too!: $Q_{\ell q}^{(3)} = (\bar{q}\vec{\tau}\gamma^\mu q_L)\cdot(\bar{\ell}\vec{\tau}\gamma_\mu \ell_L)$ $\Leftrightarrow$ $b \to c\tau\nu$

So consider $\mathcal{L}^{\rm NP} = \frac{1}{\Lambda^2}\left[(\bar{q}_L C_q^{(1)}\gamma^\mu q_L)(\bar{\ell}_L F(\hat{Y}_e\hat{Y}_e^\dagger)\gamma_\mu \ell_L) + (\bar{q}_L C_q^{(3)}\gamma^\mu\vec{\tau} q_L)\cdot(\bar{\ell}_L F(\hat{Y}_e\hat{Y}_e^\dagger)\gamma_\mu\vec{\tau}\ell_L)\right]$

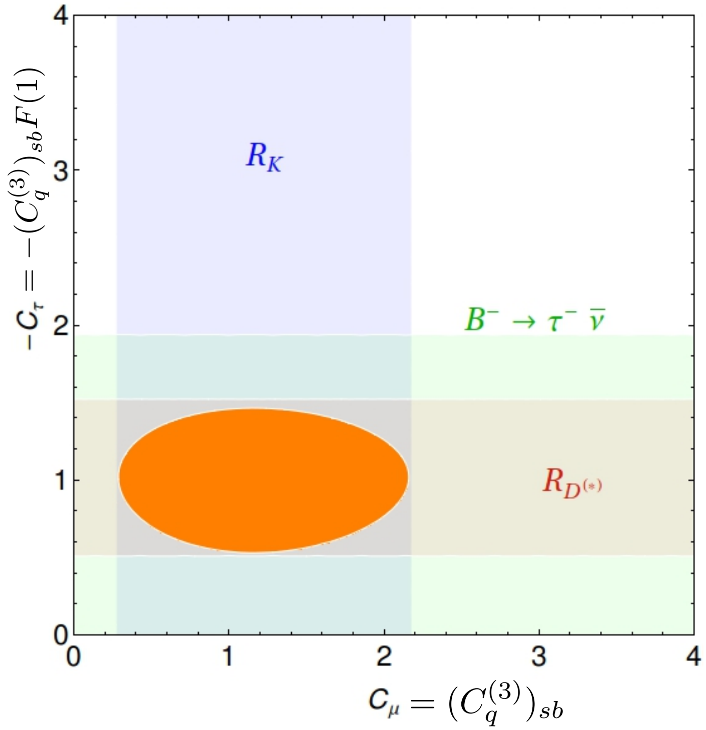
with $F'(1) = 1, F(1) = f$

Need **τ** charged current $= 0.16 * V_{cb} = -\frac{v^2}{\Lambda^2}\left(V_{cs}(C_q^{(3)})_{sb} + V_{cb}(C_q^{(3)})_{bb}\right) f$

$F = \hat{Y}_e\hat{Y}_e^\dagger \quad \Lambda = 1\ \mathrm{TeV}$



$\Lambda = 3\ \mathrm{TeV} \qquad (C_q^{(3)})_{bb} \ll 1$



Comments

1. Surely wrong. At least one anomaly will go away (Feynman?)
2. Easy to include MFV on quark sector too
3. Can produce this EFT from integrating out leptoquarks.
   i. Need MFV fields Extended to leptons)
   ii. Classify all models (scalars and vectors):
      - Get relations between CWs
      - One stands out: vector, $SU(2)_W$-singlet, Y = 2/3, $SU(3)_c$-fundamental

Arnold, Pospelov, Trott & Wise, 0911.2225
BG, Kagan, Trott & Zupan, 1102.3374 & 1108.4027

Gauging Flavor

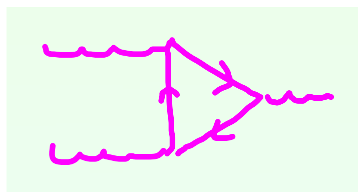
Issues

- Black holes: No global symmetry (other than accidental) (... "why have we made no progress")
- If we insist: how do we make sense of transforming Yukawas?
  - Spurions: VEVs of fields:

    under $G_F = SU(3)_q \times SU(3)_u \times SU(3)_d$ introduce new fields

    $$Y_U = (\bar{3}, 3, 1)$$
    $$Y_D = (\bar{3}, 1, 3)$$

    and Yukawa coupling constants are $\langle Y_U \rangle, \langle Y_D \rangle,$
  - New Problems
    1. Goldstone' s theorem ⇒ 8+8+8 Nambu-Goldstone Bosons ⇒ FCNC disaster
    2. Renormalizability? $H\bar{q}_L Y_U u_R, \tilde{H}\bar{q}_L Y_D d_R,$ are operators of dimension 5
- Solution to problem 1: gauge G_F
  - New Problems:
    i. Anomalies: G_F^3 and $G_F^2 \times U(1)_Y$
    ii. Invisibility (high scale): next slide
    iii. Renormalizability (problem 2) still

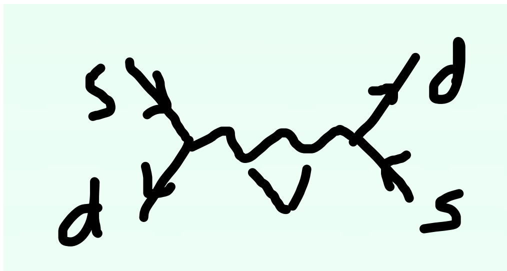


“Invisibility”

Massive vector bosons mediate FCNC

Masses: $$M_V \sim g\langle Y_{U,D}\rangle$$

K^0-mixing:



$$\sim \frac{1}{\langle Y_{U,D}\rangle^2}(\bar{s}d)(\bar{s}d)$$

$$\Rightarrow \langle Y_{U,D}\rangle \gtrsim 10^5 \text{ TeV}$$

And this is for the light generations. Expect much higher scales for heavy generations!

Hence “invisible.”

And then a miracle happens...

The minimal anomaly free extension of the SM gives

1. Renormalizable couplings

2. Inverted hierarchy $$M_V \sim \frac{1}{y_{U,D}}$$

where $y_{\rm U,D}$ are the usual Yukawa couplings

so that if $M_V \sim 10^5$ TeV for mediators among light generations, we can have

$$M_V \sim \frac{m_u}{m_t} 10^5 \text{ TeV} \sim \text{few TeV}$$

for mediators among heaviest generations

I am going to show you a model as a table of fields and their transformation properties

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When I see this in talks it induces this response

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When I see this in talks it induces this response

I promise it is not so bad...

The Model

	$SU(3)_{Q_L}$	$SU(3)_{U_R}$	$SU(3)_{D_R}$	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$
Q_L	3	1	1	3	2	1/6
U_R	1	3	1	3	1	2/3
D_R	1	1	3	3	1	-1/3
Ψ_{uR}	3	1	1	3	1	2/3
Ψ_{dR}	3	1	1	3	1	-1/3
Ψ_u	1	3	1	3	1	2/3
Ψ_d	1	1	3	3	1	-1/3
Y_u	$\overline{3}$	3	1	1	1	0
Y_d	$\overline{3}$	1	3	1	1	0
H	1	1	1	1	2	1/2

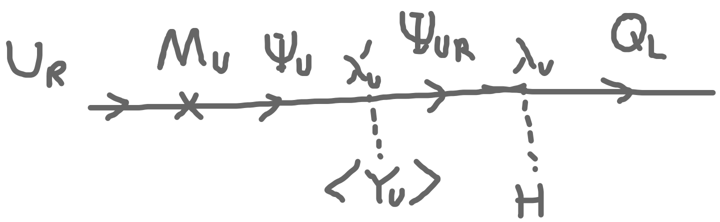
$$\begin{aligned}\mathcal{L} =&\mathcal{L}_{kin} - V(Y_u, Y_d, H)+ \\ &\big(\lambda_u \overline{Q}_L \tilde{H} \Psi_{uR} + \lambda'_u \overline{\Psi}_u Y_u \Psi_{uR} + M_u \overline{\Psi}_u U_R + \\ &\lambda_d \overline{Q}_L H \Psi_{dR} + \lambda'_d \overline{\Psi}_d Y_d \Psi_{dR} + M_d \overline{\Psi}_d D_R + h.c.\big)\ ,\end{aligned}$$

Note: all λ's and M's are 1×1 matrices

$$\mathcal{L} = \mathcal{L}_{kin} - V(Y_u, Y_d, H) + \left(\lambda_u \overline{Q}_L \tilde{H} \Psi_{uR} + \lambda'_u \overline{\Psi}_u Y_u \Psi_{uR} + M_u \overline{\Psi}_u U_R + \lambda_d \overline{Q}_L H \Psi_{dR} + \lambda'_d \overline{\Psi}_d Y_d \Psi_{dR} + M_d \overline{\Psi}_d D_R + h.c.\right),$$

For example:

With $Y_{u,d} \gg M_{u,d}$ get see-saw:



$$\Rightarrow \quad y_u = \frac{\lambda_u M_u}{\lambda'_u \langle Y_u \rangle}$$

and similarly $y_d = \dfrac{\lambda_d M_d}{\lambda'_d \langle Y_d \rangle}$

But still $M_V \sim g \langle Y_{u,d} \rangle \quad \Rightarrow \quad M_V \sim \dfrac{1}{y_{u,d}}$

1st generation flavor change $\Leftrightarrow$ heaviest vectors

3rd generation $\Leftrightarrow$ lightest, light enough for LHC?

Example

Choose

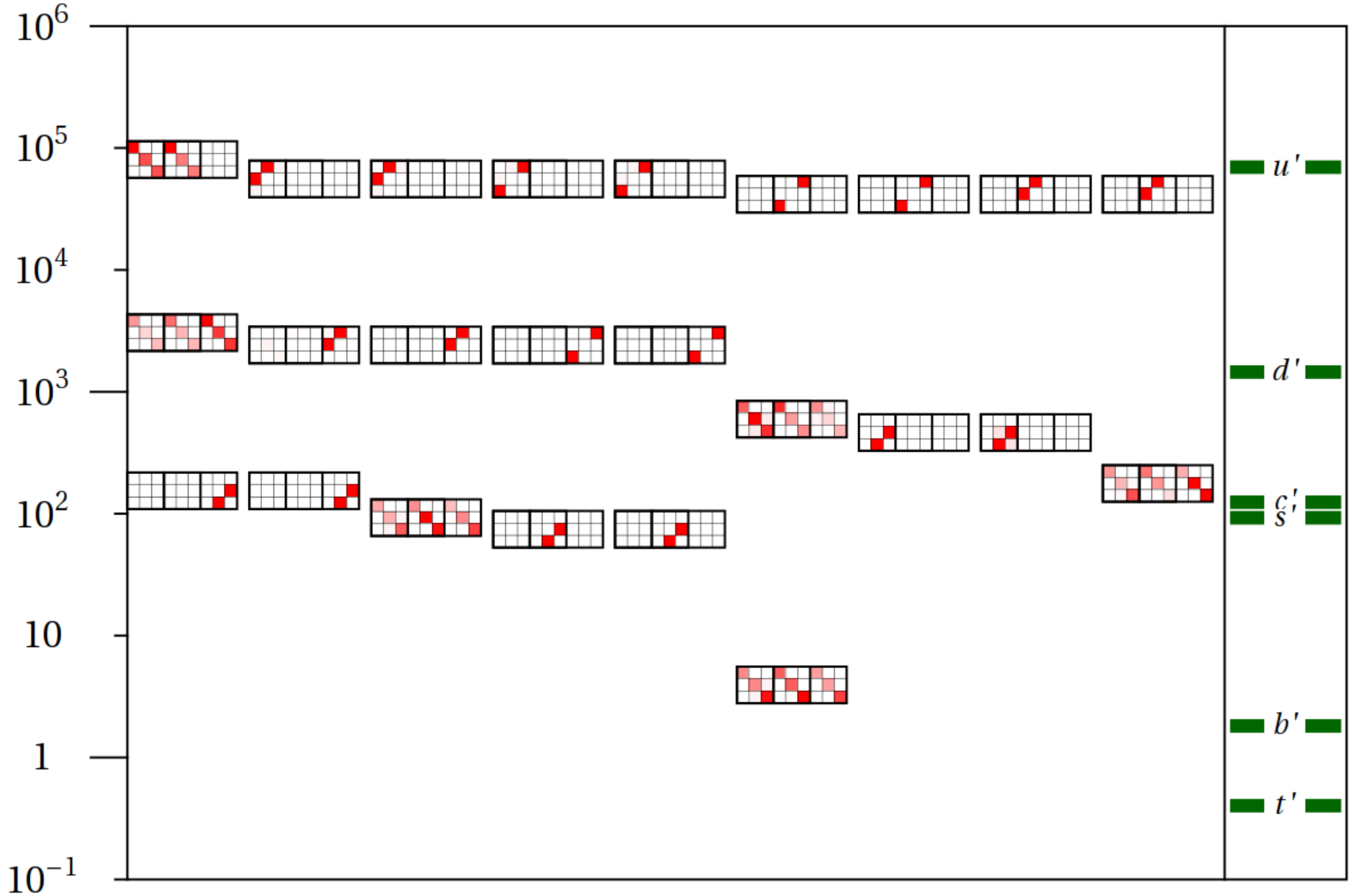
M_u (GeV)	M_d (GeV)	λ_u	λ'_u	λ_d	λ'_d	g_Q	g_U	g_D
400	100	1	0.5	0.25	0.3	0.4	0.3	0.5

Compute

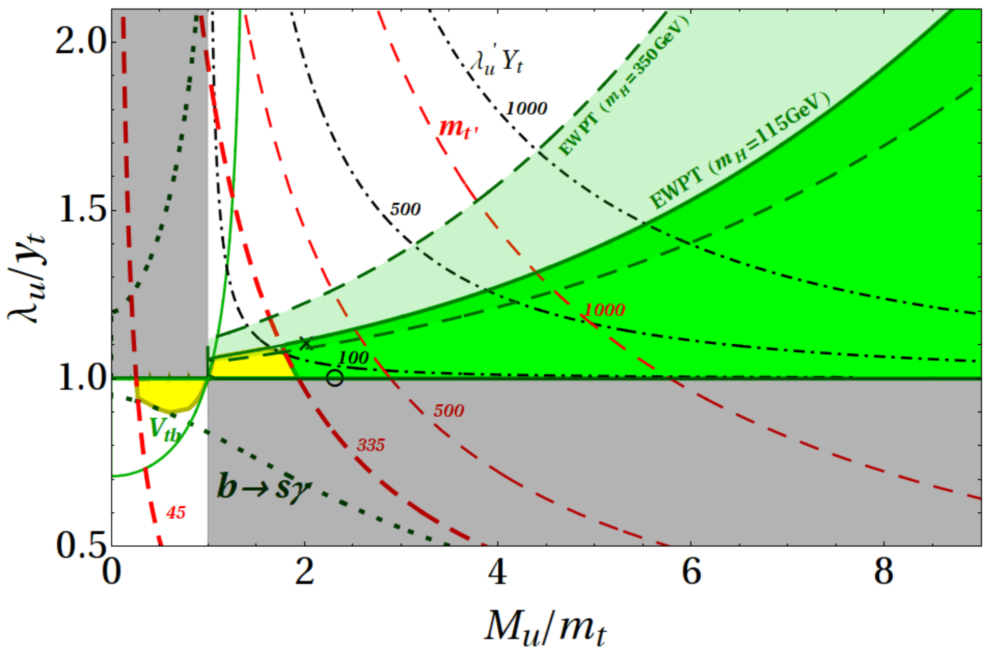
$$Y_u \approx \text{Diag}\left(1 \cdot 10^5\,,\ 2 \cdot 10^2\,,\ 8 \cdot 10^{-2}\right) \cdot V\ \text{TeV}\,,$$

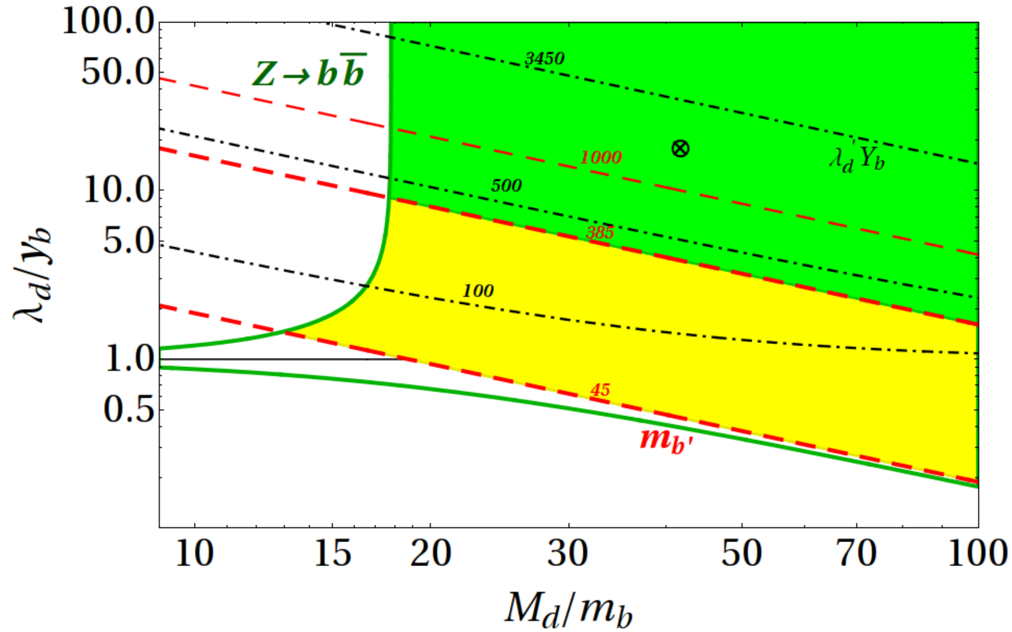
$$Y_d \approx \text{Diag}\left(5 \cdot 10^3\,,\ 3 \cdot 10^2\,,\ 6\right)\ \text{TeV}\,,$$

Spectrum:



Excluded/allowed regions of parameter space





Dirty laundry:

Can minimizing a G_F-invariant potential give the desired values of Yukawas?
See: R. Alonso et al, JHEP 1311 (2013) 187 arXiv:1306.5927

Orbit of enhanced symmetry are always extrema.
So the natural outcome would be not fully broken G_F.

Example: SU(3) with scalar field in adjoint, A. Two independent invariants, Tr(A^2) and det(A)

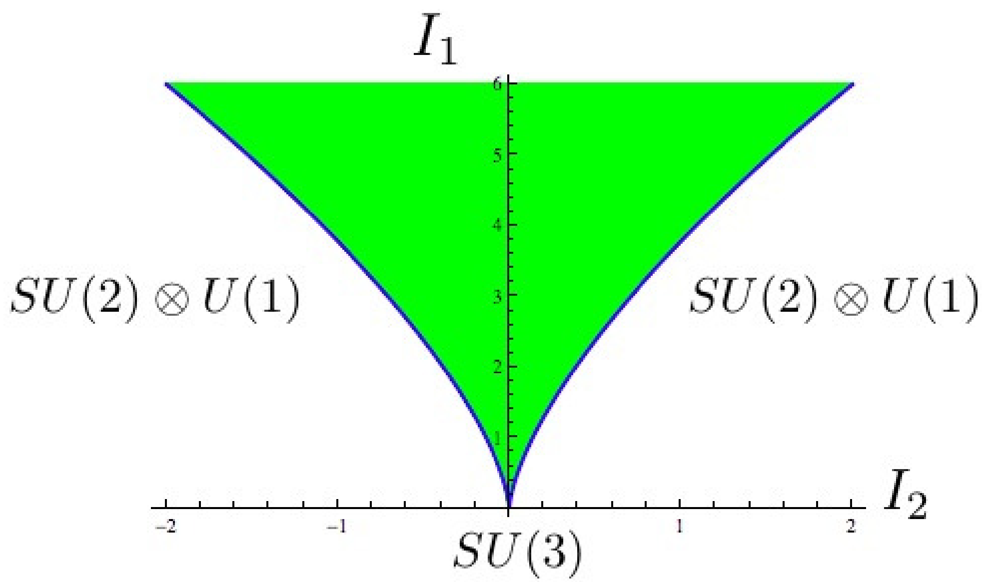


Figure 1: Manifold $\mathcal{M}$ of the $SU(3)$ invariants constructed from x=octet=hermitian, 3×3, traceless matrix (green region). Each point of $\mathcal{M}$ represents the orbit of x, namely the set of points in octet space given by: $x_g = gxg^{-1}$, when g runs over $SU(3)$. Boundaries of $\mathcal{M}$ are represented by Eq. (3.1). The little groups of the elements of different boundaries are indicated.

Take Home

- Flavor anomalies:
  - Several different processes
  - Several observed by N > 1 experiments
  - Several persistent
  - All involve leptons
  - Suggestive pattern: the heavier the lepton, the larger the anomaly
- Fit
  - Assuming linearized HE-EFT, few operators (modulo flavor)
  - Flavor can be incorproated to limit further opertaors
    - MFV+MLFV works well
- Gauged Flavor
  - Neat for quarks
  - Can it explain anomalies in gauged LF case? Ongoing (w R Alonso)

The End