“Possible origin(s) of RD(*) flavor anomalies"

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Based in part on 1704.06659
With Wolfgang Altmannshofer
and Bhupal Dev & in progress
[ADS’]

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Univ of Pitsburgh
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Outline

- **Recapitulate: expt situation**
- **Assess Theory: SM predictions**
- **Model independent collider implications**
- **Assuming deviation is real:**

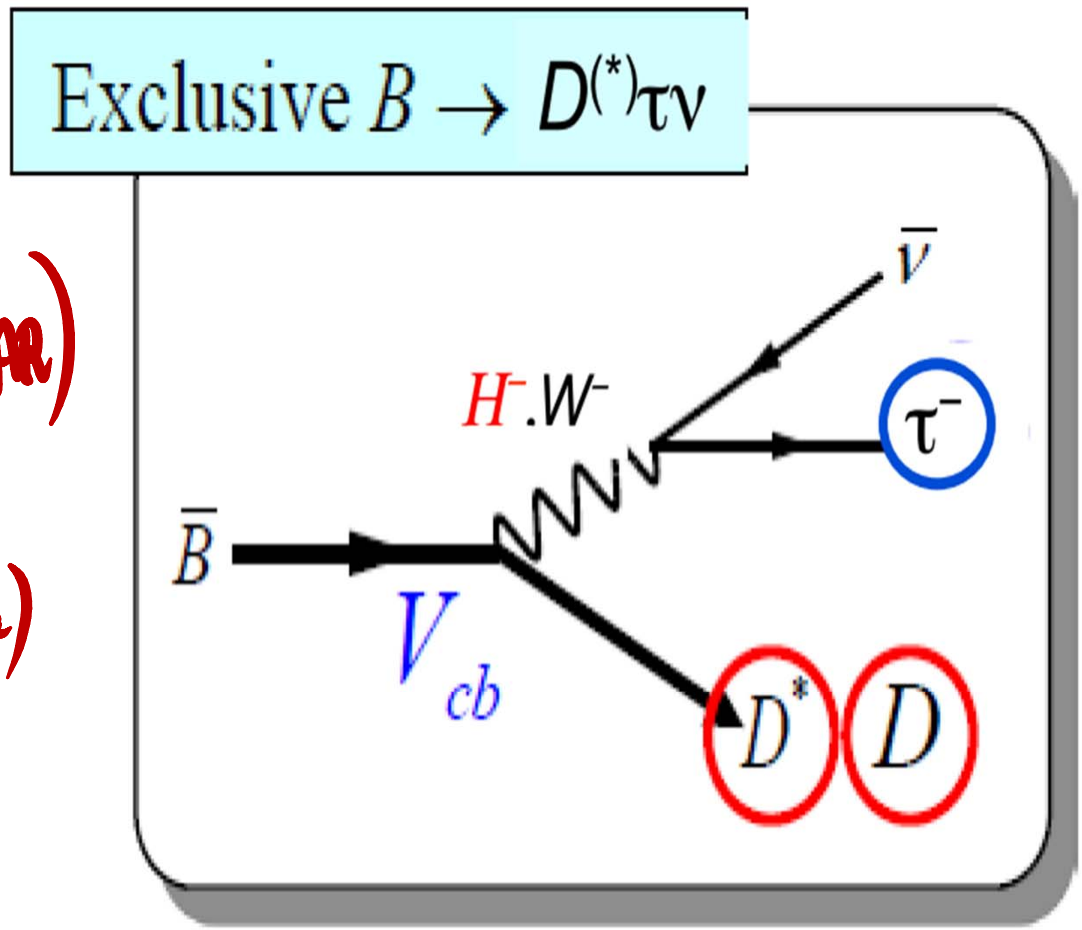
An interesting BSM origin

A minimal setup

Constraints on it

- **Summary & Outlook**

RA LUTH (BABAR)
'CP May 2012
(CHEFEI, China)



MANUEL FRANCO
SEVILLA
PhD Thesis

Independent of Vcb!

- To test the SM Prediction, we measure

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

Leptonic τ decays only

Several experimental and theoretical uncertainties cancel in the ratio!

- BB events are fully reconstructed:

PHYSICAL REVIEW D VOLUME 56, NUMBER 9 1 NOVEMBER 1997

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

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

- S.L. decays involving a $\tau^{\pm}$ have an additional helicity amplitude (for D

$$\frac{d\Gamma_\tau}{dq^2} = \frac{G_F^2 |V_{cb}|^2 |\mathrm{p}| q^2}{96\pi^3 m_B^2} \left(1 - \frac{m_\tau^2}{q^2}\right)^2 \left[\left(|H_{++}|^2 + |H_{--}|^2 + |H_{00}|^2\right) \left(1 + \frac{m_\tau^2}{2q^2}\right) + \frac{3}{2}\frac{m_\tau^2}{q^2} |H_t\right.$$

For $D\tau\nu$, only H_{00} and H_t contribute!

- 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:
  - full reconstruction of hadronic B decay: Btag (tag efficiency improved)
  - reconstruction of $D^{(*)}$ and $e^{\pm}$ or $\mu^{\pm}$ (extend to lower momenta)
  - no additional charged particles
  - kinematic selections: $q^2 > 4\ \mathrm{GeV}^2$

Decay	N_{sig}	N_{norm}	$R(D^{(*)})$	$\mathcal{B}(B \to D^{(*)}\tau\nu)$ (%)	$\Sigma_{tot}(\sigma$
$D^0\tau^-\overline{\nu}_\tau$	314 ± 60	1995 ± 55	$0.429 \pm 0.082 \pm 0.052$	$0.99 \pm 0.19 \pm 0.13$	4.7
$D^{*0}\tau^-\overline{\nu}_\tau$	639 ± 62	8766 ± 104	$0.322 \pm 0.032 \pm 0.022$	$1.71 \pm 0.17 \pm 0.13$	9.4
$D^+\tau^-\overline{\nu}_\tau$	177 ± 31	986 ± 35	$0.469 \pm 0.084 \pm 0.053$	$1.01 \pm 0.18 \pm 0.12$	5.2
$D^{*+}\tau^-\overline{\nu}_\tau$	245 ± 27	3186 ± 61	$0.355 \pm 0.039 \pm 0.021$	$1.74 \pm 0.19 \pm 0.12$	10.4
$D\tau^-\overline{\nu}_\tau$	489 ± 63	2981 ± 65	$0.440 \pm 0.058 \pm 0.042$	$1.02 \pm 0.13 \pm 0.11$	6.8
$D^*\tau^-\overline{\nu}_\tau$	888 ± 63	11953 ± 122	$0.332 \pm 0.024 \pm 0.018$	$1.76 \pm 0.13 \pm 0.12$	13.2

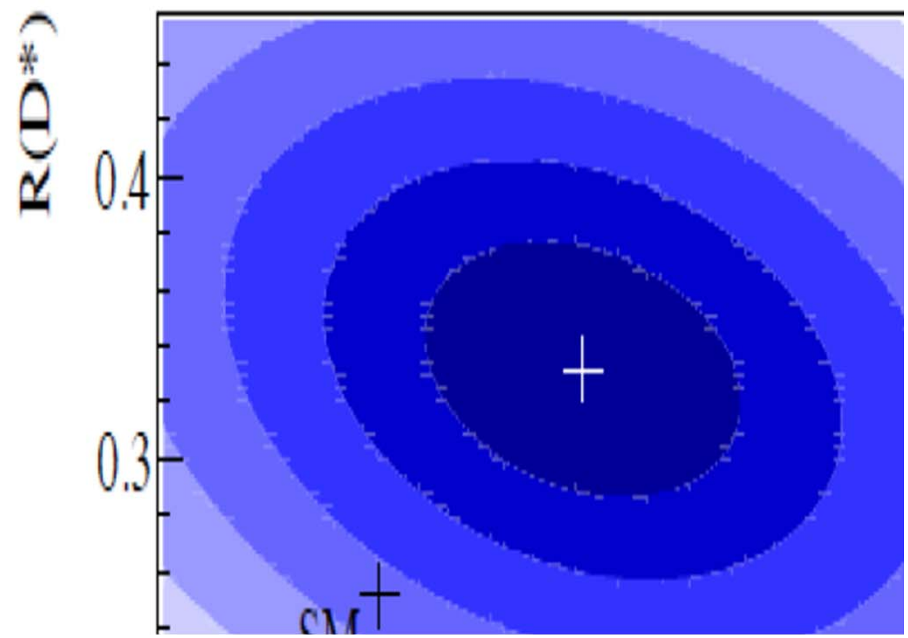
omparison with SM calculation:

4UTH

Combined 3.4σ

BABAR

	R(D)	R(D*)
BABAR	0.440 ± 0.071	0.332 ± 0.029
SM	0.297 ± 0.017	0.252 ± 0.003
Difference	**2.0 σ**	**2.7 σ**



he combination of the two measurements
).27 correlation) yields χ^2/NDF=14.6/2,
Prob = 6.9 x10-4 !!

A charged Higgs (2HDM type II) of spin 0 couples to the τ and will only affect H_t

$$H_t^{2\mathrm{HDM}} = H_t^{\mathrm{SM}} \times \left(1 - \frac{\tan^2\beta}{m_{H\pm}^2} \frac{q^2}{1 \mp m_c/m_b}\right)$$

- for $D\tau\nu$

\+ for $D^*\tau\nu$

This could enhance or decrease the ratios R(D*) depending on $\tan\beta/m_H$

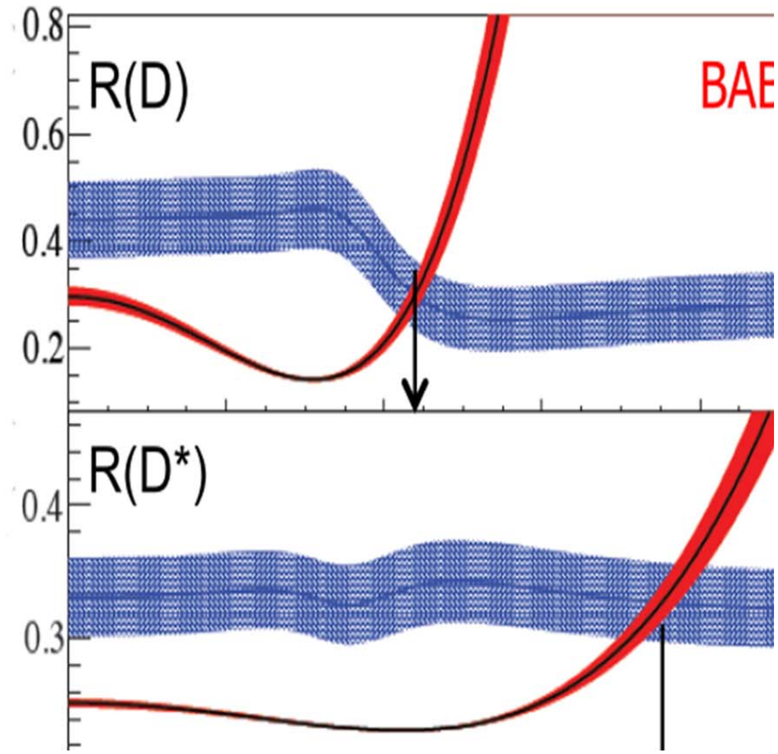
We estimate the effect of 2DHM, accounting for difference in efficiency, and its uncertainty

The data match 2DHM Type II at

$\tan\beta/m_H = 0.44 \pm 0.02$ for R(D)

$\tan\beta/m_H = 0.75 \pm 0.04$ for R(D*)

However, the combination of R(D) and R(D*) excludes the Type II 2HDM in the full $\tan\beta$-m_H parameter space with a probability



■ $R(D^{(*)})$ by HFAG

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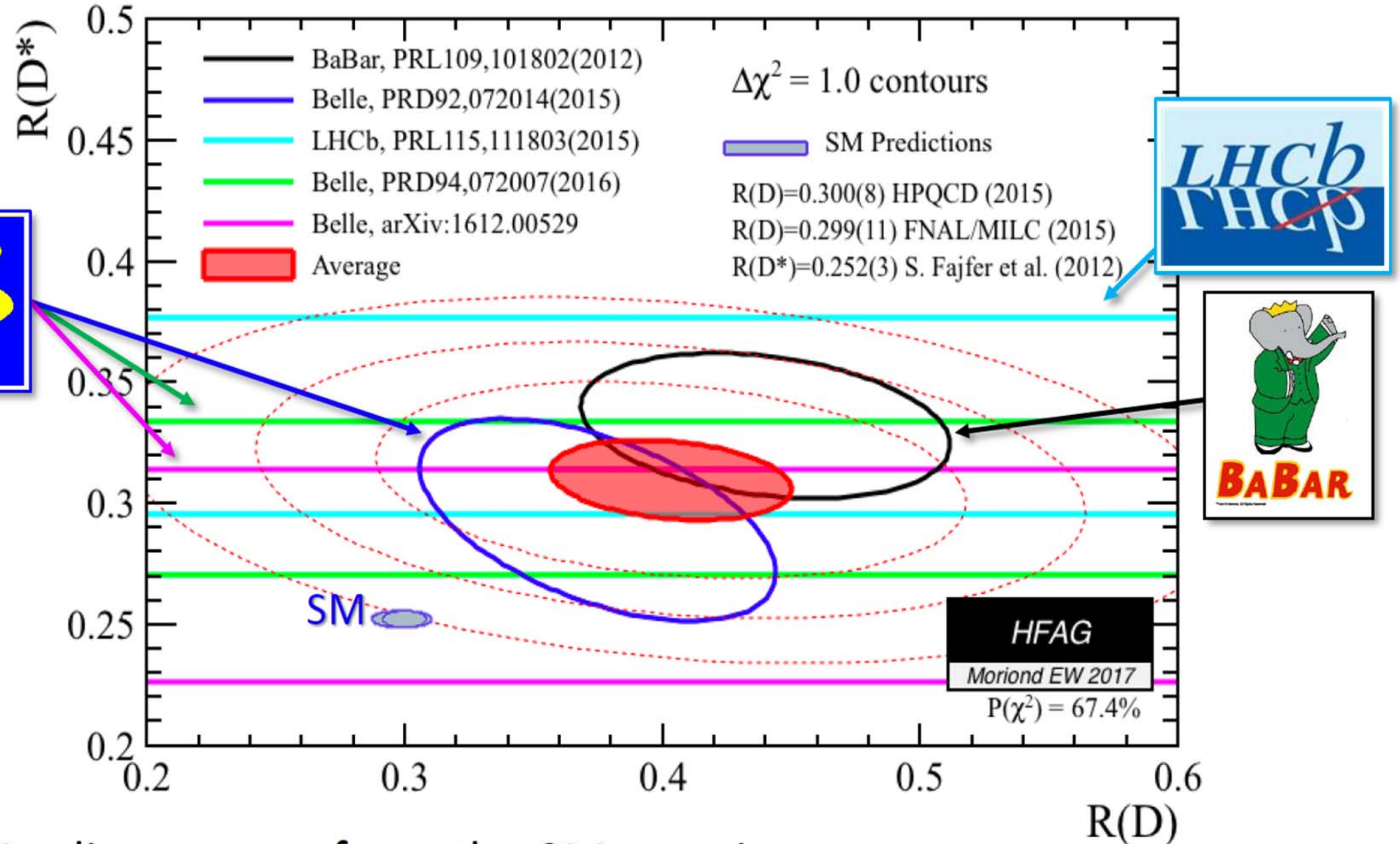
11/15



- ~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

Concern on experiments

- Belle measurements persistently have found consistency with SM with ~1.5 σ or at most 2σ
- Recall that also BABAR has claimed for past many years weak BSM indications in B=>tau nu; BELLE originally said yes but later no on more data and further analysis
- Main point: B=> τ ν is intertwined with RD(*) as stressed in Nandi + Patra +AS:1605.07191

Bernlochner, Ligeti, Papucci and Robinson, 1703.05330

Scenario	$R(D)$	$R(D^*)$	Correlation
$\mathrm{L}_{w=1}$	0.292 ± 0.005	0.255 ± 0.005	41%
$\mathrm{L}_{w=1}$+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%
$\mathrm{L}_{w\geq1}$	0.298 ± 0.003	0.261 ± 0.004	19%
$\mathrm{L}_{w\geq1}$+SR	$\mathbf{0.299 \pm 0.003}$	$\mathbf{0.257 \pm 0.003}$	**44%**
th:$\mathrm{L}_{w\geq1}$+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'll take $RD^* = 0.257 \pm .005$

Fajfer, Kamenik, Nisandzic, PRD'12

Concerns on SM-theory

- **Good news is that lattice study largely confirms pheno calculations for R_D**
- **For B=>D* no complete lattice study so far; 4 rather than 2 FF and D* is unstable…..Thus, from the lattice perspective, anticipate larger errors than for B=>D; lattice results should come in some months**
- **For now, for RD*, we take central value from Bernlochner et al but take full spread between two cen values for 1-σ error; so:**

$$R_D^{\rm SM} = 0.299 \pm 0.003 \quad R_{D^*}^{\rm SM} = 0.257 \pm 0.005$$

Model independent implications for collider experiments

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

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

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

BSM

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

"S" ← $$\mathcal{O}_{S_{R,L}} = (\bar{c}P_{R,L} b)(\bar{\tau}P_L \nu)\,, \qquad (6)$$

$$\mathcal{O}_T = (\bar{c}\sigma^{\mu\nu} P_L b)(\bar{\tau}\sigma_{\mu\nu} P_L \nu)\,. \qquad (7)$$

skip 4 now

Backgrounds and such [WIP…]

- **Anomaly implies BSM signals in pp=> b tau nu..**
- **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**
- **Series of cuts(on j, b, l): pt> 20GeV; pseudo-rapidity (on all 3) < 2.5; isolation Δ[jl,jb,bl]>0.4 manages to reduce the XS to 0.014 fb whereas signal XS for Vector (scalar) case for Λ/[700 GeV]~ 0.079(0.034)fb @14TeV….can do a lot more optimization by increasing pt, M_bl etc , see figs and of course experimentalists can surely do much better job and may evenutally be sensitive to ~2TeV**

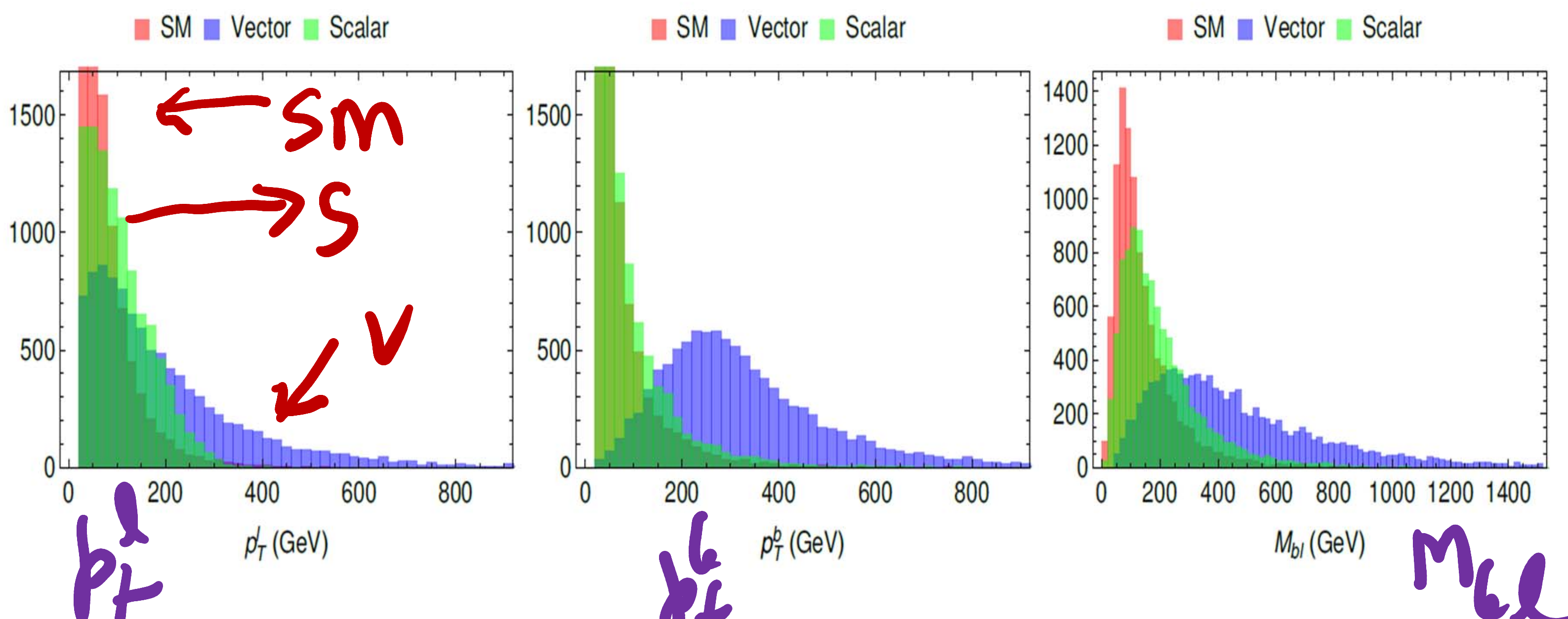


FIG. 1. Kinematic distributions for $pp \to b\tau\nu \to b\ell + \not{E}_T$ signal and background. The scalar and vector cases correspond to the operators given in Eqs. (6) and (5) respectively, whereas the SM case corresponds to Eq. (4).

Anomaly: Possibly a hint for (natural) SUSY-with RPV

- ASSUMING ITS REAL & HERE TO STAY
- Anomaly involves simple tree-level semi-leptonic decays
- Also b => tau (3rd family)
- Speculate: May be related to Higgs naturalness
- Perhaps 3rd family super-partners(a lot) lighter than other 2 gens > proton decay concerns may not be relevant=> RPV ["natural" SUSY as argued in Brust, Katz, Lawrence and Sundrum 1110.6670]
- 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.

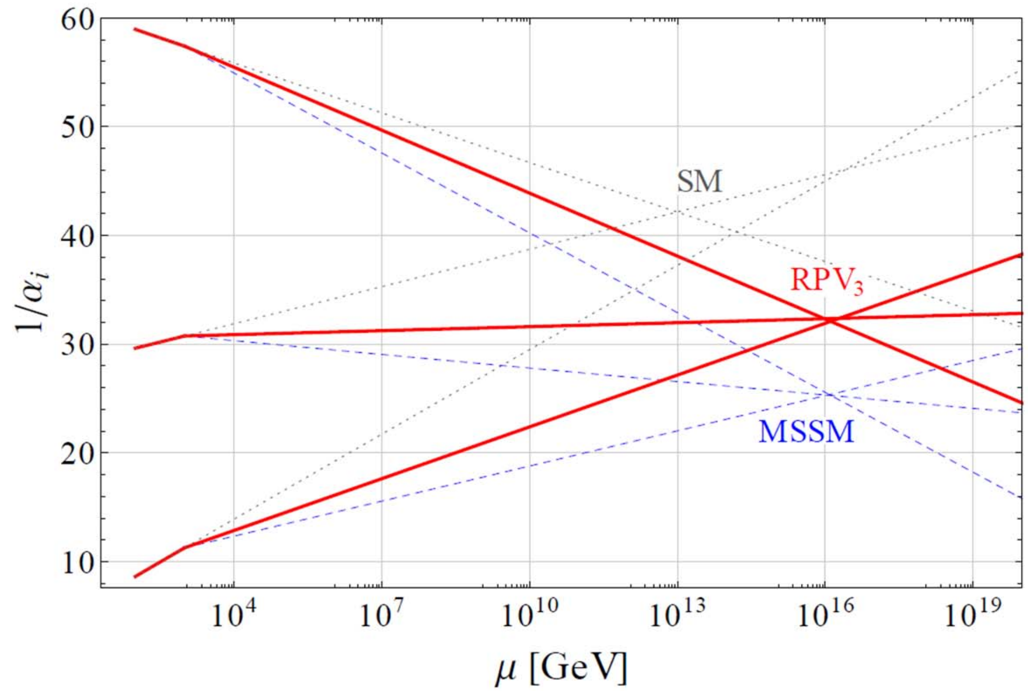


FIG. 2. RG evolution of the gauge couplings in the SM, MSSM and with partial supersymmetrization.

Unification scale ~stays same, only value of coupling shifts

For pheno relevant terms:

C also Deshpande + He,1608.04817

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

} RPV$_3$ interaction

Dim 6

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

→ For $R_{D(*)}$

NOTE: ITS SM-like!

CONSTRAINTS

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	$\sim$ SM/New Phases	Suppressed	$B \to X_s\gamma$, $B \to X_s\tau\tau$	Big Effect
2HDM	$\sim$ SM/Same Phase	Suppressed	$B \to X_s\gamma$	No Effect
Quark Singlets	Yes/New Phases	Yes	Saturates Limits	$Q = 2/3$
Fourth Generation	$\sim$ SM/New Phases	Yes	Saturates Limits	Big Effect
LRM – $V_L = V_R$	No Effect	No Effect	$B \to X_s\gamma$, $B \to X_s l^+ l^-$	No Effect
– $V_L \neq V_R$	Big/New Phases	Yes	$B \to X_s\gamma$, $B \to X_s l^+ l^-$	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.

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
⇒RD(*) can only be partly explained

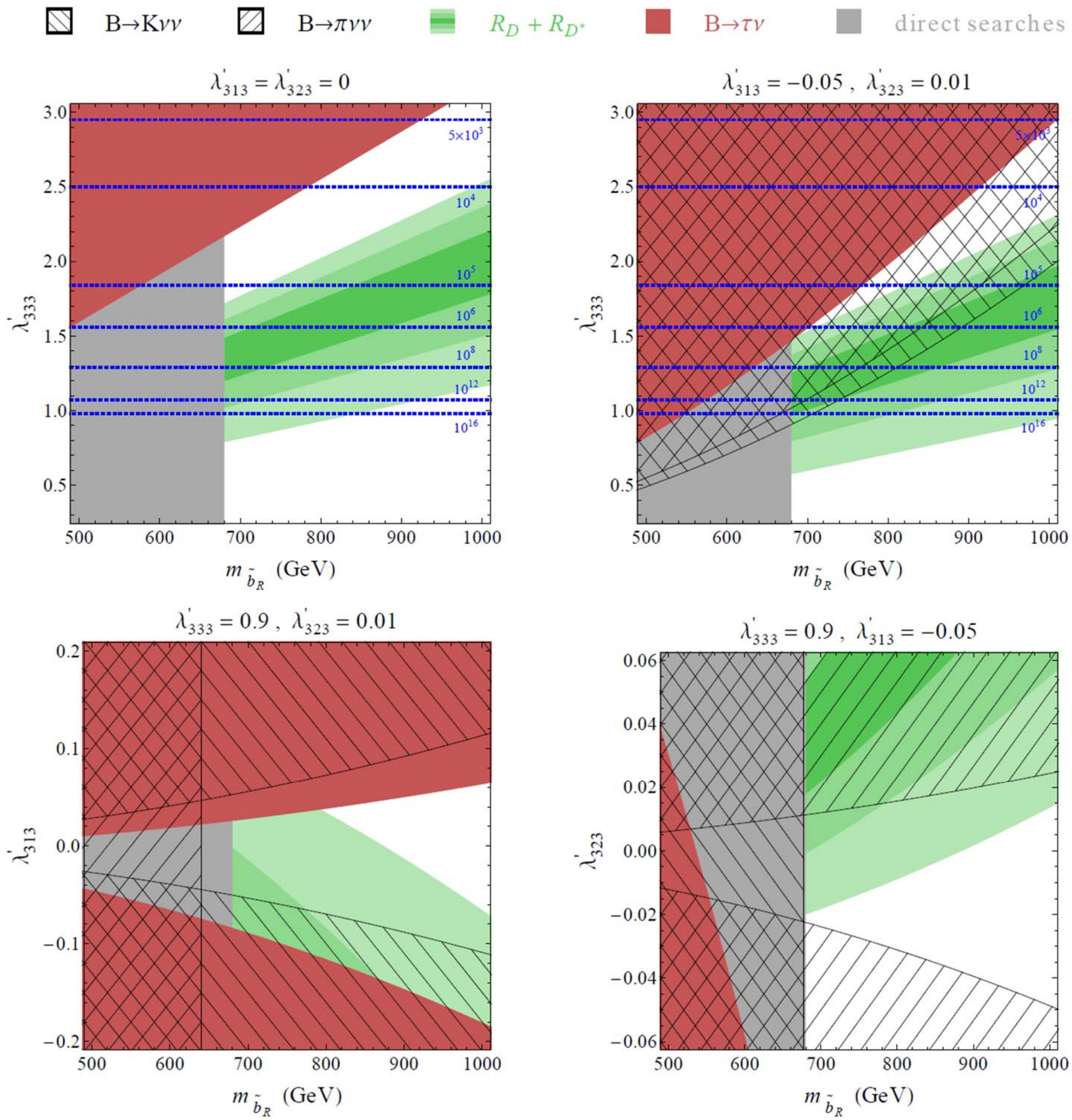


FIG. 3. RPV parameter space satisfying the $R_{D^{(*)}}$ anomaly and other relevant constraints.

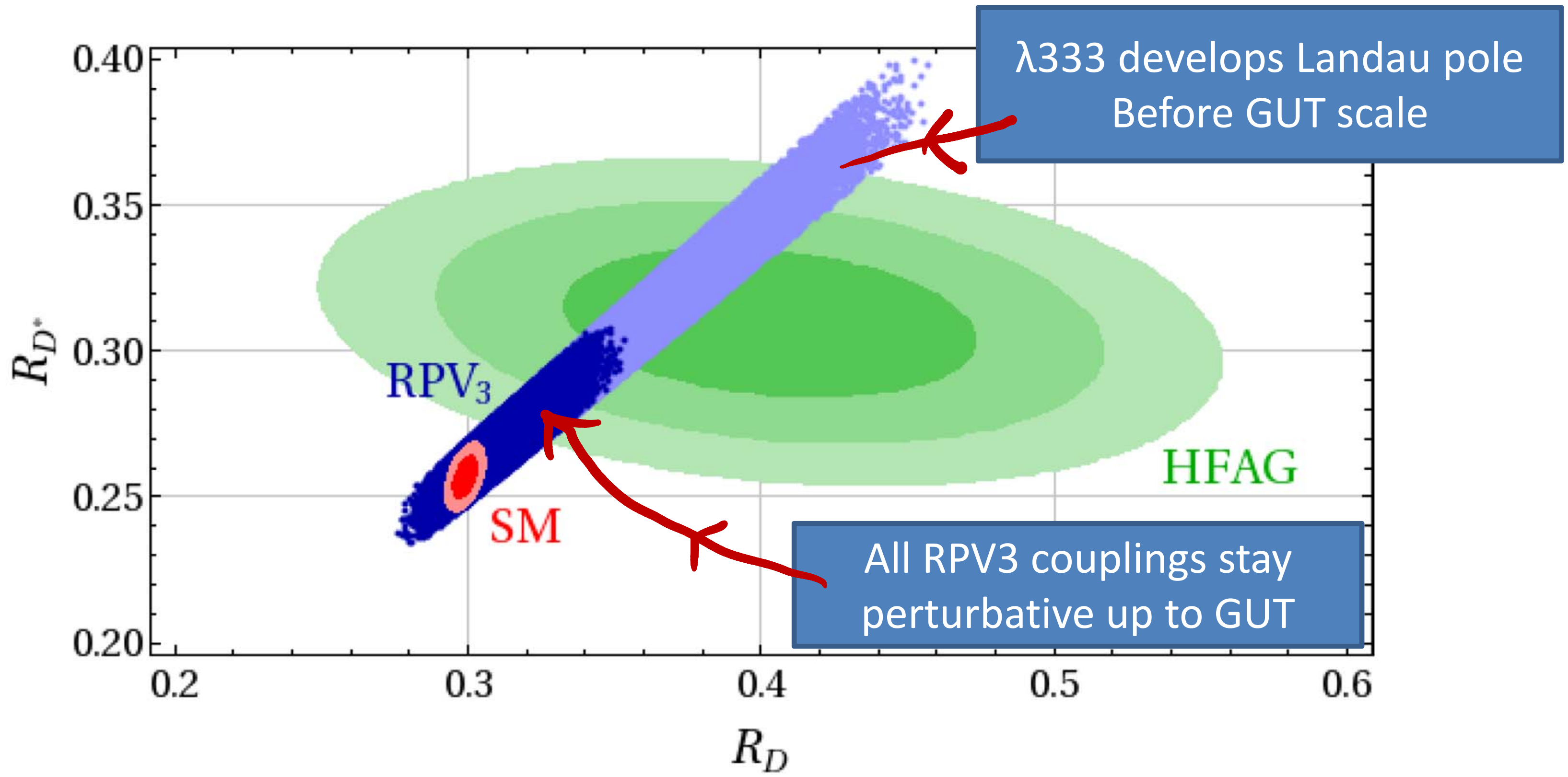


FIG. 4. The R_D vs. R_{D^*} plane. Shown are the SM predictions (red), experimental world average (green), values accessible in the MSSM with RPV (blue). For the SM we take, $R_D^{\rm SM} = 0.299 \pm 0.003$ [cf. Eq. (3)] and $R_{D^*}^{\rm SM} = 0.257 \pm 0.005$; see text for details.

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

Summary and Outlook

- **More independent theory effort on and off lattice for determination of SM value for RD* are urgently needed**
- **ATLAS, CMS ought to vigorously search for BSM in : b τ ν and in t τ**
- **More info from expts on R(D), R(D*), R(π), R(ρ), analogous Bs, B-baryon, B=>tau nu are all urgently needed ; as also detection of tau via other modes ….**
- **In particular 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**
- **=> classic large missing energy hunt for SUSY not relevant**
- **=> many RPV signatures tend to be challenging**
- **=> our version gives new interesting avenues in b τ ν; t τ …..final states**
- **More studies in progress (inc e,g. RK(*), Bs=>mu mu and much more): see ADS' II**