$R(D)$ and $R(D^*)$ anomalies and their phenomenological implications

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and **paper to appear soon**

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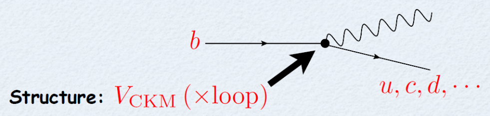
Outline

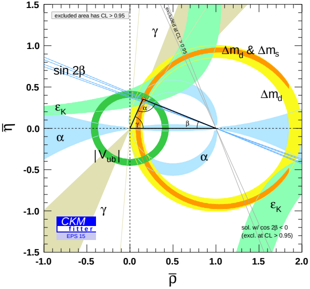
- ▷ $R(D)$ and $R(D^*)$ anomalies
- ▷ Solution with a charged Higgs
- ▷ Solution with a scalar leptoquark
- ▷ Conclusion and Outlook

Why B physics?

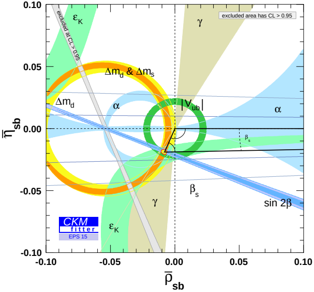
- B-hadron decays: various final states, investigate the flavour structure in fermionic sector; [Y. Amhis *et al.* HFAG, 1412.7515]



- BaBar, Belle, Tevatron, LHCb, and Belle-II: more and more precise data; to validate SM and NP flavor structures;



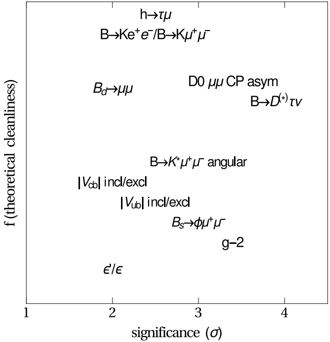
$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0,$$



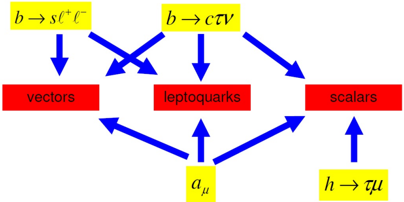
$$V_{us}V_{ub}^* + V_{cs}V_{cb}^* + V_{ts}V_{tb}^* = 0$$

Current status of flavour anomalies

- While being in good agreement, NP contributions of order $\mathcal{O}(20\%)$ to most low-energy FCNC processes are still allowed;
- Several intriguing deviations from the SM predictions: $2 \sim 4\sigma$ level; [T. Becher, 1607.01165; Z. Ligeti, 1606.02756; A. Crivellin, 1606.06861]



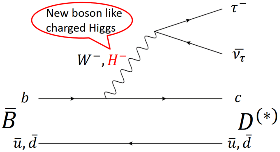
see previous talks at this workshop!



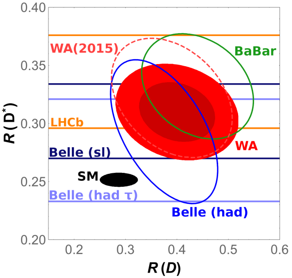
- While various cross-checks are still needed, some of them would be unambiguous NP signals! $\hookrightarrow$ A unified explanation within a specific NP model? [A. Crivellin, 1606.06861]

Why $B \to D^{(*)}\tau\nu_\tau$ decays?

- Tree-level processes: mediated by $W^\pm$ in SM; sensitive to tree-level NP like RH currents, charged Higgs, lepto-quarks, $\cdots$;



- $R(D^{(*)}) = \frac{\mathrm{Br}(B \to D^{(*)}\tau\nu_\tau)}{\mathrm{Br}(B \to D^{(*)}\ell\nu_\ell)}$: uncertainties from FFs and V_{cb} largely cancelled; [BaBar, 1205.5442; Belle, talk by Shigeki Hirose; LHCb, talk by Kristof De Bruyn]



▷ $R(D)_{\mathrm{SM}} = 0.299 \pm 0.003$

[exp.: $0.397 \pm 0.040 \pm 0.028$]

[D. Bigi, P. Gambino, 1606.08030]

▷ $R(D^*)_{\mathrm{SM}} = 0.252 \pm 0.003$

[exp.: $0.316 \pm 0.016 \pm 0.010$]

[S. Fajfer *et al.*, 1203.2654]

- The combined WA for $R(D)$ and $R(D^*)$ shows a 4.0σ deviation from the SM.

Why $B \to D^{(*)}\tau\nu_\tau$ decays?

- 4.0σ $R(D^{(*)})$ anomaly: the most significant in B physics, and motivate many studies both within the SM and in various NP models;

  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 | EndN
  ADS Abstract Service; Link to DISCOVERY; Link to PHYSICS; SI
  详细记录 - Cited by 320 records 250+

- The observed tension is model independent: exclusive already over-saturates inclusive; [M. Freytsis, Z. Ligeti, J. Ruderman, 1506.08896]

  - The data on $R(D)$ and $R(D^*)$ imply:

  $$\mathrm{Br}(\bar{B} \to D^*\tau\bar{\nu}) + \mathrm{Br}(\bar{B} \to D\tau\bar{\nu}) = (2.71 \pm 0.18)\%$$

  - Including the four lightest orbitally excited D meson states:

  $$\mathrm{Br}(\bar{B} \to D^{(*)}\tau\bar{\nu}) + \mathrm{Br}(\bar{B} \to D^{**}\tau\bar{\nu}) \sim 3\%$$

  - From inclusive=$\sum$exclusive, $\sim 3\sigma$ tension with inclusive modes;

  $$\mathrm{Br}(\bar{B} \to X_c\tau\bar{\nu}) = (2.42 \pm 0.05)\%, \qquad \mathrm{Br}(b \to X\tau^+\nu) = (2.41 \pm 0.23)\%$$

Possible to explain the observed $R(D^{(*)})$ anomaly?

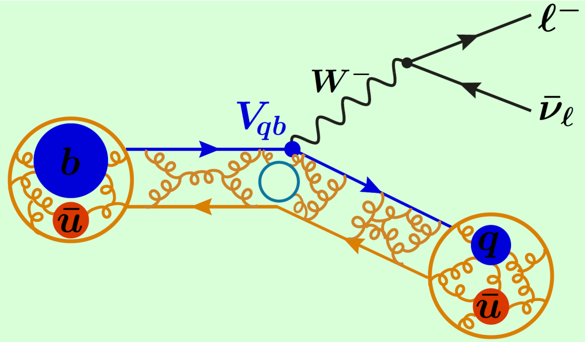
- Questions to be asked:
  - ⥁ the observed tension can or cannot be explained within the SM?
    $\hookrightarrow$ explanations with QCD effects quite unlikely.
  - ⥁ how precise should we know $B \to D^{(*)}$ FFs? LQCD improvements! [FNAL/MILC, 1403.0635, 1503.07237; HPQCD, 1505.03925]
  - ⥁ If LFU is really violated in B-meson decays, could we probe LFU violations in Λ_b and B_s decays?

- Remind: LFU in purely leptonic $D_{(s)}$, π, and K, hadronic τ decays already tested, and holds up to 1% level.

  $\rightsquigarrow$ these decays should put much stronger constraints on the NP contribution! [S. Fajfer *et al.*, 1206.1872; A. Celis *et al.*, 1210.8443]

- Our strategy for $R(D^{(*)})$ anomaly: firstly perform a model-indep. analysis; then specific to some NP models [2HDM and scalar leptoquark], to see their pheno. implications;
  [A. Celis *et al.*, 1210.8443, in preparation; Xin-Qiang Li *et al.*, 1605.09308]

Solution with a charged Higgs



- Solutions with a charged Higgs and pheno. implications:

A. Celis, M. Jung, X. Q. Li and A. Pich, "Sensitivity to charged scalars in $B \to D^{(*)}\tau\nu_\tau$ and $B \to \tau\nu_\tau$ decays," JHEP **1301** (2013) 054 [arXiv:1210.8443 [hep-ph]].

A. Celis, M. Jung, X. Q. Li and A. Pich, "Tree-level constraints on a charged Higgs," in preparation.

The effective Lagrangian

- $\mathcal{L}_{\text{eff}}$: charged-scalar mediated semileptonic transitions (neglect neutrino-mass-related terms):

$$\mathcal{L}_{\text{eff}} = -\frac{4G_F V_{q_u q_d}}{\sqrt{2}} \left[\bar{q}_u \left(g_L^{q_u q_d \ell} \mathcal{P}_L + g_R^{q_u q_d \ell} \mathcal{P}_R\right) q_d\right] \left[\bar{\ell} \mathcal{P}_L \nu_\ell\right]$$

- Processes considered: charged-scalar contributes at tree-level;

Observable	SM prediction	Exp. Value
$R(D)$	$0.284^{+0.010}_{-0.007} \pm 0.014$	0.379 ± 0.044
$R(D^*)$	$0.252 \pm 0.001 \pm 0.003$	$0.327 \pm 0.020^\dagger$
$R(X_c)$	0.222 ± 0.004	0.225 ± 0.022
$\mathrm{Br}(B \to \tau\bar{\nu}_\tau)$	$(1.06^{+0.27}_{-0.24}) \times 10^{-4}$	$(1.06 \pm 0.20) \times 10^{-4}$
$\mathrm{Br}(B^0 \to \pi\tau\bar{\nu}_\tau)$	$1.15^{+0.30}_{-0.27} \times 10^{-4}$	$\leq 2.8 \times 10^{-4}$ (95% CL)
$\mathrm{Br}(D_s \to \tau\bar{\nu}_\tau)$	$(4.99 \pm 0.20) \times 10^{-2}$	$(5.55 \pm 0.24) \times 10^{-2}$
$\mathrm{Br}(D_s \to \mu\bar{\nu}_\mu)$	$(5.13 \pm 0.20) \times 10^{-3}$	$(5.57 \pm 0.24) \times 10^{-3}$
$\mathrm{Br}(D \to \mu\bar{\nu}_\mu)$	$(3.78 \pm 0.16) \times 10^{-4}$	$(3.74 \pm 0.17) \times 10^{-4}$
$\mathrm{Br}(D \to \tau\bar{\nu}_\tau)$	$(1.01 \pm 0.04) \times 10^{-3}$	$\leq 1.2 \times 10^{-3}$ (90% CL)
$\Gamma(K \to \mu\bar{\nu}_\mu)/\Gamma(\pi \to \mu\bar{\nu}_\mu)$	1.340 ± 0.025	1.337 ± 0.003
$\Gamma(\tau \to K\nu_\tau)/\Gamma(\tau \to \pi\nu_\tau)$	$(6.58 \pm 0.07) \times 10^{-2}$	$(6.43 \pm 0.09) \times 10^{-2}$
$\mathrm{Br}(\tau \to \pi\nu)/\mathrm{Br}(\pi \to \mu\nu)$	$(9.784 \pm 0.014) \times 10^{3}$	$(9.713 \pm 0.056) \times 10^{3}$
$\mathrm{Br}(\tau \to \mu\nu_\tau\bar{\nu}_\mu)/\mathrm{Br}(\tau \to e\nu_\tau\bar{\nu}_e)$	0.9725 ± 0.0000	0.9764 ± 0.0030

Strategy for the global fit

- CKM elements: the ones not sensitive to the charged scalar;
  - $|V_{ud}|$ from super-allowed $0^+ \to 0^+$ nuclear β decays;
  - $|V_{cb}|$ from exclusive and inclusive semileptonic $b \to c\ell\bar{\nu}_\ell$ decays;
  - $|V_{ub}|$ from exclusive and inclusive semileptonic $b \to u\ell\bar{\nu}_\ell$ decays.
- Hadronic parameters: taken from the latest FLAG, HFAG and PDG averages; [FLAG, 1607.00299; PDG 2015 version; HFAG, 1412.7515]
- Statistical analysis: choose frequentist statistics and Rfit scheme, as implemented by CKMfitter group; [Höcker *et al.*, 2001]
  - theo. uncertainties treated by defining allowed ranges, and within the range no contribution to $\Delta\chi^2$, while set to infinity outside the range;
  - theo. errors chosen conservatively and added linearly;
  - syst. errors treated as above, while stat. errors "normally".

What's new compared to A. Celis, M. Jung, X. Q. Li and A. Pich, 1210.8443?

- Both Belle and LHCb measurements are well consistent with BaBar's, implying now 4.0σ deviation from the SM predictions; [BaBar, 1205.5442, 1303.0571; Belle, 1507.03233, 1603.06711, 1607.07923, 1608.06391; LHCb, 1506.08614]

- The q^2 distributions $d\Gamma(B \to D^{(*)}\tau\nu)/dq^2$ also available by Belle and BaBar, yielding additional information to distinguish NP from the SM, and different NP models from each other; [BaBar, 1303.0571; Belle, 1507.03233]

- Constraints from the inclusive semi-leptonic decay $B \to X_c\tau\nu$, measured at LEP, also taken into account, providing further complementary constraints; [Freytsis, Ligeti, Ruderman, 1506.08896; LEP, hep-ex/0112028]

- Constraints from direct charged-Higgs searches at the LHC now become available; [ATLAS, 1302.3694, 1412.6663, 1603.09203; CMS, CMS-PAS-HIG-14-020, 1510.04252; A. G. Akeroyd *et al.*, 1607.01320]

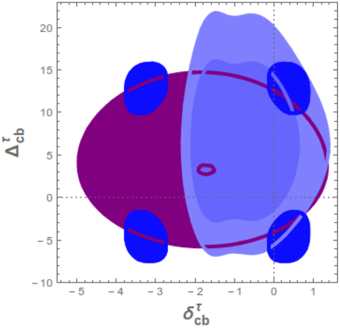
  $\rightsquigarrow$ combined with the LEP bound, $M_{H^\pm} \geq 80~\mathrm{GeV} \gg m_b$, one can safely integrate out $M_{H^\pm}$ at $\mu_b \sim 5~\mathrm{GeV}$, to get $\mathcal{H}_{\text{eff}} \propto C_i O_i$.

Model-independent analysis of $B \to D^{(*)}\tau\nu$

- With no assumptions on flavour structure, the only observables governed by $b \to c\tau\nu_\tau$: $R(D)$, $R(D^*)$, $R(X_c)$, $d\Gamma(B \to D^{(*)}\tau\nu)/dq^2$;

$$\delta^{\ell}_{cb} \equiv \frac{(g_L^{cb\ell} + g_R^{cb\ell})(m_B - m_D)^2}{m_\ell(\bar{m}_b - \bar{m}_c)}\ [scalar]\,, \quad \Delta^{\ell}_{cb} \equiv \frac{(g_L^{cb\ell} - g_R^{cb\ell})m_B^2}{m_\ell(\bar{m}_b + \bar{m}_c)}\ [pseudo-scalar]$$

- For real couplings: allowed parameter spaces in $\delta^{\tau}_{cb} - \Delta^{\tau}_{cb}$-plane;

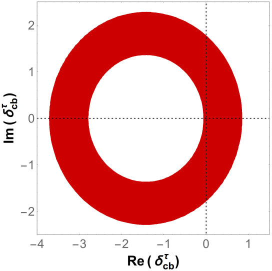


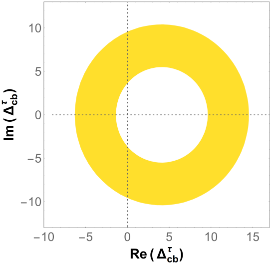
  - ▷ $R(D^{(*)})$ yield four solutions (blue);
  - ▷ $d\Gamma(B \to D^{(*)}\tau\nu)/dq^2$ exclude two of them; favour the one with large Δ^{τ}_{cb} (95% CL);
  - ▷ Model-independent tension with the inclusive $B \to X_c\tau\nu_\tau$ decay reflected by small overlap regions;

- Conclusion: the current data can be explained simultaneously by a charged scalar, but only with both $g_L^{cb\tau}$ and $g_R^{cb\tau}$ present!

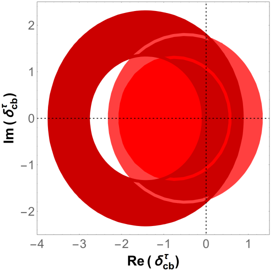
Model-independent analysis of $B \to D^{(*)}\tau\nu$

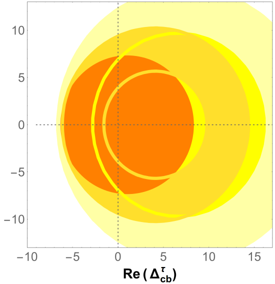
- Individual fit to $R(D)$ and $R(D^*)$ with complex couplings:





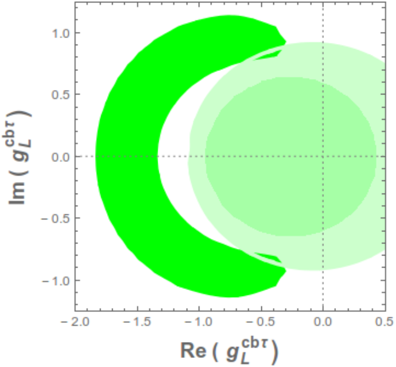
- Fits including the measured q^2 spectrum and $B_c^- \to \tau^-\bar{\nu}_\tau$:





Cases with only $g_L^{cb\tau}$ or $g_R^{cb\tau}$ present

- **Only $g_L^{cb\tau}$ present:** possible to resolve $R(D)$ and $R(D^*)$, but in conflict with the measured q^2 differential distributions;



  - ▷ Dark green: fits at 95% CL; light green: at 99.7% CL;
  - ▷ Having only a real $g_L^{cb\tau}$ as the common explanation for $R(D)$ and $R(D^*)$ is now highly disfavoured by the q^2 differential distributions;
    [A. Crivellin *et al.*, 1206.2634; A. Crivellin *et al.*, 1507.07567]

- **Only $g_R^{cb\tau}$ present:** does improve the fit to $R(D^{(*)})$ compared to SM, but does not yield a good fit, when combining all data;

- **Conclusion:** charged scalar alone do can explain all the data, but only with both $g_L^{cb\tau}$ and $g_R^{cb\tau}$ added simultaneously!

Scenarios without tree-level FCNCs

- The model-indep. scalar-mediated charged-current interaction:

$$\mathcal{L}_{\text{eff}} = -\frac{4G_F V_{q_u q_d}}{\sqrt{2}} \left[\bar{q}_u \left(g_L^{q_u q_d \ell} \mathcal{P}_L + g_R^{q_u q_d \ell} \mathcal{P}_R\right) q_d\right] \left[\bar{\ell} \mathcal{P}_L \nu_\ell\right]$$

- Scenarios without tree-level FCNCs: $g_{L,R}$ must be diagonal; [“Yukawa Alignment in the Two-Higgs-Doublet Model, A. Pich, P. Tuzon, 0908.1554]

$$\mathcal{L}_Y = -\frac{\sqrt{2}}{v} H^+ \left\{\bar{u}\left[V \varsigma_D M_D \mathcal{P}_R - \varsigma_U M_U V \mathcal{P}_L\right] d + \bar{\nu} \varsigma_L M_L \mathcal{P}_R \ell\right\}$$

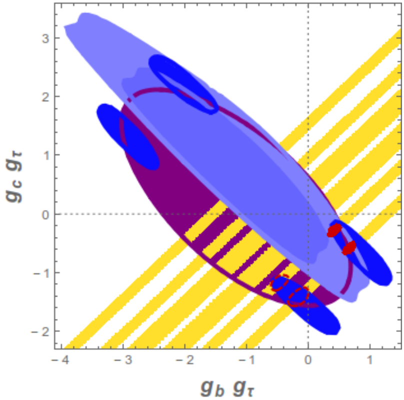
$$g_L^{q_u q_d l} = \varsigma_u \varsigma_l^* \frac{m_{q_u} m_l}{m_{H^\pm}^2}, \qquad g_R^{q_u q_d l} = -\varsigma_d \varsigma_l^* \frac{m_{q_d} m_l}{m_{H^\pm}^2}$$

- Family-universal: $\varsigma_{D,U,L} \equiv \varsigma_{d,u,\ell} \mathbf{1}$, 2HDMs with NFC easily recovered;

  $\hookrightarrow$ different decay modes are automatically connected;

Scenarios without tree-level FCNCs

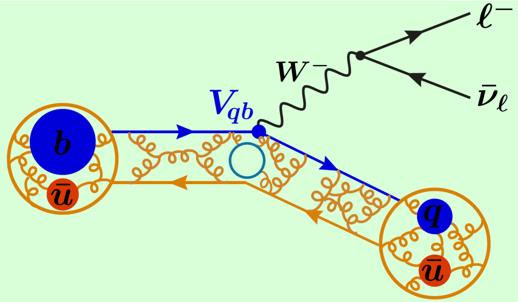
- New observables involving τ: $\mathrm{Br}(B \to \tau\nu)$, $\mathrm{Br}(D_{d,s} \to \tau\nu)$, $\Gamma(\tau \to K\nu)/\Gamma(\tau \to \pi\nu), \cdots$;
- Global fit using the available data with τ lepton: 95% CL



- dark blue: constraints from $R(D^{(*)})$;
- light blue: constraints from q^2 distributions;
- dark yellow: the other measurements above, not depending on both couplings simultaneously;
- red: dashed rings excluded by $D_d \to \tau\nu$ and incompatible with the distributions;
- joined fit still remains viable: $\chi^2 = 62.7$ for 55 dof, compared to $\chi^2 = 81.1$ for 60 dof in SM;

- Conclusion: the scenario with charged-scalar interactions can explain $B \to D^{(*)}\tau\nu$ and the remaining tree-level observables!

Solution with a scalar leptoquark



- Solutions with a scalar leptoquark and pheno. implications:

X. Q. Li, Y. D. Yang and X. Zhang, "Revisiting the one leptoquark solution to the $R(D^{(*)})$ anomalies and its phenomenological implications," arXiv:1605.09308 [hep-ph].

M. Bauer and M. Neubert, "Minimal Leptoquark Explanation for the R$_{D^{(*)}}$, R$_K$, and $(g-2)_\mu$ Anomalies," Phys. Rev. Lett. **116** (2016) no.14, 141802 [arXiv:1511.01900 [hep-ph]].

M. Freytsis, Z. Ligeti and J. T. Ruderman, "Flavor models for $\bar{B} \to D^{(*)}\tau\bar{\nu}$,"

Phys. Rev. D **92** (2015) no.5, 054018 [arXiv:1506.08896 [hep-ph]].

The one scalar leptoquark scenario

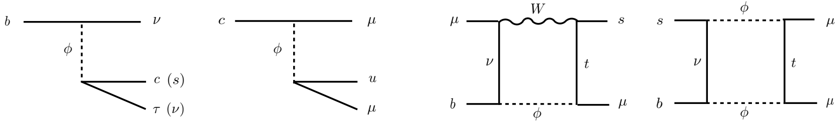
- The LQ model: one single scalar LQ with $M_\phi \sim 1$ TeV and $(\mathbf{3}, \mathbf{1}, -\frac{1}{3})$ added to SM; [M. Bauer and M. Neubert, 1511.01900]

$$\mathcal{L}_\phi = (D_\mu \phi)^\dagger D_\mu \phi - M_\phi^2 \, |\phi|^2 - g_{h\phi} \, |\Phi|^2 |\phi|^2$$

$$+ \bar{Q}^c \boldsymbol{\lambda}^L i\tau_2 L \, \phi^* + \bar{u}_R^c \, \boldsymbol{\lambda}^R e_R \, \phi^* + \text{h.c.}\,,$$

- ϕ interactions with fermions: rotating from the weak to the mass basis for quarks and charged leptons, to get $\mathcal{L}_{\rm int}^\phi$;

$$\mathcal{L}_{\rm int}^\phi = \bar{u}_L^c \boldsymbol{\lambda}_{ul}^L l_L \phi^* - \bar{d}_L^c \boldsymbol{\lambda}_{d\nu}^L \nu_L \phi^* + \bar{u}_R^c \boldsymbol{\lambda}_{ul}^R l_R \phi^* + \text{h.c.}\,,$$



- Both tree- and loop-level four-fermion operators $(\bar{u}_i d_j)(\bar{\nu}\ell)$, $(\bar{u}_i u_j)(\ell^+\ell^-)$ and $(\bar{d}_i d_j)(\bar{\nu}\nu)$ generated; $\hookrightarrow$ $\bar{B} \to D^{(*)}\tau\bar{\nu}_\tau$, $B_c^- \to \tau^-\bar{\nu}_\tau(\gamma)$, $B \to X_c\tau\bar{\nu}_\tau$, $D^0 \to \mu^+\mu^-$, $D^+ \to \pi^+\mu^+\mu^-$, $B \to X_s\nu\bar{\nu}$, $B \to K^{(*)}\nu\bar{\nu}$, $K \to \pi\nu\bar{\nu}$, $(g-2)_\mu$;

[M. Bauer and M. Neubert, 1511.01900]

LQ-mediated $b \to c\tau\bar{\nu}_\tau$ decays

- Total $\mathcal{H}_{\text{eff}}$ for $b \to c\tau\bar{\nu}_\tau$ transitions: integrating out ϕ and performing the proper Fierz transformation;

$$\mathcal{H}_{\text{eff}} = \frac{4G_F}{\sqrt{2}} V_{cb} \Big[C_V(M_\phi)\, \bar{c}\gamma_\mu P_L b\, \bar{\tau}\gamma^\mu P_L \nu_\tau + C_S(M_\phi)\, \bar{c} P_L b\, \bar{\tau} P_L \nu_\tau - \frac{1}{4} C_T(M_\phi)\, \bar{c}\sigma_{\mu\nu} P_L b\, \bar{\tau}\sigma^{\mu\nu} P_L \nu_\tau \Big]$$

- C_V, C_S, C_T: the WCs at the matching scale $\mu = M_\phi$; the latter two need be run down to $\mu_b \sim m_b$;

$$C_V(M_\phi) = 1 + \frac{\lambda^L_{b\nu_\tau} \lambda^{L*}_{c\tau}}{4\sqrt{2} G_F V_{cb} M_\phi^2}, \quad C_S(M_\phi) = C_T(M_\phi) = -\frac{\lambda^L_{b\nu_\tau} \lambda^{R*}_{c\tau}}{4\sqrt{2} G_F V_{cb} M_\phi^2}$$

- Four best-fit solutions for $R(D^{(*)})$ along with acceptable q^2 spectra: $M_\phi = 1\ \mathrm{TeV}$; [M. Freytsis, Z. Ligeti, J. T. Ruderman, 1506.08896]

$$(\lambda^L_{b\nu_\tau} \lambda^{L*}_{c\tau}, \lambda^L_{b\nu_\tau} \lambda^{R*}_{c\tau}) = (C''_{S_R}, C''_{S_L}) = \begin{cases} (\ \ 0.35, & -0.03), \quad P_A \\ (\ \ 0.96, & \ \ 2.41), \quad P_B \\ (-5.74, & \ \ 0.03), \quad P_C \\ (-6.34, & -2.39), \quad P_D \end{cases}$$

LQ-mediated $b \to c\tau\bar{\nu}_\tau$ decays

- Solution P_A: explain in a natural way three of the most striking anomalies of particle physics, while satisfying the other low-energy constraints without fine-tuning; [M. Bauer and M. Neubert, 1511.01900]

One Leptoquark to Rule Them All:
A Minimal Explanation for $R_{D^{(*)}}$, R_K and $(g-2)_\mu$

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We show that by adding a single new scalar particle to the Standard Model, a TeV-scale leptoquark with the quantum numbers of a right-handed down quark, one can explain in a natural way three of the most striking anomalies of particle physics: the violation of lepton universality in $\bar{B} \to \bar{K}\ell^+\ell^-$ decays, the enhanced $\bar{B} \to D^{(*)}\tau\bar{\nu}$ decay rates, and the anomalous magnetic moment of the muon. Constraints from other precision measurements in the flavor sector can be satisfied without fine-tuning. Our model predicts enhanced $\bar{B} \to \bar{K}^{(*)}\nu\bar{\nu}$ decay rates and a new-physics contribution to $B_s - \bar{B}_s$ mixing close to the current central fit value.

- Question: these four best-fit solutions could be discriminated from each other using the low-energy processes mediated by the same quark-level $b \to c\tau\nu_\tau$ transition?

  $\hookrightarrow$ in addition to $\bar{B} \to D^{(*)}\tau\bar{\nu}_\tau$, we shall examine the scalar LQ effects on $B_c^- \to \tau^-\bar{\nu}_\tau$, $B_c^- \to \gamma\tau^-\bar{\nu}_\tau$ and $B \to X_c\tau\bar{\nu}_\tau$ decays.

The purely leptonic $B_c^- \to \tau^- \bar{\nu}_\tau$ decay

- The decay width with LQ-exchanged contribution:

$$\Gamma(B_c^- \to \tau^- \bar{\nu}_\tau) = \frac{G_F^2}{8\pi} |V_{cb}|^2 f_{B_c}^2 m_{B_c}^3 \frac{m_\tau^2}{m_{B_c}^2} \left(1 - \frac{m_\tau^2}{m_{B_c}^2}\right)^2 \left| C_V - C_S \frac{m_{B_c}^2}{m_\tau \left[m_b(\mu_b) + m_c(\mu_b)\right]} \right|^2$$

- Numerical results with the four best-fit solutions:

$$\Gamma(B_c^- \to \tau^- \bar{\nu}_\tau) = \begin{cases} 2.22 \times 10^{-2}\, \Gamma_{B_c}, & \text{SM} \\ 2.45 \times 10^{-2}\, \Gamma_{B_c}, & P_A \\ 1.33\, \Gamma_{B_c}, & P_B \\ 2.39 \times 10^{-2}\, \Gamma_{B_c}, & P_C \\ 1.31\, \Gamma_{B_c}, & P_D \end{cases}$$

- Conclusion: Clearly, P_B and P_D already excluded by $B_c^- \to \tau^- \bar{\nu}_\tau$, because the predicted decay widths have already overshot the total width. $\hookrightarrow$ need only consider solutions P_A and P_C!

Comparison between P_A and P_C

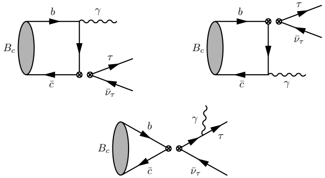
- $\mathcal{H}_{\text{eff}}$ with fitted values of the effective couplings in P_A and P_C:

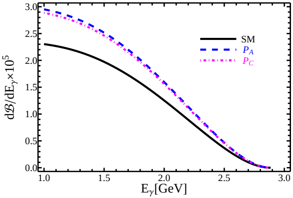
$$\mathcal{H}_{\text{fit}} = \frac{4G_F}{\sqrt{2}} V_{cb} \Bigg\{ \underbrace{\left[1 + \begin{pmatrix} 0.129 & \text{for } P_A \\ -2.117 & \text{for } P_C \end{pmatrix} \right]}_{C_V^{\text{fit}}} \bar{c}\gamma_\mu P_L b \, \bar{\tau}\gamma^\mu P_L \nu_\tau + \underbrace{\begin{pmatrix} 0.018 & \text{for } P_A \\ -0.018 & \text{for } P_C \end{pmatrix}}_{C_S^{\text{fit}}} \bar{c} P_L b \, \bar{\tau} P_L \nu_\tau + \underbrace{\begin{pmatrix} -0.002 & \text{for } P_A \\ 0.002 & \text{for } P_C \end{pmatrix}}_{C_T^{\text{fit}}} \bar{c}\sigma_{\mu\nu} P_L b \, \bar{\tau}\sigma^{\mu\nu} P_L \nu_\tau \Bigg\}$$

- C_V^{fit}: nearly same absolute values but with opposite signs, enhance SM by $\sim 12\%$;
- C_S^{fit} and C_T^{fit}: same (tiny) values but with opposite signs;
- Conclusion: it should be difficult to discriminate P_A from P_C;

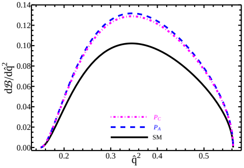
Some other decay modes considered:

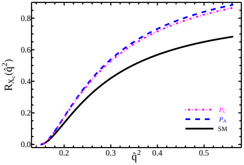
- The radiative leptionic decay $B_c^- \to \gamma\tau\bar{\nu}_\tau$:

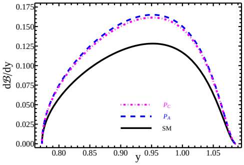




- The inclusive semileptonic $B \to X_c\tau^-\bar{\nu}_\tau$ decay:







- The other observables in $\bar{B} \to D^{(*)}\tau\nu_\tau$: q^2 distribution of $R(D)$ and $R(D^*)$, polarizations of τ and D^*, and lepton forward-backward asymmetry;
- Conclusion: these observables are enhanced by the scalar LQ contribution, but difficult to distinguish between the two solutions P_A and P_C.

Conclusion and outlook

- $R(D)$ and $R(D^*)$ anomalies: BaBar, Belle and LHCb results consistent with each other; The latest 2016 WA has now a 4.0σ deviation from the SM predictions (Remind: theoretical predictions are on solid footing; first NP signal?);

- The current data can be explained by a charged scalar, but only when both $g_L^{cb\tau}$ and $g_R^{cb\tau}$ couplings are considered simultaneously;

- In scenarios without tree-level FCNCs [like A2HDM: A. Celis, M. Jung, X. Q. Li and A. Pich, 1210.8443]: $R(D)$, $R(D^*)$ and the other low-energy processes can be consistently explained; however, the allowed regions are severely constrained;

- The current flavour anomalies can be explained by adding just one scalar leptoquark; we have discussed its effects on $\mathcal{B}(B_c^- \to \tau^- \bar{\nu}_\tau)$, $\mathcal{B}(B_c^- \to \gamma\tau^- \bar{\nu}_\tau)$, $R_{D^{(*)}}(q^2)$, $\mathrm{d}\mathcal{B}(\bar{B} \to D^{(*)}\tau\bar{\nu}_\tau)/\mathrm{d}q^2$, $\mathcal{B}(\bar{B} \to X_c\tau\bar{\nu}_\tau)$;

- Very interesting to study the inclusive $\bar{B} \to X_c\tau\bar{\nu}_\tau$, and the semileptonic Λ_b and B_s decays, $\cdots$;

Thank You for Your Attention!