The Full $B \to D^* \tau^- \bar{\nu_\tau}$ Angular Distribution and CP violating Triple Products

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Based on 1302.7031 with A. Datta and 1206.3760 with A. Datta and D . Ghosh

Outline

1. Introduction

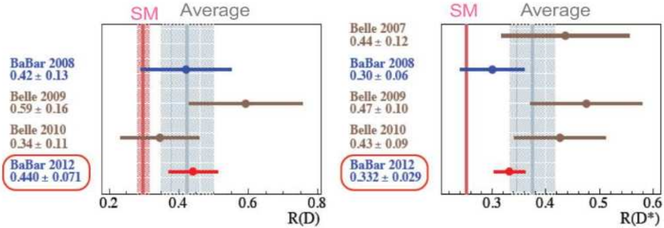
$R(D)$ and $R(D^*)$ measurements

- **Recently, the BABAR collaboration has reported the BR measurements of $\bar{B} \to D^*\tau^-\bar{\nu_\tau}$ and $\bar{B} \to D\tau^-\bar{\nu_\tau}$**

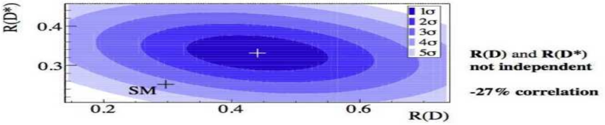
Experimental Results: BaBar: 1205.5442

$$R(D) = \frac{BR(\bar{B} \to D\tau^-\bar{\nu_\tau})}{BR(\bar{B} \to D\ell^-\bar{\nu_\ell})} = 0.440 \pm 0.058 \pm 0.042\,,$$

$$R(D^*) = \frac{BR(\bar{B} \to D^*\tau^-\bar{\nu_\tau})}{BR(\bar{B} \to D^*\ell^-\bar{\nu_\ell})} = 0.332 \pm 0.024 \pm 0.018\,.$$



$R(D)$ and $R(D^*)$ measurements



Vera Luth(FPCP)

SM predictions

$$R(D) = 0.297 \pm 0.017\,,$$
$$R(D^*) = 0.252 \pm 0.003\,.$$

- **Measurements exceed the SM calculations by 2.0 σ and 2.7 σ .**
- **Combined measurements disagree at 3.4σ level**

Explanation

- **Many NP explanations for these puzzles (2HDM type II, III, R-parity violating (RPV) SUSY, W' models, Lepto-quark models)**
- **Require progress in QCD calculations to reduce the form factor uncertainties**
- **We performed a model independent study using four-fermi operators with non-SM VA and SP couplings** (Datta, Duraisamy, Ghosh: PRD 86, 034027 (2012), arXiv:1206.3760)
- **Performed complete angular analysis on various observables (FB asymmetries, D^* and τ polarization fractions, Triple Products)** (Duraisamy and Datta :JHEP09(2013)059, arXiv:1302.7031)

Two Higgs Doublet Model II

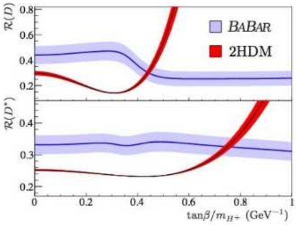
- **Can we explain the observed results with 2HDM type II ?**
- **In $\bar{B} \to D^* \tau^- \bar{\nu_\tau}$ and $\bar{B} \to D \tau^- \bar{\nu_\tau}$ the relevant interaction is**

$$\mathcal{A} \sim V_{cb} \frac{G_F}{\sqrt{2}} \frac{m_W^2}{m_H^2} \left[\frac{m_c}{m_W} \cot\beta \; \bar{c} P_L b + \frac{m_b}{m_W} \tan\beta \; \bar{c} P_R b \right] \frac{m_\tau}{m_W} \tan\beta \; \bar{\nu}_\tau P_L \tau$$

$$\sim V_{cb} \frac{G_F}{\sqrt{2}} \frac{m_W^2}{m_H^2} \left[\frac{m_b m_\tau}{m_W^2} \tan^2\beta \right] \; \bar{c} P_R b \bar{\nu}_\tau P_L \tau$$

- **Only the RH quark interactions survive. This causes problems to explain the data.**

2DHM Scan



$\tan\beta/m_{H^+} =$
0.44 ± 0.02 GeV^{-1}

$\tan\beta/m_{H^+} =$
0.75 ± 0.04 GeV^{-1}

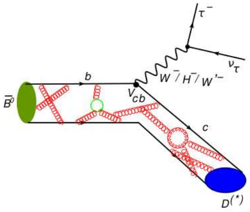
Phys.Rev.Lett. 109, 101802 (2012): BABAR Collaboration

- $R(D)$ **and** $R(D^*)$ **results together excludes the type II 2HDM charged Higgs boson at 98% C.L., in the full** $\tan\beta - m_{H^+}$ **parameter space**

2. Theory

$\bar{B} \to D^{(*)}\ell^- \bar{\nu}_\ell$

- $\bar{B} \to D^{(*)}\ell^- \bar{\nu}_\ell$ **proceeds through a virtual particle exchange (W, W', H). Note can also have leptoquarks.**



$$A_{SM} = \frac{G_F}{\sqrt{2}} V_{cb} \left[\langle D^{(*)}(p')|\bar{c}\gamma^\mu(1-\gamma_5)b|\bar{B}(p)\rangle \right] \bar{\ell}\gamma_\mu(1-\gamma_5)\nu_\ell$$

$\langle D^{(*)}(p')|J^\mu|\bar{B}(p)\rangle$ **represents hadronic matrix element.**

Model independent NP analysis

- **Effective Hamiltonian for $b \to c l^- \bar{\nu}_l$ with Non-SM couplings**

$$\mathcal{H}_{eff} = \frac{4G_F V_{cb}}{\sqrt{2}}\Big[(1+V_L)\,[\bar{c}\gamma_\mu P_L b]\;[\bar{l}\gamma^\mu P_L \nu_l] + V_R\,[\bar{c}\gamma^\mu P_R b]\;[\bar{l}\gamma_\mu P_L \nu_l]$$
$$+ S_L\,[\bar{c}P_L b]\,[\bar{l}P_L\nu_l] + S_R\;[\bar{c}P_R b]\;[\bar{l}P_L\nu_l] + T_L\,[\bar{c}\sigma^{\mu\nu}P_L b]\;[\bar{l}\sigma_{\mu\nu}P_L\nu_l]\Big]$$

- **Droping tensor interactions**

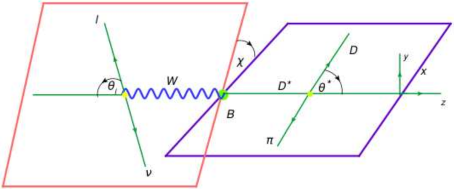
$$\mathcal{H}_{eff} = \frac{G_F V_{cb}}{\sqrt{2}}\Big\{\Big[\bar{c}\gamma_\mu(1-\gamma_5)b + g_V\bar{c}\gamma_\mu b + g_A\bar{c}\gamma_\mu\gamma_5 b\Big]\bar{l}\gamma^\mu(1-\gamma_5)\nu_l$$
$$+\Big[g_S\bar{c}b + g_P\bar{c}\gamma_5 b\Big]\bar{l}(1-\gamma_5)\nu_l + h.c\Big\}$$

$\Longrightarrow g_{V,A} = V_R \pm V_L$ **and** $g_{S,P} = S_R \pm S_L$

Helicity Amplitudes

- **In $\bar{B} \to D^* \tau^- \bar{\nu_\tau}$**
  - **we can think of the decay as $\bar{B} \to D^* W^* \quad W^* \to \tau \nu_\tau$**
  - **For an on shell W there are 3 helicity amplitudes just like in $B \to VV$ Decays ($++, --$ and $0, 0$). However because W^* is off shell it has four polarization states and we can construct four helicity amplitudes.**
- **In $\bar{B} \to D \tau^- \bar{\nu_\tau}$**
  - **we can think of the decay as $\bar{B} \to D W^* \quad W^* \to \tau \nu_\tau$**
  - **For an on shell W there is 1 helicity amplitude just like in $B \to VP$ Decays. However because W^* is off shell can construct two helicity amplitudes.**

$B \to D^* \tau \nu_\tau$ Full Angular DA



$$\frac{d^4\Gamma}{dq^2\, d\cos\theta_l\, d\cos\theta_{D^*}\, d\chi} = \frac{9}{32\pi} NF \Big\{ \cos^2\theta_{D^*}\left(V_1^0 + V_2^0\cos 2\theta_l + V_3^0\cos\theta_l\right)$$
$$+ \sin^2\theta_{D^*}\left(V_1^T + V_2^T\cos 2\theta_l + V_3^T\cos\theta_l\right)$$
$$+ V_4^T\sin^2\theta_{D^*}\sin^2\theta_l\cos 2\chi + V_1^{0T}\sin 2\theta_{D^*}\sin 2\theta_l\cos\chi$$
$$+ V_2^{0T}\sin 2\theta_{D^*}\sin\theta_l\cos\chi + V_5^T\sin^2\theta_{D^*}\sin^2\theta_l\sin 2\chi$$
$$+ V_3^{0T}\sin 2\theta_{D^*}\sin\theta_l\sin\chi + V_4^{0T}\sin 2\theta_{D^*}\sin 2\theta_l\sin\chi \Big\}\,.$$

- **Decay $\bar{B} \to D^*(\to D\pi)l^-\bar{\nu}_l$ is completely described in terms of twelve angular coefficients V_i. These angular coefficients depend on the couplings, kinematic variables and form factors.**

The longitudinal V^0's ($\lambda_1\lambda_2 = 00$) are given by

$$V_1^0 = 2\Big(1 + \frac{m_l^2}{q^2}\Big)|A_0|^2 + \frac{4m_l^2}{q^2}|A_{tP}|^2\,,$$
$$V_2^0 = -2\Big(1 - \frac{m_l^2}{q^2}\Big)|A_0|^2\,,$$
$$V_3^0 = -8\frac{m_l^2}{q^2}\mathrm{Re}[A_{tP}A_0^*]\,.$$

The transverse V^T's ($\lambda_1\lambda_2 = ++, --, +-, -+$) are given by

$$V_1^T = \frac{1}{2}\Big(3 + \frac{m_l^2}{q^2}\Big)\Big(|A_\parallel|^2 + |A_\perp|^2\Big)\,,$$
$$V_2^T = \frac{1}{2}\Big(1 - \frac{m_l^2}{q^2}\Big)\Big(|A_\parallel|^2 + |A_\perp|^2\Big)\,,$$
$$V_3^T = -4\mathrm{Re}[A_\parallel A_\perp^*]\,,$$
$$V_4^T = -\Big(1 - \frac{m_l^2}{q^2}\Big)\Big(|A_\parallel|^2 - |A_\perp|^2\Big)\,,$$
$$V_5^T = \Big(1 - \frac{m_l^2}{q^2}\Big)\mathrm{Im}[A_\parallel A_\perp^*]\,.$$

The mixed V^{0T}'s ($\lambda_1\lambda_2 = 0\pm, \pm 0$) are given by

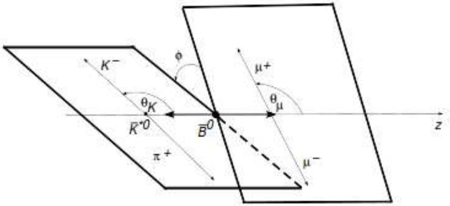
$$V_1^{0T} = \sqrt{2}\Big(1 - \frac{m_l^2}{q^2}\Big)\mathrm{Re}[A_\parallel A_0^*]\,,$$
$$V_2^{0T} = 2\sqrt{2}\mathrm{Re}\Big[-A_\perp A_0^* + \frac{m_l^2}{q^2}A_\parallel A_{tP}^*\Big]\,,$$
$$V_3^{0T} = 2\sqrt{2}\mathrm{Im}\Big[-A_\parallel A_0^* + \frac{m_l^2}{q^2}A_\perp A_{tP}^*\Big]\,,$$
$$V_4^{0T} = \sqrt{2}\Big(1 - \frac{m_l^2}{q^2}\Big)\mathrm{Im}[A_\perp A_0^*]\,.$$

$$N_F = \Big[\frac{G_F^2|p_{D^*}||V_{cb}|^2q^2}{3\times 2^6\pi^3 m_B^2}\Big(1 - \frac{m_l^2}{q^2}\Big)^2 Br(D^* \to D\pi)\Big]$$

$$\mathcal{A}_{tP} = \Big(\mathcal{A}_t + \frac{\sqrt{q^2}}{m_\tau}\mathcal{A}_P\Big)\,.$$

$B \to K^*\mu^+\mu^-$ Full Angular DA–Comparison

- **The form of $B \to D^*\tau\nu_\tau$ Angular DA is similar to that of $B \to K^*\mu^+\mu^-$**



$$\frac{d^4\Gamma}{dq^2 d\cos\theta_\mu d\cos\theta_K d\phi} = N_F \times$$
$$\Big\{ \cos^2\theta_K \Big(I_1^0 + I_2^0 \cos 2\theta_\mu + I_3^0 \cos\theta_\mu \Big) + \sin^2\theta_K \Big(I_1^T + I_2^T \cos 2\theta_\mu + I_3^T \cos\theta_\mu$$
$$+ I_4^T \sin^2\theta_\mu \cos 2\phi + I_5^T \sin^2\theta_\mu \sin 2\phi \Big) + \sin 2\theta_K \Big(I_1^{LT} \sin 2\theta_\mu \cos\phi$$
$$+ I_2^{LT} \sin 2\theta_\mu \sin\phi + I_3^{LT} \sin\theta_\mu \cos\phi + I_4^{LT} \sin\theta_\mu \sin\phi \Big) \Big\} , \qquad (7.4)$$

where the normalization factor N_F is

$$N_F = \frac{3\alpha_{em}^2 G_F^2 |V_{ts}^* V_{tb}|^2 |\vec{p}_{K^*}^B| \beta_\mu}{2^{14}\pi^6 m_B^2} Br(K^* \to K\pi) . \qquad (7.5)$$

(Alok et.al JHEP 1111 (2011) 121)

3. $B \to D^* \tau \nu_\tau$ Numerical Analysis

Based on : Duraisamy and Datta :JHEP09(2013)059, arXiv:1302.7031

$B \to D^*\tau\nu_\tau$ Numerical Analysis

- **Many angular observables can be constructed from the angular distribution. These can be used to test the SM and find the nature of NP.**
- **NP couplings are constrained by measured**

$$
\begin{aligned}
R(D) &= \frac{BR(\bar{B} \to D\tau^-\bar{\nu_\tau})}{BR(\bar{B} \to D\ell^-\bar{\nu_\ell})} = 0.440 \pm 0.058 \pm 0.042\,, \\
R(D^*) &= \frac{BR(\bar{B} \to D^*\tau^-\bar{\nu_\tau})}{BR(\bar{B} \to D^*\ell^-\bar{\nu_\ell})} = 0.332 \pm 0.024 \pm 0.018\,.
\end{aligned}
$$

(BaBar: 1205.5442)

Observable	SM	Only new $g_A = V_R - V_L$	Only new $g_V = V_R + V_L$	Only new $g_P = S_R - S_L$
DBR		• Significant E	• No effect	• Significant E
$R_{D^*}(q^2)$	• $0 \to 0.55$ (low$\to$high q^2)	• Significant E at high q^2	• No effect	• Significant E at $q^2 \approx 7.5\mathrm{GeV}^2$
$f_L(q^2)$	• $0.75 \to 0.35$ (low$\to$high q^2)	• No effect	• No effect	• Marginal E
$A_{FB}(q^2)$	• ZC $\approx$ 5.64 GeV^2	• Significant S at low q^2 • ZC may or may not exist	• Significant S at low q^2 • ZC may / may not exist	• Significant E/ S at low q^2 • ZC may / may not exist
$A_C^{(1)}(q^2)$	• $0.0 \to -0.2$ (low$\to$high q^2) • No ZC	• No effect	• No effect	• Marginal E at $q^2 \approx 8.0\mathrm{GeV}^2$
$A_C^{(2)}(q^2)$	• $0.3 \to 0.0$ (low$\to$high q^2) • No ZC	• Significant S • ZC may / may not exist	• Significant S • ZC may / may not exist	• Significant S • ZC may / may not exist
$A_C^{(3)}(q^2)$	• $0.0 \to 0.15$ (low$\to$high q^2) • No ZC	• No effect	• No effect	• Marginal S
$A_T^{(1)}(q^2)$		• Significant E/ S at $q^2 \approx 8.0\mathrm{GeV}^2$ • ZC may / may not exist	• Significant E/ S at $q^2 \approx 8.0\mathrm{GeV}^2$ • ZC may / may not exist	• No effect
$A_T^{(2)}(q^2)$		• Significant E/ S at low q^2 • ZC may / may not exist	• Significant E/ S at low q^2 • ZC may / may not exist	• Significant E/ S at low q^2 • ZC may / may not exist
$A_T^{(3)}(q^2)$		• Significant E/ S at $q^2 \approx 8.0\mathrm{GeV}^2$ • ZC may / may not exist	• Significant E/ S at $q^2 \approx 8.0\mathrm{GeV}^2$ • ZC may / may not exist	• No effect

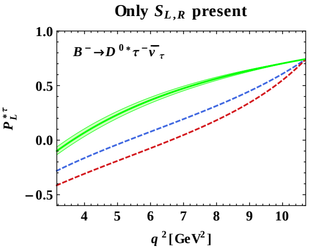
Table 2: The effect of NP couplings on observables. E: enhancement, S: suppression, ZC:

$\bar{B} \to D^*\tau^-\bar{\nu_\tau}$– polarization fraction of the τ lepton

- The τ polarization can be measured from the decays of the τ.

$$P_L^{*\tau}(q^2) \quad = \quad \frac{\frac{d\Gamma^{D^*}[\lambda_\tau=-1/2]}{dq^2} - \frac{d\Gamma^{D^*}[\lambda_\tau=1/2]}{dq^2}}{\frac{d\Gamma^{D^*}}{dq^2}} = \frac{|\mathcal{A}_T|^2\left(1-\frac{m_\tau^2}{2q^2}\right) - \frac{3m_\tau^2}{2q^2}|\mathcal{A}_{tP}|^2}{|\mathcal{A}_T|^2\left(1+\frac{m_\tau^2}{2q^2}\right) + \frac{3m_\tau^2}{2q^2}|\mathcal{A}_{tP}|^2}.$$

- τ lepton's longitudinal polarization fraction is generally sensitive to scalar (pseudoscalar) couplings
- $P_L^{*\tau}(q^2)$ can $\sim$ 0.5 and negative at very low q^2
- $P_L^{*\tau}(q^2)$ can have different ZCP than SM



4.$\bar{B} \to D\tau^- \bar{\nu_\tau}$ Numerical Analysis

Based on :Datta, Duraisamy, Ghosh: PRD 86, 034027 (2012), arXiv:1206.3760

$\bar{B} \to D\tau^- \bar{\nu_\tau}$ –Angular Distribution

$$\frac{d\Gamma^D}{dq^2 d\cos\theta_l} = N|p_D| \left[2|H_0|^2 \sin^2\theta_l + 2\frac{m_\tau^2}{q^2}(H_0\cos\theta_l - H_{tS})^2\right],$$

$$H_0 = \frac{2m_B|p_D|}{\sqrt{q^2}} F_+(q^2)(1+g_V), \quad H_t = \frac{m_B^2 - m_D^2}{\sqrt{q^2}} F_0(q^2)(1+g_V),$$

$$H_S = \frac{m_B^2 - m_D^2}{m_b(\mu) - m_c(\mu)} F_0(q^2) g_S,$$

$$H_{tS} = \left(H_t - \frac{\sqrt{q^2}}{m_\tau} H_S\right).$$

$\bar{B} \to D\tau^-\bar{\nu}_\tau$– Differential branching ratio: Only g_V present

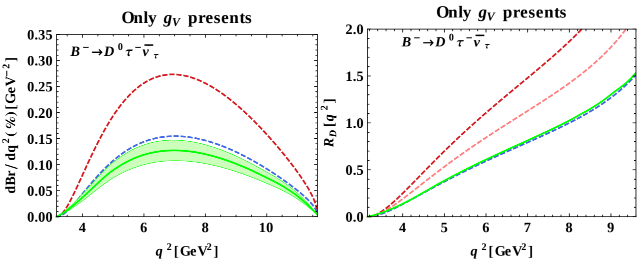
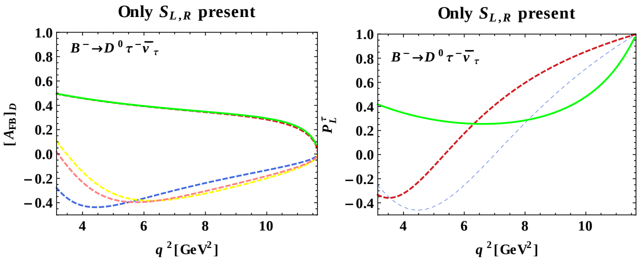


Figure: **Green: SM, Red and Blue: NP**

- g_V **can enhance DBR upto 0.25% at** $q^2 \approx 7\text{GeV}^2$
- $R_D(q^2)$ **is proportional to** $(1+g_V)^2$ **and increases with** q^2
- **For pure** $g_S = S_L + S_R$, q^2 **dependence of DBR and** $R_D(q^2)$ **are similar to pure** g_V **coupling**

$\bar{B} \to D\tau^-\bar{\nu_\tau}$– FBA and tau Pol.Frac



- FBA and τ-polarization fraction are very sensitive to S_L and S_R couplings
- FBA can be either positive or negative, and may have zero-crossing. No zero-crossing in SM
- τ-polarization fraction can be negatively enhanced to more than 40% at low q^2 and may have the zero-crossing

5. Conclusion

Conclusion

- **New physics with third family leptons are often weakly constrained.**
- $\bar{B} \to D^* \tau^- \bar{\nu_\tau}$ **and** $\bar{B} \to D \tau^- \bar{\nu_\tau}$ **are good places to constrain this kind of NP.**
- **Present measurements allow several NP models.**
- **Asymmetries and Polarization fractions can find the nature of NP.**
- **Full angular distribution can probe the CP violation.**

Back up

$B \to D\tau\nu_\tau$ helicity amplitudes

$$H_0 = \frac{2m_B|p_D|}{\sqrt{q^2}} F_+(q^2)(1+g_V)\,, \quad H_t = \frac{m_B^2 - m_D^2}{\sqrt{q^2}} F_0(q^2)(1+g_V)\,,$$

$$H_S = \frac{m_B^2 - m_D^2}{m_b(\mu) - m_c(\mu)} F_0(q^2) g_S\,.$$

Here

$g_V = V_R + V_L$ ✓ $g_S = S_R + S_L$ ✓

- **Heavy Quark limit for b and c quarks** $(m_{b,c} \gg \Lambda_{QCD})$

$$F_+(q^2) = \frac{V_1(w)}{R_D}\,, \quad F_0(q^2) = \frac{(1+w)R_D}{2} S_1(w)\,,$$

Form Factors $\bar{B} \to D\tau^- \bar{\nu_\tau}$

- **Use the parametrization of the form factor $V_1(w)$ as given by (Caprini et.al.)**

$$V_1(w) = V_1(1)[1 - 8\rho_1^2 z + (51\rho_1^2 - 10)z^2 - (252\rho_1^2 - 84)z^3]$$

Here $w = v_B.v_D = (m_B^2 + m_D^2 - q^2)/2m_B m_D$,
$z = (\sqrt{w+1} - \sqrt{2})/(\sqrt{w+1} + \sqrt{2})$.

- **For the form factor $S_1(w)$ we employ the parametrization as in (Sakaki)**

$$S_1(w) = [1.0036 - 0.0068(w-1) + 0.0017(w-1)^2]V_1(w)$$

$\bar{B} \to D\tau^-\bar{\nu_\tau}$– Differential branching ratio

$$\frac{dBr[\bar{B} \to D\tau^-\bar{\nu_\tau}]}{dq^2} = \frac{8N|p_D|\tau_B}{3\hbar}\left[|H_0|^2(1+\frac{m_\tau^2}{2q^2}) + \frac{3m_\tau^2}{2q^2}|H_{tS}|^2\right]$$

$$R_D(q^2) = \frac{dBr[\bar{B} \to D\tau^-\bar{\nu_\tau}]/dq^2}{dBr[\bar{B} \to D\ell^-\bar{\nu_\ell}]/dq^2}\,.$$

$\bar{B} \to D\tau^-\bar{\nu_\tau}$– FBA and tau Pol.Frac

$$
\begin{aligned}
[A_{FB}]_D(q^2) &= \frac{(\int_{-1}^{0} - \int_{0}^{1}) d\cos\theta_l \frac{d\Gamma^D}{dq^2 d\cos\theta_l}}{\frac{d\Gamma^D}{dq^2}} \\
&= \frac{3m_\tau^2}{2q^2} \frac{Re[H_0 H_{tS}^*]}{|H_0|^2(1+\frac{m_\tau^2}{2q^2}) + \frac{3m_\tau^2}{2q^2}|H_{tS}|^2} .
\end{aligned}
$$

Longitudinal polarization fraction of τ in the q^2 rest frame

$$
P_L^\tau(q^2) = \frac{\frac{d\Gamma^D[\lambda_\tau=1/2]}{dq^2} - \frac{d\Gamma^D[\lambda_\tau=-1/2]}{dq^2}}{\frac{d\Gamma^D}{dq^2}} = \frac{|H_0|^2(\frac{m_\tau^2}{2q^2} - 1) + \frac{3m_\tau^2}{2q^2}|H_{tS}|^2}{|H_0|^2(1+\frac{m_\tau^2}{2q^2}) + \frac{3m_\tau^2}{2q^2}|H_{tS}|^2} .
$$

$B \to D^* \tau \nu_\tau$ helicity amplitudes

$$
\begin{aligned}
\mathcal{A}_0 &= \frac{1}{2m_{D^*}\sqrt{q^2}}\Big[(m_B^2 - m_{D^*}^2 - q^2)(m_B + m_{D^*})A_1(q^2) \\
&\quad - \frac{4m_B^2|p_{D^*}|^2}{m_B + m_{D^*}}A_2(q^2)\Big](1 - g_A)\,, \\
\mathcal{A}_\parallel &= \sqrt{2}(m_B + m_{D^*})A_1(q^2)(1 - g_A)\,, \\
\mathcal{A}_\perp &= -\sqrt{2}\frac{2m_B V(q^2)}{(m_B + m_{D^*})}|p_{D^*}|(1 + g_V)\,, \\
\mathcal{A}_t &= \frac{2m_B|p_{D^*}|A_0(q^2)}{\sqrt{q^2}}(1 - g_A)\,, \\
\mathcal{A}_P &= -\frac{2m_B|p_{D^*}|A_0(q^2)}{(m_b(\mu) + m_c(\mu))}g_P\,.
\end{aligned}
$$

Here

$g_V = V_R + V_L$ ✓ $g_A = V_R - V_L$ ✓ $g_P = S_R - S_L$ ✓

- **Heavy Quark limit for b and c quarks**

$B \to D^* \tau \nu_\tau$ Form Factors

- **Heavy Quark limit for b and c quarks** $(m_{b,c} \gg \Lambda_{QCD})$**,** $A_{0,1,2}, V$ **reduce to one form factor** $h_{A_1}(w)$

$$
\begin{aligned}
A_1(q^2) &= R_{D^*}\frac{w+1}{2}h_{A_1}(w) \\
A_0(q^2) &= \frac{R_0(w)}{R_{D^*}}h_{A_1}(w) \\
A_2(q^2) &= \frac{R_2(w)}{R_{D^*}}h_{A_1}(w) \\
V(q^2) &= \frac{R_1(w)}{R_{D^*}}h_{A_1}(w)
\end{aligned}
$$

$$w = v_B . v_{D^*} = (m_B^2 + m_{D^*}^2 - q^2)/2m_B m_{D^*}$$

Caprini et al., hep-ph/9712417

- **Most of the** w **dependence comes from** $h_{A_1}(w)$ **and hence we construct observables where this FF cancels and reducing FF dependence.**

$$
\begin{aligned}
h_{A_1}(w) &= h_{A_1}(1)\Big[1 - 8\rho^2 z + (53\rho^2 - 15)z^2 - (231\rho^2 - 91)z^3\Big], \\
R_1(w) &= R_1(1) - 0.12(w-1) + 0.05(w-1)^2, \\
R_2(w) &= R_2(1) + 0.11(w-1) - 0.06(w-1)^2, \\
R_0(w) &= R_0(1) - 0.11(w-1) + 0.01(w-1)^2,
\end{aligned}
$$

$B \to D^* \tau \nu_\tau$ Form Factors

- **Numerical values Dungel *et al.*:1010.5620 (Belle) from angular distribution of $\bar{B} \to D^* \ell^- \bar{\nu}_\ell$ where $\ell = e, \mu$.**

$$\begin{aligned} h_{A_1}(1)|V_{cb}| &= (34.6 \pm 0.2 \pm 1.0) \times 10^{-3}\,, \\ \rho^2 &= 1.214 \pm 0.034 \pm 0.009\,, \\ R_1(1) &= 1.401 \pm 0.034 \pm 0.018\,, \\ R_2(1) &= 0.864 \pm 0.024 \pm 0.008\,, \\ R_0(1) &= 1.14 \end{aligned}$$

- **R_0 term goes with the lepton mass. Hence for $l = e, \mu$ one is not sensitive to this. For $l = \tau$ this FF is important. Hence important uncertainty here.**

$B \to D^* \tau \nu_\tau$ Differential branching ratio

$$\frac{d\Gamma}{dq^2} = \frac{8\pi N_F}{3}(A_L + A_T)\,,$$

$$A_L = \Big(V_1^0 - \frac{1}{3}V_2^0\Big), \quad A_T = 2\Big(V_1^T - \frac{1}{3}V_2^T\Big)\,.$$

$$R_{D^*}(q^2) = \frac{dBr[\bar{B} \to D^* \tau^- \bar{\nu_\tau}]/dq^2}{dBr[\bar{B} \to D^* \ell^- \bar{\nu_\ell}]/dq^2}\,,$$

$B \to D^*\tau\nu_\tau$– Differential branching ratio

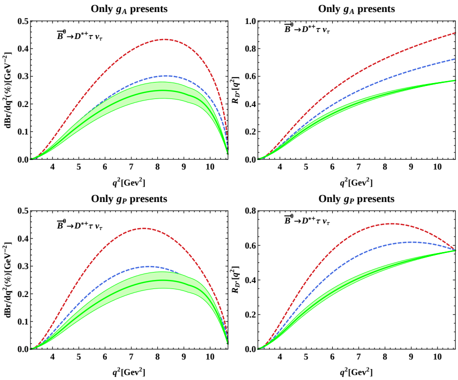


Figure: **Green: SM, Red and Blue: NP**

- **BaBar (e-Print: arXiv:1303.0571) finds shape of the distribution similar to the SM- points towards V/A new physics.**

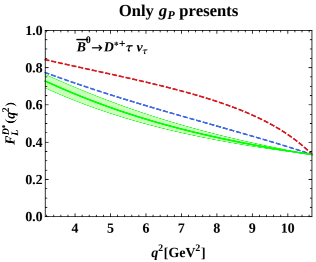
$B \to D^* \tau \nu_\tau$– Polarization fraction

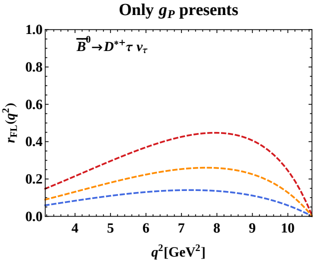
$$\frac{d^2\Gamma}{dq^2 d\cos\theta_{D^*}} = \frac{1}{4}\frac{d\Gamma}{dq^2}(2F_L^{D^*}\cos^2\theta_{D^*} + (1 - F_L^{D^*})\sin^2\theta_{D^*})$$

$$F_L^{D^*}(q^2) = \frac{A_L}{A_L + A_T}$$

$$r_{F_L} = [F_L^{D^*}]^{NP}/[F_L^{D^*}]^{SM}$$

- **Polarization fractions are sensitive to S_L and S_R couplings**
- **Ratio r_{F_L} reaches 40% around $q^2 \approx 8.0\ \mathrm{GeV}^2$**





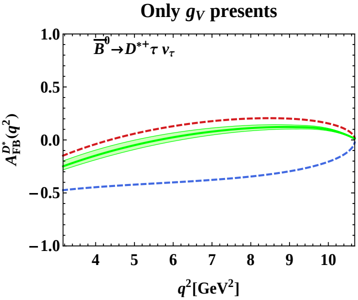
$B \to D^*\tau\nu_\tau$– Forward-Backward asymmetry

$$A_{FB}(q^2) = \frac{\int_0^1 d\cos\theta_l \frac{d^2\Gamma}{dq^2 d\cos\theta_l} - \int_{-1}^0 d\cos\theta_l \frac{d^2\Gamma}{dq^2 d\cos\theta_l}}{\int_0^1 d\cos\theta_l \frac{d^2\Gamma}{dq^2 d\cos\theta_l} + \int_{-1}^0 d\cos\theta_l \frac{d^2\Gamma}{dq^2 d\cos\theta_l}}$$

- A_{FB} **is sensitive to all three couplings** g_A, g_V, **and** g_P

$B \to D^* \tau \nu_\tau$– Forward-Backward asymmetry

- g_V **appears only in** $\mathcal{A}_\perp$ **: Significant effects only on AFB**



- g_V **can enhance** $[A_{FB}]_{D^*}$ **up to** 50% **at low** q^2
- $[A_{FB}]_{D^*}$ **can have different zero-crossing point (ZCP) than SM**
  $\Rightarrow$ **SM ZCP at** $q^2 \approx 5.64 GeV^2$

Green band: SM prediction. Dashed lines: SM + NP prediction for some g_V

Triple Product Asymmetry

- **If CPT is conserved (local and lorentz invariant field theory) then CP violation implies T violation**
- **Triple Products are products of vectors of the type**

$$T.P = \vec{v}_1.(\vec{v}_2 \times \vec{v}_3)$$

Here $\vec{v}_i$ are spin or momentum vectors.

- **Under (naive) time reversal $\hat{T}$: t→ -t ⇒ T.P→- T.P : hence they are T-odd**
- **T-odd CPV in B decays can be measured via Triple Product Correlations (TP)[G.Valencia].**

$\bar{B} \to D^* \tau^- \bar{\nu_\tau}$–Triple Product Asymmetries

- **If the NP couplings are complex then that will leads to CP violation which are sensitive to the angular terms** $\sin\chi$ **and** $\sin 2\chi$**.**

- **The coefficients of these terms are TPs and have the structure** $\sim Im[\mathcal{A}_i \mathcal{A}_j^*] \sim \sin(\phi_i - \phi_j)$**, where** $\mathcal{A}_{i,j} = |\mathcal{A}_{i,j}| e^{i\phi_{i,j}}$**.**

- **In the SM these terms vanish as there is only one contribution to the decay and so all amplitudes have the same weak phase.**

- **There are 3 T.P. terms** $\sim Im[\mathcal{A}_i \mathcal{A}_\perp^*]$ **in the angular distribution. Also, there are 3 transverse asymmetry terms** $\sim Re[\mathcal{A}_i \mathcal{A}_\perp^*]$

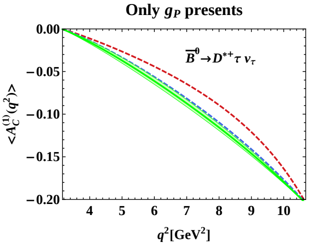
$\bar{B} \to D^* \tau^- \bar{\nu}_\tau$– Transverse Asymmetry $A_C^{(1)}$

- **Transverse asymmetry $A_C^{(1)}$ is defined through the angular distribution in χ as**

$$\frac{d^2\Gamma}{dq^2 d\chi} = \frac{1}{2\pi}\frac{d\Gamma}{dq^2}\left[1 + \left(A_C^{(1)}\cos 2\chi + A_T^{(1)}\sin 2\chi\right)\right]$$

$$A_C^{(1)}(q^2) = \frac{4V_4^T}{3(A_L + A_T)}$$

- **$A_C^{(1)}$ is only sensitive to g_P**
- **Ratio $r_1(q^2) = |[A_C^{(1)}(q^2)]^{NP}/[A_C^{(1)}(q^2)]^{SM}|$ reaches more than 25% at $q^2 \approx 5.0\text{GeV}^2$**



$\bar{B} \to D^* \tau^- \bar{\nu}_\tau$– Transverse Asymmetry $A_C^{(2)}$

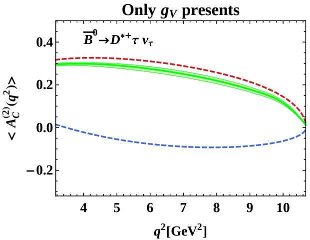
- **Transverse asymmetry $A_C^{(2)}$ is defined through the angular distribution in χ as**

$$\frac{d^2\Gamma^{(2)}}{dq^2 d\chi} = \frac{1}{4}\frac{d\Gamma}{dq^2}\left[A_C^{(2)} \cos\chi + A_T^{(2)} \sin\chi\right]$$

$$A_C^{(2)}(q^2) = \frac{V_2^{0T}}{(A_L + A_T)}$$

- **$A_C^{(2)}$ depends on all the three couplings g_A, g_V, and g_P**

- **$A_C^{(2)}$ is generally suppressed by these new couplings**



$\bar{B} \to D^* \tau^- \bar{\nu_\tau}$ – Transverse Asymmetry $A_C^{(3)}$

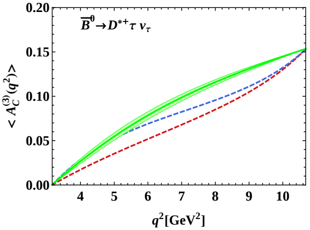
- **Transverse asymmetry $A_C^{(3)}$ is defined through the angular distribution in χ as**

$$\frac{d^2\Gamma^{(3)}}{dq^2 d\chi} = \frac{2}{3\pi} \frac{d\Gamma}{dq^2} \left[A_C^{(3)} \cos\chi + A_T^{(3)} \sin\chi \right]$$

$$A_C^{(3)}(q^2) = \frac{V_1^{0T}}{(A_L + A_T)}$$

- $A_C^{(3)}$ **is only sensitive to g_P**
- $r_3(q^2) = [A_C^{(3)}(q^2)]^{NP} / [A_C^{(3)}(q^2)]^{SM}$ **can reach values $\gtrsim 30\%$ at low q^2**

Only g_P presents



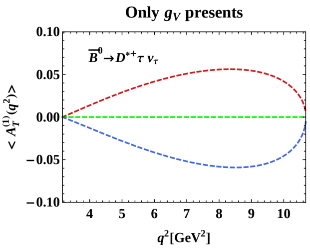
$\bar{B} \to D^* \tau^- \bar{\nu_\tau}$– **TPA** $A_T^{(1)}$

- $A_T^{(1)}$ **is defined through the angular distribution in χ as**

$$\frac{d^2\Gamma}{dq^2 d\chi} = \frac{1}{2\pi}\frac{d\Gamma}{dq^2}\left[1 + \left(A_C^{(1)}\cos 2\chi + A_T^{(1)}\sin 2\chi\right)\right]$$

$A_T^{(1)}(q^2) = \frac{4V_5^T}{3(A_L + A_T)}$,

- $A_T^{(1)}$ **is only sensitive to g_A and g_V , but NOT to g_P**
- g_V **can enhance the magnitude of $A_T^{(1)}$ up to 5% at** $q^2 \approx 8.0\text{GeV}^2$



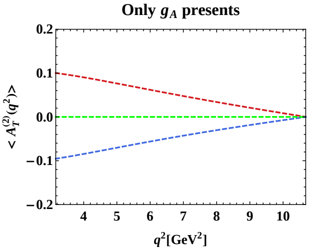
$\bar{B} \to D^{*}\tau^{-}\bar{\nu}_{\tau}$– TPA $A_T^{(2)}$

- $A_T^{(2)}$ is defined through the angular distribution in χ as

$$\frac{d^2\Gamma^{(2)}}{dq^2 d\chi} = \frac{1}{4}\frac{d\Gamma}{dq^2}\left[A_C^{(2)}\cos\chi + A_T^{(2)}\sin\chi\right]$$

$A_T^{(2)}(q^2) = \frac{V_3^{0T}}{(A_L + A_T)}$,

- $A_T^{(2)}$ depends on all the three couplings g_A, g_V, and g_P
- $A_T^{(2)}$ is proportional to m_l^2
- All NP couplings can enhance $A_T^{(2)}$ up to 10% at low q^2.



$\bar{B} \to D^{*}\tau^{-}\bar{\nu_{\tau}}$– **TPA** $A_T^{(3)}$

- $A_T^{(3)}$ **is defined through the angular distribution in** χ **as**

$$\frac{d^2\Gamma^{(3)}}{dq^2 d\chi} = \frac{2}{3\pi}\frac{d\Gamma}{dq^2}\left[A_C^{(3)}\cos\chi + A_T^{(3)}\sin\chi\right]$$

$A_T^{(3)}(q^2) = \frac{V_4^{0T}}{(A_L + A_T)}$,

- $A_T^{(3)}$ **is only sensitive to** g_A **and** g_V **, but NOT to** g_P
- g_V **can enhance the magnitude of** $A_T^{(3)}$ **up to 5% at** $q^2 \approx 8.0\mathrm{GeV}^2$