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Revisiting the $b \to cl\nu$ anomalies with charged Higgs boson

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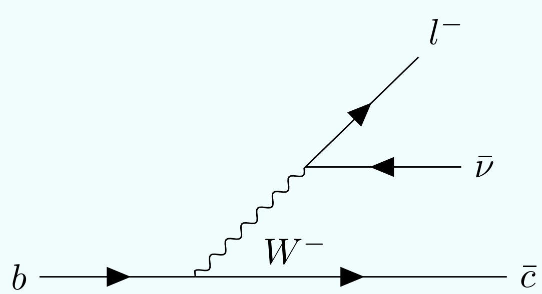
Anomalies in B decays

In Standard Model (SM), three flavours of charged leptons has the same gauge coupling strength, known as lepton flavour universality (LFU).

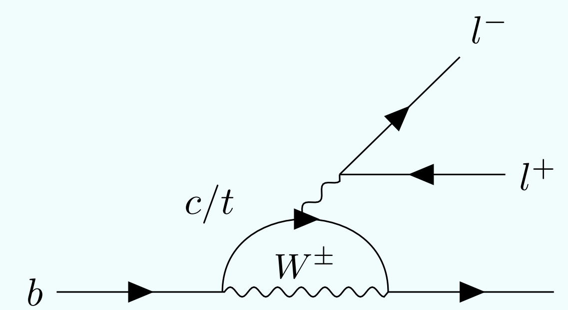
Violation of LFU is first observed in semi-leptonic B decays :



Charged current (main focus)

e.g. $B \to D^* l\nu, B_c \to J/\psi\ l\nu \ldots$

Observables: $R_D, R_{D^{(*)}}, R_{J/\psi}, P_\tau^{D^*} \ldots$



Neutral current

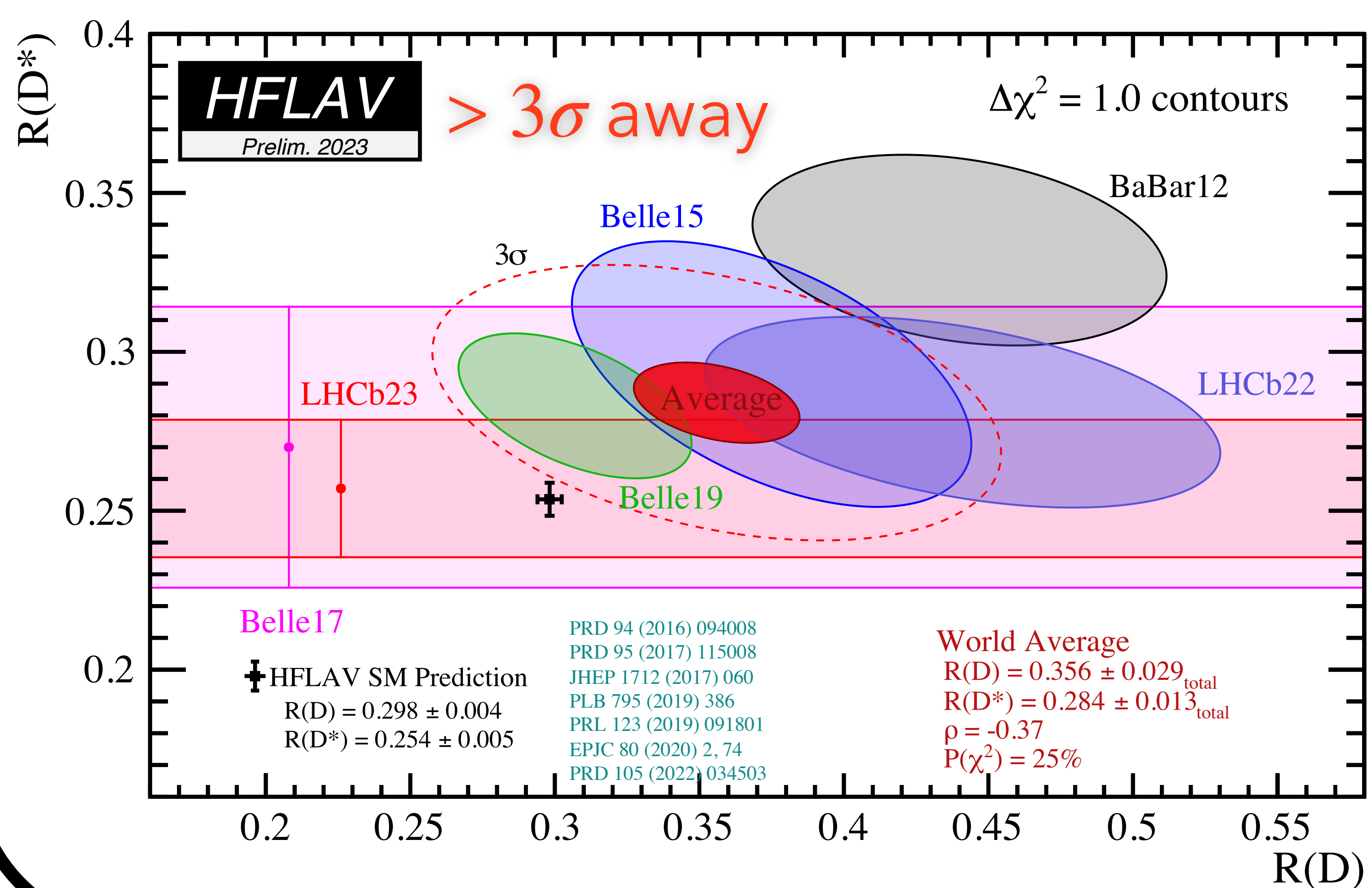
e.g. $B \to K^* l^+ l^-, B_s \to \phi \mu^+ \mu^- \ldots$

Observables: ~~$R_K, R_{K^{(*)}}$~~, $P_5' \ldots$

…Talk by Monica Pepe Altarelli
LHCb-PAPER-2022-046

Present status of $b \to c\tau\nu$ anomalies

$$R_D = \frac{\mathcal{B}(B \to D\tau\nu_\tau)}{\mathcal{B}(B \to Dl\nu_l)} \qquad R_{D^*} = \frac{\mathcal{B}(B \to D^*\tau\nu_\tau)}{\mathcal{B}(B \to D^*l\nu_l)}$$



$$R_{J/\psi} = \frac{\mathcal{B}(B_c \to J/\psi\ \tau\nu_\tau)}{\mathcal{B}(B_c \to J/\psi\ \mu\nu_\mu)}$$

$R^{SM}_{J/\psi} = 0.258 \pm 0.004$ Phys. Rev. Lett. 125, 222003 (2020)

$R^{ex}_{J/\psi} = 0.71 \pm 0.17 \pm 0.18$ Phys. Rev. Lett. 120, 121801 (2018)

$$F_L^{D^*} = \frac{\Gamma(B \to D_L^*\ \tau\nu_\tau)}{\Gamma(B \to D^*\ \tau\nu_\tau)}$$

$F_L^{D^*\ SM} = 0.46 \pm 0.04$ Iguro et.al. Report No.: P3H-22-103

$F_L^{D^*\ ex} = 0.60 \pm 0.08 \pm 0.035$

Report: BELLE-CONF-1805
1903.03102

$$R_{\Lambda_c} = \frac{\mathcal{B}(\Lambda_b \to \Lambda_c\ \tau\nu_\tau)}{\mathcal{B}(\Lambda_b \to \Lambda_c\ \mu\nu_\mu)}$$

$R^{SM}_{\Lambda_c} = 0.324 \pm 0.004$ Phys. Rev. D 99, 055008 (2019)

$R^{ex}_{\Lambda_c} = 0.242 \pm 0.026 \pm 0.040 \pm 0.059$

Phys. Rev. Lett. 128, 191803 (2022)

$$P_\tau^{D^*} = \frac{\Gamma(B \to D^*\ \tau^{\lambda=+1/2}\nu_\tau) - \Gamma(B \to D^*\ \tau^{\lambda=-1/2}\nu_\tau)}{\Gamma(B \to D^*\ \tau\nu_\tau)}$$

$P_\tau^{D^*\ SM} = -0.497 \pm 0.013$ 2210.10751 Iguro et.al. Report No.: P3H-22-103

$P_\tau^{D^*\ ex} = -0.38 \pm 0.51^{+0.21}_{-0.16}$ Phys. Rev. Lett. 118, 211801 (2017)

New physics explanations

Model independent approach:

$$\mathcal{H}_{eff} = \frac{4G_F}{\sqrt{2}} V_{cb}(1 + C^V_{LL})\mathcal{O}_{C^V_{LL}} + C^V_{RL}\mathcal{O}_{C^V_{RL}} + C^S_{LL}\mathcal{O}_{C^S_{LL}} + C^S_{RL}\mathcal{O}_{C^S_{RL}} + C^T_{LL}\mathcal{O}_{C^T_{LL}} +$$
$$C^V_{LR}\widetilde{\mathcal{O}}_{C^V_{LR}} + C^V_{RR}\widetilde{\mathcal{O}}_{C^V_{RR}} + + C^S_{LR}\widetilde{\mathcal{O}}_{C^S_{LR}} + C^S_{RR}\widetilde{\mathcal{O}}_{C^S_{RR}} + C^T_{RR}\widetilde{\mathcal{O}}_{C^T_{RR}} + h.c.$$

Cirigliano et.al.
Phys. Rev. D 85, 054512

$$\mathcal{O}_{C^S_{LL}} = (\bar{c}_R b_L)(\bar{\tau}_R \nu_{\tau L}) \qquad \widetilde{\mathcal{O}}_{C^S_{LL}} = (\bar{\tau}_L \nu_{\tau R})(\bar{c}_R b_L)$$

$$\mathcal{O}_{C^S_{RL}} = (\bar{\tau}_R \nu_{\tau L})(\bar{c}_L b_R) \qquad \widetilde{\mathcal{O}}_{C^S_{RL}} = (\bar{\tau}_L \nu_{\tau R})(\bar{c}_L b_R)$$

Model dependent approach:

W' boson — Charged Higgs boson — Leptoquark

Model independent approach - χ^2 fit

χ^2 fit using iminuit

Observables : R_D, $R_{D^{(*)}}$, $R_{J/\psi}$, $P_\tau^{D^*}$, R_{Λ_c}, $F_L^{D^*}$

1D scenario (Real) : $C^S_{LL} = 0.15$ $C^S_{RL} = 0.16$ $C^S_{RR}/C^S_{LR} = -0.51$

1D scenario (Complex) :

$C^S_{LL} = -0.67 - i\ 0.84$ $C^S_{RL} = 0.16 - i\ 6.4 \times 10^{-6}$ $C^S_{RR}/C^S_{LR} = -0.49 - i\ 0.14$

2D scenario :

$(C^S_{LL},\ C^S_{RL}) = (-0.37 + i\ 0,\ 0.48 + i\ 0)$

$(C^S_{LL},\ C^S_{RR}/C^S_{LR}) = (-0.67 - i\ 0.5,\ -0.63 - i\ 0.26)$

$(C^S_{RL},\ C^S_{RR}/C^S_{LR}) = (0.16 - i\ 1.6 \times 10^{-4},\ \sim 0 + i\ 0)$

$(C^S_{RR},\ C^S_{LR}) = (-0.88 - i\ 0.62,\ 0.50 + i\ 0.45)$

Contour Plots

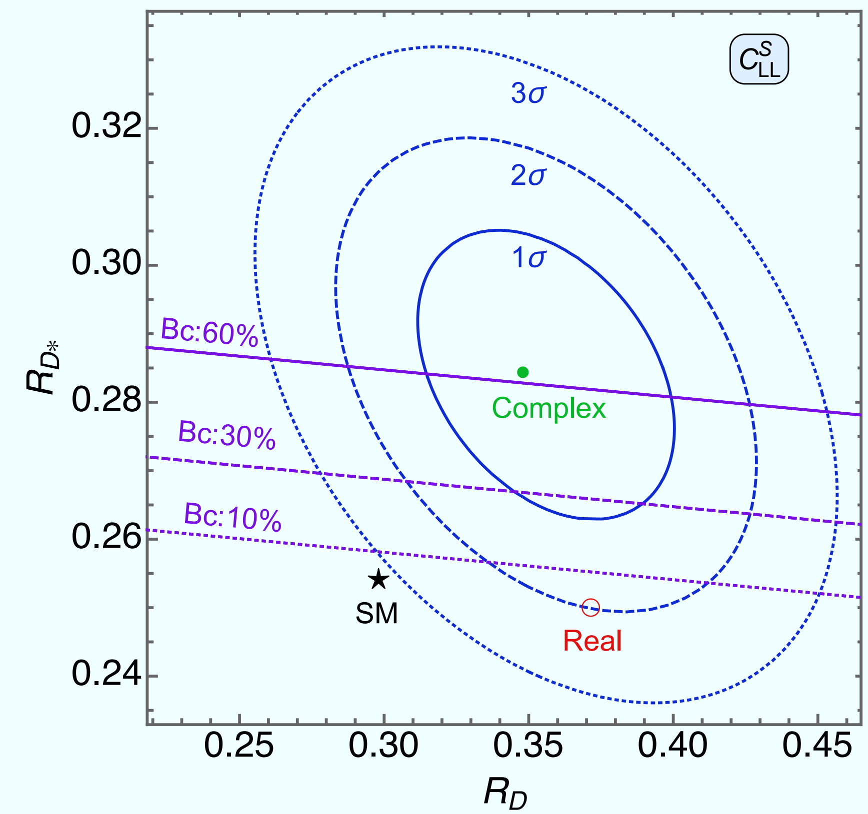
$R_D - R_{D*}$ plane

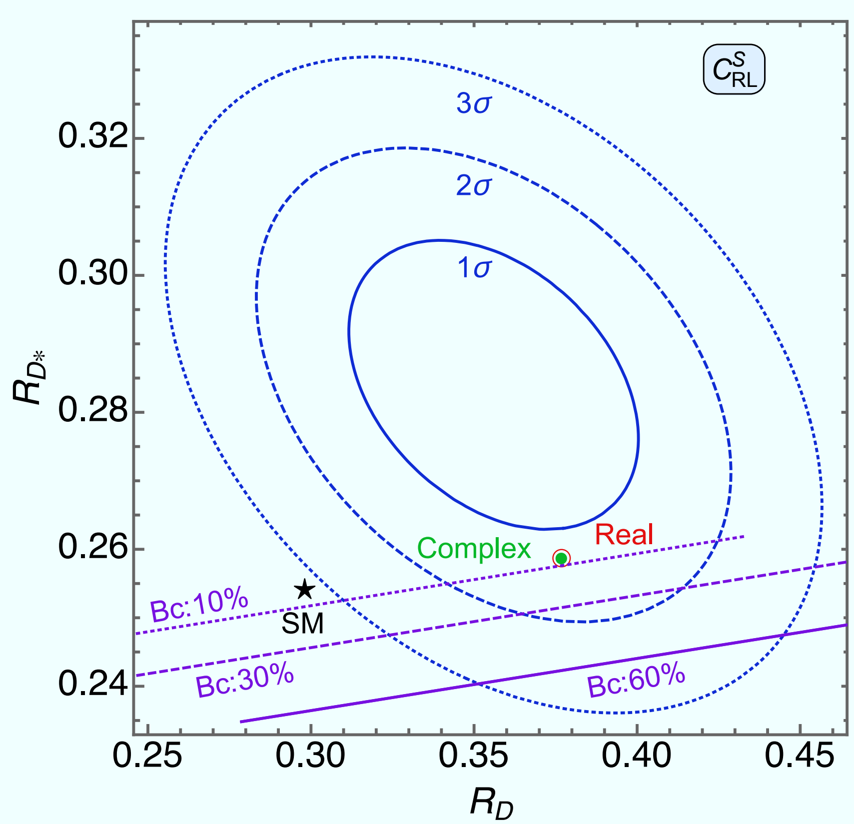
Blue: 1σ, 2σ, 3σ contours

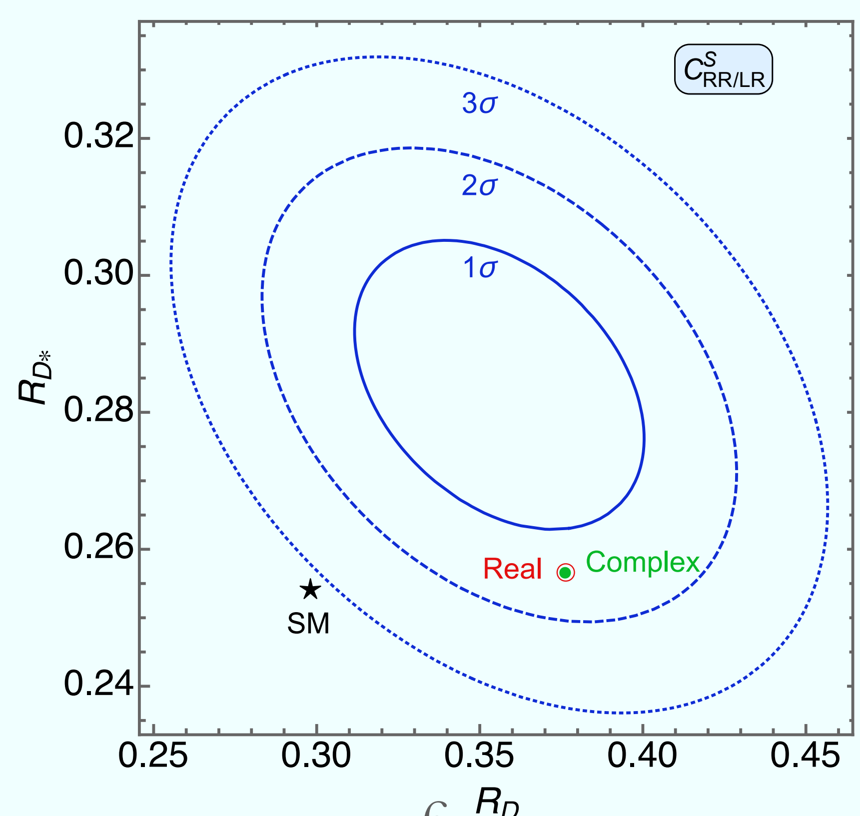
★ : SM prediction, o : Real fit, ● : Complex fit

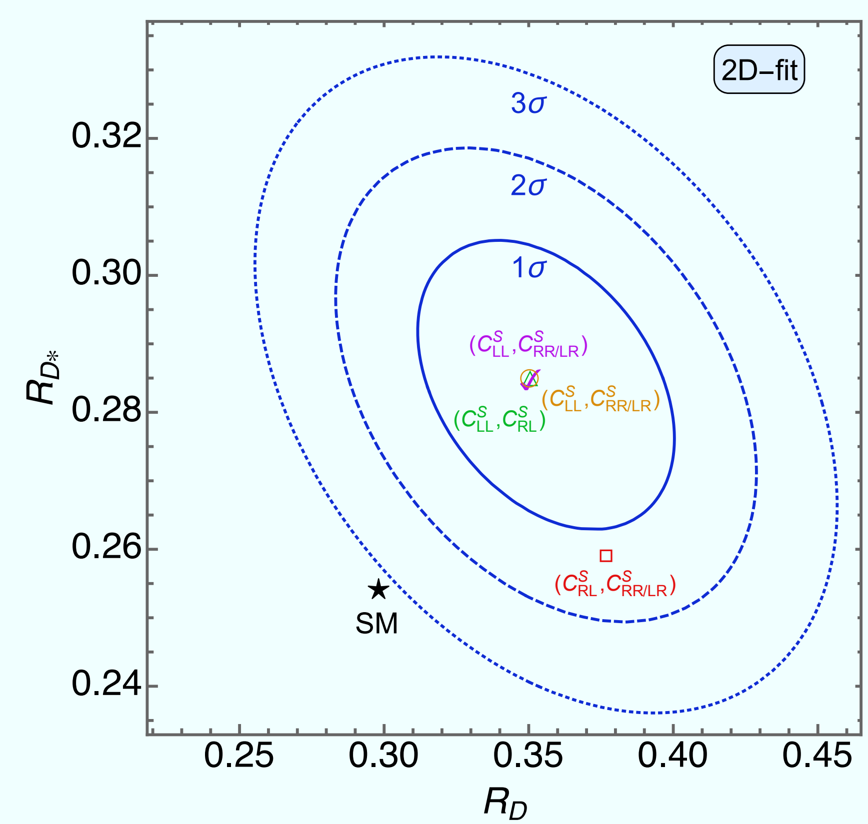
Purple: $\mathscr{B}(B_c \to \tau\bar{\nu}_\tau) = Bc = 60\,\%\,,\,30\,\%\,,\,10\,\%$

Blanke et.al. Phys. Rev. D 99, 075006 (2019)
Aebischer et.al. JHEP 07, 130 (2021)



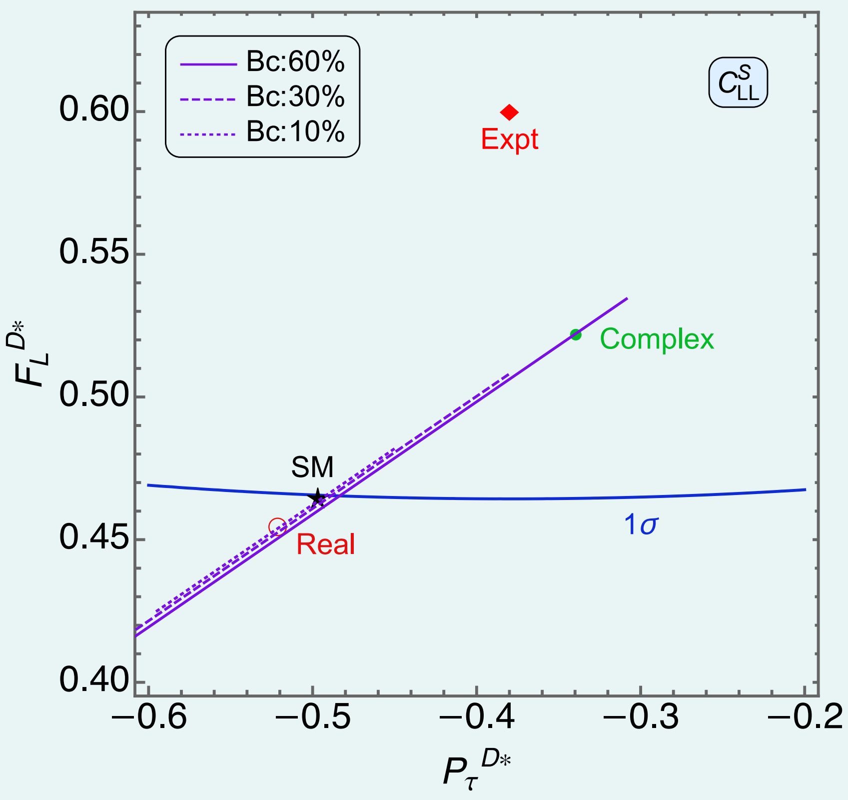




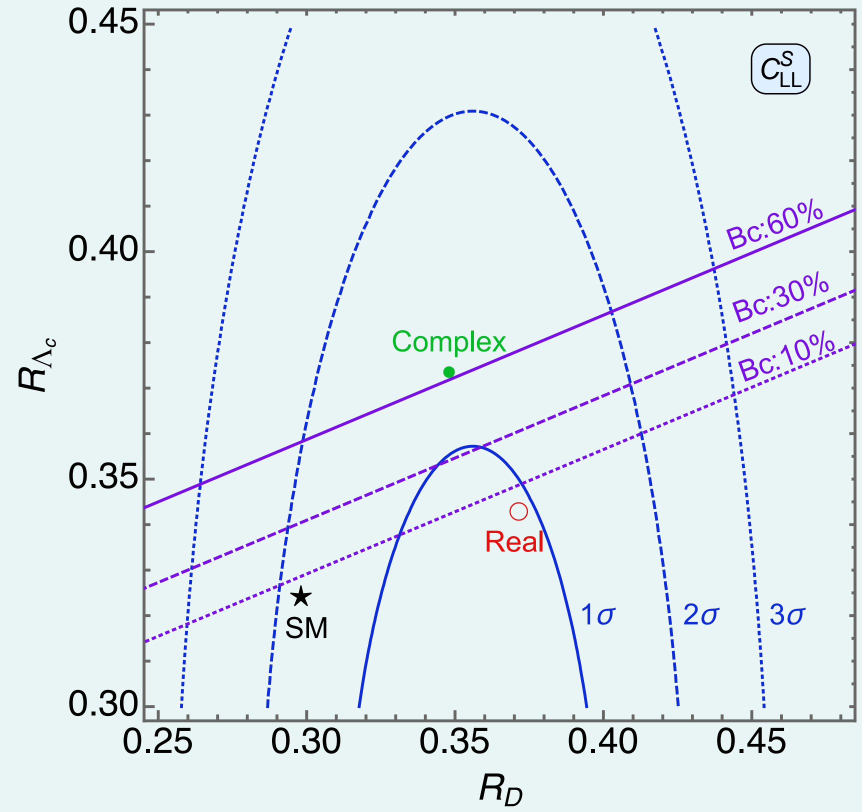


Contour Plots

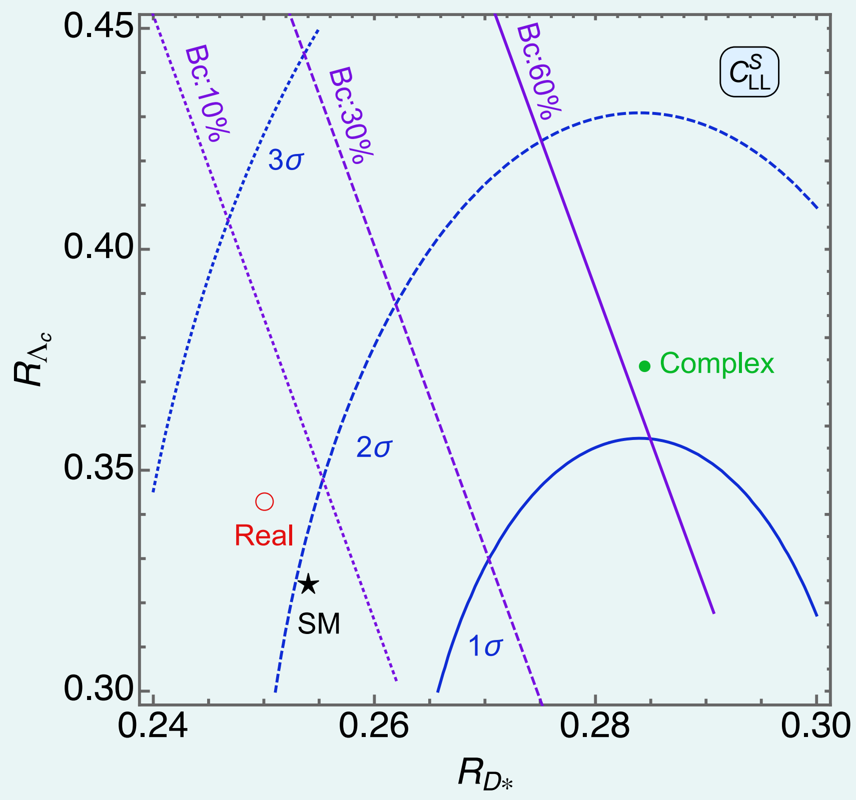
$F_L^{D*} - P_\tau^{D*}$ plane



$R_D - R_{\Lambda_c}$ plane

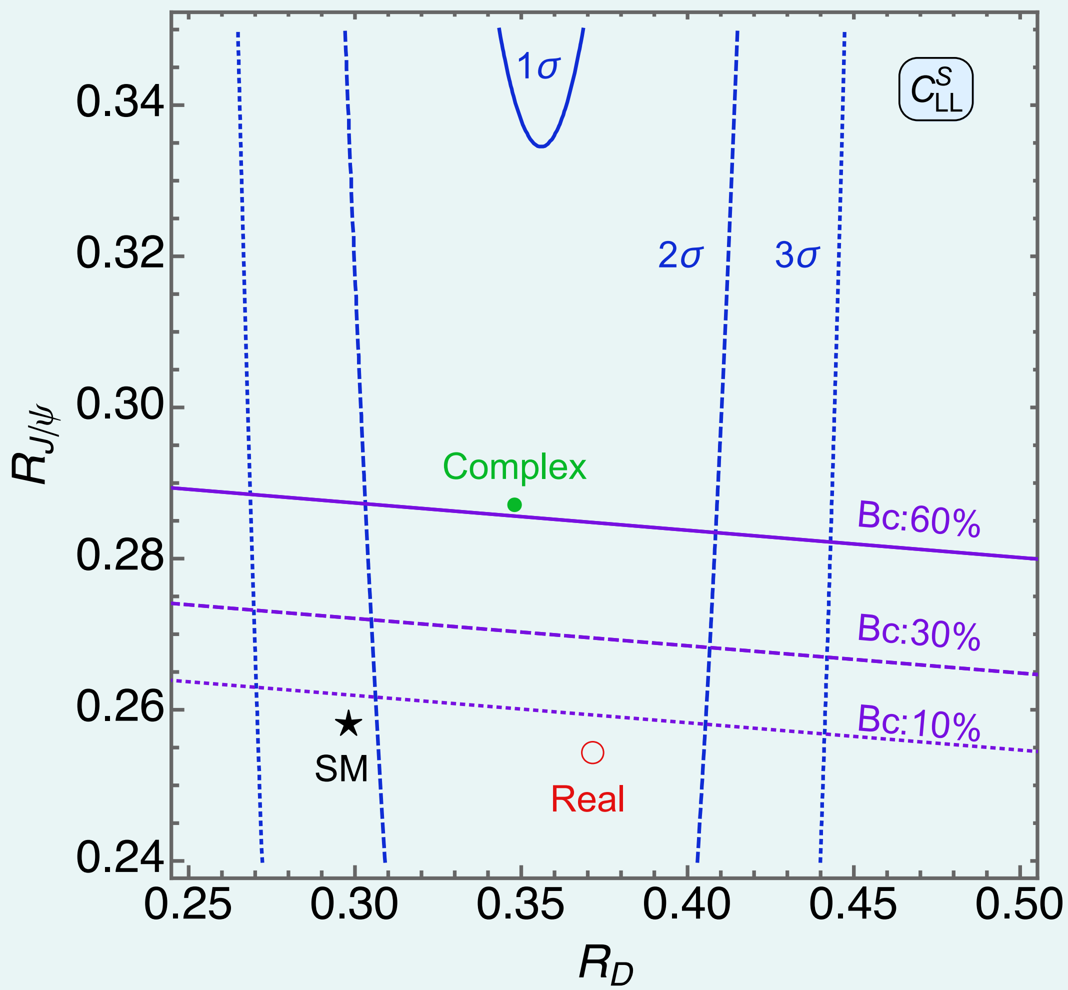


$R_{D*} - R_{\Lambda_c}$ plane

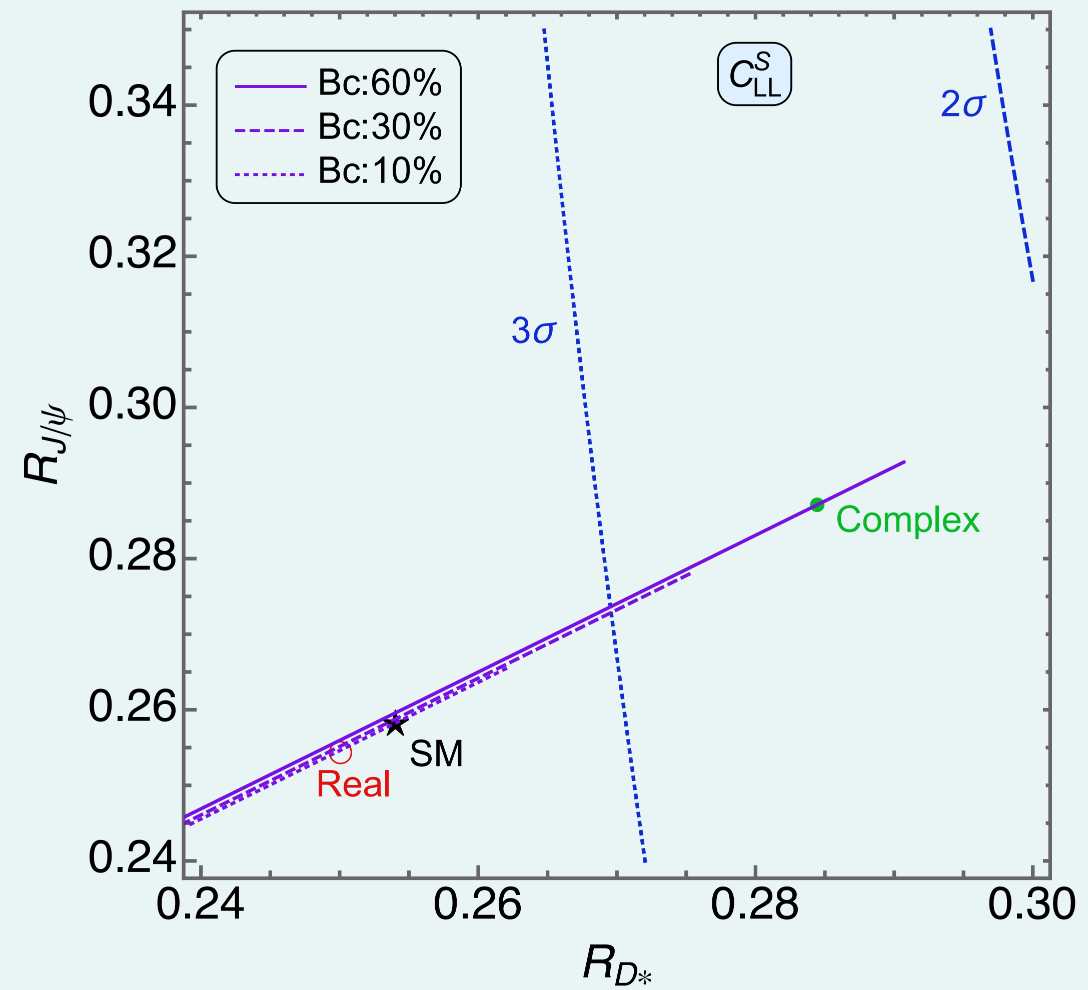


Contour Plots

$R_D - R_{J/\psi}$ plane



$R_{D*} - R_{J/\psi}$ plane



Model dependent approach

Charged Higgs boson in generic two Higgs doublet model (2HDM) :

$$\mathscr{L}_{\rm int} = y^u_{bc} H^-(\bar{b}P_R c) - y^d_{bc} H^-(\bar{b}P_L c) - y_{\tau\nu} H^-(\bar{\tau}P_L \nu_\tau) + h.c.$$

$y^u_{bc} = y_{bc}$

y^d_{bc} constrained by $B_s - \bar{B}_s$ mixing

~~C^S_{RL}~~

Phys.Rev.D 105 (2022) 9, 095011

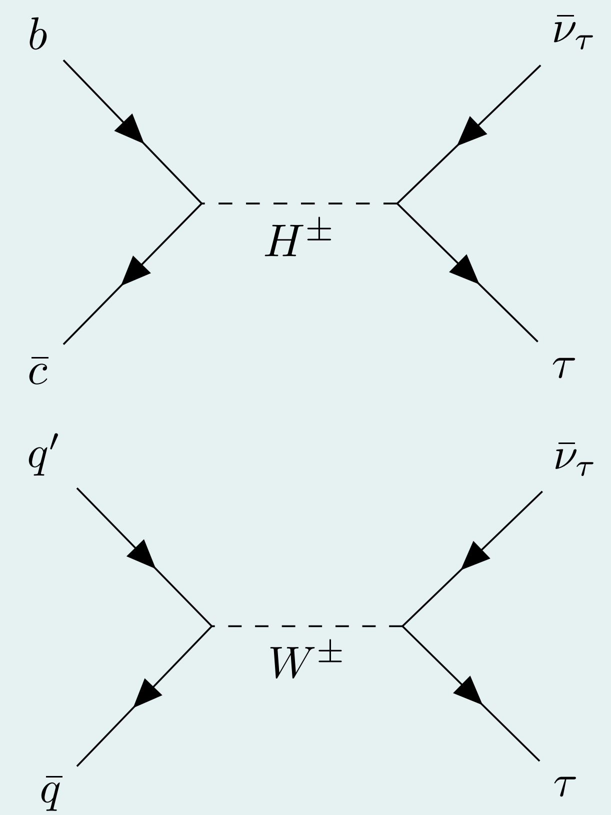
Effective Hamiltonian for the $b \to c\tau\nu$ transition :

$$\mathscr{H}_{\rm eff} = 2\sqrt{2} G_F V_{cb} \, [(\bar{c}_R \gamma_\mu b_L)(\bar{\tau}_R \gamma^\mu \nu_{\tau L}) + C^S_{LL}(\bar{c}_R b_L)(\bar{\tau}_R \nu_{\tau L})] \, .$$

At the $m_{H^\pm}$ scale, $$C^S_{LL} = \frac{y_{bc} \; y_{\tau\nu}}{2\sqrt{2} G_F V_{cb} m^2_{H^\pm}} \, .$$

← Collider search

Collider Analysis : b-veto category



Signal process : $bc \to H^\pm \to \tau\nu$

Dominant background process : $pp \to W^\pm \to \tau\nu$

Other background processes : Drell-Yan (DY) + jets, Misid. τ_h ($j \to \tau_h$ fake), $t\bar{t}$, $VV(V = W/Z)$+jets, single t

Trigger cuts:

$N_{\tau_h} = 1,\ N_\ell = 0$

b-veto : $N_{\text{b-jets}} = 0$

$N_j \le 2$

Selection cuts:

$\Delta\phi(p_{T,\tau_h}, \not{p}_T) \ge 2.4$

$0.7 \le p_{T,\tau_h}/\not{p}_T \le 1.3$

Optimised selection cuts:

$p_{T,\tau_h} \ge [50,50,70,80,90,110]$ GeV

$m_T \ge [100,110,150,170,200,220]$ GeV

$\not{E}_T \ge [50,50,60,80,90,100]$ GeV

for $m_{H^\pm} = [180,200,250,300,350,400]$ GeV

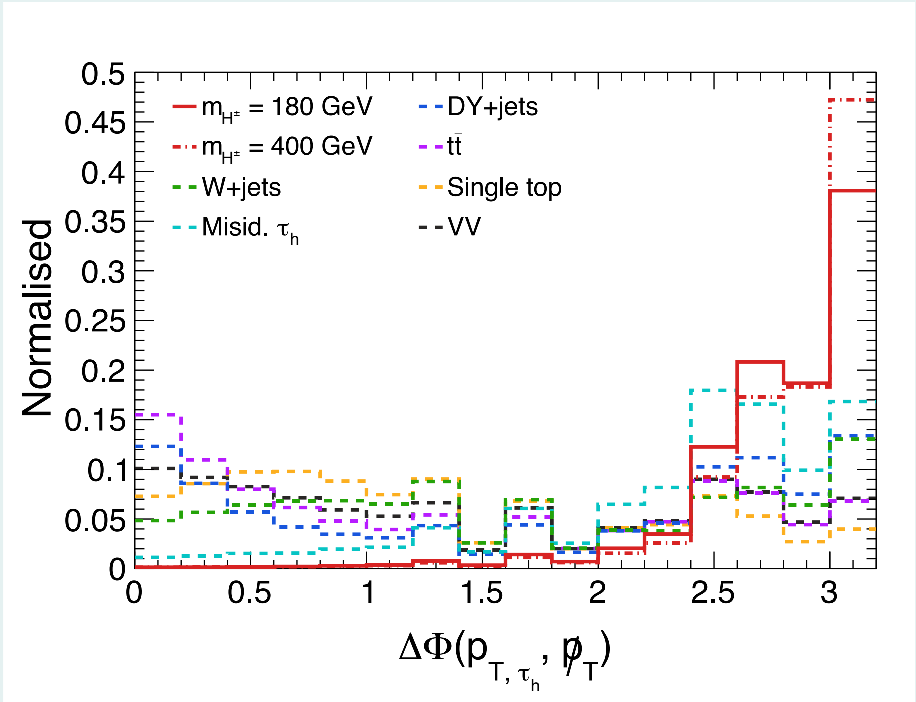
Signal Significance:

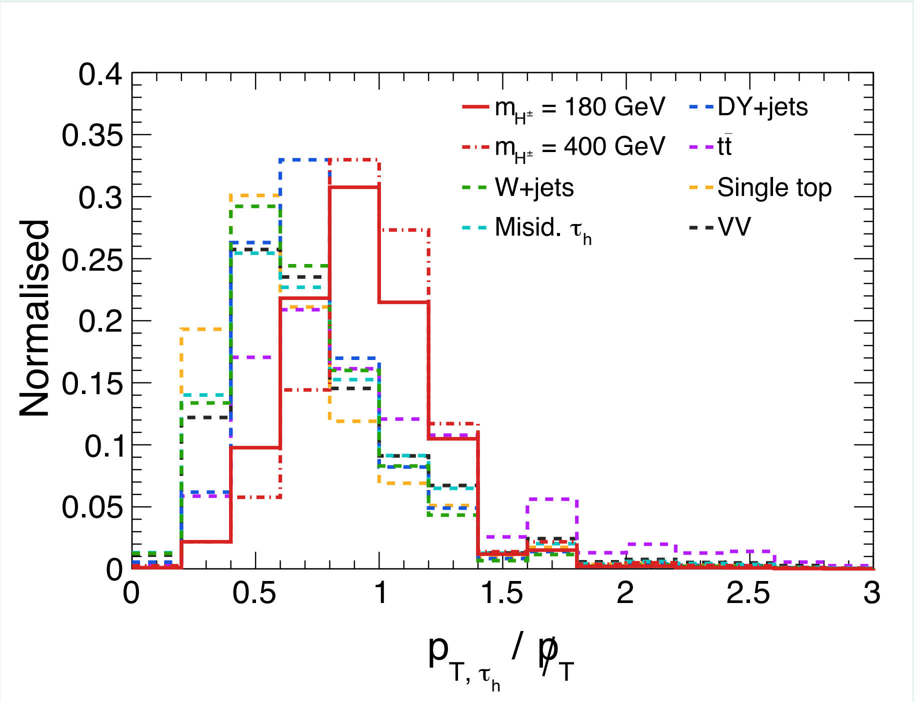
$\sigma_s = \frac{S}{\sqrt{B}}$

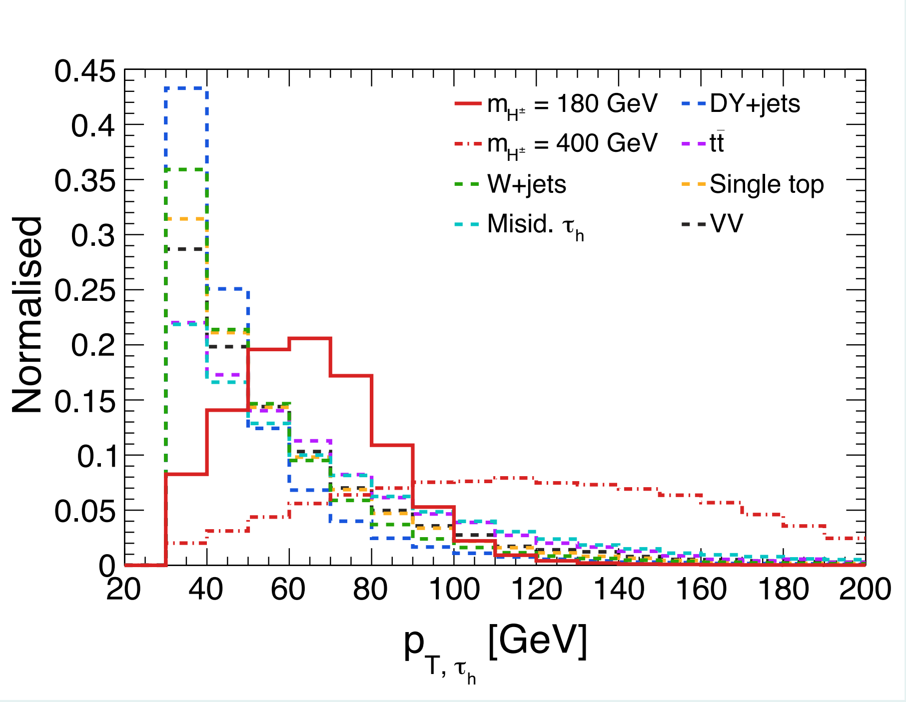
CMS Collaboration
Report No.: CMS-EXO-21-009

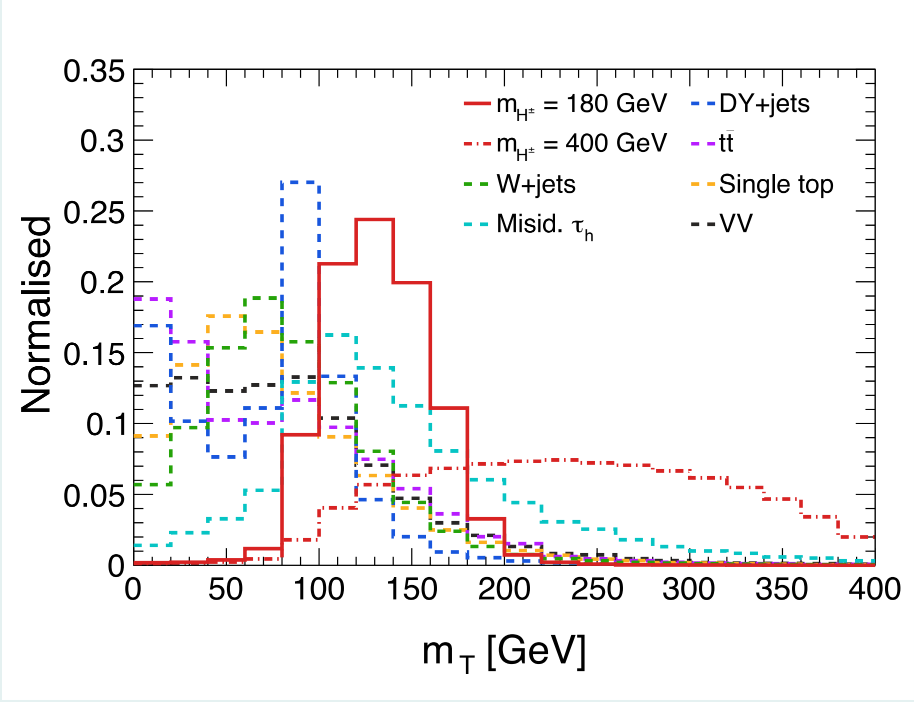
Collider Analysis : b-veto category

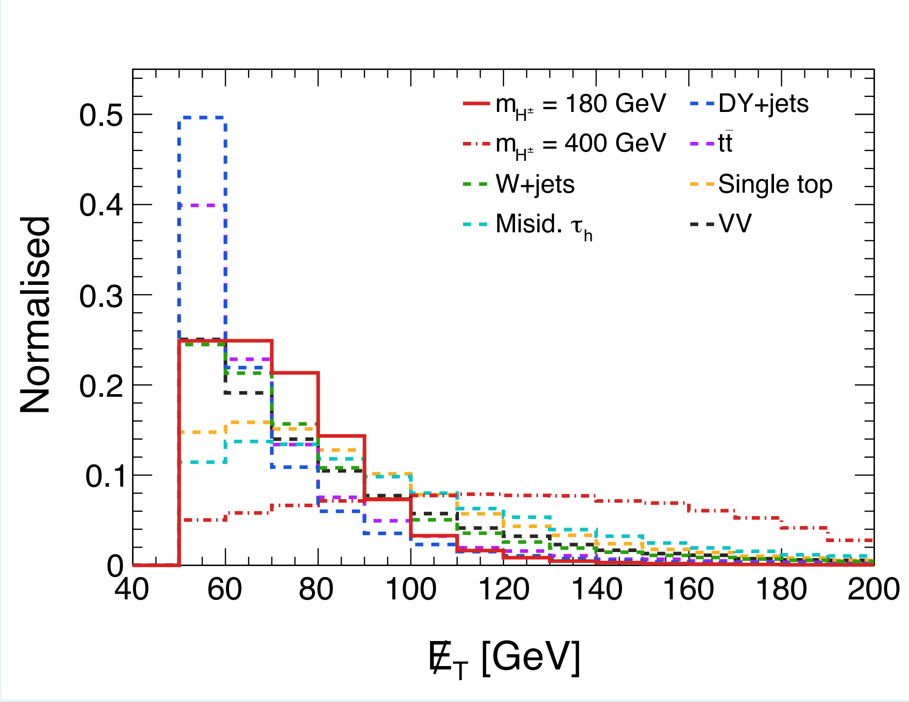
Kinematic variables







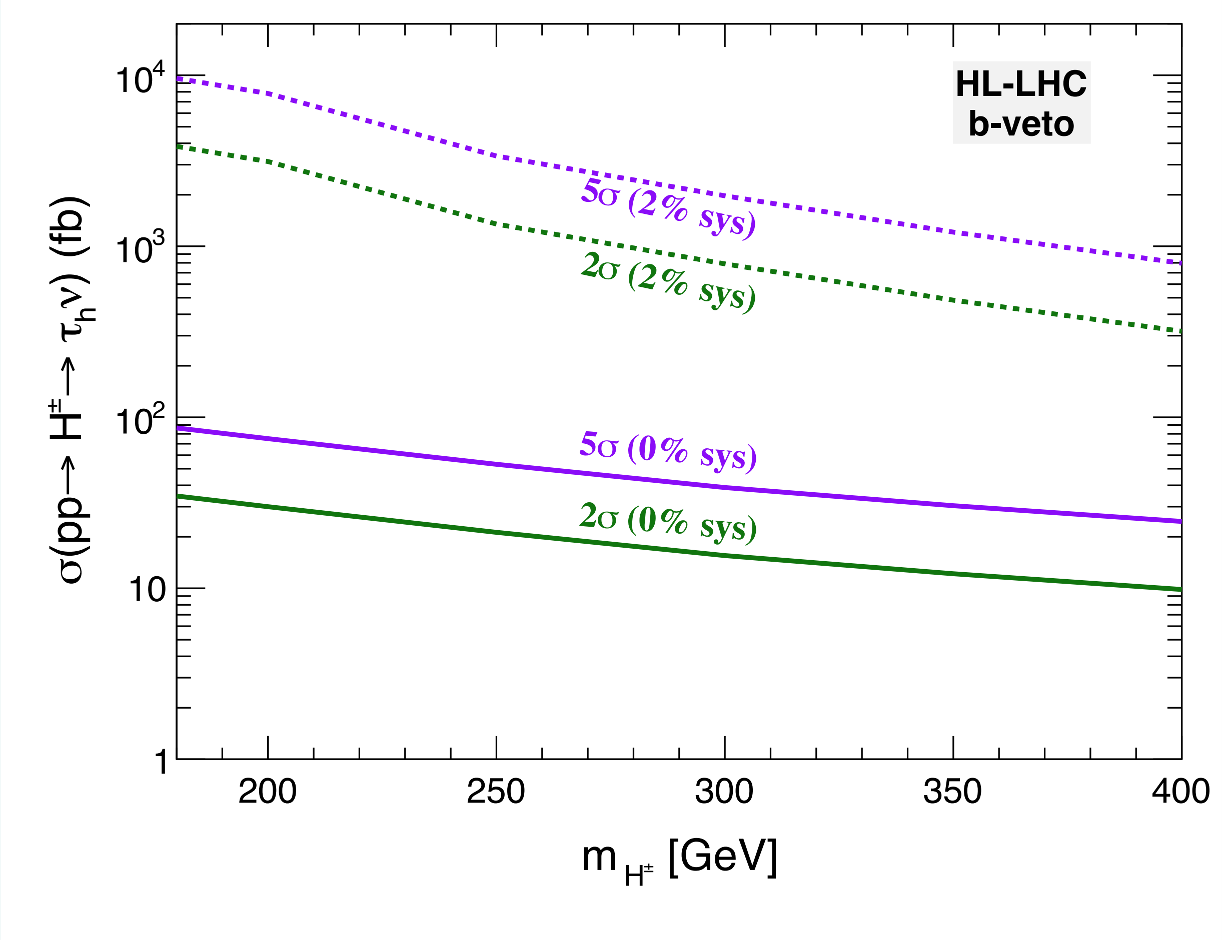




Collider Analysis : b-veto category

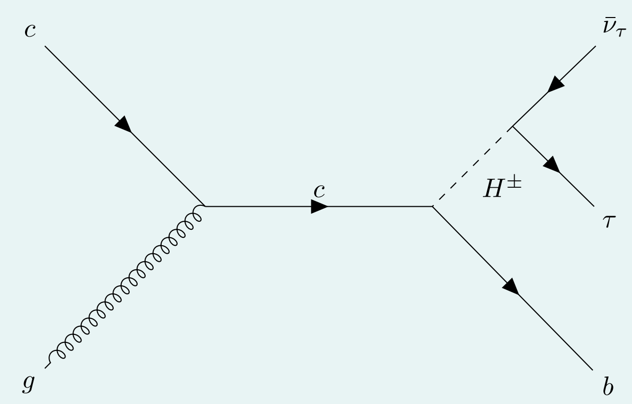
Upper limit on the signal production cross-section :

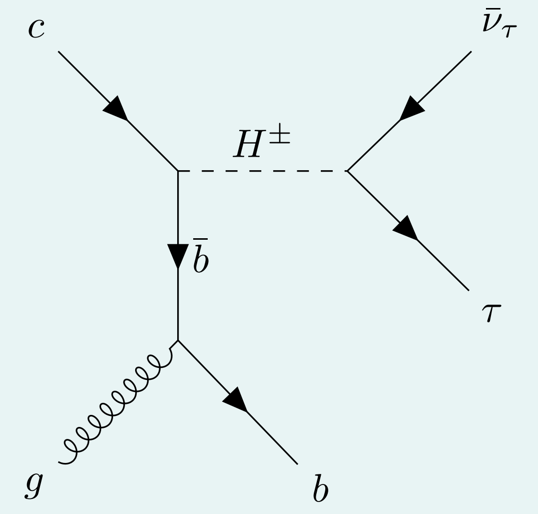
$$\sigma(pp \to H^{\pm} \to \tau_h \nu)_{\mathrm{UL}} = \frac{N \cdot \sqrt{B}}{\epsilon \cdot \mathscr{L}}$$



Collider Analysis : b-tag category

Signal process : $gc \to bH^{\pm} \to b\tau\nu$



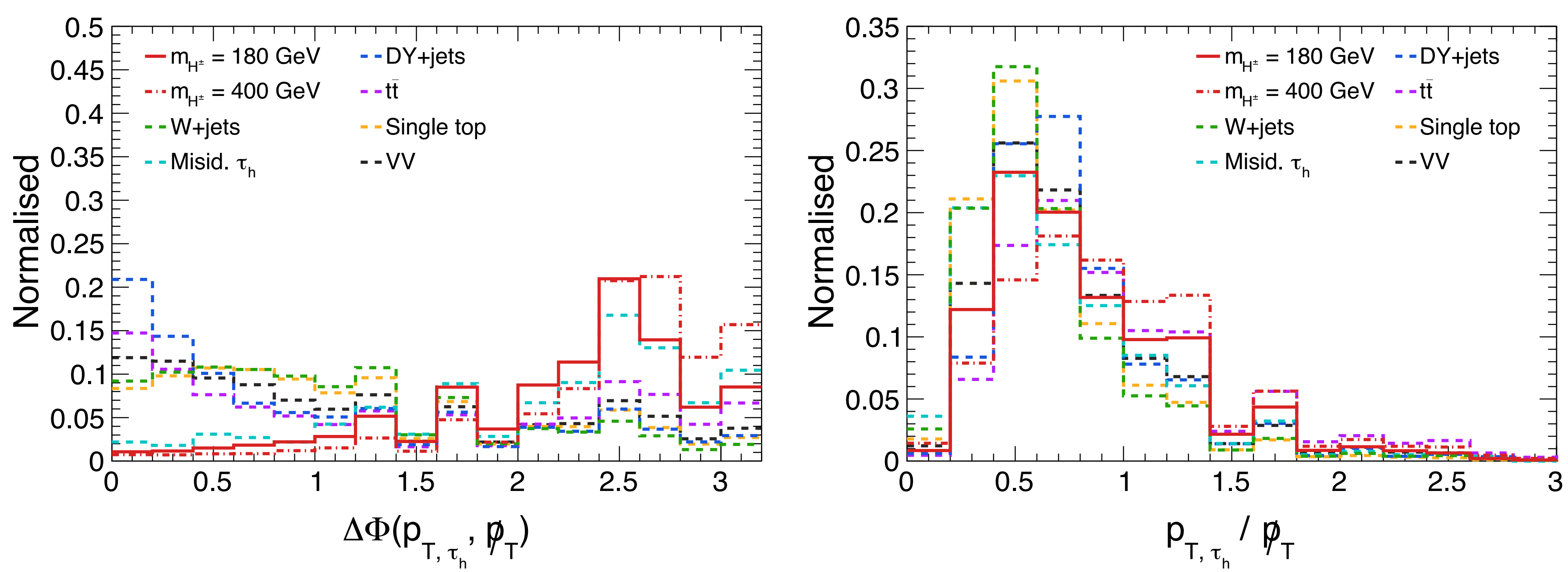


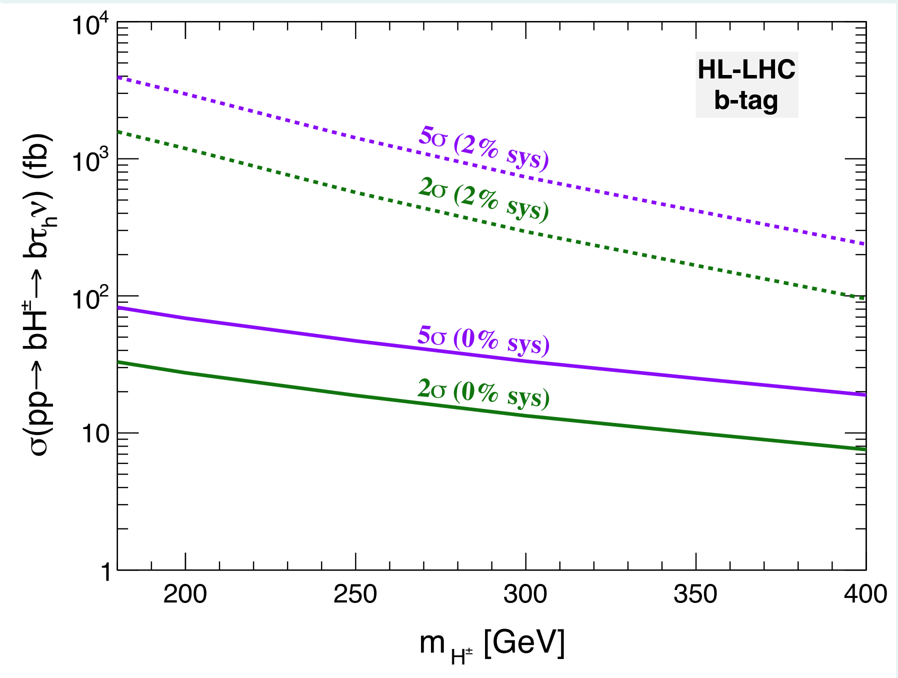
b-tag : $N_{\text{b-jets}} = 1$

Optimise over (p_{T,τ_h} , $\Delta\phi(p_{T,\tau_h}, \not{p}_T)$, m_T , $\not{E}_T$)

Kinematic variables

Upper limit



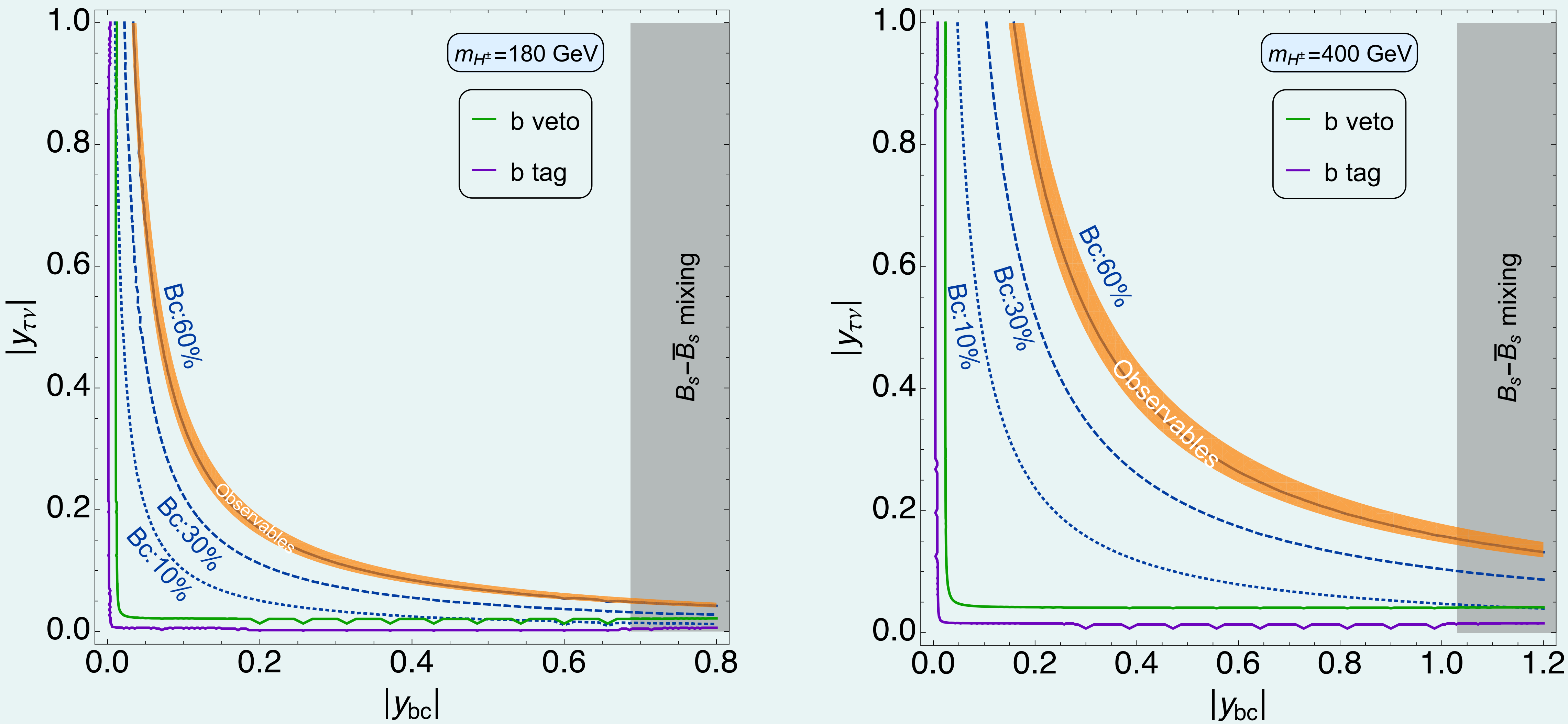


Constraining the Yukawa plane

Orange: 1σ favoured region by all six observable measurements

Green: Constraints from $bc \to H^{\pm} \to \tau\nu$

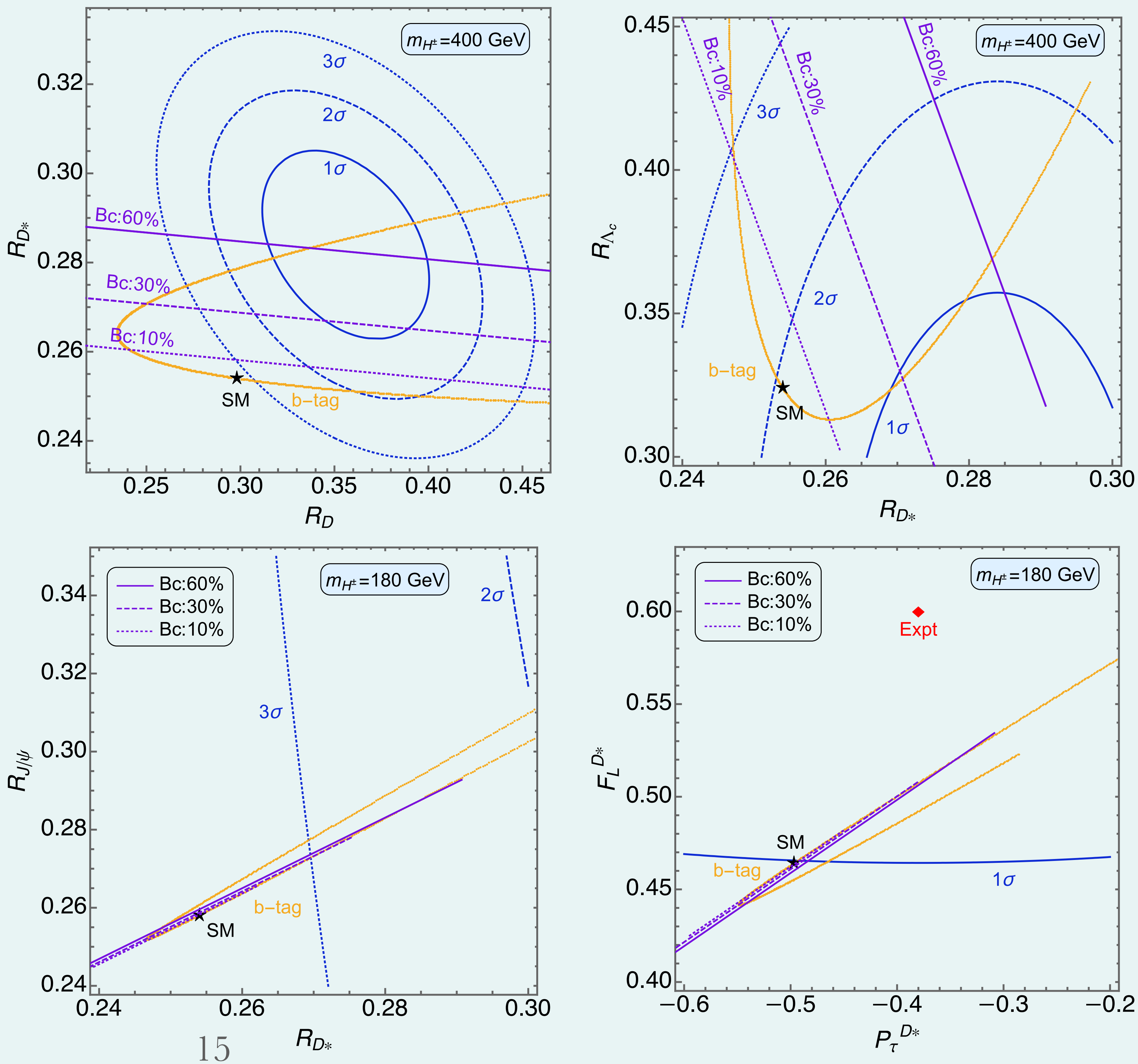
Purple: Constraints from $gc \to bH^{\pm} \to b\tau\nu$



Collider constraint on flavour observables

Preliminary

Orange: reach of HL-LHC in the b-tag category



Right-handed Neutrino scalar coupling!

Summary

- We look at the $b \to c\tau\nu$ transition anomalies in both the model independent and model dependent way.

- We fit the scalar couplings to the six $b \to c\tau\nu$ observables, assuming either real or complex, in 1D and 2D scenario.

- We show how these scalar coupling fits are in various 2D planes of flavour observables.

- A collider search in the $\tau\nu$ and $b\tau\nu$ final state is performed, where the b-tag channel gives stronger constraints on the charged Higgs production cross-section.

- Finally, we use these collider limits to estimate the reach of HL-LHC for interpreting these six anomalies.