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

Amarjit Soni
HET-BNL
Anomalies galore!

- RD(*)
- RK(*)
- g -2…T.Blum on the lat~04
- DCP(K->pi pi) epsilon’: obsession….for a long^3 time

See below \( \sim 4.15 \)

MH Schune CERN Apr’17 \( \sim 2.66 \) RK < \( \sim 22 \pm 2.5 \) \( \sigma \) RK

\( \sim 3.66 \)

216[PRL 2015] => \( \sim 720 \) now => \( \sim 1200 \)

[2.1\( \sigma \) (2.9\( \sigma \))? => ?? ] .....some months
Today’s primary focus: RD(*)
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
Exclusive $B \rightarrow D^{(*)}\tau\nu$
To test the SM Prediction, we measure

\[ R(D) = \frac{\Gamma(\bar{B} \rightarrow D\tau\nu)}{\Gamma(\bar{B} \rightarrow D\ell\nu)} \quad R(D^*) = \frac{\Gamma(\bar{B} \rightarrow D^*\tau\nu)}{\Gamma(\bar{B} \rightarrow D^*\ell\nu)} \]

Several experimental and theoretical uncertainties cancel in the ratio!

- BR events are fully reconstructed!

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

Ken Kiers* and Amarjit Soni†

Department of Physics, Brookhaven National Laboratory, Upton, New York 11973-5000

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We study the $q^2$ dependence of the exclusive decay mode $B \to D \tau \bar{\nu}$ in type-II two Higgs doublet models (2HDM’s) and show that this mode may be used to put stringent bounds on $\tan\beta/m_H$. There are currently rather large theoretical uncertainties in the $q^2$ distribution, but these may be significantly reduced by future measurements of the analogous distribution for $B \to D(e,\mu)\bar{\nu}$. We estimate that this reduction in the theoretical uncertainties would eventually (i.e., with sufficient data) allow one to push the upper bound on $\tan\beta/m_H$ down to about 0.06 GeV$^{-1}$. This would represent an improvement on the current bound by about a factor of 7. We
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 contribute; Now 4 FF, again contribution of one FF is prop. to lepton mass
Semi-leptonic (exclusive) form factors

Basics

\[ H_{int} = \frac{G_F}{\sqrt{2}} \left[ \mathcal{J}^{had} + \mathcal{J}^{\mu \nu \, lep} \right] V^c_{\mu i} \]

\[ D^u + A^u = \frac{\bar{u} \gamma_\mu b}{m_u} + \frac{\bar{t} \gamma_\nu s}{m_t} \]

\[ \langle \pi(p_f) | J^{\frac{1}{2}}_\mu | B(p_i) \rangle = (p_i + p_f) f_+(q^2) + (p_i - p_f) f_-(q^2) \]

\[ = f_+(q^2) \left[ (p_i + p_f)^2 + \frac{m_f - m_i}{q^2} (p_i - p_f)^2 \right] + \]

\[ f_0(q^2) \frac{m^2_f - m^2_i}{q^2} \left( \frac{q^2}{q^2} \right) (p_f - p_i)^2 ; \quad q \equiv p_f - p_i \]
- S.L. decays involving a $\tau^\pm$ have an additional helicity amplitude (for $D^*$):

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

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

- To test the SM Prediction, we measure:

$$R(D) = \frac{\Gamma(B \to D_{\tau \nu})}{\Gamma(B \to D\ell\nu)}$$

and

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

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: $a^2 > 4$ GeV$^2$
<table>
<thead>
<tr>
<th>Decay</th>
<th>$N_{\text{sig}}$</th>
<th>$N_{\text{norm}}$</th>
<th>$R(D^{(*)})$</th>
<th>$B(B \to D^{(*)}\tau\nu)$ (%)</th>
<th>$\Sigma_{\text{tot}}(\sigma)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D^0_T \bar{\nu}_T$</td>
<td>314 ± 60</td>
<td>1995 ± 55</td>
<td>0.429 ± 0.082 ± 0.052</td>
<td>0.99 ± 0.19 ± 0.13</td>
<td>4.2</td>
</tr>
<tr>
<td>$D^{*0}_T \bar{\nu}_T$</td>
<td>639 ± 62</td>
<td>8766 ± 104</td>
<td>0.322 ± 0.032 ± 0.022</td>
<td>1.71 ± 0.17 ± 0.13</td>
<td>9.4</td>
</tr>
<tr>
<td>$D^+_T \bar{\nu}_T$</td>
<td>177 ± 31</td>
<td>986 ± 35</td>
<td>0.469 ± 0.084 ± 0.053</td>
<td>1.01 ± 0.18 ± 0.12</td>
<td>5.5</td>
</tr>
<tr>
<td>$D^{*+}_T \bar{\nu}_T$</td>
<td>245 ± 27</td>
<td>3186 ± 61</td>
<td>0.355 ± 0.039 ± 0.021</td>
<td>1.74 ± 0.19 ± 0.12</td>
<td>10.4</td>
</tr>
<tr>
<td>$D_T \bar{\nu}_T$</td>
<td>489 ± 63</td>
<td>2981 ± 65</td>
<td>0.440 ± 0.058 ± 0.042</td>
<td>1.02 ± 0.13 ± 0.11</td>
<td>6.8</td>
</tr>
<tr>
<td>$D^{*}_T \bar{\nu}_T$</td>
<td>888 ± 63</td>
<td>11953 ± 122</td>
<td>0.332 ± 0.024 ± 0.018</td>
<td>1.76 ± 0.13 ± 0.12</td>
<td>13.2</td>
</tr>
</tbody>
</table>

**Comparison with SM calculation:**

<table>
<thead>
<tr>
<th></th>
<th>R(D)</th>
<th>R(D*)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BABAR</td>
<td>0.440 ± 0.071</td>
<td>0.332 ± 0.029</td>
</tr>
<tr>
<td>SM</td>
<td>0.297 ± 0.017</td>
<td>0.252 ± 0.003</td>
</tr>
</tbody>
</table>

**Difference**

- 2.0 $\sigma$
- 2.7 $\sigma$

The combination of the two measurements (0.27 correlation) yields $\chi^2/\text{NDF}=14.6/2$, Prob. = 6.9 x 10^{-4}.
A charged Higgs (2HDM type II) of spin 0 couples to the $\tau$ and will only affect $H_t$.

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

- 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

$$\tan\beta/m_H = 0.44 \pm 0.02 \quad \text{for } R(D)$$
$$\tan\beta/m_H = 0.75 \pm 0.04 \quad \text{for } R(D^*)$$

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

- ~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
# 39. Statistics

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

<table>
<thead>
<tr>
<th>$\alpha$</th>
<th>$\delta$</th>
<th>$\alpha$</th>
<th>$\delta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.3173</td>
<td>$1\sigma$</td>
<td>0.2</td>
<td>$1.28\sigma$</td>
</tr>
<tr>
<td>$4.55 \times 10^{-2}$</td>
<td>$2\sigma$</td>
<td>0.1</td>
<td>$1.64\sigma$</td>
</tr>
<tr>
<td>$2.7 \times 10^{-3}$</td>
<td>$3\sigma$</td>
<td>0.05</td>
<td>$1.96\sigma$</td>
</tr>
<tr>
<td>$6.3 \times 10^{-5}$</td>
<td>$4\sigma$</td>
<td>0.01</td>
<td>$2.58\sigma$</td>
</tr>
<tr>
<td>$5.7 \times 10^{-7}$</td>
<td>$5\sigma$</td>
<td>0.001</td>
<td>$3.29\sigma$</td>
</tr>
<tr>
<td>$2.0 \times 10^{-9}$</td>
<td>$6\sigma$</td>
<td>$10^{-4}$</td>
<td>$3.89\sigma$</td>
</tr>
</tbody>
</table>
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

• $B \rightarrow \tau \nu$ 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 $B \rightarrow \tau \nu$; 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 $\sim 1.5 \sigma$ and milder discrepancy with SM compared to BABAR and to LHCb
Concern on Experiments

• Leptonic decays: $\tau \rightarrow \mu \nu \nu \ldots$ total 3 $\nu$’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: $B \rightarrow D^{*} \tau \nu; \tau \rightarrow 3\pi + \nu$
• Consistent with the SM at $\sim 1-\sigma$=> heightens anxiety about $D^{**}$....contaminations in $\tau \rightarrow \mu \nu \nu$
• Similarly new Belle result with hadronic tau decay With only 1 $\nu$.......consistent with SM well within 1 sigma!
**World average**

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

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

- In combination with the muonic LHCb measurement:

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

  the LHCb average is:

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

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

- Naïve $R(D)/R(D^*)$ combination at $4.1\sigma$ from SM.
Conclusions

- We have measured the ratio $K_{\text{had}}(D^*) = \frac{\text{BR}(B^0 \to D^*\tau\nu)}{\text{BR}(B^0 \to D^*3\pi)}$ using the $3\pi(\pi^0)$ hadronic decay of the $\tau$ 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.
Results

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

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

**Result**

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

Consistent with SM and previous measurements!

Error can be reduced in Belle II
New status of $\mathcal{R}(D^*)$

$B \rightarrow D^{*\tau}\nu$ with semileptonic tag

$B \rightarrow D^{*\tau}\nu$ with hadronic $\tau$ decays

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

Excess still $4\sigma$: central value moved towards SM; on $\mathcal{R}(D^*)$, discrepancy increased from $3.0\sigma$ to $3.4\sigma$
REGARDING (SM) THEORY
Concerns on SM-theory

• Good news is that lattice[FERMI-MILC] study largely confirms pheno calculations for $R_D$ [our RBC-UKQCD; witzel et al needs some more months; hope for another effort at BNL-centric]

• For $B \rightarrow D^*$ 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 $B \rightarrow D$

• Therefore, $O(1\%)$ errors in $R_{D^*}$ (and in fact smaller than in $R_D$) are difficult to understand; lattice results should come in some months

• 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 $R_{D^*}$, we take central value from Bernlochner et al but unlike them we take full spread between two cen values i.e. with the famous

$$R_{D^*}^{SM} = 0.299 \pm 0.003$$

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

**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.

Very timely & useful phenomenological study by BLPR 2017
Overview on Sources of Uncertainty

- 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 $B \to D^*\ell\nu$. |
| $\delta R(D^*) = 0.005$ |

| Theory error due to sum rule parameters. |
| $\delta R(D^*) = 0.002$ |

| Theory error due to higher order effects. |
| $\delta R(D^*) = \frac{+0.007}{-0.006}$ |

| Total Result |
| (Experiment: $0.310 \pm 0.015 \pm 0.008$ (HFAG, [1612.07233])) |
| $R(D^*) = 0.258^{+9}_{-8}$ |

Stefan Schacht

Venice July 2017

ICNFP (CRETE) Aug-2017; HET-BNL; soni
SUMMARY OF THEORETICAL CALCULATIONS
\[ R(D) = 0.300(8) \text{ HPQCD (2015)} \]
\[ R(D) = 0.299(11) \text{ FNAL/MILC (2015)} \]
\[ 0.299 \pm 0.003 \]

\[ R(D^*) = 0.252(3) \text{ S. Faifer et al. (2012)} \]
\[ 0.257 \pm 0.003 \]

\[ R(D^*) = 0.258^{+9}_{-8} \]
FOR RD* CENTRAL VALUE OF BEST THEORY ESTIMATE APPEARS BIT LOWER THAN ALL ~6 MEASUREMENTS!

+ 2 σ_{F_{RD}}
Bottom line

• NP or not depends critically not just on precise experiment but also reliable SM prediction from the lattice is mandatory....familiar story

• Experimental results often attained at huge cost can only be used effectively, if commesurate theory predictions are available.......mantra for past several decades
Anomalies galore!

- RD(*)
- RK(*)
- ..........................................................
- g -2
- ..........................................................
- epsilon': my lattice effort ~35 years!
  216[PRL 2015] => ~720 now => ~1200
  [2.1σ (2.9σ?) => ???? ] .....some months

LATTICE is VITAL for all!
MODEL INDEPENDENT IMPLICATIONS OF RD(*) ANOMALIES FOR [LHC] COLLIDER EXPERIMENTS
• In a nut-shell B-experiments seem to find anomalous behavior in the underlying $b \Rightarrow c \tau \nu$

• This necessarily [by XSym] implies there should be analogous anomaly in $g + c \Rightarrow b \tau \nu \ldots \Rightarrow pp \Rightarrow b \tau \nu$

• **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 $b \rightarrow c \tau \bar{\nu}$ in the SM is given by

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

$$\text{SM}$$

$$O_{V_{R,L}} = (\bar{c} \gamma_\mu P_{R,L} b) (\bar{\tau} \gamma_\mu P_L \nu) \quad (5)$$

$$O_{S_{R,L}} = (\bar{c} P_{R,L} b) (\bar{\tau} P_L \nu), \quad (6)$$

$$O_T = (\bar{c} \sigma^{\mu\nu} P_L b) (\bar{\tau} \sigma_{\mu\nu} P_L \nu). \quad (7)$$

$$\text{BSM}$$

$$\text{Dim 6 ops}$$

ICNFP (CRETE) Aug-2017; HET-BNL; soni
Backgrounds and such

- Anomaly implies BSM signals in $pp \rightarrow b \tau \nu \ldots$ with $\tau \Rightarrow l + \nu$’s....FOR ATLAS, CMS!
- There is SM contribution too[though suppressed by $V_{cb} \sim 0.04$] but in addition there is potentially a huge background from $W+j$ with about $\sim 1\%$ misidentification of light jets as $b$’s...At 13TeV, SM+BG (with cuts)$XS=1.5pb$
- Signal $XS$ for Vector (scalar) case for $\Lambda/[1TeV] \sim gNP \sim 1$ is about $1.1(1.8)pb$ @13TeV ...With 300/fb may $b$ probe to $\sim 4TeV$ ...Moreover, distinctive kinematic distributions can $b$ exploited with say $ptb > 100$ GeV, $M_{bl} > 200$ GeV to enhance searched for higher mediator masses $\sim 5TeV$
Fig. 1. Kinematic distributions for $pp \rightarrow b\tau\nu \rightarrow b\ell + E_T$ signal (vector and scalar) and SM background. We have set the total number of events to be the same for all three cases to make a fair comparison of the distributions. This corresponds to Eq. (4), whereas the scalar and vector cases correspond to the operators given in Eqs. (6) and (5) respectively, where 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 [BIG ASSUMPTION due to caveats mentioned]
• Anomaly involves simple tree-level semi-leptonic decays
• Also $b \Rightarrow \tau$ (3\textsuperscript{rd} family)
• Speculate: May be related to Higgs naturalness
• Perhaps 3\textsuperscript{rd} 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
RPV$_3$ preserves gauge coupling unification irrespective of the effective number of effective gen. 1, 2, or 3.

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

Unification scale $\mu$ stays same, only value of couplings shifts.
For pheno relevant terms:

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

\[
\mathcal{L}_{\text{eff}} \supset \frac{\lambda'_{ijk} \lambda'_{mnk}}{2m^2_{d_{kR}}} \left[ \bar{\nu}_{mL} \gamma^{\mu} \nu_{iL} \bar{d}_{nL} \gamma_{\mu} d_{jL} \\
- \nu_{mL} \gamma^{\mu} e_{iL} \bar{d}_{nL} \gamma_{\mu} \left( V_{\text{CKM}}^\dagger u_{L} \right)_j + \text{h.c.} \right] \\
- \frac{\lambda'_{ijk} \lambda'_{mkn}}{2m^2_{e_{jL}}} \bar{e}_{mL} \gamma^{\mu} e_{iL} \bar{d}_{kR} \gamma_{\mu} d_{nR} ,
\]

\text{C also Deshpande + He,1608.04817 (but with key diffs)}

\text{)} RPI_3 \text{  interaction}

\text{Dim-6}

\text{FnRd(x)}

\text{NOTE: ITS SM-like!}
CONSTRAINTS
<table>
<thead>
<tr>
<th>Model</th>
<th>$B^0_d - \bar{B}^0_d$ Mixing</th>
<th>Decay Ampl.</th>
<th>Rare Decays</th>
<th>$D^0 - \bar{D}^0$ Mixing</th>
</tr>
</thead>
<tbody>
<tr>
<td>MSSM</td>
<td>$O(20%)$ SM Same Phase</td>
<td>No Effect</td>
<td>$B \rightarrow X_s \gamma$ - yes $B \rightarrow X_s l^+ l^-$ - no</td>
<td>No Effect</td>
</tr>
<tr>
<td>SUSY – Alignment</td>
<td>$O(20%)$ SM New Phases</td>
<td>$O(1)$</td>
<td>Small Effect</td>
<td>Big Effect</td>
</tr>
<tr>
<td>SUSY – Approx. Universality</td>
<td>$O(20%)$ SM New Phases</td>
<td>$O(1)$</td>
<td>No Effect</td>
<td>No Effect</td>
</tr>
<tr>
<td>$R$-Parity Violation</td>
<td>Can Do</td>
<td>Everything</td>
<td>Except Make</td>
<td>Coffee</td>
</tr>
<tr>
<td>MHDM</td>
<td>$\sim$ SM/New Phases</td>
<td>Suppressed</td>
<td>$B \rightarrow X_s \gamma, B \rightarrow X_s \tau \tau$</td>
<td>Big Effect</td>
</tr>
<tr>
<td>2HDM</td>
<td>$\sim$ SM/Same Phase</td>
<td>Suppressed</td>
<td>$B \rightarrow X_s \gamma$</td>
<td>No Effect</td>
</tr>
<tr>
<td>Quark Singlets</td>
<td>Yes/New Phases</td>
<td>Yes</td>
<td>Saturates Limits</td>
<td>Q = 2/3</td>
</tr>
<tr>
<td>Fourth Generation</td>
<td>$\sim$ SM/New Phases</td>
<td>Yes</td>
<td>Saturates Limits</td>
<td>Big Effect</td>
</tr>
<tr>
<td>LRM – $V_L = V_R$</td>
<td>No Effect</td>
<td>No Effect</td>
<td>$B \rightarrow X_s \gamma, B \rightarrow X_s l^+ l^-$</td>
<td>No Effect</td>
</tr>
<tr>
<td>$- V_L \neq V_R$</td>
<td>Big/New Phases</td>
<td>Yes</td>
<td>$B \rightarrow X_s \gamma, B \rightarrow X_s l^+ l^-$</td>
<td>No Effect</td>
</tr>
<tr>
<td>DEWSB</td>
<td>Big/Same Phase</td>
<td>No Effect</td>
<td>$B \rightarrow X_s \ell \ell, B \rightarrow X - s \bar{t} \bar{t}$</td>
<td>Big Effect</td>
</tr>
</tbody>
</table>

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 $pp \rightarrow \tilde{b}\tilde{b} \rightarrow \tau^+ \tau^- t\bar{t}$

Indirect constraints considered due $B \rightarrow \tau \nu; \pi \tau \nu; \pi(K) \nu \nu \ldots$.
Also $B_C \Rightarrow \tau \nu \ldots$.

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

⇒ 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. 3. RPV parameter space satisfying the $R_{D(\pi)}$ anomaly and other relevant constraints.
Ensured that all RPV3 couplings stay perturbative up to GUT

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

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

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

• Semi-leptonic B-decays are claimed to indicate ~4.1 sigma deviation from SM

• IMMEDIATE & URGENT IMPLICATION: ATLAS, CMS ought to vigorously search for BSM in : b m ν and in t m

• 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=>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 [if it persists!]

• => classic large missing energy hunt for SUSY not relevant for that scenario

• => many RPV signatures tend to become rather challenging; therefore, clues can be crucial.

• => 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
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 $\lambda_{333}'$ 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 $\lambda_{333}'$ 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.
\[
\frac{g_{Z\tau_L\tau_L}}{g_{Z\ell_L\ell_L}} = 1 - \frac{3(\lambda'_{333})^2}{16\pi^2} \frac{1}{1 - 2s_W^2} \frac{m_t^2}{m_{b_R}^2} f_Z \left( \frac{m_t^2}{m_{b_R}^2} \right)
\]

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

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 approximation,
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

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).  

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 $\beta$-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
AIDA X E-K THESIS: 1$^{\text{ST}}$ PHD THESIS (~’89) INITIATING THE USE OF LATTICE METHODS FOR DEDUCING SL FF’S
Semileptonic decays on the lattice: The exclusive $0^-$ to $0^-$ case

Claude W. Bernard*

Institute for Theoretical Physics, University of California, Santa Barbara, California 93106

Aida X. El-Khadra

Theory Group, Fermi National Accelerator Laboratory, P. O. Box 500, Batavia, Illinois 60510

Amarjit Soni

Institute for Theoretical Physics, University of California, Santa Barbara, California 93106
and Department of Physics, Brookhaven National Laboratory, Upton, New York 11973
(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 threemomenta to the initial- and final-state mesons. We study the pseudoscalar decays $K \rightarrow \pi \ell \nu$, $D \rightarrow K \ell \nu$, $D \rightarrow \pi \ell \nu$, $D_s \rightarrow \eta \ell \nu$, and $D_s \rightarrow K \ell \nu$ 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.

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.

Department of Physics, Brookhaven National Laboratory, Upton, New York 11973
(Received 30 September 1991)

We present our lattice calculation of the semileptonic form factors for the decays $D \rightarrow K^*$, $D_s \rightarrow \phi$, and $D \rightarrow \rho$ using Wilson fermions on a $24^3 \times 39$ lattice at $\beta=6.0$ with 8 quenched configurations. For $D \rightarrow K^*$, we find for the ratio of axial form factors $A_2(0)/A_1(0) = 0.70 \pm 0.16 \pm 0.19$. Results for other form factors and ratios are also given.