(Rare) Semileptonic B Decays and Lepton Flavour Universality

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UNIVERSITY OF Cincinnati

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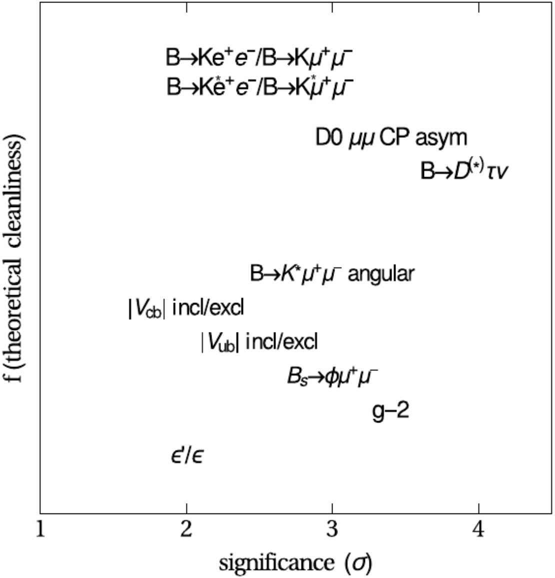
Shanghai Jiao Tong University,
May 19, 2017

Anomalies in Flavor Physics



Zoltan Ligeti

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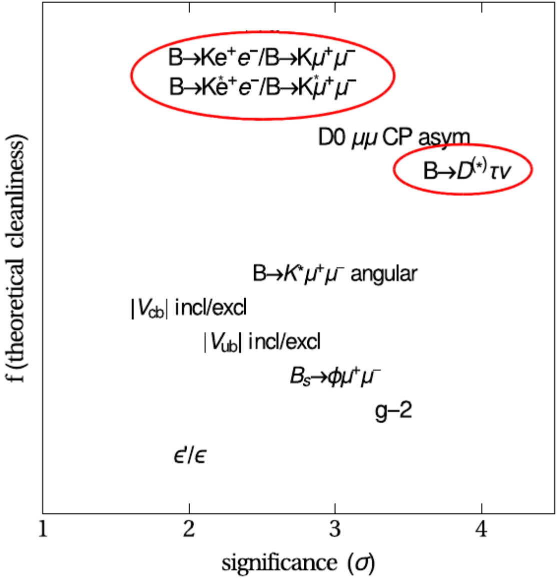
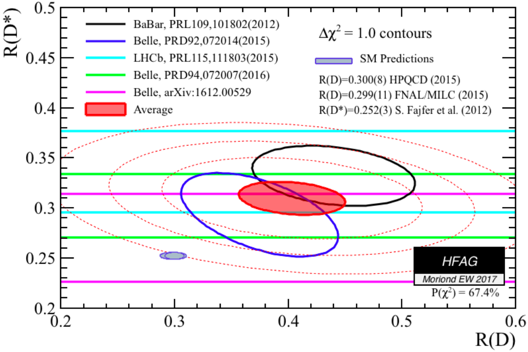


Zoltan Ligeti

R_D and R_{D^*}

The Experimental Situation

world average from the heavy flavor averaging group



$$R_D = \frac{BR(B \to D\tau\nu)}{BR(B \to D\ell\nu)}$$

$$R_{D^*} = \frac{BR(B \to D^*\tau\nu)}{BR(B \to D^*\ell\nu)}$$

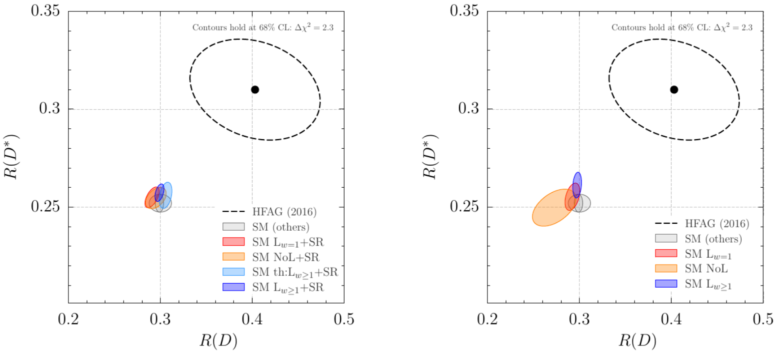
$\ell = \mu, e$ (BaBar/Belle)
$\ell = \mu$ (LHCb)

$$R_D = 0.403 \pm 0.040 \pm 0.024 \quad , \qquad R_{D^*} = 0.310 \pm 0.015 \pm 0.008$$

discrepancies with the SM by 2.2σ and 3.4σ, respectively

Standard Model Predictions for R_D and R_{D^*}

Bernlochner, Ligeti, Papucci, Robinson 1703.05330



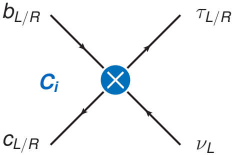
heavy quark expansion + $B \to D^{(*)}\ell\nu$ data + lattice input + QCD sum rule input

$$R_D = 0.299 \pm 0.003 \quad , \quad R_{D^*} = 0.257 \pm 0.003$$

(see also Fajfer, Kamenik, Nisandzic 1203.2654; Bailey et al. 1503.07237; Na et al. 1505.03925; Bigi, Gambino 1606.08030)

Model Independent New Physics Analysis

$$\mathcal{H}_{\rm eff} = \frac{4G_F}{\sqrt{2}} V_{cb} \mathcal{O}_{V_L} + \frac{1}{\Lambda^2} \sum_i C_i \mathcal{O}_i$$



$\mathcal{O}_i$ = 4 fermion contact interactions with vector, scalar or tensor currents

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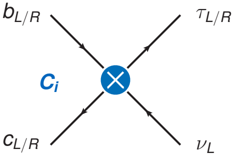

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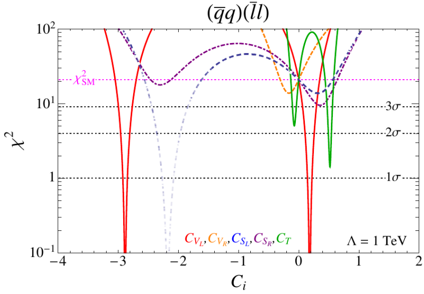
rescaling of the SM operator fits the data best

combinations of operators are also possible



Freytsis, Ligeti, Ruderman 1506.08896

Implications for the New Physics Scale

unitarity bound	$\frac{4\pi}{\Lambda_{\rm NP}^2}(\bar{c}\gamma_\nu P_L b)(\bar{\tau}\gamma^\nu P_L \nu)$	$\Lambda_{\rm NP} \simeq 8.4$ TeV
generic tree	$\frac{1}{\Lambda_{\rm NP}^2}(\bar{c}\gamma_\nu P_L b)(\bar{\tau}\gamma^\nu P_L \nu)$	$\Lambda_{\rm NP} \simeq 2.4$ TeV
MFV tree	$\frac{1}{\Lambda_{\rm NP}^2}\, V_{cb}\, (\bar{c}\gamma_\nu P_L b)(\bar{\tau}\gamma^\nu P_L \nu)$	$\Lambda_{\rm NP} \simeq 0.5$ TeV

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lepto-quarks

Becirevic, Fajfer, Kosnik, Sumensari 1608.08501
Sahoo, Mohanta, Giri 1609.04367
Hiller, Loose, Schonwald 1609.08895
Barbieri, Murphy, Senia 1611.04930
Crivellin, Muller, Ota 1703.09226

charged Higgses

Celis, Jung, Li, Pich 1612.07757

RPV SUSY

Deshpande, He 1608.04817
WA, Dev, Soni 1704.06659

W prime

Boucenna et al. 1608.01349
Bhattacharya et al. 1609.09078
Megias, Quiros, Salas 1703.06019

Many Constraints on New Physics Explanations

- obvious constraints from $B \to \tau\nu$ and $B \to K\nu\nu$ etc.

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  Li, Yang, Zhang 1605.09308; Alonso, Grinstein, Martin Camalich 1611.06676

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  Feruglio, Paradisi, Pattori 1606.00524 + 1705.00929

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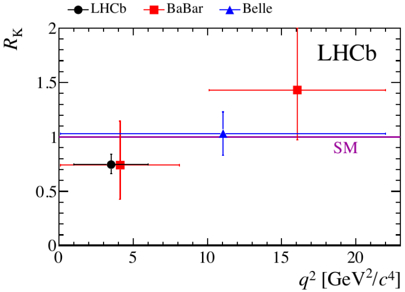
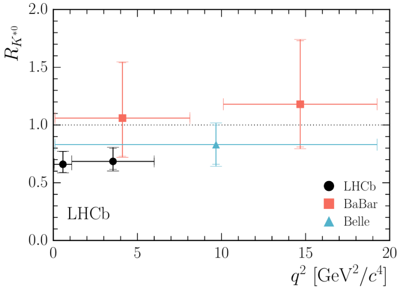
$\to$ model building is non-trivial

R_K and R_{K^*}

Experimental Situation





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

$$R_K^{[1,6]} = 0.745^{+0.090}_{-0.074} \pm 0.036$$

$$R_{K^*}^{[0.045,1.1]} = 0.66^{+0.11}_{-0.07} \pm 0.03$$

$$R_{K^*}^{[1.1,6]} = 0.69^{+0.11}_{-0.07} \pm 0.05$$

3 observables
deviating by $\sim 2\sigma - 2.5\sigma$
from the SM predictions

Standard Model Predictions for R_K and R_{K^*}

$R_{K^{(*)}} = 1$

Standard Model Predictions for R_K and R_{K^*}

$$R_{K^{(*)}} = 1 + \mathcal{O}\left(\frac{m_\mu^2}{q^2}\right)$$

phase space
(tiny effect)

Standard Model Predictions for R_K and R_{K^*}

$$R_{K^{(*)}} = 1 + \mathcal{O}\left(\frac{m_\mu^2}{q^2}\right) \times \left(1 + \mathcal{O}\left(\frac{\Lambda_{\text{QCD}}}{m_b}\right) + \mathcal{O}\left(\alpha_s\right)\right)$$

phase space
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hadronic corrections
(tiny effect)

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QED corrections
(soft and collinear photon emission)

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phase space (tiny effect)

hadronic corrections (tiny effect)

QED corrections (soft and collinear photon emission)

Bordone, Isidori, Pattori 1605.07633

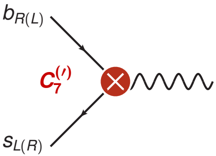
$$R_K^{[1,6]} = 1.00 \pm 0.01 \ , \quad R_{K^*}^{[1.1,6]} = 1.00 \pm 0.01 \ , \quad R_{K^*}^{[0.045,1.1]} = 0.91 \pm 0.03$$

- QED corrections are well modeled by monte carlo
- additional corrections at low q^2 from $B \to K^* \eta (\to ee\gamma)$

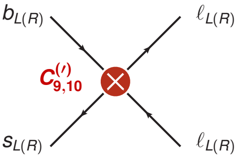
Model Independent New Physics Analysis

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

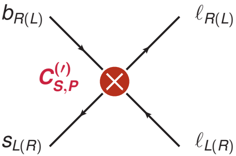
magnetic dipole operators



semileptonic operators



scalar operators



$$C_7^{(\prime)} (\bar{s}\sigma_{\mu\nu} P_{R(L)} b) F^{\mu\nu} \quad , \quad C_9^{(\prime)} (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{\ell}\gamma^\mu \ell) \quad , \quad C_S^{(\prime)} (\bar{s} P_{R(L)} b)(\bar{\ell} P_{L(R)} \ell)$$

$$C_{10}^{(\prime)} (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{\ell}\gamma^\mu \gamma_5 \ell)$$

Anatomy of the New Physics Effect

- ✗ dipole operators do not break lepton flavor universality
- ✗ scalar operators are strongly constrained by $B_s \to \ell^+\ell^-$

  WA, Niehoff, Straub 1702.05498; Alonso, Grinstein, Martin Camalich 1407.7044
- ✓ semi-leptonic operators are required

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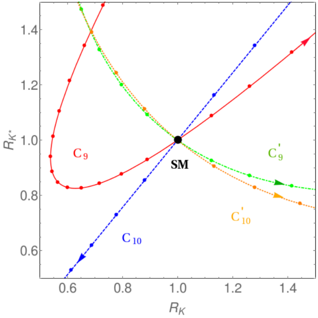
✓ semi-leptonic operators are required

right-handed quark currents result in a anti-correlation of R_K and R_{K^*}

left-handed quark currents result in a correlation of R_K and R_{K^*}



Geng et al. 1704.05446

Fits to Wilson Coefficients

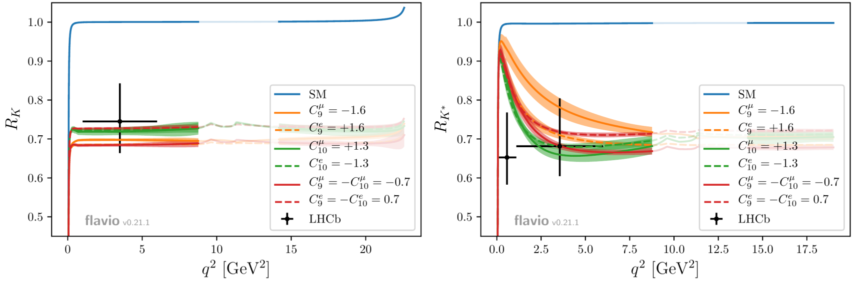
WA, Stangl, Straub 1704.05435

Coeff.	best fit	1σ	2σ	pull
C_9^μ	-1.56	$[-2.12, -1.10]$	$[-2.87, -0.71]$	4.1σ
C_{10}^μ	$+1.20$	$[+0.88, +1.57]$	$[+0.58, +2.00]$	4.2σ
C_9^e	$+1.54$	$[+1.13, +1.98]$	$[+0.76, +2.48]$	4.3σ
C_{10}^e	-1.27	$[-1.65, -0.92]$	$[-2.08, -0.61]$	4.3σ

suppress the muon rate with $C_9^\mu < 0$ or $C_{10}^\mu > 0$
or enhance the electron rate with $C_9^e > 0$ or $C_{10}^e < 0$
(or linear combinations)

(see also Capdevila, Crivellin, Descotes-Genon, Matias, Virto 1704.05340;
D'Amico, Nardecchia, Panci, Sannino, Strumia, Torre, Urbano 1704.05438;
Hiller, Nisandzic 1704.05444; Geng, Grinstein, Jager, Martin Camalich, Ren, Shi 1704.05446;
Ciuchini, Coutinho, Fedele, Franco, Paul, Silvestrini, Valli 1704.05447;
(+ many others, apologies for the omission...)

WA, Stangl, Straub 1704.05435



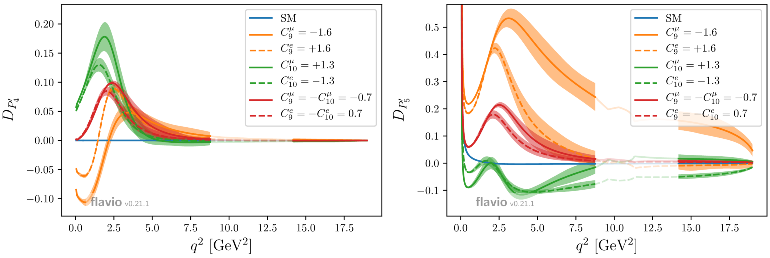
$B \to K^* \ell^+ \ell^-$ decays at low q^2 are dominated by the (lepton flavor universal) photon pole $B \to K^* \gamma$

$\to$ Effect of (heavy) new physics in R_{K^*} gets diluted at low q^2.

This behavior is not seen in the data (yet?).

Distinguishing New Physics Scenarios

WA, Stangl, Straub 1704.05435



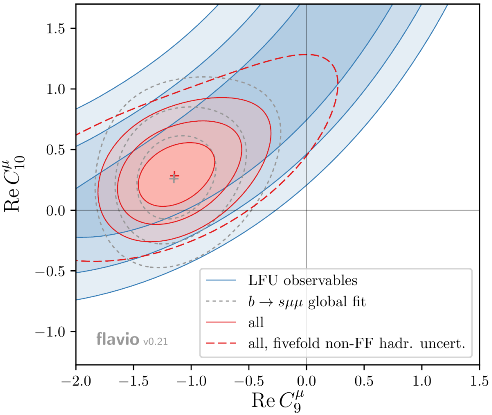
$$D_{P_i'} = P_i'(B \to K^* \mu\mu) - P_i'(B \to K^* \mu\mu)$$ (WA, Yavin 1508.07009)

(for additional proposals of angular LFU tests see e.g.

Capdevila, Descotes-Genon, Matias, Virto 1605.03156

Serra, Silva Coutinho, van Dyk 1610.08761)

LFU differences of angular observables can be used to distinguish between different new physics explanations



WA, Stangl, Straub 1704.05435

WA, Niehoff, Stangl, Straub 1703.09189

the LFU observables are fully compatible with the other anomalies!

Best description of all anomalies by:

new physics in final states with muons

$$C_9^{\mu}(\bar{s}\gamma_{\mu}P_L b)(\bar{\mu}\gamma^{\mu}\mu)$$

SM-like final states with electrons

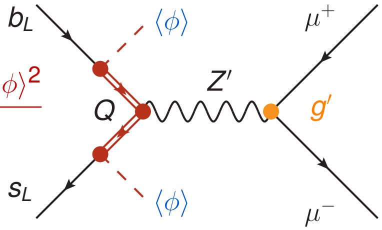
Implications for the New Physics Scale

unitarity bound	$\frac{4\pi}{\Lambda_{\rm NP}^2}(\bar{s}\gamma_\nu P_L b)(\bar{\mu}\gamma^\nu \mu)$	$\Lambda_{\rm NP} \simeq 120 \text{ TeV} \times (C_9^{\rm NP})^{-1/2}$
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	$\frac{1}{\Lambda_{\rm NP}^2}\frac{1}{16\pi^2}\, V_{tb}V_{ts}^*\, (\bar{s}\gamma_\nu P_L b)(\bar{\mu}\gamma^\nu \mu)$	$\Lambda_{\rm NP} \simeq 0.6 \text{ TeV} \times (C_9^{\rm NP})^{-1/2}$

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

WA, Gori, Pospelov, Yavin 1403.1269; WA, Yavin 1508.07009

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



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

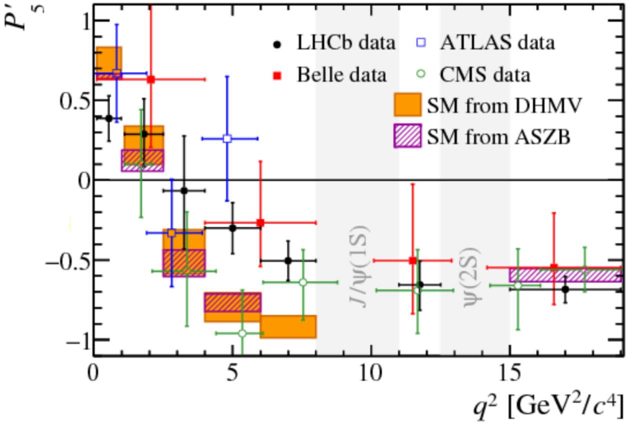
Q: heavy vectorlike fermions with mass $\sim 1 - 10$ TeV
ϕ: scalar that breaks $L_\mu - L_\tau$

Summary

- The LFU ratios $R_{D^{(*)}}$ and $R_{K^{(*)}}$ are theroretically clean.
- Experimental uncertainties are still statistics dominated.
- With more data we will be able to understand if these are first signs of new physics!

Back Up

The P_5' Anomaly



ASZB = WA, Straub 1411.3161 + Bharucha, Straub, Zwicky 1503.05534

DHMV = Descotes-Genon, Hofer, Matias, Virto 1510.04239

(talk by Tim Gershon at Moriond EW 2017)