Future of Flavor

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Workshop on High Energy Physics Phenomenology
WHEPP XIV
4th -13th December, 2015
Indian Institute of Technology
Kanpur, India

The Flavor Puzzle

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

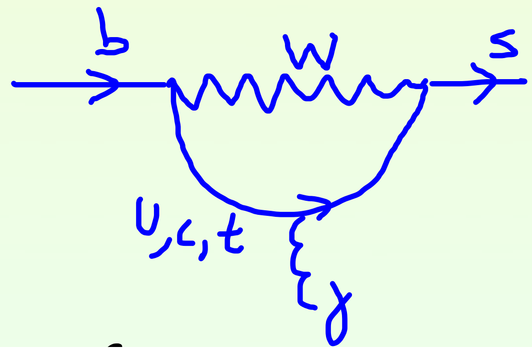
and more importantly

- Why have we made no progress?

Flavor:
why we care
(according to Mr Pragmatic)

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

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	$\mathbf{+3.1}$
	$[16, 19]$	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	$\mathbf{+2.2}$

$B \to X_s\gamma$

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 $q^2_{\max}$

Future of Flavor THEORY

? ? ?

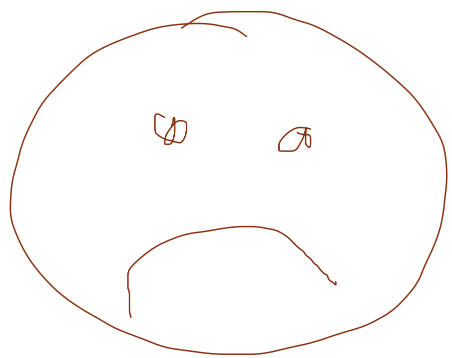
- Future of calculations
- Future of phenomenology
- Theory : prospects for answering anything

Future of ...

Computations:

Theme: will lattice dominate?

WILL THE REST OF US BECOME COMPLETELY IRRELEVANT?



ANSWER: YES/MAYBE/NO, IT DEPENDS

it depends... on → what questions you ask

→ what methods you employ

e.g.

π, K, D, B decay constants f_π, f_K, f_D, f_B

LATTICE ✓✓✓

~~QCD SUM RULES~~

~~POTENTIAL MODELS (NR, or rel)~~

~~NJL MODELS~~

So the "what" (f_X) is coupled to the "how" !

ρ, K^*, D^*, B^* decay constants

LATTICE ✓ ✗ ?

QCD SUM RULES ✓

POTENTIAL MODELS ✓

NOTES:

1. WHY CARE?
   → section 2 (pheno)

2. Lattice difficulties from fundamentals: no "states", fictitious.

Exacerbated for $B^{***\cdots}$

(and more obviously a fiction)

moving on

$$\langle 0 | J^\mu | M \rangle$$

form factors

$$\langle M' | J^\mu | M \rangle$$

. . .

LATTICE ✓✓✓

~~QCD SUM RULES~~

~~POTENTIAL MODELS (NR, or rel)~~

~~NJL MODELS~~

⋮

ISGW, HQET, ...

Caveat emptor

"lattice" calculations often piggyback on non-lattice work:

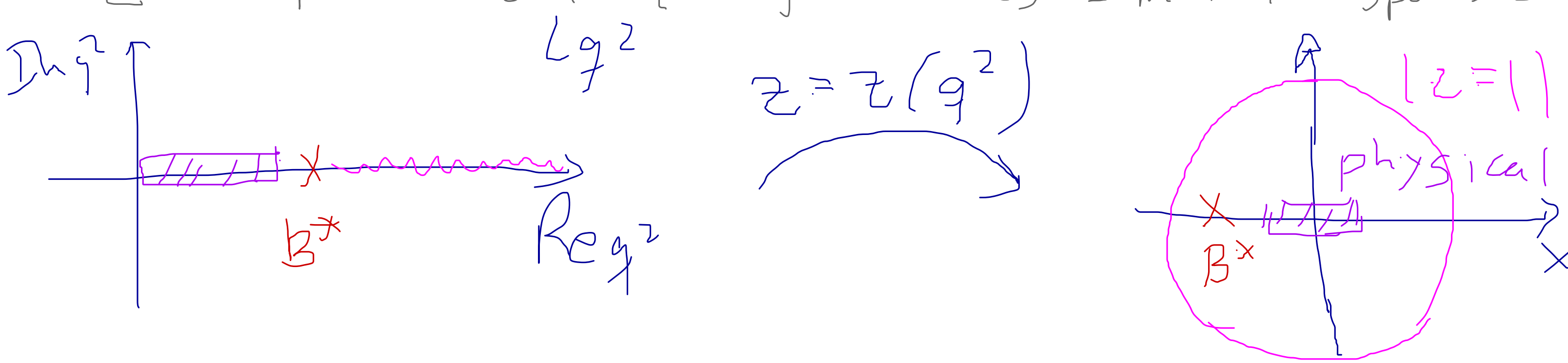
there may be life after lattice!

Examples:

- z-expansion (awful name, I'm not responsible)

$B \to \pi \underbrace{\ell \nu}$

inv mass $= q^2$



- HQET, NRET, χPT for extrapolations/interpolations

(eg m_b from interpolating between $m_Q = m_c$ & $m_Q = \infty$)

chain $0 \to 1 \to 2 \to 3 \to$ cohomology?

☆ Unlikely lattice can go much beyond 3 bodies

lattice can and will clean up CPV (2 body decays)

Long term. Guaranteed employment...

☆ Virtually impossible for lattice to do inclusive decay rates

eg $\Gamma(B\to X_u \ell \nu) = \Gamma(B\to\pi\ell\nu) + \Gamma(B\to\pi\pi\ell\nu) + \Gamma(B\to K\bar{K}\ell\nu) + \cdots$

but (depending on case) good control analytically

and lattice could help: ME's of ops in OPE (currently extracted from experiment)

Other calculations?

- Rates
- Angular distributions
- Wilson coefficients
- ...

We know how to do these

Will be done as accuracy demands it.

Future of ...

Phenomenology

30 years of + 60 yrs of Kaon physics....

- $B\bar{B}$ mixing
- $b \to (u \text{ or } c)\, l\nu$ .. (tree level) :
- $b \to s\gamma$, $b \to sll$ (loop, "rare")
- $B \to M_1 M_2$ CPV

Is there anything new?

What is left to do?

Surprisingly the answers are yes and yes.

From "new" leave out X, Y, Z:

fascinating QCD, not flavor

... and other such.

Future $\longrightarrow$ Full distributions in

e.g., $d\Gamma(B \to K^{(*)} \mu\mu)$.

Eventually want $\mu\mu$ replaced by $\tau\tau$, $\nu\nu$, even ee

Future: CPV in $b \to s\gamma$ & $b \to s\ell\ell$

Future: we'll be creative, explore new avenues to get to the physics.

Ex: $B_s^* \to e^+e^-$ $\quad B_s^* \to \mu^+\mu^-$

Why? These are $b \to s\, \ell^+\ell^-$,

as in $B \to K^{(*)}\ell^+\ell^-$ and $B_s \to \ell^+\ell^-$

$B_s \to \ell^+\ell^-$ is chirality supressed, $\mathcal{A}mp \sim m_\ell C_{10}$

(recall $\mathcal{H}_{eff} \propto G_F V_{tb} V_{ts}^* [\bar{s}_L \gamma^\mu b_L][C_9\, \bar{e}\, \gamma_\mu e + C_{10}\, \bar{e}\, \gamma_\mu \gamma_5 e]$)

Now $B_s^* \to B_s \gamma$ 100% of the time, but $B_r(B_s^* \to \ell\ell) \approx 10^{-11}$

(similar to $B^0 \to \mu^+\mu^-$)

Direct exploration of short distance flavor physics

Connections between short & long distances

"short" $\sim \frac{1}{v_{ew}}$ "long" $\sim \frac{1}{m_K \sim m_B}$

Picture: mutually exclusive

$SU(2)_W \times U(1)_Y$ LINEAR realization

← · most common
· focus on this
· if excluded, most interesting

LIGHT D.O.F.s

$SU(2)_W \times U(1)_Y$ non-LINEAR (strong EWB)

LowEnergy-EFT as parametrization

- SM described by EFT at low energies (or LE-EFT) (or “Fermi theory”) (pedantic reminder: “low” is ≪ M_W, “high” is M_W)
- Operators are Lorentz 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:

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

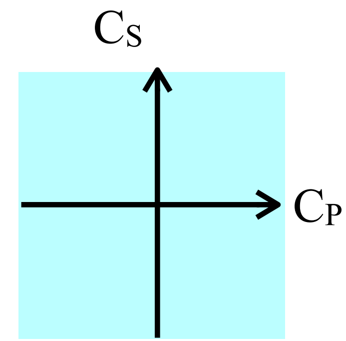
BSM include also $P_R \leftrightarrow P_L$ above, denote by adding a prime

and in addition 4 scalar and 2 tensor new operators:

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

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

Example: $b \to s\, l^+ l^-$



Model Independent approach: use LE-EFT

Problem: too many parameters,

Aha! We have seen the Higgs.

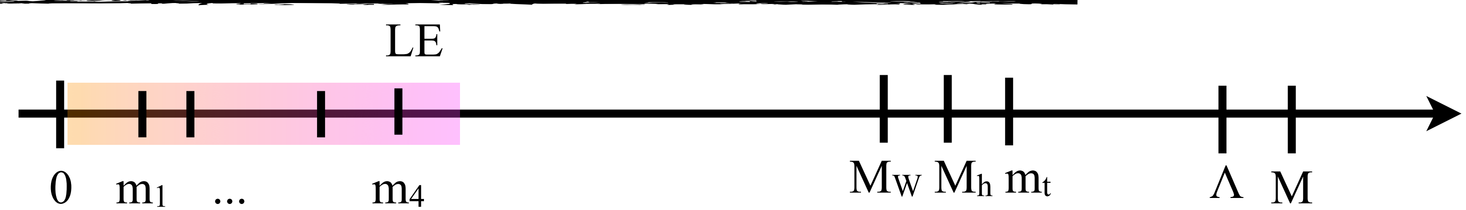
BSM: assume LE-EFT follows from HE-EFT:

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:

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

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

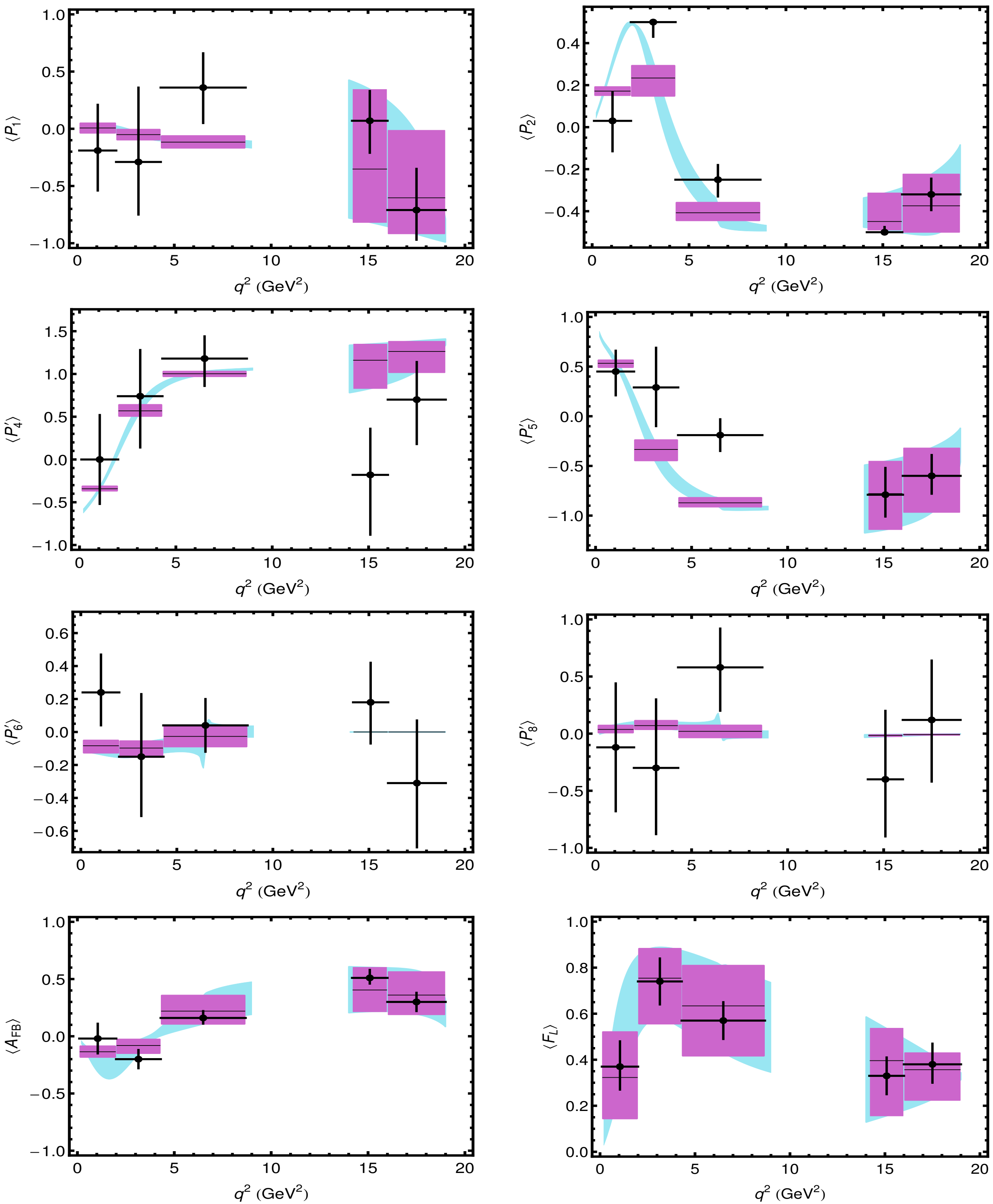
$$C_T = C_{T5} = 0$$

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 $(M_{w,t,h} / \Lambda)^2$


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



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

and many more (apologies)

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

For example:

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

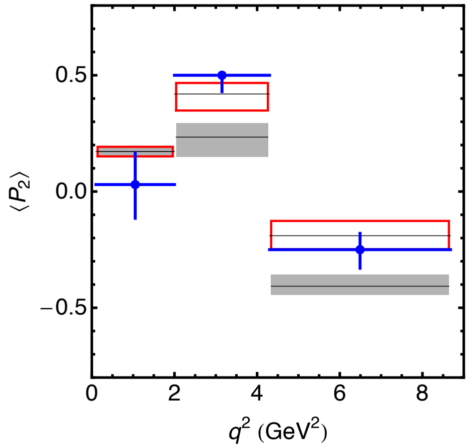
$$P_5' = \frac{\mathrm{Re}[(H_V^- - H_V^+)H_A^{0*} + (H_A^- - H_A^+)H_V^{0*}]}{\sqrt{(|H_V^0|^2 + |H_A^0|^2)(|H_V^+|^2 + |H_V^-|^2 + |H_A^+|^2 + |H_A^-|^2)}}$$

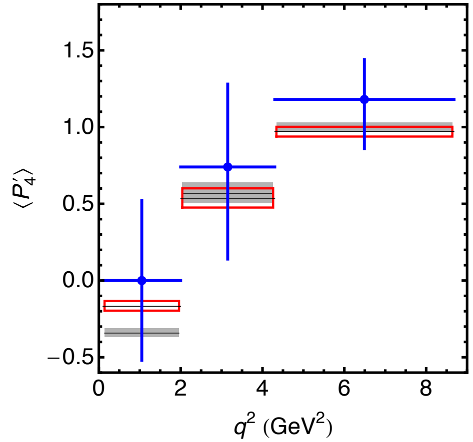
Neglect charm, use HQ/LE sym, neglect α_s

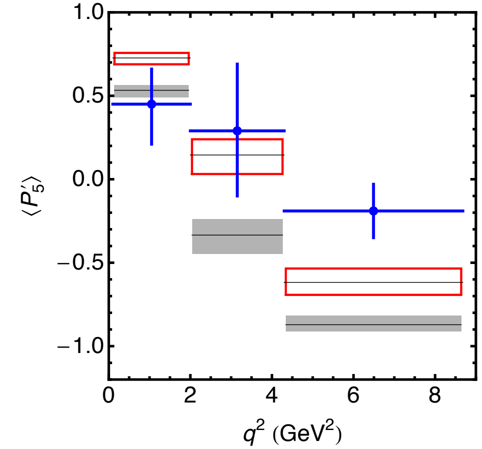
$$P_1 = 0$$

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

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

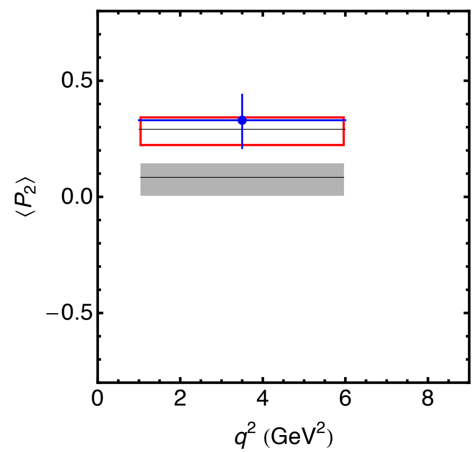


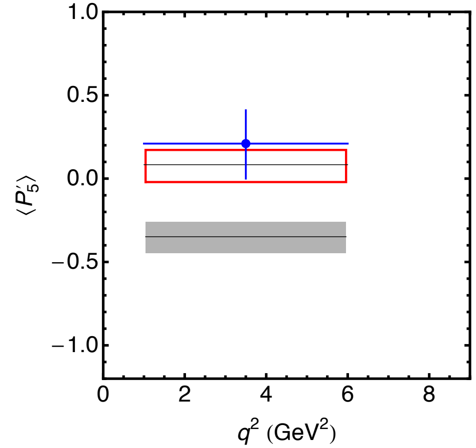


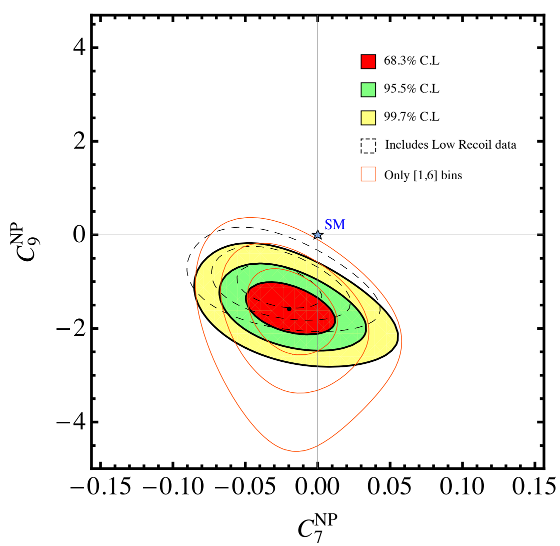


SM

$\Delta C_9 = -1.5$







The R_K anomaly

LHCb, 1406.6482

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

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)

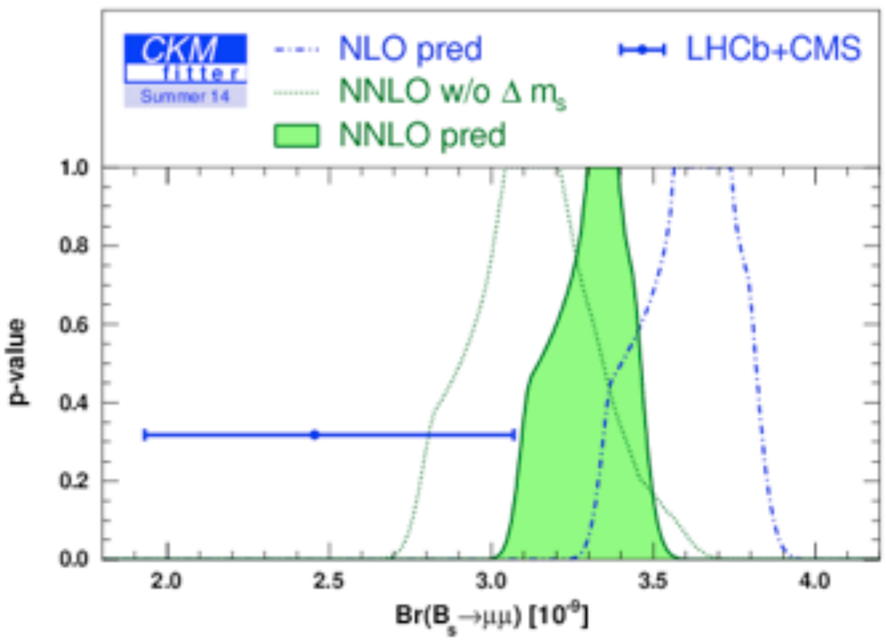
Will return to it:

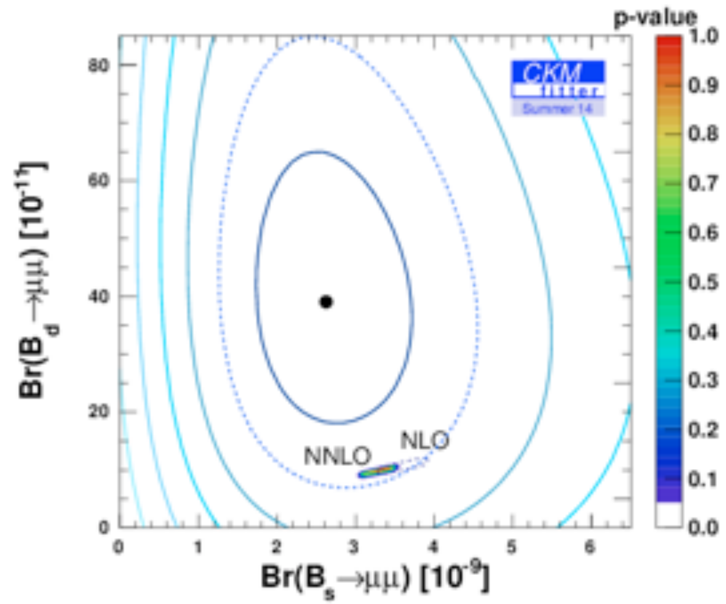
First limit possible contributions from scalar/pseudoscalar. In their absence

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

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

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



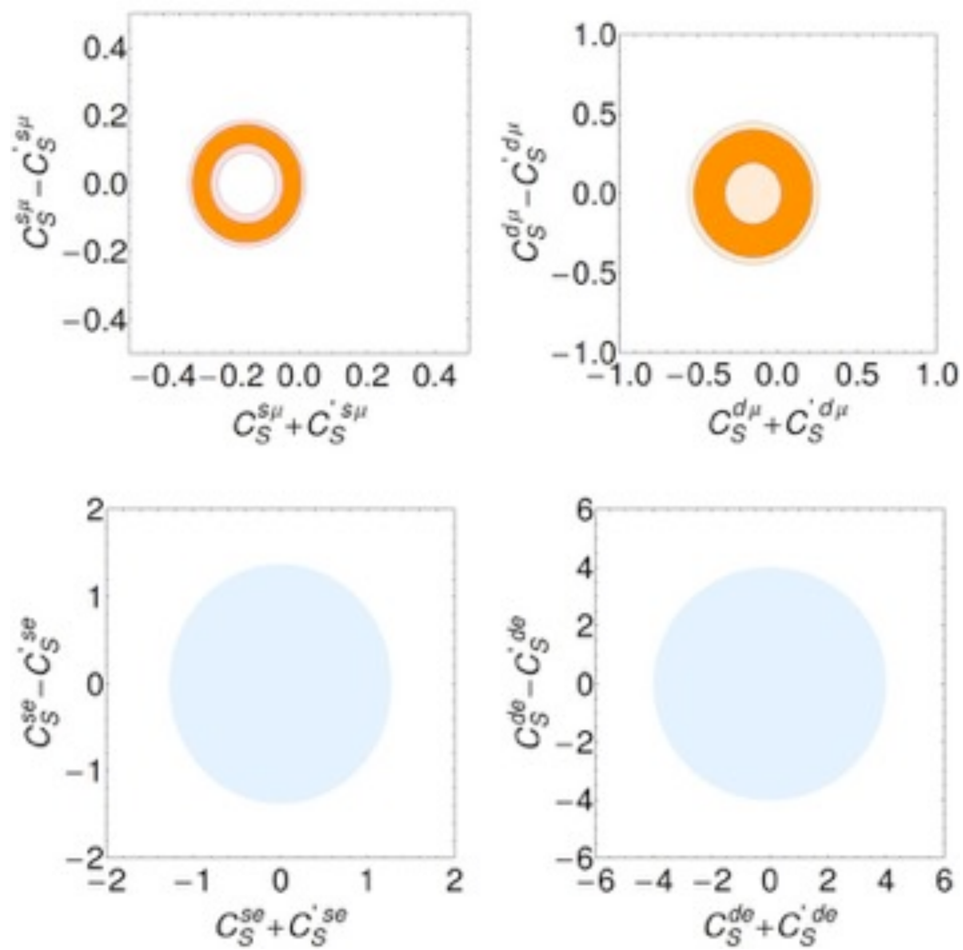


$$\frac{\overline{\mathcal{B}}_{ql}}{\left(\overline{\mathcal{B}}_{ql}\right)_{\rm SM}} = \frac{1 + \mathcal{A}^{ll}_{\Delta\Gamma}\, y_q}{1 + y_q} \left(|S|^2 + |P|^2\right),$$

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

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

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



(1-σ and 3-σ)

(3-σ)

Moral: only "vector × vector" operators may significantly contribute to R_K

R_K | P_5'

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

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

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

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. Often additional assumptions, like MFV & MLFV.

Application: R_K anomaly.

There are claims that violation to lepton universality implies unacceptably large charged 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

Recall: 4-fermion operators inducing $b \to sll$

Alonso, BG, Martin Camalich, arXiv:1505.05164

$$
\begin{aligned}
Q_{\ell q}^{(1)} &= (\bar{q}\gamma^\mu q_L)(\bar{\ell}\gamma_\mu \ell_L) & Q_{\ell q}^{(3)} &= (\bar{q}\vec{\tau}\gamma^\mu q_L)\cdot(\bar{\ell}\vec{\tau}\gamma_\mu \ell_L)\\
Q_{\ell d} &= (\bar{d}\gamma^\mu d_R)(\bar{\ell}\gamma_\mu \ell_L) & Q_{qe} &= (\bar{q}\gamma_\mu q_L)(\bar{e}\gamma^\mu e_R)\\
Q_{ed} &= (\bar{d}_R\gamma^\mu d_R)(\bar{e}\gamma_\mu e_R) & Q_{\ell edq} &= (\bar{\ell}_L e_R)(\bar{d}_R q) + \text{h.c.}
\end{aligned}
$$

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

Coefficients constrained by MFV+MFLV

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

$$
\begin{aligned}
C_{\ell q}^{(1)} &= c_{\ell q}^{(1)}\,\hat{Y}_u\hat{Y}_u^\dagger \otimes \hat{Y}_e\hat{Y}_e^\dagger, & C_{\ell q}^{(3)} &= c_{\ell q}^{(3)}\,\hat{Y}_u\hat{Y}_u^\dagger \otimes \hat{Y}_e\hat{Y}_e^\dagger,\\
C_{qe} &= c_{qe}\,\hat{Y}_u\hat{Y}_u^\dagger \otimes \hat{Y}_e^\dagger\hat{Y}_e, & C_{\ell edq} &= c_{\ell eqd}\,\varepsilon_e\varepsilon_d^*\,\hat{Y}_d^\dagger\hat{Y}_u\hat{Y}_u^\dagger \otimes \hat{Y}_e.
\end{aligned}
$$

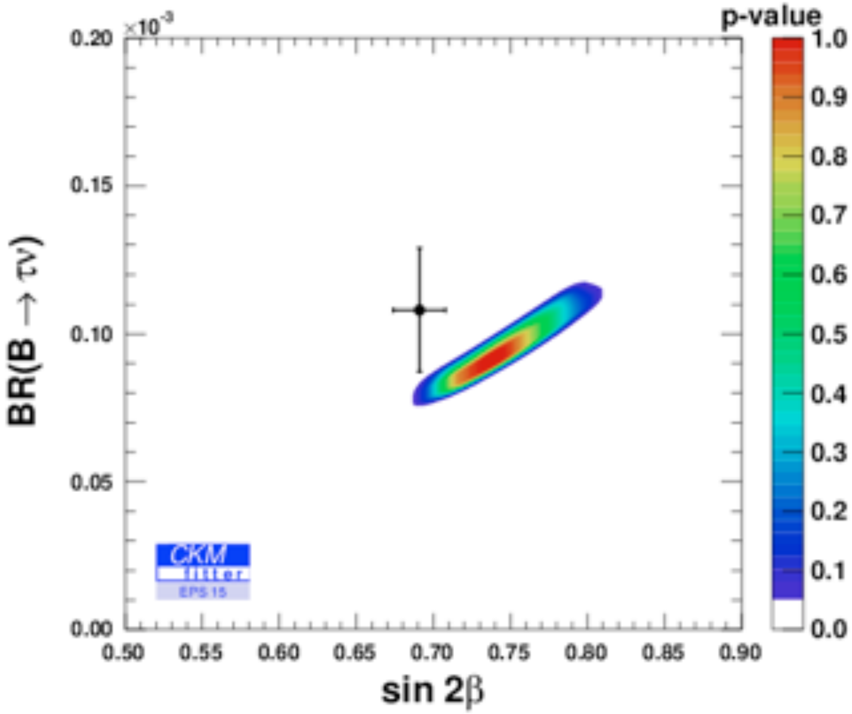
Lessons: 1. Scalar operator additionally suppressed! 2. Prediction: τ-enhancement:

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

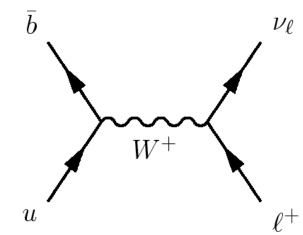
Enhancement shows up in $b \to s\nu\nu$ too. This sets $\left(C_q^{(1)} - C_q^{(3)}\right)_{sb} \lesssim 0.03\,\left(C_q^{(1)} + C_q^{(3)}\right)_{sb}$

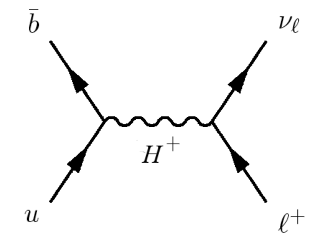
looks fine tuned, but appears naturally in models

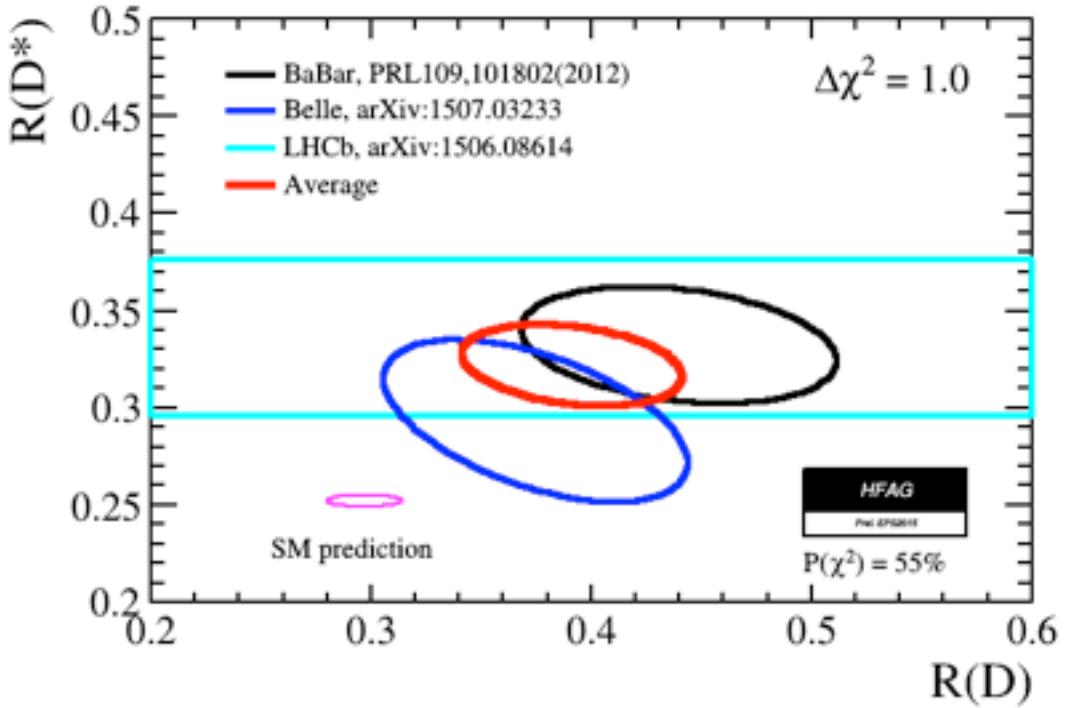

Care



τ







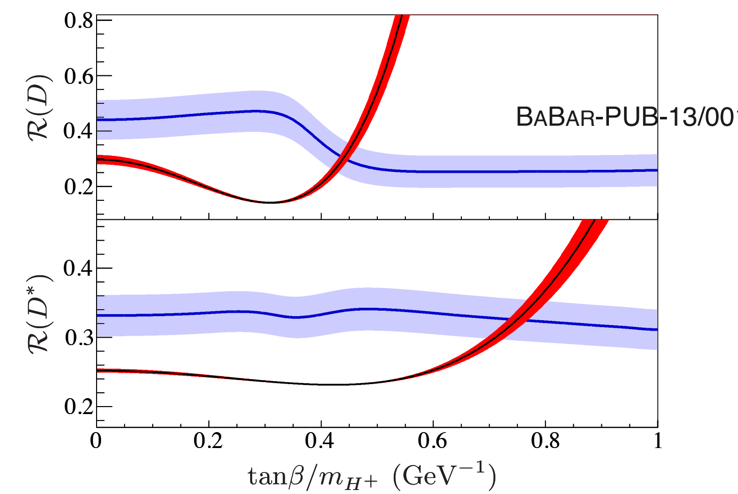


FIG. 20. (Color online). Comparison of the results of this analysis (light band, blue) with predictions that include a charged Higgs boson of type II 2HDM (dark band, red). The widths of the two bands represent the uncertainties. The SM corresponds to $\tan\beta/m_{H^+} = 0$.

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

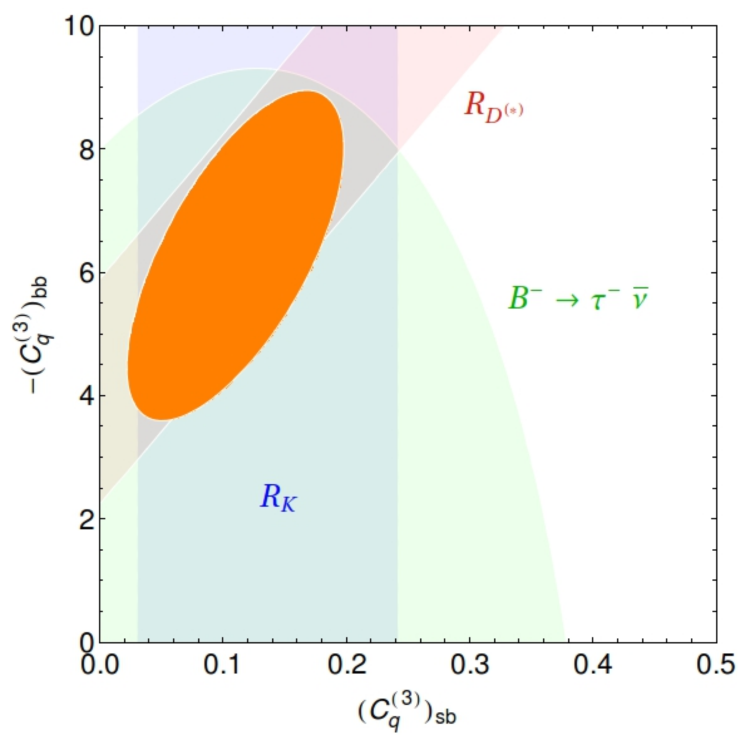
Charged currents too!: $Q_{\ell q}^{(3)} = (\bar{q}\vec{\tau}\gamma^{\mu}q_L)\cdot(\bar{\ell}\vec{\tau}\gamma_{\mu}\ell_L)$ $\Leftrightarrow$ $b \to c\tau\nu$

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

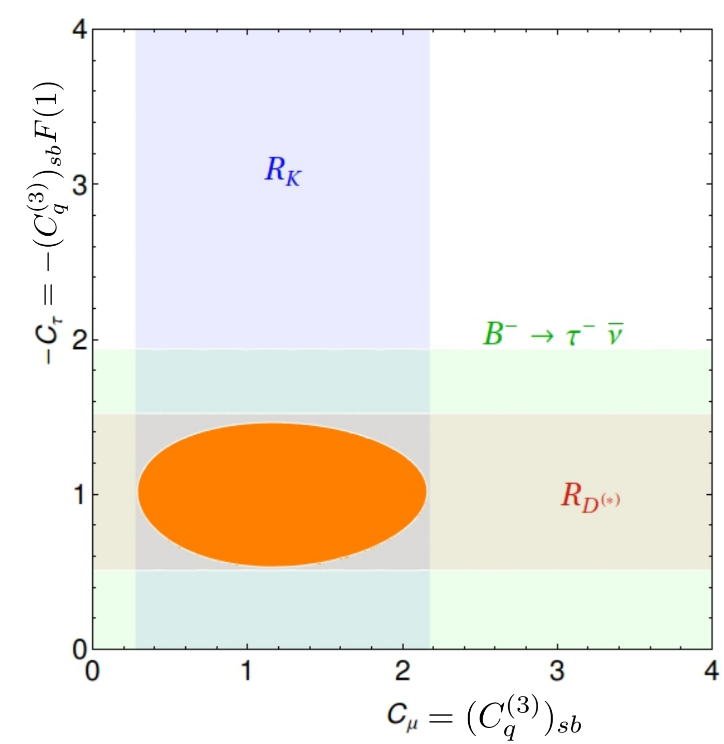
with $F'(1) = 1, F(1) = f$

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

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



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



Comments

1. Surely wrong. At least one anomaly will go away (Feynman?)

   and in case of questions:

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 Wilson Coefficients

      - 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

Future of ...

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

Future of ...

Theory: Prospects for learning anything (← !)

$(U_{PMNS})_{ij} = \frac{1}{\sqrt{3}}$

gen's = 3

who ordered THAT?

$\frac{m_\nu}{m_e}$

$m_u \ll m_c \ll m_b$

$V_{CKM} = \begin{pmatrix} 1 & \lambda & \lambda^3 \\ \lambda & 1 & \lambda^2 \\ \lambda^3 & \lambda^2 & 1 \end{pmatrix}$

Flavorists have tried, e.g.

- Radiative Hierarchies
- Textures
- Hierarchies from small order parameter
- String thy: generations = zero modes, hierarchies = intersection
- Extra dimensions

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Flavorists have tried, e.g.

- Radiative Hierarchies
- Textures ← same as previous
- Hierarchies from small order parameter
- String thy: generations = zero modes, hierarchies = intersection
- Extra dimensions ← same as previous

- NOT MANY
  lot's of variations on these ⇒ HARD
- HOW GOOD ARE THESE

Radiative Hierarchies

H. Fritzsch, Z.Z. Xing, PLB 353, 114, '95 for references

idea: $m_3 \neq 0$, $m_1 = m_2 = 0 \xrightarrow[\text{corr}]{\text{rad}} m_3 \gg m_2 \neq 0$ $m_1 = 0 \xrightarrow[\text{corr}]{\text{rad}} m_3 \gg m_2 \gg m_1$

$\Rightarrow$ Mass matrix texture (enforce: symmetry, often discrete)

Ex: $M = \begin{pmatrix} 0 & a & 0 \\ a^* & 0 & b \\ 0 & b^* & c \end{pmatrix}$

- original Fritzsch texture
- restricted # parameters
  - $\rightarrow$ predictive (relations)

(· modern version has $M_{22} \neq 0$.)

This gives, for example

$$\sin\theta_c = \frac{\sqrt{m_d m_c} - \sqrt{m_u m_s}}{\sqrt{(m_u + m_c)(m_d + m_s)}} \approx \sqrt{\frac{m_d}{m_s}}$$

- problematic as precision improves
  (true also of, eg, $A_4 \to$ tribimaximal U_{PMNS})
- imposed global symmetry:
  - all known examples are approximate, accidental (Isospin, CP, B−L?)
  - Gravity . BH ...

Frogatt & Nielsen, NPB147, 277 ('79)

Hierarchies from small order parameter(s).

IDEA: (i) Small parameter $\epsilon = \frac{\langle\phi\rangle}{M} \ll 1$

(ii) Symmetry group G prevents mass terms $\bar{\Psi}_{Li}\Psi_{Rj}$

(iii) Terms $\left(\frac{\phi}{M}\right)^{\Delta_{ij}} \bar{\Psi}_{Li}\Psi_{Rj}$ allowed by G

(iv) $\langle\phi\rangle \neq 0$ breaks G spontaneously

(v) Different charges under G for different $\Psi_{L/R\,i}$

Simplest if $G = U(1)$, with $Q(\phi) = 1$, $Q(\Psi_{Li}) = c + b_i$ $Q(\Psi_{Ri}) = c - a_i$

Then $Q(\bar{\Psi}_{Li}\Psi_{Rj}) = -(a_i + b_i)$. If $a_i + b_i > 0$ $\left(\frac{\phi}{M}\right)^{\Delta_{ij}} \bar{\Psi}_{Li}\Psi_{Rj}$ $\Delta_{ij} = a_i + b_j$

else $\left(\frac{\phi^*}{M}\right)^{\Delta_{ij}} \bar{\Psi}_{Li}\Psi_{Rj}$

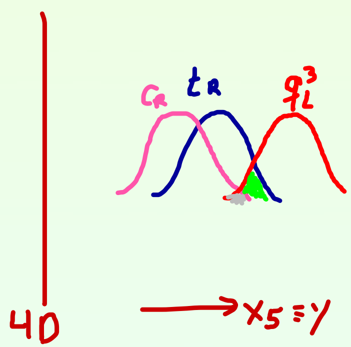
String theory: 10^{500} vacua
Resort to baby versions:

Hierarchies from extra-dimensions

Arkani-Hamed & Schmaltz
PRD 61, 033005 (2000)

(RS-version: Gherghetta & Pomarol, NPB 586 (2000) 141)

IDEA:



$$S \sim \int d^5x \; HQT + HQC$$

$$\psi(x^\mu, y) \sim \sum_n \psi_n(x^\mu)\, \Psi_n(y)$$

$$\Rightarrow S \sim \int d^4x \left(\int dy\, H_0(y) Q_0(y) T_0(y) \right) h(x)\, \bar{q}_L(x)\, t_R(x) + \cdots$$

A curious proposal:
an example of how there
are creative directions to take

?

- “why have we made no progress”
  (Why 3? Why hierarchy of quark/lepton masses? Wherefrom texture of CKM and PMNS?)

- Black holes: No global symmetry (other than accidental)

- Try these:
  - Use local symmetries
  - Make Yukawas dynamical fields (not just spurions of Global Flavor Symmetry)
  - Get global symmetries as automatic, and non-exact

Issues

- Can we make sense of dynamical Yukawa couplings?
  - In MFV we take Yukawa coupling constants as Spurions: VEVs of fields. Take seriously!

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

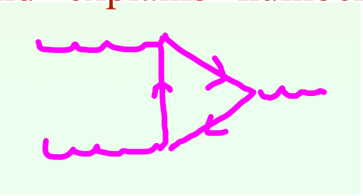
    $$Y_U = (\bar{3}, 3, 1)$$
    $$Y_D = (\bar{3}, 1, 3)$$

    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 (hey, 2 things we wanted are now linked) And "explains" number of generations!
  - New Problems:

    i. Anomalies: $G_F{}^3$ and $G_F{}^2 \times \mathrm{U}(1)_Y$

    ii. Invisibility (high scale): next slide

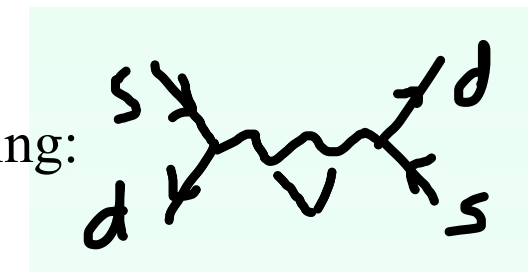
    iii. Renormalizability (problem 2) still



"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 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 $y_{\mathrm{U,D}}$ 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

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

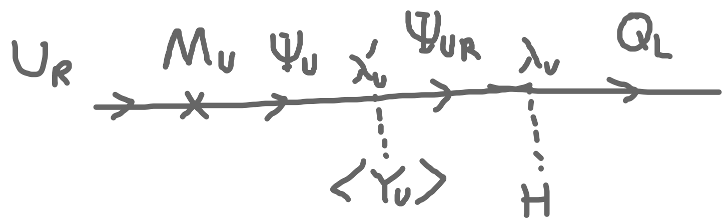
$$\begin{aligned}\mathcal{L} =& \mathcal{L}_{kin} - V(Y_u, Y_d, H) + \\ & \big(\lambda_u \overline{Q}_L \tilde{H} \Psi_{uR} + \lambda'_u \overline{\Psi}_u Y_u \Psi_{uR} + M_u \overline{\Psi}_u U_R + \\ & \lambda_d \overline{Q}_L H \Psi_{dR} + \lambda'_d \overline{\Psi}_d Y_d \Psi_{dR} + M_d \overline{\Psi}_d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

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

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

For example:

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



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

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

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

1st generation flavor change $\Leftrightarrow$ heaviest vectors

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

Example

Choose

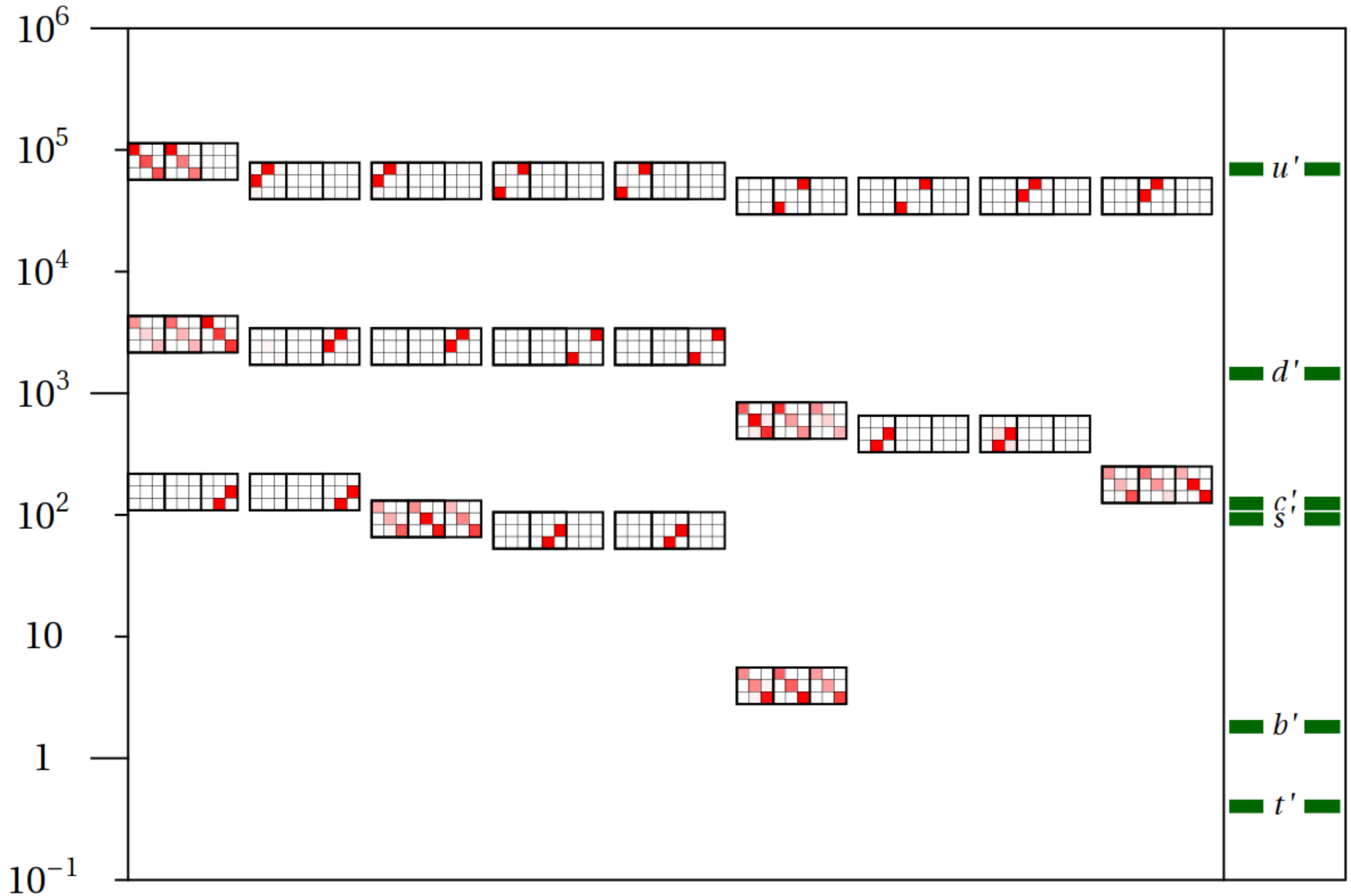
M_u (GeV)	M_d (GeV)	λ_u	λ'_u	λ_d	λ'_d	g_Q	g_U	g_D
400	100	1	0.5	0.25	0.3	0.4	0.3	0.5

Compute

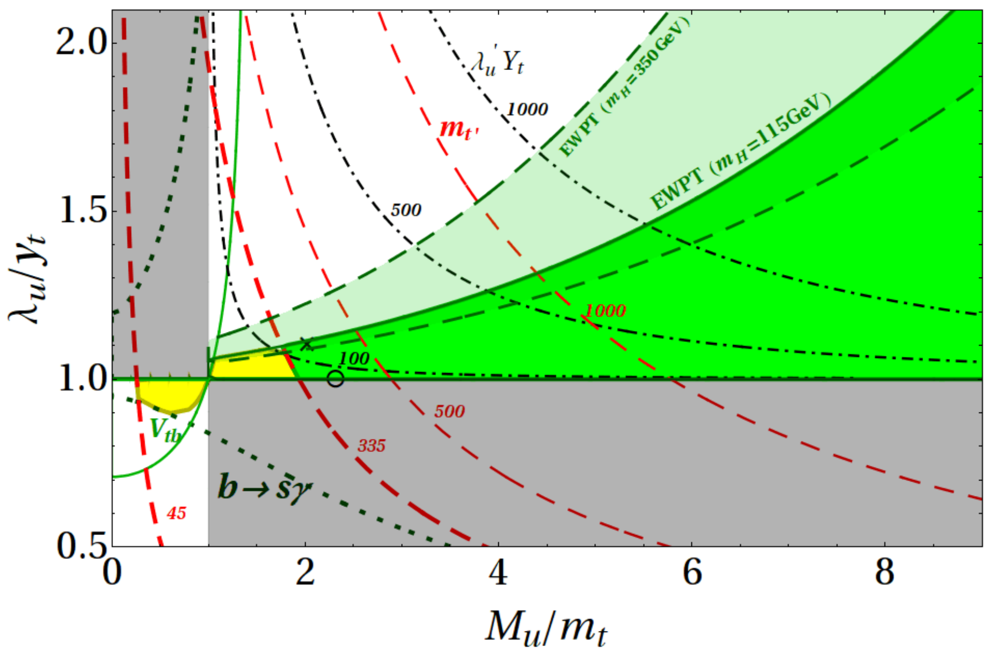
$$Y_u \approx \mathrm{Diag}\left(1\cdot 10^5\,,\ 2\cdot 10^2\,,\ 8\cdot 10^{-2}\right)\cdot V\ \ \mathrm{TeV}\,, \qquad (V^\dagger V = 1)$$

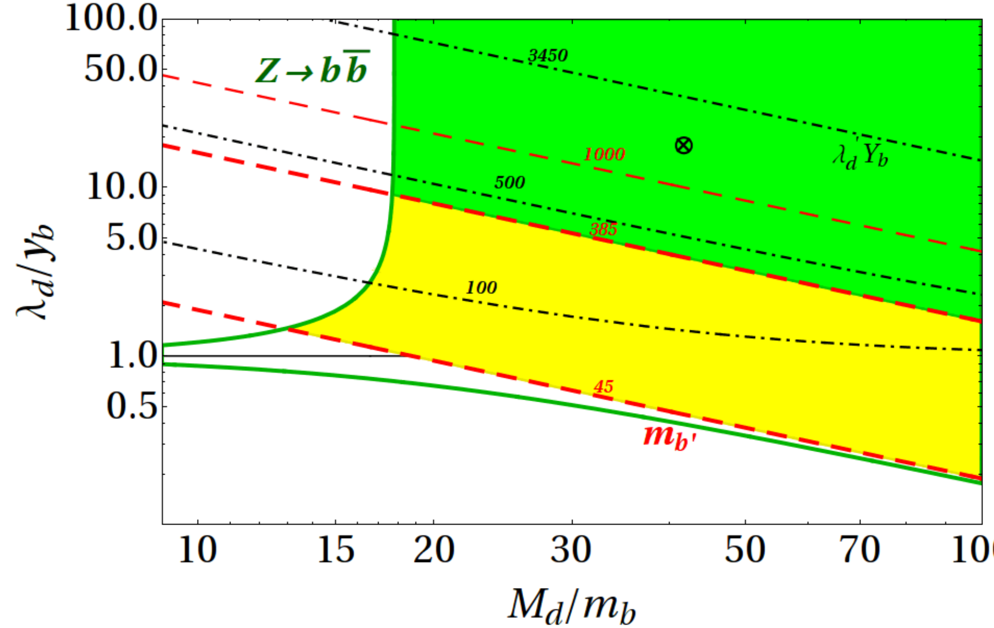
$$Y_d \approx \mathrm{Diag}\left(5\cdot 10^3\,,\ 3\cdot 10^2\,,\ 6\right)\ \ \mathrm{TeV}\,,$$

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)

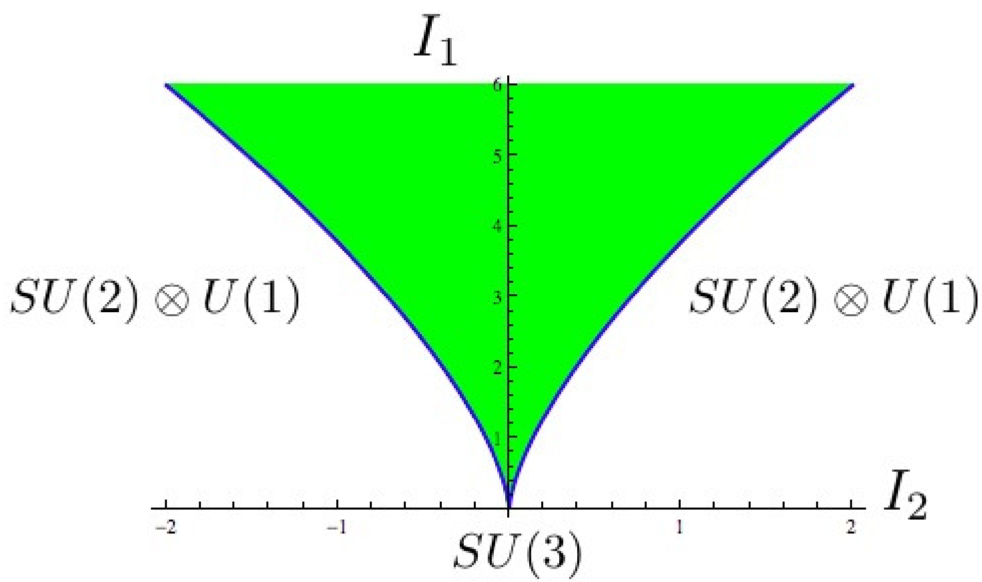


Figure 1: Manifold $\mathcal{M}$ of the $SU(3)$ invariants constructed from x=octet=hermitian, 3×3, traceless matrix (green region). Each point of $\mathcal{M}$ represents the orbit of x, namely the set of points in octet space given by: $x_g = gxg^{-1}$, when g runs over $SU(3)$. Boundaries of $\mathcal{M}$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

Conclusions ??? Wizardry?

I can’t tell the future. But I see

- Comp:
  - Growing effort in lattice calculations for 1,2,3, body MEs
  - Need for progress in inclusive rates. Probably lattice-analytic symbiosis
- Pheno:
  - New rare to ultra-rare processes hitherto ignored
  - EFT: low-high energy connections
    - Flavor can be incorproated to limit further opertaors
      - MFV+MLFV works well
  - Explicit models: surely many but Flavor useful to place limits on them (not to learn about Flavor)
- Theory of Flavor
  - Rebirth: New ideas will keep coming
    - Gauged Flavor is one example
      - Neat for quarks
      - Can it explain anomalies in gauged LF case? Ongoing.

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.

The End