BSM interpretations of B-physics and muon (g-2) anomalies

Amarjit Soni

Amarjit Soni
HET-BNL

Based primarily on:

1) arXiv:1704.06659 [Altmannshofer, Dev+A.S]=>PRD (2017)

2) arXiv:2002.12910 [Altmannshofer, Dev, Yicong Sui+A.S]=>PRD(2020)

3) arXiv:2106.15647 [Fang Xu+ Dev + AS]

+ works in progress [us three] with Wolfgang Altmannshofer and with Yoav Afik

[see also Fang Xu talk on Tues]

PPC-meeting 06/6-10/22; Washington Univ; ST Louis, MO 63130
06/9/22

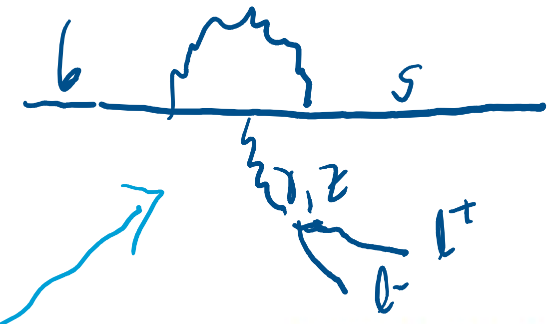
outline

- Recapitulate flavor anomalies….Pros & Cons
- Why RPV3
- Tests for IF
- Implications for LHC & beyond
- Summary

Each of the 3 anomalies have concern(s)

Improve Theory Predictions: on & off the Lattice

- **As a member of RBC-UKQCD use DWQ which at the expense of a 5th dim. have vastly improved chiral symm and thus behave as "continuum-like" fermions with very good renormalization properties.**
- **Use lattice for semi-lep form factors for B(Bs, Bc) decays to D(*)(Ds(*), erta_C(psi) + l(tau) nu and also for muon (g-2)**
- **With Enrico Lunghi => Vub, rare K , eps', K-UT**
- **With Yoav Afik, Shaouly Bar-Shalom, Kuntal Pal and Jose Wudka, use SM(EFT) and simulations for collider signals**



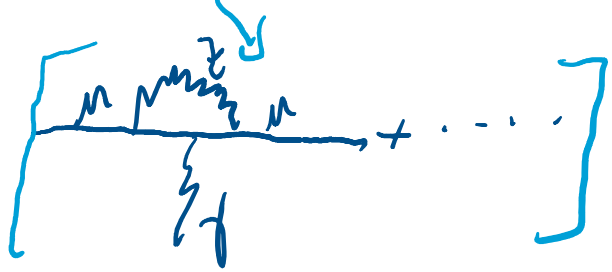
See also Nazila's talk

As of 2020

TABLE I. Summary of the anomalies in the observables $R_{D^{(*)}}$, $R_{J/\psi}$, $R_{K^{(*)}}$, and $(g-2)_\mu$. Listed are the pulls of various subsets of observables. The pulls are combined assuming the observables are independent from each other. The values in parentheses exclude the *BABAR* results for $R_{D^{(*)}}$.

Observable	$R_{D^{(*)}}, R_{J/\psi}$	$R_{K^{(*)}}$	$(g-2)_\mu$	All but $(g-2)_\mu$	All
Pull	3.3σ (2.2σ)	3.4σ	3.3σ	4.5σ (3.7σ)	5.3σ (4.6σ)

See ALTMANNSHOFER, DEV, Sui + AS 2020



Must stress that even if one of these three anomalies survives further scrutiny SM will need to be extended to BSM

PHYSICAL REVIEW D VOLUME 56, NUMBER 9 1 NOVEMBER 1997

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

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 $B\rightarrow D\tau\overline{\nu}$ 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 $B\rightarrow D(e,\mu)\overline{\nu}$. 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

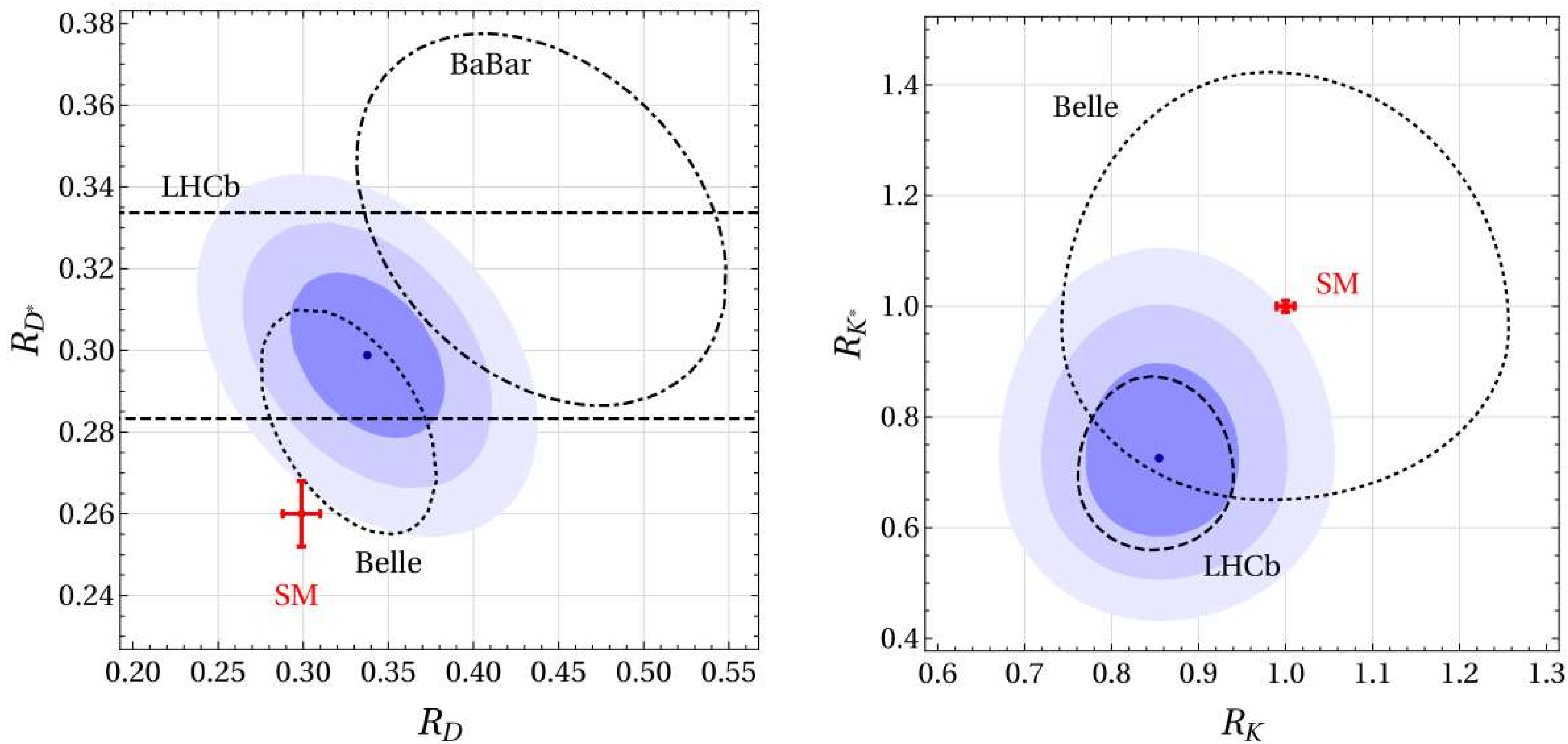


FIG. 1. Experimental averages (shown by the blue dot for the best-fit and darker-to-lighter shaded regions for $1\sigma, 2\sigma, 3\sigma$) and SM predictions (shown by red error bars) for the LFUV observables R_D and R_{D^*} (left), as well as R_K and R_{K^*} (right). The values for $R_{K^{(*)}}$ correspond to a dilepton invariant mass squared of $1.1\ \text{GeV}^2 < q^2 < 6\ \text{GeV}^2$. Individual 1σ regions from Belle, LHCb, and *BABAR* are also shown by the dotted, dashed, and dash-dotted contours, respectively.

Two vitally important details

- In B=>D* tau(l) nu, not just the R-ratio of the integrated rates but also

D* polarization is an observable….While the R(D*) is off from the SM by ~2-3 sigma, the D* polarization is found to be consistent with the SM

- Rather intriguing and important is also the fact that both RK and RK*

are below the SM…i.e. they are correlated. This is an important clue about the weak current in the underlying BSM i.e. they are dominantly LH just as the SM.

Both these features arise naturally in RPV as chirality therein subsumes the SM

FACT OR FARCE? [Charge Current only]

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

~ O(6) are independent

IMPORTANT CAUTION

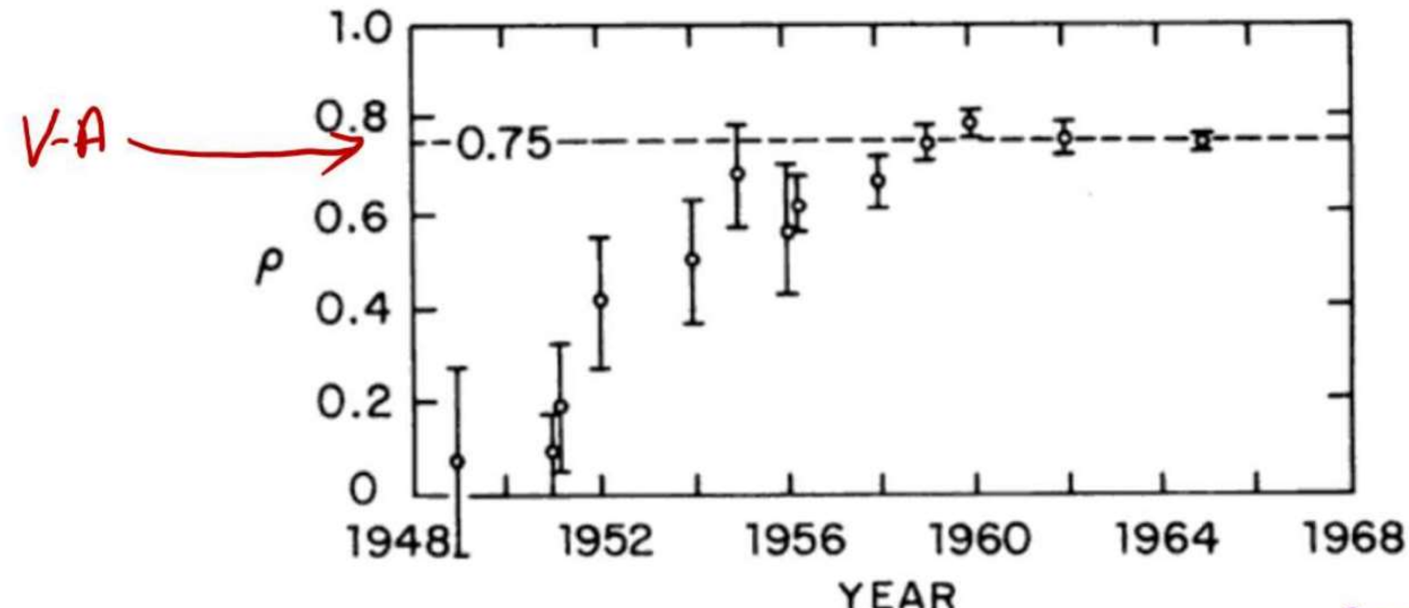
4

experiment	tag method	τ decay mode	R_D	R_D^*	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; see 2002.12910

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 TD Lee + CS Wu

Conclusions

Recently also b_baryons used but low stats

LHCb-PAPER-2021-044
arxiv:2201:03497

- The decay $\Lambda_b^0 \rightarrow \Lambda_c^+ \tau^- \overline{\nu}_\tau$ has been observed for the first time with a significance of 6.1 σ
  - $\mathcal{K}(\Lambda_c^+)$ = 2.46 ± 0.27 (stat) ± 0.40 (syst)
  - $\mathcal{B}(\Lambda_b^0 \rightarrow \Lambda_c^+ \tau^- \overline{\nu}_\tau)$= (1,50 ± 0,16 (stat) ± 0,25 (sys) ± 0,23 (ext)) %
  - $\mathcal{R}(\Lambda_c^+)$=0.242 ± 0.026 (stat) ± 0.040 (syst) ± 0.059 (ext)
- Everything compatible with SM (~1 σ below)
- A fraction of the parameter space of effective theories with only one vector, axial-vector or tensor couplings can be excluded

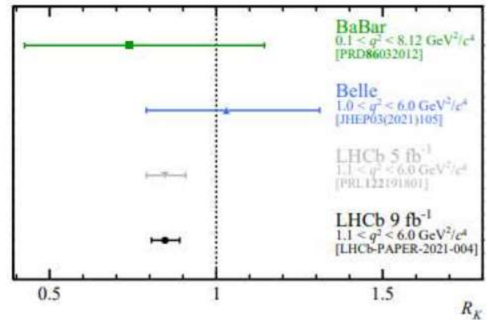
R_K with full Run1 and Run2 dataset

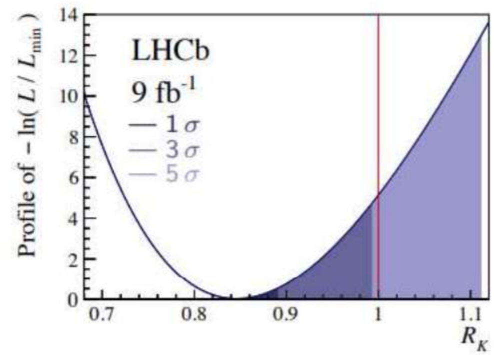
[LHCb-PAPER-2021-004]**Submitted to Nature Physics**

→ unchanged

$$R_K = 0.846\ ^{+0.042}_{-0.039}\ (\text{stat})\ ^{+0.013}_{-0.012}\ (\text{syst})$$

- *p*-value under SM hypothesis: 0.0010
  → Evidence of LFU violation at 3.1σ
- Compatibility with the SM obtained by integrating the profiled likelihood as a function of R_K above 1
  - Taking into account the 1% theory uncertainty on R_K [EPJC76(2016)8,440]





Previously (2019) $R_K = 2.5\sigma$ 5 → 9/fb

$$a_\mu(\mathrm{FNAL}) = 116\,592\,040(54) \times 10^{-11} \quad (0.46\,\mathrm{ppm}),$$

← Unchanged from BNL 2001, 2006

where the statistical, systematic, and fundamental constant uncertainties that are listed in Table II are combined in quadrature. Our result differs from the SM value by $3.3\,\sigma$ and agrees with the BNL E821 result. The combined experimental (Exp) average[68] is

Huge exptl step forward!

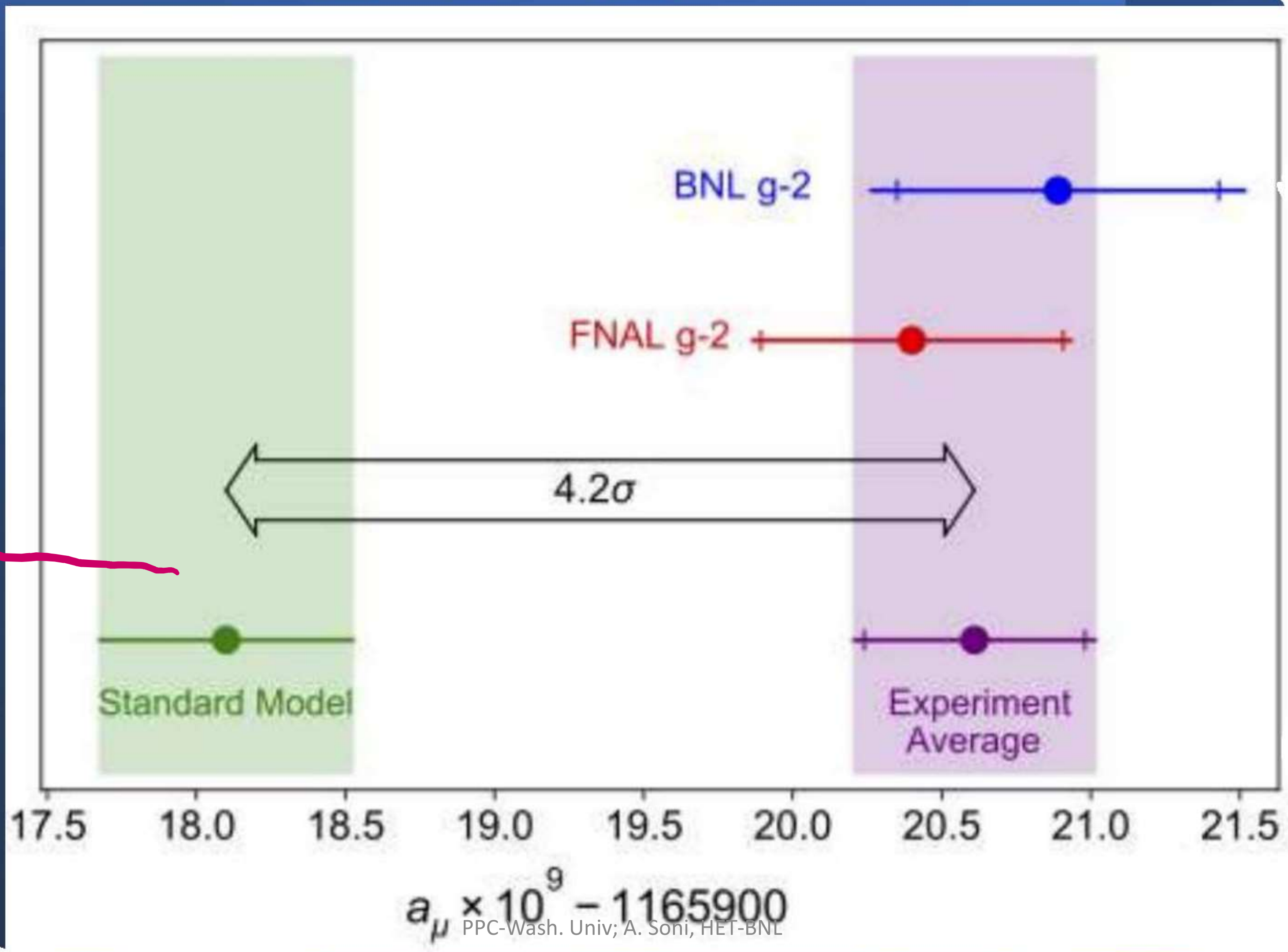
$$a_\mu(\mathrm{Exp}) = 116\,592\,061(41) \times 10^{-11} \quad (0.35\,\mathrm{ppm}).$$

" " → DATA Driven

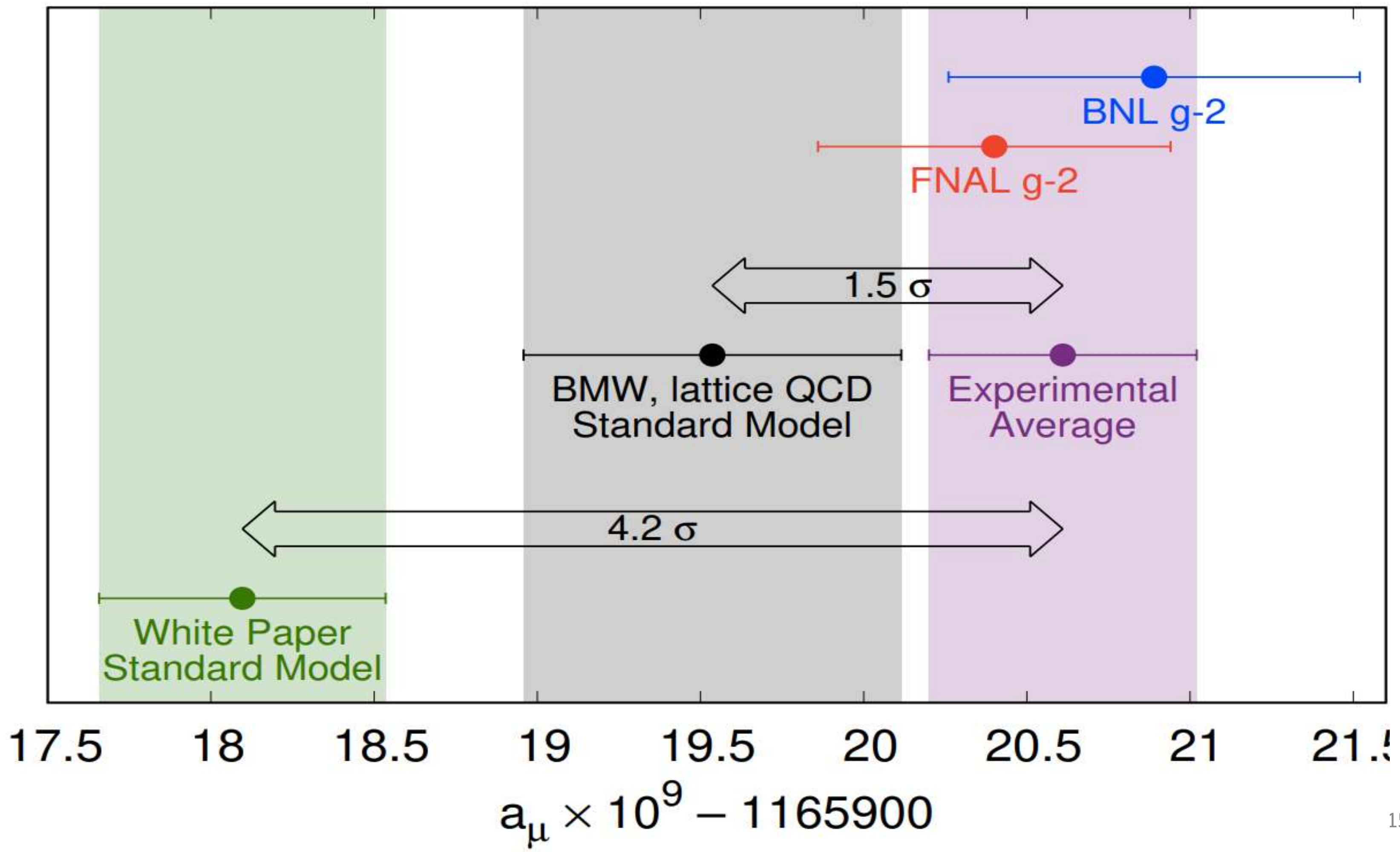
The difference, $a_\mu(\mathrm{Exp}) - a_\mu(\mathrm{SM}) = (251 \pm 59) \times 10^{-11}$, has a significance of $4.2\,\sigma$. These results are displayed in Fig. 4.

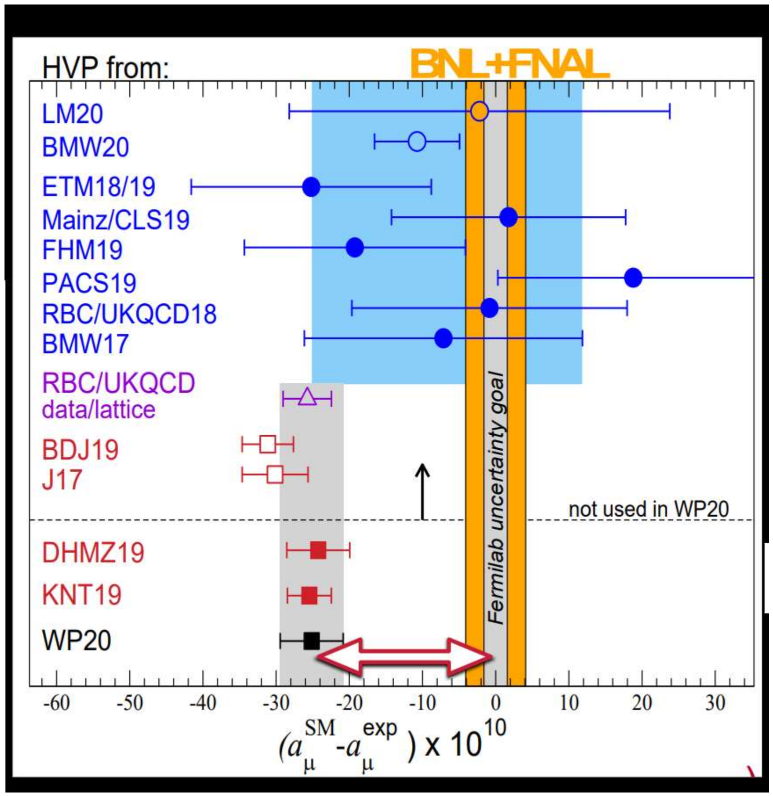
DATA DRIVEN

See White Paper



KALMAN SZABO (BMW) Talk @ "BNL"

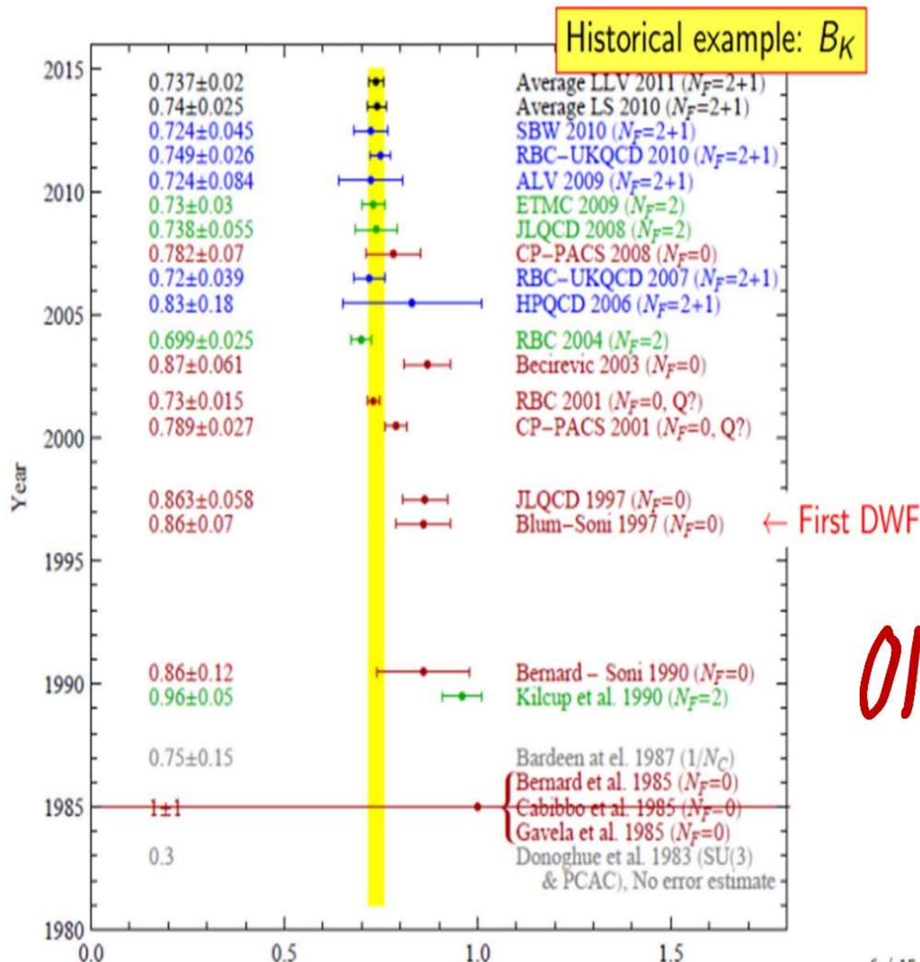



HVP from:
BNL+FNAL
LM20
BMW20
ETM18/19
Mainz/CLS19
FHM19
PACS19
RBC/UKQCD18
BMW17
RBC/UKQCD
data/lattice
BDJ19
J17
not used in WP20
DHMZ19
KNT19
WP20
Fermilab uncertainty goal
-60 -50 -40 -30 -20 -10 0 10 20 30
$(a_\mu^{SM} - a_\mu^{exp}) \times 10^{10}$

BDe
pheno21

POWER & PITFALLs of lattice calculations: few examples from personal experience

Power of the lattice: Only method to systematically reduce the NP error!



6 / 15

AB-initio Calculat

$$B_K = \frac{\langle K | (\bar{s} \ldots)^2 | \bar{K} \rangle}{8/3 f_K^2 m_K^2}$$

ONE ILLUSTRATION

Standard Model Prediction for Direct *CP* Violation in $K \to \pi\pi$ Decay

Z. Bai,[1] T. Blum,[2] P. A. Boyle,[3] N. H. Christ,[1] J. Frison,[3] N. Garron,[4] T. Izubuchi,[5,6] C. Jung,[5] C. Kelly,[6] C. Lehner,[5] R. D. Mawhinney,[1] C. T. Sachrajda,[7] A. Soni,[5] and D. Zhang[1]

(RBC and UKQCD Collaborations)

[1]*Physics Department, Columbia University, New York, New York 10027, USA*
[2]*Physics Department, University of Connecticut, Storrs, Connecticut 06269-3046, USA*
[3]*SUPA, School of Physics, The University of Edinburgh, Edinburgh EH9 3JZ, United Kingdom*
[4]*School of Computing & Mathematics, Plymouth University, Plymouth PL4 8AA, United Kingdom*
[5]*Physics Department, Brookhaven National Laboratory, Upton, New York 11973, USA*
[6]*RIKEN-BNL Research Center, Brookhaven National Laboratory, Upton, New York 11973, USA*
[7]*School of Physics and Astronomy, University of Southampton, Southampton SO17 1BJ, United Kingdom*
(Received 4 June 2015; revised manuscript received 18 August 2015; published 17 November 2015)

We report the first lattice QCD calculation of the complex kaon decay amplitude A_0 with physical kinematics, using a $32^3 \times 64$ lattice volume and a single lattice spacing a, with $1/a = 1.3784(68)$ GeV. We find $\mathrm{Re}(A_0) = 4.66(1.00)(1.26) \times 10^{-7}$ GeV and $\mathrm{Im}(A_0) = -1.90(1.23)(1.08) \times 10^{-11}$ GeV, where

correlated, single-state fit over the interval $6 \le t \le 25$, obtaining $\chi^2/\mathrm{dof} = 1.56(68)$. A correlated, two-state fit using $3 \le t \le 25$ gives consistent results. We find $M_K = 490.6(2.4)$ MeV and $E_{\pi\pi} = 498(11)$ MeV. Using the Lüscher quantization condition [39,40] we find an $I = 0$, $\pi\pi$ phase shift $\delta_0 = 23.8(4.9)(1.2)^\circ$, smaller than phenomenological expectations [41,42]. Here, the first error is

TABLE II. Representative, fractional systematic errors for the individual operator contributions to $\mathrm{Re}(A_0)$ and $\mathrm{Im}(A_0)$.

Description	Error	Description	Error
Finite lattice spacing	12%	Finite volume	7%
Wilson coefficients	12%	Excited states	$\leq 5\%$
Parametric errors	5%	Operator renormalization	15%
Unphysical kinematics	$\leq 3\%$	Lellouch-Lüscher factor	11%
Total (added in quadrature)			27%

PHYSICAL REVIEW D 102, 054509 (2020)

Editors' Suggestion   Featured in Physics

Direct CP violation and the $\Delta I = 1/2$ rule in $K \to \pi\pi$ decay from the standard model

R. Abbott,[1] T. Blum,[2,3] P. A. Boyle,[4,5] M. Bruno,[6] N. H. Christ,[1] D. Hoying,[3,2] C. Jung,[4] C. Kelly,[4] C. Lehner,[7,4] R. D. Mawhinney,[1] D. J. Murphy,[8] C. T. Sachrajda,[9] A. Soni,[4] M. Tomii,[2] and T. Wang[1]

(RBC and UKQCD Collaborations)

[1]Physics Department, Columbia University, New York, New York 10027, USA
[2]Physics Department, University of Connecticut, Storrs, Connecticut 06269-3046, USA
[3]RIKEN-BNL Research Center, Brookhaven National Laboratory, Upton, New York 11973, USA
[4]Brookhaven National Laboratory, Upton, New York 11973, USA
[5]SUPA, School of Physics, The University of Edinburgh, Edinburgh EH9 3JZ, United Kingdom
[6]Theoretical Physics Department, CERN, 1211 Geneve 23, Switzerland
[7]Universität Regensburg, Fakultät für Physik, 93040 Regensburg, Germany
[8]Center for Theoretical Physics, Massachusetts Institute of Technology, Boston, Massachusetts 02139, USA
[9]School of Physics and Astronomy, University of Southampton, Southampton SO17 1BJ, United Kingdom

(Received 18 May 2020; accepted 13 August 2020; published 17 September 2020)

We present a lattice QCD calculation of the $\Delta I = 1/2$, $K \to \pi\pi$ decay amplitude A_0 and ε', the measure of direct CP violation in $K \to \pi\pi$ decay, improving our 2015 calculation [1] of these quantities. Both calculations were performed with physical kinematics on a $32^3 \times 64$ lattice with an inverse lattice spacing of $a^{-1} = 1.3784(68)$ GeV. However, the current calculation includes nearly 4 times the statistics and numerous technical improvements allowing us to more reliably isolate the $\pi\pi$ ground state and more accurately relate the lattice operators to those defined in the standard model. We find $\mathrm{Re}(A_0) = 2.99(0.32)(0.59) \times 10^{-7}$ GeV and $\mathrm{Im}(A_0) = -6.98(0.62)(1.44) \times 10^{-11}$ GeV, where the errors are statistical and systematic, respectively. The former agrees well with the experimental result $\mathrm{Re}(A_0) = 3.3201(18) \times 10^{-7}$ GeV. These results for A_0 can

In Ref. [17] we demonstrate that a simultaneous fit to the 3×3 matrix of $\pi\pi$ two-point correlation functions in which the two-pion states are created or annihilated by one of these three operators, results in a substantial reduction in the statistical and systematic errors. We find that, once the excited states are taken into account, the resulting $I = 0$ $\pi\pi$-scattering phase shift at $E_{\pi\pi}^{\rm lat} = 479.5$ MeV is $\delta_0(E_{\pi\pi}^{\rm lat}) = 32.3(1.0)(1.8)^\circ$, where the errors are statistical and systematic, respectively. This significant increase in our result for $\delta_0(E_{\pi\pi}^{\rm lat})$ brings us into much closer agreement with the dispersive prediction, which at our present value of $E_{\pi\pi}^{\rm lat}$ is $\delta_0(E_{\pi\pi}^{\rm lat})_{\rm disp} = 35.9^\circ$, obtained using Eqs. (17.1)–(17.3) of Ref. [16] with $m_\pi = 139.6$ MeV. (We refer the reader to Ref. [16] for estimates of the error on the dispersive prediction.) In this paper we present results for the $\Delta I = 1/2$ $K \to \pi\pi$ matrix elements obtained from our expanded dataset of 741 measurements, using all three $\pi\pi$ interpolating operators.

Conclusion on "SM" theory value for muon (g-2)

- 1. Given the significant discrepancy of the BMW lattice result with the data-driven R-ratio method as well as some tension amongst the lattice calculations, it is much better to wait till there is a consensus value in the continuum limit amongst the different lattice collabs.

- 2. It is difficult to find significant fault with the R-ratio method of the WP; from all accounts it appears that the WP results are fairly cautious.

PHYSICAL REVIEW D **96,** 095010 (2017)

$R_{D^{(*)}}$ anomaly: A possible hint for natural supersymmetry with *R*-parity violation

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

[1]*Department of Physics, University of Cincinnati, Cincinnati, Ohio 45221, USA*

[2]*Department of Physics and McDonnell Center for the Space Sciences, Washington University, St. Louis, Missouri 63130, USA*

[3]*Physics Department, Brookhaven National Laboratory, Upton, New York 11973, USA*

(Received 5 July 2017; published 15 November 2017)

Recently, several *B*-physics experiments have reported an appreciable deviation from the standard model (SM) in the tree-level observables $R_{D^{(*)}}$; the combined weighted average now stands at $\approx 4\sigma$. We first show the anomaly necessarily implies model-independent collider signals of the form $pp \to b\tau\nu$ that should be expeditiously searched for at ATLAS/CMS as a complementary test of the anomaly. Next we suggest a possible interconnection of the anomaly with the radiative stability of the standard model Higgs boson and point to a minimal effective supersymmetric scenario with *R*-parity violation as the underlying cause. We also comment on the possibility of simultaneously explaining the recently reported $R_{K^{(*)}}$ anomaly in this setup.

If current hints of LUV survive the test of time

- **Under such a watershed departure from the past, we believe, it is very likely that nature is also trying to address some long-standing, persistent issue(s) with the SM. One such basic concern with the SM is the fact that it is exceedingly fine-tuned, i.e. unnatural due to radiative instability of the Higgs which primarily originates from the heaviness of the top quark, a member of the third generation.**

PHYSICAL REVIEW D **96,** 095010 (2017)

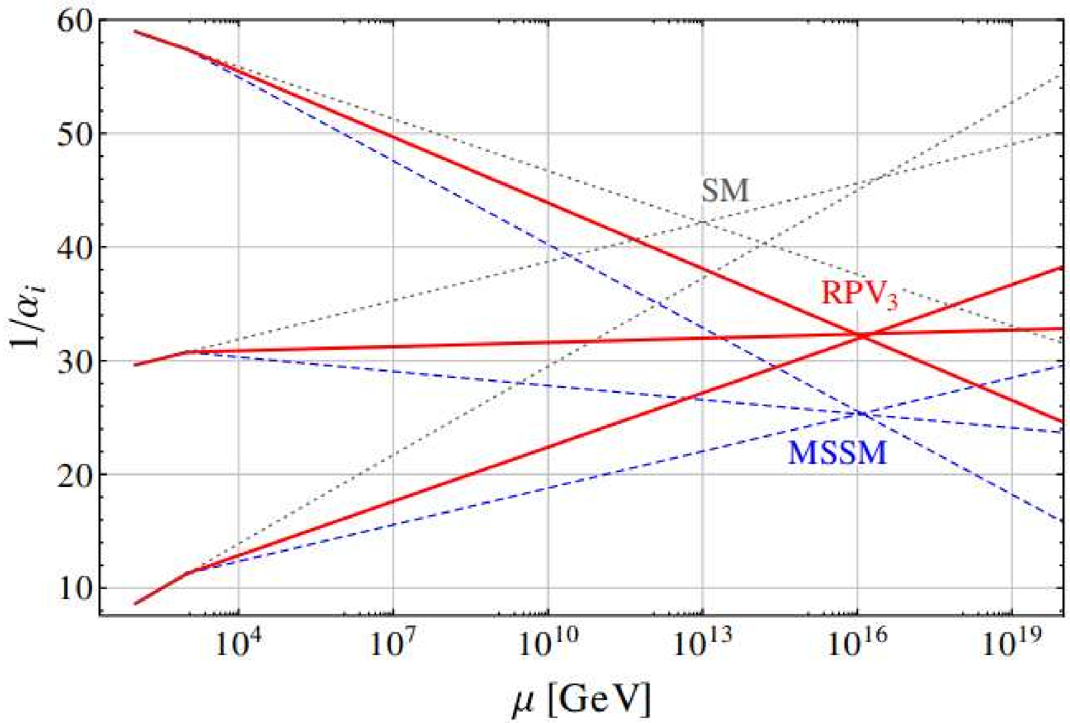


FIG. 2. RG evolution of the gauge couplings in the SM, MSSM and in our natural RPV SUSY scenario.

RPV_3

3rd gen superpartners are lightest

Generalization of YM=> RPV LUV arises rather naturally

- Note also that, as a necessary **generalization of the Yang-Mills theory [42], all the interactions allowed by the enlarged internal [Bose-Fermi] symmetry readily remove the accidental flavor symmetry of the SM and lead naturally to LFUV**.

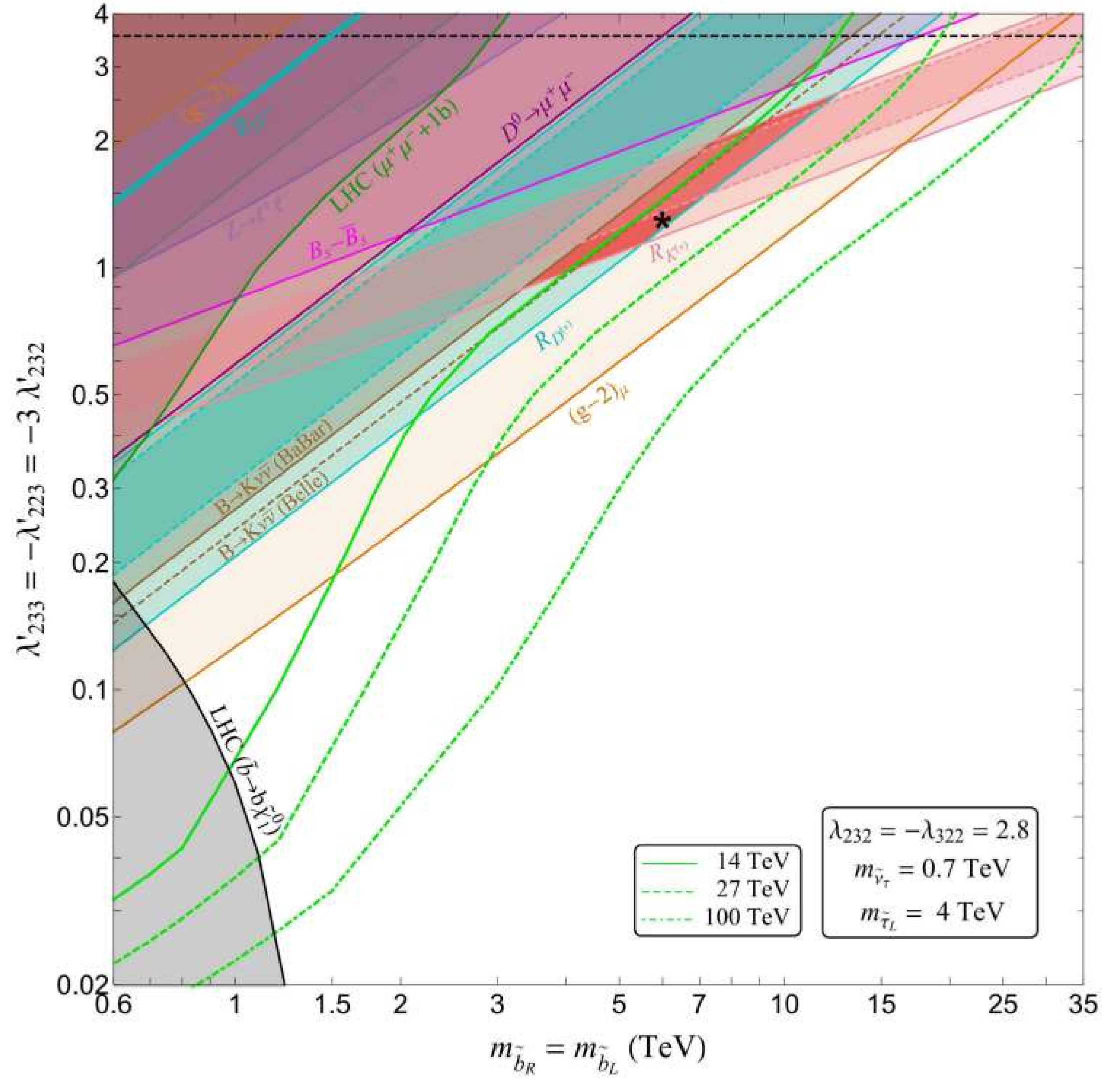
Hints of Natural Supersymmetry in Flavor Anomalies?

P. S. Bhupal Dev,[1,*] Amarjit Soni,[2,†] and Fang Xu[1,‡]

[1] *Department of Physics and McDonnell Center for the Space Sciences, Washington University, St. Louis, MO 63130, USA*

[2] *Physics Department, Brookhaven National Laboratory, Upton, NY 11973, USA*

The recent results from the Fermilab muon $g-2$ experiment, as well as the persisting hints of lepton flavor universality violation in B-meson decays, present a very strong case for flavor-nonuniversal new physics beyond the Standard Model. We assert that a minimal R-parity violating supersymmetric scenario with relatively light third-generation sfermions (dubbed as 'RPV3') provides a natural, well-motivated framework for the simultaneous explanation of all flavor anomalies, while being consistent with a multitude of low-energy flavor constraints, as well as with limits from high-energy collider searches. We further propose complementary tests and distinct signatures of this scenario in the high-p_T searches at current and future colliders. Specifically, we find that an sbottom in the mass range of 2–12 TeV accounts for $R_{D^{(*)}}$ and $R_{K^{(*)}}$ flavor anomalies and it only plays a minor role in the $(g-2)_\mu$ anomaly, whereas a sneutrino with mass between 0.7–1 TeV is the dominant player for $(g-2)_\mu$. In this context, we propose specific collider signatures of sbottom via its decays to $\bar{t}(t)\mu^+\mu^-$, and of sneutrino pairs with their decays leading to a highly distinctive and spectacular four-muon final state, which can be used to completely probe the RPV3 parameter space of interest.



(a) BP1 (Red)

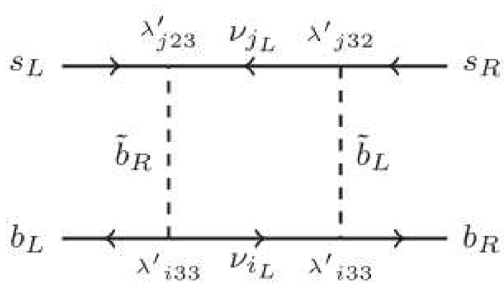
Note the multitude of LEC, in part. Bs mixing and B=>K(*) nu nu………

FIG. 5. Three RPV3 benchmark cases in the $(m_{\tilde{b}_R}, \lambda'_{233})$ parameter space explaining the flavor anomalies. The cyan, pink and orange shaded regions with solid (dashed) boundaries explain the $R_{D^{(*)}}$, $R_{K^{(*)}}$ and $(g-2)_\mu$ anomalies at 3σ (2σ) respectively. The black-shaded region is excluded by the current LHC search for sbottoms in the bottom+neutralino channel, whereas the dark green-shaded region is the LHC exclusion derived from a $\mu^+\mu^- + 1b$ search. The horizontal dotted line shows the perturbativity limit of $\sqrt{4\pi}$. Other shaded regions show the relevant low-energy flavor constrains on the parameter space from $B \to K\nu\bar{\nu}$ (brown), $B_s - \bar{B}_s$ mixing (magenta), $D^0 \to \mu^+\mu^-$ (purple), $b \to s\gamma$ (grey) and $Z \to \ell^+\ell^-$ (violet). The allowed overlap regions simultaneously explaining the $R_{D^{(*)}}$, $R_{K^{(*)}}$ and $(g-2)_\mu$ anomalies are shown by the red (top), yellow (bottom left) and blue (bottom right) shaded regions for the three benchmark cases. The $*$ mark on the top panel gives representative values of $m_{\tilde{b}_R}$ and λ'_{233} in the BP1 scenario that are used in Fig. 6. The green solid, dashed and dot-dashed contours respectively show the 2σ sensitivities of the 14 TeV LHC, 27 TeV and 100 TeV pp colliders in the $\bar{t}\mu^+\mu^-$ channel discussed in the text.

$$\mathcal{L}_{LQD} = \lambda'_{ijk}[\tilde{\nu}_{iL}\bar{d}_{kR}d_{jL} + \tilde{d}_{jL}\bar{d}_{kR}\nu_{iL} + \tilde{d}^*_{kR}\bar{\nu}^c_{iL}d_{jL} - \tilde{e}_{iL}\bar{d}_{kR}u_{jL} - \tilde{u}_{jL}\bar{d}_{kR}e_{iL} - \tilde{d}^*_{kR}\bar{e}^c_{iL}u_{jL}] + \text{H.c.} \tag{21}$$

$$\mathcal{L}_{LLE} = \frac{1}{2}\lambda_{ijk}[\tilde{\nu}_{iL}\bar{e}_{kR}e_{jL} + \tilde{e}_{jL}\bar{e}_{kR}\nu_{iL} + \tilde{e}^*_{kR}\bar{\nu}^c_{iL}e_{jL} - (i \leftrightarrow j)] + \text{H.c.} \tag{22}$$

$$\Delta a_\mu = \frac{m_\mu^2}{96\pi^2}\sum_{k=1}^{3}\left(\frac{2(|\lambda_{32k}|^2 + |\lambda_{3k2}|^2)}{m^2_{\tilde{\nu}_\tau}} - \frac{|\lambda_{3k2}|^2}{m^2_{\tilde{\tau}_L}} - \frac{|\lambda_{k23}|^2}{m^2_{\tilde{\tau}_R}} + \frac{3|\lambda'_{2k3}|^2}{m^2_{\tilde{b}_R}}\right).$$



(c)

ADSS '20

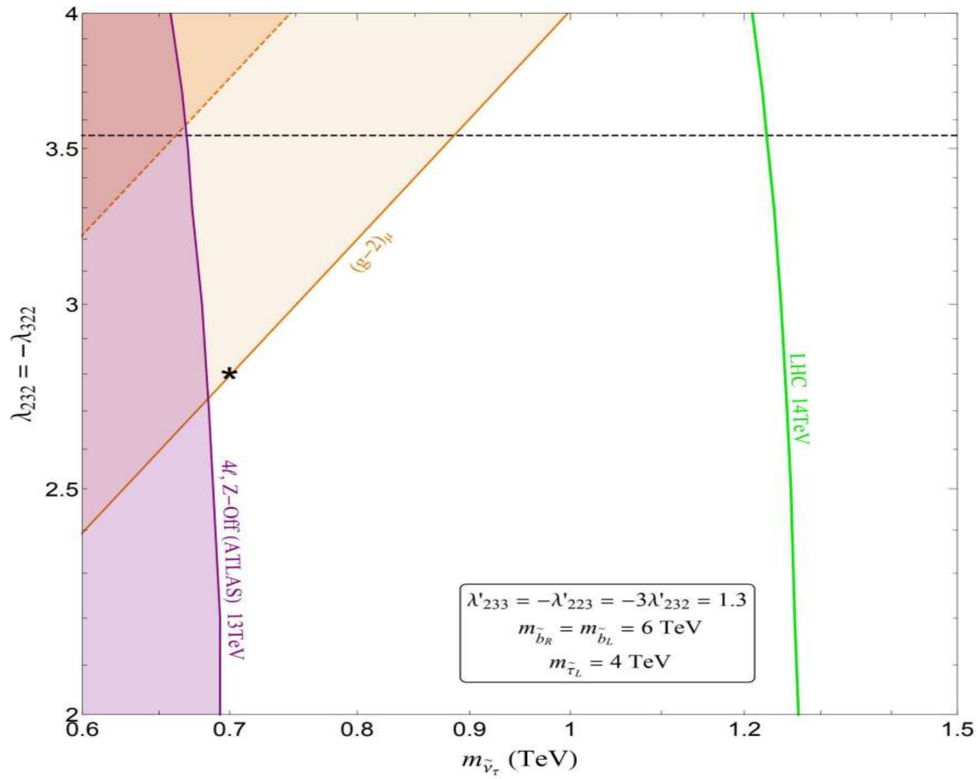


FIG. 6. The $(g-2)_\mu$-preferred region (orange-shaded) of the RPV3 parameter space. The purple-shaded region is excluded by a 13 TeV LHC multi-lepton search [98], whereas the green curve is the 14 TeV HL-LHC sensitivity. The horizontal dashed line is the perturbativity limit. The $*$ gives representative values of $m_{\tilde{\nu}_\tau}$ and λ_{232} used in Fig. 5.

Summary /Outlook/Conclusion

- **Hints of LUV are extremely interesting, intriguing and important.** ***There is nothing we know of that tells us that these hints cannot be true.***
- ***Babar deviations for RD(*) are the largest amongst the three experiments. Should this be a concern?***
- ***For the above reason as well as for confirming (or refuting) LHCb results on RK(*), Belle-II results with increased luminosity are eagerly awaited. Also correlated RD-RD* from LHCb and from Belle-II would help a lot.***
- **An update from Fermilab with much larger data set on muon (g-2) is anticipated in some months.**

- **Fortunately significant experimental/theoretical progress should occur in < ~2 years and would be greatly welcome. Only one of the 3 anomalies need survive the test of time for some BSM to become relevant.**

- **Meantime, 3rd generation centric RPV_SUSY is an interesting theoretical framework that can accommodate such deviations from SM if they survive**

Conclusion

B Dev@LBL
April 2022

- Mounting evidence for the violation of lepton flavor universali[ty].
  [Crivellin, Hoferichter, 2111.1273 (Science '21)]
- Can be explained by invoking BSM physics.
- Leptoquarks and RPV-SUSY remain as the most attractive scenarios for a simultaneous explanation of B-anomalies and muon $g-2$.
- Personal choice: **RPV3** – motivated by Higgs naturalness and other beautiful features of SUSY, while being consistent with null searches at the LHC.
  - Removes the accidental flavor symmetry of the SM.
  - Same chiral structure as the SM $\Longrightarrow$ correct D^* and τ polarizations, as well as $R_K - R_{K(*)}$ correlation come automatically.
  - Highly predictive and testable at Belle II, LHCb and high-p_T LHC experiments.
  - Improved lattice input for $B \to K\nu\bar{\nu}$ and $B_s - \overline{B}_s$ will be crucial.
  - **Flavor anomalies might be providing the first experimental hint of SUSY!**

RPV-SUSY
Subsumes
chirality SM

XTRAS

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

Parameters and benchmark scenario

- Furthermore, assume $(\lambda_{232}, \lambda'_{233} = -\lambda'_{223} = -3\lambda'_{232}, m_{\tilde{b}_R} = m_{\tilde{b}_L}, m_{\tilde{\nu}_\tau}, m_{\tilde{\tau}_L} = 4\mathrm{TeV})$ then we can plot the anomalies and constraints in the two-dimensional parameter space: $(\lambda'_{233}, m_{\tilde{b}_R})$ and $(\lambda_{232}, m_{\tilde{\nu}_\tau})$
  - $m_{\tilde{b}_R} = m_{\tilde{b}_L}$ for simplicity.
  - $m_{\tilde{\tau}_L}$ has opposite contribution for $(g-2)_\mu$. The influence is not important as long as $m_{\tilde{\tau}_L} \gtrsim O(1\mathrm{TeV})$. Here we choose 4 TeV.
  - $\lambda'_{233} = -\lambda'_{223} \Leftarrow \lambda'_{233}$, λ'_{223} and $m_{\tilde{b}_R}$ are the only parameters that influence $R_{D^{(*)}}$ and $R_{K^{(*)}}$ in our scenario. Assuming $\lambda'_{233} = \epsilon_1 \lambda'_{223}$, we found that $\epsilon_1 \sim (-3, -1)$ will give an overlap region of $R_{D^{(*)}}$ and $R_{K^{(*)}}$. When $|\epsilon_1|$ decrease, the coupling λ'_{233} of the overlap region will also decrease, so we choose $\epsilon_1 = -1$ here.
  - $\lambda'_{233} = -\lambda'_{223} = -3\lambda'_{232} \Leftarrow \lambda'_{233}$, λ'_{223}, λ'_{232}, $m_{\tilde{b}_R}$ and $m_{\tilde{b}_L}$ are relevant for the constraints of $B \to K\nu\bar{\nu}$, $B_s - \overline{B}_s$ mixing and $D^0 \to \mu^+\mu^-$. Assuming $\lambda'_{233} \approx -\lambda'_{223} = \epsilon_2 \lambda'_{232}$, we found that $\epsilon_2 \sim (-6, -2)$, where $\epsilon_2 = -3$ gives the best fit.

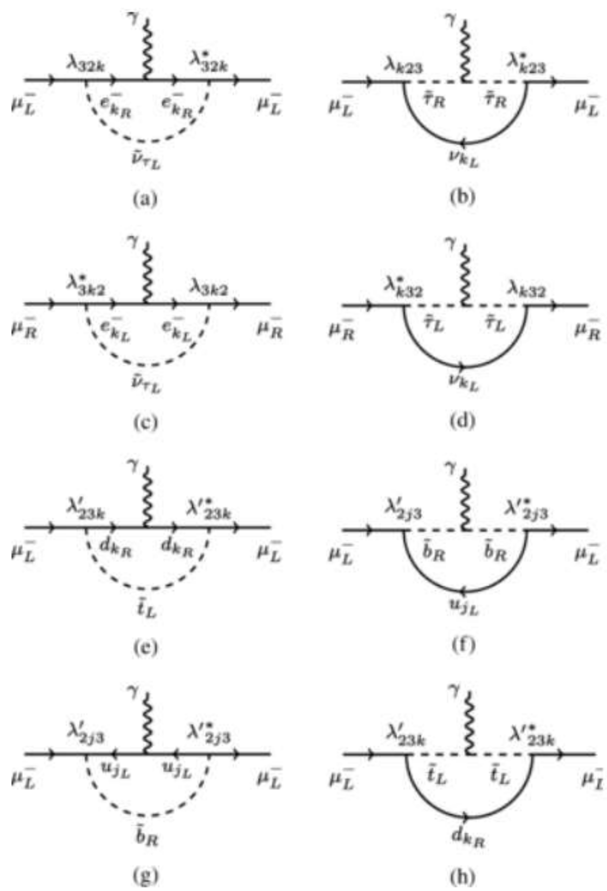
RECAP

- **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'** → Total 3ν's/event
- **2 with tau => hadron + nu** → 2ν's/event
- **Each and everyone of the 11 experimental results seem to imply tau is NOT just a heavy muon(electron) as dictated by SM.**
- **Does it mean then a breakdown of LU in charge currents?**

Similarly, we do not include the $(g-2)_e$ anomaly, because of a $> 5\sigma$ discrepancy between the Cs [73] and Rb [74] measurements of the fine-structure constant, so it is not clear which of these results should be used for comparison of the experimental value with the SM prediction [75] for $(g-2)_e$.

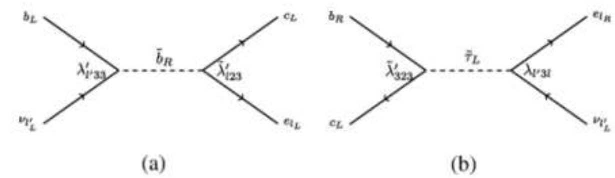
Explanation of anomalies in RPV3 SUSY

$(g-2)_\mu$ Kim, Kyae, Lee (PLB 2001)



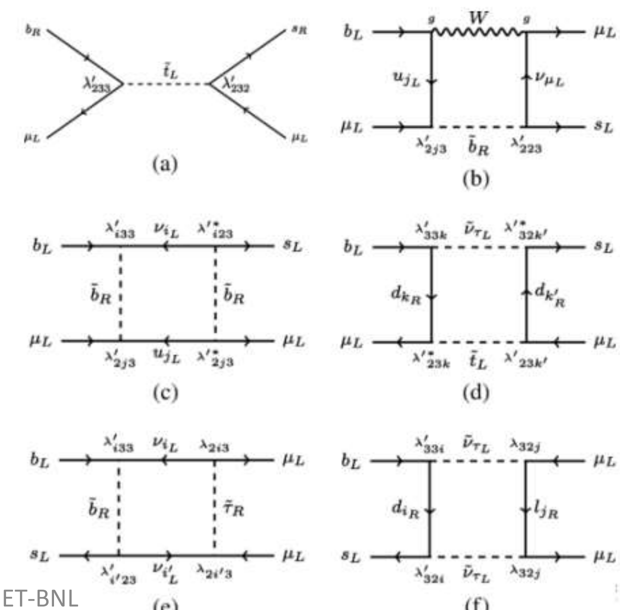
$R_{D^{(*)}}$ Deshpande, He (EPJC 2017); Altmannshofer, Dev, Soni (PRD 2017) etc.

RPV



RPV3

$R_{K^{(*)}}$ Das, Hati, Kumar, Mahajan (PRD 2017); Trifinopoulos (EPJC 2018) etc.



For $R_K + R_{K^*}$ BOTH Tree + LOOP ARE ESSENTIAL

PPC-Wash. Univ; A. Soni, HET-BNL

Crossing-symmetry on RD(*); RK(*)=> c ADS'[17]; ADSS[20]

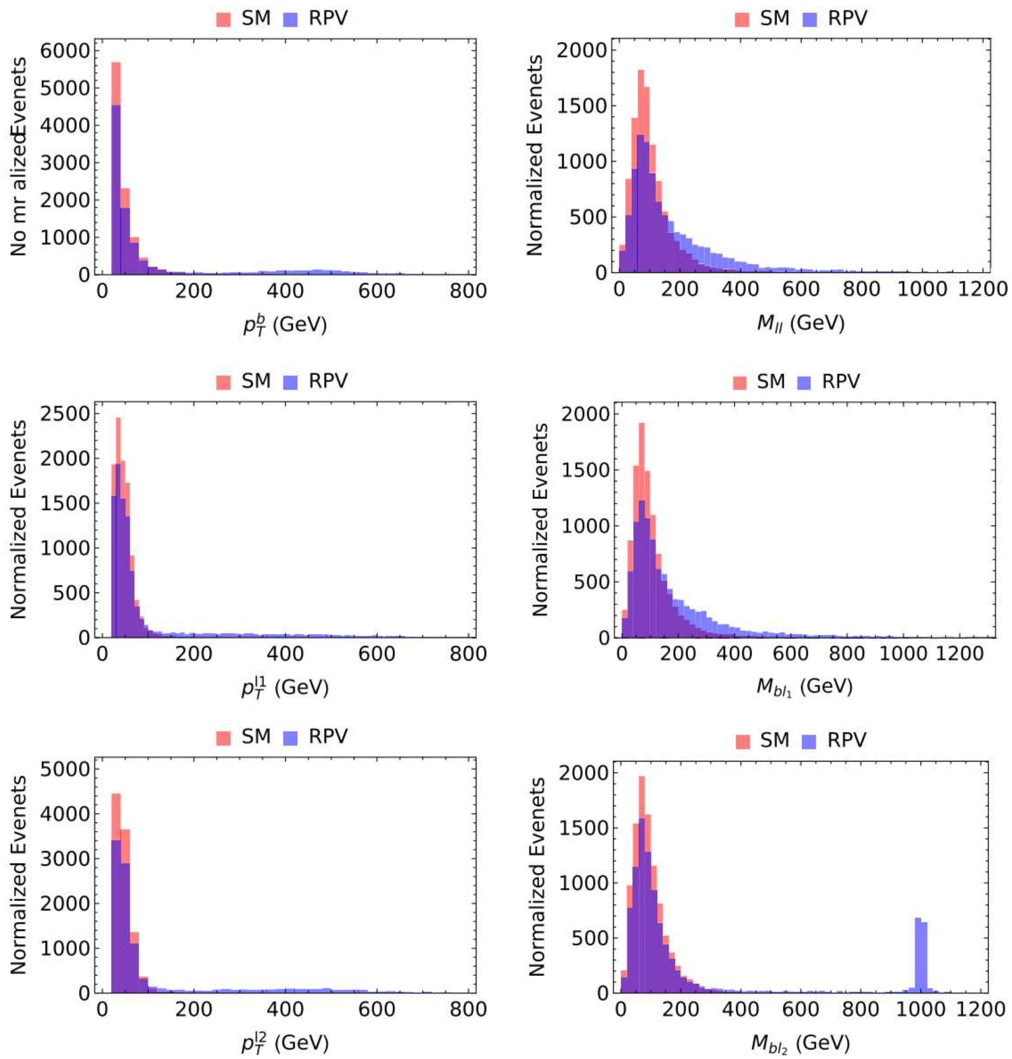
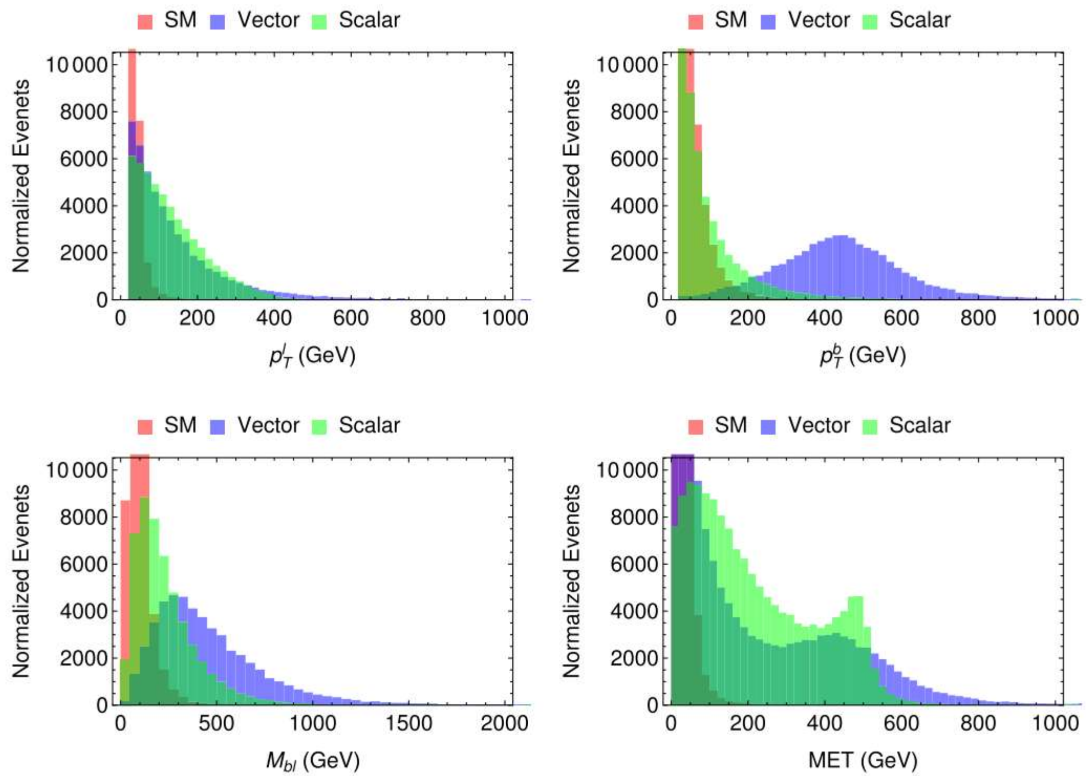


FIG. 23. Kinematic distributions for the $pp \to b\ell_1\ell_2$ signal in the RPV model (blue) and the corresponding SM background (red). The left panels show the transverse momentum distributions for the bottom quark and the two charged leptons, whereas the right panel shows the invariant mass distributions for the dilepton and the two bottom quark–lepton combinations. In the RPV3 model under consideration, the right combination of M_{bl} gives a peak at the squark mass, as shown in the last plot.



$c+g\to b\ell\nu$

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

RPV3 SUSY

- More natural to include RPV couplings. [Brust, Katz, Lawrence, Sundrum (JHEP '12)]
- Preserves gauge coupling unification. [Altmannshofer, BD, Soni (PRD '17)]
- **RPV3**: RPV SUSY with light 3rd-generation sfermions.
- Can naturally accommodate $R_{D^{(*)}}$ ($b \to c\tau\nu$) via *LQD* interactions. [Deshpande, He (EPJC '17); Altmannshofer, BD, Soni (PRD '17); Trifinopoulos (EPJC '18); Hu, Li, Muramatsu, Yang (PRD '19)]

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

- Can *simultaneously* explain $R_{K^{(*)}}$ ($b \to s\ell\ell$) by invoking *LLE* interactions, together with *LQD*. [Das, Hati, Kumar, Mahajan (PRD '17); Earl, Grégoire (JHEP '18); Trifinopoulos (EPJC '18); Hu, Huang (PRD '20); Altmannshofer, BD, Soni, Sui '20]

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

- Restricting to RPV3 and using some ansatz, we'll limit the number of independent λ' and λ couplings.

7'

B-anomalies in RPV3

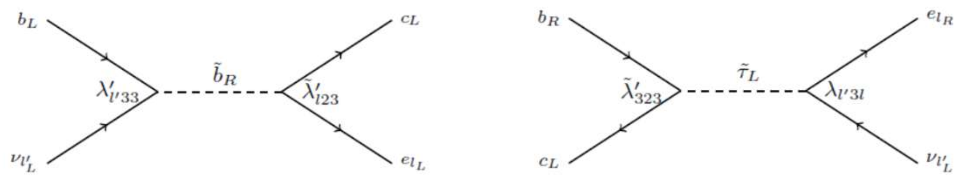


Figure: RPV3 contributions to $R_{D^{(*)}}$. [Deshpande, He (EPJC '17); Altmannshofer, BD, Soni (PRD '17); · · ·]

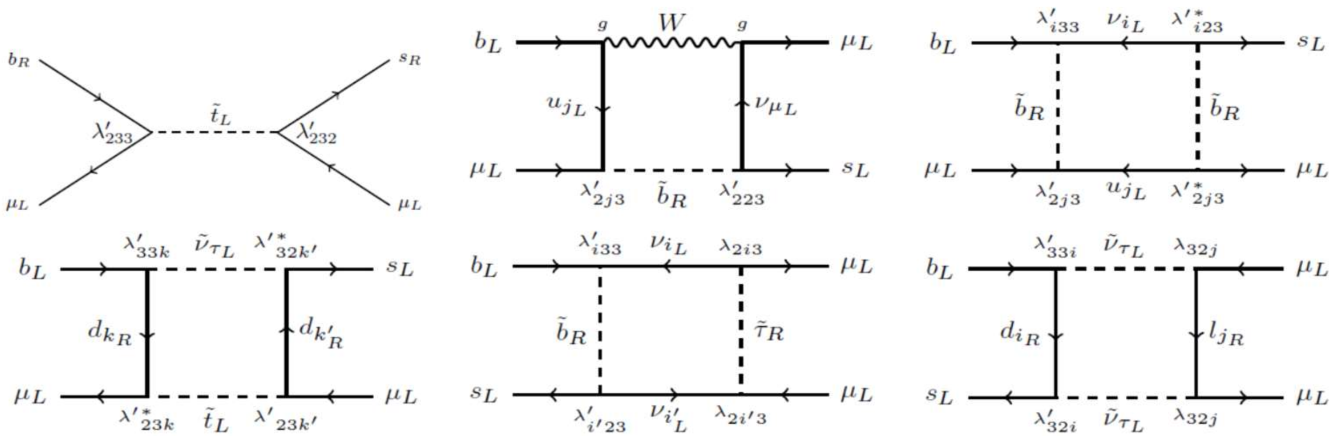


Figure: RPV3 contributions to $R_{K^{(*)}}$. [Das, Hati, Kumar, Mahajan (PRD '17); Trifinopoulos (EPJC '18)]

8

Muon $g-2$ and ANITA

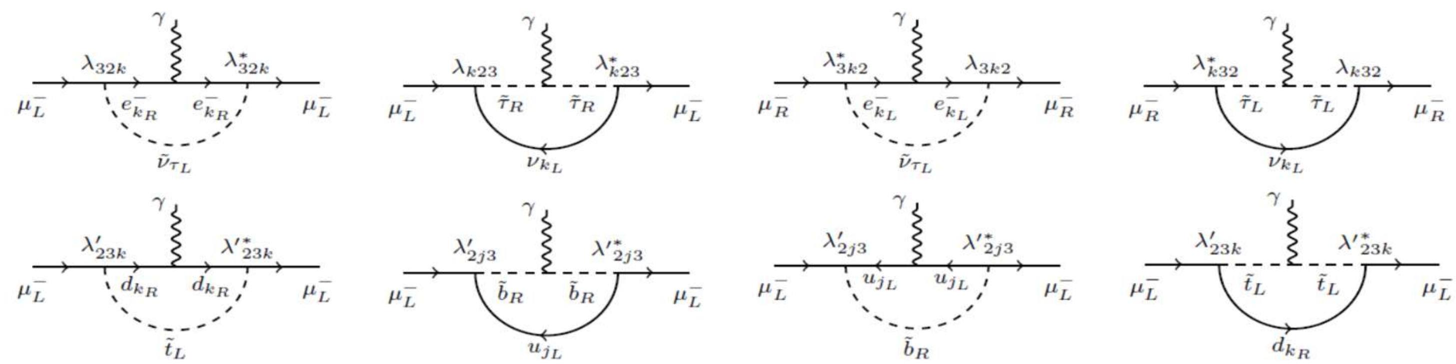


Figure: RPV3 contributions to $(g-2)_\mu$. [Kim, Kyae, Lee (PLB '01)]

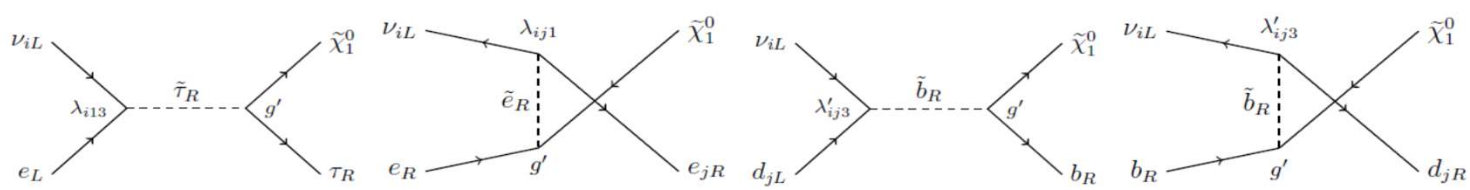
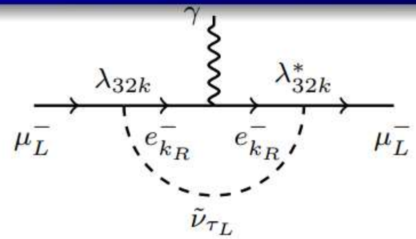
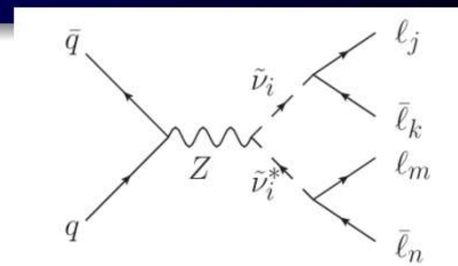


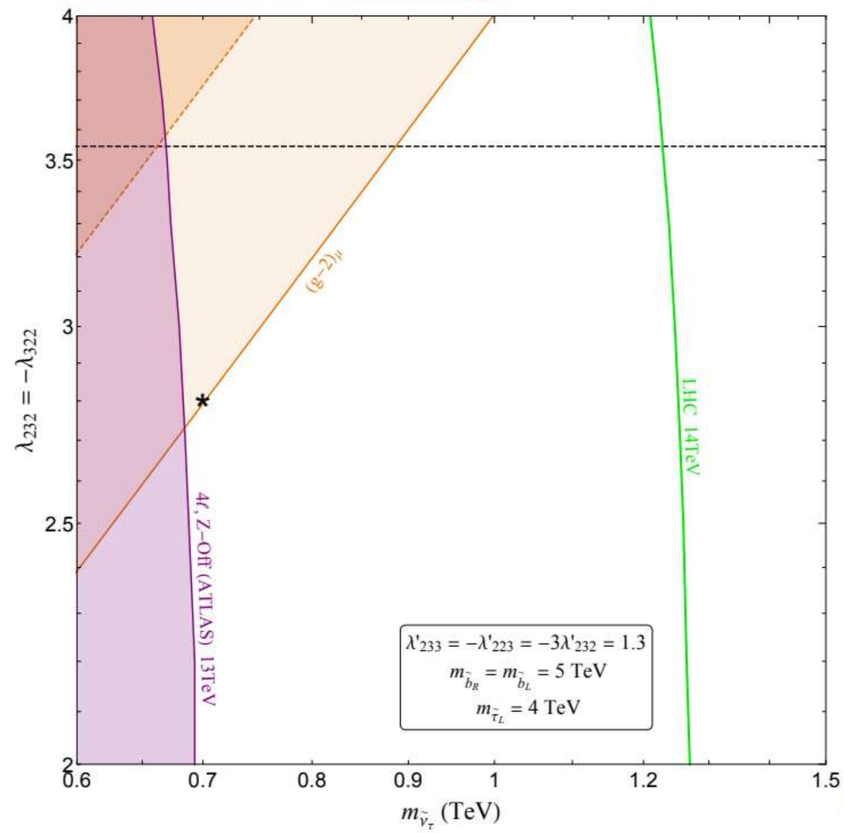
Figure: RPV3 contributions to ANITA anomalous events. [Collins, BD, Sui (PRD '19)]

9

An LHC Test of Muon $g-2$







[BD, Soni, Xu (2106.15647)]

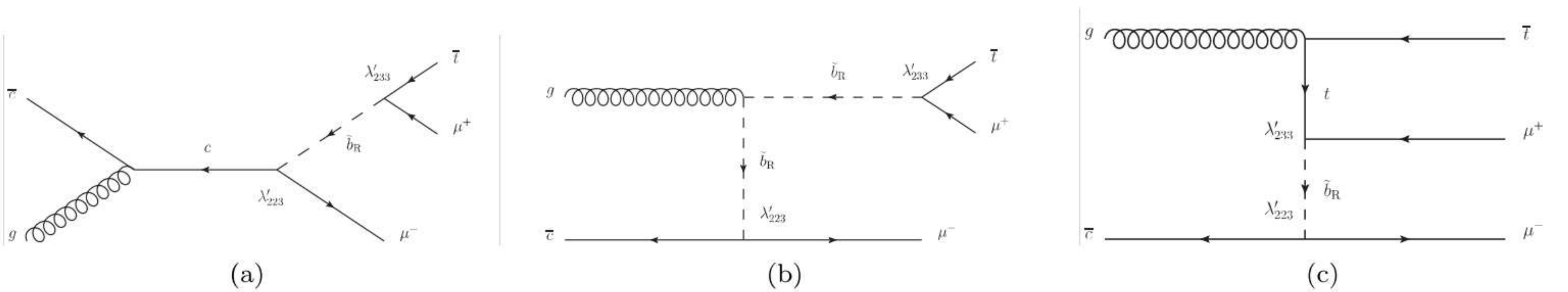


FIG. 7. Representative Feynman diagrams for the signal process $pp \to \bar{t}\mu^+\mu^-$. There are similar diagrams for the process $pp \to t\mu^+\mu^-$, however the SM background is larger for top-quark final states, compared to the anti-top, so we only consider the latter case for drawing the sensitivity contours in Fig. 5.