flavor anomalies: model independent and RPV3 considerations

ZPW2018 - Flavours: light, heavy and dark

University of Zurich

01/15/18

Based in part on 1704.06659 PRD with Wolfgang Altmannshofer and Bhupal Dev & in progress [ADS']

Anomalies galore!

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

216[PRL 2015] => ~1200 now => ~1400

[2.1σ (2.9σ?) => ??] …..few more months to new results

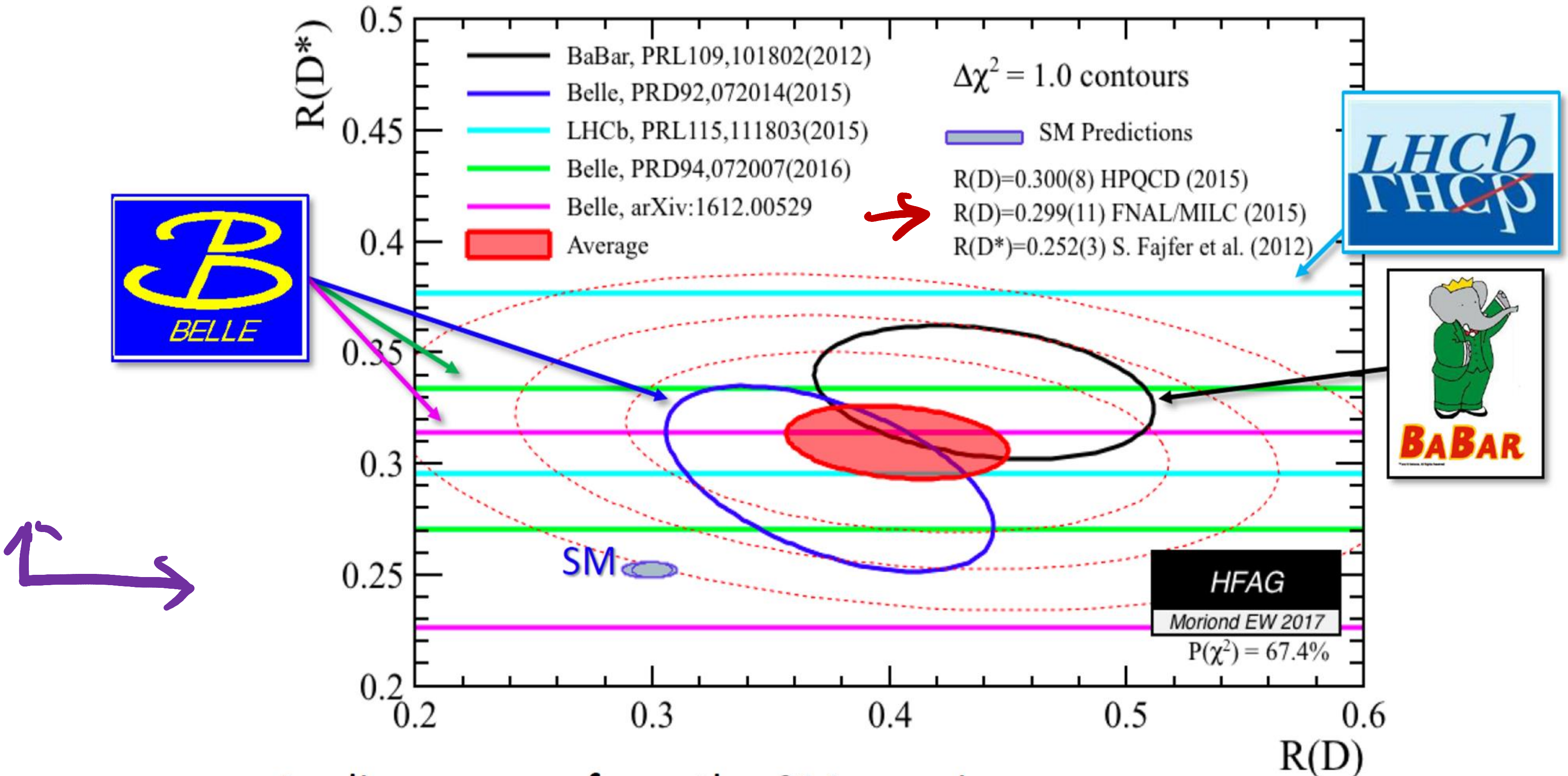
In seeking BSM scenarios it is important to keep all these [INCLUDING ε'] + Higgs radiative stability in mind

Outline

- **For each case:**
- **briefly mention reservations for expt & for theory/comments**
- **Model independent collider implications** ATLAS+CMS
- **Assuming NP is a source: An interesting, minimal setup for a BSM origin**
- **Summary & Outlook**

■ $R\left(D^{(*)}\right)$ by HFAG

Hirose [BELLE]@EW MORIOND Mar. 2017



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

Belle deviations quite mild

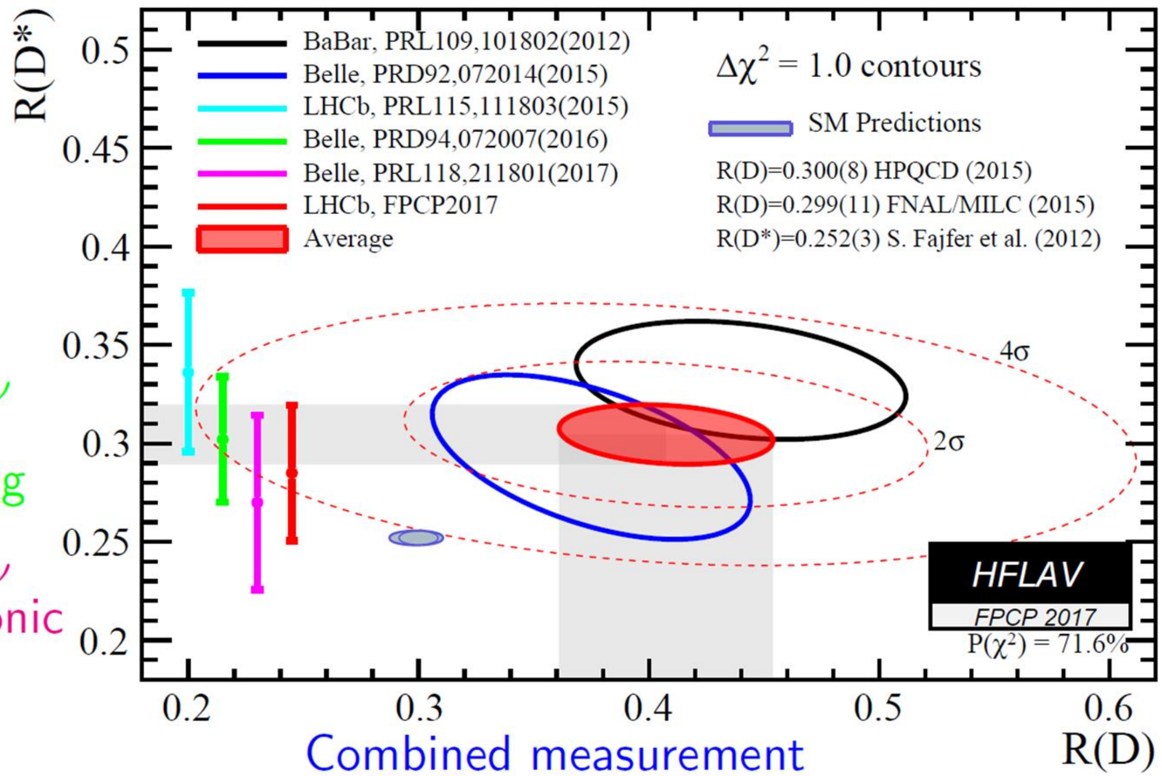
Concern on Experiments

- **Leptonic decays: τ=> μνν…total 3 ν's in event**
- **Higher D** etc resonances….use of theo models for subtraction of these backgrounds is fraught with danger…..Backgrounds should be measured experimentally for reliable estimate of errors**
- **Bearing that in mind, it is striking that LHCb new result june 2017: B=>D* τ ν; τ =>3π+ν is**

consistent with the SM at ~1-σ=> heightens anxiety about D….contaminations in τ=> μνν**

- **Furthermore, new Belle result with hadronic tau decay also consistent with SM well within 1 sigma!**
- **Claimed ~"4 sigma" probably not that solid**

New status of $\mathcal{R}(D^*)$



$B \to D^* \tau \nu$ with semi-leptonic tag

$B \to D^* \tau \nu$ with hadronic τ decays

Combined measurement of $\mathcal{R}(D)$ and $\mathcal{R}(D^*)$

TALK BY S. FALKE @ EPS 2017, July LIDO, IT

Excess still 4σ: central value moved towards SM;

on $\mathcal{R}(D^*)$, discrepancy increased from 3.0σ to 3.4σ

REGARDING (SM) THEORY

Concerns on SM-theory

- **Good news is that lattice[FERMIL-MILC] study largely confirms pheno calculations for R_D [our RBC-UKQCD, Witzel et al needs bit more time]**
- **For B=>D^* no complete lattice study so far; 4 rather than 2 FF, so , from the lattice perspective, anticipate appreciably larger errors than for B=>D**
- **Therefore, O(1%) errors in RD* (and in fact smaller than in RD) are difficult to understand; lattice results should come in some months**
- **HFAG should update the SM-theory with more realistic errors otherwise their fig is bit misleading**
- **Meantime recent phenomenological study of** Bernlochner, Ligeti, Papucci and Robinson, 1703.05330 [and even more recently…is/are very timely and greatly appreciated.
- **For now, for RD*, keeping these recent calculations and other reservations in mind best (conservative) guess is RD* ~ 0.258 +-0.020 [based on FERMIL-MILC error for RD]**

REMARKABLY: FOR RD* CENTRAL VALUE OF BEST THEORY ESTIMATE APPEARS BIT LOWER THAN ALL ~6 MEASUREMENTS!

+2 for R_D

Bottom line

- **NP or not depends critically not just on precise experiment but also reliable SM prediction from the lattice become mandatory….familiar story**

- **Experimental results often attained at huge cost can be used effectively, iff commensurate theory predictions are available…….mantra for past several decades**

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]

For simplicity: 1st strategy via ChPT

PHYSICAL REVIEW D VOLUME 32, NUMBER 9 1 NOVEMBER 1985

Application of chiral perturbation theory to $K \to 2\pi$ decays

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H. David Politzer and Mark B. Wise
Department of Physics, California Institute of Technology, Pasadena, California 91125

(Received 3 December 1984)

Chiral perturbation theory is applied to the decay $K \to 2\pi$. It is shown that, to quadratic order in meson masses, the amplitude for $K \to 2\pi$ can be written in terms of the unphysical amplitudes $K \to \pi$ and $K \to 0$, where 0 is the vacuum. One may then hope to calculate these two simpler amplitudes with lattice Monte Carlo techniques, and thereby gain understanding of the $\Delta I = \frac{1}{2}$ rule in K decay. The reason for the presence of the $K \to 0$ amplitude is explained: it serves to cancel off unwanted renormalization contributions to $K \to \pi$. We make a rough test of the practicability of these ideas in Monte Carlo studies. We also describe a method for evaluating meson decay constants which does not require a determination of the quark masses.

USED extensively on lattice for ~20 years ⇒ NLO J. LAIHO PhD Thesis ~ '03

PHYSICAL REVIEW D VOLUME 56, NUMBER 1 1 JULY 1997

InspiredI.P. by papers of Shamir [+Furman]

QCD with domain wall quarks

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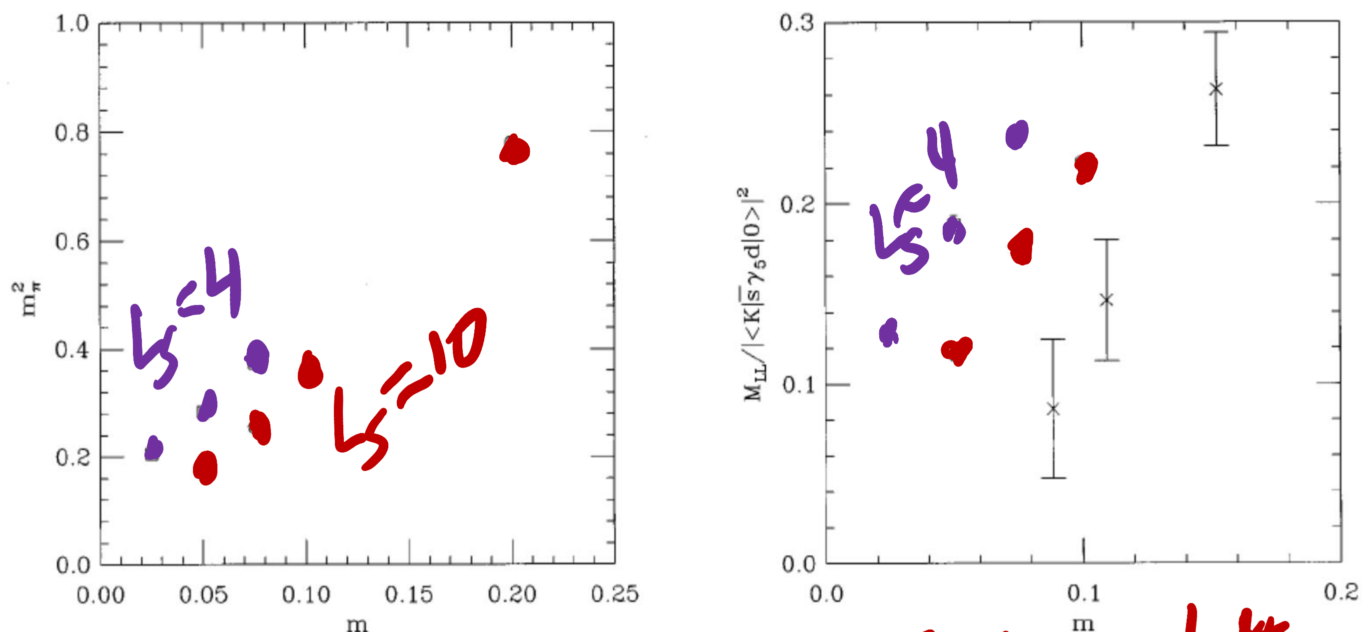
(Received 27 November 1996)

We present lattice calculations in QCD using Shamir's variant of Kaplan fermions which retain the continuum $SU(N)_L \times SU(N)_R$ chiral symmetry on the lattice in the limit of an infinite extra dimension. In particular, we show that the pion mass and the four quark matrix element related to K_0-$\overline{K}_0$ mixing have the expected behavior in the chiral limit, even on lattices with modest extent in the extra dimension, e.g., $N_s=10$. [S0556-2821(97)00113-6]

1st Simulation with DWQ ~'96-97



excellent Chiral symmetry with ~10 sites in 5th dim.

MAJOR BREAKTHROUGH FOR K→ππ Lattice Calculations

K→2π ChPT

With DWQ in Quench Approx

1st application of BDSPW'84 with DWQ

RBC: Founding members Christ, Mawhinney, Blum, AS ~'98

K→ππ & ε'/ε, "Flagship Project" Now ~20 yrs!

1st Large Scale Simulation with DWQ

(Also CP_PACS PRD'03

PHYSICAL REVIEW D 68, 114506 (2003)

Kaon matrix elements and *CP* violation from quenched lattice QCD: The 3-flavor case

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(Received 19 July 2002; published 30 December 2003)

We report the results of a calculation of the $K\to\pi\pi$ matrix elements relevant for the $\Delta I=1/2$ rule and ϵ'/ϵ in quenched lattice QCD using domain wall fermions at a fixed lattice spacing $a^{-1}\sim 2$ GeV. Working in the three-quark effective theory, where only the u, d, and s quarks enter and which is known perturbatively to next-to-leading order, we calculate the lattice $K\to\pi$ and $K\to|0\rangle$ matrix elements of dimension six, four-fermion operators. Through lowest order chiral perturbation theory these yield $K\to\pi\pi$ matrix elements, which we then normalize to continuum values through a nonperturbative renormalization technique. For the ratio of isospin amplitudes $|A_0|/|A_2|$ we find a value of 25.3 ± 1.8 (statistical error only) compared to the experimental value of 22.2, with individual isospin amplitudes 10%–20% below the experimental values. For ϵ'/ϵ, using known central values for standard model parameters, we calculate $(-4.0\pm 2.3)\times 10^{-4}$ (statistical error only) compared to the current experimental average of $(17.2\pm 1.8)\times 10^{-4}$. Because we find a large cancellation between the $I=0$ and $I=2$ contributions to ϵ'/ϵ, the result may be very sensitive to the approximations employed. Among these are the use of quenched QCD, lowest order chiral perturbation theory, and continuum perturbation theory below 1.3 GeV. We also calculate the kaon B parameter B_K and find $B_{K,\overline{MS}}(2\text{ GeV})=0.532(11)$. Although currently unable to give a reliable systematic error, we have control over statistical errors and more simulations will yield information about the effects of the approximations on this first-principles determination of these important quantities.

PRD'03

QCDSP ~98→~'05 1TF

RBC Collaboration

CMP /01.

(a powerful new method

Direct K-> $\pi\pi$ (a la Lellouch-Luscher), using finite volume correlation functions, [i.e. w/o ChPT] RBC initiates around 2005.*

Boyle, Sachrajda et al

~ 2007 RBC-UKQCD {(mostly) Edinburgh — Southampton}

* Allows to bypass Maini-Testa theorem

COMMON Interest: Use of DWQ for simulations

Results for ε'

DIRECT $K \to \pi\pi$
[NO ChPT]

- Using Re(A_0) and Re(A_2) from experiment and our lattice values for Im(A_0) and Im(A_2) and the phase shifts,

USING 216 independent measurements

RBC-UKQCD PRL'15
EDITOR'S CHOICE

$$\mathrm{Re}\left(\frac{\varepsilon'}{\varepsilon}\right) = \mathrm{Re}\left\{\frac{i\omega e^{i(\delta_2-\delta_0)}}{\sqrt{2}\varepsilon}\left[\frac{\mathrm{Im}A_2}{\mathrm{Re}A_2} - \frac{\mathrm{Im}A_0}{\mathrm{Re}A_0}\right]\right\}$$

EWP (ImA2/ReA2); QCDP (ImA0/ReA0)

LARGE CANCELLATION!! (80-85%)

$$= 1.38(5.15)(4.43) \times 10^{-4}, \quad \text{(this work)}$$
$$16.6(2.3) \times 10^{-4} \quad \text{(experiment)}$$

Bearing in mind the largish errors in this first calculation, we interpret that our result are consistent with experiment at ~2σ level

$$\omega = \frac{\mathrm{Re}A_2}{\mathrm{Re}A_0} \sim 0.045$$

Computed ReA2 excellent agreement with expt
Computed ReA0 good agreement with expt
Offered an "explanation" of the Delta I=1/2 Enhancement [c later]

Generation of New gauge configs
For past ~2.5 years

SUPERCOMPUTERS OVER 3 CONTINENTS!

LAT/17

Progress in the calculation of ε′ on the lattice C. Kelly

Resource	Million BG/Q equiv core-hours	Independent cfgs.
USQCD (BNL 512 BG/Q nodes)	50	220
RBRC/BNL (BNL 512 BG/Q nodes)	17	50
UKQCD (DiRAC 512 BG/Q nodes)	17	50
NCSA (Blue Waters)	108	380
KEK (KEKSC 512 BG/Q nodes)	74	296
Total	266	996

Table 1: A breakdown of the various resources we intend to utilize. Note that we require 4 molecular dynamics time units per independent configuration.

4 diff streams

Total of ~1400 independent configs

By now ~1200 measurements done

WHY FOCUS with SUCH intense DETERMINATION
All these many many years?

UNDERLYING REALIZATION

ε': MOST LIKELY A GEM IN SEARCH OF NEW PHENOMENA

Contrarian/Complementary view

- **flavor physics is actually hanging by perhaps the weakest link i.e. a single CP-phase endowed by the 3g –SM.**
- **In many ways this is a contrarian (or complementary) point of view, in sharp contrast to the overwhelming majority following the naturalness lamp post via Higgs radiative stability.**
- **Ɛ' due to its miniscule value, esp because it results from unnatural large cancellations seemed clearly highly vulnerable…The mantra being followed for a very long time**

MODEL INDEPENDENT IMPLICATIONS OF RD(*) ANOMALIES FOR [LHC] COLLIDER EXPERIMENTS

- **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***

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

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

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

ADS'

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

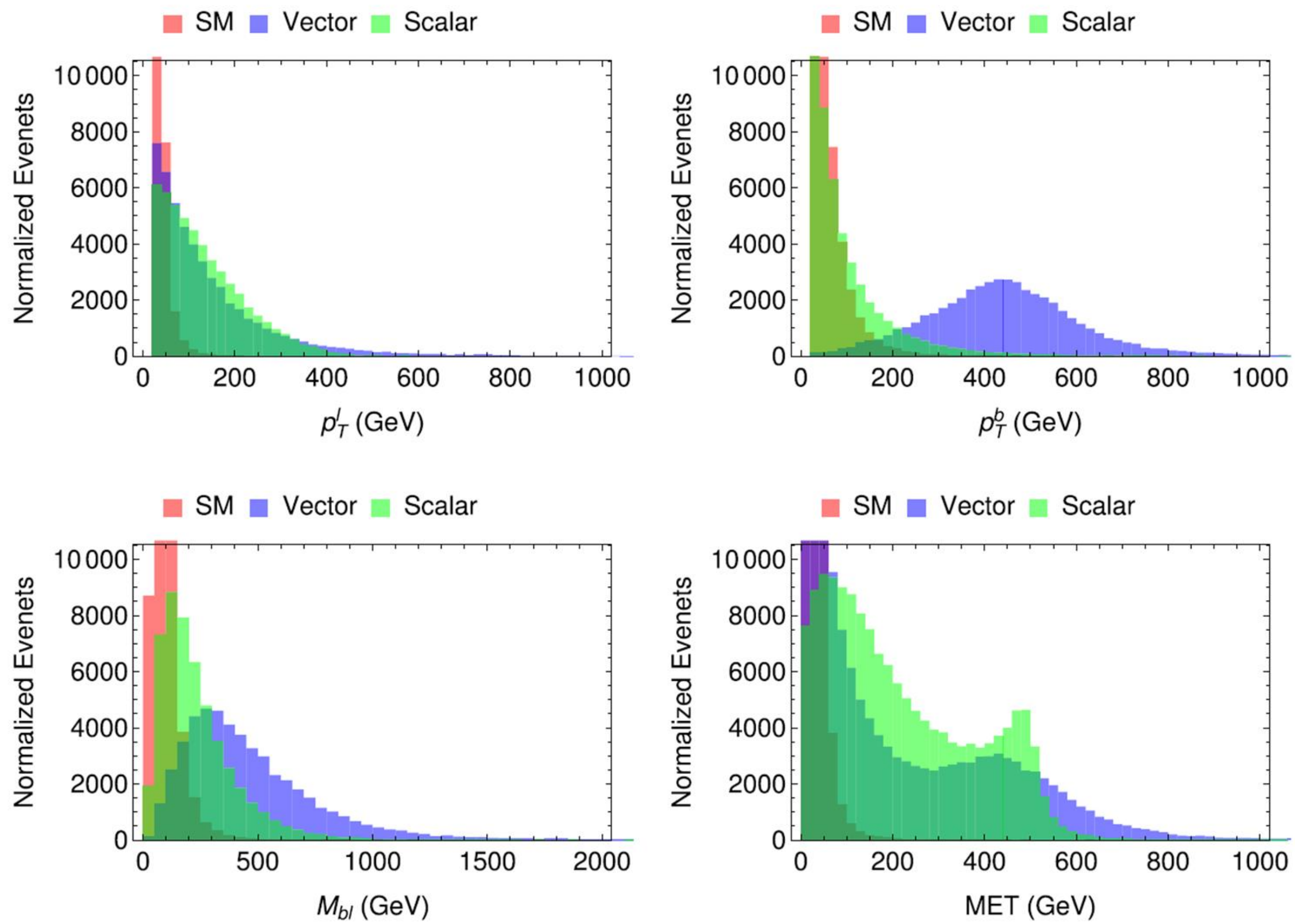

FIG. 1. Normalized kinematic distributions for the $pp \to b\tau\nu \to b\ell + \not{E}_T$ signal and background.

EXPECT DISTINCTIVE NP CONTRIBUTIONS IN COLLIDERS

Backgrounds and such

- **Anomaly implies BSM signals in pp=> b tau nu..with tau => l + nu's….FOR ATLAS, CMS!**
- **There is SM contribution too[though suppressed by Vcb~0.04] but in addition there is potentially a huge background from W+j with about ~1% misidentification of light jets as b's…At 13TeV, SM+BG (with cuts)XS=1.5pb**
- **signal XS for Vector (scalar) case for Λ/[1TeV]~ gNP~1 is about 1.1(1.8)pb @13TeV …With 300/fb may b probe to ~ 4TeV …Moreover, distinctive kinematic distributions can b exploited with say ptb >100 GeV, Mbl>200 GeV to enhance searches for higher mediator masses.** ~ 5TeV

ANOMALY: POSSIBLY A HINT FOR (NATURAL) SUSY-WITH RPV

- **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 as argued also in Brust, Katz, Lawrence and Sundrum 1110.6670 …….]**
- **RPV natural setting for LUV …can accommodate g-2 and eps' if needs be**
- **Collider signals tend to get a lot harder than (usual-RPC) SUSY**

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

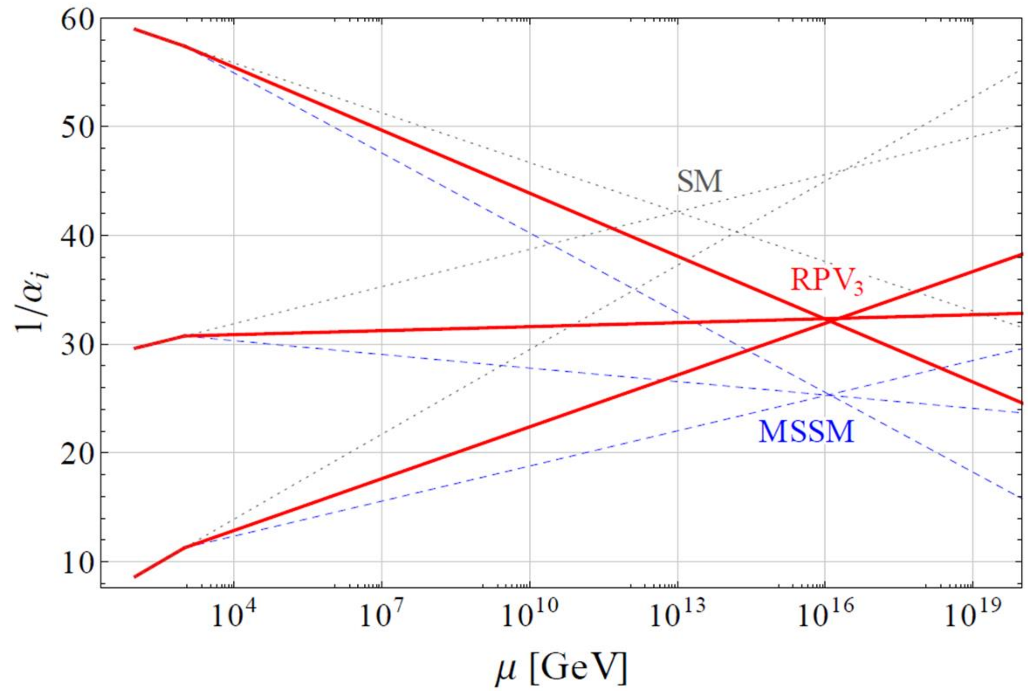

FIG. 2. RG evolution of the gauge couplings in the SM, MSSM and with partial supersymmetrization.

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

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!

For addressing RK(*) in RPV, see e.g. Das et al , 1705.09188

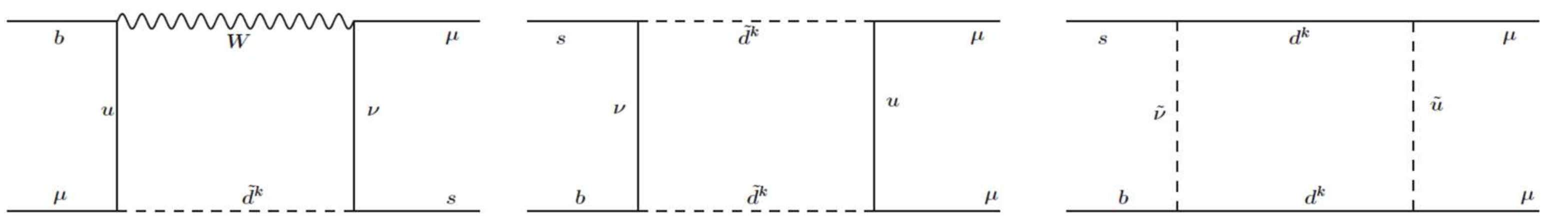

FIG. 1: Representative diagrams for $b \to s\mu^+\mu^-$ transition in R-parity violating interactions.

g-2 with RPV has a long history, see, e.g.Kim, Kyae and Lee, PLB 2001

We [ALTMANNSHOFER+DEV+AS] are examining + update in light of current flavor anomalies

WORK IN Progress

CONSTRAINTS

constraints

- Direct searches via $pp \to \tilde{b}\tilde{b} \to \tau^+\tau^- t\bar{t}$

Indirect constraints considered due B=>τ ν; π τ ν; π(K) ν ν….
Also B_C =>τν….

To a/c (within 1σ) of expt for RD(*) needs largish λ'333 ~1 – 2 range with quite heavy sbottoms but such large couplings develop landau pole below GUT scale.We require couplings stay perturbative below GUT so with λ'333 < ~1 ,

⇒ TAKE HOME: This version of RPV is actually (surprisingly) well constrained

⇒ With improved measurements RD(*) in RPV3 may be difficult

As a specific illustration

Constraints imposed

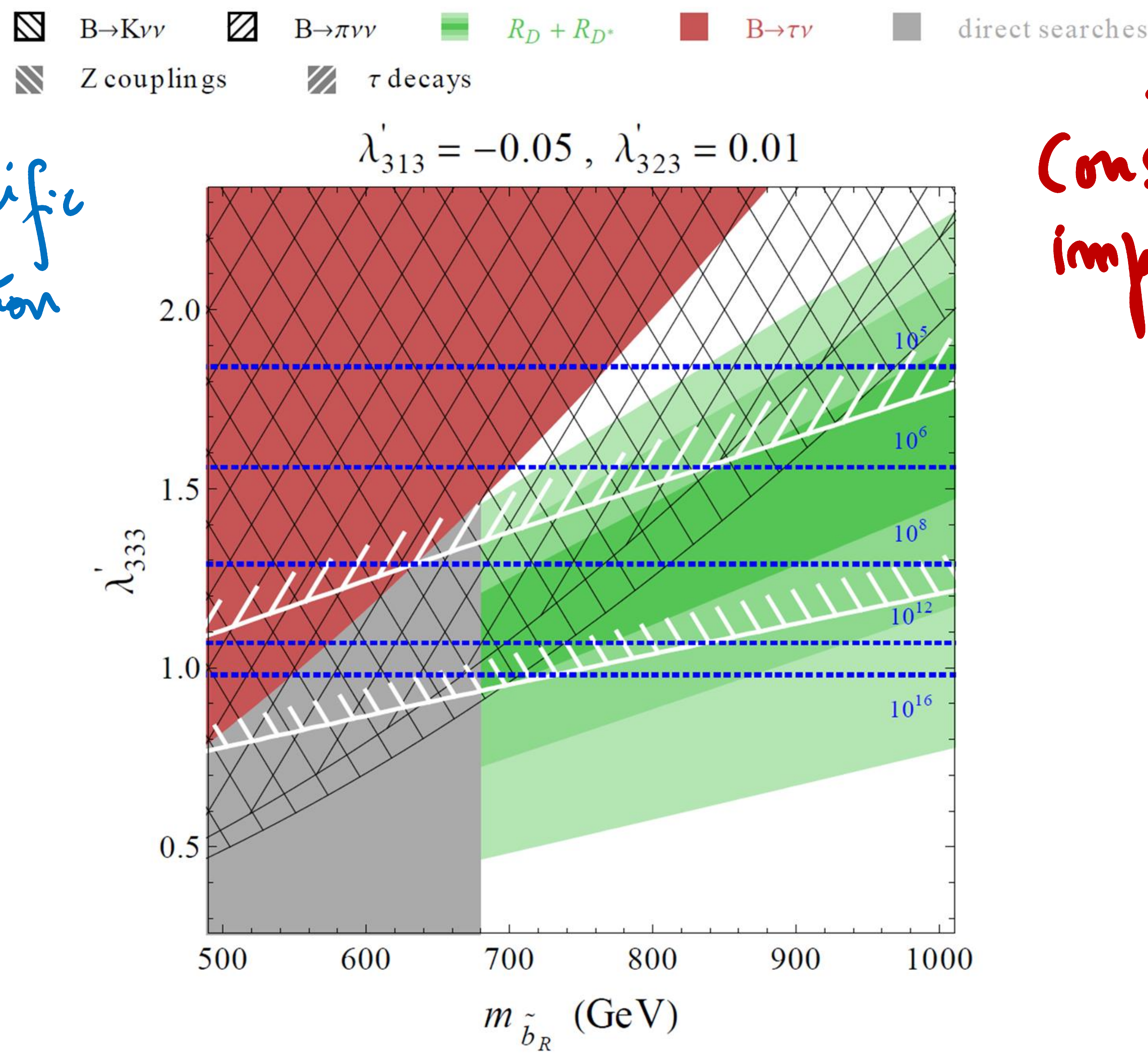

FIG. 3. RPV parameter space satisfying the $R_{D(*)}$ anomaly and other relevant constraints.

ALTMANNSHOFER, BHUPAL DEV, and SONI PRD2017

RPV3 allows
RD=(.254-.371)
RD*=(.220-.320)

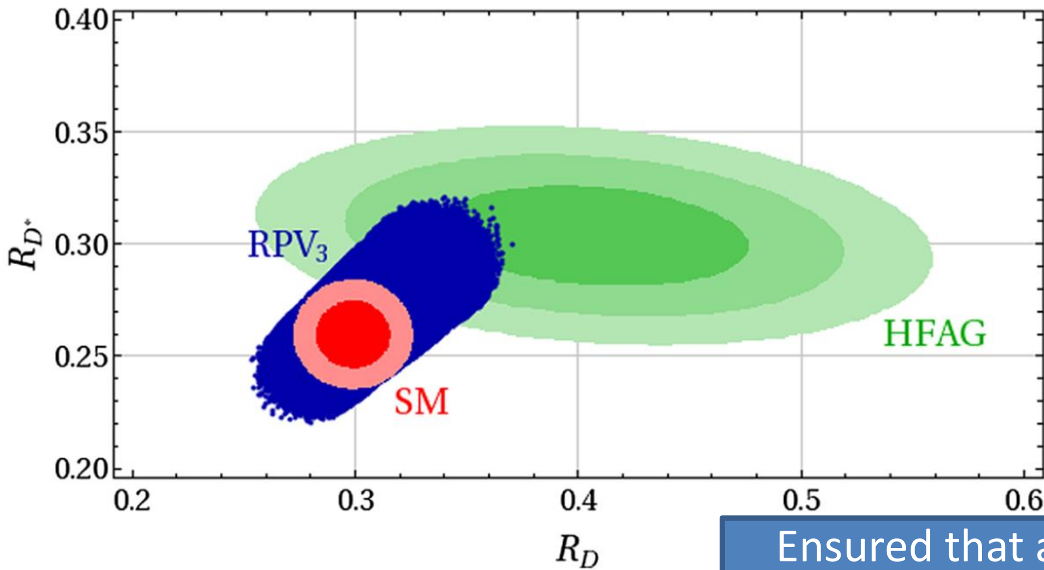

FIG. 4. The SM predictions (red), experimental world average (green), and accessible values in our RPV-SUSY scenario (blue) in the R_D vs. R_{D^*} plane. For the SM, bearing in mind recent works [17,20,22] we are taking $(R_D^{SM}, R_{D^*}^{SM}) = (0.299 \pm 0.011, 0.260 \pm 0.010)$.

HFAG dec2016
RD=.403+-.040+-.024
RD*=.310+-.015+-.008
LHCb 06/06/17
RD* 0.305

Ensured that all RPV3 couplings stay perturbative up to GUT

all constraints……RPV(blue) region obtained by scanning with sbottom mass 680-1000Gev, 0<λ333<2;|λ323|<0.1;|λ313|<0.3 ….

summary

- **Have reservations about the stated ~4 σ anomaly in sl b decays. I. P. concerned about contaminations esp when tau =>mu + 2nu's detection is used.**
- **Due to recent theo estimates for RD*, HFAG should revise their fig**
- **Lattice results for B=> D* are eagerly awaited**
- **Exploiting XSym and looking for possible signatures @ ATLAS/CMS may be very worthwhile**
- **RK(*): it is important to have confirmation from BELLE (II)**

  as well as in (many) other b decays
- **If LUV persists then RPV is a natural candidate**
- **Single CP phase of CKM is unnatural and eps' is exceedingly sensitive to NP => rationale for decades of its pursuit on the lattice…look forward to improved lattice results …**
- **RPV3 can accommodate these anomalies [inc. g-2 & eps'] and may also address higgs radiative stability but improved measurements [esp RD(*), RK(*)] may cause difficulties for RPV3**

XTRAS

Lambda' develop landau pole

Overall, we make the following observations: To explain the $R_{D^{(*)}}$ anomaly at the 1σ level, large values of $\lambda'_{333} \sim 1-2$ are required for sbottom masses that are not in conflict with direct searches at the LHC. We find that for such large values of λ'_{333} at the TeV scale, this coupling develops a Landau pole below the GUT scale. In the top panel plots of Figure 3, the position of the Landau pole in GeV is indicated by the dotted blue lines. The position of the pole is obtained by numerically solving the coupled system of 1-loop RGEs of the λ'_{333} coupling from [76], the top Yukawa, and the three gauge couplings in the presence of only one light generation of sfermions. The position of the pole hardly changes when we include all three generations of sfermions. Perturbativity up to the GUT scale requires $\lambda'_{333} \lesssim 1$. Also the Z coupling constraints limits the possible effects in $R_{D^{(*)}}$. In the viable parameter space the $R_{D^{(*)}}$ anomaly can be partially resolved.

$$\frac{g_{Z\tau_L\tau_L}}{g_{Z\ell_L\ell_L}} = 1 - \frac{3(\lambda'_{333})^2}{16\pi^2}\frac{1}{1-2s_W^2}\frac{m_t^2}{m_{\tilde{b}_R}^2} f_Z\left(\frac{m_t^2}{m_{\tilde{b}_R}^2}\right)$$

$$\frac{g_{W\tau_L\nu_\tau}}{g_{W\ell_L\nu_\ell}} = 1 - \frac{3(\lambda'_{333})^2}{16\pi^2}\frac{1}{4}\frac{m_t^2}{m_{\tilde{b}_R}^2} f_W\left(\frac{m_t^2}{m_{\tilde{b}_R}^2}\right) \ ,$$

and the loop functions are given by $f_Z(x) = \frac{1}{x-1} - \frac{\log(x)}{(x-1)^2}$, $f_W(x) = \frac{1}{x-1} - \frac{(2-x)\log(x)}{(x-1)^2}$. In the leading log aprroxima-

Explicitly checked gauge coupling unification in RPV3

Despite the minimality of this setup, one of the key features of SUSY, namely, gauge coupling unification is still preserved, as shown in Fig. 2. Here we show the renormalization group (RG) evolution of the inverse of the gauge coupling strengths $\alpha_i^{-1} = 4\pi/g_i^2$ (with $i = 1, 2, 3$ for the $SU(3)_c$, $SU(2)_L$ and $U(1)_Y$ gauge groups, where the hypercharge gauge coupling is in SU(5) normalization) in the SM (dotted) and the full MSSM with all SUSY partners at the TeV scale (dashed), and the RPV SUSY scenario with only third generation fermions supersymmetrized at the TeV scale (solid).[6] We find it intriguing that the gauge coupling unification in SUSY occurs regardless of whether only one, two or all three fermion generations are supersymmetrized at low scale, which only shifts the unified coupling value, but not the unification scale. The main reason is that the β-functions receive the dominant contributions from the gaugino and Higgsino sector, so as long as they are not too heavy, the coupling unification feature is preserved, even in presence of RPV.

PHYSICAL REVIEW D VOLUME 43, NUMBER 7 1 APRIL 1991

Semileptonic decays on the lattice: The exclusive 0^- to 0^- case

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(Received 21 December 1990)

We present our results for the meson form factors of several semileptonic decays. They are computed from the corresponding matrix elements evaluated on the lattice as ratios of Green's functions. The renormalization of the local operators is calculated nonperturbatively. The dependence of the form factors on the four-momentum transfer q^2 is studied by injecting external three-momenta to the initial- and final-state mesons. We study the pseudoscalar decays $K \to \pi l \nu$, $D \to K l \nu$, $D \to \pi l \nu$, $D_s \to \eta l \nu$, and $D_s \to K l \nu$ on different lattices. We also analyze scaling, finite-size, and SU(3)-symmetry-breaking effects. The uncertainties in some lattice parameters, e.g., a^{-1}, as a source of systematic errors in this calculation are discussed.

PHYSICAL REVIEW D VOLUME 45, NUMBER 3 1 FEBRUARY 1992

Lattice study of semileptonic decays of charm mesons into vector mesons

data before publication. The computing for this project was done at the National Energy Research Supercomputer Center in part under the "Grand Challenge" program and at the San Diego Supercomputer Center.

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(Received 30 September 1991)

We present our lattice calculation of the semileptonic form factors for the decays $D \to K^*$, $D_s \to \phi$, and $D \to \rho$ using Wilson fermions on a $24^3 \times 39$ lattice at $\beta = 6.0$ with 8 quenched configurations. For $D \to K^*$, we find for the ratio of axial form factors $A_2(0)/A_1(0) = 0.70 \pm 0.16^{+0.20}_{-0.15}$. Results for other form factors and ratios are also given.

RBC Collaboration

Since ~'98

- BNL
  - Chulwoo Jung
  - Taku Izubuchi (RBRC)
  - Christoph Lehner
  - Meifeng Lin
  - Amarjit Soni
- RBRC
  - **Chris Kelly**
  - Tomomi Ishikawa
  - Taichi Kawanai
  - Shigemi Ohta (KEK)
  - Sergey Syritsyn
- Columbia
  - Ziyuan Bai
  - Xu Feng
  - Norman Christ
  - Luchang Jin
  - Robert Mawhinney
  - Greg McGlynn
  - David Murphy
  - **Daiqian Zhang**
- Connecticut
  - **Tom Blum**

FOUNDING Members of RBC Collab: Blum, Christ, Mawhinney + AS

UKQCD Collaboration

Since ~'07

- Edinburgh
  - Peter Boyle
  - Luigi Del Debbio
  - Julien Frison
  - Jamie Hudspith
  - Richard Kenway
  - Ava Khamseh
  - Brian Pendleton
  - Karthee Sivalingam
  - Oliver Witzel
  - Azusa Yamaguchi
- Plymouth
  - Nicolas Garron
- York (Toronto)
  - Renwick Hudspith
- Southampton
  - Jonathan Flynn
  - Tadeusz Janowski
  - Andreas Juttner
  - Andrew Lawson
  - Edwin Lizarazo
  - Antonin Portelli
  - Chris Sachrajda
  - Francesco Sanfilippo
  - Matthew Spraggs
  - Tobias Tsang
- CERN
  - Marina Marinkovic

Bernlochner, Ligeti, Papucci and Robinson, 1703.05330

Scenario	$R(D)$	$R(D^*)$	Correlation
$L_{w=1}$	0.292 ± 0.005	0.255 ± 0.005	41%
$L_{w=1}$+SR	0.291 ± 0.005	0.255 ± 0.003	57%
NoL	0.273 ± 0.016	0.250 ± 0.006	49%
NoL+SR	0.295 ± 0.007	0.255 ± 0.004	43%
$L_{w\geq1}$	0.298 ± 0.003	0.261 ± 0.004	19%
$L_{w\geq1}$+SR	$\mathbf{0.299 \pm 0.003}$	$\mathbf{0.257 \pm 0.003}$	**44%**
th:$L_{w\geq1}$+SR	0.306 ± 0.005	0.256 ± 0.004	33%
Data [9]	0.403 ± 0.047	0.310 ± 0.017	−23%
Refs. [48, 52, 54]	0.300 ± 0.008	—	—
Ref. [53]	0.299 ± 0.003	—	—
Ref. [34]	—	0.252 ± 0.003	—

TABLE IV. The $R(D)$ and $R(D^*)$ predictions for our fit scenarios, the world average of the data, and other theory predictions. The fit scenarios are described in the text and in Table I. The bold numbers are our most precise predictions.

SM Prediction

we took RD* = 0.257 ± .005

Fajfer, Kamenik, Nisandzic, PRD'12

Very timely & useful phenomenological study by BLPR 2017

Overview on Sources of Uncertainty

preliminary results

SCHACHT
@ EPS

- Our analysis leads to a central value $R(D^*) = 0.258$.
  Very good agreement to [BLPR, 1703.05330].

Error due to experimental error of measurement of $B \to D^* l\nu$.

$$\delta R(D^*) = 0.005$$

Theory error due to sum rule parameters.

$$\delta R(D^*) = 0.002$$

Theory error due to higher order effects.

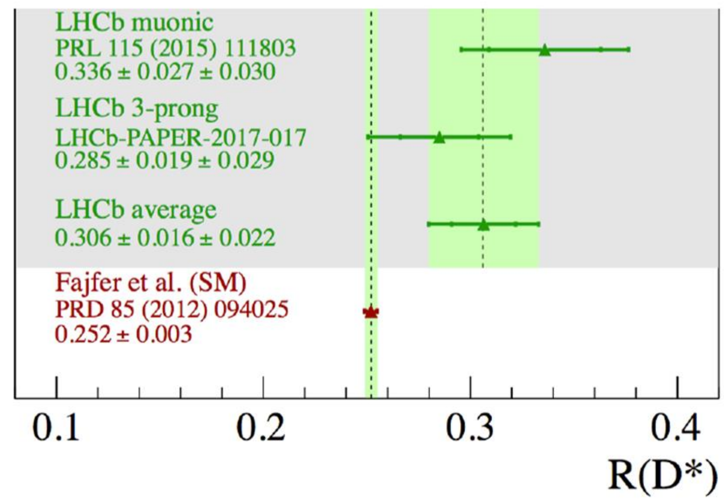
$$\delta R(D^*) = {}^{+0.007}_{-0.006}$$

Total Result (Experiment: $0.310 \pm 0.015 \pm 0.008$ (HFAG, [1612.07233]))

$$R(D^*) = 0.258^{+9}_{-8}$$) ~4%

Conclusions

- We have measured the ratio $K_{had}(D^*)=BR(B^0 \rightarrow \mathbf{D^{*-}\tau\nu})/BR(B^0 \rightarrow D^{*-}3\pi)$ using the $3\pi(\pi^0)$ hadronic decay of the τ lepton.
- The result regarding R(D*) is compatible with all other measurements and with the SM, having the smallest statistical error.
- This analysis was made possible due to the unique LHCb capabilities for separating secondary and tertiary vertices with excellent resolution.



06/06/17 A. Romero Vidal 45

LHCb Seminar CERN 6/6/'17

World average

- Using $BR(B^0 \to D^* \mu \nu) = (4.93 \pm 0.11)\%$ [PDG-2016] we measure:

  $R(D^*) = 0.285 \pm 0.019(stat) \pm 0.025(syst) \pm 0.014(ext)$

- In combination with the muonic LHCb measurement:

  $R(D^*) = 0.336 \pm 0.027 \pm 0.030$,

  the LHCb average is:

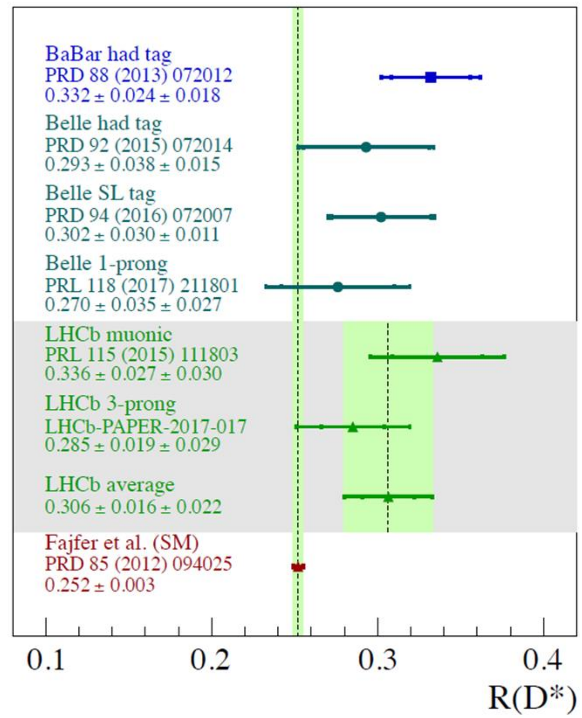
  - $R_{LHCb}(D^*) = 0.306 \pm 0.016 \pm 0.022$
  - 2.1σ above the SM.

- Naïve new WA:
  - $R(D^*) = 0.305 \pm 0.015$
  - 3.4σ above the SM.

- Naïve R(D)/R(D*) combination at 4.1σ from SM.

Total of 6

LHCb-PAPER-2017-017



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BABAR Phy Book '97

Table 13-6. *Model-dependent effects of new physics in various processes.*

Model	*CP* Violation: B_d^0–$\overline{B}_d^0$ Mixing	*CP* Violation: Decay Ampl.	Rare Decays	D^0–$\overline{D}^0$ Mixing
MSSM	$\mathcal{O}(20\%)$ SM Same Phase	No Effect	$B \to X_s\gamma$ – yes $B \to X_s\, l^+ l^-$ – no	No Effect
SUSY – Alignment	$\mathcal{O}(20\%)$ SM New Phases	$\mathcal{O}(1)$	Small Effect	Big Effect
SUSY – Approx. Universality	$\mathcal{O}(20\%)$ SM New Phases	$\mathcal{O}(1)$	No Effect	No Effect
R-Parity Violation	Can Do	Everything	Except Make	Coffee
MHDM 2HDM	$\sim$ SM/New Phases $\sim$ SM/Same Phase	Suppressed Suppressed	$B \to X_s\gamma$, $B \to X_s\tau\tau$ $B \to X_s\gamma$	Big Effect No Effect
Quark Singlets Fourth Generation	Yes/New Phases $\sim$ SM/New Phases	Yes Yes	Saturates Limits Saturates Limits	$Q = 2/3$ Big Effect
LRM – $V_L = V_R$ – $V_L \neq V_R$	No Effect Big/New Phases	No Effect Yes	$B \to X_s\gamma$, $B \to X_s\, l^+ l^-$ $B \to X_s\gamma$, $B \to X_s\, l^+ l^-$	No Effect No Effect
DEWSB	Big/Same Phase	No Effect	$B \to X_s\ell\ell$, $B \to X - s\nu\overline{\nu}$	Big Effect

though in many cases further data may limit the available parameter space. In the more exciting eventuality that the results are not consistent with Standard Model predictions, the full pattern of the discrepancies both in rare decays and in CP-violating effects will help point to the preferred extension, and possibly rule out others. In either case there is much to be learned.

Results

BELLE@EPS July 2017

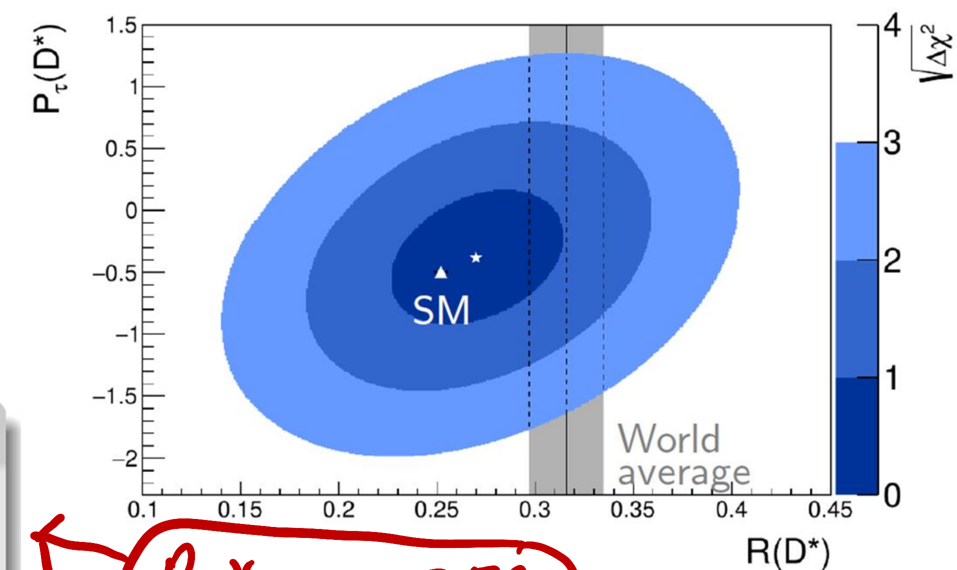
- $\mathcal{R}(D^*)$ can be calculated as before from extracted yields
- Polarisation from forward/backward asymmetry

τ→had+ν

$$\frac{\epsilon_{norm}}{\epsilon_{sig}} = 0.97 \pm 0.02\ (B^{\pm},\ \tau \to \pi\nu)$$
$$= 1.21 \pm 0.03\ (B^{0},\ \tau \to \rho\nu)$$
$$= 3.42 \pm 0.07\ (B^{\pm},\ \tau \to \rho\nu)$$
$$= 3.83 \pm 0.12\ (B^{0},\ \tau \to \rho\nu)$$

Result

$$\mathcal{R}(D^*) = 0.270 \pm 0.035^{+0.028}_{-0.025}$$
$$P_\tau(D^*) = -0.38 \pm 0.51^{+0.21}_{-0.16}$$



R_{D^*} SM ~ .258

- Consistent with SM and previous measurements!
- Error can be reduced in Belle II

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.

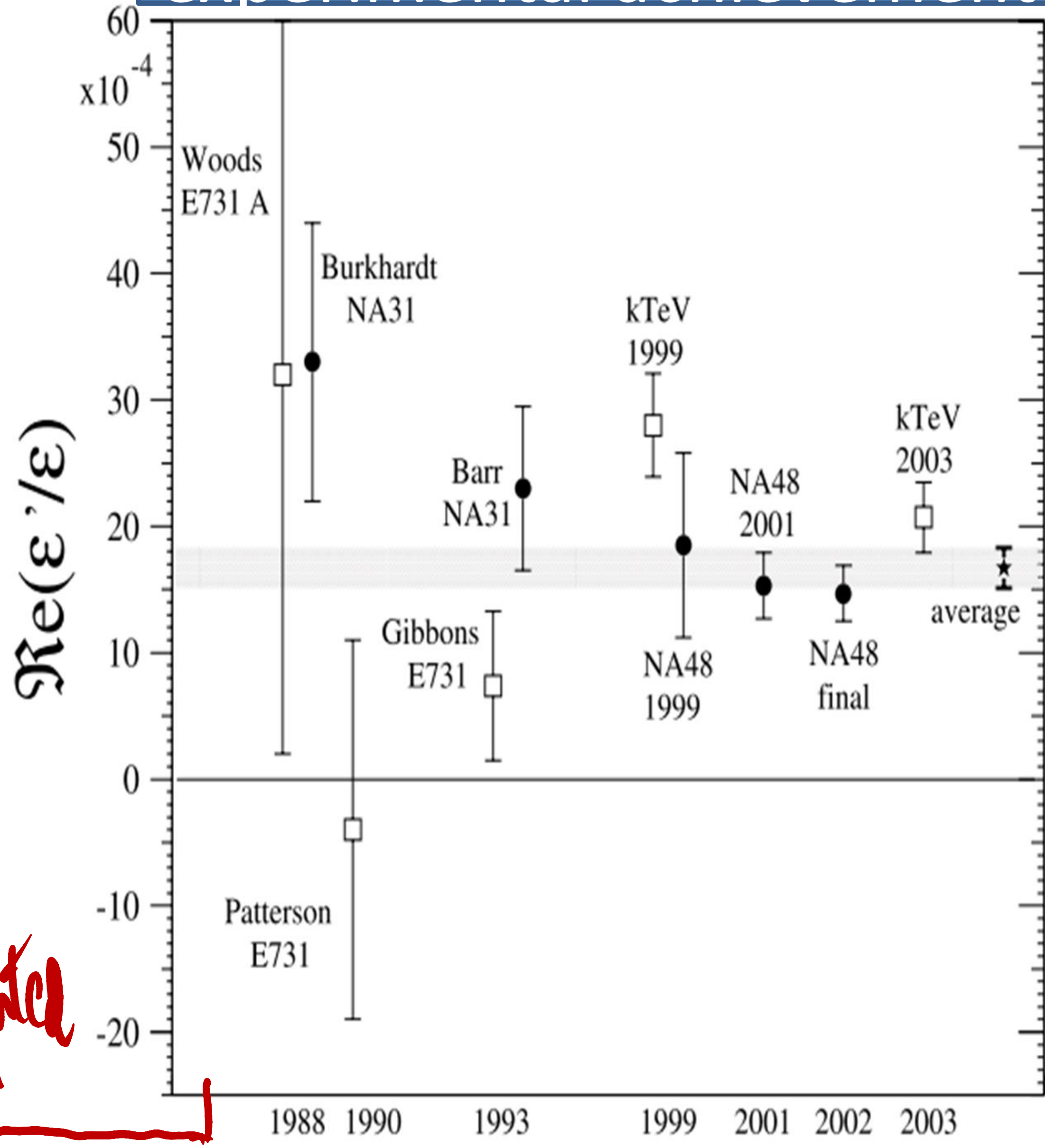
Observable	Limit
$\mathrm{Br}(\mu \to 3e)$	$< 1.0 \times 10^{-12}$ [1]
$\mathrm{Br}(\mu \to e\gamma)$	$< 5.7 \times 10^{-13}$ [1]
$\mathrm{Br}(\tau \to 3e)$	$< 2.7 \times 10^{-8}$ [1]
$\mathrm{Br}(\tau \to e^-\mu^+\mu^-)$	$< 2.7 \times 10^{-8}$ [1]
$\mathrm{Br}(\tau \to e^+\mu^-\mu^-)$	$< 1.7 \times 10^{-8}$ [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]

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

MOTHER of all (lattice) calculations to date: A Personal Perspective

- **Calculation K=> ππ & ε' were the reasons I went into lattice over 1/3 of a century ago!**
- ***9 + (3 new) PhD thesis*: Terry Draper (UCLA'84), George Hockney(UCLA'86), Cristian Calin (Columbia=CU'01), Jack Laiho(Princeton'04), Sam Li(CU'06), Matthew Lightman(CU'09), Elaine Goode(Southampton'10), Qi Liu(CU'12), Daiqian Zhang(CU'15)+ [new ones starting from CU, U Conn and Southampton] + many PD's & junior facs.. obstacles & challenges (and of course "mistakes"!) ad infinitum…..**
- **Started with CBernard (Wilson F); for this physics Chiral symm on the lattice is a pre-requisite [off-shoot B-physics] => on to DWF (with T Blum)=> RBC with ChPT + quenched => huge quench pathlogies=full QCD is mandatory for this physics; full QCD + ChPT=> large chiral corrections => RBC-UKQCD direct K=> 2 π a la Lellouch- Luscher @ threshold=> @physical kinematics……**

A monumental experimental achievement!



Konrad Kleinknecht "Uncovering CPV"

16.6(2.3) x10^{-4}
PDG

CB+AS

LATTICE work started

Its presumed importance:

- **lies in its very small size => Perhaps new phenomena has a better**

chance of showing up

- **Smallness also renders it exceedingly sensitive monitor of flavor –alignment**
- **Simple naturalness arguments strongly suggest ε' very sensitive to**

BSM – CP odd phases

- **In many ways, (superficially) ε' is rather analogous to nedm…….both being very sensitive to BSM-CP phases; however, key diff for (now) nedm expt is the key, theory has marginal role, in sharp contrast to ε'**
- **Understanding ε', nedm are extremely important for uncovering new physics and/or learning how naturalness really works in nature**

Anomalies galore!

- RD(*)
- RK(*)
- ……………………………………………
- g -2
- ………………………………………………
- epsilon': The meaning of life

216[PRL 2015] => ~720 now => ~1200

[2.1σ (2.9σ?) => ????] …..some months

few months

LATTICE is vital for all!

LFV , tree level SL BSM are natural in RPV

eps' and higgs stability are bonus

For Delta M_Bs NNLO EW corr may be appricaible?

- Semi-leptonic B-decays r claimed to indicate ~4.1 sigma deviation from SM
- ATLAS, CMS ought to vigorously search for BSM in : $b\ \tau\ \nu$ and in $t\ \tau$
- Expt BG from higher D** etc resonances a concern and should b measured; tau detection via hadronic modes should be given very high priority as its much

  less susceptible to D** contaminations
- More independent theory effort on and off lattice for determination of SM value for RD* are urgently needed
- More info from expts on R(D), R(D*), R(π), R(ρ), analogous Bs, B-baryon, B=>$\tau\ \nu$ are all urgently needed
- Also RD from LHCb as well as Belle would be helpful [since in this case theory is very solid]; BELLE-II and LHCb-upgrades would of course help a lot
- RPV-SUSY effectively involving 3rd gen is economical, minimal and natural and may be an interesting origin of the anomaly [if it persists!]
- => classic large missing energy hunt for SUSY not relevant for that scenario
- => many RPV signatures tend to become rather challenging
- **=> our version gives new interesting avenues in $b\ \tau\ \nu$; $t\ \tau$ .....final states**
- **More studies in progress (inc e,g. RK(*), Bs=>$\mu\ \mu$ and much more): see ADS' II**

PDG 2016

Table 39.1: Area of the tails α outside $\pm\delta$ from the mean of a Gaus distribution.

α	δ	α	δ
0.3173	1σ	0.2	1.28σ
4.55×10^{-2}	2σ	0.1	1.64σ
2.7×10^{-3}	3σ	0.05	1.96σ
6.3×10^{-5}	4σ	0.01	2.58σ
5.7×10^{-7}	5σ	0.001	3.29σ
2.0×10^{-9}	6σ	10^{-4}	3.89σ

Summary of Theo Calculations

R(D)=0.300(8) HPQCD (2015)

4% ← R(D)=0.299(11) FNAL/MILC (2015) * ← my Take 4 Now

1% !! 0.299 ± 0.003 Bernlochner et al 2017

1% !! $\mathbf{0.299 \pm 0.003}$ D. Bigi et al 2017

1% !! R(D*)=0.252(3) S. Fajfer et al. (2012)

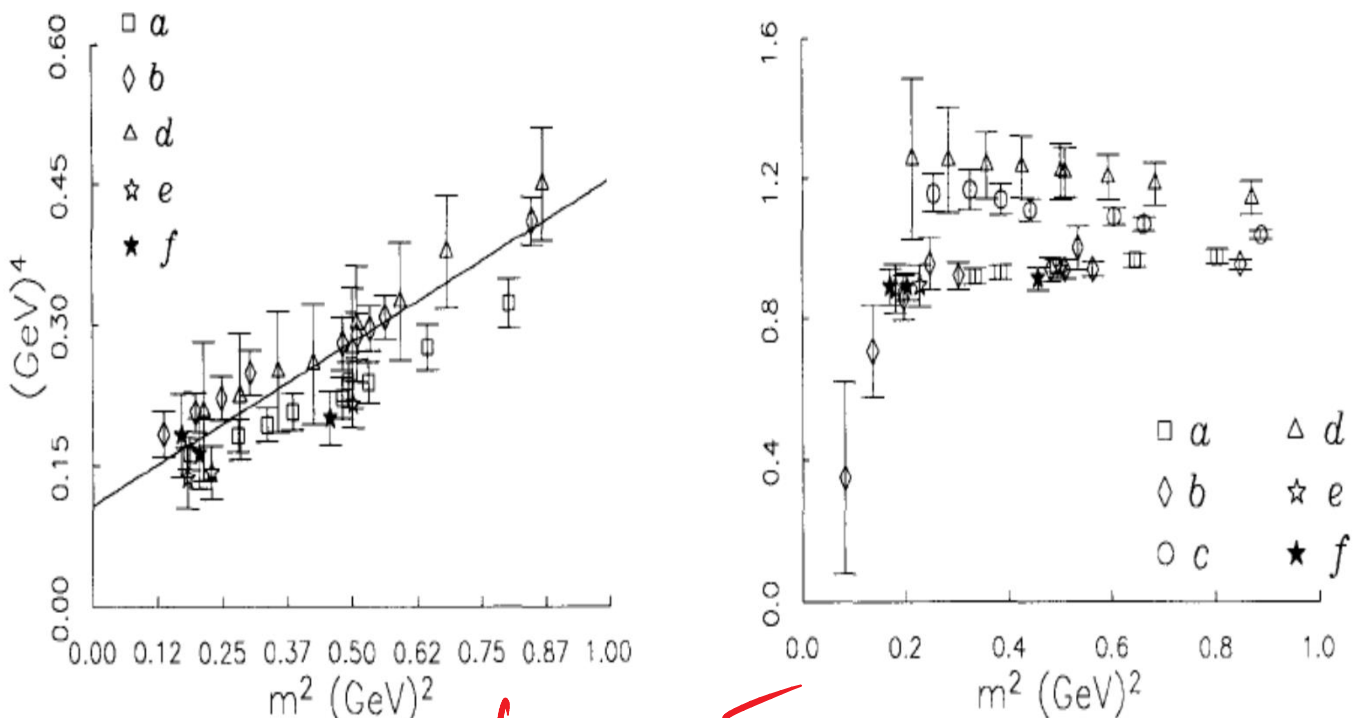
1% $\mathbf{0.257 \pm 0.003}$ Bernlochner et al

4% $R(D^*) = 0.258^{+9}_{-8}$ Bigi et al EPS July

$R_{D^*} \sim .254 \pm .020$ ⇐

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

K — $\bar{K}$ ↑ top '88



χS violation by K-$\bar{K}$ ⇒ FINE TUNING PROBLEM

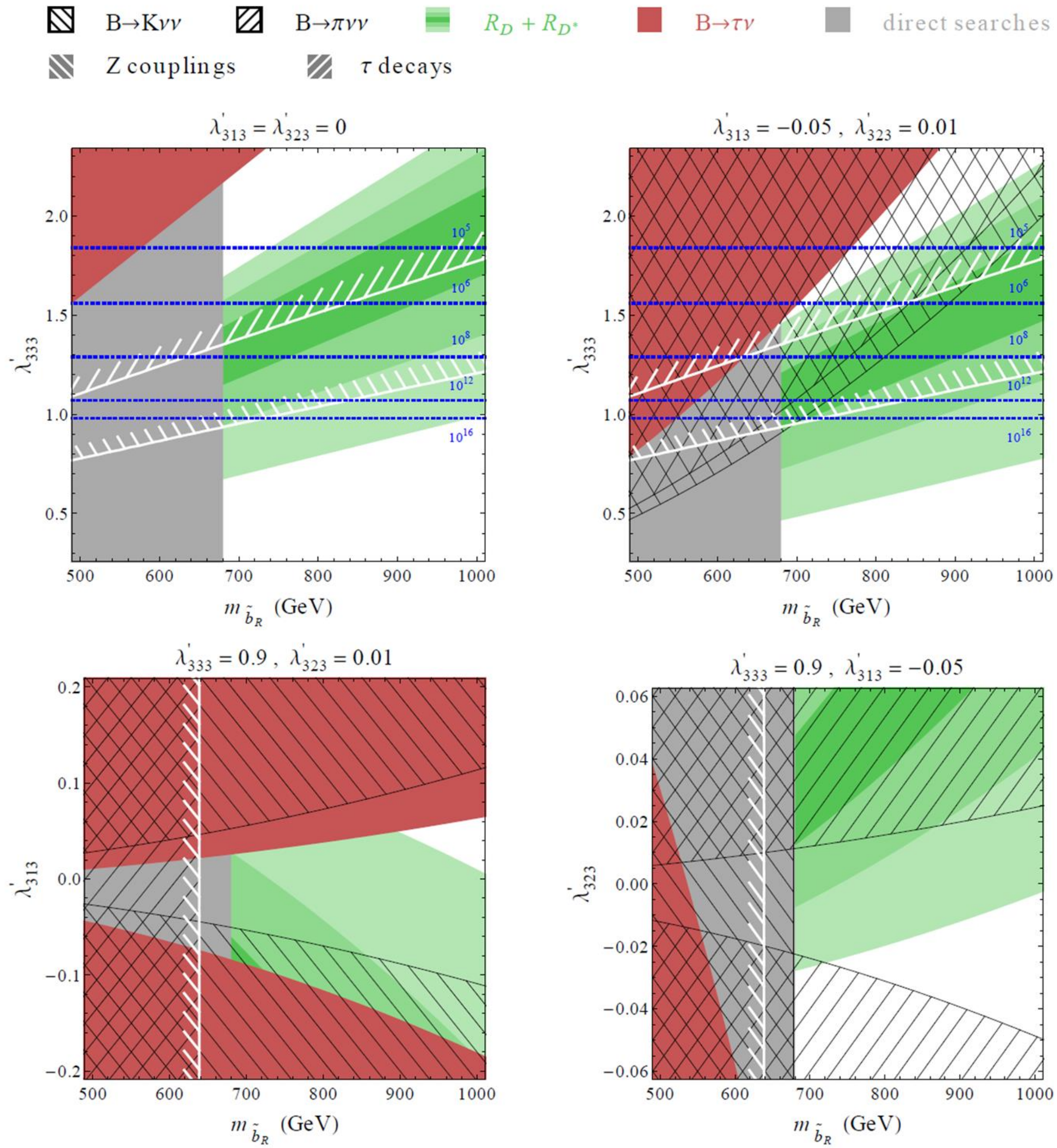


FIG. 3. RPV parameter space satisfying the $R_{D^{(*)}}$ anomaly and other relevant constraints.

PRD2017

ALTMANNSHOFER, BHUPAL DEV, and SONI

TABLE I. Signal and background cut efficiencies for the kinematic variables shown in Fig. 1.

Observable	Cut value (GeV)	Efficiency: SM background	Efficiency: Signal (Vector case)	Efficiency: Signal (Scalar case)
p_T^ℓ	100	0.01	0.52	0.56
	50	0.10	0.78	0.82
	30	0.44	0.92	0.94
p_T^b	100	0.13	0.99	0.33
	50	0.47	1.00	0.62
	30	0.75	1.00	0.84
$M_{b\ell}$	100	0.18	0.96	0.76
	50	0.63	0.99	0.94
	30	0.88	1.00	0.98
$\not{E}_T$	100	0.01	0.54	0.70
	50	0.09	0.70	0.86
	30	0.29	0.79	0.92