Heavy flavour physics: theory

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Outline

B meson anomalies $R_{D(*)}$, $R_{K(*)}$, P_5'

SM contributions to anomalous processes

New Physics explanation

- effective Lagrangian approach
- models of NP
- constraints from low-energy observables & LHC data
- from B to K (D)

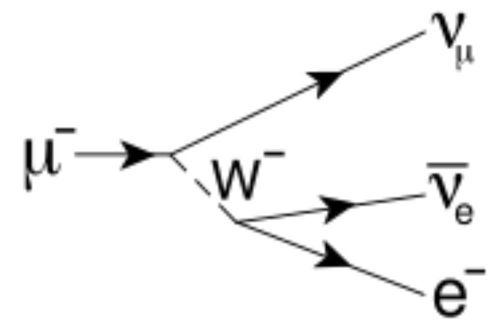
Predictions relevant for LHCb, Belle2 &LHC

Flavour puzzle?

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

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

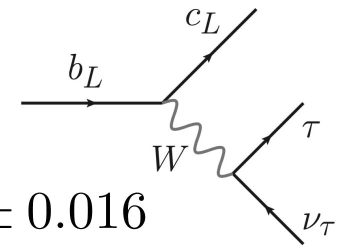
the same for all SM fermions

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

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

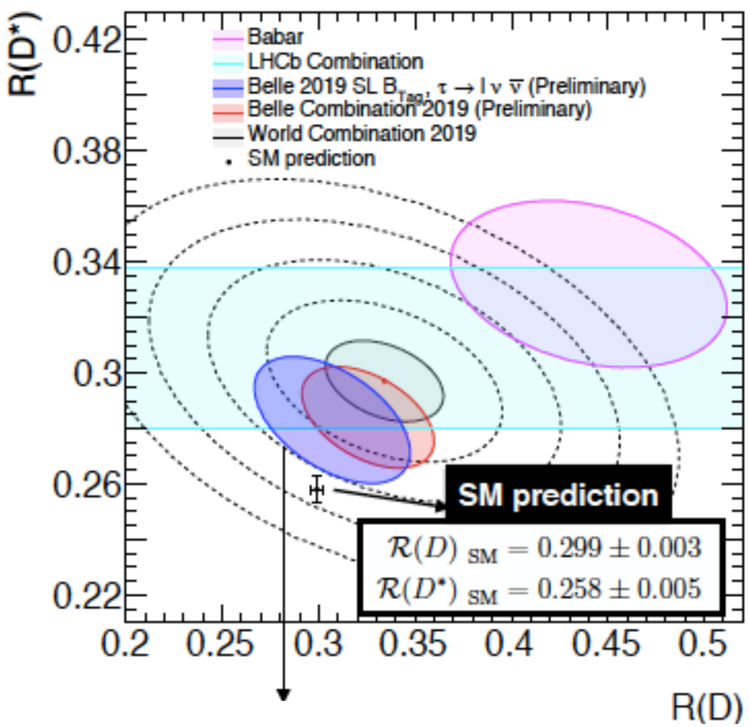
B physics anomalies: experimental results ≠ SM predictions!

charged current (SM tree level)



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

$$R_D = 0.307 \pm 0.037 \pm 0.016$$
$$R_{D^*} = 0.283 \pm 0.018 \pm 0.014$$



Belle, 2019

New Belle result R_D=0.31(4);
R_{D*}= 0.28(2);

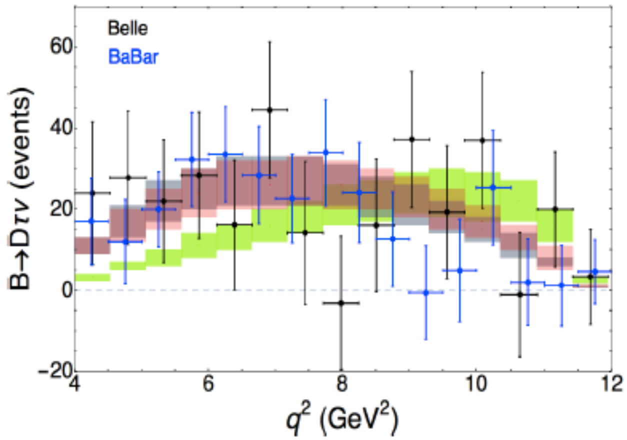
$R_{D(*)}$ discrepancy (exp./SM) decreases from 3.8 σ to 3.1σ;

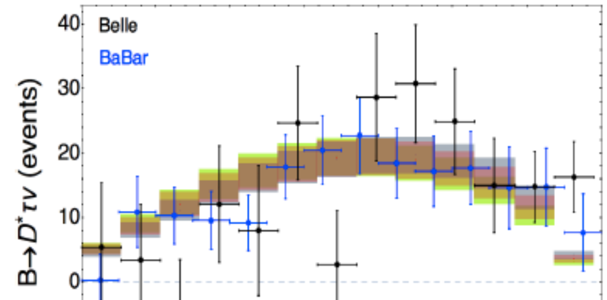
Disagreement: BaBar and Belle!

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

$$R_{J/\Psi} = 0.71 \pm 0.17 \pm 0.18$$ 2.4σ

q^2 distribution





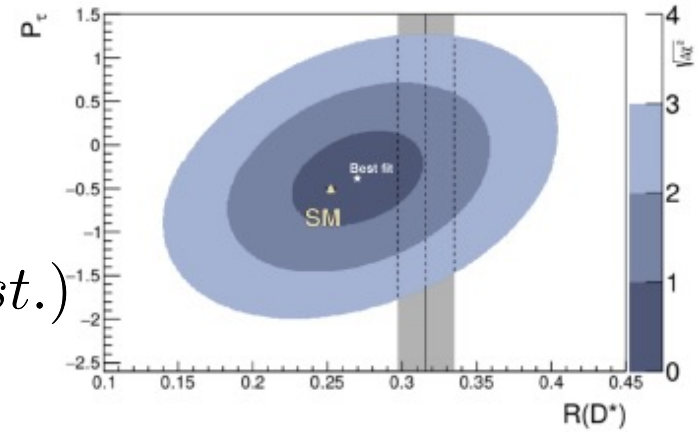
A. Cellis et al,1612.07757

τ polarization

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

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

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

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

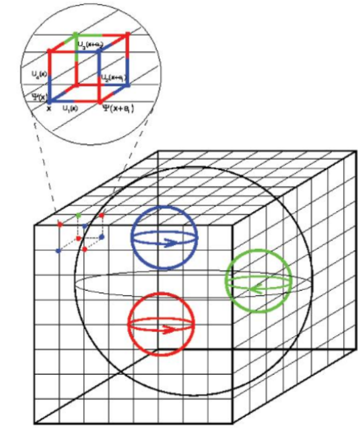
Belle, 1903.03102

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

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



SM: R_D =0.299±0.03

- two form factors in $< D|\bar{c}\gamma_\mu b|B >$
- (Fermilab Lattice and MILC Collaborations J. A. Bailey et al. 1503.0 7237).

SM: R_{D*} =0.258± 0.005 FLAV 2018

$$< D^*|\bar{c}\gamma_\mu(1-\gamma_5)b|B >$$

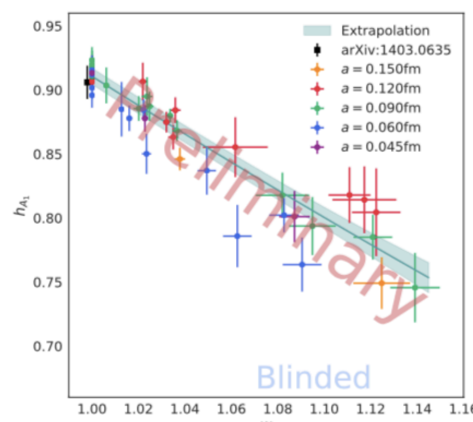
Full lattice QCD form factors necessary!

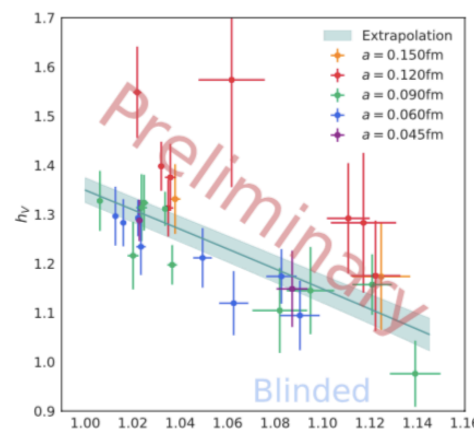
- one V form-factor, three axial form-factor
- no full lattice QCD result yet!

Bigi et al., 1707.09509, Bernlocher et al., 1703.05330, 1707.09977

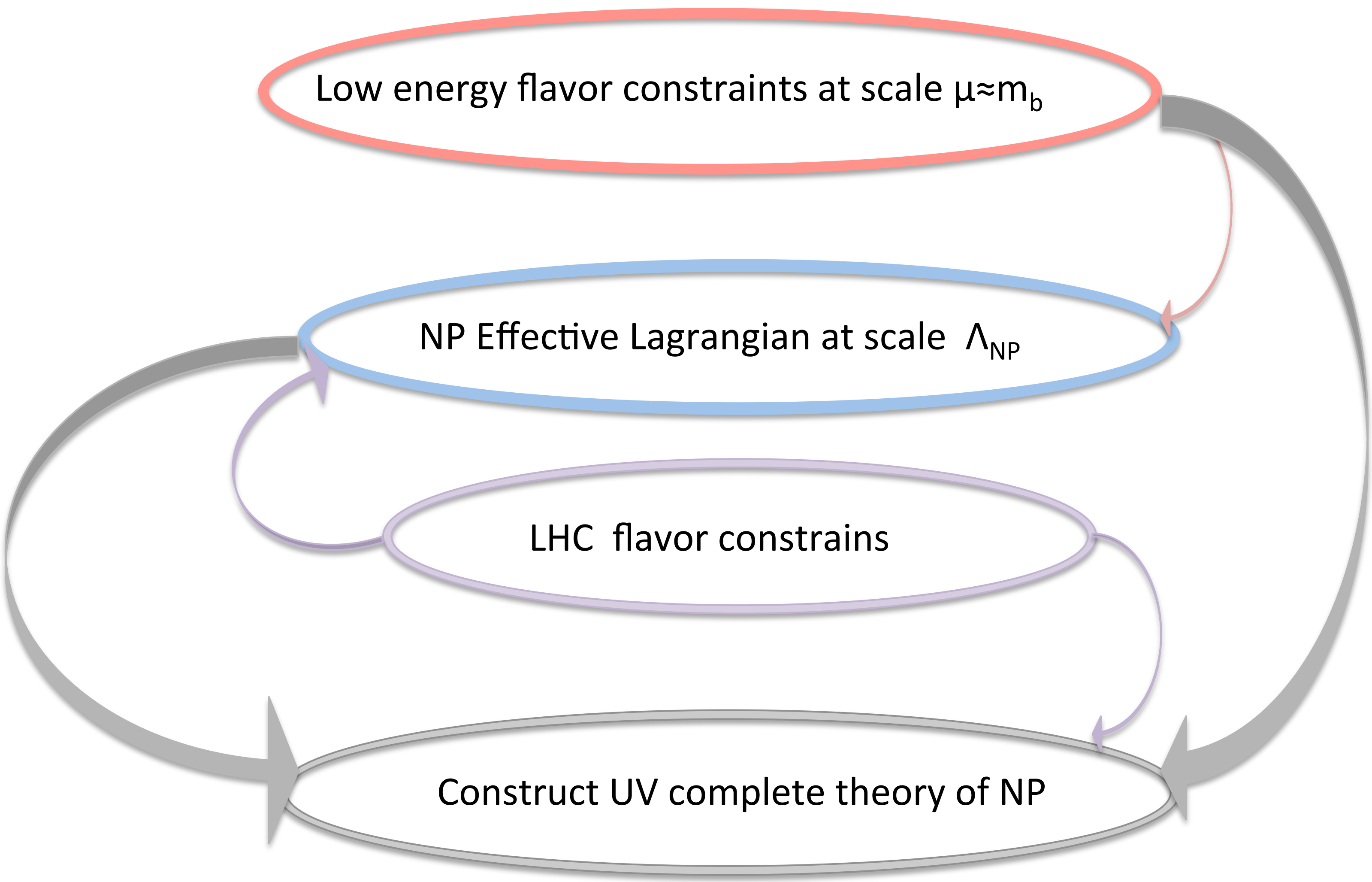
1901.00216 - Fermilab Lattice and MILC Collaborations
B → *D**lv at non-zero recoil

CLN parametrization
hep-ph/9712417,
R_{D*}=0.252(3)
BGL parametrization
Boyd et al., hep-ph/9504235,
better in explaining $|V_{cb}|$
inclusive/exclusive difference
1702.01521



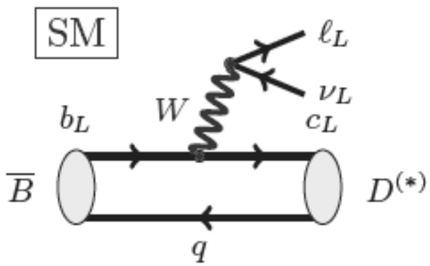


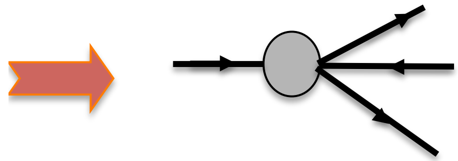
How to approach New Physics?



NP in $R_{D(*)}$

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





Left-handed neutrino
SM+ 5 new operators

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

Attempts:
right-handed neutrinos
Robinson et al. 1807.04753, 1804.04642,
Becirevic et al, 1608.08501

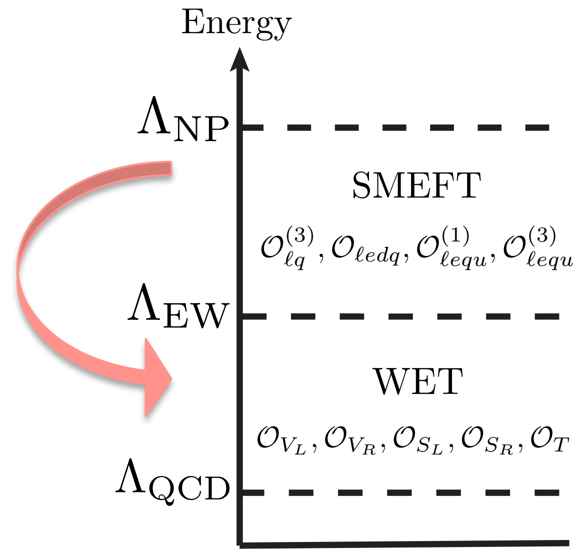
$$\mathcal{L}_R = \tilde{g} \bar{l} \gamma_\mu (1 + \gamma_5) N \, \bar{c} \gamma^\mu (1 + \gamma_5) b$$

no interference with SM $|\mathcal{M}^{SM}|^2 + |\mathcal{M}^R|^2$

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

$\chi^2_{\rm min}/{\rm d.o.f.}$	$37.4/54$
C_{V_L}	$0.09^{+0.13}_{-0.11}$
C_{S_R}	$0.14^{+0.06}_{-0.67}$
C_{S_L}	$-0.20^{+0.58}_{-0.03}$
C_T	$0.007^{+0.046}_{-0.044}$

integrating out
the top, W , Z
and the Higgs

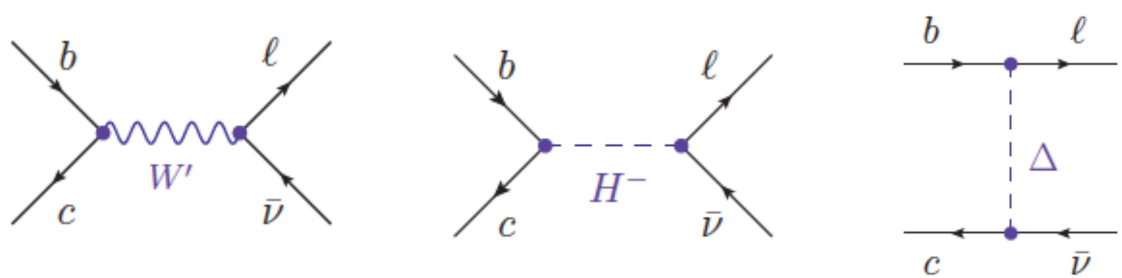


Global fit Murgui et al., 1904.09311 using $R_{D^{(*)}}$, q^2 distributions, D* polarization, $\mathcal{B}(B_c \to \tau\nu) \leq 10\%$

Becirevic et al.,1907.02257

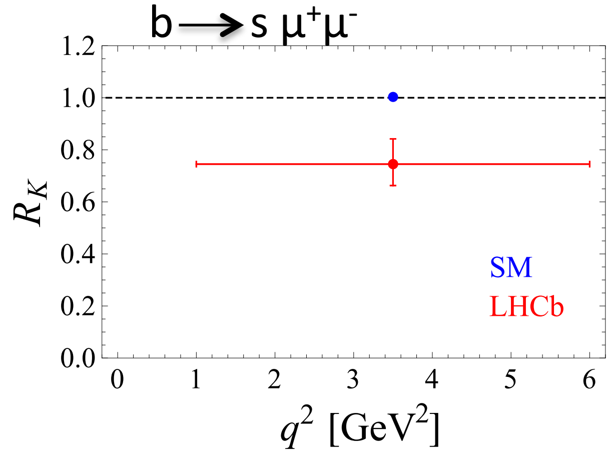
NP models for $R_{D^{(*)}}$

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

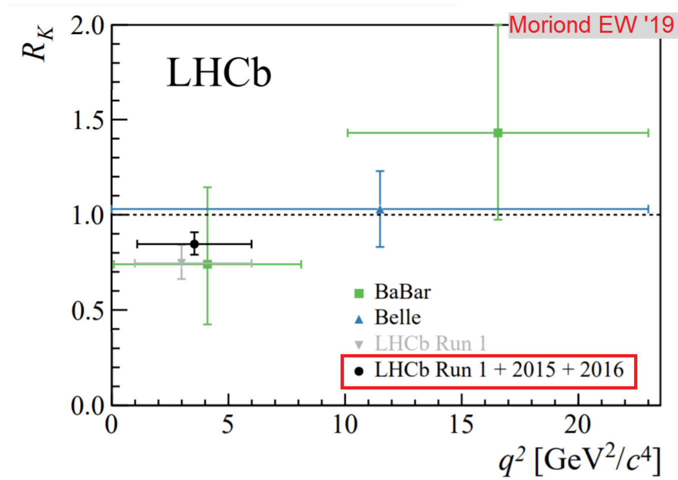


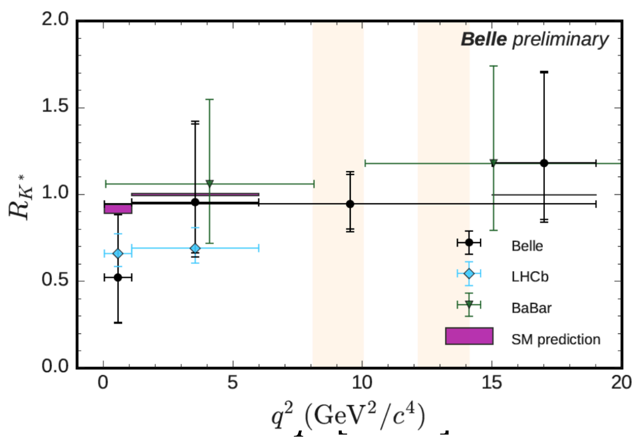
impossible to write all references!

FCNC - SM loop process: $R_{K(*)}$ anomaly



$$R_{K^{(*)}} = \frac{BR(B \to K^{(*)}\mu\mu)}{BR(B \to K^{(*)}ee)}\Big|_{q^2 \in [q^2_{min}, q^2_{max}]}$$





3.8σ from LFU

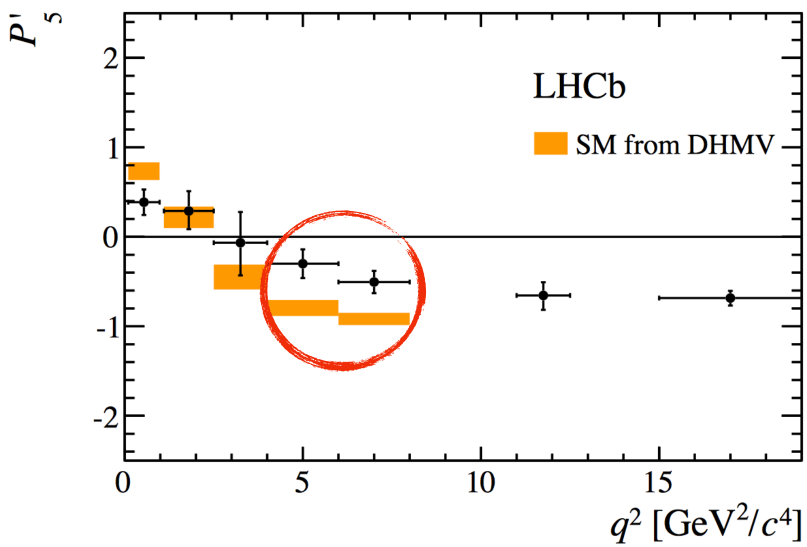
$$BR(B_s \to \mu^+\mu^-) = (3.0 \pm 0.6^{+0.3}_{-0.2}) \times 10^{-9}$$

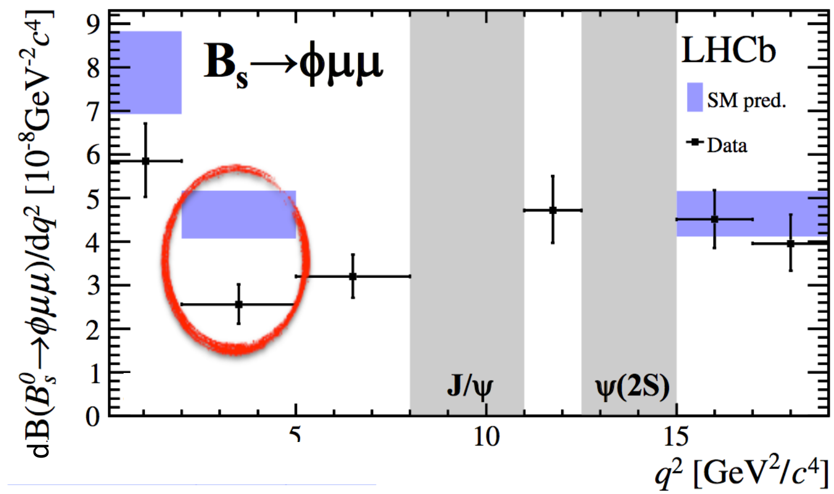
P_5' in $B \to K^*\mu^+\mu^-$ (angular distribution functions)

LHCb, CMS, ATLAS)

P_5' anomaly: Lepton Flavour 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

R_K and R_K*: SM

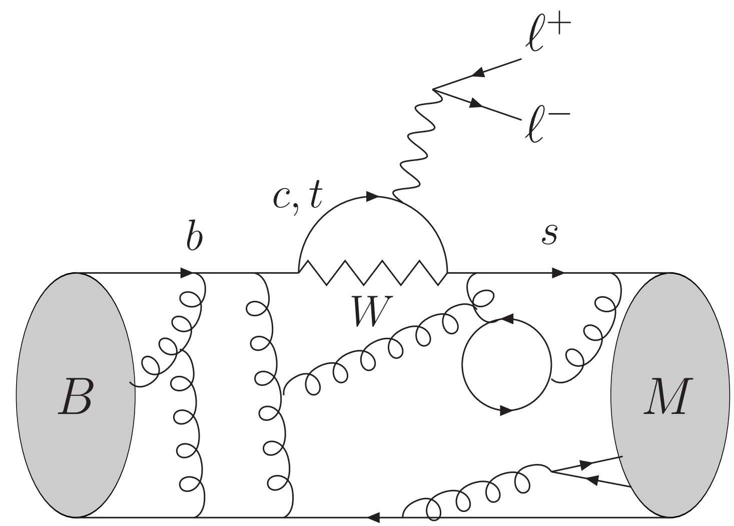
$$\mathcal{H}_{\rm eff} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \left[\sum_{i=1}^{6} C_i(\mu) \mathcal{O}_i(\mu) + \sum_{i=7,\ldots,10} \left(C_i(\mu)\mathcal{O}_i(\mu) + C_i'(\mu)\mathcal{O}_i'(\mu) \right) \right]$$

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

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

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

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



R_K and R_K*: New Physics

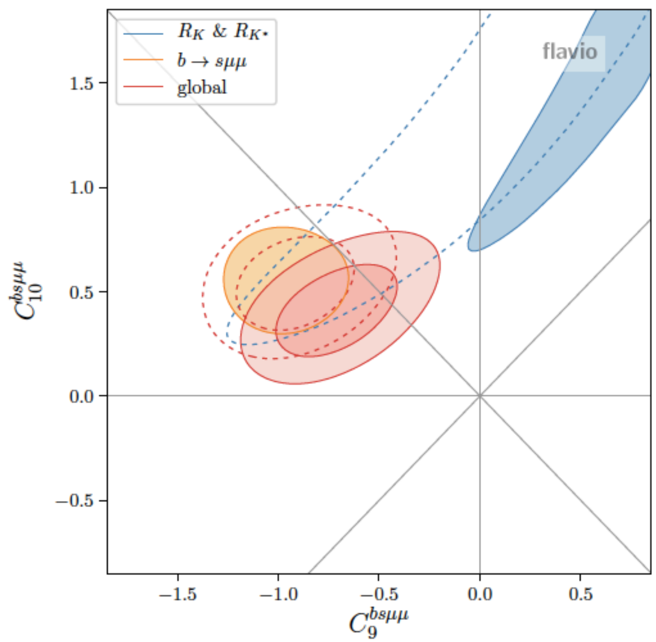
Global analysis suggests NP in $C_{9,10}$, based on R_K, R_{K^*} and $B_s \rightarrow \mu\mu$

2017

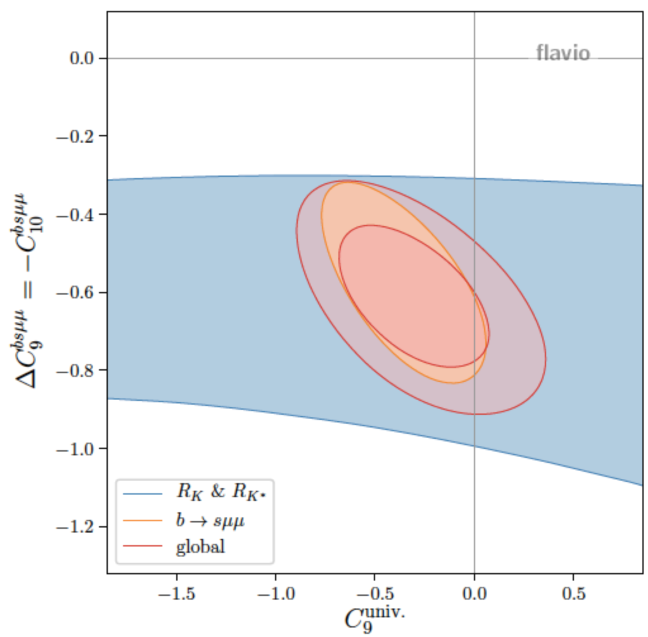
$$C_i = C_i^{SM} + C_i^{NP}$$ instead of SM values for C_9 and C_{10}

2019

NP in muonic mode!



LF universal vs. purely muonic NP



Aebischer et al., 1903.10434 (pre-Morion $C_9^{univ} \approx 0$)

Alguero et al., 1809.08447,1903.09578, Aebischer et al., 1903.10434, Altmannshofer et al., 1704.05435, Capdevila et al., 1704.05340, Ciuichini et al, 1903.09632 D'Amico et al., 1704.05438, Arbey et al, 1904.08399

NP in both B anomalies

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

$$R_{K^{(*)}}^{exp} < R_{K^{(*)}}^{SM}$$

NP at tree level

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

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

$$\Lambda_{NP}^{D} \simeq 3\,\mathrm{TeV}$$

$$\Lambda_{NP}^{K} \simeq 30\,\mathrm{TeV}$$

$$\Lambda_{NP}^{D} = \Lambda_{NP}$$

$$\frac{1}{(\Lambda_{NP}^{K})^2} = \frac{C_K}{\Lambda_{NP}^2}$$

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))

NP effective Lagrangian approach

V-A NP couples dominantly to the third generation

$$\mathcal{L}_{NP} = \frac{C_S}{\Lambda^2}\bar{q}_{3L}\gamma_\mu q_{3L}\bar{l}_{3L}\gamma^\mu l_{3L} + \frac{C_T}{\Lambda^2}\bar{q}_{3L}\gamma_\mu \tau_i q_{3L}\bar{l}_{3L}\gamma^\mu \tau_i l_{3L}$$

$SU(2)_L$ singlets $\qquad$ $SU(2)_L$ triplets

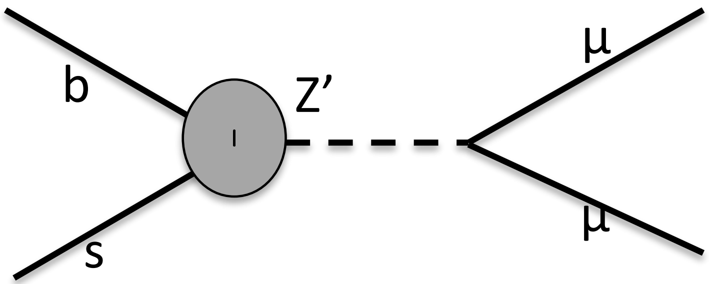
+ small correction for 2^{nd} and 1^{st} generations

$$q_L^3 \sim \begin{bmatrix} V_{ib}^* u_L^i \\ b_L \end{bmatrix}$$

Lepton flavor non-universality
Lepton flavor violation

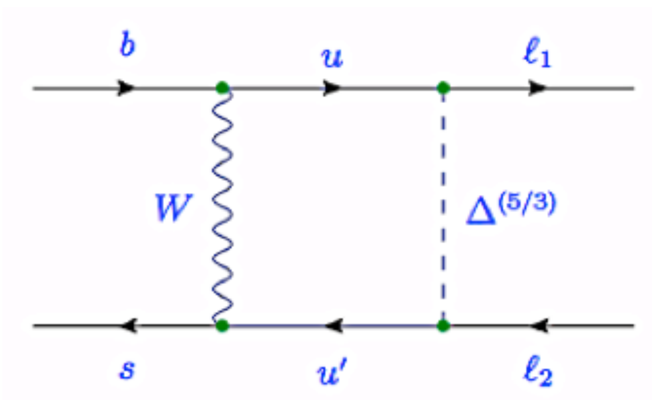
Buttazzo et al.,1706.07808,
Feruglio et al., 1606.00524; 1705.00929,
Battacharaya et al., 1412.7164; 1609.09078,
Glashow et al., 1411.0565...

New boson Z’



- different origin of Z’, e.g. by gauging L_μ- L_τ, Altmannshofer et al, 1403.1269,
- New Z’+ new vector-like quarks (UV complete theories) Kamenik et al., 1704.06005,
- Fermiophobic Z’, couples to 4th generation of the vector-like fermions, Falkowski et al, 1803.04430, Allanach et al, 1904.10954, ...

$R_{K(*)}$ explained by NP at loop level



$C_K \approx 1 / 16\pi^2$

Bauer&Neubert 1511.01900, + muon (g-2),Becirevic et al., 1608.0758 , 1904.05890

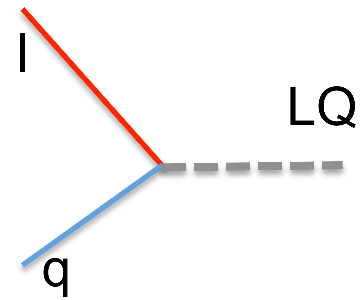
strong constraints from charm, K, leptonic decays and Δ M_{Bs} Lenz et al., 1811.12884

Leptoquarks resolving B anomalies:

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

$Q=I_3+Y$

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



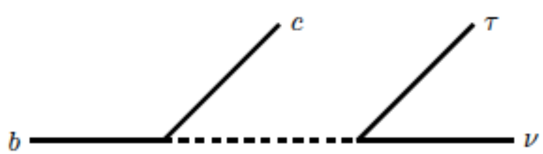
no proton decay
at tree level

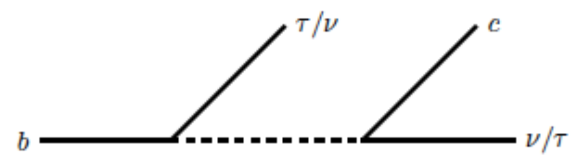
Model	$R_{D^{(*)}}$	$R_{K^{(*)}}$	$R_{D^{(*)}}$ & $R_{K^{(*)}}$
$S_1 = (\bar{3}, 1, 1/3)$	✓	✗	✗
$R_2 = (3, 2, 7/6)$	✓	✓*	✗
$S_3 = (\bar{3}, 3, 1/3)$	✗	✓	✗
$U_1 = (3, 1, 2/3)$	✓	✓	✓
$U_3 = (3, 3, 2/3)$	✗	✓	✗

Spin 0

Spin 1

U_1 is the only one to accommodate both anomalies!





Doršner, SF, Greljo, Kamenik, Košnik, 1603.04993

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

Constraints from flavor observables

$(g-2)_\mu$

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

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

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

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

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

$K \to \mu\nu_\mu$

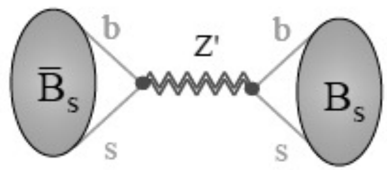
$D_{d,s} \to \tau, \mu\nu$

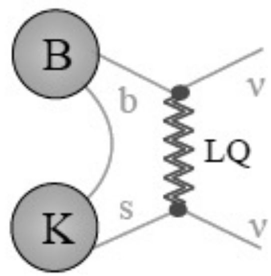
$\tau \to K(\pi)\nu$

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

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

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





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 $SU(2)_L$

$$\boxed{\mathcal{L} = x_L^{ij}\bar{Q}\gamma_\mu L_j U_1^\mu + (x_R^{ij}\bar{d}_R\gamma_\mu l_{Rj} U_1^\mu)}$$

$$\boxed{b \to c\tau\nu}$$

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

$$x_L = \begin{pmatrix} 0 & 0 & 0 \\ 0 & x_L^{s\mu} & x_L^{s\tau} \\ 0 & x_L^{b\mu} & x_L^{b\tau} \end{pmatrix}$$

$$\boxed{b \to s\mu\mu}$$

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

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

GUT Pati-Salam Model for $U_1(3,1,2/3)$
$SU(4) \times SU(3)' \times SU(2)_L \times U(1)'$
Di Luzio et al., 1708.08450, Calibbi et al., 1709.00692,
Blanke and Crivellin, 1801.07256, Heeck and Teresi, 1808.07492
Bordone et al., 1712.01368, 1805.09328

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

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,

(Dorsner et al, 1701.08322,Cata and Mannel, 1903.01799).

(3,3,1/3) + (3,1,-1/3)
S_3 S_1

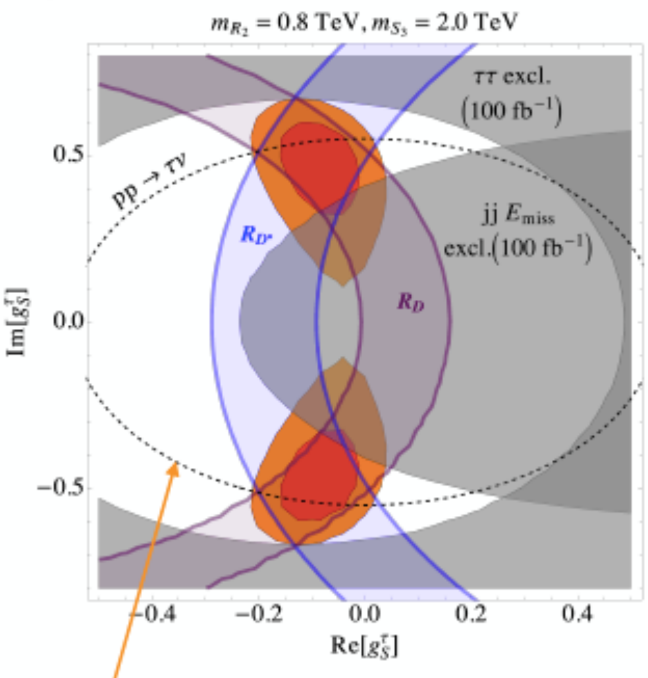
V-A form

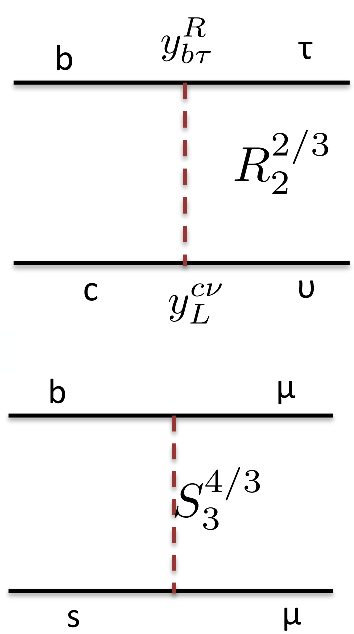
Crivellin et all1703.09226,
Marcozza, 1803.10972,
Yan etal., 1905.01795

R_2(3,2,7/6) **scalar and tensor** in $R_{D(*)}$

+and small contribution of S_3=(3,3,1/3)

Becirevic et al, 1806.05689, 1609.08895



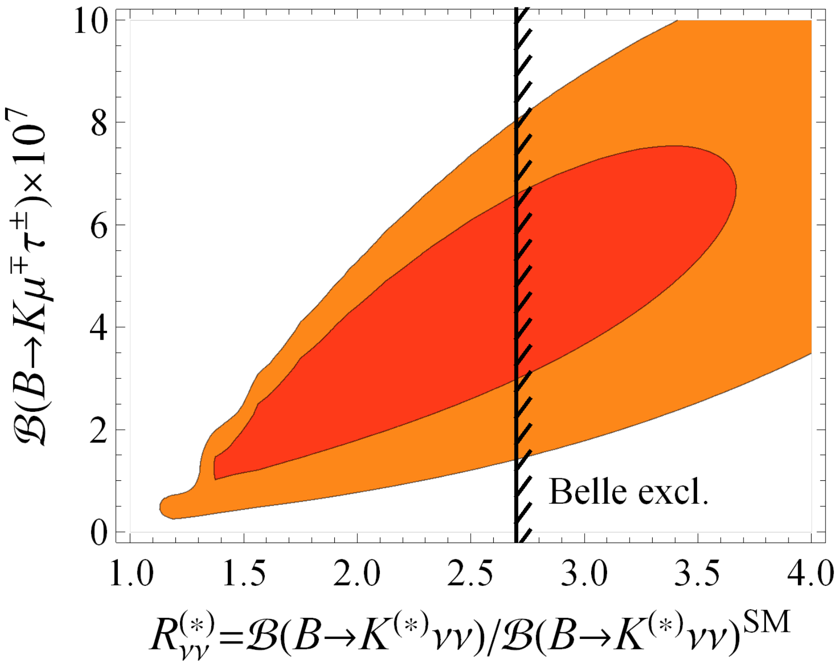


S_3 =(3,3,1/3) for $R_{K(*)}$

Both LQs can be in the same SU(5) representation

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

Predictions



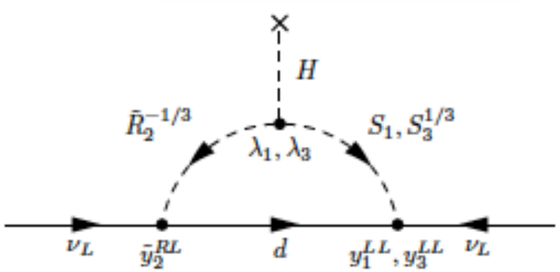
Enhancement of $\mathcal{B}(B \to K\nu\bar{\nu})$ by $\gtrsim 50\%$ of SM (Belle II)

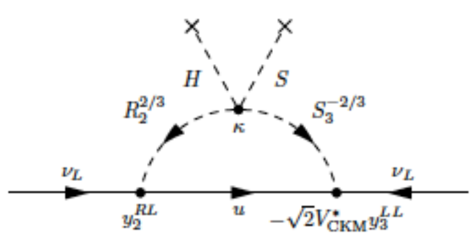
CP violation from $R_{D^{(*)}}$

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

Crivellin & Saturnino 1905.08257
From B $\to$ $\tau\nu$ EDM nucleon using S_1

Neutrino masses



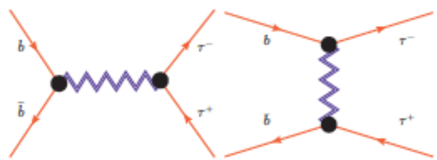


1701.08322, Dorsner, SF &Kosnik
1903.01799, Cata& Mannel

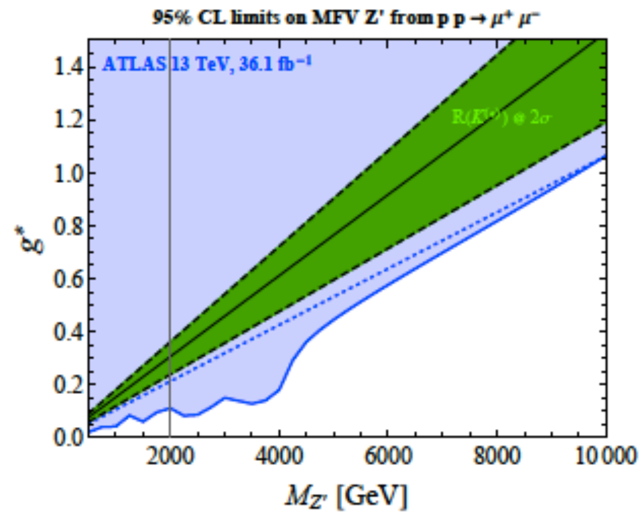
LHC constraints on NP in B mesons

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

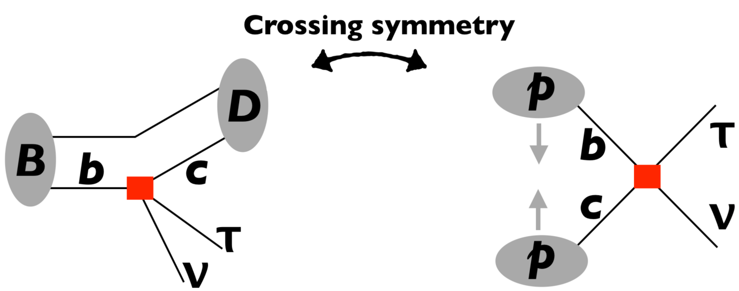
$$p\,p \rightarrow \tau\tau$$
$$p\,p \rightarrow \mu\mu$$
$$p\,p \rightarrow \tau\,\text{invisible}$$



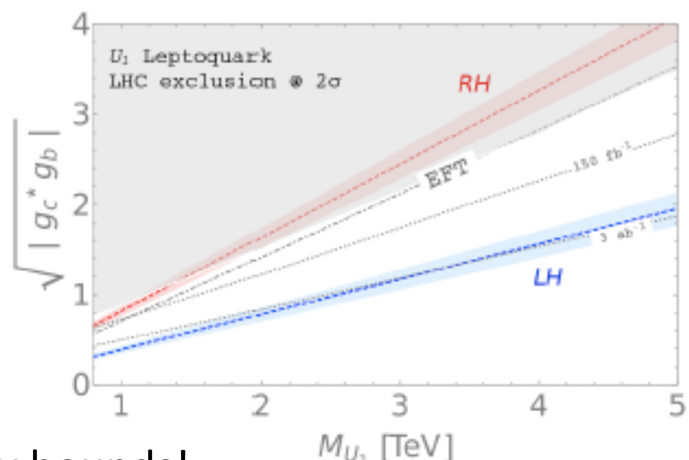
Faroughy et al.,1609.07138
Angelescu et al, 1808.08179



Greljo &Marzocca, 1704.0915

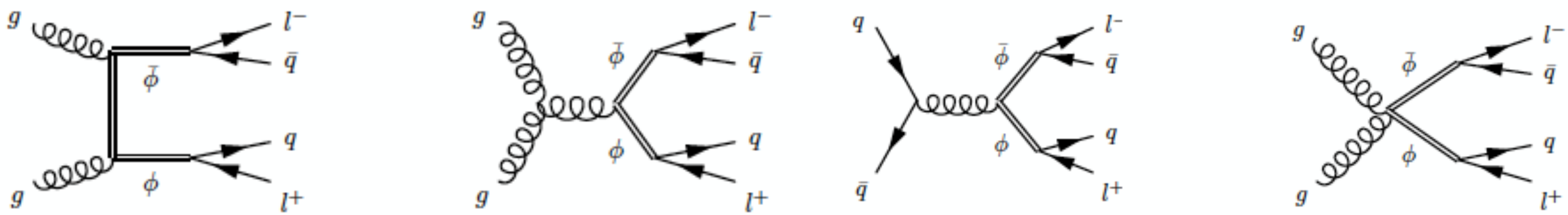


Greljo et al, 1811.07920



LHC bounds are competitive with low energy bounds!

Search of scalar and vector LQ at LHC



Scalar LQ

	j	b	t
ν	1 TeV	1.1 TeV	1 TeV
ℓ	1.5 TeV	1.5 TeV	0.8 TeV
τ		1 TeV	0.9 TeV

Vector LQ

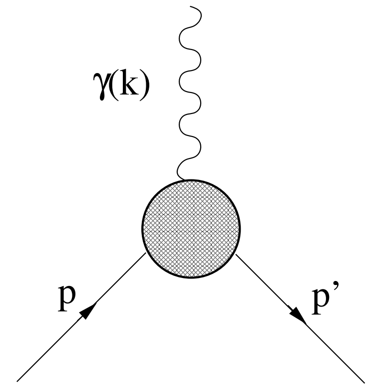
	j	b	t
ν	1.8 TeV	1.8 TeV	1.8 TeV
ℓ	2.1 TeV	2 TeV	1.4 TeV
τ		1.6 TeV	1.4 TeV

Yi-Ming-Zhong at CKM 2108;
Diaz, Schmaltz, Zhong, 1706.05033; Schmaltz, Zhong, 1810.10017

Muon anomalous magnetic moment

Do not forget!

$$ie\bar{u}_\ell(p')\left[\gamma^\mu - \frac{a_\ell}{2m_\ell} i\sigma^{\mu\nu} q_\nu\right] u_\ell(p)\epsilon^*_\mu, \qquad q_\mu = (p-p')_\mu$$



Dirac equation: g=2 $\quad a = (g-2)/2$

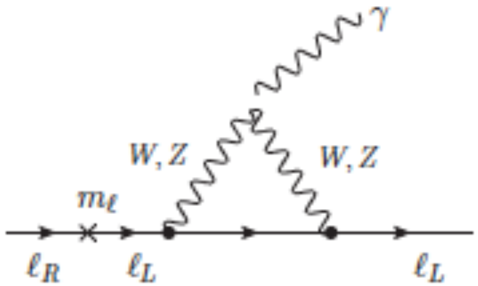
(Schwinger α/π, Kinoshita higher orders in α)

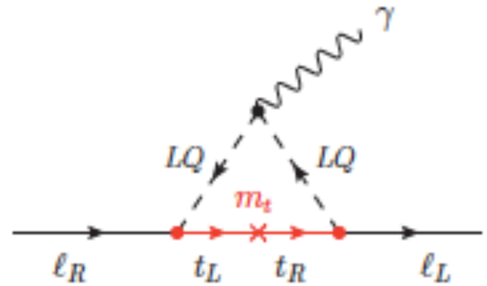
$$\boxed{a_\mu^{th} - a_\mu^{exp} = -(3.06 \pm 0.76) \times 10^{-8}} \quad 4\,\sigma$$

Theory: uncertainty in hadronic contributions to the muon g − 2, (Jägerlehner, 1802.08019).
Lattice QCD great progress light-by-light study (RBC & UKQCD, 1801.07224).

Fermilab and J-Park experiments are expected to clarify existing discrepancy!

Leptoquarks in $(g\text{-}2)_\mu$





$$\mathcal{L}_{eff} \sim \frac{1}{\Lambda^2} \bar{L} \sigma_{\mu\nu} l_R H F^{\mu\nu}$$

Leptoquark should couple to μ and quark with both chirality

$$\bar{\mu}_R t_L \, S$$
$$\bar{\mu}_L t_R \, S$$

Among scalar LQs two candidates

$$S_1 = (\bar{3}, 1, 1/3)$$ Bauer &Neubert 1511.01900

$$R_2 = (\bar{3}, 2, 7/6)$$ Coluccio Leskow et al, 1612.06858

Difficult to explain simultaneously B anomalies and $(g\text{-}2)_\mu$!

Dorsner, SF, Sumensari 19.09.xxxxx

LFU in K and D physics

- strong constraints from atomic parity violation, LFU holds at 1% level for π and K − it suggest to avoid coupling of NP to the first generation;

- in K and D FCNC decays long distance physics overshadow short distance dynamics;

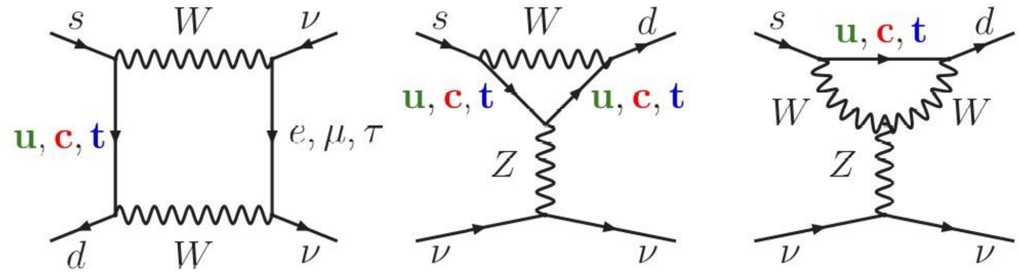
Any NP in B anomalies constrained by
$$\left\{\begin{array}{ll} K^0 - \bar{K}^0 & K \to l\nu_l \\ D^0 - \bar{D}^0 & D_s \to l\nu_l \end{array}\right.$$

How large can be effects of NP explaining B anomalies in K and D charged current and FCNC rare decays having in mind existing and planned experimental precision?

$$D_s \to l\nu_l \qquad K \to l\nu$$

In charm and K meson leptonic decays LQs explaining B anomalies give modification ~0.001 to the decay width.

K → πνν



The “cleanest” rare K meson decay- SM SD contribution dominates over LD

SM Buchalla and Buras, hep-ph/9308272, Buras et al, 1503.02693.

$$\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu})_{\rm SM} = (8.4 \pm 1.0) \times 10^{-11}$$
$$\mathcal{B}(K_L \to \pi^0 \nu\bar{\nu})_{\rm SM} = (3.4 \pm 0.6) \times 10^{-11}$$

present experiments:

$K^+ \to \pi^+\nu\nu$: NA62 experiment at CERN

$K_L \to \pi^0\nu\nu$: KOTO experiment at JPARC

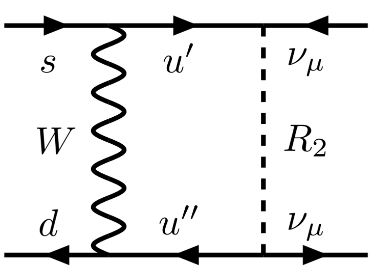
$$\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu})_{\rm exp} = 17.3^{+11.5}_{-10.5} \times 10^{-11}, \quad \text{E787}$$
$$\mathcal{B}(K_L \to \pi^0 \nu\bar{\nu})_{\rm exp} \le 2.6 \times 10^{-8} \quad (90\%\ \text{CL})$$

BNL_E949

NP from $R_{D(*)}$ to K → πνν

NP from $R_{K(*)}$ to K → πνν

Bordone et al, 1705.10729
suppression ~ 30%



max. enhancement ~15% in $K^+ \to \pi^+\nu\nu$

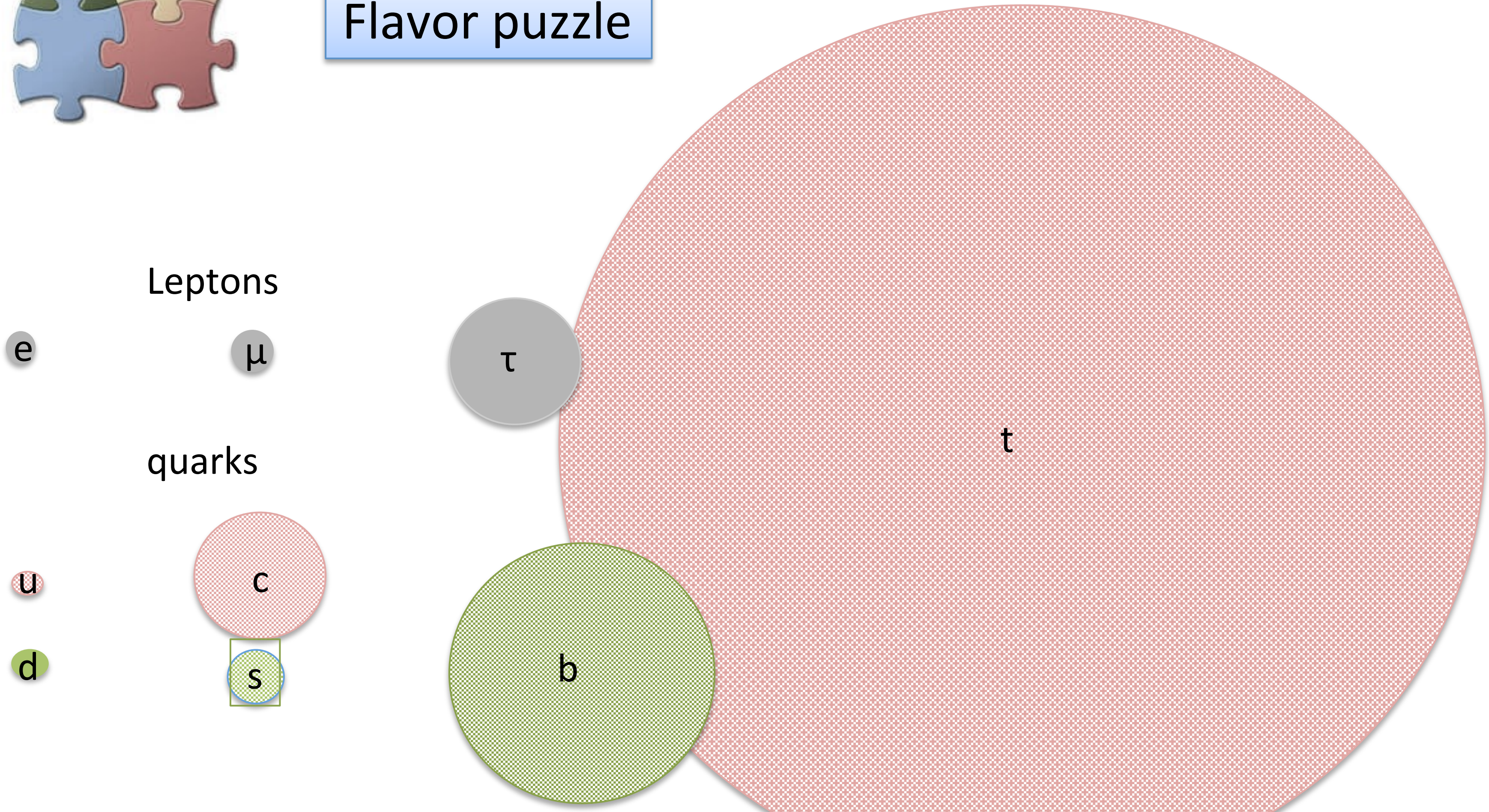
~ 10% $K^0 \to \pi^0\nu\nu$

SF, Kosnik, Vale-Silva, 1802.00786

Mandal &Pich, 1908.11155

Flavor puzzle

All properties are the same but masses are different!

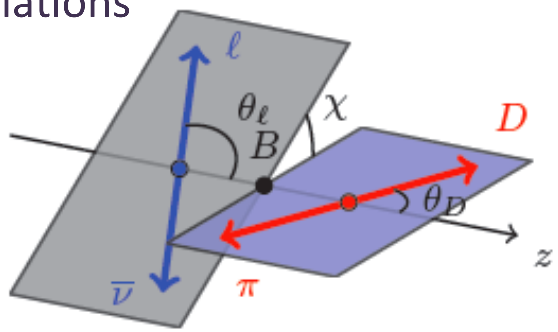


Constructing new UV complete theories based on B anomalies explanation might help in understanding SM quarks and leptons Yukawa couplings.

Barbieri et al. 1512.01560,

Outlook

- We have to wait on Belle 2 & LHCb new results on $R_{D(*)}$ and $R_{K(*)}$, also Fermilab and J-PARC on $(g-2)_\mu$;
- Complete Lattice QCD calculation of B ⟶ D* form factors and Bc ⟶ J/ψ;
- To measure all possible observables in angular correlations in b ⟶ c τυ and in b ⟶ s μμ;



- To measure b ⟶ s ττ
- b ⟶ c τ ν in baryon systems, sum rule:
  Blanke et al,1811.09603

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

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

$$\boxed{\begin{array}{lll} B \to K^{(*)}\nu\bar{\nu} & \tau \to \mu\gamma & B \to K^{(*)}\tau\mu \\ K \to \pi\nu\bar{\nu} & \tau \to 3\mu & B \to \tau\mu \end{array}}$$

- 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!

Models at TeV scale explaining both B anomalies

Scalar LQ as pseudo-Nambu-Goldstone boson

Gripaios et al, 1010.3962,
Gripaios et al., 1412.1791,
Marzocca 1803.10972

Models with scalar LQs

Hiller & Schmaltz, 1408.1627,
Becirevic et al. 1608.08501, SF and Kosnik, 1511.06024, Becirevic et al., 1503.09024,
Dorsner et al, 1706.07779,
Cox et al., 1612.03923,
Crivellin et al.,1703.09226,
Becirevic et al.,1808.08 179,
Heeck&Teresi, 1808.07492,
Luzio et al., 1808.00942,…
…

W', Z' in warped space

Megias et al.,1707.08014

Vector resonances (from techni-fermions)

Barbieri et al.,1506.09201, Buttazzo et al. 1604.03940,
Barbieri et al., 1611.04930
Blanke & Crivellin, 1801.07256,…

Gauge bosons

Greljo et al., 1804.04642
Cline, Camalich, 1706.08510
Calibbi et al.,1709.00692
Assad et al., 1708.06350
Di Luzio et al.,1708.08450
Bordone et al.,1712.01368, 1805.09328
Heeck&Teresi, 1808.07492, ….

Additional slides

References for NP in $R_{D(*)}$:

A.Greljo et al, 1804.04642,
S.F. , J.F.Kamenik, Nišandžić, 1203.2654
S.F. J.F. Kamenik, I. Nišandžić, J. Zupan, 1206.1872
Körner& Schuller, ZPC 38 (1988) 511,
Kosnik, Becirevic, Tayduganov, 1206.4977
D. Becirevic, S.F. I. Nisandzic, A. Tayduganov,
1602.03030, Fretsis et al, 1506.08896,
S. Faller et al., 1105.3679,
Sakai&Tanaka, 1205.4908.
Biancofiore , Collangelo,
DeFazio 1302.1042,
R.Alonso et al, 1602.0767,Bardhan et al., 1610.03038

Di Luzio Nardecchia, 1706.0!868,
Crivellin etal, 1703.09226,
Blanke&Crivellin,1801.07256,
Biswas et al, 1801.03375,
Freytsis et al, 150608896,
Sakaki et al, 1309.0301,
Celis et al, 1612.07757,
Altmannshofer et al, 170406659

. Baryonic modes $\mathcal{R}(\Lambda_c) \equiv \frac{\mathrm{BR}(\Lambda_b \to \Lambda_c \tau \nu_\tau)}{\mathrm{BR}(\Lambda_b \to \Lambda_c \ell \nu_\ell)}$?

Nierste sum rule, unique test based on analytic inspection of $R_{D(*)}$

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

For any model of NP current data lead to

Current data:

$$\mathcal{R}(\Lambda_c) = \mathcal{R}_{\rm SM}(\Lambda_c)\,(1.14 \pm 0.06)$$
$$= 0.38 \pm 0.02_{\rm exp} \pm 0.02_{\rm th}$$

Proposals for $R_{K(*)}$

- different origin of Z', e.g. by gauging L_μ- L_τ , Altmannshofer et al, 1403.1269,
- New Z'+ new vector-like quarks (UV complete theories) Kamenik et al., 1704.06005,
- Fermiophobic Z', couples to 4th generation of the vector-like fermions, Falkowski et al, 1803.04430, Allanach et al, 1904.10954, ...

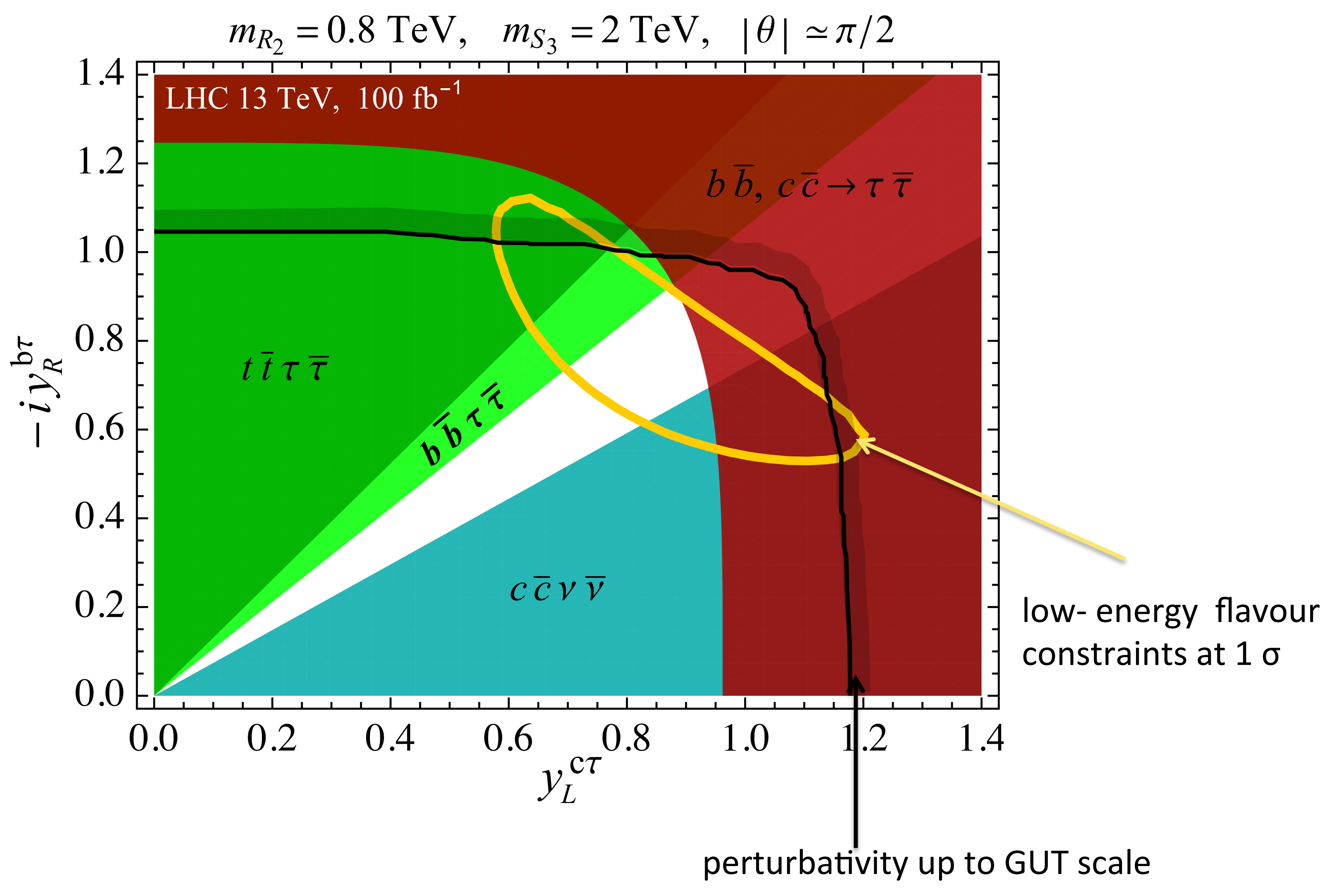
Pati Salam

Di Luzio et al.,1708.08450
Calibbi et al., 1709.00692
Blanke and Crivellin, 1801.07256.

Bordone et al., 1712.01368, 1805.0932

U_1

(see also Alonso et al., 1505.05164,
Di Luzio et al., 1708.08450;
Bordone et al., 1712.01368;
Callibi et al., 1709.00692,
Crivellin et al., 1807.02068,
Cornella et al, 1903.11517,
Azatov et al, 1807.10745....)



$m_{R_2} = 0.8$ TeV, $m_{S_3} = 2$ TeV, $|\theta| \simeq \pi/2$
LHC 13 TeV, 100 fb^{-1}
$b\,\bar{b},\, c\,\bar{c} \to \tau\,\bar{\tau}$
$t\,\bar{t}\,\tau\,\bar{\tau}$
$b\,\bar{b}\,\tau\,\bar{\tau}$
$c\,\bar{c}\,\nu\,\bar{\nu}$
$-i\,y_R^{b\tau}$
$y_L^{c\tau}$
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
low- energy flavour constraints at 1 σ
perturbativity up to GUT scale