New physics and surprises in $B \to D^{(*)}\tau\bar{\nu}$

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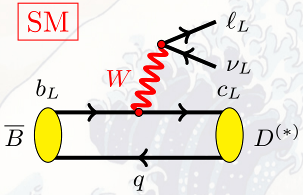
Outline

1. Study of the $\overline{B} \to D^{(*)}\tau\overline{\nu}$ decays : motivation
2. Constraining New Physics parameters
3. How to distinguish between various New Physics scenarios
4. Conclusions



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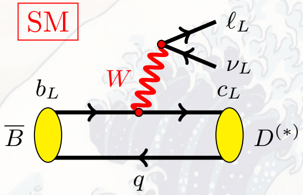

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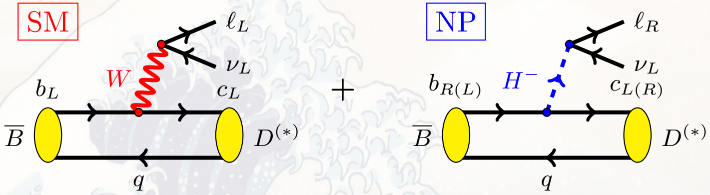

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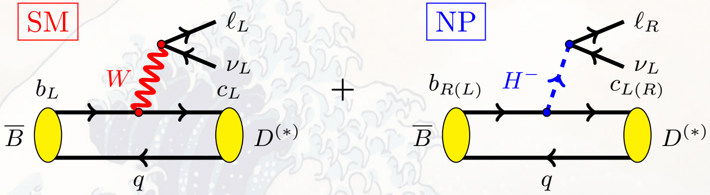
Motivation



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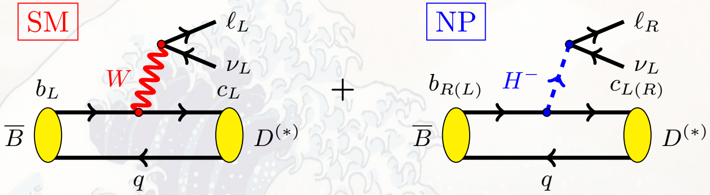

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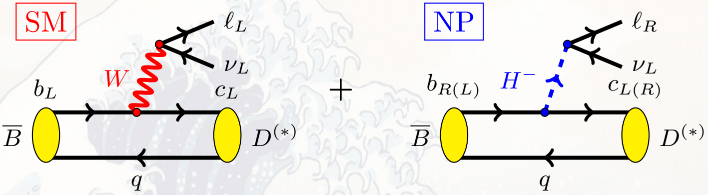

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- Hadronic uncertainties better controlled (or can be!).
- Popular NP test via

$$\boxed{R(D) = \frac{\mathcal{B}(B \to D\tau\overline{\nu}_\tau)}{\mathcal{B}(B \to D\ell\overline{\nu}_\ell)}, \quad R(D^*) = \frac{\mathcal{B}(B \to D^*\tau\overline{\nu}_\tau)}{\mathcal{B}(B \to D^*\ell\overline{\nu}_\ell)}} \quad (\ell = e, \mu)$$

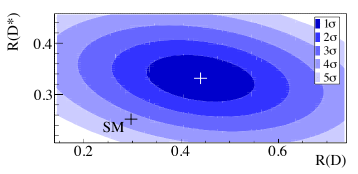
in order to cancel/reduce theoretical uncertainties in V_{cb}/FFs.

Motivation

The *BABAR* results [arXiv:1205.5442],

$$R(D)^{\rm exp} = 0.440 \pm 0.058 \pm 0.042\,, \qquad R(D)^{\rm SM} = 0.297 \pm 0.017\,,$$
$$R(D^*)^{\rm exp} = 0.332 \pm 0.024 \pm 0.018\,, \qquad R(D^*)^{\rm SM} = 0.252 \pm 0.003\,,$$

disagree with the SM at the 3.4 σ level (combining with Belle result, we obtain 3.5 σ).



[BABAR, arXiv:1303.0571]

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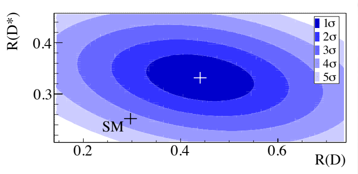

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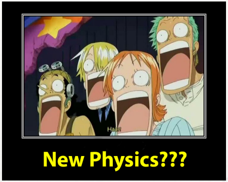

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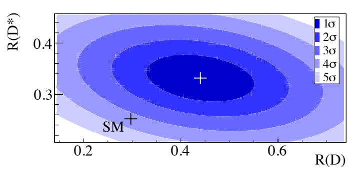

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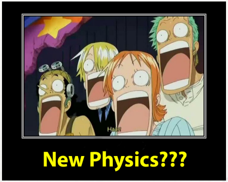

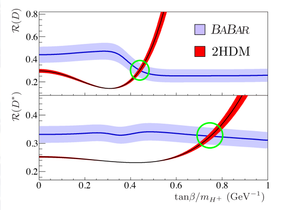

2HDM-II → $\not R$ MSSM ? ($B \to X_s \nu\bar{\nu}$) / 2HDM-III ? / leptoquarks ? / smth else ?

EXCLUDED at 99.8% C.L.

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$\mathcal{H}_{\text{eff}}$ describing the $b \to c\tau\overline{\nu}_l$ process

$$\mathcal{H}_{\text{eff}} = \frac{4G_F}{\sqrt{2}} V_{cb} \Big[(\underbrace{\delta_{\tau l}}_{\text{SM}} + \underbrace{C^l_{V_1})\mathcal{O}_{V_1} + C^l_{V_2}\mathcal{O}^l_{V_2} + C^l_{S_1}\mathcal{O}^l_{S_1} + C^l_{S_2}\mathcal{O}^l_{S_2} + C^l_T\mathcal{O}^l_T}_{\text{NP}} \Big]$$

$$\mathcal{O}^l_{V_1} = (\bar{c}_L\gamma^\mu b_L)(\tau_L\gamma_\mu\nu_{lL}), \quad \mathcal{O}^l_{V_2} = (\bar{c}_R\gamma^\mu b_R)(\tau_L\gamma_\mu\nu_{lL}),$$

$$\mathcal{O}^l_{S_1} = (\bar{c}_L b_R)(\tau_R\nu_{lL}), \quad \mathcal{O}^l_{S_2} = (\bar{c}_R b_L)(\tau_R\nu_{lL}),$$

$$\mathcal{O}^l_T = (\bar{c}_R\sigma^{\mu\nu} b_L)(\tau_R\sigma_{\mu\nu}\nu_{lL}).$$

- In the SM, $C^l_X = 0$.
- NO right-handed neutrino.

NB: the pseudotensor operator is not independent of $\mathcal{O}_T$ due to the relation $\bar{c}\sigma_{\mu\nu}\gamma_5 b = -\frac{i}{2}\epsilon_{\mu\nu\alpha\beta}\bar{c}\sigma^{\alpha\beta}b$.

The studied distributions are given by

$$\frac{d\Gamma(\overline{B}\to D\tau\overline{\nu}_l)}{dq^2} = \frac{G_F^2|V_{cb}|^2}{192\pi^3 m_B^3} q^2 \sqrt{\lambda_D(q^2)} \left(1-\frac{m_\tau^2}{q^2}\right)^2 \times \Bigg\{ |\delta_{\tau l} + C_{V_1}^l + C_{V_2}^l|^2 \left[\left(1+\frac{m_\tau^2}{2q^2}\right) H_{V,0}^{s\,2} + \frac{3}{2}\frac{m_\tau^2}{q^2} H_{V,t}^{s\,2}\right] + \frac{3}{2}|C_{S_1}^l + C_{S_2}^l|^2 H_S^{s\,2} + 8|C_T^l|^2 \left(1+\frac{2m_\tau^2}{q^2}\right) H_T^{s\,2} + 3\mathcal{R}e[(\delta_{\tau l} + C_{V_1}^l + C_{V_2}^l)(C_{S_1}^{l*} + C_{S_2}^{l*})] \frac{m_\tau}{\sqrt{q^2}} H_S^s H_{V,t}^s - 12\mathcal{R}e[(\delta_{\tau l} + C_{V_1}^l + C_{V_2}^l) C_T^{l*}] \frac{m_\tau}{\sqrt{q^2}} H_T^s H_{V,0}^s \Bigg\}$$

where H_i are the helicity amplitudes,

$$H_i(q^2) \propto \langle D^{(*)}|\mathcal{O}_i|\overline{B}\rangle$$

$\lambda_{D(*)} = ((m_B - m_{D(*)})^2 - q^2)((m_B + m_{D(*)})^2 - q^2)$

Distributions (simple yet long formulas)

The studied distributions are given by

$$\frac{d\Gamma(\overline{B}\to D^*\tau\overline{\nu}_l)}{dq^2} = \frac{G_F^2|V_{cb}|^2}{192\pi^3 m_B^3} q^2 \sqrt{\lambda_{D^*}(q^2)} \left(1-\frac{m_\tau^2}{q^2}\right)^2 \times \Bigg\{$$

$$(|\delta_{l\tau}+C^l_{V_1}|^2 + |C^l_{V_2}|^2)\left[\left(1+\frac{m_\tau^2}{2q^2}\right)(H^2_{V,+}+H^2_{V,-}+H^2_{V,0}) + \frac{3}{2}\frac{m_\tau^2}{q^2}H^2_{V,t}\right]$$

$$-2\mathcal{R}e[(\delta_{l\tau}+C^l_{V_1})C^{l*}_{V_2}]\left[\left(1+\frac{m_\tau^2}{2q^2}\right)(H^2_{V,0}+2H_{V,+}H_{V,-}) + \frac{3}{2}\frac{m_\tau^2}{q^2}H^2_{V,t}\right]$$

$$+\frac{3}{2}|C^l_{S_1}-C^l_{S_2}|^2 H_S^2 + 8|C^l_T|^2\left(1+\frac{2m_\tau^2}{q^2}\right)(H^2_{T,+}+H^2_{T,-}+H^2_{T,0})$$

$$+3\mathcal{R}e[(\delta_{l\tau}+C^l_{V_1}-C^l_{V_2})(C^{l*}_{S_1}-C^{l*}_{S_2})]\frac{m_\tau}{\sqrt{q^2}}H_S H_{V,t}$$

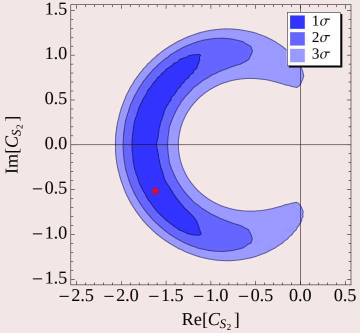
$$-12\mathcal{R}e[(\delta_{l\tau}+C^l_{V_1})C^{l*}_T]\frac{m_\tau}{\sqrt{q^2}}(H_{T,0}H_{V,0}+H_{T,+}H_{V,+}-H_{T,-}H_{V,-})$$

$$+12\mathcal{R}e[C^l_{V_2}C^{l*}_T]\frac{m_\tau}{\sqrt{q^2}}(H_{T,0}H_{V,0}+H_{T,+}H_{V,-}-H_{T,-}H_{V,+})\Bigg\}$$

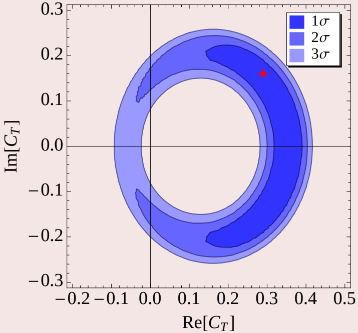
$$\lambda_{D^{(*)}} = ((m_B-m_{D^{(*)}})^2-q^2)((m_B+m_{D^{(*)}})^2-q^2)$$

Assuming the presence of only one NP type (e.g. either scalar or tensor), we do the χ^2 fit of $R(D)\&R(D^*)^{BABAR+\text{Belle}}$ and obtain the constraints on the NP Wilson coefficients:

Scalar



Tensor



Several NP "models" can explain the excess of $\overline{B} \to D^{(*)}\tau\overline{\nu}$ **simultaneously** $\Rightarrow$ Can we discriminate them?

How to distinguish between NP scenarios : various observables

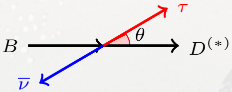
- R ratios (to be improved at Belle II)

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

- τ forward-backward asymmetry,

$$\mathcal{A}_{\rm FB} = \frac{\int_0^1 \frac{d\Gamma}{d\cos\theta} d\cos\theta - \int_{-1}^0 \frac{d\Gamma}{d\cos\theta} d\cos\theta}{\int_{-1}^1 \frac{d\Gamma}{d\cos\theta} d\cos\theta} = \frac{\int b_\theta(q^2) dq^2}{\Gamma}$$

$$\frac{d^2\Gamma}{dq^2 d\cos\theta} = a_\theta(q^2) + b_\theta(q^2)\cos\theta + c_\theta(q^2)\cos^2\theta$$



- τ polarization parameter by studying further τ decays,

$$P_\tau = \frac{\Gamma(\lambda_\tau=1/2) - \Gamma(\lambda_\tau=-1/2)}{\Gamma(\lambda_\tau=1/2) + \Gamma(\lambda_\tau=-1/2)}$$

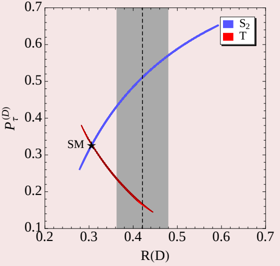
- D^* longitudinal polarization using the $D^* \to D\pi$ decay,

$$P_{D^*} = \frac{\Gamma(\lambda_{D^*}=0)}{\Gamma(\lambda_{D^*}=0) + \Gamma(\lambda_{D^*}=1) + \Gamma(\lambda_{D^*}=-1)}$$

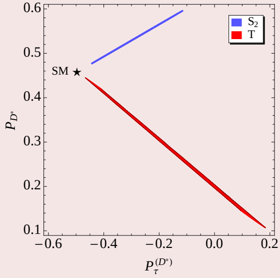
How to distinguish between NP scenarios : correlations (illustration)

Applying the constraints on $C_{S_2}^{\tau}$ or C_T^{τ} from the χ^2 fit of $R(D)\&R(D^*)$ at 3σ level,

τ polarization



D^* polarization

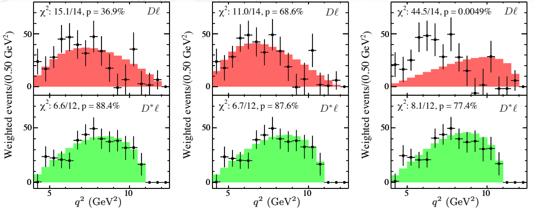


[Sakaki,Tanaka,AT,Watanabe('13), arXiv:1309.0301]

Measurements of these observables in addition to more precise determination of $R(D^{(*)})$ are the key issue in order to identify the origin of the present excess of $\overline{B} \to D^{(*)}\tau\overline{\nu}$.

BUT this is NOT an easy experimental task ☹

$d\mathcal{B}(B \to D^{(*)}\tau\overline{\nu})/dq^2$ [BABAR('13), arXiv:1303.0571]



- To reduce the FF uncertainties, one can explore the q^2-dependent ratio

$$R_{D^{(*)}}(q^2) \equiv \frac{d\mathcal{B}(\overline{B} \to D^{(*)}\tau\overline{\nu})/dq^2}{d\mathcal{B}(\overline{B} \to D^{(*)}\ell\overline{\nu})/dq^2}$$

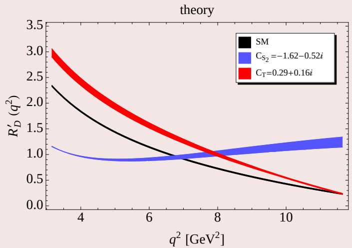
- For our convenience, to remove the divergence of R_D at $q^2 = (m_B - m_D)^2$ † and the phase space suppression of $R_{D^{(*)}}$ at $q^2 \sim m_\tau^2$, we introduce

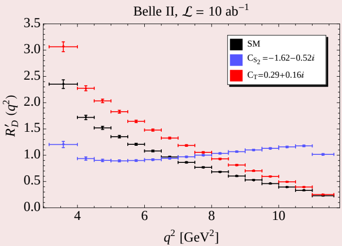
$$R'_D(q^2) \equiv R_D(q^2) \times \frac{\lambda_D(q^2)}{(m_B^2 - m_D^2)^2} \times \left(1 - \frac{m_\tau^2}{q^2}\right)^{-2}$$

$$R'_{D^*}(q^2) \equiv R_{D^*}(q^2) \times \left(1 - \frac{m_\tau^2}{q^2}\right)^{-2}$$

† Since the μ-mode is supposed to be SM-like, $\mathcal{B}_\mu^{-1} \propto (H_V^s)^{-2} \propto \lambda_D^{-1}(q^2)$.

$R'_D(q^2)$


theory
SM
$C_{S_2}=-1.62-0.52i$
$C_T=0.29+0.16i$
$R'_D(q^2)$
q^2 [GeV^2]


Belle II, $\mathcal{L}$ = 10 ab^{-1}
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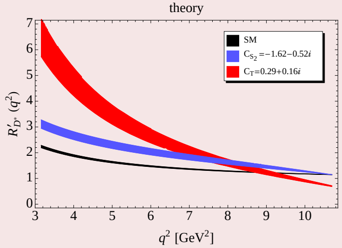
$R'_D(q^2)$
q^2 [GeV^2]

$R'_{D*}(q^2)$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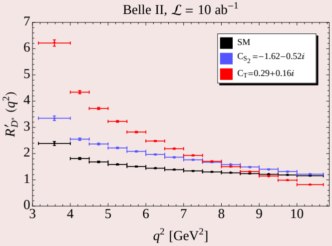
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q^2 [GeV^2]

How to distinguish between NP scenarios : $R'(q^2)$ fit (preliminary)

Both $\mathcal{O}^{\tau}_{S_2}$ and $\mathcal{O}^{\tau}_{T}$ can explain current result on $R(D)\&R(D^*)^{BABAR+\text{Belle}}$, e.g. :

1. $C^{\tau}_{S_2} = -1.62 + 0.52i$, $C^{\tau}_{i\neq S_2} = 0$
2. $C^{\tau}_{T} = 0.29 + 0.16i$, $C^{\tau}_{i\neq T} = 0$

- Lets make a "*fake*" experimental data, assuming the model #1, and test *theoretical* model #2. $\Rightarrow$ The χ^2 fit of binned $R'_D(q^2)$ and/or $R'_{D^*}(q^2)$ gives $\boldsymbol{\chi^2/N_{\text{bins}}}$,

	D	D^*	$D\&D^*$
$\int \mathcal{L}dt = 426\ \text{fb}^{-1}$	28	10	20
$\int \mathcal{L}dt = 10\ \text{ab}^{-1}$	655	225	456

- Lets make another "*fake*" experimental data, assuming the model #2, and test *theoretical* model #1. $\Rightarrow$ The χ^2 fit of binned $R'_D(q^2)$ and/or $R'_{D^*}(q^2)$ gives $\boldsymbol{\chi^2/N_{\text{bins}}}$,

	D	D^*	$D\&D^*$
$\int \mathcal{L}dt = 426\ \text{fb}^{-1}$	39	11	26
$\int \mathcal{L}dt = 10\ \text{ab}^{-1}$	903	249	600

$\Rightarrow$ Using the $R'_{D^{(*)}}(q^2)$ distributions, one can **clearly distinguish** between the scalar- and tensor-like models at Belle-II in a first couple of years of running !

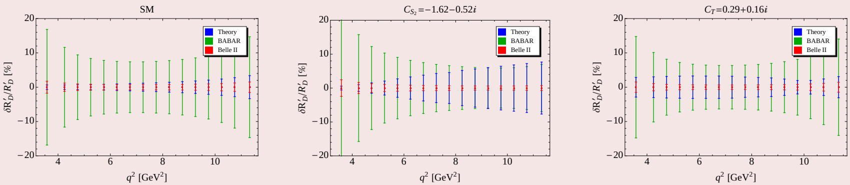
Conclusions

1. Not only FCNC processes can provide a window to NP search. Tree-level decays are as good and often even more interesting, especially when the hadronic uncertainties are well controlled.
2. Excess in $\overline{B} \to D\tau\overline{\nu}$ and $\overline{B} \to D^*\tau\overline{\nu}$, observed by *BABAR* and Belle, helped discarding 2HDM-II.
3. We showed the effects of $R(D^{(*)})$ on NP couplings using the generic set of operators.
4. Correlations among observables including the longitudinal τ polarizations and the D^* polarization are useful in distinguishing among possible NP scenarios. But it is not easy to determine them experimentally.
5. The q^2 dependence of $R'_{D^{(*)}}(q^2)$ is also very sensitive to the presence of NP and can provide precise constraints on NP at Belle II.

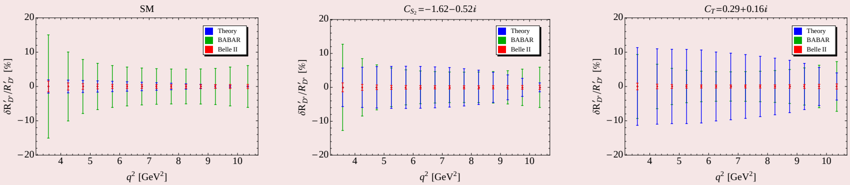
BACKUP SLIDES

Comparison of the theoretical and statistical errors at *BABAR* & Belle II for various models :

$\delta R'_D(q^2)/R'_D(q^2)$



$\delta R'_{D^*}(q^2)/R'_{D^*}(q^2)$



$\int \mathcal{L}dt|_{BABAR} = 426\ \text{fb}^{-1}$, $\int \mathcal{L}dt|_{\text{BelleII}} = 40\ \text{ab}^{-1}$

Naive estimation of the statistical errors at Belle II

- The number of reconstructed signal events in the $i^{\rm th}$ q^2 bin is

$$N_i^\ell = N_{B\overline{B}} \times \mathcal{B}_i^\ell \times \varepsilon_i^\ell\,, \quad (\ell = \tau\,, \mu\,, e)$$

where $N_{B\overline{B}} = \mathcal{L} \times \sigma(e^+e^- \to \Upsilon(4S) \to B\overline{B}) = 40\,{\rm ab}^{-2} \times 1.1\,{\rm nb} = 4.4 \times 10^{10}$;
ε_i^ℓ is the efficiency of {detector resolution, reconstruction, cuts, etc.}.

- In this way,

$$R_i \equiv \frac{\mathcal{B}_i^\tau}{\mathcal{B}_i^\mu} = \frac{N_i^\tau}{N_i^\mu}\frac{\varepsilon_i^\mu}{\varepsilon_i^\tau}$$

- Assuming that $N_{\rm tot}^\mu \gg N_{\rm tot}^\tau$ and $\delta N_i^\tau \approx \sqrt{N_i^\tau}$, one gets

$$\boxed{\delta R_i^{\rm stat} \approx \frac{\delta N_i^\tau}{N_i^\mu}\frac{\varepsilon_i^\mu}{\varepsilon_i^\tau} \approx \frac{\sqrt{N_i^\tau}}{N_i^\mu}\frac{\varepsilon_i^\mu}{\varepsilon_i^\tau} = \frac{1}{\sqrt{N_{B\overline{B}}\,\varepsilon_i^\tau}}\frac{\sqrt{\mathcal{B}_i^\tau}}{\mathcal{B}_i^\mu}}$$

- *Naively assuming the efficiency to be constant*, ε_i^τ can be estimated using the *BABAR* data [arXiv:1303.0571]:

$$\varepsilon_i^\tau \approx \varepsilon_{\rm tot}^\tau \approx \frac{N_{\rm tot}^{BABAR}(\overline{B} \to D^{(*)}\tau(\to \mu\nu\overline{\nu})\overline{\nu})}{N_{B\overline{B}}^{BABAR} \times \mathcal{B}^{BABAR}(\overline{B} \to D^{(*)}\tau\overline{\nu}) \times \mathcal{B}(\tau \to \mu\nu\overline{\nu})}$$

$$= \frac{489(888)}{471 \times 10^6 \times 1.02(1.76)\% \times 17.8\%} \simeq 6 \times 10^{-4}$$

Helicity amplitudes

$\overline{B} \to D\tau\overline{\nu}$ (3 FFs) :

$$H^s_{V,0}(q^2) \equiv H^s_{V_1,0}(q^2) = H^s_{V_2,0}(q^2) = \sqrt{\frac{\lambda_D(q^2)}{q^2}} F_1(q^2)$$

$$H^s_{V,t}(q^2) \equiv H^s_{V_1,t}(q^2) = H^s_{V_2,t}(q^2) = \frac{m_B^2 - m_D^2}{\sqrt{q^2}} F_0(q^2)$$

$$H^s_S(q^2) \equiv H^s_{S_1}(q^2) = H^s_{S_2}(q^2) = \frac{m_B^2 - m_D^2}{m_b - m_c} F_0(q^2)$$

$$H^s_T(q^2) \equiv H^s_{T,+-}(q^2) = H^s_{T,0t}(q^2) = -\frac{\sqrt{\lambda_D(q^2)}}{m_B + m_D} F_T(q^2)$$

with hadronic amplitudes defined as,

$$\begin{aligned} H^{\lambda_M}_{V_{1,2},\,\lambda}(q^2) =& \varepsilon^*_\mu(\lambda) \langle M(\lambda_M)|\bar{c}\gamma^\mu(1 \mp \gamma_5)b|\overline{B}\rangle\,, \\ H^{\lambda_M}_{S_{1,2},\,\lambda}(q^2) =& \langle M(\lambda_M)|\bar{c}(1 \pm \gamma_5)b|\overline{B}\rangle\,, \\ H^{\lambda_M}_{T,\,\lambda\lambda'}(q^2) =& \varepsilon^*_\mu(\lambda)\varepsilon^*_\nu(\lambda') \langle M(\lambda_M)|\bar{c}\sigma^{\mu\nu}(1 - \gamma_5)b|\overline{B}\rangle \end{aligned}$$

where λ_M and λ denote the meson and virtual intermediate boson helicities in the B rest frame respectively.

$\overline{B} \to D^*\tau\overline{\nu}$ (7 FFs) :

$$H_{V,\pm}(q^2) \equiv H^{\pm}_{V_1,\pm}(q^2) = -H^{\mp}_{V_2,\mp}(q^2) = (m_B + m_{D^*})A_1(q^2) \mp \frac{\sqrt{\lambda_{D^*}(q^2)}}{m_B + m_{D^*}}V(q^2)$$

$$H_{V,0}(q^2) \equiv H^{0}_{V_1,0}(q^2) = -H^{0}_{V_2,0}(q^2) = \frac{m_B + m_{D^*}}{2m_{D^*}\sqrt{q^2}}\left[-(m_B^2 - m_{D^*}^2 - q^2)A_1(q^2) + \frac{\lambda_{D^*}(q^2)}{(m_B + m_{D^*})^2}A_2(q^2)\right]$$

$$H_{V,t}(q^2) \equiv H^{0}_{V_1,t}(q^2) = -H^{0}_{V_2,t}(q^2) = -\sqrt{\frac{\lambda_{D^*}(q^2)}{q^2}}A_0(q^2)$$

$$H_S(q^2) \equiv H^{0}_{S_1}(q^2) = -H^{0}_{S_2}(q^2) = -\frac{\sqrt{\lambda_{D^*}(q^2)}}{m_b + m_c}A_0(q^2)$$

$$H_{T,\pm}(q^2) \equiv \pm H^{\pm}_{T,\pm t}(q^2) = \frac{1}{\sqrt{q^2}}\left[\pm(m_B^2 - m_{D^*}^2)T_2(q^2) + \sqrt{\lambda_{D^*}(q^2)}T_1(q^2)\right]$$

$$H_{T,0}(q^2) \equiv H^{0}_{T,+-}(q^2) = H^{0}_{T,0t}(q^2) = \frac{1}{2m_{D^*}}\left[-(m_B^2 + 3m_{D^*}^2 - q^2)T_2(q^2) + \frac{\lambda_{D^*}(q^2)}{m_B^2 - m_{D^*}^2}T_3(q^2)\right]$$