Implications of B Physics Anomalies

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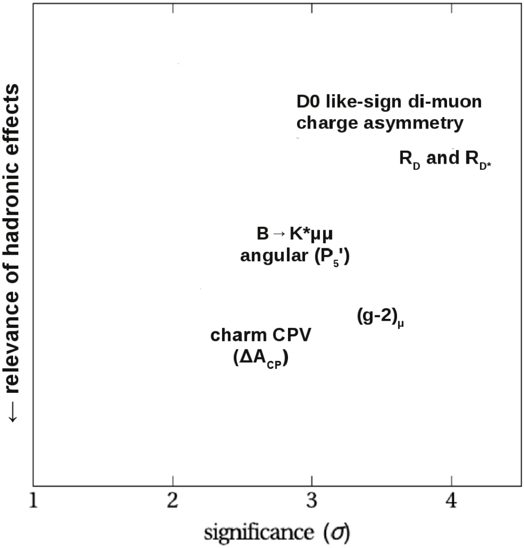
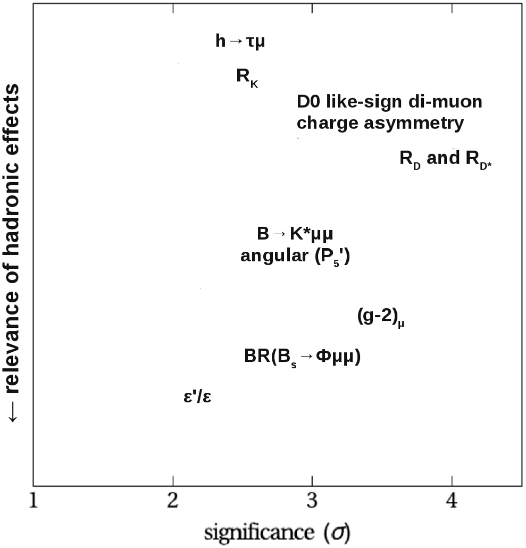
The State of Flavor Anomalies Winter 2014



adapted from
Zoltan Ligeti



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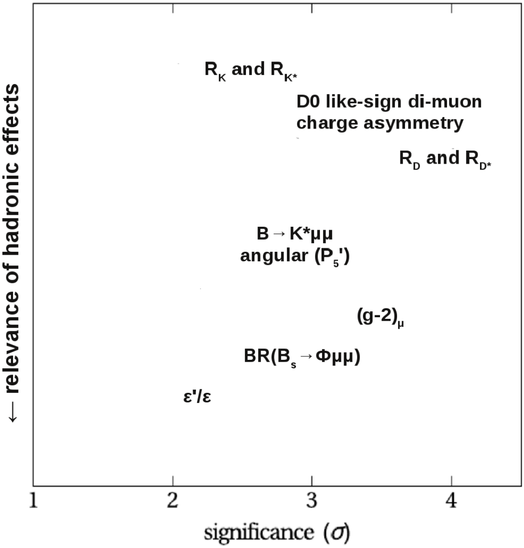
The State of Flavor Anomalies Winter 2018



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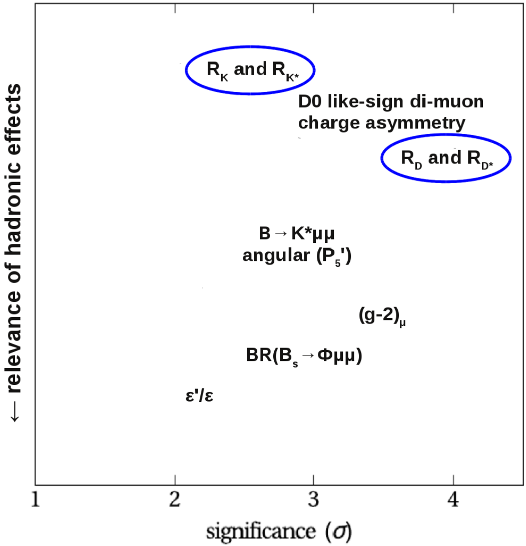
The State of Flavor Anomalies Winter 2018



adapted from

Zoltan Ligeti

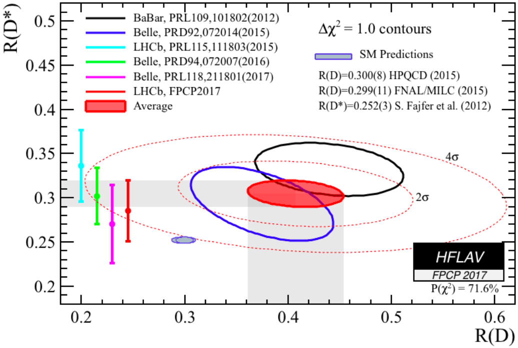
R_D and R_{D^*}

Lepton Universality tests in tree level charged current decays

$$b \to c\ell\nu$$

The Experimental Situation

world average from the heavy flavor averaging group



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

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

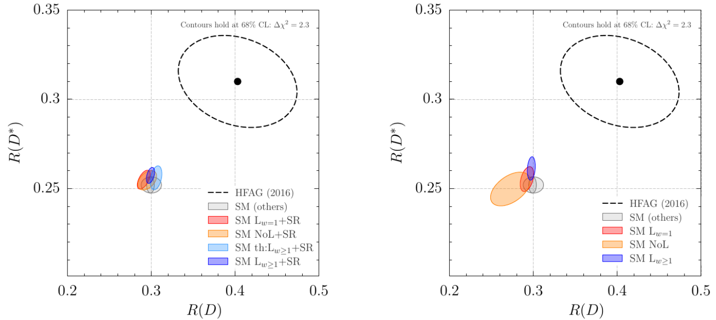
$\ell = \mu, e$ (BaBar/Belle)
$\ell = \mu$ (LHCb)

$$R_D^{\text{exp}} = 0.407 \pm 0.039 \pm 0.024 \ , \qquad R_{D^*}^{\text{exp}} = 0.304 \pm 0.013 \pm 0.007$$

discrepancies with the SM by 2.3σ 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

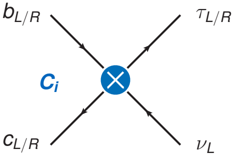
$$R_D^{\rm SM} = 0.298 \pm 0.003 \quad , \qquad R_{D^*}^{\rm SM} = 0.261 \pm 0.004$$

(see also Bigi, Gambino, Schacht 1707.09509; Jaiswal, Nandi, Patra 1707.09977)

relevance of QED corrections? de Boer, Kitahara, Nisandzic 1803.05881

Model Independent New Physics Analysis

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



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

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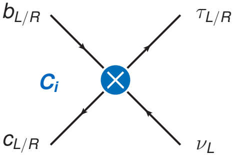
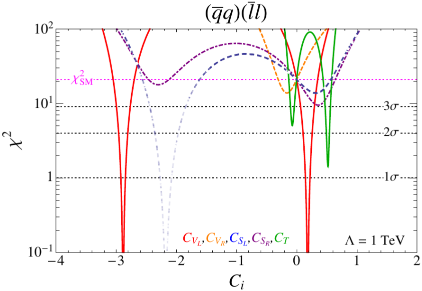


$\mathcal{O}_i$ = 4 fermion contact interactions with vector, scalar or tensor currents

rescaling of the SM operator fits the data best

combinations of operators are also possible



Freytsis, Ligeti, Ruderman 1506.08896

New Physics Effects can be Highly Non-Trivial

In the presence of New Physics, the measured R_D and R_{D^*} values become a moving target!

New Physics affects

- acceptances
- efficiencies
- backgrounds

Bernlochner, Ligeti, Robinson 1711.03110

$\rightarrow$ proper BSM fits can only be performed by the experimental collaborations

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Bernlochner, Ligeti, Robinson 1711.03110

→ proper BSM fits can only be performed by the experimental collaborations

tools are becoming available that allow an efficient reweighting of fully simulated events

Helicity Amplitude Module for Matrix Element Reweighting

Bernlochner, Duell, Ligeti, Papucci, Robinson

180?.?????

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

(MFV = Minimal Flavor Violation)

Many Constraints on New Physics Models

- the $B_c \to \tau\nu$ rate and the total B_c life-time strongly constrain scalar explanations of R_D and R_{D^*}

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

- in many models strong constraints are obtained from $pp \to \tau\tau$ searches at the LHC

  Faroughy, Greljo, Kamenik 1609.07138

- in many models one finds strong constraints from Z couplings, W couplings, or tau decays, etc. that are modified at the loop level

  Feruglio, Paradisi, Pattori 1606.00524 + 1705.00929

  Cornella, Feruglio, Paradisi 1803.00945

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$\to$ model building is very challenging

lepto-quarks? RPV SUSY? W' bosons?

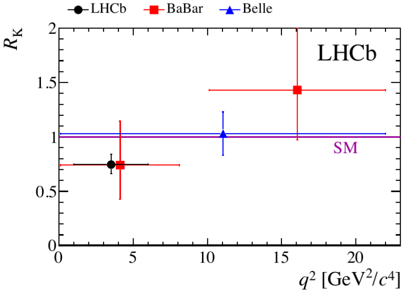
(... Greljo et al. 1506.01705; Bauer, Neubert 1511.01900; Deshpande, He 1608.04817; Bhattacharya et al. 1609.09078; WA, Dev, Soni 1704.06659; ...)

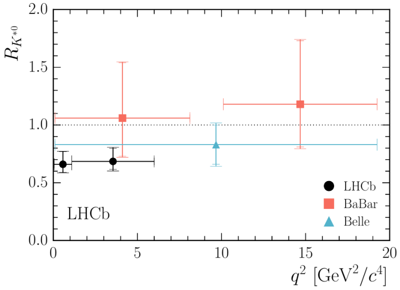
R_K and R_{K^*}

Lepton Universality tests in flavor changing neutral current decays

$$b \to s\ell\ell$$

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^*}

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

phase space
(tiny effect)

hadronic corrections
(tiny effect)

QED corrections
(soft and collinear photon emission)

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

$$R_{K^{(*)}} = 1 + \mathcal{O}\left(\frac{m_\mu^2}{q^2}\right) \times \left(1 + \mathcal{O}\left(\frac{\Lambda_{\rm QCD}}{m_b}\right) + \mathcal{O}(\alpha_s)\right) + \mathcal{O}\left(\frac{\alpha_{\rm em}}{\pi} \log^2\left(\frac{m_e^2}{m_\mu^2}\right)\right)$$

phase space (tiny effect)

hadronic corrections (tiny effect)

QED corrections (soft and collinear photon emission)

Bordone, Isidori, Pattori 1605.07633

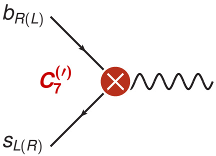
$$R_K^{[1,6]} = 1.00 \pm 0.01 \ , \quad R_{K^*}^{[1.1,6]} = 1.00 \pm 0.01 \ , \quad R_{K^*}^{[0.045,1.1]} = 0.91 \pm 0.03$$

- QED corrections seem to be well modeled by Monte Carlo (PHOTOS)

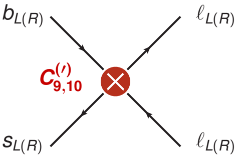
Model Independent New Physics Analysis

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

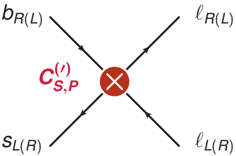
magnetic dipole operators



semileptonic operators



scalar operators



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

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

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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parity of the final state mesons implies:

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

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

Hiller, Schmaltz 1411.4773

Fits to Wilson Coefficients

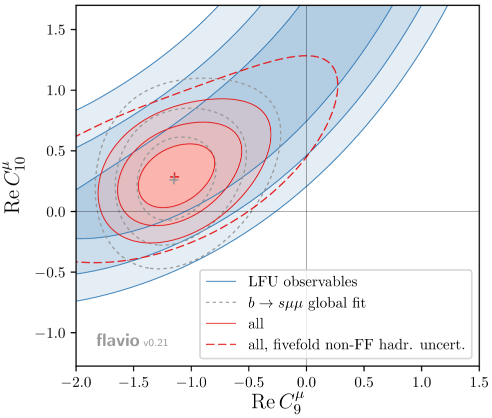
WA, Stangl, Straub 1704.05435

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;
Alok, Bhattacharya, Datta, Kumar, Kumar, London 1704.07397;
(+ many others, apologies for the omission...)

Compatibility with Other $b \to s\mu\mu$ Anomalies



WA, Stangl, Straub 1704.05435

WA, Niehoff, Stangl, Straub 1703.09189

(+ many others ...)

the LFU observables are **fully compatible** with other anomalies that are seen in $b \to s\mu\mu$ transitions ("P_5' and friends")

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

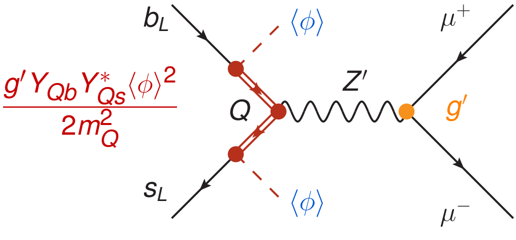
Implications for the New Physics Scale

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

My Favorite Model

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



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

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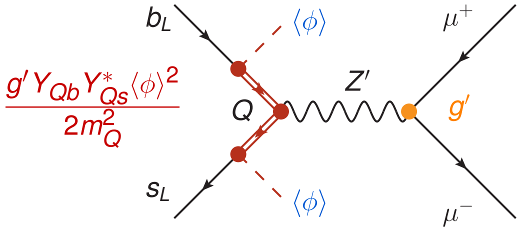
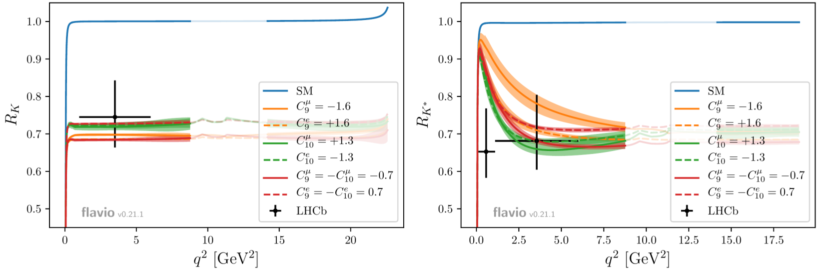


predicted Lepton Universality Violation!

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

The low q^2 Bin in R_{K^*}

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.
Hint for new light degrees of freedom?

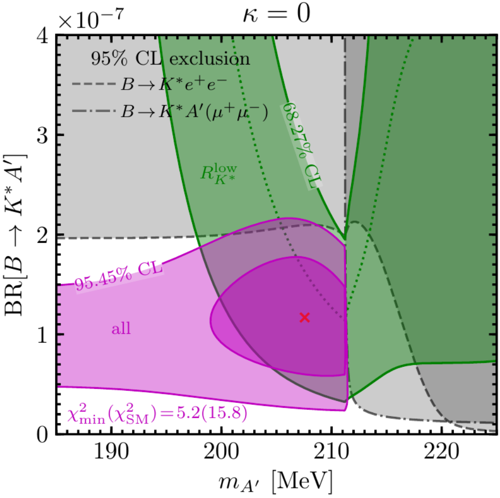
A Light Resonance at the Di-Muon Threshold?

Example: Dark photon* with $m_{A'} \sim 2m_\mu$

$B \to K^* A'$

$A' \to e^+ e^-$

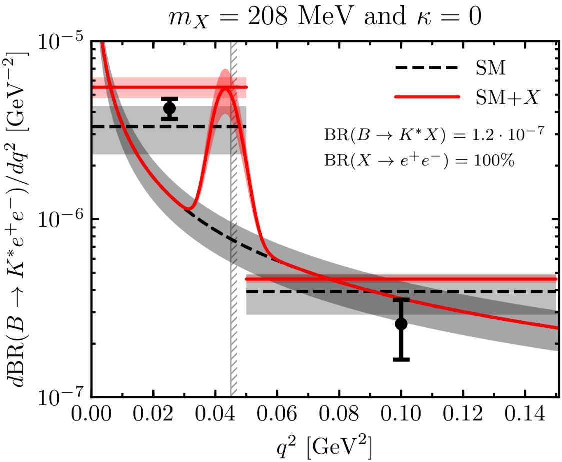
(* a dark photon that for some reason has a large flavor violating $b \to s$ coupling)



WA, Baker, Gori, Harnik, Pospelov, Stamou, Thamm 1711.07494

Smoking Gun Signature

Resonance in the di-electron spectrum in $B \to K^* e^+ e^-$
right around $q^2 \sim 4m_\mu^2$



WA, Baker, Gori, Harnik, Pospelov, Stamou, Thamm 1711.07494

Summary

- The LFU ratios $R_{D^{(*)}}$ and $R_{K^{(*)}}$ are theoretically clean probes of new sources of flavor violation.
- If anomalies are confirmed with more data from LHCb and Belle II
  $\rightarrow$ clear signs of new physics
- The low q^2 bin in R_{K^*} looks a bit funny ...

Back Up

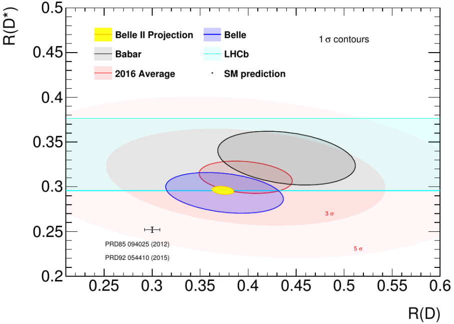
Prospects for R_D and R_{D^*}

- R_D measurement from LHCb
- cross checks with other hadronic systems

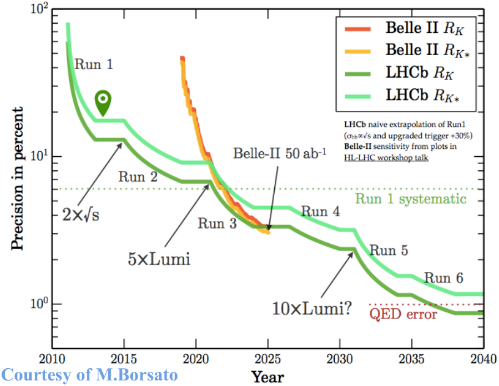
$$R_{J/\psi} = \frac{BR(B_c \to J/\psi \tau\nu)}{BR(B_c \to J/\psi \mu\nu)} = 0.71 \pm 0.17 \pm 0.18 \quad \text{(LHCb 1711.05623)}$$

$$R_{\Lambda_c} = \frac{BR(\Lambda_b \to \Lambda_c \tau\nu)}{BR(\Lambda_b \to \Lambda_c \mu\nu)}$$

- Belle II can significantly improve current $R_{D^{(*)}}$ uncertainties
- precise measurements of q^2 spectra, angular distributions, tau polarization, ...



- LHCb and Belle II can push uncertainties down to few percent
- with sufficient statistics, LFU of angular distrib. can be tested
- LHCb can cross check electron efficiencies with $\phi \to \mu\mu$ vs. $\phi \to ee$



- cross checks in many other modes:

$$R_\phi \ , \quad R_\Lambda \ , \quad R_{\Lambda^*} \ , \quad R_{K\pi\pi} \ , \quad \ldots$$