New Physics in $B \to D^{(*)}\ell\nu$

KSETA Plenary workshop, Durbach

Monika Blanke, **Marta Moscati**, Ulrich Nierste | February 26, 2019

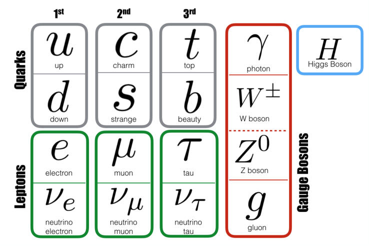
INSTITUTE FOR THEORETICAL PARTICLE PHYSICS - KARLSRUHE INSTITUTE OF TECHNOLOGY

Outline

1. Introduction
   - Lepton Flavour Universality
   - $B \to D^{(*)}\ell\nu$
2. New Physics in $B \to D^{(*)}\tau\nu$
   - Polarisation observables
   - Fit results
   - Predicted observables
3. Summary

Lepton Flavour Universality

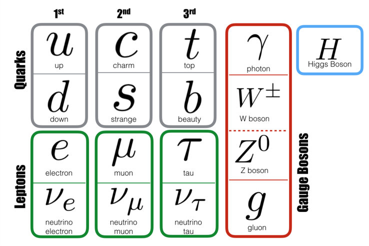
Standard Model



Leptons have the same charges $\Rightarrow$ **Lepton Flavour Universality**: same couplings with force carriers

Lepton Flavour Universality

Standard Model



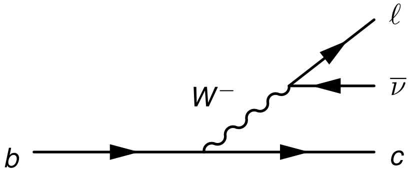
Leptons have the same charges $\Rightarrow$ **Lepton Flavour Universality**: same couplings with force carriers

New Physics – Beyond the Standard Model

Additional particles might couple differently to each lepton $\Rightarrow$ **Lepton Flavour Universality Violation**

$B \to D^{(*)}\ell\nu$ in the Standard Model

In the Standard Model, the decay $b \to c\ell\nu$ is mediated by the W boson



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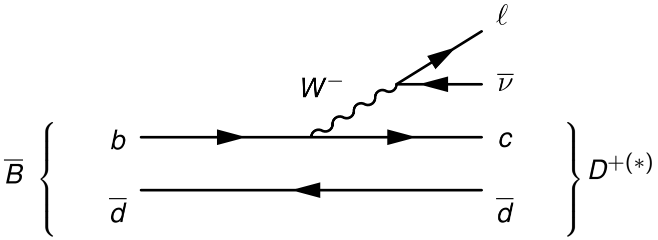
In the Standard Model, the decay $B \to D^{(*)}\ell\nu$ is mediated by the W boson



W couples in the same way to $\ell = e, \mu, \tau$ $\Rightarrow$ **Lepton Flavour Universality in $B \to D^{(*)}\ell\nu$**

$B \to D^{(*)}\ell\nu$ beyond the Standard Model

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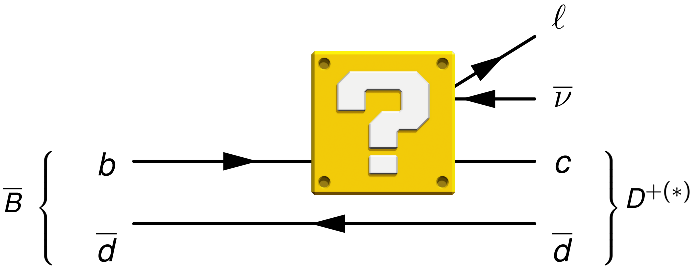
New physics particles can mediate the decay $B \to D^{(*)}\ell\nu$

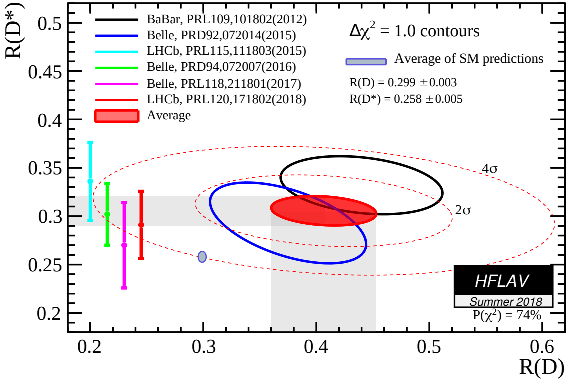


These can couple differently to $\ell = e, \mu, \tau$ $\Rightarrow$ **Lepton Flavour Universality Violation in $B \to D^{(*)}\ell\nu$**

$B \to D^{(*)}\ell\nu$ – Lepton flavour universality

We can test new physics by comparing final states with different leptons

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



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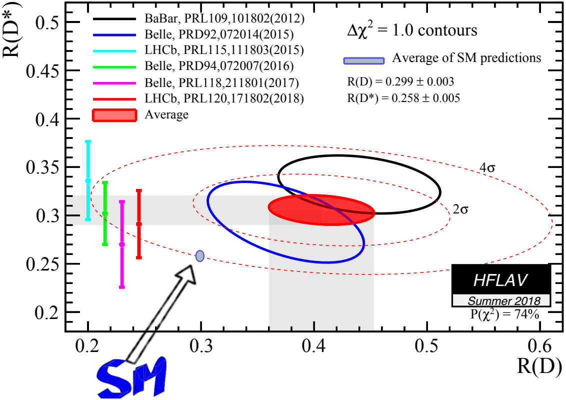

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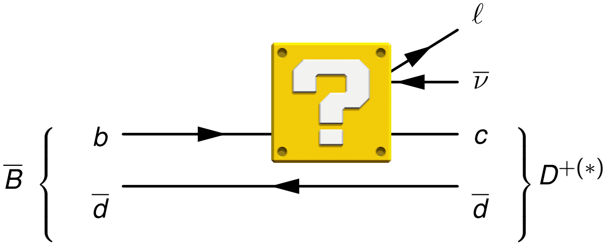


- 3.8σ tension: the large deviation hints to a tree-level contribution
- the particle mediating the decay is necessarily charged
- to solve the tension: $M_{\text{NP}} \sim$ TeV

$B \to D^{(*)}\ell\nu$ – Effective field theory

Energy scale of the process:

$$\sim m_b \sim 4.2\text{GeV}$$

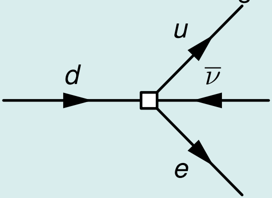
Mass of the particle mediating the decay:

$$M \gg m_b$$

$\Rightarrow$ Effective field theory (Four-fermion interaction)

Standard Model

The interaction is analogous to Fermi interaction in beta decays



$$V_{ud}\frac{4G_F}{\sqrt{2}}\left(\bar{u}\gamma^{\mu}P_L d\right)\left(\bar{e}\gamma_{\mu}P_L\nu\right)$$

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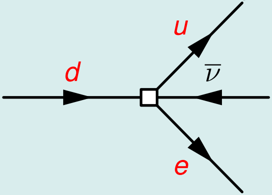

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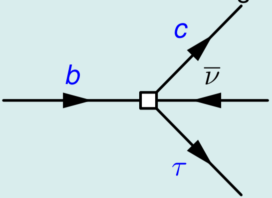
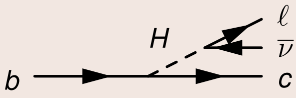
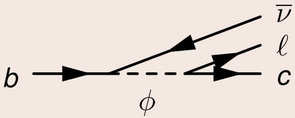
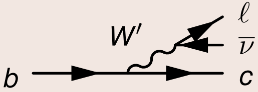
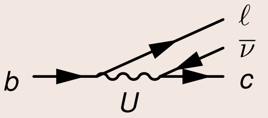


$$V_{cb}\frac{4G_F}{\sqrt{2}}\left(\bar{c}\gamma^\mu P_L b\right)\left(\bar{\tau}\gamma_\mu P_L \nu\right)$$

$B \to D^{(*)}\ell\nu$ – Effective field theory

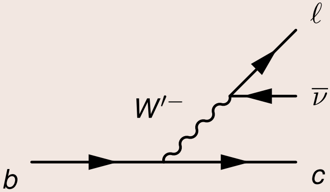
New Physics

	Color Singlet	Color triplet
Scalar	Charged Higgs H^- 	Scalar Leptoquark $\phi^{-1/3}$ 
Vector	Gauge boson W'^- 	Vector Leptoquark $U^{2/3}$ 

$B \to D^{(*)}\ell\nu$ – Effective field theory

New Physics

Different new particles involve different combinations of Dirac matrices



$$C_V^L\,(\bar{c}\gamma^\mu P_L b)\,(\bar{\tau}\gamma_\mu P_L \nu_\tau)$$

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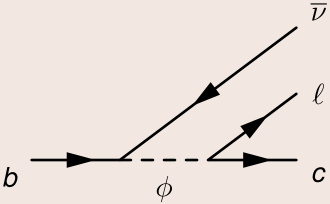

$$C_S^L\,(\bar{c}P_Lb)\,(\bar{\tau}P_L\nu_\tau)+C_V^L\,(\bar{c}\gamma^\mu P_Lb)\,(\bar{\tau}\gamma_\mu P_L\nu_\tau)+C_T\,(\bar{c}\sigma^{\mu\nu}P_Lb)\,(\bar{\tau}\sigma_{\mu\nu}P_L\nu_\tau)$$

$B \to D^{(*)}\ell\nu$ – angular observables

Different coefficients give a different angular distribution

$$C_V^L\,(\bar{c}\gamma^\mu P_L b)\,(\bar{\tau}\gamma_\mu P_L \nu_\tau) + C_S^R\,(\bar{c}P_R b)\,(\bar{\tau}P_L\nu_\tau) + C_S^L\,(\bar{c}P_L b)\,(\bar{\tau}P_L\nu_\tau) + C_T\,(\bar{c}\sigma^{\mu\nu}P_L b)\,(\bar{\tau}\sigma_{\mu\nu}P_L\nu_\tau)$$

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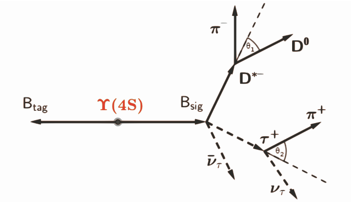

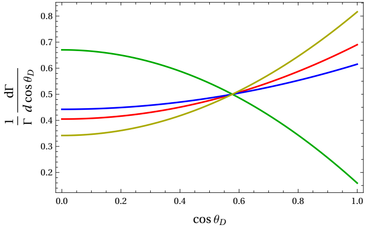

Experimental inputs: polarisation observables

$$P_\tau(D^*) = \frac{\Gamma(\tau^{\lambda=+1/2}) - \Gamma(\tau^{\lambda=-1/2})}{\Gamma(\tau^{\lambda=+1/2}) + \Gamma(\tau^{\lambda=-1/2})} \qquad F_L(D^*) = \frac{\Gamma(D^*_L)}{\Gamma(D^*)}$$

$B \to D^{(*)}\ell\nu$ – Fit

Fitting:

- R_D, R_{D^*}
- polarisations: $P_\tau(D^*), F_L(D^*)$

Assumptions:

- Only one particle
- Only coupling with τ

[Blanke, Crivellin, de Boer, Kitahara, M.M., Nierste, Nišandžić 2018]

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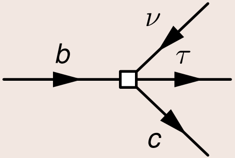
Decay rate of $B_c \to \tau\nu$

The same particles mediate the decay of the B_c meson



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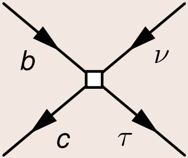


$\text{BR}(B_c \to \tau\nu)$ not measured

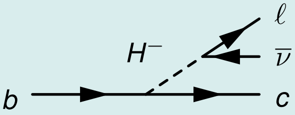
$\Downarrow$

using measured lifetime, set upper limit $\text{BR}(B_c \to \tau\nu) \leq 1$

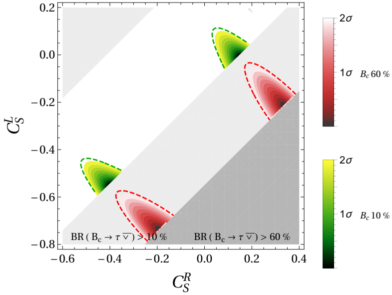
$B \to D^{(*)}\ell\nu$ – Fit

The preferred scenario changes depending on the limit on $\mathrm{BR}(B_c \to \tau\nu)$

Example: Charged Higgs H^-



$$C_S^R\,(\bar{c}P_R b)\,(\bar{\tau}P_L\nu_\tau) + C_S^L\,(\bar{c}P_L b)\,(\bar{\tau}P_L\nu_\tau)$$



$\mathrm{BR}(B_c \to \tau\nu)$	p-value (%)
$\leq 60\%$	68.5
$\leq 10\%$	0.6

[Blanke, Crivellin, de Boer, Kitahara, M.M., Nierste, Nišandžić 2018]

$B \to D^{(*)}\ell\nu$ – Predictions from the fit

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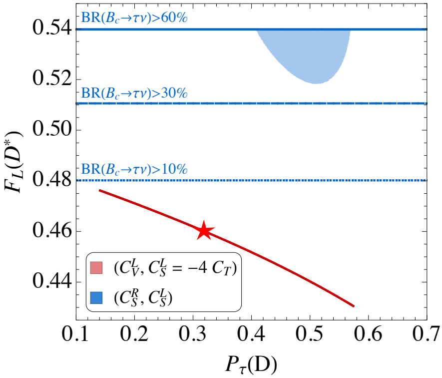
- Correlations between polarisation observables can distinguish between models



$\star$: Standard Model

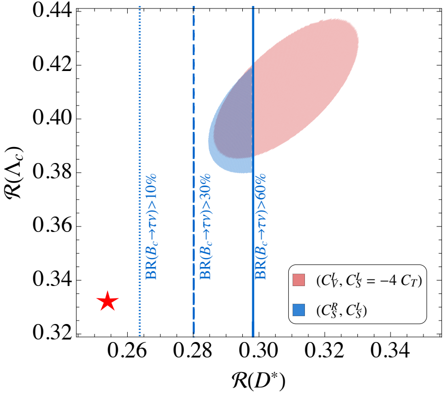
Red: scalar leptoquark ϕ

Blue: charged Higgs H^-

[Blanke, Crivellin, de Boer, Kitahara, M.M., Nierste, Nišandžić 2018]

$B \to D^{(*)}\ell\nu$ – Predictions from the fit

- Describing the current central values for $R_{D^{(*)}}$ enhances $\mathrm{BR}(\Lambda_b \to \Lambda_c\tau\nu)$, irrespective of which additional particle mediates the decay



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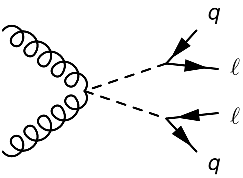
[Blanke, Crivellin, de Boer, Kitahara, M.M., Nierste, Nišandžić 2018]

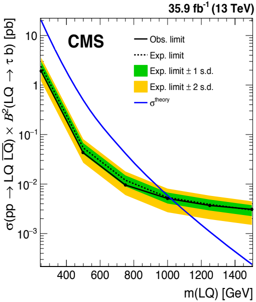
$\Lambda_b \to \Lambda_c\ell\nu$ will serve as a consistency check for the $R_{D^{(*)}}$ measurements

Collider searches

Collider data

- already severely constrain explanations involving right handed neutrinos
- put bounds on the mass of leptoquarks (pair production via QCD)





Summary

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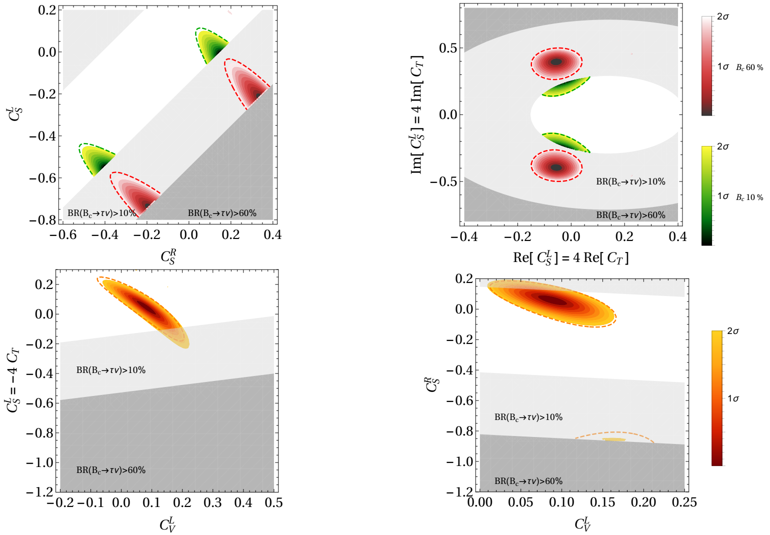
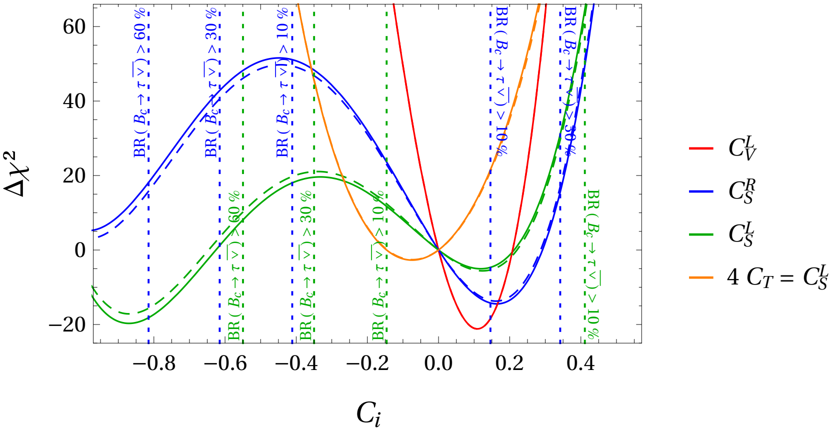
- The decays $B \to D^{(*)}\ell\nu$ seem to violate lepton flavour universality, which is a cornerstone of the weak interaction in the Standard Model
- Beyond the Standard Model exercise: check which additional particle exchange describes data in a better way
  - $B \to D^{(*)}\tau\nu$ polarisation observables discriminate between new physics models
  - $\Lambda_b \to \Lambda_c\tau\nu$ serves as a cross-check of the $B \to D^{(*)}\tau\nu$ measurements
  - the models solving the $B \to D^{(*)}\ell\nu$ tension can be confirmed or ruled out with CMS and ATLAS searches for new particles in the LHC run 3

Fits


BR(B_c→τν)>10%
BR(B_c→τν)>60%
C_S^L
C_S^R
Im[C_S^L] = 4 Im[C_T]
Re[C_S^L] = 4 Re[C_T]
2σ
1σ B_c 60 %
1σ B_c 10 %
$C_S^L = -4\,C_T$
C_V^L
C_S^R
C_V^L

Fits



$\Delta\chi^2$
C_i
60
40
20
0
−20
−0.8
−0.6
−0.4
−0.2
0.0
0.2
0.4
BR ($B_c \to \tau \overline{\nu}$) > 60 %
BR ($B_c \to \tau \overline{\nu}$) > 30 %
BR ($B_c \to \tau \overline{\nu}$) > 10 %
C_V^L
C_S^R
C_S^L
$4\ C_T = C_S^L$

$$\mathcal{R}(\Lambda_c) \equiv \frac{\mathrm{BR}(\Lambda_b \to \Lambda_c \tau \nu_\tau)}{\mathrm{BR}(\Lambda_b \to \Lambda_c \ell \nu_\ell)}$$

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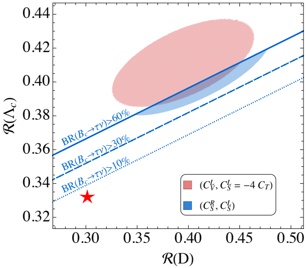

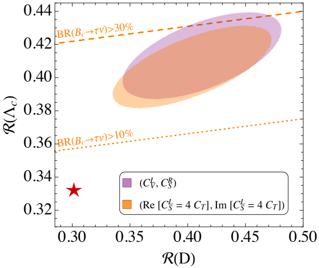

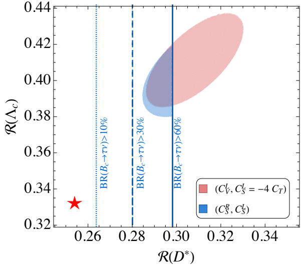

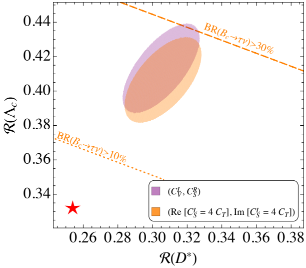

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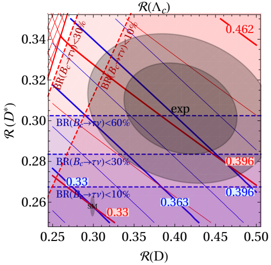

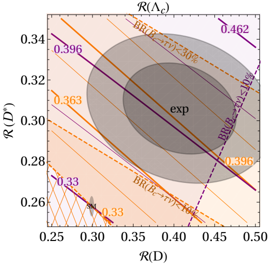

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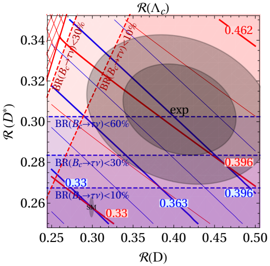
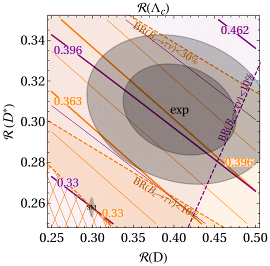
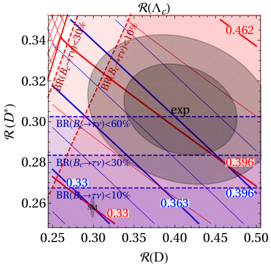
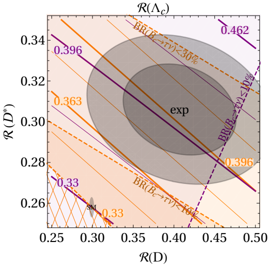




$$\frac{\mathcal{R}(\Lambda_c)}{\mathcal{R}_{\mathrm{SM}}(\Lambda_c)} = 0.262 \frac{\mathcal{R}(D)}{\mathcal{R}_{\mathrm{SM}}(D)} + 0.738 \frac{\mathcal{R}(D^*)}{\mathcal{R}^{\mathrm{SM}}(D^*)} + x$$

$$\mathcal{R}(\Lambda_c) \equiv \frac{\mathrm{BR}(\Lambda_b \to \Lambda_c \tau \nu_\tau)}{\mathrm{BR}(\Lambda_b \to \Lambda_c \ell \nu_\ell)}$$





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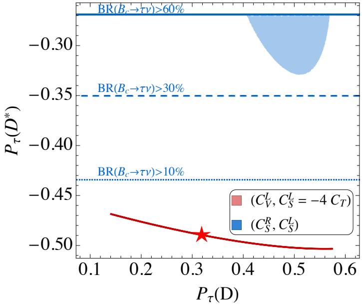
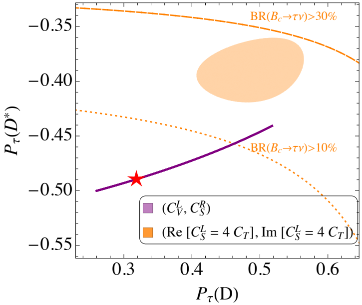
$$1.76|C_T|^2 - \mathrm{R}\left[(1+C_V^L)(0.32C_T^* + 0.03C_S^{L*})\right] - 0.0075|C_S^L|^2 - 0.033\mathrm{R}(C_S^L C_S^{R*})$$





⋆ : Standard Model

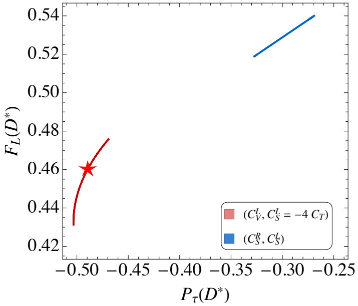
Red: scalar leptoquark ϕ

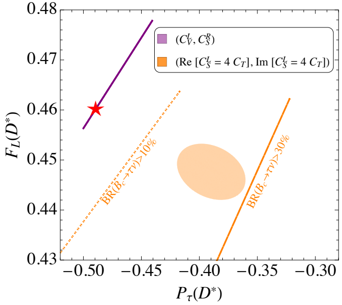
Blue: charged Higgs H^-

⋆ : Standard Model

Orange: vector leptoquark U

Purple: scalar leptoquark S_2





⋆ : Standard Model

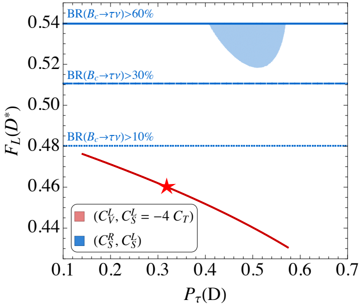
Red: scalar leptoquark ϕ

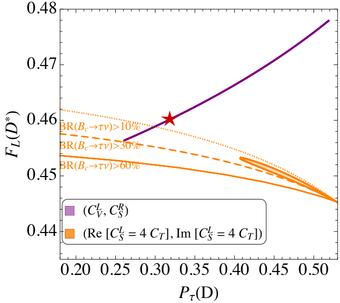
Blue: charged Higgs H^-

⋆ : Standard Model

Orange: vector leptoquark U

Purple: scalar leptoquark S_2





★ : Standard Model

Red: scalar leptoquark ϕ

Blue: charged Higgs H^-

★ : Standard Model

Orange: vector leptoquark U

Purple: scalar leptoquark S_2

More particles

	Color Singlet	Color triplet
Scalar	Charged Higgs H^- $(1,2)_{1/2}$ (C_S^R, C_S^L)	Scalar Leptoquark $\phi^{-1/3}$ $(3,1)_{-1/3}$ or $(3,2)_{7/6}$ $(C_V^L, C_S^L = -4C_T)$ or $C_S^L = 4C_T$
Vector	Gauge boson W'^- $(1,3)_0$ C_V^L	Vector Leptoquark $U^{2/3}$ $(3,1)_{2/3}$ (C_V^L, C_S^R)

B_c

$$\text{BR}(B_c \to \tau\nu) \propto \left| 1 + \epsilon_\text{L} + \frac{m_{B_c}^2}{m_\tau(m_b + m_c)}\epsilon_\text{P} \right|$$

10% limit

$$\text{BR}_\text{eff} = \text{BR}(B_u \to \tau\nu)\left(1 + \frac{f_c}{f_u}\frac{\text{BR}(B_c \to \tau\nu)}{\text{BR}(B_u \to \tau\nu)}\right)$$

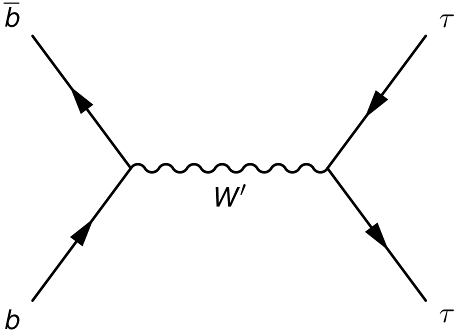
- $\frac{f_c}{f_u}$ @TEVATRON, LHC
- BR_eff @LEP
- $\text{BR}(B_u \to \tau\nu)$ @BABAR, BELLE

30% limit

$$\tau_{B_c}^\text{exp} = 0.507(8)\ \text{ps} \qquad \tau_{B_c}^\text{SM} = 0.52^{+0.18}_{-0.12}\ \text{ps}$$

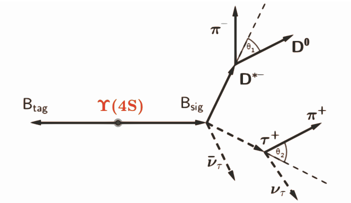
Collider searches

Above the Electro-Weak scale, we need to consider an EFT invariant under the SM group (SMEFT)
$SU(2)$ relates charged currents to neutral currents



$$\sqrt{s} \sim \frac{M}{x_b x_{\overline{b}}}$$

Polarisation observables



$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_1} = \frac{3}{4}[2F_L(D^*)\cos^2\theta_1 + (1 - F_L(D^*))\sin^2\theta_1]$$

$$\frac{d\Gamma}{d\cos\theta_2} = \frac{1}{2}(1 + \alpha P_\tau(D^*)\cos\theta_2)$$

$\alpha = 1.0$ for $\tau \to \pi\nu$ $\quad$ $\alpha = 0.45$ for $\tau \to \rho\nu$