Is the muon just a heavy electron?

01/10/20

HET Lunch Talk

An update on LFUV

outline

- **This is mostly a progress report supplemented with some interesting developments of past some months**
- **+ Some implications for the HEF and for the IF**

Anomalies galore!

- RD(*) ~4σ(?) ; ALSO Rψ ~2σ LHCb
- RK(*): 2.6σ(RK) ; 2.2 & 2.5σ RK* => ~3.5σ
- g -2…BNL =>FNAL expt… ~3.6σ major lattice progress
- Ɛ': a personal obsession….for a long^3 time=>'cause of the strong belief that it is super-sensitive to NP

216[PRL 2015] => ~1400 of which ~740 g c analyzed

[2.1σ => ??] …..few more months to new results

- **Notice in each case, because of the omnipresence of non-perturbative effects, lattice methods provide crucial info for experiments to be able to use the data in the most economical manner**

Why lattice is needed?

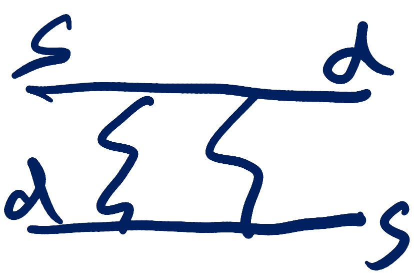
expt measurement $\sim f[G_F, m_t \ldots, V_{ckm} \sum C_i \langle O_i \rangle]$

$(2.232 \pm .007) \times 10^{-3}$

BNL '64 Nobel P

Nonpert ME

$$|\varepsilon_K| = \frac{G_F^2 m_W^2 f_K^2 m_K}{12\sqrt{2}\pi^2 \Delta m_K^{\rm exp}} \hat{B}_K \kappa_\varepsilon \, {\rm Im}\Big(\eta_1 S_0(x_c)\left(V_{cs}V_{cd}^*\right)^2 + 2\eta_3 S_0(x_c, x_t) V_{cs}V_{cd}^* V_{ts}V_{td}^* + \eta_2 S_0(x_t)\left(V_{ts}V_{td}^*\right)^2\Big). \quad (2.3)$$



$\langle K | (\bar{s}\gamma_\mu{}_L d)^2 | \bar{K} \rangle$

MUST HAVE THIS TO ALL orders in α_s

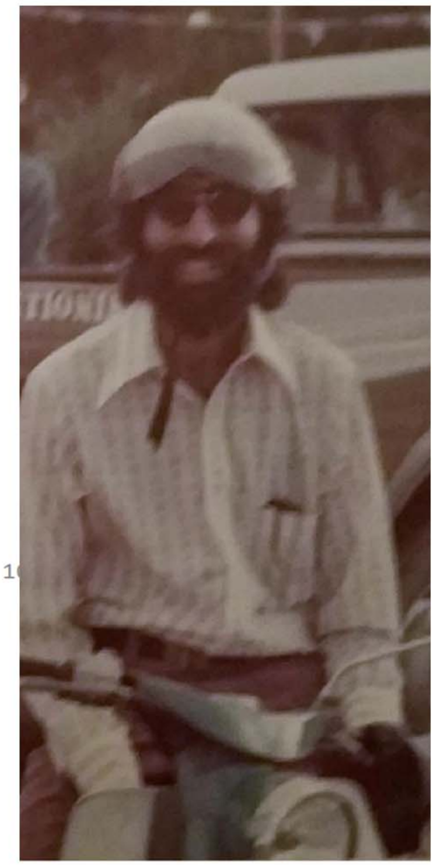
A.S. in Proceedings of Lattice '85 (FSU)..1st Lattice meeting ever attended

The matrix elements of some penguin operators control in the standard model another CP violation parameter, namely ϵ'/ϵ.[6,8) Indeed efforts are now underway for an improved measurement of this important parameter.[10) In the absence of a reliable calculation for these parameters, the experimental measurements, often achieved at tremendous effort, cannot be used effectively for constraining the theory. It is therefore clearly important to see how far one can go with MC techniques in alleviating this old but very difficult

With C. Bernard [UCLA]

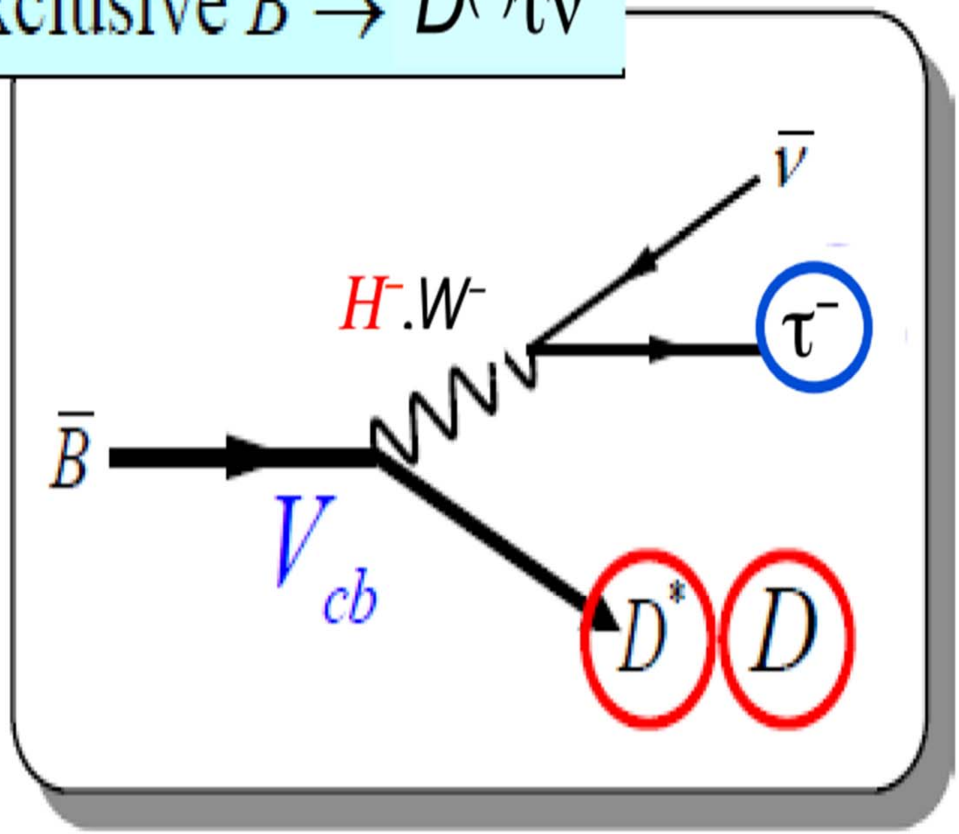
Theo Summary; 16th FPCP; A Soni

$\epsilon' \sim 10^{-6}$



[SEEMINGLY] BEST CHANCE IN A LONG TIME FOR POSSIBLE SIGHTINGS OF NEW PHYSICS

Exclusive $B \to D^{(*)}\tau\nu$



RA LUTH (BABAR)
CP May 2012
(HEFEI, China)

MANUEL FRANCO
SEVILLA
PhD Thesis

Independent of Vcb!

- To test the SM Prediction, we measure

$$R(D) = \frac{\Gamma(\bar{B} \to D\tau\nu)}{\Gamma(\bar{B} \to D\ell\nu)} \qquad R(D^*) = \frac{\Gamma(\bar{B} \to D^*\tau\nu)}{\Gamma(\bar{B} \to D^*\ell\nu)}$$

Leptonic τ decays only

Several experimental and theoretical uncertainties cancel in the ratio!

- BB events are fully reconstructed:

Some expt-al & also some Theory errors tend to cancel

$\ell = \mu$ or e

PHYSICAL REVIEW D VOLUME 56, NUMBER 9 1 NOVEMBER 1997

Improving constraints on $\tan\beta/m_H$ using $B \to D\tau\bar{\nu}$

Ken Kiers* and Amarjit Soni†
Department of Physics, Brookhaven National Laboratory, Upton, New York 11973-5000

(Received 12 June 1997)

We study the q^2 dependence of the exclusive decay mode $B \to D\tau\bar{\nu}$ in type-II two Higgs doublet models (2HDM's) and show that this mode may be used to put stringent bounds on $\tan\beta/m_H$. There are currently rather large theoretical uncertainties in the q^2 distribution, but these may be significantly reduced by future measurements of the analogous distribution for $B \to D(e,\mu)\bar{\nu}$. We estimate that this reduction in the theoretical uncertainties would eventually (i.e., with sufficient data) allow one to push the upper bound on $\tan\beta/m_H$ down to about 0.06 GeV^{-1}. This would represent an improvement on the current bound by about a factor of 7. We

FF

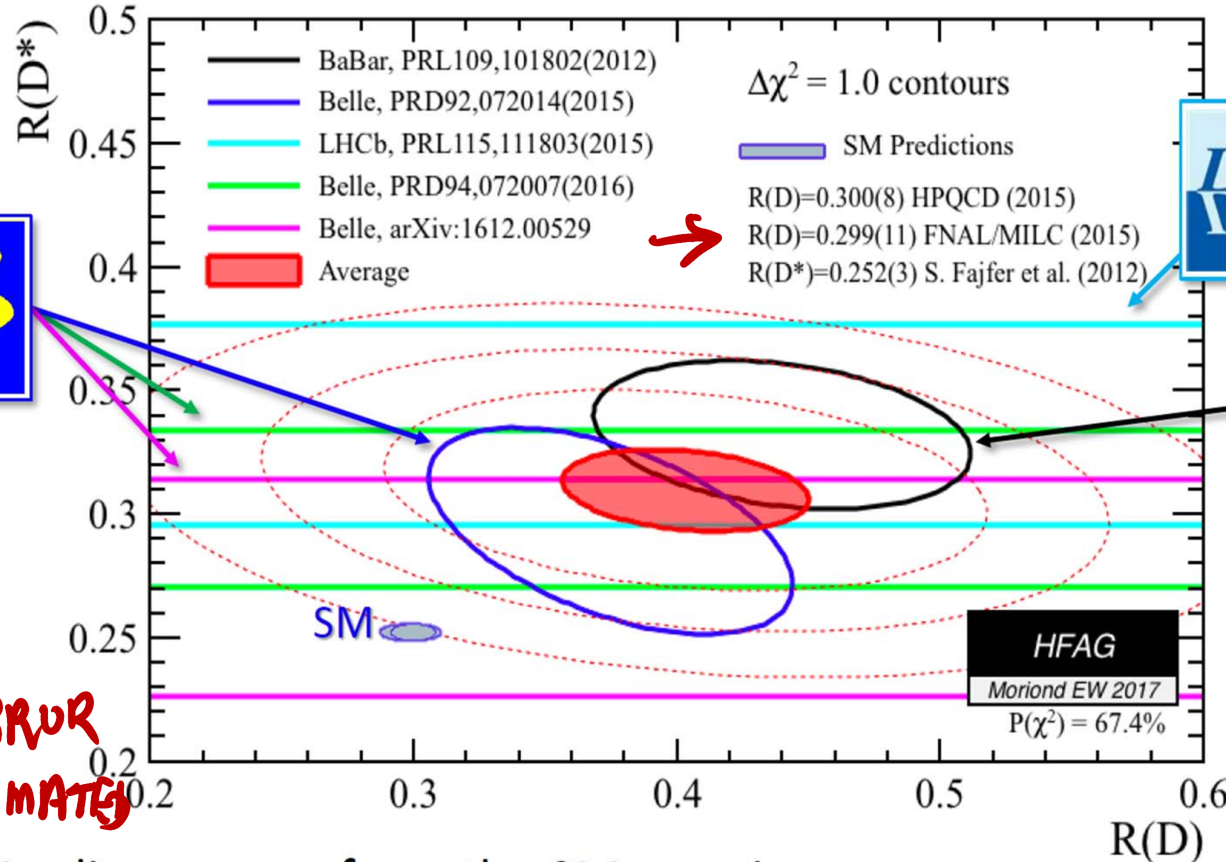
f_1 f_0

used HQS

⇒ Followed up by Nierste et al '08; Fajfer et al '12

■ $R(D^{(*)})$ by HFAG

Hirose [BELLE]@EW MORIOND Mar. 2017



THEORY ERROR UNDERESTIMATED ESP R_{D^*}

- ~4σ discrepancy from the SM remains
  - All the experiments show the larger $R(D^{(*)})$ than the SM
- More precise measurements at Belle II and LHCb are essential

Belle deviations quite mild

Semileptonic B decays

BaBar measured an excess of $B^0 \to D^{(*)}\tau^- \nu_\tau$ (**3σ away from SM!**) [PRD 88 (2013) 072012] [Nature 546 (2017) 227]

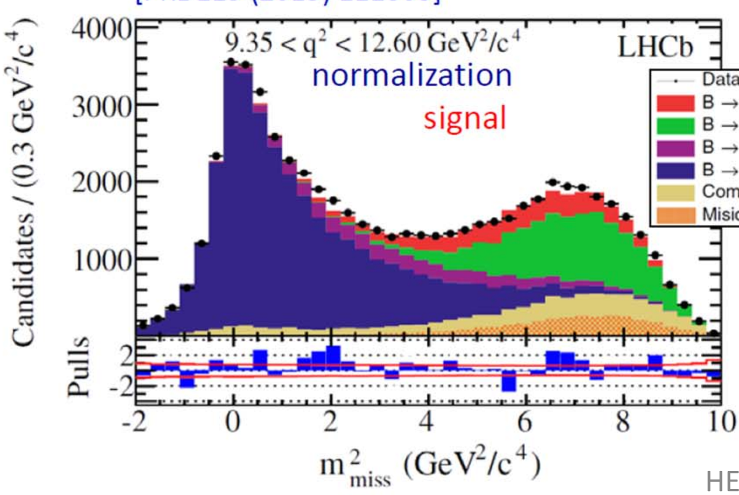
LHCb:

- R(D*)
  - $\overline{B}^0 \to D^{*+} \tau^- \overline{\nu}_\tau$, with $\tau^- \to \mu^- \overline{\nu}_\mu \nu_\tau$ [PRL 115 (2015) 111803]
  - $B^0 \to D^{*-} \tau^+ \nu$, with $\tau^+ \to \pi^+\pi^-\pi^+(\pi^0)\overline{\nu}_\tau$ [PRL 120 (2018) 171802]
- R(J/ψ)
  - $B^+_c \to J/\psi\, \tau^+ \nu$, with with $\tau^- \to \mu^- \overline{\nu}_\mu \nu_\tau$ [PRL 120 (2018) 121801]

- Using $\tau^- \to \mu^- \overline{\nu}_\mu \nu_\tau$

Information from the missing mass squared $m_{miss}^2 = (P_B - P_{D*} - P_\mu)^2$ and muon energy

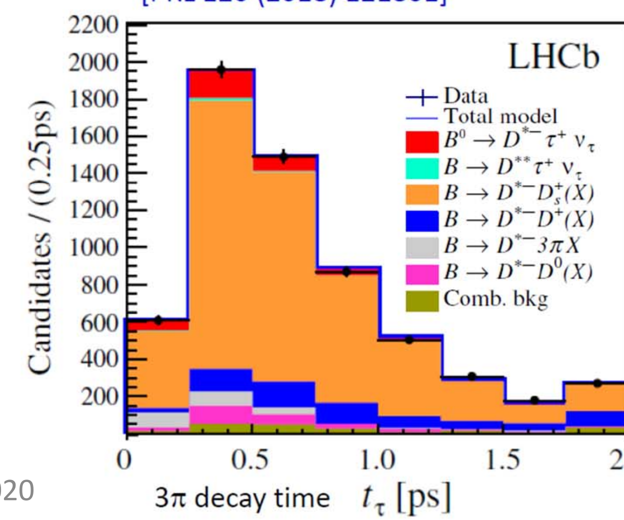
[PRL 115 (2015) 111803]



- Using $\tau^+ \to \pi^+\pi^-\pi^+\overline{\nu}_\tau$

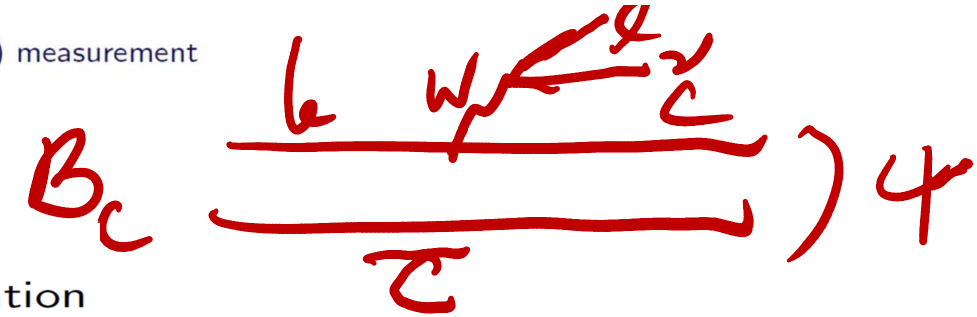
Information from the position of the pions. Normalized to $B^0 \to D^{*-}\pi^+\pi^-\pi^+$

[PRL 120 (2018) 121801]

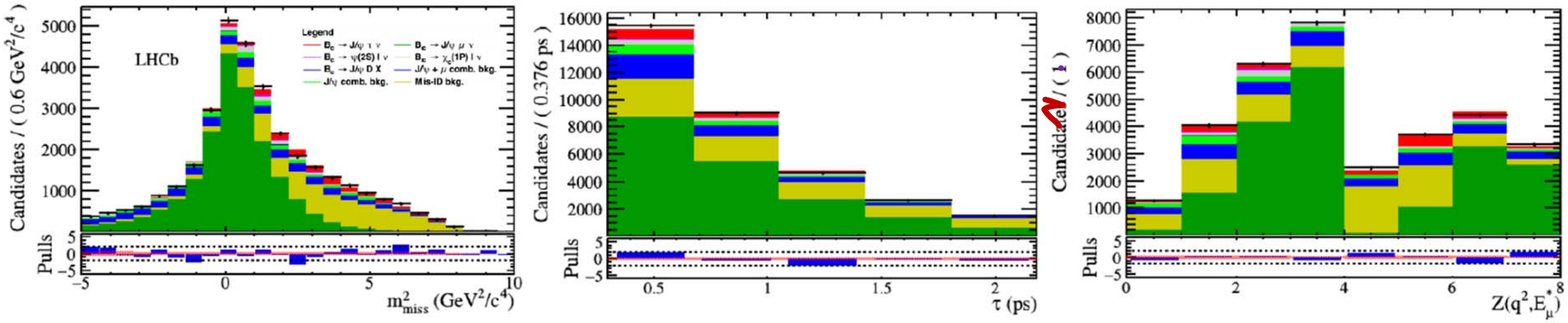


$B_c \to J/\psi \tau \nu$

2PW Jan 2018



Greg Ciezarek,
on behalf of the LHCb collaboration



- $R_{J/\psi} \equiv B_c \to J/\psi \tau\nu / B_c \to J/\psi \mu\nu$ c ALSO MARK SMITH eFFeP 2018
- Measured using very similar techniques to $\mathcal{R}(D^*)$, on run 1 data
- $R_{J/\psi} = 0.71 \pm 0.17 \pm 0.18$ REMAINING ISSUES
  - $\sim 2\sigma$ from SM
  - But nearly as far from consistency with $\mathcal{R}(D^*)$ PRIMARILY EXPTAL
- LHCb-PAPER-2017-035(Run 1 data) 1. Stat 2. D^{**} 3. $\tau \to$ had $+ 2\nu$

SM $R_\psi \sim .265 \pm .025$
QUITE ROBUST!
ESSENTIALLY A NR Bound State

Bc => psi tau(l) nu…Th/ph

PHYSICAL REVIEW D **98,** 094026 (2018)

Model-independent determination of $B_c^+ \to \eta_c \ell^+ \nu$ form factors

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(Received 31 August 2018; published 27 November 2018)

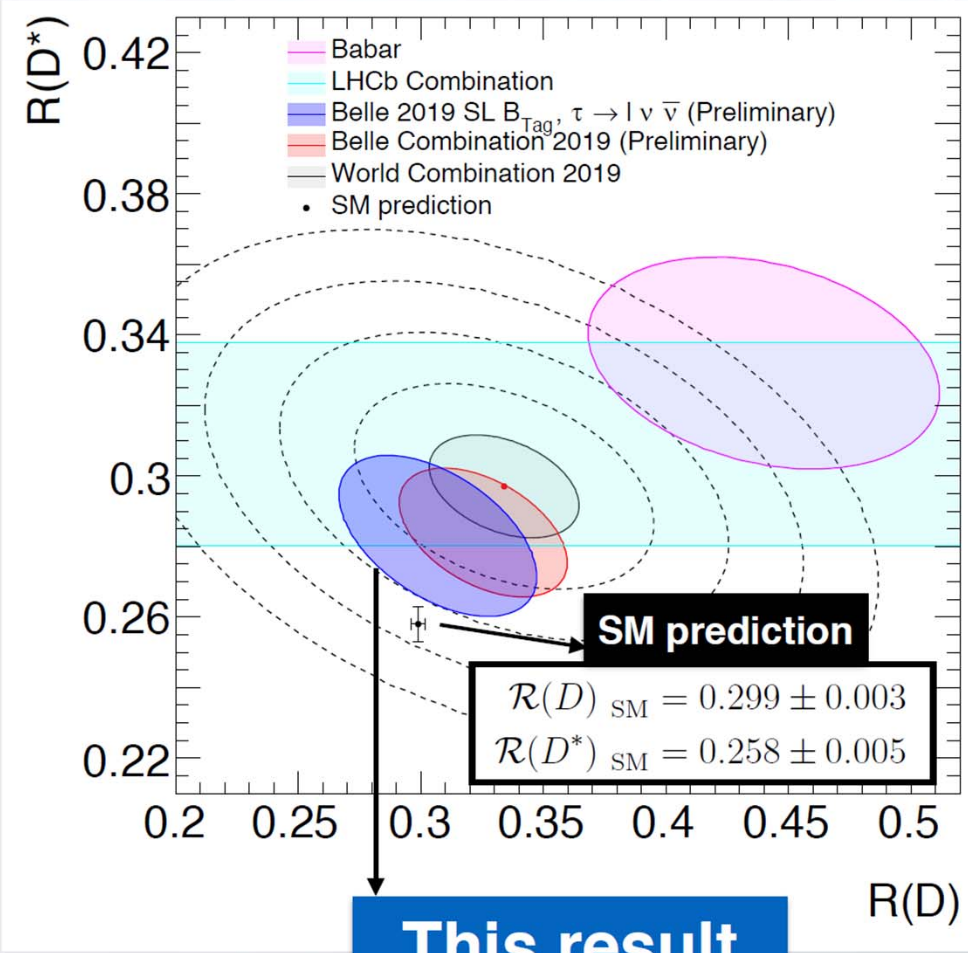
We derive model-independent bounds on the form factors for the decay $B_c^+ \to \eta_c \ell^+ \nu$ including full mass effects, i.e., $\ell = e, \mu$, and τ. The bounds are obtained by using the Boyd-Grinstein-Lebed parametrization for the form factors, and fitting to the preliminary lattice data of the HPQCD Collaboration. Our main result after bounding the form factors is the Standard Model prediction for the ratio of branching fractions $R(\eta_c) = \mathcal{B}(B_c^+ \to \eta_c \tau^+ \nu_\tau)/\mathcal{B}(B_c^+ \to \eta_c \mu^+ \nu_\mu)$. We find $R(\eta_c)|_{\mathrm{SM}} = 0.31^{+0.04}_{-0.02}$, and argue that a measurement of $R(\eta_c)$ is within the reach of LHCb during the high-luminosity run of the LHC. In addition, using the heavy-quark spin symmetry of the B_c meson we relate our results for $B_c^+ \to \eta_c \ell^+ \nu$ to those for $B_c^+ \to J/\psi \ell^+ \nu$ yielding the estimate $R(J/\psi)|_{\mathrm{SM}} = 0.26 \pm 0.02$ in good agreement with other determinations.

R_ψ	Ref
.26±.02	Murphy + AS
.29±.07	Ivanov + Issadykov PLB'18
.283±.048	Watanabe PLB'18

c also Berns + Lamm JHEP'18

Conclusion / Preliminary $R(D^{(*)})$ averages

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

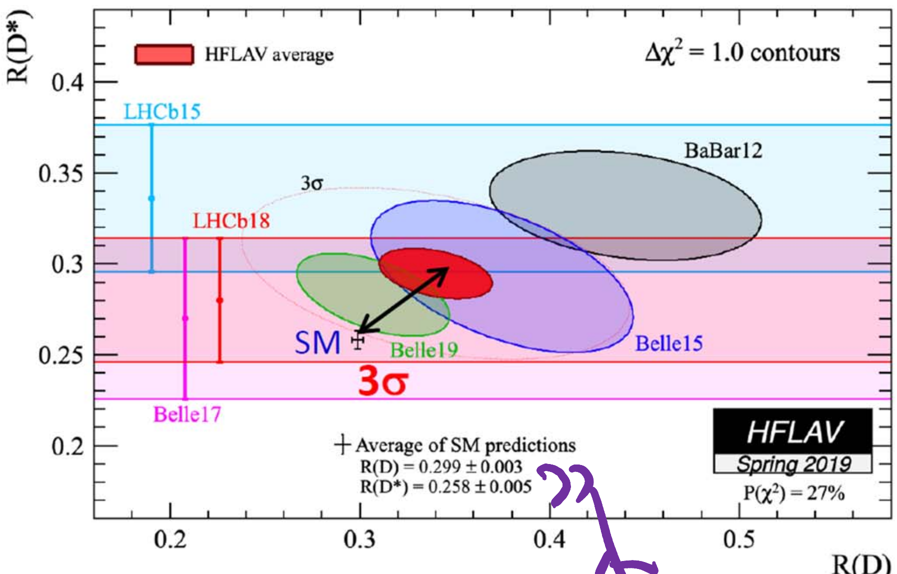


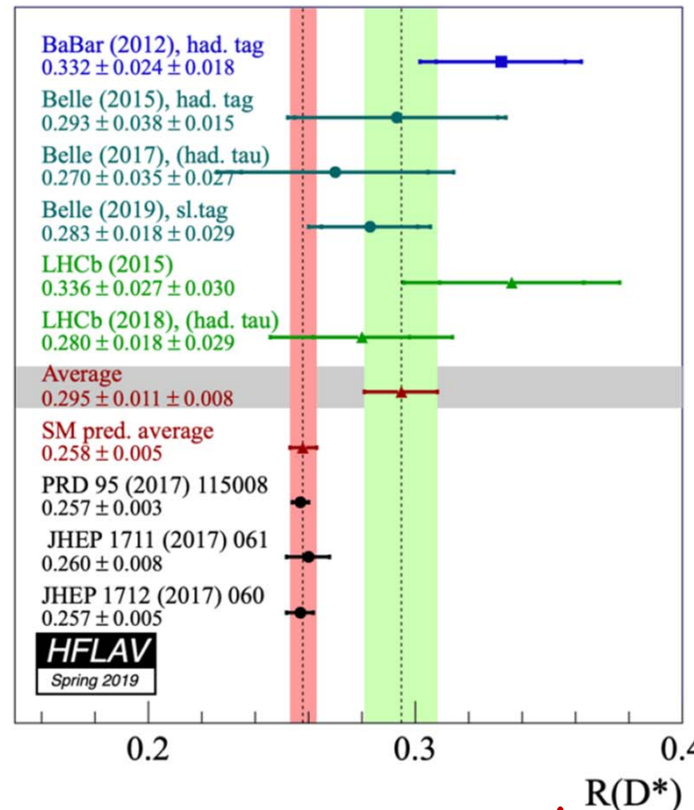
$$\mathcal{R}(D) = 0.307 \pm 0.037 \pm 0.016$$
$$\mathcal{R}(D^*) = 0.283 \pm 0.018 \pm 0.014$$

Semileptonic B decays

New results (Moriond 2019) from Belle:

- Global picture of R_D and R_{D*}





6 R_{D^*} measurements

→ New results from Belle: **4σ →3σ** deviation from SM

R_D: 3 Babar, + Belle

B→D* Form factors from Lattice still cooking

The bottom line

Therefore, it is an excellent approximation to combine the LHCb and B factory results as done in section II. In that case we find

$$\frac{R_D}{R_D^{\rm SM}} = \frac{R_{D^*}}{R_{D^*}^{\rm SM}} = 1.15 \pm 0.04 \,, \qquad (24)$$

both for the LHCb and the B-factory expressions in Eqs. (21,22).

FACT OR FARCE?

11 exptal results [not all independent]; ALL central values above theory!

4

experiment	tag method	τ decay mode	R_D	$R_D^\star$	R_ψ
Babar (2012)[1]	hadronic	$l\ \nu\nu$	$0.440 \pm 0.058 \pm 0.042$	$0.332 \pm 0.024 \pm 0.0.018$	
Belle (2015)[2]	hadronic	$l\ \nu\nu$	$0.375 \pm 0.064 \pm 0.026$	$0.293 \pm 0.038 \pm 0.015$	
LHCb (2015)[5]	hadronic	$l\ \nu\nu$	-	$0.336 \pm 0.027 \pm 0.030$	
Belle (2016)[2]	semileptonic	$l\ \nu\nu$	-	$0.302 \pm 0.030 \pm 0.011$	
Belle (2017)[4]	hadronic	$\pi(\rho)\nu$	-	$0.270 \pm 0.035 \pm 0.027$	
LHCb (2017)[6]	hadronic	$3\pi\nu$	-	$0.291 \pm 0.019 \pm 0.029$	
Belle (2019)[7]	semileptonic	$l\ \nu\nu$	$0.307 \pm 0.037 \pm 0.016$	$0.283 \pm 0.018 \pm 0.014$	
LHCb(2016) [9]	hadronic	$l\ \nu\nu$	-	-	$0.71 \pm 0.17 \pm 0.18$
SM	-	-	0.299 ± 0.011	0.260 ± 0.008	0.26 ± 0.02

TABLE I: All experimental results announced to date on R_D, R_{D^*} and on R_ψ versus the predictions of those for the SM

ALTMANNSHOFER, DEV+AS, Yicong Sui (in prep)

excellent g.s

RECAP

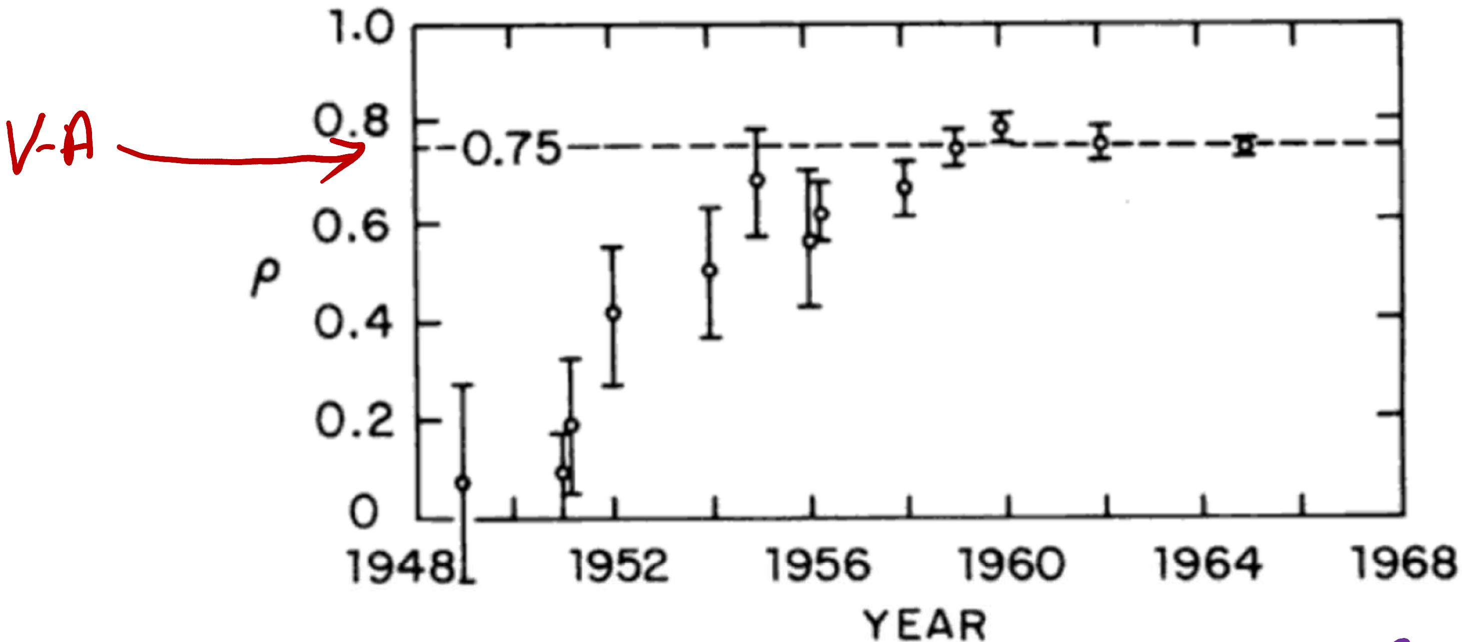
- **3 different major B-experiments**
- **3 with B => D**
- **7 with B=> D***
- **1 with Bc => ψ**
- **9 with tau => l (l=μ or e) nu nu'**
- **2 with tau => hadron + nu**

- **Each and everyone of the 11 experimental results seem to imply tau is NOT just a heavy muon(electron) as dictated by SM.**

PAUSE

CAN THERE BE SOME EXPERIMENTAL ISSUE(S) CAUSING THIS DEVIATION?

Imp. Historical ~~Aside~~ CAUTION



From M Purohit

Figure 16. The change of the Michel parameter ρ from year to year.

From T. D. Lee's text

Cs Wu & T.D.Lee defn of rho

20200108_095440.jpg

$$i\psi_l^\dagger\gamma_4\gamma_\lambda(C_V - C_A\gamma_5)\psi_{\nu_l} = (C_V - C_A)i\psi_l^\dagger\gamma_4\gamma_\lambda\psi_{\nu_l}$$
$$= (C_V - C_A)i\psi_l^\dagger\gamma_4\gamma_\lambda\gamma_5\psi_{\nu_l}$$

Insofar as μ decay is concerned, there is no difference between a $(V-A$
interaction and a, say, $(V+10A)$ interaction, provided the two-componen
theory holds for both ν_e and ν_μ. At present, all experimental evidences in μ d
cay are in excellent agreement with the above form of $(V-A)$ interactio

1. *The electron spectrum and the Michel parameter.*—The decay electr
momentum spectrum from μ decay is

$$N(x) = x^2\left\{\left(2 - \frac{4}{3}\rho\right) - \left(2 - \frac{16}{9}\rho\right)x\right\}$$

where

$$x = \frac{|p_e|}{m_\mu/2}$$

The constant ρ is called the Michel parameter. If the conservation lav
leptonic numbers L_e and L_μ hold and if the two-component theory is
for both ν_e and ν_μ, then [independent of whether the μ-decay intera
consists of (V, A) or (S, P) couplings]

$$\rho = 3/4$$

Flag 2019: sample [Nf=2 +1]

- BK^hat = 0.7625(97) ….1.5%
- fB= 192.0 (4.3) MeV…….2.2 %
- \xi = 1.206 (17)…………1.5% → SU(3) breaking
- B=>D, δ[sl FF (q^2)] ~ 10%
- RD ~ 4%
- B=>D* [incomp]

Need lot more wakesp due expts on the horizon

PROCEEDINGS OF SCIENCE

Semileptonic $B \to \pi\ell\nu$, $B \to D\ell\nu$, $B_s \to K\ell\nu$, and $B_s \to D_s\ell\nu$ decays

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CP3-Origins and IMADA, University of Southern Denmark, Campusvej 55, 5230 Odense M, Denmark

Oliver Witzel*
Department of Physics, University of Colorado Boulder, Boulder, CO 80303, USA
E-mail: Oliver.Witzel@colorado.edu

We present updates for our nonperturbative lattice QCD calculations to determine semileptonic form factors for exclusive $B \to \pi\ell\nu$, $B \to D\ell\nu$, $B_s \to K\ell\nu$, and $B_s \to D_s\ell\nu$ decays. Our calculation is based on RBC-UKQCD's set of 2+1-dynamical-flavor gauge field ensembles. In the valence sector we use domain wall fermions for up/down, strange and charm quarks, whereas bottom quarks are simulated with the relativistic heavy quark action. The continuum limit is based on three lattice spacings. Using kinematical z expansions we aim to obtain form factors over the full q^2 range. These form factors are the basis for predicting ratios addressing lepton flavor universality or, when combined with experimental results, to obtain CKM matrix elements $|V_{ub}|$ and $|V_{cb}|$.

9.5

months away from completion

	$L^3 \times T$	a^{-1} / GeV	am_l	M_π / MeV	# Configurations	# Time Sources
C1	$24^3 \times 64$	1.784	0.005	338	1636	1
C2	$24^3 \times 64$	1.784	0.010	434	1419	1
M1	$32^3 \times 64$	2.383	0.004	301	628	2
M2	$32^3 \times 64$	2.383	0.006	362	889	2
M3	$32^3 \times 64$	2.383	0.008	411	544	2
F1	$48^3 \times 96$	2.774	0.002144	234	98	24

Table 1: The RBC-UKQCD 2+1 domain-wall fermion ensembles used in this work [50 – 53]. The F ensemble is a new element of the RBC/UKQCD *b*-physics project analysis and is a key difference betwee this work and the prior analysis. Presently the properties of the F1 ensemble are re-evaluated and may chang slightly.

M_π, M_K physical not yet complete

PoS PROCEEDINGS OF SCIENCE

Radiative leptonic decays on the lattice

Christopher Kane[a], Christoph Lehner[b,c], Stefan Meinel[*a,d], Amarjit Soni[c]

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[b] Department of Physics, University of Regensburg, 93040 Regensburg, Germany
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E-mail: smeinel@email.arizona.edu

Adding a hard photon to the final state of a leptonic pseudoscalar-meson decay lifts the helicity suppression and can provide sensitivity to a larger set of operators in the weak effective Hamiltonian. Furthermore, radiative leptonic B decays at high photon energy are well suited to constrain the first inverse moment of the B-meson light-cone distribution amplitude, an important parameter in the theory of nonleptonic B decays. We demonstrate that the calculation of radiative leptonic decays is possible using Euclidean lattice QCD, and present preliminary numerical results for $D_s^+ \to \ell^+ \nu\gamma$ and $K^- \to \ell^- \bar{\nu}\gamma$.

$\frac{Br(B \to \mu\nu\gamma_{hard})}{Br(B \to \mu\nu)} \sim 12$

Atwood, Eilam, A S '94

g.s excellent

↑ hard "γ" evades helicity supp

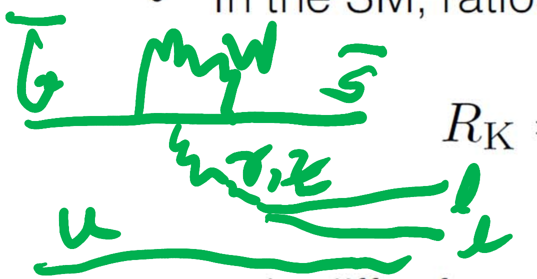
non-local ME

Well effort: our Roman friends: G.M. et al

Lepton universality tests

LHCb introduced such v well defined ratios

- In the SM, ratios



$$R_K = \frac{\int \mathrm{d}\Gamma[B^+ \to K^+\mu^+\mu^-]/\mathrm{d}q^2 \cdot \mathrm{d}q^2}{\int \mathrm{d}\Gamma[B^+ \to K^+e^+e^-]/\mathrm{d}q^2 \cdot \mathrm{d}q^2}$$

only differ from unity by phase space — the dominant SM processes couple equally to the different lepton flavours.

- Theoretically clean since hadronic uncertainties cancel in the ratio.
- Experimentally challenging due to differences in muon/electron reconstruction (in particular Bremsstrahlung from the electrons).
  - ➡ Take double ratios with $B \to J/\psi X$ decays to cancel possible sources of systematic uncertainty.
  - ➡ Correct for migration of events in q^2 due to FSR/Bremsstrahlung using MC (with PHOTOS).

LHCb

Lepton Flavour Universality

Arantza Oyanguren

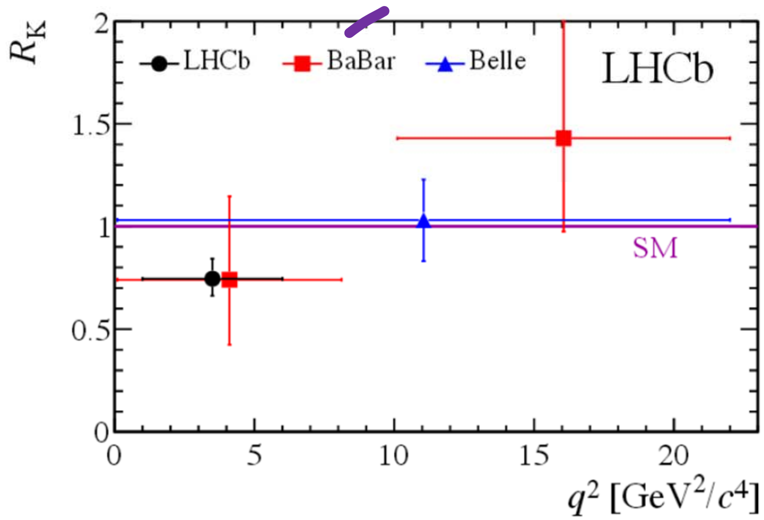
- In the SM all leptons are expected to behave in the sa

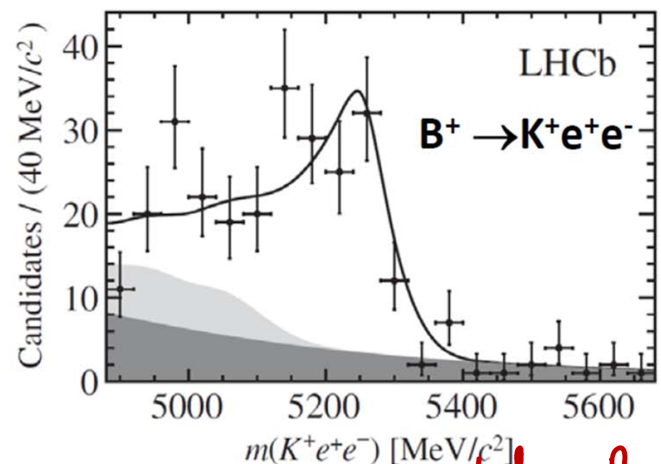
$$R_K = \frac{\mathcal{B}(B^+ \to K^+\mu^+\mu^-)}{\mathcal{B}(B^+ \to K^+e^+e^-)}$$ = 1.000 + $O(m_\mu^2/m_b^2)$ (SM)

[PRL 113 (2014) 151601]

- Experimentally, use the $B^+ \to K^+ J/\psi(\to e^+e^-)$ and $B^+ \to K^+ J/\psi(\to \mu^+\mu^-)$ to perform a double ratio

- Precise theory prediction due to cancellation of hadronic form factor uncertainties





1 GeV < q^2 < 6 GeV ← should be safe from Rad corr

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

→ Consistent, but lower, than the SM at **2.6σ**

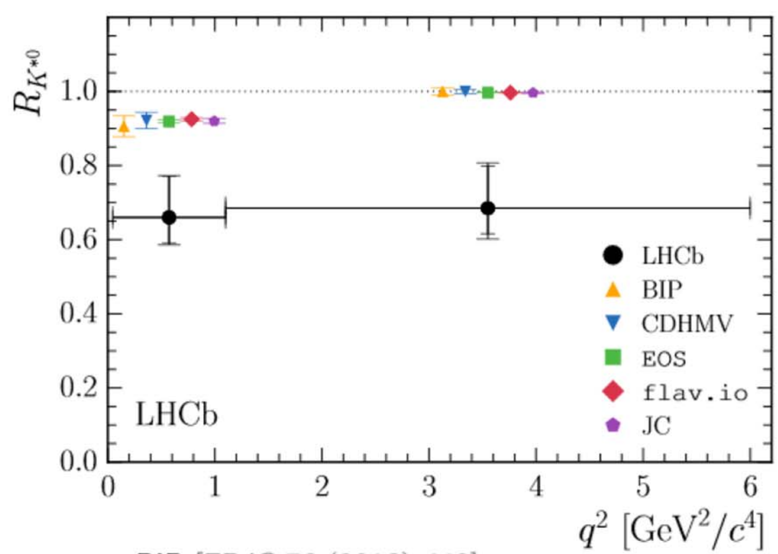
Arantza Oyanguren

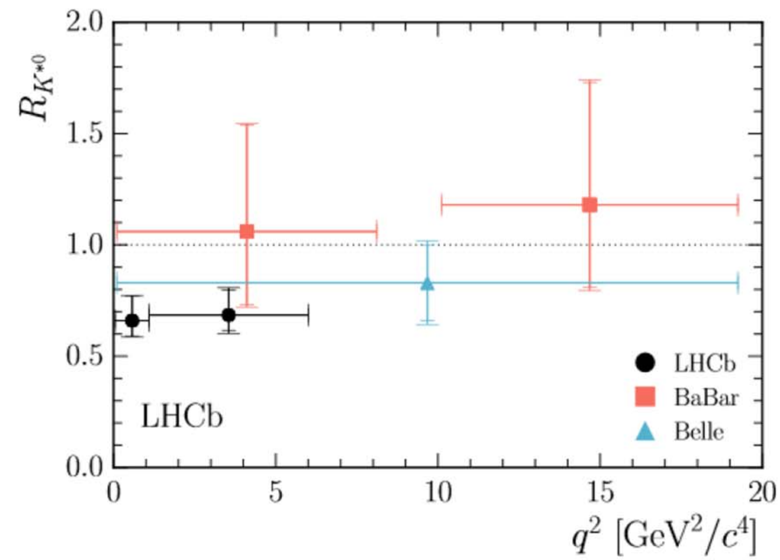
Lepton Flavour Universality

LHCb

- Results:

LHCb, JHEP08(2017)055





- BIP [EPJC 76 (2016) 440]
- CDHMV [JHEP 04 (2017) 016]
- EOS [PRD 95 (2017) 035029]
- flav.io [EPJC 77 (2017) 377]
- JC [PRD 93 (2016) 014028]

- LHCb [PRL 113 (2014) 151601]
- Belle [PRL 103 (2009) 171801]
- BaBar [PRD 86 (2012) 032012]

$\lesssim 3.4\sigma$

Low q² [0.045-1.1 GeV²]: SM = 0.922(22)

$$R_{K^{*0}} = 0.66 \,^{+\,0.11}_{-\,0.07}\,(\text{stat}) \pm 0.03\,(\text{syst})$$

Central q²: [1.1-6 GeV²]: SM = 1.000(6)

$$R_{K^{*0}} = 0.69 \,^{+\,0.11}_{-\,0.07}\,(\text{stat}) \pm 0.05\,(\text{syst})$$

→ Consistent, but lower than the SM at **2.1-2.3σ** (low q²) and **2.4-2.5σ** (central q²)

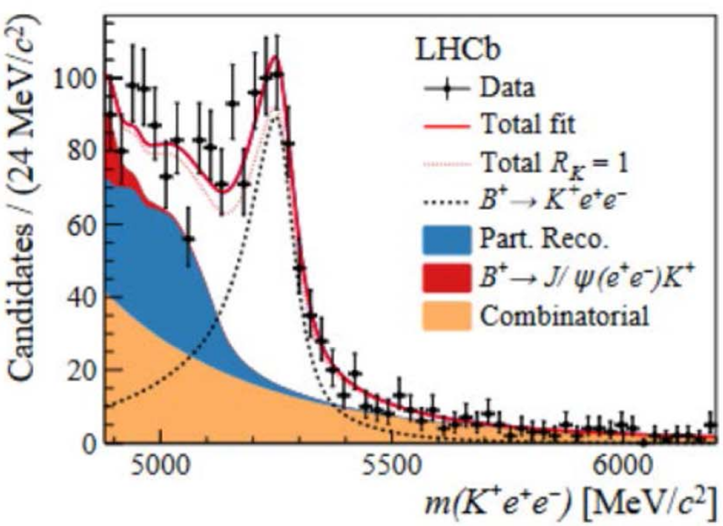
Rare B decays: R_K

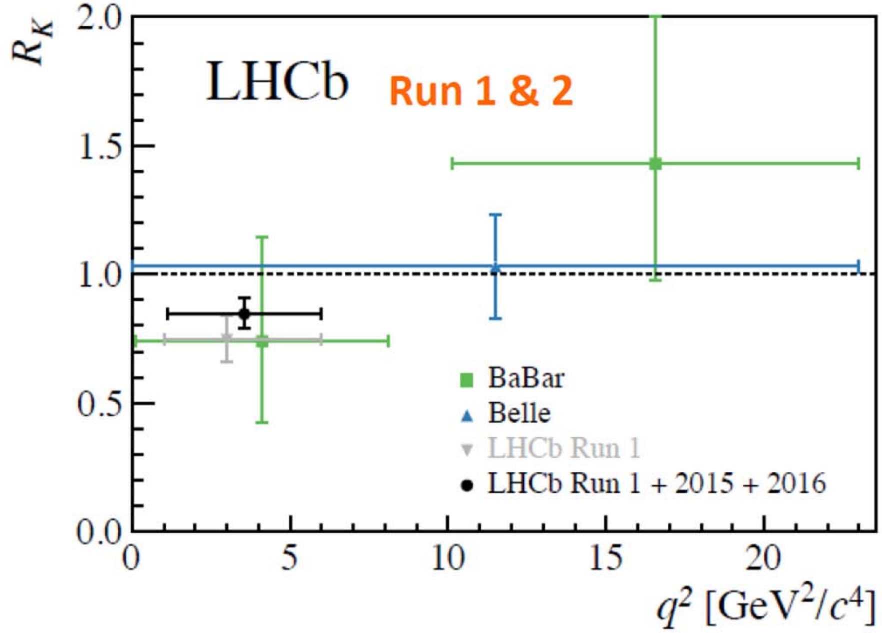
New results (Moriond 2019):

Including partial sample of Run2 (2fb^{-1})

[LHCb, *PRL* 122 (2019) 191801]

With improved reconstruction and re-optimized analysed strategy





1.1 GeV < q^2 < 6 GeV

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

→ Still consistent, lower, than the SM at **2.5σ**

Not confirmed, not ruled out…

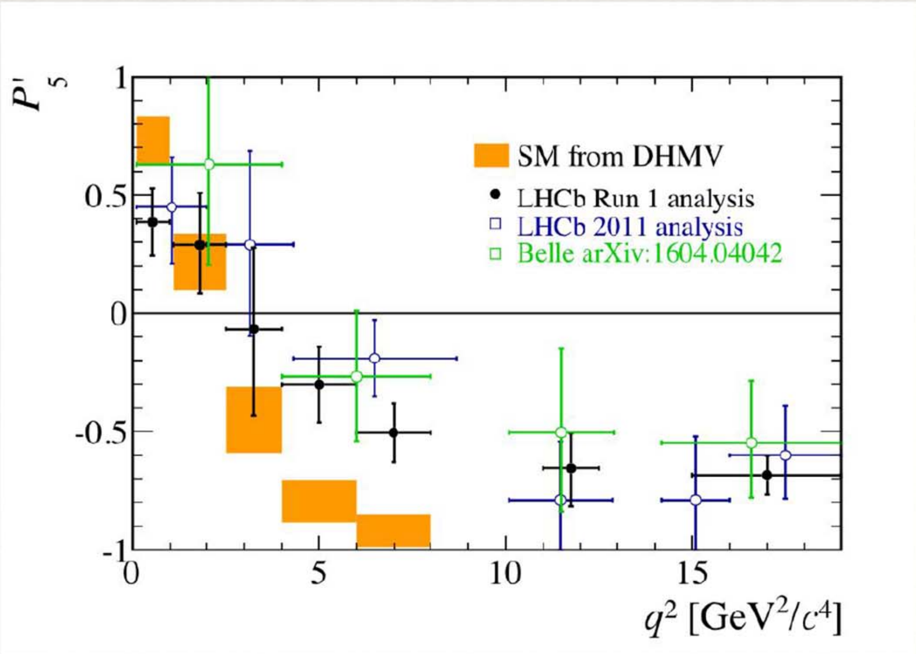
B-flavor anomalies: P_5'

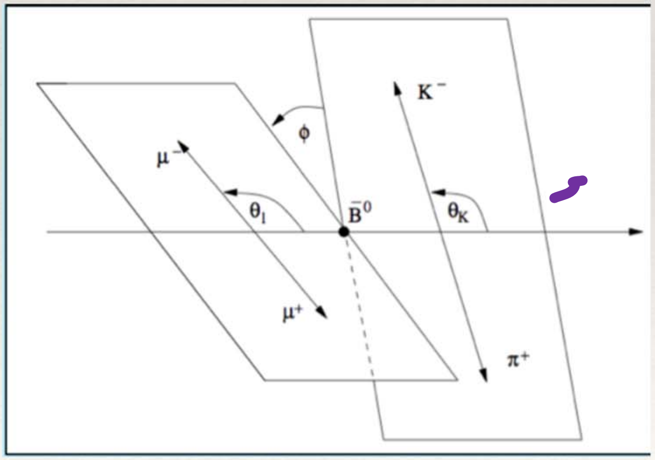
B→Kμμ

much LESS clean esp in low q^2

REMAIN CONCERNED ABOUT NON-local contributions

- Several angular observables measured as functions of q^2
- Some, like P_5', are optimized to be insensitive to hadronic uncertainties: [Descotes-Genon, Matias, Ramon, Virto: 1207.2753]





LHCb also finds deficit in observed $B_s \to \phi\mu\mu$ compared to "SM"

$\sim 2.5\,\sigma$

Less reliable due to LD contamination

URGENTLY Needed! FROM LHCb $\Rightarrow$ $R_\phi = \dfrac{B_s \to \phi\mu\mu}{B_s \to \phi ee}$

MUON (G-2) ANOMALY….VERY SPECIAL FOR BNL

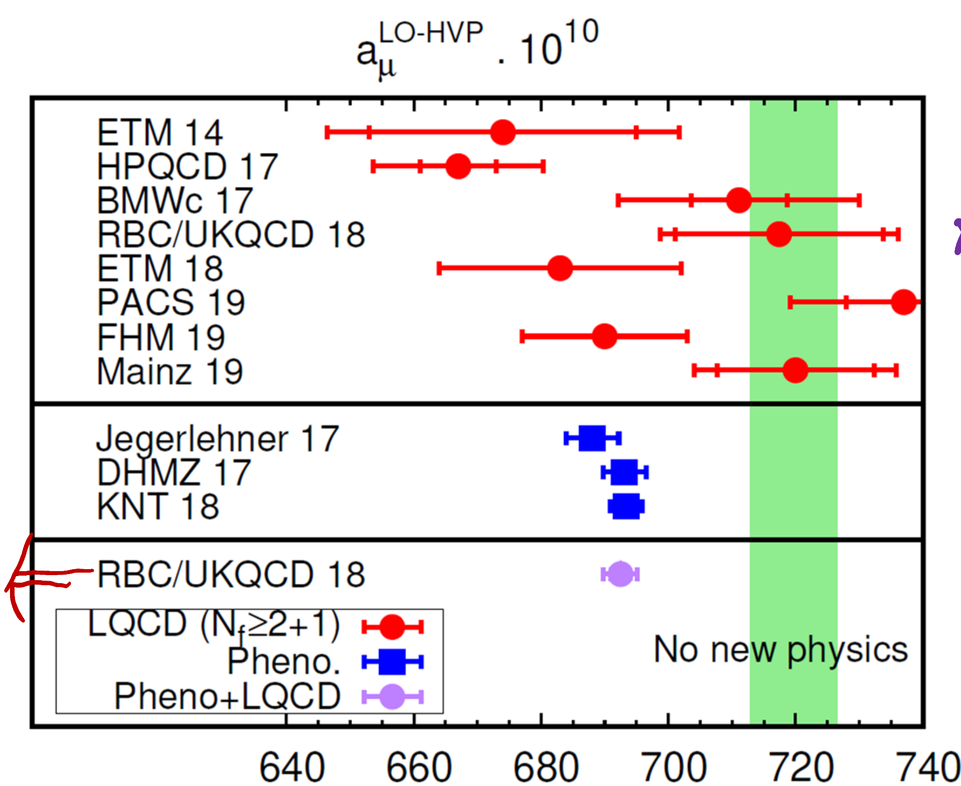
A. El-Khadra's talk at Seattle INT workshop.

Sept 2019

$(g-2)_\mu$

[prepared by K. Miura for WP]

[V.

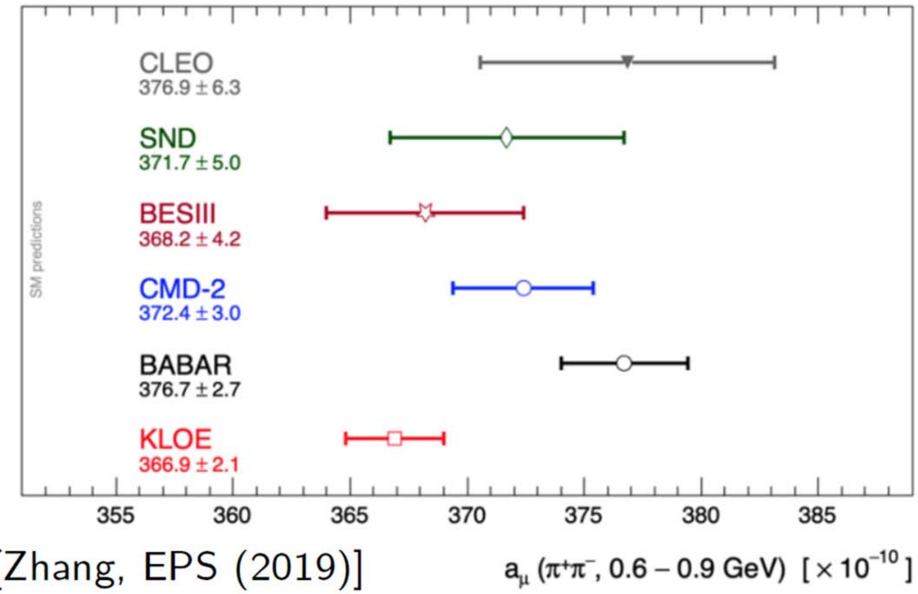


C. L et al ⇐

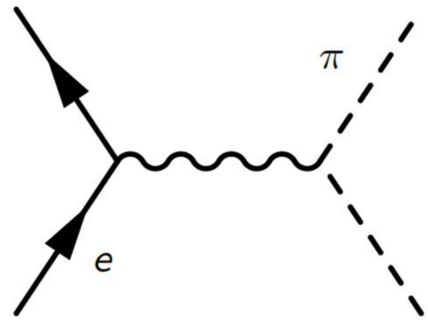
x 1/3 reduction in errors very soon by RBC-UKQCD [CL]

Lattice work started by Tom Blum @BNL ~'04

Tensions in Experiment



[Zhang, EPS (2019)]



R-ratio data for $ee \to \pi\pi$ exclusive channel, $\sqrt{s} = 0.6 - 0.9\ \mathrm{GeV}$ region
Tension between most precise measurements (BABAR/KLOE)
R-ratio a_μ^{HVP} uncertainty < difference in this channel

Avoid tension by computing precise lattice-only estimate of a_μ^{HVP}
Use lattice QCD to inform experiment, resolve discrepancy

Speculation

1st gen not sensitive to NP + $(g-2)_\mu$ + $R_{K^{(*)}}$ + $R_{D^{(*)}}$

Kile, Kobach + AS PRD2015

Table 1

Constraints on lepton-flavor violating and conserving processes. For the last four observables, the experimental null results are given in terms of a dimension-6 operator, suppressed by two orders of Λ, which can be interpreted as the nominal scale of new physics.

Observable	Limit
$\mathrm{Br}(\mu \to 3e)$	$< 1.0 \times 10^{-12}$ [1]
$\mathrm{Br}(\mu \to e\gamma)$	$< 5.7 \times 10^{-13}$ [1]
$\mathrm{Br}(\tau \to 3e)$	$< 2.7 \times 10^{-8}$ [1]
$\mathrm{Br}(\tau \to e^-\mu^+\mu^-)$	$< 2.7 \times 10^{-8}$ [1]
$\mathrm{Br}(\tau \to e^+\mu^-\mu^-)$	$< 1.7 \times 10^{-8}$ [1]
$\mathrm{Br}(\tau \to \mu^-e^+e^-)$	$< 1.8 \times 10^{-8}$ [1]
$\mathrm{Br}(\tau \to \mu^+e^-e^-)$	$< 1.5 \times 10^{-8}$ [1]
$\mathrm{Br}(\tau \to 3\mu)$	$< 2.1 \times 10^{-8}$ [1]
$\mathrm{Br}(\tau \to \mu\gamma)$	$< 4.4 \times 10^{-8}$ [1]
$\mathrm{Br}(\tau \to e\gamma)$	$< 3.3 \times 10^{-8}$ [1]
μ–e conversion	$\Lambda \gtrsim 10^3$ TeV [5]
$e^+e^- \to e^+e^-$	$\Lambda \gtrsim 5$ TeV [3]
$e^+e^- \to \mu^+\mu^-$	$\Lambda \gtrsim 5$ TeV [3]
$e^+e^- \to \tau^+\tau^-$	$\Lambda \gtrsim 4$ TeV [3]

Possibly interesting inter-related story reg. LUV evolving over the past ~15 years

- **muon (g-2)…….BNL ~2004; FermiL ~2017=>?**
- **RD(*)…………   BaBar, Belle, LHCb ….~2012-----→**
- **RK(*) …………..LHCb ~2014--------→**
- **Intriguing rather long tell- tale signs of LUV or few sigma flukes?**
- **Fortunately, wont have to wait too long < ~ 2 years due to FermiL, LHCb & Belle-II AND LATTICE**

MODEL INDEPENDENT TESTS AT HIGH PT

- **In a nut-shell B-experiments seem to find anomalous behavior in the underlying b=>c tau nu**
- **This necessarily [by XSym] implies there should be analogous anomaly in g + c => b tau nu…=>pp => b tau nu**

- ***Thus it immediately leads to inescapable search channels for possible NP at the high energy frontier for ATLAS & CMS and these are urgently urged***

Low pt <=>high pt interplay

- XS of b=> c tau nu $\Rightarrow$ $pp \Rightarrow g + c \Rightarrow b\,\tau\,\nu$
- XS of b=> s ll $\quad g + s \Rightarrow b\,l\,l$ $\qquad g \equiv$ gluon
- C Altmannshofer, Dev, AS , PRD 2017

IF

exptl hints stay then

Altmannshofer, Dev, A.S. 2017 + WIP

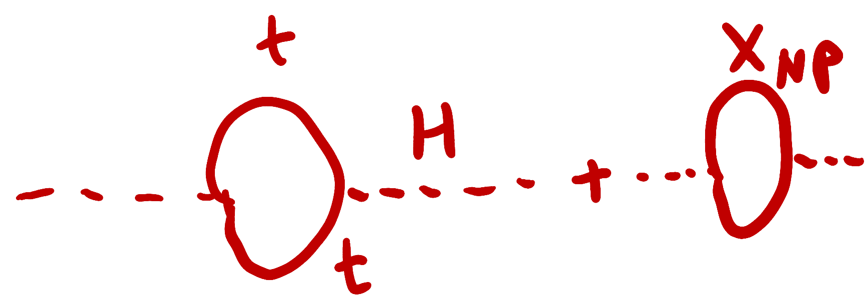
ANOMALIES: POSSIBLY A HINT FOR (NATURAL) SUSY-WITH RPV3

then RPV - SUSY extremely well motivated

+ New

- ASSUMING the anomaly is REAL & HERE TO STAY [BIG ASSUMPTION due to caveats mentioned]
- Anomaly involves simple tree-level semi-leptonic decays
- Also b => tau (3rd family)
- Speculate: May be related to Higgs naturalness
- Seek minimal solution: perhaps 3rd family super-partners(a lot) lighter than other 2 gens > proton decay concerns may not be relevant=> RPV [“natural” SUSY]
- RPV natural setting for LUV …can accommodate g-2, RK(*) if needs be
- Collider signals tend to get a lot harder than (usual-RPC) SUSY
- RPV makes leptoquarks natural [and respectable]
- Moreover, RPV should be viewed as an umbrella i.e. under appropriate limits other models are incorporated

$m_H \lesssim 126\ GeV$



RPV$_3$ preserves gauge coupling unification irrespective of # of effective gens. 1, 2 or 3.

ADS - PRD '17

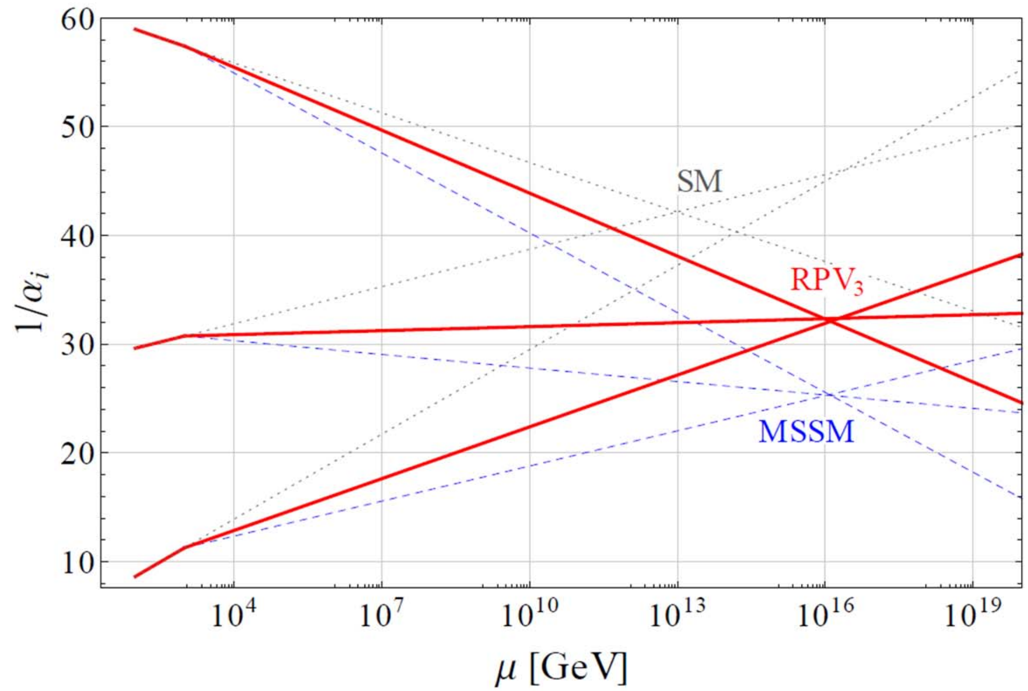


FIG. 2. RG evolution of the gauge couplings in the SM, MSSM and with partial supersymmetrization.

Unification scale ~ stays same, only value of couplings shifts

For pheno relevant terms:

ADS' PRD 2017

$$\mathcal{L} = \lambda'_{ijk}\left[\tilde{\nu}_{iL}\bar{d}_{kR}d_{jL} + \tilde{d}_{jL}\bar{d}_{kR}\nu_{iL} + \tilde{d}^*_{kR}\bar{\nu}^c_{iL}d_{jL} - \tilde{e}_{iL}\bar{d}_{kR}u_{jL} - \tilde{u}_{jL}\bar{d}_{kR}e_{iL} - \tilde{d}^*_{kR}\bar{e}^c_{iL}u_{jL}\right] + \text{H.c.}$$

} RPV$_3$ interaction

Analogue of $\frac{G_F}{\sqrt{2}}$

Dim 6

$$\mathcal{L}_{\text{eff}} \supset \frac{\lambda'_{ijk}\lambda'^*_{mnk}}{2m^2_{\tilde{d}_{kR}}}\left[\bar{\nu}_{mL}\gamma^\mu\nu_{iL}\bar{d}_{nL}\gamma_\mu d_{jL} - \nu_{mL}\gamma^\mu e_{iL}\bar{d}_{nL}\gamma_\mu\left(V^\dagger_{\text{CKM}}u_L\right)_j + \text{h.c.}\right] - \frac{\lambda'_{ijk}\lambda'^*_{mjn}}{2m^2_{\tilde{u}_{jL}}}\bar{e}_{mL}\gamma^\mu e_{iL}\bar{d}_{kR}\gamma_\mu d_{nR},$$

→ For $R_{D(*)}$

NOTE: ITS SM-like!

SM

RPV

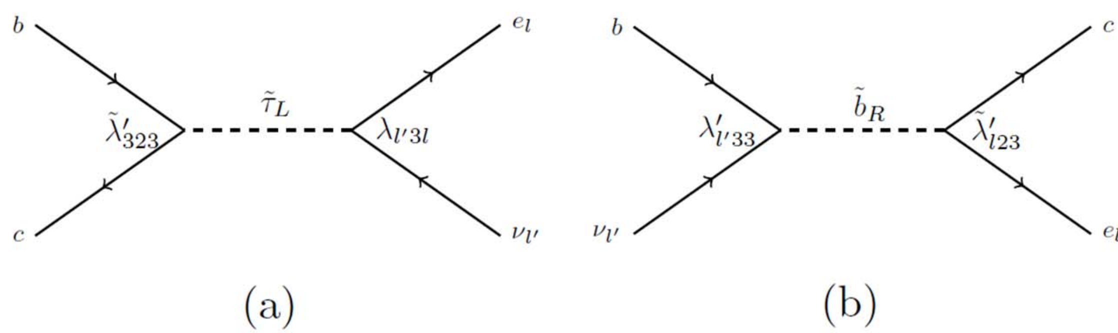
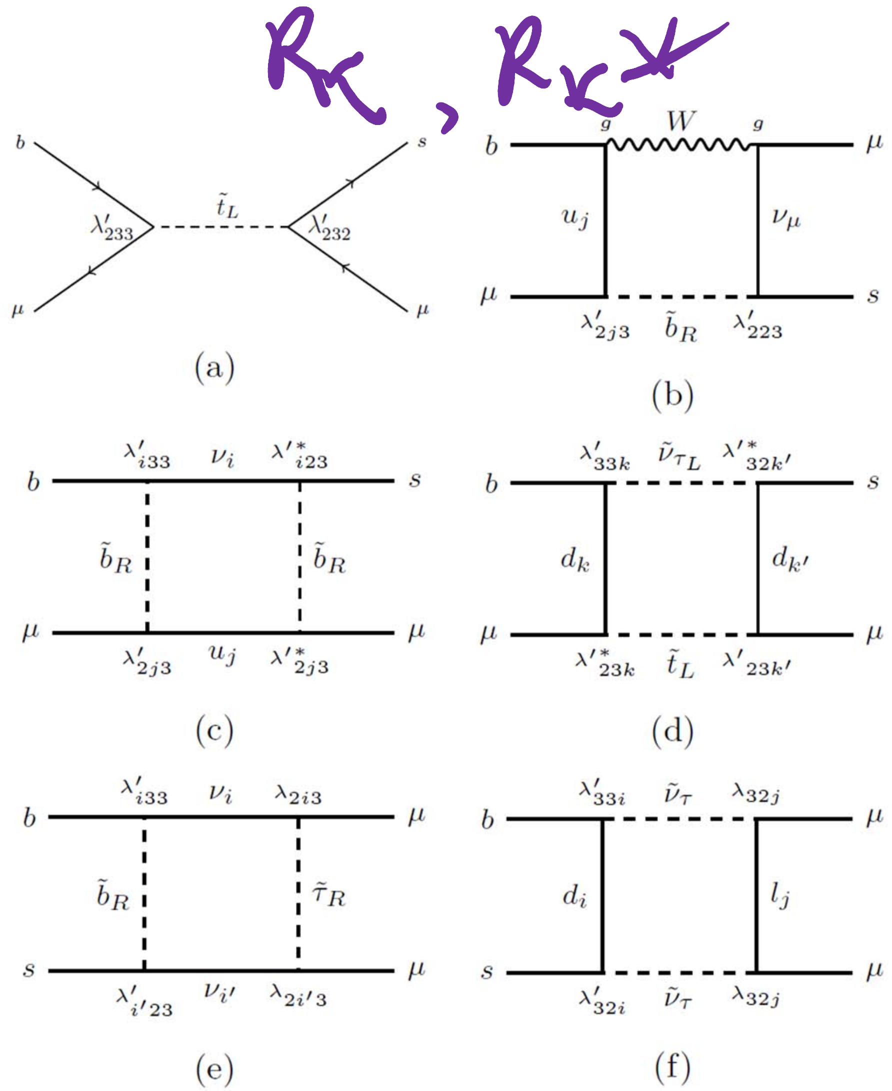


FIG. 3: Contribution to the R_D and R_{D^*} from λ' and λ in RPV SUSY. (a) both LLE and LQD; (b) LQD only.

LLE

only 3 $\tilde{g}$

$$\mathcal{L}_{\rm LLE} = \frac{1}{2}\lambda_{ijk}\Big[\tilde{\nu}_{iL}\bar{e}_{kR}e_{jL} + \tilde{e}_{jL}\bar{e}_{kR}\nu_{iL} + \tilde{e}^*_{kR}\bar{\nu}^c_{iL}e_{jL} - (i \leftrightarrow j)\Big] + {\rm H.c.}\,. \quad (19)$$



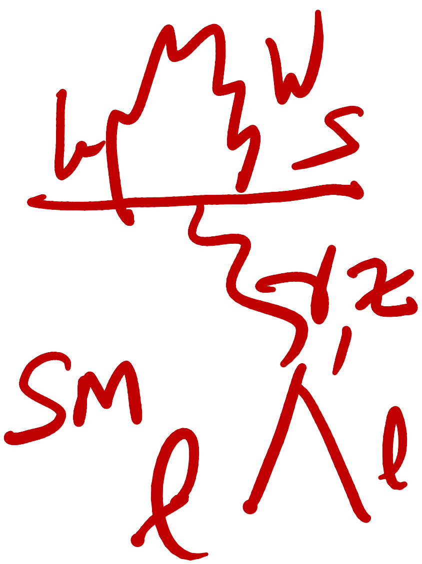


FIG. 4: Different classes of contribution to the $b \to s\ell\ell$ transitions in RPV SUSY. a) tree level stop exchange; b) sbottom-W boson loops; c) sbottom loops; d) stop-sneutrino loops; e) sbottom-stau loops; f) sneutrino loops.

$(g-2)_\mu$

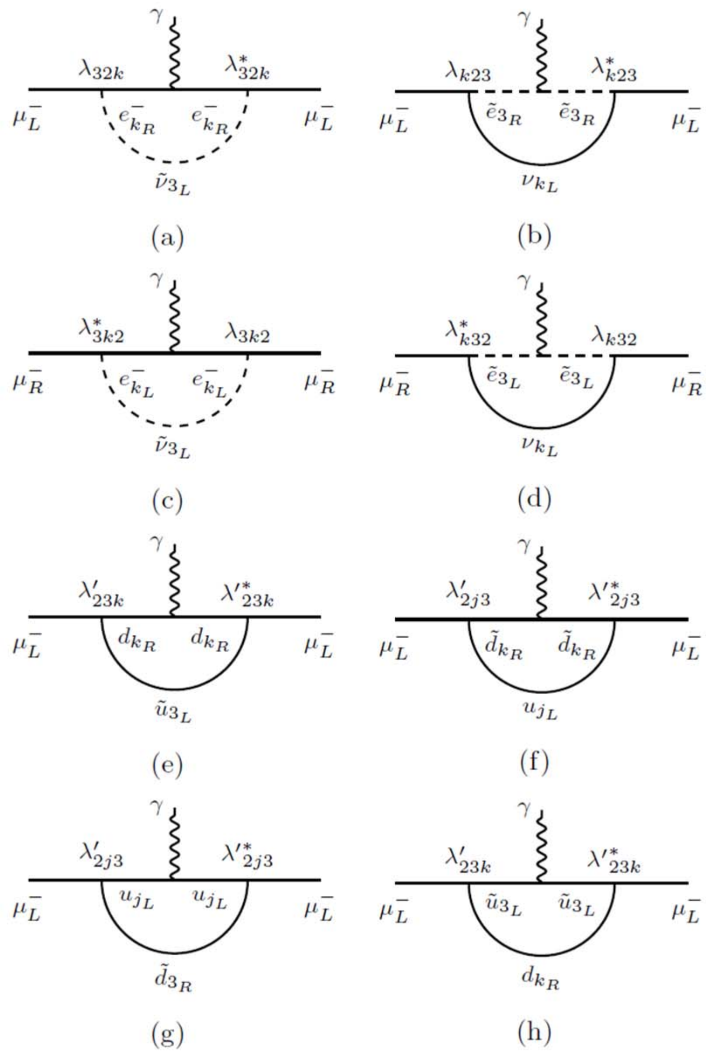


FIG. 5: Contribution to the $(g-2)_\mu$ from λ in RPV SUSY. a, c $\tilde{\nu}$ loop with different external handiness; b, d $\tilde{e}_3$ loop.

List of important constraints imposed

- B=> K(pi) nu nu
- Z=> tau tau/Z=> l l
- tau => l nu nu
- B=> tau nu
- Bc => tau nu
- Bs mixing

  + many more . . . . .

- As a result parameter space of RPV3 gets significantly constrained (see below)

PRD'17

ALTMANNSHOFER, BHUPAL DEV, and SONI

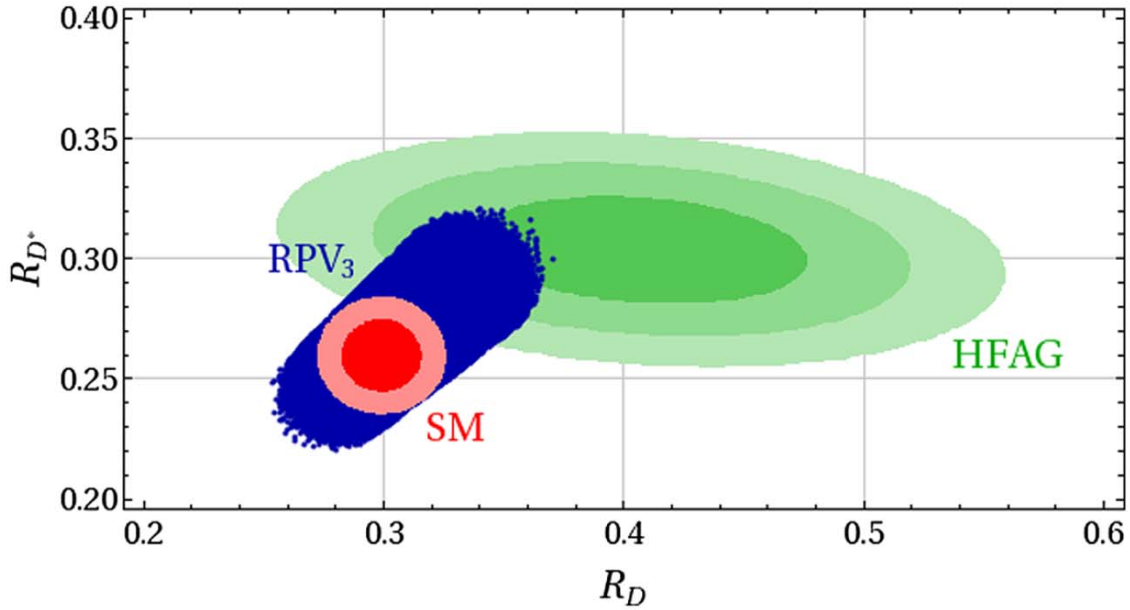


FIG. 4. The SM predictions (red), experimental world average (green), and accessible values in our RPV-SUSY scenario (blue) in the R_D vs. R_{D^*} plane. For the SM, bearing in mind recent works [17,20,22] we are taking $(R_D^{SM}, R_{D^*}^{SM}) = (0.299 \pm 0.011, 0.260 \pm 0.010)$.

Because of numerous constraints, despite huge # of param RPV$_3$ "barely survives"

Recent developments

- **For B=D* tau(l) nu, Belle has provided I.q^2 distribution [not just the integrated rate],**

II. the D^* polarization and III> tau polarization (though the last one has rather large errors). These additional info are very useful for discriminating amongst models

- **Very nice model independent analysis by**

Clara Murgui, Ana Peñuelas , Martin Jung & Antonio Pich, arXiv:1904.09311

- **For RK and RK* both are larger compare to SM.**
- **This positive correlation rather than anti is of particular importance for telling us about the Lorentz structure of the currents**

$C_{V_L} \neq 0 \Rightarrow$ corresponds to our RPV3

MURGUI et al 1904.09311 MARTIN J. ....

2 Theoretical framework

2.1 Effective Hamiltonian

We adopt the most general $SU(3)_C \otimes U(1)_Q$-invariant effective Hamiltonian describing $b \to c\ell\bar{\nu}_\ell$ transitions at the bottom quark scale, not considering the possibility of light right-handed neutrinos:

$$\mathcal{H}_{\text{eff}}^{b\to c\ell\nu} = \frac{4G_F}{\sqrt{2}} V_{cb}\left[(1 + C_{V_L})\, \mathcal{O}_{V_L} + C_{V_R}\mathcal{O}_{V_R} + C_{S_R}\mathcal{O}_{S_R} + C_{S_L}\mathcal{O}_{S_L} + C_T\mathcal{O}_T\right] + \text{h.c.}. \quad (2.1)$$

The above fermionic operators are given by[4]

$$\mathcal{O}_{V_{L,R}} = (\bar{c}\gamma^\mu b_{L,R})\,(\bar{\ell}_L\gamma_\mu\nu_{\ell L})\,, \quad \mathcal{O}_{S_{L,R}} = (\bar{c}\, b_{L,R})\,(\bar{\ell}_R\nu_{\ell L})\,, \quad \mathcal{O}_T = (\bar{c}\,\sigma^{\mu\nu} b_L)\,(\bar{\ell}_R\sigma_{\mu\nu}\nu_{\ell L})\,, \quad (2.2)$$

Very useful work includes constraints from $R_{D(*)}$, q^2 distribution, D^* pol & $B_c \to \tau\nu$

not only

Murgui et al

- On the other hand, considering scenarios with only a single Wilson coefficient present, there *is* a clear preference for C_{V_L}: removing the other three Wilson coefficients increases χ^2 only by 1.4, corresponding to 0.14σ. Hence, Min 1 is well compatible with a global modification of the SM, that is, C_{V_L} being the only non-zero coefficient.

Inc.. Belle EW Moriond

central values do change. Again all individual coefficients are roughly compatible with zero at 1σ. C_{V_L} alone also still provides an excellent fit to all the data, now with a smaller central value of ~ 0.08. Interestingly, the fit with only C_T is improved by the new results, which,

A striking endorsement for RPV3 ∴ IF NP is needed!

But in the current context any NP solution needs to be accompanied by a concern

[relevant only for small non-vanishing CVL]

- It may just be SM + (expt + theory) errors
- This is why further reduction in errors of both experiment AND theory are highly desirable…
- THIS IS THE MOTIVATION DRIVING OUR LATTICE EFFORT
- Belle-II and LHCb in the next few years are of course going to provide better experimental numbers

- Assuming NP is needed then RPV3 is a very good candidate

ADSS' (WIP)

$R_K(K^*)$

Try a/c for N.P. need via shifts in W.C

$$\mathcal{H}_{\rm eff} = -\frac{4G_F}{\sqrt{2}} V_{ts}^* V_{tb} \frac{e^2}{16\pi^2} \sum_{i=9,10} \Big((C_i)^\ell (Q_i)^\ell + (C_i')^\ell (Q_i')^\ell \Big) , \tag{30}$$

with the operators

$$(Q_9)^\ell = (\bar{s}\gamma_\alpha P_L b)(\bar{\ell}\gamma^\alpha \ell) , \ (Q_{10})^\ell = (\bar{s}\gamma_\alpha P_L b)(\bar{\ell}\gamma^\alpha \gamma_5 \ell) , \tag{31}$$

and $Q'_{9,10}$ are obtained from $Q_{9,10}$ by $P_L \to P_R$. Fits of R_K and R_{K^*} show that the observed pattern can be accommodated with new physics in the coefficients $(C_9)^e$, $(C_{10})^e$, $(C_9)^\mu$, $(C_{10})^\mu$. New physics in the primed coefficients is disfavored as it leads to an anti-correlated effect in R_K and R_{K^*}, contradicting the current data.

Data Needs $C_9^\mu = -C_{10}^\mu$

Global fits of all relevant data on rare B decays finds a particular consistent new physics picture which is characterized by non-standard effects in muonic coefficients in the combination of Wilson coefficients $(C_9)^\mu = -(C_{10})^\mu$ [49] (see also [50–54]). As we will see below, our RPV SUSY scenario will generate contributions to both $(C_9)^\mu = -(C_{10})^\mu$ and $(C_9')^\mu = -(C_{10}')^\mu$. Such a scenario provides an excellent fit to the data for the following values [49]

No change in e

$$(C_9)^e \simeq (C_{10})^e \simeq (C_9')^e \simeq (C_{10}')^e \simeq 0 , \tag{32}$$
$$(C_9)^\mu = -(C_{10})^\mu \simeq -0.55 \pm 0.10 , \tag{33}$$
$$(C_9')^\mu = -(C_{10}')^\mu \simeq 0.20 \pm 0.11 . \tag{34}$$

Effect ~15% in amplitude

Note that the combination $(C_9)^\mu \simeq -(C_{10})^\mu$ corresponds to new physics that mainly affects left-handed muons. All other coefficients are compatible with zero at the 2σ level. The correction to the SM values of the Wilson coefficients $C_9^{\rm SM} \simeq -C_{10}^{\rm SM} \simeq 4$ is at the level of -15%. The

2 +'s & 1-

- q^2 distribution in slB of NP seems similar to SM…+
- RK and RK* are positively correlated as in SM….+
- But because the q^2 distribution in slB is SM-like => D* polarization must stay as in SM;

current Belle data disfavors SM at 1.6 sigma

LHCb, BELLE-II input would be crucial

Sequel to our work on RPV3 nearing completion

Addressing B-anomalies, muon $g-2$ and ANITA anomaly in a Minimal R-parity violating supersymmetric framework

Wolfgang Altmannshofer[1], P. S. Bhupal Dev[2], Amarjit Soni[3], Yicong Sui[2]

g.s @ WUSTL

IN CLOSING: A REMINDER

Importance of the "IF": score card

- Beta decay => Gf => W….
- Huge suppression of KL => mu mu; miniscule ΔmK=> charm
- KL =>2 pi but very rarely; mostly to 3pi =>CP violation => 3 families
- Largish Bd –mixing => large top mass
- etc…….

History may repeat yet again!

- => extremely unwise to put all eggs in HEF
- info from IF complementary to HEF can be a crucial guide for pointing to new thresholds as well as to provide important clues to the nature of the signals there from

Summary + Outlook

- **Hints of LUV are extremely interesting, intriguing and important. *There is nothing we know of that tells us that these hints cannot be true.***

- **While these indications are rather serious, personally I don't find them compelling enough weighing in the fact that they ask for too radical a departure from conventional understanding so it is best we exercise extreme caution and care before accepting them. Moreover, in each of the 3 cases there are features that cause some concern.**

- **Fortunately significant experimental/theoretical progress on these issues should occur in < ~2 years and is eagerly awaited.**
- **Anticipate new g-2 results from Fermilab in 2020; improved results from LHCb in 2020 & 2021 and Belle-II results starting ~2021 and many improved theory results from Lattice**

- **IF the current hints survive further scrutiny, RPV3, with 3g more amenable to NP, is not only interesting and has significant theoretical appeal, this early on there appears to be some important experimental support for it.**

- **Given all the above hints, may be with some luck the IF will lead us to the gem of NP and once again, as many times in the past, guide collider physics et al**

arXiv:1807.01638v1 [hep-ph] 4 Jul 2018

Revisiting R-parity violating interactions as an explanation of the B-physics anomalies

Sokratis Trifinopoulos*[1]

"S-T" sym

[1] *Physik-Institut, Universität Zürich, CH-8057 Zürich, Switzerland*

introduces a nice formal sym arguement to implement our RPV3 [3rd gen $\tilde{s}$ lightest]

Abstract

In the last few years, the ratios $R_{D^{(*)}}$ and of $R_{K^{(*)}}$ have reportedly exhibited significant deviations from the relevant Standard Model predictions, hinting towards a possible violation of Lepton Flavor Universality and a window to New Physics. We investigate to what extent the inclusion of R-parity violating couplings in the Minimal Supersymemtric Standard Model can provide a better fit to the anomalies simultaneously. We perform this analysis employing an approximate, non-abelian $\mathcal{G}_f = U(2)_q \times U(2)_\ell$ flavour symmetry, which features a natural explanation of the appropriate hierarchy of the R-parity violating couplings. We show that, under the requirement of a supersymmetric spectrum with much heavier left-handed doublet superpartners, our assumption favors a considerable enhancement in the tree-level charged-current $B \to D^{(*)}\tau\overline{\nu}$, while the the anomalies induced by $b \to s\ell^+\ell^-$ receive up to an approximate 30% improvement. The consistency with all relevant low-energy constraints is assessed.

Implementing S-T sym simplifies things considerably by reducing # of parameters.

BUT cannot a/c for $(g-2)_\mu$

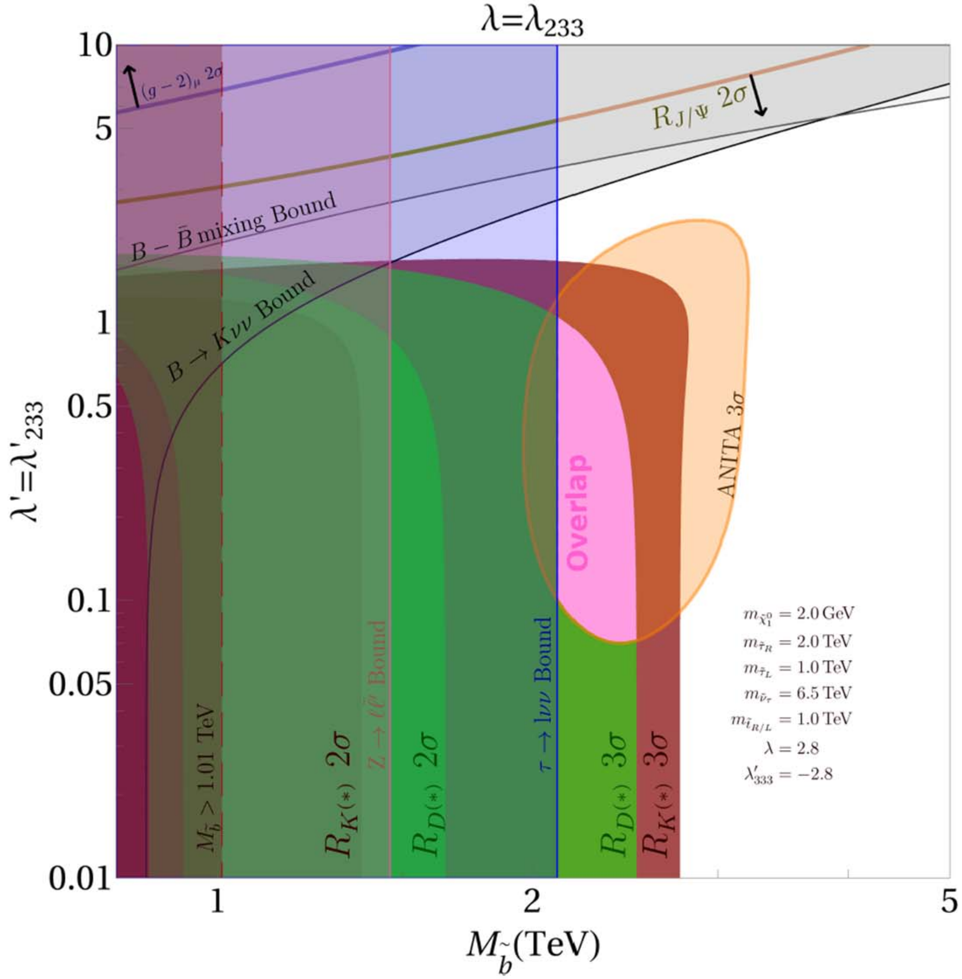


FIG. 5: Benchmark scenario for ST symmetry with overlapping $R_D^{(*)}$, $R_{J/\Psi}$, $R_K^{(*)}$ and ANITA regions. The total overlap is shown as pink area. $R_D^{(*)}$ $2, 3\sigma$ flavored regions are denoted as green regions; $R_K^{(*)}$ $2, 3\sigma$ flavored regions are shown in red regions; $(g-2)_\mu$ and $R_{J/\Psi}$ 2σ flavored region is marked by thick blue and dark yellow edges, respectively, with arrows pointing inwards to the allowed regions; ANITA anomaly 3σ flavored region is shown in orange regions. $B \to K\nu\nu$ bound is shown as black curve with forbidden region indicated as dark gray region while $B - \bar{B}$ mixing bound shown as gray curve with forbidden region in gray; $Z \to \ell\bar{\ell}'$ bound is shown as pink vertical line with forbidden region in light pink; $\tau \to \ell\nu\nu$ bound is shown as blue vertical line with forbidden region in light blue.

BACK TO LOW PT: NOTABLE LFV DECAYS OF TAU AND B [IN RPV3]

LFV of τ & of B's

→ 3-g centric RPV_3 : Altmannshofer, Dev, AS, YS

in prep

Mode	Model dependent BR	Current bound
$\tau \to \mu\phi$	2×10^{-10}	8×10^{-8}
$\tau \to \mu K K$	3×10^{-11}	4×10^{-8}
$\tau \to \mu K_s^0$	6×10^{-11}	2×10^{-8}
$\tau \to 3\mu$	1.5×10^{-10}	2×10^{-8}
$\tau \to \mu\gamma$	1.1×10^{-11}	4×10^{-8}
$\tau \to \mu l^+ l^-$	6×10^{-12}	2×10^{-8}
$b \to s\mu\tau$	7×10^{-7}	4.5×10^{-5}
$B_s \to \tau\mu$	1.3×10^{-8}	N/A

TABLE I: Few examples of lepton flavor violating decay modes of τ and of $B-mesons$. Shown are also loop decays $\tau \to \mu\gamma$ and $\tau \to \mu l^+ l^-$; see text

$Br[B \to K\mu\tau \sim 10^{-7}]$! ⇐ Recall $B \to X_c \ell\nu \propto V_{cb} \sim \lambda^2$

& $B \to K\tau\tau$ also deserves attention

Implications of anomaly for colliders

At low energies, the effective 4-fermion Lagrangian for the quark-level transition $b \to c\tau\bar{\nu}$ in the SM is given by

$$-\mathcal{L}_{\rm eff} \;=\; \frac{4G_F V_{cb}}{\sqrt{2}} \left(\bar{c}\gamma_\mu P_L b\right)\left(\bar{\tau}\gamma^\mu P_L \nu_\tau\right) + \text{H.c.}\,, \qquad (4)$$

SM

BSM

DIM 6 OPS

"V"

"S"

$$\mathcal{O}_{V_{R,L}} \;=\; \left(\bar{c}\gamma^\mu P_{R,L} b\right)\left(\bar{\tau}\gamma_\mu P_L \nu\right) \qquad (5)$$

$$\mathcal{O}_{S_{R,L}} \;=\; \left(\bar{c} P_{R,L} b\right)\left(\bar{\tau} P_L \nu\right)\,, \qquad (6)$$

$$\mathcal{O}_{T} \;=\; \left(\bar{c}\sigma^{\mu\nu} P_L b\right)\left(\bar{\tau}\sigma_{\mu\nu} P_L \nu\right)\,. \qquad (7)$$

SKIP 4 NOW

$R_{D^{(*)}}$ ANOMALY: A POSSIBLE HINT FOR … PHYSICAL REVIEW D **96,** 095010 (2017)

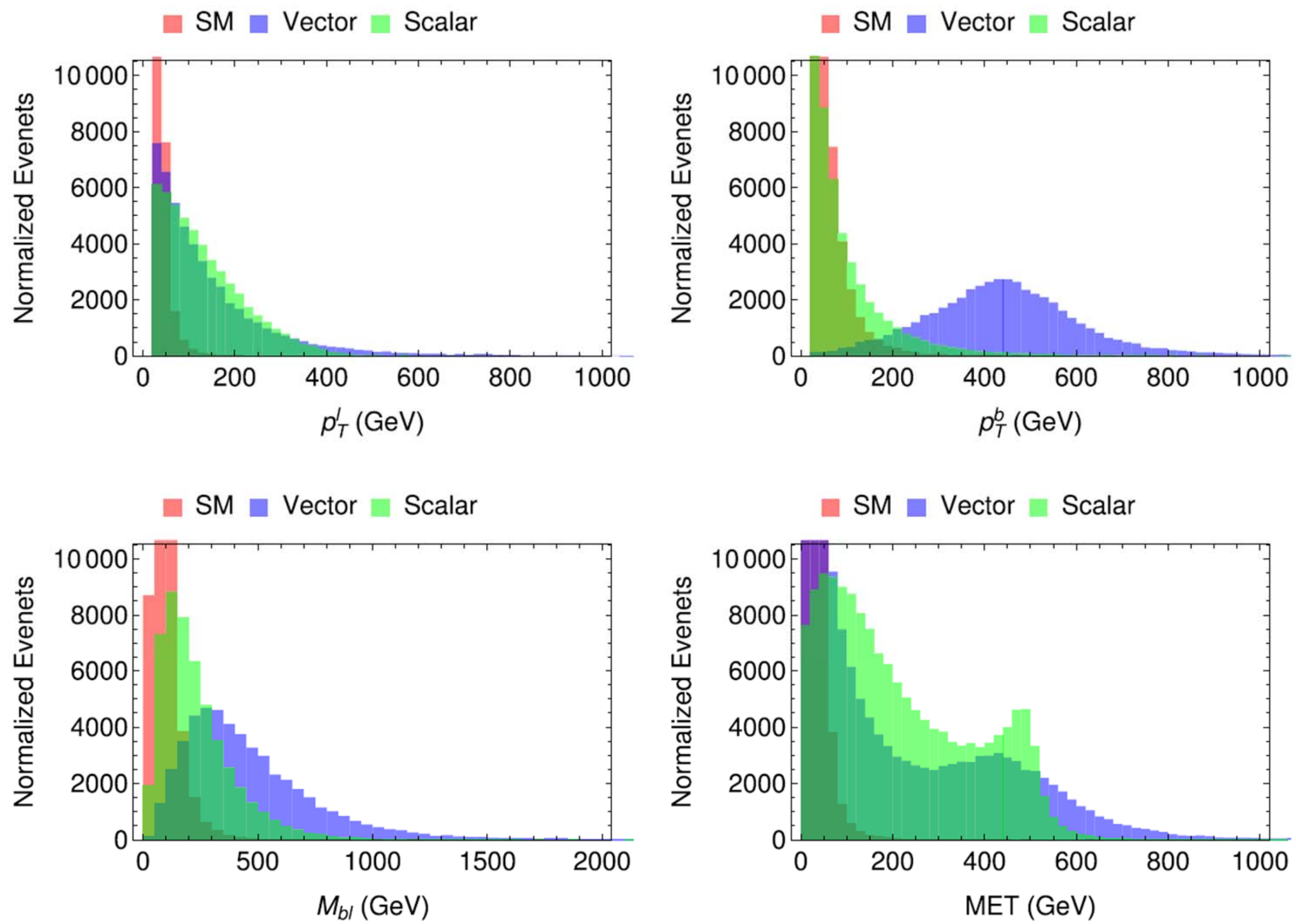


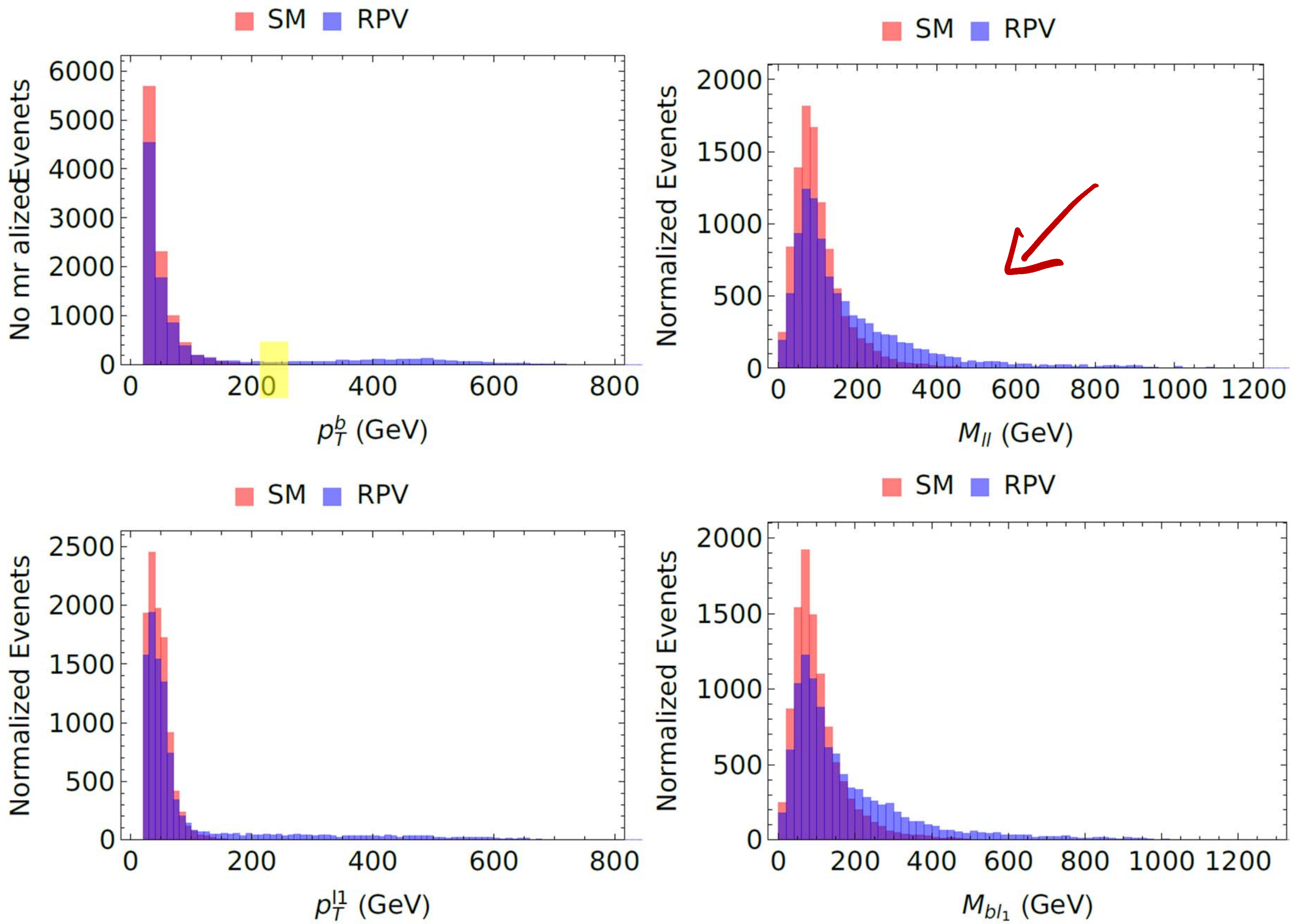
FIG. 1. Normalized kinematic distributions for the $pp \to b\tau\nu \to b\ell + \not{E}_T$ signal and background.

EXPECT DISTINCTIVE NP CONTRIBUTIONS IN COLLIDERS

Following RK(*) => model independent high pt implications

- **In a similar vein to the charged current case**
- **B=K(*) l l ……RK(*) anomaly**
- **b=> s l l**
- **g + b=> sl l**
- **g + s => b l l** ← Most suited due signal, backgrounds & such

Thus collider searches for NP in $pp \to b\,l\,l$ are urged . . .



we have used the minimal trigger cuts: $p_T^{j,b\ell} > 20$ GeV, $|\eta^{j,b,\ell}| < 2.5$ and $\Delta R^{\ell\ell} > 0.4$ and an average b-tagging efficiency of 70%. From the distributions (give cut flow

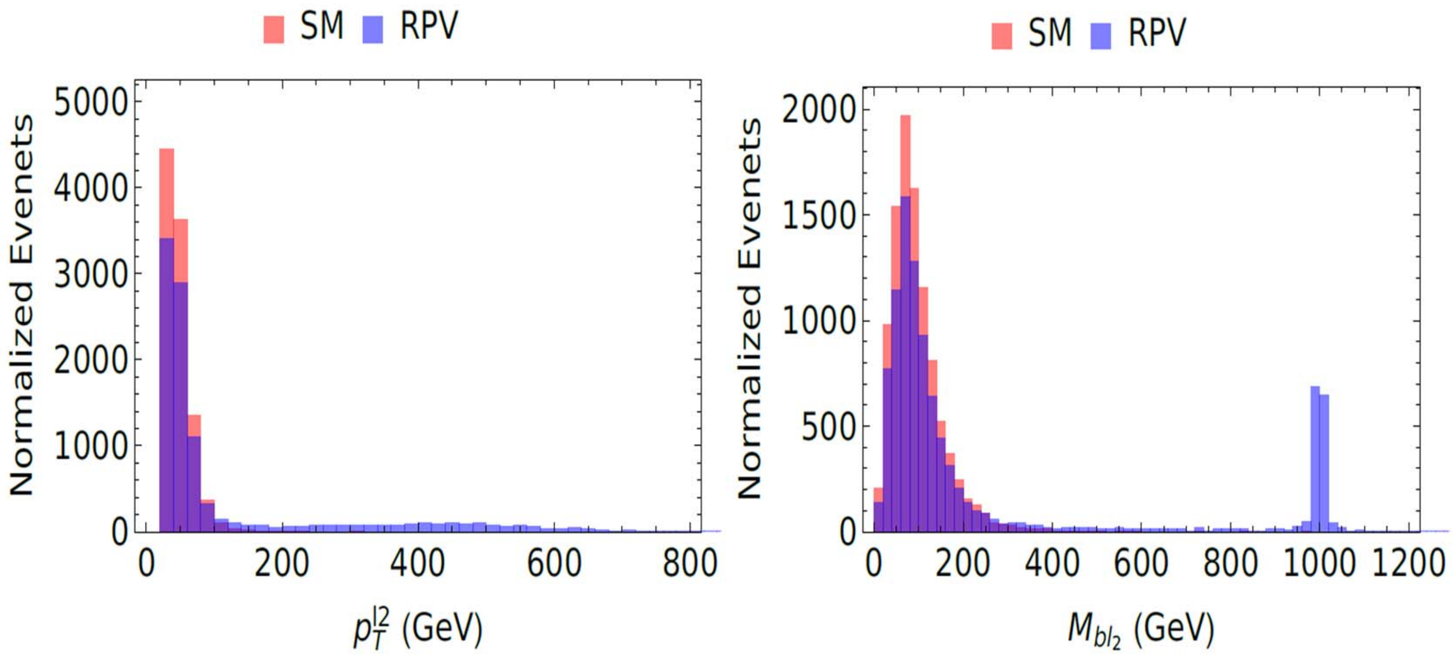


FIG. 2: Kinematic distributions for the $pp \to b\ell\ell$ signal in the RPV model (blue) and the corresponding SM background (red). The left panels show the transverse momentum distributions for the bottom quark and the two charged leptons, whereas the right panel shows the invariant mass distributions for the dilepton and the two bottom quark-lepton cominations. In the RPV model under consideration, the right combination of M_{bl} gives a peak at the squark mass, as shown in the last plot. Minimal trigger cuts have been imposed here.

In passing, a side remark, please

- **QCD and therefore non-perturbative dynamics critically effects SM and or BSM**
- **In almost all of these "IF" experiments, quantitative understanding of non-perturbative [non-P] effects is of crucial importance to make most economical use of experimental data, often obtained at huge cost. The non-P methods do not just need humungous computing hardware, (wo)man power needs are also very large. Given their vital use, they deserve greater support from the (experimental) community.**

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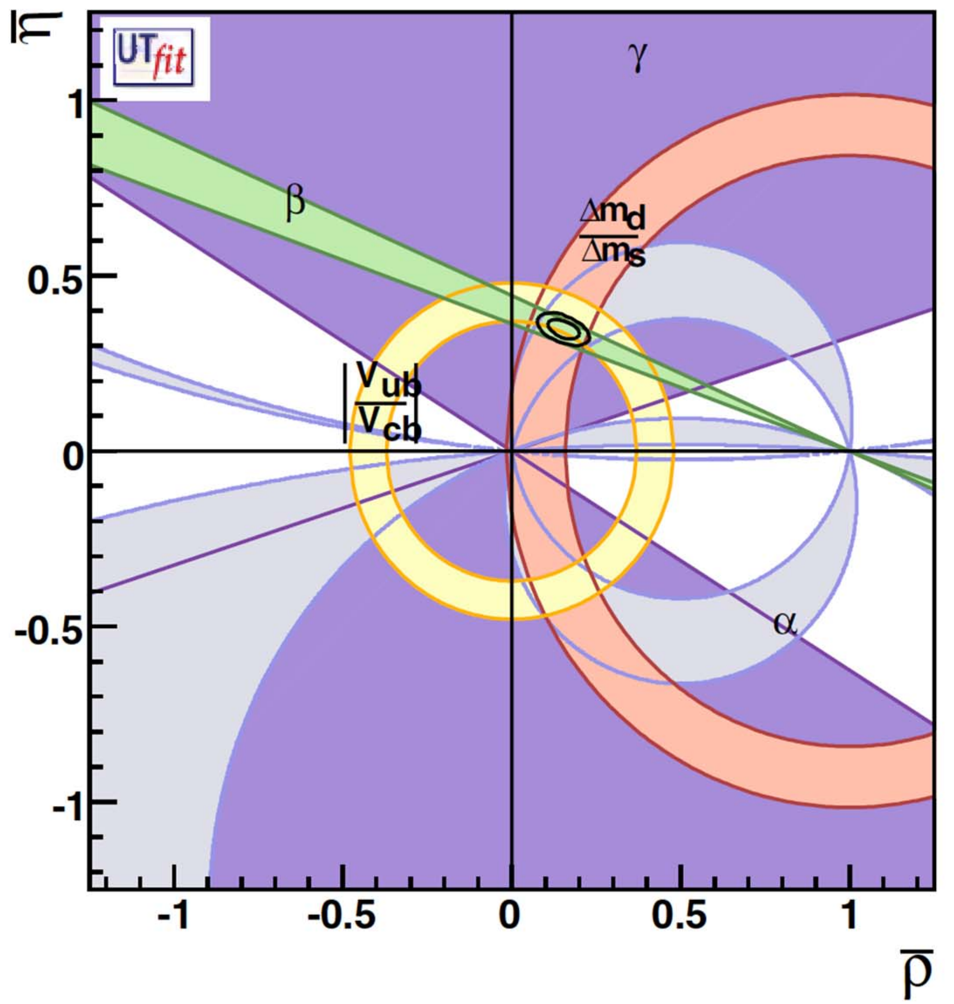


MARCELLA BONA ~2007

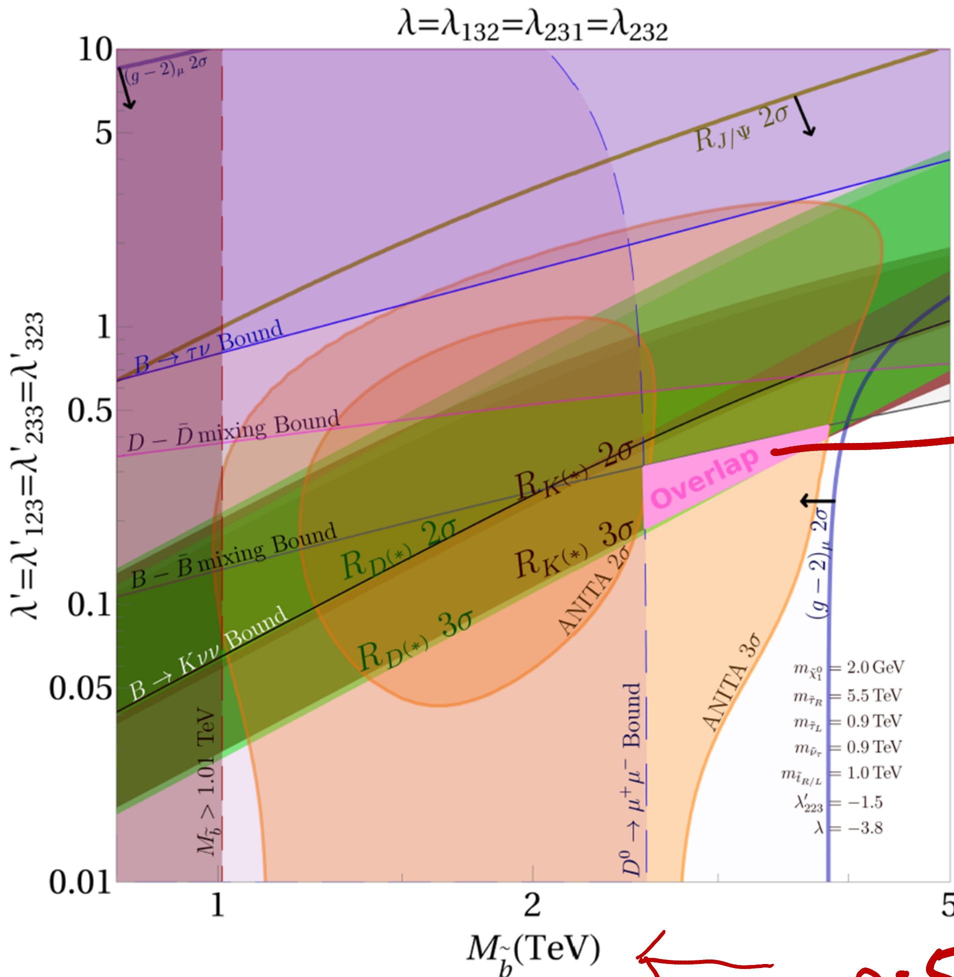
COUPLINGS BETWEEN CWB+ AS & PBM ET AL

ALL 11 EXPERIMENTAL CENTRAL VALUES ARE ABOVE THEORY!

$(g-2)_\mu \oplus R_{D(*)} \oplus R_{K(*)}$ + ANITA anomalies

10

+ ALL known exptal constraints

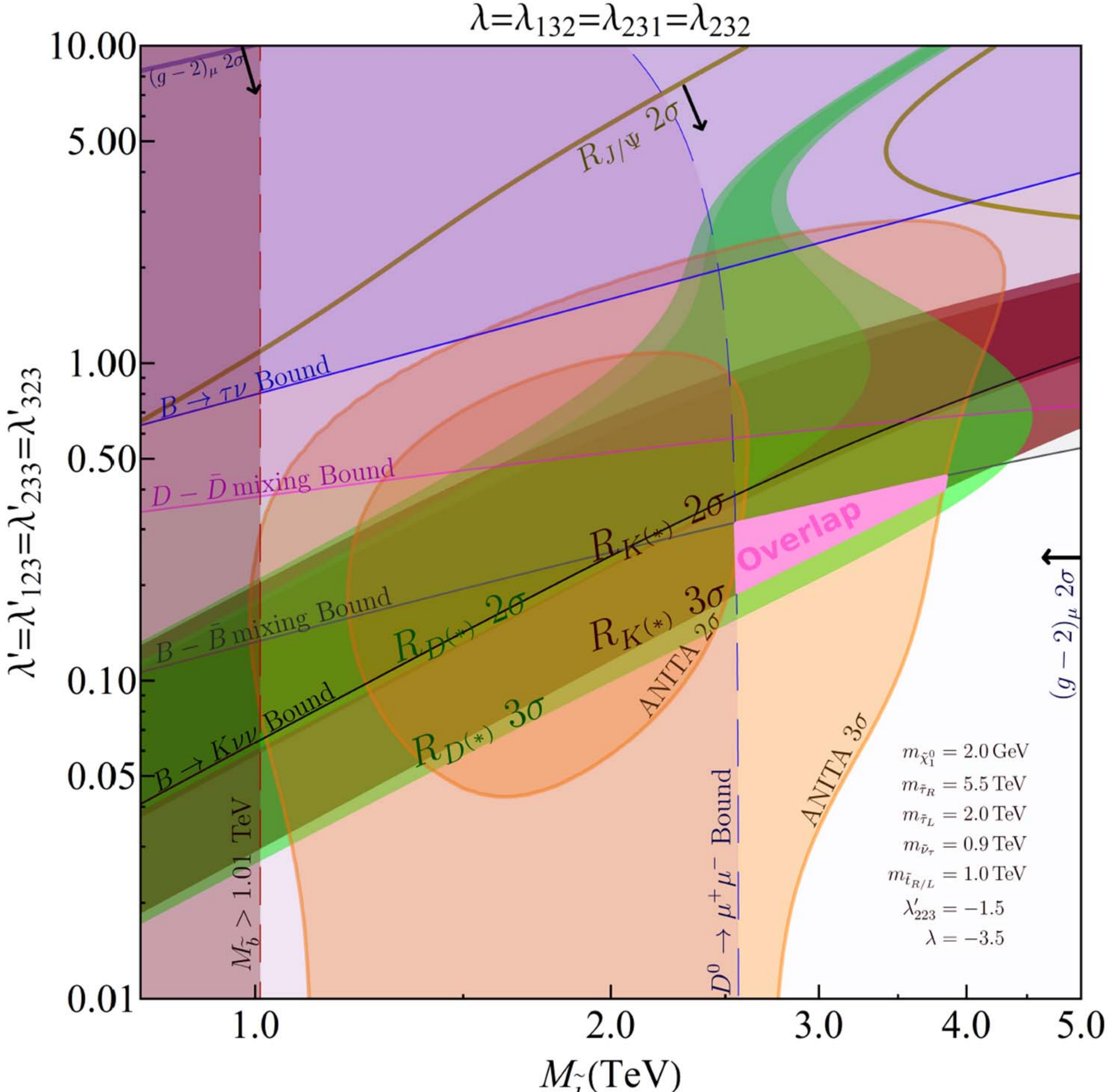


overlap

m sups 1→5 TeV

$2.5 \lesssim m_{\tilde{b}} \lesssim 3.5$ TeV

FIG. 4: Benchmark scenario with overlapping $R_D^{(*)}$, $R_{J/\Psi}$, $R_K^{(*)}$, $(g-2)_\mu$ and ANITA regions. The total overlap is shown as pink area. $R_D^{(*)}$ 2, 3 σ flavored regions are denoted as green regions; $R_K^{(*)}$ 2, 3 σ flavored regions are shown in red regions; $(g-2)_\mu$ and $R_{J/\Psi}$ 2 σ flavored region is marked by thick blue and dark yellow edges, respectively, with arrows pointing inwards to the allowed regions; ANITA anomaly 2, 3 σ flavored regions are shown in orange regions. $B \to K\nu\nu$ bound is shown as dark gray curve with forbidden region indicated as dark gray region while $B-\bar{B}$ mixing bound shown as gray curve with forbidden region in gray; $D \to \mu\mu$ is shown as dashed light purple curve with forbidden region in light purple. $D-\bar{D}$ mixing bound is shown as the pink curve with forbidden region in light pink.


λ=λ132=λ231=λ232
λ'=λ'123=λ'233=λ'323
M_b̃(TeV)
10.00
5.00
1.00
0.50
0.10
0.05
0.01
1.0
2.0
3.0
4.0
5.0
(g − 2)μ 2σ
RJ/Ψ 2σ
B → τν Bound
D − D̄ mixing Bound
RK(*) 2σ
Overlap
B − B̄ mixing Bound
RD(*) 2σ
RK(*) 3σ
ANITA 2σ
B → Kνν Bound
RD(*) 3σ
ANITA 3σ
M_b̃ > 1.01 TeV
D0 → μ+μ− Bound
(g − 2)μ 2σ
m_χ̃0_1 = 2.0 GeV
m_τ̃R = 5.5 TeV
m_τ̃L = 2.0 TeV
m_ν̃τ = 0.9 TeV
m_t̃R/L = 1.0 TeV
λ'223 = −1.5
λ = −3.5