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

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HET-BNL

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

EPS 2017
Venezia
07/06/17

Outline

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

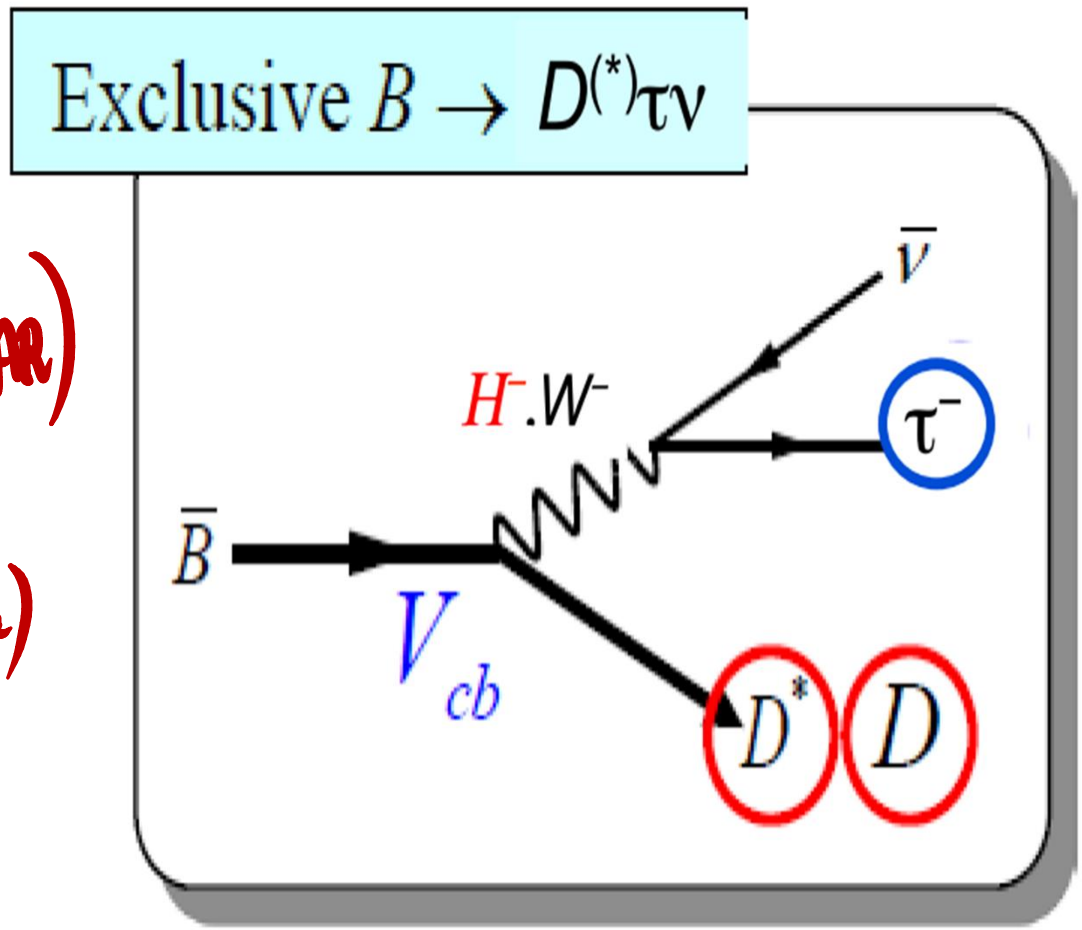
An interesting BSM origin

A minimal setup

Constraints on it

- Summary & Outlook

RA LUTH (BABAR)
CP May 2012
(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!

PHYSICAL REVIEW D VOLUME 56, NUMBER 9 1 NOVEMBER 1997

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

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 $B \to D\tau\overline{\nu}$ 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

Form factors: B=>D vs B=>D*

- **For B to D [0- to 0-] due to Parity,**

Only vector current contributes: 2 form factor of which, contribution of one is prop. to lepton mass

For B to D* both vector and axial vector conribute;

Now 4 FF, again contribution of one FF is

prop. to lepton mass

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

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

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

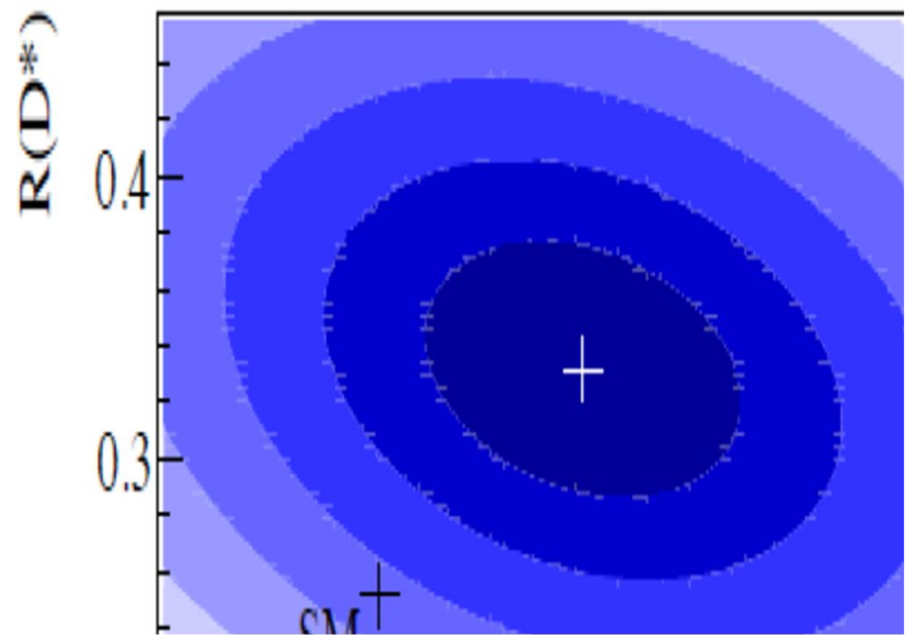
omparison with SM calculation:

LUTH

Combined 3.4σ

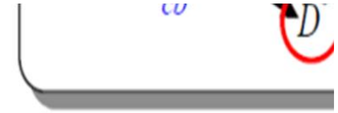
	R(D)	R(D*)
BABAR	0.440 ± 0.071	0.332 ± 0.029
SM	0.297 ± 0.017	0.252 ± 0.003
Difference	**2.0 σ**	**2.7 σ**

BABAR



he combination of the two measurements (0.27 correlation) yields χ^2/NDF=14.6/2,

→ Prob = 6.9 x10^{-4} !!



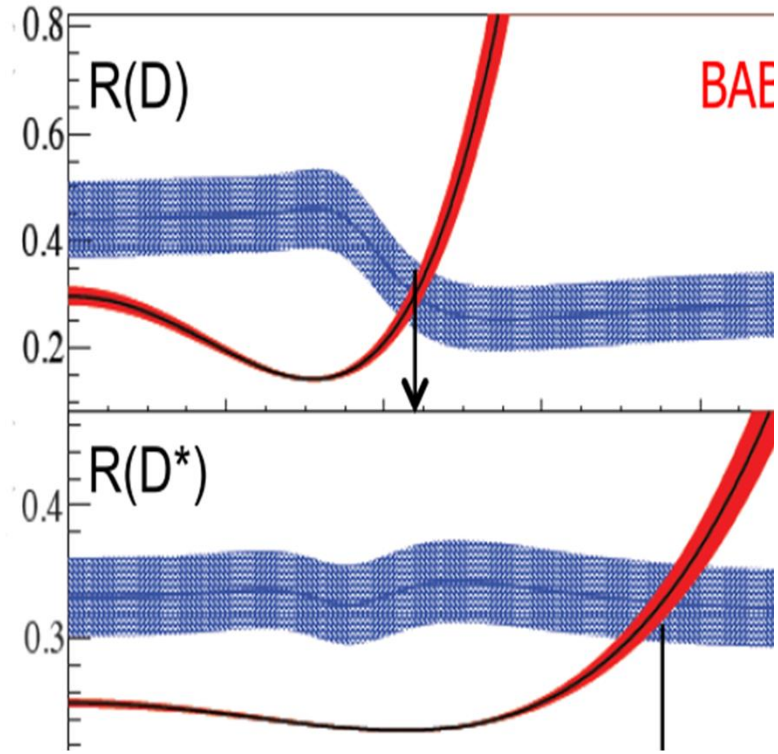
A charged Higgs (2HDM type II) of spin 0 couples to the τ and will only affect H_t

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

- 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

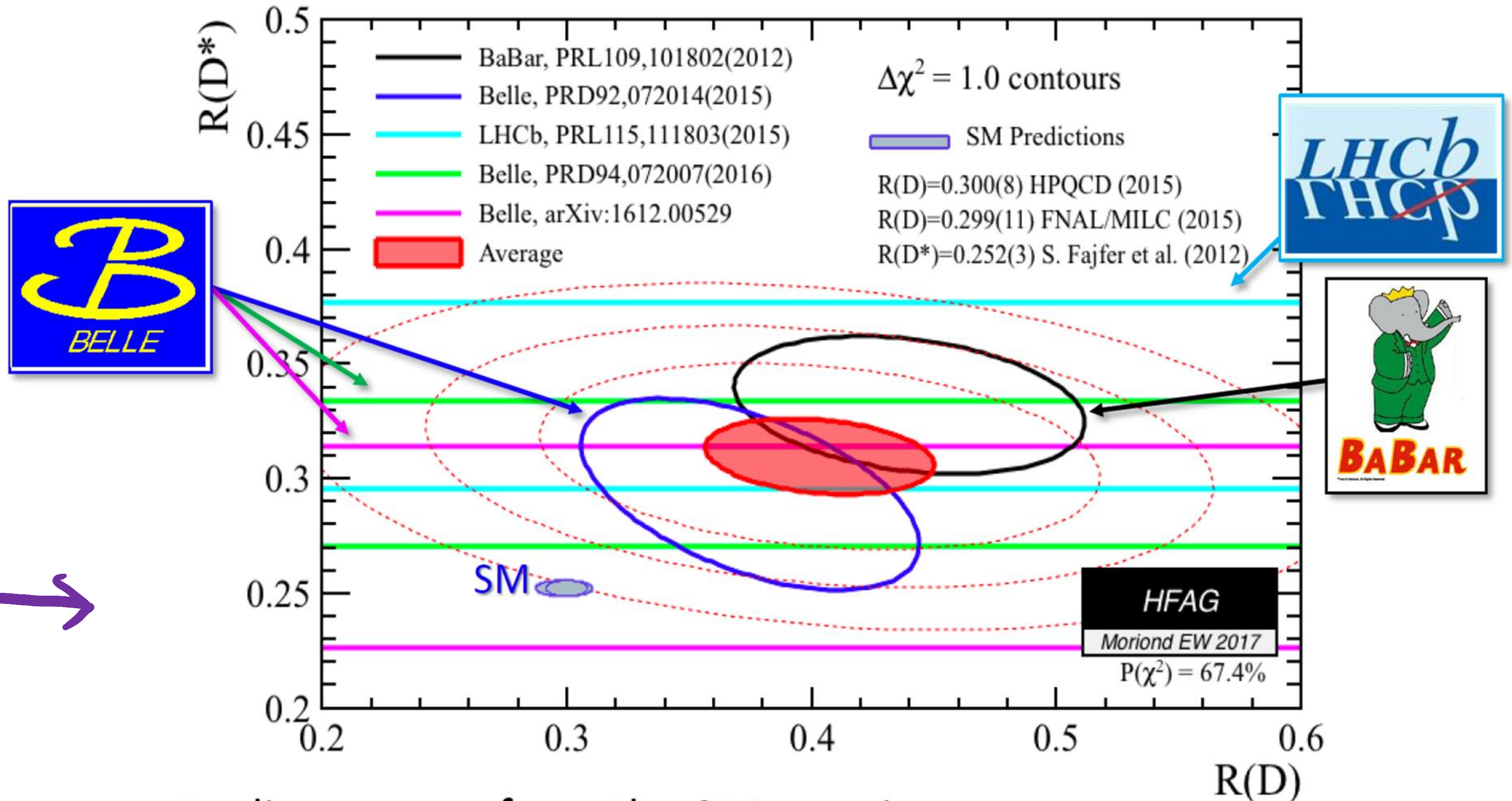
$\tan\beta/m_H = 0.44 \pm 0.02$ for R(D)

$\tan\beta/m_H = 0.75 \pm 0.04$ 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

Hirose [BELLE]@EW MORIOND Mar. 2017



- ~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

- **Main concern reg. experiments is contamination from higher D**-like resonances….it is exceedingly important to measure these BGs as model calculations are not reliable**
- **B=> τ ν is intimately intertwined with RD(*)**

as stressed in Nandi + Patra +AS:1605.07191, but unfortunately for now stats are very poor

- **Nevertheless recall that infact BABAR had also claimed for past many years weak BSM indications in B=>tau nu; BELLE originally said yes but later no on with more data and further analysis asserted consistency with SM.**
- **Bearing that (slight) tension in mind, it is noteworthy that Belle measurements of RD and RD* persistently have found consistency with SM within ~1.5 σ and milder discrepancy with SM compared to BABAR and to LHCb**

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 appreciately 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**
- **Meantime recent phenomenological study of** Bernlochner, Ligeti, Papucci and Robinson, 1703.05330 is very timely and greatly appreciated.
- **For now, for RD*, we take central value from Bernlochner et al but unlike them we take full spread between two cen values i.e. with the famous work Fajfer et al (2012) for 1-σ error; SO**

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

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'll take $RD^* = 0.257 \pm .005$

Fajfer, Kamenik, Nisandzic, PRD'12

Very timely & useful phenomenological study by BLPR 2017

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**
- **Note LHCb new result june 2017: B=>D* τ ν; τ =>3π+ν**
- **Consistent with the SM at ~1-σ=> heightens anxiety about D**….contaminations in τ=> μνν**

World average

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

  R(D*) = 0.285 ± 0.019(stat) ± 0.025(syst) ± 0.014(ext)

- In combination with the muonic LHCb measurement:

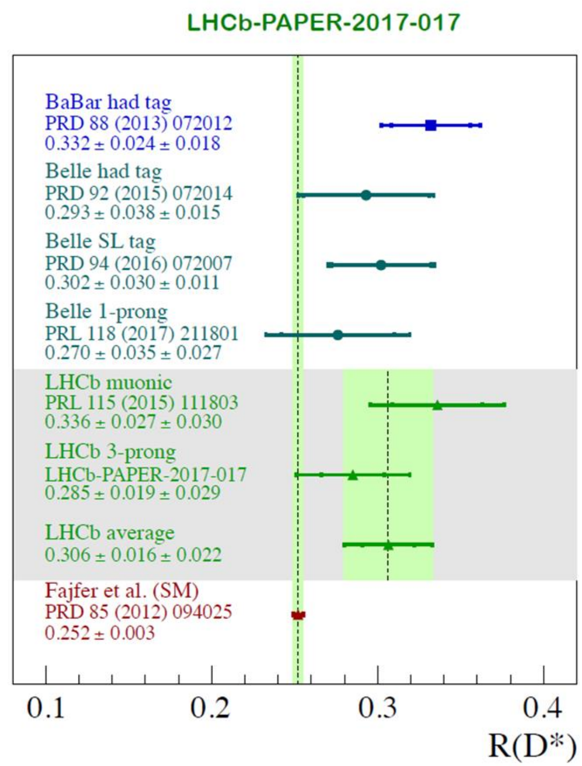
  R(D*) = 0.336 ± 0.027 ± 0.030,

  the LHCb average is:

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

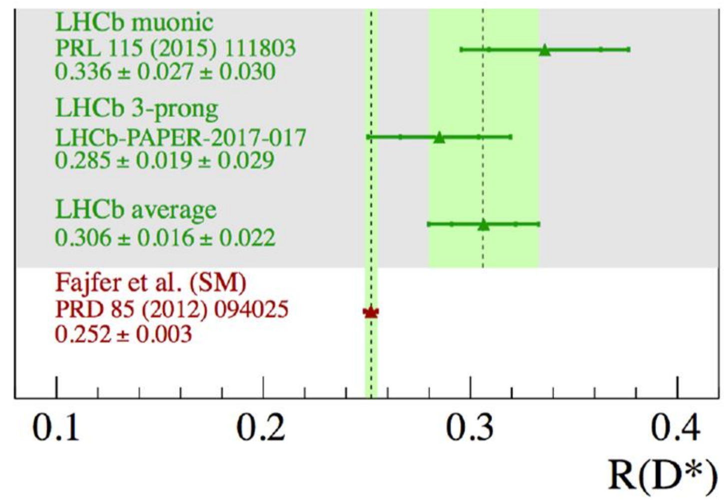
- Naïve new WA:
  - R(D*) = 0.305 ± 0.015
  - 3.4σ above the SM.

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



Conclusions

- **We have measured the ratio $K_{had}(D^*)=BR(B^0\to \mathbf{D^{*-}\tau\nu})/BR(B^0\to D^{*-}3\pi)$ 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.**



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**

- ***Thus it immediately leads to inescapable search channels at the high energy frontier for ATLAS & CMS and there 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

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

SM

C also M. Freytsis et al
arXiv:1506.08896

BSM

"V" ←

"S" ←

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

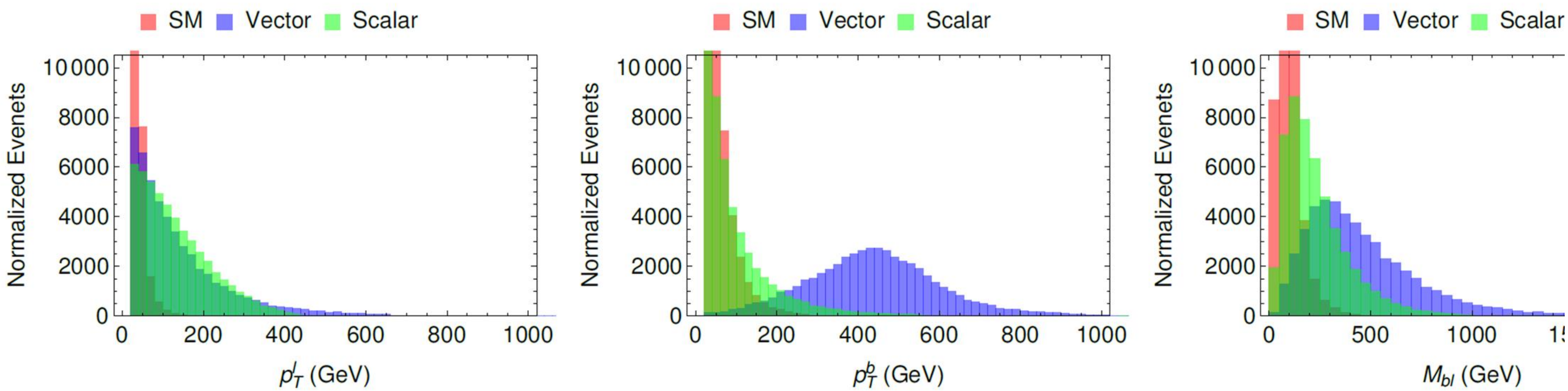
$$\mathcal{O}_{S_{R,L}} = (\bar{c}P_{R,L} b)(\bar{\tau} P_L \nu)\,, \qquad (6)$$

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

SKIP 4 NOW

Backgrounds and such

- **Anomaly implies BSM signals in pp=> b tau nu..with tau => l + nu's**
- **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 searched for higher mediator masses.** ~ 5TeV



'IG. 1. Kinematic distributions for $pp \to b\tau\nu \to b\ell + \not{E}_T$ signal (vector and scalar) and SM background. We have he total number of events to be the same for all three cases to make a fair comparison of the distributions. Th orresponds to Eq. (4), whereas the scalar and vector cases correspond to the operators given in Eqs. (6) and (5) r vhere we have chosen the new physics scale $\Lambda = 1$ TeV for illustration.

EXPECT DISTINCTIVE NP CONTRIBUTIONS IN COLLIDERS

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

- **ASSUMING the anomaly is 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 also in Brust, Katz, Lawrence and Sundrum 1110.6670]**
- **Collider signals tend to get a lot harder than (usual-RPC) SUSY**

RPV3 preserves gauge coupling unification irrespective of # of effective gens. 1, 2 or 3.

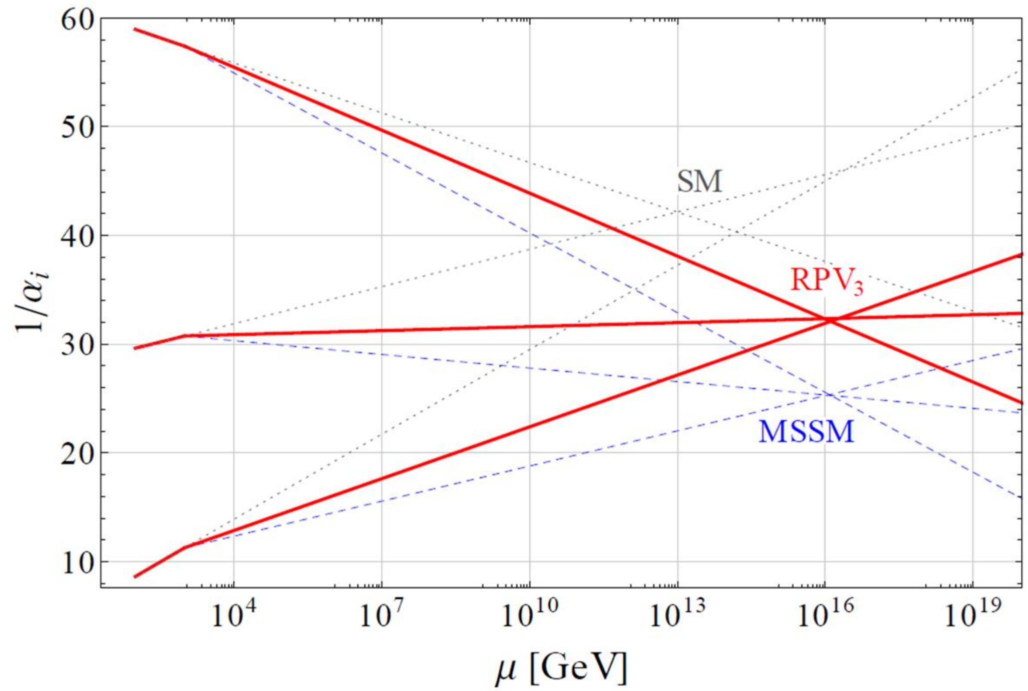


FIG. 2. RG evolution of the gauge couplings in the SM, MSSM and with partial supersymmetrization.

Unification scale ~ stays same, only value of couplings shifts

For pheno relevant terms:

C also Deshpande + He,1608.04817

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

} RPV₃ 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!

CONSTRAINTS

BABAR Phy Book '97

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

	CP Violation			D^0–$\overline{D}^0$
Model	B^0_d–$\overline{B}^0_d$ Mixing	Decay Ampl.	Rare Decays	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.

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

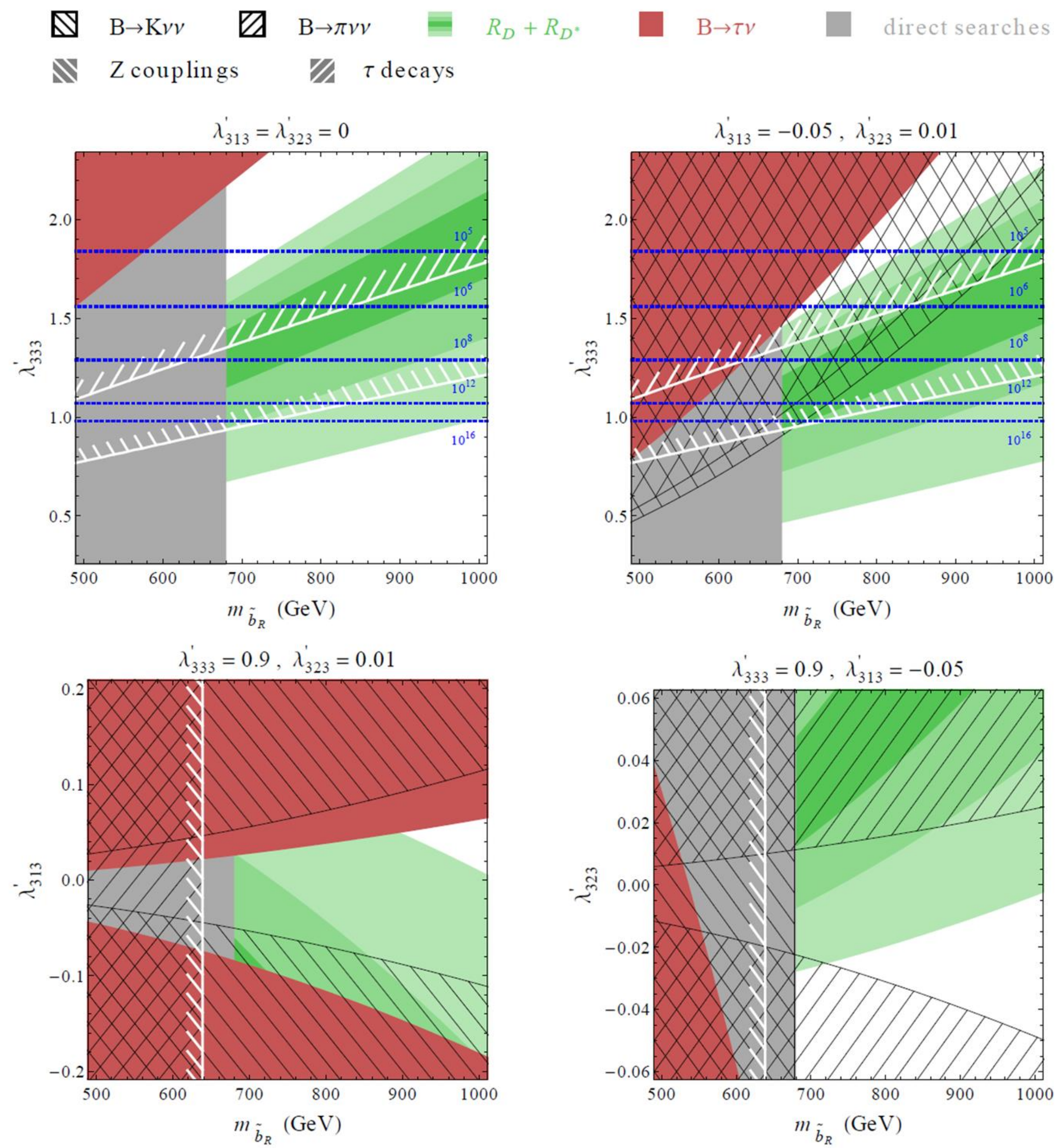
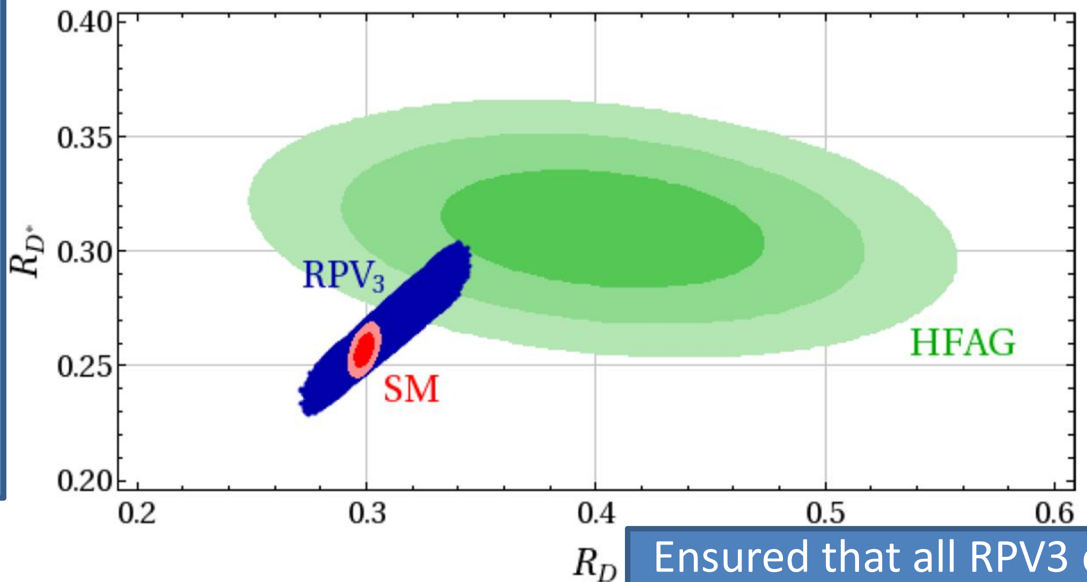


FIG. 3. RPV parameter space satisfying the $R_{D^{(*)}}$ anomaly and other relevant constraints.

RPV3 allows
RD=(.272-.347)
RD*=(.229-.305)



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

FIG. 4. The SM predictions (red), experimental world average (green), and values accessible in the MSSM with RPV (blue) in the R_D vs. R_{D^*} plane. 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

- ATLAS, CMS ought to vigorously search for BSM in : b τ ν and in t τ
- More independent theory effort on and off lattice for determination of SM value for RD* are urgently needed
- Expt BG from higher D** etc resonances a concern and should b measured
- Detection of τ via modes entailing only 1 nu would be very helpful
- More info from expts on R(D), R(D*), R(π), R(ρ), analogous Bs, B-baryon, B=>τ ν 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
- => classic large missing energy hunt for SUSY not relevant for that scenario
- => 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=>μ μ and much more): see ADS' II

XTRAS

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