Asymmetry Observables and the Origin of $R_{D^{(*)}}$ Anomalies

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Based on : 1810.06597, 1904.XXXXX
In collaboration with : Matthew Buckley, David Shih

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Outline

- $R_{D^{(*)}}$ Solutions
- Some Asymmetry Observables
- More On $F^L_{D^*}$

New Physics in the Flavor Experiments

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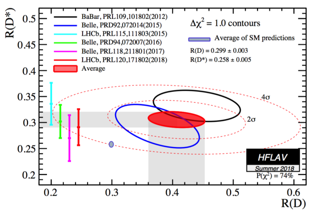
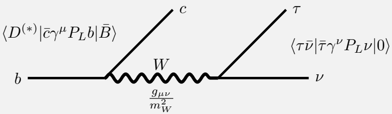


$$R_D^{obs} = 0.407 \pm 0.046, \qquad R_{D^*}^{obs} = 0.304 \pm 0.015,$$

$$R_D^{SM} = 0.299 \pm 0.003, \qquad R_{D^*}^{SM} = 0.258 \pm 0.005.$$

The Most General EFT

- SM contribution :



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

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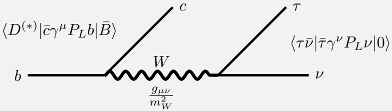

$$\langle D^{(*)}\tau\nu|\,(\bar{c}\gamma^\mu P_L b)\,(\bar{\tau}\gamma^\nu P_L\nu)\,|\bar{B}\rangle$$

- The most general dim-6 effective Hamiltonian:

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

$$\begin{aligned}
\mathcal{O}^S_{MN} &\equiv (\bar{c}P_M b)(\bar{\tau}P_N\nu), \\
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\mathcal{O}^T_{MN} &\equiv (\bar{c}\sigma^{\mu\nu} P_M b)(\bar{\tau}\sigma_{\mu\nu} P_N\nu),
\end{aligned}$$

for $M, N = R$ or L (SM : $C^V_{LL} = 1$).

Minimal Models

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

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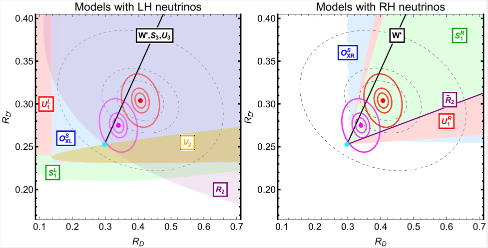

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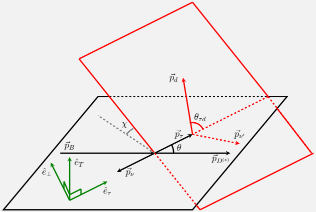

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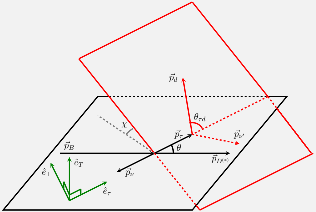

$$\mathcal{P}_{\hat{e}}^{(*)} = \frac{\Gamma^{(*)}_{+\hat{e}} - \Gamma^{(*)}_{-\hat{e}}}{\Gamma^{(*)}_{+\hat{e}} + \Gamma^{(*)}_{-\hat{e}}}, \quad \mathcal{A}_{FB}^{(*)} = \frac{1}{\Gamma^{(*)}} \left(-\int_{\theta=0}^{\theta=\pi/2} + \int_{\theta=\pi/2}^{\theta=\pi} \right) d\theta \frac{d\Gamma^{(*)}}{d\theta}.$$

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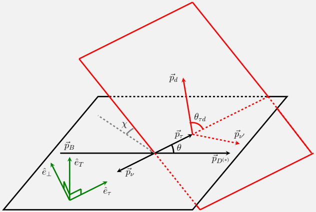

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Observable	$\mathcal{A}_{FB}$	$\mathcal{A}^*_{FB}$	$\mathcal{P}_\tau$	$\mathcal{P}^*_\tau$	$\mathcal{P}_\perp$	$\mathcal{P}^*_\perp$	$\mathcal{P}_T$	$\mathcal{P}^*_T$
SM value	-0.360	0.063	0.325	-0.497	-0.842	-0.499	0	0
Projected Precision	10%	–	3%	–	10%	–	–	–

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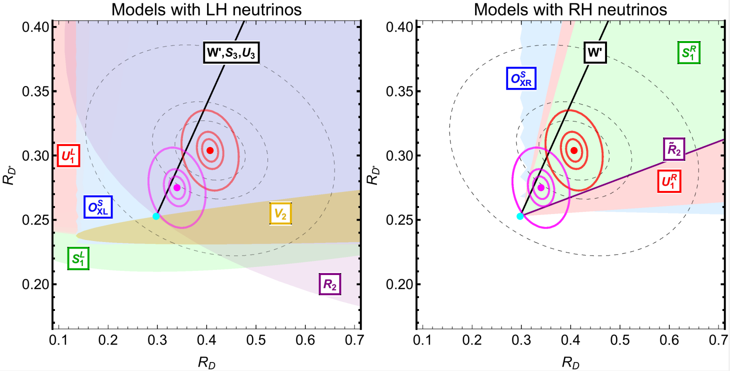
- In each model, the range of the Wilson coefficients explaining the $R_{D^{(*)}}$ has a different imprint on other observables. Can we leverage that to distinguish models from one another?
- It highly depends on the measured $R_{D^{(*)}}$ value.

Two Extreme Outcomes for $R_{D^{(*)}}$



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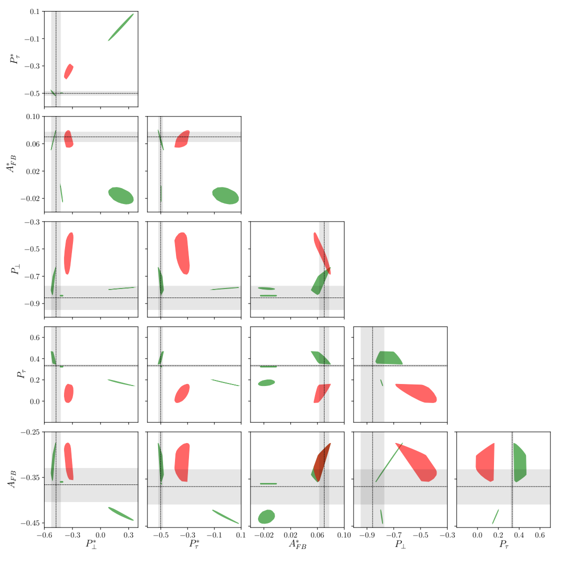

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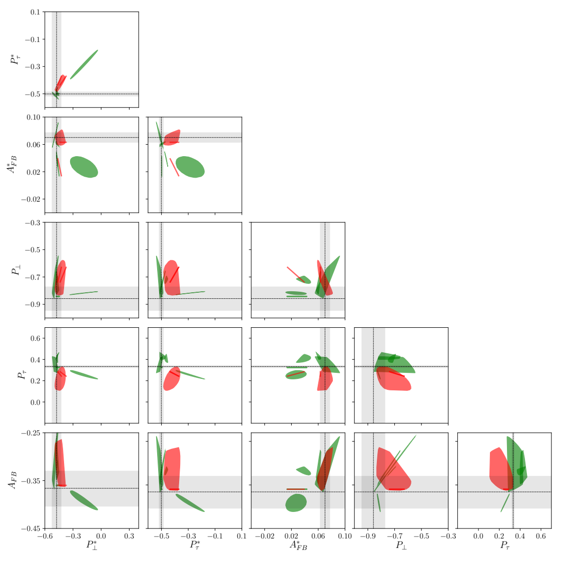

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- We develop a simple χ^2 test to see how well each pair of models can be distinguished.
- Can tell all the models apart; we may need to resort the CP-odd observable $\mathcal{P}_T^{(*)}$ in the second scenario.

$F^L_{D^*}$: Another Asymmetry Observable

$$F^L_{D^*} = \frac{\Gamma(\bar{B} \to D^*_L \tau\nu)}{\Gamma(\bar{B} \to D^*_L \tau\nu) + \Gamma(\bar{B} \to D^*_T \tau\nu)}.$$

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

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- Is there any combination of the dim-6 operators that can explain the observed value?

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  We show it can be achieved with all real WCs.

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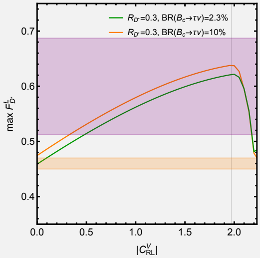

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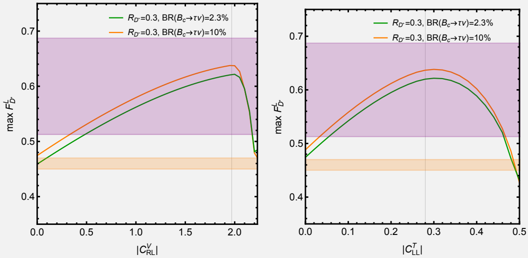

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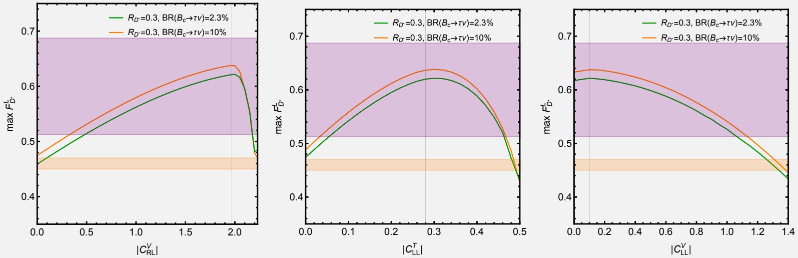

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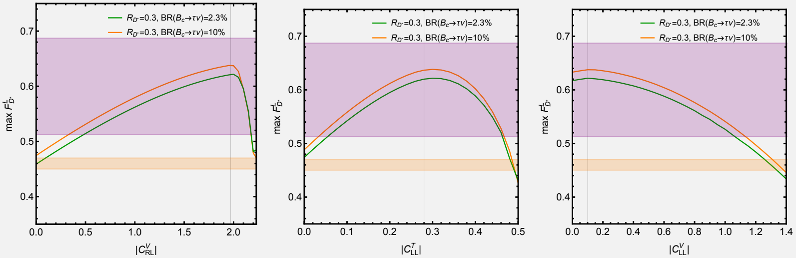

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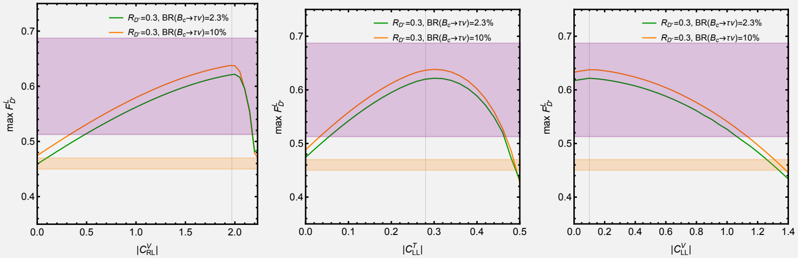

- Relatively large C^V_{RL}, C^T_{LL}, and C^V_{LL} are required to explain the observed $F^L_{D^*}$.
- Not sensitive to individual operators. Need a combination of all.

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

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THANK YOU!

BACK UP SLIDES

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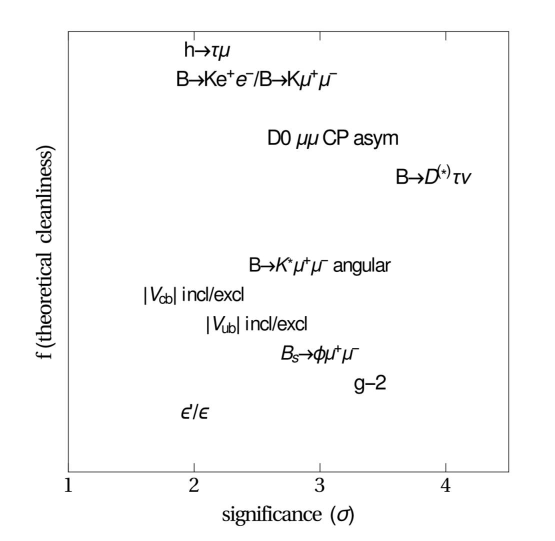
Other Anomalies



Uncertainties

BaBar@Hadronic(τ→l)

Source of uncertainty	$\mathcal{R}(D)$ (%)	$\mathcal{R}(D^*)$ (%)
Additive uncertainties		
PDFs		
MC statistics	4.4	2.0
$B \to D^{(*)}(\tau^-/\ell^-)\bar{\nu}$ FFs	0.2	0.2
$D^{**} \to D^{(*)}(\pi^0/\pi^\pm)$	0.7	0.5
$\mathcal{B}(\bar{B} \to D^{**}\ell^-\bar{\nu}_\ell)$	0.8	0.3
$\mathcal{B}(\bar{B} \to D^{**}\tau^-\bar{\nu}_\tau)$	1.8	1.7
$D^{**} \to D^{(*)}\pi\pi$	2.1	2.6
Cross-feed constraints		
MC statistics	2.4	1.5
$f_{D^{**}}$	5.0	2.0
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
$B \to D^{(*)}(\tau^-/\ell^-)\bar{\nu}$ FFs	1.6	0.4
Lepton PID	0.6	0.6
$\pi^0/\pi^\pm$ from $D^* \to D\pi$	0.1	0.1
Detection/Reconstruction	0.7	0.7
$\mathcal{B}(\tau^- \to \ell^-\bar{\nu}_\ell\nu_\tau)$	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	$\mathcal{R}(D^*)$ [%] $\ell^{\rm sig} = e, \mu$
MC size for each PDF shape	2.2
PDF shape of the normalization in $\cos\theta_{B\text{-}D^*\ell}$	$^{+1.1}_{-0.0}$
PDF shape of $B \to D^{**}\ell\nu_\ell$	$^{+1.0}_{-1.7}$
PDF shape and yields of fake $D^{(*)}$	1.4
PDF shape and yields of $B \to X_c D^*$	1.1
Reconstruction efficiency ratio $\varepsilon_{\rm norm}/\varepsilon_{\rm sig}$	1.2
Modeling of semileptonic decay	0.2
$\mathcal{B}(\tau^- \to \ell^-\bar{\nu}_\ell\nu_\tau)$	0.2
Total systematic uncertainty	$^{+3.4}_{-3.5}$

Scales with MC statistics

Scales with DATA statistics

Theory/External

Irreducible
Requires additional studies

Belle@Hadronic(τ→h)

Source	$R(D^*)$	P_τ
Hadronic B composition	$^{+7.8\%}_{-6.9\%}$	$^{+0.14}_{-0.11}$
MC statistics for each PDF shape	$^{+3.5\%}_{-2.8\%}$	$^{+0.13}_{-0.11}$
Fake D^* PDF shape	3.0%	0.010
Fake D^* yield	1.7%	0.016
$\bar{B} \to D^{**}\ell^-\bar{\nu}_\ell$	2.1%	0.051
$\bar{B} \to D^{**}\tau^-\bar{\nu}_\tau$	1.1%	0.003
$\bar{B} \to D^*\ell^-\bar{\nu}_\ell$	2.4%	0.008
τ daughter and ℓ^- efficiency	2.1%	0.018
MC statistics for efficiency calculation	1.0%	0.018
EvtGen decay model	$^{+0.8\%}_{-0.0\%}$	$^{+0.016}_{-0.000}$
Fit bias	0.3%	0.008
$\mathcal{B}(\tau^- \to \pi^-\nu_\tau)$ and $\mathcal{B}(\tau^- \to \rho^-\nu_\tau)$	0.3%	0.002
P_τ correction function	0.1%	0.018
Common sources		
Tagging efficiency correction	1.4%	0.014
D^* reconstruction	1.3%	0.007
D sub-decay branching fractions	0.7%	0.005
Number of $B\bar{B}$	0.4%	0.005
Total systematic uncertainty	$^{+10.4\%}_{-9.5\%}$	$^{+0.20}_{-0.17}$

Individual Operator Effects

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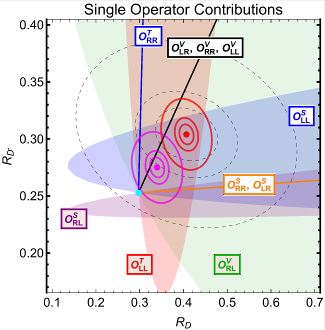

All Operators

	Operator	Fierz identity	Allowed Current	$\delta\mathcal{L}_{\rm int}$
$\mathcal{O}_{V_L}$	$(\bar{c}\gamma_\mu P_L b)\,(\bar{\tau}\gamma^\mu P_L \nu)$		$(\mathbf{1},\mathbf{3})_0$	$(g_q \bar{q}_L \boldsymbol{\tau}\gamma^\mu q_L + g_\ell \bar{\ell}_L \boldsymbol{\tau}\gamma^\mu \ell_L)W'_\mu$
$\mathcal{O}_{V_R}$	$(\bar{c}\gamma_\mu P_R b)\,(\bar{\tau}\gamma^\mu P_L \nu)$			
$\mathcal{O}_{S_R}$	$(\bar{c} P_R b)\,(\bar{\tau} P_L \nu)$		$(\mathbf{1},\mathbf{2})_{1/2}$	$(\lambda_d \bar{q}_L d_R \phi + \lambda_u \bar{q}_L u_R i\tau_2 \phi^\dagger + \lambda_\ell \bar{\ell}_L e_R \phi)$
$\mathcal{O}_{S_L}$	$(\bar{c} P_L b)\,(\bar{\tau} P_L \nu)$			
$\mathcal{O}_T$	$(\bar{c}\sigma^{\mu\nu} P_L b)\,(\bar{\tau}\sigma_{\mu\nu} P_L \nu)$			
$\mathcal{O}'_{V_L}$	$(\bar{\tau}\gamma_\mu P_L b)\,(\bar{c}\gamma^\mu P_L \nu)$	$\longleftrightarrow \mathcal{O}_{V_L}$	$(\mathbf{3},\mathbf{3})_{2/3}$	$\lambda\,\bar{q}_L \boldsymbol{\tau}\gamma_\mu \ell_L \boldsymbol{U}^\mu$
$\mathcal{O}'_{V_R}$	$(\bar{\tau}\gamma_\mu P_R b)\,(\bar{c}\gamma^\mu P_L \nu)$	$\longleftrightarrow -2\mathcal{O}_{S_R}$	$(\mathbf{3},\mathbf{1})_{2/3}$	$(\lambda\,\bar{q}_L\gamma_\mu \ell_L + \tilde{\lambda}\,\bar{d}_R \gamma_\mu e_R)U^\mu$
$\mathcal{O}'_{S_R}$	$(\bar{\tau} P_R b)\,(\bar{c} P_L \nu)$	$\longleftrightarrow -\frac{1}{2}\mathcal{O}_{V_R}$		
$\mathcal{O}'_{S_L}$	$(\bar{\tau} P_L b)\,(\bar{c} P_L \nu)$	$\longleftrightarrow -\frac{1}{2}\mathcal{O}_{S_L} - \frac{1}{8}\mathcal{O}_T$	$(\mathbf{3},\mathbf{2})_{7/6}$	$(\lambda\,\bar{u}_R \ell_L + \tilde{\lambda}\,\bar{q}_L i\tau_2 e_R)R$
$\mathcal{O}'_T$	$(\bar{\tau}\sigma^{\mu\nu} P_L b)\,(\bar{c}\sigma_{\mu\nu} P_L \nu)$	$\longleftrightarrow -6\mathcal{O}_{S_L} + \frac{1}{2}\mathcal{O}_T$		
$\mathcal{O}''_{V_L}$	$(\bar{\tau}\gamma_\mu P_L c^c)\,(\bar{b}^c\gamma^\mu P_L \nu)$	$\longleftrightarrow -\mathcal{O}_{V_R}$		
$\mathcal{O}''_{V_R}$	$(\bar{\tau}\gamma_\mu P_R c^c)\,(\bar{b}^c\gamma^\mu P_L \nu)$	$\longleftrightarrow -2\mathcal{O}_{S_R}$	$(\bar{\mathbf{3}},\mathbf{2})_{5/3}$	$(\lambda\,\bar{d}^c_R\gamma_\mu \ell_L + \tilde{\lambda}\,\bar{q}^c_L \gamma_\mu e_R)V^\mu$
$\mathcal{O}''_{S_R}$	$(\bar{\tau} P_R c^c)\,(\bar{b}^c P_L \nu)$	$\longleftrightarrow \frac{1}{2}\mathcal{O}_{V_L}$	$(\bar{\mathbf{3}},\mathbf{3})_{1/3}$	$\lambda\,\bar{q}^c_L i\tau_2 \boldsymbol{\tau}\ell_L \boldsymbol{S}$
$\mathcal{O}''_{S_L}$	$(\bar{\tau} P_L c^c)\,(\bar{b}^c P_L \nu)$	$\longleftrightarrow -\frac{1}{2}\mathcal{O}_{S_L} + \frac{1}{8}\mathcal{O}_T$	$(\bar{\mathbf{3}},\mathbf{1})_{1/3}$	$(\lambda\,\bar{q}^c_L i\tau_2 \ell_L + \tilde{\lambda}\,\bar{u}^c_R e_R)S$
$\mathcal{O}''_T$	$(\bar{\tau}\sigma^{\mu\nu} P_L c^c)\,(\bar{b}^c\sigma_{\mu\nu} P_L \nu)$	$\longleftrightarrow -6\mathcal{O}_{S_L} - \frac{1}{2}\mathcal{O}_T$		

Figure: [1506.08896]

Constrain I : $Br(B_c \to \tau\nu)$

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

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- Enhanced contribution from the scalar operators (same combination appearing in R_{D^*}).
- $Br(B_c \to \tau\nu) \leqslant 10\%$ from the $B_u \to \tau\nu$ at Z peak at LEP.

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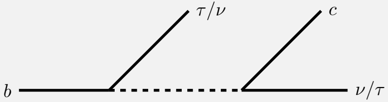
$$



(b)

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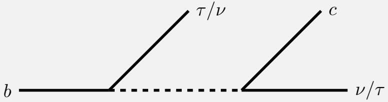

(b)

These are neutral current constraints so will put severe bounds on the affected models.

Constrain II : $b \to s\nu\nu$

$$
\begin{aligned}
BR\left(B \to X_s\nu\nu\right) &\leqslant 6.4 \times 10^{-4}, \\
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\mathcal{H}_{\rm eff} &= -2\sqrt{2} G_F V_{tb} V_{ts}^* \frac{\alpha}{4\pi} \left[C_L^\nu \left(\bar{s}\gamma^\mu (1-\gamma^5) b\right) \left(\bar{\nu}\gamma_\mu (1-\gamma^5)\nu\right) \right. \\
&+ \left. C_R^\nu \left(\bar{s}\gamma^\mu (1+\gamma^5) b\right) \left(\bar{\nu}\gamma_\mu (1-\gamma^5)\nu\right) \right],
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\epsilon \equiv \frac{\sqrt{|C_L^\nu|^2 + |C_R^\nu|^2}}{|(C_L^\nu)^{SM}|}, \quad \eta \equiv -\frac{\mathcal{R}e\left(C_L^\nu C_R^{\nu *}\right)}{|C_L^\nu|^2 + |C_R^\nu|^2}.
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$$

$$
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BR\left(B \to K\nu\nu\right) &= 4.5 \times 10^{-6}(1-2\eta)\epsilon^2,\\
BR\left(B \to K^*\nu\nu\right) &= 6.8 \times 10^{-6}(1+1.31\eta)\epsilon^2,\\
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$C_{LL}^V \leqslant 0.006,\quad C_{RR}^S \leqslant 0.01.$

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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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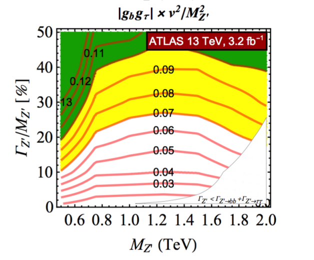

Figure: [1609.07138]

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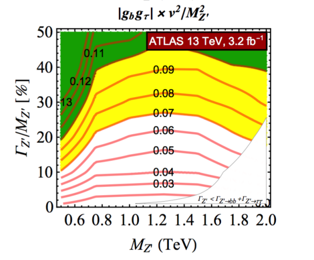

Figure: [1609.07138]

Things are better with RH neutrinos. But still severely tight from the LHC direct searches.

Constrain III : Collider Bounds

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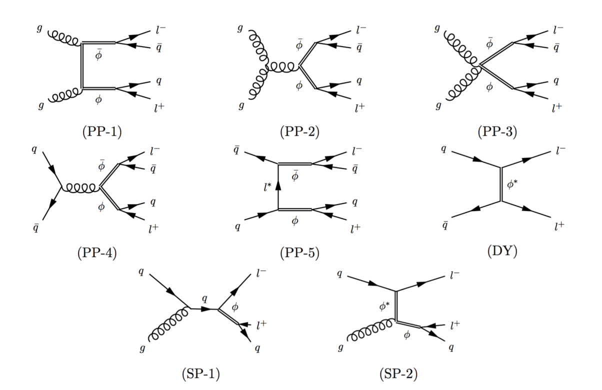

Figure: [1810.10017]

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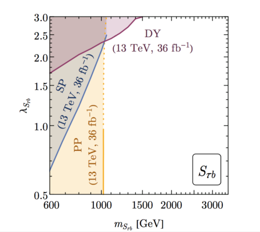

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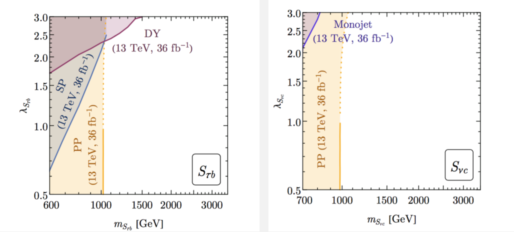

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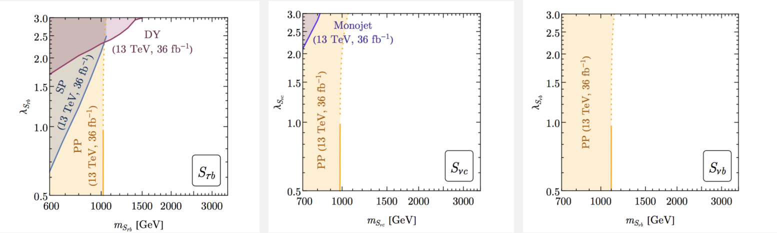

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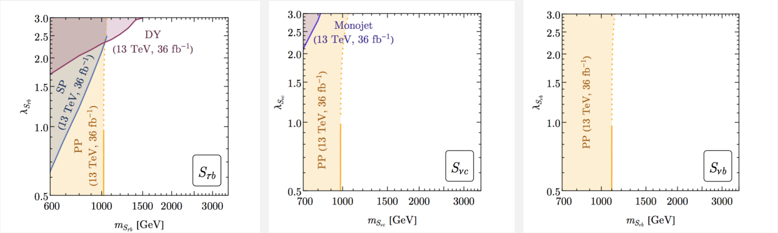

Figure: [1810.10017]

- Not quite strong enough to kill any LQ yet.

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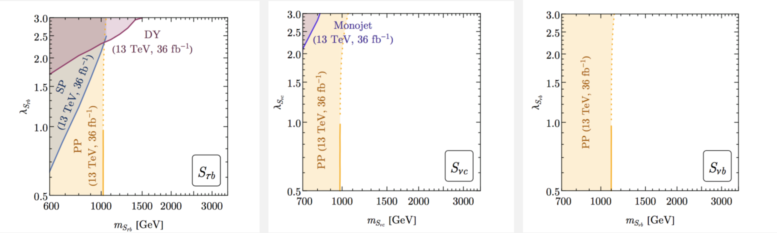

Figure: [1810.10017]

- 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.

Other Constraints

Numerous other bounds including :

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- $B_s \to \tau\tau$: very loose experimental bounds
- Electroweak precision bounds : When introducing new gauge bosons or fermion mixings.

Constraining Hidden Channels

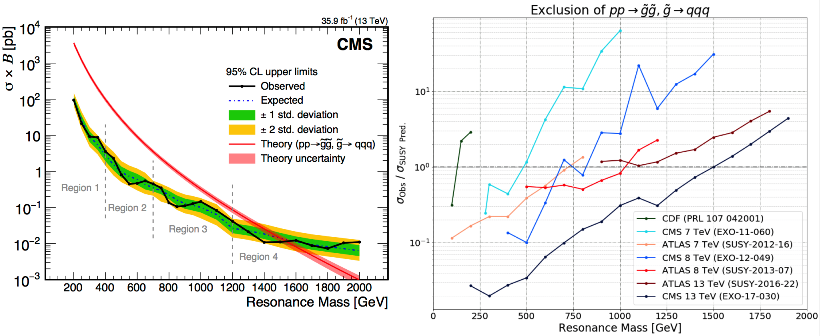
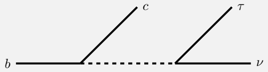


Figure: Talk by Abhijith Gandrakota

Calculation Steps



(a)

- 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.

LH $\leftrightarrow$ RH

$$h_\tau \to -h_\tau, \qquad C^{S,T}_{LL} \leftrightarrow \left(C^{S,T}_{RR}\right)^* \quad , \qquad C^X_{RL} \leftrightarrow \left(C^X_{LR}\right)^*,$$
$$1 + C^V_{LL} \leftrightarrow \left(C^V_{RR}\right)^* \quad ,$$

$$R_{D^{(*)}} \to R_{D^{(*)}}, \quad \mathcal{P}_x \to -\mathcal{P}_x, \quad \mathcal{A}_{FB} \to \mathcal{A}_{FB}.$$

Numerical Equations

$$
\begin{aligned}
\mathcal{A}_{FB} &\approx \frac{1}{R_D}\Big\{-0.11\left(\left|1+C^V_{LL}+C^V_{RL}\right|^2+\left|C^V_{RR}+C^V_{LR}\right|^2\right) \\
&- 0.35\mathcal{R}e\left[(C^S_{LL}+C^S_{RL})(C^T_{LL})^*+(C^S_{RR}+C^S_{LR})^*(C^T_{RR})\right] \\
&- 0.24\mathcal{R}e\left[(1+C^V_{LL}+C^V_{RL})(C^T_{LL})^*+(C^V_{RR}+C^V_{LR})^*(C^T_{RR})\right] \\
&- 0.15\mathcal{R}e\left[(1+C^V_{LL}+C^V_{RL})(C^S_{LL}+C^S_{RL})^*+(C^V_{RR}+C^V_{LR})^*(C^S_{RR}+C^S_{LR})\right] \\
\mathcal{A}^*_{FB} &\approx \frac{1}{R_{D^*}}\Big\{-0.813\left(\left|C^T_{LL}\right|^2+\left|C^T_{RR}\right|^2\right) \\
&+ 0.016\left(\left|1+C^V_{LL}\right|^2+\left|C^V_{RR}\right|^2\right)-0.082\left(\left|C^V_{RL}\right|^2+\left|C^V_{LR}\right|^2\right) \\
&+ 0.066\mathcal{R}e\left[C^V_{RL}(1+C^V_{LL})^*+(C^V_{LR})^*C^V_{RR}\right] \\
&+ 0.095\mathcal{R}e\left[(C^S_{RL}-C^S_{LL})(C^T_{LL})^*+(C^S_{LR}-C^S_{RR})^*C^T_{RR}\right] \\
&+ 0.395\mathcal{R}e\left[(1+C^V_{LL}-C^V_{RL})(C^T_{LL})^*+(C^V_{RR}-C^V_{LR})^*(C^T_{RR})\right] \\
&+ 0.023\mathcal{R}e\left[(C^S_{LL}-C^S_{RL})(1+C^V_{LL}-C^V_{RL})^*+(C^S_{RR}-C^S_{LR})^*(C^V_{RR}-C^V_{LR})\right. \\
&- 0.142\mathcal{R}e\left[(C^T_{LL})(1+C^V_{LL}+C^V_{RL})^*+(C^T_{RR})^*(C^V_{RR}+C^V_{LR})\right]\Big\},
\end{aligned}
$$

Numerical Equations

$$
\begin{aligned}
\mathcal{P}_\tau &\approx \frac{1}{R_D}\Big\{0.402\left(\left|C^S_{LL}+C^S_{RL}\right|^2-\left|C^S_{RR}+C^S_{LR}\right|^2\right)\\
&+ 0.013\left[\left|C^T_{LL}\right|^2-\left|C^T_{RR}\right|^2\right]+0.097\left[\left|1+C^V_{LL}+C^V_{RL}\right|^2-\left|C^V_{RR}+C^V_{LR}\right|^2\right]\\
&+ 0.512\mathcal{R}e\left[(1+C^V_{LL}+C^V_{RL})(C^S_{LL}+C^S_{RL})^*-(C^V_{RR}+C^V_{LR})^*(C^S_{RR}+C^S_{LR})\right]\\
&- 0.099\mathcal{R}e\left[(1+C^V_{LL}+C^V_{RL})(C^T_{LL})^*-(C^V_{RR}+C^V_{LR})^*(C^T_{RR})\right]\Big\}\\
\mathcal{P}^*_\tau &\approx \frac{1}{R_{D^*}}\Big\{-0.127\left(\left|1+C^V_{LL}\right|^2+\left|C^V_{RL}\right|^2-\left|C^V_{RR}\right|^2-\left|C^V_{LR}\right|^2\right)\\
&+ 0.011\left(\left|C^S_{LL}-C^S_{RL}\right|^2-\left|C^S_{RR}-C^S_{LR}\right|^2\right)+0.172\left(\left|C^T_{LL}\right|^2-\left|C^T_{RR}\right|^2\right)\\
&+ 0.031\mathcal{R}e\left[\left(1+C^V_{LL}-C^V_{RL}\right)\left(C^S_{RL}-C^S_{LL}\right)^*-\left(C^V_{RR}-C^V_{LR}\right)^*\left(C^S_{LR}-C^S_{RR}\right)\right.\\
&+ 0.350\mathcal{R}e\left[\left(1+C^V_{LL}\right)\left(C^T_{LL}\right)^*-\left(C^V_{RR}\right)^*\left(C^T_{RR}\right)\right]\\
&- 0.481\mathcal{R}e\left[(C^V_{RL})(C^T_{LL})^*-(C^V_{LR})^*(C^T_{RR})\right]\\
&+ 0.216\mathcal{R}e\left[(1+C^V_{LL})(C^V_{RL})^*-(C^V_{RR})^*(C^V_{LR})\right]\Big\}\,.
\end{aligned}
$$

Numerical Equations

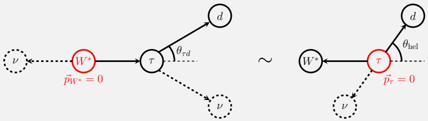
$$
\begin{aligned}
\mathcal{P}_\perp &\approx \frac{1}{R_D}\mathcal{R}e\left\{-0.350\left[\left(C^T_{LL}\right)\left(C^S_{LL}+C^S_{RL}\right)^* - \left(C^T_{RR}\right)^*\left(C^S_{RR}+C^S_{LR}\right)\right]\right.\\
&- 0.357\left[\left(1+C^V_{LL}+C^V_{RL}\right)\left(C^S_{LL}+C^S_{RL}\right)^* - \left(C^V_{RR}+C^V_{LR}\right)^*\left(C^S_{RR}+C^S_{LR}\right)\right]\\
&- 0.247\left[(1+C^V_{LL}+C^V_{RL})^*(C^T_{LL}) - (C^V_{RR}+C^V_{LR})(C^T_{RR})^*\right]\\
&- \left.0.250\left[\left|1+C^V_{LL}+C^V_{RL}\right|^2 - \left|C^V_{RR}+C^V_{LR}\right|^2\right]\right\}\\
\mathcal{P}^*_\perp &\approx \frac{1}{R_{D^*}}\mathcal{R}e\left\{\left(C^S_{RR}-C^S_{LR}\right)\left[0.099C^T_{RR} - 0.054\left(C^V_{RR}-C^V_{LR}\right)\right]^*\right.\\
&- \left(C^S_{LL}-C^S_{RL}\right)^*\left[0.099C^T_{LL} - 0.054\left(1+C^V_{LL}-C^V_{RL}\right)\right]\\
&+ \left(C^T_{RR}\right)\left[0.146C^V_{RR} - 0.478C^V_{LR} - 1.855C^T_{RR}\right]^*\\
&- \left(C^T_{LL}\right)^*\left[0.146(1+C^V_{LL}) - 0.478C^V_{RL} - 1.855C^T_{LL}\right]\\
&+ \left(C^V_{LR}\right)\left[-0.081C^T_{RR} + 0.025C^V_{LR} - 0.075C^V_{RR}\right]^*\\
&- \left(C^V_{RL}\right)^*\left[-0.081C^T_{LL} + 0.025C^V_{RL} - 0.075(1+C^V_{LL})\right]\\
&+ \left(C^V_{RR}\right)\left[-0.071C^T_{RR} - 0.075C^V_{LR} + 0.126C^V_{RR}\right]^*
\end{aligned}
$$

Numerical Equations

$$
\begin{aligned}
\mathcal{P}_T &\approx \frac{1}{R_D}\mathcal{I}m\Big\{-0.350\left[\left(C^T_{LL}\right)\left(C^S_{LL}+C^S_{RL}\right)^* - \left(C^T_{RR}\right)^*\left(C^S_{RR}+C^S_{LR}\right)\right] \\
&- 0.357\left[\left(1+C^V_{LL}+C^V_{RL}\right)\left(C^S_{LL}+C^S_{RL}\right)^* - \left(C^V_{RR}+C^V_{LR}\right)^*\left(C^S_{RR}+C^S_{LR}\right)\right] \\
&- 0.247\left[(1+C^V_{LL}+C^V_{RL})^*(C^T_{LL}) - (C^V_{RR}+C^V_{LR})(C^T_{RR})^*\right]\Big\} \\
\mathcal{P}^*_T &\approx \frac{1}{R_{D^*}}\mathcal{I}m\Big\{\left(C^S_{RR}-C^S_{LR}\right)\left[0.099C^T_{RR} - 0.054\left(C^V_{RR}-C^V_{LR}\right)\right]^* \\
&- \left(C^S_{LL}-C^S_{RL}\right)^*\left[0.099C^T_{LL} - 0.054\left(1+C^V_{LL}-C^V_{RL}\right)\right] \\
&+ \left(C^T_{RR}\right)\left[0.146C^V_{RR} - 0.478C^V_{LR}\right]^* - \left(C^T_{LL}\right)^*\left[0.146(1+C^V_{LL}) - 0.478C^V_{RL}\right] \\
&- \left(C^V_{LR}\right)\left[0.081C^T_{RR}\right]^* + \left(C^V_{RL}\right)^*\left[0.081C^T_{LL}\right] \\
&- \left(C^V_{RR}\right)\left[0.071C^T_{RR}\right]^* + (1+C^V_{LL})^*\left[0.071C^T_{LL}\right]\Big\}
\end{aligned}
$$

$\mathcal{P}_\tau$ Measurement

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

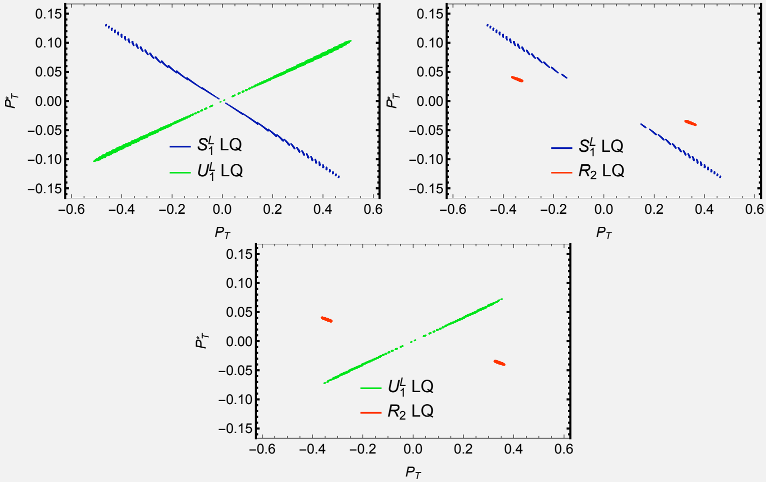


$$\cos\theta_{\tau d} = \frac{2E_\tau E_d - m_\tau^2 - m_d^2}{2|\vec{p}_\tau||\vec{p}_d|} \quad q^2 - \text{frame}$$

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

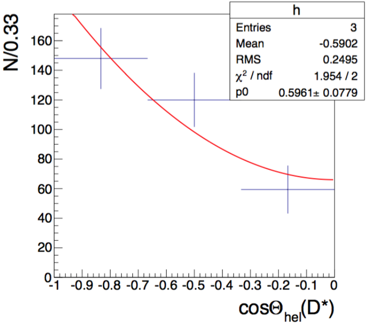
$$|\vec{p}_d^{\tau}|\cos\theta_{\rm hel} = -\gamma\frac{|\vec{p}_\tau|}{E_\tau}E_d + \gamma|\vec{p}_d|\cos\theta_{\tau d} \quad \tau - \text{frame}$$

$\mathcal{P}_T^{(*)}$



$F^L_{D^*}$ Measurement

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_{\rm hel}(D^*)} = \frac{3}{4}[2F_L^{D^*}\cos^2(\theta_{\rm hel}(D^*)) + (1 - F_L^{D^*})\sin^2(\theta_{\rm hel}(D^*))]$$



Number of events in:
I bin: 151±21
II bin: 125±19
III bin: 55±15
- signal yields corrected for accaptance variations

Dominant systematics:
- MC statistics (AR shape and peaking backgroud) = ±0.03

Figure: Talk by Karol Adamczyk @ CKM 2018