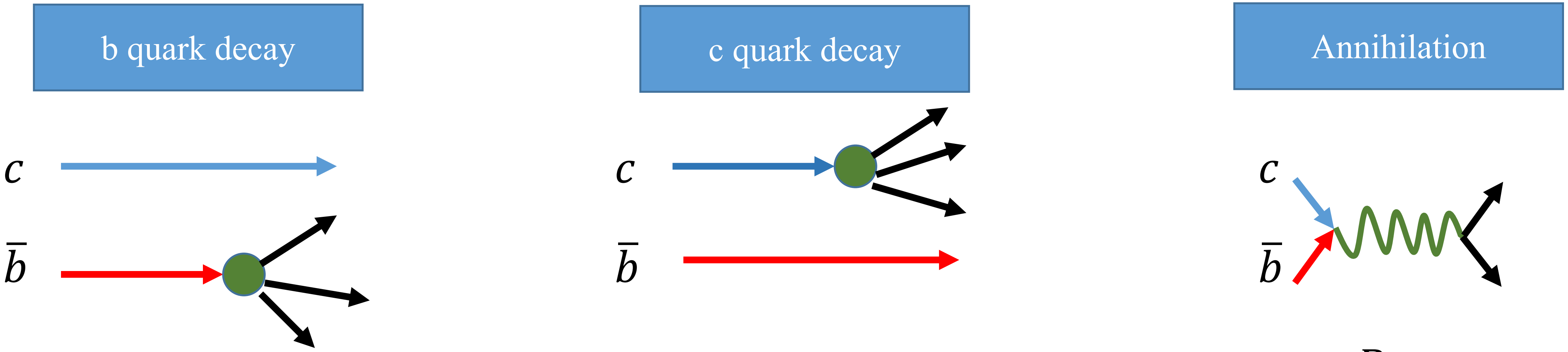
Analysis of $B_c^+ \to \tau^+\nu_\tau$ at CEPC

Introduction

The B_c meson is the heaviest weakly decaying meson. It is made two heavy quarks: $b\bar{c}$ or $c\bar{b}$. Compared to other B mesons, it has heavier mass and low production cross section, and only a handful of its properties have been measured. In terms of decay, it has three decay categories:



e.g. $B_c \rightarrow \tau\nu$

$B_c \rightarrow \tau\nu$ decay within SM

*The channel has not been discovered yet

$B_c \rightarrow \tau\nu$ decay width in SM:

$$\Gamma_{SM}(B_c^+ \to l^+ \nu_l) = \frac{G_F^2}{8\pi} |V_{cb}|^2 f_{B_c}^2 m_{B_c} m_l^2 \left(1 - \frac{m_l^2}{m_{B_c}^2}\right)^2$$

Interest within SM:

- The channel is sensitive to both decay constant f_{B_c} and the CKM matrix element $|V_{cb}|$
- The quark dynamics of B_c is very hard to calculate
- Improve $|V_{cb}|$ measurement. So far it is measured using inclusive simileptonic $b \rightarrow c$ transitions or exclusive channel of $\bar{B} \rightarrow D^* l \bar{\nu}_l$

Interest beyond SM

In recent years, a few discrepancies with SM has been found in the bottom sector, especially the tauonic decay modes of B meson (mostly $B \to D^{(*)}\tau\nu$) (arXiv:1205.5442; 1904.08794; 1708.08856) gave hints for lepton flavor universality violation.

While these decay modes are sensitive to the vector/axial-vector type interactions, the (pseudo)scalar type interactions which can be induced in many popular NP models (such as 2HDM and leptoquark) are less constrained by them.

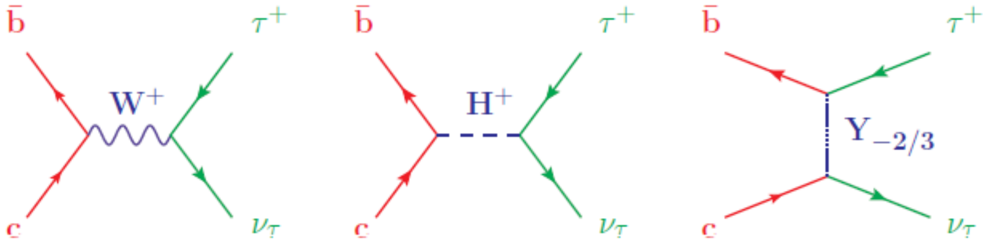


Fig. 1: Feynman diagrams for tauonic B_c decays in the SM, 2HDM and LQ models.

Due to helicity suppression from V-A interactions in $B_c \to \tau\nu$, this channel has a better sensitivity to the (pseudo)scalar NP interactions (arXiv: 1605.09308; 1611.06676)

Theoretical approach to beyond SM analysis

Effective Hamiltonian of $b \to c\tau\nu$ can be written as:

$H_{eff} = \frac{4G_F}{\sqrt{2}} V_{cb}\left[\left(1 + C_{V_1}\right)O_{V_1} + C_{V_2}O_{V_2} + C_{S_1}O_{S_1} + C_{S_2}O_{S_2}\right]$ +h.c.,

Where O_i are four-fermion operators and C_i are corresponding Wilson coefficients.

- O_{V_1} is the only operator present in the SM
- 2HDM can contribute to O_{S_1}
- Leptoquarks can have more versatile contributions depending on their spin and chirality in couplings

Current status of Wilson coefficients

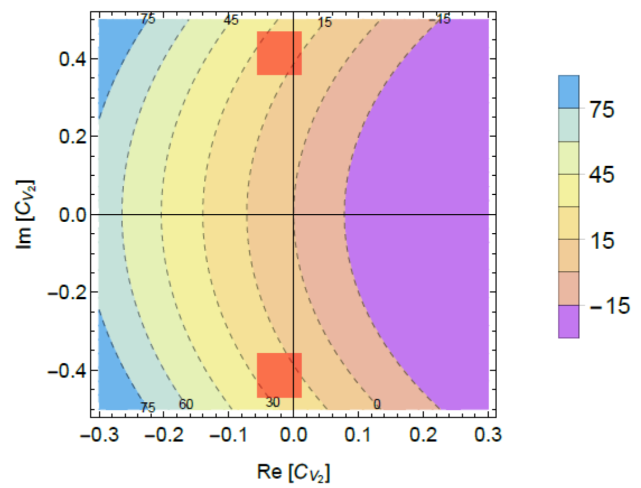


Fig. 2: Sensitivities of $(\Gamma_{\rm eff}-\Gamma_{\rm SM})/\Gamma_{\rm SM}(\%)$ to C_{V_2}. The SM lies at the origin with Re$[C_{V_2}]=$ Im$[C_{V_2}]=0$. Labels (in units of %) on contours denote the modification of branching ratios (decay widths) with respect to the SM values. The red shaded area corresponds to the global fitted results of available data on $b\to c\tau\nu$ decays, as shown in Eq. (9). These areas deviate from the SM predictions by about a few σ.

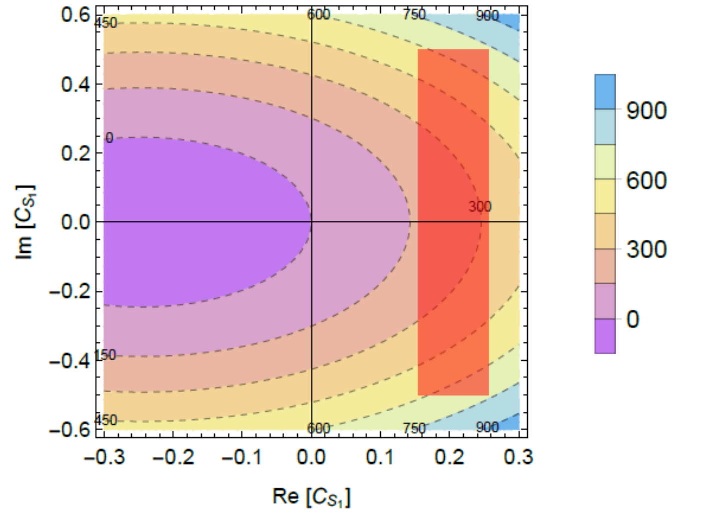


Fig. 3: Sensitivities of $(\Gamma_{\rm eff}-\Gamma_{\rm SM})/\Gamma_{\rm SM}(\%)$ to C_{S_1}. The SM lies at the origin with Re$[C_{S_1}]=$ Im$[C_{S_1}]=0$. Labels (in units of %) on contours denote the modification of branching ratios (decay widths) with respect to the SM values. The red shaded area corresponds to the global fitted results of available data on $b\to c\tau\nu$ decays, as shown in Eq. (10).

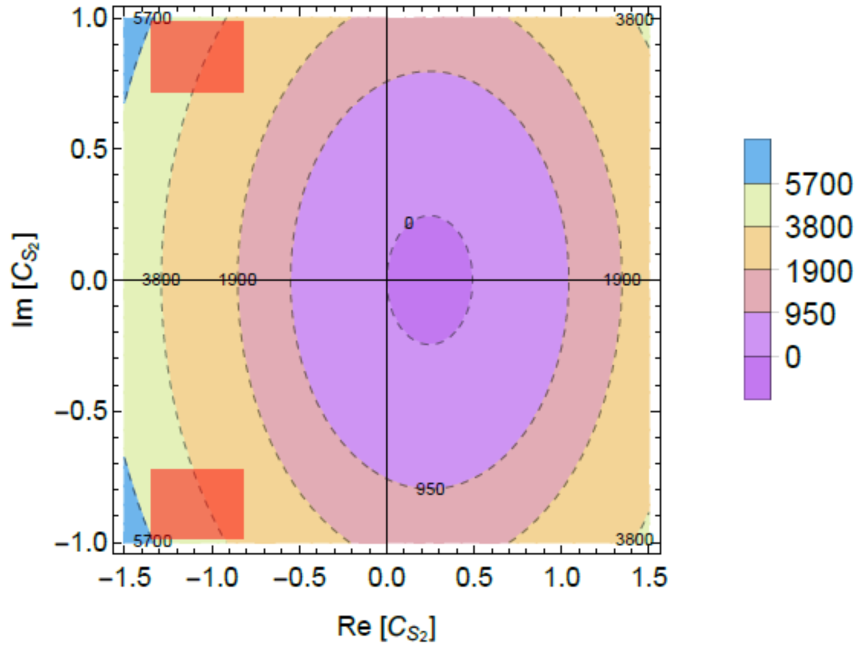
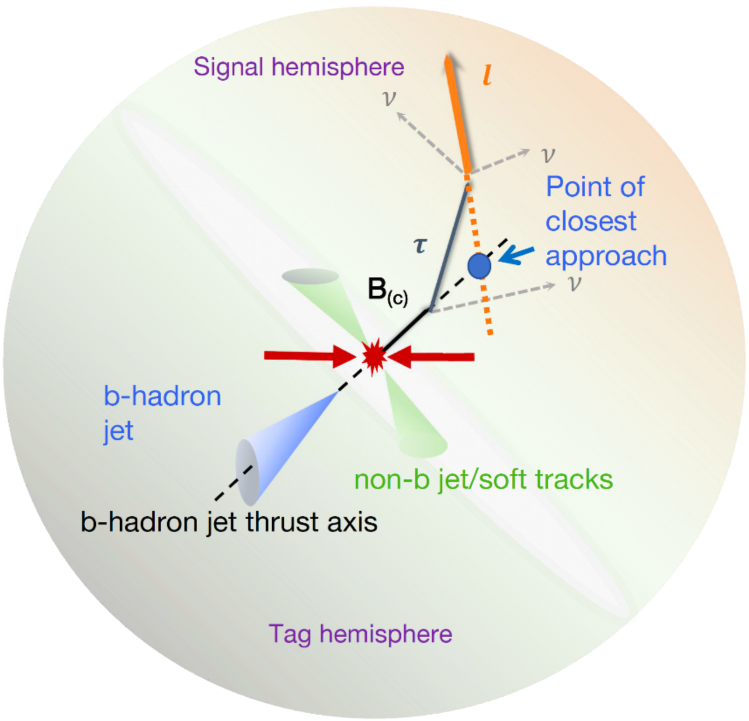


Fig. 4: Similar to Fig. 3 with red shaded area as parameter space of C_{S_2} given in Eq. (11).

Γ_{eff} and Γ_{SM} denote the width of the $B_c\to\tau\nu$ decay with and without new physics contributions, respectively.

Studying $B_c \to \tau\nu$ at CEPC

Lepton colliders such as CEPC, FCC-ee etc. will provide a good opportunity for the study of $B_c \to \tau\nu$. The CEPC will produce up to 1 trillion Z bosons (Tera-Z).



$B_{(c)} \to \tau\nu, \tau \to l\nu\bar{\nu}$ in $Z \to b\bar{b}$. The most critical background for $B_c \to \tau\nu$ is $B \to \tau\nu$, which share similar event topology.

Event yield at CEPC

We conduct the analysis with one billion Z bosonsLet's start with $B \to \tau\nu$:

$$N(B^{\pm} \to \tau^{\pm}\nu_{\tau}) = N_Z \times \mathscr{B}(Z \to b\bar{b}) \times 2 \times f(\bar{b} \to B^{+}X) \times \mathscr{B}(B^{+} \to \tau^{+}\nu_{\tau}),$$

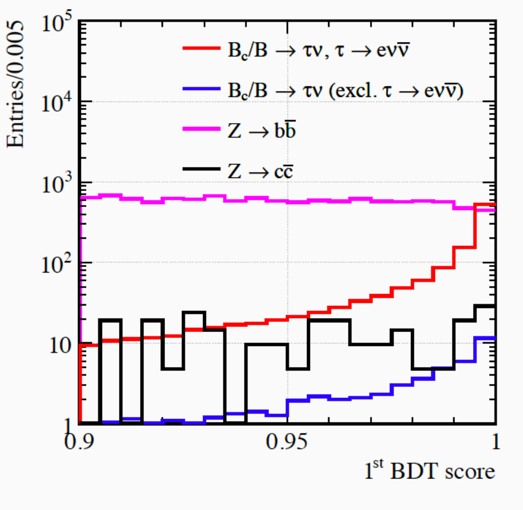
in which,
N_Z: total number of Z bosons (=10^9)
$B(Z \to bb) = 0.1512 \pm 0.0005$,
$f(\bar{b} \to B^{+}X) = 0.408 \pm 0.007$,
$B(B^{+} \to \tau\nu) = (1.09 \pm 0.024)\times 10^{-4}$.
These give $N(B^{\pm} \to \tau\nu) = (1.3 \pm 0.3)\times 10^{4}$.

For B_c, we have $N(B_c^{\pm} \to \tau\nu) = 0.36\times 10^{4}$, with much larger uncertainty.
For the moment, assume the two yields are same and discuss other cases at the end.

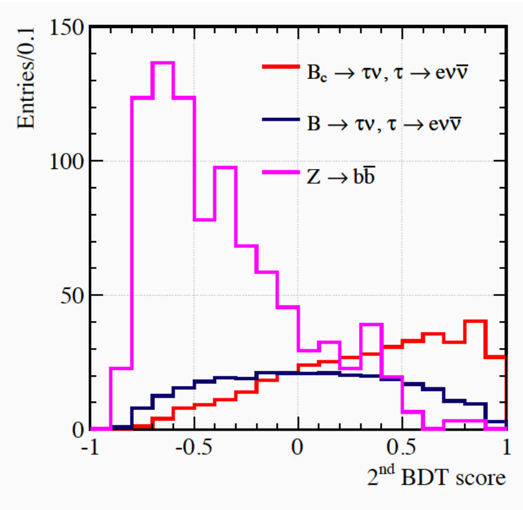
Event cut chain

We focus on $B_c \to \tau\nu, \tau \to e/\mu\nu\bar{\nu}$, this page is for electron final states

	$B_c^{\pm} \to \tau\nu_\tau(0.013)$ $\tau \to e\nu\bar{\nu}$	$B_c^{\pm} \to \tau\nu_\tau(0.013)$ excl. $\tau \to e\nu\bar{\nu}$	$B^{\pm} \to \tau\nu_\tau(0.013)$ $\tau \to e\nu\bar{\nu}$	$B^{\pm} \to \tau\nu_\tau(0.013)$ excl. $\tau \to e\nu\bar{\nu}$	$d\bar{d}(15) + u\bar{u}(12) + s\bar{s}(15)$	$c\bar{c}(4.8)$	$b\bar{b}(3.25)$
All events	2,303	10,691	2,270	10,633	419,928,342	119,954,033	151,286,603
b-tag > 0.6	1,611	7,463	1,547	7,151	2,134,617	7,344,014	116,723,067
Energy asymmetry > 10 GeV	1,425	6,184	1,389	5,801	486,762	1,609,771	30,064,030
Has electron in signal hemisphere	1,273	1,300	1,243	1,132	143,595	625,670	15,905,613
Electron is the most energetic particle	915	116	859	93	8,490	79,190	4,587,248
$E_B > 20$ GeV	909	112	852	88	981	34,147	3,203,073
1^{st} BDT score > 0.99	390	12	259	4	—	48	910
2^{nd} BDT score > 0.4	199	—	73	—	—	—	33

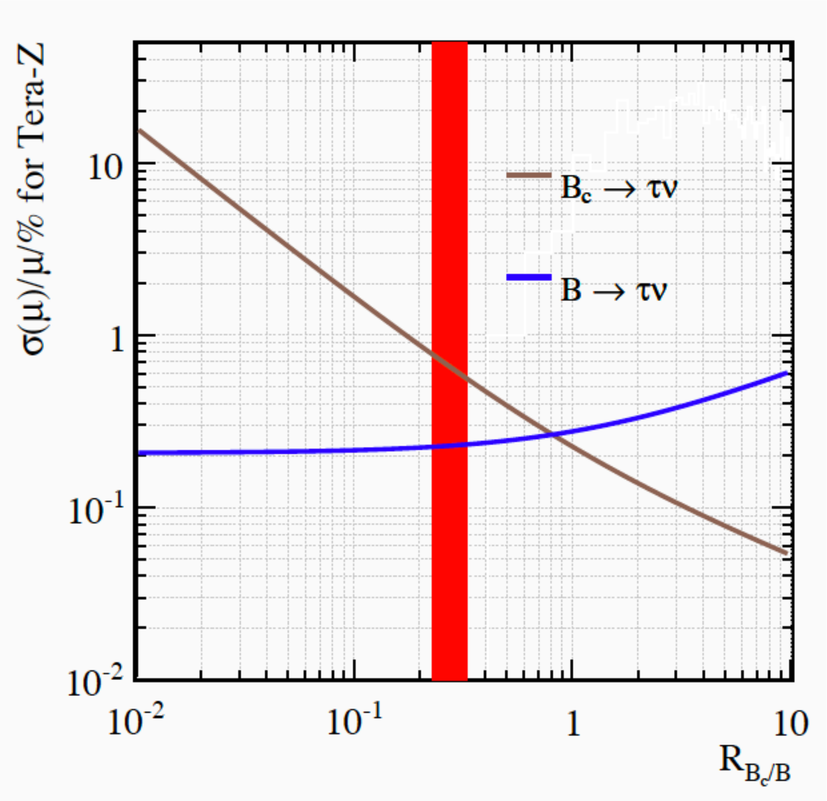


Without the impact parameter



With the impact parameter

Signal strength accuracy



- Combine the electron and muon final state results.
- Extrapolate to Tera-Z
- $R_{B_c/B} = \frac{N(B_c \to \tau\nu)}{N(B \to \tau\nu)}$
- Red band: expected region of $R_{B_c/B}$
- The figure shows the signal strength accuracy of both $B_c \to \tau\nu$ and $B \to \tau\nu$

Conclusion

Result of the sensitivity study for $B_c \to \tau\nu, \tau \to e/\mu\nu\nu$ at CEPC

- Signal strength accuracy could reach around 1% at Tera-Z
- $B_c \to \tau\nu$ could be discovered with $\sim 10^8$ Z bosons
- $|V_{cb}|$ could be determined up to $O(1\%)$ under certain conditions
- Constraints on the C_{V_2}
- Similar constraints could be applied to C_{S_1} and C_{S_2}, but they will change the $\Gamma(B_c \to \tau\nu)$ so much that they will likely be verified or ruled out much earlier.

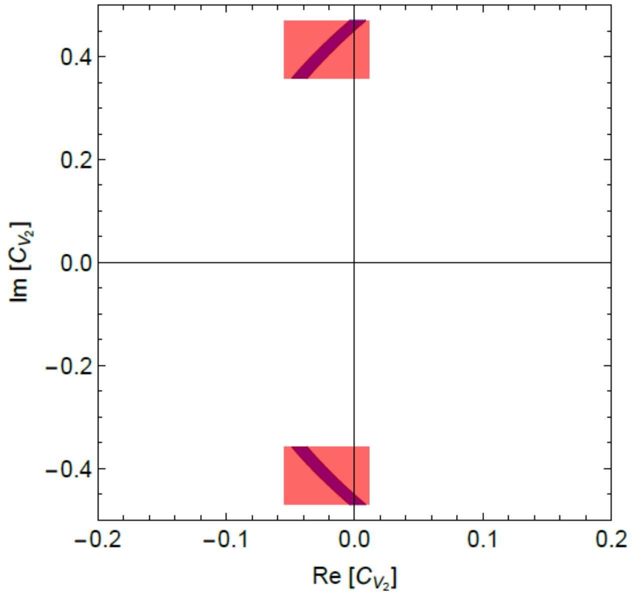


Fig. 11: Constraints on the real and imaginary parts of C_{V_2}. The red shaded area corresponds to the current constraints using available data on $b \to c\tau\nu$ decays. If the central values in Eq. (9) remain while the uncertainty in $\Gamma(B_c^+ \to \tau^+\nu_\tau)$ is reduced to 1%, the allowed region for C_{V_2} shrinks to the dark-blue region.

Thank you!