Developments in the Theory of Flavor Mixing and Rare Decays

Wolfgang Altmannshofer
altmanwg@ucmail.uc.edu

UNIVERSITY OF Cincinnati

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Flavor in the Standard Model and Beyond

$$\mathcal{L}_{\rm SM} \sim \Lambda^4 + \Lambda^2 H^2 + \lambda H^4$$

$$+ \bar{\Psi} \not{D} \Psi + (D_\mu H)^2 + (F_{\mu\nu})^2 + F_{\mu\nu} \tilde{F}^{\mu\nu}$$

$$+ Y H \bar{\Psi} \Psi$$

CC problem

Hierarchy problem

Vacuum stability?

Strong CP problem

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SM flavor puzzle

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SM flavor puzzle

Neutrino masses

NP flavor puzzle
...

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Neutrino masses

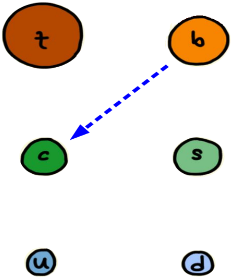
NP flavor puzzle
...

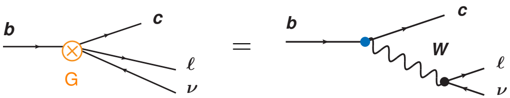
Q1: What is the origin of the hierarchies in the SM sources of flavor violation?

Q2: Are there other sources of flavor violation beyond the SM?

Flavor Changing Quark Decays in the SM

In the Standard Model, flavor changing charged current decays arise at the tree level; rates are suppressed by small CKM elements





$$G \sim G_F V_{cb}$$

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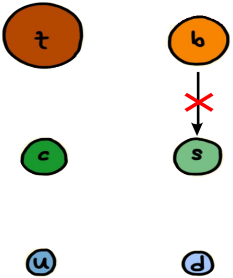
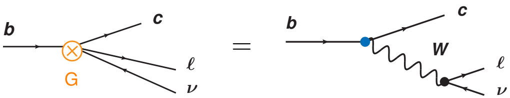


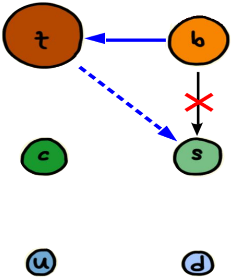


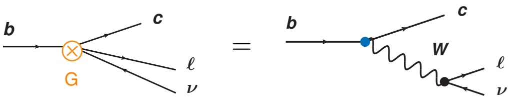
$$G \sim G_F V_{cb}$$

Flavor Changing Quark Decays in the SM

In the Standard Model, flavor changing charged current decays arise at the tree level; rates are suppressed by small CKM elements

Flavor changing neutral current decays can arise at the loop level; they are suppressed by loop factors and small CKM elements





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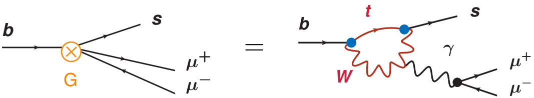
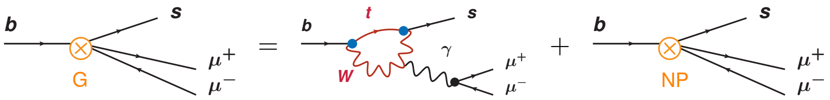


$$G \sim \frac{e^2}{16\pi^2} G_F \frac{m_t^2}{m_W^2} V_{tb} V_{ts}^*$$

New Physics in B Decays

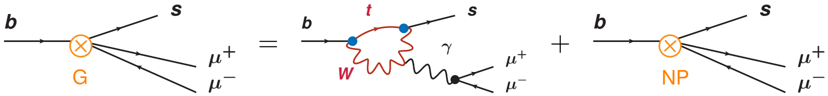


$$G \sim \frac{e^2}{16\pi^2} G_F \frac{m_t^2}{m_W^2} V_{tb} V_{ts}^* + \frac{C_{NP}}{\Lambda_{NP}^2}$$

measure precisely

calculate precisely the SM contribution

get information on NP coupling and scale



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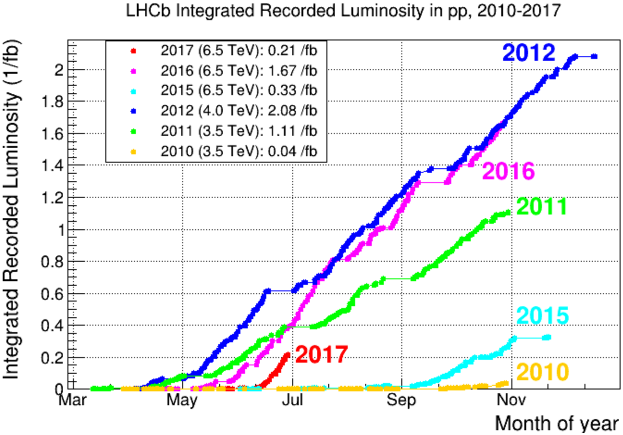
measure precisely	calculate precisely the SM contribution	get information on NP coupling and scale

Anomalies in B decays could establish a new scale in particle physics

LHC is a "b-factory"



more than $\sim 10^{12}$ b quarks produced in the LHCb detector so far

$\Rightarrow$ unique sensitivity to many b decays

Theory Predictions

SM predictions for b hadron decays require non-perturbative input

1. form factors ($\rightarrow$ lattice QCD)
2. non-factorizable effects (sometimes only estimates exist)

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clever way to reduce/eliminate hadronic uncertainties:
lepton flavor universality (LFU) tests

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

LFU ratios of
charged current decays

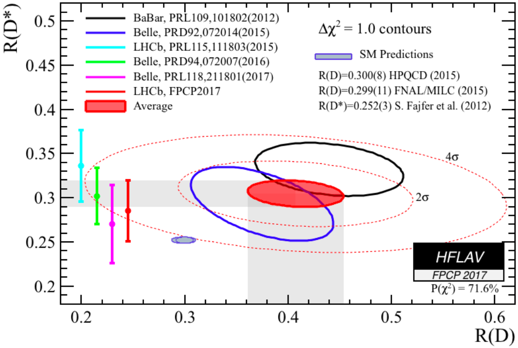
$$R_{K^{(*)}} = \frac{BR(B \to K^{(*)}\mu\mu)}{BR(B \to K^{(*)}ee)}$$

LFU ratios of
neutral current decays

R_D and R_{D^*}

The Experimental Situation

world average from the heavy flavor averaging group



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

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

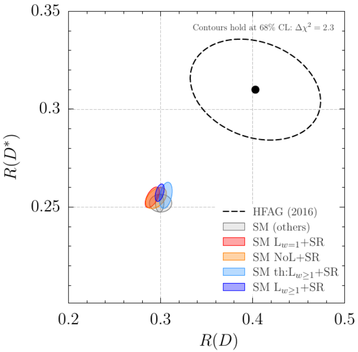
$\ell = \mu, e$ (BaBar/Belle)
$\ell = \mu$ (LHCb)

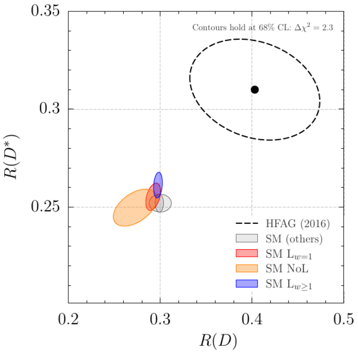
$$R_D^{\rm exp} = 0.407 \pm 0.039 \pm 0.024 \ , \qquad R_{D^*}^{\rm exp} = 0.304 \pm 0.013 \pm 0.007$$

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





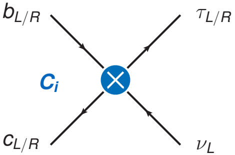
heavy quark expansion + $B \to D^{(*)}\ell\nu$ data + lattice input + QCD sum rule input

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

(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

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



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

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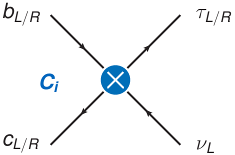

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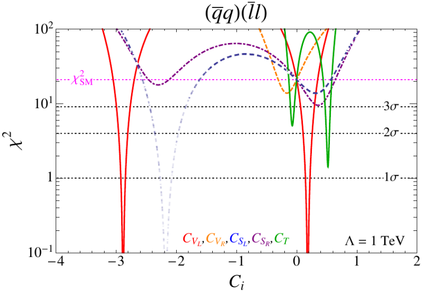
rescaling of the SM operator fits the data best

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

(MFV = Minimal Flavor Violation)

Many Constraints on New Physics Models

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

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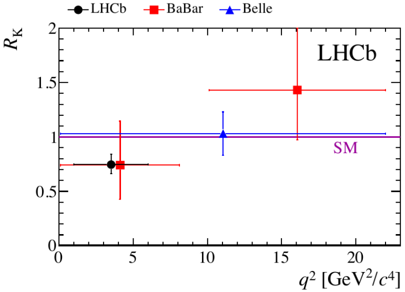
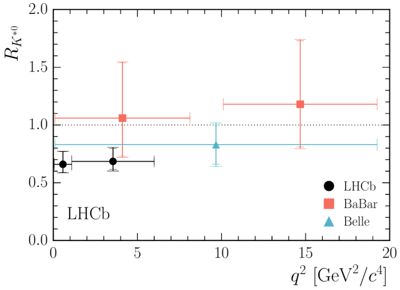
$\to$ model building is non-trivial

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^*}

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

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

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

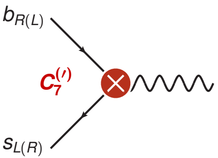
$$R_K^{[1,6]} = 1.00 \pm 0.01 \;, \quad R_{K^*}^{[1.1,6]} = 1.00 \pm 0.01 \;, \quad R_{K^*}^{[0.045,1.1]} = 0.91 \pm 0.03$$

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

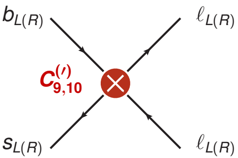
Model Independent New Physics Analysis

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

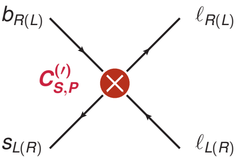
magnetic dipole operators



semileptonic operators



scalar operators



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

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

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

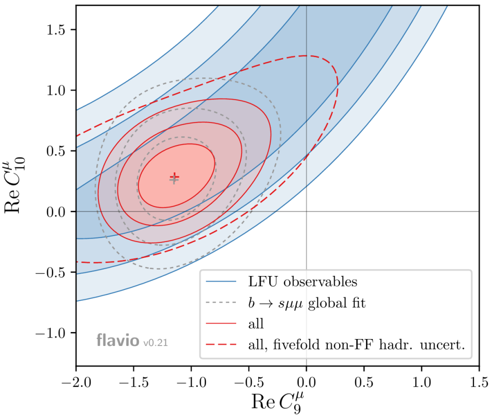
WA, Stangl, Straub 1704.05435

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;
(+ 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

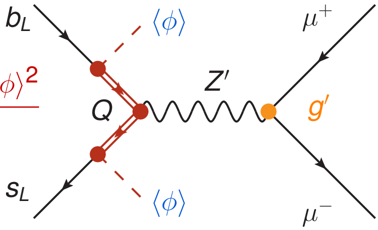
Implications for the New Physics Scale

unitarity bound	$\frac{4\pi}{\Lambda_{\text{NP}}^2}(\bar{s}\gamma_\nu P_L b)(\bar{\mu}\gamma^\nu \mu)$	$\Lambda_{\text{NP}} \simeq 120\text{ TeV} \times (C_9^{\text{NP}})^{-1/2}$
generic tree	$\frac{1}{\Lambda_{\text{NP}}^2}(\bar{s}\gamma_\nu P_L b)(\bar{\mu}\gamma^\nu \mu)$	$\Lambda_{\text{NP}} \simeq 35\text{ TeV} \times (C_9^{\text{NP}})^{-1/2}$
MFV tree	$\frac{1}{\Lambda_{\text{NP}}^2}\, V_{tb}V_{ts}^*\, (\bar{s}\gamma_\nu P_L b)(\bar{\mu}\gamma^\nu \mu)$	$\Lambda_{\text{NP}} \simeq 7\text{ TeV} \times (C_9^{\text{NP}})^{-1/2}$
generic loop	$\frac{1}{\Lambda_{\text{NP}}^2}\frac{1}{16\pi^2}(\bar{s}\gamma_\nu P_L b)(\bar{\mu}\gamma^\nu \mu)$	$\Lambda_{\text{NP}} \simeq 3\text{ TeV} \times (C_9^{\text{NP}})^{-1/2}$
MFV loop	$\frac{1}{\Lambda_{\text{NP}}^2}\frac{1}{16\pi^2}\, V_{tb}V_{ts}^*\, (\bar{s}\gamma_\nu P_L b)(\bar{\mu}\gamma^\nu \mu)$	$\Lambda_{\text{NP}} \simeq 0.6\text{ TeV} \times (C_9^{\text{NP}})^{-1/2}$

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 vector-like fermions with mass $\sim 1 - 10$ TeV
ϕ: scalar that breaks $L_\mu - L_\tau$

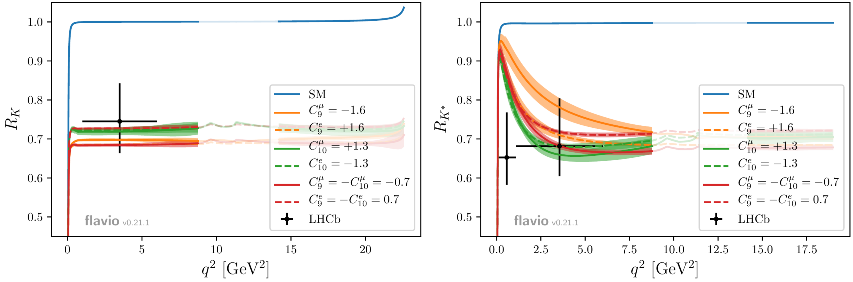
Summary

- The LFU ratios $R_{D^{(*)}}$ and $R_{K^{(*)}}$ are theoretically clean probes of new sources of flavor violation.
- Experimental uncertainties are still statistics dominated.
- With more data from LHCb and Belle II we will be able to understand if these are signs of new physics!

Back Up

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

WA, Stangl, Straub 1704.05435



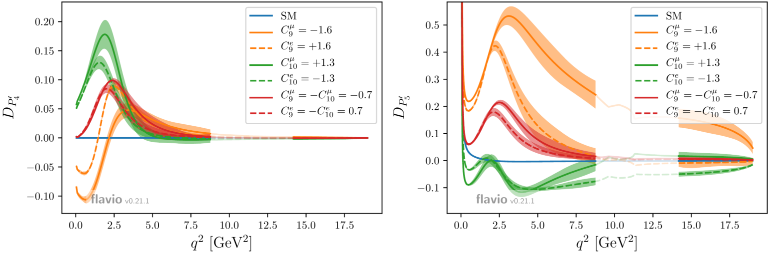
$B \to K^* \ell^+ \ell^-$ decays at low q^2 are dominated by the (lepton flavor universal) photon pole $B \to K^* \gamma$

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

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

Distinguishing New Physics Scenarios

WA, Stangl, Straub 1704.05435



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

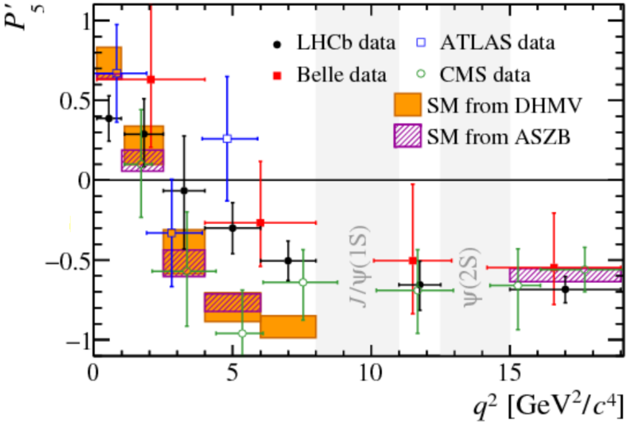
(for additional proposals of angular LFU tests see e.g.

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

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)