Asymmetry Observables and the Origin of $R_D(\ast)$ Anomalies

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Outline

- \( R_{D(*)} \) Solutions
- Discerning Different Models
- More On \( F_{D*}^L \) - And A New Solution
New Physics in the Flavor Experiments

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$$R_{D(*)} \equiv \frac{\Gamma(B \to D^{(*)}\tau\nu)}{\Gamma(B \to D^{(*)}l\nu)}, \quad l = e, \mu$$

$R_{D(*)}$

$R_{D}^{obs} = 0.407 \pm 0.046, \quad R_{D}^{SM} = 0.299 \pm 0.003, \quad R_{D}^{obs} = 0.304 \pm 0.015, \quad R_{D}^{SM} = 0.258 \pm 0.005.$
The Most General EFT

- SM contribution:

\[ \langle D^{(*)} | \bar{c} \gamma^{\mu} P_L b | \bar{B} \rangle \]

\[ \langle \tau \bar{\nu} | \bar{\tau} \gamma^{\nu} P_L \nu | 0 \rangle \]

\[ \langle D^{(*)} \tau \nu | (\bar{c} \gamma^{\mu} P_L b) (\bar{\tau} \gamma^{\nu} P_L \nu) | \bar{B} \rangle \]
The Most General EFT

- **SM contribution:**

\[
\langle D^{(*)} | \bar{c} \gamma^{\mu} P_L b | \bar{B} \rangle
\]

\[
\frac{g_{\mu\nu}}{m_W^2} \langle \bar{\tau} \gamma^\nu P_L \nu | 0 \rangle
\]

\[
\langle D^{(*)} \tau \nu | (\bar{c} \gamma^{\mu} P_L b) (\bar{\tau} \gamma^\nu P_L \nu) | \bar{B} \rangle
\]

- **The most general dim-6 effective Hamiltonian:**

\[
\mathcal{H}_{\text{eff}} = \frac{4G_F V_{cb}}{\sqrt{2}} \sum_{X=S, V, T} \sum_{M, N=L, R} C_{MN}^X O_{MN}^X,
\]

\[
O_{MN}^S \equiv (\bar{c} P_M b)(\bar{\tau} P_N \nu),
\]

\[
O_{MN}^V \equiv (\bar{c} \gamma^{\mu} P_M b)(\bar{\tau} \gamma^\mu P_N \nu),
\]

\[
O_{MN}^T \equiv (\bar{c} \sigma^{\mu\nu} P_M b)(\bar{\tau} \sigma_{\mu\nu} P_N \nu),
\]

for \( M, N = R \) or \( L \) (SM : \( C_{LL}^V = 1 \)).
# Minimal Models

| Mediator                              | Operator Combination | Viability                      |
|---------------------------------------|----------------------|--------------------------------|
| Colorless Scalars                     | $\mathcal{O}^S_{XL}$ | $\times$ ($Br (B_c \rightarrow \tau \nu)$) |
| $W'$ (LH fermions)                    | $\mathcal{O}^V_{LL}$ | $\times$ (collider bounds)     |
| $S_1$ LQ (3, 1, 1/3) (LH fermions)   | $\mathcal{O}^S_{LL} - x\mathcal{O}^T_{LL}$, $\mathcal{O}^V_{LL}$ | $\checkmark$                     |
| $U_1'$ LQ (3, 1, 2/3) (LH fermions)  | $\mathcal{O}^S_{RL}$, $\mathcal{O}^V_{LL}$ | $\checkmark$                     |
| $R_2$ LQ (3, 2, 7/6)                  | $\mathcal{O}^S_{LL} + x\mathcal{O}^T_{LL}$ | $\checkmark$                     |
| $S_3$ LQ (3, 3, 1/3)                  | $\mathcal{O}^V_{LL}$ | $\times$ ($b \rightarrow s\nu\nu$) |
| $U_3'$ LQ (3, 3, 2/3)                 | $\mathcal{O}^V_{LL}$ | $\times$ ($b \rightarrow s\nu\nu$) |
| $V_2'$ LQ (3, 2, 5/6)                 | $\mathcal{O}^S_{RL}$ | $\times$ ($R_{D(\ast)}$ value) |
| Colorless Scalars                     | $\mathcal{O}^S_{XR}$ | $\times$ ($Br (B_c \rightarrow \tau \nu)$) |
| $W'$ (RH fermions)                    | $\mathcal{O}^V_{RR}$ | $\checkmark$                     |
| $\tilde{R}_2$ LQ (3, 2, 1/6)         | $\mathcal{O}^S_{RR} + x\mathcal{O}^T_{RR}$ | $\times$ ($b \rightarrow s\nu\nu$) |
| $S_1$ LQ (3, 1, 1/3) (RH fermions)   | $\mathcal{O}^V_{RR}$, $\mathcal{O}^S_{RR} - x\mathcal{O}^T_{RR}$ | $\checkmark$                     |
| $U_1'$ LQ (3, 1, 2/3) (RH fermions)  | $\mathcal{O}^S_{LR}$, $\mathcal{O}^V_{RR}$ | $\checkmark$                     |
Discerning Different Solutions

Different models generate effective operators with different Lorentz structures. Hence, some asymmetry observables can help.

\[
\begin{align*}
\vec{p}_B &\rightarrow \vec{p}_D(\ast) \\
\vec{p}_\tau &\rightarrow \vec{p}_\nu \\
\vec{p}_d &\rightarrow \vec{p}_\nu' \\
\theta &\rightarrow \theta_{\tau d} \\
\hat{e}_\tau &\rightarrow \hat{e}_{\perp} \\
\hat{e}_T &\rightarrow \hat{e}_{T} \\
\end{align*}
\]

\[
P_{\ast} = \Gamma_{\ast} + \hat{e} - \Gamma_{\ast} - \hat{e} + \Gamma_{\ast} + \hat{e} \Gamma_{\ast} - \hat{e}
\]

Observable

\[
A_{FB} = \frac{1}{\Gamma_{\ast}} \left( - \int_{\theta = 0}^{\theta = \pi} d\theta + \int_{\theta = \pi/2}^{\theta = \pi} d\theta \right)
\]

SM value

-0.360
-0.063
0.325
-0.497
-0.842
-0.499
0
Discerning Different Solutions

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\[ \mathcal{P}^{(\ast)}(\hat{e}) = \frac{\Gamma^{(\ast)} + \hat{e} - \Gamma^{(\ast)} - \hat{e}}{\Gamma^{(\ast)} + \Gamma^{(\ast)}}, \quad \mathcal{A}_{FB}^{(\ast)} = \frac{1}{\Gamma^{(\ast)}} \left( -\int_{\theta=0}^{\theta=\pi/2} + \int_{\theta=\pi/2}^{\theta=\pi} \right) d\theta \frac{d\Gamma^{(\ast)}}{d\theta}. \]
Discerning Different Solutions

Different models generate effective operators with different Lorentz structures. Hence, some asymmetry observables can help.

\[
\mathcal{P}^{(*)} = \frac{\Gamma^{(*)} - \Gamma^{(*)}}{\Gamma^{(*)} + \Gamma^{(*)}}, \quad \mathcal{A}_{FB}^{(*)} = \frac{1}{\Gamma^{(*)}} \left( -\int_{\theta=0}^{\theta=\pi/2} + \int_{\theta=\pi} \right) d\theta \frac{d\Gamma^{(*)}}{d\theta}.
\]

| Observable | \( A_{FB} \) | \( A_{FB}^{*} \) | \( \mathcal{P}_{\tau} \) | \( \mathcal{P}_{\tau}^{*} \) | \( \mathcal{P}_{\perp} \) | \( \mathcal{P}_{\perp}^{*} \) | \( \mathcal{P}_{T} \) | \( \mathcal{P}_{T}^{*} \) |
|------------|---------------|----------------|----------------|----------------|----------------|----------------|-------------|-------------|
| SM value   | −0.360        | 0.063          | 0.325          | −0.497         | −0.842         | −0.499         | 0           | 0           |
Discerning Different Solutions at Belle II

• Let us assume we measure $R_{D(*)}$ in Belle II and discover NP.
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- In each model, the range of the Wilson coefficients explaining $R_{D(*)}$ has a different imprint on other observables. Can we leverage that to distinguish models from one another?
Discerning Different Solutions at Belle II

- Let us assume we measure $R_{D(*)}$ in Belle II and discover NP.
- In each model, the range of the Wilson coefficients explaining $R_{D(*)}$ has a different imprint on other observables. Can we leverage that to distinguish models from one another?
- It highly depends on the measured $R_{D(*)}$ value.
Discerning Different Solutions: Two Extreme Outcomes

\[ R_D = 0.407 \quad R_{D^*} = 0.304 \quad R_D = 0.340 \quad R_{D^*} = 0.275 \]
• We develop a simple $\chi^2$ test to see how well each pair of models can be distinguished.
Discerning Different Solutions: Two Extreme Outcomes

- We develop a simple $\chi^2$ test to see how well each pair of models can be distinguished.

- Can tell almost all the models apart; we may need to resort to the $CP$-odd observables $\mathcal{P}_T^{(\ast)}$, for which there are currently no measurement proposals, in the second scenario.
\( F_{D^*}^L : \) Another Asymmetry Observable

\[
F_{D^*}^L = \frac{\Gamma(\bar{B} \rightarrow D^*_L \tau \nu)}{\Gamma(\bar{B} \rightarrow D^*_L \tau \nu) + \Gamma(\bar{B} \rightarrow D^*_T \tau \nu)}.
\]
$F_{D^*}^L : \text{Another Asymmetry Observable}$

$$F_{D^*}^L = \frac{\Gamma(\bar{B} \rightarrow D^*_L \tau \nu)}{\Gamma(\bar{B} \rightarrow D^*_L \tau \nu) + \Gamma(\bar{B} \rightarrow D^*_T \tau \nu)}.$$  

$(F_{D^*}^L)_{SM} = 0.457 \pm 0.01, \quad (F_{D^*}^L)_{obs} = 0.60 \pm 0.08 \pm 0.04.$

- None of the existing minimal models can accommodate this new observation.
**$F_{D^*}^L$ : Another Asymmetry Observable**

\[
F_{D^*}^L = \frac{\Gamma(\bar{B} \rightarrow D_L^{*}\tau\nu)}{\Gamma(\bar{B} \rightarrow D_L^{*}\tau\nu) + \Gamma(\bar{B} \rightarrow D_T^{*}\tau\nu)}.
\]

\[
(F_{D^*}^L)_{SM} = 0.457 \pm 0.01, \quad (F_{D^*}^L)_{obs} = 0.60 \pm 0.08 \pm 0.04.
\]

- None of the existing minimal models can accommodate this new observation.

- Is there any combination of the dim-6 operators that can explain the observed value?
Explaining the Observed $F_{D^*}^L$

- We look for the maximum of $F_{D^*}^L$. We show it can be achieved with all real WCs and only Left-Handed $\nu$s.
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- We look for the maximum of $F_{D^*}^L$. We show it can be achieved with all real WCs and only Left-Handed $\nu$s.
- We use some observables/constraints ($R_D$, $R_{D^*}$, and $Br(B_c \rightarrow \tau\nu)$) to fix three of these parameters; then maximize $F_{D^*}^L$ over the remaining two.
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![Graphs showing the maximum of $F_{D^*}^L$ over different parameters with different BR(B_c → τν) values.]
Explaining the Observed $F_{D^*}^L$

- We look for the maximum of $F_{D^*}^L$. We show it can be achieved with all real WCs and only Left-Handed $\nu$s.
- We use some observables/constraints ($R_D$, $R_{D^*}$, and $Br(B_c \rightarrow \tau\nu)$) to fix three of these parameters; then maximize $F_{D^*}^L$ over the remaining two.

- Relatively large $C_{RL}^V$, $C_{LL}^T$, and $C_{LL}^V$ are required to explain the observed $F_{D^*}^L$. 

![Graphs showing the variation of $F_{D^*}^L$ with $|C_{RL}|$, $|C_{LL}^T|$, and $|C_{LL}^V|$ for different branching ratios.](image-url)
More on $C_{RL}^V$

$$O_{RL}^V = (\bar{c}_R \gamma^\mu b_R)(\bar{\tau}_L \gamma_\mu \nu_L),$$
More on $C_{RL}^V$

\[ O_{RL}^V = (\bar{c}_R \gamma^\mu b_R)(\bar{\tau}_L \gamma_\mu \nu_L), \]

- Given their role in explaining $F_{D^*_L}$, can we devise a model generating them?
More on $C^V_{RL}$

$$O^V_{RL} = (\bar{c}_R \gamma^\mu b_R)(\bar{\tau}_L \gamma^\mu \nu_L),$$

- Given their role in explaining $F^L_{D^*}$, can we devise a model generating them?
- The main obstacle: they violate the SM gauge invariance. Need two Higgs insertions.
More on $C_{RL}^V$

\[ O_{RL}^V = (\bar{c}_R \gamma^\mu b_R)(\bar{\tau}_L \gamma_\mu \nu_L), \]

- Given their role in explaining $F_{D*}^L$, can we devise a model generating them?
- The main obstacle: they violate the SM gauge invariance. Need two Higgs insertions.
- So what if new particles are introduced and mixed after EWSB?
A New Leptoquark Solution

Merging two existing minimal models will do the job:

\[
R_2 = \left( \begin{array}{c} R_2^{5/3} \\ R_2^{2/3} \end{array} \right) = (3, 2, 7/6), \quad \tilde{R}_2 = \left( \begin{array}{c} \tilde{R}_2^{2/3} \\ \tilde{R}_2^{-1/3} \end{array} \right) = (3, 2, 1/6),
\]
A New Leptoquark Solution

Merging two existing minimal models will do the job:

\[ R_2 = \left( \frac{R_2^{5/3}}{R_2^{2/3}} \right) = (3, 2, 7/6), \quad \tilde{R}_2 = \left( \frac{\tilde{R}_2^{2/3}}{\tilde{R}_2^{-1/3}} \right) = (3, 2, 1/6), \]

\[ \mathcal{L}_R \supset |\partial R_2|^2 + |\partial \tilde{R}_2|^2 - M_{R_2}^2 |R_2|^2 - M_{\tilde{R}_2}^2 |\tilde{R}_2|^2, \]

\[ + \lambda_R \left\{ |R_2^\dagger H|^2 + |\tilde{R}_2^\dagger \tilde{H}|^2 + (\tilde{R}_2^\dagger \tilde{H} H^\dagger R_2 + \text{h.c.}) \right\}, \]

\[ + g_1^{ij} \bar{u}_R^i R_2 \epsilon L^j + \tilde{g}_1^{ij} \bar{L}^j \epsilon \tilde{R}_2^\dagger d_R^i + \text{h.c.}, \]

\[ + g_2^{ij} \bar{e}_R^i Q_L R_2^\dagger + \tilde{g}_2^i \tilde{R}_2 \tilde{Q}_L \nu_R + \text{h.c.}, \]
A New Solution

We can safely generate $C_{RL}$ or $C_{LR}$ without any constraining bounds from flavor physics. We can evade the EWP bounds and the collider bounds (after introducing a new decay channel) as well.
A New Solution

We can safely generate $C_{V_{RL}}$ or $C_{V_{LR}}$ without any constraining bounds from flavor physics. We can evade the EWP bounds and the collider bounds (after introducing a new decay channel) as well.
A New Solution

- We can safely generate $C_{VV}$ or $C_{LL}$ without any constraining bounds from flavor physics.
- We can evade the EWP bounds and the collider bounds (after introducing a new decay channel) as well.
A New Solution

- We can safely generate $C_{RL}^V$ or $C_{LR}^V$ without any constraining bounds from flavor physics.
• We can safely generate $C^V_{RL}$ or $C^V_{LR}$ without any constraining bounds from flavor physics.

• We can evade the EWP bounds and the collider bounds (after introducing a new decay channel) as well.
Summary

• There are many viable minimal models with a heavy mediator that can explain the $R_D(\ast)$ anomalies.

• We can resort to some asymmetry observables ($P(\ast)\tau, A(\ast)FB, P(\ast)\perp$) to distinguish various models from one another.

• $F_LD^\ast$ measurement sees $\sim 1.5 - 2\sigma$ discrepancy with the SM.

• None of the existing models can explain the observed $F_LD^\ast$.

• NP with Wilson coefficients $C_{VLRL}, C_{CTLL},$ and $C_{VLLL}$ (or their counterparts with right-handed neutrinos) are required to explain $F_LD^\ast$.

• We proposed the first model generating $C_{VLRL}$ using two LQs. Our model evades various flavor and collider bounds.
Summary

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- We can resort to some asymmetry observables ($P_{\tau}^{(*)}$, $A_{FB}^{(*)}$, $P_{\bot}^{(*)}$) to distinguish various models from one another.
• There are many viable minimal models with a heavy mediator that can explain the $R_{D(*)}$ anomalies.

• We can resort to some asymmetry observables ($\mathcal{P}_\tau^{(*)}$, $A_{FB}^{(*)}$, $\mathcal{P}_\perp^{(*)}$) to distinguish various models from one another.

• $F_D^{L*}$ measurement sees $\sim 1.5 - 2\sigma$ discrepancy with the SM.
Summary

- There are many viable minimal models with a heavy mediator that can explain the $R_{D(*)}$ anomalies.
- We can resort to some asymmetry observables ($\mathcal{P}_{\tau}^{(*)}$, $\mathcal{A}_{FB}^{(*)}$, $\mathcal{P}_{\perp}^{(*)}$) to distinguish various models from one another.
- $F_{D*}^L$ measurement sees $\sim 1.5 - 2\sigma$ discrepancy with the SM. None of the existing models can explain the observed $F_{D*}^L$. 
Summary

- There are many viable minimal models with a heavy mediator that can explain the $R_{D(*)}$ anomalies.

- We can resort to some asymmetry observables ($\mathcal{P}_T^{(*)}$, $\mathcal{A}_{FB}^{(*)}$, $\mathcal{P}_\perp^{(*)}$) to distinguish various models from one another.

- $F_{D*}^L$ measurement sees $\sim 1.5 - 2\sigma$ discrepancy with the SM. None of the existing models can explain the observed $F_{D*}^L$.

- NP with Wilson coefficients $C_{RL}^V$, $C_{LL}^T$, and $C_{LL}^V$ (or their counterparts with right-handed neutrinos) are required to explain $F_{D*}^L$. 
Summary

- There are many viable minimal models with a heavy mediator that can explain the $R_D(*)$ anomalies.
- We can resort to some asymmetry observables ($\mathcal{P}_T^{(*)}$, $A_{FB}^{(*)}$, $\mathcal{P}_{\perp}^{(*)}$) to distinguish various models from one another.
- $F_{D^*}^L$ measurement sees $\sim 1.5 - 2\sigma$ discrepancy with the SM. None of the existing models can explain the observed $F_{D^*}^L$.
- NP with Wilson coefficients $C_{RL}^V$, $C_{LL}^T$, and $C_{LL}^V$ (or their counterparts with right-handed neutrinos) are required to explain $F_{D^*}^L$.
- We proposed the first model generating $C_{RL}^V$ using two LQs. Our model evades various flavor and collider bounds.
BACK UP SLIDES
Other Anomalies

- $h \rightarrow \tau \mu$
- $B \rightarrow K e^+ e^- / B \rightarrow K \mu^+ \mu^-$
- $D0 \mu \mu$ CP asym
- $B \rightarrow D^{(*)} \tau \nu$
- $B \rightarrow K^* \mu^+ \mu^-$ angular
- $|V_{ub}|$ incl/excl
- $|V_{cb}|$ incl/excl
- $B_s \rightarrow \phi \mu^+ \mu^-$
- $\epsilon'/\epsilon$
- $g-2$
# Uncertainties

## BaBar@Hadronic(τ→l)

| Source of uncertainty | % | R(D) | R(D*) |
|-----------------------|---|------|-------|
| Additive uncertainties |   |      |       |
| **PDFs**              |   |      |       |
| MC statistics         | 4.4 | 2.0  |       |
| B → D*(2010) → l(μ)π+π− FFs | 0.2 | 0.2  |       |
| D* → D∗(π+π−)         | 0.7 | 0.5  |       |
| B(→ D∗+μ−ν)           | 0.8 | 0.3  |       |
| B(→ D∗τ−ν)            | 1.8 | 1.7  |       |
| D* → D(π+π−)          | 2.1 | 2.6  |       |
| Cross-feed constraints |   |      |       |
| MC statistics         | 2.4 | 1.5  |       |
| Feed-up/feed-down     | 1.3 | 0.4  |       |
| Isospin constraints    | 1.2 | 0.3  |       |
| Fixed backgrounds      |   |      |       |
| MC statistics         | 3.1 | 1.5  |       |
| Efficiency corrections | 3.9 | 2.3  |       |
| Multiplicative uncertainties | | | |
| MC statistics         | 1.8 | 1.2  |       |
| B → D(π+)τ−ν          | 1.6 | 0.4  |       |
| Lepton PID            | 0.6 | 0.6  |       |
| π+/π− from D* → Dπ     | 0.1 | 0.1  |       |
| Detection/Reconstruction | 0.7 | 0.7  |       |
| B(τ→ l−νl)            | 0.2 | 0.2  |       |
| Total syst. uncertainty | 9.6 | 5.5  |       |
| Total stat. uncertainty | 13.1 | 7.1  |       |
| Total uncertainty     | 16.2 | 9.0  |       |

## Belle@Semileptonic(τ→l)

| Sources | R(D*) | [%] |
|---------|-------|-----|
| MC size for each PDF shape | 2.2 |
| PDF shape of the normalization in cosθB,D∗+ | +0.1 |
| PDF shape of B → D∗+τν | +1.0 |
| PDF shape and yields of fake D(∗) | 1.4 |
| PDF shape and yields of B → X,D∗ | 1.1 |
| Reconstruction efficiency ratio εnorm/εsig | 1.2 |
| Modeling of semileptonic decay | 0.2 |
| Total systematic uncertainty | +3.4 |

## Belle@Hadronic(τ→h)

| Source | R(D*) | [%] | Pτ |
|--------|-------|-----|-----|
| Hadronic B composition | +7.8% | +0.14 |
| MC statistics for each PDF shape | +3.5% | +0.13 |
| Fake D* PDF shape | 3.6% | 0.010 |
| Fake D* yield | 1.7% | 0.016 |
| B → D∗+τν | 2.1% | 0.051 |
| B → D∗τ−ν | 1.1% | 0.003 |
| B → D*τ−ν | 2.4% | 0.008 |
| τ daughter and τ− efficiency | 2.1% | 0.018 |
| MC statistics for efficiency calculation | 1.0% | 0.018 |
| EvtGen decay model | +0.8% | +0.016 |
| Fit bias | −0.6% | −0.006 |
| B(τ→ π+ντ) and B(τ→ ρ−ντ) | 0.3% | 0.002 |
| Pτ correction function | 0.1% | 0.018 |

### Scales with MC statistics

### Scales with DATA statistics

### Theory/External

### Irreducible

**Requires additional studies**
Individual Operator Effects

\[ \mathcal{H}_{\text{eff}} = \frac{4G_F V_{cb}}{\sqrt{2}} \sum_{X=S,V,T} \sum_{M,N=L,R} C_{MN}^X O_{MN}^X, \]

\[ O_{MN}^S \equiv (\bar{c}P_M b)(\bar{\tau}P_N \nu), \]

\[ O_{MN}^V \equiv (\bar{c}\gamma^\mu P_M b)(\bar{\tau}\gamma^\mu P_N \nu), \]

\[ O_{MN}^T \equiv (\bar{c}\sigma^{\mu\nu} P_M b)(\bar{\tau}\sigma_{\mu\nu} P_N \nu), \]
Individual Operator Effects

\[ \mathcal{H}_{\text{eff}} = \frac{4G_F V_{cb}}{\sqrt{2}} \sum_{\substack{X=S,V,T \\ M,N=L,R}} C^X_{MN} O^X_{MN}, \]

\[ O^S_{MN} \equiv (\bar{c} P_M b)(\bar{\tau} P_N \nu), \]
\[ O^V_{MN} \equiv (\bar{c} \gamma^\mu P_M b)(\bar{\tau} \gamma^\mu P_N \nu), \]
\[ O^T_{MN} \equiv (\bar{c} \sigma^{\mu\nu} P_M b)(\bar{\tau} \sigma^{\mu\nu} P_N \nu), \]
## All Operators

| Operator | Fierz identity | Allowed Current | $\delta L_{\text{int}}$ |
|----------|----------------|-----------------|-------------------------|
| $\mathcal{O}_{VL}$ | $(\bar{c}\gamma_\mu P_L b) (\bar{\tau}\gamma^\mu P_L \nu)$ | | $(1, 3)_0 \left( g_{q_L q_L} T^\mu q_L + g_{\ell_L \ell_L} T^\mu \ell_L \right) W^\mu_\nu$ |
| $\mathcal{O}_{VR}$ | $(\bar{c}\gamma_\mu P_R b) (\bar{\tau}\gamma^\mu P_L \nu)$ | $(1, 2)_{1/2}$ | $(\lambda_d \bar{q}_L d_R \phi + \lambda_u \bar{q}_L u_R i\tau_2 \phi^\dagger + \lambda_e \bar{\ell}_L e_R \phi)$ |
| $\mathcal{O}_{SR}$ | $(\bar{c} P_R b) (\bar{\tau} P_L \nu)$ | | |
| $\mathcal{O}_{SL}$ | $(\bar{c} P_L b) (\bar{\tau} P_L \nu)$ | | |
| $\mathcal{O}_{T}$ | $(\bar{c}\sigma^{\mu\nu} P_L b) (\bar{\tau}\sigma_{\mu\nu} P_L \nu)$ | | |
| $\mathcal{O}'_{VL}$ | $(\bar{\tau}\gamma_\mu P_L b) (\bar{c}\gamma^\mu P_L \nu)$ | $\leftrightarrow$ $\mathcal{O}_{VL}$ | $(3, 3)_{2/3}$ | $\lambda \bar{q}_L \gamma_\mu \ell_L U^\mu$ |
| $\mathcal{O}'_{VR}$ | $(\bar{\tau}\gamma_\mu P_R b) (\bar{c}\gamma^\mu P_L \nu)$ | $\leftrightarrow$ $\mathcal{O}_{SR}$ | $(3, 1)_{2/3}$ | $(\lambda \bar{q}_L \gamma_\mu \ell_L + \bar{\lambda} d_R \gamma_\mu \ell_R) U^\mu$ |
| $\mathcal{O}'_{SR}$ | $(\bar{\tau} P_R b) (\bar{c} P_L \nu)$ | $\leftrightarrow$ $\mathcal{O}_{VR}$ | $(3, 2)_{7/6}$ | $(\lambda \bar{u}_R \ell_L + \bar{\lambda} \bar{q}_L i\tau_2 e_R) R$ |
| $\mathcal{O}'_{SL}$ | $(\bar{\tau} P_L b) (\bar{c} P_L \nu)$ | $\leftrightarrow$ $-\frac{1}{2} \mathcal{O}_{SL} - \frac{1}{8} \mathcal{O}_{T}$ | | |
| $\mathcal{O}'_{T}$ | $(\bar{\tau}\sigma^{\mu\nu} P_L b) (\bar{c}\sigma_{\mu\nu} P_L \nu)$ | $\leftrightarrow$ $-6 \mathcal{O}_{SL} + \frac{1}{2} \mathcal{O}_{T}$ | | |
| $\mathcal{O}''_{VL}$ | $(\bar{\tau}\gamma_\mu P_L c) (\bar{b}\gamma^\mu P_L \nu)$ | $\leftrightarrow$ $-\mathcal{O}_{VR}$ | $(3, 2)_{5/3}$ | $(\lambda \bar{d}_R \gamma_\mu \ell_L + \bar{\lambda} \bar{q}_L^c \gamma_\mu \ell_R) V^\mu$ |
| $\mathcal{O}''_{VR}$ | $(\bar{\tau}\gamma_\mu P_R c) (\bar{b}\gamma^\mu P_L \nu)$ | $\leftrightarrow$ $-2 \mathcal{O}_{SR}$ | $(3, 3)_{1/3}$ | $\lambda \bar{q}_L^c i\tau_2 \ell_R S$ |
| $\mathcal{O}''_{SR}$ | $(\bar{\tau} P_R c) (\bar{b} \nu)$ | $\leftrightarrow$ $\frac{1}{2} \mathcal{O}_{VL}$ | | |
| $\mathcal{O}''_{SL}$ | $(\bar{\tau} P_L c) (\bar{b} \nu)$ | $\leftrightarrow$ $-\frac{1}{2} \mathcal{O}_{SL} + \frac{1}{8} \mathcal{O}_{T}$ | $(\bar{3}, 1)_{1/3}$ | $(\lambda \bar{q}_L^c i\tau_2 \ell_L + \bar{\lambda} \bar{u}_R^c e_R) S$ |
| $\mathcal{O}''_{T}$ | $(\bar{\tau}\sigma^{\mu\nu} P_L c) (\bar{b}\sigma_{\mu\nu} P_L \nu)$ | $\leftrightarrow$ $-6 \mathcal{O}_{SL} - \frac{1}{2} \mathcal{O}_{T}$ | | |

Figure: [1506.08896]
Constrain 1: \( Br(B_c \rightarrow \tau \nu) \)

- Other processes can limit these large coefficients; in particular \( Br(B_c \rightarrow \tau \nu) \). In SM: \( Br(B_c \rightarrow \tau \nu) \approx 2.3\% \)
Constrain 1: $Br(B_c \rightarrow \tau \nu)$

- Other processes can limit these large coefficients; in particular $Br(B_c \rightarrow \tau \nu)$. In SM: $Br(B_c \rightarrow \tau \nu) \approx 2.3\%$

$$\frac{Br(B_c \rightarrow \tau \nu)}{Br(B_c \rightarrow \tau \nu)|_{SM}} = \left| 1 + (C^V_{LL} - C^V_{RL}) + \frac{m^2_{B_c}}{m_\tau (m_b + m_c)} (C^S_{RL} - C^S_{LL}) \right|^2$$

$$+ \left| (C^V_{RR} - C^V_{LR}) + \frac{m^2_{B_c}}{m_\tau (m_b + m_c)} (C^S_{LR} - C^S_{RR}) \right|^2.$$

Enhanced contribution from the scalar operators (same combination appearing in $R_D^*$).

$Br(B_c \rightarrow \tau \nu) \leq 10\%$ from the $B_u \rightarrow \tau \nu$ at $Z$ peak at LEP.
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+ \left| (C_{RR}^V - C_{LR}^V) + \frac{m_{B_c}^2}{m_\tau (m_b + m_c)} (C_{LR}^S - C_{RR}^S) \right|^2 .
\]

- Enhanced contribution from the scalar operators (same combination appearing in \( R_{D^*} \)).
Constrain I: $Br(B_c \rightarrow \tau \nu)$

- Other processes can limit these large coefficients; in particular $Br(B_c \rightarrow \tau \nu)$. In SM: $Br(B_c \rightarrow \tau \nu) \approx 2.3\%$

$$\frac{Br(B_c \rightarrow \tau \nu)}{Br(B_c \rightarrow \tau \nu)|_{SM}} = \left| 1 + (C_{LL}^V - C_{RL}^V) + \frac{m_{B_c}^2}{m_\tau (m_b + m_c)} (C_{RL}^S - C_{LL}^S) \right|^2 + \left| (C_{RR}^V - C_{LR}^V) + \frac{m_{B_c}^2}{m_\tau (m_b + m_c)} (C_{LR}^S - C_{RR}^S) \right|^2.$$ 

- Enhanced contribution from the scalar operators (same combination appearing in $R_{D^*}$).

- $Br(B_c \rightarrow \tau \nu) \leq 10\%$ from the $B_u \rightarrow \tau \nu$ at Z peak at LEP.
Constrain II: $b \rightarrow s\nu\nu$

Some of the mediators generating the $C_{\nu\nu}$ or the $C_{\nu\nu}^T$ can generate $b \rightarrow s\nu\nu$ with the same couplings.

These are neutral current constraints so will put severe bounds on the affected models.
Constrain II: $b \rightarrow s\nu\nu$

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Some of the mediators generating the $C_{LL}^V$ or the $C_{RR}^S + x C_{RR}^T$ can generate $b \to s\nu\nu$ with the same couplings.

\[
O_{LL}^V = (\bar{c}_L \gamma^\mu b_L)(\bar{\tau}_L \gamma^\mu \nu_L),
\]

\[
O_{RR}^S = (\bar{c}_L b_R)(\bar{\tau}_L \nu_R),
\]
Constrain II : $b \rightarrow s\nu\nu$

Some of the mediators generating the $C_{LL}^V$ or the $C_{RR}^S + xC_{RR}^T$ can generate $b \rightarrow s\nu\nu$ with the same couplings.

\[
\begin{align*}
O_{LL}^V & = (\bar{c}_L \gamma^{\mu} b_L)(\bar{\tau}_L \gamma^{\mu} \nu_L), \\
O_{RR}^S & = (\bar{c}_L b_R)(\bar{\tau}_L \nu_R),
\end{align*}
\]

These are neutral current constraints so will put severe bounds on the affected models.
Constrain II: \( b \to s\nu\nu \)

\[
\begin{align*}
BR (B \to X_s\nu\nu) & \leq 6.4 \times 10^{-4}, \\
BR (B \to K\nu\nu) & \leq 1.6 \times 10^{-5}, \\
BR (B \to K^*\nu\nu) & \leq 2.7 \times 10^{-5}.
\end{align*}
\]
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$$BR (B \to K^* \nu\nu) \leq 2.7 \times 10^{-5}.$$  

$$\mathcal{H}_{\text{eff}} = -2\sqrt{2} G_F V_{tb} V_{ts}^* \frac{\alpha}{4\pi} \left[ C_L^\nu \left( \bar{s} \gamma^\mu (1 - \gamma^5) b \right) \left( \bar{\nu} \gamma_\mu (1 - \gamma^5) \nu \right) ight. + C_R^\nu \left( \bar{s} \gamma^\mu (1 + \gamma^5) b \right) \left( \bar{\nu} \gamma_\mu (1 - \gamma^5) \nu \right),$$

$$\epsilon \equiv \frac{\sqrt{|C_L^\nu|^2 + |C_R^\nu|^2}}{|(C_L^\nu)^{SM}|}, \quad \eta \equiv -\frac{\text{Re} (C_L^\nu C_R^{\nu*})}{|C_L^\nu|^2 + |C_R^\nu|^2}.$$
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$$\epsilon \equiv \frac{\sqrt{|C_L^\nu|^2 + |C_R^\nu|^2}}{|(C_L^\nu)^{SM}|}, \quad \eta \equiv -\frac{\text{Re}(C_L^\nu C_R^{\nu*})}{|C_L^\nu|^2 + |C_R^\nu|^2}.$$

$$BR(B \to K\nu\nu) = 4.5 \times 10^{-6} (1 - 2\eta)\epsilon^2,$$

$$BR(B \to K^*\nu\nu) = 6.8 \times 10^{-6} (1 + 1.31\eta)\epsilon^2,$$

$$BR(B \to X_s\nu\nu) = 2.7 \times 10^{-5} (1 + 0.09\eta)\epsilon^2.$$
Constrain II: $b \to s\nu\nu$

$$BR(B \to X_s\nu\nu) \leq 6.4 \times 10^{-4},$$  
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$$BR(B \to K^*\nu\nu) \leq 2.7 \times 10^{-5}.$$  

$$\mathcal{H}_{\text{eff}} = -2\sqrt{2}G_F V_{tb} V_{ts} \frac{\alpha}{4\pi} \left[ C_L^{\nu} \left( \bar{s}\gamma^\mu (1 - \gamma^5)b \right) \left( \bar{\nu}\gamma_\mu (1 - \gamma^5)\nu \right) 
+ \ C_R^{\nu} \left( \bar{s}\gamma^\mu (1 + \gamma^5)b \right) \left( \bar{\nu}\gamma_\mu (1 - \gamma^5)\nu \right) \right],$$

$$\epsilon \equiv \frac{\sqrt{|C_L^{\nu}|^2 + |C_R^{\nu}|^2}}{|(C_L^{\nu})^{SM}|}, \quad \eta \equiv -\Re \left( C_L^{\nu} C_R^{\nu\ast} \right) \frac{|C_L^{\nu}|^2 + |C_R^{\nu}|^2}{|C_L^{\nu}|^2 + |C_R^{\nu}|^2}.$$  

$$BR(B \to K\nu\nu) = 4.5 \times 10^{-6}(1 - 2\eta)\epsilon^2,$$  
$$BR(B \to K^*\nu\nu) = 6.8 \times 10^{-6}(1 + 1.31\eta)\epsilon^2,$$  
$$BR(B \to X_s\nu\nu) = 2.7 \times 10^{-5}(1 + 0.09\eta)\epsilon^2.$$  

$$C_L^{\nu \nu} \leq 0.006, \quad C_R^{S \nu \nu} \leq 0.01.$$
Constrain III: Collider Bounds

On a $W'$ coupled to the LH particles: The accompanying $Z'$ is severely constrained. Ruled out unless $Z'$ is a wide resonance.
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Figure: [1609.07138]
Constrain III: Collider Bounds

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Figure: [1609.07138]

Things are better with RH neutrinos. But still severely constrained from the LHC direct searches.
Constrain III : Collider Bounds

- For the LQs, the pair production, single production, high pT tails and interference with DY, and the monojet searches are relevant.
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Figure: [1810.10017]
Constrain III : Collider Bounds

- Not quite strong enough to kill any LQ yet.
- Can always introduce a new decay channel that the direct searches are blind too. LHC is trying to close that gap.
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Figure: [1810.10017]
Constraining Hidden Channels

Figure: Talk by Abhijith Gandrakota
• Calculate the leptonic side matrix element.
• Use the available results (e.g. HQET or Lattice) for the Hadronic side.
• Integrate over various final state labels to get the numerical results.
\[ \begin{align*}
    h_T &\rightarrow -h_T, & C_{LL}^{S,T} &\leftrightarrow (C_{RR}^{S,T})^*, & C_{RL}^{X} &\leftrightarrow (C_{LR}^{X})^*, \\
    1 + C_{LL}^{V} &\leftrightarrow (C_{RR}^{V})^*, \\
    R_{D(*)} &\rightarrow R_{D(*)}, & \mathcal{P}_x &\rightarrow -\mathcal{P}_x, & \mathcal{A}_{FB} &\rightarrow \mathcal{A}_{FB}.
\end{align*} \]
Numerical Equations

\[ A_{FB} \approx \frac{1}{R_D} \left\{ -0.11 \left( |1 + C_{LL}^V + C_{RL}^V|^2 + |C_{RR}^V + C_{LR}^V|^2 \right) \right. \]

\[ + 0.35 \Re \left[ (C_{LL}^S + C_{RL}^S)(C_{LL}^T)^* + (C_{RR}^S + C_{LR}^S)^*(C_{RR}^T) \right] \]

\[ - 0.24 \Re \left[ (1 + C_{LL}^V + C_{RL}^V)(C_{LL}^T)^* + (C_{RR}^V + C_{LR}^V)^*(C_{RR}^T) \right] \]

\[ - 0.15 \Re \left[ (1 + C_{LL}^V + C_{RL}^V)(C_{LL}^S + C_{RL}^S)^* + (C_{RR}^V + C_{LR}^V)^*(C_{RR}^S + C_{LR}^S) \right] \]

\[ A_{FB}^* \approx \frac{1}{R_D^*} \left\{ -0.813 \left( |C_{LL}^T|^2 + |C_{RR}^T|^2 \right) \right. \]

\[ + 0.016 \left( |1 + C_{LL}^V|^2 + |C_{RR}^V|^2 \right) - 0.082 \left( |C_{RL}^V|^2 + |C_{LR}^V|^2 \right) \]

\[ + 0.066 \Re \left[ C_{RL}^V(1 + C_{LL}^V)^* + (C_{LR}^V)^*C_{RR}^V \right] \]

\[ + 0.095 \Re \left[ (C_{RL}^S - C_{LL}^S)(C_{LL}^T)^* + (C_{LR}^S - C_{RR}^S)^*(C_{RR}^T) \right] \]

\[ + 0.395 \Re \left[ (1 + C_{LL}^V - C_{RL}^V)(C_{LL}^T)^* + (C_{RR}^V - C_{LR}^V)^*(C_{RR}^T) \right] \]

\[ + 0.023 \Re \left[ (C_{LL}^S - C_{RL}^S)(1 + C_{LL}^V - C_{RL}^V)^* + (C_{RR}^S - C_{LR}^S)^*(C_{RR}^V - C_{LR}^V) \right] \]

\[ - 0.142 \Re \left[ (C_{LL}^T)(1 + C_{LL}^V + C_{RL}^V)^* + (C_{RR}^T)^*(C_{RR}^V + C_{LR}^V) \right] \}

\]
Numerical Equations

\[ P_\tau \approx \frac{1}{R_D} \left\{ 0.402 \left( |C_{LL}^S + C_{RL}^S|^2 - |C_{RR}^S + C_{LR}^S|^2 \right) \right. \\
\left. + 0.013 \left[ |C_{LL}^T|^2 - |C_{RR}^T|^2 \right] + 0.097 \left[ |1 + C_{LL}^V + C_{RL}^V|^2 - |C_{RR}^V + C_{LR}^V|^2 \right] \right. \\
\left. + 0.512 \Re \left[ (1 + C_{LL}^V + C_{RL}^V)(C_{LL}^S + C_{RL}^S)^* - (C_{RR}^V + C_{LR}^V)^*(C_{RR}^S + C_{LR}^S) \right] \right. \\
\left. - 0.099 \Re \left[ (1 + C_{LL}^V + C_{RL}^V)(C_{LL}^T)^* - (C_{RR}^V + C_{LR}^V)^*(C_{RR}^T) \right] \right\} \\

\[ P_{\tau}^* \approx \frac{1}{R_D^*} \left\{ -0.127 \left( |1 + C_{LL}^V|^2 + |C_{RL}^V|^2 - |C_{RR}^V|^2 - |C_{LR}^V|^2 \right) \right. \\
\left. + 0.011 \left( |C_{LL}^S - C_{RL}^S|^2 - |C_{RR}^S - C_{LR}^S|^2 \right) + 0.172 \left( |C_{LL}^T|^2 - |C_{RR}^T|^2 \right) \right. \\
\left. + 0.031 \Re \left[ (1 + C_{LL}^V - C_{RL}^V)(C_{RL}^S - C_{LL}^S)^* - (C_{RR}^V - C_{LR}^V)^*(C_{LR}^S - C_{RR}^S) \right] \right. \\
\left. + 0.350 \Re \left[ (1 + C_{LL}^V)(C_{LL}^T)^* - (C_{RR}^V)^*(C_{RR}^T) \right] \right. \\
\left. - 0.481 \Re \left[ (C_{RL}^V)(C_{LL}^T)^* - (C_{LR}^V)^*(C_{RR}^T) \right] \right. \\
\left. + 0.216 \Re \left[ (1 + C_{LL}^V)(C_{RL}^V)^* - (C_{RR}^V)^*(C_{LR}^V) \right] \right\}. \]
Numerical Equations

\[ \mathcal{P}_\perp \approx \frac{1}{R_D} \text{Re} \left\{ -0.350 \left[ (C_{LL})^*(C_{LL} + C_{RL})^* - (C_{RR})^* (C_{RR} + C_{LR}) \right] \right. \\
- 0.357 \left[ (1 + C_{LL}^V + C_{RL}^V) (C_{LL}^S + C_{RL}^S)^* - (C_{RR}^V + C_{LR}^V)^* (C_{RR}^S + C_{LR}^S) \right] \right. \\
- 0.247 \left[ (1 + C_{LL}^V + C_{RL}^V)^*(C_{LL}^T) - (C_{RR}^V + C_{LR}^V)(C_{RR}^T)^* \right] \right. \\
- 0.250 \left[ \left| 1 + C_{LL}^V + C_{RL}^V \right|^2 - \left| C_{RR}^V + C_{LR}^V \right|^2 \right] \right\} \\
\mathcal{P}_\perp^* \approx \frac{1}{R_D^*} \text{Re} \left\{ (C_{RR}^S - C_{LR}^S)^* \left[ 0.099C_{RR}^T - 0.054 (C_{RR}^V - C_{LR}^V) \right] \right. \\
- (C_{LL}^S - C_{RL}^S)^* \left[ 0.099C_{LL}^T - 0.054 (1 + C_{LL}^V - C_{RL}^V) \right] \right. \\
+ (C_{RR}^T) \left[ 0.146C_{RR}^V - 0.478C_{LR}^V - 1.855C_{RR}^T \right] \right. \\
- (C_{LL}^T)^* \left[ 0.146(1 + C_{LL}^V) - 0.478C_{RL}^V - 1.855C_{LL}^T \right] \right. \\
+ (C_{LR}^V) \left[ -0.081C_{RR}^T + 0.025C_{LR}^V - 0.075C_{RR}^V \right] \right. \\
- (C_{RL}^V)^* \left[ -0.081C_{LL}^T + 0.025C_{RL}^V - 0.075(1 + C_{LL}^V) \right] \right. \\
+ (C_{RR}^V) \left[ -0.071C_{RR}^T - 0.075C_{LR}^V + 0.126C_{RR}^V \right] \right\} \]
**Numerical Equations**

\[ \mathcal{P}_T \approx \frac{1}{R_D} \text{Im} \left\{ -0.350 \left[ (C_{LL}^T) (C_{LL}^S + C_{RL}^S)^* - (C_{RR}^T)^* (C_{RR}^S + C_{LR}^S) \right] \\
- 0.357 \left[ (1 + C_{LL}^V + C_{RL}^V) (C_{LL}^S + C_{RL}^S)^* - (C_{RR}^V + C_{LR}^V)^* (C_{RR}^S + C_{LR}^S) \right] \\
- 0.247 \left[ (1 + C_{LL}^V + C_{RL}^V) (C_{LL}^T) - (C_{RR}^V + C_{LR}^V) (C_{RR}^T) \right] \right\} \]

\[ \mathcal{P}_T^* \approx \frac{1}{R_{D^*}} \text{Im} \left\{ (C_{RR}^S - C_{LR}^S) [0.099 C_{RR}^T - 0.054 (C_{RR}^V - C_{LR}^V)]^* \\
- (C_{LL}^S - C_{RL}^S)^* [0.099 C_{LL}^T - 0.054 (1 + C_{LL}^V - C_{RL}^V)] \\
+ (C_{RR}^V) [0.146 C_{RR}^V - 0.478 C_{LR}^V]^* - (C_{LL}^V)^* [0.146(1 + C_{LL}^V) - 0.478 C_{RL}^V] \\
- (C_{LR}^V) [0.081 C_{RR}^T]^* + (C_{RL}^V)^* [0.081 C_{LL}^T] \\
- (C_{RR}^V) [0.071 C_{RR}^T]^* + (1 + C_{LL}^V)^* [0.071 C_{LL}^T] \right\} \]
$R_D = 0.407$ and $R_{D^*} = 0.304$
$R_D = 0.340$ and $R_{D^*} = 0.275$
$P_T^{(*)}$

![Graphs showing different models]

- $S_1^L$ LQ
- $U_1^L$ LQ
- $S_2^L$ LQ
- $R_2$ LQ
\( \mathcal{P}_\tau \) Measurement

\[
\frac{1}{\Gamma} \frac{d\Gamma}{d\theta_{\text{hel}}} = \frac{1}{2} \left( 1 + \alpha_d \mathcal{P}_\tau^* \cos \theta_{\text{hel}} \right)
\]

\[
\cos \theta_{\tau d} = \frac{2E_\tau E_d - m_\tau^2 - m_d^2}{2|\vec{p}_\tau||\vec{p}_d|} \quad q^2 - \text{frame}
\]

\[
|\vec{p}_\tau| = \frac{q^2 - m_\tau^2}{2\sqrt{q^2}} \quad q^2 - \text{frame}
\]

\[
|\vec{p}_d^\tau| \cos \theta_{\text{hel}} = -\gamma \frac{|\vec{p}_\tau|}{E_\tau} E_d + \gamma |\vec{p}_d| \cos \theta_{\tau d} \quad \tau - \text{frame}
\]
$F_{D^{*}}^L$ Measurement

\[
\frac{1}{R} \frac{dR}{d \cos \theta_{\text{hel}}(D^{*})} = \frac{3}{4} \left[ 2 F_{L}^{D^{*}} \cos^2(\theta_{\text{hel}}(D^{*})) + (1 - F_{L}^{D^{*}}) \sin^2(\theta_{\text{hel}}(D^{*})) \right]
\]

\[
\begin{array}{|c|c|}
\hline
h & \text{Number of events in:} \\
\hline
& \text{I bin: } 151 \pm 21 \\
& \text{II bin: } 125 \pm 19 \\
& \text{III bin: } 55 \pm 15 \\
\hline
\end{array}
\]

- signal yields corrected for acceptance variations

Dominant systematics:
- MC statistics (AR shape and peaking background) 
  \[ = \pm 0.03 \]

Figure: Talk by Karol Adamczyk @ CKM 2018
Other Constraints

Numerous other bounds including:

- Meson Mixings
- $D_s \to \tau \nu$
- $b \to s \gamma$
- $B_s \to \tau \tau$: very loose experimental bounds
- Electroweak precision bounds: When introducing new gauge bosons or fermion mixings.
Other Constraints

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- Meson Mixings
Other Constraints

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- $B_s \rightarrow \tau \tau$: very loose experimental bounds
- Electroweak precision bounds: When introducing new gauge bosons or fermion mixings.
Flavor Constraints on the New Model

\[ b \rightarrow \tilde{g}^{33} \tilde{g}_2^{1/3} \tilde{g}_1^{33} \nu_{\tau} \]

\[ s \rightarrow \tilde{g}^{2*} \tilde{R}_{\alpha}^{-1/3} \tilde{g}_1^{33*} \nu_L \]

\[ \bar{c} \rightarrow \tilde{g}_2 \tilde{g}_1 \tilde{g}_2 \nu_R \]

\[ \bar{s} \rightarrow \tilde{g}_2^{1/3} \tilde{g}_1 \tilde{g}_2 \nu \]

\[ \bar{b} \rightarrow \tilde{g}_2^{1/3} \tilde{g}_1 \tilde{g}_2 \nu \]

\[ \gamma / Z \]

All the constraints only affect the $C_S$ operator. Cannot generate $C_V$ simultaneously.
Flavor Constraints on the New Model

All the constraints only affect $C_{RR}^S = 4C_{RR}^T$ operator. Can not generate $C_{RL}^V$ and $C_{LR}^V$ simultaneously either.
Collider Constraints on the New Model

- These are the main constraints on the model.
Collider Constraints on the New Model

- These are the main constraints on the model.
- The $C_{RL}^V$ is secretly a dim-8 operator so suppressed by $\nu^2/M_{NP}^2$. Hence, the NP scale should be lower.
Collider Constraints on the New Model

- These are the main constraints on the model.
- The $C^V_{RL}$ is secretly a dim-8 operator so suppressed by $v^2/M^2_{NP}$. Hence, the NP scale should be lower.
- The LQ signature appears in direct pair production, direct single production, monojet searches, some SUSY searches too, and as interference with the SM DY processes.
Collider Constraints on the New Model

- These are the main constraints on the model.
- The $C_{RL}^V$ is secretly a dim-8 operator so suppressed by $\nu^2/M_{NP}^2$. Hence, the NP scale should be lower.
- The LQ signature appears in direct pair production, direct single production, monojet searches, some SUSY searches too, and as interference with the SM DY processes.
- The former four are reducible and can be avoided by new decay channels.
Collider Constraints on the New Model

- These are the main constraints on the model.
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Explaining the Observed $R_{J/\psi}$

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