Signatures of Complex New Physics in $b \to c\,\tau\,\nu$ Transitions

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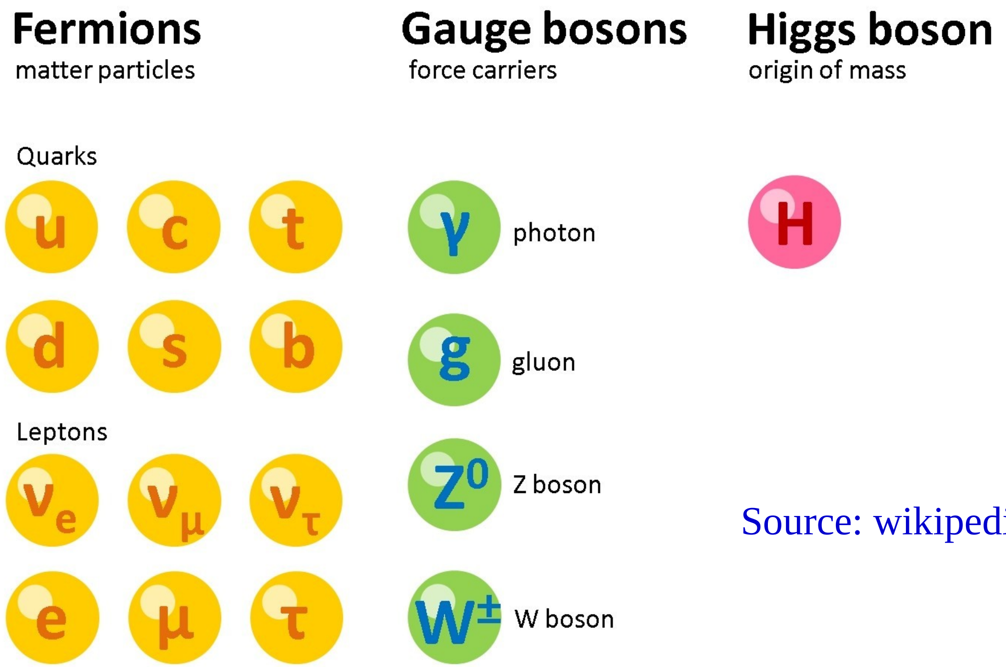
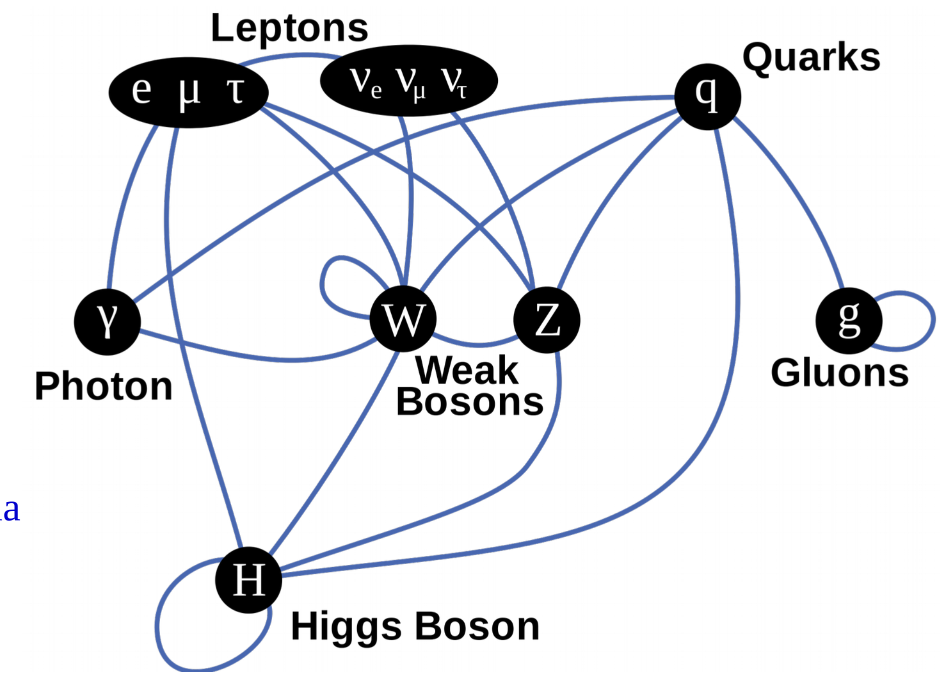
Outline

- Anomalies in $b \to c\ \tau\ \nu$
- Effective Hamiltonian
- Fitting Methodology and Results
- CP Violating Triple Product Asymmetries
- Summary

The Standard Model



Source: wikipedia



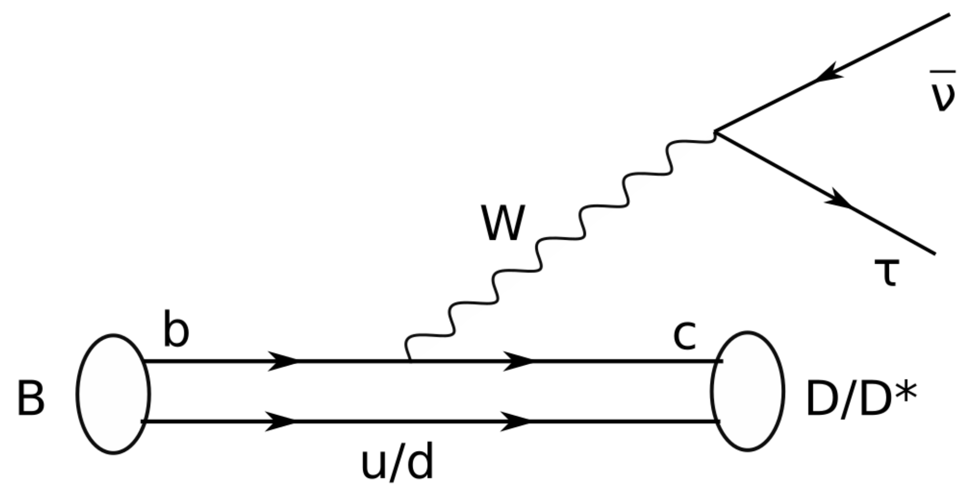
- The SM becomes highly successful after the Higgs discovery in 2012.
- All interactions are gauge interactions.
- The gauge interactions are identical for three generations/ flavours.

Lepton Flavour Universality

Falvour ratios in $b \to c\, l\, \nu$ decays

$$R_D = \frac{\mathcal{B}(B \to D\,\tau\,\bar{\nu})}{\mathcal{B}(B \to D\,\{e/\mu\}\,\bar{\nu})}, \quad R_{D^*} = \frac{\mathcal{B}(B \to D^*\,\tau\,\bar{\nu})}{\mathcal{B}(B \to D^*\,\{e/\mu\}\,\bar{\nu})}$$

- Good candidates to test LFU.
- Minimal theoretical uncertainty due to almost cancellation of hadronic form-factors.
- The SM uncertainty is ~1%



Global Picture

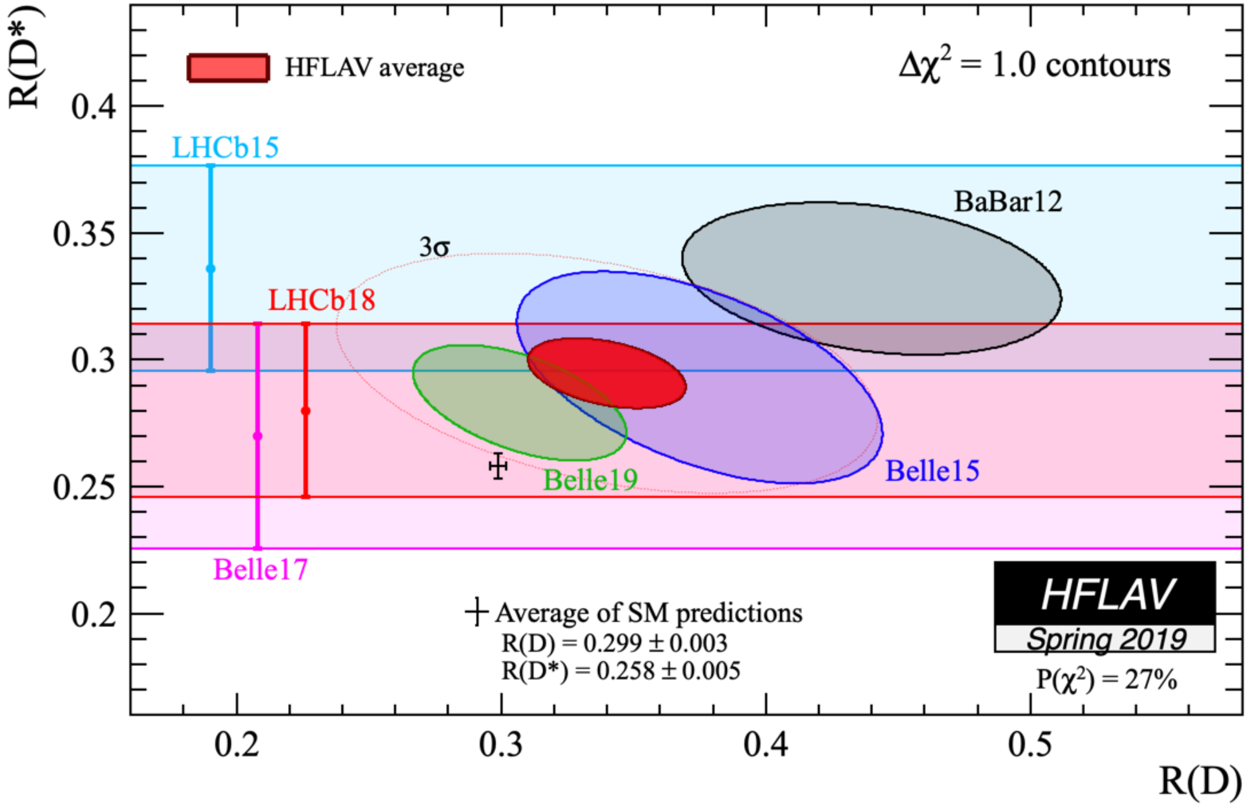
- Belle reported new measurements on these ratios at Moriond'19 which are consistent with the SM.

[Abdesselam et al. [Belle Cn], arXiv:1904.08794]

- Tension reduced from $\sim 4\sigma$ to $\sim 3\sigma$ which is still significant.

Present world averages

$$\boxed{\begin{aligned} \mathrm{R}_D &= 0.340 \pm 0.027 \pm 0.013 \\ \mathrm{R}_{D^*} &= 0.295 \pm 0.011 \pm 0.008 \end{aligned}}$$



Violation of Lepton Flavour Universality

What do anomalies tell us?

- All decays are mediated by $b \to c\, l\, \bar{\nu}$ transitions which occur at tree level in the SM.
- Measurements of flavour ratios $R_D - R_{D^*}$ indicate the mechanism of $b \to c\, \tau\, \bar{\nu}$ is not identical to that of $b \to c\, \{e/\mu\}\, \bar{\nu}$.
- New Physics in $b \to c\, \{e/\mu\}\, \bar{\nu}$ transition is highly disfavoured by other measurements $R_D^{\mu/e}$ and $R_{D^*}^{e/\mu}$.

[Alok, Kumar, Kumar, Kumbhakar, UmaSankar; JHEP 1809 (2018) 152]

- Assume New Physics in $b \to c\, \tau\, \bar{\nu}$ transition!

$R_{J/\psi}$ and $P_\tau^{D^*}$

- LHCb measured a ratio [LHCb PRL 120 (2018) no.12, 121801]

$$R_{J/\psi} = \frac{\mathcal{B}(B_c^- \to J/\psi\, \tau^- \bar{\nu})}{\mathcal{B}(B_c^- \to J/\psi\, \mu^- \bar{\nu})} = 0.71 \pm 0.17\,(\mathrm{stat.}) \pm 0.18\,(\mathrm{syst.})$$

1.7σ larger than the SM prediction 0.289 ± 0.010

[Dutta, Bhol; PRD 96 (2017) no.7, 076001]

- A measurement of tau polarization in the decay $B \to D^* \tau \bar{\nu}$ by Belle Cn. [Belle PRL 118, no. 21, 211801 (2017)]

$$P_\tau^{D^*} = \frac{\Gamma_{\lambda_\tau = 1/2} - \Gamma_{\lambda_\tau = -1/2}}{\Gamma_{\lambda_\tau = 1/2} + \Gamma_{\lambda_\tau = -1/2}} = -0.38 \pm 0.51\,(\mathrm{stat.})^{+0.21}_{-0.16}\,(\mathrm{syst.})$$

Large stat. error; consistent with the SM prediction -0.497 ± 0.013 [Sakaki, Tanaka, Watanabe; PRD 88 (2013) no.9, 094012]

D* longitudinal polarization

Belle cn measured longitudinal polarization fraction of D* meson [Adamczyk (Belle cn); arXiv:1901.06380]

$$f_L^{D^*} = \frac{\Gamma_{\lambda_{D^*}=0}}{\Gamma_{\lambda_{D^*}=0} + \Gamma_{\lambda_{D^*}=-1} + \Gamma_{\lambda_{D^*}=+1}}$$
$$= 0.60 \pm 0.08\,(\mathrm{stat.}) \pm 0.04\,(\mathrm{syst.})$$

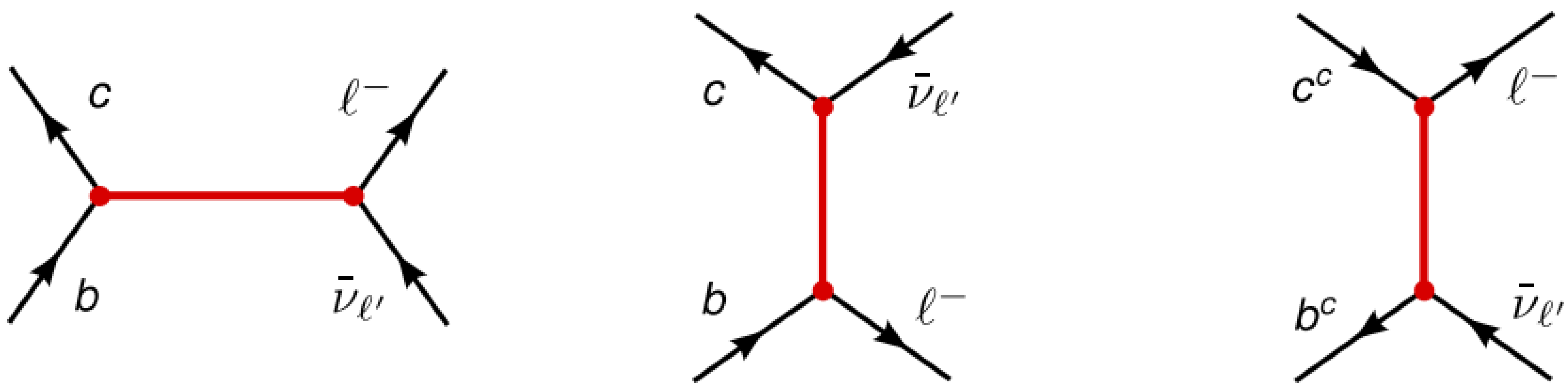
which is about 1.6σ higher than the SM prediction 0.46 ± 0.04 . [Alok, Kumar, Kumbhakar, UmaSankar; PRD 95 (2017) no.11, 115038]

Effective Hamiltonian

The most general effective Hamiltonian for $b \to c\tau\bar{\nu}$ transition at $\Lambda = 1$ TeV scale

$$\mathcal{H}_{\rm eff} = \frac{4G_F}{\sqrt{2}} V_{cb} \left[\underbrace{\mathcal{O}_{V_L}}_{\textbf{SM}} + \underbrace{\frac{\sqrt{2}}{4G_F V_{cb} \Lambda^2} \sum_i C_i^{(',\prime\prime)} \mathcal{O}_i^{(',\prime\prime)}}_{\textbf{New Physics}} \right]$$

Three ways to connect four fermions keeping gauge invariance



$\mathcal{O}_i$ $\quad$ $\mathcal{O}_i'$ $\quad$ $\mathcal{O}_i''$

Lorentz structures of NP Operators

[Freytsis, Ligeti, Ruderman; PRD92 (2015) no.5, 054018]

	Operator	Fierz tranformation
$\mathcal{O}_{V_L}$	$(\bar{c}\gamma_\mu P_L b)\,(\bar{\tau}\gamma^\mu P_L \nu)$	
$\mathcal{O}_{V_R}$	$(\bar{c}\gamma_\mu P_R b)\,(\bar{\tau}\gamma^\mu P_L \nu)$	
$\mathcal{O}_{S_R}$	$(\bar{c} P_R b)\,(\bar{\tau} P_L \nu)$	
$\mathcal{O}_{S_L}$	$(\bar{c} P_L b)\,(\bar{\tau} P_L \nu)$	
$\mathcal{O}_{T}$	$(\bar{c}\sigma^{\mu\nu} P_L b)\,(\bar{\tau}\sigma_{\mu\nu} P_L \nu)$	
$\mathcal{O}'_{V_L}$	$(\bar{\tau}\gamma_\mu P_L b)\,(\bar{c}\gamma^\mu P_L \nu)$	$\mathcal{O}_{V_L}$
$\mathcal{O}'_{V_R}$	$(\bar{\tau}\gamma_\mu P_R b)\,(\bar{c}\gamma^\mu P_L \nu)$	$-2\mathcal{O}_{S_R}$
$\mathcal{O}'_{S_R}$	$(\bar{\tau} P_R b)\,(\bar{c} P_L \nu)$	$-\frac{1}{2}\mathcal{O}_{V_R}$
$\mathcal{O}'_{S_L}$	$(\bar{\tau} P_L b)\,(\bar{c} P_L \nu)$	$-\frac{1}{2}\mathcal{O}_{S_L} - \frac{1}{8}\mathcal{O}_T$
$\mathcal{O}'_{T}$	$(\bar{\tau}\sigma^{\mu\nu} P_L b)\,(\bar{c}\sigma_{\mu\nu} P_L \nu)$	$-6\mathcal{O}_{S_L} + \frac{1}{2}\mathcal{O}_T$
$\mathcal{O}''_{V_L}$	$(\bar{\tau}\gamma_\mu P_L c^c)\,(\bar{b}^c\gamma^\mu P_L \nu)$	$-\mathcal{O}_{V_R}$
$\mathcal{O}''_{V_R}$	$(\bar{\tau}\gamma_\mu P_R c^c)\,(\bar{b}^c\gamma^\mu P_L \nu)$	$-2\mathcal{O}_{S_R}$
$\mathcal{O}''_{S_R}$	$(\bar{\tau} P_R c^c)\,(\bar{b}^c P_L \nu)$	$\frac{1}{2}\mathcal{O}_{V_L}$
$\mathcal{O}''_{S_L}$	$(\bar{\tau} P_L c^c)\,(\bar{b}^c P_L \nu)$	$-\frac{1}{2}\mathcal{O}_{S_L} + \frac{1}{8}\mathcal{O}_T$
$\mathcal{O}''_{T}$	$(\bar{\tau}\sigma^{\mu\nu} P_L c^c)\,(\bar{b}^c\sigma_{\mu\nu} P_L \nu)$	$-6\mathcal{O}_{S_L} - \frac{1}{2}\mathcal{O}_T$

Assuming that Neutrinos are left chiral

Fitting Method

- Take all data (available up to summer 2019) in $b \to c\tau\bar{\nu}$ sector and define χ^2 as a function of NP Wcs (assumed to be complex)

$$\chi^2(C_i) = \sum_{R_D, R_{D^*}, R_{J/\psi}, P_\tau^{D^*}, f_L^{D^*}} \left(O^{\rm th}(C_i) - O^{\rm exp}\right)^T \mathcal{C}^{-1} \left(O^{\rm th}(C_i) - O^{\rm exp}\right).$$

  where $\mathcal{C}$ is the covariance matrix which includes theory and expt. Correlations.

- Use MINUIT library to minimize the χ^2 function and get the values of NP WCs. We perform the fit by taking only One operator at a time.

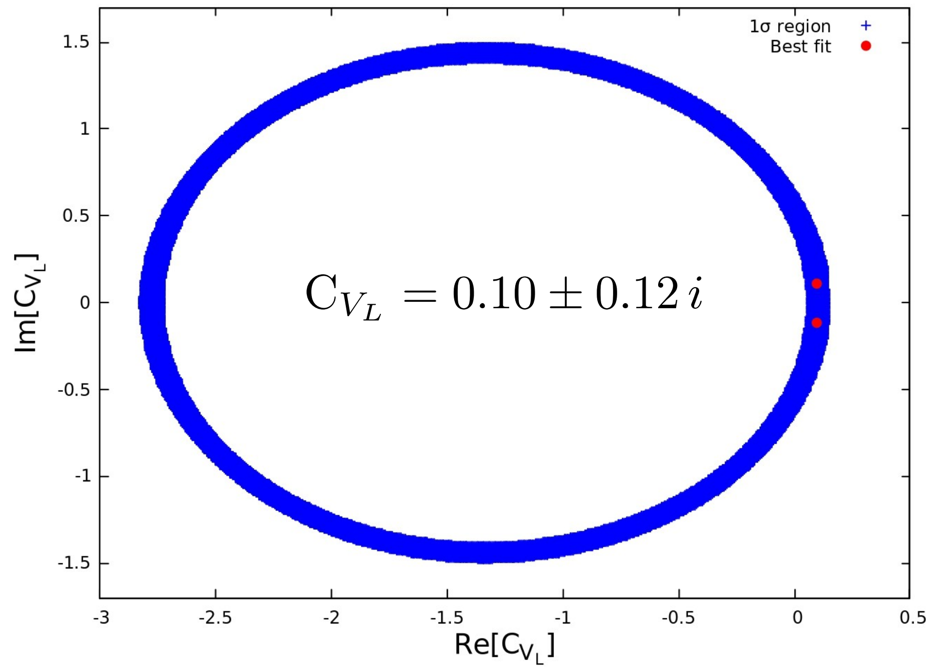
NP Solutions

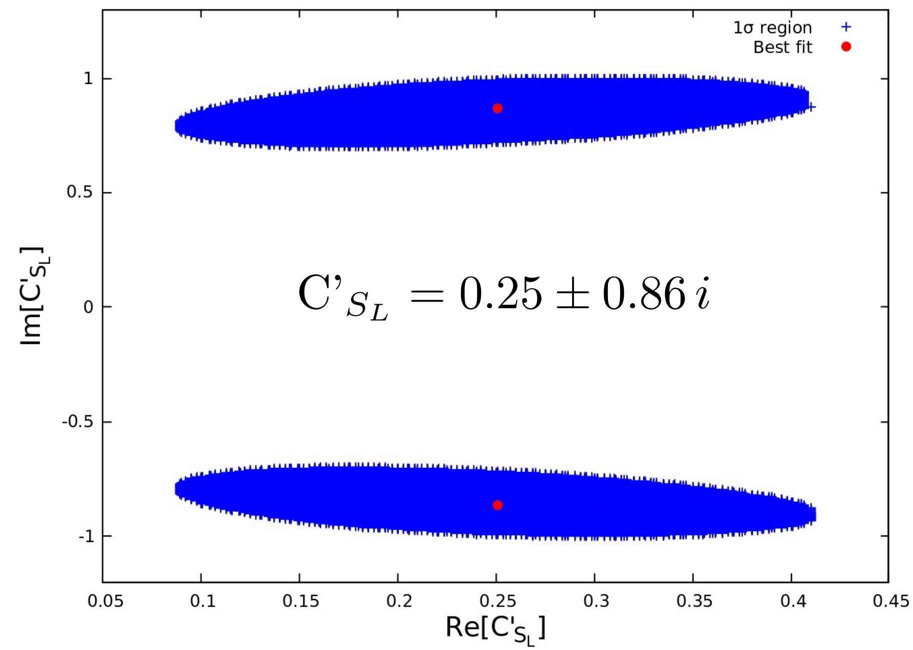
We choose the NP WCs as best fit solutions which fall in $\chi^2_{\rm min} \leq 4.5$.

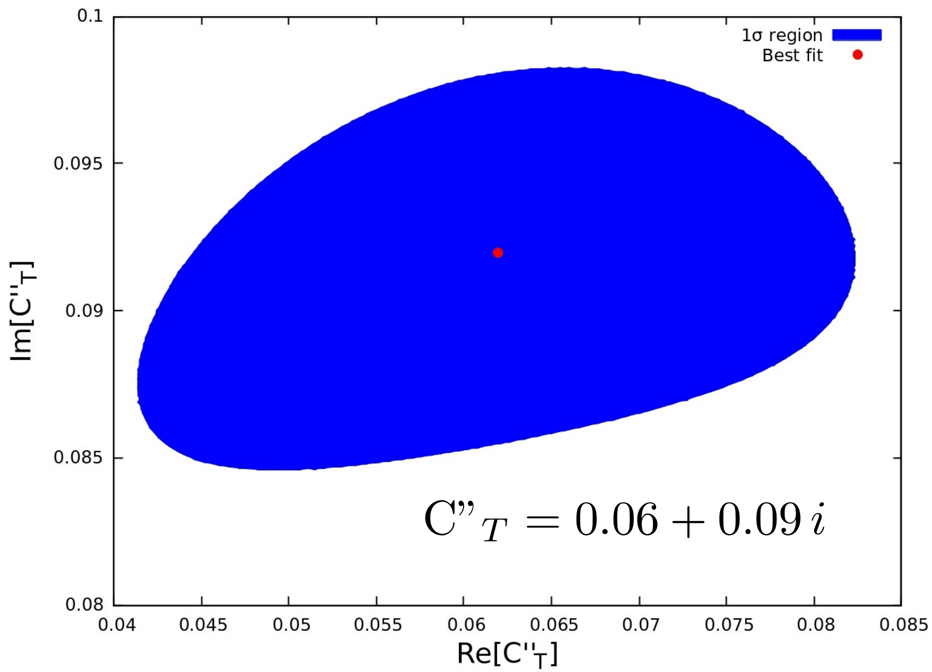
NP type	Best fit value(s)	$\chi^2_{\rm min}$	pull
C_{V_L}	$0.10 \pm 0.12\, i$	4.55	4.1
C'_{S_L}	$0.25 \pm 0.86\, i$	4.50	4.2
C''_T	$0.06 + 0.09\, i$	3.45	4.3
C_{S_L}	$-0.82 \pm 0.45\, i$	2.50	4.4

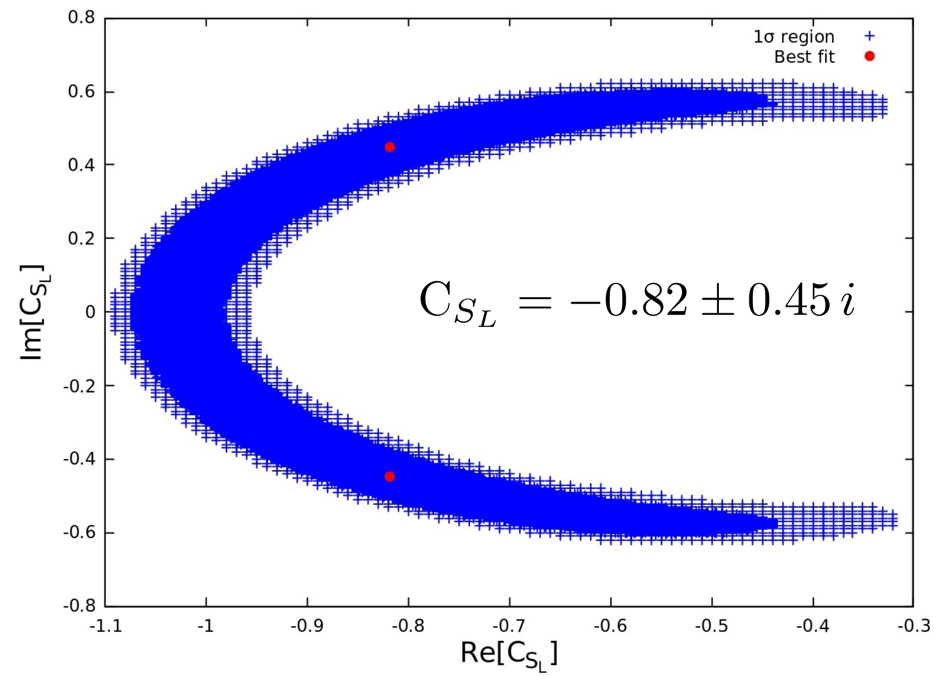
Recent analysis on glabal fits:: Bhattacharya, Nandi, Patra, arXiv: 1805.08222; Hu, Li, Yang, arXiv: 1810.04939; Alok, Kumar Kumbhakar, UmaSankar, arXiv: 1903.10486; Murgui, Peñuelas, Jung, Pich, arXiv:1904.09311; Bardhan, Ghosh, arXiv:1904.10432; Blanke, Crivellin, Kitahara, Moscati, Nierste, Nišandžić, arXiv:1905.08253; Shi, Geng, Grinstein, Jäger, Camalich, arXiv:1905.08498

NP Parameter Space









Role of Purely leptonic B_c decay

- Strong constraint from purely leptonic decay $B_c \to \tau\bar{\nu}$ especially on the scalar/pseudoscalar NP.

$$\mathcal{B}(B_c \to \tau\bar{\nu}) = \frac{|V_{cb}|^2 G_F^2 f_{B_c}^2 m_{B_c} m_\tau^2 \tau_{B_c}^{exp}}{8\pi}\left(1 - \frac{m_\tau^2}{m_{B_c}^2}\right)^2 \times \left|1 + C_{V_L} - C_{V_R} + \frac{m_{B_c}^2}{m_\tau(m_b + m_c)}(C_{S_R} - C_{S_L})\right|^2$$

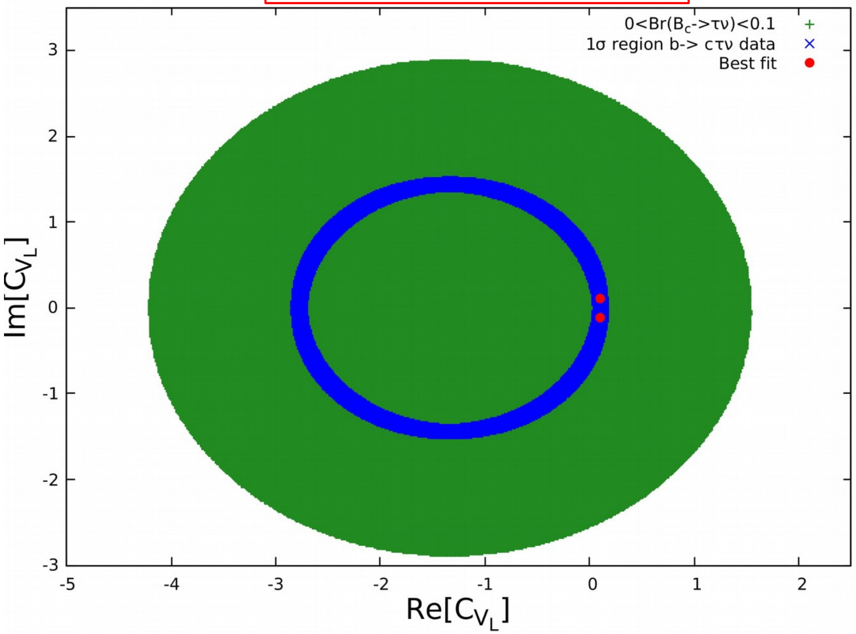
- The SM prediction is ~ 2%. An upper limit on this quantity is set to be 10% from LEP data which are admixture of $B_c \to \tau\bar{\nu}$ and $B_u \to \tau\bar{\nu}$ decays at Z peak.
[Akeroyd and Chen, PRD 96, no. 7, 075011 (2017)]

- An upper limit of ~30% is obtained from the life time of B_c meson by considering that the $B_c \to \tau\bar{\nu}$ decay rate does not exceed the fraction of the total decay width. [Alonso, Grinstein and Camalich, PRL 118, no. 8, 081802 (2017)]

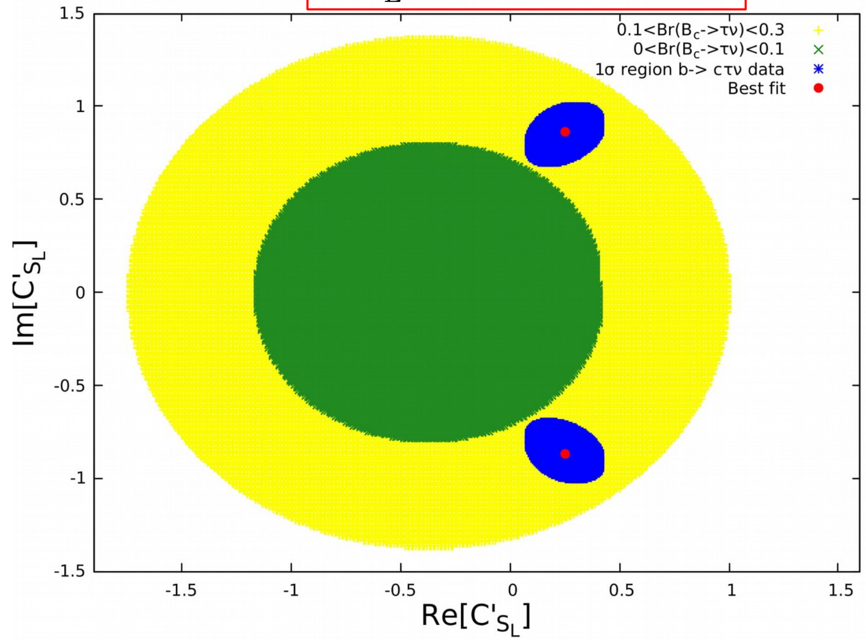
- However, taking all uncertainties into account the decay width of B_c meson can be relaxed up to ~60% which is not that much conservative.
[Blanke, Crivellin et al, PRD 99, no. 7, 075006 (2019)]

A Complete Picture of NP Solutions

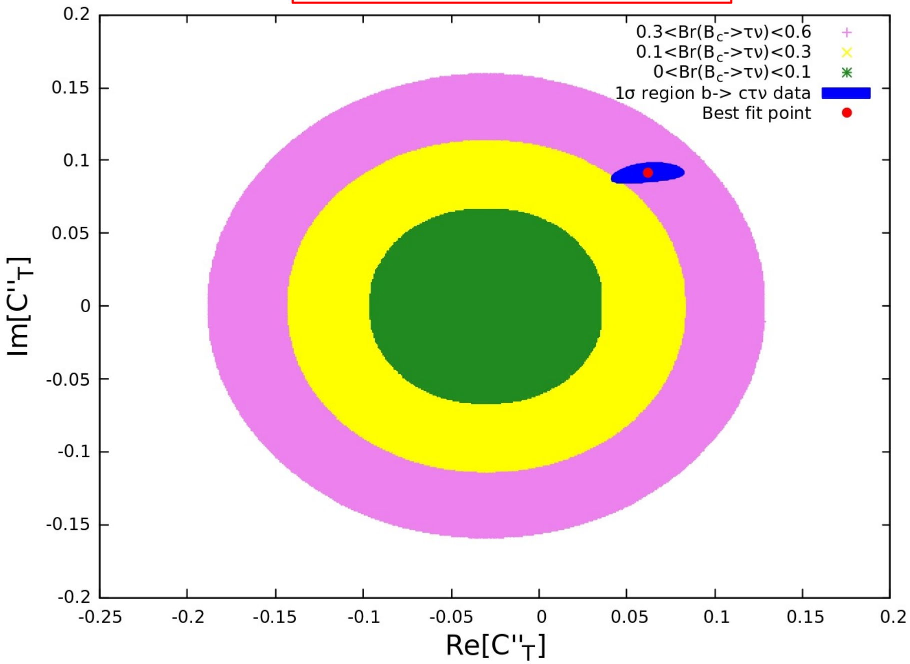
$\mathrm{C}_{V_L} = 0.10 \pm 0.12\, i$



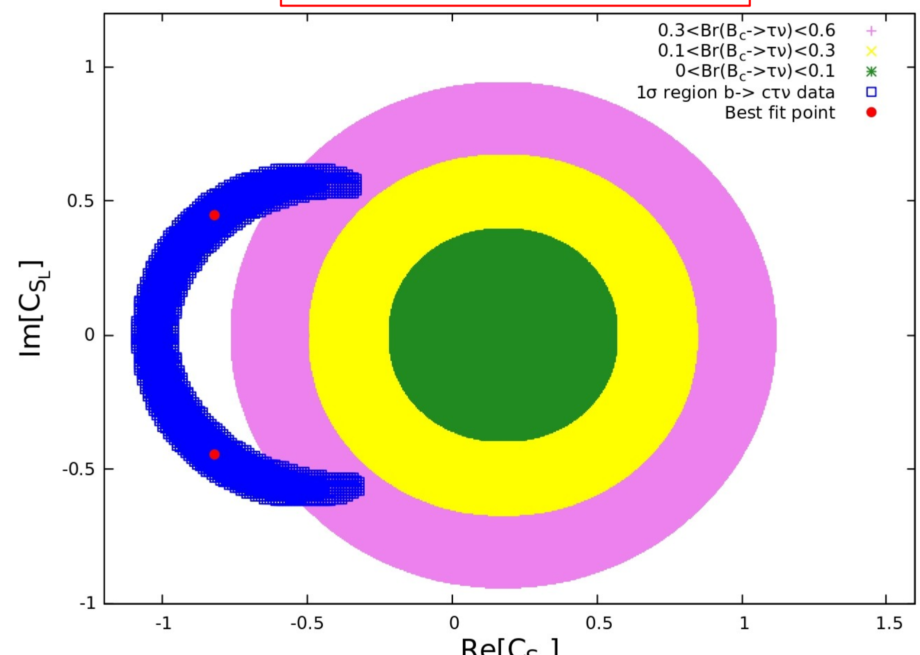
$\mathrm{C'}_{S_L} = 0.25 \pm 0.86\, i$



$\mathrm{C''}_{T} = 0.06 + 0.09\, i$

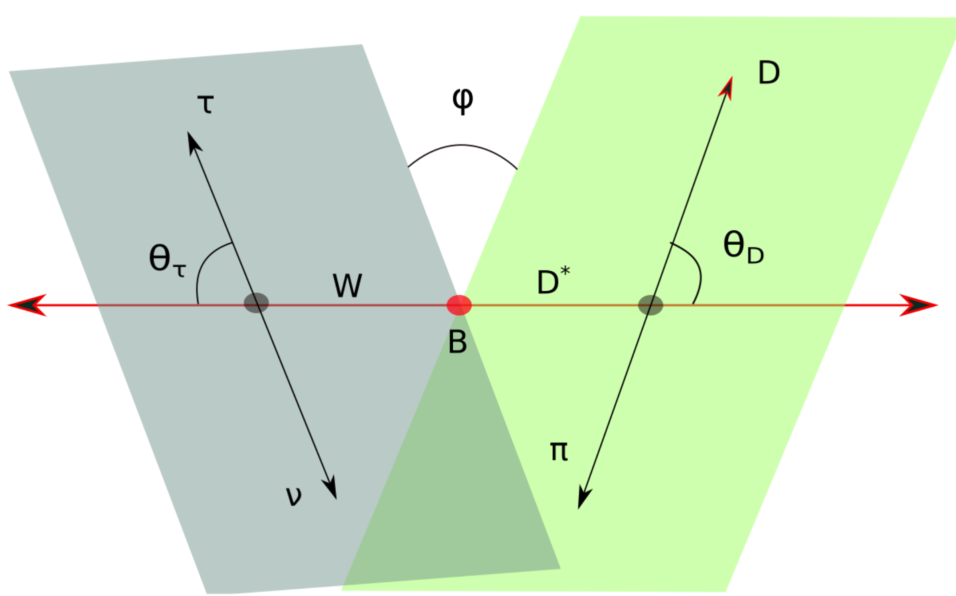


$\mathrm{C}_{S_L} = -0.82 \pm 0.45\, i$



Kinematics of B→ D*τν

- $q^2 = (p_B - p_{D^*})^2$, p_B and p_{D^*} are the four momentum of B and D* meson.
- θ_D is the angle between $\vec{p}_D$ in Dπ rest frame and the $\vec{p}_{D^*}$ in B rest frame.
- θ_τ is the angle between $\vec{p}_\tau$ in $\tau\bar{\nu}$ rest frame and the di-lepton momentum in B rest frame.
- Φ is the angle between two decay planes spanned by three momentum of Dπ and $\tau\bar{\nu}$ systems in B rest frame.



CPV Triple Products in B→ D*τν

Three triple products can be defined in $B \to D^* \tau \bar{\nu}$ decay. These are [Duraisamy, Datta, JHEP 1309, 059 (2013)]

$$
\begin{aligned}
\frac{d^2\Gamma^{(1)}}{dq^2 d\phi} &= \int_{-1}^{1}\int_{-1}^{1} \frac{d^4\Gamma}{dq^2 d\cos\theta_\tau d\cos\theta_D d\phi} d\cos\theta_\tau d\cos\theta_D \\
&= \frac{1}{2\pi}\frac{d\Gamma}{dq^2}\left[1 + \left(A_C^{(1)} \cos 2\phi + A_T^{(1)} \sin 2\phi\right)\right]
\end{aligned}
$$

$$
\begin{aligned}
\frac{d^2\Gamma^{(2)}}{dq^2 d\phi} &= \int_{-1}^{1} d\cos\theta_\tau \left[\int_0^1 - \int_{-1}^{0}\right] \frac{d^4\Gamma}{dq^2 d\cos\theta_\tau d\cos\theta_D d\phi} d\cos\theta_D \\
&= \frac{1}{4}\frac{d\Gamma}{dq^2}\left[A_C^{(2)} \cos\phi + A_T^{(2)} \sin\phi\right]
\end{aligned}
$$

$$
\begin{aligned}
\frac{d^2\Gamma^{(3)}}{dq^2 d\phi} &= \left[\int_0^1 - \int_{-1}^{0}\right] d\cos\theta_\tau \left[\int_0^1 - \int_{-1}^{0}\right] \frac{d^4\Gamma}{dq^2 d\cos\theta_\tau d\cos\theta_D d\phi} d\cos\theta_D \\
&= \frac{2}{3\pi}\frac{d\Gamma}{dq^2}\left[A_C^{(3)} \cos\phi + A_T^{(3)} \sin\phi\right]
\end{aligned}
$$

For the CP conjugate decay mode these triple products can be denoted as $\bar{A}_T^{(i)}$ where the weak phase changes sign.

CPV TP Asymmetries

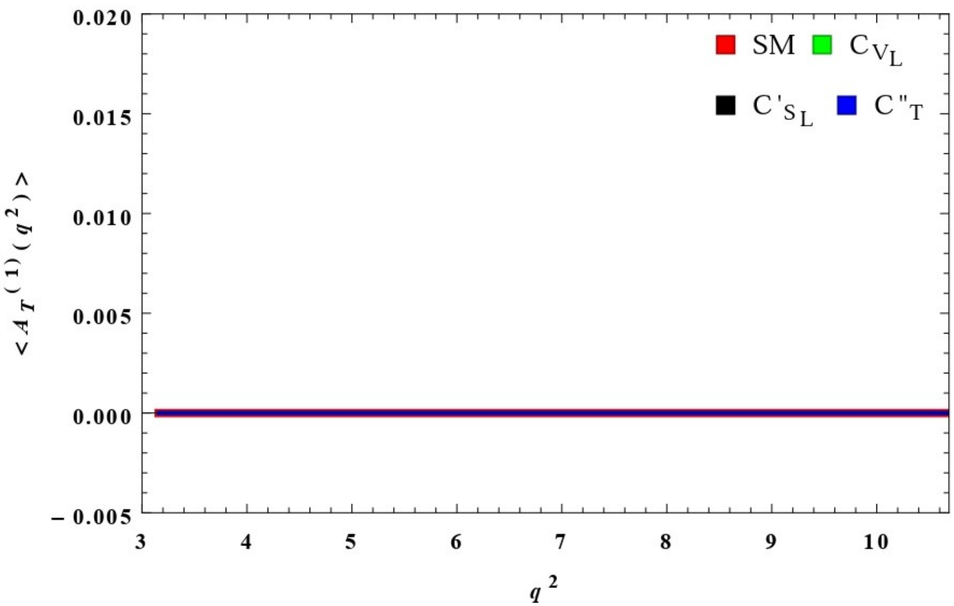
The TP asymmetries are defined between the decay and its CP conjugate mode.

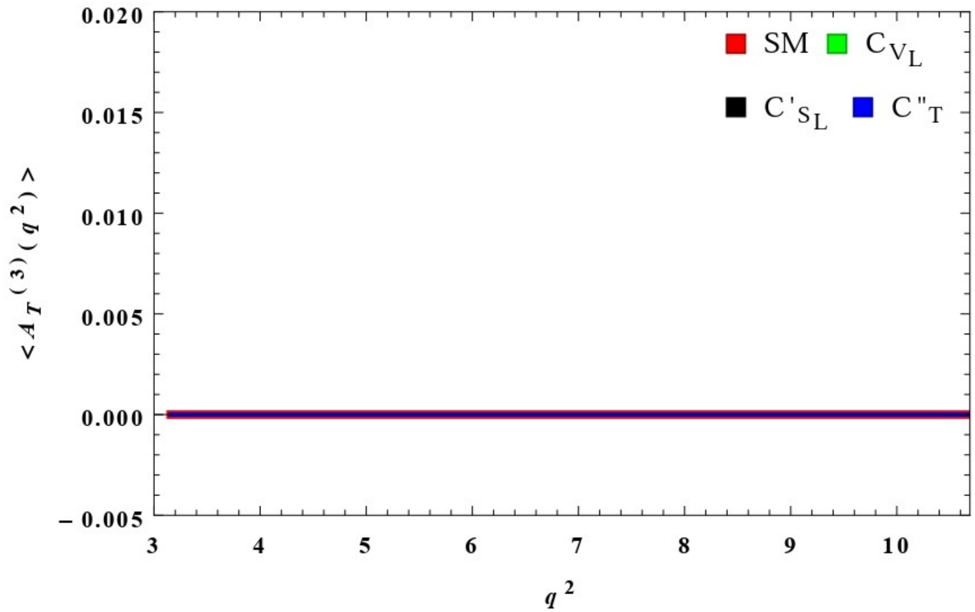
$$
\begin{aligned}
\langle A_T^{(1)}(q^2)\rangle &= \frac{1}{2}\left(A_T^{(1)}(q^2) + \bar{A}_T^{(1)}(q^2)\right) \\
\langle A_T^{(2)}(q^2)\rangle &= \frac{1}{2}\left(A_T^{(2)}(q^2) - \bar{A}_T^{(2)}(q^2)\right) \\
\langle A_T^{(3)}(q^2)\rangle &= \frac{1}{2}\left(A_T^{(3)}(q^2) + \bar{A}_T^{(3)}(q^2)\right) .
\end{aligned}
$$

The SM predictions of these TPAs are almost zero.

Papers on CPV TPAs: Alok, Datta, Dighe et al. JHEP 11 (2011), 122; Bhattacharya, Datta, Kamali, London, JHEP 05 (2019), 191

TPAs for best fit solutions

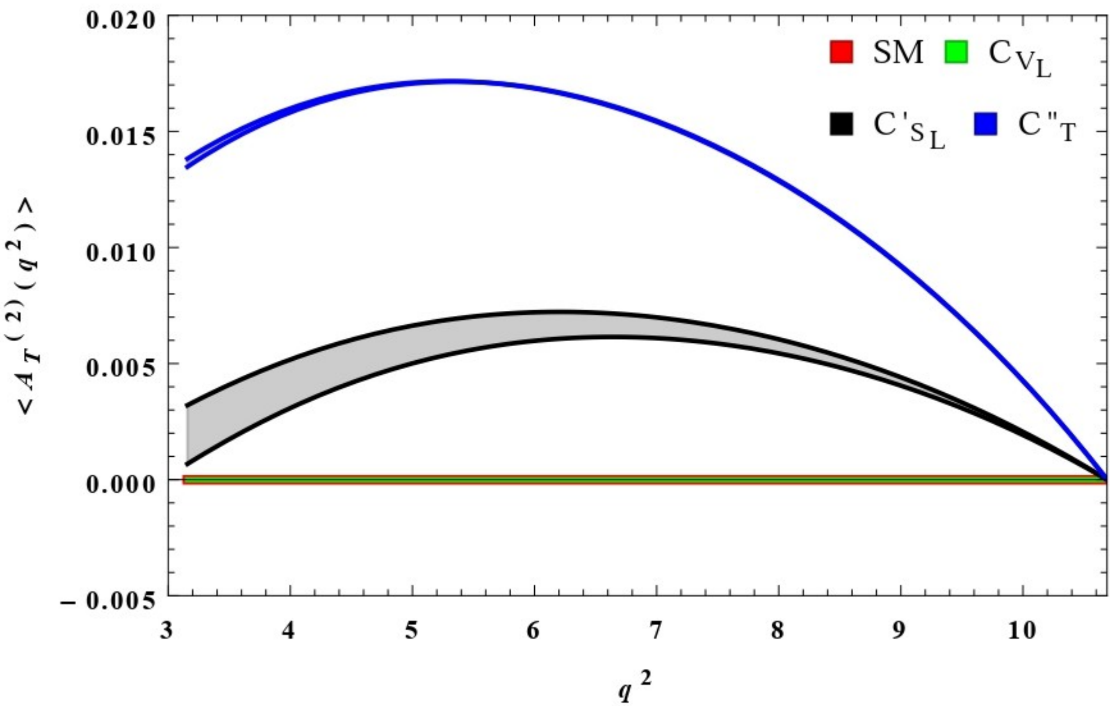




The first and third TPAs depend only on (V-A)*(V-A) interaction which has the same Lorentz structure as the SM. We find that

- The $\mathcal{O}_{V_L}$ solution predicts these two TPAs to be zero for whole q^2 range.
- For the other two NP solutions, these predictions are zero because they do not depend on scalar or tensor interactions.

TPAs for best fit solutions

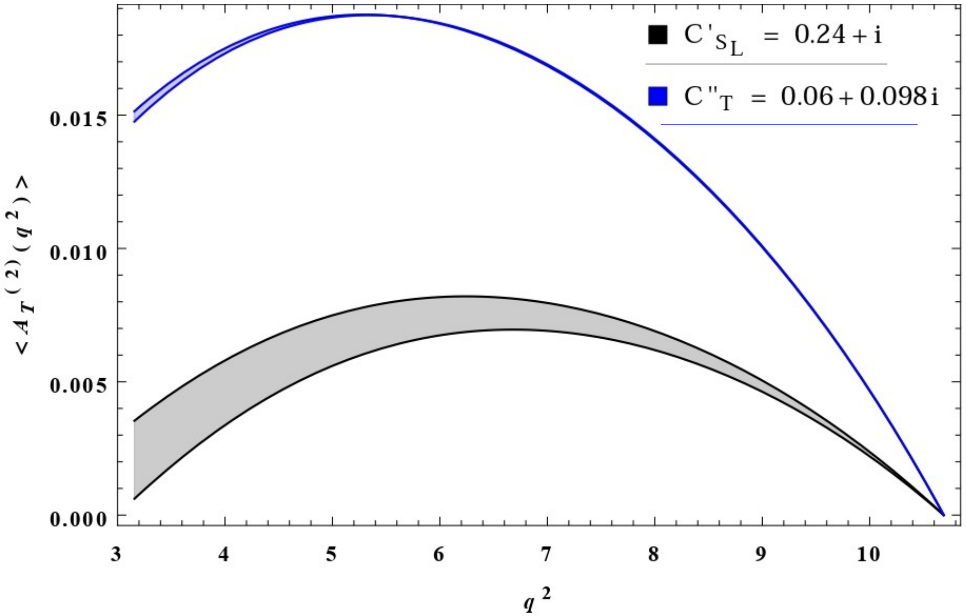


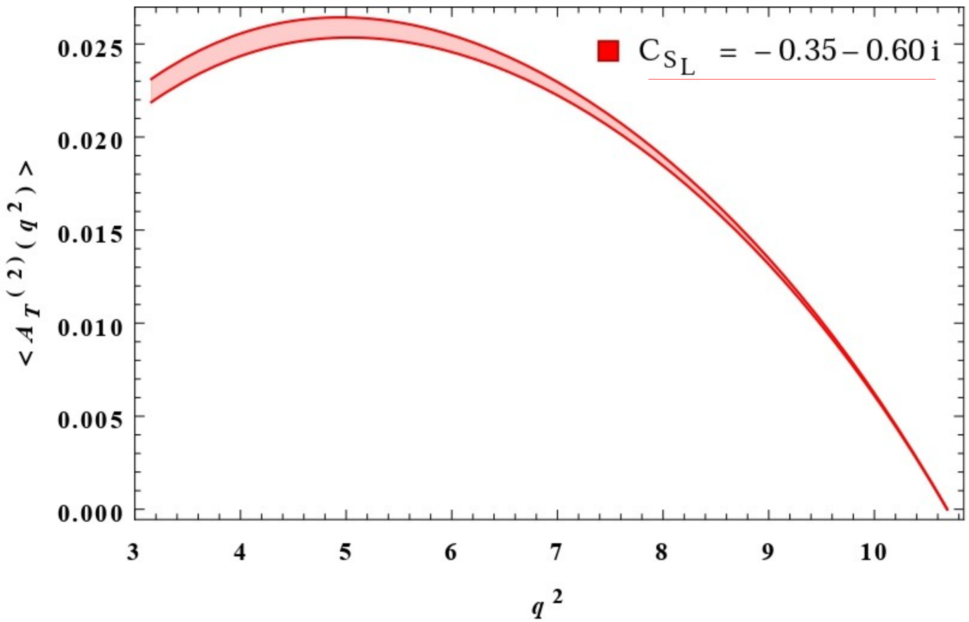
The second TPA depends on $\mathcal{O}_{V_L}$, $\mathcal{O}_{S_L}$ and $\mathcal{O}_T$ operators. It is obvious that the prediction of this TPA is zero for the $\mathcal{O}_{V_L}$ solution, consistent with the SM.

The $\mathcal{O}'_{S_L}$ and $\mathcal{O}''_T$ operators are linear combiations of $\mathcal{O}_{S_L}$ and $\mathcal{O}_T$ operators. Therefore we find that

- For $\mathcal{O}'_{S_L}$ solution, the second TPA reaches a maximum value of ~0.7% at q^2 = 6 GeV^2.
- For $\mathcal{O}''_T$ solution, this TPA reaches a maximum value of ~1.7% at q^2 = 5.4 GeV^2.

Maximum TPAs





Choose a benchmark point from allowed 1σ region of each NP solution which could give rise to maximum value of CPV TPAs. We find that

- The maximum values of second TPA are almost same as the predictions given by the best fit values for C'_{S_L} and C''_T .
- For marginally disfavored solution $\mathcal{O}_{S_L}$, the second TPA reaches a maximum value of ~ 2.7% at q^2 = 5 GeV^2 and decreases to zero at the maximum value of q^2 .

Maximum value of CPV TPA ~3% is only due to the scalar NP solution.

Predictions of angular observables

Three quantities are yet to be measured.

- The tau polarization P_τ^D and forward-backward asymmetry A_{FB}^D in $B \to D\tau\bar{\nu}$
- The forward-backward asymmetry $A_{FB}^{D^*}$ in $B \to D^*\tau\bar{\nu}$ decay.

NP type	Best fit value(s)	P_τ^D	A_{FB}^D	$A_{FB}^{D^*}$
SM	$C_i = 0$	$0.325\,(1)$	$0.360\,(2)$	$-0.063\,(5)$
$C_{V_L}\|_{10\%}$	$0.10 \pm 0.12\,i$	0.325	0.360	-0.063
$C'_{S_L}\|_{30\%}$	$0.25 \pm 0.86\,i$	0.420	0.212	0.0001
$C''_T\|_{60\%}$	$0.06 + 0.09\,i$	0.414	0.100	0.009

Our observations:

- The predictions of all three observables for the $\mathcal{O}_{V_L}$ solution are same as the SM.
- The P_τ^D has very poor discriminating capability.
- The predictions of the forward-backward asymmetries for the O'_{S_L} and $\mathcal{O}''_T$ solutions are markedly different. These two solutions can be distinguished by forward-backward asymmetries.

Summary

- The discrepancy in $R_D - R_{D^*}$ has reduced from 4.1σ to 3.1σ
- Assuming NP WCs to be complex, we find that $\mathcal{O}_{V_L}$ is the only NP solution allowed by the constraint $Br(B_c \to \tau\bar{\nu}) < 10\%$
- If you relax the constraint to 30% or 60%, then we get one or two additional allowed NP solutions.
- The forward-backward asymmetries in $B \to (D, D^*)\tau\bar{\nu}$ decays are useful tools to distinguish the two solutions other than the $\mathcal{O}_{V_L}$ solution.
- The mildly disfavored scalar NP solution predicts the maximum value of ~2.7% for the second TPA among all other solutions.
- Measuring the A_{FB} and TPAs needs the reconstruction of the tau lepton momentum which would be quite difficult. However HL-LHC may have potential to do this. [A. Cerri et al, arXiv:1812.07638; D. Marangotto, arXiv:1812.08144]

Thank You !