Theoretical Advances in Flavor Physics

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Aspen Winter Conference
"Particle Physics on the Verge of Another Discovery?"

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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

CC problem

Hierarchy problem

Vacuum stability?

Strong CP problem

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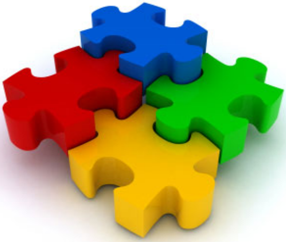
SM flavor puzzle

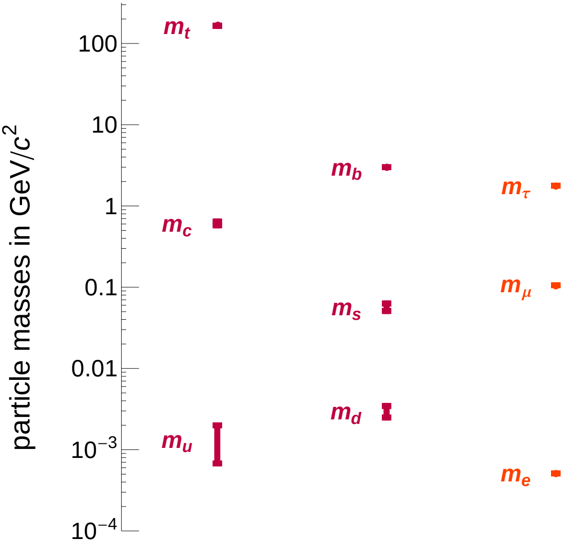
Neutrino masses

NP flavor puzzle
...



The Standard Model Flavor Puzzle

Flavor Hierarchies



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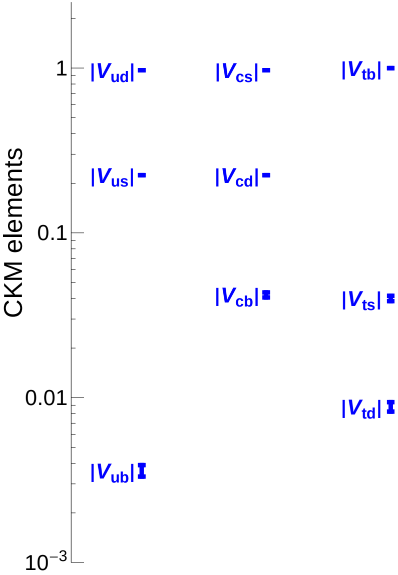
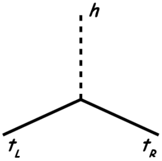
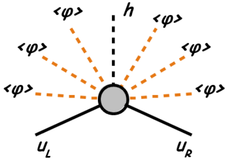


(Froggatt, Nielsen ’79; ...)

fermion masses are forbidden by flavor symmetries
and arise only after spontaneous breaking of the symmetry





Simple U(1) model:

$Q(t_L)=Q(t_R)=0$
$Q(u_L)=-Q(u_R)=3$
$Q(h)=0$
$Q(\varphi)=-1$

$h\bar{t}_R t_L$

$\frac{\varphi^6}{M^6} h\bar{u}_R u_L$

mass and mixing hierarchies given by powers of the spurion $\langle\varphi\rangle/M$

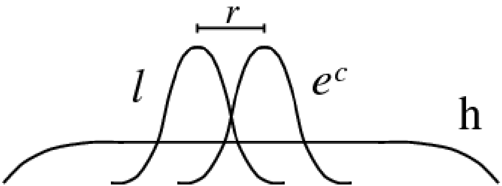
$$\frac{m_u}{m_t} \sim \left(\frac{\langle\varphi\rangle}{M}\right)^n$$

(see recent work by Bauer, Carena, Gemmler ’15)

Hierarchy without Symmetry: Geometry

(Arkani-Hamed, Schmaltz '99; Grossman, Neubert '99; ...)

fermions are localized at different positions in an extra dimension



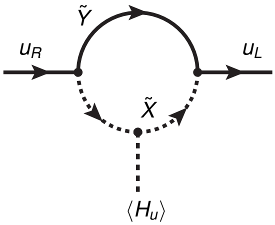
hierarchies from exponentially small wave-function overlap
between left-handed and right-handed fermions and the Higgs

$$\frac{m_u}{m_t} \sim e^{-\Delta}$$

Hierarchy without Symmetry: Loops

(Weinberg '72; ...)

light fermion masses arise only from quantum effects



light fermions do not couple to the higgs directly

couplings are loop-induced by flavor violating new particles

mass and mixing hierarchies from loop factors

$$\frac{m_u}{m_t} \sim \left(\frac{1}{16\pi^2} \right)^n$$

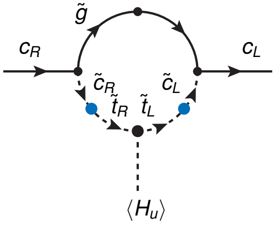
(various studies in recent years:

Arkani-Hamed et al. '12; Baumgart, Stolarski, Zorawski '14; WA, Frugiuele, Harnik '14;

Ibarra, Solaguren-Beascoa '14; Joaquim, Penedo '14; ...)

A simple setup for
loop induced fermion masses:

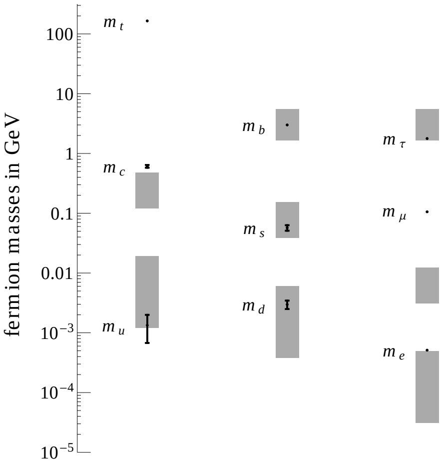
- MSSM field content
- rank 1 Yukawa couplings
- flavor anarchic sfermion masses



Works remarkably well!

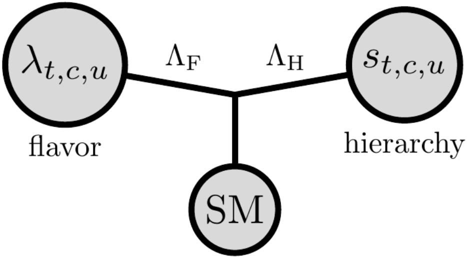
(muon mass can be fixed by
adding new gauge interactions)

WA, Frugiuele, Harnik '14



Disentangeling Mass and Mixing Hierarchies

Knapen, Robinson '15

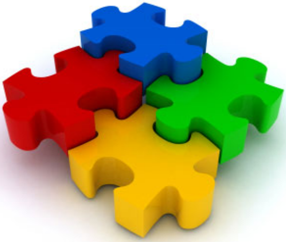


one sector with scale Λ_F
responsible for flavor mixing

Λ_F is strongly constrained by low energy flavor observables (in some cases at the level of 1000s or 100,000s of TeV)

separate sector with scale Λ_H
responsible for mass hierarchies

Λ_H could be much lower, close to the electroweak scale and in reach of the LHC



A Flavorful Higgs

The Flavor of the Higgs

$$\mathcal{L}_{\text{Yukawa}} = Y_{ij} \, \bar{\Psi}_i \Psi_j \, H$$

In the Standard Model the Yukawa couplings are
the only sources of flavor and CP violation

$\rightarrow$ the couplings of the Higgs to fermion mass eigenstates are
flavor diagonal and CP conserving

$$\frac{1}{v} \begin{pmatrix} m_{u,d,e} & 0 & 0 \\ 0 & m_{c,s,\mu} & 0 \\ 0 & 0 & m_{t,b,\tau} \end{pmatrix}$$

The Flavor of the Higgs

$$\mathcal{L}_{\text{Yukawa}} = Y_{ij}\, \bar{\Psi}_i \Psi_j\, H + \frac{\tilde{Y}_{ij}}{\Lambda^2}\, \bar{\Psi}_i \Psi_j\, H^3$$

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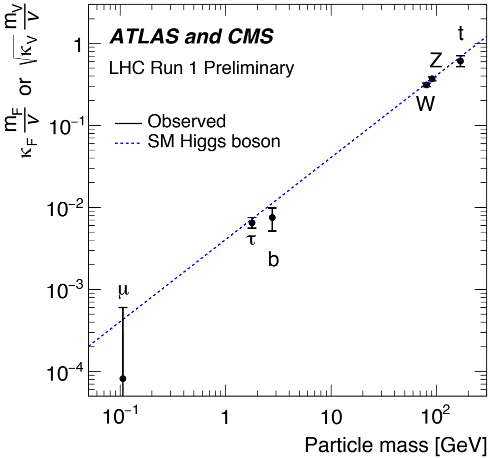
$$\frac{1}{v}\begin{pmatrix} m_{u,d,e} & 0 & 0 \\ 0 & m_{c,s,\mu} & 0 \\ 0 & 0 & m_{t,b,\tau} \end{pmatrix} + \frac{v^2}{\Lambda^2}\begin{pmatrix} \star & \star & \star \\ \star & \star & \star \\ \star & \star & \star \end{pmatrix}$$

1) New Physics can modify the flavor diagonal Higgs couplings
2) New Physics can lead to flavor and CP violating Higgs couplings

flavor diagonal couplings directly measured at the LHC with current accuracy for 3rd gen. $\sim 30\%$

can be improved to:
$\sim 5\% - 10\%$ at a HL-LHC
few % at a ILC

we know that the Higgs provides (at least part of) the mass of the 3rd gen.



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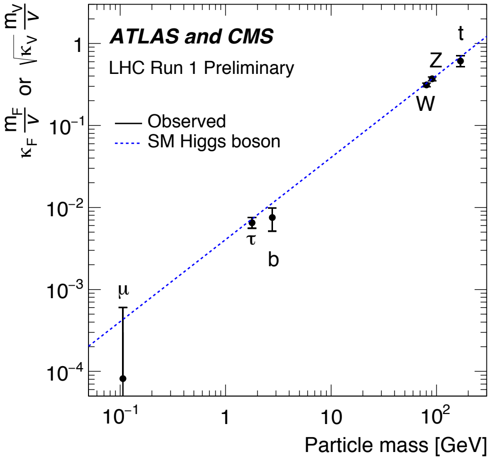
What about the 1st and 2nd generation?



Higgs Coupling to Electrons

$$\left(\frac{m_e}{v} + \tilde{Y}_{ee} \frac{v^2}{\Lambda^2} \right) \, h\bar{e}e \; = \; \frac{m_e}{v} \, \kappa_e \, h\bar{e}e \qquad\qquad (\kappa_e^{\rm SM} = 1)$$

$h \to e^+e^-$	LHC8 (25/fb)	$\lvert\kappa_e\rvert \lesssim 600$	$M \gtrsim 6$ TeV
	LHC14 (300/fb)	$\lvert\kappa_e\rvert \sim 260$	$M \sim 9$ TeV
	LHC14 (3/ab)	$\lvert\kappa_e\rvert \sim 150$	$M \sim 12$ TeV
	100 TeV (3/ab)	$\lvert\kappa_e\rvert \sim 75$	$M \sim 17$ TeV
$e^+e^- \to h$	LEP II	$\lvert\kappa_e\rvert \lesssim 2000$	$M \gtrsim 3$ TeV
	TLEP (1/fb)	$\lvert\kappa_e\rvert \sim 50$	$M \sim 20$ TeV
	TLEP (100/fb)	$\lvert\kappa_e\rvert \sim 10$	$M \sim 50$ TeV
d_e	current	$\text{Im}\,\kappa_e \lesssim 0.017$	$M \gtrsim 1000$ TeV
	future	$\text{Im}\,\kappa_e \sim 0.0001$	$M \sim 10^4$ TeV
$(g-2)_e$	current	$\text{Re}\,\kappa_e \lesssim 3000$	$M \gtrsim 2.5$ TeV
	future	$\text{Re}\,\kappa_e \sim 300$	$M \sim 8$ TeV

WA, Brod, Schmaltz, 1503.04830

Sequestered Fermion Mass Generation

What if the SM Higgs gives mass only to the 3rd generation?

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

$$\mathcal{M}_0 \sim \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & m_\tau \end{pmatrix} ,$$

(WA, Gori, Kagan, Silvestrini, Zupan '15; Ghosh, Perez '15)

Sequestered Fermion Mass Generation

What if the SM Higgs gives mass only to the 3rd generation?

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

$$\mathcal{M}_0 \sim \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & m_\tau \end{pmatrix} \quad , \quad \Delta\mathcal{M} \sim \begin{pmatrix} m_e & m_e & m_e \\ m_e & m_\mu & m_\mu \\ m_e & m_\mu & m_\mu \end{pmatrix}$$

$\Delta\mathcal{M}$ could be due to a second source of electroweak symmetry breaking, e.g. a second Higgs, strong dynamics, ...

(WA, Gori, Kagan, Silvestrini, Zupan '15; Ghosh, Perez '15)

Generic Expectations for the 125 GeV Higgs

Sequestered mass generation for leptons

$$\text{BR}(h \to \tau\tau) \sim \text{ SM-like}$$

$$\text{BR}(h \to \mu\mu) \sim \text{ typically suppressed}$$

$$\text{BR}(h \to \tau\mu) \sim \frac{m_\mu^2}{m_\tau^2} \times \text{BR}(h \to \tau\tau) \sim 10^{-3}$$

$$\text{BR}(h \to \tau e) \sim \frac{m_e^2}{m_\mu^2} \times \text{BR}(h \to \tau\mu) \sim 10^{-7}$$

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$$\text{BR}(h \to \tau e) \sim \frac{m_e^2}{m_\mu^2} \times \text{BR}(h \to \tau\mu) \sim 10^{-7}$$

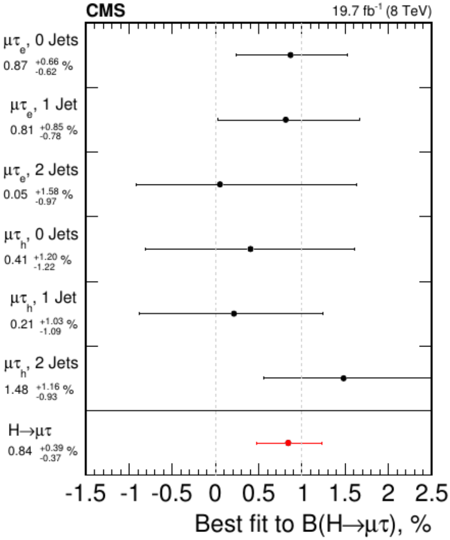
Sequestered mass generation for quarks

$$\text{BR}(t \to ch) \text{ could be as large as } \sim |V_{cb}|^2 \sim 10^{-3}$$

$$\text{BR}(t \to uh) \text{ could be as large as } \sim |V_{ub}|^2 \sim 10^{-5}$$

$$\text{BR}(B_s \to \tau\mu) \text{ could be as large as } \sim 10^{-7}$$

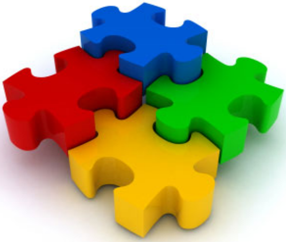
A Hint for Higgs Flavor Violation?



$$B(h \to \tau\mu) = (0.84^{+0.39}_{-0.37})\%$$

CMS 1502.07400

compatible with the
generic expectation of
“sequestered” fermion masses
(a bit on the high side, though ...)



Flavor Anomalies

(see also talk by Andreas Crivellin)

(Incomplete) List of Anomalies in Flavor Physics

$\sim 3.5\sigma$ $(g-2)_\mu$ anomaly

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$2-3\sigma$ anomaly in $B \to K^*\mu^+\mu^-$ angular distributions

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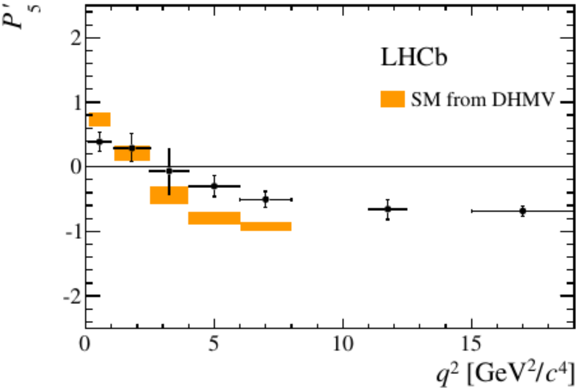
$\sim 2.5\sigma$ non-zero $h \to \tau\mu$

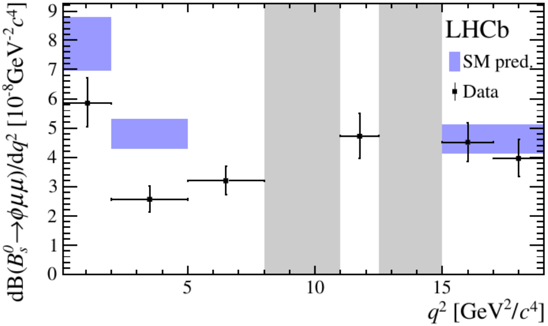
LHCb 1512.04442



2.8σ deviation in [4,6] GeV^2 bin ($+3.0\sigma$ in [6,8] GeV^2 bin)

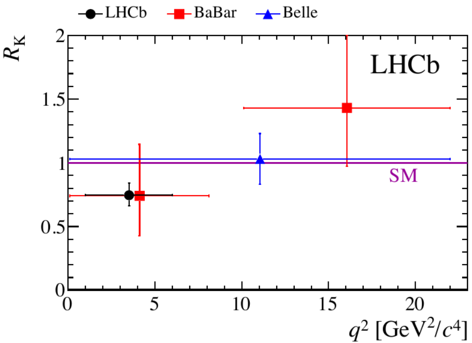
“The $B_s \to \phi\mu^+\mu^-$ Anomaly”

LHCb 1506.08777



branching ratio is 3.5σ below SM prediction for $1\,\text{GeV}^2 < q^2 < 6\,\text{GeV}^2$

LHCb 1406.6482



2.6σ hint for violation of lepton flavor universality (LFU)

$$R_K = \frac{\text{BR}(B \to K\mu^+\mu^-)_{[1,6]}}{\text{BR}(B \to Ke^+e^-)_{[1,6]}} = 0.745^{+0.090}_{-0.074} \pm 0.036$$

What Could It Be?

	branching ratios	angular observables	LFU ratios

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millisecond pulsars?	?	?	?

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millisecond pulsars?	?	?	?
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parametric uncertainties?	√	×	×

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	branching ratios	angular observables	LFU ratios
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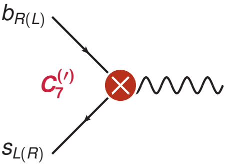
underestimated hadronic effects?	✓	✓	✗

What Could It Be?

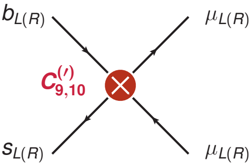
	branching ratios	angular observables	LFU ratios
millisecond pulsars?	?	?	?
statistical fluctuations?	✓	✓	✓
parametric uncertainties?	✓	✗	✗
underestimated hadronic effects?	✓	✓	✗
New Physics?	✓	✓	✓

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

magnetic dipole operators



semileptonic operators



	C_7, C_7'	C_9, C_9'	C_{10}, C_{10}'
$B \to (X_s, K^*)\,\gamma$	★		
$B \to (X_s, K, K^*)\,\mu^+\mu^-$	★	★	★
$B_s \to \phi\,\mu^+\mu^-$	★	★	★
$B_s \to \mu^+\mu^-$			★

neglecting tensor operators (secretly dimension 8)

neglecting scalar operators (strongly constrained by $B_s \to \mu^+\mu^-$)

Global Fits of $b \to s$ Data

many processes and many observables
are modified simultaneously

$\Rightarrow$ global fits are required

WA, Straub, Paradisi '11; Bobeth, Hiller, van Dyk, Wacker '11; WA, Straub '12 - '15;

Beaujean, Bobeth, van Dyk, Wacker; '12; Descotes-Genon, Matias, Virto '13, '14;

Beaujean, Bobeth, van Dyk '13; Hurth, Mahmoudi '13; Ghosh, Nardecchia, Renner '14;

Hurth, Mahmoudi, Neshatpour '14; Jäger, Martin Camalich '14;

Beaujean, Bobeth, Jahn '15; Descotes-Genon, Hofer, Matias, Virto '15;

Ciuchini, Fedele, Franco, Mishima, Paul, Silvestrini, Valli '15; ...

A Hint for Flavorful New Physics

favored new physics parameter space

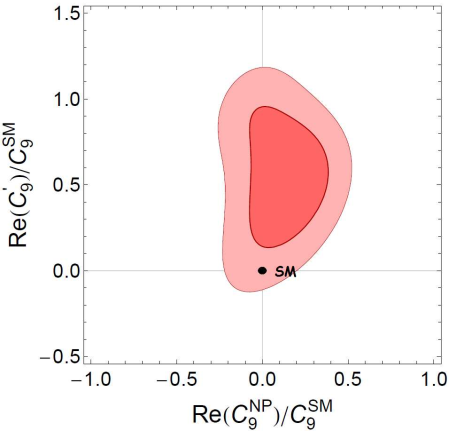
(WA, Straub '11 - '15)

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

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

muonic vector current

2011



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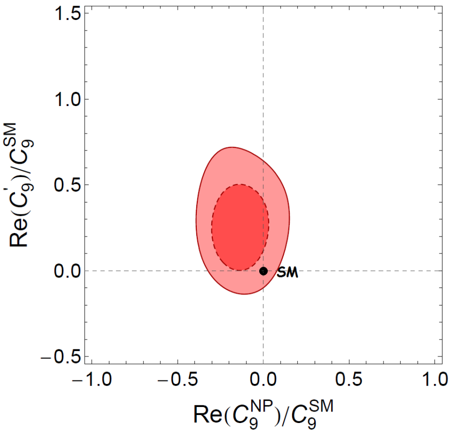
2012



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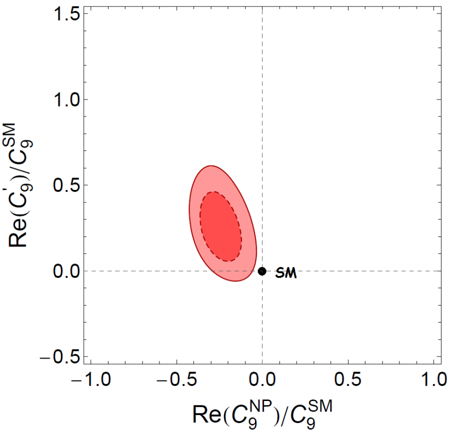
muonic vector current

2013



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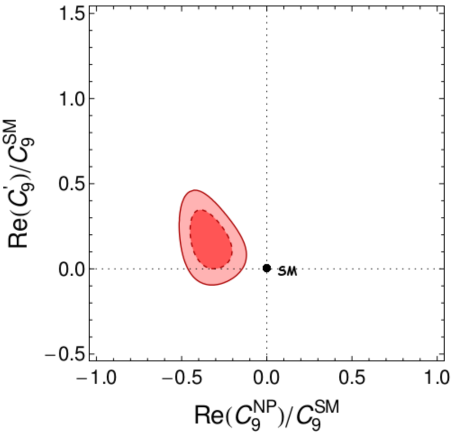
muonic vector current

2014



A Hint for Flavorful New Physics

favored new physics parameter space

(WA, Straub '11 - '15)

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

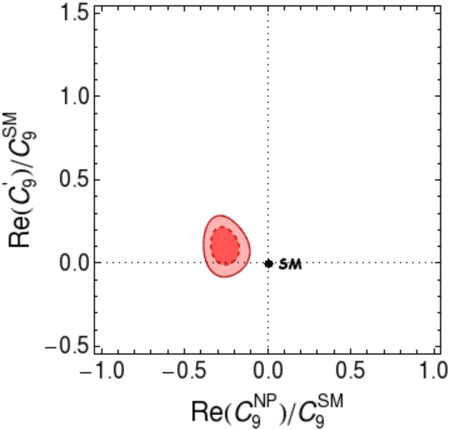
$O_9' \propto (\bar{s}\gamma_\mu P_R b)(\bar{\mu}\gamma^\mu \mu)$

muonic vector current

- $\Delta\chi^2 = 15.2$
- p-value: 12.4% (2.1% in the SM)

(only $b \to s\mu^+\mu^-$ data)

2015



Distinguishing New Physics from Hadronic Effects

	LFU violation
hadronic effects?	✗
New Physics?	✓

Distinguishing New Physics from Hadronic Effects

	LFU violation	RH currents
hadronic effects?	✗	✗
New Physics?	✓	✓

Distinguishing New Physics from Hadronic Effects

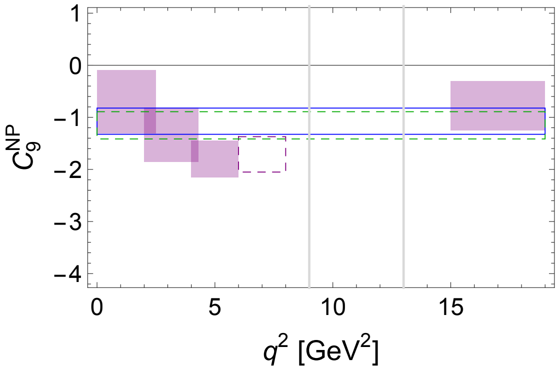
	LFU violation	RH currents	CP violation
hadronic effects?	✗	✗	✗
New Physics?	✓	✓	✓

Distinguishing New Physics from Hadronic Effects

	LFU violation	RH currents	CP violation	non-trivial q^2 dependence
hadronic effects?	✗	✗	✗	✓
(heavy) New Physics?	✓	✓	✓	✗

q^2 Dependence of the Effect

(WA), Straub 1503.06199



compatible with a q^2 independent short distance contribution from new physics

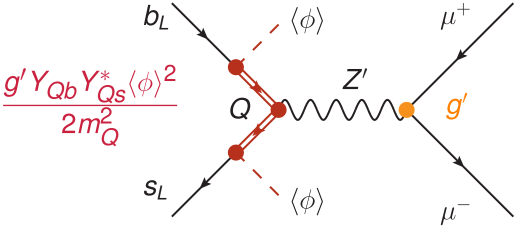
preferred value for C_9 seems to increase closer to the J/ψ
$\rightarrow$ indication for a charm loop effect?

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

(assumes New Physics has O(1) coupling to muons)

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

WA, Gori, Pospelov, Yavin 1403.1269



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 Observables

ratios of branching ratios

$$R_K = \frac{\mathrm{BR}(B \to K\mu\mu)}{\mathrm{BR}(B \to Kee)}$$

$$R_{K^*} = \frac{\mathrm{BR}(B \to K^*\mu\mu)}{\mathrm{BR}(B \to K^*ee)}$$

$$R_\phi = \frac{\mathrm{BR}(B_s \to \phi\mu\mu)}{\mathrm{BR}(B_s \to \phi ee)}$$

...

$$R_i^{\mathrm{SM}} \simeq 1$$

Predictions for LFU Observables

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...

$$R_i^{\text{SM}} \simeq 1$$

differences of angular observables

$$D_{P_5'} = P_5'(B \to K^*\mu\mu) - P_5'(B \to K^*ee)$$

$$D_{A_{\text{FB}}} = A_{\text{FB}}(B \to K^*\mu\mu) - A_{\text{FB}}(B \to K^*ee)$$

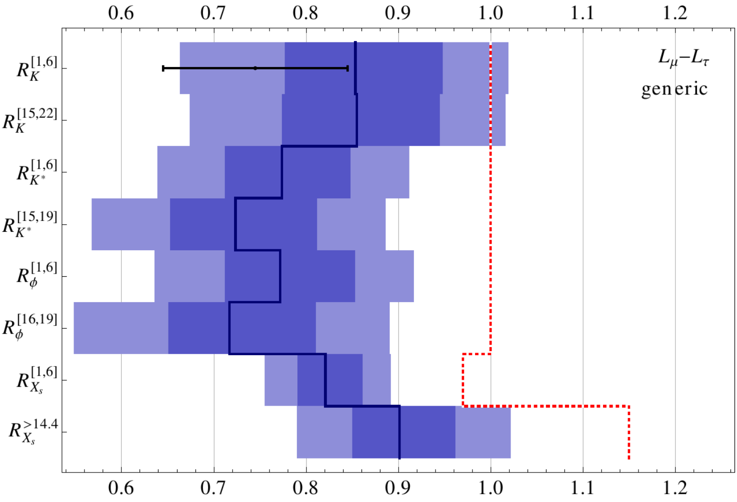
$$D_{F_L} = F_L(B \to K^*\mu\mu) - F_L(B \to K^*ee)$$

...

$$D_i^{\text{SM}} \simeq 0$$

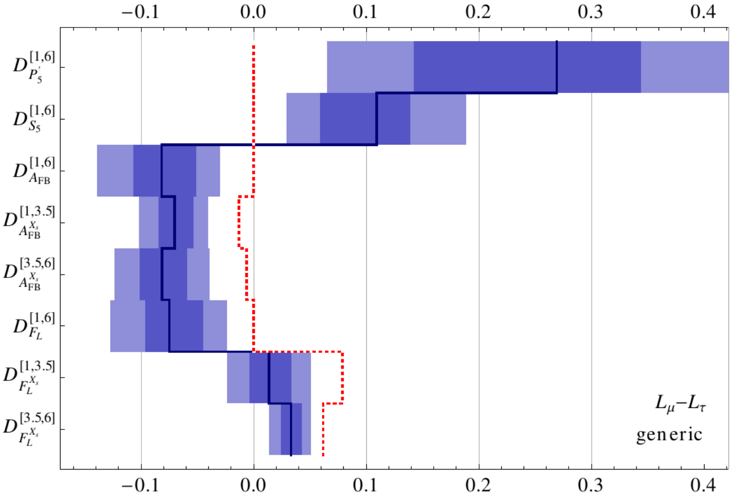
Predictions for LFU Observables

WA, Yavin '15



Predictions for LFU Observables

WA, Yavin '15



Conclusions

- the origin of the hierarchical flavor structure of the SM fermions remains mysterious
- it is crucial to verify that the Higgs provides mass to all 3 generations and to investigate alternative setups
- various experimental results in flavor physics show $\sim 3\sigma$ discrepancies with the Standard Model predictions
- statistical fluctuations? hadronic effects? New Physics?
- looking forward to an exciting future with new data from LHC(b) and Belle II

Back Up

Allowed Z' Parameter Space