B Physics Anomalies 2019

18-23 August 2019

SANDPINE, Gangneung, Korea

1. Anomalies in B Decays

2. Standard Model and Beyond for B Physics

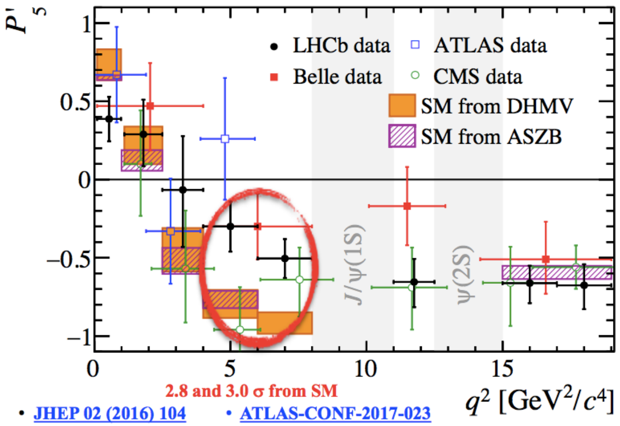
3. Models for $R(D^{(*)})$ and $b \to s\ \mu^+\mu^-$ Anomalies

4. Conclusions

1. Anomalies in B Decays

B physics anomalies Previously

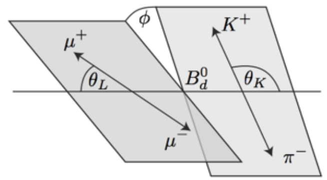
B -> K* μ μ

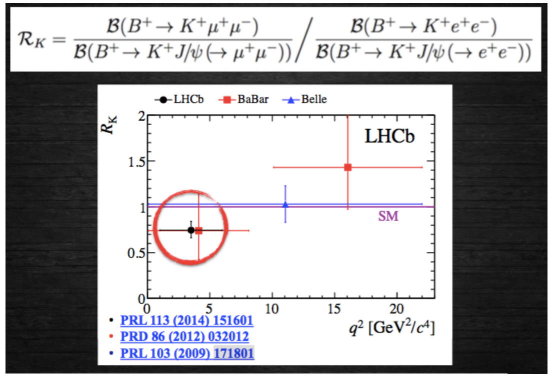


- JHEP 02 (2016) 104
- PRL 118 (2017)
- ATLAS-CONF-2017-023
- CMS-PAS-BPH-15-008

$$\frac{1}{\mathrm{d}\Gamma/\mathrm{d}q^2}\frac{\mathrm{d}^4\Gamma}{\mathrm{d}\cos\theta_L\,\mathrm{d}\cos\theta_K\,\mathrm{d}\phi\,\mathrm{d}q^2} = \frac{9}{32\pi}\Big[\frac{3(1-F_L)}{4}\sin^2\theta_K + F_L\cos^2\theta_K + \frac{1-F_L}{4}\sin^2\theta_K\cos 2\theta_L$$
$$-F_L\cos^2\theta_K\cos 2\theta_L + S_3\sin^2\theta_K\sin^2\theta_L\cos 2\phi$$
$$+S_4\sin 2\theta_K\sin 2\theta_L\cos\phi + S_5\sin 2\theta_K\sin\theta_L\cos\phi$$
$$+S_6\sin^2\theta_K\cos\theta_L + S_7\sin 2\theta_K\sin\theta_L\sin\phi$$
$$+S_8\sin 2\theta_K\sin 2\theta_L\sin\phi + S_9\sin^2\theta_K\sin^2\theta_L\sin 2\phi\Big].$$

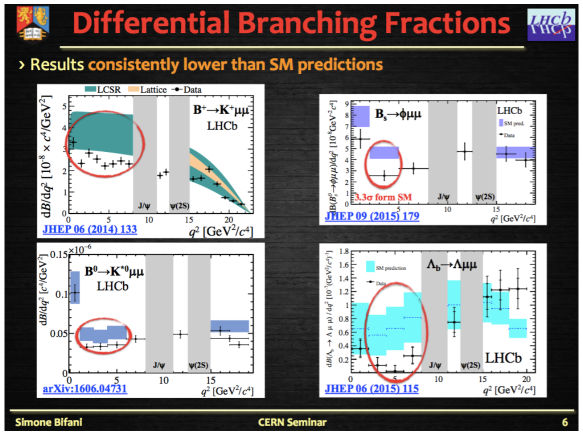
$$P_1 = \frac{2S_3}{1-F_L}$$
$$P_2 = \frac{2}{3}\frac{A_{FB}}{1-F_L}$$
$$P_3 = -\frac{S_9}{1-F_L}$$
$$P'_{i=4,5,6,8} = \frac{S_{j=4,5,7,8}}{\sqrt{F_L(1-F_L)}}.$$

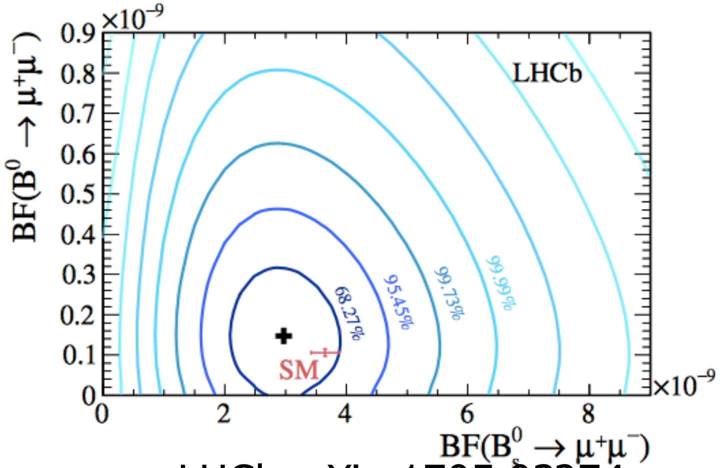




$R_K = 0.745^{+0.090}_{-0.074}\,(\text{stat}) \pm 0.036\,(\text{syst})$

$1\ \text{GeV}^2 < q^2 < 6\ \text{GeV}^2,$





LHCb arXiv:1705.03274

New data on B_s -> $\mu^+\mu^-$ from LHCb, lowered the differences

$\overline{\mathcal{B}}(B_s\to\mu^+\mu^-)_{\rm LHCb} = (3.0\pm 0.6^{+0.3}_{-0.2})\times 10^{-9}$,

$\overline{\mathcal{B}}(B_s\to\mu^+\mu^-)_{\rm CMS} = (3.0^{+1.0}_{-0.9}\times 10^{-9}$,

$\overline{\mathcal{B}}(B_s\to\mu^+\mu^-)_{\rm avrage} = (3.0\pm 0.5)\times 10^{-9}$,

$B(B_s\to\mu^+\mu^-)=(3.65\pm0.23)\times10^{-9}$.

$B(B_d\to\mu^+\mu^-)=(1.06\pm0.09)\times10^{-10}$

[Bobeth et al, PRL 112 (2014) 101801]

All these processes are induced by b -> s ll interaction.

Consistently lower than SM predictions. Combined effects are now about 4σ !

2017: The R_{K*} Anomaly previously

S. Bifani, CERN Seminar, 18th April, 2017

› $R_{K^{*0}}$ determined as double ratio to reduce systematic effects

$$\mathcal{R}_{K^{*0}} = \frac{\mathcal{B}(B^0 \to K^{*0}\mu^+\mu^-)}{\mathcal{B}(B^0 \to K^{*0}J/\psi(\to \mu^+\mu^-))} \Big/ \frac{\mathcal{B}(B^0 \to K^{*0}e^+e^-)}{\mathcal{B}(B^0 \to K^{*0}J/\psi(\to e^+e^-))}$$

› Control of the absolute scale of the efficiencies via the ratio

$$r_{J/\psi} = \frac{\mathcal{B}(B^0 \to K^{*0}J/\psi(\to \mu^+\mu^-))}{\mathcal{B}(B^0 \to K^{*0}J/\psi(\to e^+e^-))}$$

which is expected to be unity and measured to be

$$1.043 \pm 0.006\,(\text{stat}) \pm 0.045\,(\text{syst})$$

LHCb Preliminary	low-q^2	central-q^2
$\mathcal{R}_{K^{*0}}$	$0.660\ ^{+\ 0.110}_{-\ 0.070} \pm 0.024$	$0.685\ ^{+\ 0.113}_{-\ 0.069} \pm 0.047$
95% CL	[0.517–0.891]	[0.530–0.935]
99.7% CL	[0.454–1.042]	[0.462–1.100]

LHCb arXiv: 1705.05802

$R_{K^{(*)}}$ anomalies in earlier data

Previous R_{K^*} and R_K results (LHCb Run 1 data)

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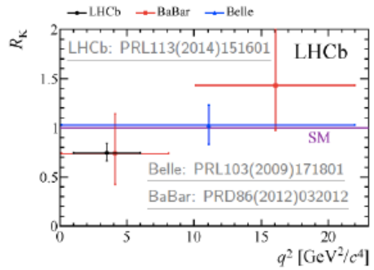
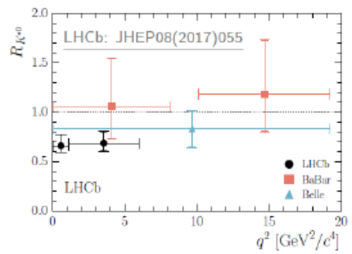
T Humair @ Moriond 2019





All LHCb results below SM expectations:

- $R_K = 0.745^{+0.090}_{-0.074} \pm 0.036$ for $1.0 < q^2 < 6.0\ \text{GeV}^2$, $\sim 2.6\,\sigma$ from SM;
- $R_{K^*} = 0.66^{+0.11}_{-0.07} \pm 0.03$ for $0.045 < q^2 < 1.1\ \text{GeV}^2$, $\sim 2.2\,\sigma$ from SM;
- $R_{K^*} = 0.69^{+0.11}_{-0.07} \pm 0.05$ for $1.1 < q^2 < 6.0\ \text{GeV}^2$, $\sim 2.4\,\sigma$ from SM;

Together with $b \to s\mu\mu$ results, R_K and R_{K^*} constitute an interesting pattern of anomalies, but the significance is still low.

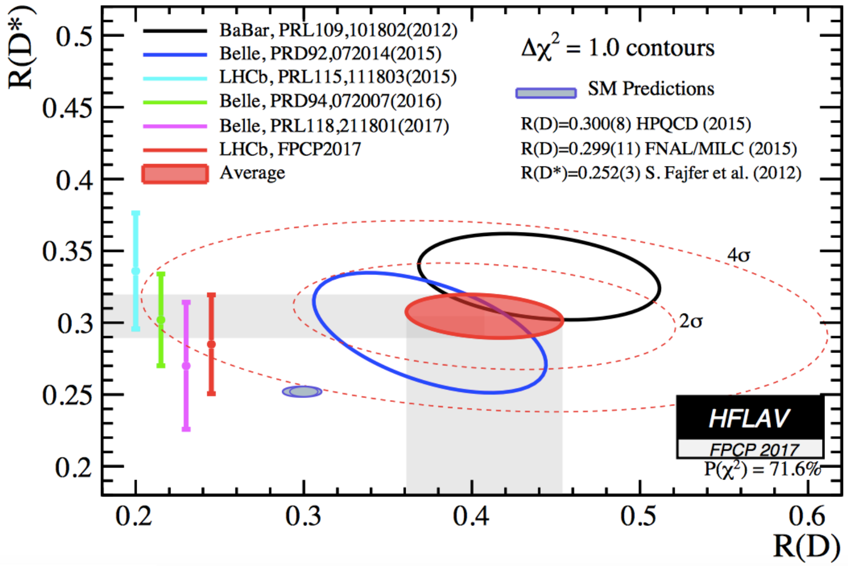
$$R_{K^{(*)}} = \frac{\mathcal{B}(B \to K^{(*)}\mu^+\mu^-)}{\mathcal{B}(B \to K^{(*)}e^+e^-)} \overset{\text{SM}}{=} 1.0$$

R(D(*)) anomalies (previously)

$$R(D^{(*)}) = \frac{Br(D^{(*)} \to \tau\bar{\nu}_\tau)}{Br(D^{(*)} \to l\bar{\nu})}$$

$$R(D) = \frac{B(\bar{B} \to D\tau^-\bar{\nu}_\tau)}{B(\bar{B} \to D\ell^-\bar{\nu}_\ell)} = 0.407 \pm 0.039 \pm 0.024$$

$$R(D^\star) = \frac{B(\bar{B} \to D^\star\tau^-\bar{\nu}_\tau)}{B(\bar{B} \to D^\star\ell^-\bar{\nu}_\ell)} = 0.304 \pm 0.013 \pm 0.007$$



4σ effects!

$$R(J/\psi) = \frac{B(B_c^+ \to J/\psi\tau^+\nu_\tau)}{B(B_c^+ \to J/\psi\mu^+\nu_\mu)} = 0.71 \pm 0.17 \pm 0.18$$

R. Aaij *et al.* [LHCb Collaboration], arXiv:1711.05623 [hep-ex]

SM prediction

$$R(J/\psi) = 0.283 \pm 0.048$$

What's new in 2019?

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

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

New results: R_K from LHCb

R_K result with 2011 to 2016 data LHCb-Paper-2019-009

Imperial College London

T Humair @ Moriond 2019

Using 2011 and 2012 LHCb data, R_K was:

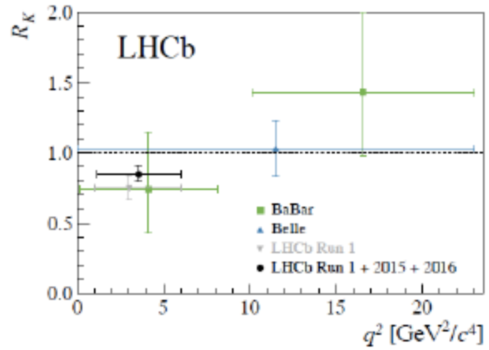
$$R_K = 0.745^{+0.090}_{-0.074}(\text{stat.}) \pm 0.036(\text{syst.}),$$

$\sim 2.6\,\sigma$ from SM (PRL113(2014)151601).

Adding 2015 and 2016 data, R_K becomes:

$$\boldsymbol{R_K = 0.846\ ^{+0.060}_{-0.054}(\text{stat.})\ ^{+0.016}_{-0.014}(\text{syst.})}$$

$\sim$ **2.5** σ from SM.



Search for lepton-universality violation in $B^+ \to K^+\ell^+\ell^-$ decays

LHCb collaboration[†]

Abstract

A measurement of the ratio of branching fractions of the decays $B^+ \to K^+\mu^+\mu^-$ and $B^+ \to K^+e^+e^-$ is presented. The proton-proton collision data used correspond to an integrated luminosity of 5.0 fb^{-1} recorded with the LHCb experiment at centre-of-mass energies of 7, 8 and 13 TeV. For the dilepton mass-squared range $1.1 < q^2 < 6.0\,\text{GeV}^2/c^4$ the ratio of branching fractions is measured to be $R_K = 0.846\,^{+0.060}_{-0.054}\,^{+0.016}_{-0.014}$, where the first uncertainty is statistical and the second systematic. This is the most precise measurement of R_K to date and is compatible with the Standard Model at the level of 2.5 standard deviations.

New results: R_K from LHCb

Branching fractions and other results LHCb-Paper-2019-009

Imperial College London

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If instead the Run 1 and Run 2 were fitted separately:

$$R_{K\ \text{Run 1}}^{\text{new}} = 0.717^{+0.083}_{-0.071}{}^{+0.017}_{-0.016}, \quad R_{K\ \text{Run 2}} = 0.928^{+0.089}_{-0.076}{}^{+0.020}_{-0.017},$$

$$R_{K\ \text{Run 1}}^{\text{old}} = 0.745^{+0.090}_{-0.074} \pm 0.036 \quad \text{(PRL113(2014)151601)}\ .$$

Compatibility taking correlations into account:

- Previous Run 1 result vs. this Run 1 result (new reconstruction selection): $< 1\,\sigma$;
- Run 1 result vs. Run 2 result: 1.9 σ.

$B^+ \to K^+\mu^+\mu^-$ **branching fraction**:

- Compatible with previous result (JHEP06(2014)133) at $< 1\,\sigma$;
- Run 1 and Run 2 results compatible at $< 1\,\sigma$.

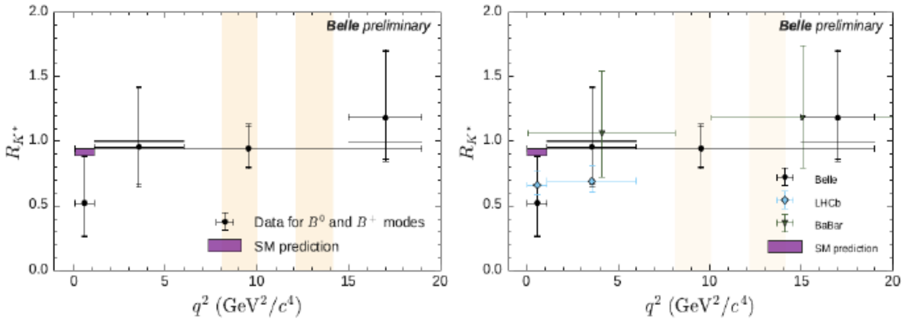
Test of lepton flavor universality in $B \to K^* \ell^+ \ell^-$ decays at Belle

arXiv:1904.02440

We present a measurement of R_{K^*}, the ratio of the branching fractions $\mathcal{B}(B \to K^* \mu^+ \mu^-)$ and $\mathcal{B}(B \to K^* e^+ e^-)$, for both charged and neutral B mesons. The ratio for charged B mesons, $R_{K^{*+}}$, is the first measurement ever performed. The analysis is based on a data sample of 711 fb^{-1}, containing 772×10^6 $B\bar{B}$ events, recorded at the $\Upsilon(4S)$ resonance with the Belle detector at the KEKB asymmetric-energy e^+e^- collider. The obtained results are compatible with standard model expectations.

$R(K^*)$: (Preliminary) Result

M Prim @ Moriond 2019



q^2 in GeV^2/c^4	All modes	B^0 modes	B^+ modes
[0.045, 1.1]	$0.52^{+0.36}_{-0.26} \pm 0.05$	$0.46^{+0.55}_{-0.27} \pm 0.07$	$0.62^{+0.60}_{-0.36} \pm 0.10$
[1.1, 6]	$0.96^{+0.45}_{-0.29} \pm 0.11$	$1.06^{+0.63}_{-0.38} \pm 0.13$	$0.72^{+0.99}_{-0.44} \pm 0.18$
[0.1, 8]	$0.90^{+0.27}_{-0.21} \pm 0.10$	$0.86^{+0.33}_{-0.24} \pm 0.08$	$0.96^{+0.56}_{-0.35} \pm 0.14$
[15, 19]	$1.18^{+0.52}_{-0.32} \pm 0.10$	$1.12^{+0.61}_{-0.36} \pm 0.10$	$1.40^{+1.99}_{-0.68} \pm 0.11$
[0.045,]	$0.94^{+0.17}_{-0.14} \pm 0.08$	$1.12^{+0.27}_{-0.21} \pm 0.09$	$0.70^{+0.24}_{-0.19} \pm 0.07$

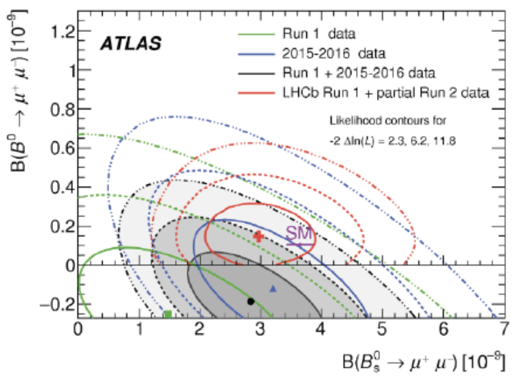
- All measured values are in accordance with the SM and other recent measurements.
- First measurement of R(K^{*+}).

Bs -> $\mu^+\mu^-$ from ATLAS

Results

ATLAS, arXiv:1812.03017

O Igonkina @ Moriond 2019



- SM :
  - Br($B_s \to \mu\mu$) =(3.65±0.23)x10^{-9}
  - Br($B^0 \to \mu\mu$) =(1.06±0.09)x10^{-10}
- Best fit of Run 2 data :
  - Br($B_s \to \mu\mu$) =(3.2±0.9)x10^{-9}
  - Br($B^0 \to \mu\mu$) =(-1.3±2.1)x10^{-10}
- Run 1 + Run 2 result @ 95% CL
  - Br($B_s \to \mu\mu$) =(2.8±0.8)x10^{-9}
  - Br($B^0 \to \mu\mu$) < 2.1x10^{-10}

PDG 2018: $\mathcal{B}(B_s \to \mu\mu) = (2.7^{+0.6}_{-0.5}) \times 10^{-9}$

B^0 limit is most stringent at the moment

Processes induced by b -> s ll interaction are still consistently lower than SM predictions. Combined effects are about 3.8σ !

Measurement of $\mathcal{R}(D)$ and $\mathcal{R}(D^*)$ with a semileptonic tagging method arXiv:1904.08794

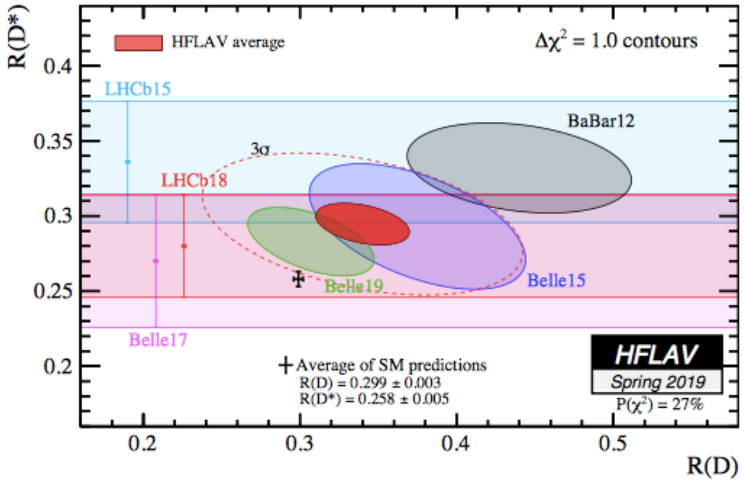
We report a measurement of the ratios of branching fractions $\mathcal{R}(D) = \mathcal{B}(\bar{B} \to D\tau^-\bar{\nu}_\tau)/\mathcal{B}(\bar{B} \to D\ell^-\bar{\nu}_\ell)$ and $\mathcal{R}(D^*) = \mathcal{B}(\bar{B} \to D^*\tau^-\bar{\nu}_\tau)/\mathcal{B}(\bar{B} \to D^*\ell^-\bar{\nu}_\ell)$, where ℓ denotes an electron or a muon. The results are based on a data sample containing 772×10^6 $B\bar{B}$ events recorded at the $\Upsilon(4S)$ resonance with the Belle detector at the KEKB e^+e^- collider. The analysis utilizes a method where the tag-side B meson is reconstructed in a semileptonic decay mode, and the signal-side τ is reconstructed in a purely leptonic decay. The measured values are $\mathcal{R}(D) = 0.307 \pm 0.037 \pm 0.016$ and $\mathcal{R}(D^*) = 0.283 \pm 0.018 \pm 0.014$, where the first uncertainties are statistical and the second are systematic. These results are in agreement with the Standard Model predictions within 0.2 and 1.1 standard deviations, respectively, while their combination agrees with the Standard Model predictions within 1.2 standard deviations.

$$F^L_{D^*} = \frac{\Gamma(\bar{B} \to D^*_L \tau\nu)}{\Gamma(\bar{B} \to D^* \tau\nu)}$$

$$(F^L_{D^*})^{SM} = 0.457 \pm 0.010$$

arXiv:1903.03102
1.7σ deviation

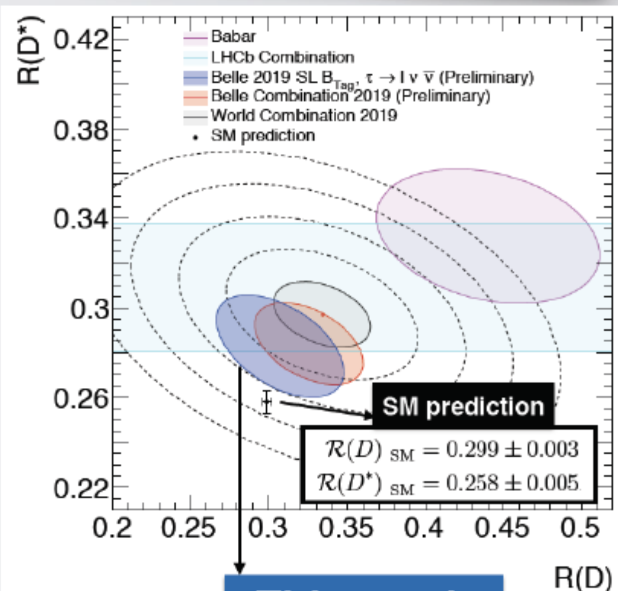
$$F^L_{D^*} = 0.60 \pm 0.08\ (\text{stat}) \pm 0.035\ (\text{sys})$$



Still 3.1 sigma effect for world average.

Preliminary $R_{D^{(*)}}$ results from Belle — G Caria @ Moriond 2019

- **Most precise measurement** of R(D) and R(D*) to date
- First **R(D)** measurement performed with a **semileptonic tag**
- Results **compatible with SM** expectation within **1.2σ**
- **R(D) - R(D*) Belle average** is now within **2σ** of the SM prediction
- **R(D) - R(D*) exp. world average** tension with SM expectation **decreases from 3.8σ to 3.1σ**



This result

$$\mathcal{R}(D) = 0.307 \pm 0.037 \pm 0.016$$
$$\mathcal{R}(D^*) = 0.283 \pm 0.018 \pm 0.014$$

What Anomalies tell us?

anomaly – Cambridge Dictionary

noun [C or U] · UK /əˈnɒm.ə.li/ US /əˈnɑː.mə.li/ FORMAL

a person or thing that is different from what is usual, or not in agreement with something else and therefore not satisfactory:

Statistical anomalies can make it difficult to compare economic data from one year to the next.

The anomaly of the social security system is that you sometimes have more money without a job.

B decays that are different from SM predictions and therefore not satisfactory.

The B physics anomalies might be some hints of something more that just SM.

Will these anomalies stand with time??? More Data!!!

Measurement of the branching ratio of $\bar{B} \to D^{(*)}\tau^-\bar{\nu}_\tau$ relative to $\bar{B} \to D^{(*)}\ell^-\bar{\nu}_\ell$ decays with hadronic tagging at Belle
Belle Collaboration (M. Huschle (Karlsruhe U., EKP) *et al.*). Jul 12, 2015. 14 pp.
Published in **Phys.Rev. D92 (2015) no.7, 072014**
KEK-REPORT-2015-18
DOI: 10.1103/PhysRevD.92.072014
e-Print: **arXiv:1507.03233** [hep-ex] | **PDF**
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
ADS Abstract Service; OSTI.gov Server; Link to Scientific American article
Detailed record - Cited by 476 records 250+

Evidence for an excess of $\bar{B} \to D^{(*)}\tau^-\bar{\nu}_\tau$ decays
BaBar Collaboration (J.P. Lees (Annecy, LAPP) *et al.*). May 2012. 8 pp.
Published in **Phys.Rev.Lett. 109 (2012) 101802**
BABAR-PUB-12-012, SLAC-PUB-15028
DOI: 10.1103/PhysRevLett.109.101802
e-Print: **arXiv:1205.5442** [hep-ex] | **PDF**
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
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ed by 664 records 500+

Measurement of the ratio of branching fractions $\mathcal{B}(\bar{B}^0 \to D^{*+}\tau^-\bar{\nu}_\tau)/\mathcal{B}(\bar{B}^0 \to D^{*+}\mu^-\bar{\nu}_\mu)$
LHCb Collaboration (Roel Aaij (CERN) *et al.*). Jun 29, 2015. 10 pp.
Published in **Phys.Rev.Lett. 115 (2015) no.11, 111803**, Erratum: **Phys.Rev.Lett. 115 (**
CERN-PH-EP-2015-150, LHCB-PAPER-2015-025
DOI: 10.1103/PhysRevLett.115.159901, 10.1103/PhysRevLett.115.111803
e-Print: **arXiv:1506.08614** [hep-ex] | **PDF**
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
CERN Document Server; ADS Abstract Service; Link to livescience article; Link
Detailed record - Cited by 580 records 500+

Test of lepton universality using $B^+ \to K^+\ell^+\ell^-$ decays
LHCb Collaboration (Roel Aaij (NIKHEF, Amsterdam) *et al.*). Jun 25, 2014. 10 pp.
Published in **Phys.Rev.Lett. 113 (2014) 151601**
CERN-PH-EP-2014-140, LHCB-PAPER-2014-024
DOI: 10.1103/PhysRevLett.113.151601
e-Print: **arXiv:1406.6482** [hep-ex] | **PDF**
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
CERN Document Server; ADS Abstract Service
Detailed record - Cited by 802 records 500+

Angular analysis of the $B^0 \to K^{*0}\mu^+\mu^-$ decay using 3 fb^{-1}
LHCb Collaboration (Roel Aaij (CERN) *et al.*). Dec 14, 2015.
Published in **JHEP 1602 (2016) 104**
CERN-PH-EP-2015-314, LHCB-PAPER-2015-051
DOI: 10.1007/JHEP02(2016)104
e-Print: **arXiv:1512.04442** [hep-ex] | **PDF**
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
CERN Document Server; ADS Abstract Service; Link to Article from SCOAP3; Link to Figures, tables and
Data: INSPIRE | HepData
Detailed record - Cited by 453 records 250+

Lepton-Flavor-Dependent Angular Analysis of $B \to K^*\ell^+\ell^-$
Belle Collaboration (S. Wehle (DESY) *et al.*). Dec 15, 20
Published in **Phys.Rev.Lett. 118 (2017) no.11, 111801**
BELLE-PREPRINT-2016-15, KEK-PREPRINT-2016-54
DOI: 10.1103/PhysRevLett.118.111801
e-Print: **arXiv:1612.05014** [hep-ex] | **PDF**
References | BibTeX | LaTeX(US) | LaTeX(EU) | H
ADS Abstract Service
Detailed record - Cited by 197 records 100+

Search for lepton-universality violation in $B^+ \to K^+\ell^+\ell^-$ decays
LHCb Collaboration (Roel Aaij (NIKHEF, Amsterdam) *et al.*). Mar 21, 2019. 28 pp.
LHCb-PAPER-2019-009, CERN-EP-2019-043
e-Print: **arXiv:1903.09252** [hep-ex] | **PDF**
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
CERN Document Server; ADS Abstract Service
Detailed record - Cited by 16 records

After 2019 new data

Citing LHCb R_K arXiv: 1903.09252: 1903.03016;1093.09632;1903.10086; 1903.10440;1903.10434;1903.10302;1903.10932;1093.11517;1903.05890;1904.08399; 1904.10954;1905.00315;1905.04074;1905.04046;1905.06339;1905.06614;1905.07690; 1905.07982…

Citing Belle R_{K*} arXiv: 1903.02440: 1904.08267;1904.08399;1905.04245; 1905.07690;1905.07982…

Citing Belle $F_L(D)$ arXiv: 1903.03102: 1903.10486;1904.07530;1904.10432; 1905.01795;1905.03311;1905.08209;1905.08498…

Citing Belle $R_{D(*)}$ arXiv: 1904.08794: 1903.03016;1904.09311;1905.01795; 1905.02702;1905.03311;1905.04074;1905.05211;1905.08257;1905.08253; 1905.08498…

Compared with 2017 LHCb R_{K*} arXiv: 1705.05802 and the CERN seminar 18/4/2016 talk by S. Bifani cited 35 times (now ~ 410) the end of May. Although the excitement went down a little bit, people are still very much concerned with the B anomalies!

Theoretical issues

How robust are SM theoretical calculations?

Why $R_{K(*)}(exp) < R_{K(*)}(SM)$?

Why $R_{D(*)}(exp) > R_{D(*)}(SM)$?

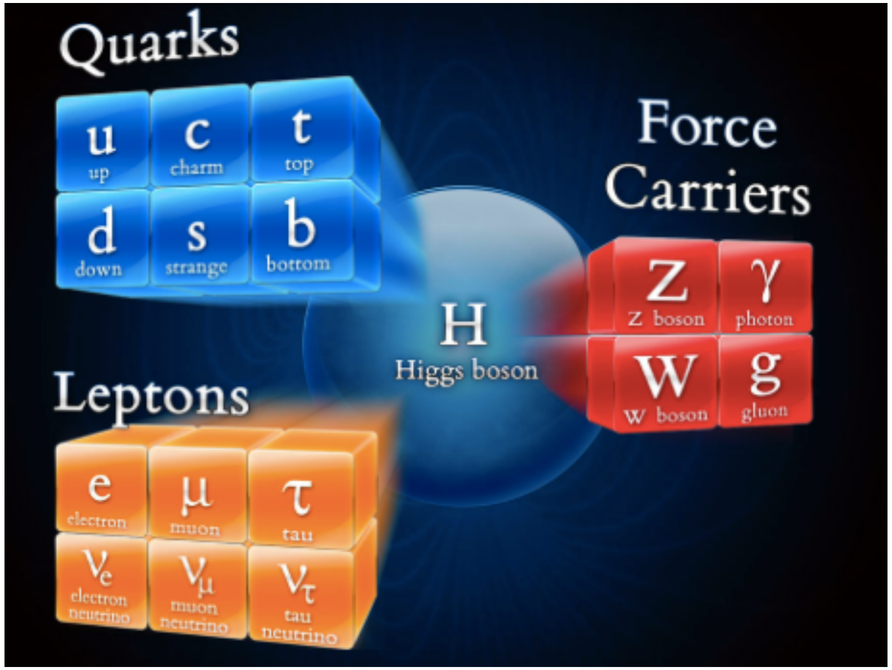
Is there a q^2 dependence, why?

2. Standard Model and Beyond for B Physics

Standard Model is based on $SU(3)_C x SU(2)_L x U(1)_Y$ gauge interaction.

In SM mis-match of weak and mass eigen-bases, leads to flavor mixing and CP violation, part of the story of flavor physics.

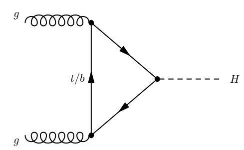
The theory for B physics!



Number of SM generations

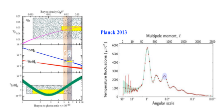
In the SM, only 3 generations of quarks and leptons are allowed.

gg -> Higgs ~ (number of heavy quarks)^2, if fourth generation exist, their mass should be large, 9 times bigger production of Higgs. LHC data ruled out more than 3 generations of quarks.

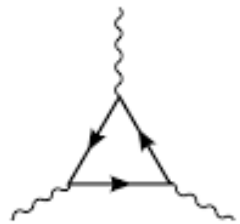


LEP already ruled out more than 3 neutrinos with mass less than $m_Z/2$.

Cosmology and astrophysics, number of light neutrinos also less than 4.



SM, triangle anomaly cancellation: equal number of quarks and leptons!



There are only three generations of sequential quarks and leptons!

Why 3 generations? How do they mix with each other?

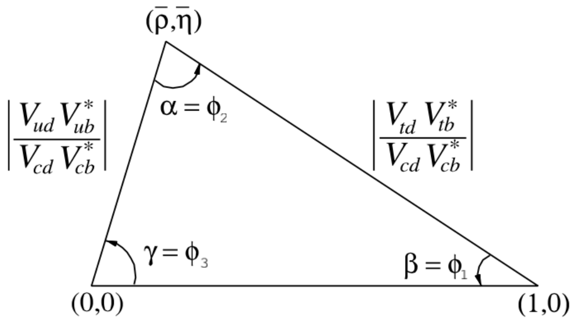
Beyond SM, conclusions may change, X-G He and G. Valencia, PPLB707 (2012)

Quark and Lepton mixing patterns

- The mis-match of weak and mass eigen-state bases lead quark and lepton mix within generations.

Quark mixing — the Cabibbo -Kobayashi-Maskawa (CKM) matrix $V_{\rm CKM}$,

lepton mixing — the Pontecorvo -Maki-Nakawaga-Sakata (PMNS) matrix $U_{\rm PMNS}$



$$L = -\frac{g}{\sqrt{2}}\overline{U}_L\gamma^\mu V_{\rm CKM} D_L W^+_\mu - \frac{g}{\sqrt{2}}\overline{E}_L\gamma^\mu U_{\rm PMNS} N_L W^-_\mu + H.C.\,,$$

$U_L = (u_L, c_L, t_L, ...)^T$, $D_L = (d_L, s_L, b_L, ...)^T$, $E_L = (e_L, \mu_L, \tau_L, ...)^T$, and $N_L = (\nu_1, \nu_2, \nu_3, ...)^T$

For n-generations, $V = V_{\rm CKM}$ or $U_{\rm PMNS}$ is an $n \times n$ unitary matrix.

A commonly used form of mixing matrix for three generations of fermions is given by

$$V = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix},$$

where $s_{ij} = \sin\theta_{ij}$ and $c_{ij} = \cos\theta_{ij}$ are the mixing angles and δ is the CP violating phase.

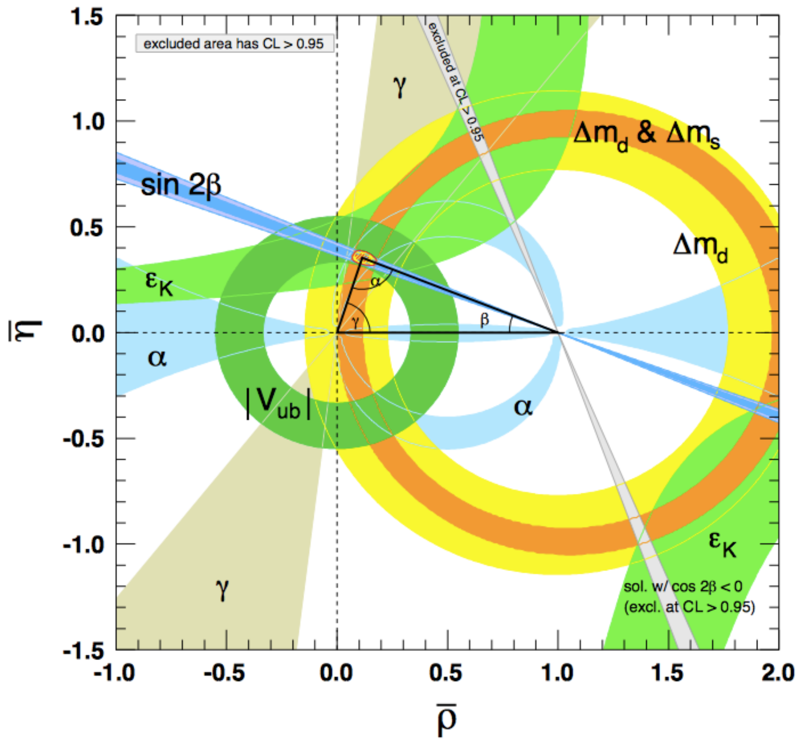
If neutrinos are of Majorana type, for the PMNS matrix one should include an additional diagonal matrix with two Majorana phases $\mathrm{diag}(e^{i\alpha_1/2}, e^{i\alpha_2/2}, 1)$ multiplied to the matrix from right in the above.

Status of Quark and Lepton

Quark Mixing

PDG

Neutrino Mixing



$\Delta m^2 = \Delta m^2_{31} - \Delta m^2_{21}/2 > 0$, if $m_1 < m_2 < m_3$, and $\Delta m^2 = \Delta m^2_{32} + \Delta m^2_{21}/2 < 0$ for $m_3 < m_1 < m_2$.

Parameter	best-fit	3σ
Δm^2_{21} $[10^{-5}$ eV $^2]$	7.37	6.93 – 7.97
$\lvert\Delta m^2\rvert$ $[10^{-3}$ eV $^2]$	2.50 (2.46)	2.37 – 2.63 (2.33 – 2.60)
$\sin^2\theta_{12}$	0.297	0.250 – 0.354
$\sin^2\theta_{23}$, $\Delta m^2 > 0$	0.437	0.379 – 0.616
$\sin^2\theta_{23}$, $\Delta m^2 < 0$	0.569	0.383 – 0.637
$\sin^2\theta_{13}$, $\Delta m^2 > 0$	0.0214	0.0185 – 0.0246
$\sin^2\theta_{13}$, $\Delta m^2 < 0$	0.0218	0.0186 – 0.0248
δ/π	1.35 (1.32)	(0.92 – 1.99)
		((0.83 – 1.99))

$$\begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

$$\lambda = 0.22537 \pm 0.00061\,, \qquad A = 0.814^{+0.023}_{-0.024}\,,$$
$$\bar\rho = 0.117 \pm 0.021\,, \qquad \bar\eta = 0.353 \pm 0.013\,.$$

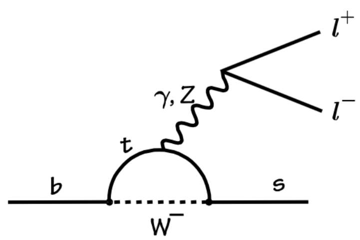
b -> s ll induced anomalies

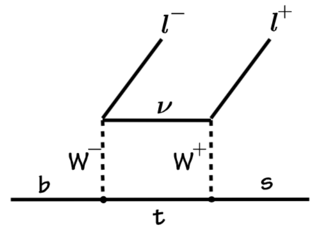
B -> s ll in the SM and beyond

$$\mathcal{H}^{bs\ell\ell}_{\text{eff, NP}} = -\mathcal{N}\left(C_7^{bs}O_7^{bs} + C_7^{\prime bs}O_7^{\prime bs} + \sum_{\ell=e,\mu}\sum_{i=9,10,S,P}\left(C_i^{bs\ell\ell}O_i^{bs\ell\ell} + C_i^{\prime bs\ell\ell}O_i^{\prime bs\ell\ell}\right)\right) + \text{h.c.}\,,$$

with the normalization factor

$$\mathcal{N} = \frac{4G_F}{\sqrt{2}} V_{tb}V_{ts}^* \frac{e^2}{16\pi^2}\,.$$





The dipole operators are given by[1]

$$O_7^{bs} = \frac{m_b}{e}(\bar{s}\sigma_{\mu\nu}P_R b)F^{\mu\nu}\,, \qquad O_7^{\prime bs} = \frac{m_b}{e}(\bar{s}\sigma_{\mu\nu}P_L b)F^{\mu\nu}\,,$$

where $\sigma^{\mu\nu} = \frac{i}{2}[\gamma^\mu, \gamma^\nu]$, and the semi-leptonic operators

$$\begin{aligned}
O_9^{bs\ell\ell} &= (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \ell)\,, & O_9^{\prime bs\ell\ell} &= (\bar{s}\gamma_\mu P_R b)(\bar{\ell}\gamma^\mu \ell)\,,\\
O_{10}^{bs\ell\ell} &= (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \gamma_5 \ell)\,, & O_{10}^{\prime bs\ell\ell} &= (\bar{s}\gamma_\mu P_R b)(\bar{\ell}\gamma^\mu \gamma_5 \ell)\,,\\
O_S^{bs\ell\ell} &= \quad (\bar{s}P_R b)(\bar{\ell}\ell)\,, & O_S^{\prime bs\ell\ell} &= \quad (\bar{s}P_L b)(\bar{\ell}\ell)\,,\\
O_P^{bs\ell\ell} &= \quad (\bar{s}P_R b)(\bar{\ell}\gamma_5 \ell)\,, & O_P^{\prime bs\ell\ell} &= \quad (\bar{s}P_L b)(\bar{\ell}\gamma_5 \ell)\,.
\end{aligned}$$

$$C^{\text{SM}}_{7\text{eff},9,10}(\mu_b) = (-0.29, 4.07, -4.31) \qquad \mu_b = 4.8\ \text{GeV}$$

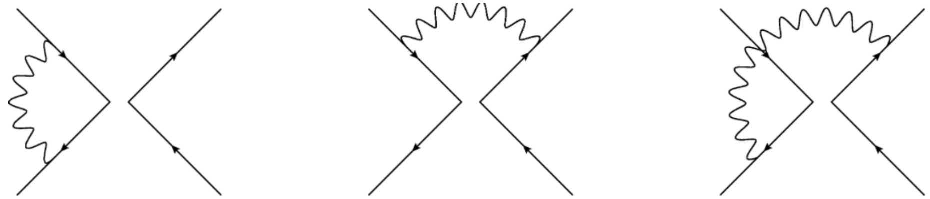
Coeff.	best fit	1σ	2σ	pull
$C_9^{bs\mu\mu}$	-0.95	$[-1.10, -0.79]$	$[-1.26, -0.63]$	5.8σ
$C_9'^{bs\mu\mu}$	$+0.09$	$[-0.07, +0.24]$	$[-0.23, +0.39]$	0.5σ
$C_{10}^{bs\mu\mu}$	$+0.73$	$[+0.59, +0.87]$	$[+0.46, +1.01]$	5.6σ
$C_{10}'^{bs\mu\mu}$	-0.19	$[-0.30, -0.07]$	$[-0.41, +0.04]$	1.6σ
$C_9^{bs\mu\mu} = C_{10}^{bs\mu\mu}$	$+0.20$	$[+0.05, +0.35]$	$[-0.09, +0.51]$	1.4σ
$C_9^{bs\mu\mu} = -C_{10}^{bs\mu\mu}$	-0.53	$[-0.62, -0.45]$	$[-0.70, -0.36]$	6.5σ
C_9^{bsee}	$+0.88$	$[+0.62, +1.15]$	$[+0.36, +1.44]$	3.4σ
$C_9'^{bsee}$	$+0.32$	$[+0.09, +0.61]$	$[-0.16, +0.91]$	1.3σ
C_{10}^{bsee}	-0.82	$[-1.06, -0.59]$	$[-1.31, -0.37]$	3.7σ
$C_{10}'^{bsee}$	-0.27	$[-0.52, -0.05]$	$[-0.78, +0.17]$	1.2σ
$C_9^{bsee} = C_{10}^{bsee}$	-1.65	$[-1.93, -1.36]$	$[-2.19, -1.02]$	4.0σ
$C_9^{bsee} = -C_{10}^{bsee}$	$+0.45$	$[+0.31, +0.59]$	$[+0.19, +0.74]$	3.6σ
$(C_S^{bs\mu\mu} = -C_P^{bs\mu\mu}) \times \text{GeV}$	-0.005	$[-0.008, -0.003]$	$[-0.013, -0.001]$	2.6σ
$(C_S'^{bs\mu\mu} = C_P'^{bs\mu\mu}) \times \text{GeV}$	-0.005	$[-0.008, -0.003]$	$[-0.013, -0.001]$	2.6σ

Latest fit: J. Aebischer et a;., arxiv:1903.10434
Older fits: arXiv:1307.5683, 1510.04239, 1703.09189

b -> c τ ν_τ

$$\mathcal{H}_{\text{eff}} = 2\sqrt{2}G_F V_{cb}\left[(1+C_V^L)O_V^L + C_S^R O_S^R + C_S^L O_S^L + C_T O_T\right]$$

M. Blanke et al., arXiv:1901811.09603



$$O_V^L = (\bar{c}\gamma^\mu P_L b)\,(\bar{\tau}\gamma_\mu P_L \nu_\tau)\ ,$$

$$O_S^R = (\bar{c}P_R b)\,(\bar{\tau}P_L \nu_\tau)\ ,$$

$$O_S^L = (\bar{c}P_L b)\,(\bar{\tau}P_L \nu_\tau)\ ,$$

$$O_T = (\bar{c}\sigma^{\mu\nu}P_L b)\,(\bar{\tau}\sigma_{\mu\nu}P_L \nu_\tau)\ ,$$

1D hyp.	best-fit	$1\,\sigma$ range	$2\,\sigma$ range	p-value (%)	pull$_{\text{SM}}$
C_V^L	0.11	[0.09, 0.13]	[0.06, 0.15]	35	4.6
$C_S^R\vert_{10\%}$	0.15	[0.13, 0.15]	[0.08, 0.15]	1.7	3.8
$C_S^R\vert_{30\%,60\%}$	0.16	[0.13, 0.20]	[0.08, 0.23]	1.8	3.8
C_S^L	0.12	[0.07, 0.16]	[0.01, 0.20]	0.02	2.2
$C_S^L = 4C_T$	−0.07	[−0.12, −0.03]	[−0.15, 0.02]	0.01	1.6

Similar work: P. Asadi and D. Shih, arXiv: 1905.03311

3. Models for $R(D^{(*)})$ and $b\text{->}s\mu^+\mu^-$ Anomalies

A lot of model building activities trying to provide solutions to $R(D^{(*)})$ and b->s $\mu^+\mu^-$ induced anomalies.

Making b->s $\mu^+\mu^-$ smaller or b->s e^+e^- larger than SM predictions.

Z' and W' models, Multi-Higgs models, leptoquark models,

Susy, R-parity violating models,

.....

Solve two types of anomalies separately or solve them simultaneously. Hundreds of papers written on related subjects!

Theoretical modeling for b -> s ll anomalies

A Z' model based on gauge family symmetry

A Variation of each generation has a SU(2)xU(1) , Ernest Ma and X-Y Li

$$SU(3) \times SU(2)_l \times SU(2)_h \times U(1)_Y$$

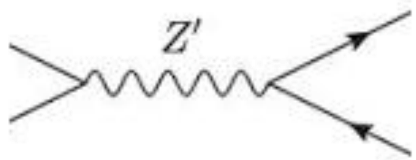
C-W. Chiang, X-G He, G. Valencia,PRD93,074003.

Motivated by the fact that the third generation mass is bigger than the first two generations.)

$$Q_L^{1,2} : (3,2,1,1/3)\ ,\quad Q_L^3 : (3,1,2,1/3)\ ,\quad U_R^{1,2,3} : (3,1,1,4/3)\ ,\quad D_R^{1,2,3} : (3,1,1,-2/3)\ ,$$

$$L_L^{1,2} : (1,2,1,-1)\ ,\quad L_L^3 : (1,1,2,-1)\ ,\quad E_R^{1,2,3} : (1,1,1,-2)\ ,$$

$$\mathcal{L} = \bar{\psi}\gamma_\mu \left[eA^\mu Q + \frac{g}{c_W} Z_L^\mu \left(T_3^l + T_3^h - Q s_W^2\right) + g Z_H^\mu \left(\frac{s_E}{c_E} T_3^l - \frac{c_E}{s_E} T_3^h \right) \right] \psi\ ,$$



$$Z_L = -\sin\xi Z_h + \cos\xi Z_l\ ,\quad Z_H = \cos\xi Z_h + \sin\xi Z_l\ ,$$

$$\xi \approx \frac{s_E c_E}{c_W}(s_\beta^2 - s_E^2)\epsilon^2\ ,\quad \frac{m_{Z_l}^2}{m_{Z_h'}^2} \approx \epsilon^2 \frac{s_E^2 c_E^2}{c_W^2}\ ,$$

$$R_K = 0.745 \Rightarrow \sin^2\theta = 0.37\ ,$$

$$\frac{\mathcal{B}(B \to K\tau\bar{\tau})}{\mathcal{B}(B \to K\mu\bar{\mu})} = 1.36\ ,$$

$$\frac{\mathcal{B}(B \to K(e\bar{\tau}, \tau\bar{e}))}{\mathcal{B}(B \to K\mu\bar{\mu})} = 0.037\ .$$

going to fermion mass eigenstates via unitary matrices T, introduces FCNC

$$\tilde{\Delta}_{sb}^q = T_{bs}^{q*} T_{bb}^q,\quad \tilde{\Delta}_{ij}^\ell = T_{3i}^{\ell *} T_{3j}^\ell$$

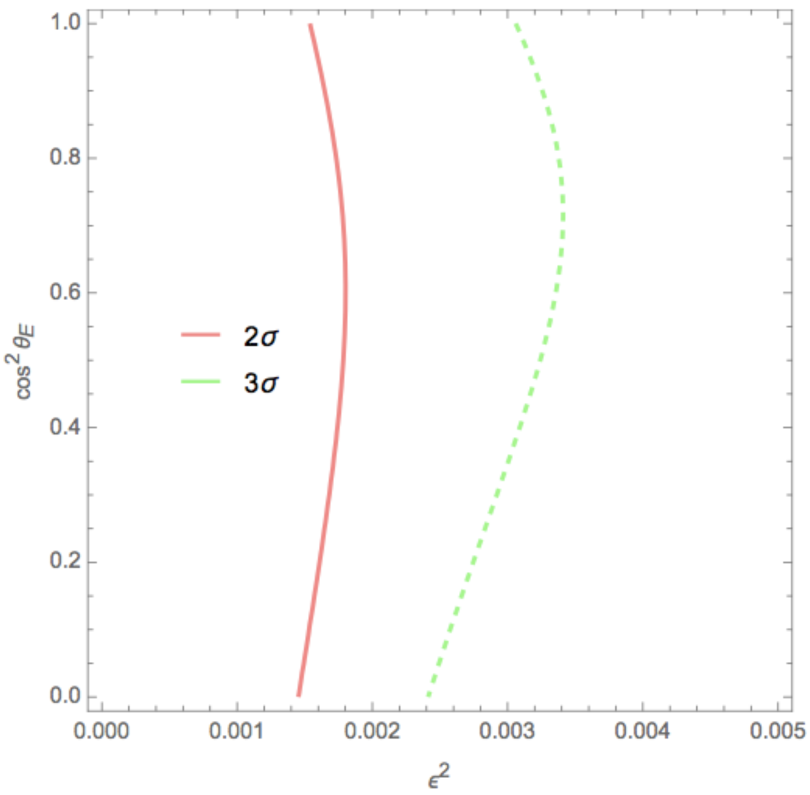
$$\begin{aligned} \mathcal{H}_{\rm eff} \quad = \quad & -\frac{4G_F}{\sqrt{2}} V_{tb}V_{ts}^* \frac{\pi}{\alpha}\epsilon^2 c_E^2 \frac{\tilde{\Delta}_{sb}^q}{V_{tb}V_{ts}^*}\delta_{ij}\left[(4s_W^2 - 1)\mathcal{O}_9^{ij} + \mathcal{O}_{10}^{ij}\right] \\ & -\frac{4G_F}{\sqrt{2}} V_{tb}V_{ts}^* \frac{\pi}{\alpha}\epsilon^2 \frac{\tilde{\Delta}_{sb}^q}{V_{tb}V_{ts}^*}(s_E^2\delta_{ij} - \tilde{\Delta}_{ij}^\ell)\left(\mathcal{O}_9^{ij} - \mathcal{O}_{10}^{ij}\right)\ , \end{aligned}$$

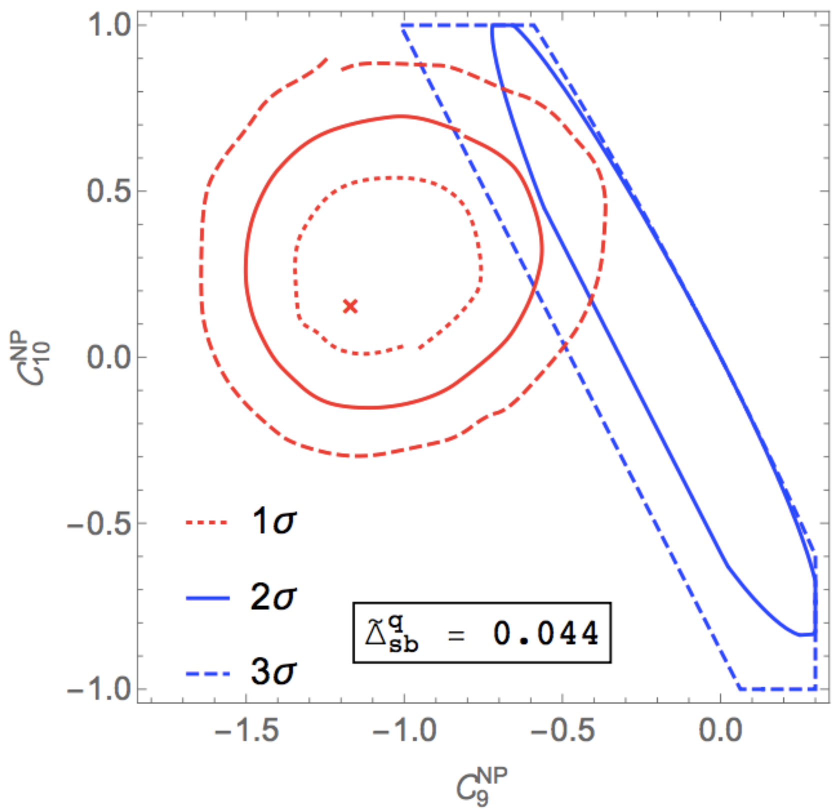
Lμ- Lτ model (He, Joshi, Lew and Volkas, 1991; Foot, He, Lew and Volkas,1994) can help to resolve the anomalies too.

Very constraining electroweak precision data!

Chiang, Deshpande, He, Jiang, PRD81, 015006(2010). Chiang, He, Valencia, PRD93, 074003(2016)

Updated by Fang Ye, 2017 Updated by G. Valencia 2017

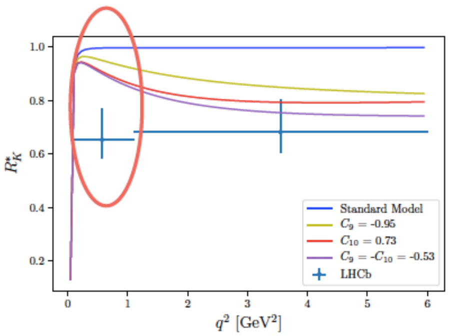




Difficult to explain why lower q^2 has lower event number

Peisi Huang's talk at susy2019

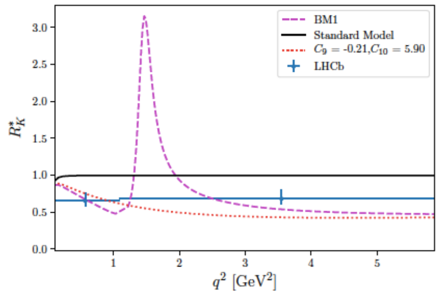
Conclusion

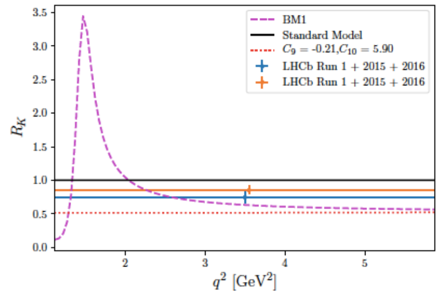


Tension in the low q^2 bin

- Hadron effects become important when introducing new physics
- The hadron effects are not well understood in the interested q^2 region
- Possible explain both bins with modified form factors
- Calls for lattice calculation in the low q^2 bin
- New physics with light and heavy mediators

BM Scenarios





A wide peak (dip-peak structure) near the light Z' pole

Low q^2 bin receives extra suppression from the light Z'

The asymptotic value smaller than the measured value because of the peak

A light Z' exchange

A. Datta et al., arXiv: 1702.01099…

The corresponding Wilson coefficients are

$$C_{9,10}^{l,NP} = \frac{\sqrt{2}\pi}{G_F\, V_{tb}\, V_{ts}^*\, \alpha} \frac{g_{bs}\, g_\mu^{V,A}}{q^2 - m_{Z'}^2 + i\, m_{Z'} \Gamma_{Z'}}$$

The B ->D$^{(*)}$ $\tau\,\nu$ anomalies

If one neglects differences between $(R_{D*}/R_D)_{EXP}$ = 1.3 and $(R_{D*}/R_D)_{SM}$ = 1.16, then modification of the form

$$H_{eff} = -\frac{4G_F}{\sqrt{2}} V_{m3}(\delta_l^{l'} + \Delta_l^{l'm}) \bar{l}\gamma^\mu P_L \nu_{l'} \bar{u}^m \gamma_\mu P_L b_L$$

V_{ij} – KM matrix element

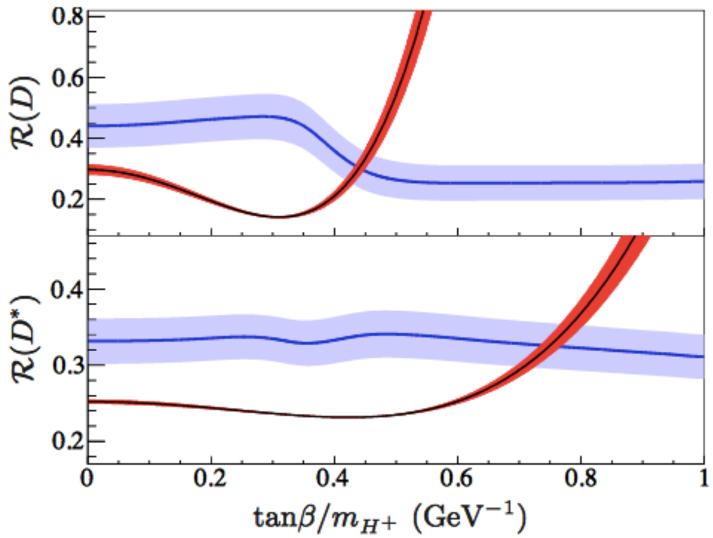
With $\Delta_2^{2,3} \sim 0.13$ and other $\Delta_i^{j,k} = 0$ will solve the problem.

But if one cares, then needs to have different modifications for R_{D*} and R_D.

New Physics modify charged current interaction… in a way that

a) The first two and third generations interact differently;

b) Modification for charged current interaction in SM!



Charged Higgs contribution is not enough

Babar collaboration, arXiv 1303.0571

A sample model modify R_{D*} and R_D differently

$$SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$$

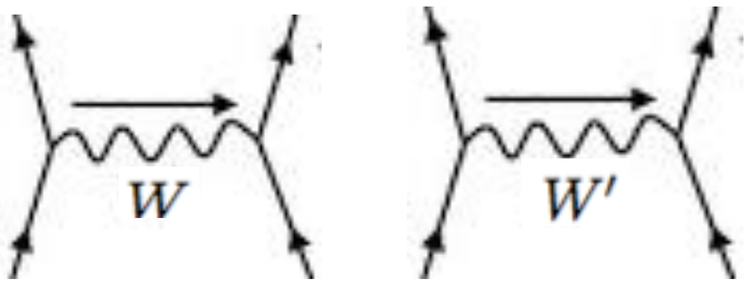
X-G He, G. Valencia, PRD87, 014014(2013)

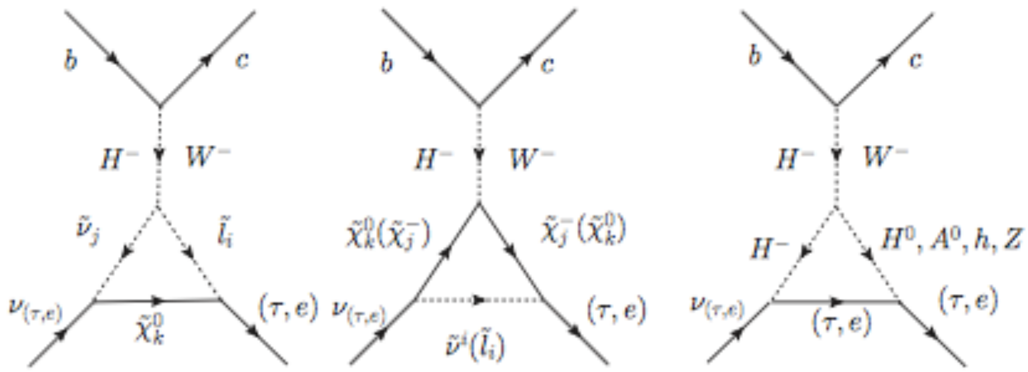
$$Q_L^3 : (3,2,1)(1/3)\,, \quad Q_R^3 : (3,1,2)(1/3)\,,$$
$$L_L^3 : (1,2,1)(-1)\,, \quad L_R^3 : (1,1,2)(-1)\,.$$

$$Q_L^{1,2} : (3,2,1)(1/3)\,, \quad U_R^{1,2} : (3,1,1)(4/3)\,, \quad D_R^{1,2} : (3,1,1)(-2/3)\,,$$
$$L_L^{1,2} : (1,2,1)(-1)\,, \quad E_R^{1,2} : (1,1,1)(-2)\,.$$

The 3rd generation is differnt than other generations. Motivated by Rb problem in EW precision test.

$$\mathcal{L}_W = -\frac{g_L}{\sqrt{2}}(\bar\nu_L\gamma^\mu U^{\ell\dagger}\ell_L + \bar\nu^c_{R3}\gamma^\mu U^{\ell *}_{RLj3}\ell_{Lj})W^+_\mu(\cos\xi_W W^+_\mu - \sin\xi_W W'^+_\mu)$$
$$-\frac{g_R}{\sqrt{2}}(\bar\nu^c_{Li}\gamma^\mu U^\ell_{LRij}\ell_{Rj} + \bar\nu_{R3}\gamma^\mu U^\ell_{R3j}\ell_{Rj})(\sin\xi_W W^+_\mu + \cos\xi_W W'^+_\mu) \;+\; \text{h. c.}$$





R(D(*)) anomalies can be solved.

$$\frac{d\Gamma(B \to D\tau\nu)}{dq^2} = \left.\frac{d\Gamma(B \to D\tau\nu)}{dq^2}\right|_{SM} \left(F^{bc}_{\rm dir} + 2\, F^{bc}_{\rm mix}\right)$$

$$\Gamma(B \to D\tau\nu) = \Gamma(B \to D\tau\nu)_{SM} \left(F^q_{W'} + 2\, F^q_{\rm Mix}\right)$$

$$F^q_{\rm Mix} = \xi_W \frac{g_R}{g_L} \frac{{\rm Re}\left(V^\star_{qb} V_{Rqb}\right)}{|V_{qb}|^2} \left(1 - \left(\frac{M_W}{M_{W'}}\right)^2\right) \left(1 + \left(\frac{g_R M_W}{g_L M_{W'}}\right)^2 |V^\ell_{R3\ell}|^2\right)$$

$$F^q_{W'} = \left(1 + \left(\frac{g_R M_W}{g_L M_{W'}}\right)^4 \frac{|V^\ell_{R3\ell}|^2 |V_{Rqb}|^2}{|V_{qb}|^2}\right)$$

$$1.2 \lesssim F^c_{W'} \lesssim 1.6$$

$$0.009 \lesssim F^c_{\rm Mix} \lesssim 0.08$$

$$\frac{\Gamma(B^-_c \to \tau^-\nu)}{\Gamma(B^-_c \to \tau^-\nu_\tau)_{SM}} = F^{bc}_{\rm dir} - 2\, F^{bc}_{\rm Mix}$$

He and Valencia, arXiv:1711.09525, PLB779, 52(2018)

$$\frac{d\Gamma(B \to D^\star \tau\nu)}{dq^2} = \left.\frac{d\Gamma(B \to D^\star \tau\nu)}{dq^2}\right|_{SM} \left(F^{bc}_{\rm dir} + 2\, F^{bc}_{\rm mix} \frac{|V|^2 - |A|^2}{|V|^2 + |A|^2}\right)$$

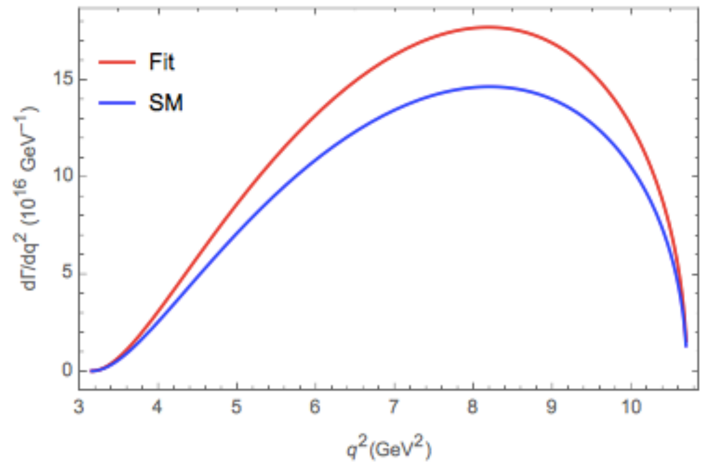
$$\frac{d\Gamma(B_c \to J/\psi \tau\nu)}{dq^2} = \left.\frac{d\Gamma(B_c \to J/\psi \tau\nu)}{dq^2}\right|_{SM} \left(F^{bc}_{\rm dir} + 2\, F^{bc}_{\rm mix} \frac{|V'|^2 - |A'|^2}{|V'|^2 + |A'|^2}\right)$$

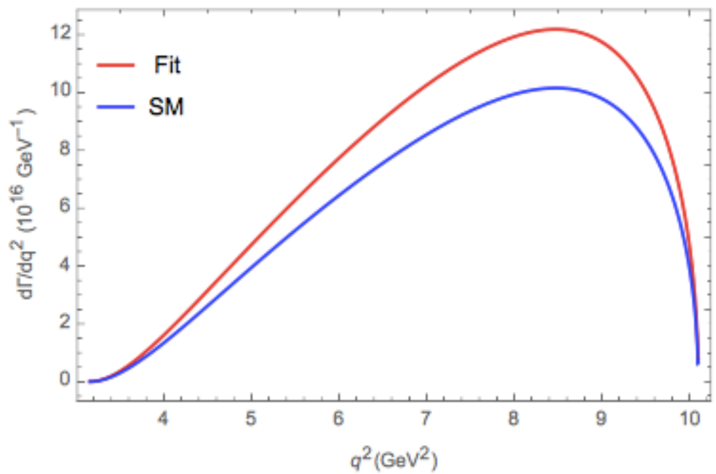
$$V =< D^\star|\bar{c}\gamma_\mu b|B >, \quad A =< D^\star|\bar{c}\gamma_\mu \gamma_5 b|B >$$

$$V' =< J/\psi|\bar{c}\gamma_\mu b|B_c >, \quad A' =< J/\psi|\bar{c}\gamma_\mu \gamma_5 b|B_c >$$

$$R(D^\star) \approx R(D^\star)_{SM} \left(F^{bc}_{\rm dir} - 1.77 F^{bc}_{\rm mix}\right)$$

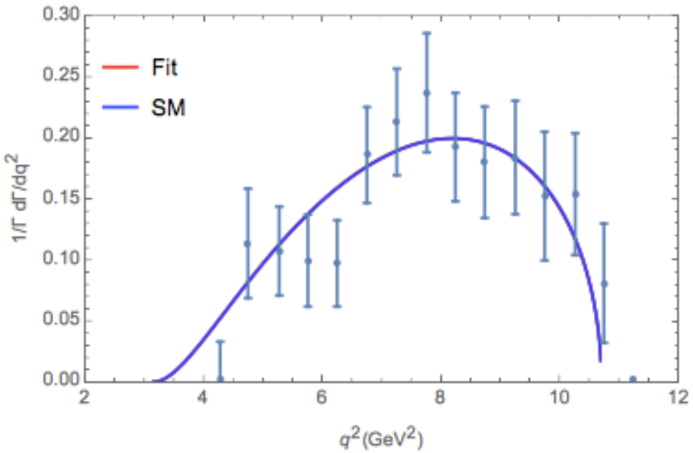
$$R(J/\psi) \approx R(J/\psi)_{SM} \left(F^{bc}_{\rm dir} - 1.94 F^{bc}_{\rm mix}\right)$$

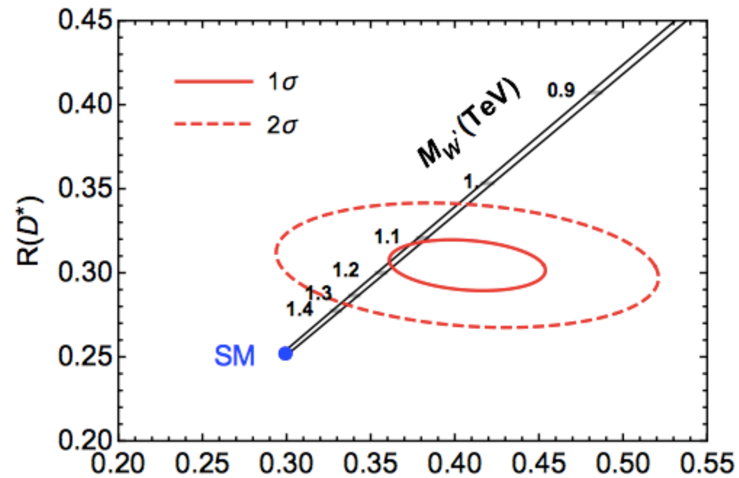




$$B \to D^\star \tau\nu$$

$$B_c \to J/\psi\tau\nu$$





Normalized distributions

$$F_{\rm dir}^{bc} = 1.28, \quad F_{\rm mix}^{bc} = 0.04.$$

Bring $R(D^{(*)})$ and b -> s mu mu anomalies together

A. Scalar Leptoquarks

Leptoquark interaction, Bauer&Neubert, arXiv: 1511.01900 — Yes

R-parity violating interaction, N. Deshpande&X-G He, arXiv:1608.04817 — No

Leptoquark, D. Becirevic et al., arXiv: 1608.07583 — No. A different one

A. Crivellin et al., arXiv:1703.09226 — Also a different one

Y. Cai et al, arXiv: 1704.05849. — Yes

A. Angelescu et al, arXiv:1808.08179. — Conditional

Scalar Leptoquarkls

$$\bar{Q}_L e_R R_1\ ,\ \ \bar{U}_R L_L R_2\ ,\ ;\bar{D}_R L_L\ ,\ \ \bar{L}^c_L Q_L S_{1,3}\ ,\ \ \bar{e}^c_R U_R S_1\ ,\bar{e}^c_R D_R S_2\ ,$$

$$S_1 : (\bar{3},1)(1/3)\ ,\ \ S_3 : (\bar{3},3)(1/3)\ ,\ \ R_2 : (3,2)(7/6)\ ,\ \ \tilde{R}_2 : (3,2)(1/6\ .$$

$R_2 : C_9 = C_{10}$ *out* ; $\tilde{R}_2$ cannot explain $R_{D^{(*)}}$ *out* ;

S_2 cannot explain $R_{D^{(*)}}$ *out* ; S_3 dose not allow $R^{exp}_{D^{(*)}} > R^{SM}_{D^{(*)}}$ *out*

S_3 and $S_1 = \phi$ interactions

$$L_1 = \bar{L}^c_L X Q_L \phi + \bar{U}_R Y e^c_R \phi^* + h.c.\ ,\ \ X = (x_{ij})\ ,\ \ X V^\dagger_{KM} = (z_{ij})\ ,\ \ Y = (y_{ij})$$

$$L_3 = \bar{L}^c_L \tilde{X} Q_L S_3 + \bar{U}_R \tilde{Y} e^c_R S^*_3 + h.c.\ ,\ \ \tilde{X} = (\tilde{x}_{ij})\ ,\ \ \tilde{X} V^\dagger_{KM} = (\tilde{z}_{ij})\ ,\ \ Y = (\tilde{y}_{ij})\ .$$

The S_3 case: problem with $R_{D(*)}$

$$
\begin{aligned}
H_3 = \quad & -\frac{\tilde{x}_{ij}\tilde{x}^*_{kl}}{m^2_{S_3}}\Big(\bar{d}^l_L\gamma_\mu d^j_L\bar{e}^k_L\gamma^\mu e^i_L + (\bar{u}_L V_{KM})^l\gamma_\mu(V^\dagger_{KM}u_L)^j\bar{\nu}^k_L\gamma^\mu\nu^i_L \\
& +\frac{1}{2}((\bar{u}_L V_{KM})^l\gamma_\mu d^j_L\bar{e}^k_L\gamma^\mu\nu^i_L + \bar{d}^l_L\gamma_\mu(V^\dagger_{KM}u_L)^j\bar{\nu}^k_L\gamma^\mu e^i_L) \\
& +\frac{1}{2}(\bar{d}^l_L\gamma_\mu d^j_L\bar{\nu}^l_L\gamma^\mu\nu^i_L + (\bar{u}_L V_{KM})^l\gamma_\mu(V^\dagger_{KM}u_L)^j\bar{e}^k_L\gamma^\mu e^i_L)\Big) \ ,
\end{aligned}
$$

The contribution to $R_{D^{(*)}}$ is proportional to

$$
-\tilde{x}_{33}(\tilde{x}^*_{33} + \frac{V_{cd}}{V_{cb}}\tilde{x}^*_{31} + \frac{V_{cs}}{V_{cb}}\tilde{x}^*_{32}) \ .
$$

The first term dominate.

This make $R^{exp}_{D^{(*)}} < R^{SM}_{D^{(*)}}$, and therefore is ruled out.

The S_1 case: tree and one loop level

$$L_{int} = \frac{1}{2m_\phi^2}[x_{ij}x_{i'j'}\bar{\nu}_L^{i'}\gamma^\mu\nu_L^i\bar{d}_L^{j'}\gamma_\mu d_L^j + z_{ij}z_{i'j'}\bar{e}_L^{i'}\gamma^\mu e_L^i\bar{u}_L^{j'}\gamma_\mu u_L^j]$$

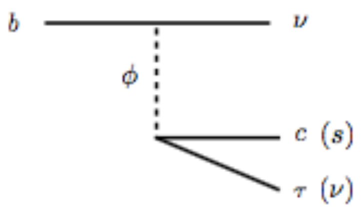
K-> π $\nu\nu$, B-> $K^{(*)}$ $\nu\nu$ D->$\mu\mu$, $\pi\mu\mu$

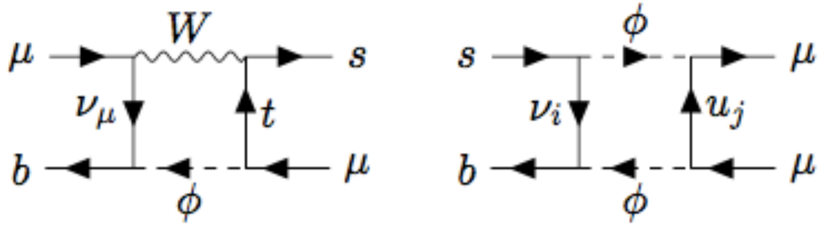
$$-\frac{1}{2m_\phi^2}[x_{ij}z_{i'j'}\bar{\nu}_L^{i'}\gamma^\mu e_L^i\bar{d}_L^{j'}\gamma_\mu u_L^j - x_{ij}z_{i'j'}\bar{e}_L^{i'}\gamma^\mu\nu_L^i\bar{u}_L^{j'}\gamma_\mu d_L^j]$$

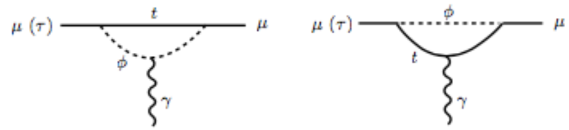
$R(D^{(*)})$, B->$D^{(*)}$ (ρ,π) lν, B_c -> τ ν

$$+\frac{1}{2m_\phi^2}[y_{ij}y_{i'j'}\bar{e}_R^{i'}\gamma^\mu e_R^i\bar{u}_R^{j'}\gamma_\mu u_R^j + x_{ij}y_{i'j'}(\bar{e}_R^{i'}\nu_L^i\bar{u}_R^{j'}\gamma_\mu d_L^j - \frac{1}{2}\bar{e}_R^i\sigma_{\mu\nu}\nu_L^{i'}\bar{u}_R^{j'}\sigma_{\mu\nu}d_L^j)]$$

D->$\mu\mu$, π $\mu\mu$ $R(D^{(*)})$, B->$D^{(*)}$ (ρ,π) lν, B_c -> τ ν







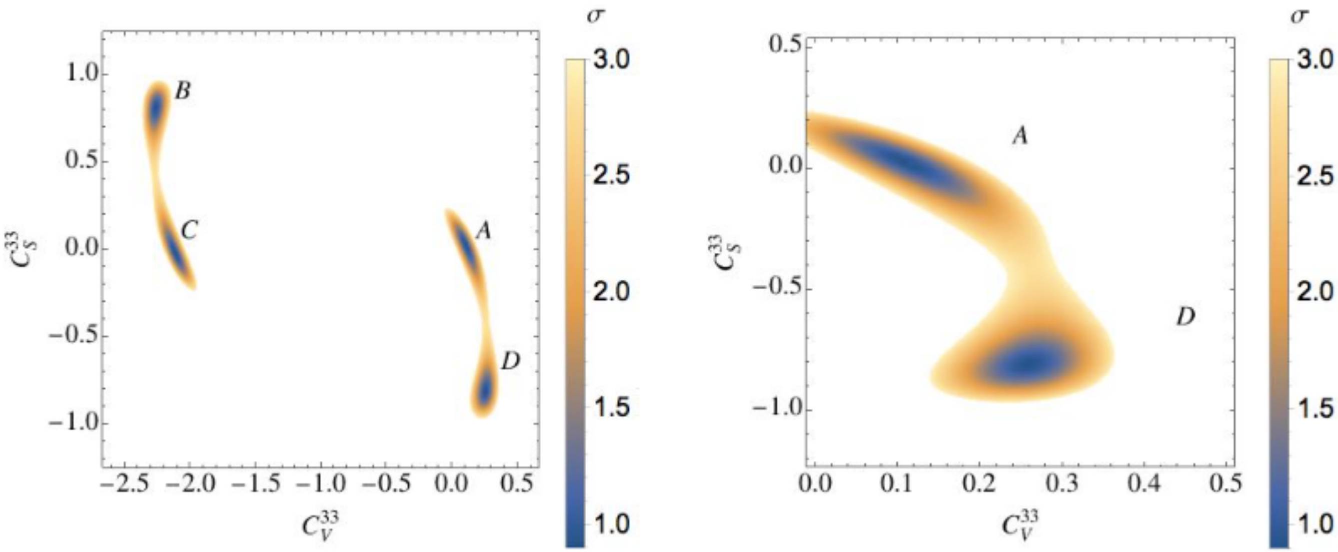
Solution to $R(D^{(*)})$ Solution to b-> s$\mu^+\mu^-$ induced anomalies Solution to $(g-2)_\mu$

If R-parity violating interaction, exchange sd-quark, the last line is absent. That is the reason why R-parity cannot solve $R(_{D(*)})$ and b -> s $\mu^+\mu^-$ anomalies (Deshpande and He)

Also why Baur&Neubert, and Becrivic et al could not work, neglect last term contributions to R(D(*)) and lead to conflict for b -> s $\mu^+\mu^-$when other constraints are included, important one B -> K(*) $\nu\nu$! (R = B(B -> $K^{(*)}$ $\nu\nu)_{exp}$/ B(B -> K(*) $\nu\nu)_{SM}$ < 4.3! (Becirevic et al.)

Solution to R(D$^{(*)}$) anomalies

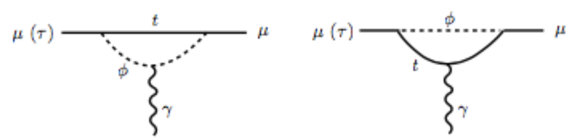
$$\mathscr{L}_{\rm CC}^{ij} = -\frac{4G_F}{\sqrt{2}} V_{cb} \Big[C_V^{ij} (\bar{c}\gamma^\mu P_L b)(\bar{\ell}_i \gamma_\mu P_L \nu_j) + C_S^{ij} (\bar{c} P_L b)(\bar{\ell}_i P_L \nu_j)$$
$$+ C_T^{ij} (\bar{c}\sigma^{\mu\nu} P_L b)(\bar{\ell}_i \sigma_{\mu\nu} P_L \nu_j) \Big] + \text{ h.c.},$$



$$C_V^{ij} = \frac{1}{2\sqrt{2}G_F V_{cb}} \frac{z_{i2}^* x_{j3}}{2m_\phi^2} + \delta_{ij},$$
$$C_S^{ij} = \frac{1}{2\sqrt{2}G_F V_{cb}} \frac{y_{i2} x_{j3}}{2m_\phi^2},$$
$$C_T^{ij} = -\frac{1}{4} C_S^{ij}.$$

Y. Cai et al, arXiv: 1704.05849

Figure 2: The values for C_V^{33} and C_S^{33} corresponding to a good fit to the R_D and R_{D^*} data at $\Lambda = 1$ TeV. The colors indicate the σ values of our fit. The right plot is zoomed to the area around regions A and D.



Significant contribution needed from $\bar{e}_R Y U_R^c \phi$ coupling! Can also solve (g-2)$_\mu$ anomaly!

Solution to and b -> s $\mu^+\mu^-$ induced anomalies

$$\mathscr{L}_{\rm NC} = \frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \frac{\alpha}{4\pi} \sum_{IJ} C_{IJ}^{\mu} \mathscr{O}_{IJ}^{\mu},$$

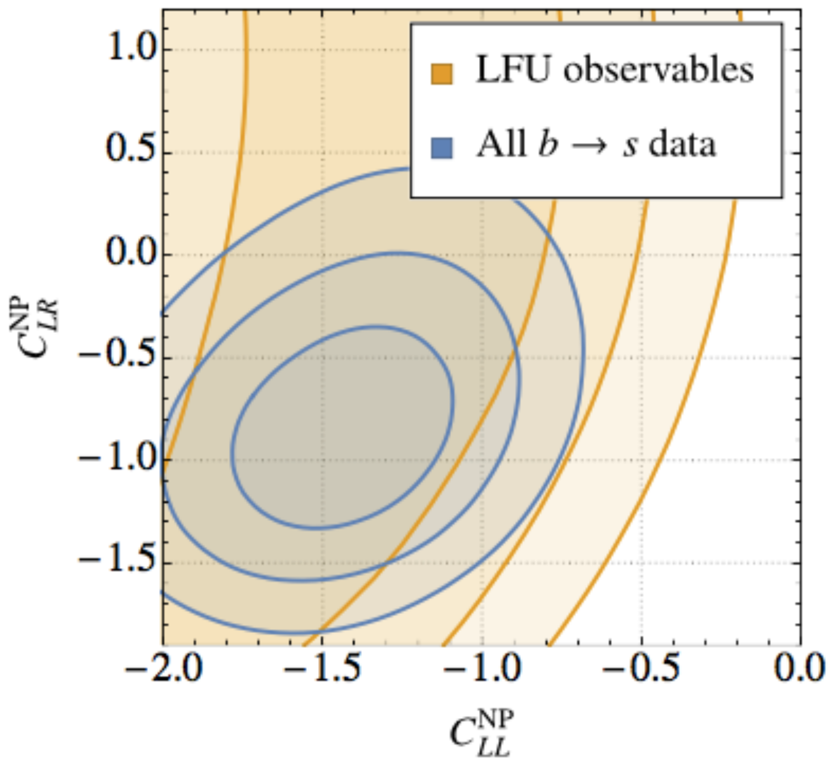
$$\mathscr{O}_{LL}^{\mu} \equiv \frac{1}{2}(\mathscr{O}_9^{\mu} - \mathscr{O}_{10}^{\mu}) = (\bar{s}\gamma^{\mu} P_L b)(\bar{\mu}\gamma_{\mu} P_L \mu),$$

$$\mathscr{O}_{LR}^{\mu} \equiv \frac{1}{2}(\mathscr{O}_9^{\mu} + \mathscr{O}_{10}^{\mu}) = (\bar{s}\gamma^{\mu} P_L b)(\bar{\mu}\gamma_{\mu} P_R \mu)$$

$$C_{LL}^{\phi,\mu} = \frac{m_t^2}{8\pi\alpha m_\phi^2}|z_{23}|^2 - \frac{\sqrt{2}}{64\pi\alpha G_F m_\phi^2 V_{tb} V_{ts}^*} \sum_i x_{i3} x_{i2}^* \sum_j$$

$$C_{LR}^{\phi,\mu} = \frac{m_t^2}{8\pi\alpha m_\phi^2}|y_{23}|^2 \left[\ln \frac{m_\phi^2}{m_t^2} - f\left(\frac{m_t^2}{m_W^2}\right)\right] - \frac{\sqrt{2}}{64\pi\alpha G_F m_\phi^2 V_{tb} V_{ts}^*} \sum_i x_{i3} x_{i2}^* \sum_j |y_{2j}|^2,$$

$$f(x) = 1 - \frac{3}{x-1} + \frac{3}{(x-1)^2} \ln x.$$



Y. Cai et al, arXiv: 1704.05849

Without $\bar{e}_R Y U^c_R \phi$ coupling (R-parity violating model) Satisfying B -> $K^{(*)}$ νν constraints

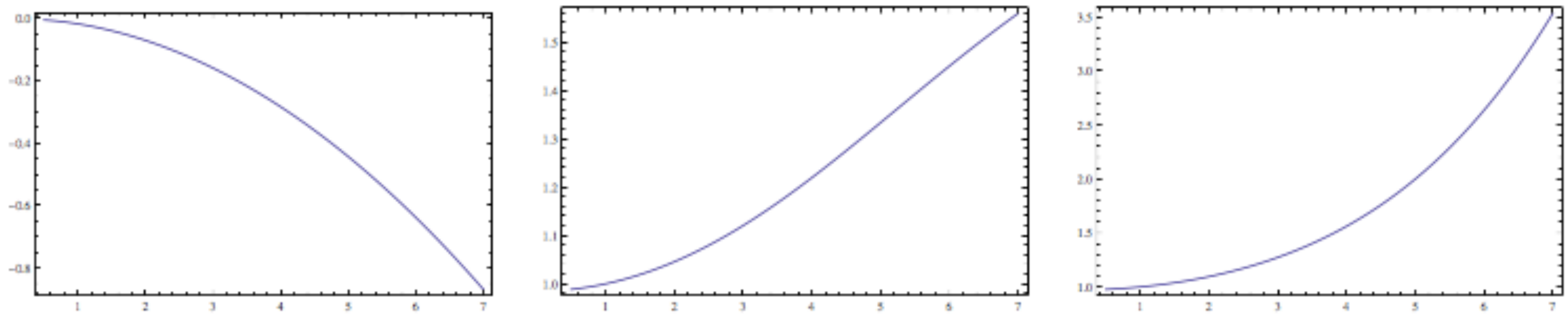


FIG. 1: C_9^{NP}, r_{ave} and $R_\mu^{SM}(c)$ as functions of λ'_{23k} from left to right, respectively. To get $R_\mu^{SM}(c) - 1$ down to 10%, one needs to go to the lower range the 3σ range for C_9^{NP} to about -0.18[7]. However, in that case, r_{ave} also comes down and cannot explain the observed $R(D^{(*)})$ anomaly.

N. Deshpande&X-G He, arXiv:1608.04817

$$r(\bar{B} \to D^{(*)}\tau\bar{\nu}) = R(\bar{B} \to D^{(*)}\tau\bar{\nu})/R(\bar{B} \to D^{(*)}\tau\bar{\nu})_{SM}$$
$$r(B \to D^{(*)}\tau\bar{\nu})_{ave} = 1.266 \pm 0.070$$

Include dark matter also help to easy the problem. This meeting Trifinopoulos

$$R_l^{SM}(c) = Br(\bar{B} \to D^{(*)}l\nu)/Br(\bar{B} \to D^{(*)}l\nu)_{SM}$$

S1 + S3 in Pati-Salam model, Heeck.

B. Vector Leptoquark

R. Barbieri et al., arXiv:1512.01560; G. Hiller et al., arXiv:1609.08895; B. Bhattacharya et al, arXiv: 1609.09078; L. Luzio et al., arXiv:1708.08450; L. Calibbi et al., arXiv:1709.00692; A. Angelescu et al., arXiv: 1808.08179; C. Comella et al., arXiv: 1903.11517.

$$\bar{Q}_L\gamma_\mu L_L U^\mu_{1,3}\ ,\ \ \bar{U}_R\gamma_\mu e_R U^\mu_{5/3}\ ,\ \ \bar{D}_R\gamma_\mu e_R U^\mu_1\ ,$$

$$\bar{Q}_L\gamma_\mu L^c_L R^\mu_{-5/6}\ ,\ \ \bar{U}_R\gamma_\mu L^c_L R^\mu_{1/6}\ ,\ \ \bar{D}_R\gamma_\mu L^c_L R^\mu_{-5/6}$$

$$U^\mu_1 : (3,1)(2/3)\ ,\ \ U^\mu_3 : (3,3)(2/3)\ ,\ \ U^\mu_{5/3} : (3,1)(5/3)\ ,$$

$$R^\mu_{-5/6} : (3,2)(-5/6)\ ,\ \ R^\mu_{1/6} : (3,2)(1/6)\ .$$

Potential vector leptoquarks can solve $R_{D^{(*)}}$ and $R_{K^{(*)}}$ are $U^\mu_{1,3}$

$$H_3 \sim \bar{d}_l\gamma_\mu d_L\bar{e}_L\gamma^\mu e_L - \bar{u}_L\gamma_\mu d_L\bar{e}_L\gamma^\mu\nu_L + ...$$

Similar problem as S_3, U^μ_3 cannot obtain $R^{exp}_{D^{(*)}} > R^{SM}_{D^{(*)}}$ out.

U_1^μ interactions

$$L_1 = \bar{Q}_L X \gamma_\mu L_L U_1^\mu + \bar{D}_R Y e_R U_1^\mu + h.c.$$

$$X = (x_{ij}) \,, \;\; V_{KM} X = (z_{ij}) \,, \;\; Y = (y_{ij})$$

$$\begin{aligned} H_1 \;&=\; \frac{1}{m_{U_1}^2} \left(x_{ij}((\bar{u}_L V_{KM})^i \gamma_\mu \nu_L^j + \bar{d}_L^i \gamma_\mu e_L^j) + y_{ij} \bar{d}_L^i \gamma^\mu d_L^j\right) \\ &\times \left(x_{lk}^* (\bar{\nu}_L^k \gamma^\mu (V_{KM}^\dagger u_L)^l + \bar{e}_L^k \gamma^\mu d_L^l) + y_{lk}^* \bar{d}_L^k \gamma^\mu d_L^l\right) \end{aligned}$$

$$Heff \;=\; \frac{x_{22} X_{32}^*}{m_{U_1}^2} \bar{s}_L \gamma_\mu b_L \bar{\mu}_L \gamma^\mu \mu_L + \frac{x_{33}^* (V_{cd} x_{13} + V_{cs} x_{23} + V_{cb} x_{33})}{m_{U_1}^2} \bar{c}_L \gamma_\mu b_L \bar{\tau}_L \gamma^\mu \nu_L \,.$$

Has solutions for both $R_{D(*)}$ and $R_{K(*)}$ anomalies!

C. Triplet vector and $SU(3)_C \times SU(2)_h \times SU(2)_l \times U(1)_Y$

D. Buttazzo et al., arXiv: 1706.07808, X-G He, G. Valencia and C.-W. Chiang

X_μ: (3,1)(0)

$$X_\mu = \frac{1}{\sqrt{2}} \begin{pmatrix} X^0_\mu & \sqrt{2} X^+_\mu \\ \sqrt{2} X^-_\mu & -X^0_\mu \end{pmatrix} \qquad L_{int} = \bar{Q}_L \gamma^\mu X_\mu \Delta^Q Q_L + \bar{L}_L \gamma^\mu X_\mu \Delta^L L_L$$

$$\begin{aligned} H_{eff} = & \frac{1}{m^2_{X^\pm}} [\bar{u}_L \gamma^\mu V_{KM} \Delta^Q d_L \bar{e}_L \gamma_\mu \Delta^L \nu_L + \bar{d}_L \gamma^\mu \Delta^Q V^\dagger_{KM} u_L \bar{\nu}_L \gamma_\mu \Delta^L e_L] \\ + & \frac{1}{2m^2_{X^0}} [\bar{u}_L \gamma^\mu V_{KM} \Delta^Q V^\dagger_{KM} u_L \bar{\nu}_L \gamma_\mu \Delta^L \nu_L - \bar{d}_L \gamma^\mu \Delta^Q d_L \bar{\nu}_L \gamma_\mu \Delta^L \nu_L \\ & - \bar{u}_L \gamma^\mu V_{KM} \Delta^Q V^\dagger_{KM} u_L \bar{e}_L \gamma_\mu \Delta^L e_L + \bar{d}_L \gamma^\mu \Delta^Q d_L \bar{e}_L \gamma_\mu \Delta^L e_L] \,. \end{aligned}$$

Exchange Xμ obtains

$$H_{eff}(R_{D^{(*)}}) = \frac{(V_{KM}\Delta^Q)_{23}\Delta^L_{3l}}{m^2_{X^\pm}} \bar{c}_L\gamma^\mu b_L \bar{\tau}_L\gamma_\mu\nu^l_L \ ,$$

$$H_{eff}(R_{K^{(*)}}) = \frac{\Delta^Q_{23}\Delta^L_{22}}{2m^2_{X^0}} \bar{s}_L\gamma^\mu b_L \bar{\mu}_L\gamma_\mu\mu_L \ .$$

For $R_{D(*)}$

$$H_{eff} = \frac{4G_F}{\sqrt{2}} V_{cb}(\delta_{3,l} + \epsilon_{3,l})\bar{c}\gamma^\mu P_L b\bar{\tau}\gamma_\mu P_L\nu^l \ ,$$

$$\epsilon_{3,l} = \frac{\sqrt{2}}{4G_F V_{cb}} \frac{V_{2i}\Delta^Q_{i3}\Delta^L_{3l}}{m^2_{X^\pm}} \ .$$

$$H_{eff} = -\frac{4G_F}{\sqrt{2}} V_{tb}V^*_{ts} \sum C_i O_i$$

For $R_{K(*)}$

$$C_9^{NP} = -C_{10}^{NP} = -\frac{\sqrt{2}\pi}{\alpha G_F V_{tb}V^*_{ts}} \frac{\Delta^Q_{23}\Delta^L_{22}}{4m^2_{X^0}} \ .$$

Numbers OK for both anomalies and also satisfy all known bounds.

Try the best fit values: $\epsilon_{3,\tau} = 0.11$ **and** $C_9^N = -0.53$. $V_{cb} \approx 0.04$, $V_{ts} \approx -0.04$

Allow $\frac{\Delta m_{B_s}^{NP}}{\Delta m_{B_s}^{SM}}$ **to be 0.1 (2**σ **bound),** $\Delta_{23}^Q \approx \pm 0.0068$ **with** $m_X = 1TeV$.

Solve $R_{K^{(*)}}$ **anomaly,** $C_9^{NP} \approx -0.56 \rightarrow \Delta_{22}^L \approx \mp 0.26$.

Solve $R_{D^{(*)}}$ **anomaly,** $\sum_l \epsilon_{3,l} \approx 0.11$.

$\epsilon \sim (V_{cd}\Delta_{13}^Q + V_{cs}\Delta_{23}^Q + V_{cb}\Delta_{33}^Q)\Delta_{33}^L$

Prefer to have Δ_{23}^Q **positive.**

Then $\Delta_{33}^Q \Delta_{33}^L \approx 4$, **taking each about 2,**

large, but OK solution, although kind of large.

limit from $R_{B\rightarrow K\nu\bar{\nu}} < 4$, **OK**

$D \rightarrow \mu^+\mu^-$ **OK, since can set** $\Delta_{12}^Q = 0$.

A gauge model realization

S. Bouncenna et al., arxiv:1604.03088
C-W. Chiang, X-G He, G. Valencia, PRD93,074003.

$$SU(3) \times SU(2)_l \times SU(2)_h \times U(1)_Y$$

$$Q_L^{1,2} : (3,2,1,1/3)\ ,\ \ Q_L^3 : (3,1,2,1/3)\ ,\ \ U_R^{1,2,3} : (3,1,1,4/3)\ ,\ \ D_R^{1,2,3} : (3,1,1,-2/3)\ ,$$

$$L_L^{1,2} : (1,2,1,-1)\ ,\ \ L_L^3 : (1,1,2,-1)\ ,\ \ E_R^{1,2,3} : (1,1,1,-2)\ ,$$

The charged quark currents can be in the quark mass eigen-basis as

$$\mathcal{L}_{charged} = \frac{g}{\sqrt{2}s_E c_E} W_h^{+\mu}\left(s_E^2 \bar U_L \gamma_\mu V_{KM} D_L - \bar U_L T_U N T_D^\dagger D_L\right) + \frac{g}{\sqrt{2}} W_l^{+\mu}\left(\bar U_L \gamma_\mu V_{KM} D_L\right) + h.c.\ .$$

The matrices $T_{\psi,U,D}$ diagonalize the left handed fermion weak eigen-states to obtain the mass eigen-states. The weak eigen-states are given by $T_\psi \psi$. In the limit $s_E^2 c_\beta^2 - c_E^2 s_\beta^2 = 0$, $Z_{l,h}$ and $W_{l,h}$ are mass eigen-states with

$$m^2_{Z_h,W_h} = \frac{u^2 g^2}{2c_E^2 s_E^2} + \frac{v^2 g^2}{4}\ ,\ \ m^2_{Z_l} = \frac{v^2(g^2+g'^2)}{4}\ ,\ \ m^2_{W_l} = \frac{v^2 g^2}{4}\ .$$

The quark neutral currents can be expressed in the physical basis as

$$\mathcal{L}_{NC} = \bar\psi \gamma_\mu \left\{ eA^\mu Q + g Z_h^\mu T_\psi \left[\frac{s_E}{c_E} T_3^l - \frac{c_E}{s_E} T_3^h\right] T_\psi^\dagger + \frac{g Z_l^\mu}{c_W}\left[-s_W^2 Q + T_3\right]\right\}\psi$$
$$= \bar\psi \gamma_\mu \left\{ eA^\mu Q + \frac{g}{s_E c_E} Z_h^\mu \left[s_E^2 T_3 - T_\psi T_3^h N T_\psi^\dagger\right] + \frac{g Z_l^\mu}{c_W}\left[-s_W^2 Q + T_3\right]\right\}\psi$$

with $T_3 = T_3^l + T_3^h$, $Q = Y + T_3$ and $N = \mathrm{diag}(0,0,1)$.

Exchange W_h solve $R_{D(*)}$!

Exchange Z_H solve $R_{K(*)}$!

$$\mathcal{L}_{NC} = \frac{g}{s_E c_E} Z_h^\mu \left[\bar D_L \gamma_\mu (s_E^2 T_3 + \frac{1}{2} T_D N T_D^\dagger) D_L + \bar U_L \gamma_\mu (s_E^2 T_3 - \frac{1}{2} V_{KM} T_D N T_D^\dagger V_{KM}^\dagger) U_L\right]$$

$$\mathcal{L}_{charged} = \frac{g}{\sqrt{2}s_E c_E} W_h^{+\mu}\left(s_E^2 \bar U_L V_{KM} \gamma_\mu D_L - \bar U_L V_{KM} \gamma_\mu T_D N T_D^\dagger D_L\right)$$

Similar for Z_h and W_h interactions with leptons.

S_E small limit works well !

5. Conclusions

Anomalies exist in $R(D^{(*)})$ and $b \to s\, \mu^+\mu^-$ anomalies at about 3 ~4σ.

$R(D^{(*)})$: NP add to SM contributions.

$b \to s\, \mu^+\mu^-$: NP destructively contributes to loop SM contributions.

New data seems to moving the trend back towards SM.

Still need confirmation whether the anomalies are real!

Models exist for solve the above two types of anomalies separately.

Can also have model to solve both simultaneously.

Rich B physics ahead with future new data from LHCb and Belle II.

A lot to do for theorists!

A lot for experiments to do also.