Leptoquark scenarios of lepton non-universality in B decays

Nejc Košnik

collaboration with

D. Bečirević, S. Fajfer, O. Sumensari, R. Zukanovich-Funchal

IJS

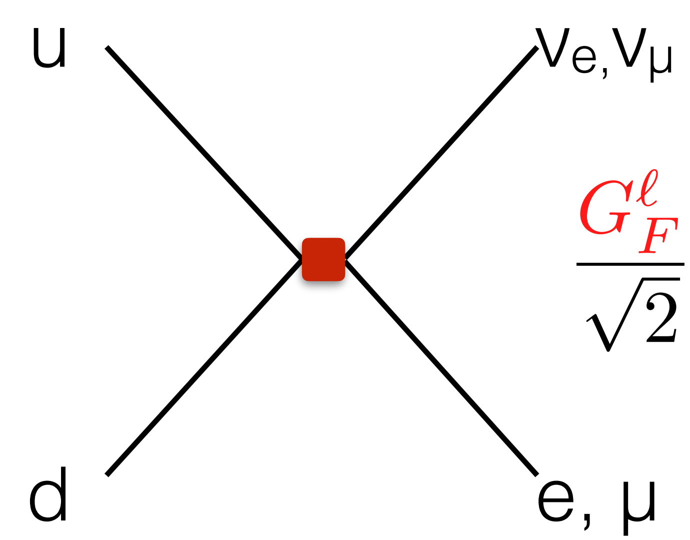
University *of Ljubljana*
Faculty *of Mathematics and Physics*

IHP, Paris, Nov. 8 '16

Lepton flavour universality

Lepton Flavor Universality (**LFU)** first observed in the framework of Fermi theory

$G_F^e \approx G_F^\mu$



$$\frac{G_F^\ell}{\sqrt{2}} \bar{\nu}_\ell \gamma^\lambda (1-\gamma_5)\ell \; \bar{n}\gamma_\lambda(1-\gamma_5)p$$

Standard Model: LFU is the consequence of replication of fermions with equal properties. Broken by the lepton Yukawa couplings.

$$U(3)_L \times U(3)_e \to U(1)_e \times U(1)_\mu \times U(1)_\tau$$

Well tested in pion, kaon decays, LEP physics …

$$\Gamma_{ll}^{SM} = \frac{GM_Z^3}{6\sqrt{2}\pi}\left((C_V^f)^2 + (C_A^f)^2\right) = 83.42\text{MeV}$$

$$C_V^\ell = -1$$
$$C_A^\ell = -1 + 4\sin^2\theta_W$$

$$\Gamma_{ee} = (83.94 \pm 0.14)\text{MeV}$$
$$\Gamma_{\mu\mu} = (83.84 \pm 0.20)\text{MeV}$$
$$\Gamma_{\tau\tau} = (83.68 \pm 0.24)\text{MeV}$$

LFU tests at low energies

- **LFU ratios are theoretically clean, blind to universal features (CKM, couplings, hadronic parameters)**

$$\Gamma_{P\to\ell\nu} \sim G_F^2 |V_{ij}|^2 f_P^2 m_P {m_\ell}^2 \underbrace{\left(1 - \frac{{m_\ell}^2}{m_P^2}\right)}_{\text{chiral SM interaction}} \underbrace{\left(1 - \frac{{m_\ell}^2}{m_P^2}\right)}_{\text{phase space}}$$

- **Numerous LFU ratios are in good agreement with the SM**

	SM	exp. value
$R^{\pi}_{e/\mu} = \frac{\Gamma(\pi\to e\bar\nu)}{\Gamma(\pi\to\mu\bar\nu)}$	$(1.2352 \pm 0.0001) \times 10^{-4}$	$(1.2327 \pm 0.0023) \times 10^{-4}$
$R^{K}_{e/\mu} = \frac{\Gamma(K\to e\bar\nu)}{\Gamma(K\to\mu\bar\nu)}$	$(2.477 \pm 0.001) \times 10^{-5}$	$(2.488 \pm 0.010) \times 10^{-5}$
$R^{K}_{\tau/\mu} = \frac{\Gamma(\tau\to K\bar\nu)}{\Gamma(K\to\mu\bar\nu)}$	$(1.1162 \pm 0.00026) \times 10^{-2}$	$(1.101 \pm 0.016) \times 10^{-2}$
$R^{B}_{\tau/\mu} = \frac{\Gamma(B\to\tau\nu)}{\Gamma(B\to\mu\bar\nu)}$	223	$\gtrsim 100$

Motivation: LFU in neutral current b→s$\ell^+\ell^-$

- First proposal and prediction of R_K, R_{K^*}, R_{X_s} [Kruger, Hiller, hep-ph/0310219]

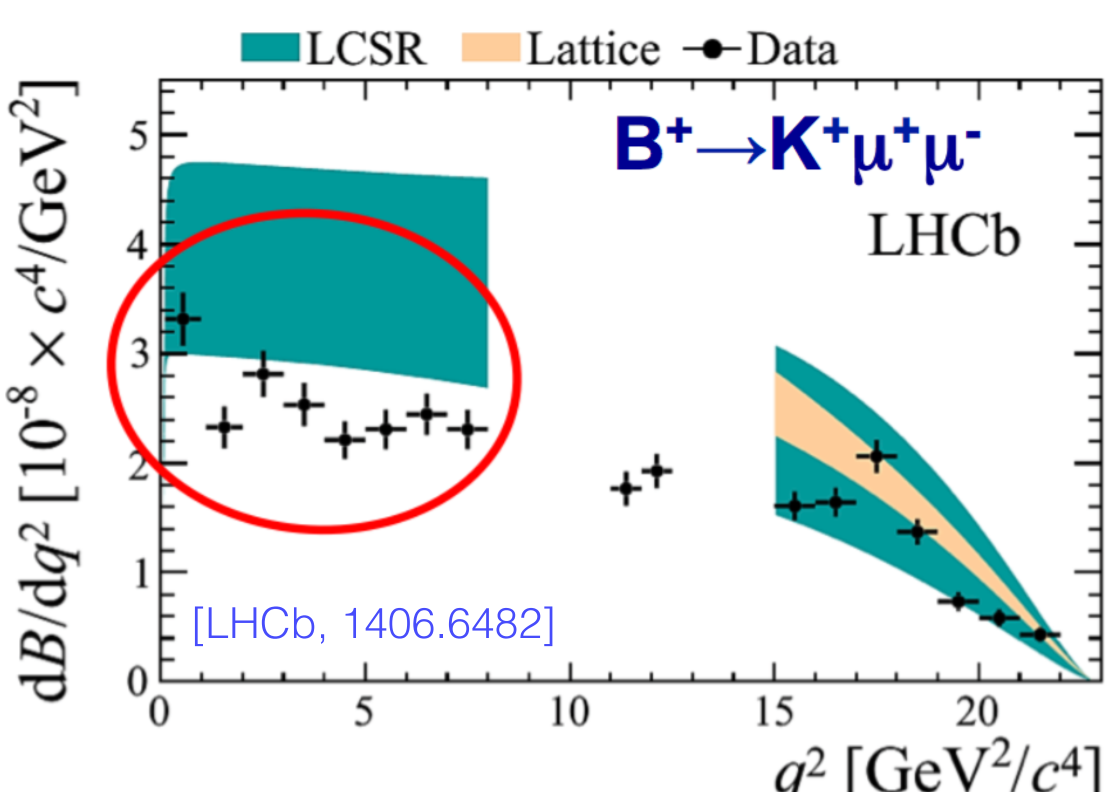
$$R_K = \frac{\mathcal{B}(B \to K\mu^+\mu^-)_{q^2\in[1,6]\ \mathrm{GeV}^2}}{\mathcal{B}(B \to Ke^+e^-)_{q^2\in[1,6]\ \mathrm{GeV}^2}} = 1.00 + \mathcal{O}(m_\mu^2/m_B^2) \pm 0.03\big|_{\mathrm{rad.corr.}}$$

[Bordone, Isidori, Pattori, 1605.07633]

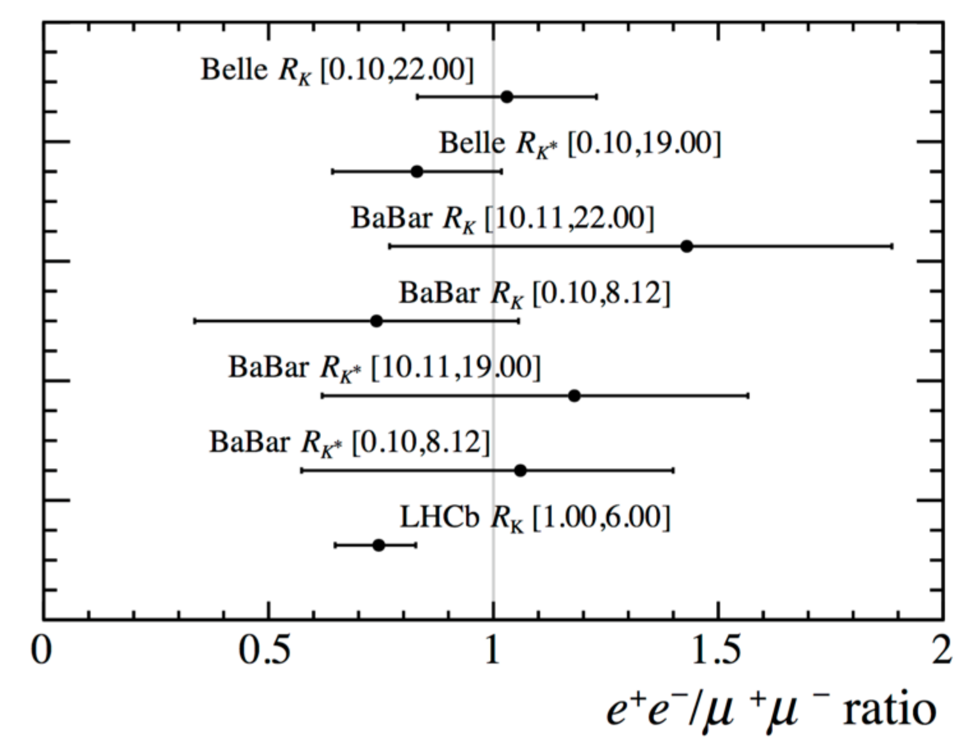
- LHCb observed a small hint (2.4σ) of LFU violation (2014)

$$R_K^{\mathrm{exp}} = 0.745 \pm^{0.090}_{0.074} \pm 0.036$$

[LHCb 1403.8044]



Muons rates are too small.



[Blake, Lanfranchi, Straub 1606.00916]

Effective operator analysis

Standard Model + dim-6 operators at scale Λ (SM-EFT)

$$\mathcal{L}_{BSM} = \frac{1}{\Lambda^2}\sum_i C_i Q_i$$

$$Q_i \sim (HD_\mu H)(\bar{q}\gamma^\mu q)$$ "Higgs current"

$$(\bar{q}\sigma^{\mu\nu}V_{\mu\nu}q)H$$ "dipoles"

$$\bar{q}q\bar{\ell}\ell$$ "4-fermion"

Assume linear realisation of the EW symmetry. RG running to b-energy scale

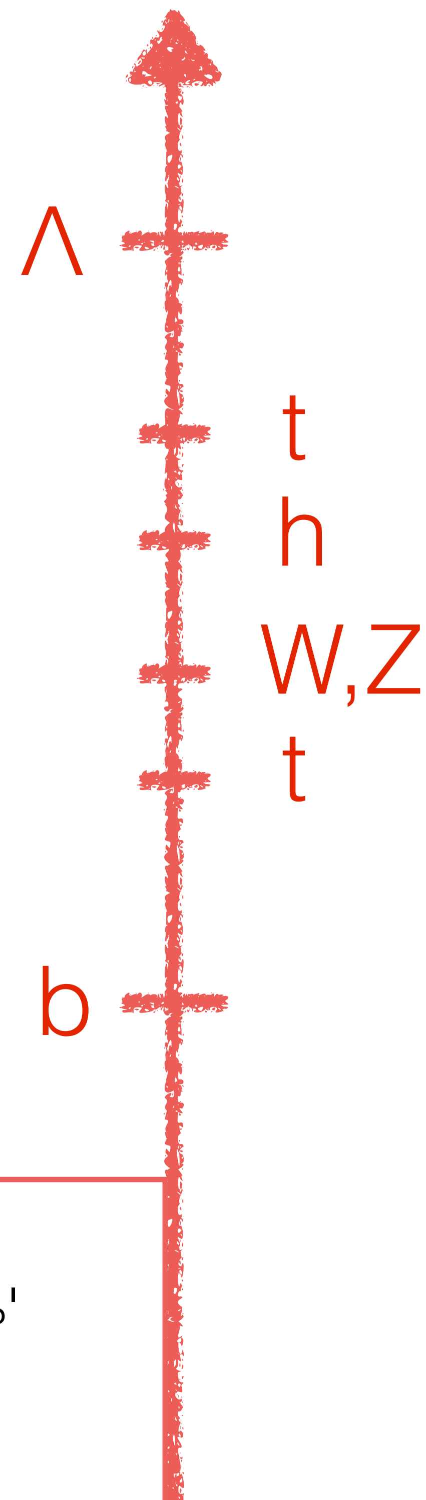
$$\mathcal{L}_{\text{eff}} = \frac{4G_F}{\sqrt{2}}V_{tb}V_{ts}^*\left[\sum_{i=1}^{6}C_i\mathcal{O}_i + \sum_{i=7,8,9,10,S,P}(C_i\mathcal{O}_i + C_i'\mathcal{O}_i')\right]$$

$$\mathcal{O}_7^{(\prime)} = \frac{e}{(4\pi)^2}m_b(\bar{s}\sigma_{\mu\nu}P_{R(L)}b)F^{\mu\nu}$$

$$\mathcal{O}_9^{(\prime)} = \frac{e^2}{(4\pi)^2}(\bar{s}\gamma_\mu P_{L(R)}b)(\bar{\ell}\gamma^\mu\ell) \qquad \mathcal{O}_{10}^{(\prime)} = \frac{e^2}{(4\pi)^2}(\bar{s}\gamma_\mu P_{L(R)}b)(\bar{\ell}\gamma^\mu\gamma_5\ell)$$

$$\mathcal{O}_S^{(\prime)} = \frac{e^2}{(4\pi)^2}(\bar{s}P_{R(L)}b)(\bar{\ell}\ell) \qquad \mathcal{O}_P^{(\prime)} = \frac{e^2}{(4\pi)^2}(\bar{s}P_{R(L)}b)(\bar{\ell}\gamma_5\ell)$$

[Grinstein, Camalich, Alonso, 1407.7044]
[Grinstein, Camalich, Alonso, 1505.05164]
[Cata, Jung, 1505.05804]
[Feruglio, Paradisi, Pattori, 1606.00524]



1. no tensor currents
2. scalars: $C_S=-C_P$, $C_S'=C_P'$
3. $C_{9,SM}=-C_{10,SM}=4.2$
4. **LFU violation from semileptonic operators**

Effective operator analysis

$$\mathcal{O}_9^\ell = \frac{e^2}{(4\pi)^2}(\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \ell) \qquad \mathcal{O}_{10}^\ell = \frac{e^2}{(4\pi)^2}(\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \gamma_5 \ell)$$

$$\mathcal{O}_S^\ell = \frac{e^2}{(4\pi)^2}(\bar{s} P_R b)(\bar{\ell}\ell) \qquad \mathcal{O}_P^\ell = \frac{e^2}{(4\pi)^2}(\bar{s} P_R b)(\bar{\ell}\gamma_5 \ell)$$

Leading LFUV effects

- Assume that B → Kee is purely SM. Fits well with data.
- Scalar operators $C_S=-C_P$, $C_S'=C_P'$: excluded by $Br(B_s \to \mu\mu)$ ✗
- Preferable operators have (axial)vector structure

[Hiller, Schmaltz, 1408.1627]
[Hiller, Schmaltz, 1411.4773]

LFU in charged current b→cτν

$$R_D^{\rm SM} = \frac{\Gamma(B\to D\tau\nu)}{\Gamma(B\to D\ell\nu)} = 0.299 \pm 0.003$$

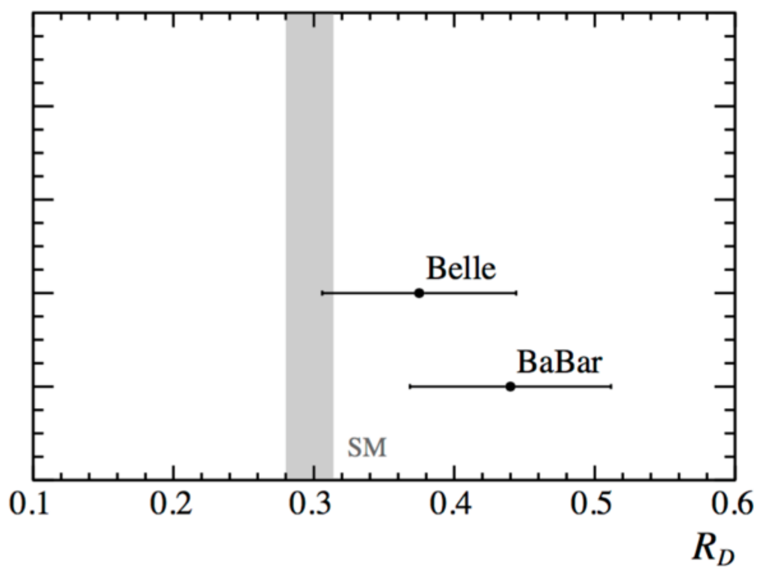
$$R_{D^*}^{\rm SM} = \frac{\Gamma(B\to D^*\tau\nu)}{\Gamma(B\to D^*\ell\nu)} = 0.252 \pm 0.003$$

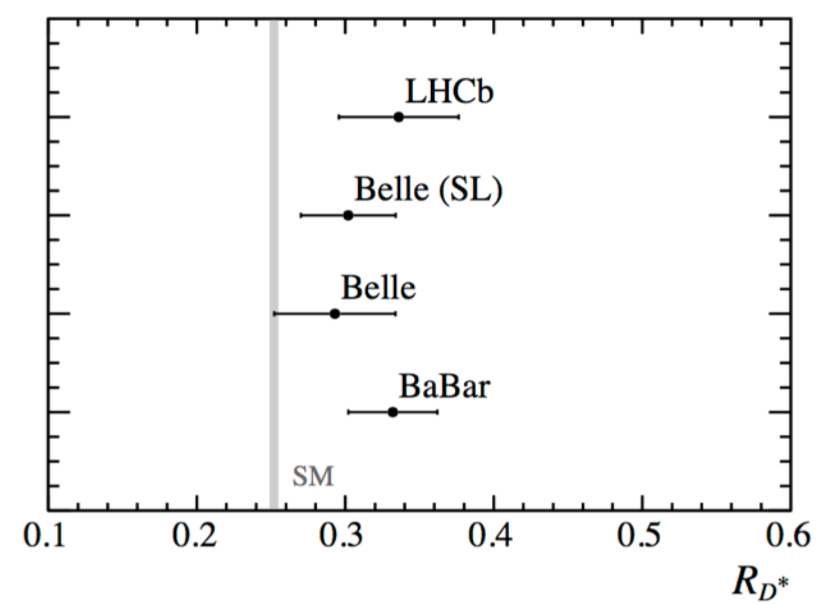
[Bigi, Gambino, 1606.08030]
[Fajfer, Kamenik, Nisandzic, 1203.2654]

$$R_D^{\rm exp} = \frac{\Gamma(B\to D\tau\nu)}{\Gamma(B\to D\ell\nu)} = 0.440 \pm 0.072$$

$$R_{D^*}^{\rm exp} = \frac{\Gamma(B\to D^*\tau\nu)}{\Gamma(B\to D^*\ell\nu)} = 0.332 \pm 0.030$$

[BaBar, 1205.5442]





[Blake, Lanfranchi, Straub 1606.00916]

Large effect - 25% enhancement of the charged current!

SM hypothesis excluded at ~4σ level.

Leptoquarks

Their origin can be traced to gauge bosons or Higgs sector of Grand Unified Theories. Consider SU(5):

gauge bosons: 24 gauge bosons $(8,1,0) \oplus (1,3,0) \oplus (1,1,0) \oplus (3,2,-5/6) \oplus (3,2,1/6)$

fermions: $5_i = (3,1,-1/3)_i \oplus (1,2,1/2)_i$

$10_i = (3,2,1/6)_i \oplus (3^*,1,-2/3)_i \oplus (1,1,1)_i$

scalar sector: 5, 10, 15, 24, 45

e.g. Georgi-Jarlskog mechanism uses 5-, and 45-dim. scalars to reproduce observed fermion masses

$5 = (1,2,1/2) \oplus (3,1,-1/3)$

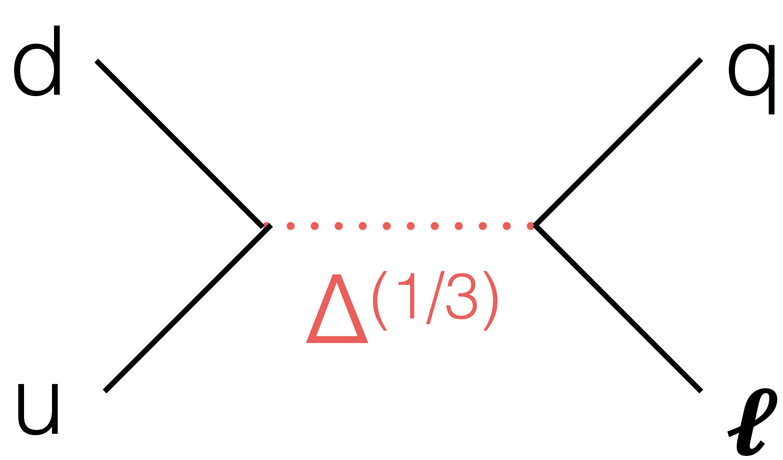
$10 = (3,2,1/6) \oplus \ldots$

$45 = (8,2,1/2) \oplus (6^*,1,-1/3) \oplus (3,3,-1/3) \oplus (3^*,2,-7/6) \oplus (3,1,-1/3) \oplus (3^*,1,4/3)$

Leptoquarks and proton stability

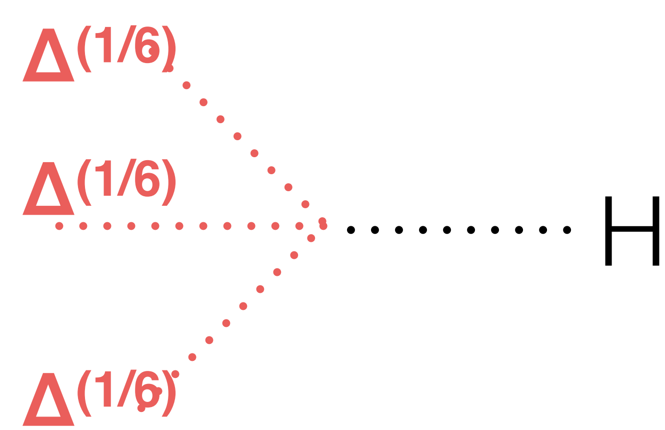
		F	B	L	
gauge bosons:	(3,2,-5/6)	2	/	/	
	(3,2,1/6)	2	/	/	
scalar sector:	(3,1,-1/3)	2	/	/	
	(3,3,-1/3)	2	/	/	
	$\Delta^{(7/6)}$(3,2,7/6)	**0**	**1/3**	**-1**	(R_2)
	$\Delta^{(1/6)}$(3,2,1/6)	**0**	**/**	**/**	($\tilde{R}_2$)
	$\Delta^{(1/3)}$(3,1,-1/3)	**2**	**/**	**/**	(S_1)
	(3*,1,4/3)	2	/	/	

STATES WITH F=2 (IN GENERAL) COUPLE TO 2 QUARKS:



$p \to M^0 \ell,\ M^+ \nu$

INDUCED BY SCALAR POTENTIAL

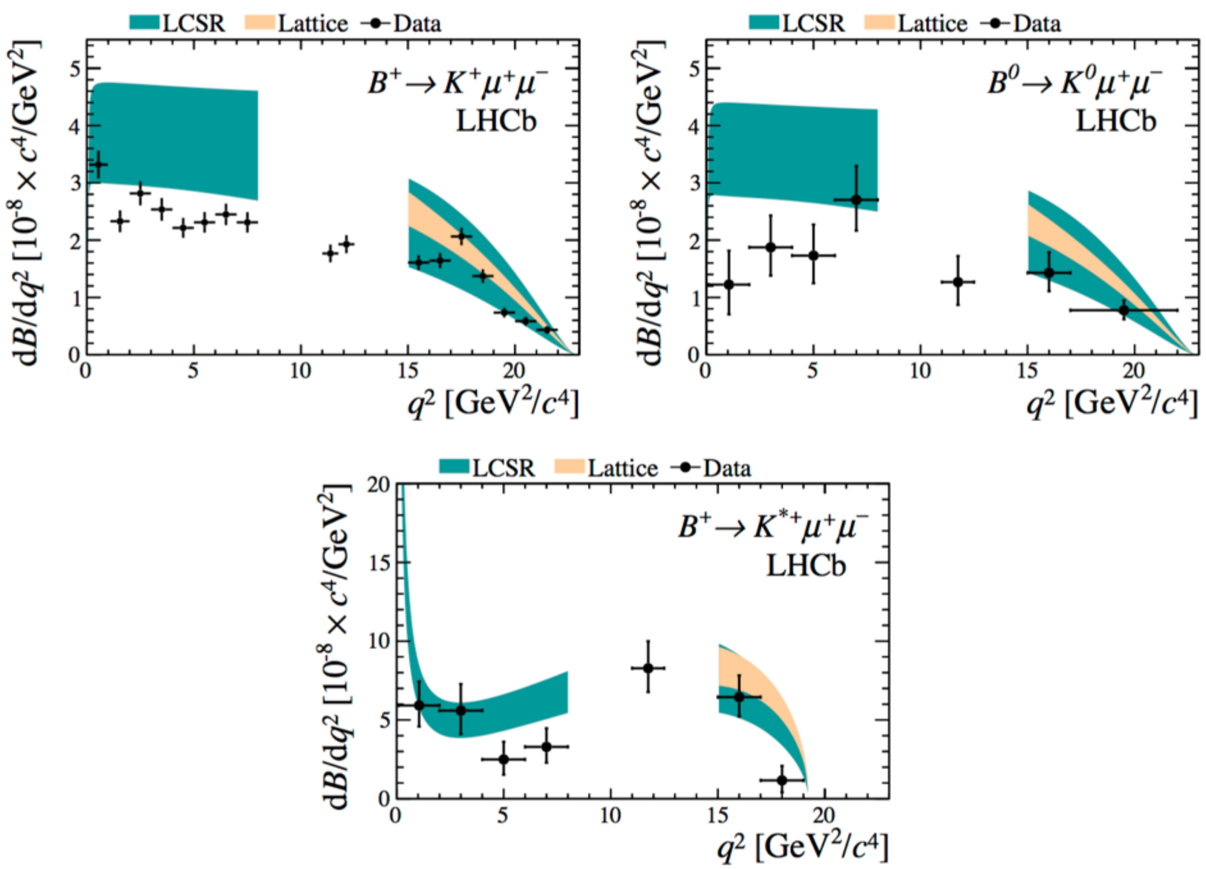


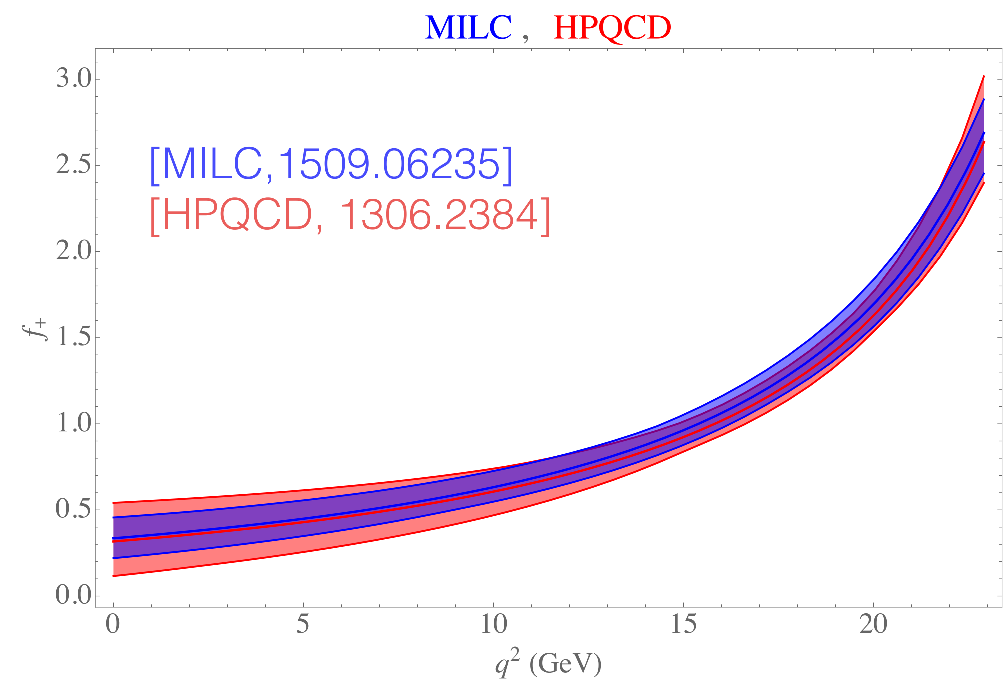
$p \to M^+ M^+ \ell \nu \nu$

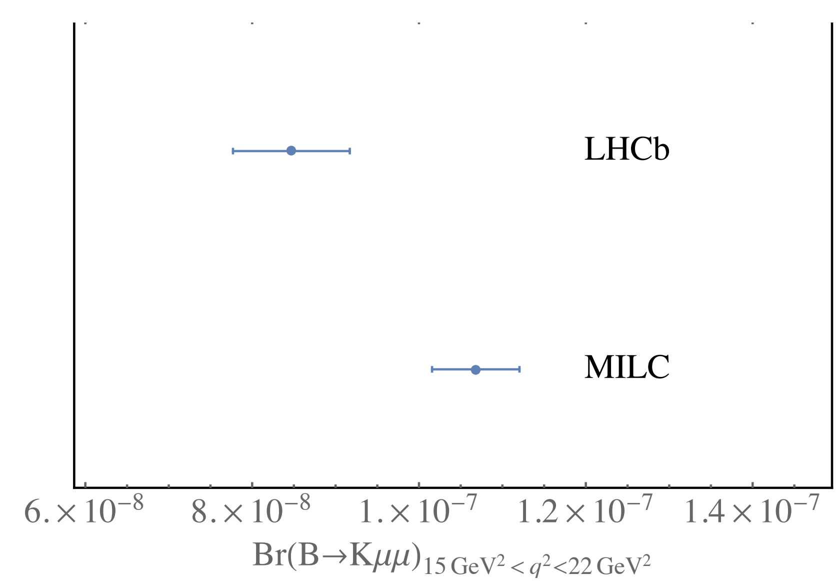
[Arnold, Fornal, Wise '13]
[Dorsner et al 16]

LFUV and LFV

Selection of b→sμμ observables



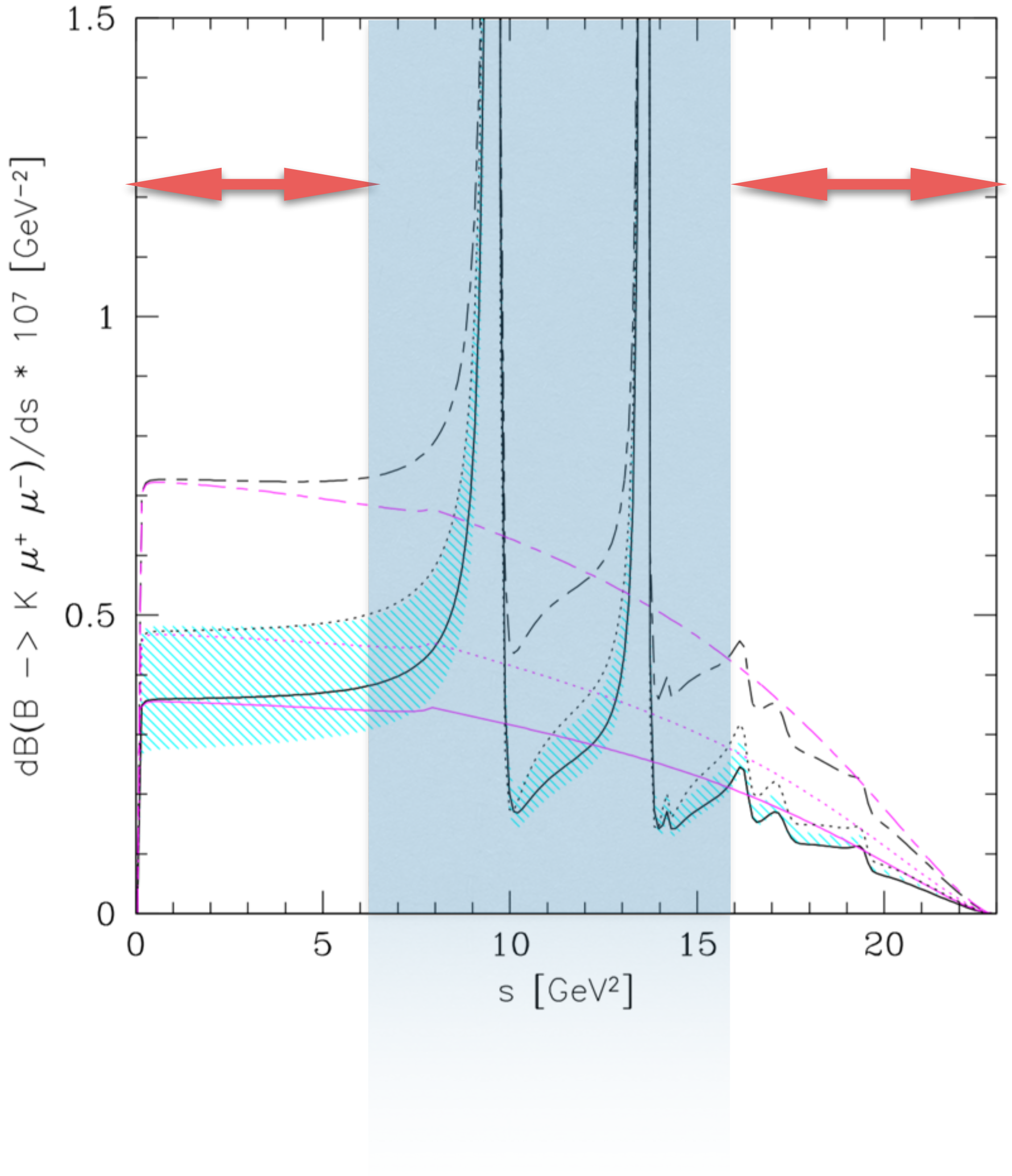




$$\mathcal{B}(B^+ \to K^+\mu^+\mu^-)|_{q^2\in[15,22]\mathrm{GeV}^2} = (8.5 \pm 0.3 \pm 0.4) \times 10^{-8}$$ [LHCb,1403.8044]

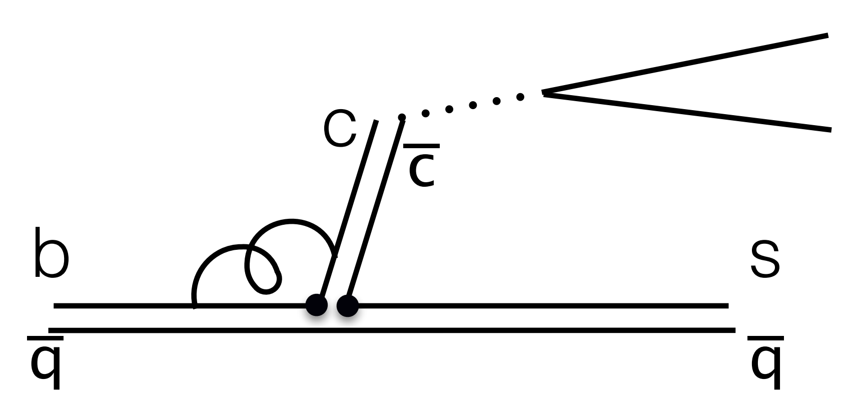
$$\mathcal{B}(B_s \to \mu^+\mu^-)^{\mathrm{exp}} = (2.8^{+0.7}_{-0.6}) \times 10^{-9}$$ [LHCb+CMS,1411.4413]

High q²

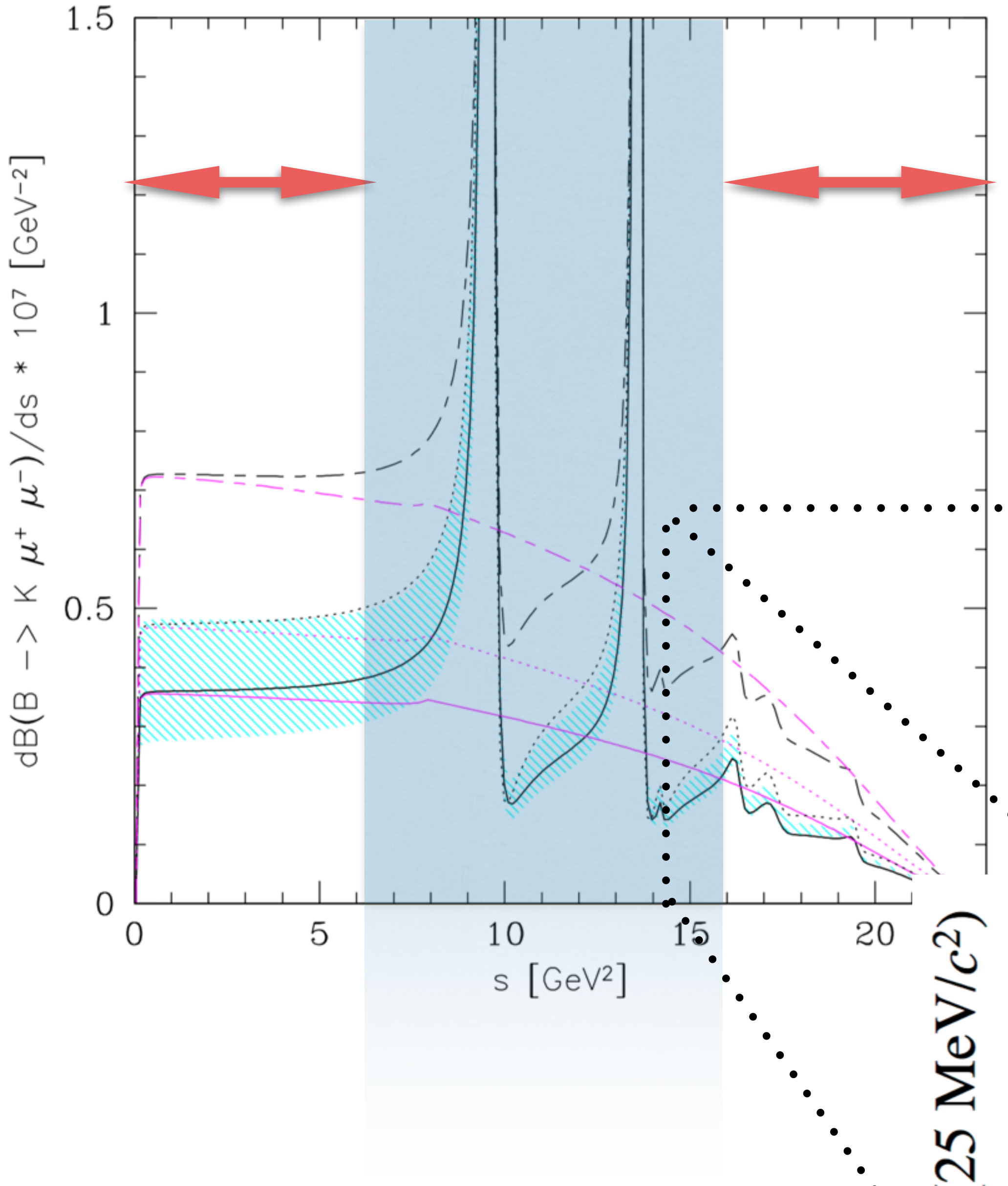


[Ali et al,hep-ph/9910221]

Factorable and non-factorizable contributions of charmonium resonances

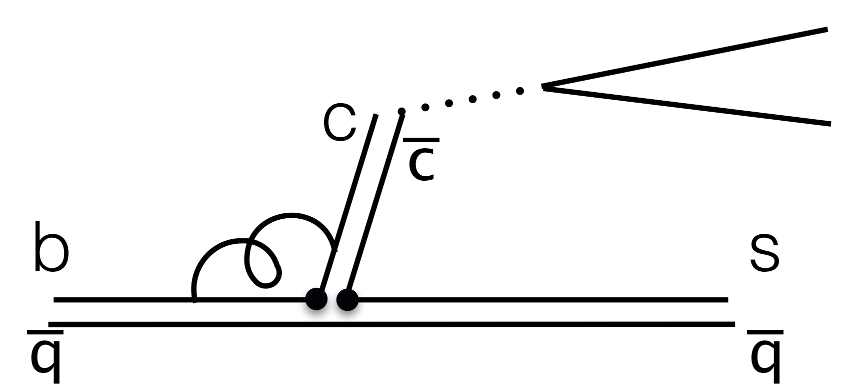


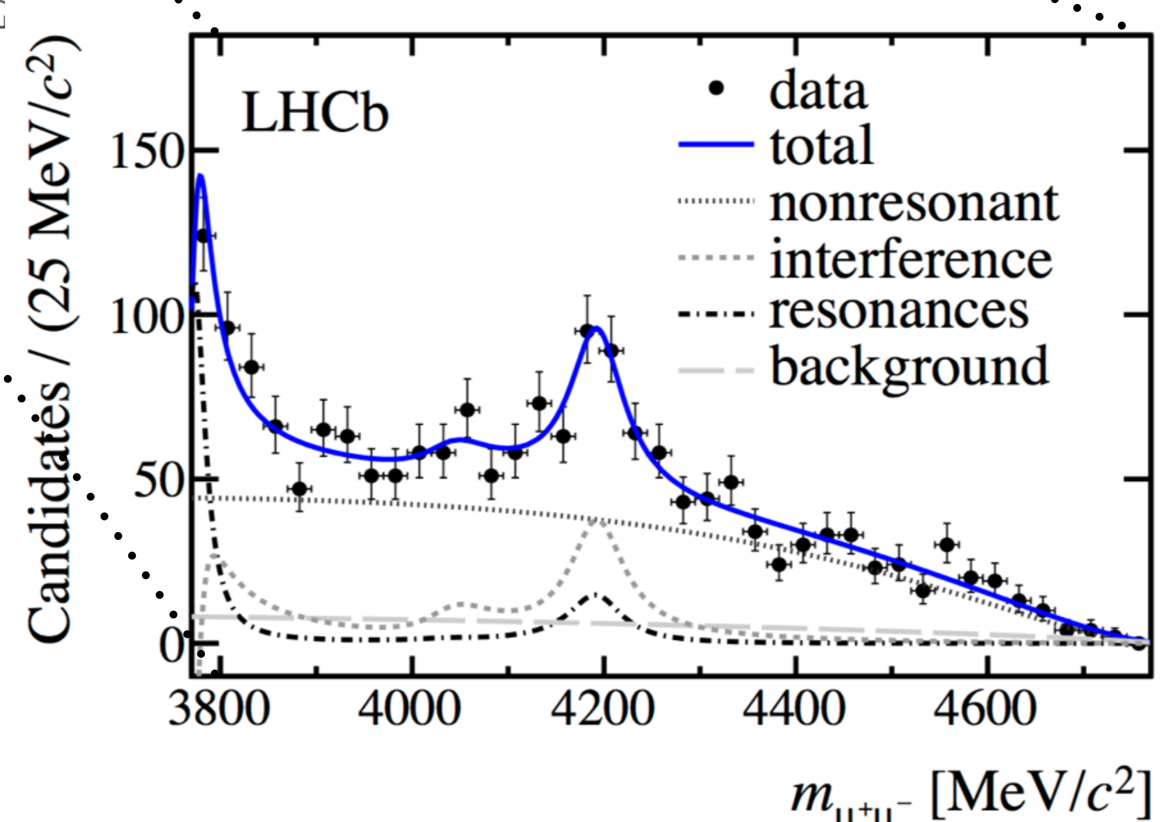
High q^2



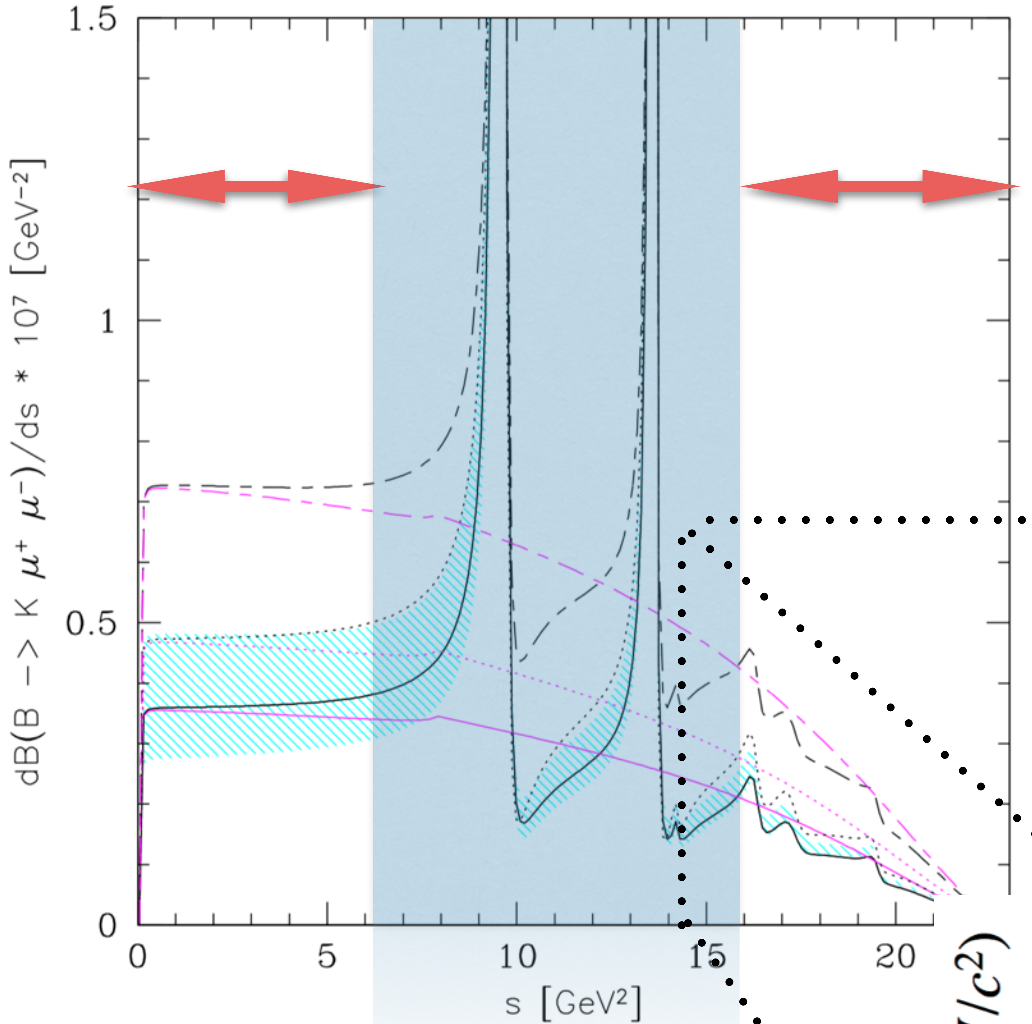
[Ali et al,hep-ph/9910221]

Factorable and non-factorizable contributions of charmonium resonances



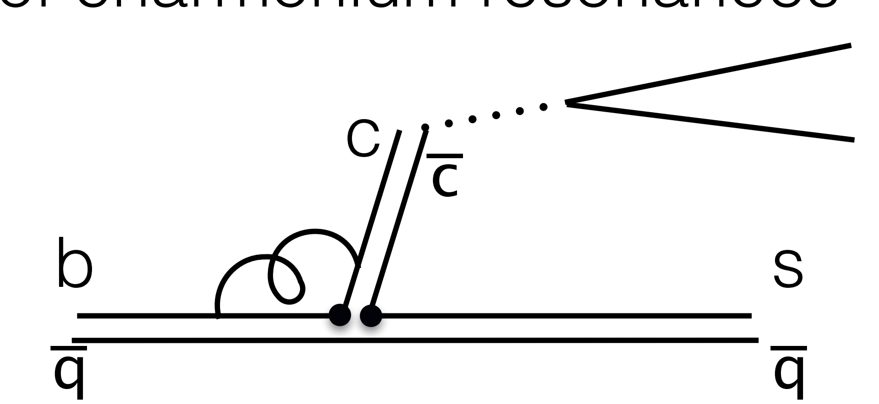


High q²



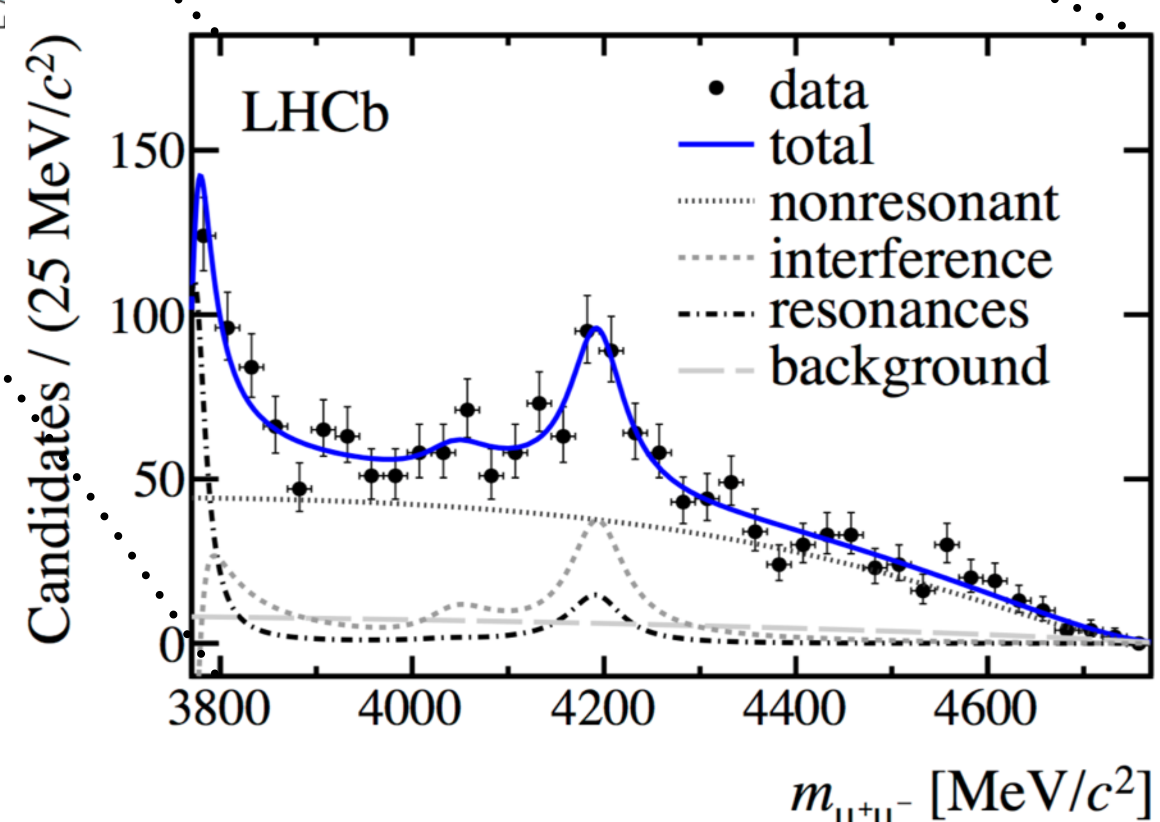
[Ali et al,hep-ph/9910221]

Factorable and non-factorizable contributions of charmonium resonances



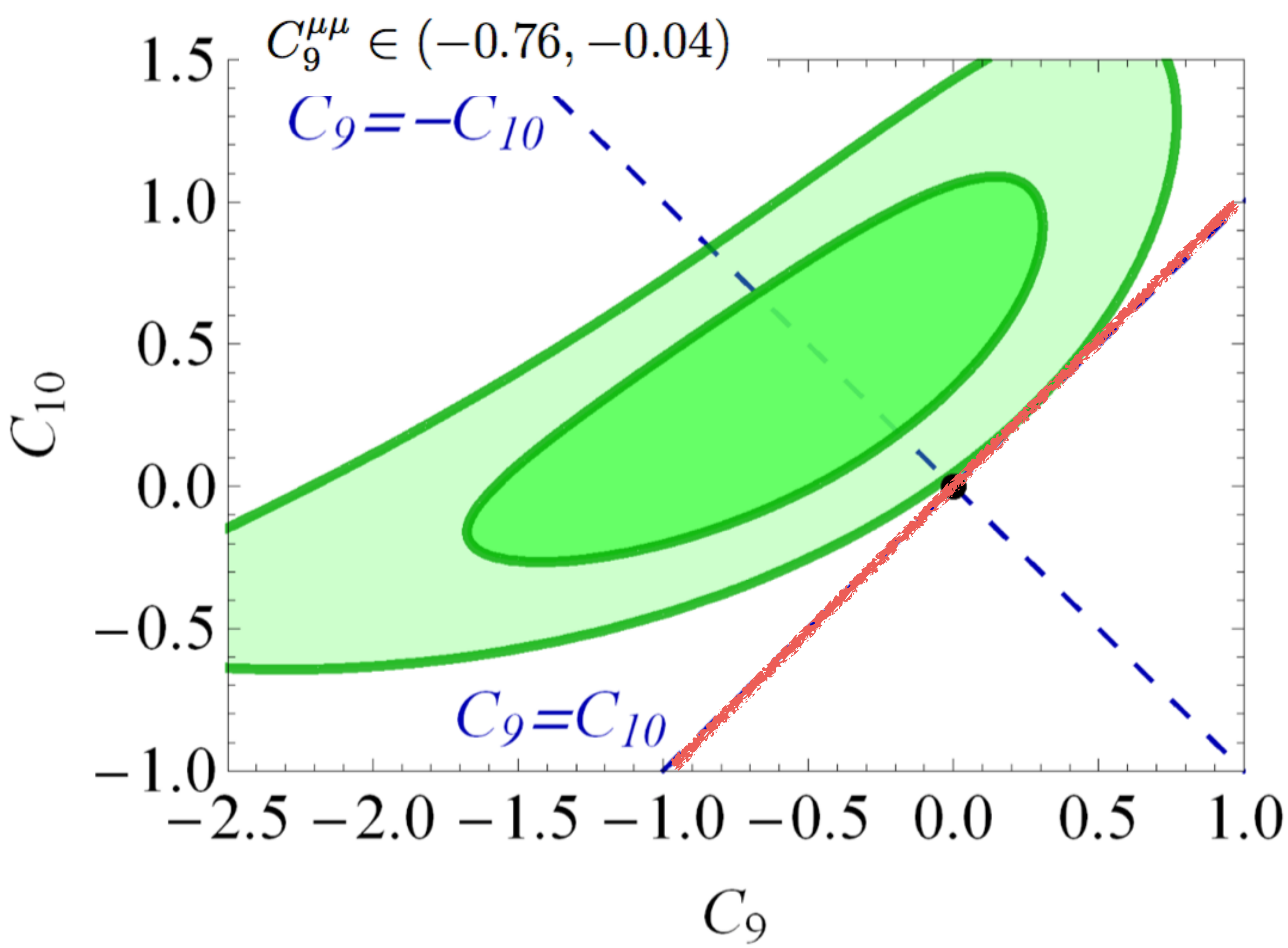
Quark-hadron duality expected to work in large enough bins

See e.g. Brass, Hiller, Nisandzic



LQ features - $\Delta^{(7/6)}(3,2,7/6)$

$$\mathcal{L}_{\Delta^{(7/6)}} = (g_R)_{ij}\bar{Q}_i\boldsymbol{\Delta}^{(7/6)}\ell_{Rj}, \\ = (Vg_R)_{ij}\bar{u}_iP_R\ell_j\,\Delta^{(5/3)} + (g_R)_{ij}\bar{d}_iP_R\ell_j\,\Delta^{(2/3)}$$



$$C_9^{\ell_1\ell_2} = C_{10}^{\ell_1\ell_2} = -\frac{\pi v^2}{2V_{tb}V_{ts}^*\alpha_{\rm em}}\frac{(g_R)_{s\ell_1}(g_R)^*_{b\ell_2}}{m_\Delta^2}$$

Increases B→Kμμ

LQ features - $\Delta^{(1/3)}(3,1,-1/3)$

$$\mathcal{L}_{\Delta^{(1/3)}} = (g_L)_{ij}\overline{Q_i^C} i\tau_2 L_j \Delta^{(1/3)*} + (g_R)_{ij}\overline{u_{Ri}^C}\ell_{Rj}\Delta^{(1/3)*}$$
$$= \Delta^{(1/3)*}\left[(V^* g_L)_{ij}\overline{u_i^C}P_L\ell_j - (g_L)_{ij}\overline{d_i^C}P_L\nu_j + (g_R)_{ij}\overline{u_i^C}P_R\ell_j\right]$$

Rare charm and charged currents at tree-level!

$$g_L = \begin{pmatrix} 0 & 0 & 0 \\ 0 & (g_L)_{s\mu} & (g_L)_{s\tau} \\ 0 & (g_L)_{b\mu} & (g_L)_{b\tau} \end{pmatrix}$$

$$C_9^{\ell_1\ell_2} - C_{10}^{\ell_1\ell_2} = \frac{m_t^2}{8\pi\alpha_{\rm em} m_\Delta^2}(g_L)^*_{t\ell_1}(g_L)_{t\ell_2} - \frac{1}{32\pi\alpha_{\rm em}}\frac{v^2}{m_\Delta^2}\frac{(g_L\cdot g_L^\dagger)_{bs}}{V_{tb}V_{ts}^*}(g_L^\dagger\cdot g_L)_{\ell_1\ell_2}$$
$$C_9^{\ell_1\ell_2} + C_{10}^{\ell_1\ell_2} = \frac{m_t^2}{16\pi\alpha_{\rm em} m_\Delta^2}(g_R)^*_{t\ell_1}(g_R)_{t\ell_2}\left[\log\frac{m_\Delta^2}{m_t^2} - f(x_t)\right] - \frac{1}{32\pi\alpha_{\rm em}}\frac{v^2}{m_\Delta^2}\frac{(g_L\cdot g_L^\dagger)_{bs}}{V_{tb}V_{ts}^*}(g_R^\dagger\cdot g_R)_{\ell_1\ell_2}$$

Putting g_R=0, $\Delta^{(1/3)}$ mimicks the C_9 = -C_{10} scenario and must satisfy

$$C_9^{\mu\mu} \in (-0.76, -0.04)$$

Proposed by Neubert, Bauer, '15

LQ features - $\Delta^{(1/3)}(3,1,-1/3)$

Rich semileptonic phenomenology

$$\mathcal{L}_{\text{eff}} = -2\sqrt{2}G_F V_{ud}\Big[(1+g_V)(\overline{u}_L\gamma_\mu d_L)(\overline{\ell}_L\gamma^\mu\nu_L) + g_S(\mu)(\overline{u}_R d_L)(\overline{\ell}_R\nu_L) + g_T(\mu)(\overline{u}_R\sigma_{\mu\nu}d_L)(\overline{\ell}_R\sigma^{\mu\nu}\nu_L)\Big]\,.$$

Also a candidate also for R_D?

To be considered: $K\to\mu\nu$, $D_s\to\mu\nu,\tau\nu$, $B\to\tau\nu$

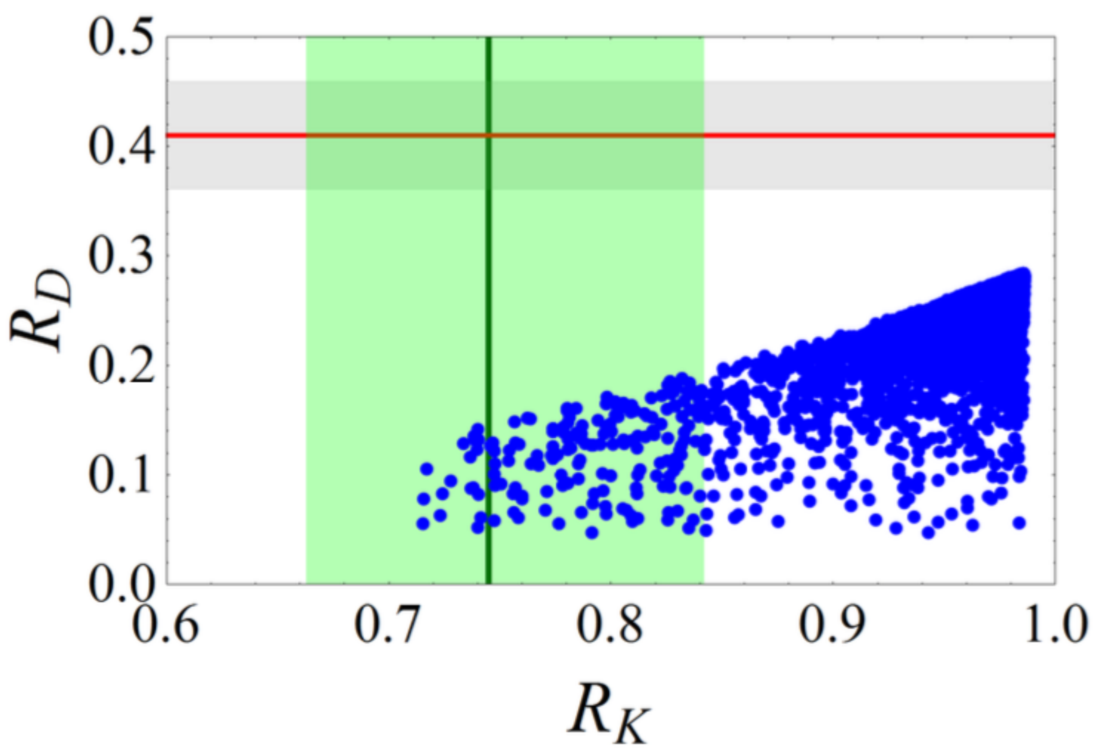
Additional neutral current constraints

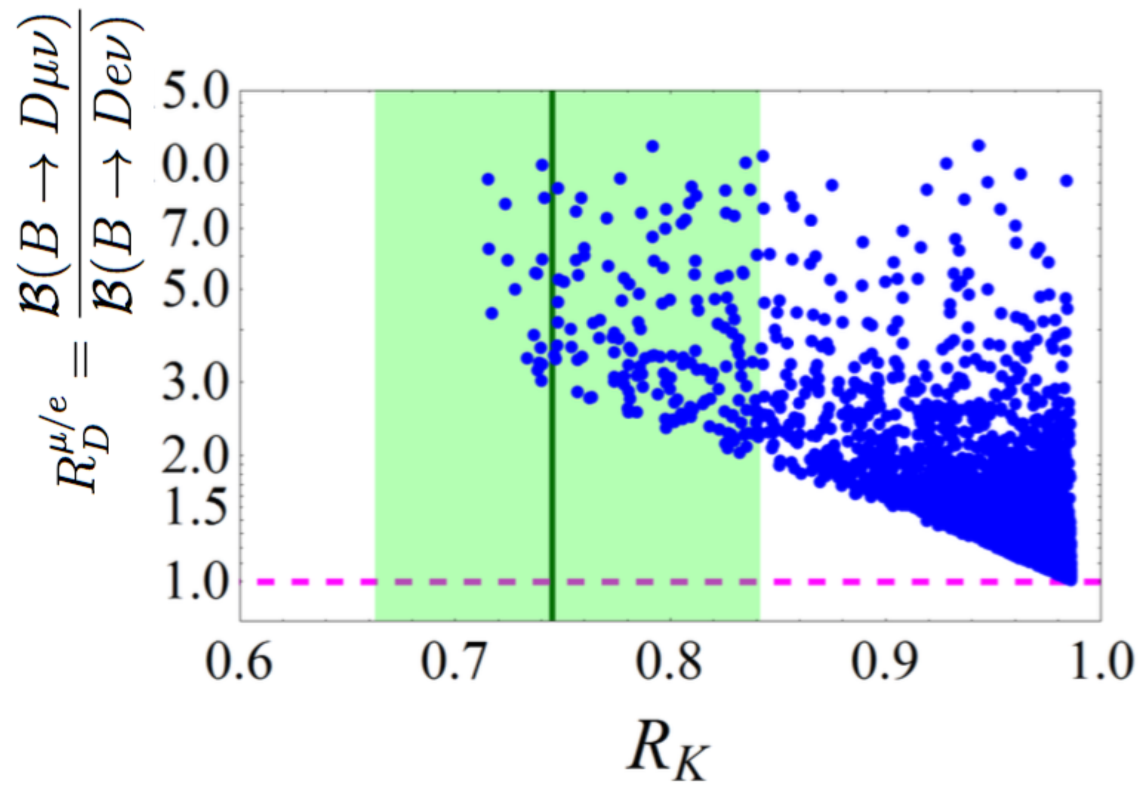
$$\frac{\Delta m_{B_s}^{\text{th}}}{\Delta m_{B_s}^{\text{SM}}} = 1 + \frac{\eta_1(g_L\cdot g_L^\dagger)_{bs}^2}{32G_F^2 m_W^2|V_{tb}V_{ts}^*|^2\eta_B S_0(x_t)m_\Delta^2} = 1.02(10)$$

$$\frac{\text{Br}(B\to K\nu\nu)^{\text{th}}}{\text{Br}(B\to K\nu\nu)^{\text{SM}}} < 4.3$$

$$\tau\to\mu\gamma$$

LQ features - $\Delta^{(1/3)}(3, 1, -1/3)$





LQ features - $\Delta^{(1/6)}(3,2,1/6)$

$$\mathcal{L}_{\Delta^{(1/6)}} = (g_L)_{ij}\bar{d}_{Ri}\widetilde{\mathbf{\Delta}}^{(1/6)\dagger}L_j$$
$$= (g_L)_{ij}\bar{d}_i P_L \nu_j\, \Delta^{(-1/3)} - (g_L)_{ij}\bar{d}_i P_L \ell_j\, \Delta^{(2/3)}$$

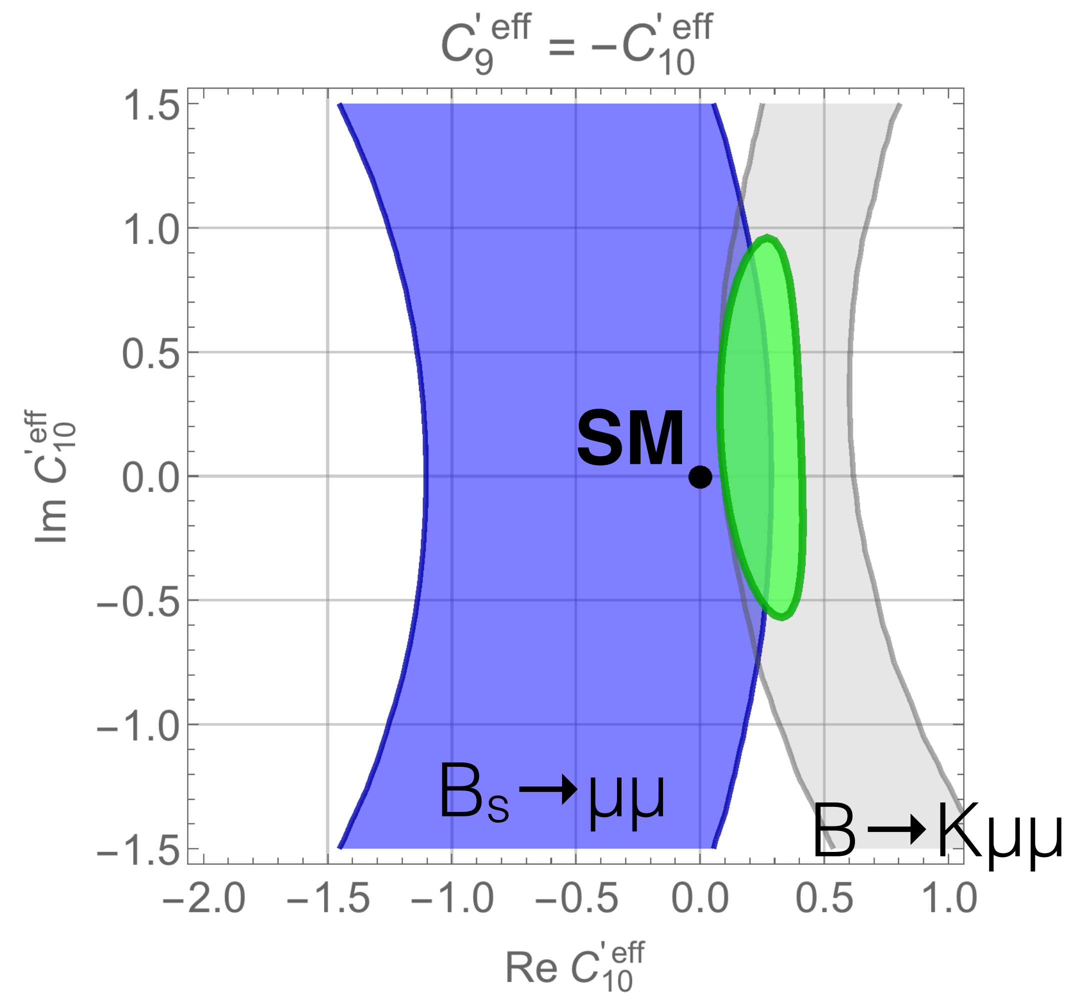
"PMNS = 1"

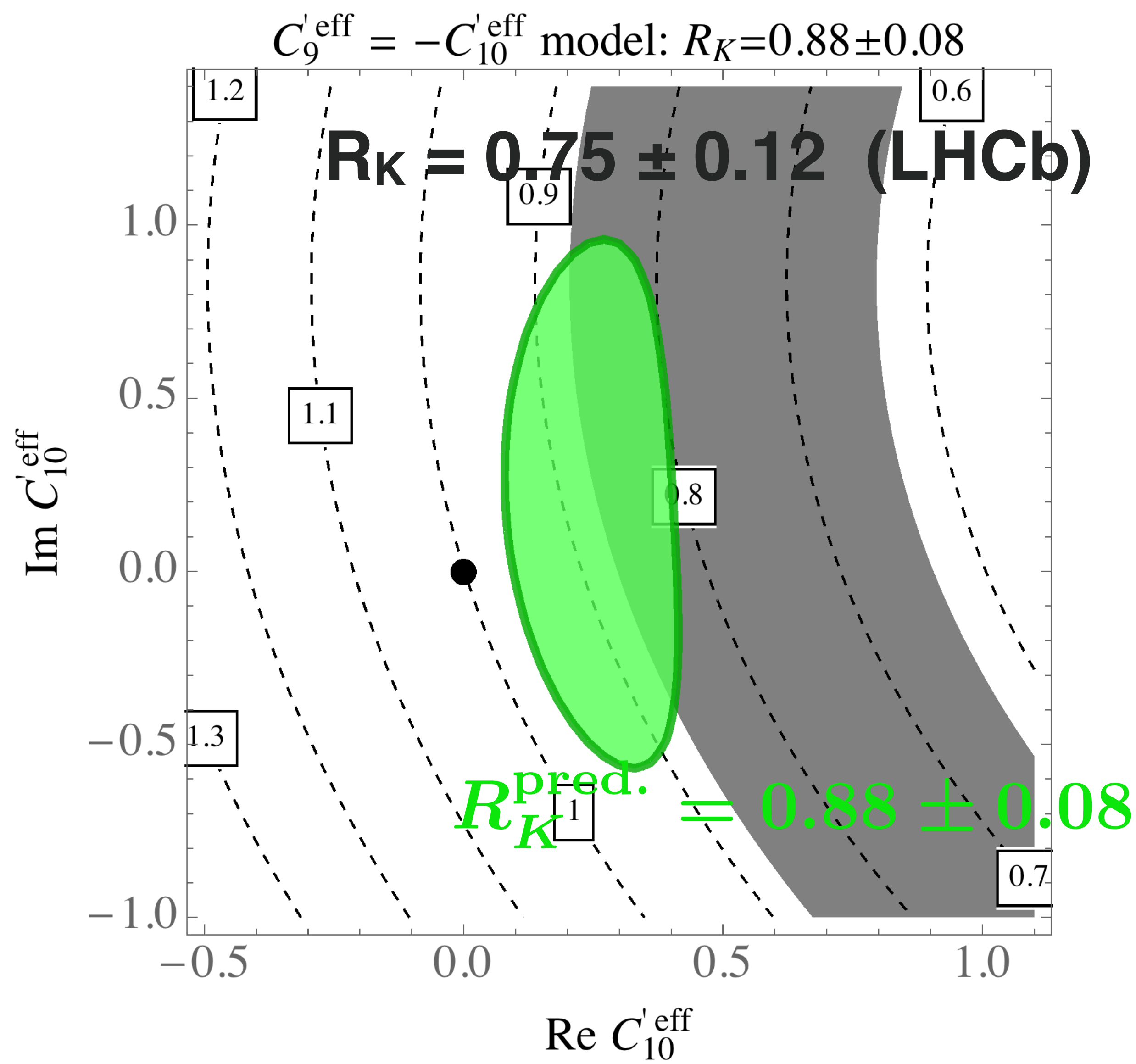
$$\left(C_9^{\ell_1\ell_2}\right)' = -\left(C_{10}^{\ell_1\ell_2}\right)' = -\frac{\pi v^2}{2V_{tb}V_{ts}^*\alpha_{\rm em}}\frac{(g_L)_{s\ell_1}(g_L)^*_{b\ell_2}}{m_\Delta^2},$$

$$g_L = \begin{pmatrix} 0 & 0 & 0 \\ 0 & (g_L)_{s\mu} & (g_L)_{s\tau} \\ 0 & (g_L)_{b\mu} & (g_L)_{b\tau} \end{pmatrix}$$

Experiment: $(C_9^{\mu\mu})' \in (-0.48, -0.08)$

LQ features: $C_9' = -C_{10}'$ $\Delta^{(1/6)}(3,2,1/6)$





Further signatures:

$R_{K^*} = 1.11(8)$

$$R_{\text{fb}} = \frac{A^{\mu}_{\text{fb}[4,6]}}{A^{e}_{\text{fb}[4,6]}} = 0.84(12)$$

[Becirevic, Fajfer, NK, ‘15]

LQ features - $\Delta^{(1/6)}(3,2,1/6)$

$$\mathcal{L}_{\Delta^{(1/6)}} = (g_L)_{ij}\bar{d}_{Ri}\widetilde{\mathbf{\Delta}}^{(1/6)\dagger}L_j$$
$$= (g_L)_{ij}\bar{d}_i P_L \nu_j\, \Delta^{(-1/3)} - (g_L)_{ij}\bar{d}_i P_L \ell_j\, \Delta^{(2/3)}$$

"PMNS = 1"

And take into account:

$$g_L = \begin{pmatrix} 0 & 0 & 0 \\ 0 & (g_L)_{s\mu} & (g_L)_{s\tau} \\ 0 & (g_L)_{b\mu} & (g_L)_{b\tau} \end{pmatrix}$$

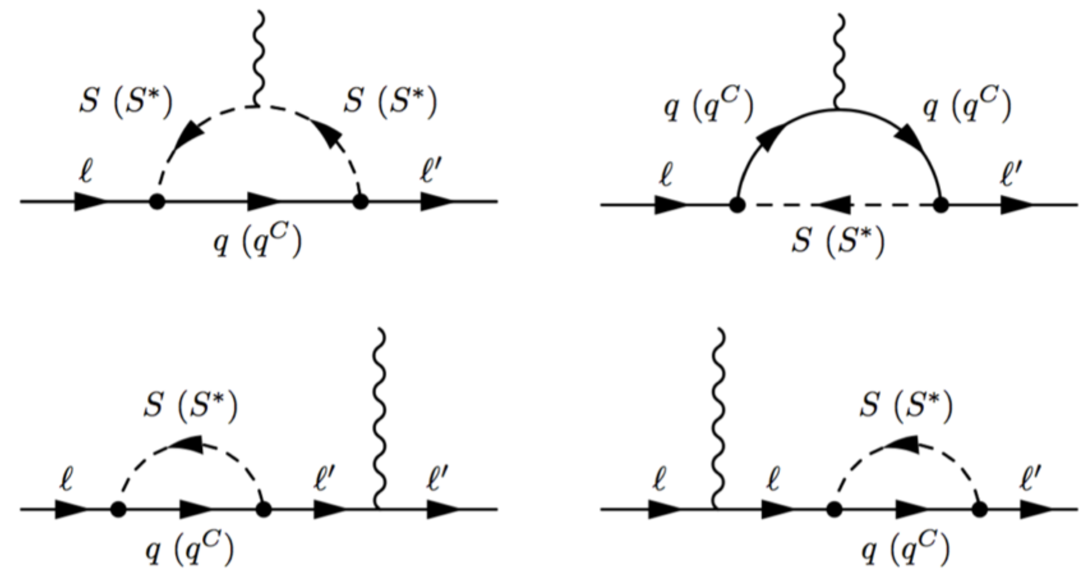
$$\frac{\Delta m_{B_s}^{\rm th}}{\Delta m_{B_s}^{\rm SM}} = 1 + \frac{\eta_1 (g_L \cdot g_L^\dagger)_{bs}^2}{16 G_F^2 m_W^2 |V_{tb}V_{ts}^*|^2 \eta_B S_0(x_t) m_\Delta^2}$$

$$R_{\nu\nu} = 1 - \frac{1}{6\,C_L^{\rm SM}}{\rm Re}\left[\frac{(g_L \cdot g_L^\dagger)_{sb}}{N m_\Delta^2}\right] + \frac{1}{48 (C_L^{\rm SM})^2}\frac{(g_L \cdot g_L^\dagger)_{ss}(g_L \cdot g_L^\dagger)_{bb}}{|N|^2 m_\Delta^4}$$

$$\mathcal{B}(\tau \to \mu\phi)^{\rm exp} < 8.4 \times 10^{-8} \longrightarrow \frac{|(g_L)_{s\tau}(g_L)_{s\mu}^*|}{m_\Delta^2} < 0.036\ {\rm TeV}^{-2} \quad (90\%\,{\rm CL})$$

LQ features - $\Delta^{(1/6)}(3,2,1/6)$

Radiative LFV is suppressed:



$$\Gamma(\ell \to \ell'\gamma) = \frac{\alpha_{\rm em} m_\ell^3 \left(1 - m_{\ell'}^2/m_\ell^2\right)^3}{4} \left(|\sigma_L^{\ell\ell'}|^2 + |\sigma_R^{\ell\ell'}|^2\right)$$

$$\sigma_L^{\ell\ell'} = \frac{iN_c}{16\pi^2 m_{\rm LQ}^2} \sum_q \Big\{ \left(l_{q\ell'}^* l_{q\ell} m_\ell + r_{q\ell'}^* r_{q\ell} m_{\ell'}\right) \underline{\left[Q_S f_S(x_q) - f_F(x_q)\right]} + l_{q\ell'}^* r_{q\ell} m_q \left[Q_S g_S(x_q) - g_F(x_q)\right] \Big\},$$

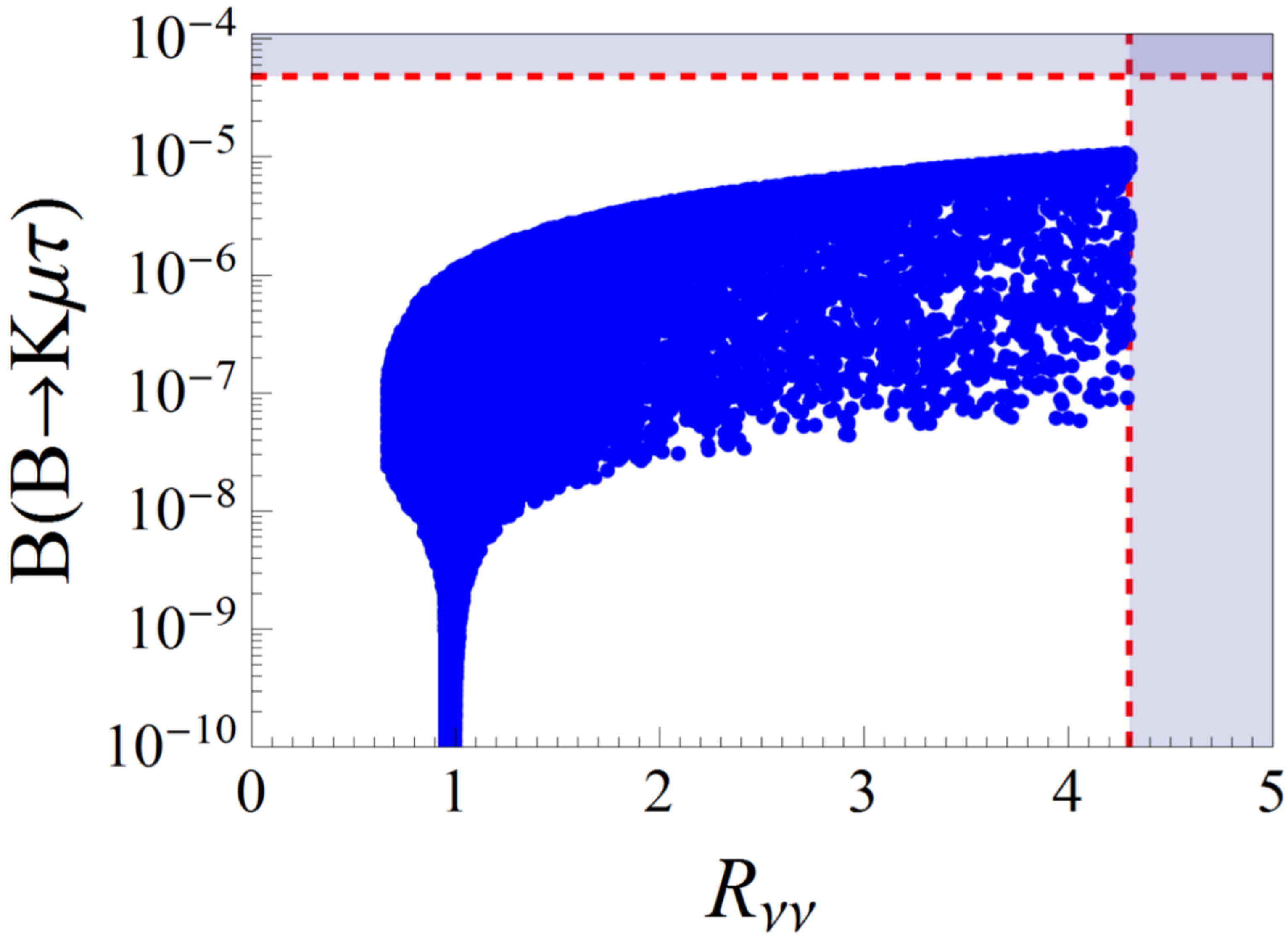
$$\sigma_R^{\ell\ell'} = \frac{iN_c}{16\pi^2 m_{\rm LQ}^2} \sum_q \Big\{ \left(r_{q\ell'}^* r_{q\ell} m_\ell + l_{q\ell'}^* l_{q\ell} m_{\ell'}\right) \underline{\left[Q_S f_S(x_q) - f_F(x_q)\right]} + r_{q\ell'}^* l_{q\ell} m_q \left[Q_S g_S(x_q) - g_F(x_q)\right] \Big\}.$$

When $Q_S = 2/3$ vanishes as $x_q = m_q^2/m_{LQ}^2 \to 0$

Applies also for anomalous magnetic moment of the muon

[Dorsner et al '16]

LQ predictions - $\Delta^{(1/6)}(3,2,1/6)$



Quantity	$m_\Delta = 1$ TeV	$m_\Delta = 5$ TeV	$m_\Delta = 10$ TeV
$\mathcal{B}(B_s \to \mu\tau)$	$< 1.0 \times 10^{-5}$	$< 3.0 \times 10^{-6}$	$< 1.8 \times 10^{-7}$
$\mathcal{B}(B \to K\mu\tau)$	$< 1.1 \times 10^{-5}$	$< 3.4 \times 10^{-6}$	$< 2.0 \times 10^{-7}$
$\mathcal{B}(B \to K^*\mu\tau)$	$< 2.0 \times 10^{-5}$	$< 6.1 \times 10^{-6}$	$< 3.7 \times 10^{-7}$

Table 2: *Predictions for exclusive $B_{(s)}$ meson decays at 90% CL for the $\mathbf{\Delta}^{(1/6)}$-model.*

[Becirevic, NK, Sumensari, Zukanovich-Funchal '16]

LQ predictions - $\Delta^{(1/6)}(3, 2, 1/6)$

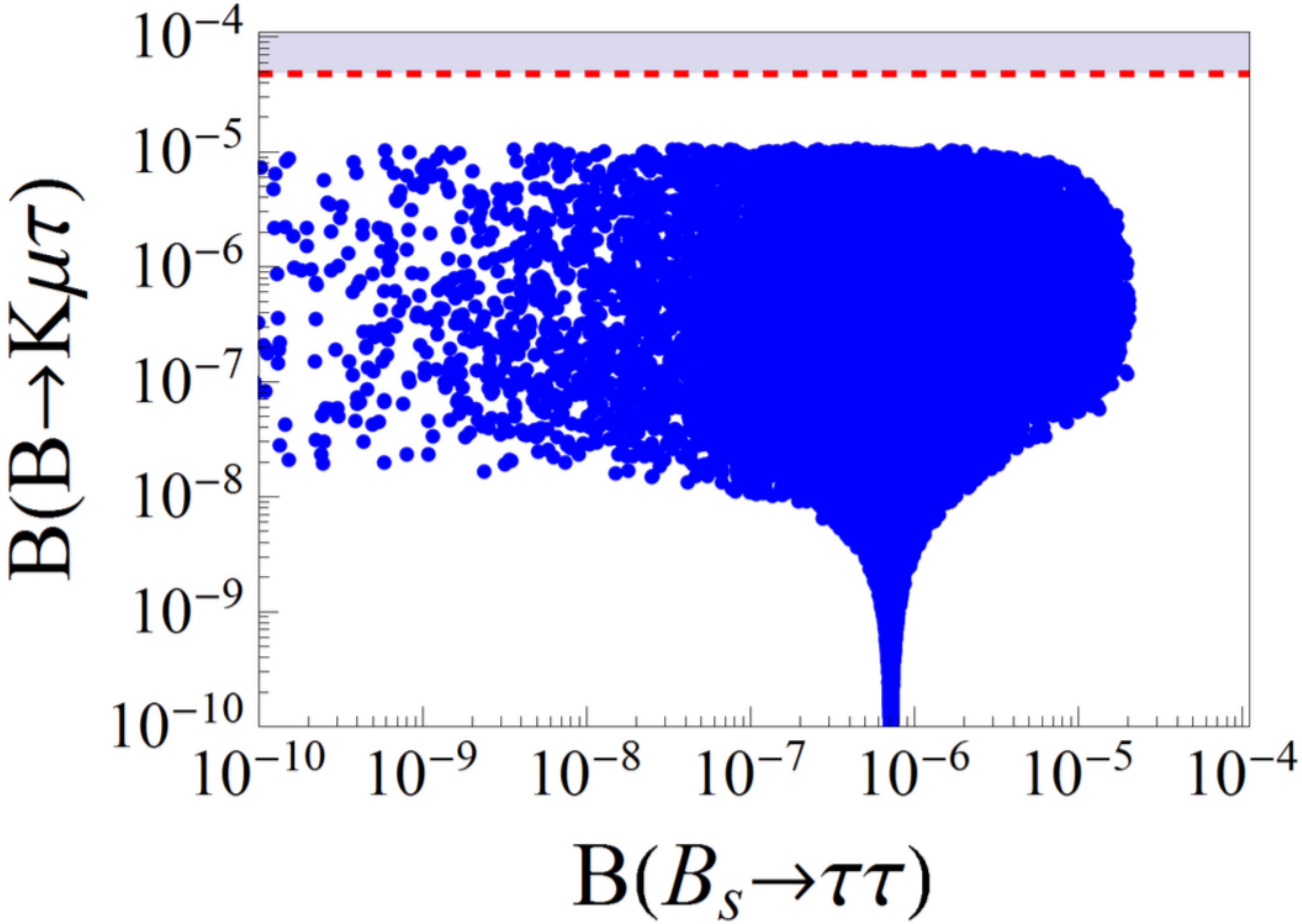
Quantity	$m_\Delta = 1$ TeV	$m_\Delta = 5$ TeV	$m_\Delta = 10$ TeV
$\mathcal{B}(B_s \to \mu\tau)$	$< 1.0 \times 10^{-5}$	$< 3.0 \times 10^{-6}$	$< 1.8 \times 10^{-7}$
$\mathcal{B}(B \to K\mu\tau)$	$< 1.1 \times 10^{-5}$	$< 3.4 \times 10^{-6}$	$< 2.0 \times 10^{-7}$
$\mathcal{B}(B \to K^*\mu\tau)$	$< 2.0 \times 10^{-5}$	$< 6.1 \times 10^{-6}$	$< 3.7 \times 10^{-7}$

Table 2: *Predictions for exclusive $B_{(s)}$ meson decays at 90% CL for the $\boldsymbol{\Delta}^{(1/6)}$-model.*

$$\frac{\mathcal{B}(B \to K^*\mu\tau)}{\mathcal{B}(B \to K\mu\tau)} \approx 1.8 \qquad \frac{\mathcal{B}(B_s \to \mu\tau)}{\mathcal{B}(B \to K\mu\tau)} \approx 0.9$$

… consequence of distinct chiral structure

LQ predictions - $\Delta^{(1/6)}(3, 2, 1/6)$



LQ features - $\Delta^{(1/6)}(3,2,1/6)$

* Can we stretch the model to fit R_D? Yes we can …

$$\mathcal{L}_\Delta = \overline{d_R}' Y_L (\widetilde{\Delta})^\dagger L' + \overline{Q}' Y_R \Delta \nu'_R$$

(not a model of neutrino masses)

$$\mathcal{L}_\Delta = \overline{d_R}\,(Y_L U_{\rm PMNS})\,\nu_L \Delta^{(-1/3)} - \bar{d}_R Y_L \ell_L \Delta^{(2/3)} + \bar{u}_L\,(V_{\rm CKM} Y_R)\,\nu_R \Delta^{(2/3)} + \bar{d}_L Y_R \nu_R \Delta^{(-1/3)}$$

The semileptonic "portal"

$$Y_{L,R} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & Y^{s\mu}_{L,R} & Y^{s\tau}_{L,R} \\ 0 & Y^{b\mu}_{L,R} & Y^{b\tau}_{L,R} \end{pmatrix}$$

$$V_{\rm CKM} Y_R = \begin{pmatrix} 0 & V_{us} Y_R^{s\mu} + V_{ub} Y_R^{b\mu} & V_{us} Y_R^{s\tau} + V_{ub} Y_R^{b\tau} \\ 0 & V_{cs} Y_R^{s\mu} + V_{cb} Y_R^{b\mu} & V_{cs} Y_R^{s\tau} + V_{cb} Y_R^{b\tau} \\ 0 & V_{ts} Y_R^{s\mu} + V_{tb} Y_R^{b\mu} & V_{ts} Y_R^{s\tau} + V_{tb} Y_R^{b\tau} \end{pmatrix}$$

[Becirevic, Fajfer, NK, Sumensari '16]

LQ features - $\Delta^{(1/6)}(3,2,1/6)$

$$\mathcal{L}_\Delta = \overline{d_R}\left(Y_L U_{\rm PMNS}\right)\nu_L \Delta^{(-1/3)} - \bar{d}_R Y_L \ell_L \Delta^{(2/3)} + \overline{u}_L \left(V_{\rm CKM} Y_R\right)\nu_R \Delta^{(2/3)} + \bar{d}_L Y_R \nu_R \Delta^{(-1/3)}$$

The (semi)leptonic "portal"

$$\mathcal{L}_{\rm eff} = -2\sqrt{2} G_F V_{ud}\left[\overline{u}\gamma_\mu P_L d\, \bar{\ell}\gamma_\mu P_L \nu + g_S \overline{u} P_R d \bar{\ell} P_R \nu + g_T\, \overline{u}\sigma_{\mu\nu} P_R d \bar{\ell}\sigma^{\mu\nu} P_R \nu\right]$$

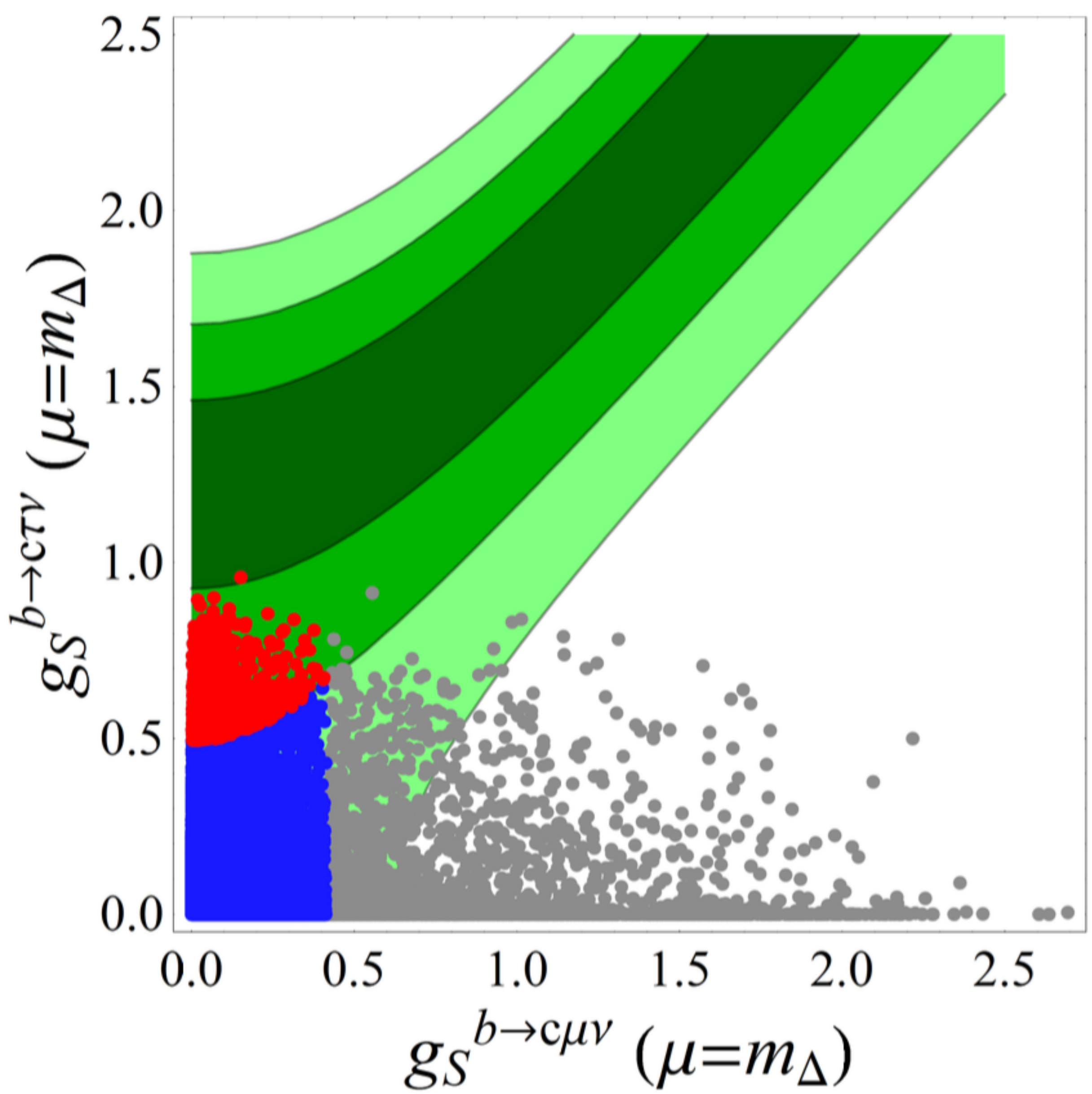
R_D

$$\frac{d\mathcal{B}}{dq^2} = \mathcal{B}_0 |V_{cb}|^2 |f_+(q^2)|^2 \left\{ c_+^\ell(q^2) + |g_T|^2 c_T^\ell(q^2)\left|\frac{f_T(q^2)}{f_+(q^2)}\right|^2 + \left(1 + |g_S|^2 \frac{q^4}{m_\ell^2 (m_b - m_c)^2}\right) c_0^\ell(q^2)\left|\frac{f_0(q^2)}{f_+(q^2)}\right|^2 \right\},$$

using FFs from [MILC, 1503.07237]

leptonic $\quad K\to\mu\nu,\ \tau\to K\nu,\ D_s\to\tau\nu,\ D_s\to\mu\nu,\ B\to\tau\nu$

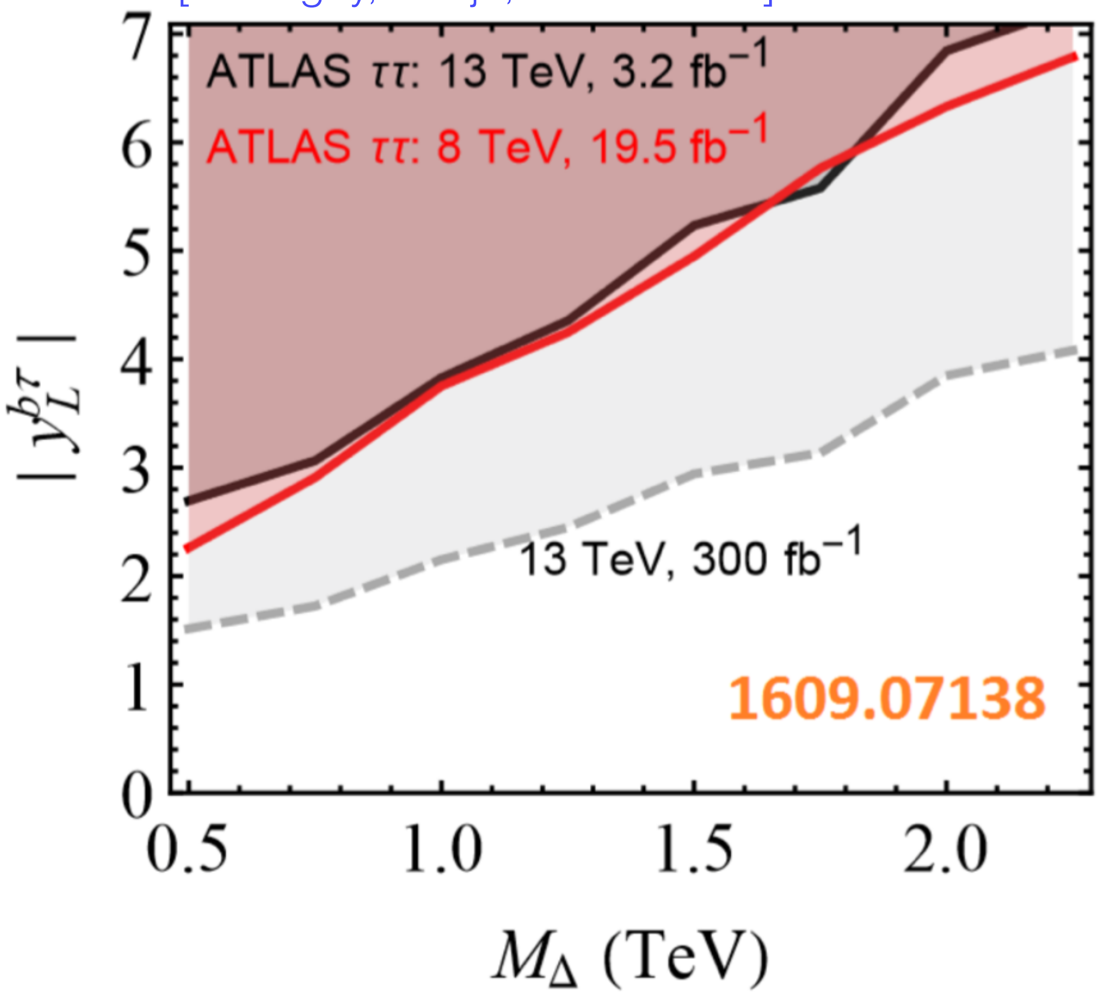
LQ features - $\Delta^{(1/6)}(3, 2, 1/6)$



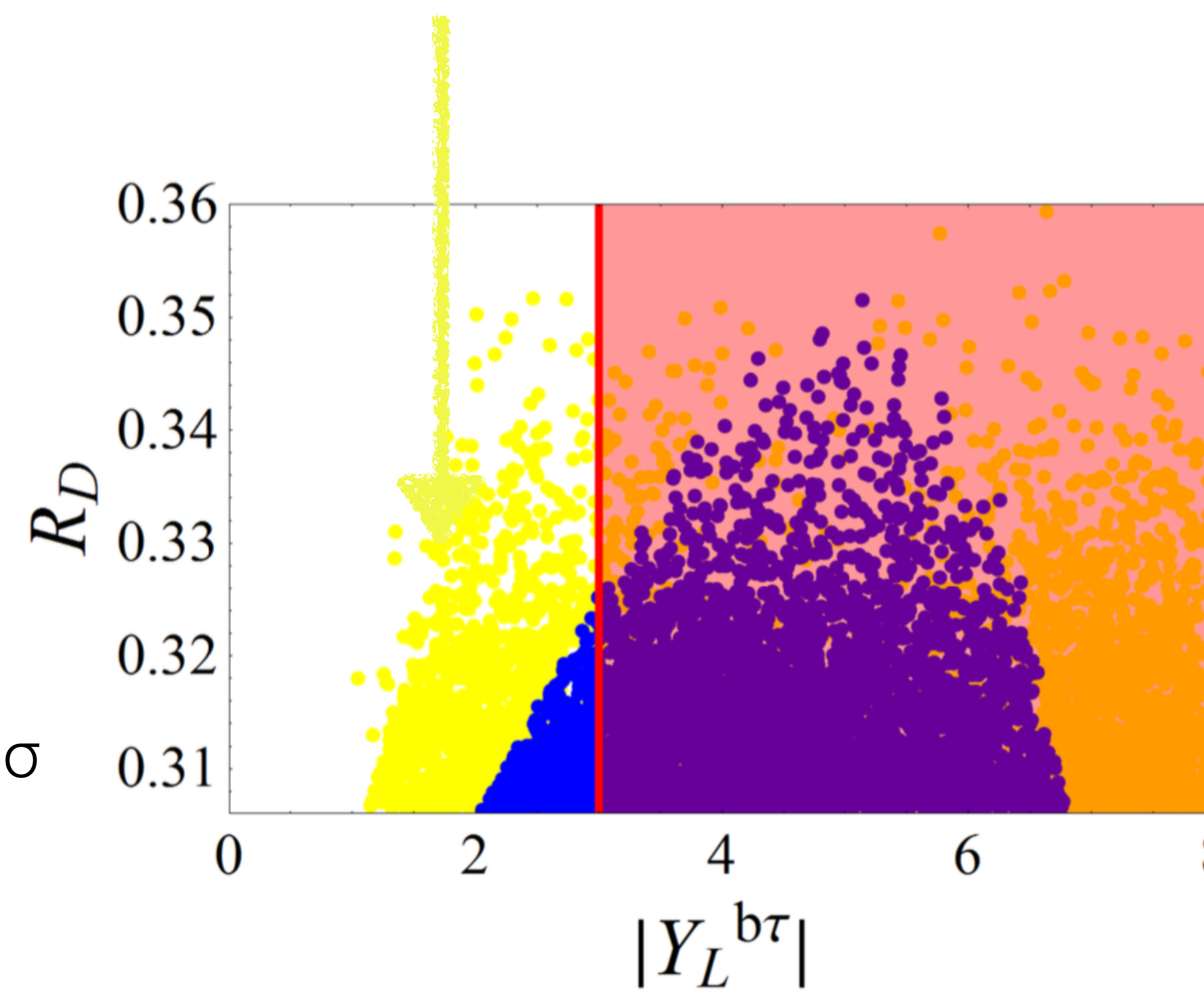
- Modification of semi-muonic and semi-tauonic required
- Only possible with known form factors

Additional constraints on $\Delta^{(1/6)}(3,2,1/6)$

[Faroughy, Greljo, Kamenik '16]



- pp($b\bar{b}$) → τ τ searches
- probes only left-handed couplings
- $\Gamma/m_{LQ} < 1$ is a stronger constraint

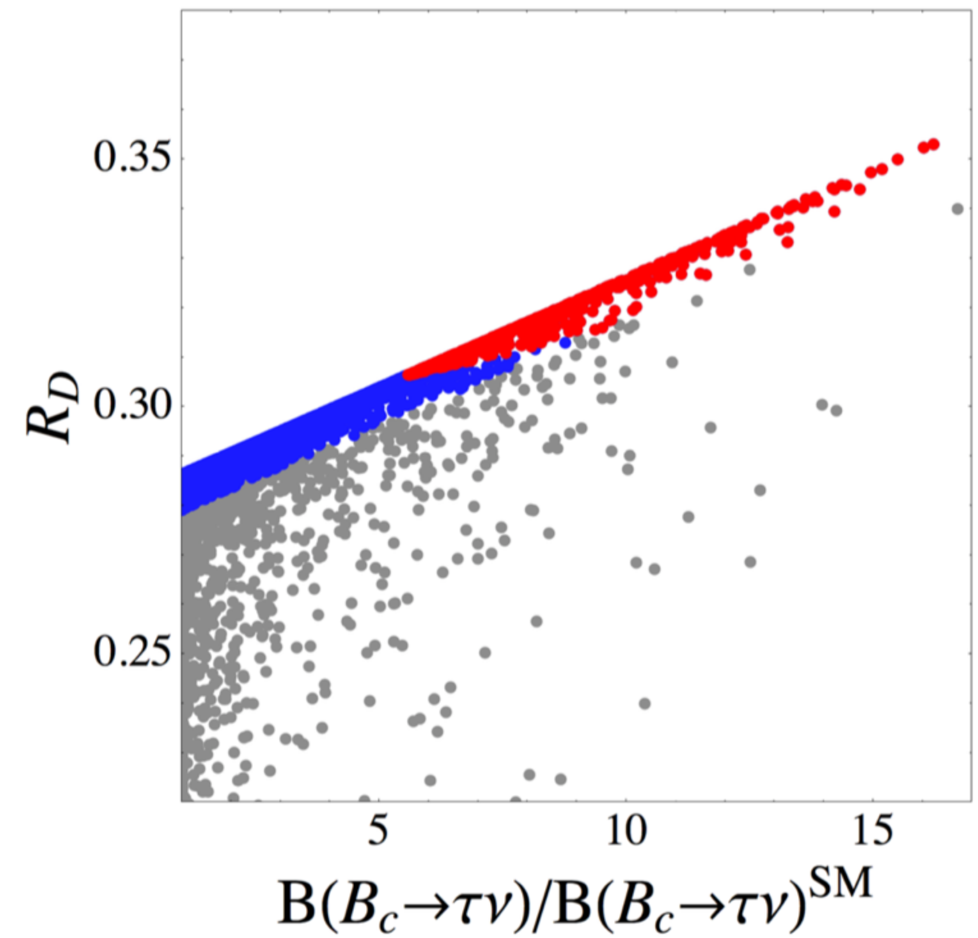


- The model can explain R_D at 1.5σ

Predictions with $\Delta^{(1/6)}(3, 2, 1/6)$

$$2.1 \times 10^{-10} \leq \mathcal{B}(B \to K\mu\tau) \leq 6.7 \times 10^{-6}$$

1.02< $\mathcal{B}(B_c \to \eta_c \tau\nu)/(\bar{B}_c \to \eta_c l\nu)$ < 1.21



$$5.5 \leq \mathcal{B}(B_c \to \tau\nu)/\mathcal{B}(B_c \to \tau\nu)^{\mathrm{SM}} \leq 16.1$$

Summary

- LFU ratios offer very precise validation of the Standard Model
- R_K is an interesting and plausible NP hint
- $R_{D(*)}$ is the charged current LFU violation. Several measurements point at significantly increased semi-tauonic rates. Tree-level new physics needed.
- Light scalar leptoquark is a plausible explanation of both puzzles with further LFUV and LFV signals.
- Embedding LQ in GUT connects the LQ to fermion masses and proton decay bounds.