The interpretation and future prospects of the B meson anomalies

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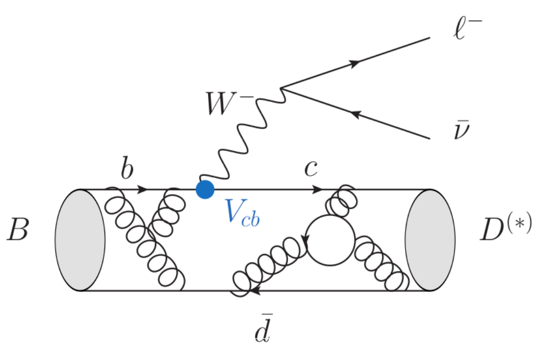
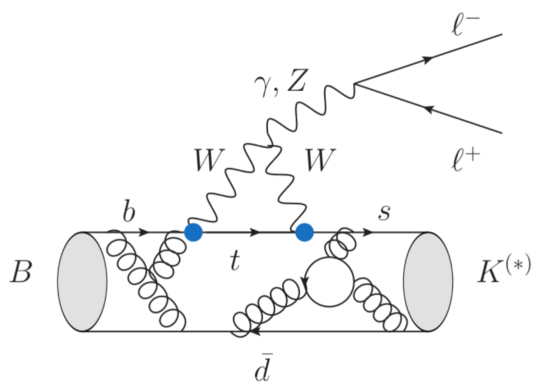




ISMD2021, virtual conference, 12-16 July 2021

Outline

B meson anomalies $R_{D(*)}$ and $R_{K(*)}$

SM contributions to anomalous processes

New Physics explanation

- effective Lagrangian approach
- models of NP
- constraints from low-energy observables & LHC data

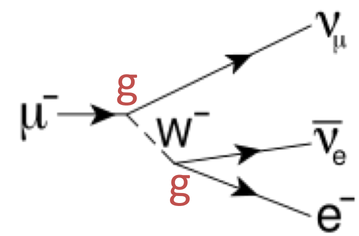
Predictions relevant for LHCb, Belle2 &LHC

Outlook

Lepton Flavour Universality (LFU)

the same coupling of lepton and its neutrino with W for all three lepton generations!

$$\frac{\Gamma(\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau)}{\Gamma(\tau^- \to e^- \bar{\nu}_e \nu_\tau)} \simeq 1 \quad (0.9762 \pm 0.0028)$$



Basic property of the SM: universal g

$$\mathcal{L}_f = \bar{f} i D_\mu \gamma^\mu f \qquad f = l_L^i,\ q_L^i,\ i = 1, 2, 3$$

for each of three generations in weak interactions

$$D_\mu = \partial_\mu + ig\frac{1}{2}\vec{\tau}\cdot\vec{W}_\mu + ig'\frac{1}{2}Y_W B_\mu$$

the same for all SM fermions

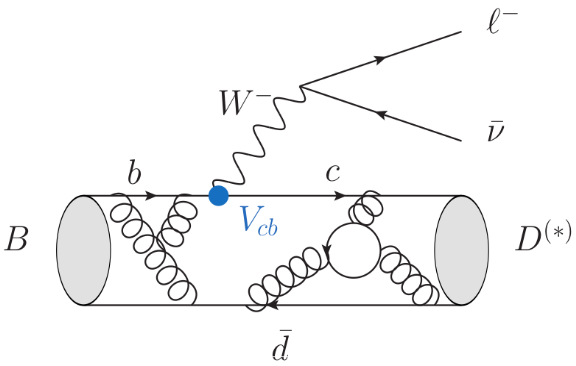
$$\mathcal{L}_{eff} = -\frac{G_F}{\sqrt{2}} J_\mu^\dagger J^\mu$$

$$\frac{g^2}{8m_W^2} = \frac{G_F}{\sqrt{2}}$$

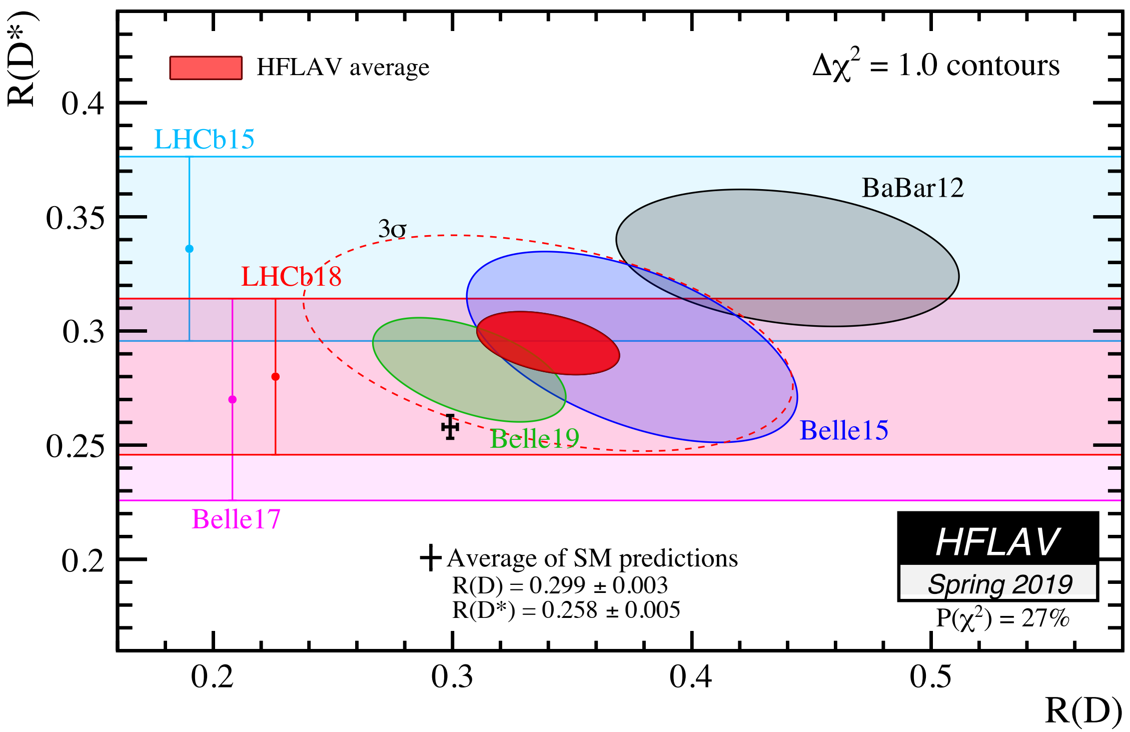
$$G_F = 1.1663787(6) \times 10^{-5}\,\mathrm{GeV}^{-2}$$

B physics anomalies: experimental results ≠ SM predictions!

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



charged current (SM tree level)



$R_{D^{(*)}}$ discrepancy (exp./SM)
Disagreement ≈ 4σ

$$R_{J/\Psi} = \frac{BR(B_c \to J/\Psi\tau\nu)}{BR(B_c \to J/\Psi l\nu)}$$

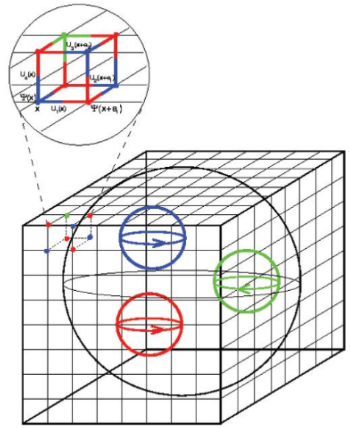
$$R_{J/\Psi} = 0.71 \pm 0.17 \pm 0.18$$

2.4σ

$R_{D(*)}$ in SM lattice QCD in action!

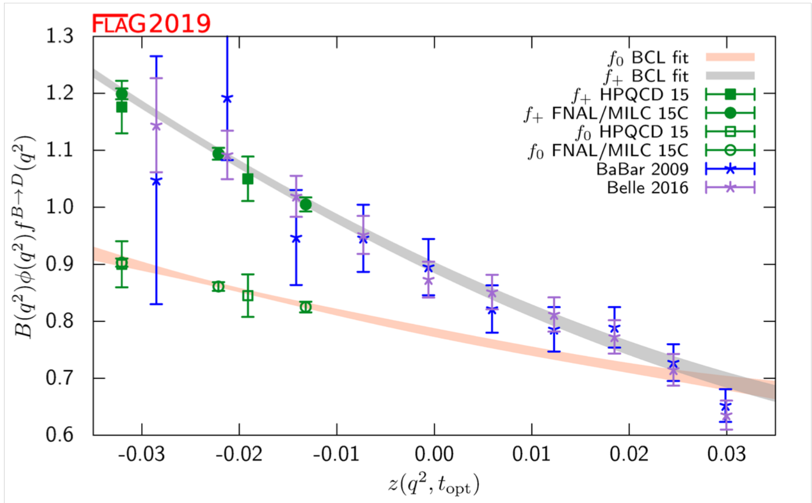
SM: R_D =0.300(8)

- two form factors in $< D|\bar{c}\gamma_\mu b|B >$
- (Fermilab Lattice and MILC Collaborations J. A. Bailey et al. 1503.07237)



$$< D(k)|\bar{c}\gamma^\mu b|B(p) >= \left[(p+K)^\mu - \frac{m_B^2 - m_K^2}{q^2} q^\mu\right] f_+(q^2) + \frac{m_B^2 - m_K^2}{q^2} q^\mu f_0(q^2)$$

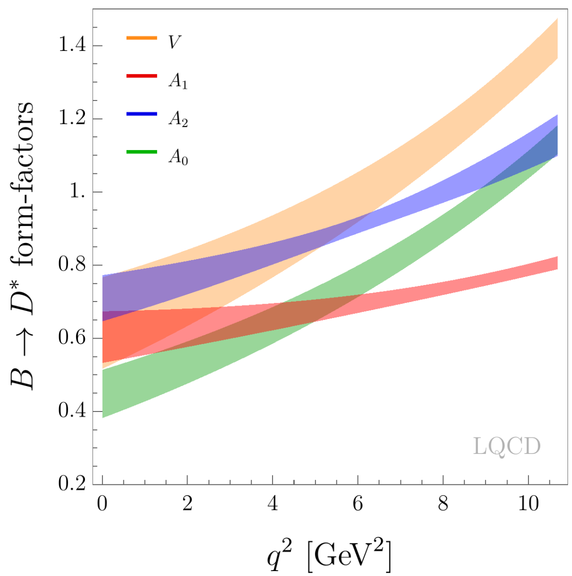
$$q^\mu = (p-K)^\mu$$

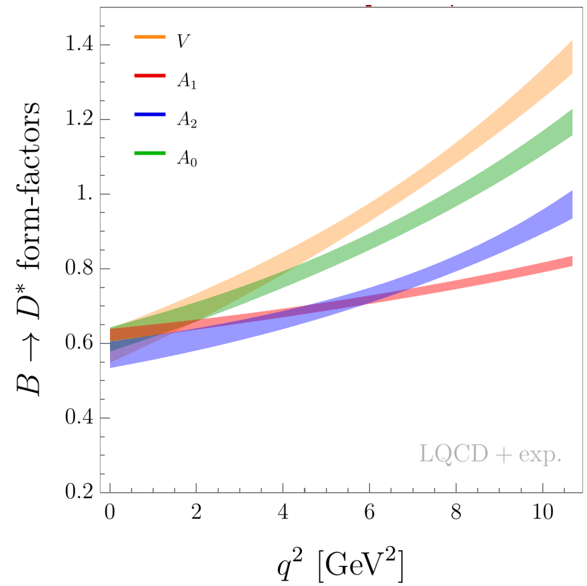


FLAG average

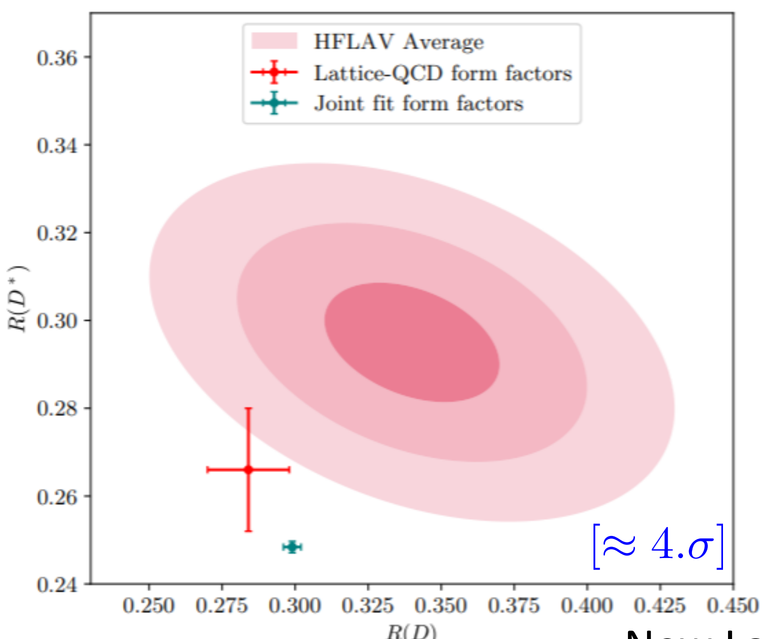
$$R_D^{SM} = 0.300(8)$$

$< D^*|\bar{c}\gamma_\mu(1-\gamma_5)b|B >$ one vector form-factor + three axial form-factor





2105.14019
Fermilab Lattice and MILC Collaborations
$B \to D*l\nu$ at non-zero recoil



SM: R_{D^*} =0.258(3)

HFLAV: $R_{D^*}^{\rm SM} = 0.258(3)$

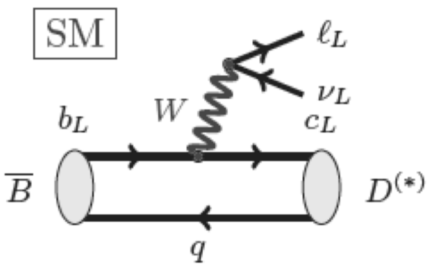
Lattice: $R_{D^*}^{\rm SM} = 0.266(14)$

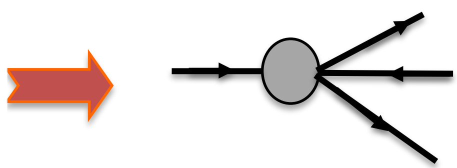
Lattice+exp: $R_{D^*}^{\rm SM} = 0.2484(13)$

New Lattice QCD results confirm discrepancy SM/exp

NP in $R_{D(*)}$

Effective Lagrangian approach for $b \to c\tau\nu_\tau$ decay





Left-handed neutrino
SM+ 5 new operators

$$\frac{G_F}{\sqrt{2}} = \frac{g^2}{8m_W^2} = \frac{1}{2v^2}$$

CKM matrix element V_{cb} = 0.0410±0.0014

$$\mathcal{L}_{eff} = -2\sqrt{2}G_F V_{cb}\,[(1+g_{V_L})(\bar{c}_L\gamma_\mu b_L)(\bar{l}_L\gamma^\mu\nu_L) + g_{V_R}(\bar{c}_R\gamma_\mu b_R)(\bar{l}_L\gamma^\mu\nu_L)$$
$$+g_{S_R}(\bar{c}_L\, b_R)(\bar{l}_R\,\nu_L) + g_{S_L})(\bar{c}_R\, b_L)(\bar{l}_R\,\nu_L) + g_T(\bar{c}_R\sigma_{\mu\nu}b_L)(\bar{l}_R\sigma^{\mu\nu}\nu_L)] + h.c.$$

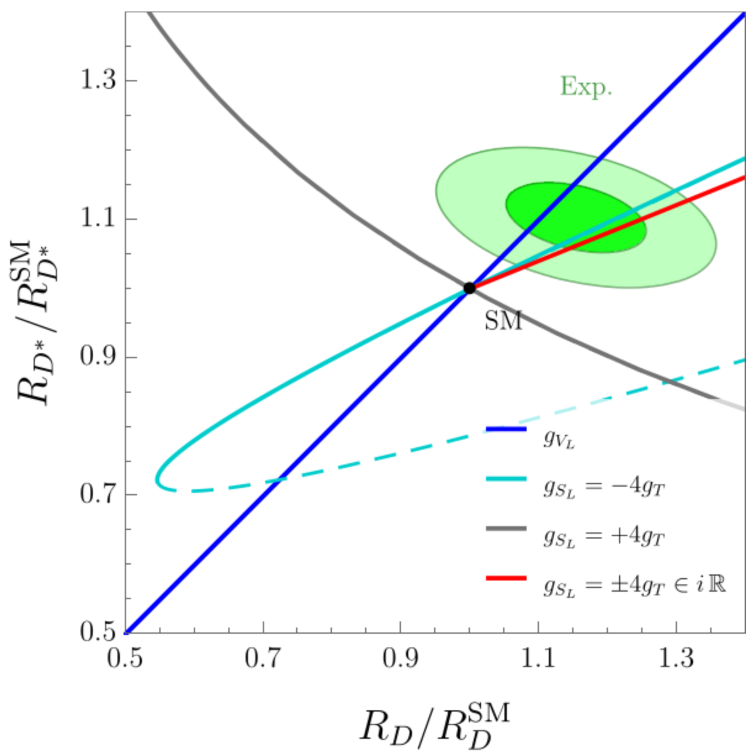
S.F. J.F. Kamenik, I. Nišandžić, J. Zupan, 1206.1872; Freytsis et al, 1506.08896, Ligeti,
Blanke et al., 1811.09603
Recent global fit Murgui et al.,1904.09311, Bardhan &Ghosh, 1904.10432, Becirevic et al, 1907.02257,
Angelescu et al., 2103.12504

Two solutions

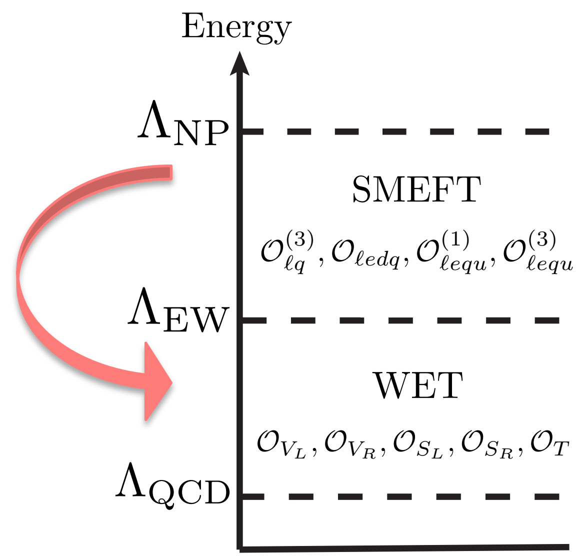
$$g_{V_L} \in (0.06,\, 0.11)$$

$$g_{S_L} = \pm 4\, g_T$$

Global fit Murgui et al., 1904.09311
using $R_{D^{(*)}}$, q^2 distributions, D* polarizatiozation,



integrating out
the top, W , Z
and the Higgs



$$\mathcal{B}(B_c \to \tau\nu) \leq 10\%$$

Angelescu et al., 2103.12504

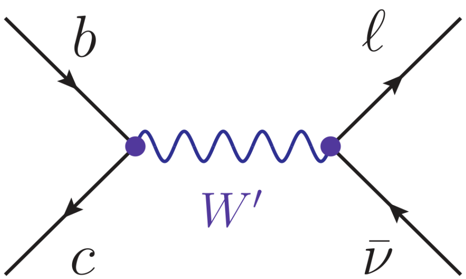
Electroweak-observables useful in the fit!

NP models for $R_{D(*)}$

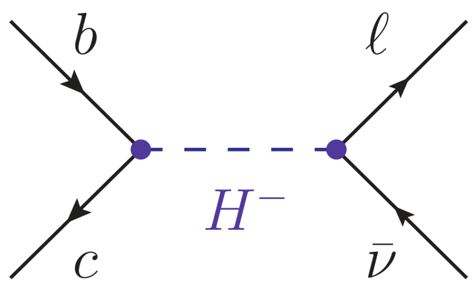
$$R_{D(*)}^{\text{exp}} > R_{D(*)}^{\text{SM}}$$

require new boson at TeV scale

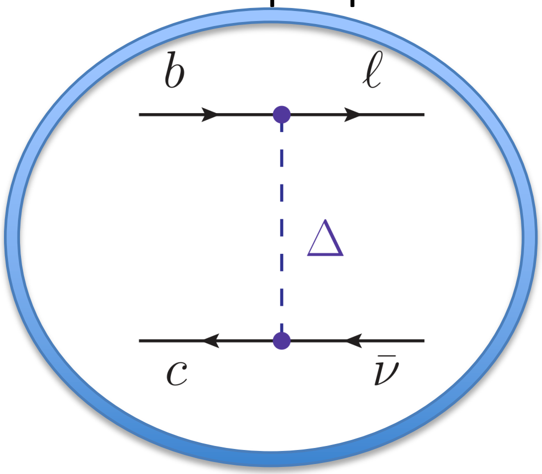
Scenarios
- New gauge bosons
- New Higgses
- Scalar Leptoquarks
- Vector Leptoquarks



New gauge bosons



New Higgses



Leptoquarks
Spin 0 or 1

impossible to write all references!

R_K and R_{K^*}: SM

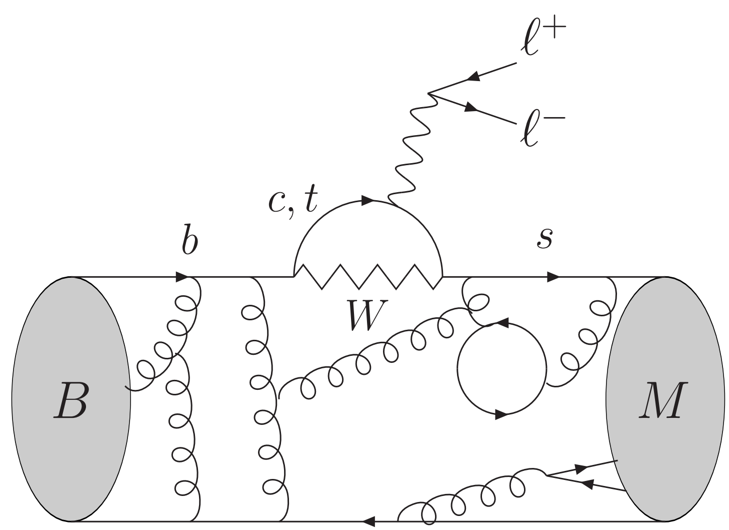
$$\mathcal{H}_{\rm eff} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \left[\sum_{i=1}^{6} C_i(\mu) \mathcal{O}_i(\mu) + \sum_{i=7,\ldots,10} \left(C_i(\mu) \mathcal{O}_i(\mu) + C_i'(\mu) \mathcal{O}_i'(\mu) \right) \right]$$

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

$$C_7^{SM} = 0.29;\; C_9^{SM} = 4.1;\; C_{10}^{SM} = -4.3;$$

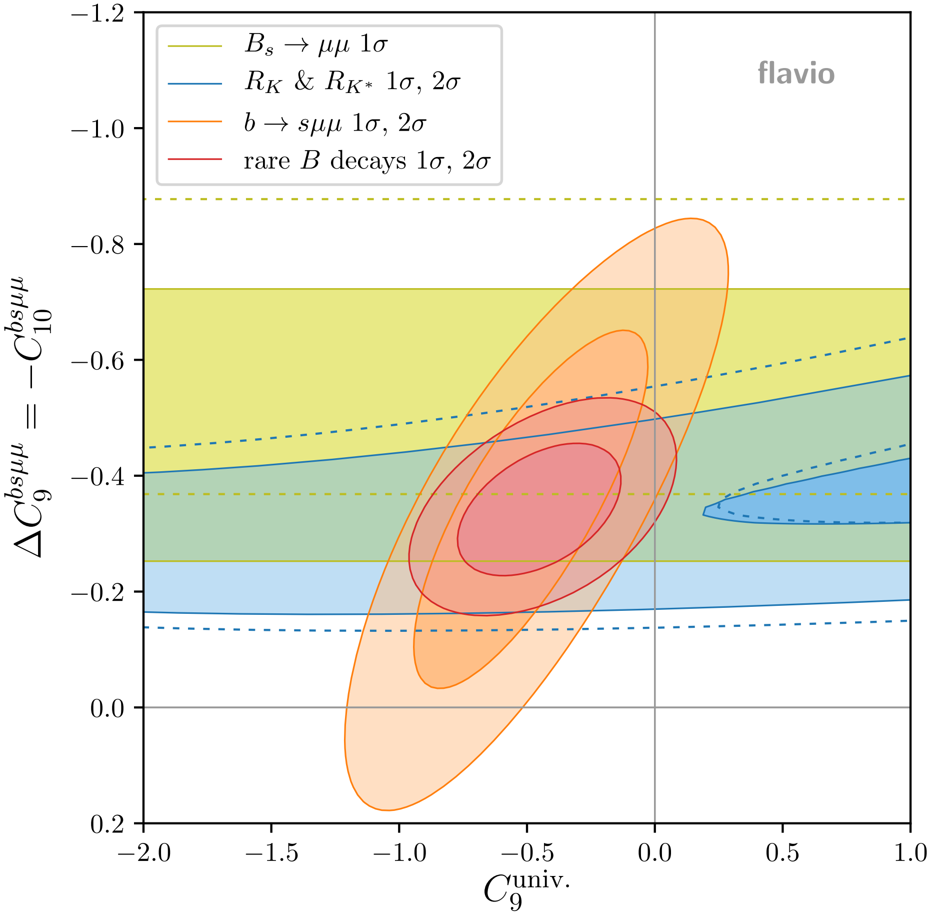
$$\mu_b = 4.8\,\mathrm{GeV}$$

Buras et al, hep-ph/9311345;
Altmannshofer et al, 0811.1214;
Bobeth et al, hep-ph/9910220



R_K and R_K*: New Physics

Global analysis suggests NP in $C_{9,10}$, based on R_K, R_{K^*} and $B_s \rightarrow \mu\mu$



Preferred solution

$$\Delta C_9^{bs\mu\mu} = -\Delta C_{10}^{bs\mu\mu} = -0.41 \pm 0.09$$

tension ≥ 4 σ for fits to "clean" subset of data

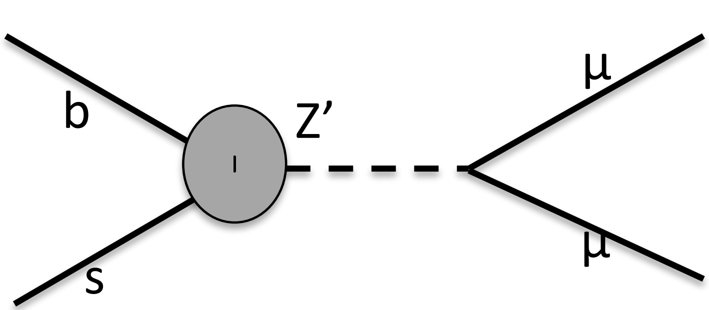
See also Alguero et al., 2104.08921
Hurth et al., 2104.10058,
Geng et al. 2103.12738

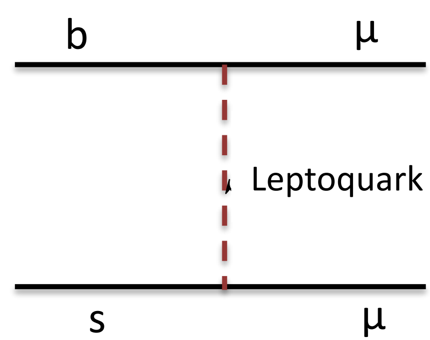
From Altmannsofer &Stangl 2103.13370

NP Models fopre FCNC B anomaly

- New vector bosons (preferably gauge bosons)+ vector-like quarks…
- Leptoquarks (scalar or vector)
- $R_{K(*)}$ explained by NP at loop level

different origin of Z’, e.g. by gauging L_{μ}- L_{τ} ,

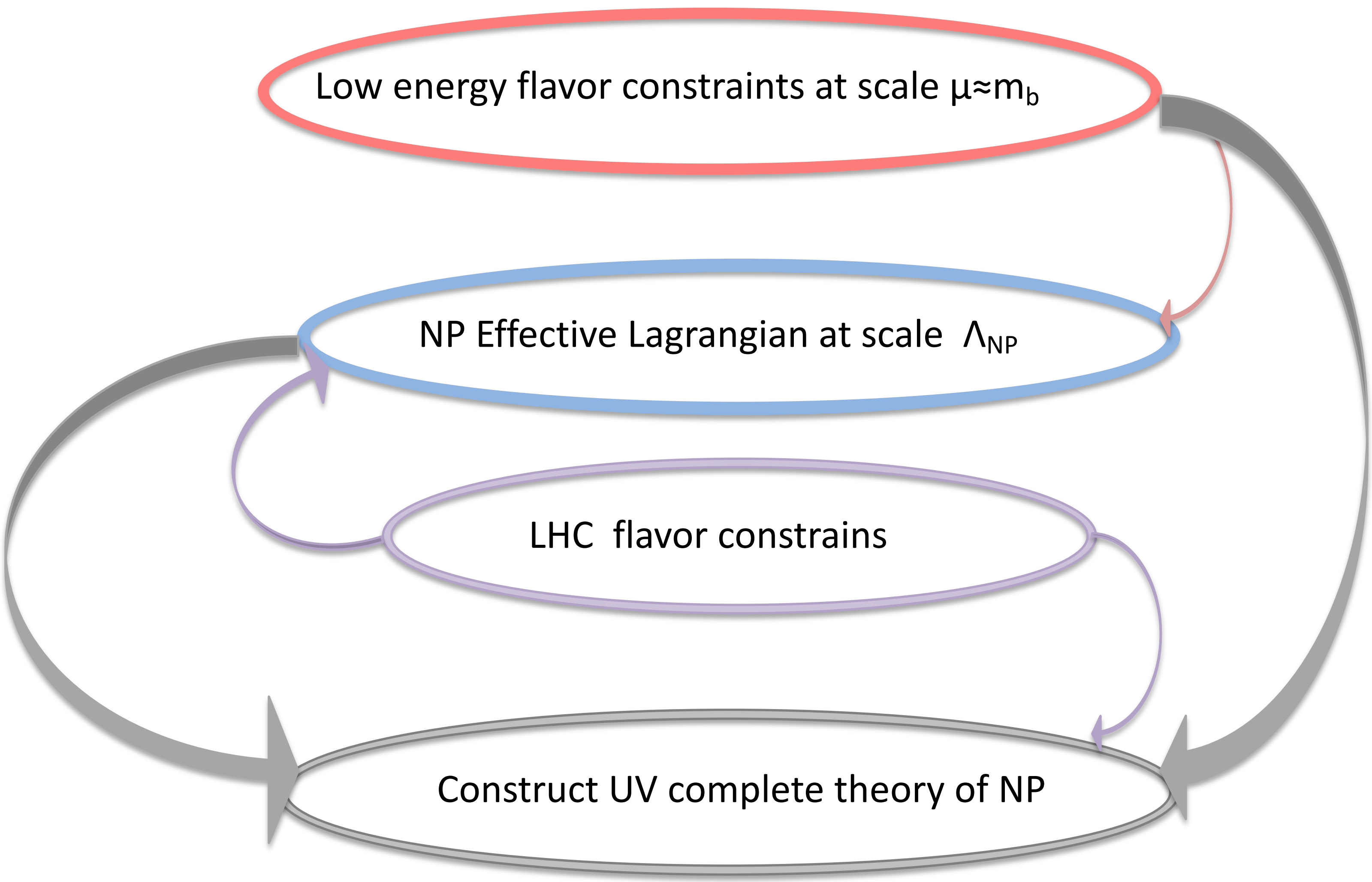




Lepton flavor non-universality → Lepton flavor violation

Glashow et al., 1411.0565…

How to approach New Physics?



NP in both B anomalies

$$R^{exp}_{D^{(*)}} > R^{SM}_{D^{(*)}}$$

$$R^{exp}_{K^{(*)}} < R^{SM}_{K^{(*)}}$$

NP at tree level

$$\mathcal{L}_{NP} = \frac{1}{(\Lambda^D_{NP})^2} 2\,\bar{c}_L \gamma_\mu b_L \bar{\tau} \gamma^\mu \nu_L$$

$$\mathcal{L}_{NP} = \frac{1}{(\Lambda^K_{NP})^2} \bar{s}_L \gamma_\mu b_L \bar{\mu}_L \gamma^\mu \mu_L$$

$$\Lambda^D_{NP} \simeq 3\,\mathrm{TeV}$$

$$\Lambda^K_{NP} \simeq 30\,\mathrm{TeV}$$

$$\Lambda^D_{NP} = \Lambda_{NP}$$

$$\frac{1}{(\Lambda^K_{NP})^2} = \frac{C_K}{\Lambda^2_{NP}}$$

If we want the same NP explaining both B anomalies, then

NP in FCNC $B \to K^{(*)}\mu^+\mu^-$ should be suppressed in comparison with NP in $B \to D^{(*)}\tau\nu$ $\quad C_K \simeq 0.01$

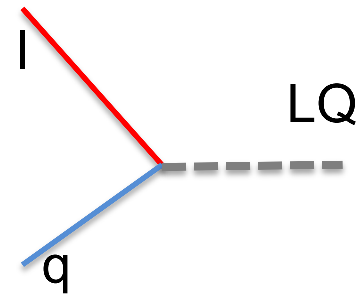
Di Luzio &Nardecchia, 1706.01868 (scales are ~9 TeV (~80 TeV))

Leptoquarks resolving B anomalies

LQ=$(SU(3)_c, SU(2)_L)_Y$

or LQ=$(SU(3)_c, SU(2)_L, Y)$

$Q=I_3+Y$



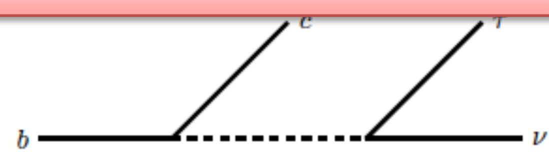
no proton decay at tree level

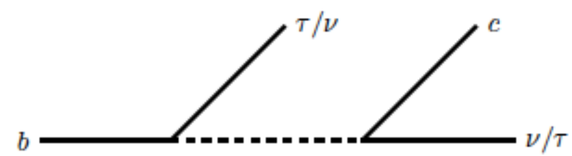
Model	$R_{D^{(*)}}$	$R_{K^{(*)}}$	$R_{D^{(*)}}$ & $R_{K^{(*)}}$
$S_1 = (\bar{3}, 1, 1/3)$	✓	✗	✗
$R_2 = (3, 2, 7/6)$	✓	✓*	✗
$S_3 = (\bar{3}, 3, 1/3)$	✗	✓	✗
$U_1 = (3, 1, 2/3)$	✓	✓	✓
$U_3 = (3, 3, 2/3)$	✗	✓	✗

Spin 0

Spin 1

U_1 is the only one to accommodate both anomalies!





LQs explaining B anomalies cannot explain $(g-2)_\mu$!

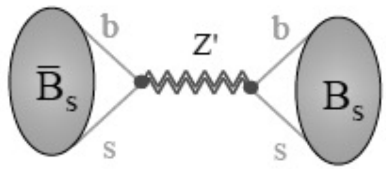
Doršner, SF, Greljo, Kamenik, Košnik, 1603.04993

Constraints from flavor observables

$(g-2)_\mu$

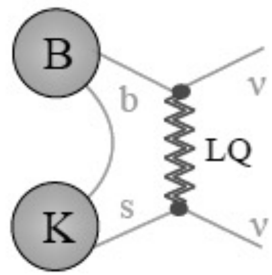
$B_c \to \tau\nu \quad B \to \tau\nu$

$B \to K^{(*)}\nu\bar{\nu}$



$B_s^0 - \bar{B}_s^0$

$D^0 - \bar{D}^0$



$B \to D\mu\nu_\mu$

$K \to \mu\nu_\mu$

$D_{d,s} \to \tau, \mu\nu$

$\tau \to K(\pi)\nu$

$K \to \pi\mu\nu_\mu$

$W \to \tau\bar{\nu},\ \tau \to \ell\bar{\nu}\nu$

$Z \to b\bar{b} \qquad Z \to l^+l^-$

Constraints from LFV

$\tau \to \mu\gamma$

$\mu \to e\gamma$

$\tau \to K(\pi)\mu(e)$

$K \to \mu e$

$B \to K\mu e$

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

$\tau \to \phi\mu$

$t \to c\ell^+\ell'^-$

Becirevic et al., 1806.05689, 1608.07583, 1608.08501, Alonso et al., 1611.06676,…
Radiative constraints Feruglio et al.,1606.00524;
Mandal &Pich, 1908.11155

Vector leptoquark $U_1(3,1,2/3)$ resolving both B anomalies

Buttazzo et al, 1706.07808
Cornella et al, 1903.11517

couples to doublets and singlet of $SU(2)_L$

$b \to c\tau\nu$

$$C_{V_L} = \frac{v^2}{2m_{U_1}^2}(x_L^{b\tau})^*(x_L^{b\tau} + \frac{V_{cs}}{V_{cb}} x_L^{s\tau})$$

$b \to s\mu\mu$

$$C_9 = -C_{10} = -\frac{\pi v^2}{m_{U_1}^2}(x_L^{b\mu})^* x_L^{s\mu}$$

If vector LQ is not a gauge boson – difficult to handle!

GUT Pati-Salam Model for $U_1(3,1,2/3)$
$SU(4) \times SU(3)' \times SU(2)_L \times U(1)'$
Isidori's group, 1712.01368, 1805.09328
2103.16558

$$[\ PS\ ]^3 = [\ SU(4)\times SU(2)_L\times SU(2)_R\ ]^3$$

New gauge bosons:
new colored octet, a triplet and three SM singlets; their masses ~ TeV region
$M_{Z'}$ = 1.3 TeV, M_U = 1.5 TeV, and $M_{g'}$ = 1.9 TeV.
Unification scale rather low ~10^6 GeV. No proton decays!

Two scalar LQs solution of $R_{D(*)}$ and $R_{K(*)}$

Why 2 scalar LQs?

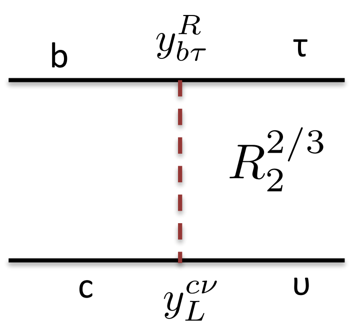
- GUT possible with 2 light scalar LQs within SU(5),
- Neutrino masses generated with 2 light LQs,

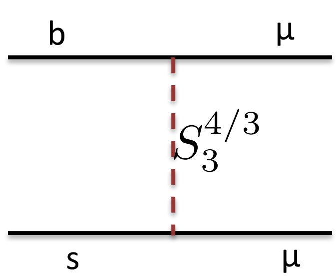
$S_3(3,3,1/3) + S_1(3,1,-1/3)$ V-A form

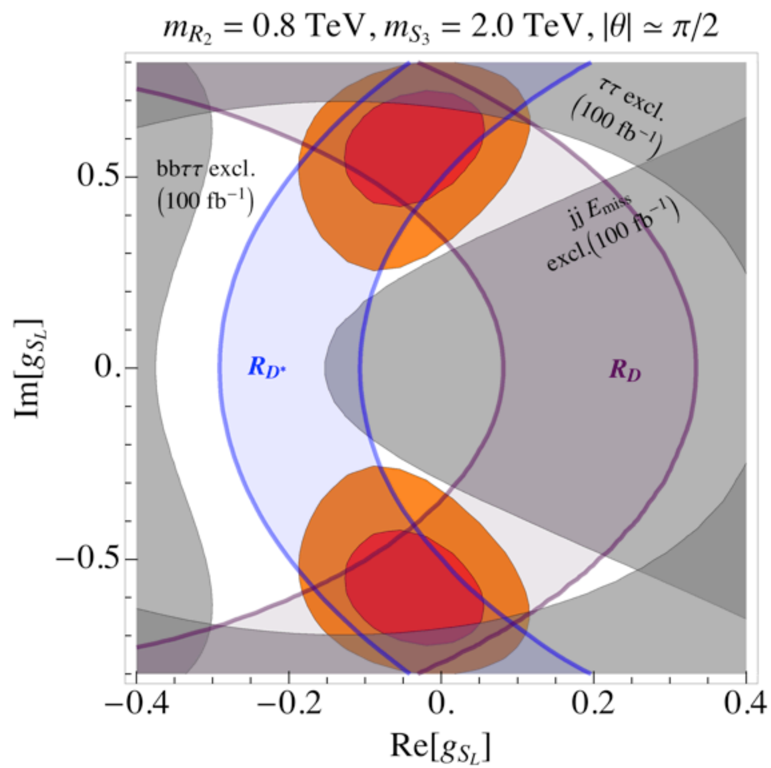
Crivellin et al, 1703.09226, Marcozza, 1803.10972, Yan etal., 1905.01795

$R_2(3,2,7/6)$ **scalar and tensor** in $R_{D(*)}$
$S_3\,(3,3,1/3)$ for $R_{K(*)}$

Becirevic et al, 1806.05689, 1609.08895







$Y^{b\tau}{}_R \sim i$ (Imaginary!)

Predictions

soon Belle result on

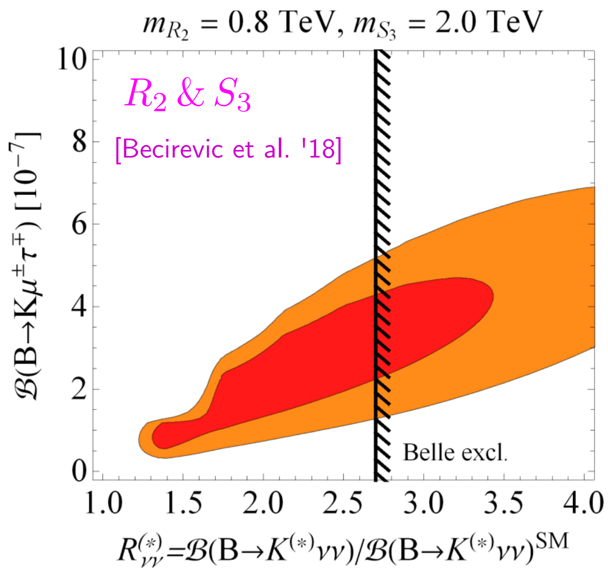
$$\mathcal{B}(B \to K \nu \bar{\nu})$$

NP EFT predictions
V-A interaction

$$\frac{\mathcal{B}(B_s \to \mu\tau)}{\mathcal{B}(B \to K\mu\tau)} \simeq 0.8\,, \qquad \frac{\mathcal{B}(B \to K^*\mu\tau)}{\mathcal{B}(B \to K\mu\tau)} \simeq 1.8$$

$$\frac{\mathcal{B}(B_s \to \mu\tau)}{\mathcal{B}(B \to K^{(*)}\mu\tau)} \gg 1$$

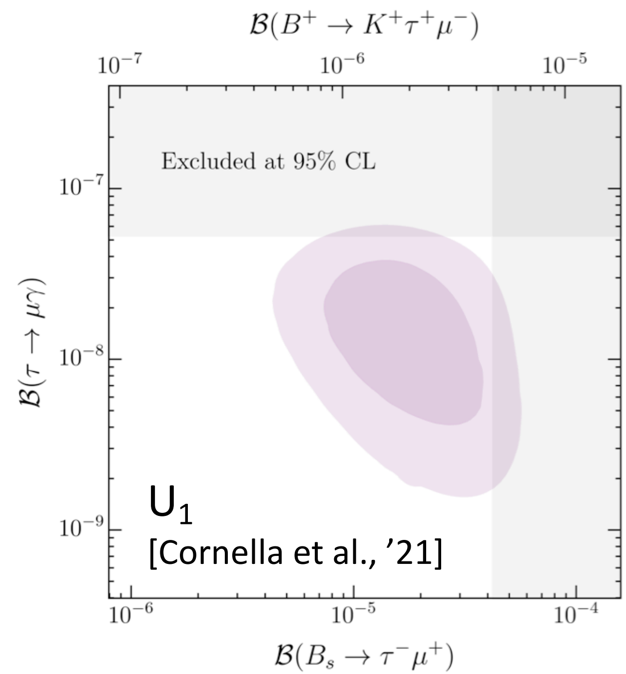
For a scalar interaction



Lepton flavor violation

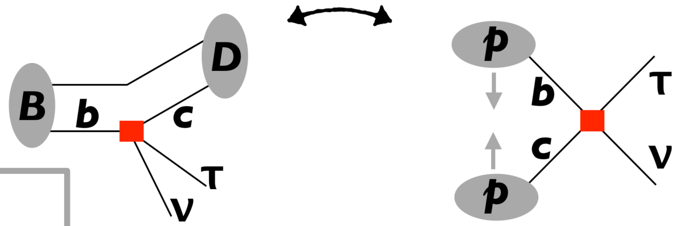
$$B_s \to \mu\tau \qquad B \to K^{(*)}\mu\tau$$

$$\mathcal{B}(B_s \to \mu^\pm\tau^\mp)^{\rm exp} < 4.2 \times 10^{-5}$$
$$\mathcal{B}(B^+ \to K^+\mu^-\tau^+)^{\rm exp} < 4.5 \times 10^{-5}$$



LHC constraints on NP in B mesons

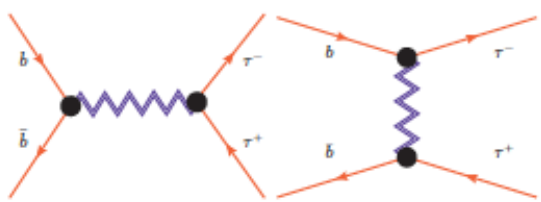
Suggested NP as solution of B anomalies can be searched at LHC



$$p\,p \to \tau\tau$$

$$p\,p \to \mu\mu$$

$$p\,p \to \tau\,\text{invisible}$$



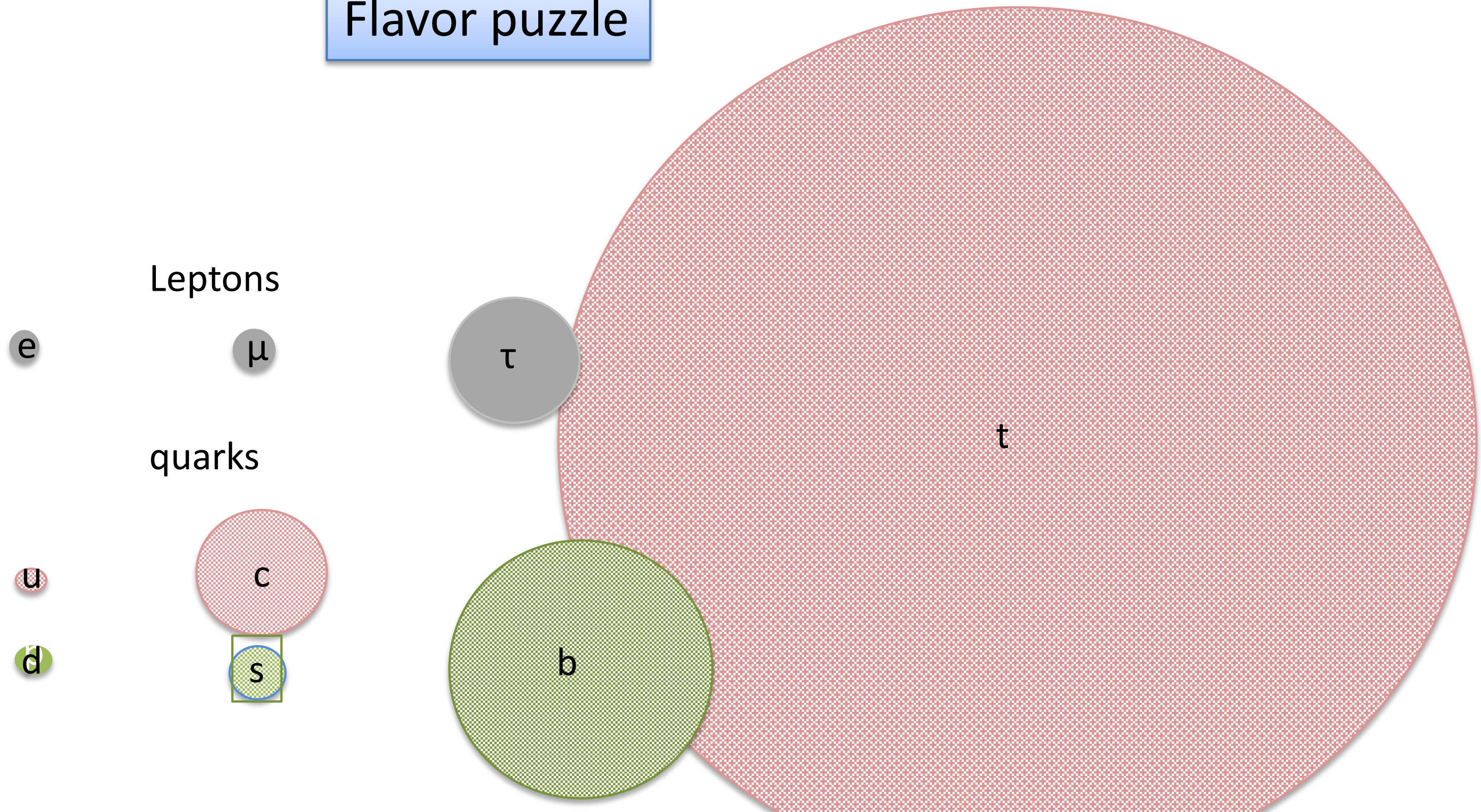
Decays	Scalar LQ limits	Vector LQ limits
$jj\,\tau\bar{\tau}$	–	–
$b\bar{b}\,\tau\bar{\tau}$	1.0 (0.8) TeV	1.5 (1.3) TeV
$t\bar{t}\,\tau\bar{\tau}$	1.4 (1.2) TeV	2.0 (1.8) TeV
$jj\,\mu\bar{\mu}$	1.7 (1.4) TeV	2.3 (2.1) TeV
$b\bar{b}\,\mu\bar{\mu}$	1.7 (1.5) TeV	2.3 (2.1) TeV
$t\bar{t}\,\mu\bar{\mu}$	1.5 (1.3) TeV	2.0 (1.8) TeV
$jj\,\nu\bar{\nu}$	1.0 (0.6) TeV	1.8 (1.5) TeV
$b\bar{b}\,\nu\bar{\nu}$	1.1 (0.8) TeV	1.8 (1.5) TeV
$t\bar{t}\,\nu\bar{\nu}$	1.2 (0.9) TeV	1.8 (1.6) TeV

LHC bounds are competitive with low energy bounds!

Angelescu et al.,2103.12504

Flavor puzzle

All properties are the same but masses are different!



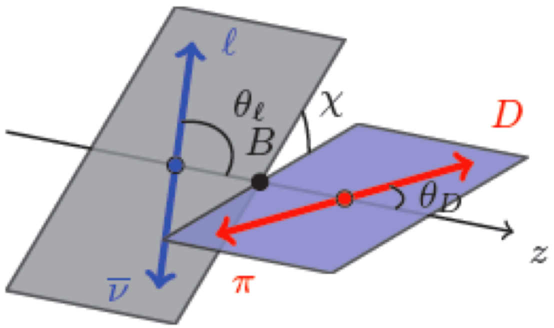
Constructing new UV complete theories based on B anomalies explanation might help in understanding SM quarks and leptons masses (Yukawa couplings).

Cornella et al., 2103.16558

Outlook

- We have to wait on Belle 2 & LHCb new results on $R_{D(*)}$ and R_K
- To measure all possible observables in angular correlations in b $\longrightarrow$ c τυ and in b $\rightarrow$ s μμ;
- To measure b $\longrightarrow$ s ττ
- b $\rightarrow$ c τ ν in baryon systems, sum rule: Blanke et al,1811.09603

$$\frac{\mathcal{R}(\Lambda_c)}{\mathcal{R}_{SM}(\Lambda_c)} = 0.262\frac{\mathcal{R}(D)}{\mathcal{R}_{SM}(D)} + 0.738\frac{\mathcal{R}(D^*)}{\mathcal{R}_{SM}(D^*)} + x.$$



- If there is NP in $R_{D(*)}$ and $R_{K(*)}$, it has to be present in

$$B \to K^{(*)}\nu\bar{\nu} \qquad \tau \to \mu\gamma \qquad B \to K^{(*)}\tau\mu$$
$$K \to \pi\nu\bar{\nu} \qquad \tau \to 3\mu \qquad B \to \tau\mu$$

- Further test of all flavor couplings at LHC;
- To check LFU in the first and second generations as precise as possible- below 1%!
- Continue to build UV complete models of NP models.

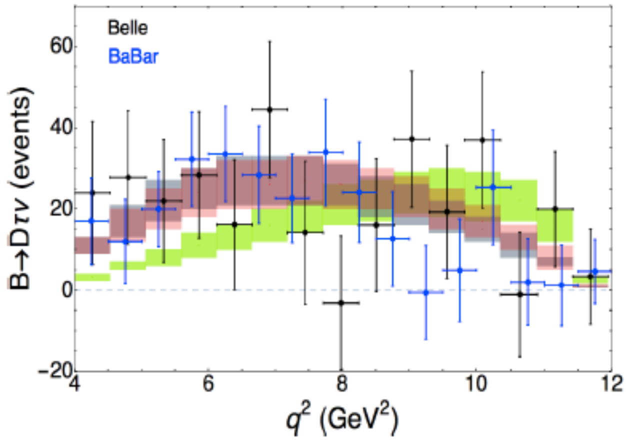
Future experimental facilities

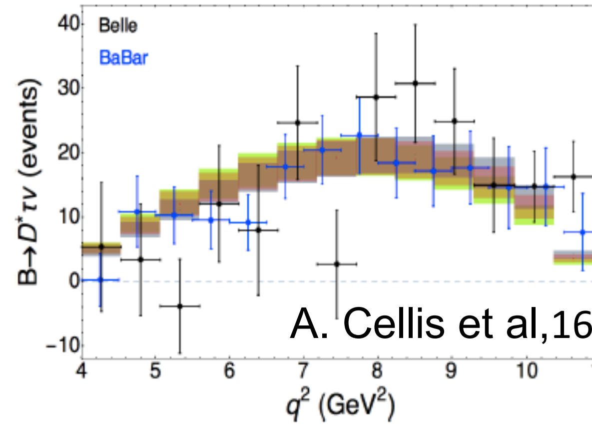
Solutions of B anomalies by NP require high energy scale ($R_{K(*)}$ NP scales not accessible by LHC).

Precision low energy experiment to study all possible b (c, s) quark decays!

Thanks!

q^2 distribution





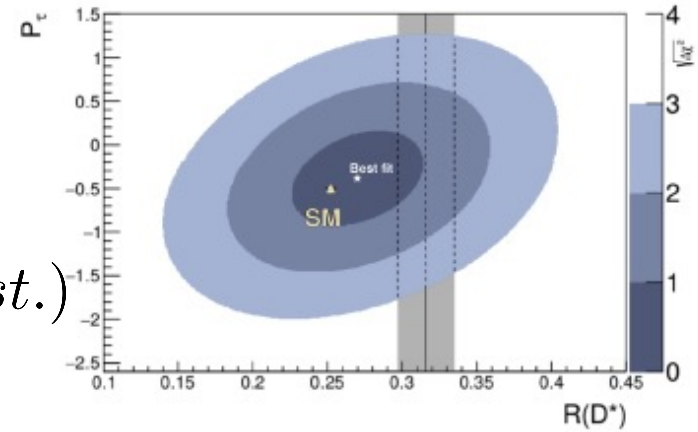
A. Cellis et al,1612.07757

τ polarization

$$\mathcal{P}_\tau^{D^{(*)}}(q^2) = \left(\frac{d\Gamma^{D^{(*)}}_{\lambda_\tau=1/2}}{dq^2} - \frac{d\Gamma^{D^{(*)}}_{\lambda_\tau=-1/2}}{dq^2} \right) \bigg/ \frac{d\Gamma^{D^{(*)}}}{dq^2}$$

Belle: 1612.00529

$$P(D^*)_\tau = -0.38 \pm 0.51(stat.)^{+0.21}_{-0.16}(syst.)$$



Longitudinal D* polarization in B → D* τ ν

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

$$F_L(D^*) = 0.60 \pm 0.07 \pm 0.035$$

Belle, 1903.03102

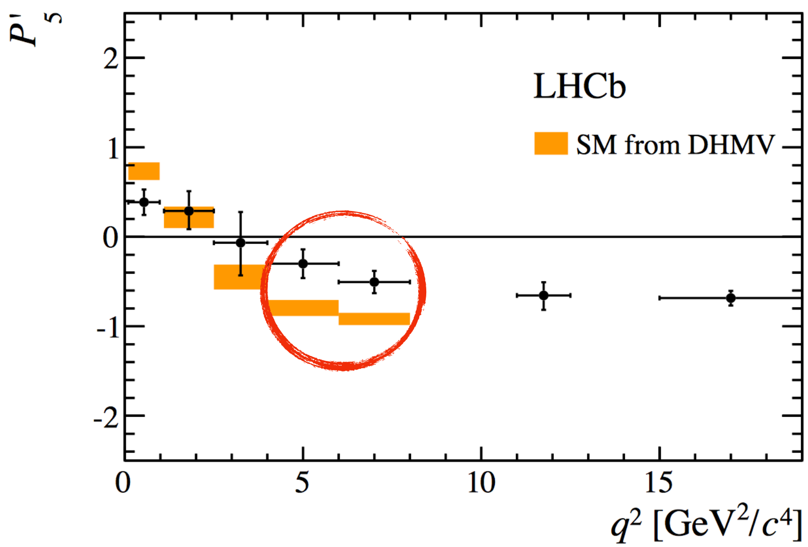
1.5 σ far from SM (0.46 ± 0.04)

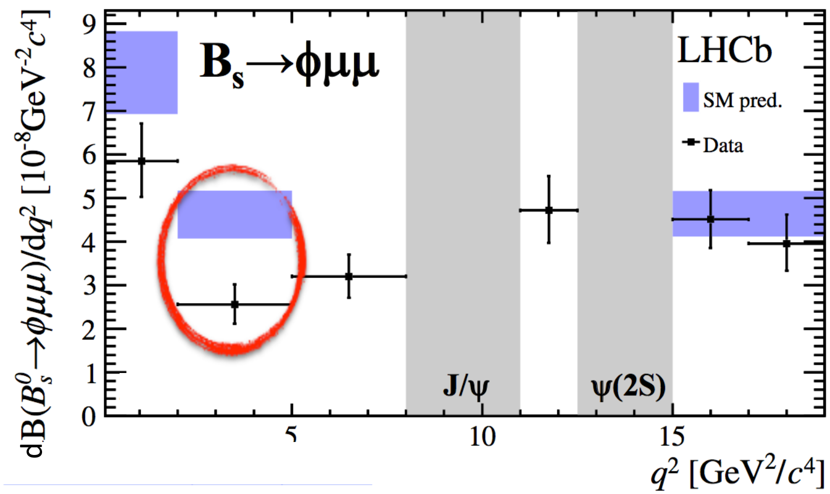
Blanke et al., 1811.09603

Alok et al, 1606.03164
SF, Nisandzic, Kamenik, 1206.1782
Tanaka, Watanabe 1212.1878
Murgui et al.,1904.09311

P$_5$' anomaly: Lepton Flavor Dependent

Decotes-Genot et al., 1207.2753





~3.5 **σ**

~2.5 **σ**

LHCb collaboration 1512.04442

LHCb collaboration, 1506.08777

Alguero et al, 1809.08447, 1903.09578

CP violation from $R_{D(*)}$

$Y^{b\tau}{}_R \sim i$ (Imaginary!)
τ and c quark electric(chromoelectric) dipole moments, Jung et al., 1809.09114
Mandal & Pich, 1908.11155

Crivellin & Saturnino 1905.08257
From B $\longrightarrow$ τυ EDM nucleon using S_1

Neutrino masses

1701.08322, Doršner, SF &Košnik
1903.01799, Cata& Mannel